Pacific Northwest NATIONAL LABORATORY

PNNL-37744

Hazardous Material Commodity Flow

Pipeline and Hazardous Materials Safety Administration

May 2025

Jonathan L. Barr
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Summary

The Hazardous Material Commodity Flow project for the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration report focuses on the evaluation, testing, and implementation of systems for monitoring the transportation of hazardous materials (Hazmat) on roadways. This report details the current state of technology for hazardous material flow as well as approaches to increase public safety on roadways through the application of cost-saving automated monitoring systems employing Artificial Intelligence (AI) to enhance Hazmat identification, flow modeling, and flow monitoring on U.S. roadways.

States collect and utilize Hazmat material data in a breadth of ways, including through visual collection and manual record keeping. These periodic collection methods are labor intensive, inconsistent and ultimately fail to allow effective cross state collaboration and hazard mitigation. The use of AI tools will allow states and the Federal government to quickly, consistently, and accurately identify HazMat loads for situational awareness, and during events and emergencies, enable effective direction of first responders and re-routing of traffic. AI will also enable the ability to route loads on and off roadways, prevent accidents, minimize exposure risks, and ensure compliance with regulations.

Several commercial off the shelf (COTS) software tools and technologies are available and suitable for use in the design and implementation of a test bed and eventually broad implementation of a Hazmat tracking monitoring system. Currently, no single COTS tool provides a solution, with a combination of several tools and customization and integration into an AI model required to ensure stakeholder requirements are satisfied.

Establishment of testbeds is recommended to define protocols including criteria like accuracy, sensitivity, and efficiency of placard readers. Testbeds aim to identify, track, and analyze Hazmat transport, with details on location, areas of transport, and quality reporting. Various testbed configurations are available, allowing scaling options, including laboratory-scale and single-point roadside testbeds, to validate system performance under controlled and real-world conditions. The use of functional testing and communication testing procedures at testbeds should be defined and outlined for verifying system capabilities.

The ultimate objective of this effort is to develop a reliable, integrated system for hazardous materials tracking that can be deployed across multiple regions, ensuring efficient monitoring and effective response to hazardous material incidents. Efficient and effective real-time monitoring will save lives and ensure compliance.

Acknowledgments

This work was supported by the Pacific Northwest National Laboratory operated for the U.S. Department of Energy (DOE) by Battelle under Contract DE-AC06-76RL01830. The authors would like to acknowledge the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration team for their leadership, consultation, and support in this research and development designed to improve safety of hazardous materials on America's roadways.

Acronyms and Abbreviations

Application Programming Interface	API
Artificial Intelligence	AI
Commercial Off the Shelf	COTS
Environmental Protection Agency	EPA
Federal Highway Administration	FHWA
Federal Motor Carrier Safety Administration	FMCSA
Hazardous Materials	HazMat
Information Technology	IT
Intelligent Transportation Systems	ITS
Interstate-5	I-5
Local Area Network	LAN
Pipeline and Hazardous Materials Safety Administration	PHMSA
Pacific Northwest National Laboratory	PNNL
Tire Anomaly and Classification System	TACS™
United Nations	UN
United States Department of Transportation	USDOT
USDOT Commercial Vehicle Information Exchange Window	CVIEW
Washington State	WA
Washington State Department of Transportation	WSDOT
Weigh-In-Motion	WIM

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1.0 Introduction

Federal transportation regulations require that trucks carrying hazardous materials display placards that convey the category or type of material being transported. First responders use this information in the development of action plans as part of their response to hazardous materials incidents. State, county, and city planners need information on the type and quantity of hazardous materials for hazards and vulnerability assessments. Such information is also critical for developing plans for preventing, mitigating, responding to, and recovering from hazardous materials incidents. However, common methods of collecting information on type and quantity of hazardous materials involve manual data collection (e.g., individuals observing placards periodically and documenting the information.) Manual data collection can be inefficient, prone to human error, and not continuous. Thus, there is a need for a system that can automatically collect, analyze, and share hazardous materials information from placards on trucks with stakeholders.

The Hazardous Materials (Hazmat) Commodity Flow project aims to evaluate the capability and feasibility of implementing a testbed environment to monitor systems for identifying, tracking, and analyzing the movement of Hazmat on America's roadways. The statewide highway and interstate testbed (testbed) will use information obtained from placards mounted on trucks operating throughout Washington state on all major roadways, in all weather, and during all hours of the day to inform decision-making for hazards and vulnerability assessment. Information provided from the testbed could also inform the development of plans for preventing, mitigating, responding to, and recovering from Hazmat incidents.

This report will outline a proposed design, which is built upon the technology of computer vision, for a system that will effectively track hazardous material traversing various locations. A comparative analysis of commercial off-the-shelf (COTS) systems, their capabilities, and how they can be integrated into our existing infrastructure to ensure a seamless transition and optimal performance will be evaluated. A system is expected to address problem areas and challenges that the current system fails to address, notably the basic reading of the Hazmat placard system. The key features in this new computer vision system include the ability to read Hazmat placards and associate them with other vehicle records for complete vehicle identification and tracking, with a preference for a technology or platform that can be incorporated into the existing weigh-in-motion (WIM) system to limit the amount of new equipment that needs to be installed.

