Automated Driving System Demonstration (ADS) Grant Application | NOFO693JJ319NF00001

Safe Integration of Automated Vehicles into Work Zones | PKG 00247169

FINAL EVALUTION REPORT
for the
Safe Integration of Automated Vehicles into Work Zones Project

JANUARY 2025

Pennsylvania
Department of Transportation

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16. Abstract

This final report provides a comprehensive overview of the Safe Integration of Automated Vehicles (AVs) in Work Zones project, conducted under the USDOT Automated Driving Systems (ADS) Demonstration Grants Program. The Project aimed to explore and address the challenges of integrating AVs into work zone environments. The Project involved extensive research and development, simulation testing, and physical deployment, including closed test track and live on-road testing. The report details the Project's objectives, methodologies, key findings, and outcomes, as well as key technical challenges and solutions. Additionally, the report highlights the lessons learned throughout the Project, providing valuable insights for future AV deployments in work zones and similar dynamic environments. Finally, the report identifies recommendations, next steps, and future needs, including recommendations for improving simulation tools, enhancing data management systems, advancing Vehicle-to-Everything (V2X) communication technologies, and addressing the scalability and standardization of AV systems in general and particularly in work zones. This report serves as a key resource for guiding ongoing research and the continued integration of AVs into real-world transportation systems.

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Executive Summary

The **Safe Integration of Automated Vehicles (AVs) into Work Zones** project (the Project) was conducted under the United States Department of Transportation (USDOT) Automated Driving Systems (ADS) Demonstration Grants Program[1]. The goal was to advance the integration of AV technologies into dynamic and complex work zone environments, ensuring that these vehicles can navigate safely while improving efficiency and safety for all road users. This initiative, led by the Pennsylvania Department of Transportation (PennDOT), aimed to address the challenges posed by work zones, which often involve moving construction equipment, varying road conditions, and vulnerable workers.

The Project followed a phased approach, starting with the planning and systems engineering phase, followed by deployment phase including simulation, deployment in closed test track and live on-road work zones, and concluding with post-deployment evaluation. The core objectives of the Project were to enhance the operational safety of AVs in work zones, advance technology integration including Cellular Vehicle-to-Everything (C-V2X) communications, High Definition (HD) mapping, and perception systems, and contribute valuable data for future safety regulations and policy development. The Project team included Carnegie Mellon University (CMU), Deloitte consulting (Deloitte), Drive Engineering (Drive), HNTB Corporation (HNTB), Michael Baker International (MBI), PennDOT, the Pennsylvania State University (PSU), and the Pennsylvania Turnpike Commission (PTC).

The Project successfully demonstrated AV operation within simulated, closed test track, and real-world active work zone environments. Key technologies integrated into the Project included C-V2X communication, which allowed for real-time interaction between AVs and work zone objects, HD mapping that provided detailed road information for AVs, and AV perception assessments of Light Detection and Ranging (LiDAR) and cameras to detect a range of work zone objects and markings to ensure collision avoidance and lane-keeping. The integration of these technologies demonstrated that AVs could more safely navigate work zones, even in dynamic and rapidly changing conditions, when provided accurate, real-time information about the road environment.

A significant portion of the Project involved simulation testing, closed test track testing, and live on-road testing, which allowed the team to evaluate AV performance in diverse work zone scenarios. The data collected during these tests was processed, analyzed, and uploaded to a cloud-based Data Management System (DMS) for sharing with stakeholders. Despite several management and technical challenges such as procurement delays and technical difficulties

[1] https://www.transportation.gov/policy-initiatives/automated-vehicles/ads-demoaddenstration-grants

with simulation toolsets, the team made significant progress—ultimately demonstrating that AVs can safely navigate several work zone scenarios and improve safety for workers and other road users while collecting almost 10 terabytes (TBs) worth of data that can be used by other third parties and researchers. Refer to Table 1 below for Project highlights and major accomplishments.

The project successfully achieved its primary goal of integrating AVs into work zones, improving both safety and traffic flow. Through testing in simulated, closed test track and live work zone environments, the AVs demonstrated safe navigation with minimal impact on surrounding traffic—except for speed-related differences due to AV speed limit adherence. The integration of connectivity technologies, such as C-V2X, proved critical in improving AV performance, including lane-keeping and speed consistency. The project also evaluated the role of work zone-specific reflectivity and HD maps, which significantly enhanced object detection and AV recognition of work zone boundaries.

Although safety metrics showed inconclusive results from AV data, the project made strides in understanding how work zone-specific reflectivity and connectivity tools, like C-V2X, improved AV operational safety. HD maps were essential but showed limited benefit in terms of safety metrics improvement due to the limited benefits of ultra-high accuracy. While the use of C-V2X for lane- and speed-keeping was evident, future efforts will need to focus on improving simulation and data collection systems to enhance real-time operational safety in complex, dynamic work zones.

The project was able to meet its objective of evaluating the impacts of connectivity and safety enhancements on AV operation in work zones. It also successfully highlighted the challenges faced with existing HD mapping standards and data-sharing protocols. Key contributions include advancements in vehicle control, simulation testing, and sensor fusion technologies. Despite these significant achievements, further work is required to address gaps in data-sharing and simulation toolsets, particularly in terms of real-world applicability and standardization across AV manufacturers. The lessons learned throughout the Project provided valuable insights into the complexities of AV integration into work zones. Notable challenges included the interoperability of various software and hardware platforms, the difficulty in accurately simulating real-world conditions within traffic and AV simulations, and the market readiness of the smart devices. The Project also identified several areas for future research and development, including the need for improved simulation tools, enhanced data processing capabilities, and further investigation into Vehicle to everything (V2X) systems and messaging.

Future needs and next steps identified by the Project include expanding the use of open-source tools for data sharing, refining simulation environments to better replicate real-world conditions, and conducting further research into Artificial Intelligence (AI) trustworthiness—particularly addressing the issue of “hallucinations” or inaccurate environmental interpretations by AVs. Additionally, continued investment into AV technology by USDOT and greater coordination among stakeholders—including government agencies, industry experts, and academic institutions—is critical for continuing advancements in AV technology and ensuring the scalability of work zone solutions across the nation.

In conclusion, this Project has provided significant contributions to the field of AV integration in work zones, demonstrating the potential for these technologies to improve safety, mobility, and operational efficiency. The findings, challenges, and lessons learned from this Project will inform future AV deployments and provide a foundation for ongoing research and policy development in this critical area.

Table 1. Project Highlights and Major Accomplishments

Project Highlights & Major Accomplishments	
Scope	Completed the extremely complex and challenging Project on time (4 years) and within budget (approximately $8.4 M in federal funding).
	Addressed ADS grant focus areas and met the ADS demonstration requirement.
	Developed 10+ project management and systems engineering related Project documents.
	Considered 17 common work zone scenarios.
	Simulated 16 scenarios using co-sim platform including Connected and Autonomous Driving Research and Engineering (CADRE), CAR Learning to Act (CARLA), and Simulation of Urban Mobility (SUMO). Co-simulation videos are available online.[2]
	Conducted closed test track testing for 16 scenarios, all with same-day replicates, with before/after mapping and including day/night and inclement weather tests, and across a range of channelizer devices (two sizes of barrels, flat panels, and cones). Closed test track demonstration videos are available online.[3]
	Conducted live on-road testing for three scenarios (highway, signalized intersection, mobile work zones) across six site visits including replicates and day/night testing. Live on-road testing demonstration videos are available online.[4]
Outcome	Developed codebases for seven core safety performance metrics for Project evaluation and demonstrated a unifying time-space framework for calculation of these.
	Recorded 50+ AV video demonstrations, totaling more than 500 minutes of footage.
	Collected and shared more than 10+ TB of Simulation, AV, and mapping data.
	Conducted 30+ outreach meetings at various conferences and meetings to reach out to multiple stakeholders.
	Published 15+ accepted papers in various journals, conferences, and peer-reviewed venues.

[2] https://drive.google.com/drive/u/2/folders/1Hs3VjVJ12ByQH5BaiAk_casUxplG6hjM

[3] https://drive.google.com/drive/folders/1Hdj4F4wEL3e1xLTewAJIhhK1B23xcDs1?usp=drive_link

[4] https://drive.google.com/drive/folders/13s0iHB8g93SBkHAuCpv7FfYnzB2-C3Vz?usp=drive_link

Project Highlights & Major Accomplishments	
	Developed 10+ new capabilities for AV stack.
	Documented 30+ challenges encountered and their corresponding solutions.
	Identified 45+ lessons learned for future projects.
	Recommended 30 next steps for further research and project ideas.

1 Project Overview

1.1 Introduction

The **Safe Integration of AVs into Work Zones** (the Project) is part of the **USDOT ADS Demonstration Grants Program**, which was established to fund research and development efforts aimed at advancing the safe integration of AV technologies into the nation's transportation system. The Project specifically focused on addressing the unique challenges posed by work zones—which often involve temporary road conditions, work zone objects, moving construction equipment, and the presence of vulnerable road users (i.e., the workers). Through this initiative, PennDOT is continuing to advance its leadership in AV technology while working toward enhancing road safety and improving operational efficiency in dynamic, real-world environments.

The USDOT ADS Demonstration Grants Program has the following goals:

- **Safety:** Testing the safe integration of ADS into the nation's roadways.
- **Data for Safety Analysis and Rulemaking:** Gathering and sharing data.
- **Collaboration:** Collaborating with innovative state and local governments, universities, and private partners.

This document offers a comprehensive overview of the Project's purpose, objectives, key technologies, and methodologies, along with a summary of the Project's results and outcomes, challenges encountered, lessons learned throughout its lifecycle, and recommendations and future steps.

1.2 Project Purpose and Rationale

The Project was initiated to address the unique challenges that AVs face in work zones—areas with configurations unfamiliar to drivers, dynamic operational conditions, varying lighting conditions, conflicting pavement markings, displaced work zone objects, and presence of vulnerable road users. The Project's primary purpose was to demonstrate how AV technologies could be successfully deployed in these dynamic environments to enhance safety, improve traffic flow, and reduce the risk posed to construction workers and other road users.

Through the USDOT ADS Demonstration Grant, PennDOT received $8,409,444 in federal match to support the research, development, testing, and demonstration activities necessary for this initiative. The Project aimed to develop a comprehensive, scalable approach to safely integrate AVs into work zones—utilizing technologies such as C-V2X communication, HD mapping, and perception systems. This Project is aligned with PennDOT's leadership in AV deployment, as the department continues to drive advancements in AV technologies within the Commonwealth.

1.3 Project Scope

The Project focused on developing, testing, and demonstrating AV technologies that enable AVs to safely operate in complex, temporary environments such as dynamic road operations, pavement markings, road maintenance conditions—situations designated collectively hereafter as work zones. The Project followed a phased approach, ensuring that the necessary technology components were rigorously tested and validated at each stage.

The Project vision, mission, goals, and objectives include:

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

Mission: Reduce traffic fatalities and increase mobility for all road users in work zones through AVs.

Goals and objectives:

- Goal 1: Achieve safe navigation of AVs through a work zone.
    - Objective 1.1: Evaluate overall safety impacts of AVs.
    - Objective 1.2: Evaluate AV performance in work zones through work zone connectivity.
    - Objective 1.3: Evaluate the perception of work zones by AV sensors.
    - Objective 1.4: Evaluate the impact of providing HD mapping.
    - Objective 1.5: Evaluate the applicability and use of existing map standards for work zone data sharing.
- Goal 2: Ensure data gathering and sharing.
    - Objective 2.1: Identify consistency between similar measurements across data sources.
    - Objective 2.2: Identify consistency between similar measurements across data collection modalities.
    - Objective 2.3: Identify differences and similarities in data needs across data users.
- Goal 3: Coordinate with varied stakeholders.
    - Objective 3.1: Identify stakeholders and their contributions within Stages of the Project.
    - Objective 3.2: Engage stakeholders in Project activities.

1.4 Focus Areas

The Project concentrated on several key areas in alignment with ADS Demonstration Grant focus areas:

- **Significant public benefits:** Improved safety in work zones by eliminating distracted driving using AVs and other technologies.

- **Addressing market failure and other compelling public needs:** Enabled safe AV operation in work zones with complex road conditions.
- **Economic vitality:** Supported domestic AV tech development and created local jobs through multiple internships, assistantships, and hourly work.
- **Complexity of technology:** Integrated Level 4 automation and advanced sensor systems for safe navigation and simulation using co-sim platform.
- **Diversity of the Project:** Tested in urban, suburban, and rural environments.
- **Transportation-challenged populations:** Improved AV operations to benefit all populations.
- **Prototypes:** Utilized operational AV prototypes while meeting or exceeding testing safety standards.

1.5 Demonstration Requirements

The Project complied with all ADS Demonstration requirements as described below:

- **Research & Development of automation and ADS technology:** The Project advanced AV technology for work zones—focusing on connectivity, various elements of perception, and standardized HD mapping—allowing AVs to share uniform road maps and receive real-time updates.
- **Physical demonstration:** The Project included simulation, closed test track testing (17 work zone configurations), and live on-road testing in freeway, urban, and rural settings.
- **Gathering and sharing of data with USDOT:** Data collected from PSU's mapping vehicle and CMU's AV were shared with USDOT via a secure cloud based DMS, ensuring public access and compliance with data privacy rules.
- **Allow users with varied abilities:** Improved AV operations to benefit all users with varied abilities.
- **Scalability of demonstration:** The Project's methodologies and technologies are scalable for various work zone scenarios nationwide.
- **Outreach task:** The Project team maintained a public webpage, conducted webinars, developed open-source software, presented at conferences, and published articles to share findings.

1.6 Key Technologies

The Project employed several critical technologies to address the challenges associated with integrating AVs into work zones:

1. **Integration of simulation-based analysis with real-world data:** The Project integrated simulation-based analysis of traffic impacts with simulated AV data. This combination allowed for a comprehensive understanding of AV performance in work zones—

including the ability to assess traffic flow, safety, and operational efficiency under various conditions.

2. **Connectivity between AVs and work zone objects:** This Project involved the use of connectivity equipment, including 5.9 GHz C-V2X radios, to enable real-time communication between AVs and work zone objects—such as roadside units (RSUs), construction vehicles, and smart roadside devices. This connectivity was essential for ensuring situational awareness for AVs.
3. **High-Definition work zone mapping:** The Project utilized a mapping van equipped with Differential Global Positioning Systems (DGPS), Light Detection and Ranging (LiDAR), and cameras, HD maps were developed to provide detailed, up-to-date information to AVs. These maps were crucial for enabling AVs to navigate complex and frequently changing work zone environments with high accuracy.
4. **AV perception:** The Project explored the impacts of reflectivity from various work zone objects (worker vests, road tape, different types of channelizers, and different paint types) on AV operations.

In addition, a cloud-based DMS was used to collect, process, and store data from AVs, instrumented work zone infrastructure, and mapping-vehicle sensors, facilitating data sharing with relevant stakeholders.

1.7 Document Structure

This document provides a detailed account of the Project, its methodology, key technologies, and outcomes. It is structured as follows:

- **Section 2: Methodology and Approach:** Provides a detailed description of the methodology and approach used throughout the Project. It covers both the technical methodology employed to develop and implement the AV system in work zones, as well as the management approach that guided the Project's execution.
- **Section 3: Project Results and Findings:** Summarizes the key findings, results, and conclusions of the Project—highlighting the most significant achievements and insights.
- **Section 4: Challenges, Lessons Learned, and Recommendations:** Discusses the major management and technical challenges encountered and the solutions implemented to address them. In addition, Section 4 shares valuable lessons learned and offers recommendations for future AV deployments in work zones and other dynamic environments and suggests next steps to continue advancing the integration of AV technologies.

1.8 Major Changes to the Project

Several changes occurred during the execution of the Project:

1. **Dropped PPG Industries as a team member:** PPG Industries, who was originally expected to provide special coatings for work zone objects, was excluded due to

contracting challenges. The original scope of the Project included testing if PPG's innovative coatings could improve AV navigation in work zones. Once the specialized coatings were no longer part of the Project, the Project team modified this element of the scope of the Project to test if the reflectivity from different work zone objects had an impact on AV perception.

