Automated Driving System Demonstration (ADS)
Grant Application| NOFO693JJ319NF00001
Safe Integration of Automated Vehicles into Work Zones
|PKG 00247169

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

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Deployment Plan Safe Integration of Automated Vehicles into Work Zones		5. Report Date 6. Performing Organization Code
7. Author(s) Carnegie Mellon University HTNB, Inc.		8. Performing Organization Report No.
9. Performing Organization Name and Address Pennsylvania Department of Transportation 400 North Street, 6th Floor, Harrisburg, PA 17120		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address ITS Joint Program Office 1200 New Jersey Avenue, S.E., Washington, DC 20590		13. Type of Report and Period Covered Deployment Plan, 03/16/2022 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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

This document presents the deployment strategies and approach for demonstrating the three goals of the project: safe navigation of AVs in each work zone with improved connectivity, high-definition mapping, and stakeholder coordination. The document includes the schedule, approach, requirements, and risks involved. This document presents detailed information on the deployment scenario development and approach for project demonstration. 19 test scenarios and their corresponding deployment configurations are presented.

This document supplements the *Testing Plan* and *Operations and Maintenance (O&M) Plan* that are developed for the project, which helps in following a rigorous deployment approach. The plan also explains roles and responsibilities of various team members based on the different deployment scenarios

17. Keywords	18. Distribution Statement		
Data, Automated Vehicle, Connected Vehicle, Work Zone, Mapping, Safety, Demonstration			
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The U.S. Government is not endorsing any manufacturers, products, or services cited herein and any trade name that may appear in the work has been included only because it is essential to the contents of the work.

ACKNOWLEDGEMENT OF SUPPORT

This material is based upon work supported by the U.S. Department of Transportation under Agreement No. NOFO693JJ319NF00001.

DISCLAIMER

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the Author(s) and do not necessarily reflect the view of the U.S. Department of Transportation.

VERSION HISTORY

Version	Date	Author(s)	Reviewer(s)	Summary of Changes
1.1	03/16/22			Initial Draft Version
1.2	04/29/22			Internal Team Reviewed Draft
1.3	05/27/22			Core Team Reviewed Draft
1.4	06/13/22			QC Reviewed Draft
1.5	06/15/22			Final First Draft

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1 INTRODUCTION

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

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

PennDOT applied for the USDOT ADS Grant Program and received a total funding award of $8,409,444 over four (4) years. PennDOT plans to utilize these funds for research and development, planning, testing, demonstrating, and deploying the safe integration of AVs in each work zone.

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

2 DOCUMENT SCOPE AND PURPOSE

The *Deployment Plan* is developed as part of Phase I – the planning phase – of the project. The team will implement and deploy the plan developed as part of Phase II – the deployment phase.

2.1 Deployment Overview

Based on PennDOT's work zone knowledge, the team has identified common work zone scenarios / configurations to provide a diverse set of experiences for the AV to navigate. Chosen scenarios include urban, rural, and suburban settings, as well as on limited access facilities and urban arterials. These scenarios are typical in Pennsylvania, but also relevant to other states across the country. Each work zone scenario setup includes the lane configuration and traffic control devices as identified in PennDOT's *Publication 213 - Temporary Traffic Control Guidelines*[1]. In addition, connectivity equipment, including V2X communications technology, is added to the selected traffic control devices, construction workers, and vehicles (collectively called *work zone objects*). Pavement markings and work zone objects are enhanced with special coatings developed by PPG Industries, Inc. (PPG) to improve visibility, specifically for the AV sensors.

For each of the work zone scenarios, the team is conducting simulation and closed track testing at the Penn State University (PSU) test track. The *Deployment Plan* discusses the process to conduct live on-road testing for at least three (3) of the work zone scenarios including one (1) long-term, one (1) short-term, and one (1) mobile work zone.

The simulation and testing processes include the detailed mapping of each work zone with PSU's enhanced mapping vehicle, making the map accessible to the AV owned by Carnegie Melon University (CMU), and operating the AV through each simulated and staged work zone, first in the closed track and then in the live on-road environment. The mapping data produced by the PSU team has resolution sufficient for both importing the environment into AV simulation toolsets – the CARLA simulation tool is used in this project – as well as for sharing with the AV itself. Throughout the simulation and testing process, mapping data, AV data, connectivity ecosystem data, operational data, and safety performance data is collected and stored in a cloud-based Data Management System (DMS). These data are made available for open access by the United States Department of Transportation (USDOT) and, (with approval from the USDOT), by the public. Specific information about interacting with the DMS is included in the *Data Management Plan*.

2.2 Purpose of the Deployment Plan

The *Deployment Plan* details the steps required to set up each testing environment in preparation for testing and operation. Detailed deployment processes for each of the testing environments are included and broken down into the following areas:

- Software descriptions
- Needs and requirements
- Approach
- Tools
- Roles and responsibilities
- Risks, challenges, and mitigation strategies

2.3 Relation to Project Documents and Systems Engineering Context

The project has developed several complementary plans as part of the project for planning, implementation, deployment, evaluation, and operations. Specifically, three plans developed as part of this project describe the detailed steps necessary to complete demonstrations successfully and collect the data necessary to evaluate the efficacy of the work zone AV support systems being tested. These are

[1] http://www.dot.state.pa.us/public/pubsforms/publications/pub%20213.pdf

the *Deployment Plan*, the *Testing Plan*, and the *Operations and Maintenance (O&M) Plan*. Section 2.3.1 gives an overview of each plan in relation to the systems engineering "V" diagram (Figure 1). Section 2.3.1.1 discusses the overall purpose of and differences between the plans. Section 2.3.1.2 gives an example of the plans in action for the roadside unit (RSU) installation, testing, and use.

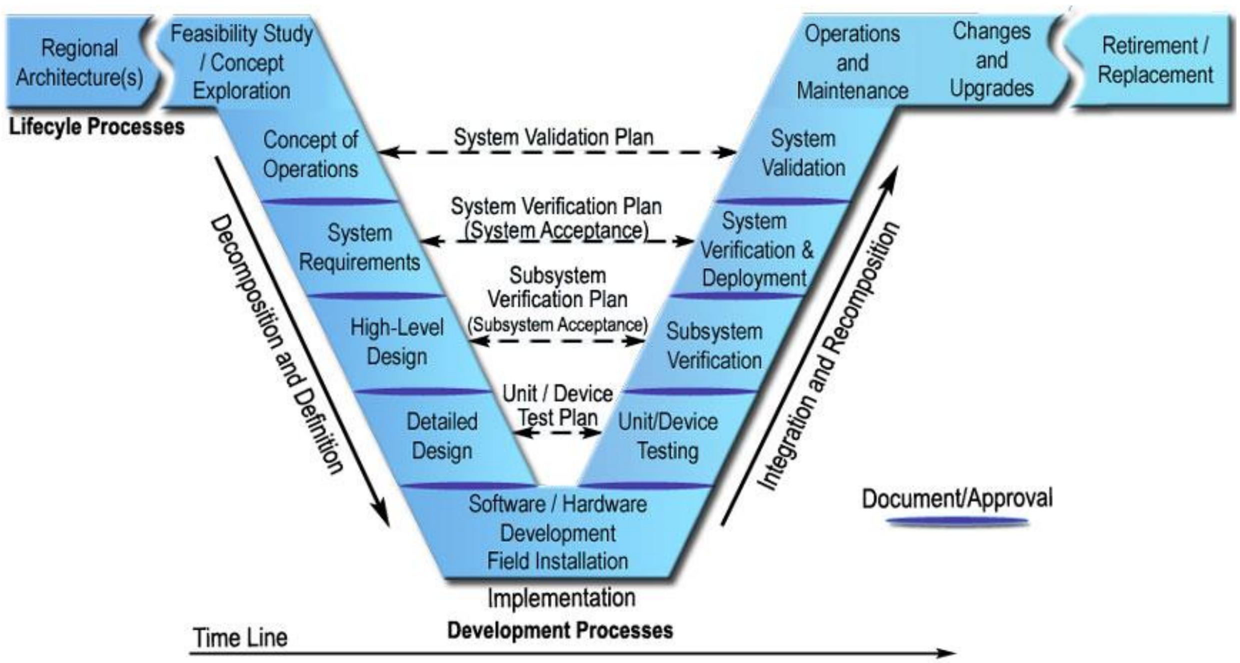


Figure 1. Systems Engineering "V" Diagram

2.3.1 Overview of Deployment, Testing, and O&M Plans

Each of these documents discusses the implementation steps for the different testing and deployment environments (i.e., simulation, closed-track, and live on-road contexts), each of the operational subsystems (i.e., mapping van and AV), and various roadside infrastructure support system (such as roadside units and work zone objects,). Integration with the DMS is also discussed in each of the following plans.

1. The *Deployment Plan* is a part of the definition of the "System Requirements" step and utilized during the System Verification and Deployment" step. The plan details the steps required to set up the environments with all needed elements and prepare operational and support systems to be ready for successful demonstration and data collection.
2. The *Testing Plan* is a part of the "Detailed Design" step and utilized during the "Unit/Device Testing" step. The plan details the steps required to test each operational and support system before and during deployment. This includes inspection, demonstration, test, and analysis techniques. The plan also covers system requirements, which overlaps with the *Deployment Plan*.
3. The *O&M Plan* is developed throughout the "Decomposition and Definition" phase and utilized during the "Operations and Maintenance" step. The plan details the steps required to operate the operational and support systems within each environment. The plan also covers maintenance requirements for all operational and support systems.

There is some inevitable overlap across these plans; where this overlap exists, the project team will ensure consistency.

2.3.1.1 Purpose of Plans

- **Deployment Plan**
  - Which support systems are required for a successful deployment in each environment?
  - How is each environment set up for deployment?
  - Who will supply and setup each operational and support system?
  - How and when will systems be configured for each scenario and permutation?
- **Testing Plan**
  - What is the setup required for test procedures for each operational and support system?
  - Which systems are used for data collection and what are their requirements?
  - Which data will be collected and how will it be collected?
  - How will data be analyzed and tested?
- **O&M Plan**
  - How is each operational and support system operated in each location?
  - Who operates the systems and how specifically will this operation progress?
  - How do support systems interact with each system?
  - How are systems maintained and who is responsible for maintenance?

2.3.1.2 Example of Plans for RSU Implementation

- **Deployment Plan**
  - Where is the RSU placed?
  - Who places and sets up the RSU?
  - When is the RSU placed?
  - How is the RSU placed?
  - **Example step: RSU(s) installed in the work zone testing area**
- **Testing Plan**
  - Who will test the RSU operation before and during deployment?
  - What constitutes successful setup of the RSU?
  - What data will be transmitted from the RSU during deployment?
  - **Example step: Demonstrate the RSU(s) shall broadcast SAE J2745 compliant MAP messages.**
- **O&M Plan**
  - Who is responsible for operating and maintaining the RSU during deployment?
  - How will the RSU be communicated with during the deployment?
  - When does the AV interact with the RSU?
  - **Example step: AV receives a MAP from an RSU**

3 DEPLOYMENT METHODOLOGY

During the *Concept of Operations* phase of the project, the project team selected 19 scenarios for use in this project. Scenarios were selected to provide a good cross-section of common work zone types. These will allow for the AV to perform several tasks that are relevant to many additional work zone situations. Scenarios may need to be modified in order to complete closed-track testing, and this procedure is discussed in Chapter 8. It is possible that certain scenarios will not be feasible and will need to be removed from this study. This will be determined after scenarios are mapped by the mapping van and data is processed. Updates will be made to this document as necessary.

During the deployment phase of this project, an AV will be deployed and tested within different work zone scenarios in various environments including simulation, closed-track testing, and an on-road live testing environment as shown in Figure 2. Figure 2 shows the linear nature of the deployment methodology. At every step, the team will review the data and make an assessment about moving forward to the next step by addressing any issues that arise before and during the process. For instance, after closed-track testing is complete, the simulations will be re-reviewed to check and see how well the simulation methodology represents the real world. Following this review, the simulation may need to be tweaked or re-calibrated to be more accurate. The exact process of transitioning between testing methodologies and the decision gates is discussed in the following sections.

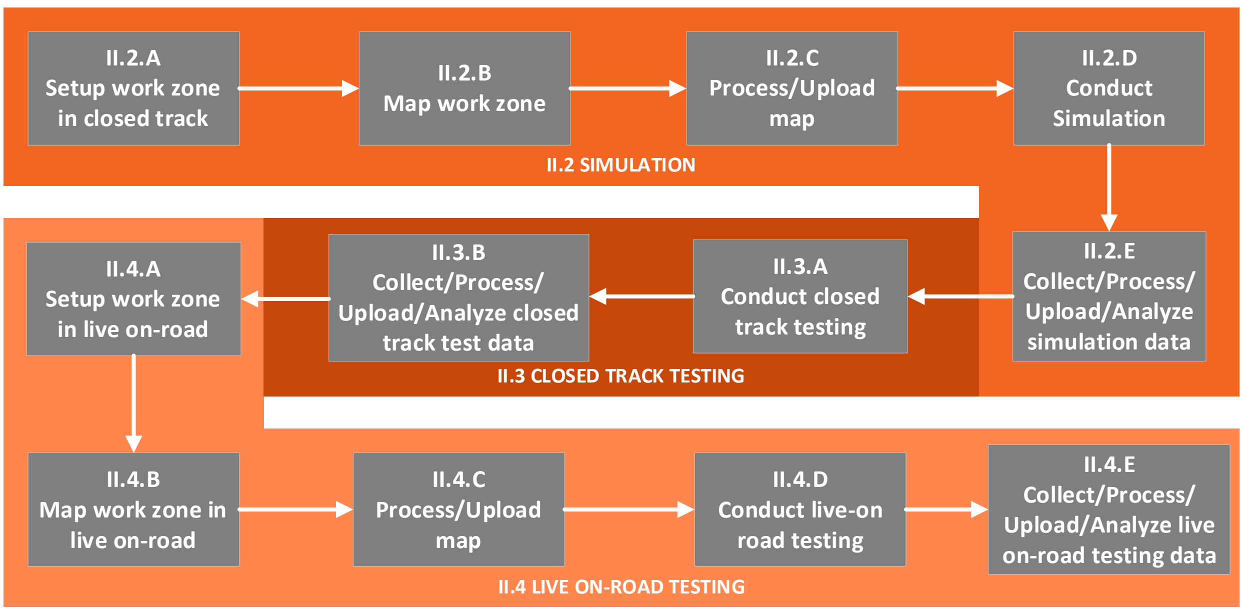


Figure 2. High-level Deployment Flowchart

Table 1 maps each item in Figure 2 flowchart to the corresponding section of the *Deployment Plan* where the deployment specifics for the given item are discussed in detail.

Table 1. Mapping of Deployment Steps and Deployment Plan Sections

Deployment Step	Step Name	Section of Deployment Plan
II.2.A	Setup work zone in closed track	8.4.2
II.2.B	Map work zone	8.4.3
II.2.C	Process/upload map	8.4.3
II.2.D	Conduct simulation	0
II.2.E	Collect/process/upload/analyze simulation data	0
II.3.A	Conduct closed-track testing	9.3
II.3.B	Collect/process/upload/analyze closed-track testing data	9.3
II.4.A	Setup work zone in live on-road	10.3
II.4.B	Map work zone in live on-road	10.3
II.4.C	Process/upload map	10.3
II.4.D	Conduct live on-road testing	10.3
II.4.E	Collect/process/upload/analyze live on-road testing data	10.3

4 DEPLOYMENT PARTNERS

PennDOT has identified a group of representatives as deployment partners who will be part of the project deployment team. The deployment partners include CMU, PSU, PPG, Deloitte, Pennsylvania Turnpike Commission (PTC), and PennDOT.

The following deployment partners will lead various portions of the project:

- CMU's CAV experts will lead the simulation efforts and support the closed track and live on-road testing particularly in the operation of the AV. The deployment lead for CMU is Raj Rajkumar.
- PSU, which hosts the closed-track testing facility, will lead the closed-track testing and support simulation and live on-road testing particularly in the operation of the mapping vehicle and road-side equipment. The deployment lead for PSU is Sean Brennan.
- PPG will supply coatings as required for the project needs. The deployment lead for PPG is to be determined.
- Deloitte, with DMS expertise, will lead the deployment and operations and maintenance of the DMS. The deployment lead for Deloitte is Maggie Hailemariam.
- PTC will accommodate on-road testing and support the project as needed. The deployment lead for PTC is Michael Pack.
- PennDOT will bring in necessary roadside infrastructure with its work zone field experience, will lead on-road testing and support simulation and closed-track testing. The deployment lead for PennDOT is Gunnar Rhone.

5 DEPLOYMENT SCHEDULE

The deployment phase of the project is planned to take place over two years. Closed-track testing and simulation will demonstrate the CMU-AV's ability to navigate through seventeen (17) PATA and two (2) PTS work zone scenarios as designed in the project under multiple conditional permutations. This section includes an estimated schedule of activities. Simulation and closed-track testing will run in tandem, using groups of scenarios. These are explained in the following sections.

5.1 Deployment Scenarios

There are 19 deployment scenarios, shown in Table 2, and these scenarios will be applied to simulation and closed-track testing. Three scenarios (to be chosen later) will be completed for live on-road testing. Appendix A includes PennDOT standard drawings for each scenario along with CAD drawings specific to the test track setup. All deviations from PennDOT standards will be detailed during the mapping phase.

Table 2. Complete list of Deployment Scenarios

Scenario No.	Scenario Description			PennDOT/PTS Standard[2]
	No. of Lanes	Short Name	Scenario	
1	**Conventional Highways – Short-Term**			
1-1	Any	Shoulder Work	Work on or Beyond the Shoulder – Single-Lane Approach – Shoulder Work with Minor or No Roadway Encroachment	PATA 102
1-2	Any	Orange Detour	Road Closure with Detour – Standard Orange Detour Signs	PATA 116-A
1-3	3	Opposing Lane	Work on Single-Lane Approach – Self-Regulating Lane Shift into Opposing Lane	PATA 118
1-4	3	Center Lane Shift	Work on Single-Lane Approach – Self-Regulating Lane Shift into Center Left-Turn Lane	PATA 121
1-5	3 or More	Center Lane Work	Work on Single-Lane Approach – Work in Center Left-Turn Lane	PATA 122
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
2	**Conventional Highways – Long-Term**			
2-1	Any	Route Detour	Road Closure with Detour – Detour of a Numbered Traffic Route	PATA 214
2-2	2	Stop Control	Work on a Single-Lane Approach – Self-Regulating Stop-Control	PATA 205
2-3	2	Temporary Roadway	Temporary Roadway	PATA 203
2-4	Temporary Signals	Trailer-Mounted Signals	Complex Conditions – Trailer-Mounted Signals	PATA 706
3	**Conventional Highways – Mobile**			
3-1	2 or More	Moving Closure	Work on Single-Lane Approach – Moving Lane Closure	PATA 303
4	**Freeways and Expressways – Short-Term**			
4-1a	2 or More	Freeway Work	Work on Two-Lane Approach – Work in Left or Right Lane	PATA 402-A or 402-B
4-1b	2 or More	Turnpike Work	Work on Two-Lane Approach – Work in Left or Right Lane	PTS 915-4
4-2	Divided	Off-Ramp	Work Near Interchange Ramps – Work in Right Lane Near Right-Exit Ramp	PATA 404-A
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
5	**Freeways and Expressways – Mobile**			
5-1a	2 or More	Mobile Freeway	Work on Two-Lane Approach – Work in Left or Right Lane	PATA 602-A or 602-B
5-1b	2 or More	Mobile Turnpike	Work on Two-Lane Approach – Work in Left or Right Lane	PTS 915-2
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
6	**Freeways and Expressways – Others**			
6-1	2 or More	Shoulder Use	Freeways and Expressways – Long-Term Shoulder Use	PATA 508-B

[2] 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.

5.1.1 Scenario Definitions

Definitions (from PennDOT Publication 213) for some of the key terms used in Table 2 are as follows:

- Conventional Highway - Any highway / roadway other than a freeway or expressway. Conventional highways are further characterized as either Rural Highways or Urban Highways
- Expressway - A divided arterial highway for through traffic with partial control of access and generally with grade separations at major intersections.
- Freeway - A limited access highway to which the only means of ingress and egress is by interchange ramps.
- Short-Term Stationary Operation - An operation that will occupy a location for up to 72 hours. The work zone will have stationary beginning and ending points. Work activity may move freely within these limits.
- Long-Term Stationary Operation - Work that occupies a location for a period of more than 72 hours.
- Mobile Operation - A moving operation that proceeds downstream at least 100' every 15 minutes. Every component of the operation, excluding advanced warning signs and flagger locations, must proceed in the direction of normal traffic flow. The distance/time threshold must be met for the entire duration of the operation to utilize PATA 300 or 600 Series plans.
- Self-Regulating work zone (not defined in 213) – A work zone that is defined by a combination of signs, channelizing devices, barriers, pavement markings, and/or work vehicles that effectively regulates traffic without the use of a flagger.

5.1.2 Scenario Setup Data Flow

Each scenario may be modified as needed during various deployment phases to allow for a successful test. The flowchart in Figure 3 shows the steps required for each scenario from the original PATA diagram through to the final post-run diagram. The goal is to stay as close to the PATA diagram as possible while allowing for a successful demonstration.

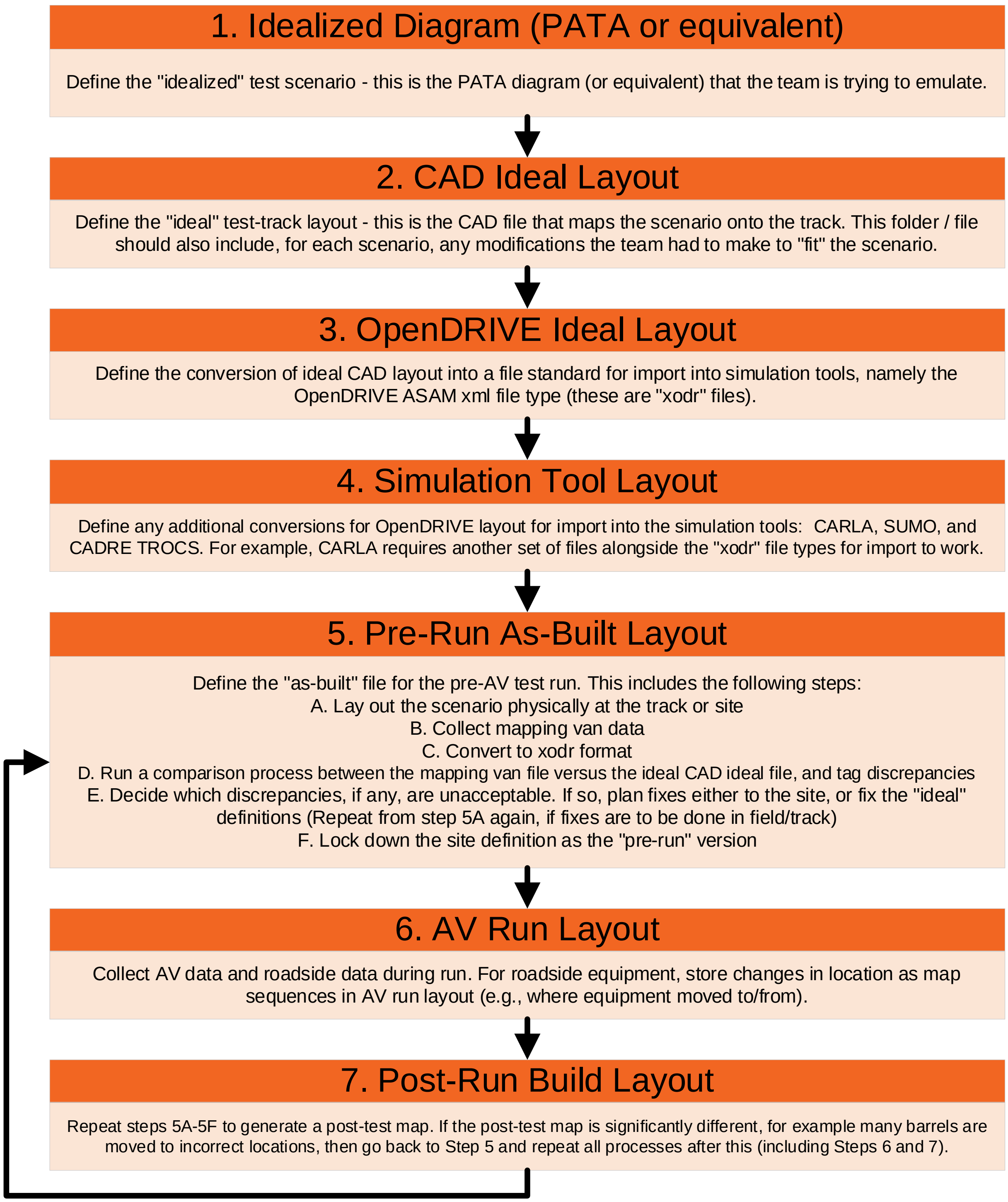


Figure 3. Data Flow for Scenario Setup

5.2 Deployment Permutations

Deployment scenarios developed will include several permutations based on several key variables. Each variable grows the number of tests by a factor of 2^n, which makes full testing of each permutation infeasible for this project. For example, four binary variables will require 16 permutations for each scenario, or 304 total tests. Adding a fifth variable will require 608 total tests. Any additional variables will increase the total permutations for testing to an untenable amount.

It is expected that some variables will have a much larger impact on AV performance, and some variables may end up being insignificant. For this reason, initial testing will be completed to determine which variables should be pursued for simulation testing (see Chapter 6 for further information).