Performance metrics or key performance indicators that the new system should meet include a read accuracy comparable to existing license plate reader units, which is over 90%. The system must also perform reliably under any typical environmental condition found on the roadway within reason, including heavy fog, torrential downpours, or moderate snow.

The timeline for the deployment of this new system depends on its complexity. If new equipment and integration is minimal, initial deployment could be relatively rapid, within 12-18 months. There are also specific security or privacy concerns that need to be addressed in the new system, including record retention and management.

The Hazmat Commodity Flow project comprises the phases and deliverables outlined below and in Figure 1:

Task 1: Project Management

Task 2: Conduct Technology and Data Scan

Task 3: Perform Capability Analysis

Task 4: Identification of Stakeholders and User Engagement

Task 5: Develop Testbed Selection Criteria

- Deliverable: Testbed evaluation framework, including procedural instructions for evaluations

Task 6: Create Testing Protocol

- Deliverable: Testing protocols for basic, intermediate, and advanced testbeds

Optional: Test Protocol Implementation

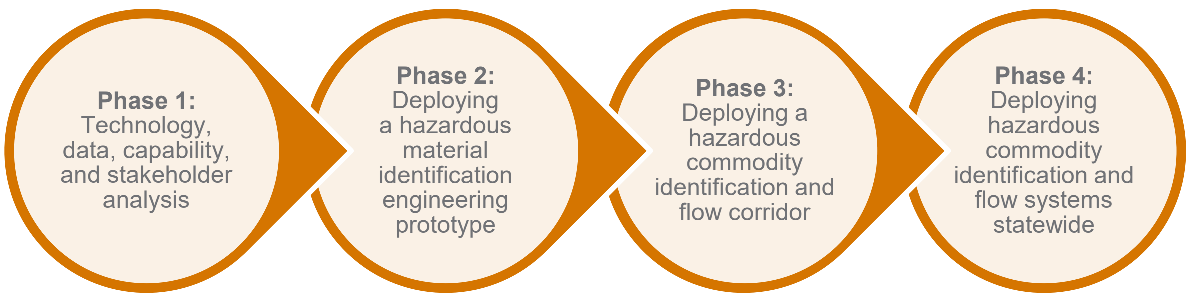

Figure 1. Hazmat Commodity Flow Testbed Implementation

2.0 Task 2 Technology and Data Scan

The process of identifying and vetting vendors for the new hazardous material tracking system is a critical step in ensuring the successful implementation of the project. This process involves both online research and in-person discussions to ensure that the selected vendors can meet the Department of Transportation's specific requirements.

Key factors to consider during this stage include vendor's experience in developing similar systems, technological capabilities, understanding of the hazardous material tracking industry, and reputation for delivering quality products on time and within budget.

2.1 Technology Scan

Pacific Northwest National Laboratory (PNNL) identified both commercially available and potential future technologies to identify and verify Hazmat in transport. Technologies were evaluated on the ability to capture United Nations (UN) placard numbers, U.S. Department of Transportation (USDOT) numbers, and vehicle license numbers. In addition, the team identified infrastructure requirements and what is currently available at strategic highway and other roadway locations, rest areas, and state weigh stations.

2.1.1 Technology Requests for Information

To collect information on various commercial off-the-shelf technologies, a USDOT and Hazard Placard Recognition System Information Gathering Form was developed. The form is formatted to allow technology vendors to provide company contact information and technical details about their products. Key factors to consider during this stage include the vendor's experience in developing similar systems, technological capabilities, understanding of the hazardous material tracking industry, and reputation for delivering quality products on time and within budget. The form is provided in Appendix A.

The following types of technologies were evaluated:

- Existing roadside cameras
- Washington state weigh station existing sensors and detectors
- License plate readers
- USDOT number readers

Once survey responses are reviewed and potential vendors shortlisted, in-depth discussions and demonstrations were scheduled. These meetings provide an opportunity to delve deeper into the vendor's proposed solution and convey to the vendor project's requirements.

Beyond the vendor demonstrations, evaluation of technical data sheets was only conducted. For convenience and where available, links to existing resources relevant to specific technologies are provided on the Reference page. Table 1 outlines technologies evaluated to determine applicability to this project.

Table 1. Hardware and Software Companies

Company	System Description	Status	Applicability	Notes
Perceptics	Hazmat Placard Reader[1]	Commercialized	Mature but would require an integration effort with state-level database.	Perceptics typically works with integrators (i.e., commercial entities that integrate and support deployed systems and solutions); Quarterhill Corp. is the integrator in Washington state. Hardware and software system would require integration into existing state-level highway patrol database systems. Federal-level database system integration is TBD.
	USDOT Number Reader[2]			AI-powered USDOT number reader.
	License Plate Reader			
Quarterhill Corp. *(*Formerly International Road Dynamics)	Ramp E-Screening System - Oct 2023[3]	Commercialized Large-scale installation (California)	Mature but would require an integration effort with state-level database.	Partners with Perceptics to deploy Hazmat Placard Reader, USDOT Number Reader, and License Plate Capture Reader Deployed and integrated the following systems into the WA State Patrol and WSDOT data networks: Cameras Weigh-in-Motion License Plate Readers Over-Height Detection Electronic Credential Screening Minimal integration should be needed to deploy and integrate vendor's Hazmat placard system. Has systems that can be integrated into weigh stations and mobile units that can be deployed and integrated. <u>Issues</u>: While a comprehensive solution for hazardous commodity flow has not been implemented in a statewide deployment (e.g., real time hazardous commodity flow, predictive analysis) No technical roadblocks have been identified in this solution. Section