2. **Adjusted scenarios:** A few of the work zone scenarios initially considered for testing were excluded. Nearly all excluded scenarios were found to be functional replicates and/or overlapping combinations of scenarios that were chosen for testing—offering limited added value to the overall understanding of AV behavior in work zones. The one exception was a scenario that required stop-controlled, two-way access of a single lane. This scenario required the AV to "look" further than it was capable and to negotiate shared lane usage with a human driver even if the human-driven vehicle is stopped, which was technically infeasible. The resulting adjustments allowed the Project to focus on the most impactful and unique scenarios.
3. **Shifted from Dedicated Short-Range Communications (DSRC) to C-V2X technology:** The Project originally planned to use DSRC for communication between vehicles and infrastructure (V2I). However, as the Project progressed, the team transitioned to 5.9 GHz C-V2X technology. This shift was made to improve scalability, reliability, and futureproofing of the V2X communication system by aligning with the current standards in the United States.
4. **Removed safety worker vest implementation:** The planned implementation of safety worker vests equipped with real-time location data was not executed due to the technology not being commercially available during the Project's timeline. Research versions were unavailable as they were in use in other projects.
5. **Delivered HD Mapping through C-V2X:** The delivery of HD maps to the AV was originally planned for DSRC technology, but this was phased into C-V2X during the Project. Map sharing was tested using both C-V2X technologies as well as sharing the HD map with the AV prior to the encounter of the AV within the work zone. This allowed evaluation of whether C-V2X latency, data formats, etc., affected AV performance.

2 Methodology and Approach

Due to the technical and complex nature of the demonstration Project, a combination of project management and systems engineering approach was used to deliver the Project. The project management aspect of the Project dealt with describing all activities, including technical activities, to be integrated and controlled during the life of the Project. The Project team used "A Guide to Project Management Body of Knowledge (PMBOK® Guide) – Sixth Edition" as a fundamental resource for effective project management as applicable on a scale commensurate with the Project scope. The Systems Engineering (SE) aspect of the Project defined the processes and methodologies used on the Project and the relationship of SE activities to other Project activities. The Project team used "Guide to the Systems Engineering Body of Knowledge (SEBoK)" as a fundamental resource for SE management as applicable on a scale commensurate with the Project scope.

2.1 Management Approach

The management approach for the Project included two key areas—project management structure (detailing team roles and organization) and project management approach (outlining methodologies for execution and control).

2.1.1 Project Management Structure

The project management structure for the Project shown in **Figure 1** was designed to effectively manage tasks and ensure successful execution. The structure included the core team, Project team, deployment partners, technical advisors, and community of support.

The core team consisted of key management from PennDOT, PTC, PSU, CMU, and HNTB Corporation. The Core Team held weekly meetings to monitor and control the scope, schedule, budget, quality, and risks associated with the Project. Also, the core team provided technical direction for Project execution.

The Project team's key responsibilities of the team members are as identified below:

- **CMU:** Led simulation and testing of automated systems and perception technologies for AVs.
- **Drive Engineering:** Assisted with developing the *Testing Plan* and *Coordination, Communication and Outreach Plan*. Provided general project guidance, deliverables review, and feedback.

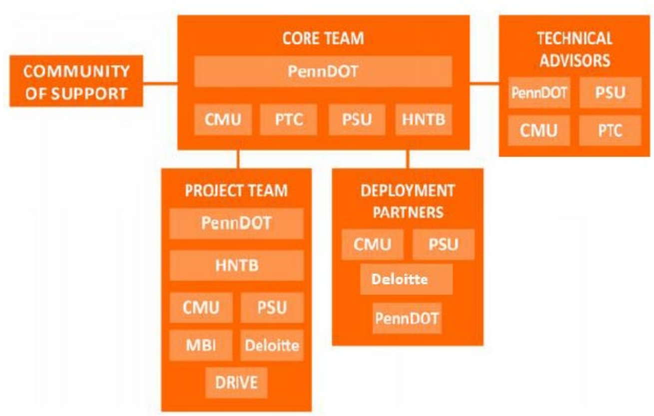

Figure 1. Project Management Structure

- **Deloitte:** Assisted with developing and implementing the *Data Management Plan* (DMP) and developed the DMS.
- **HNTB:** Provided overall project management and SE support, project evaluation support, and developed the *Final Evaluation Report*.
- **Michael Baker International:** Assisted with developing the *Operations and Maintenance* (O&M) *Plan* and provided general project guidance, deliverables review, and feedback.
- **PSU:** Led traffic simulations, HD mapping, and the setup of connected infrastructure for AVs. Assisted with developing the *Project Evaluation Plan* (PEP) and developing evaluation results.
- **PTC:** Provided overall support and general project guidance, deliverables review, and feedback.

Deployment Partners such as CMU, PSU, and PennDOT played critical roles in simulation, closed track testing, live on-road testing, and data management deployment, while **technical advisors** from Deloitte, PennDOT, PSU, and CMU provided ongoing technical guidance.

Additionally, the **Community of Support**, consisting of various stakeholders, was kept informed through regular outreach efforts, ensuring strong collaboration throughout the Project lifecycle. They also provided feedback on the Project. Federal Highway Administration (FHWA), as a funding partner, was involved in weekly meetings to be kept informed of the Project, to review draft and final deliverables, to review quarterly and annual financials, to process invoices, and to provide project funding.

2.1.2 Project Management Approach

The *Project Management Plan* (PMP) governed the execution of the Project, ensuring systematic management of all Project components—including integration, scope, schedule, cost, quality, and stakeholder communication. The PMP detailed processes for initiating, planning, executing, monitoring, controlling, and closing for each aspect.

A kick-off meeting with USDOT and the Project team was held within three weeks of the award—outlining the Project background, team roles, critical milestones, and risks. The Project management team, led by PennDOT and supported by HNTB, coordinated activities through weekly meetings to monitor scope, schedule, budget, and quality.

The Scope Management and Schedule Management components ensured clear definitions of tasks, dependencies, and timelines. **Table 2** below shows the overall schedule for the Project.

Table 2. Project Schedule

Phase	Timeline	Key Activities
Phase I: Project Planning and Systems Engineering	2021 - 2022	Development of *Project Management Plan* and Systems Engineering documentation Initial simulation work and preparation for system design and testing
Phase II: Deployment	2022 - 2024	Deployment of DMS Simulation-based testing for various work zone scenarios Closed test track testing at PSU closed test track Real-world live on-road testing in actual PennDOT work zones
Phase III: Post-Deployment	2023-2024	Update of Systems Engineering documentation Final system evaluation and analysis of real-world testing data Final Project reporting including challenges and solutions, lessons learned, and recommendations

A Cost Management plan was established with detailed budgeting, and Quality Management was enforced through a dedicated quality assurance/quality check (QA/QC) team.

The weekly meetings, along with regular quarterly progress reports and annual budget reviews, supported transparent communication and reporting. Risk Management strategies were in place to mitigate Project uncertainties, while Procurement Management followed established PennDOT processes.

Each task had clear deliverables, including PMP updates, schedules, safety plans, and invoices, which were reviewed by USDOT.

2.2 Technical Approach

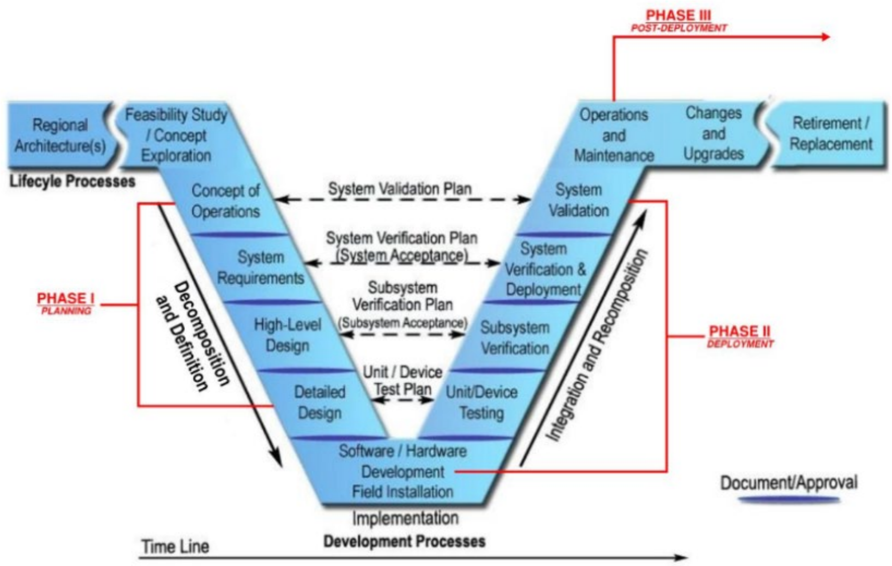

Figure 2. Systems Engineering "V" Diagram

The Project team used a three-phase approach for the demonstration of AVs in work zones—planning, deployment, and post-deployment. **Figure 2** shows the Systems Engineering "V" diagram, recommended by USDOT, and adopted for this Project along with the proposed Project phases. **Phase I (Planning)** included the planning phase from concept of operations through detailed design. **Phase II (Deployment)** included the deployment and testing phase. **Phase III (Post-Deployment)** included the evaluation phase.

Several project management and SE-related deliverables were completed as part of the Project. For each of these deliverables, a draft version was developed with input from the core team and technical advisors, then submitted to USDOT for their review and comments. Once comments were received, they were addressed, and a final version of the deliverable was submitted to USDOT.

For all the SE-related documents, the Project team leveraged the FHWA recommended document template[5].

[5] https://www.fhwa.dot.gov/cadiv/segb/views/deliverable/index.cfm

2.2.1 Phase I – Planning

In Phase I (the Planning phase) several key tasks were performed to lay the foundation for the Project. These tasks included detailed planning and the development of necessary documents to guide the Project’s execution:

1. **Task 1.1: Project Management**
   Project management activities focused on the overall structure, planning, and deliverables for the Project. The *Safety Management Plan* was integrated into this task to ensure comprehensive safety management.
2. **Task 1.2: Risk Management/Mitigation Plan**
   A *Risk Management Plan* (RMP) was developed as part of the PMP to identify potential risks and establish mitigation strategies, ensuring the Project proceeded without unforeseen disruptions.
3. **Task 1.3: Systems Engineering Management Plan (SEMP)**
   The Project adopted a SEMP that outlined the technical plans and systems engineering processes and activities required to develop, test, and deploy the Project.
4. **Task 1.4: Concept of Operations (ConOps)**
   The team developed a ConOps to outline user needs, stakeholder roles, and operational scenarios—ensuring the AV system's compatibility with work zone environments. Refer to Appendix C for the high-level graphic depicting the Concept of Operations.
5. **Task 1.5: System Requirements and Testing Plan**
   The team created *System Requirements Specifications* based on ConOps inputs and developed a *Testing Plan* to ensure AV systems met all requirements with validation through stakeholder feedback.
6. **Task 1.6: System Architecture and Standards Plan (SASP)**
   A *SASP* was developed, employing USDOT’s Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) framework and defining technical standards for system components.
7. **Task 1.7: Deployment Plan**
   A *Deployment Plan* was crafted to define testing protocols for simulation, closed test track, and live on-road testing, as well as identifying deployment locations, schedules, and necessary equipment.
8. **Task 1.8: O&M Plan**
   An *O&M Plan* was created to identify the necessary procedures for maintaining systems, ensuring seamless operation during deployment and testing.
9. **Task 1.9: Data Privacy and DMP**
   A DMP was developed to ensure data was managed appropriately, including data privacy, and outlined the process for public data sharing after the Project concluded.
10. **Task 1.10: PEP**
    A PEP focused on performance metrics, outlining methods for evaluating the Project’s success based on quantitative and qualitative data.

11. **Task 1.11: Human Use Approval**
    Human drivers were involved in testing, and Institutional Review Board (IRB) exemptions were obtained to comply with ethical and regulatory standards for human research.
12. **Task 1.12: Coordination, Communication, and Outreach**
    A *Coordination, Communication and Outreach Plan* was developed and implemented, which included creating a Project webpage, hosting webinars, attending, presenting at conferences, and publishing articles to share progress, findings, and lessons learned with stakeholders and the public.

Each of the tasks resulted in specific deliverables, which have been documented and are available as reference documents for further review. An initial set of the deliverables was developed early in the Planning phase. As the research continued, a final set of the deliverables was developed towards the end of the Project to capture the research progress and updates.

2.2.2 Phase II – Deployment

Phase II focused on deploying and testing the AV systems in multiple work zone scenarios. The deployment approach included simulation, closed test track testing, and live on-road testing in varied environments as shown in **Figure 3**. The team deployed and tested the AVs in the most commonly occurring work zone configurations based on the discussions with PennDOT Work Zone maintenance crews. A total of 17 work zone scenarios, each detailed in **Appendix B**, were considered for the Project. Within each scenario, there were multiple testing variants including:

- AV operations with and without connectivity using C-V2X to update AV map information.
- AV operations during daytime and nighttime.
- AV operations with variations in work zones that affect perception—particularly varying the types of channelizers, varying types of work zone objects with varying reflectivity and/or varying the use of flashing lights on channelizers.

Not every variant was tested in every scenario due to situational conditions, similarity of results, and the scenario layouts. For example, some scenarios did not use channelizers so variations in channelizer perception could not be tested. Similarly, for on-road or closed test track tests, some

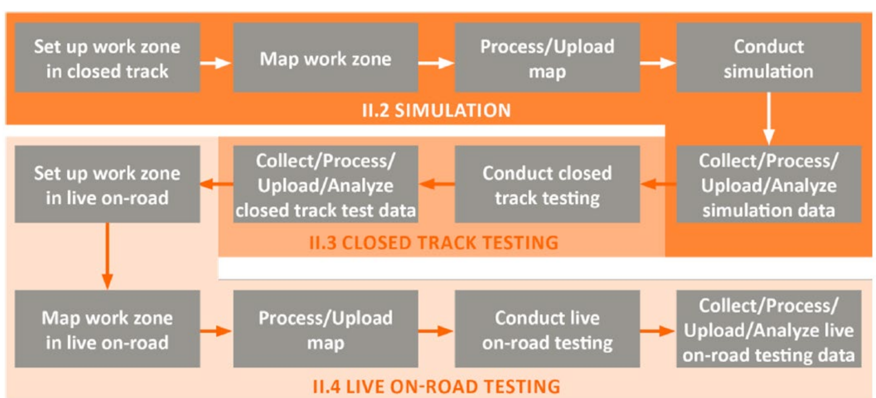

Figure 3: Project Deployment/Testing Approach

tests were performed only in daytime or nighttime due to their similarity to previously conducted tests.

To minimize the number of permutations and combinations, simulations were planned for all 17 work zone scenarios. However, upon further analysis, it was determined that some of these scenarios were highly similar in both perception and behavior requirements of the AV—offering limited additional value in terms of evaluating AV behavior in work zones. As a result, these few redundant scenarios were excluded, allowing the Project to focus on the most impactful and unique scenarios. Following the simulation, closed test track testing was conducted for the most promising work zone scenarios based on simulation results. Finally, live on-road testing was conducted for three work zone scenarios. The tasks conducted as part of Phase II are listed below:

1. **Task 2.1: DMS**
   The existing PennDOT's DMS (Azure cloud platform) was developed by Deloitte to manage and store collected data. The data was stored securely and made available for analysis and sharing.
2. **Task 2.2: Simulation**
   Simulation tasks involved setting up virtual work zones at a simulated version of the team's closed test track facility, simulating AV operations in simulated traffic, and introducing different object types (channelizers, equipment, etc.) to test the AV's sensor perception.
3. **Task 2.3: Closed Test Track Testing**
   After simulation, AV testing was conducted at a closed test track facility using the same work zone setups. AVs navigated the work zones with and without real-time C-V2X-provided map updates, under different perception configurations of channelizers, lighting conditions, road markings (paint and road tape), and weather, and with and without previously recorded maps of the environment. HD map data was also collected from a mapping vehicle including data from cameras, LiDAR, and connectivity systems. For work zone devices such as signage and channelizers, all devices were new and thus in pristine condition, and site configurations were very carefully deployed to exactly match state and/or federal standards. The closed test track testing was conducted at the Penn State Larson Transportation Institute test track in State College, PA.
4. **Task 2.4: Live On-Road Testing**
   Live on-road testing was performed in three selected work zones representing long-term, short-term, and mobile work zones. Other than preparation of sites with C-V2X connectivity equipment, each site was tested without changing the sites in any way different than used by the public, and all sites were in public use during testing. Thus, the perception conditions for on-road testing necessarily included in-use and older channelizers, aged signage, and typical placement variations and errors in channelizers. Video data from these tests were collected, processed, and uploaded to the DMS and

HD map information for each site is included within the Project's data summary. The work zones were located at the following sites:

- **Site 1, Interstate I-376 near Pittsburgh, PA:** This is a three-lane highway with one or more long-term lane closures on both sides of the highway.
- **Site 2, Traffic signal controlled single lane roadway in Normalville, PA:** This is an undivided two-lane state road that was reduced to one-lane that shared use in both directions in short-term.
- **Site 3, Route 51 in Aliquippa, PA:** This is mobile work zone with line painting operations along a divided highway with two-lanes in both directions with line striping occurring in both directions and in both lanes.