The list of possible variables for testing includes:

- Enhanced coatings on work zone objects and markings
- Infrastructure connectivity (RSUs, V2X work zone objects, digital worker vest)
- High-definition map
- Sunlight (daytime/nighttime)
- Location of dynamic elements (workers, work trucks, etc.)
- Level of service (LOS) of additional traffic

After the completion of the preliminary closed-track testing, these variables will be broken down into three categories: primary, secondary, and tertiary variables. Primary variables will be tested both on and off for each scenario. Secondary variables will be chosen at random to be tested for each scenario. Tertiary variables will not be tested on the track, but may be tested in simulation. For example, if there are three primary variables and five secondary variables, each scenario could include the primary variables and one random secondary variable. This results in four variables totaling 16 permutations per scenario.

Table 3 shows an example set of permutations for four variables: HD map, RSU connectivity, PPG enhanced coatings, and time of day. Table 3, including permutation IDs, will be updated upon completion of closed-track initial testing. Permutations will apply to both closed-track and live on-road testing.

Table 3. Testing Permutations

Permutation ID	HD Map	RSU Connectivity	PPG Enhanced Coatings	Time of Day
Base Case 1 (P0A)	No	No	No	Daytime
Base Case 2 (P0B)	No	No	No	Nighttime
Permutation 1 (P1)	No	No	Yes	Daytime
Permutation 2 (P2)	No	No	Yes	Nighttime
Permutation 3 (P3)	No	Yes	No	Daytime
Permutation 4 (P4)	No	Yes	No	Nighttime
Permutation 5 (P5)	No	Yes	Yes	Daytime
Permutation 6 (P6)	No	Yes	Yes	Nighttime
Permutation 7 (P7)	Yes	No	No	Daytime
Permutation 8 (P8)	Yes	No	No	Nighttime
Permutation 9 (P9)	Yes	No	Yes	Daytime
Permutation 10 (P10)	Yes	No	Yes	Nighttime
Permutation 11 (P11)	Yes	Yes	No	Daytime
Permutation 12 (P12)	Yes	Yes	No	Nighttime
Permutation 13 (P13)	Yes	Yes	Yes	Daytime
Permutation 14 (P14)	Yes	Yes	Yes	Nighttime

5.3 Grouping of Scenarios and Their Permutations

Given the number of tests needed on the closed track along with the many scenarios and permutations, there is a need to make operations more practical.

5.3.1 Scenario Groups

Scenarios will be demonstrated in small groups of three to five where the scenario setup is similar. Since paint striping is one of the more semi-permanent tasks, scenarios are generally grouped by lane configuration. Table 4 shows the scenario groupings. Scenarios A, B, and C are labeled as such only so that they can be referenced later during closed-track setup for deployment.

Table 4. Groups of Deployment Scenarios for Closed-track Testing

Group ID	Group Name	Scenario A	Scenario B	Scenario C
CT0	Preliminary Testing	1-1*	--	--
CT1	Two-Lane - One Direction	4-1 (a,b)	4-3	5-1 (a,b)
CT2	Two-Lane - Shift / Ramp	4-2	6-1	--
CT3	Three-Lane	1-6	5-2	--
CT4	Two Way Left Turn Lane	1-4	1-5	--
CT5	Two-Lane - Bi-Directional	2-2	2-4	--
CT6	Detour Route	1-2	2-1	--
CT7	Shoulder Work	1-1	3-1	--
CT8	Unique Striping	1-3	2-3	--

*Track will be setup for this scenario as a pre-test only, the scenario will be tested later

There are three on-road tests. Each of the three scenarios chosen will be completed separately, as OR1, OR2, and OR3.

5.3.2 Permutation Groups

All permutations will be completed for each scenario group during the same testing day(s). A group of permutations based on the sample ones from Section 5.2 are shown in Table 5. These groupings are split based upon coatings and time of day. Regardless of the permutations chosen, coatings and time of day will likely be in separate permutation groups. These groups will be updated once final testing permutations are selected. Permutations A, B, C, and D are labeled as such only so that they can be referenced later during closed-track setup for deployment.

Table 5. Groups of Permutations for All Testing

Group ID	Group Name	Permutation A	Permutation B	Permutation C	Permutation D
PG1	Daytime, No Coatings	P0A	P3	P7	P11
PG2	Nighttime, No Coatings	P0B	P4	P8	P12
PG3	Daytime, Coatings	P1	P5	P9	P13
PG4	Nighttime, Coatings	P2	P6	P10	P14

5.4 Deployment Timeline

Each deployment group is split into a roughly three-month time window for completion of the simulation and the closed-track or on-road test. In general, closed-track testing will begin with the mapping van, followed by simulation, and conclude with the AV test. The plan is to complete each of these steps for each scenario group before transitioning to the next scenario group. The estimated schedule is shown in Table 6. A detailed schedule is included in Appendix C.

Table 6. Phase 2 Deployment Timeline – Overview by Scenario Group

	2022						2023											
Scenario Group	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
CT0	■																	
CT1		■	■															
CT2				■	■													
CT3							■	■										
CT4									■	■								
CT5											■	■						
CT6													■	■				
CT7															■	■		
CT8																	■	■
OR1											■	■						
OR2													■	■				
OR3															■	■		

For live on-road testing, effort should be made to conduct tests during the main construction season, which may modify the timing shown above.

Once testing time estimates for scenario and permutation testing are determined, they will be added to this section in the form of a precise timeline.

6 PRELIMINARY CLOSED-TRACK DATA GATHERING, CALIBRATION, AND TESTING

To ensure the success of closed-track scenario testing, a preliminary closed-track evaluation study will be performed. This process (Step CT0 in the deployment timeline) will occur before official scenario testing and will last approximately one week.

The track will be set up according to Scenario 1.1 plans. Initial steps will be completed to prepare the track for the preliminary test. These include:

- Collecting and inventorying all road-side equipment items, including numbering all deployment items (e.g., to avoid mixing conventional equipment with those with specialized coatings)
- Installing RSUs and other fixed track equipment
- Striping lanes as per the scenario description
- Ensuring batteries are charged on any battery-powered systems
- Verifying connectivity on any connected items
- Checking power demands and connectivity for the road-side computer

This evaluation will involve the following procedures:

- Setting up and validating an example of each piece of test equipment element (e.g., RSUs, work zone objects, etc.)
- Configuring the track for one example scenario
- Running several tests and checks on the track using the mapping van to ensure functionality of the vehicle, data gathering systems, and track components
- Calibrating all data inputs and sensors and other system components of interest
- Completing test runs of all permutations of interest for all primary variables and a random sampling of secondary variables
- Transmitting data from the mapping van to the DMS and simulation
- Transmitting data to the AV and completing at least one test run (may be onsite or offsite)

The evaluation is being completed to meet the following objectives:

- Prepare track for closed-track scenario testing by installing all long-term infrastructure (e.g., RSUs, permanent pavement markings, etc.)
- Train staff on all aspects of testing
- Determine if any additional equipment, software, or personnel are needed for scenario testing
- Determine the number of replicates that are needed for each permutation run by doing a convergence analysis for several mapping runs
- Narrow down the list of permutations to a reasonable amount by completing a significance test for all permutation variables
- Determine how many scenarios/permutations can reasonably be completed each day and adjust testing calendar accordingly
- Determine noise thresholds and statistical variability for each sensor to inform algorithms for data processing
- Confirm GPS availability on all areas of test track
- Ensure staged equipment not being used for the scenario are not detected by the mapping van
- Ensure small equipment markers, placed to allow for precise equipment locations, will not be visible to the mapping van or AV
- Determine additional testing equipment and setup equipment needed to run tests and create a list of these items so that they will be available for all scenario tests.
- Determine precise staffing requirements for testing.

7 ADS DEPLOYMENT DELIVERABLES

The ADS project deployment deliverables will include:

- A summary of the simulation test results
- A summary of the closed-track test results
- A summary of the live on-road test results

These summaries will include:

- Datasets for public and USDOT use
- Videos and photos of testing
- Scenario-specific results

Data produced as part of the deployments will be fed into the analyses in the *Project Evaluation Plan* in order to produce the metrics described in that plan.

8 SIMULATION

8.1 Simulation Summary

The project includes AV performance in a variety of simulation and demonstration environments. Vehicle simulators/simulation tools such as CARLA[3], CADRE TROCS[4], and SUMO[5] are being used as part of the project deployment. Modeling and simulation tasks will be carried out by both CMU and PSU. The CMU research management center (RMC) will be conducting microsimulations while the PSU RMC will conduct macrosimulations. The two university teams will work together as the software packages will interact with each other, when needed in real-time, to complete the simulations.

8.2 Simulation Software Descriptions

CARLA – CARLA (CAR Learning to Act) is an open-source 3D macro-simulator that supports the development, training, and validation of automated driving systems. In addition to open-source code and protocols, CARLA provides open digital assets (e.g., urban layouts, buildings, vehicles) that were created for this purpose. The simulation platform supports flexible specification of sensor suites, a variety of environmental conditions, full control of all static and dynamic actors, maps generation, and much more.

CADRE TROCS - CADRE (Connected and Autonomous Driving Research and Engineering) TROCS (Tartan Racing Operator Control System), developed by CMU, is a micro-simulator that will be used by CMU for analysis and measuring performance of AV simulations. It consists of six main functional components: a real-world model plotter, an XML-based scenario loader, a playback facility for historical data logs, a zoom/panning tool, a simulator/planner stop/go toggle tool, and a user control panel. A graphical user interface for facilitates real-time monitoring and manipulation. It is assumed this system is existing, integrated, and fully functional prior to the start of simulation testing for this project.

SUMO - SUMO (Simulation of Urban Mobility) is a free and open-source traffic simulation suite. It allows modelling of intermodal traffic systems - including road vehicles, public transport, and pedestrians. Included with SUMO is a wealth of supporting tools which automate core tasks for the creation, the execution, and the evaluation of traffic simulations, such as network import, route calculations, visualization, and emission calculation. SUMO can be enhanced with custom models and provides various APIs to remotely control the simulation.

8.3 Simulation Needs and Requirements

- CMU and PSU shall train staff (including undergraduate, graduate students, and academic staff) in the use of simulation software, algorithms, and other necessary applications as needed throughout the project.
- CMU and PSU shall use the CARLA Simulator software, which requires many application programs to run. Although CARLA is an existing, open-source application, the program requires several modifications to integrate and make fully functional prior to the start of simulation. The CMU and PSU teams shall determine and make any needed modifications and test functionality prior to scenario simulation.
- The CADRE TROCS software shall be used by CMU for analyzing and measuring performance of AV simulations. It is assumed this system is existing, integrated, and fully functional prior to the start of this project.
- The simulation requires pre-generated data and shall receive HD map files from the DMS, which is not a real-time data system.
- A basic configuration for the CADRE TROCS stack shall be established using the generated HD map provided by the DMS.

[3] https://carla.org/
[4] Tools and Methodologies for Autonomous Driving Systems
[5] https://www.eclipse.org/sumo/about/

- The system shall verify that the generated map can be loaded correctly.
- The system shall verify that the AV can read the map correctly
- The system shall verify the AV can drive along the given path navigating {X m/ft.} from the mapped construction zone boundary.
- PSU is currently undertaking a separate effort to implement the SUMO traffic simulation software with CARLA.
- PSU shall conduct traffic simulations to understand how a construction zone and the CMU ADS navigating that work zone would affect traffic flow, both before and after.
- The closed-track roadway layout in the virtual environment shall be created to resemble the real-world closed-track roadway network.
- The live on-road roadway layout in the virtual environment shall be created to resemble the real-world live on-road roadway network.
- Source destination densities shall be calibrated such that the simulator is able to match real-world traffic flows at particular measurement locations, which should include intersections with traffic light timing calibrations to the real world as well.

8.4 Simulation Approach

This section discusses the approach to setup and deploy a successful test in the simulator system. Many of the specific steps outlined in this section defer to the *Operations and Maintenance Plan* for specific directions on how to operate the software systems. To clarify, these steps discuss the setup of the track and all assets needed for deployment. Please refer to the *Testing Plan* for the specifics of the testing process, and the *Operations and Maintenance Plan* for details on operating the equipment during testing.

8.4.1 Background Information on the Simulation Setup

Two flowcharts were developed to explain the data interactions among the simulators, the DMS, the AV, and the mapping van. Figure 4 displays simulation process flow for the AVs. Figure 5 displays the data delivery process to the AV, the map, and the CARLA simulation.

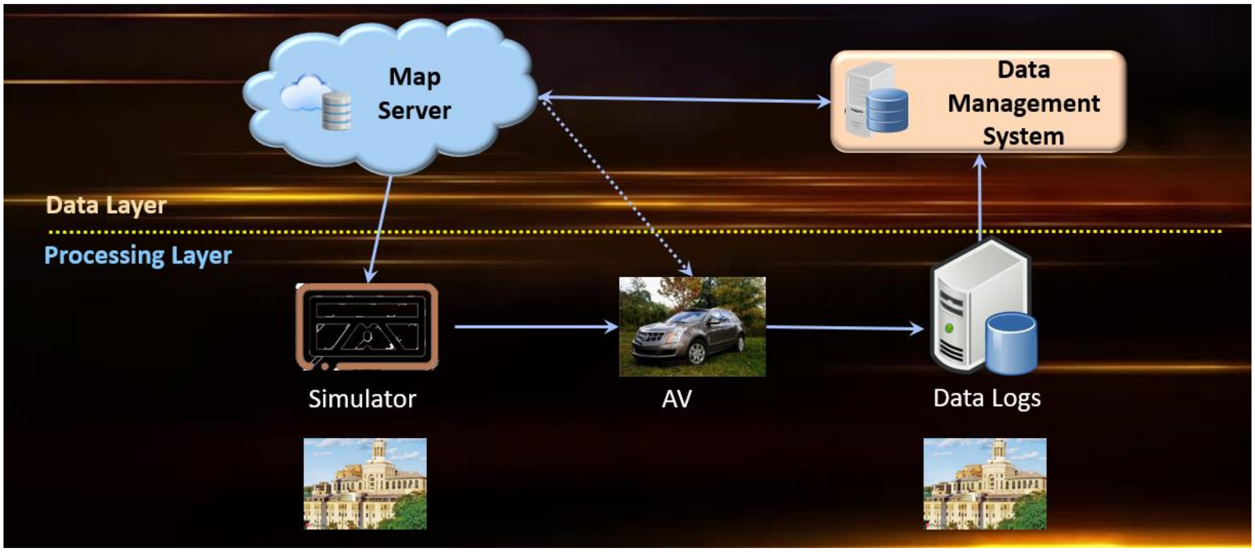


Figure 4. Simulation Process Flow for AV Simulation

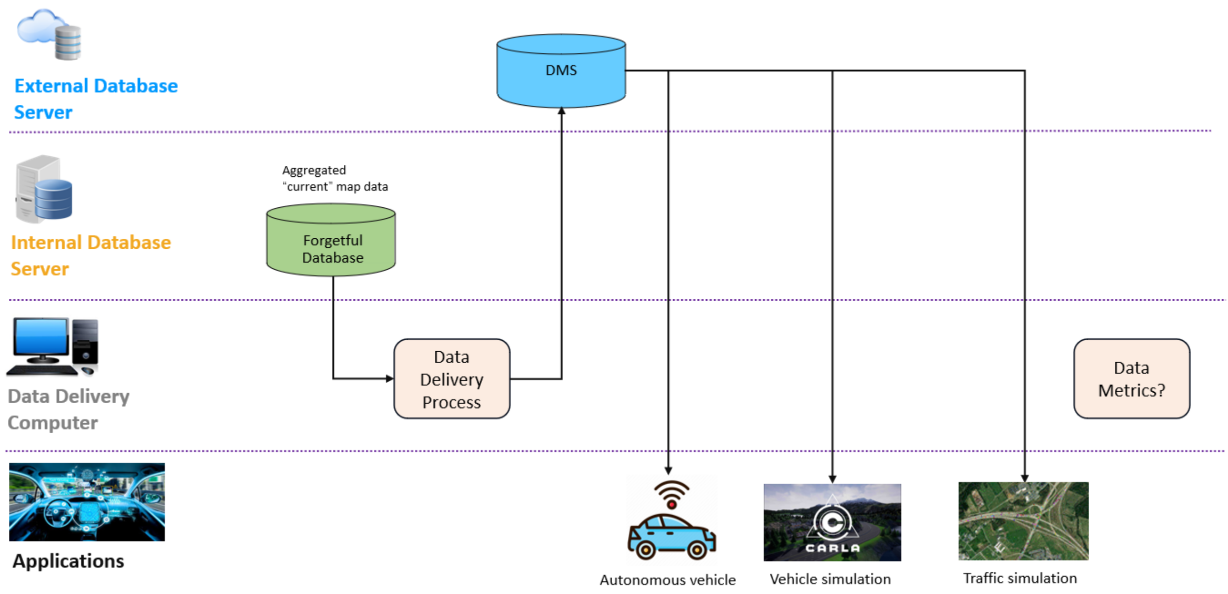


Figure 5. Simulation Process Flow with AV Data

8.4.2 Initial Closed-Track Setup of Course for Mapping Van

A variety of tasks can be done prior to all mapping van runs, and then verified throughout the deployment process. These steps are listed in Table 7.

Table 7. Initial Closed-Track Deployment Steps for Mapping

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
Initial Preparation	CTSS1	Install RSU and RSE and test	RSU(s) and roadside equipment (RSE) installed in the work zone testing area and tested	Three months before mapping	PSU
	CTSS2	Mapping van setup	Mapping van is outfitted with all necessary additional hardware and software	Three months before mapping	PSU
	CTSS3	Acquire work zone objects	Collect and prepare all needed work zone objects for each scenario and permutation	Two months before mapping	PennDOT / PSU
	CTSS4	Schedule track time	Schedule track time for use for mapping	Two months before mapping	PSU
	CTSS5	Set up V2X work zone objects	Put together and set up all work zone V2X objects and verify functionality	One month before mapping	PSU
	CTSS6	Prepare work zone objects with coatings	Place coatings on set of work zone objects for coating permutations	One month before mapping	PPG

A portion of an example scenario setup for Scenario 1.3 (PATA 118) is shown in Figure 6. All 19 scenario CAD drawings are included in Appendix A.

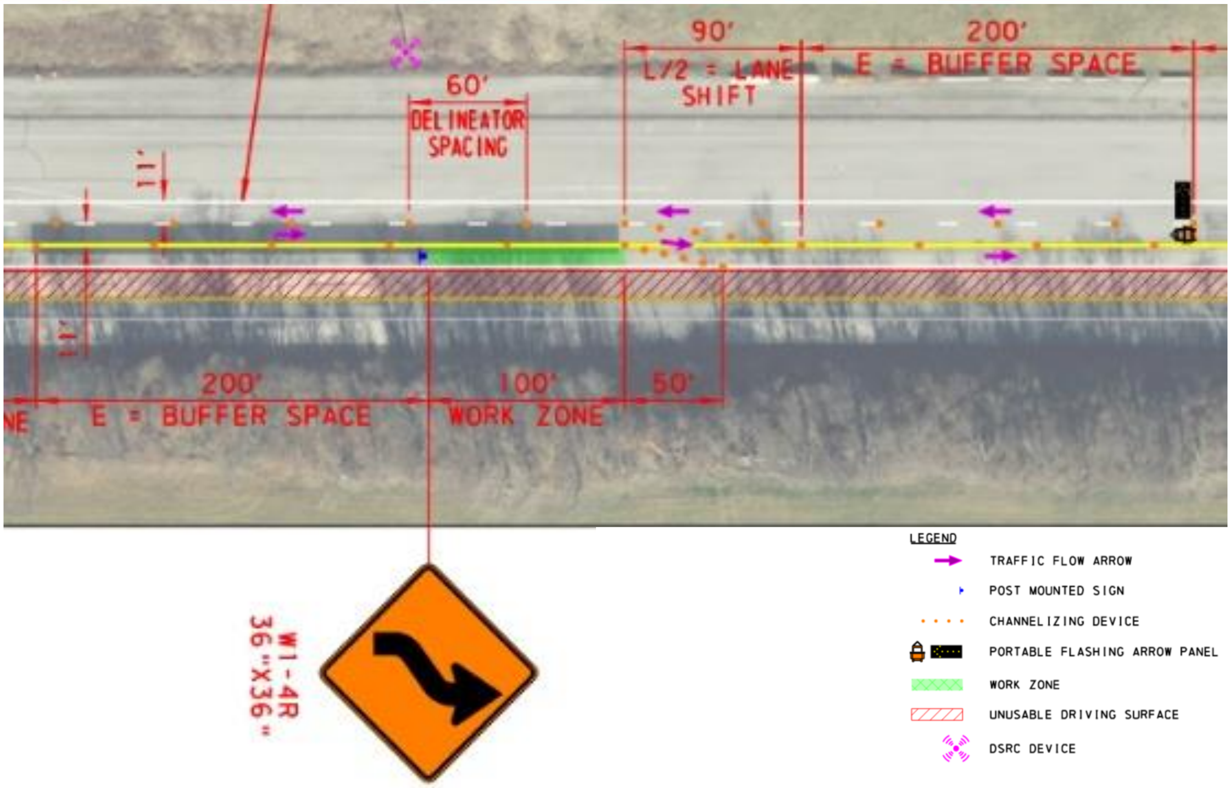


Figure 6. Excerpt of Scenario Setup for Scenario 1.3 (PATA 118)

8.4.3 Mapping Van Deployment Steps

Scenarios are grouped into work zone setups that are similar, shown in Section 5.3.1. For example, Scenarios 1-4 and 1-5 only differ in where precisely the work is being done, with the configuration changes being minimal between each scenario. From Figure 2, the closed-track will be utilized at two separate times for each group of scenarios, once for work zone mapping with the mapping van, and once for conducting the closed-track test with the AV (see Section 9.3). Each group of scenarios will be completed together during one or multiple sessions at the test track for each necessary activity.

For each group of scenarios, the Larson Transportation Institute (LTI) track will need to be prepared for deployment. Any deviations that are necessary from the PennDOT/PTS standard scenarios must be noted and updated in the CAD files. The mapping van will then be deployed according to the schedule in

Table 8, with specifics for the deployment process described in the *O&M Plan*. Note that if weather or other conditions require some scenarios/permutations to be delayed, the team will return as soon as feasible to test the remaining scenarios. Contingency plans will be put in place for prolonged delays (greater than one week).

Between scenario tests and whenever the vehicle is idle for over 30 minutes, the vehicle should be stored in the secure, locked location as specified by the PSU team.

Table 8. Mapping Van Closed-Track Deployment Steps

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
Site Preparation and Setup	CTMV1	Calibrate and prepare all test equipment	Calibrate all sensors and equipment on the mapping van and additional equipment needed for testing; charge batteries and prepare all equipment	Two days before mapping	PSU
	CTMV2	Prepare mapping van	Prepare mapping van according to *O&M Plan*	Two days before mapping	PSU
	CTMV3	Test RSE and GNSS	Ensure RSU and V2X equipment are sending messages and CORS for GNSS correction is working in the field before the van arrives	Two days before mapping	PSU
	CTMV4	Apply lane striping	Stripe lanes with normal coatings	Day before mapping	PennDOT
	CTMV5	Install standard work zone objects	Set up work zone objects according to CAD plans; make sure equipment for each scenario in the group is available; place markers for each item so they will go in the same place each time scenarios are configured	Day before mapping	PSU
Site Verification	CTMV6	Verify site	Verify site is still configured for scenario A	Morning 1 of mapping	PSU
Deployment	CTMV7	Complete group scenario A for first set of permutations	Complete the first scenario in the group by performing up to five replicate runs of each permutation in PG1	Day 1 of mapping	PSU
	CTMV8, CTMV10	Reconfigure for scenario B, then C	Move work zone objects into configuration for subsequent scenarios	Day 1 of mapping	PSU
	CTMV9, CTMV11	Complete scenario B, then C for first set of permutations	Complete the remaining scenarios in the group by performing up to five replicate runs of each permutation in PG1	Day 1 of mapping	PSU
	CTMV12	Complete scenario C for second set of permutations	Complete the last scenario in the group by performing up to five replicate runs of each permutation in PG2	Night 1 of mapping	PSU
	CTMV13, CTMV15	Reconfigure for scenario A, then B	Move work zone objects into configuration for subsequent scenarios	Night 1 of mapping	PSU

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
	CTMV14, CTMV16	Complete scenario A, then B for second set of permutations	Complete the remaining scenarios in the group by performing up to five replicate runs of each permutation in PG2	Night 1 of mapping	PSU
	CTMV17	Apply temporary PPG striping and replace work zone objects	Apply temporary PPG coatings to lane striping and replace work zone objects with PPG coated objects	Morning 2 of mapping	PPG
	CTMV18	Complete scenario B for third set of permutations	Complete scenario B in the group by performing up to five replicate runs of each permutation in PG3	Day 2 of mapping	PSU
	CTMV19, CTMV21	Reconfigure for scenario C, then A	Move work zone objects into configuration for subsequent scenarios	Day 2 of mapping	PSU
	CTMV20, CTMV22	Complete scenario C, then A for third set of permutations	Complete the remaining scenarios in the group by performing up to five replicate runs of each permutation in PG3	Day 2 of mapping	PSU
	CTMV23	Complete scenario A for last set of permutations	Complete scenario A in the group by performing up to five replicate runs of each permutation in PG4	Night 2 of mapping	PSU
	CTMV24, CTMV26	Reconfigure for scenario B, then C	Move work zone objects into configuration for subsequent scenarios	Night 2 of mapping	PSU
	CTMV25, CTMV27	Complete scenario B, then C for last set of permutations	Complete the remaining scenarios in the group by performing up to five replicates runs of each permutation in PG4	Night 2 of mapping	PSU
Post Deployment	CTMV28	Data uploaded to DMS	Map is processed and uploaded to DMS based on *O&M Plan*	Night 2 of mapping	PSU
Site Cleanup	CTMV29	Remove work zone objects	Remove work zone objects from the track and store for next event	Day after mapping	PSU
	CTMV30	Remove paint striping	Remove temporary PPG striping and regular paint striping from test track	Day after mapping	PennDOT

8.4.4 Steps for Conducting the Simulations

Each simulation step is marked as an SS# in Table 9. Before simulations are conducted, each of the three software environments must be set up on the computer(s) that will be running the software, as shown in Steps SS1-SS3. For each specific scenario and permutation, each simulation software environment will be prepared for simulation, then simulations will be run, and data will be collected. PSU and CMU will work together on their respective software systems. The simulation steps are listed in Table 9, with specifics for the simulation process described in the *O&M Plan*. All simulation work should be completed in the two weeks following the closed-track mapping.