Company	System Description	Status	Applicability	Notes
				5.0 outlines benefits and challenges of various types of testbeds, in which technologies will be implemented.
NASCENT Technologies	enVision - Hazard Placard Identification[4]	Commercialized	Mature but would require an integration effort with state-level database.	Offers an integrated software/hardware solution, including: Modular system High-resolution imaging (i.e. greater than 300 dots or pixels per inch) High-performance optical character recognition Handling of non-stop vehicle traffic up to 25 miles per hour Issues: No technical roadblocks have been identified.
Drivewyze	Hazmat Placard Reader	Commercialized	Mature but would require an integration effort with state-level database.	Minimal integration should be needed to deploy and integrate vendor's Hazmat placard system. Has systems that can be integrated into weigh stations and mobile units that can be deployed and integrated. Drivewyze has deployed and integrated the Smart Roadside system in all but four States. Drivewyze can capture images at highway speeds. Issues: No technical roadblocks have been identified.
Note: Perceptics/Quarterhill currently offers a Hazmat detection system mounted on a trailer that can be deployed at various temporary locations. The trailer is customizable and can include Hazmat placard detection, license plate reader, USDOT number identification, and camera systems.				

2.2 Data and Software Scan

PNNL conducted a broad market survey of available software that could be integrated into a system for Hazmat identification, tracking, and analysis. Table 2 provides a summary of the evaluated software. The software and artificial intelligence solutions were assessed on their ability to provide different levels of reporting, risk assessment, and mitigations. All software provides a basic awareness into assessment of Hazmat travel with high-level reports and insights at the level of tens or hundreds of mile resolution. All have the limited ability to assess risk and provide potential response options. The tools utilize partial organizational historical data/records, combined with data from a limited number of fixed data targeted at specific collection sites. Solution costs vary and will be determined by location layout, current capabilities and stakeholder requirements. It is anticipated that states may own assets such as cameras, software or tools that could be utilized and/or repurposed to reduce expenses. Consideration should be given to reducing costs while also ensuring systems conform across states. Cost variability by location is expected based on requirements and assets available to the state that are already on-hand.

All tools evaluated require a level of effort to customize algorithms and to allow extensive data ingestion evaluation and completion. The following are definitions of customization level requirements**:**

- **Moderate:** Modular system, basic data format translator, established Application Programming Interface (API) connections. Will require cost to integrate.
- **Moderate to High**: Multiple data translators, third party integration without full network definition to ensure successful integration of systems. Unknowns could create high costs to integrate.
- **High**: System design required. No container, code sandbox only. Will require network and connectivity diagraming. High cost to integrate.

PNNL reviewed and identified data sources and software that could be integrated into the Hazmat Commodity Flow system as additional metadata that will likely enhance the capabilities and confidence of a testbed and associated systems. Data sources could include:

- Weather
- Mapping

PNNL reviewed existing Washington State software systems that could be integrated into the Hazmat Commodity Flow system. State by state evaluations will be required as the effort expands. The most relevant existing software systems within Washington State include:

- USDOT Commercial Vehicle Information Exchange Window (CVIEW) system
- Washington State Department of Transportation (WSDOT) software.

Both state systems could benefit from the output of the Hazmat identification and tracking system. A second benefit is the software systems have established communications with WSDOT and Washington State Patrol networks.

Table 2. Software Assessment

Company	System Description	Customization Level	Considerations
Rekor Discover	End-to-end system for vehicle recognition, data analysis, and report generation. Not a modular system.	High	Requires full integration of required features.
Esri ArcGIS Pro	Geospatial intelligence analysis tool	Moderate	N/A
ESPY OSINT Profiling tools	Tool suite for analyzing different kinds of open-source data	Moderate	N/A
TomTom Developer	Developer hub for TomTom with access to APIs for traffic data ingest and analysis	High	N/A
INRIX AI Traffic	Tool for analyzing historical traffic data and generating traffic predictions	High	N/A
Pandell Roads	Tool for road usage management	N/A	Does not address many requirements.
Adaptive Recognition America Corporation	Vidar USDOT Code and Hazard Placard Recognition Camera[5] Back-end optical character recognition.	Moderate	System is built for shipping container number identification and would need to be adapted for USDOT hazard placards.
Rekor	Discover - End-to-end system for vehicle recognition, data analysis, and report generation[6]	Level 1 – Mature	Mature but would require an integration effort with state database. Captures complete, accurate vehicle analytics. Currently developed for FHWA classification and vehicle tracking, would need to be adapted to identify placards.
ABB Inc.	Hazmat placard, USDOT number, and license plate recognition technologies	Level 1 – Mature	Mature optical character recognition software. Could be incorporated into a Hazmat identification solution.
PlacardPass	Hazmat placard, USDOT number, and license plate recognition technologies Cloud-based software solution to identify USDOT placards	Level 1 – Mature	Mature, but other technologies are more applicable to this task. Demonstration of technology to team. Cloud based or on premises infrastructure. Updated with current regulations and standards. Could be a solution to part of the system data pipeline but several issues need to be addressed Could require high internet bandwidth to work in high-traffic environments. Images would be transmitted across county/state lines to be analyzed, creating data security concerns.