Figure 4 below identifies the locations of these three sites.

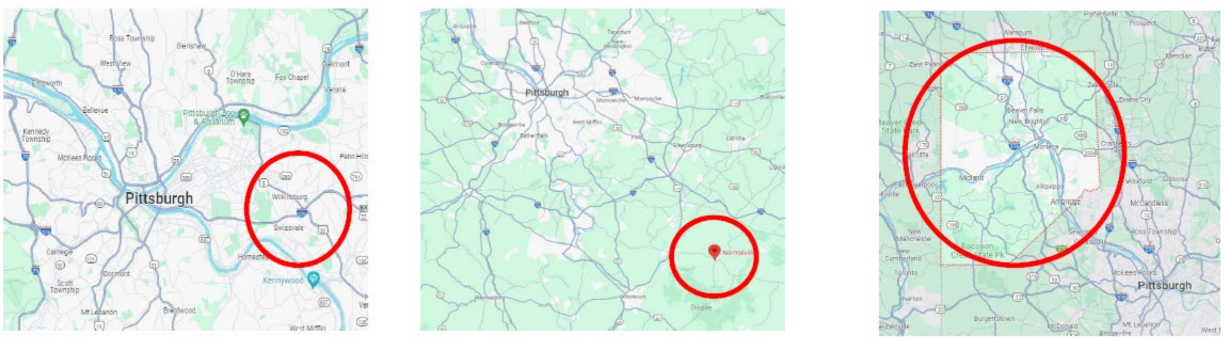

Figure 4. Locations of Live On-Live Road Testing

This deployment phase allowed for the comprehensive testing of AV behavior in various work zone environments, advancing the Project's goal of demonstrating the safe operation of AVs in these dynamic and challenging settings.

2.2.3 Phase III – Post-Deployment

In Phase III, after the completion of deployment and testing, the Project entered the evaluation phase. The Project was assessed based on the PEP, and the *Final Evaluation Report* was prepared to document the findings and lessons learned from both the planning and deployment phases. In addition, a final *Project Metrics Report* was also developed to present the Project performance metrics analyses and results in detail.

3 Project Results and Findings

This section identifies key results and findings from the Project. The results and findings presented in this section are based on the comprehensive evaluation conducted throughout the Project in alignment with the PEP. The purpose of this evaluation was to assess the effectiveness of the technologies and strategies deployed, measure the progress against the defined goals and objectives, and derive key insights for future AV applications in work zones.

This section provides an overview of the key outcomes and findings from the various testing phases—including simulations, closed test track testing, and live on-road deployments—and key Project accomplishments. The evaluation process focused on key metrics such as safety performance, operational efficiency, technology effectiveness, and stakeholder collaboration. By integrating data from multiple sources—such as AV systems, infrastructure, and sensors—the Project team was able to evaluate the real-world viability of AVs in work zones which is a critical aspect for enhancing transportation safety and efficiency. Additionally, new capabilities were developed as part of the Project, which are also identified within this report.

Due to on-vehicle processing and power limitations, some in-stack AV data could not be collected while the vehicle was in motion, as this would disrupt AV behavior and thereby change Project outcomes. To address this, videos were produced during the navigation process that show vehicle behaviors from “over the shoulder” driver’s view. As a result, the project team was unable to collect some of the AV data needed for evaluating the performance metrics—hence, some of the results were inconclusive. In addition, since the PPG team was unable to provide special coatings, the Project team measured the impacts of reflectivity of the work zone objects (instead of special coatings). Also, note that the findings presented here are high-level outcomes and results. For a more detailed analysis, results, and outcomes, refer to the *Project Metrics Report*. Metrics were individually defined for each goal, objective, and hypothesis to ensure that specific criteria were addressed to evaluate the Project’s success comprehensively.

3.1 Project Results and Findings

This subsection presents the primary results of the Project as shown in Table 3, emphasizing the tangible outcomes achieved in alignment with the initial goals, objectives, and key hypothesis evaluation questions.

Table 3. Project Results and Findings

Description	Key Hypothesis Evaluation Questions	Results
Goal 1. Achieve safe navigation of AVs through a work zone.	Was AV safety in work zones improved, without impacting surrounding traffic flow?	The Project's AV testing in simulated, closed test track, and on-road work zones demonstrated that safe and autonomous navigation is feasible in a wide variety of work zones. This was confirmed across 16 of 17 closed test track scenarios. One scenario, which requires very reliable long-range perception, was recognized as infeasible with current AV sensing technologies. In early deployments, there were scenarios setup incorrectly at first within closed test track and there were occasional near-misses of objects when lane widths were incorrectly setup at less than 9.5 feet. These near-misses were reduced once the correct lane were setup with correct lane widths. Successful AV operation was observed in both day and night tests and across a range of weather conditions (dry versus rain weather, dry versus wet road surfaces) during the closed test track tests and the three live on-road sites. Impacts to surrounding traffic were only noted due to speed—the AV was programmed to maintain speed limits, whereas human-driven vehicles generally did not.
Objective 1.1 Evaluate overall safety impacts of AVs.	Have safety metrics improved? Is traffic flow improved or unchanged? Has AV recognition of work zone boundaries improved?	Many construction zone workers die every year due to inattentive drivers who speed through work zones and crash into work zones. AVs on the other hand are always sensing their environment, detecting and reacting to the presence of work zones by slowing down and changing lanes as necessary. With C-V2X support, work zone information can be communicated to AVs with enough time for them to safely, smoothly, and comfortably navigate work zones. It remains inconclusive whether safety metrics improved based on the available AV data. To address this, the Project team created a toolbox to calculate AV surrogate safety metrics (SSMs) from vehicle data, which has been shared in open-source software. For traffic flow, the SSMs did not show statistically significant differences in AV behavior in simulations both with and

Description	Key Hypothesis Evaluation Questions	Results
		without surrounding traffic, relative to human drivers. In live on-road testing, the primary observed impact on traffic flow was that the AV was programmed to navigate work zones using the posted speed limit, which was observed in videos and in C-V2X data analysis to be slower than human-driven vehicles. The use of C-V2X particularly improved the recognition of work zone boundaries but required customized packets. Refer to Appendix D on this topic for more information.
Objective 1.2 Evaluate AV performance in work zones through work zone connectivity.	Is connectivity robust enough for data sharing in a work zone? Is connectivity improving safety metrics? Are the data identified from HD maps suited for work zone map sharing via communication?	Yes, connectivity was robust enough for data sharing from RSUs to the AV's Onboard Units (OBU). The team found that C-V2X connectivity from just one RSU near an entry point was sufficient to transfer work zone map updates to the AV, if the RSU was located before the start of the work zone with at least 200 meters or more of coverage. Within all the tested live on-road sites, the nominal C-V2X ranges, which in line-of-sight are approximately 1 km from the RSU, were limited by blockages in the environment to working ranges of typically 200 to 400 meters. C-V2X connectivity improved the consistency of AV lane- and speed-keeping behaviors as seen in the video recordings. It was inconclusive, from the available AV data, whether safety metrics improved in field operations or closed test track scenarios. The data within the HD maps consisting of lane boundaries, work zone boundaries, and object locations was suited for sharing via C-V2X communication but only if custom packets were used. Refer to Appendix D on this topic for more information.
Objective 1.3 Evaluate the impact of increased visibility.	Do work zone specific coatings improve object detection by the AV? Do work zone specific coatings change human vehicle metrics? Does the AV recognition of work zone boundaries improve with coatings? Are work zone objects better recognized with coatings?	Yes, work zone reflective coatings significantly improved object detection. The primary finding was that work zone objects with reflective markings were highly visible to AV LiDAR sensors. Road markings specific to work zones, such as road tapes, were also highly visible. The coatings tested in the field were those nominally sold and used, so no change in human metrics was measured. If not informed via C-V2X, the AV recognition of work zone boundaries was primarily associated with reflectivity of work zone objects. However, in one test configuration (at the closed test track), paint crews accidentally omitted

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Description	Key Hypothesis Evaluation Questions	Results
		glass beads in the paint mix. In visible images and to the human eye in daytime, it was not possible for humans to discern this error. However, the LiDAR had a substantial degradation in the intensity of return and in the effective marker detection range of the lane marking.
Objective 1.4 Evaluate the impact of providing HD Mapping.	Does the use of HD maps improve the AV safety metrics? Does the use of HD maps reduce AV data errors? Does increasing HD map resolution improve AV performance? Is the work zone static enough that HD mapping assists the AV?	It was inconclusive, based on available AV data, whether HD maps improved safety metrics or reduced data errors. However, maps were required by the AV stack—not only to operate in work zones but also nominally. In one live on-road site, the AV performed well without maps (due to time limitations of creating an HD map). The CMU AV only needs lane-level maps but not fine-grained HD maps. Map resolution did not need to be accurate in position resolution but did need to be accurate in lane assignments and availability and lane/intersection connectivity. It was observed that lane positions and blockages produced internally by the AV during one or few human-driven traversals were sufficient for AV operations later. In summary, HD map representations containing simply the lane edge designations and geolocations of work zone boundaries were sufficient for AV navigation. Accuracies better than 10 cm did not change AV performance versus 10 cm accuracy. The accuracy of lane re-marking steps was also tested, and typical paint crew operations were observed to have repainting errors of 10 to 20 cm (2-sigma). Similar errors were observed between map origins depending on the source of differential corrections for Global Positioning System (GPS) at each site. Thus, mapping at resolutions better than 10 cm accuracy had little-to-no benefit to the AV. In live on-road sites, the tests at two of the locations were conducted during generally static operations and it was not possible to determine "static enough" criteria. The third site, with a mobile work zone performing lane-striping on local highways, proved to be highly dynamic and the CMU AV did behave as expected during these tests. However, maturation is required from the perspective of consistent performance for real-world deployments.

Description	Key Hypothesis Evaluation Questions	Results
		On the closed test track work zones (1km), these could only be changed with a work crew of approximately 10 personnel in two to four hours and for complex scenarios, eight hours or more. However, high fidelity HD maps that included centimeter-level accuracy from the mapping van required substantial data collection and post-processing to where the latency between data collection and HD map availability—days to weeks—made HD map generation process particularly slow relative to work zone operational changes. Refer to Appendix D for more information.
Objective 1.5 Evaluate the applicability of existing map standards for work zone data sharing.	Are existing mapping standards applicable to the project?	Existing map standards showed gaps in their suitability for work zone data sharing and/or simulations. Two open-source standards for HD maps were considered—Association for Standardization of Automation and Measuring Systems (ASAM) OpenDrive and Open Street Maps. Both were chosen as these are the only two formats that, at the time of the Project, could be natively imported into the CARLA/CARMA open-source simulation suites. However, neither standard could be used without modifications across all three stages of testing. In simulations, differing coordinate conventions—Latitude/Longitude/Altitude (LLA), East/North/UP (ENU), and Mercator)—across simulation toolsets made integration difficult between traffic sims, AV stack simulations, and 3D immersive environment simulations. In closed test track and live on-road testing, there were few tools that could quickly process large volumes of point cloud data and/or image data into HD maps. Nor was there support in CARLA for hands-off importing of HD map data from AV or mapping vehicles without third-party proprietary software. The team found great need for additional open-source toolsets and HD map standards that better bridge the simulation/reality technology gap. CMU's AVs used their own mapping formats called COSMOS and use converters to and from OSM and sometimes OpenDrive.
Goal 2 Ensure data gathering and sharing.	Does the Project data inform methodologies for ADS systems in work zones?	The results of the Project suggest that ADS systems in work zones use local data collection, data processing, and data sharing methodologies as cloud access at live on-road sites and even the closed test track was often limited or nonexistent. The four primary sources of data in the Project—the AV, the

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Description	Key Hypothesis Evaluation Questions	Results
		mapping vehicle, the C-V2X system, and the instrumented roadside devices—each had their own data collection modalities, and each had challenges relating to particular data silos. AV data was difficult to collect during AV operations without degrading safe AV performance. Mapping vehicle data was generally too "dense" for real-time data sharing. C-V2X software/hardware integration changed frequently during the Project such that updating and versioning was challenging. Roadside device equipment required fundamental integration support to move from research-level deployments into mediums supporting AV data sharing. Key methodologies emerged that became common practice within the team—using GPS, LLA, and ENU coordinates when possible, utilizing GPS time stamps for data synchronization, using/testing connectivity with Basic Safety Messages (BSM), and using local near-road data processing rather than cloud services due to the latency in upload/download. Map information supplied from C-V2X RSUs regarding stationary work zones can also be supplied from the cloud (i.e., through V2C but using 4G/5G cellular technologies). However, the Project did not implement and evaluate this approach due to time and budget limitations. Reliable cellular coverage and sufficient bandwidth availability will be key considerations.
Objective 2.1 Identify consistency between similar measurements across data sources.	Do the data sources have sufficient overlap? Are the data sources repeatable? How does each data source's cost change with quality of data? What are specific advantages and drawbacks of each data source? How does the data quality degrade over time? Can data sources be merged?	The HD map data from closed test track and live on-road data appeared to overlap with 10 centimeters 2-sigma accuracy. This was evaluated from measuring lane markings between hand-surveyed and mapping van data. The agreement in position information between simulated environment positions (generated by Computer Aided Design (CAD) drawings of scenarios) was poor—errors of one meter or larger were regularly observed. In comparing replicates of data across available data sources (mapping van), the repeatability in lateral position (right/left relative to direction of travel) was within approximately 10 cm or less. In longitudinal (direction of travel) repeatability, this was worse—0.5 meters of error—due to time delays that occurred in sensor data captures. The quality versus cost for each data source was primarily affected by GPS availability at each site and how frequently data could be measured from

Description	Key Hypothesis Evaluation Questions	Results
		each mode. There were not any clear sensing modalities. The primary factor affecting data quality over time was, across closed test track and live on-road operations, the repainting of lines or repositioning of channelizers. The accuracy of lane markings, from before/after lane paint-truck repainting was approximately 20 cm and thus HD mapping was required for each repainting, even when painting was "on top of" old markings. Except for CAD data, all the data collected for HD maps were sufficiently consistent with each other to allow data merging. However, some data sources—particularly from the AV itself—were far more useful. The accuracy of C-V2X lane center positions, as measured from RSU data on instrumented human-driven vehicles following lanes within work zones, was generally within 0.5 meters relative to surveyed centerline lane positions. In contrast, the consistency of CAD drawings of work zones versus in-field measurements was observed to be 1.5 meters in error—even after correcting for rotational and origin misalignments—and this error was inconsistent depending on map locations. Of note, different data sources did not typically measure the same quantities—C-V2X, for example, measured antenna position as mounted on vehicles and thus measured only an estimate of lane centers. Mapping vehicle data primarily measured lane markers and fixed-object positions, e.g., road edges and channelizers. The primary inconsistency between data sources was the time to collect and process data from each source. The least-costly data sources were, in order, instrumented roadside devices (barrels) that could provide data every second, C-V2X data from OBUs which could be updated every few minutes, AV data which the team could update each "pass" through the work zone (every 20 minutes), and finally mapping vehicle data which could only be updated after processing for several days. However, the quality of the data followed the inverse of this trend. The roadside device data had large errors (meters) and only the AV and mapping van data were less than 0.2 meters error in accuracy—thus being the only sources observed to be suited in the Project for HD map-building.