Table 9. Simulation Deployment Steps

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
Initial Preparation	SS1	CARLA setup	Initial setup of CARLA on PSU simulation computer	One month before simulation	PSU
	SS2	SUMO setup	Initial setup of SUMO on PSU simulation computer	One month before simulation	PSU
	SS3	CADRE TROCS setup	Initial setup of CADRE TROCS on CMU simulation computer	One month before simulation	CMU
First Scenario	SS4a	Upload maps	Upload all replicate maps for Scenario A, Permutation P0A to CARLA and CADRE TROCS	Day 1 of simulation	PSU
	SS4b	SUMO simulation	Begin SUMO simulation and complete Scenario A, Permutation P0A, collecting all necessary data	Day 1 of simulation	PSU
	SS4c	Process SUMO data	Process SUMO simulation data and share data with CMU team	Day 1 of simulation	PSU
	SS4d	CADRE TROCS simulation	Begin CADRE TROCS simulation and complete Scenario A, Permutation P0A, collecting all necessary data	Day 2 of simulation	CMU
	SS4e	Process CADRE TROCS data	Process CADRE TROCS simulation data and share data with PSU team	Day 2 of simulation	CMU
	SS4f	CARLA simulation	Begin CARLA simulation and complete Scenario A, Permutation P0A, collecting all necessary data	Day 3 of simulation	PSU
	SS4g	Process CARLA data	Process CARLA simulation data and upload to DMS	Day 3 of simulation	PSU

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
Subsequent Scenarios	SS5a-SS5g	Scenario A, Permutation P0B	Repeat Step 4 for Scenario A, Permutation P0B	Day 1 through Day 3 of simulation	PSU/CMU
	SS6-SS19	Scenario A, Permutations P1 through P14	Repeat Step 4 for Scenario A, Permutations P1 through P14	Day 1 through Day 3 of simulation	PSU/CMU
	SS20-SS35	Scenario B, Permutations P0A through P14	Repeat Step 4 for Scenario B, Permutations P0A through P14	Day 4 through Day 6 of simulation	PSU/CMU
	SS36-SS51	Scenario C, Permutations P0A through P14	Repeat Step 4 for Scenario C, Permutations P0A through P14	Day 7 though Day 9 of simulation	PSU/CMU

8.5 Simulation Tools

The CADRE stack is responsible for operating the CMU-AV (i.e., the host vehicle) in a limited virtual world. The simulated host vehicle is provided with a map and navigates a computed path from an origin to a destination. A variety of objects can be injected into the simulator for testing.

The CADRE simulator represents the software running on the AV and is connected to the CARLA simulator, which represents the environment in which the AV runs. In other words, CARLA outputs simulated sensor readings to the CADRE simulator, which in turn will engage and invoke AV functions running inside CADRE to operate the host vehicle in the virtual world. This synchronous co-simulation process happens in near-real-time.

The macro-simulation of the broader traffic environment is conducted by PSU and involves simulated host vehicle interactions with traffic as it navigates through a work zone. SUMO is used to send live vehicle positions to CARLA, and to receive the AV position, allowing vehicles within the traffic network to react to the AV's behavior. Traffic simulations will be used to perform before and after assessments on how the host vehicle navigating work zone impacts traffic flow. The integration of SUMO and CARLA is intended to provide an estimate of traffic flow and impacts.

The purpose of simulating traffic is to understand how the work zone itself and the CMU-AV navigating that work zone would affect traffic flow, with both *before* and *after* traffic conditions being considered. The challenge with before-after comparisons in closed-track testing is that there will be no traffic present. To mitigate this challenge, the project will initialize simulation runs at exactly the same conditions to get repeatable outputs. This in turn can enable useful comparisons of behavior by integrating the SUMO traffic simulator with the CARLA driving simulator for processing high-resolution, high-accuracy, low-vehicle-density test runs.

8.6 Simulation Roles and Responsibilities

The teams at CMU and PSU will be responsible for the simulations. The distinct roles and responsibilities of the project team-members are as follows:

- CMU
  - Maintenance of the CADRE TROCS system
  - Preparation of the CADRE TROCS simulation environment
  - Running microsimulations, completing data analysis, and sharing results
- PSU
  - Preparation of the CARLA and the SUMO simulation environments
  - Creation of the work zone scenarios in the environment in CARLA
  - Running macrosimulations, completing data analysis, and sharing results
- CMU and PSU
  - Preparation of the data sharing environment between CADRE and CARLA as they relate to work zone maps.

8.7 Simulation Risks, Challenges, and Mitigation Strategies

Overall project risks are discussed in the *Risk Management Plan*. Table 10 addresses the risks specific to running the simulations and describes mitigations to reduce or eliminate the risks.

Table 10. Risks, Challenges, and Mitigation Strategies for Simulation Deployment

Risks / Challenges	Importance to Project	Mitigation Strategies
Procuring computer hardware	High performance computers are needed to run simulations.	Ordered hard-to-get parts well in advance of their need.
Simulation latency	Simulations will take a long time to run, causing extended delays.	Prioritize most important scenarios and do a triage system to ensure delays do not compound.
Simulation synchronization process	Simulations work together via a feedback loop of data between simulations.	Manually do the interactions between simulation programs. Record traffic data from CADRE, import into CARLA, import back into CADRE and iterate through until simulations converge. This does not typically take too many iterations, so should not be a large burden.
Simulation software compatibility issues - general	PSU and CMU are using multiple software packages such as SUMO, CARLA, CADRE, Aimsun/Vissim, and VOICES.	Keep simulations separate and run them in series as much as possible. May not use software such as VOICES if compatibility cannot be attained.
CARLA/CADRE model compatibility issues	Physics modeling in simulation software must not conflict (e.g., vehicle chassis model and behaviors such as skidding)	CADRE will check to see if there are any warnings associated with the model, and if so, the problem can be investigated and fixed.
Managing software updates	Need consistent software versions that will not cause large redesign efforts mid-project	Freeze software updates after simulation is designed, unless there is a fix that directly impacts the project

9 CLOSED-TRACK TESTING

9.1 Closed-Track Testing Summary

Closed-track testing involves real-world physical tests at the PSU Larson Transportation Institute (LTI) test track located near State College, Pennsylvania. Closed-track testing serves to test the core functionalities of the ADS (and its subsystems) in a highly controlled environment, prior to testing in a limited live on-road environment. Closed-track testing will demonstrate the CMU-AV's ability to navigate through seventeen (17) PATA and two (2) PTS work zone scenarios including all permutations.

9.2 Closed-Track Testing Needs and Requirements

The project scenarios are grouped together in related subsets to allow for more efficient testing. PennDOT will work with the team to verify testing is following best practices. All scenarios being tested at the LTI shall have been previously simulated in a traffic simulator, drive simulator, and vehicle actuation simulator (CADRE TROCS). Additionally, each scenario must be approved/cleared by the project team for closed-track testing. These tests shall be recorded, and the data shall be shared with the project team through the DMS.

9.3 Closed Track Testing Approach

This section discusses the approach to setup and deploy a successful AV test on the LTI test track.

PSU's LTI test track (Figure 7) is located between State College and Bellefonte, PA, about 6 miles from the PSU team's lab. The site will be used for setting up and running work zone scenarios in a closed-track setting. LTI features a one-mile oval loop with an in-field area that can be used for staging, as well as fueling stations, and offices which can be utilized by the testers.

Figure 7. Larson Transportation Institute (Source: PSU)

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

Similar to the mapping van, scenarios for the AV are grouped into work zone setups that are similar in nature. Each group of scenarios will be completed together during one or multiple sessions at the test track for each necessary activity. It is assumed that site setup activities (as per Section 8.4.2) have been completed prior to this testing. If they have not, that section must be referred to and the recommended steps must be completed before proceeding. Table 11 shows detailed deployment steps for the AV closed-track deployment.

Between scenario tests and whenever the AV is idle for over 30 minutes, the vehicle should be stored in the secure, locked location as specified by the PSU team.

Table 11. AV Closed-Track Deployment Steps

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
Site Preparation and Setup	CTAV1	Calibrate and prepare all test equipment	Calibrate all sensors and equipment on the AV and additional equipment needed for testing; charge batteries and prepare all equipment	Two days before mapping	CMU
	CTAV2	Prepare AV	Prepare AV according to *O&M P*lan	Two days before AV test	CMU
	CTAV3	Test RSE and GNSS	Ensure RSU is sending messages and CORS for GNSS correction is working in the field before the van arrives	Two days before AV test	PSU
	CTAV4	Apply lane striping	Stripe lanes with normal coatings	Day before AV test	PennDOT
	CTAV5	Install standard work zone objects	Set up work zone objects according to CAD plans; make sure each scenario in the group is prepared	Day before AV test	PSU
Site Verification	CTAV6	Verify site	Verify site is still configured for scenario A	Morning 1 of AV test	PSU
Deployment	CTAV7	Complete group scenario A for first set of permutations	Complete the first scenario in the group by performing up to five replicate runs of each permutation in PG1	Day 1 of AV test	CMU
	CTAV8, CTAV10	Reconfigure for scenario B, then C	Move work zone objects into configuration for subsequent scenarios	Day 1 of AV test	PSU
	CTAV9, CTAV11	Complete scenario B, then C for first set of permutations	Complete the remaining scenarios in the group by performing up to five replicate runs of each permutation in PG1	Day 1 of AV test	CMU

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
	CTAV12	Complete scenario C for second set of permutations	Complete the last scenario in the group by performing up to five replicate runs of each permutation in PG2	Night 1 of AV test	CMU
	CTAV13, CTAV15	Reconfigure for scenario A, then B	Move work zone objects into configuration for subsequent scenarios	Night 1 of AV test	PSU
	CTAV14, CTAV16	Complete scenario A, then B for second set of permutations	Complete the remaining scenarios in the group by performing up to five replicate runs of each permutation in PG2	Night 1 of AV test	CMU
	CTAV17	Apply temporary PPG striping and replace work zone objects	Apply temporary PPG coatings to lane striping and replace work zone objects with PPG coated objects	Morning 2 of AV test	PPG
	CTAV18	Complete scenario B for third set of permutations	Complete scenario B in the group by performing up to five replicate runs of each permutation in PG3	Day 2 of AV test	PSU
	CTAV19, CTAV21	Reconfigure for scenario C, then A	Move work zone objects into configuration for subsequent scenarios	Day 2 of AV test	PSU
	CTAV20, CTAV22	Complete scenario C, then A for third set of permutations	Complete the remaining scenarios in the group by performing up to five replicate runs of each permutation in PG3	Day 2 of AV test	CMU
	CTAV23	Complete scenario A for last set of permutations	Complete scenario A in the group by performing up to five replicate runs of each permutation in PG4	Night 2 of AV test	CMU
	CTAV24, CTAV26	Reconfigure for scenario B, then C	Move work zone objects into configuration for subsequent scenarios	Night 2 of AV test	PSU
	CTAV25, CTAV27	Complete scenario B, then C for last set of permutations	Complete the remaining scenarios in the group by performing up to five replicate runs of each permutation in PG4	Night 2 of AV test	CMU
Post Deployment	CTAV28	Data uploaded to DMS	AV Test data uploaded to DMS based on *O&M Plan*	Night 2 of AV test	CMU

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
Site Cleanup	CTAV29	Remove work zone objects	Remove work zone objects from the track and store for next event	Day after AV test	PSU
	CTAV30	Remove paint striping	Remove temporary PPG striping and regular paint striping from test track	Day after AV test	PPG

9.4 Closed-Track Testing Tools

The following subsections list all of the tools required to complete the setup for deployment and testing on the closed track. A complete list of device quantities for all equipment needed to setup each scenario are included in Appendix B. Specifics on the costs and procurement information is available in the *Procurement Plan*.

9.4.1 Connected Vehicle Equipment

An OBU and RSU are integral in relaying information between the infrastructure and the AV or the mapping van for testing purposes. Connected vehicle hardware is capable of transmitting and receiving several message types. The RSU will be set up in the field prior to mapping and the OBU will be set up in each vehicle before testing.

9.4.2 High-Performance Computer (HPC)

The edge HPC aggregates and logs data from the AV. It serves as the facilitator of information exchange between the RSU and DMS. The HPC is capable of collecting and transmitting smart roadside data from work zone field devices and objects and transmit data to the DMS. The HPC will support internet connectivity via ethernet and optionally 4G/5G connectivity and GPS. The HPC will be set up on the closed track prior to mapping.

9.4.3 Roadside Support Equipment

In order to set up the test track as needed for each scenario, roadside support equipment including channelizers, a truck-mounted attenuator (TMA), portable message signs (PMSs), barrels, cones, barriers, signs, a temporary traffic signal, flagger equipment, and arrow board trailers will be deployed. There will likely be duplicate equipment for any objects that will need to be treated with PPG coatings for the tests. Temporary and permanent lane striping will also be deployed, along with PPG striping. This equipment will be prepared and set up as needed for each simulation group and specific simulation.

9.4.4 V2X Work Zone Objects

V2X work zone objects including traffic cones, barrels, barriers, and signs will be needed to locate objects using V2X. This equipment will be prepared and set up as needed for each simulation group and specific scenario and permutation.

9.4.5 Digital Worker Vest

Virginia Tech Transportation Institute (VTTI) is providing digital worker vests for use in testing. These devices will utilize Zigbee connectivity to transmit data to a processing computer station that will process the data. These data will be transmitted to the HPC for use by the mapping van.

9.4.6 Manual data recording device

Although the mapping van and AV will be responsible for all performance data collection, it is possible that certain events beyond the scope of the system data collection capabilities will need to be recorded as part of the testing. For this purpose, a tablet or field notebook is recommended to record any abnormalities or additional information.

9.4.7 Additional testing equipment

Additional testing equipment may be needed as determined during the pre-test on the track. This could include equipment such as packet sniffers and calibration mats. A full list will be created after the pre-test period (described in Chapter 6).

9.4.8 Additional setup equipment

Additional setup equipment may be needed as determined during the pre-test on the track. This could include equipment such as tents and walkie talkies. A full list will be created after the pre-test period (described in Chapter 6).

9.5 Closed-Track Testing Roles and Responsibilities

The PSU team will be responsible for managing all aspects of the closed-track testing environment at LTI. This includes staffing for tests, scenario setup, and administration. Work zone designs are provided by HNTB (see Appendix A). From these designs, PennDOT will use any necessary equipment to set up each work zone in collaboration with the PSU team.

Specific details on staffing requirements and responsibilities will be added to this section once the closed-track pre-testing is completed.

9.6 Closed-Track Testing Risks, Challenges, and Mitigation Strategies

Overall project risks are discussed in the *Risk Management Plan*. Table 12 addresses the risks specific to closed-track testing and describes mitigations to reduce or eliminate the risks.

Table 12. Risks, Challenges, and Mitigation Strategies for Closed-Track Deployment

Risks / Challenges	Importance to Project	Mitigation Strategies
Satellite signal unavailability during testing and poor GPS connection	Need GPS for AV localization to function accurately.	Verify the number of visible GPS satellites before testing begins. The test track has a spot where satellite visibility can vary. Plan to avoid this location and/or verify satellites again once driving through location.
Use of the test track during weekends and off-hours	Tests may need to be run on weekends (track is currently open 24/5, Monday through Friday).	Ask for key for access in advance. Ensure track personnel are available in advance, as there must be at least two people to operate including one test track employee.
Physical security of the vehicles at the track	Need to secure vehicle assets when not actively testing.	Look into setting up a secure, lockable location.
Track scheduling	Track time is valuable and limited. Other projects use the facility which puts pressure on completing tasks.	Schedule all track time well in advance of when needed. Coordinate with track manager to allow for weekend testing if needed.
Weather impacts	Weather, such as precipitation, is not a variable being tested as part of the project and should be relatively consistent.	If weather or other conditions require some scenarios/permutations to be delayed, the team will return as soon as feasible to test the remaining scenarios. Contingency plans will be put in place for prolonged delays (greater than one week).
Testing equipment unavailability	All testing equipment is necessary to be available for valid testing procedures.	Acquire all basic roadside testing equipment (cones, barrels, etc.) well in advance and any specialized equipment as far as possible before testing.
Pavement coatings not recognized by AV during testing	AV recognition of pavements coatings is required for safe navigation in a work zone.	The safety driver will be available to take over as needed in case any markings are not recognized.
Roadway infrastructure not recognized by AV during testing and deployment	AV recognition of RSU and work zone objects is required for safe navigation in work zone	If connectivity to the RSU and/or any V2X work zone objects is lost during a test, the test will be stopped, and equipment repaired before continuing further testing.
AV interactions with other vehicles	There may be other vehicles on the test track or near the vehicle while in operation.	Ensure no other vehicles are near the work zone test site before commencing test.
Communications (V2X) protocol needs to change	There is currently volatility in the selection of C-V2X or DSRC for testing.	A memorandum has been prepared for this contingency, allowing for primary C-V2X deployment along with select DSRC deployment.
Availability and functionality of V2X work zone objects	Work zone objects need to be set up with V2X. Will be either procuring or building these.	Verify functionality of a V2X object setup well in advance of the closed-track testing.

10 LIVE ON-ROAD TESTING

10.1 Live On-Road Testing Summary

Live on-road testing will be conducted on one long-term work zone setup on a freeway, one short-term work zone setup in an urban environment, and one mobile work zone setup in a rural environment. If possible, locations will be chosen such that at least one rural and one urban site are selected. Additionally, one of the sites shall include a Turnpike work zone, if possible. On-road testing will only be completed once simulations and closed-track tests are complete and the project team decides that on-road tests will be feasible and safe. As work zone locations and setups change rapidly with construction needs, the exact location of the live on-road testing will be determined closer to when on-road tests are performed. It should be noted that testing in an urban environment will have many constraints to allow a test to begin or continue, including verifying that no pedestrians are present and verifying constant GPS connectivity.

10.2 Live On-Road Testing Needs and Requirements

Identify items the contractor must provide for the test, as well as noting that we will first look for long-term work zones. All scenarios being tested live on-road shall have been previously simulated in a traffic simulator, drive simulator, and vehicle actuation simulator (i.e., CADRE), and approved/cleared by the project team for closed-track testing. All scenarios being tested on live road shall have been previously tested at the PSU closed-track and approved/cleared by the project team for open-road testing. Care will be used to select testing times with limited additional traffic (e.g., not during rush hour or periods of increased seasonal travel demand).

10.3 Live On-Road Testing Approach

Due to inherent risk associated with live on-road testing, only three of the 19 scenarios will be tested in this environment. The core team will select one scenario in each of the long-term, short-term, and mobile work zone scenarios for live on-road testing. Scenario selection will depend on work zone availability and the team’s consensus on what site will work best. Selection will be completed well in advance of the on-road testing. The team will identify an existing or proposed work zone in which to conduct live on-road testing with live traffic. To minimize risk, the core team will select work zones with minimal traffic to conduct this testing.

Each on-road step is marked as OR# in Table 13.

Table 13. AV Live On-Road Deployment Steps

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
Advanced Coordination	OR1	Approve experimental coatings and V2X devices for use in live work zone	Coordinate with legal department and determine process to go through to get approval to use all equipment not currently authorized for use on PA highways. May need to send coatings to materials lab for assessment.	12-24 months before mapping	PennDOT
	OR2	Determine work zone for test	Each Work zone needs to be selected well in advance of testing. For the long-term work zone, 12-24 months of lead time is needed to allow for bid items, specs, and coordination. Each short-term work zone will require about 6 months of lead time.	6-24 months before mapping	Full Deployment Team
	OR3	Coordinate with work zone team	Since the live on-road testing will be conducted in a real work zone, the work zone setup specifically for this testing is not required. Prior to testing, PennDOT will coordinate with the work zone construction team including the work zone contractor to ensure all involved parties are aware of the on-road testing. Follow the procedures as needed in Section 178.4.2 to complete setup.	3-6 months before mapping	PennDOT
	OR4	Verify satellite and cellular connectivity at the site	Drive near the site and check for satellite visibility before committing to a test site (make sure there are 7+ satellites available). Also, verify if cellular service is available for internet connectivity.	3-6 months before mapping	PSU
	OR5	Verify functionality of all V2X	Prepare all V2X equipment needed for the on-road test at the	Two weeks	PSU

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
		equipment for tests	closed track and ensure it is ready for testing	before mapping	
Deployment	OR6	Set Up Work Zone in Live On-Road Testing	All connectivity equipment and coatings will be installed and tested in the work zone, as needed for Permutation P0A. Best practices determined from the prior stages of testing should be used for work zone setup.	Week prior to mapping	PSU/ work zone contractor
	OR7	Map Work Zone	Map the live on-road work zone for Permutation P0A following the same process followed during the simulation testing phase, in Section 8.4.3. Mapping will commence for as many replicates as needed as determined during the closed-track testing phase.	Day 1 of on-road test	PSU
	OR8	Process/Upload Map	Once complete, process and upload the map to the DMS. The map will either be downloaded to the AV prior to the start of the testing or may be updated "on the fly" using a cellular or V2X map update, depending on best practices determined by closed-track tests.	Day 1 of on-road test	PSU
	OR9	Conduct Live On-Road Testing	Once the map is downloaded, the AV will navigate the work zone for Permutation P0A, collecting the camera images, sensor data, and connectivity data, following the steps in Section 9.3.	Day 1 of on-road test	CMU
	OR10	Collect/Process/ Upload/ Evaluate	Collect, process, and upload the data, then evaluate it in a manner similar to the closed-track testing phase. Following the evaluation, the AV will	Day 1 of on-road testing	CMU

Deployment Step	Control Number	Activity	Details	When?	Responsible Party
			be calibrated to adjust its behavior to ensure safe and correct behaviors are obtained under multiple runs. Test results from the testing and evaluation will be documented in the Test Results document.		
	OR11-OR25	Repeat Steps OR6-OR10 for 15 remaining permutations	Continue to coordinate with the work zone team as needed and complete the five listed steps for each permutation. If changes are made to the work zone between permutation runs, the team will note any changes as part of the data collection process. If significant changes are made, prior permutations will need to be re-run.	Days 2 through 5 of testing	PSU/CMU
Site Cleanup	OR26	Remove work zone objects	Remove work zone objects from the site and store for next event	Day after AV test	PSU
	OR27	Remove paint striping	Remove temporary PPG striping and regular paint striping from test track	Day after AV test	PPG/ work zone contractor

10.4 Live On-Road Testing Tools

The majority of tools needed for live on-road testing are similar to closed-track testing. Refer to Sections 9.4.1 through 9.4.8 for specific information regarding connected vehicle equipment, HPC, roadside support equipment, V2X work zone objects, digital worker vest, manual data recording device, additional testing equipment, and additional setup equipment.

There will also be equipment needed specific to the on-road testing, including charging equipment for the mapping van, internet connectivity (via a hot spot or similar mechanism), mobile office space in a construction trailer, and signage regarding "AV testing in progress." Additional equipment may be necessary and will be added to this section after sites are selected.

10.5 Live On-Road Testing Roles and Responsibilities

The work zone team plays a large role in live on-road testing. Each work zone will be set up according to the work zone team following PennDOT work zone procedures. Additional equipment will be coordinated between PSU and the work zone team for installation as necessary. CMU and PennDOT will work together to ensure the mapping and AV testing can occur sequentially during the same testing window.

PennDOT will be responsible for safety at the live construction zone. Additionally, the team will coordinate with law enforcement and PennDOT/County/Municipal officials as needed during the on-road tests.

Specific details on staffing requirements and responsibilities will be added to this section once on-road work zone sites are selected and during coordination with the construction management team for the work zone.

10.6 Live On-Road Testing Risks, Challenges, and Mitigation Strategies

Overall project risks are discussed in the *Risk Management Plan*. Table 14 addresses the risks specific to live on-road testing and describes mitigations to reduce or eliminate the risks. Many of these risks overlap with those in the closed-track testing phase. In cases of overlap, the best practices from the closed-track tests will be followed to ensure smooth deployment.