2.2.1 Weather Services

PNNL surveyed several weather API services and contacted WSDOT to determine the API service used. State resources, such as the WSDOT weather API, should be considered for testbed integration due to the familiarity of services at the state and local level. Table 3 highlights companies that offer viable weather APIs. Weather data is an optional source of meta data that could be used to determine if weather affects quality of image output. This meta data is not required for a system to function optimally. Summaries of mapping API services are summarized in Table 4.

Table 3. Weather API Services

Company	System Description	Output Formats
WSDOT Traffic APIs	Current weather information and weather stations.	JSON, XML
Baron Weather	Weather Data: Current weather conditions such as temperature, humidity, wind speed and direction, atmospheric pressure, and precipitation. Forecasts: Hourly and daily weather forecasts, including temperature and precipitation predictions.	JSON, REST, TMS, GeoTiff, RSS, XML
Tomorrow.io	Current Weather Conditions: Details such as temperature, humidity, wind speed, wind direction, atmospheric pressure, and precipitation. Forecasts: Hourly and daily weather forecasts, including temperature and precipitation predictions.	JSON
Vaisala XWeather	Current observations and conditions are available in near real time for any location. Forecasts: Short-term and long-term weather forecasts, including temperature and precipitation predictions.	JSON, XML, CSV
Visual Crossing Corporation	Current Weather Conditions: Details such as temperature, humidity, wind speed, wind direction, atmospheric pressure, precipitation (rain, snow), a weather description, and icon. Forecasts: Hourly and daily weather forecasts, including temperature and precipitation predictions.	JSON, CSV, Excel
WeatherBit	Current Weather Conditions: Details such as temperature, humidity, wind speed, wind direction, atmospheric pressure, precipitation (rain, snow), a weather description, and icon. Forecasts: Hourly and daily weather forecasts, including temperature and precipitation predictions.	JSON

2.2.2 Mapping Services

PNNL contacted WSDOT to determine what API service they use and surveyed several mapping API services. Numerous existing commercial map APIs could be incorporated into the end product. Table 4 provides a sampling of map API options. Mapping services are not required for initial testbed deployment but should be evaluated for future use when systems and organizations require the tracking of shipments across the state and/or country.

Table 4. Mapping API Services

Company	System Description
Washington Geospatial Open Data	Local government links to geospatial open data sites in Washington State
Google	Traffic Layer Maps – JavaScript API
Google	Add a map to a web page – JavaScript API
Google	Add a map to a web page – Embed API
TomTom	Robust maps, places, routing, traffic, and tracking APIs
Mapbox	Mapbox offers maps, location searches, navigations, and custom map features with its Mapbox Studio
HERE	HERE offers high-quality mapping tools to help visualize data, generate insights, and construct maps
MapTiler	Static Maps API

3.0 Task 3 Capability Analysis

PNNL assessed Washington state's infrastructure that potentially could benefit this project. The state has numerous e-weigh stations along its major highways and virtual weigh stations (Figure 2). Virtual weigh stations are instrumented checkpoints usually on two-lane highways that provide digital images of the vehicles, license plate recognition, weight in motion, Tire Anomaly and Classification System (TACS™), over height sensors, and a transponder. The sensor data is transmitted to a manned weigh station.