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Description	Key Hypothesis Evaluation Questions	Results
Objective 2.2 Identify consistency between similar measurements across data collection modalities.	Do the data from each modality have sufficient overlap? Are the modality data consistent and repeatable? What are the costs of data collection from each data modality? What data have specific advantages and disadvantages from each modality? How does the relevance of data from each modality degrade over time? Can data collection modalities be merged?	There was weak to moderate overlap between testing results observed in simulations to results observed in operations at the closed test track or live on-road, but good overlap between closed test track behavior and on-road behavior. Each testing modality was observed to have different utility. For example, simulations were particularly useful to evaluate AV behaviors such as lane changes and AV perception—particularly for camera-based vision and LiDAR point clouds. Nevertheless, synthetic virtual world images from simulators must still be augmented by real-world visual frames. A key observation is if the AV cannot traverse a work zone in simulation, it would not succeed in practice at the closed test track or live on-road testing. However, successful completion in simulations did not guarantee successful behaviors at the closed test track. Closed test track evaluations were useful to capture repeatability and sensor performance test data, as the geolocations for features were easily hand-measured for verification and marked on the road surface itself to confirm, over many days of testing, that there were no changes in configuration. The closed test track data appeared to have the least change or degradation over time. Live on-road testing was the only modality that tested AV behaviors in work zones with other human drivers present. The one exception is when a mobile work zone was used at the closed test track and the CMU AV had to navigate around the mobile work zone, which it successfully did. A key difference in comparing data across modalities was caused by the different representation modalities in simulations versus road data. Particularly for traffic simulations (SUMO), the representation of work zones was not possible in native formats. The team had to approximate road closures and lane closures by constructing artificial road networks of similar geometries. Results from closed test track and on-road tests are generally indistinguishable from surrounding traffic and thus these data could be merged. However, data from simulations were more difficult to directly compare to real-world, even for simulations constructed to match closed test

Description	Key Hypothesis Evaluation Questions	Results
		track geometries. The closed test track at Penn State is not entirely flat and there are several areas where lanes dip and rise again. Such unevenness was not captured in the CARLA simulations, and real-world behavior is certainly different from much smoother performance visible in the simulation runs.
Objective 2.3 Identify differences and similarities in data needs across data users.	What are the data aggregation processes used by each user? What resolution, accuracy, and operational domain of data collection appears to have most benefit to AV safety and/or operation? How can old data remain beneficial for each user, particularly to the AV? What merging and storage methods have most benefit to each user? How do data formats and data resolution affect safety metrics?	For each data user, significant differences were observed related to the typical data sources of that user. For example, the turnkey-C-V2X toolboxes and software were exclusively focused on intersection deployments, including visualizations and customizations for these. However, limited software existed for newer C-V2X devices to act simply as transceivers to/from the AV automation stack and/or road-side computers that were aggregating data to produce map information. The CMU team designed and implemented a new transport-layer one-way broadcast protocol called MPMP (Multi-Packet Memo Protocol) to transmit detailed information about a work zone that spans multiple C-V2X packets. (In traditional V2X message protocols before MPMP, all information had to be contained within a single packet. Refer to Appendix D for more information). Similarly, simulation toolsets were clearly developed with focus on a human's manual input of a scenario as an import process, rather than a scriptable process connecting real-world data sources to simulation inputs. For example, the key tool for importing HD maps into CARLA—the RoadRunner toolset—did not support fully scripted data flows at the time of the Project. This was a key challenge in a project with two dozen scenarios, each tested across six or more variants with testing cycles in the field changing every few hours. Each data user had similar needs—including geolocated and time-aligned data, usually in ENU or LLA formats. In assessing AV behaviors, the closed test track data collection has significant benefit for safety analysis because of its high repeatability and verifiability yet ability to capture real-time AV performance statistics, weather conditions, and similar real-world effects. The resolution/accuracy of data collection of 10 cm (2 sigma) appeared sufficient for assessments. Real-world live on-road tests in contrast had to deal with uncontrolled traffic on a high-speed highway, extended delays at a traffic signal on a bridge being worked upon,

Description	Key Hypothesis Evaluation Questions	Results
		and work in real-time with maintenance crews fulfilling their operational duties to paint lane stripes. Demonstrating that the CMU AV can deal with all of these real-world constraints is highly reassuring and showcases the potential of this technology. As will be noted later, substantive investments are needed to mature and productize these core technologies for day-to-day usage by normal human drivers. The team did not test "shelf life" or aging of data to the AV. The range of tests and scenarios conducted by the team meant that most scenarios were set up, tested, and then reconfigured within one to two days (often including into the dawn hours). In the live on-road work zones, the team observed that each site was unique in how quickly it was reconfigured and thus the "age" of data is a highly site-specific question beyond the scope of possible work by the team. In merging and storing data, the most common and useful method was to maintain a field office station or office at the closed test track where data could be uploaded or downloaded manually from a roadside computing device or devices. At all live on-road sites, and even at the closed test track, there was insufficient bandwidth to enable cloud-based data sharing or data merging. The team is still processing data to assess how data storage and processing steps affect data accuracy. The results thus far suggest that the fitting of point-cloud or geospatial information into map primitive geometries (lines, arcs, splines, etc.) is a large source of error—there were not any true "lines" or "line segments" observed in measured or closed test track field data, and thus approximations are required to generate these primitives. These approximations involve trade-offs between map representation accuracy versus map simplicity. This analysis is ongoing, and future work will address this but may likely require months to years after project completion to fully assess. The raw data to allow others to engage in this assessment has been pushed to PennDOT's DMS for public data-sharing.
Goal 3 Coordinate with varied stakeholders.	Are key stakeholders engaged?	Yes, it appeared that key stakeholders were highly engaged. The team held yearly stakeholder engagement meetings to ensure that the Community of Support had opportunities to provide input into the project. The team

Description	Key Hypothesis Evaluation Questions	Results
		members attended more than a half dozen conferences each year to present the findings and hosted a similar number of online meetings and presentations each year. During live on-road testing, work crews and contractors were regularly engaging in planning, discussion, and deployment of the team's AV tests. Vendors of key roadside hardware—the instrumented traffic barrels, the C-V2X hardware providers, the road tape manufacturers—were in regular contact with the team and provided invaluable feedback. The archival sharing of results can be seen in the team's list of publications and code repositories.
Objective 3.1 Identify stakeholders and their contribution within stages of the Project.	Are there more stakeholders at the end of the Project than the beginning? Are the contributions of specific stakeholders changing during the scope of the Project?	It is unclear if there are more/less stakeholders at the end of the Project versus other stages, as the stakeholders engaged by the team changed at each stage. Early in the Project, much of the engagement was with simulation experts. However, by the end of the Project, many of the team engagements were with deployed work zone operators. The contributions from specific stakeholders very clearly changed during the Project scope. The coordination mechanisms were also very dependent on the stakeholders. For example, coordination of the team with work zone contractors was seen to be best facilitated by direct contact methods—phone calls and on-site meetings. For government agencies, methods including online calls, technical meetings, and conferences were found to be the most common methods of coordination. For academic research, code repositories and academic conference publications were the preferred means of information sharing.
Objective 3.2 Engage stakeholders in Project activities.	Does the stakeholders' ability to monitor Project progress improve throughout the Project, and how? Are the Project contributions useful to external stakeholders?	The stakeholder engagement improved during the Project, most notably once the team could host ride-alongs and on-site visits during testing events. The team hosted numerous on-site visits during testing to demonstrate AV behaviors in ride-alongs. During field testing at live on-road sites, the team worked shoulder-to-shoulder with PennDOT crews during field deployments—including sharing office space for several weeks alongside the crews. All work zone equipment in the Project was provided from PennDOT suppliers or PennDOT personnel directly, and even the line painting at the

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Description	Key Hypothesis Evaluation Questions	Results
		closed test track was conducted by the regional line painting team for PennDOT. The feedback thus far from stakeholders is that the Project contributions are useful. The code repositories used by the team have, presently, about 100 active research "watchers" who are following code updates and changes online, including many overseas. The team is still fielding meeting requests and phone calls, roughly one a week, from industry professionals (C-V2X, RSU Vendors, roadside equipment manufacturers, sensor manufacturers, etc.) seeking additional information about the Project.

3.2 Project Major Accomplishments

This subsection outlines the key milestones and achievements throughout the Project with the list captured as shown in Table 4. It includes the successful deployment of AVs in work zones, the integration of innovative technologies, and the validation of results through simulations and real-world testing. This section underscores the significant progress made in overcoming challenges and fulfilling the Project's mission.

Table 4. Project Highlights and Major Accomplishments

Project Highlights & Major Accomplishments	
Scope	Completed the extremely complex and challenging Project on time (4 years) and within budget (approximately $8.4M in federal funding).
	Addressed ADS grant focus areas and met ADS demonstration requirement.
	Developed 10+ project management and systems engineering related Project documents.
	Considered more than 17 common work zone scenarios.
	Simulated 16 scenarios using co-sim platform including CADRE, CARLA, and SUMO. Co-simulation videos are available online.[6]
	Conducted closed test track testing for 16 scenarios, all with same-day replicates, with before/after mapping and often including day/night and inclement weather tests, and across a range of channelizer devices (two sizes of barrels, flat panels, and cones). Closed test track demonstration videos are available online.[7]
	Conducted live on-road testing for three scenarios (highway, signalized intersection, mobile work zones) across six site visits including replicates and day/night testing. Live on-road testing demonstration videos are available online.[8]
Outcome	Developed codebases for seven core safety performance metrics for Project evaluation and demonstrated a unifying time-space framework for calculation of these.
	Recorded 50+ AV video demonstrations, totaling more than 500 minutes of footage.
	Collected and shared more than 10+ TB of Simulation, AV, and mapping data.
	Conducted 30+ outreach meetings at various conferences and meetings to reach out to multiple stakeholders.
	Published 15+ accepted papers in various journals, conferences, and peer-reviewed venues.
	Developed 10+ new capabilities for AV stack.

[6] https://drive.google.com/drive/u/2/folders/1Hs3VjVJ12ByQH5BaiAk_casUxplG6hjM

[7] https://drive.google.com/drive/folders/1Hdj4F4wEL3e1xLTewAJIhhK1B23xcDs1?usp=drive_link

[8] https://drive.google.com/drive/folders/13s0iHB8g93SBkHAuCpv7FfYnzB2-C3Vz?usp=drive_link

Project Highlights & Major Accomplishments	
	Documented 30+ challenges encountered and their corresponding solutions.
	Identified 45+ lessons learned for future projects.
	Recommended 30 next steps for further research and project ideas.

3.3 New Capabilities

This section details the new capabilities developed during the Project that were not initially anticipated. These new capabilities fall under the categories of advances in simulation, connectivity, sensor fusion, routing and behavior, and vehicle control. These new capabilities represent valuable contributions to the field and offer significant potential benefits for future applications of AVs in work zones.

- **Perception**
  - Co-Simulation

    The Project successfully integrated CMU's CADRE autonomous software stack with the CARLA open-source simulator and the SUMO traffic simulator. This integration enabled the demonstration of repeatable and controllable simulations, including the ability to test edge-case scenarios. The simulation platform was able to replicate a wide range of challenging conditions—including rain, low-lighting environments, and dynamic work zones—providing valuable insights into the AV's performance under diverse real-world conditions. This comprehensive testing approach ensured that the AV systems could navigate and respond to a variety of challenging scenarios encountered in work zones, contributing to the overall validation of AV safety and operational readiness.
- **Connectivity**
  - Integration of C-V2X with onboard-sensor-based perception:

    The integration of C-V2X with onboard sensor-based perception was a critical advancement in enhancing the AVs situational awareness within work zones. This integration involved defining specific data packets for transmitting crucial work zone information from a RSU to the AV in real-time. This data—when combined with onboard sensors like LiDAR, cameras, and radar—enabled the AV to interpret its surroundings and adapt to dynamic work zone environments more effectively. By merging C-V2X communication with sensor-based perception, the Project advanced the ability of AVs to navigate work zones with greater accuracy and safety—ensuring reliable detection of work zone objects like barrels and cones and changing traffic conditions including traffic signals.

- A new (broadcast, one-way) transport protocol for transmitting voluminous work zone information (that does not fit into a single C-V2X packet) over multiple C-V2X packets:

  The Project introduced this new transport protocol called the MPMP, designed for transmitting work zone information over multiple C-V2X packets. Each memo contained comprehensive details about the work zone, including critical elements such as work zone objects, a map of the work zone, lane closures, and detour information. This protocol enabled efficient and reliable one-way broadcast transmission of work zone data, ensuring real-time communication between the infrastructure and Connected and Autonomous Vehicles (CAVs). MPMP was tested across various work zone configurations, demonstrating its scalability and ability to adapt to dynamic work zone environments and providing AVs with the necessary data to navigate safely and efficiently.

- Enhanced Safety Messages (ESMs) to replace BSM:

  The Project enhanced the BSMs by introducing ESMs as a BSM replacement to improve communication reliability in real-world environments. ESMs were specifically designed to address GPS errors and unavailability, particularly in challenging environments such as urban canyons and tunnels where GPS signals are obstructed or unavailable. ESMs ensure that AVs can continue to receive accurate and usable safety messages despite these conditions. Additionally, ESMs were upward compatible with BSM, maintaining interoperability with existing systems while providing more robust and reliable data for safer navigation in complex environments.

- **Sensor Fusion**
  - Fusion of LiDAR data with GPS, across replicated data traversals, to generate HD map formats:

    The Project successfully integrated LiDAR data with GPS data across multiple replicated data traversals to generate HD map formats. This fusion process allowed for more accurate and detailed mapping of work zones—overcoming the limitations of individual sensor data. By combining the precise spatial data from LiDAR with the geospatial context provided by GPS, the resulting HD maps provided a comprehensive and reliable representation of the work zone environment. This fusion improved both AV navigation and perception while enhancing the safety and efficiency of autonomous operations within work zones.

  - Fusion of LiDAR inputs, cameras, and C-V2X inputs to detect work zone objects and safely navigate work zones:

    The Project integrated LiDAR, camera, and C-V2X data to enhance the detection of work zone objects—enabling safe navigation through work zones. This fusion of sensor inputs provided a comprehensive understanding of the environment—allowing the AV to accurately identify obstacles, construction vehicles, and workers while ensuring safe and efficient operation within dynamic work zone conditions.

- **Routing and Behaviors**
  - SafeRoute: a cooperative route-planning and behavioral framework

    The Project developed SafeRoute, which is a cooperative route-planning and behavioral framework designed to address high-risk conditions such as work zones, low-visibility environments, and adverse weather. By explicitly considering these factors, SafeRoute minimized associated risks while avoiding unnecessarily long detours. It effectively captured a wide range of challenging work zone scenarios and enabled an AV to perform safe and efficient route planning in dynamic environments. Support for dynamic lane changes in work zones, construction-vehicle following, and driving in moving work zones was also available in SafeRoute.

- **Open-Source Contribution**

  The Project developed many open-source codebases which are available in the public domain through GitHub. These codebases included transformation methods between the various coordinate systems used among simulation tools and live on-road testing (LLA, ENU, World Geodetic System (WGS), Mercator), conversion tools for data formats to be imported/exported into simulations or HD maps, tools to process raw data from the team's vehicles in both raw and processed forms, tools to geometrically fit point-cloud data into HD map primitives, and tools to export HD maps in common formats. In total, 22 GitHub repos are available. A summary along with the codebases can be found at https://psuadsworkzone.github.io/.

- **Vehicular Control**

  The integration of map-free and map-based operations in vehicular control enhanced the flexibility and adaptability of autonomous vehicles. By fusing, when necessary, the precision of high-definition maps with the robustness of sensor-driven map-free navigation, vehicles can seamlessly switch between these modes and/or merge data based on available data—ensuring safe and efficient operations in both mapped and unmapped environments. This integration was crucial for handling dynamic and unpredictable work zones while maintaining optimal control and navigation.

4 Challenges, Lessons Learned and Recommendations

This section highlights the key obstacles encountered and the Project team's solutions developed during the Project's execution, along with the valuable insights gained through overcoming these challenges. It offers a reflection on the management and technical difficulties faced, as well as the solutions implemented. Furthermore, this section provides actionable recommendations to guide future projects, ensuring continuous improvement and more effective integration of AVs in dynamic environments such as work zones. The lessons and recommendations outlined here are aimed at advancing the development of AV technologies and optimizing their deployment in real-world settings.

4.1 Challenges and Solutions

Throughout the course of the Project, the team encountered a variety of challenges spanning management and technical areas. The team implemented a series of innovative solutions to address each challenge, ensuring the continued progress and success of the Project. This section outlines the challenges faced and the strategies developed to overcome them. The effective solutions contributed significantly to the successful navigation and testing of AV systems within real-world work zones, providing valuable insights for future AV projects and infrastructure integration.

4.1.1 Management Challenges and Solutions

4.1.1.1 PROCUREMENT CHALLENGES AND SOLUTIONS

Several procurement challenges arose during the Project—particularly around hardware and device availability during and after COVID-related closures, which occurred during the Project.

4.1.1.1.1 Graphics Card Shortages

Challenge: The computing platforms necessary to perform CARLA simulations require graphics card capability which was not readily available at the start of the Project, which coincided with the COVID-19 Pandemic. The minimum graphics card necessary for CARLA simulation was three times the pre-COVID costs and had a six-month backorder delay.

Solution: The team mitigated this issue by securing alternative suppliers and scaling back non-essential simulation tasks until the hardware was available.