Table 14. Risks, Challenges, and Mitigation Strategies for Live On-Road Deployment

Risks / Challenges	Importance to Project	Mitigation Strategies
Loss of mapping van data before entered into DMS	If data is lost before transmission to the DMS, data collections runs would need to be re-done.	The mapping van will not push information directly to the DMS. Instead, data is stored on the mapping van and transferred to the DMS in the lab. Team will set up a chain of custody and duplicate data on-site (after each run) before returning to the lab.
Interface incompatibility between the AV and the DMS	AV must ideally receive data directly from the DMS in real-time. Loss of AV-DMS connectivity will prevent the AV from having prior knowledge of the work zone before the latter is encountered.	Download map to the AV before starting its journey so the AV does have prior knowledge of the work zone
Satellite signal unavailability during testing and poor GPS connection	Need good-quality GPS for AV localization to be accurate.	Drive near the site and check for satellite visibility before committing to a test site (make sure there are 7+ satellites available). Do not work with a construction site under an overpass if possible.
Coordinating with work zone team while running the test	The work zone team needs to be available for smooth testing and deployment.	Meet with the work zone management team as far in advance of testing as possible and coordinate shift leads to be responsible for working with the PSU/CMU teams.
V2X equipment unavailability	All equipment required for testing shall be available for undisturbed deployment and testing purposes	If possible, keep all V2X equipment from the closed-track testing phase, so that it is ready for on-road deployment.
Pavement coatings not recognized by AV during on-road test	Pavement coatings should be recognized for safe navigation of AVs in each work zone	The safety driver will be available to take over as needed in case any markings are not recognized.
Roadway infrastructure not recognized by AV during on-road test	Roadway infrastructure shall be recognized for safe navigation in each work zone	If connectivity to the RSU and/or any V2X work zone objects is lost during a test, the test will be stopped, and equipment repaired before continuing further testing.
AV interactions with other vehicles, many at high speeds	The work zone will be functioning in normal traffic conditions during testing and the safety of all vehicles and other road users is paramount.	Ensure that the AV operator is always immediately available to take over and end test. Impacted test will be re-run.
Communications (V2X) protocol needs to change	There is currently volatility in the selection of C-V2X or DSRC for testing.	Develop a memorandum to prepare this contingency allowing for primary C-V2X deployment along with select DSRC deployment.
Availability and functionality of V2X work zone objects	Work zone objects need to be set up with V2X. Will be either procuring or building these.	Verify functionality of V2X object setup well in advance of the live on-road testing.

APPENDIX A: WORK ZONE CAD DRAWINGS

This appendix includes all work zone CAD drawings for all 19 possible scenarios (Figure 8 through Figure 26). These drawings will be used for simulation and closed-track setup and testing. Larger, higher resolution drawings are available for the project team.

Any deviations necessary for the closed-track testing are either shown in the CAD drawings or will be determined during closed-track testing and updated on the CAD drawings.

The start point for all scenarios will be the same and is shown in each diagram. This will make testing easier by providing a common origin point for all simulations and speeding up testing as teams always know where to begin tests.

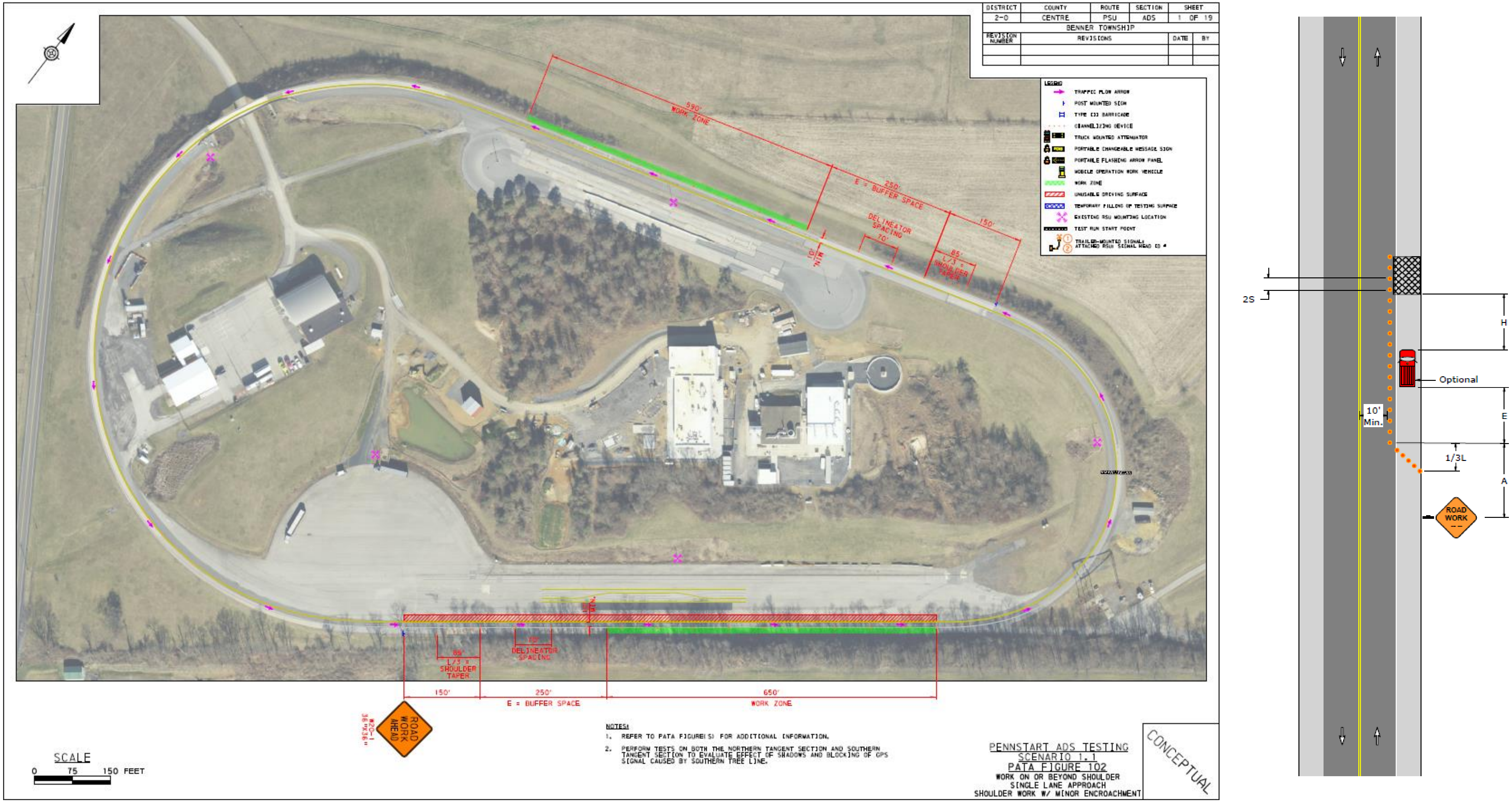
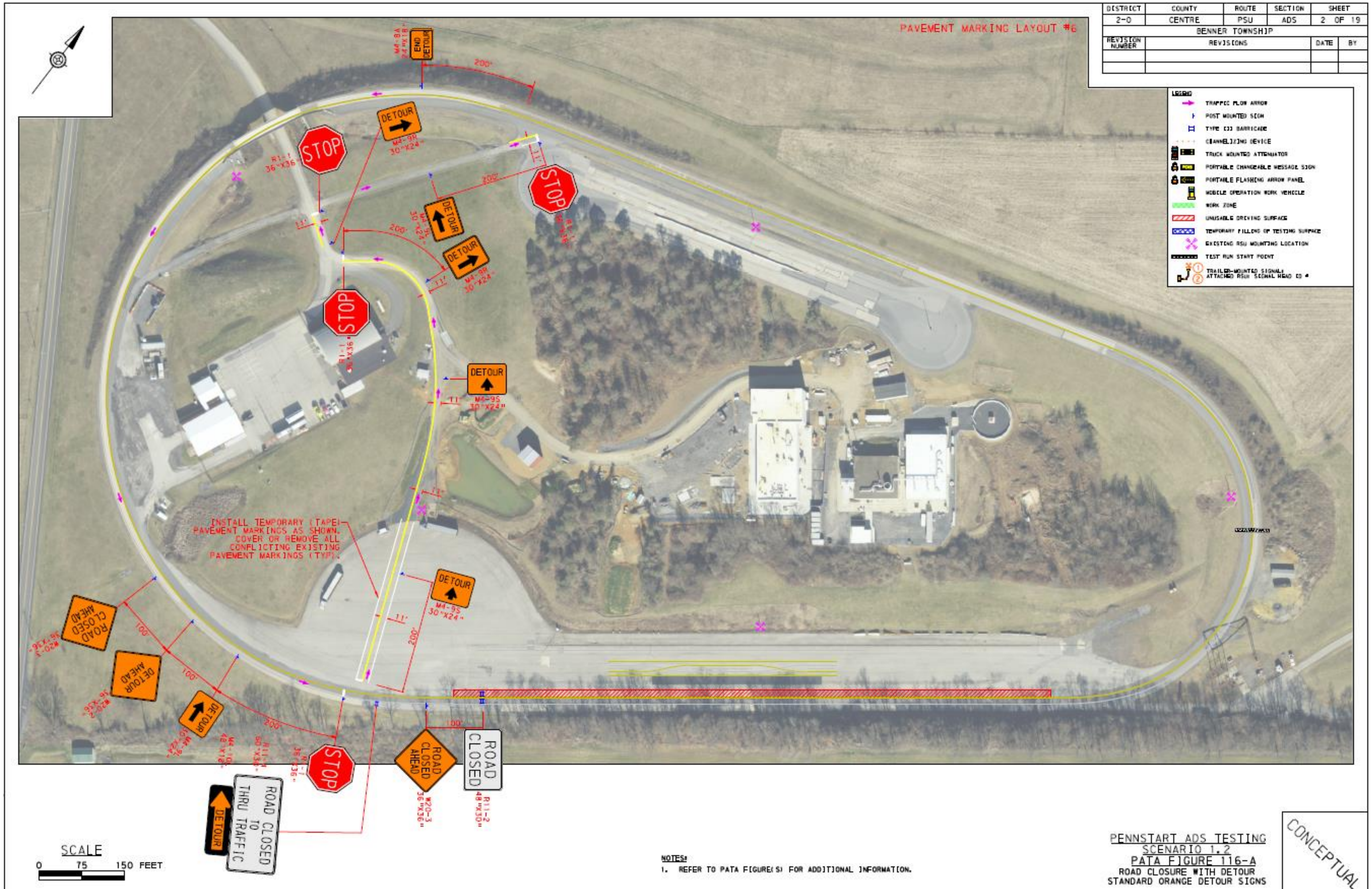


Figure 8. Scenario Setup for Scenario 1-1 (PATA 102)



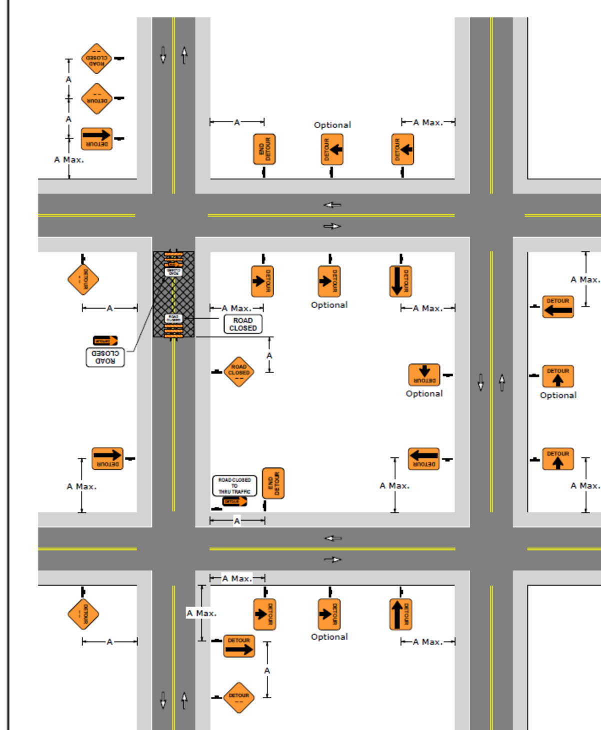
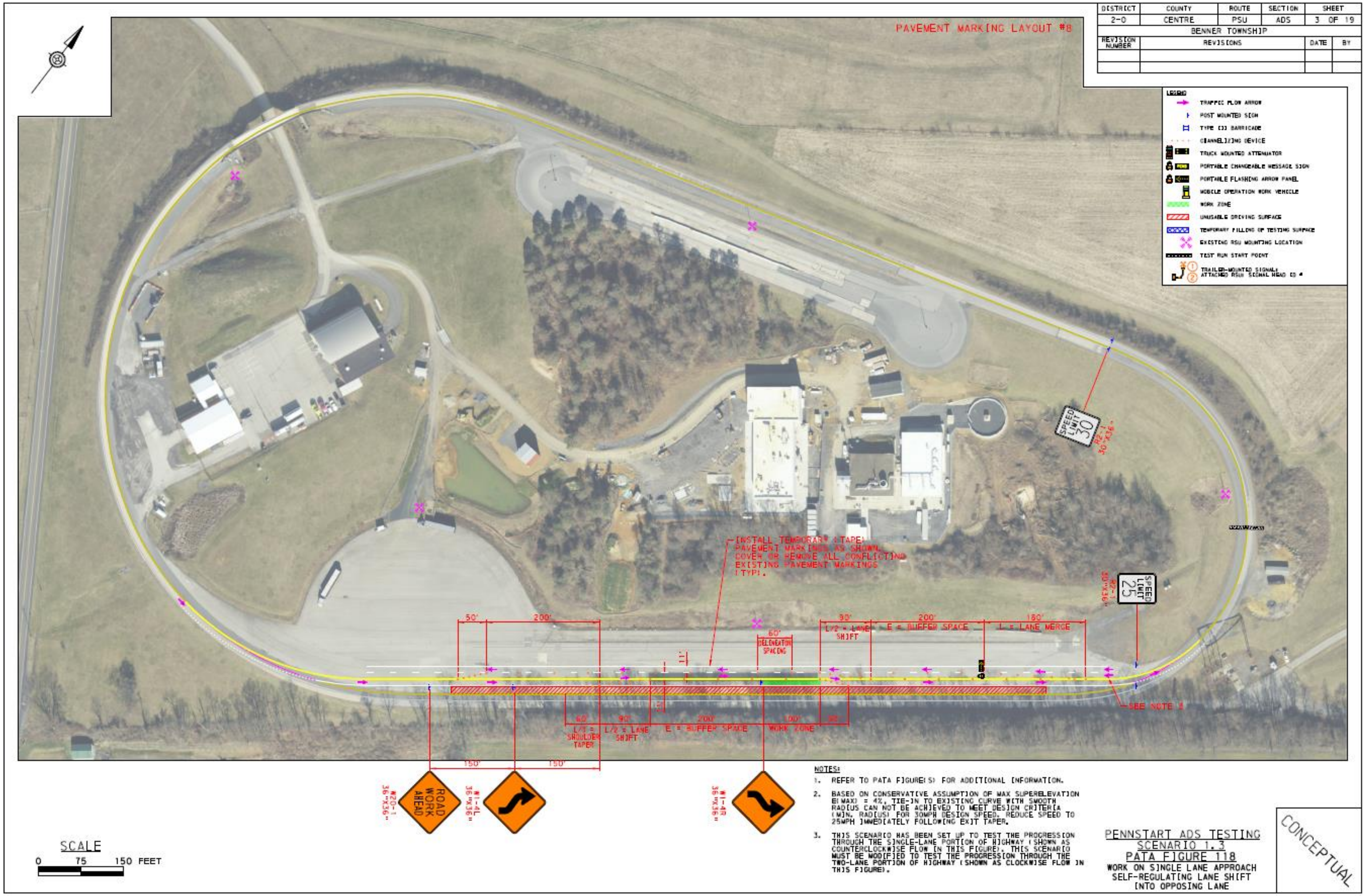


Figure 9. Scenario Setup for Scenario 1-2 (PATA 116-A)



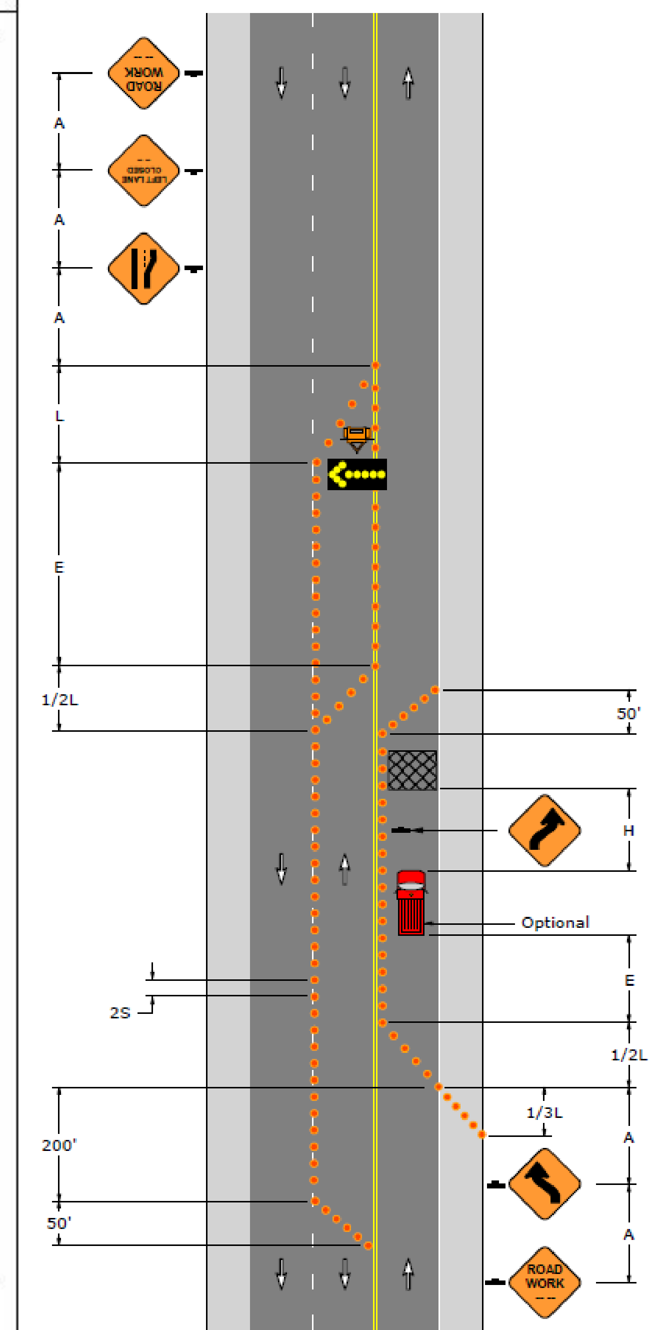
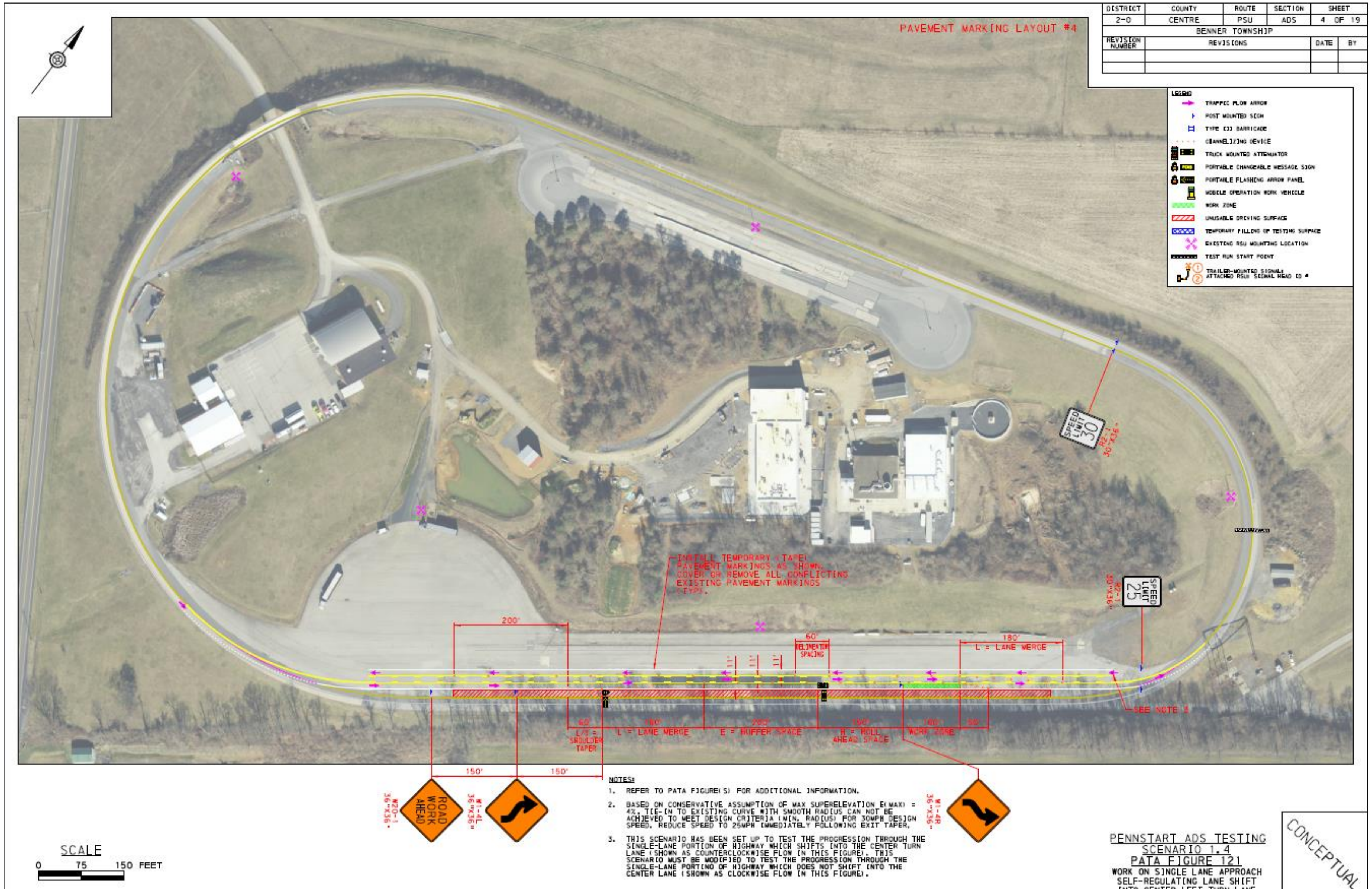


Figure 10. Scenario Setup for Scenario 1-3 (PATA 118)



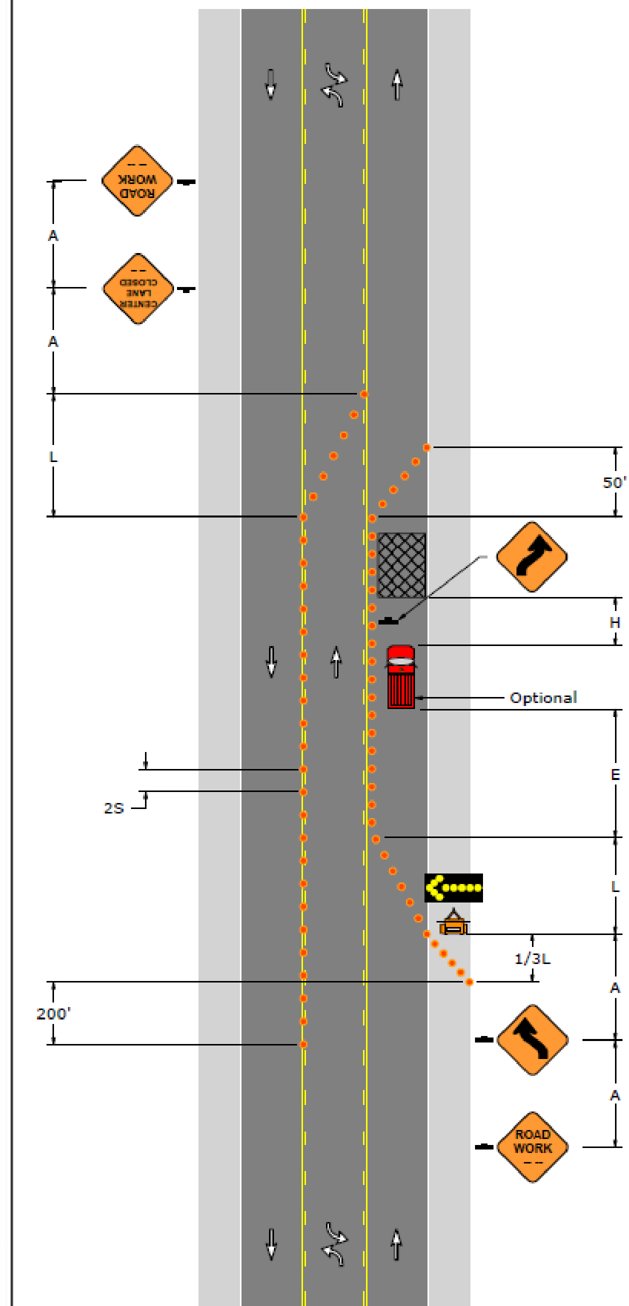


Figure 11. Scenario Setup for Scenario 1-4 (PATA 121)