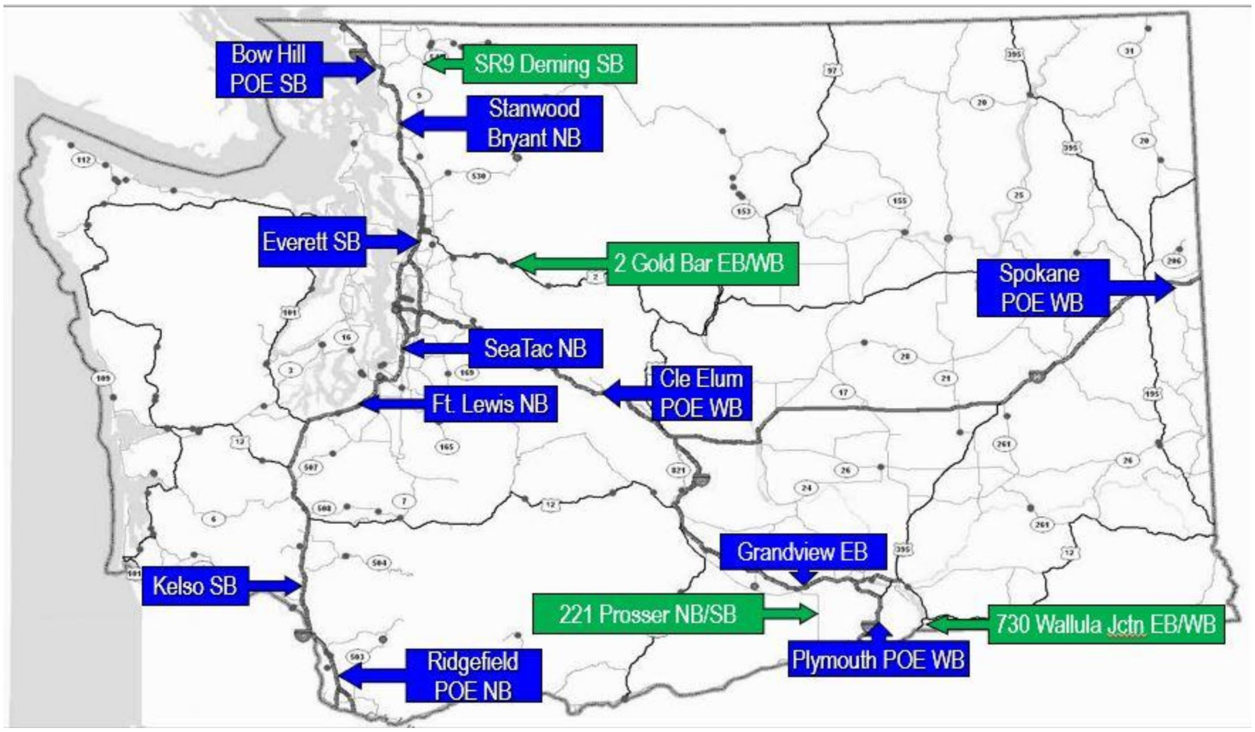

Figure 2. Locations of Washington State e-screening Weigh Stations.[7]

The state's digital network presents another potentially applicable capability. The state's digital network connects the WSDOT and Washington State Patrol, which would be the primary users of any new system.

During the technology scanning, PNNL developed a capability analysis of the digital network's technology, software, and data. Table 5 outlines the criteria that will be used in an independent evaluation once a testbed has been established.

Table 5. Evaluation Criteria

Criteria	Description
Accuracy	Accuracy to correctly identify and interpret information
Sensitivity	Ability to detect true positives
Specificity	Ability to avoid false positives
Speed and efficiency	Speed at which the component can process and analyze information
Scanning range and angle	Scanning range and angle of the placard reader
Integration	Ability of components to integrate seamlessly with transportation management systems, allowing real-time monitoring and data exchange
Compatibility	Ability to read and interpret different designs and formats commonly used
Adaptability to environmental conditions	How the component performs under varying environmental conditions, including lighting, weather, and distances from the placards
Faded or damaged placards	Accurately read information from faded or damaged placards
Maintenance and calibration	Routine maintenance schedule and calibration process to enable ongoing accuracy and reliability
Training and support	Adequacy and availability of training and troubleshooting resources available for users
Compliance	System complies with all relevant regulatory standards
Scalability	System's scalability to accommodate varying transportation volumes
Redundancy and reliability	Availability of redundancy features to maintain continued functionality in event of hardware or software failures
Cost effectiveness	Overall cost effectiveness of the system, including initial costs, maintenance expenses, and potential cost savings associated with improved efficiency and reduced incidents
Data encryption and security measures	Ability to implement robust data encryption and security measures to protect the information processed and stored by the placard reader system

4.0 Task 4 Identification of Stakeholders and User Engagement

The strategy for engaging Hazmat tracking stakeholders and users involves identification of stakeholders, (state, local, federal, tribal, commercial, public). Initial meetings will focus on identifying the correct stakeholders and discussing the project's vision and objectives. Stakeholder engagement is a multi-step, iterative process. Stakeholders must be considered and engaged through multiple steps including:

- Identifying and engaging stakeholders
- System(s) identification and use
- Deployment of an engineering prototype
- Deployment of a small-scale Hazmat identification system
- Deployment of Hazmat identification systems statewide

4.1 Identifying and Engaging Stakeholders

Stakeholders for hazardous commodity flow are identified by researching the intended local jurisdiction. This research should include internet searches and discussions with federal, state, and local parties involved in Hazmat monitoring and transportation. The strategic plan for engaging hazardous commodity flow stakeholders and users involves in-person or virtual meetings with stakeholders, users, and commercial transport vendors. Initial meetings should discuss the vision and objectives of implementing the Hazmat tracking system and identify the correct and/or additional stakeholders. Funding discussions should be conducted early, with all stakeholders and requirements should be outlined, resources available and requested should be documented, and typical funding and grant cycles should be considered. The scope of a pilot and specific systems can be scaled based on the anticipated funding profile. Stakeholders should represent the following parties:

Federal Partners

- Federal Highway Administration (FHWA)
- Environmental Protection Agency (EPA)
- Federal Motor Carrier Safety Administration (FMCSA)
- U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)

State Partners

- Commercial Vehicle Services
- Emergency Response
- Hazmat Teams
- Intelligent Transportation Systems (ITS)
- Operations
- Spill Response and Safety

- State Department of Transportation
- State or Highway Patrol
- Tribes

Local Partners – City or County

- Emergency Management
- Hazmat Shippers/Carriers

PNNL identified primary and secondary stakeholders within the state of Washington that would likely be interested in adopting a technology testbed for Hazmat commodity flow. Appendix B, outlines Washington state stakeholders.