4.1.1.1.2 C-V2X Device Transition

Challenge: For V2X devices, the Project timeline coincided with the deprecation of DSRC devices, the elimination of the DSRC frequency band operations by the Federal Communications Commission (FCC), and the concurrent deployment of new C-V2X systems. Thus, the C-V2X systems used by the team were, in many cases, first-of-its-kind units both in terms of the hardware and the software. Consequently, many of the software tools were missing key examples and extensions for broadcasting or receiving specialized messages, documentation of capabilities was limited, and many core software features were not yet functional. Additionally, the device hardware exhibited manufacturing issues that required the majority of RSUs to be repaired within months of deployment.

Solution: The team solved these challenges in two ways—the CMU sub-team "froze" their hardware/software stack implementation at start-of-project versions to allow live on-road testing without delays or modifications and the PSU sub-team worked closely with the vendor's support team to further develop the hardware/software to a level where, by the end of the Project, their hardware/software were nearly at the same functionality level as end-of-life capabilities with DSRC devices.

4.1.1.1.3 State Agency Procurement Process

Challenge: PennDOT was originally supposed to procure C-V2X RSUs and OBUs units for the Project. However, PennDOT was unable to procure the C-V2X RSUs and OBU units because the vendor required the purchaser to sign terms and conditions that PennDOT's legal office was unable to agree to within the timeframe of the Project. Additionally, the procurement of traffic control devices and some pavement marking tapes took longer than expected (more than six months) to perform due to the required quantity and the corresponding contract value. These needs were required to be figured out far in advance of any testing.

Solution: PSU was able to purchase more C-V2X RSUs and OBUs units as they were able to agree to the terms and conditions required by C-V2X vendor. The team also worked to ensure that all traffic control devices were anticipated far in advance of testing where practical. PSU was also able to procure pavement marking tape when PennDOT was not able to procure the tape within the Project timeframe.

4.1.1.1.4 PennDOT Information Technology (IT) Challenges

Challenge: The Project used PennDOT's IT Azure account to deploy the DMS. Because this account is hosted within PennDOT's domain, all users working on the DMS, both for development and for data storage, had to register with PennDOT's account system. The account system required frequent logins and password changes, and IT support from PennDOT for non-PennDOT personnel was challenged by confusion whenever a team's request would be routed to a new IT support person. Additionally, special accounts had to be created that could be shared between the rotating academic students so new accounts did not have to be created throughout the Project. This created a considerable amount of coordination effort throughout the Project.

Solution: The team members frequently communicated with the Project lead and PennDOT IT to request password resets, account resets, and account creation.

4.1.1.2 FUNDING CHALLENGES AND SOLUTIONS

4.1.1.2.1 Limited Funding for Deployment

Challenge: The Project required significant funding to implement the advanced technology solutions effectively, and the original scope that included every variational “edge” of technology was too expensive for the available budget and time constraints. This posed a challenge in executing the full range of technology implementations, such as with/without C-V2X communication, with/without HD mapping, with/without perception testing, wide range of lighting and weather conditions, across 17 different test scenarios spanning an area with a 200-miles radius around Pittsburgh, all within the planned timeframe and resources. It would have been extremely resource prohibitive to test every combination of technologies with every work zone scenario.

Solution: To address this, the team prioritized the most critical components and focused on achievable goals within the available budget. Resources were optimized by leveraging existing infrastructure and equipment. Additionally, the Project was implemented incrementally, allowing for phased deployment of technologies and ensuring cost-effective implementation. For example, once a few key tests were performed that evaluated perception differences between different channelizers (e.g., barrels versus panels versus cones), this same evaluation was not then repeated unnecessarily in subsequent tests.

4.1.1.3 STAKEHOLDER ENGAGEMENT CHALLENGES AND SOLUTIONS

4.1.1.3.1 Engagement with Maintenance Crews

Challenge: The Project team required testing support of PennDOT’s maintenance crew for painting lane markers at the closed test track. Also, at the live on-road testing site, support was needed for painting lane lines (as part of the mobile work zone) and providing truck mounted attenuators. Engaging maintenance crews for testing support proved difficult, as the maintenance crews were nearly always in-field or rotating in/out of different sites especially during summer months.

Solution: The team coordinated directly with PennDOT’s maintenance personnel early on—establishing clear lines of communication and a mutual understanding of testing requirements. The team established clear start/end dates and key kick-off meetings. At live on-road sites, pretest and post-test crew-wide team meetings were found to be essential and highly effective in building trust and partnership with field crews.

4.1.1.3.2 Effective Communication Across Stakeholders

Challenge: Ensuring effective communication among multiple stakeholders was critical but challenging.

Solution: The team implemented a clear communication plan—which included regular updates and collaboration across all partners to ensure alignment and support throughout the Project. Code repositories were used both for data sharing and code archiving. Conference attendance was found to be valuable for networking and obtaining feedback. To avoid travel becoming a burden, the team rotated members' attendance to match expertise and availability to travel.

4.1.2 Technical Challenges and Solutions

4.1.2.1 SIMULATION CHALLENGES AND SOLUTIONS

The simulation phase of the Project presented several challenges, each requiring innovative solutions to ensure accurate and effective testing of AV systems in work zones.

4.1.2.1.1 Design Drawings vs. Real-World Measurements

Challenge: Design drawings are dissimilar enough to real-world measurements such that simulations using design drawings did not directly match with simulations using real-world measurements. While gross metrics such as traffic behavior were not sensitive to these differences, many SSMs such as vehicle proximity to lane edge, proximity to object collisions, etc., would give different results depending on the map representation chosen for simulation. This illustrates a key challenge in trusting simulations for AV testing—that the AV's ego localization within the environment is extremely important for AV operation within work zones, and this localization performance can be difficult to test in simulation as it depends significantly on external signals (GPS, DGPS corrections, and external map accuracies) and features. Also, simulation toolsets could not, at the time of the Project, simulate communication dropouts that challenged real-world deployments of C-V2X, differential GPS, and cloud-based data sharing.

Solutions: The team used real-world data where possible and adjusted simulations parameters by focusing on the critical safety metrics. To account for localization issues, additional testing in real-world environments was incorporated with an emphasis on improving the AV's ego localization using GPS, DGPS corrections, and accurate maps.

4.1.2.1.2 Open-Source Simulation Tool Limitations

Challenge: Open-source simulation toolsets each utilized different standards for map representations—even exhibiting internal differences following HD map standards. For example, Open Street Map (OSM) maps imported into a software tool would, for some tools, produce different OSM results if that same imported data is exported back into OSM format. Additionally, data flows in/out of simulation tools were not always transparent or documented. For example, the team could find no open-source toolset to import texture maps that correspond to ASAM OpenDrive standards for import into CARLA.

Solution: To solve this challenge, the team developed work zone object models that could be imported into open-source CARLA simulator, software packages to transform from one coordinate representation to another and worked with tool's software support teams to identify alternative options.

4.1.2.1.3 Missing or Incorrect Work Zone Objects

Challenge: Many of the common work zone objects (such as channelizer devices, truck mounted attenuators, or work zone signage) were either missing within CARLA or not correctly represented in their implementation (sensing reflectivity, etc.).

Solution: The team built new models from scratch and modified existing ones to ensure that work zone objects were accurately represented by addressing gaps in the simulation environment.

4.1.2.1.4 Simulations can Struggle to Replicate Real-World Conditions

Challenge: Simulations that were simple enough to be fast (SUMO, for example) worked primarily as high-level abstractions of real-world environments and thus could not recreate sensor/actuator inputs/outputs at a level enabling testing of the AV stack. Conversely, environment-immersive simulations, especially in 3D environments like CARLA, were time-consuming (running 10x or 100x slower than wall time) and could not simulate certain environmental factors such as pavement marking retro-reflectivity.

Solution: To mitigate this issue, the team employed a focused simulation approach—prioritizing high-impact work zone scenarios and limiting the number of variables to improve simulation speed. The team also developed parallel processing workflows to run multiple simulations concurrently and improving overall efficiency. Additionally, the team incorporated real-world testing to validate and cross-check the simulation results to ensure the models reflected actual conditions. By combining simulations with live on-road testing and adjusting parameters based on real-world data, the team was able to overcome the limitations of purely virtual testing.

4.1.2.1.5 Coordinate System Discrepancies

Challenge: The different vehicle simulation toolsets in the Project—SUMO and CARLA—did not have common coordinate system representations (LLA, ENU, Mercator) that allowed direct import/export of data between these toolsets.

Solution: The team solved this issue by writing Project-specific software interfaces for data conversions.

4.1.2.1.6 HD Map Import Limitations in SUMO

Challenge: The SUMO traffic simulator did not allow the import of HD map data in easily obtained yet verifiable formats—for example, point sequences representing lane boundaries, high-definition (centimeter level) line segments, or even industry-standard formats such as ASAM OpenDrive.

Solution: To solve this challenge, the team developed external conversions to/from point clouds, OpenDrive standards, and OSM representations.

4.1.2.1.7 Lateral Lane Deviations

Challenge: Traffic simulations did not allow lateral lane deviations such as in-lane swerving to avoid work zone channelizers or workers nearby. Therefore, SUMO results were not useful in assessing any lateral SSMs.

Solution: Although SUMO had limitations, the team compensated by integrating real-world testing data to assess lateral safety metrics to ensure more comprehensive safety evaluations.

4.1.2.1.8 Default Parameters for Traffic Simulation

Challenge: The default parameters in SUMO's traffic simulation, particularly those related to Wideman's car-following model, did not accurately reflect real-world traffic behaviors. This mismatch resulted in unrealistic simulation outputs, requiring significant adjustments to align the model with observed conditions.

Solution: The team updated the default parameters in the Wideman model to better match real-world data. This involved iterative tuning, coordinating the model parameters with literature-reported results where others found this same issue, and finally validation against real traffic behaviors to improve the accuracy of the simulations. Establishing a structured approach to parameter calibration and maintaining detailed documentation of adjustments ensured more reliable simulation results for future use.

4.1.2.1.9 Traffic Simulation Work Zone Representation Limitations

Challenge: In traffic simulation tools, the lanes are hard coded in the sense that vehicles are not visualizing the lane markings, channelizers, etc. Rather, the traffic simulation toolsets represent work zone lane closures simply as a lane ending. In contrast, CARLA is based on lane markings and roadway objects—requiring the AV to make behavioral decisions on when to merge and thereby expanding or contracting the associated merge area. This discrepancy in representation—driven by a lack of a standard definition of work zones in traffic simulation toolsets—made the analysis of co-simulation results more difficult.

Solutions: The team separated the perception simulation aspects from traffic simulation aspects. The team used CARLA/CADRE for AV stack perception simulation and used SUMO/CARLA for traffic simulation. This avoided the difficult integration required for all three toolsets to work simultaneously together.

4.1.2.1.10 Perception Errors in Simulations

Challenge: Traffic simulations did not assess interactions between perception errors in AV sensors and/or human perception caused by work zone conditions—for example, a work zone sign whose visibility or interpretation may be unclear due to line-of-sight blockage by another sign.

Solution: In situations with ambiguous perception relative to human driving—for example, when a traffic sign whose location occludes another sign—the geolocation of one of the signs was changed slightly, consistent with what would occur in real-world testing. The team combined simulation-based testing with real-world validation to incorporate these perception challenges, thus ensuring the AV systems were tested under real-world conditions. For signage and similar perceptual tests that assess object or sign reading in isolation, the team created isolated live on-road tests wherein signage, lane markings, obstacles, and reflective outerwear were tested independently of scenarios or live on-road tests—so that testing on perception tests would not be conflated with scenario setups or artifacts.

4.1.2.1.11 Human-Driven vs. AV Behavior Comparisons

Challenge: In performing simulation comparisons of human-driven versus AV behaviors in traffic, the definition of both behaviors was unclear and required careful tuning and assessment of simulation models and parameters. Without this tuning, the team found that none of the default SUMO car-following models were able to match the field-measured traffic flow data across urban, arterial, and highway datasets provided by PennDOT for human-driven vehicles. Additionally, the calibration and implementation of AV car-following behavior—while guided directly from the AV stack algorithms themselves—also required extensive approximations. Specifically, the typical AV car-following behavior depends on significant factors (sensing/perception, road configuration, lateral/longitudinal algorithm interactions) that are not natively implemented within car-following model algorithms used in traffic simulation toolsets.

Solution: The team fine-tuned simulation models and manually calibrated AV car-following algorithms to better match real-world traffic flow. However, some approximations were required, and adjustments were made in collaboration with experts on traffic flow. For car-following models, the simulations of traffic used a simplified form of the car-following control layer in the AV software stack.

4.1.2.1.12 Computing Limitations for Co-Simulation

Challenge: With the most advanced desktop computing resources available at the time of the Project, running CMU's AV simulation stack (CADRE) in co-simulation with a 3D environment representation simulation (CARLA) and in co-simulation with network-scale traffic simulations (SUMO) was not possible.

Solution: The team solved this challenge by implementing the simulations pairwise or in off-line modalities—for example, by implementing only CADRE/CARLA without traffic simulations and implementing SUMO/CARLA without the AV stack simulation in CADRE. Even with this simplification, the team found that in nearly all cases it was not possible to run simulations faster than wall time—an analysis of one hour of simulated driving required far longer (sometimes by an order of magnitude) within the computing environment. This severely challenged the ability to generate large numbers of replicate data, particularly in the 3D simulation environments.

4.1.2.1.13 Manual Iterations in Environmental Changes

Challenge: The simulation toolsets were not built for large-scale hands-off scripting of simulated iterations—especially with frequent changes to the underlying HD map typical of work zones. For example, during the Project, there were not any public-domain tools that convert point-cloud data into the highly processed formats importable into SUMO or CARLA, and there were no tools available to convert HD map files (XODR for example) with texture maps directly into CARLA. Further, these conversion tools (RoadRunner, for example) are not open-source and are not available without significant licensing costs directly attributed to specific personal computers. Thus, all iterations of environmental changes within the traffic simulation models had to be implemented at several stages by human "hand" operations on dedicated in-lab computing environments.

Solution: The Project team developed significant code sets to do many of these conversions. Despite this work, several large gaps remain in enabling automated analysis—for example, data collection from an AV or mapping van passing directly into a "digital twin" type simulation of AVs within work zones.

4.1.2.1.14 Simulation Platform Options

Challenge: Selecting the appropriate simulation platforms for the Project was challenging due to the need for tools that could effectively model AV behavior while ensuring accessibility and reproducibility. Balancing the technical requirements with the desire for open collaboration added complexity to the decision-making process.

Solution: The team selected CARLA and SUMO as simulation platforms because they are open source and allow for transparency and reproducibility of results by other researchers and stakeholders. This choice facilitated broader collaboration and ensured that the findings could be independently validated while meeting the Project's technical requirements.

4.1.2.2 DEPLOYMENT CHALLENGES AND SOLUTIONS

Deploying AV systems in real-world work zones presented a unique set of challenges. The Project experienced challenges across both closed test track testing and live on-road deployment—including challenges related to the maps, the equipment, and how the sites were being selected.

4.1.2.2.1 HD Map Definition

Challenge: Defining HD maps for work zones presented significant challenges due to inconsistencies in how different simulations and standards define work zones. The physical representation of the world in HD maps may require, for example, that a vehicle drive over a lane marking. However, HD map standard, such as ASAM OpenDrive, do not allow lane markings other than along lane boundaries within the standard HD map definition. Thus, in building an HD map, one must arbitrarily decide whether the map should keep lane position fidelity and have incorrect lane markings or keep lane marking fidelity and have incorrect specification of lane position. This illustrates a need for work zone HD map capabilities. The team encountered several scenarios that involved vehicles needing to violate traditional traffic rules, such as crossing double yellow lines while navigating work zones.

Solution: The team established a consistent approach to work zone definitions in HD maps. This included creating standardized representations for lanes and objects to align physical and software definitions. Additionally, the team developed specific navigation protocols for AVs to handle rule exceptions, such as crossing double yellow lines, ensuring safe and compliant behavior in work zones. Future efforts should focus on establishing universal standards for HD map definitions across the AV industry to address these discrepancies and testing locations that AV companies can use to test these situations.

4.1.2.2.2 Lane Configuration Changes

Challenge: Rapid and frequent changes in lane configurations during live on-road testing disrupted testing consistency, particularly at Site 1.

Solution: The team adapted to these changes quickly, conducting testing on updated lane configurations ensuring that testing protocols remained flexible and accurate for different configurations. For Site 1, unexpected changeovers were resolved by quickly remapping the site, although this did result in several weeks of delays for the testing. For Site 2, coordinating with the contractor ahead of time for the configuration change mitigated the need to remap, because the maps were generated after the change-over.