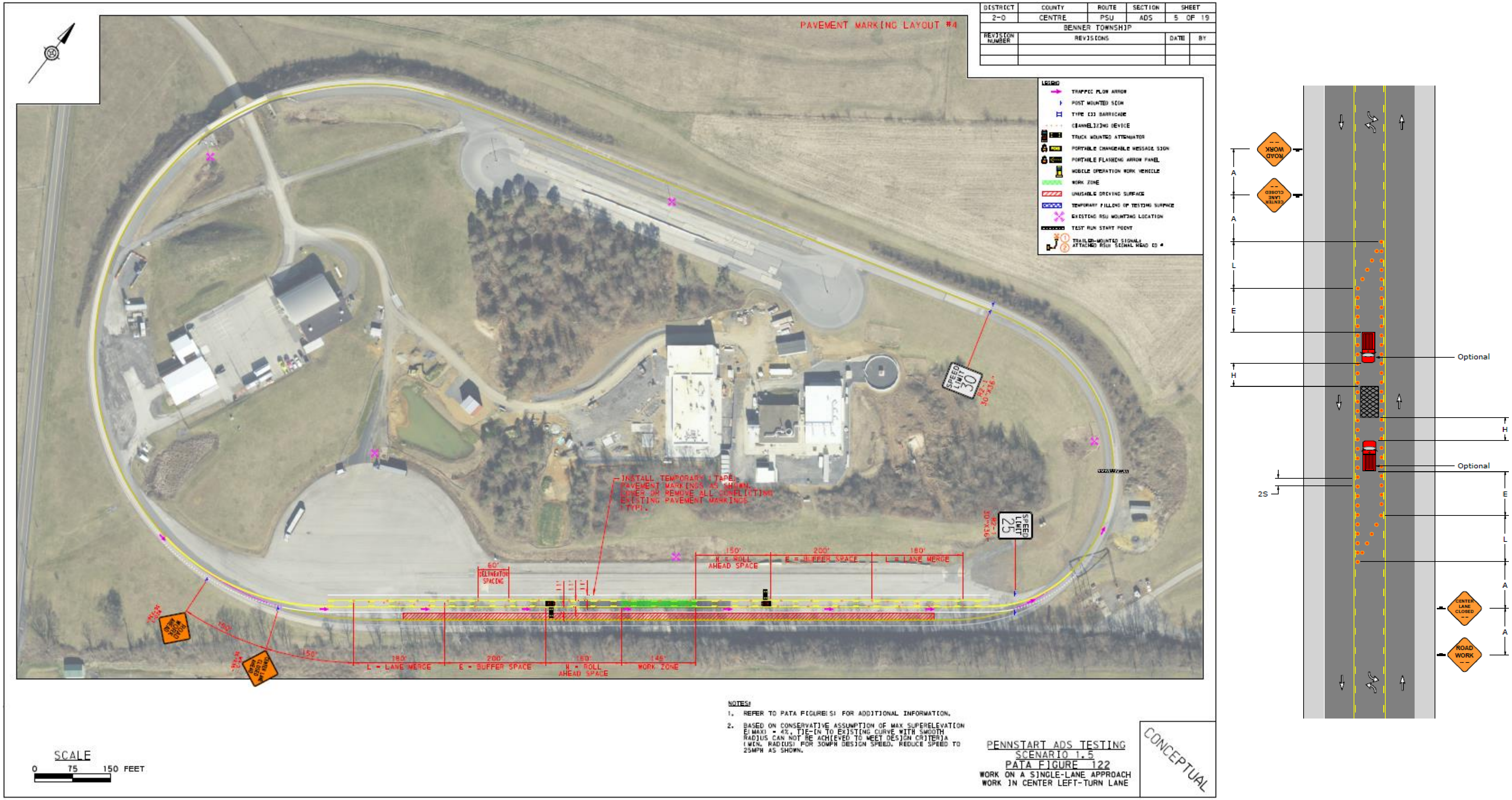


Figure 12. Scenario Setup for Scenario 1-5 (PATA 122)

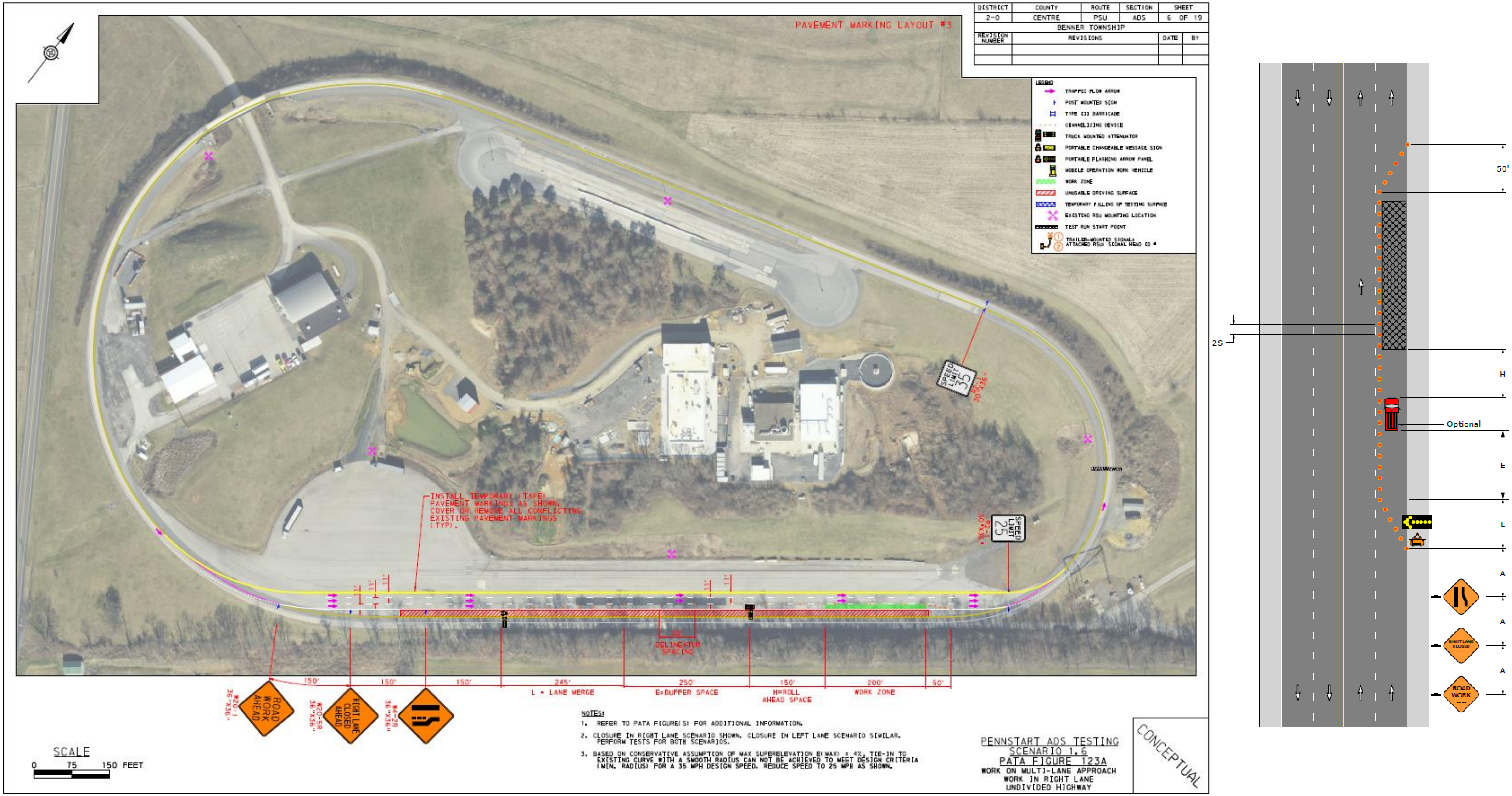
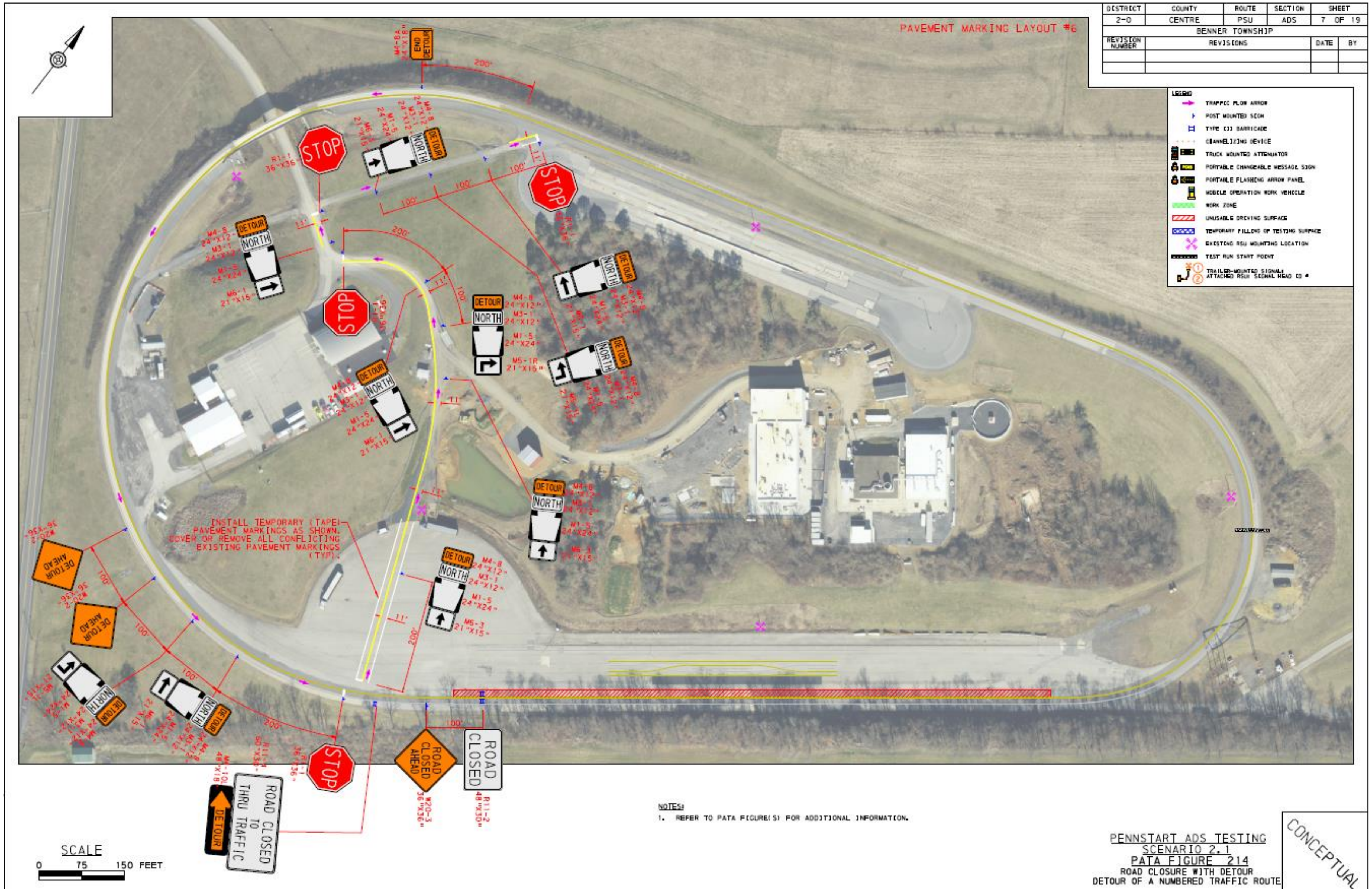


Figure 13. Scenario Setup for Scenario 1-6 (PATA 123A)



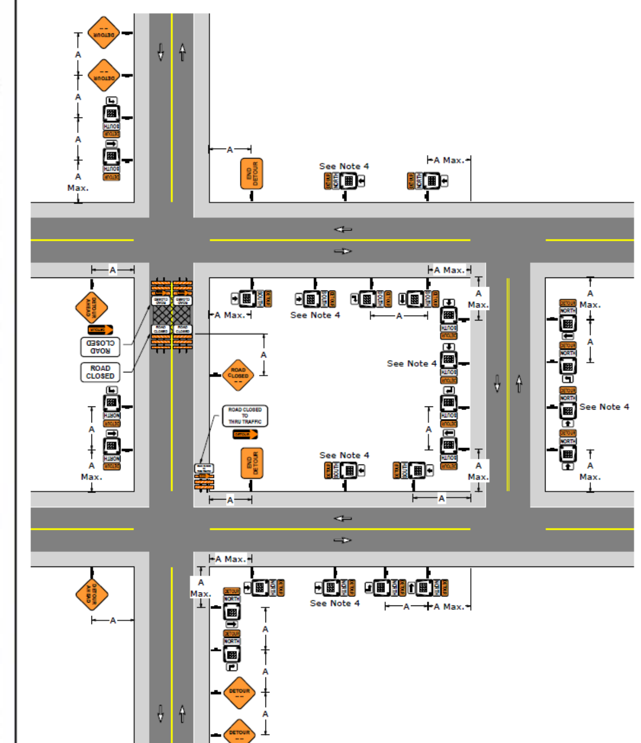


Figure 14. Scenario Setup for Scenario 2-1 (PATA 214)

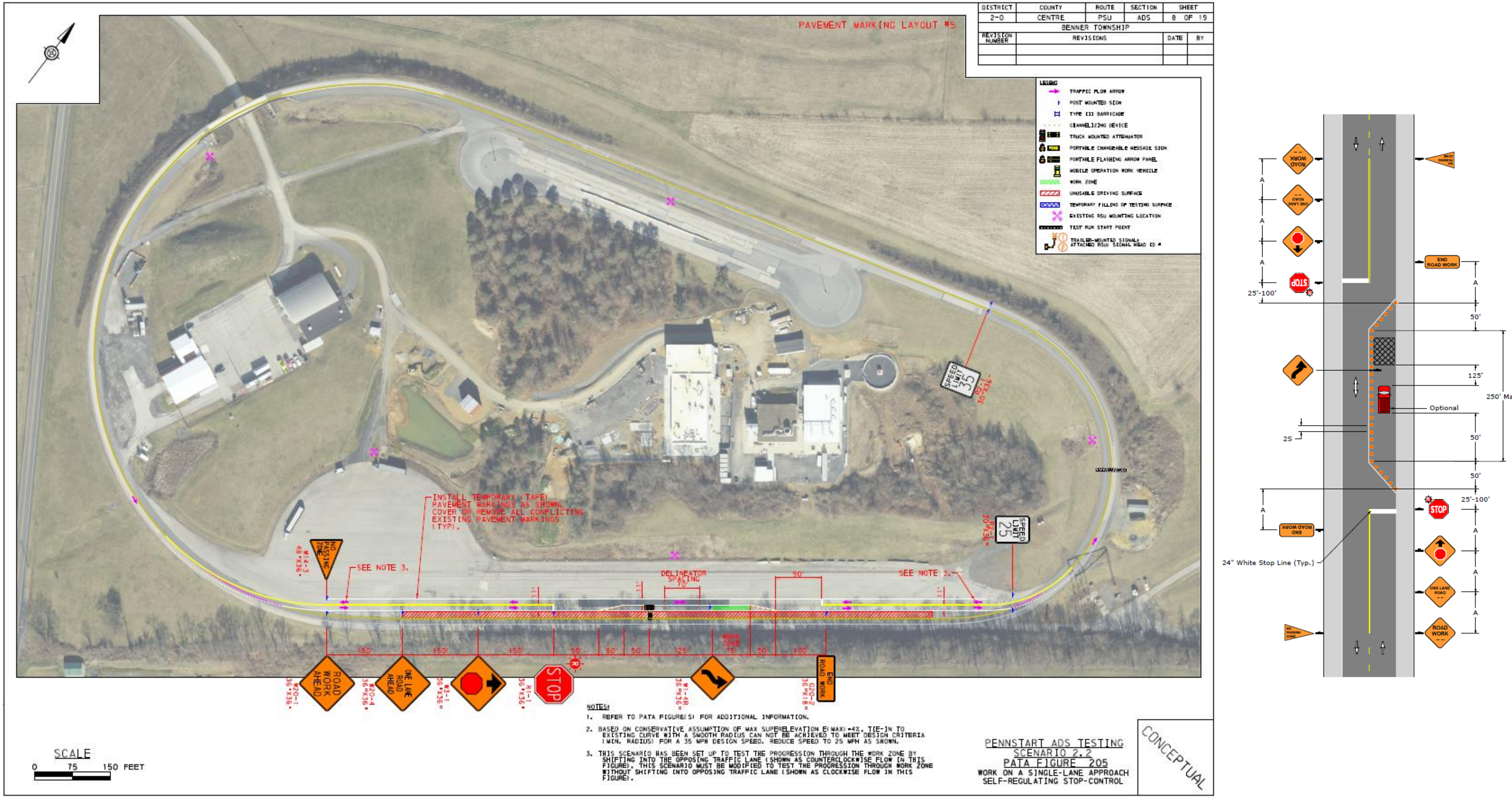


Figure 15. Scenario Setup for Scenario 2-2 (PATA 205)

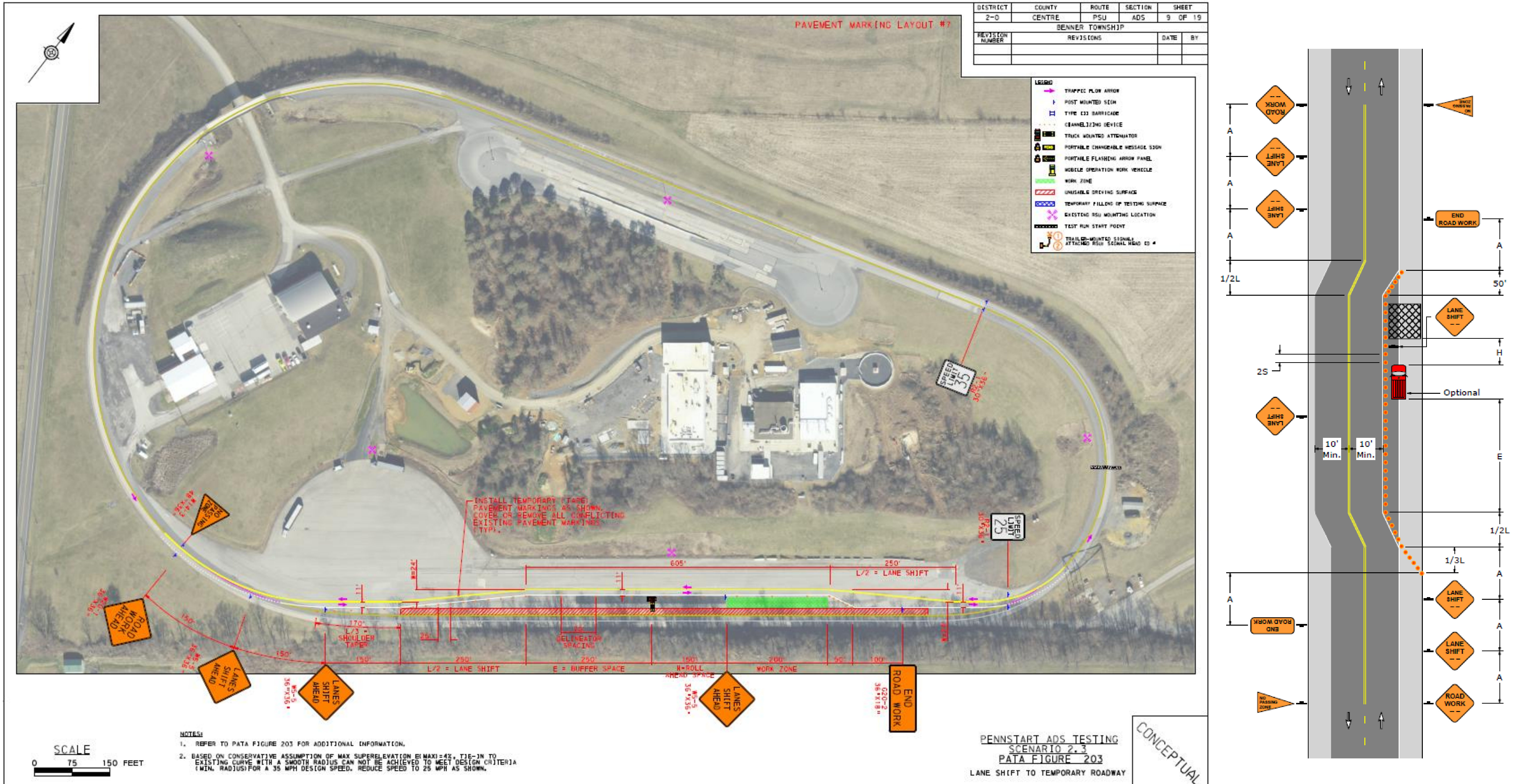


Figure 16. Scenario Setup for Scenario 2-3 (PATA 203)

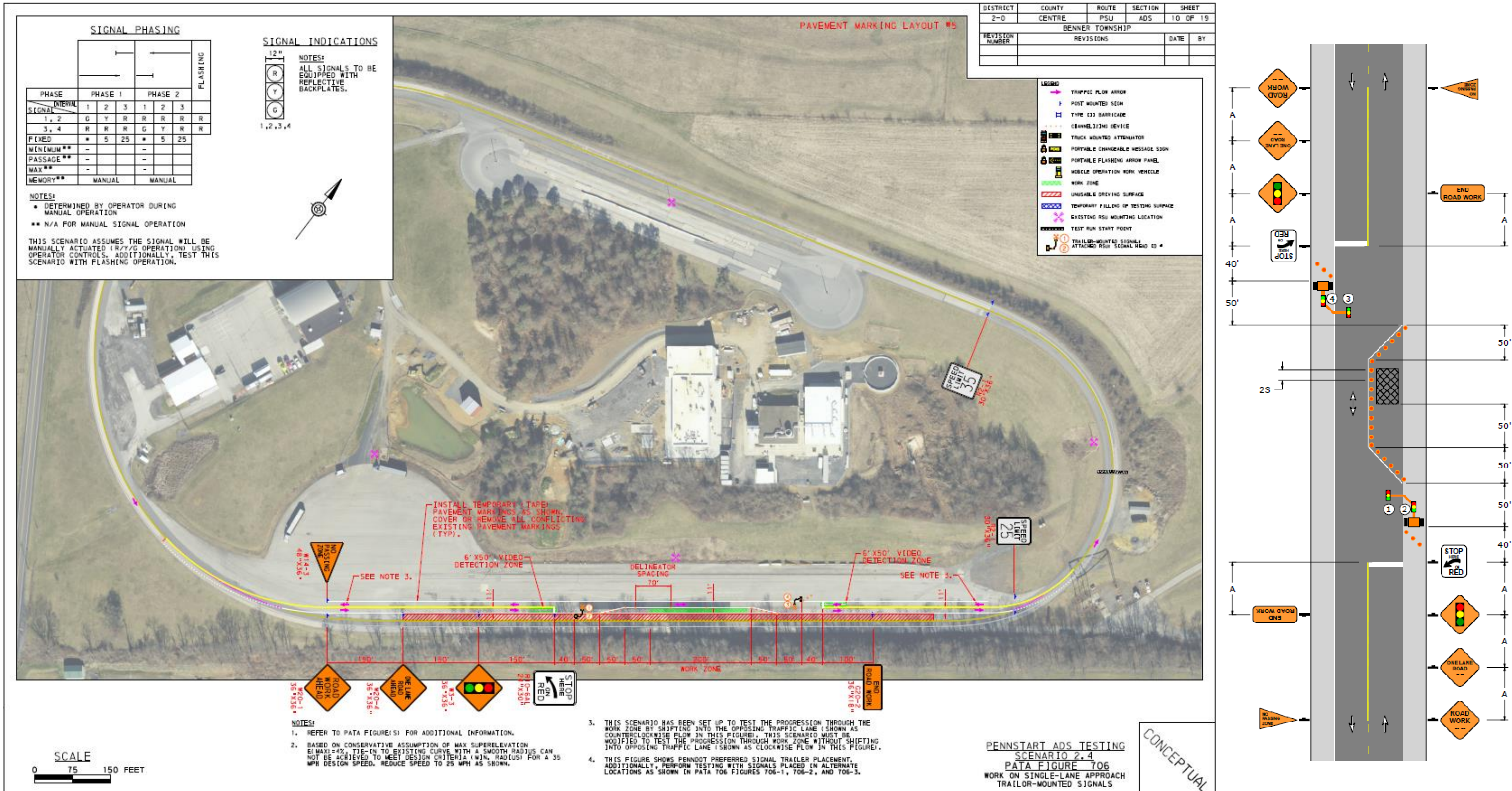
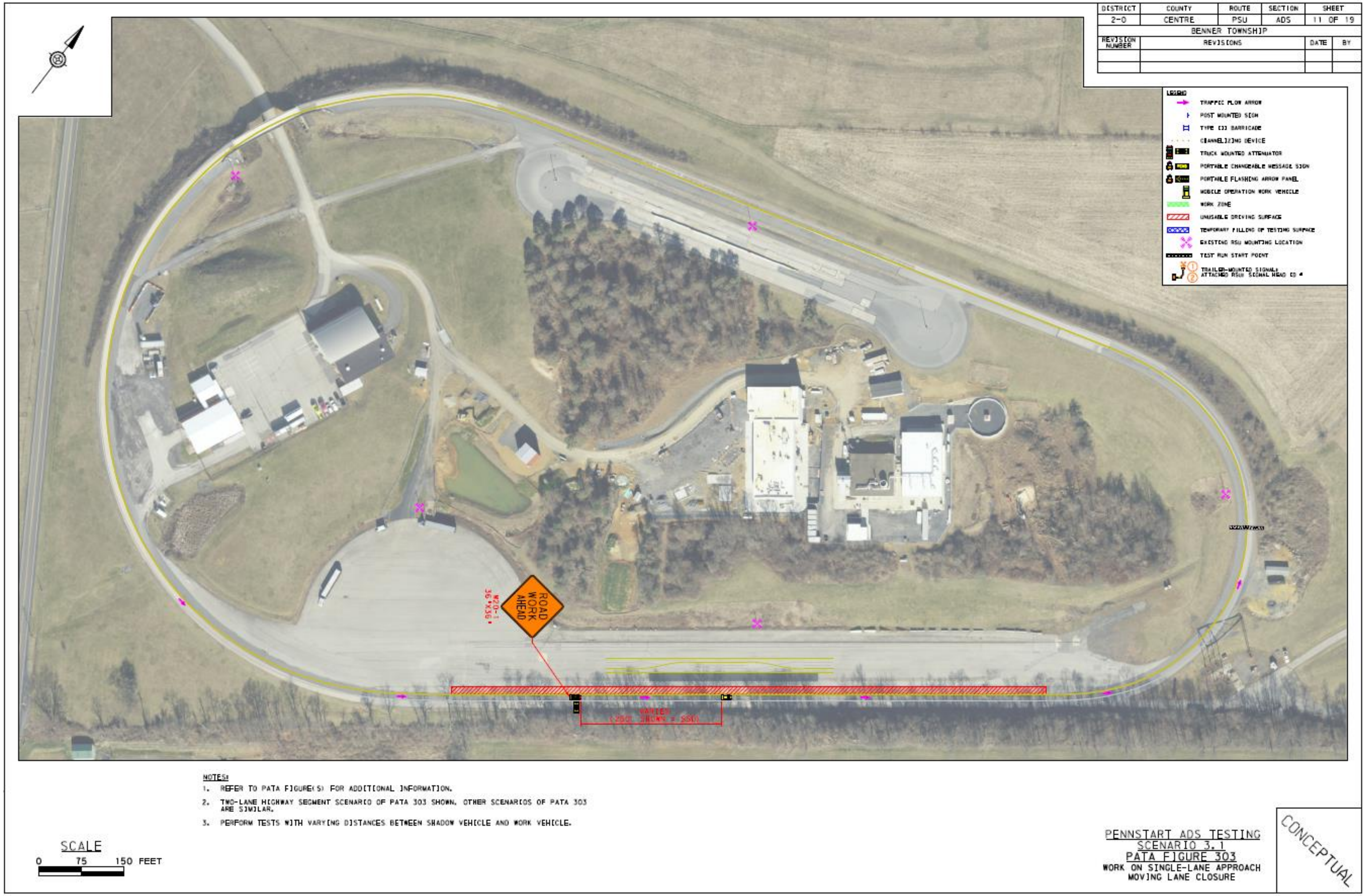