4.2 System(s) identification and use

After identifying the stakeholder team, the testbed implementation team should host working meetings to define desired functional and operational capabilities from the system users and stakeholders. Effective stakeholder engagement can garner valuable insight into the real-world experience, needs, and constraints required for the effort, thus enhancing the testbed performance, increasing buy-in from key constituents, and more effectively meeting the jurisdiction's needs.

4.3 Deployment

Several meetings with the stakeholders will be required to determine the location of the engineering prototype, when and how small scale and statewide deployment(s) will occur, and how the Hazmat detection prototype will be integrated with existing test systems, current processes, and procedures. The testbed implementation team will work with the stakeholders, commercial vendors, and contractors to stand up system(s). The testbed implementation team will also work with the stakeholders to identify a corridor for phased deployments, ideally building out the location of the prototype system deployment moving to a small-scale deployment and next to a state or regional system(s) deployment.

Progress, observations and lessons learned during all phases will be presented to the stakeholders on an ongoing and regular basis. The testbed implementation team should present the testbed's foundational progress, including the findings of a commercial systems survey (see Appendix A), a conceptual design of the engineering prototype, proposed commercial equipment, the technical approach to integrating the collected data into the state's traffic database, and potential predictive analytical approaches. These deliverables should be presented in the form of a slide deck and a technical report.

During both small scale and regional/state development and deployment, the testbed implementation team will reengage stakeholders with project updates, reconfirm the system's functional and operational capability requirements, provide details for current project state and solicit inputs from stakeholders, partners and carriers.

Several meetings with stakeholders will be required to identify locations and plan deployment and integration into existing systems and processes, to reconfirm the system's functional and operational capabilities, and complete detailed planning for deploying multiple systems throughout a region or state. The testbed implementation team will work with the stakeholders, carriers and vendors, and contractors to stand up the Hazmat systems. Observations and lessons learned will be presented to the stakeholders.

Outreach materials should be provided to all stakeholders, carriers, partners and the public. Example materials are presented in Section 6.0 of this report.

5.0 Task 5 Develop Testbed Selection Criteria

This section summarizes deliverables for Task 5: Develop Testbed Selection Criteria, including:

- Functional **criteria and requirements** for Hazmat monitoring systems and a protocol for establishing testbeds.
- **Definitions of protocols for designing and implementing** a Washington state testbed plus a repeatable process for selecting and implementing testbeds across the United States.

5.1 Testbed Criteria and Requirements

PNNL researchers conducted a literature search, in-person discussions, and demonstrations of commercial Hazmat placard detection systems and identified several integrated systems and software packages that meet the Department of Transportation's specific project requirements. PNNL recommends testing multiple systems at the initial testbed. Table 6 outlines protocols to measure and compare system to best meet stakeholder requirements

Table 6. Protocols used to measure and compare requirements

Dimension	Description
Accuracy	Assess the accuracy of the placard reader in correctly identifying and interpreting the information on Hazmat placards.
Sensitivity	Evaluate the ability to detect true positives (placards that are indeed present) from the placard reader system.
Specificity	Evaluate the ability to avoid false positives (placard is not present) from the placard reader system.
Speed and efficiency	Evaluate the speed at which the placard reader can process and analyze information.
Scanning range and angle	Assess the scanning range and angle of the placard reader. Measures the effective distance and angular range within which the placard reader can accurately detect and interpret placards.
Integration with transportation systems	Determine if the placard reader system integrates seamlessly with transportation management systems, allowing for real-time monitoring and data exchange.
Compatibility with various placard designs	Check the system's ability to read and interpret different designs and formats of Hazmat placards commonly used in transportation.
Adaptability to environmental conditions	Evaluate how well the placard reader performs under varying environmental conditions, including different lighting, weather conditions, and distances from the placards.
Recognition of faded or damaged placards	Assess whether the system can accurately read information from faded, damaged, or otherwise degraded placards.
Maintenance and calibration	Determine what is a routine maintenance schedule and calibration process to maintain ongoing accuracy and reliability of the placard reader system.
Training and user support	Determine presence of adequate training for users on how to operate the placard reader system effectively. Assess the availability of user support and troubleshooting resources.
Compliance with regulatory standards	Ensure that the placard reader system complies with all relevant regulatory standards, including those specified by the Department of Transportation, State Patrol, and others as applicable.

Dimension	Description
Scalability	Determine if placard reader system is scalable to accommodate varying transportation volumes.
Redundancy and reliability	Evaluate the system's redundancy features to ensure continued functionality in the event of hardware or software failures.
Cost effectiveness	Evaluate the overall cost effectiveness of the placard reader system, considering initial costs, maintenance expenses, and potential cost savings associated with improved efficiency and reduced incidents.
Data encryption and security measures	Assess the system's data encryption and security measures for protecting processed and stored information.