4.1.2.2.3 Site Selection Issues

Challenge: Site selection for testing presented challenges because the team was unsure of legal, insurance, coordination, and other concerns.

Solution: USDOT coordinated a peer exchange to understand how other states have done testing in live work zones. The team learned that there were no issues if the contractors were agreeable to allowing the setup of extra equipment in the work zone. The current understanding is that the AV company is liable if the AV were to not obey the traffic control devices in the work zone, meaning the contractor is not liable.

4.1.2.2.4 Map-Free vs Map-Based Driving

Challenge: Both map-free and map-based driving approaches present unique challenges in work zones. In map-free driving, faded or absent lane markers make it difficult for AVs to navigate reliably. In map-based driving, the dynamic nature of work zones, where configurations change rapidly, can render preloaded maps outdated and unreliable.

Solution: The team employed a hybrid approach, combining real-time perception systems to handle faded or missing lane markers with dynamic map updates to accommodate rapid work zone changes. This approach uses maps as a "guide" but not a constraint for AV behavior selection. This ensured that the AV could adapt to evolving conditions while maintaining navigation accuracy. Additionally, the team found that C-V2X communication provided real-time updates to enhance situational awareness, especially in situations where the initial map (without updates about the work zone) were incorrect.

4.1.2.2.5 Temporary Tape Maintenance with Snowplows

Challenge: Maintaining temporary lane marking tapes during winter proved challenging, particularly with snowplows and repeating freeze/thaw cycles. Snowplows often damaged or destroyed the tapes, requiring frequent costly and labor-intensive replacements. Even when snowplowing was done carefully to avoid the tapes, melting snow left pools of water which would wick between the road tape and pavement, freeze, and then lift the tape off the pavement further compromising the tape's adhesion and effectiveness.

Solution: The team mitigated damage by using sweepers instead of snowplows where feasible, reducing the risk of tape destruction. In areas requiring snowplowing, the team implemented adjusted techniques to minimize impact on the tapes. Additionally, enhanced tape materials and better drainage management were identified as future areas for improvement to address water pooling and adhesion issues.

4.1.2.2.6 Equipment Durability

Challenge: Equipment durability posed significant issues during the Project. Two cameras on the mapping van failed when exposed to temperatures below their operating rating and disrupted data collection. Additionally, several RSUs (four of the seven) exhibited hardware failures and required replacement under warranty, leading to delays and operational inefficiencies. One LiDAR packaged into the body of CMU's AV failed and had to be replaced with substantial effort and calibrated again. Cross-sensor calibration also needed to be carried out.

Solution: To address the camera failures, the team installed heaters on the mapping van to maintain equipment within operational temperature ranges. For C-V2X RSUs, proactive warranty claims and close communication with the manufacturer expedited replacements. The team also developed contingency plans, including maintaining spare units on hand, to minimize downtime caused by equipment failures.

4.1.2.2.7 Ubuntu Upgrade

Challenge: Managing software compatibility became a significant issue when Ubuntu 16.04 LTS reached its end-of-life support. Team members were required by their IT departments to upgrade to a newer version, but key software tools, like CARLA, did not support Ubuntu 20.04 while older hardware and vehicles were still reliant on Ubuntu 16.04. This created inconsistencies across systems, as new hardware required the latest versions while older software and dependencies were incompatible. CMU's AV required a full upgrade of their AV stack to Ubuntu 20.04 mid-Project since newer developer laptops would not support Ubuntu 16.04 anymore, which led to extensive compatibility issues with dependencies. A significant number of person-months was spent doing the port since various Applicable Programming Interface were either deprecated or had modified semantics.

Solution: The team conducted coordinated upgrades across systems to align with the requirements of key software like CARLA and CADRE, while maintaining fallback versions for older tools where feasible. This involved extensive testing of dependencies and configurations to minimize disruptions. Clear documentation of compatibility requirements and close collaboration among teams helped address issues as they arose, ensuring the successful integration of systems across different versions of Ubuntu.

4.1.2.2.8 Collecting Data During Vehicle Operation

Challenge: Collecting data while the AV is in operation presented a significant challenge due to the limited resources available. Both the data collection process and vehicle operations required the same set of resources—particularly computing power, communications bandwidth, storage bandwidth, and sensor systems. These resources were needed to ensure that the AV functions properly, safely, and smoothly in real-time and make dynamic decisions while also ensuring the collection of data for analysis. Computing platforms on the AV were at their data bandwidth and/or data processing limits, leaving little available processing or power for Project-specific logging requirements.

Solution: The conflict between the need for real-time vehicle operations and data logging led to the decision not to collect data during live testing, which limited the amount of raw data available for post-test analysis. Additionally, the simultaneous demands on the vehicle's resources—including processing power, storage, and bandwidth—resulted in difficulties balancing these tasks without compromising the vehicle's performance or data quality. This was mitigated by using the AV to test behaviors and assess these in human perception (video) as the AV stack data is far too difficult to process in raw data form. Conversely, all environmental data was logged by the mapping van as this vehicle is purpose-built for data logging.

4.1.2.2.9 Navigating Tight Turn Radii and Other Complex Scenarios During Testing

Challenge: AVs faced challenges in navigating tight turn radii and other complex testing scenarios commonly found in real-world work zones. These maneuvers required precise control over the vehicle’s steering and sensor systems as well as the ability to adapt quickly to dynamic changes in the environment such as obstacles and construction debris. In some cases, the AVs struggled to maintain accurate lane positions and avoid collisions in these confined spaces. This was particularly noted with unique detour situations imposed by the closed test track geometry for the two scenarios that involved off-route detours.

Solution: The team refined the AV algorithms related to path planning and vehicle control, with a particular focus on improving steering precision and collision avoidance in tight spaces. By incorporating real-time data from sensors such as LiDAR and cameras, the AVs could better assess the surrounding environment and adjust their course to navigate challenging turn radii and work zone obstacles. These adjustments ensured the AVs could safely navigate complex testing scenarios. However, it was noted that the native AV behavior prior to this work zone situation did not anticipate such a tight turn radius on very steep corners along operational roads at the closed test track.

4.1.2.2.10 Difficulty in Staging Conditions for Research During Active Roadwork

Challenge: Staging research conditions during active roadwork presented significant operational challenges, as it was difficult to replicate controlled environments in live, evolving work zones. Roadwork conditions were constantly changing with shifting construction equipment, changing traffic patterns, and moving obstacles, which made it difficult to simulate consistent and repeatable testing conditions. Additionally, coordinating testing around the work schedules of construction crews and active roadwork sites created logistical hurdles.

Solution: To manage these challenges, the team established close coordination with construction crews and the Contractor to schedule testing during periods of less active work or when traffic flow could be temporarily adjusted. They also implemented a dynamic staging approach, allowing the flexibility to adjust testing parameters in real-time based on changing roadwork conditions. In addition, the team worked to ensure that all safety protocols were strictly adhered to with continuous communication between the AV testing team and the roadwork crews to prevent accidents or disruptions during testing. When necessary, the team performed live on-road tests in "bursts," with several days of round-the-clock testing, so that the site measurements would remain consistent across tests.

4.1.2.2.11 Complexity of the C-V2X Stack and Difficulties in Accurate Simulation

Challenge: The C-V2X communication stack, which replaced the initially planned DSRC system, presented unexpected complexities during both simulation and real-world deployment. The simulation toolsets (CARLA) lacked in-built ability to represent communication behavior changes due to blockages. During the hardware deployment, physical power sources were missing at field installation sites. Additionally, the software development kits (SDKs) provided by the C-V2X manufacturer were in flux—the older SDKs developed by the team for Project testing were no longer supported by newer device versions. The new SDKs did not yet have working examples needed by the team—such as custom BSMs, Work Zone Data Exchange (WZDx), Traffic Incident Management (TIM), MAP messaging, or message passing to/from the AV's control stack and the OBU.

Solution: The team conducted simulations independent of C-V2X behaviors by initializing the simulation behaviors only when the simulated vehicle would nominally be in range of the first RSU on approach to a work zone. In the field deployments, the team powered RSUs using portable gas-powered generators at each test install location. To solve the software integration challenges, the team used a two-pronged approach. The core AV live on-road tests were conducted using two older RSU/OBU pairs that fully supported the AV stack and custom BSM messaging. For newer RSU and OBU installs that required the new SDK, the team logged BSM data via SD cards on each RSU and post-processed the data to analyze network coverage and vehicle behaviors.

4.1.2.2.12 Discrepancies Between CAD Drawings and Actual Maps Affecting Testing Accuracy

Challenge: The Project team encountered issues with the discrepancies between CAD drawings used in the design phase and the actual maps of the testing environments. The CAD drawings, while helpful for initial simulations, did not accurately match real-world infrastructure—leading to errors in simulations related to road configurations, lane markings, geometry, and work zone features. This discrepancy created issues in ensuring the AVs were properly tested in realistic settings.

Solution: To address this challenge, the team utilized a hybrid approach to map data integration, combining CAD drawings with real-world measurements obtained through surveying and sensor-equipped mapping vans. The team collaged updated and accurate data of the road infrastructure at the testing sites. The team also implemented a process for calibrating simulations by comparing the actual maps with CAD designs, adjusting simulation parameters based on these real-world measurements. This process ensured that discrepancies were minimized, improving testing accuracy and allowing for more precise evaluations of AV performance in the work zones.

4.1.2.2.13 Azure Upload Limitations

Challenge: The team found that cloud-based data hosting was challenged by bandwidth limitations. Over the course of the Project, the typical sustained upload speed to Azure via Virtual Private Network (VPN) access was around 10 Mb/s and sometimes as slow as 1 Mb/s even on university networks. One live on-road site had no cloud coverage whatsoever. The Project data included ~10 TB of data, requiring several weeks to upload at minimum. The duration of upload required the copy process to be repeated and restarted regularly due to regularly scheduled IT updates.

Solution: Rather than a network-based data upload, the team ordered Azure Data Box disks to physically mail the drives to the PennDOT Azure account. This wasn't without its own challenge—the Azure Data Box required specialized software which required specialized IT approvals both at PennDOT and with university IT staff. Additionally, disk transfers onto the physical drives were limited to 100k files per drive—and the Project's data included roughly three million files. To enable the transfers, the team wrote a script to compress groupings of data files for easy transfer to/from the drives and/or cloud services.

The challenges encountered during the Project were diverse and required a range of innovative solutions. Through proactive problem-solving, collaboration, and iterative testing, the team was able to successfully navigate these obstacles leading to the successful development and deployment of AV systems in work zones. These solutions helped the Project meet its goals—ensuring the safe integration of AVs into work zones while overcoming technical, operational, and logistical hurdles.

4.2 Lessons Learned

This section captures the critical insights gained throughout the Project's lifecycle. It reflects both the successes and challenges faced in deploying and testing AVs in work zones. These lessons provide valuable guidance for future projects—offering practical knowledge to improve processes, technologies, and stakeholder coordination. By sharing these experiences, this section aims to contribute to the broader understanding of AV integration and its potential to enhance safety and efficiency in dynamic environments.

4.2.1 Management

4.2.1.1 GENERAL

1. **C-V2X licenses:** PennDOT was able to procure a statewide license for C-V2X through the National Telecommunications Information Administration (NTIA) for research purposes,

avoiding the need for licensing at individual sites. At the time of the Project, there was no approval process for C-V2X, and experimental licenses were no longer being approved by the FCC. By getting an NTIA research license through USDOT, the team was able to deploy C-V2X while avoiding the FCC's lengthy and uncertain process. Although there is now a path forward for C-V2X, this workaround could be used for other technologies in the future.

2. **Start contracts as early as possible**: Contract negotiations took longer than expected—whether it was federal, partner agreements, 3rd party vendor procurement, NDAs, etc. All legal departments involved in the Project were experiencing staffing shortages, compounded by COVID. Turnover in many of the legal/financial offices exacerbated the issue as well. Contracting should be started as early as possible.
3. **Manage quality control:** The project implemented a comprehensive quality control plan. Each deliverable underwent multiple review stages—first by the development team, followed by the core team, a quality review, and ultimately a visual check. This process required substantial time and resources to track comment responses. Moving forward, it is recommended to consider a simplified quality control plan that is proportionate to the complexity of the deliverable to streamline the process while maintaining ambitious standards.

4.2.1.2 PROCUREMENT

1. **Anticipate supply chain delays:** Procurement of computers and GPUs for simulation was delayed due to global chip shortages during COVID, requiring months to build computers capable of running CARLA simulations or supporting CMU CADRE stack development. Planning ahead and ordering critical components early can mitigate such delays.
2. **Technology gets cheaper:** The cost of sensors, including LiDAR and other AV components, decreased significantly during the project timeline, highlighting the potential for cost savings by strategically timing purchases. LiDAR units that were budgeted for $40,000 at the time of the Project proposal ended up costing around $4,000-$10,000 during the Project.
3. **Avoid state agency procurement where possible:** Procurement processes under PennDOT were challenging, particularly for items over $10,000. Subsequent orders exceeding this threshold required a formal bidding process, leading to weeks of delays due to PennDOT's mandated approval processes. Leveraging approved Bulletin 15 items and having the subcontractors procure some of the items helped mitigate some challenges.
4. **Keep backups on hand:** Critical parts, like GPS units, experienced failures and were subject to backorder delays. Keeping backups—and backups for the backups—was essential for maintaining operational continuity. GPS units priced at $700 and higher-end models costing $3,000–$4,000 were affected by these delays.
5. **Most smart work zone products are easy to procure:** Many of the "smart" work zone products were readily available in the market and easy to procure, providing a smoother acquisition process for such items. The team found that the vendors were readily available to answer questions and develop interfaces to use the product data.

6. **Safety vests aren't yet procurement-ready:** Procurement of advanced worker safety vests, which could enhance work zone safety through real-time location data, was not feasible during the Project timeline. These items were still in the research stages of development and were not yet commercially ready for procurement nor within a commercial production cycle. It was discovered that some private companies, like Amazon, have matured their in-house worker safety vests for their warehouse workers, but they are not able to be procured by non-Amazon entities at this time.

4.2.2 Technical

4.2.2.1 SIMULATION

1. **Integration of software/hardware platforms and interoperability:** The integration of software/hardware platforms—such as HD maps, AV stacks, and simulation software—revealed challenges to ensuring seamless interoperability. Issues included real-time synchronization, varying map data, and tool compatibility. Early-stage integration testing and standardization of data formats are crucial for smoother system integration and deployment.
2. **Co-simulation is not easy:** Creating a co-simulation environment is highly complex and cannot be done easily. Integration of different simulation tools like CARLA and SUMO required significant customization and effort.
3. **CARLA runs at 1:1 speed:** At best, the CARLA simulations currently run approximately at real-time speeds, even with powerful computers. This limits the ability to run thousands of simulations efficiently and significantly slows progress.
4. **CARLA's sensors do not accurately model real sensors:** The sensors in CARLA do not accurately represent real-world sensors. For example, simulated fisheye lenses lack realistic warp characteristics, requiring additional calibration to approximate real-world conditions. Simulated outputs are artificially perfect unless care is taken to disrupt and corrupt simulated data in the same manner as typically observed in the real world.
5. **Some simulation platforms are not fully ready and require significant work:** Many simulation platforms, including CARLA, are not yet ready for widespread use and require heavy customization. Real-world objects, when duplicated in simulations, often appear artificial and unnatural, affecting machine learning models trained on this data. Furthermore, simulating human behavior, including reactions and decision-making, is extremely challenging. Simplifications in the AV stack introduce errors but may be acceptable for non-extreme conditions. Tuning open-source models like SUMO to replicate real-world conditions is difficult and requires careful adjustments to parameters.
6. **Available open-source simulation tools do not represent work zones well:** Open-source tools like SUMO are not designed to represent work zones adequately. Traffic behavior is oversimplified—relying on car-following models that force vehicles to trace specific lanes without accounting for uncertainty, such as deciding when to merge. SUMO does not

natively support work zone configurations and requires manual creation of new road layouts for each scenario. Careful selection of simulation tools is essential.