Figure 17. Scenario Setup for Scenario 2-4 (PATA 706)



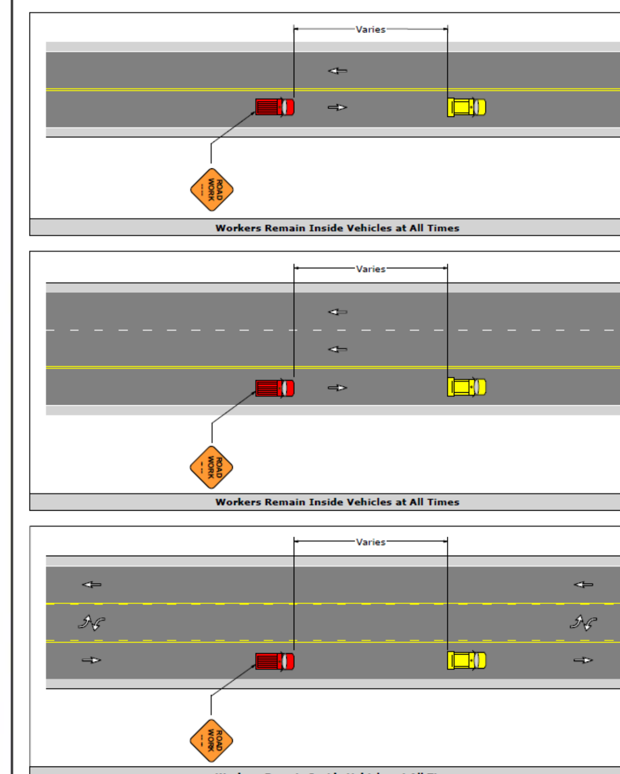
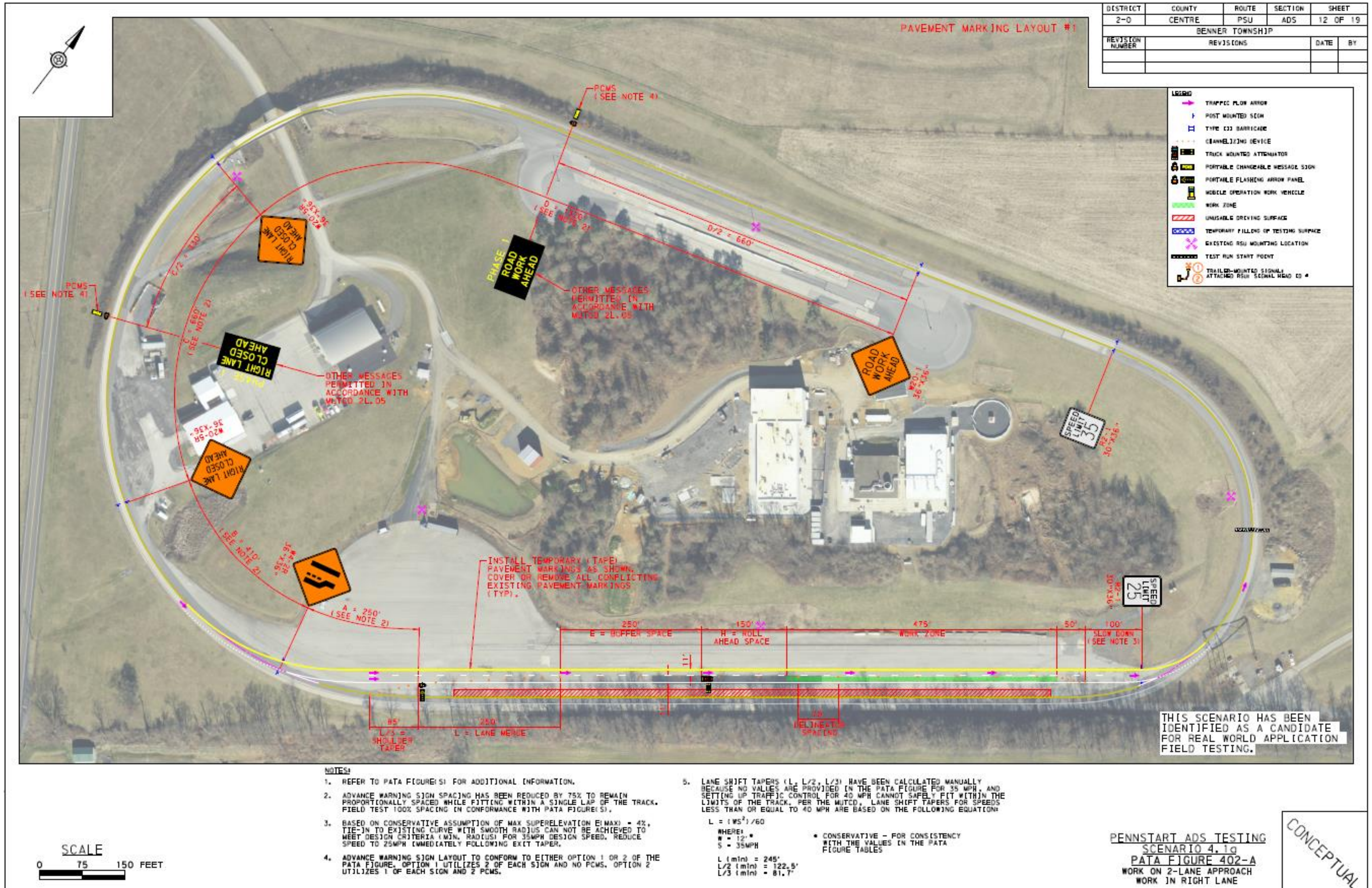
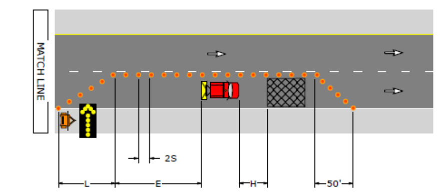


Figure 18. Scenario Setup for Scenario 3-1 (PATA 303)





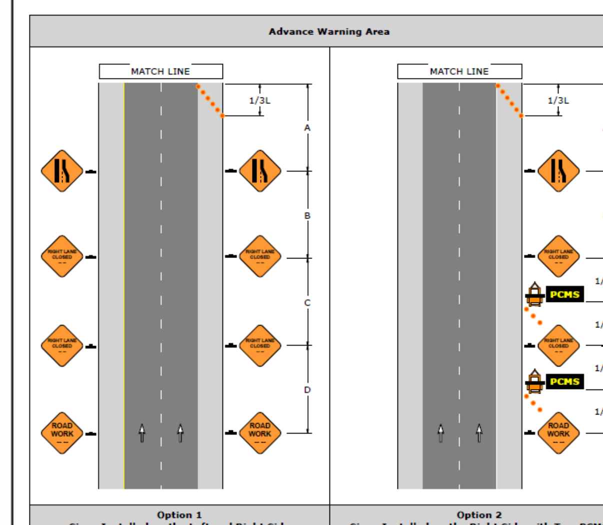
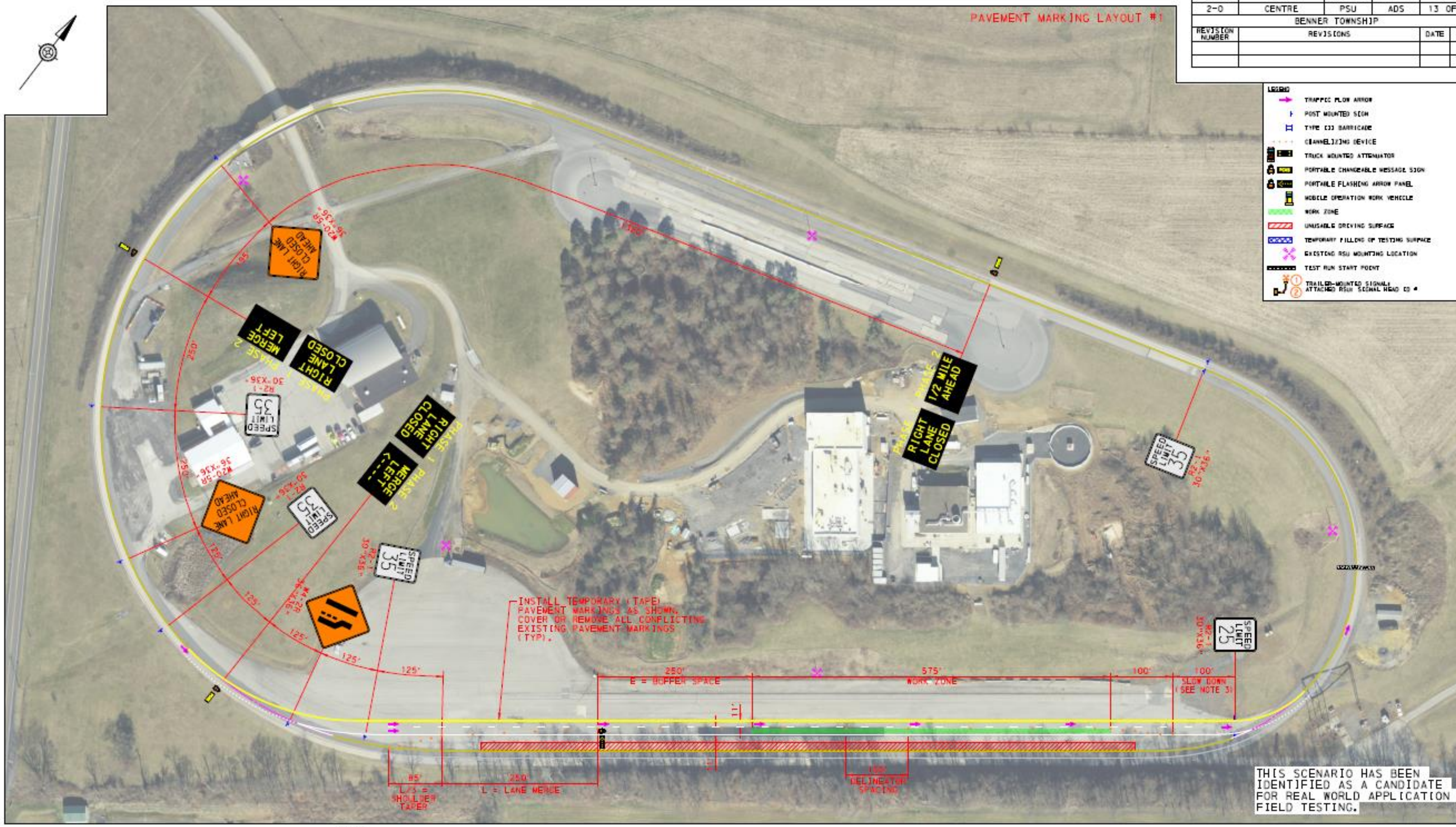


Figure 19. Scenario Setup for Scenario 4-1a (PATA 402-A)

DISTRICT	COUNTY	ROUTE	SECTION	SHEET
2-0	CENTRE	PSU	ADS	13 OF 19
BENNER TOWNSHIP				

REVISION NUMBER	REVISIONS	DATE	BY



SCALE
0 75 150 FEET

NOTES:

1. REFER TO PENNSYLVANIA TURNPIKE FIGURE PTS 915-4 FOR ADDITIONAL INFORMATION.
2. ADVANCE WARNING SIGN SPACING HAS BEEN REDUCED BY 75% TO REMAIN PROPORTIONALLY SPACED WHILE FITTING WITHIN A SINGLE LAP OF THE TRACK. FIELD TEST 100% SPACING IN CONFORMANCE WITH PTS FIGURE.
3. BASED ON CONSERVATIVE ASSUMPTION OF MAX SUPERELEVATION E(MAX) = 4%, TIE-IN TO EXISTING CURVE WITH SMOOTH RADIUS CAN NOT BE ACHIEVED TO MEET DESIGN CRITERIA (MIN. RADIUS) FOR 35MPH DESIGN SPEED. REDUCE SPEED TO 25MPH IMMEDIATELY FOLLOWING EXIT TAPER.
4. LANE SHIFT TAPERS (L, L/2, L/3) HAVE BEEN CALCULATED MANUALLY BECAUSE NO VALUES ARE PROVIDED IN THE PTS FIGURE FOR 35 MPH, AND SETTING UP TRAFFIC CONTROL FOR 55 MPH CANNOT SAFELY FIT WITHIN THE LIMITS OF THE TRACK. PER THE MUTCD, LANE SHIFT TAPERS FOR SPEEDS LESS THAN OR EQUAL TO 40 MPH ARE BASED ON THE FOLLOWING EQUATION:

$$L = (WS^2)/60$$

WHERE:
W = 12'*
S = 35MPH

* CONSERVATIVE – FOR CONSISTENCY WITH THE VALUES IN THE PATA FIGURE TABLES

L (min) = 245'
L/2 (min) = 122.5'
L/3 (min) = 81.7'

PENNSTART ADS TESTING
SCENARIO 4.1b
PTS FIGURE 915-4
WORK ON 2-LANE APPROACH
WORK IN RIGHT LANE
(PENNSYLVANIA TURNPIKE)

CONCEPTUAL

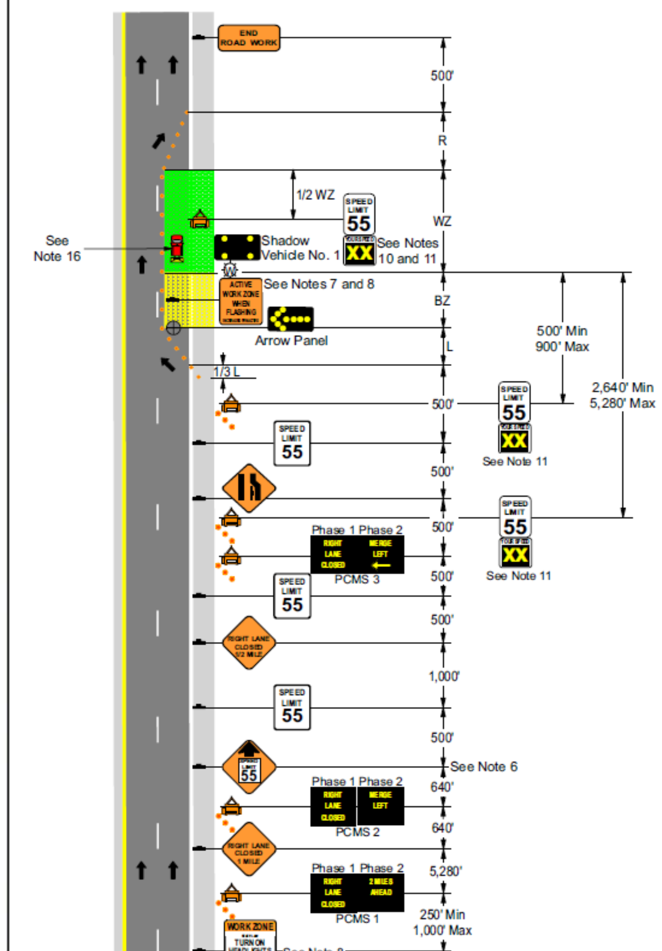
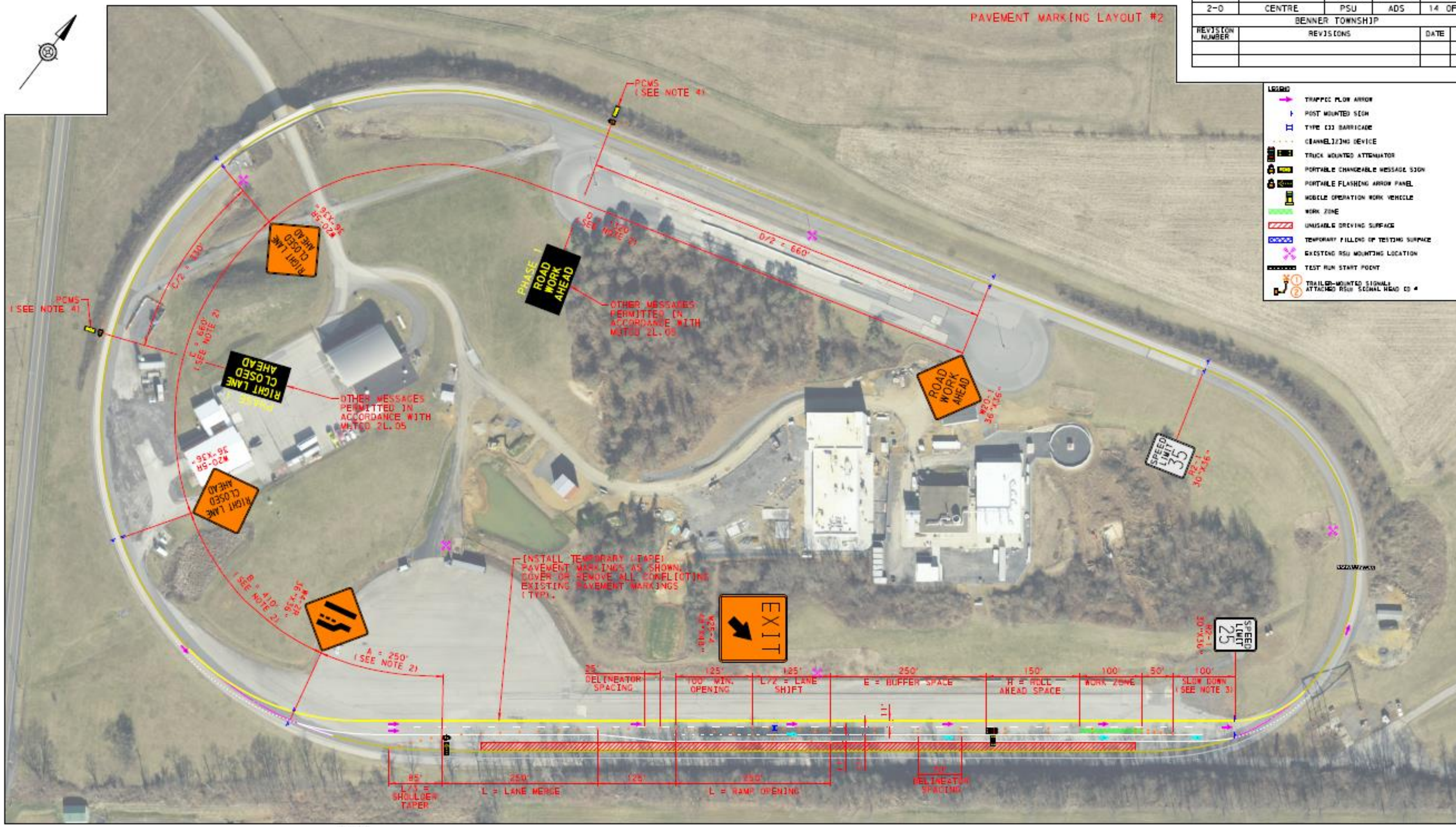


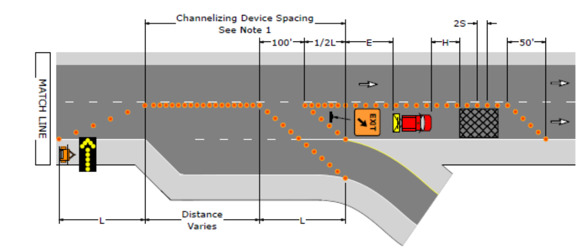
Figure 20. Scenario Setup for Scenario 4-1b (PTS 915-4)

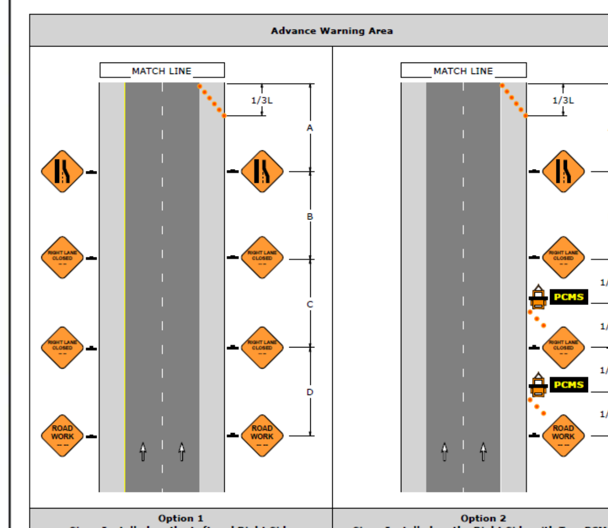
DISTRICT	COUNTY	ROUTE	SECTION	SHEET
2-0	CENTRE	PSU	ADS	14 OF 19

BENNER TOWNSHIP

REVISION NUMBER	REVISIONS	DATE	BY







NOTES:

1. REFER TO PATA FIGURE(S) FOR ADDITIONAL INFORMATION.
2. ADVANCE WARNING SIGN SPACING HAS BEEN REDUCED BY 75% TO REMAIN PROPORTIONALLY SPACED WHILE FITTING WITHIN A SINGLE LAP OF THE TRACK. FIELD TEST 100% SPACING IN CONFORMANCE WITH PATA FIGURE(S).
3. BASED ON CONSERVATIVE ASSUMPTION OF MAX SUPERELEVATION E(MAX) = 4%, TIE-IN TO EXISTING CURVE WITH SMOOTH RADIUS CAN NOT BE ACHIEVED TO MEET DESIGN CRITERIA (MIN. RADIUS) FOR 35MPH DESIGN SPEED. REDUCE SPEED TO 25MPH IMMEDIATELY FOLLOWING EXIT TAPER.
4. ADVANCE WARNING SIGN LAYOUT TO CONFORM TO EITHER OPTION 1 OR 2 OF THE PATA FIGURE. OPTION 1 UTILIZES 2 OF EACH SIGN AND NO PCMS. OPTION 2 UTILIZES 1 OF EACH SIGN AND 2 PCMS.
5. LANE SHIFT TAPERS (L, L/2, L/3) HAVE BEEN CALCULATED MANUALLY BECAUSE NO VALUES ARE PROVIDED IN THE PATA FIGURE FOR 35 MPH, AND SETTING UP TRAFFIC CONTROL FOR 40 MPH CANNOT SAFELY FIT WITHIN THE LIMITS OF THE TRACK. PER THE MUTCD, LANE SHIFT TAPERS FOR SPEEDS LESS THAN OR EQUAL TO 40 MPH ARE BASED ON THE FOLLOWING EQUATION:

$$L = (WS^2)/60$$

WHERE:
W - 12'*
S - 35MPH

L (min) = 245'
L/2 (min) = 122.5'
L/3 (min) - 81.7'