Testbeds are critical assets in the development of complex systems. A testbed provides researchers with a controlled environment to develop technology, test different approaches, and work through technical issues. This section will explore four scales of deployment: laboratory-scale, single-point, highway corridor-scale, and statewide deployment. Each phase has sub-phases that explore results of different technology maturity levels.

5.2 Protocols For Designing and Implementing a Testbed

The protocol for testbeds (multiple systems under test) for Hazmat monitoring systems requires evaluation of the functional performance and communication protocols of multiple detection systems. Each tested system will be assessed on ease of setup, functional capabilities, communication, reporting and comparison testing. Table 7 further defines these protocols, which will be outlined in depth in Section 6.

The testing phases are set up so that the earlier phases test sub-systems and assess basic intersystem communication while phase three exercises the capability of a single contained system as well as data transfer back to a central location for assessment of predictive capabilities. The latter tests will also generate training, validation and testing data for predictive analytics assessments. In general, the predictive analytic capability of the Hazmat monitoring system is complex and needs real-world, commercial data to train on. Real-world data would be collected in the Single-Point Roadside Testbed and the Highway Corridor-Scale Testbed, phases one and two respectively, however this may not be a large enough dataset to fully train a predictive tool and should be used primarily as a validation and testing dataset.

Table 7. Definition of Protocols

Protocol	Definition
Testbed environment and setup	Preparation of the testbed area/location(s).
Functional tests	Validation that system(s) correctly identify Hazmat placards.
Communication tests	Confirmation of communication protocols between system components; the local area network (LAN); and state, local, and federal databases, and systems.
Reporting	Outlining system capabilities and, where appropriate, providing a side-by-side comparison of capabilities tested.

5.2.1 Phase 0: Laboratory-Scale Testbed

Laboratory-scale testbeds are used to perform system engineering and integration of software that has not been integrated into a complete system. A laboratory-scale testbed could take the form of a benchtop or dedicated test track environment. These testbeds have the advantage of minimal infrastructure requirements, colocation to the engineering team, and low cost. All Laboratory scale testbeds require basic equipment and infrastructure, including:

- Room or laboratory space or physical test track
- Workbench, desk, and a co-located standard COTS19-inch equipment rack to house the systems under test
- Computer system
- Tripod or Poles to mount cameras and lights
- Sample placards
- Semitrailer(s) to drive around the test track
- Infrastructure and utilities such as 120VAC (voltage alternating current) ethernet/fiber optic between camera(s) and the workbench, and an internet connection
- Secure connection to the state's digital network(s) (optional)

While a laboratory test environment is more controllable, it does have limitations, including the following:

Environmental Constraints: Benchtop testbeds can lack realistic environmental variables such as varying lighting conditions, weather, or large-scale outdoor scenes. This can limit the testbed's ability to fully test a solution in a dynamic outdoor environment.

Real-world Conditions and Static Scenarios: Benchtop testbeds typically fail to achieve the same complex interactions, data and interference sources, and randomness associated with real-world conditions due to the space restrictions and field of view. Lack of diverse vehicle types, unpredictable movements, or human interactions might not effectively simulate a real-world scenario.

Sensor and Hardware Constraints: Sensors and cameras may differ in positioning, orientation, or type compared to the final field deployment. These differences could lead to discrepancies in system performance from benchtop to field testbeds.

Limited Data and Object Variety: The objects or vehicles are usually limited in variety and number to what is encountered in the field.

This phase is not required for systems that have demonstrated accuracy, repeatability, and robustness under real-world conditions.

Benchtop Testbed

The benchtop testbed is the most fundamental form of a testbed. A benchtop testbed allows for basic functional tests of commercial equipment and communication protocol tests between systems. A benchtop testbed for hazardous commodity flow would comprise of COTS equipment and open-source technologies under test. The configuration options include a lab bench and a 19-inch equipment rack with camera(s) mounted on tripods with Hazmat placards manually presented to the camera. Testing would include verifying that the system(s) can identify placards correctly and developing the communication protocols to communicate between the various pieces of equipment and the LAN. A secure connection to the state's digital networks to test network communications would allow additional digital communication testing.

Dedicated Test Track

A dedicated technology validation and demonstration test track has the advantage of complete control over the testing environment and avoids disruption to commodity flow. A dedicated test track provides a more realistic, real-world test environment with semitrucks driving at slow speeds. Tests can be done to optimize the camera and light locations and daytime or nighttime operations. A secure connection to the state's network to test network communications would allow additional digital communication testing.

Test track testbeds can achieve more real-world conditions than a benchtop setup but can only provide simulated real-world scenarios. The cost of contracting with truck drivers, modifications to the test track infrastructure, and the lack of real-world scenarios are limitations of a dedicated test track.

A dedicated quarter-mile test track with required infrastructure and commercial vehicles is available at the Interdiction Technology and Integration Laboratory at Pacific Northwest National Laboratory in Richland, Washington.

Figure 3. PNNL's Interdiction Technology and Integration Laboratory Test Track

5.2.2 Phase 1 Single-Point Roadside Testbed

A single-point roadside testbed setup facilitates the configuration, integration, and testing of multiple Hazmat placard reader systems in a controlled real-world environment. The single-point testbed allows assessors to validate and down-select systems under test to those that show promise for the Phase 2 - Highway Corridor-Scale Testbed.