7. **Work zones cause congestion with or without AVs:** Traffic backups occur in work zones regardless of whether AVs are present or not. Lane closures inherently cause congestion due to reduced capacity, making congestion management a critical challenge. AVs in nominal behavior are not the cause of congestion as seen in simulations.
8. **Limited variation in driver behavior in simulations:** Simulated traffic often exhibits minor behavioral variations, particularly in free-flow conditions. Drivers in simulations are forced to maintain speed limits, unlike in real-world scenarios where they may override speed limits.
9. **Statistical differences between AV and human behavior are not significant:** Simulations reveal no statistically significant differences between AV and human-driven vehicle behaviors across a range of variables, though discrepancies may appear in extreme conditions or edge cases.
10. **Simulation is extremely valuable:** Despite limitations, simulation is an invaluable tool for AV development. It allows entities to test scenarios efficiently—saving time and costs compared to real-world testing that is expensive, time-consuming, and challenging to replicate due to varying weather and lighting conditions. Simulation also allows the ability to test many scenarios in parallel.
11. **If simulation runs do not work, real-world runs will not work:** Failures in simulation point to failures in real-world scenarios, but success in simulation does not guarantee real-world success. Simulations are abstractions of reality, missing key complexities such as road surface conditions and environmental variability.
12. **All work zones could be simulated:** The Project successfully simulated all of the work zone scenarios, although detour scenarios presented some challenges. Some tight turns on very steep intersections were particularly difficult for vehicles to navigate, and these tight-turn detour situations required additional tuning of vehicular controls.
13. **Additional simulation effort is needed:** Significant time and effort were required to import simulation environments, including map representations, world representations, and coordinate systems. The available toolsets for simulating real-world and work zone maps were not fully ready, requiring considerable manual intervention.
14. **Traffic flow data needs to be clear, even to those who are not traffic engineers:** The traffic flow volumes reported in the public domain on several local roadways were confusing as it was unclear if they reported bi-directional or uni-directional flows. The team had to contact the traffic engineers involved in the measurement to clarify, as this issue was causing errors in comparing simulations to real-world data.

4.2.2.2 CLOSED TEST TRACK

1. **Identifying differences between simulation and closed test track performance is valuable:** Comparing simulation results with testing on a closed test track is crucial to understanding discrepancies and improving both environments.

2. **Real-time decision-making is critical:** On a closed test track, decisions often need to be made in real-time, highlighting the importance of AV systems being able to adapt dynamically to changing conditions.
3. **Parallel logging and processing are computationally intensive:** Simultaneously logging and processing data during closed test track runs is resource-intensive—underscoring the need for robust computational setups. Logging data on the vehicle may result in degraded performance.
4. **Fundamental differences exist between CAD Drawings and Real maps:** CAD drawings often differ significantly from maps created through field surveys, with discrepancies in lane widths and geometry. These differences can impact AV navigation and testing accuracy.
5. **Turning radii in simulation and real life can be different:** Tight turning radii that seem sufficient in simulations may present significant navigation challenges in real-world testing.
6. **Closed test tracks are a safe and valuable intermediate stage:** Closed test tracks represent a safe and relatively repeatable environment to bridge the gap between simulation and live on-road testing—enabling controlled experimentation.
7. **Edge cases can be difficult to navigate, yet are possible:** Creating artificial edge cases, such as narrow lanes with traffic barrels, highlighted significant challenges for AVs when road specifications like lane width being a minimum of 12’ were violated. It is possible to overcome these challenges in the future with further testing.
8. **Environmental factors and setup errors add complexity:** Traditional work zone setup of object placements, such as signs and barrels, are susceptible to fading and falling into disrepair due to environmental conditions like wind and rain. These factors can introduce additional risks and testing variability that need to be addressed.
9. **The AV sees some scenarios as the same:** Some scenarios (e.g., 1.2 versus 2.1) were perceptually the same to the AV because the CMU AV at the relevant stages of the Project does not “read” signage but references a digital map instead. Similarly, some scenarios involved the same repeating left-to-right or right-to-left lane shifting sequence (i.e., scenarios 1.3, 1.5, 1.6), which is the same to the AV as the AV used a digital map to infer the intended behavior from the presence of lane markers. The team was able to skip some of the scenarios because they would be “treated the same” to the AV.
10. **Not all scenarios are feasible on closed test tracks:** Certain scenarios, such as those requiring multiple moving vehicles and large spaces like during line painting in real-world work zones, may not be practical to execute on a closed test track due to size limitations.
11. **Coordinate systems require careful management:** Selecting and maintaining consistent coordinate systems is challenging, particularly when different software systems (e.g., DGPS providers) are used. Discrepancies of up to one meter were observed between the AV and mapping van.
12. **Some work zone features are particularly challenging to sense:** In the site 1 of the live on-road testing, there was construction on both sides of the interstate simultaneously with barrels being used on both directions of travel to redirect traffic. This situation was challenging to the perception stack as it had to disambiguate which “side of the road” for which the barrels were intended, a process which challenged the AV stack’s behavior.

Additionally, locations where cables were used to designate road boundaries were difficult to perceive, as the cables may lie "between" the relatively sparse layers of the LiDAR scanner particularly when viewed from longer distances.

13. **Work zone objects have wide perception visibility:** In normal use, the wear and tear on work zone devices are rather high, causing color and reflectivity variation that the team did not study. Notably, in one purchase order of new barrels for use at the closed test track, 20 of the 100 barrels had torn or missing reflective tape. Barrels without tape were significantly less reflective to LiDAR pulses.
14. **Secure field networks are essential:** Creating a secure field network, such as the one implemented by PSU, ensures data integrity during testing, though resolving associated security questions requires long-term planning. The security systems required constant re-authentication which is difficult in a moving vehicle.
15. **Some sensors do not have compatible firmware:** Some sensors that PSU bought did not have firmware that was compatible with their system, so they had to edit their own firmware to get the LiDAR and GPS to fully work on the mapping van.
16. **Temporary traffic signals not designed for C-V2X:** Most temporary traffic signals are not designed to be able to integrate C-V2X. They typically run on 24V DC battery power. In contrast, modern Advanced Transportation Controllers (ATC) are designed to use 120V. Thus, most temporary signals run custom, basic controller hardware which cannot be easily converted to SPaT and MAP messages.

4.2.2.3 FIELD TESTING

1. **Work zone crews naturally prioritize construction over research:** Collaborating with work zone crews is challenging, especially non-DOT construction crews, as their focus is on completing construction rather than staging conditions for research. Real-time adjustments to work zones for testing purposes are often impractical, requiring researchers to adapt to the crews' practical needs.
2. **Careful site selection is critical:** Selecting appropriate field-testing sites is essential but challenging. The three sites used in this Project provided valuable insights due to their unique characteristics:
    a. **Site 1:** A long, narrow freeway corridor with zipper barriers placed near lane markers posed significant challenges for navigation and safety. The site produced large datasets, approximately 20 times larger than closed test track data (or 100 times if accounting for lane configurations). Frequent changes in lane configuration meant that successful navigation on one day did not guarantee the same success the next day.
    b. **Site 2:** Dense tree canopies caused GPS and real-time kinematic positioning (RTK) signal issues, while poor cell phone connectivity added complications. Lane markers were faded, and a bridge bend created additional challenges. The position of the sun can impact visibility of traffic signals in one direction, rendering them unreliable to the AV perception system.

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c. **Site 3:** This site benefited from cooperative maintenance crews but still presented challenges, such as coordinating striping passes (three instead of the usual two). Dynamic speed changes, from 45 mph to 55 mph and as low as 15 mph during active striping, required careful vehicle-following and take-over scenarios.

3. **C-V2X technology is highly beneficial:** In both Sites 2 and 3, C-V2X communication proved instrumental in mitigating challenges and enhancing AV performance in terms of responsive, safe, and smooth maneuvers by providing reliable connectivity and situational awareness.
4. **Consider impacts of potholes:** Potholes disrupt AV navigation by affecting sensor accuracy, path planning, and vehicle stability. To mitigate this, AVs should use real-time HD maps, adaptive suspension systems, and pothole detection. V2X communication can provide real-time road condition updates, improving AV performance and safety while navigating challenging road surfaces. Even vehicle-based mapping, at least initially, may require low-speed mapping traversals to avoid potholes from affecting the map quality.
5. **Co-location with research teams enhances efficiency:** Having research teams physically co-located with testing facilities significantly improves collaboration, communication, and efficiency during testing and troubleshooting.
6. **More "work zone" closed test tracks are needed nationwide:** To fully develop and test AV technologies, a broader network of dedicated, closed test tracks is essential. This would enable testing under diverse geographic, environmental, and infrastructural conditions while maintaining consistent standards of testing.
7. **Physical test beds are indispensable:** While simulations provide valuable insights, physical test beds are critical for validating AV performance in real-world conditions. They enable testing scenarios that cannot be fully replicated in a virtual environment.
8. **Permanent work zone closed test track setups provide stability:** Extended use of a closed test track—over 500 days in this Project—allowed for consistent, repeatable testing. Semi-permanent setups of certain scenarios provided stability and reliability for long-term experiments.

The lessons learned from this Project highlight the significant strides made in advancing AV integration into work zones, as well as the remaining challenges. Work zone scenarios vary widely in complexity, but the feasibility of driving autonomously and safely through these environments has been successfully demonstrated. While the underlying problems are well understood and solvable, achieving scalable technological solutions for safe and scalable deployment in the real-world requires substantial funding and resources in the future. Despite the progress accomplishments in this Project, AV performance in diverse work zone scenarios is still far from achieving the depth of experience and system redundancy necessary to handle the full spectrum of real-world work zone conditions. Continued investment, iterative testing, and collaborative development are essential to address these gaps and ensure robust AV performance.

4.3 Recommendations and Next Steps

This section outlines the key management and technical actions required to further enhance and scale the advancements made during the Project. It identifies both management strategies and technical improvements necessary for the successful continuation and broader implementation of not only AV systems in work zones but AVs in general.

4.3.1 Management

1. **Documentation and knowledge transfer:** As part of the Project, a comprehensive collection of Project documentation—including best practices, lessons learned, and technical findings—was developed. These should be shared and archived for future reference to ensure continuity and leverage insights in future projects.
2. **Sustainability and long-term support:** The DMS will require long-term support for storage, maintenance, and providing access to researchers requesting the data. PennDOT has processes in place to accept and validate the data request and provide the requested data to the researchers for the next five-year period. Any request for Project related data should be routed through PennDOT.
3. **Stakeholder engagement and outreach:** Continued engagement with stakeholders—including government agencies, industry experts, and the public—is crucial for promoting the continued adoption and support of AVs. USDOT and the industry should continue outreach efforts and communication strategies to foster wider acceptance.
4. **Standardization and scalability:** USDOT should focus on standardizing systems for broader implementation across regions and environments. The scalability of the work zone solution should be prioritized for real-world testing and deployment in various transportation contexts to ensure long-term success.
5. **Public trust and safety:** AI systems need to be made trustworthy by addressing issues like hallucinations in AVs. Incorporating redundancy in AV systems is crucial to ensuring safety and trust in all scenarios.
6. **Increased funding allocation:** USDOT should actively consider increasing funding to address critical technology gaps and to support future research and development efforts—particularly in areas such as data flow management, simulation toolset enhancement, V2X communication, and broad-based AV testing. Increased funding would also accelerate the standardization processes and ensure the scalability of AV systems across the country.

4.3.2 Technical

4.3.2.1 SIMULATION TESTING

1. **Feedback loop integration:** Integrating a feedback loop from AVs to RSUs (or at least to the “cloud”) could potentially address issues like the incorrect positioning of work zone objects, thereby using AVs to build maps for other AVs.

2. **Enhance open-source toolsets:** Focus on improving open-source toolsets for seamless data sharing between simulation tools (SUMO, CARLA, etc.) and standard data formats (OSM, XODR).
3. **Improve simulation tools for work zone representation:** Develop and enhance toolsets for accurately representing work zone objects.
4. **Simulation calibration:** Enhance the calibration of simulation behaviors, particularly with real-world data, to ensure accuracy in traffic behaviors, car-following models, and perception modeling.
5. **Automation and framework development:** Create an automated simulation framework capable of handling a variety of work zone configurations which will streamline the testing process.

4.3.2.2 CLOSED TEST TRACK AND ON-ROAD TESTING

1. **Research with more vehicles:** Expand research efforts beyond CMU's AVs by incorporating a broader range of vehicles to better simulate real-world conditions.
2. **GPS signal loss research:** Investigate the effects of GPS signal loss, especially in challenging environments like bridges and underpasses, to improve AV navigation.
3. **V2X communication testing:** Continue testing the C-V2X stack, focusing on the complexities of signal drop/blockage and line-of-sight (LOS) issues. Explore the USDOT C-V2X simulation stack for further improvements in this area.
4. **AV perception distance limitations:** One of the Project's work zone scenarios (a stop-controlled intersection where the middle section of the road was closed and the AV has to look at the other end of the work zone for vehicles) required the AV to "look" further than it was capable to negotiate shared lane usage with a human driver. However, due to perception distance limitations, the AV was unable to negotiate this work zone scenario. Further research is required to deal with scenarios where the AVs are incapable of perception due to distance limitations.
5. **Need for High-Performance, Low Power On-Road and Near-Road Computing for simultaneous data collection and AV operations**: To address the challenge of parallel logging and processing being computationally intensive during closed test track and live on-road runs, exploring the potential of high-performance computing for enhanced data handling capabilities is recommended. High performance computing could offer substantial improvements in data processing speed and efficiency, enabling real-time logging and processing without compromising the AV's performance. By harnessing the power of advanced high-performance computing, the system could process large volumes of data from sensors, GPS, and other inputs simultaneously, eliminating the resource bottlenecks typically associated with vehicle-based logging and data processing. This would allow for more seamless data collection and analysis, ensuring that AV performance remains unaffected during testing.

4.3.2.3 TECHNOLOGY AND DATA NEEDS

1. **Launch a large research, development, and deployment program on AVs**: A focused "DARPA-like" program that brings together advanced research organizations, leading automotive companies, and state/local government agencies that advances and accelerates the development and deployment of a comprehensive opens-source AV stack encompassing sensors, computation, communications, and controls is sorely needed. Real-world considerations span a very wide range of operating conditions across different weather, lighting, traffic, and road conditions, creating combinations that, in a statistical sense, fall well outside the normal distribution and far into unlikely, but still possible, tails of statistical distribution of events. The "tail" is very long and requires both consolidated and coordinated support to define and constrain within Operational Design Domains (ODD), and to establish clear testing/validation/certification criteria within these. The verification and validation of the AV stack must also be deeply studied. Societal trust in AVs must continue to be built. Regulatory requirements must be addressed and accommodate many different perspectives.
2. **Enhance data flow and processing:** Improve data flow and processing capabilities, particularly with cloud data services and edge computing, to enable real-time data processing and more efficient data sharing.
3. **Automate and streamline the data collection and annotation process:** Advanced algorithms and AI can be employed to automatically generate and synthesize data from various sensors (LiDAR, cameras, radar) to ensure accurate, real-time mapping of work zone conditions. These intelligent systems can also automate the annotation of data for training AV perception systems, significantly reducing manual labor and improving data accuracy. Such automation would enable faster, more efficient data processing—helping to meet the growing demands of AV testing and deployment while enhancing overall system performance.
4. **Standardization and open data specifications:** Develop standardized formats for HD, or even "medium definition" MD maps to facilitate data exchange between AVs from different RSU manufacturers to create consistency in the work zone environment.
5. **Expanded testbeds:** Establish physical testbeds with diverse features (incorporate various weather and lighting conditions) to allow for comprehensive testing in various real-world conditions.
6. **USDOT repository:** USDOT should require the use of USDOT data repository for data collection and storage. By leveraging this centralized repository, all collected data—ranging from sensor outputs to work zone maps—can be securely stored and made available for future analysis. The USDOT repository could provide a standardized platform for sharing data with stakeholders—including government agencies, industry researchers, and the public. This approach will enhance data transparency, support ongoing research, and facilitate the development of consistent, high-quality datasets

that are critical for advancing AV technologies and ensuring safety across transportation systems.