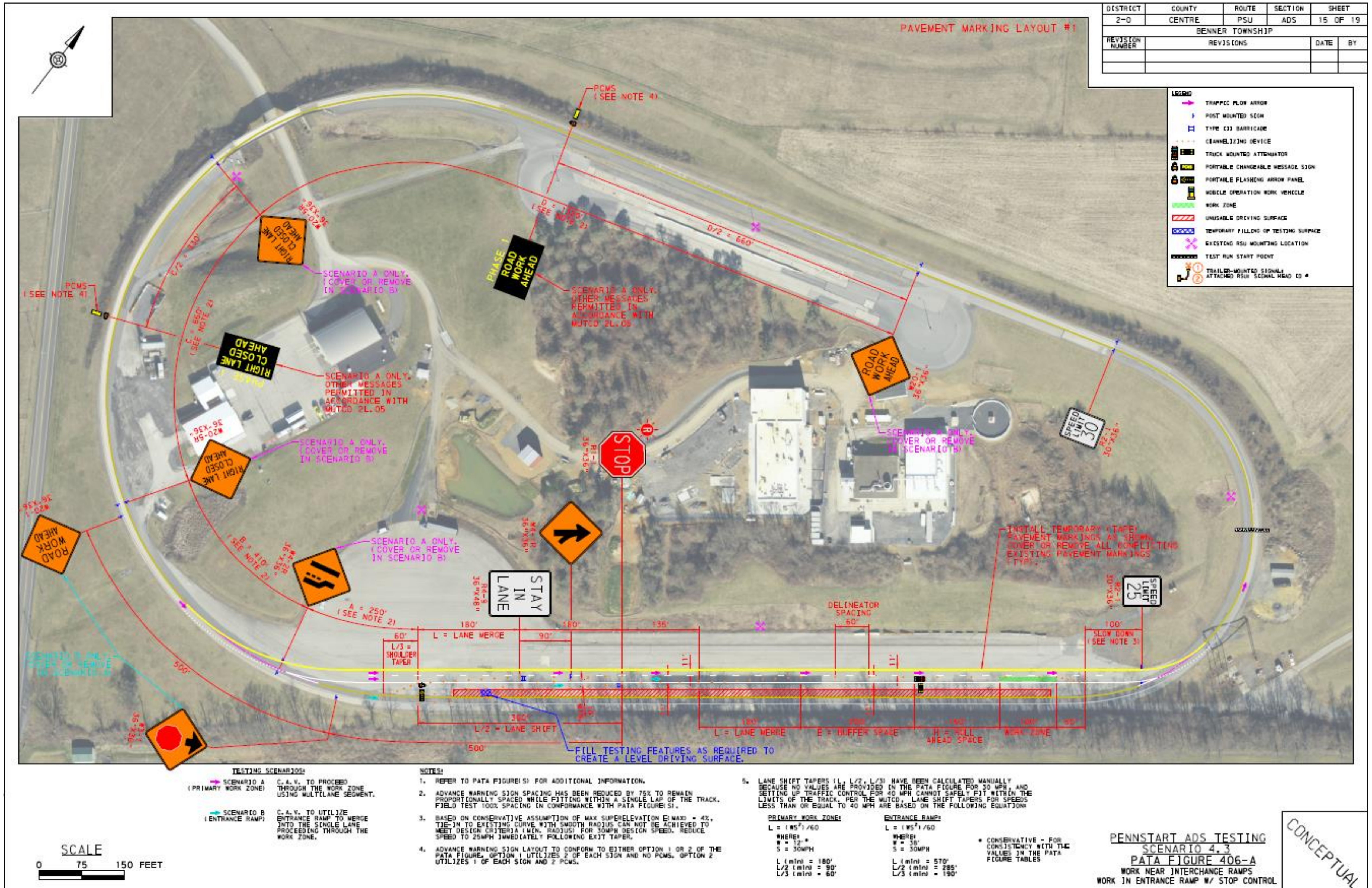
* CONSERVATIVE - FOR CONSISTENCY WITH THE VALUES IN THE PATA FIGURE TABLES

SCALE
0 75 150 FEET

PENNSTART ADS TESTING
SCENARIO 4.2
PATA FIGURE 404-A
WORK NEAR INTERCHANGE RAMPS
WORK IN RIGHT LANE NEAR EXIT RAMP

CONCEPTUAL

Figure 21. Scenario Setup for Scenario 4-2 (PATA 404-A)



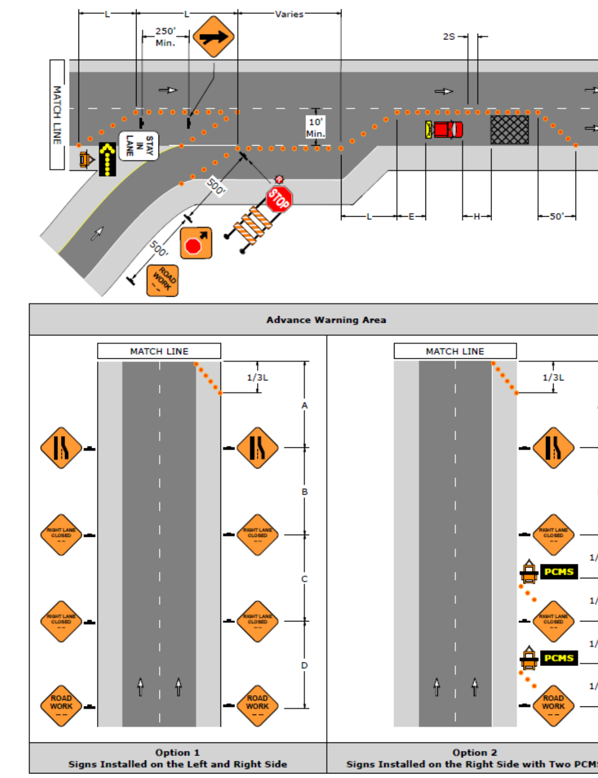
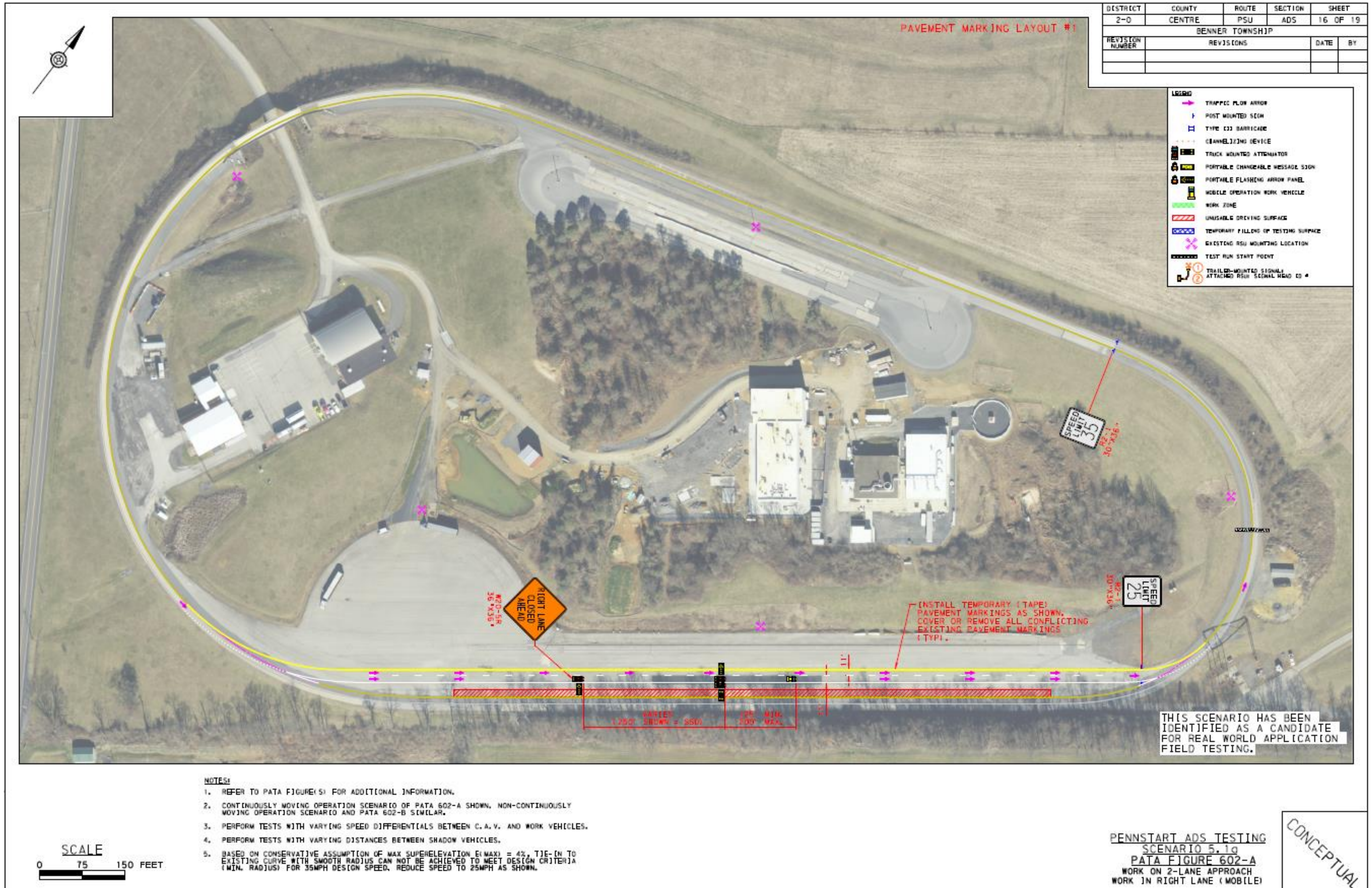


Figure 22. Scenario Setup for Scenario 4-3 (PATA 406-A)



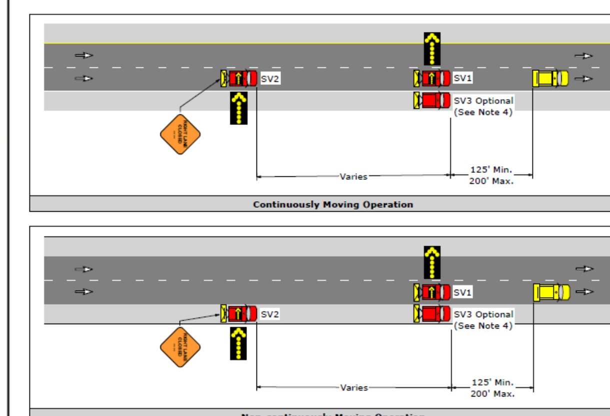


Figure 23. Scenario Setup for Scenario 5-1a (PATA 602-A)

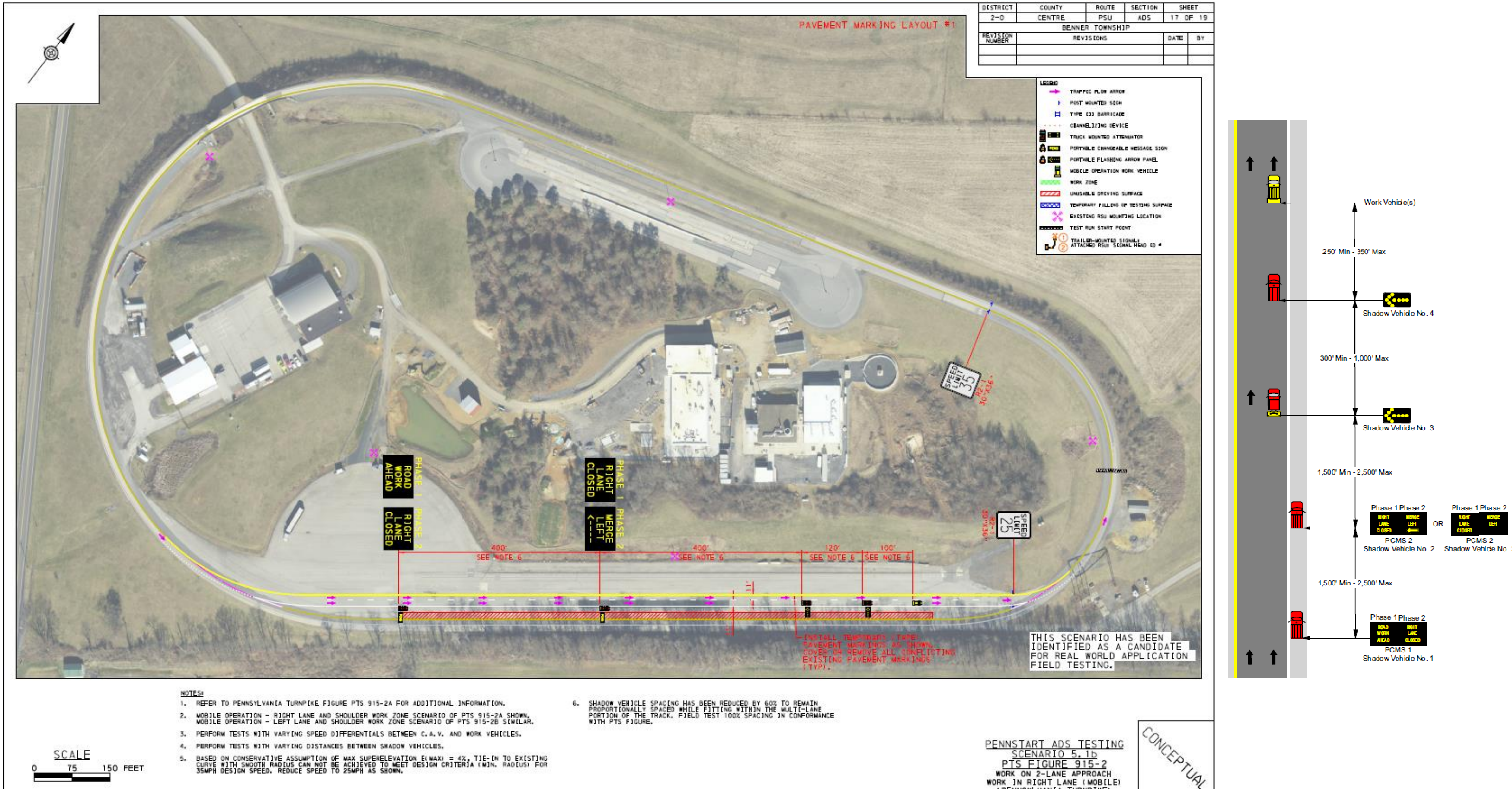
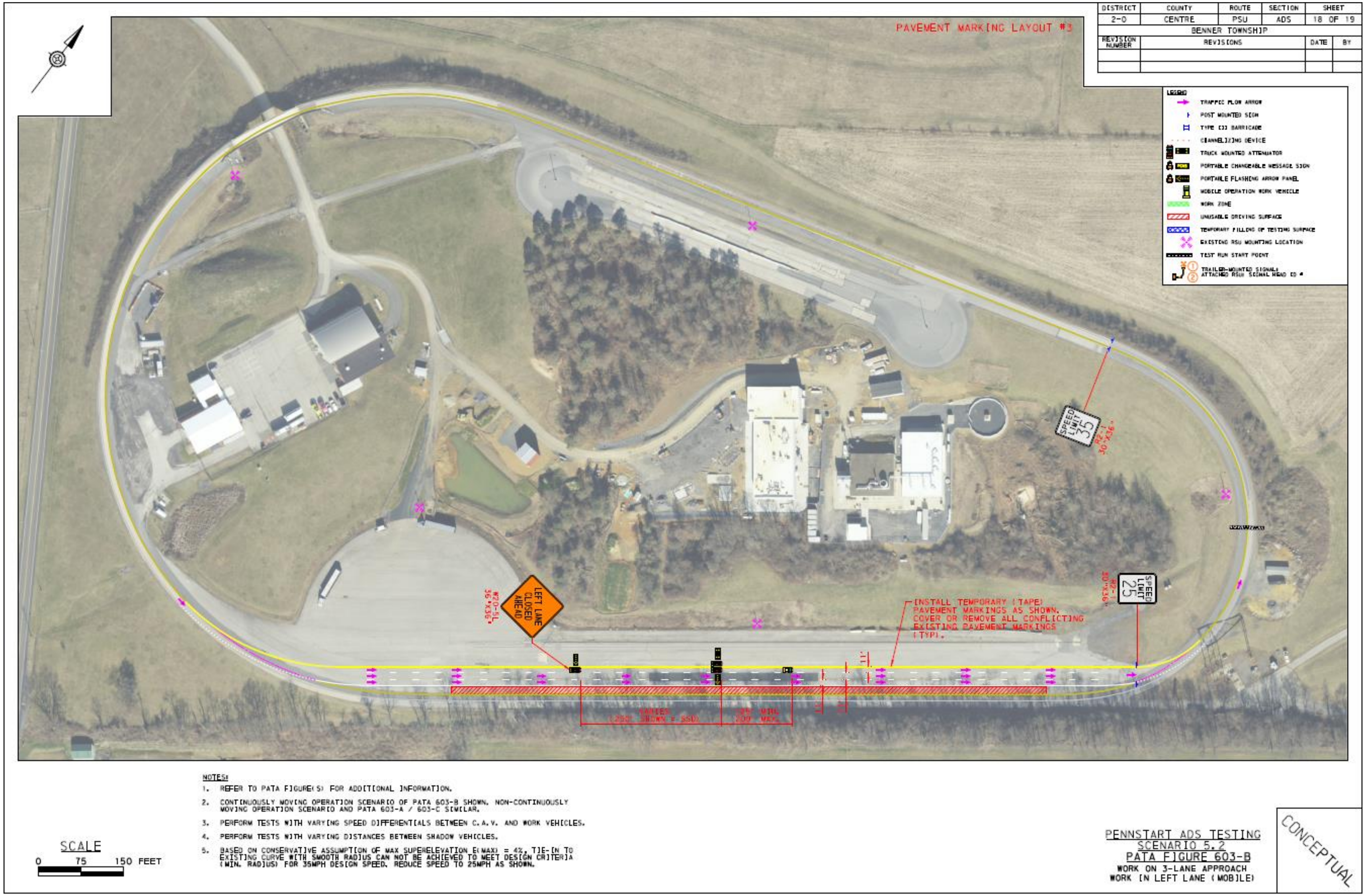


Figure 24. Scenario Setup for Scenario 5-1b (PTS 915-2A)



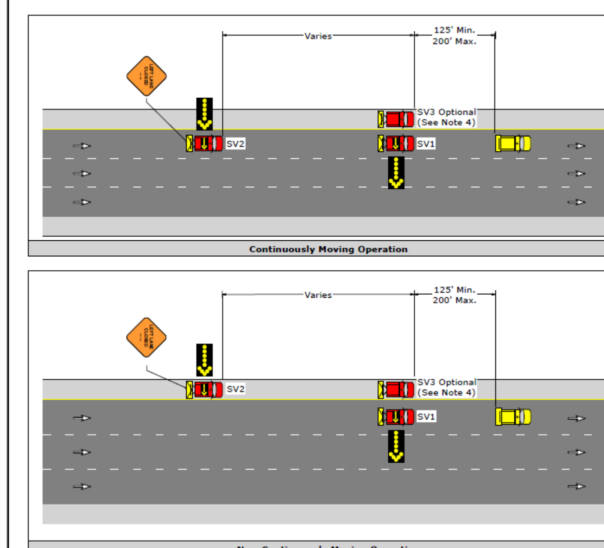
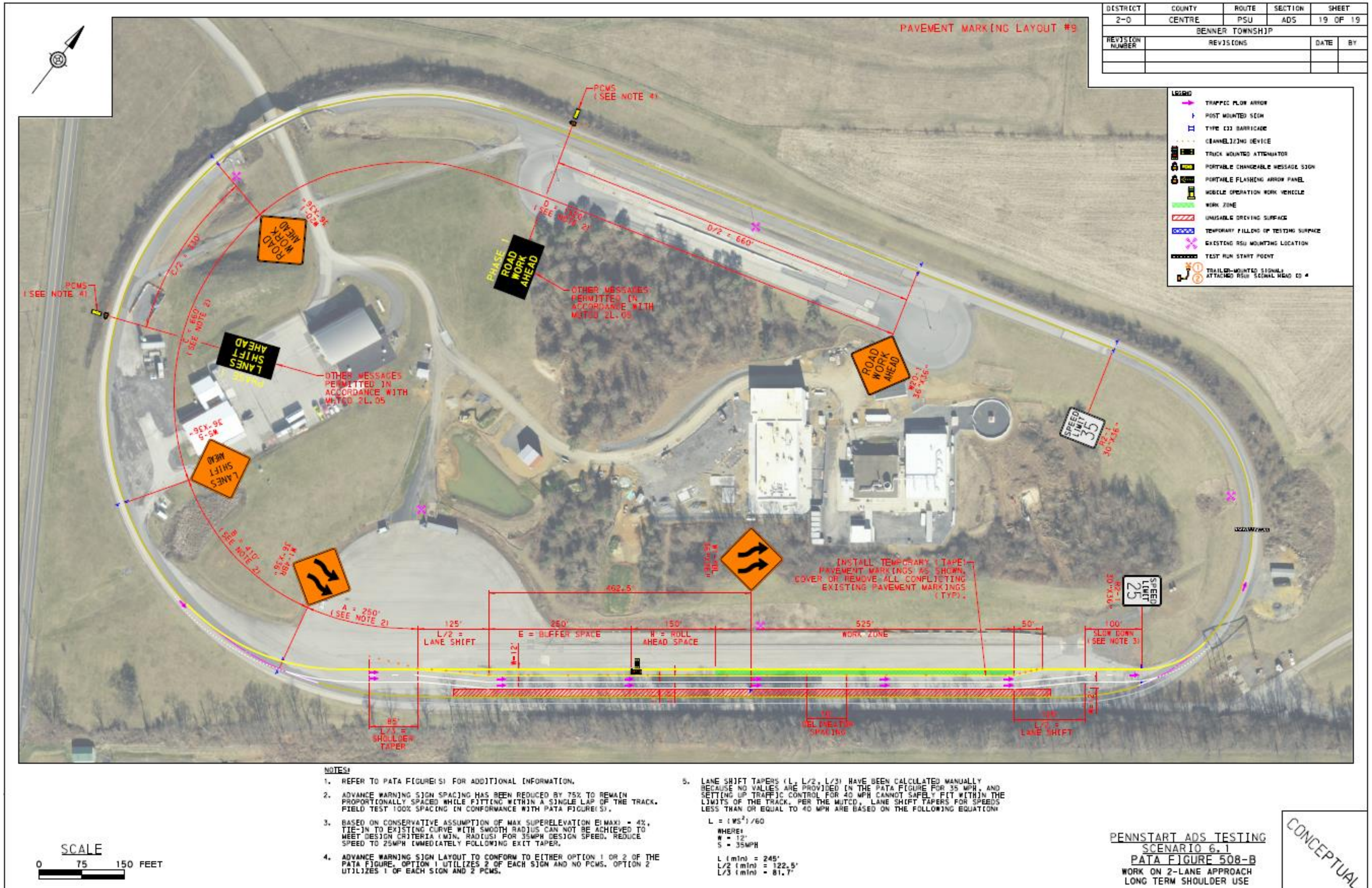
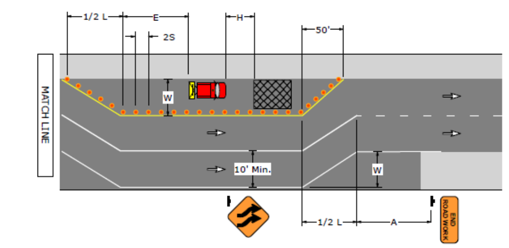


Figure 25. Scenario Setup for Scenario 5-2 (PATA 603-B)





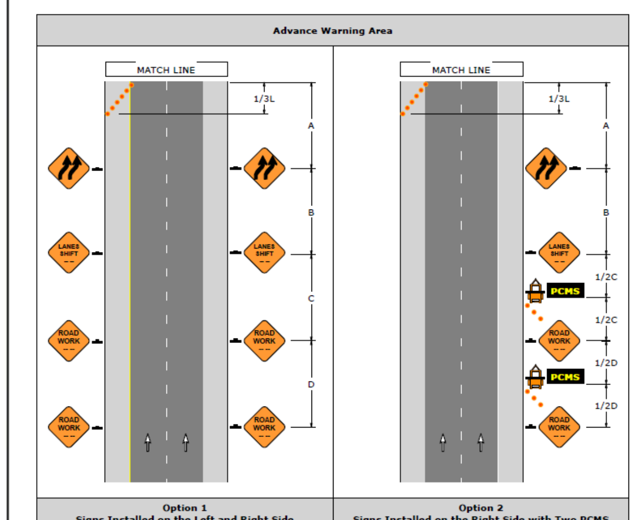


Figure 26. Scenario Setup for Scenario 6-1 (PATA 508-B)

APPENDIX B: TEST TRACK DEVICE QUANTITIES

A summary of quantities for all needed signage, markings, and devices are shown in Table 15. A contingency increase in 10% per unit should be considered due to the dynamic nature of the testing environment and the lead times needed for procurement.

Table 16 shows the summary of quantities for temporary pavement markings. Table 17 through Table 25 show the details for each of the nine distinct layouts. These are groupings of scenarios based on configuration.

Table 26 shows the summary of quantities for permanent pavement markings. Table 27 shows the quantity of permanent pavement markings that need to be removed from the test track before testing begins. Table 28 shows the quantity of pavement markings that need to be applied to the test track before testing begins.

All values were derived from the scenario CAD files. The complete spreadsheet with further details is included as a digital attachment with this plan.

Table 15. Device Quantities Needed for Closed-Track Testing

Post Mounted Signs

Series	Length (in)	Width (in)	Area (SF)	Description	TOTAL PROJECT Quantity		*Quantities (Each) for each Series*																		
					Each	SF	*1-1*	*1-2*	*1-3*	*1-4*	*1-5*	*1-6*	*2-1*	*2-2*	*2-3*	*2-4*	*3-1*	*4-1a*	*4-1b*	*4-2*	*4-3*	*5-1a*	*5-1b*	*5-2*	*6-1*
R1-1 (Small)	30	30	6.25	Stop (Small)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R1-1 (Large)	36	36	9	Stop(Large)	4	36	0	4	0	0	0	0	4	1	0	0	0	0	0	0	1	0	0	0	0
R2-1 (20)	30	36	7.5	Speed Limit (20mph)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2-1 (25)	30	36	7.5	Speed Limit (25mph)	2	15	0	0	2	2	2	2	0	2	2	2	0	2	2	2	2	2	2	2	2
R2-1 (30)	30	36	7.5	Speed Limit (30mph)	2	15	0	0	2	2	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0
R2-1 (35)	30	36	7.5	Speed Limit (35mph)	5	37.5	0	0	0	0	0	2	0	2	2	2	0	2	5	2	0	2	2	2	2
R4-9	36	48	12	Stay In Lane	1	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
R10-6AL	24	30	5	Stop Here (L) on Red	1	5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
R10-6AR	24	30	5	Stop Here (R) on Red	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R11-2	48	30	10	Road Closed	2	20	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
R11-4	60	30	12.5	Road Closed to Thru Traffic	1	12.5	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
W1-4BL	36	36	9	Two-Lane Left Reverse Curve	1	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
W1-4BR	36	36	9	Two-Lane Right Reverse Curve	2	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
W1-4L	36	36	9	Left Reverse Curve	1	9	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W1-4R	36	36	9	Right Reverse Curve	1	9	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
W3-1	36	36	9	Stop Ahead	1	9	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
W3-3	36	36	9	Signal Ahead	1	9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
W4-1L	36	36	9	Merge Left	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W4-1R	36	36	9	Merge Right	1	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
W4-2L	36	36	9	Pavement Width Transition, Left Lane Ends	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W4-2R	36	36	9	Pavement Width Transition, Right Lane Ends	2	18	0	0	0	0	0	1	0	0	0	0	0	2	1	2	2	0	0	0	0
W5-5	36	36	9	Lanes Shift (Ahead)	3	27	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	2
W9-3	36	36	9	Center Lane Closed (Ahead)	1	9	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W14-3	48	36	6	No Passing Zone	1	6	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
W20-1	36	36	9	Road Work (Ahead)	4	36	2	0	1	1	1	1	0	1	1	1	1	2	0	2	3	0	0	0	4
W20-2	36	36	9	Detour (Ahead)	2	18	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
W20-3	36	36	9	Road Closed (Ahead)	2	18	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
W20-4	36	36	9	One Lane Road (Ahead)	1	9	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
W20-5L	36	36	9	Left Lane Closed (Ahead)	1	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
W20-5R	36	36	9	Right Lane Closed (Ahead)	4	36	0	0	0	0	0	1	0	0	0	0	0	4	2	4	4	1	0	0	0
W25-4	48	48	16	Exit Gore	1	16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
M1-5	24	24	4	PA Route (Marker)	10	40	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
M3-1	24	12	2	North (Marker)	10	20	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
M3-2	24	12	2	East (Marker)	10	20	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
M3-3	24	12	2	South (Marker)	10	20	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
M3-4	24	12	2	West (Marker)	10	20	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
M4-8	24	12	2	Detour (Marker)	10	20	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
M4-8A	24	18	3	End Detour	1	3	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
M4-9L	30	24	5	Detour (Left)	2	10	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M4-9R	30	24	5	Detour (Right)	2	10	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M4-9S	30	24	5	Detour (Straight)	2	10	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M4-10L	48	18	6	Detour Arrow, Left	1	6	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
M4-10R	48	18	6	Detour Arrow, Right	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M5-1L	21	15	2.1875	Advance Left Plaque	2	4.375	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
M5-1R	21	15	2.1875	Advance Right Plaque	1	2.1875	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
M6-1	21	15	2.1875	Left/Right Plaque	4	8.75	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
M6-3	21	15	2.1875	Straight Plaque	3	6.5625	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
G20-2	36	18	4.5	End Road Work	1	4.5	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
Type III Barricades					3	EACH	0	3	0	0	0	0	3	0	0	0	0	0	0	1	2	0	0	0	0
Flashing Beacon for Signs (Red)					1	EACH	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Flashing Beacon for Signs (Yellow)					0	EACH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Flashing Beacon for Signs (White)					0	EACH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Channelizers					73	EACH	38	0	58	47	46	23	0	14	30	21	0	38	25	67	73	0	0	0	36
Channelizers w/ Specialized Coating					73	EACH	38	0	58	47	46	23	0	14	30	21	0	38	25	67	73	0	0	0	36
Truck Mount Attenuators w/ PCMS Panel					4	EACH	0	0	0	1	2	1	0	1	1	0	1	1	0	1	1	3	4	3	1
Shadow Vehicles (Pilot Vehicles)					1	EACH	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0
Trailer Mount PCMS (Arrow Panel)					4	EACH	0	0	1	1	0	1	0	0	0	0	0	3	4	3	3	0	0	0	2
Temporary Signal Trailer					2	EACH	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
"Here I Am" (V2X) Devices					15	EACH	6	0	11	8	4	4	0	4	5	8	0	9	5	13	15	0	0	0	9
Roadside Units (RSU)					8	EACH																			
Onboard Units (OBU)					3	EACH																			
Digital Worker Vest					4	EACH																			

Table 16. Temporary Pavement Marking Quantities Needed for Closed-Track Testing – Summary

Pavement Markings (Temporary, Tape)		
4" White Pavement Marking	18615	LF
6" White Pavement Marking	2851.25	LF
8" White Pavement Marking	130	LF
24" White Pavement Marking	77	LF
4" Yellow Pavement Marking	32200	LF
6" Yellow Pavement Marking	0	LF
8" Yellow Pavement Marking	0	LF

Pavement Markings (Temporary, Tape, Specialized Coating)		
4" White Pavement Marking	18615	LF
6" White Pavement Marking	2851.25	LF
8" White Pavement Marking	130	LF
24" White Pavement Marking	77	LF
4" Yellow Pavement Marking	32200	LF
6" Yellow Pavement Marking	0	LF
8" Yellow Pavement Marking	0	LF

Table 17. Temporary Pavement Marking Quantities Needed for Layout 1

Pavement Marking Layout #:	Layout 1: (2 Lane Segment, One-Directional Flow)				
Applies to Testing Scenarios:	4.1A, 4.1B, 4.3, 5.1A, 5.1B				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Left Edge Line (DY)	1840	DY/4"	2.00	3680.00	4" Yellow Pavement Marking
Lane 1/2 (BW)	1310	BW/6"	0.25	327.50	6" White Pavement Marking
Right Edge Line (DEW)	220	DEW/4"	0.33	73.33	4" White Pavement Marking
Right Edge Line (W)	1535	W/4"	1.00	1535.00	4" White Pavement Marking
Right Edge Line (DEW)	110	DEW/4"	0.33	36.67	4" White Pavement Marking
Right Edge Tie-In to Ex Loop (W)	60	W/4"	1.00	60.00	4" White Pavement Marking
Right Edge Tie-In to Ex Loop (W)	35	W/4"	1.00	35.00	4" White Pavement Marking
			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	1740	LF			
6" White Pavement Marking	327.5	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	3680	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 18. Temporary Pavement Marking Quantities Needed for Layout 2

Pavement Marking Layout #:	Layout 2: (2 Lane Segment, One-Directional Flow, w/ Exit Ramp)				
Applies to Testing Scenarios:	4.2				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Left Edge Line (DY)	1840	DY/4"	2.00	3680.00	4" Yellow Pavement Marking
Lane 1 / 2 (BW)	1310	BW/6"	0.25	327.50	6" White Pavement Marking
Lane 2 / Ramp (AW)	150	AW/8"	0.20	30.00	8" White Pavement Marking
Lane 2 / Ramp (W/8")	100	W/8"	1.00	100.00	8" White Pavement Marking
Lane 2 / Ramp (W/4")	600	W/4"	1.00	600.00	4" White Pavement Marking
Right Edge Line (DEW)	220	DEW/4"	0.33	73.33	4" White Pavement Marking
Right Edge Line (W/4")	1505	W/4"	1.00	1505.00	4" White Pavement Marking
Right Edge Line (DEW)	145	DEW/4"	0.33	48.33	4" White Pavement Marking
Right Edge Tie-In to Ex Loop (W/4")	60	W/4"	1	60.00	4" White Pavement Marking
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	2286.66667	LF			
6" White Pavement Marking	327.5	LF			
8" White Pavement Marking	130	LF			
24" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	3680	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 19. Temporary Pavement Marking Quantities Needed for Layout 3

Pavement Marking Layout #:	Layout 3: (3 Lane Segment, One-Directional Flow)				
Applies to Testing Scenarios:	1.6, 5.2				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Left Edge Line (DY)	1840	DY/4"	2.00	3680.00	4" Yellow Pavement Marking
Lane 1/2 (BW)	1310	BW/6"	0.25	327.50	6" White Pavement Marking
Lane 2/3 (BW)	1310	BW/6"	0.25	327.50	6" White Pavement Marking
Right Edge Line (DEW)	280	DEW/4"	0.33	93.33	4" White Pavement Marking
Right Edge Line (W)	1445	W/4"	1.00	1445.00	4" White Pavement Marking
Right Edge Line (DEW)	145	DEW/4"	0.33	48.33	4" White Pavement Marking
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	1586.66667	LF			
6" White Pavement Marking	655	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	3680	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 20. Temporary Pavement Marking Quantities Needed for Layout 4

Pavement Marking Layout #:	Layout 4: (3 Lane Segment, Bi-Directional Flow, w/ TWLTL)				
Applies to Testing Scenarios:	1.4, 1.5				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Right Edge Line, Clockwise (W)	1310	W/4"	1.00	1310.00	4" White Pavement Marking
TWLTL, Clockwise (Y)	1310	Y/4"	1.00	1310.00	4" Yellow Pavement Marking
TWLTL, Clockwise (BY)	1310	BY/4"	0.25	327.50	4" Yellow Pavement Marking
Left Edge Line, Counter Clockwise (DY)	360	DY/4"	2.00	720.00	4" Yellow Pavement Marking
TWLTL, Counter-Clockwise (BY)	1310	BY/4"	0.25	327.50	4" Yellow Pavement Marking
TWLTL, Counter-Clockwise (Y)	1310	Y/4"	1.00	1310.00	4" Yellow Pavement Marking
Left Edge Line, Counter Clockwise (DY)	185	DY/4"	2.00	370.00	4" Yellow Pavement Marking
Right Edge Line, Counter Clockwise (DEW)	280	DEW/4"	0.33	93.33	4" White Pavement Marking
Right Edge Line, Counter Clockwise (W)	1445	W/4"	1	1445.00	4" White Pavement Marking
Right Edge Line, Counter Clockwise (DEW)	145	DEW/4"	0.333333	48.33	4" White Pavement Marking
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	2896.66667	LF			
6" White Pavement Marking	0	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	4365	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 21. Temporary Pavement Marking Quantities Needed for Layout 5

Pavement Marking Layout #:	Layout 5: (2 Lane Segment w/ Bi-Directional Single Lane Segment)				
Applies to Testing Scenarios:	2.2, 2.4				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Right Edge Line, Clockwise (W)	1310	W/4"	1.00	1310.00	4" White Pavement Marking
Center Line (DY)	810	DY/4"	2.00	1620.00	4" Yellow Pavement Marking
Stop Bar	11	W/24"	1.00	11.00	24" White Pavement Marking
Work Zone (W)	355	W/4"	1.00	355.00	4" White Pavement Marking
Stop Bar	11	W/24"	1.00	11.00	24" White Pavement Marking
Center Line (DY)	520	DY/4"	2.00	1040.00	4" Yellow Pavement Marking
Right Edge Line, Counter Clockwise (DEW)	280	DEW/4"	0.33	93.33	4" White Pavement Marking
Right Edge Line, Counter Clockwise (W)	1445	W/4"	1.00	1445.00	4" White Pavement Marking
Right Edge Line, Counter Clockwise (DEW)	145	DEW/4"	0.333333	48.33	4" White Pavement Marking
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	3251.66667	LF			
6" White Pavement Marking	0	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	22	LF			
4" Yellow Pavement Marking	2660	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 22. Temporary Pavement Marking Quantities Needed for Layout 6

Pavement Marking Layout #:	Layout 6: (Detour Striping)				
Applies to Testing Scenarios:	1.2, 2.1				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Stop Bar 1	11	W/24"	1.00	11.00	24" White Pavement Marking
Stop Bar 2	11	W/24"	1.00	11.00	24" White Pavement Marking
Stop Bar 3	11	W/24"	1.00	11.00	24" White Pavement Marking
Stop Bar 4	11	W/24"	1.00	11.00	24" White Pavement Marking
Stop Bar 5	11	W/24"	1.00	11.00	24" White Pavement Marking
Centerline 1	865	DY/4"	2.00	1730.00	4" Yellow Pavement Marking
Centerline 2	60	DY/4"	2.00	120.00	4" Yellow Pavement Marking
Centerline 3	50	DY/4"	2.00	100.00	4" Yellow Pavement Marking
Right Edge Line, Counter Clockwise	295	W/4"	1	295.00	4" White Pavement Marking
Right Edge Line, Counter Clockwise	30	W/4"	1	30.00	4" White Pavement Marking
Right Edge Line, Clockwise	295	W/4"	1	295.00	4" White Pavement Marking
TOTALS:					
4" White Pavement Marking	620	LF			
6" White Pavement Marking	0	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	55	LF			
4" Yellow Pavement Marking	1950	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 23. Temporary Pavement Marking Quantities Needed for Layout 7

Pavement Marking Layout #:	Layout 7: (1 Lane Segment w/ Large Shift)				
Applies to Testing Scenarios:	2.3				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Left Edge Line (DY)	1850	DY/4"	2.00	3700.00	4" Yellow Pavement Marking
Right Edge Line (DEW)	280	DEW/4"	0.33	93.33	4" White Pavement Marking
Right Edge Line (W)	1455	W/4"	1.00	1455.00	4" White Pavement Marking
Right Edge Line (DEW)	145	DEW/4"	0.33	48.33	4" White Pavement Marking
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	1596.66667	LF			
6" White Pavement Marking	0	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	3700	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 24. Temporary Pavement Marking Quantities Needed for Layout 8

Pavement Marking Layout #:	Layout 8: (3 Lane Segment, Bi-Directional Flow, Single Lane for AV Testing)				
Applies to Testing Scenarios:	1.3				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Right Edge Line, Clockwise (W)	1310	W/4"	1.00	1310.00	4" White Pavement Marking
Lane 1/2, Clockwise (BW)	1310	BW/6"	0.25	327.50	6" White Pavement Marking
Center Line (DY)	1850	DY/4"	2.00	3700.00	4" Yellow Pavement Marking
Right Edge Line, Counter-Clockwise (DEW)	280	DEW/4"	0.33	93.33	4" White Pavement Marking
Right Edge Line, Counter-Clockwise (W)	1445	W/4"	1.00	1445.00	4" White Pavement Marking
Right Edge Line, Counter-Clockwise (DEW)	145	DEW/4"	0.33	48.33	4" White Pavement Marking
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	2896.66667	LF			
6" White Pavement Marking	327.5	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	3700	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 25. Temporary Pavement Marking Quantities Needed for Layout 9

Pavement Marking Layout #:	Layout 9: (2 Lane Segment, One-Directional Flow, w/ Large Shift)				
Applies to Testing Scenarios:	6.1				
	Measured		**Pay Length**		
Description	**Length (LF)**	**Type**	**Factor**	**Length (LF)**	**Pay Item**
Left Edge Line (DY)	1840	DY/4"	2.00	3680.00	4" Yellow Pavement Marking
Lane Shift, Left Edge Line (Y)	1105	Y/4"	1.00	1105.00	4" Yellow Pavement Marking
Lane 1/2 (BW)	85	BW/6"	0.25	21.25	6" White Pavement Marking
Lane Shift, Lane 1/2 (W)	1180	W/6"	1.00	1180.00	6" White Pavement Marking
Lane 1/2 (BW)	50	BW/6"	0.25	12.50	6" White Pavement Marking
Right Edge Line (DEW)	220	DEW/4"	0.33	73.33	4" White Pavement Marking
Right Edge Line (W)	1535	W/4"	1.00	1535.00	4" White Pavement Marking
Right Edge Line (DEW)	110	DEW/4"	0.33	36.67	4" White Pavement Marking
Right Edge Tie-In to Ex Loop (W)	60	W/4"	1	60.00	4" White Pavement Marking
Right Edge Tie-In to Ex Loop (W)	35	W/4"	1	35.00	4" White Pavement Marking
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	1740	LF			
6" White Pavement Marking	1213.75	LF			
8" White Pavement Marking	0	LF			
24" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	4785	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

Table 26. Permanent Pavement Marking Quantities Needed for Closed-Track Testing – Summary

Pavement Markings (Permanent, Waterborne)		
4" White Pavement Marking	505	LF
6" White Pavement Marking	0	LF
8" White Pavement Marking	0	LF
4" Yellow Pavement Marking	2045	LF
6" Yellow Pavement Marking	0	LF
8" Yellow Pavement Marking	0	LF
Removal	850	SF

Pavement Markings (Permanent, Waterborne, Specialized Coating)		
4" White Pavement Marking	505	LF
6" White Pavement Marking	0	LF
8" White Pavement Marking	0	LF
4" Yellow Pavement Marking	2045	LF
6" Yellow Pavement Marking	0	LF
8" Yellow Pavement Marking	0	LF
Removal	850	SF

Table 27. Permanent Pavement Marking Removal Quantities for Closed-Track Testing

Pavement Marking Layout #:	Removal of Existing Markings				
Applies to Testing Scenarios:	N/A				
	Length of Markings		Payment		
Description	Removed (LF)	Type	Width (FT)	Area (SF)	Pay Item
DY/4" (Western Limit of Temp Markings)	550.00	DY/4"	0.33	183.33	REMOVAL
DY/4" (Eastern Limit of Temp Markings)	290.00	DY/4"	0.33	96.67	REMOVAL
Y/4" Edge Line (Slalom Testing Area, North Edge)	400.00	Y/4"	0.33	133.33	REMOVAL
Y/4" Edge Line (Slalom Testing Area, South Edge)	400.00	Y/4"	0.33	133.33	REMOVAL
Y/4" Edge Line (Slalom Testing Area, Slalom Line)	405.00	Y/4"	0.33	135.00	REMOVAL
W/4" Edge Line (Slalom Testing Area, Slalom Line)	405.00	W/4"	0.33	135.00	REMOVAL
BW/4" Lane Line (Slalom Testing Area, Slalom Line)	100.00	BW/4"	0.33	33.33	REMOVAL
-	#N/A	0			
-	#N/A	0			
-	#N/A	0			
-	#N/A	0			
TOTALS:					
REMOVAL	850.00	SF			

Table 28. Permanent Pavement Marking Quantities Needed for Closed-Track Testing – Detail

Pavement Marking Layout #:	Restoration of Permanent Markings to Existing Condition				
Applies to Testing Scenarios:	N/A				
	Measured Length		Pay Length		
Description	(LF)	Type	Factor	Length (LF)	Pay Item
DY/4" (Western Limit of Temp Markings)	275	DY/4"	2.00	550.00	4" Yellow Pavement Marking
DY/4" (Eastern Limit of Temp Markings)	145	DY/4"	2.00	290.00	4" Yellow Pavement Marking
Y/4" Edge Line (Slalom Testing Area, North Edge)	400	Y/4"	1.00	400.00	4" Yellow Pavement Marking
Y/4" Edge Line (Slalom Testing Area, South Edge)	400	Y/4"	1.00	400.00	4" Yellow Pavement Marking
Y/4" Edge Line (Slalom Testing Area, Slalom Line)	405	Y/4"	1.00	405.00	4" Yellow Pavement Marking
W/4" Edge Line (Slalom Testing Area, Slalom Line)	405	W/4"	1.00	405.00	4" White Pavement Marking
BW/4" Lane Line (Slalom Testing Area, Slalom Line)	400	BW/4"	0.25	100.00	4" White Pavement Marking
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
-			#N/A	#N/A	#N/A
TOTALS:					
4" White Pavement Marking	505	LF			
6" White Pavement Marking	0	LF			
8" White Pavement Marking	0	LF			
4" Yellow Pavement Marking	2045	LF			
6" Yellow Pavement Marking	0	LF			
8" Yellow Pavement Marking	0	LF			

APPENDIX C: DETAILED PHASE 2 DEPLOYMENT SCHEDULE

Figure 27 shows the detailed deployment schedule for Phase 2 of the project. This will be updated after the closed-track testing (CT0) is completed.

ID	Task Name	Duration	Start	Finish	Predecessors
1	CT0	10 days	Mon 7/11/22	Fri 7/22/22	
2	**CT1**	**40 days**	**Mon 7/25/22**	**Fri 9/16/22**	
3	Mapping	10 days	Mon 7/25/22	Fri 8/5/22	1
4	Simulation	15 days	Mon 8/8/22	Fri 8/26/22	3
5	AV Testing	15 days	Mon 8/29/22	Fri 9/16/22	4
6	**CT2**	**35 days**	**Mon 10/2/23**	**Fri 11/17/23**	
7	Mapping	10 days	Mon 10/2/23	Fri 10/13/23	2
8	Simulation	10 days	Mon 10/16/23	Fri 10/27/23	7
9	AV Testing	15 days	Mon 10/30/23	Fri 11/17/23	8
10	**CT3**	**35 days**	**Mon 1/9/23**	**Fri 2/24/23**	
11	Mapping	10 days	Mon 1/9/23	Fri 1/20/23	6
12	Simulation	10 days	Mon 1/23/23	Fri 2/3/23	11
13	AV Testing	15 days	Mon 2/6/23	Fri 2/24/23	12
14	**CT4**	**35 days**	**Mon 3/6/23**	**Fri 4/21/23**	
15	Mapping	10 days	Mon 3/6/23	Fri 3/17/23	10
16	Simulation	10 days	Mon 3/20/23	Fri 3/31/23	15
17	AV Testing	15 days	Mon 4/3/23	Fri 4/21/23	16
18	**CT5**	**35 days**	**Mon 5/1/23**	**Fri 6/16/23**	
19	Mapping	10 days	Mon 5/1/23	Fri 5/12/23	14
20	Simulation	10 days	Mon 5/15/23	Fri 5/26/23	19
21	AV Testing	15 days	Mon 5/29/23	Fri 6/16/23	20
22	**CT6**	**35 days**	**Mon 7/10/23**	**Fri 8/25/23**	
23	Mapping	10 days	Mon 7/10/23	Fri 7/21/23	18
24	Simulation	10 days	Mon 7/24/23	Fri 8/4/23	23
25	AV Testing	15 days	Mon 8/7/23	Fri 8/25/23	24
26	**CT7**	**35 days**	**Mon 9/11/23**	**Fri 10/27/23**	
27	Mapping	10 days	Mon 9/11/23	Fri 9/22/23	22
28	Simulation	10 days	Mon 9/25/23	Fri 10/6/23	27
29	AV Testing	15 days	Mon 10/9/23	Fri 10/27/23	28
30	**CT8**	**35 days**	**Mon 11/6/23**	**Fri 12/22/23**	
31	Mapping	10 days	Mon 11/6/23	Fri 11/17/23	26
32	Simulation	10 days	Mon 11/20/23	Fri 12/1/23	31
33	AV Testing	15 days	Mon 12/4/23	Fri 12/22/23	32
34	OR1	30 days	Mon 5/1/23	Fri 6/9/23	
35	OR2	30 days	Mon 7/10/23	Fri 8/18/23	
36	OR3	30 days	Mon 9/11/23	Fri 10/20/23	

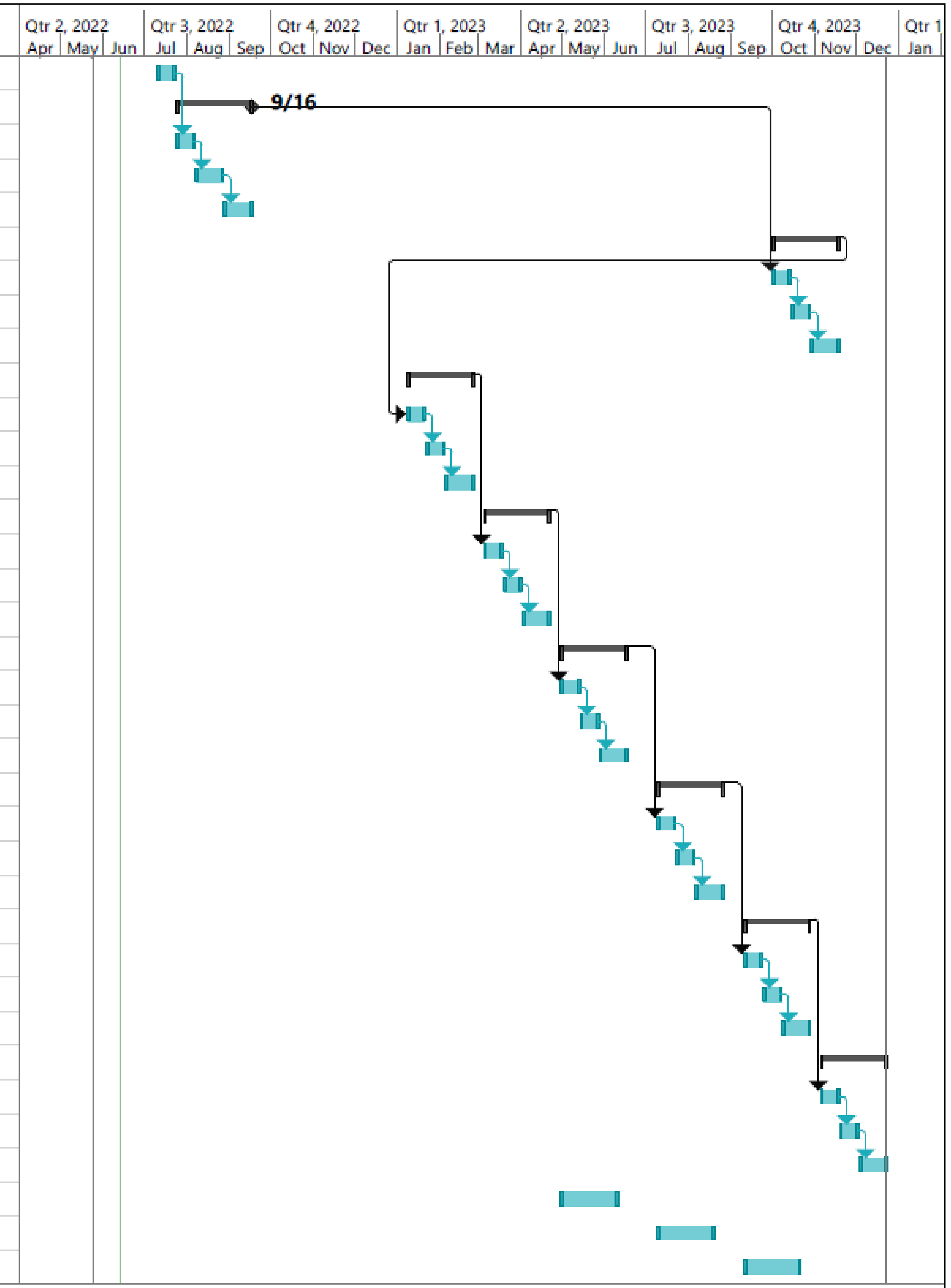


Figure 27. Phase 2 Deployment Timeline – Detailed Schedule