4.3.2.4 FUTURE RESEARCH AND TESTING NEEDS

1. **Optimal work zone layouts for AV performance**: Precision and parameters of work zone layouts are more important with AVs than human-driven vehicles, as AVs have a harder time adapting to unique situations. There is a need to understand how work zone layouts can be improved to incorporate AVs. Work zone layout features to be investigated include work zone lane widths (given the speed limit), distance between work zone channelizer devices, indication of the work zone start/end points, and the placement of the work zone channelizer devices with respect to the lane markings (on the lane marking vs adjacent).
2. **Gesture recognition:** As AVs interact with police, flaggers, pedestrians, and other road users, accurately interpreting gestures such as hand signals is crucial for ensuring safe and reliable operations. Research is needed to improve the AV's ability to recognize and respond to a wide range of gestures in real-time, particularly in dynamic and unpredictable environments like work zones. Developing robust, accurate, and scalable gesture-recognition systems will be essential for enabling AVs to navigate safely in complex traffic scenarios.
3. **Work zone impacts on computer perception:** Several research needs were identified to understand the effect of different work zone object parameters on computer perception. These include:
    a. Type of channelizers to use,
    b. Size and shape of channelizers to use,
    c. Use of less retroreflective channelizers (age),
    d. Accuracy of placement of the channelizers,
    e. Misaligned/fallen channelizers, and
    f. Width, colors, and types of pavement markings (glass beads vs no glass beads).
4. **Work Zone Connectivity:** There is a need to understand the best connectivity parameters to use for the format and content of message, the message size, broadcast frequency, and errors in the message (e.g., if a barrel has fallen over or moved).
5. **HD mapping:** There is a need to understand the best practices for HD mapping, including the format and content of the map, the mapping resolution/granularity, the mapping and transfer frequency, and the transfer process between the DMS and AV.
6. **Handling real-world challenges:** Continue research to address real-world challenges such as lighting, weather, road conditions, and varying traffic to ensure AVs can adapt to these factors.
7. **Digital road rule definitions:** Develop a digital definition of road rules that can be integrated into AV systems for improved compliance and safety.
8. **Security Credential Management System (SCMS):** Deploy a SCMS at scale to ensure the effective and reliable delivery of Safety Critical Messages. This would enable

communication between vehicles, work zones, and traffic control systems—ensuring real-time updates on road conditions, work zone activity, and the status of AVs. As AVs rely on constant and timely data updates, having an efficient message system in place will support seamless communication and coordination and reduce the risk of safety-related incidents. Moreover, ensuring that messages are securely transmitted and managed will be critical to maintaining the integrity of the communication system and guaranteeing that vital safety information reaches all stakeholders promptly.

9. **AI trustworthiness and addressing hallucinations:** Focus on improving AI systems to eliminate hallucinations (where AI makes decisions based on fabricated or incorrect information, such as erroneous identification of objects, misinterpretation of road conditions, or the failure to detect critical obstacles, which could have serious implications for safety and reliability) and ensure trustworthiness in the AV's decision-making processes, particularly in dynamic and complex work zone environments.
10. **Integrating GPS technology into lane striping vehicles:** Currently, lane striping vehicles do not use GPS for accurate placement of lane markers. By incorporating GPS into these vehicles, the precise coordinates of lane boundaries can be captured and directly shared with AV mapping companies. This would improve lane detection and navigation for AVs, especially in dynamic or temporary work zones where lane configurations change frequently. Standardizing this GPS integration would enhance the accuracy of lane markers, provide more reliable mapping data for AVs, and contribute to safer and more efficient roadways.
11. **Geographical scalability:** Develop standardized methods and performance metrics for testing AV systems that can be applied across different regions. This will enable consistent, geographically distributed testing and system improvements, ensuring regular validation and refinement of AV technologies for work zones.

These next steps and future needs will guide the continued development and deployment of AVs in general (and particularly in work zones) to ensure this technology is scalable, reliable, and effective in real-world applications.

Appendix A. Acronyms

Table 5 below lists acronyms and abbreviations used in the document.

Table 5. Acronyms

Acronym	Definition
3D	Three-Dimensional
4G	Fourth Generation
5G	Fifth Generation
ADS	Automated Driving System
AI	Artificial Intelligence
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
ASAM	Association for Standardization of Automation and Measuring Systems
ATC	Advance Transportation Controllers
AV	Automated Vehicle
BSM	Basic Safety Messages
C-V2X	Cellular Vehicle-to-Everything
CAD	Computer Aided Design
CADRE	Connected and Autonomous Driving Research and Engineering
CARLA	CAR Learning to Act
CAV	Connected and Automated Vehicle
CMU	Carnegie Mellon University
ConOps	Concept of Operations
DGPS	Differential Global Positioning System
DMP	Data Management Plan
DMS	Data Management System
ENU	East, North and Up
ESM	Enhanced Safety Messages

Acronym	Definition
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GPS	Global Positioning System
HD	High Definition
HIA	Here I Am
IRB	Institutional Review Board
IT	Information Technology
ITS	Intelligent Transportation Systems
LiDAR	Light Detection and Ranging
LLA	Latitude, Longitude, and Altitude
LOS	Line-of-Sight
MAP	Map Message
MB	Megabyte
MPMP	Multi-Packet Memo Protocol
NTIA	National Telecommunications Information Administration
O&M	Operations and Maintenance
OBU	Onboard Unit
ODD	Operational Design Domain
OSM	Open Street Map
PennDOT	Pennsylvania Department of Transportation
PMP	Project Management Plan
PMBOK	Project Management Body of Knowledge
PPG	Pittsburgh Plate Glass
PSU	Pennsylvania State University
PTC	Pennsylvania Turnpike Commission
QA/QC	Quality Assurance/Quality Check
RMP	Risk Management Plan

Acronym	Definition
RSU	Roadside Unit
RTK	Real-time kinematic positioning
SASP	System Architecture and Standards Plan
SCM	Safety Critical Messages
SCMS	Security Credential Management Systems
SDK	Software Development Kits
SE	Systems Engineering
SEBoK	Systems Engineering Body of Knowledge
SEMP	Systems Engineering Management Plan
SSM	Surrogate Safety Metrics
SPaT	Signal Phase and Timing
SUMO	Simulation of Urban Mobility
TB	Terabyte
TIM	Traffic Incident Management
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VPN	Virtual Private Network
WGS	World Geodetic System
WZDx	Work Zone Data Exchange

Appendix B. Work Zone Scenarios for Demonstrations

Table 6. List of Considered Work Zone Scenarios

Scenario No.	Scenario Description			PennDOT/ PTS Standard[9]	Simulation	Closed-Track Testing	Live On-Road Testing
	No. of Lanes	Short Name	Scenario				
Use Case 1			**Conventional Highways – Short-Term**				
Scenario 1.1	Any	Shoulder Work	Work on or Beyond the Shoulder – Single-Lane Approach – Shoulder Work with Minor or No Roadway Encroachment	PATA 102	X	X	
Scenario 1.2	Any	Orange Detour	Road Closure with Detour – Standard Orange Detour Signs	PATA 116-A	X	X	
Scenario 1.3	3	Opposing Lane	Work on Single-Lane Approach – Self-Regulating Lane Shift into Opposing Lane	PATA 118	X	X	
Scenario 1.4	3	Center Lane Shift	Work on Single-Lane Approach – Self-Regulating Lane Shift into Center Left-Turn Lane	PATA 121	X	X	
Scenario 1.5	3 or More	Center Lane Work	Work on Single-Lane Approach – Work in Center Left-Turn Lane	PATA 122	X	X	
Scenario 1.6	3 or More	Multilane Work	Work on Multi-Lane Approach – Work in Left or Right Lane – Undivided Highway	PATA 123-A or 123-B	X	X	
Use Case 2			**Conventional Highways – Long-Term**				
Scenario 2.1	Any	Route Detour	Road Closure with Detour – Detour of a Numbered Traffic Route	PATA 214	X	X	
Scenario 2.2	2	Stop Control	Work on a Single-Lane Approach – Self-Regulating Stop-Control	PATA 205	X	X	
Scenario 2.3	2	Temporary Roadway	Temporary Roadway	PATA 203	X	X	
Scenario 2.4	Temporary Signals	Trailer-Mounted Signals	Complex Conditions – Trailer-Mounted Signals	PATA 706	X	X	
Use Case 3			**Conventional Highways – Mobile**				
Scenario 3.1	2 or More	Moving Closure	Work on Single-Lane Approach – Moving Lane Closure	PATA 303	X	X	X
Use Case 4			**Freeways and Expressways – Short-Term**				
Scenario 4.1a	2 or More	Freeway Work	Work on Two-Lane Approach – Work in Left or Right Lane	PATA 402-A or 402-B	X	X	X
Scenario 4.1b	2 or More	Turnpike Work	Work on Two-Lane Approach – Work in Left or Right Lane	PTS 915-4	X	X	
Scenario 4.2	Divided	Off-Ramp	Work Near Interchange Ramps – Work in Right Lane Near Right-Exit Ramp	PATA 404-A	X	X	
Scenario 4.3	Divided	On-Ramp	Work Near Interchange Ramps – Work in Right Entrance Ramp with Stop or Yield Control	PATA 405-A or 406-A	X	X	

[9] *Note: If PennDOT Publication 213 is updated before the project is deployed, the newest publication version will be used for the equivalent work zone scenario. The scenarios will be "frozen" at that time and no longer updated for the duration of the project. The current version used is the April 2022 update.*

Scenario No.	Scenario Description			PennDOT/ PTS Standard[9]	Simulation	Closed-Track Testing	Live On-Road Testing
	No. of Lanes	Short Name	Scenario				
Use Case 5	**Freeways and Expressways – Mobile**						
Scenario 5.1a	2 or More	Mobile Freeway	Work on Two-Lane Approach – Work in Left or Right Lane	PATA 602-A or 602-B	X	X	X
Scenario 5.1b	2 or More	Mobile Turnpike	Work on Two-Lane Approach – Work in Left or Right Lane	PTS 915-2	X	X	
Scenario 5.2	Divided or One-Way	Three-Lane Work	Work on Three-Lane Approach – Work in Left, Right, or Two (Right and Center or Left and Center) Lanes	PATA 603-A, 603-B, or 603-C	X	X	
Use Case 6	**Freeways and Expressways – Others**						
Scenario 6.1	2 or More	Shoulder Use	Freeways and Expressways – Long-Term Shoulder Use	PATA 508-B	X	X	

Appendix C. Project Concept of Operations

The Project's high-level Concept of Operations is shown in Figure 5. As the mapping van traversed the work zone, it collected and processed data to generate HD maps and C-V2X messages, which were subsequently uploaded to the DMS for storage and sharing with the AV and other researchers. Here I Am (HIA) devices on the work zone objects provided their real-time location data. This information was aggregated by a field computer and transmitted to the RSU, which then relayed the data to the AV. As the AV approached the work zone, it received HD mapping data through the RSU. In addition, the AV relied on its perception system to navigate the work zone safely. GNSS and base stations ensured precise positioning and seamless communication. All data collected during the deployment was processed, stored in the DMS, and made available for sharing and future use.

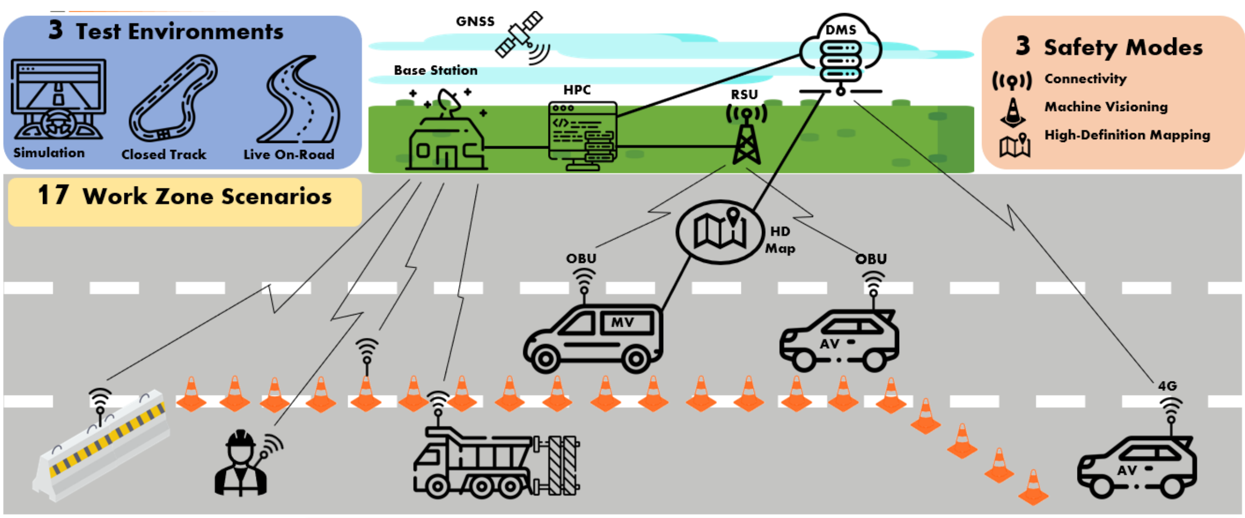

Figure 5. Project Concept of Operations

Appendix D. Papers and Publications

1. Weijing Shi and Ragunathan (Raj) Rajkumar, IEEE "Workzone Detection for Autonomous Vehicles", 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), pp. 1585-1591, September 2021.
2. Shounak Sural, "Robust Perception for Autonomous Vehicles in Adverse Operating Conditions", Technical Report, Department of Electrical and Computer Engineering, Carnegie Mellon University, 2022.
3. Gregory Su, "On the Safety of Autonomous Vehicles in Inclement Conditions and Work Zones", Technical Report, Department of Electrical and Computer Engineering, Carnegie Mellon University, 2022.
4. Gregory Su, "Detailed CV2X Evaluation", Technical Report, Department of Electrical and Computer Engineering, Carnegie Mellon University, 2024.
5. Shounak Sural, Gregory Su, Nishad Sahu, Naren, Ragunathan (Raj) Rajkumar, "CoSim: A Co-Simulation Framework for Testing AVs in Adverse Operating Conditions", 2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC), pp. 2098-2105, IEEE, 2023.
6. Putz, Marcus. "A Unified Method to Calculate Safety Surrogates for an Autonomous Vehicle in Work Zones." MS Thesis, Penn State University. May 2024.
7. Putz, Marcus, Sean Brennan. "A Unified Framework for Calculation of Surrogate Safety Metrics for Autonomous Vehicles in Work Zones." Road Safety and Simulation Conference of the Transportation Research Board (RSS – TRB). 2024. Lexington, Kentucky, USA. 28-31 October 2024.
8. Xinyu Cao, Sean Brennan. "Merging Multi-antenna GPS Data for Vehicle Pose Estimation." Road Safety and Simulation Conference of the Transportation Research Board (RSS – TRB). 2024. Lexington, Kentucky, USA. 28-31 October 2024.
9. Xinyu Cao, Sean Brennan. "Extrinsic Calibration of 3D LiDAR Using Sphere Targets and Target-Centered GPS." Road Safety and Simulation Conference of the Transportation Research Board (RSS – TRB). 2024. Lexington, Kentucky, USA. 28-31 October 2024.
10. Wagh, Vaishnavi, and Sean Brennan. "Discrepancies in AV Work Zone Mapping: Analyzing Design vs. As-built Coordinates and Their Impact on Safety." Road Safety and Simulation Conference of the Transportation Research Board (RSS – TRB). 2024. Lexington, Kentucky, USA. 28-31 October 2024
11. Lin Lyu, Wushuang Bai, Sean Brennan. "Evaluation of Autonomous Vehicle Speed Consistency Compared to Human-driven Vehicles in Work Zones." Automated Road Transportation Symposium (ARTS). 2024.
12. Xinyu Cao, Sean Brennan. "A Comparative Analysis of the Effects of Work Zone Lane Marking Materials and Marker-Painting Methods on LiDAR Point Cloud Measurements." Automated Road Transportation Symposium (ARTS). 2024.

13. Shounak Sural, Naren, Ragunathan (Raj) Rajkumar, “ContextualFusion: Context-Based Multi-Sensor Fusion for 3D Object Detection in Adverse Operating Conditions”, 27th IEEE International Conference on Intelligent Transportation Systems (ITSC), 2024.
14. Shounak Sural, Naren, Ragunathan (Raj) Rajkumar, “ContextVLM: Zero-Shot and Few-Shot Context Understanding for Autonomous Driving using Vision Language Models”, 27th IEEE International Conference on Intelligent Transportation Systems (ITSC), 2024.
15. Nishad Sahu, Ragunathan (Raj) Rajkumar, “SafeRoute: Risk-Minimizing Cooperative Real-Time Route and Behavioral Planning for Autonomous Vehicles”, 27th IEEE International Conference on Intelligent Transportation Systems (ITSC), 2024.
16. Gregory Su and Ragunathan (Raj) Rajkumar, “MPMP: A Protocol to Transmit Long Messages for V2X Applications”, 2024 IEEE 100th Vehicular Technology Conference, October 2024.
17. 16. Bai, Wushuang. “Defining the Region of Influence in Traffic Systems.” PhD Thesis. Penn State University. Nov. 25th, 2024.

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