Challenge of real-world deployments include issues like network latency, bandwidth limitations, and data transmission challenges that are not easily replicated in a testbed environment. These issues may be addressed by connecting to the state's digital network(s) to test communications.

Equipment and infrastructure required for a single-point, roadside, testbed include:

- Mounted high-resolution cameras and lights for each system being tested in an outdoor location adjacent to a highway. Cameras must have a clear view of the front, side, and rear of a commercial vehicle lane under the test. Traffic camera systems are typically mounted on poles with an unobstructed view of the side of the trucks. Cameras need to be mounted ~7 feet and lights mounted ~15 feet above ground to prevent light glare and to limit distractions to drivers. Cameras should include sun shields to minimize sun glare.
- An indoor workstation is required, the testbed team requires access to a dedicated computer workstation and potentially a co-located 19-inch equipment rack to house the systems under test. This could be in an existing weigh station building, a temporary structure, or an equipped vehicle.
- Utilities such as 120VAC at the camera and workstation locations, ethernet/fiber optic between camera(s) and workstation, and a secure internet connection to the state's digital network(s).

If deploying at a weigh station or making physical infrastructure changes to a weigh station is not feasible, or if a highway exit/on-ramp location is preferred, a trailer-mounted mobile system could be utilized. A mobile option allows testing with cameras at different heights and locations and for creation of a technological boundary between test systems and operational systems and processes.

Single-Point, Low-Speed

The single-point, low-speed weigh-in-motion testbed should be located at a highway weigh station. Alternative locations to consider are highway exits, on-ramps, or using a trailer-mounted mobile detection system. Phase 1 testing is not required for systems that have demonstrated accuracy, repeatability, and robustness under real-world conditions.

The weigh station deployment offers real-world scenarios with a variety of trucks and commodities driving past systems at slow speeds. Much of the infrastructure and utilities needed are already available at the weigh station and allow for external equipment to be positioned such that researchers remain clear of traffic dangers. A weigh station-based testbed location with the option of multiple lanes is preferred, allowing for traffic to be routed through the other lanes during the installation of physical infrastructure needed for testing and reducing interruptions to the flow of commodities.

Real-world conditions are limited at a single-point, low-speed testbed. Confined spaces restrict the field of view and complexity of scenarios. Field deployments involve larger areas and broader perspectives, which can introduce challenges like occlusions or far-range object detection.

Single-Point, Highway-Speed

A single-point, highway-speed testbed configuration can be deployed to test systems with vehicles at high speeds. If the technology supports the highspeed capture of Hazmat placards, detection systems can be deployed in many locations throughout the state. A network of highspeed Hazmat placard detection systems would greatly support future predictive analysis of Hazmat transportation within the state.

Cameras for single-point, highway-speed testbed should be located a half mile or more away from weigh stations as a portion of Hazmat commercial traffic may be slowing down to enter the weigh station. Cameras should be located along the highway at a point that all commercial vehicles pass at standard highway speeds. If installed near an exit or on-ramp, vehicles using the ramps will not be traveling at highway speeds. If the cameras are facing the highway, adjacent to a weigh station, the system would fail to see the vehicles passing through the weigh station.

A mobile detection system or co-locating the Hazmat tracking system with weigh-in-motion systems may be a solution for this phase of the testbed.

5.2.3 Phase 2: Highway Corridor-Scale Testbed

Highway corridor-scale testbeds could process Hazmat-placarded vehicles at various regional highway corridor locations across the state. The testbed should be used to continue the down-selection of technology systems and will demonstrate the networked capability of the Hazmat placard readers and database.

Data from the corridor-scale testbed will be used to test and refine the prediction ability of the highway corridor and statewide Hazmat detection systems. Specifically, artificial intelligence will be developed and deployed to analyze patterns in Hazmat transportation and assist in several critical tasks, including transportation volume prediction and planning enforcement activities.

The corridor-scale testbed could be deployed as either a low-speed or highway-speed testbed configuration contingent on the technical capabilities of the commercial Hazmat detection systems.

Corridor-Scale Multi-Point, Low-Speed

The corridor multi-point, low-speed testbed will include multiple detection locations along a highway corridor. They will be networked together with the state’s networks, allowing researchers to be located at any location with access to the network. The corridor-scale testbed requires the same equipment and infrastructure capabilities as the single-point roadside testbed but also includes the following:

- Two to four weigh stations along the site of the corridor-scale testbed
- A dedicated computer workstation and a co-located 19-inch equipment rack to house the systems under test
- This phase centralizes the Hazmat detection system operator at a single, networked location connected to the corridor locations.
    - An existing weigh station building, a temporary structure, or an equipped vehicle in proximity to one of the locations along the corridor.

Corridor-Scale Multi-Point, Highway-Speed

Equipment and infrastructure for Phase 2, corridor-scale, multi-point detection at highway speed is consistent with the requirements of previous phases, except for the location of the cameras. The cameras and lights will be positioned adjacent to highways to capture traffic "at speed.”

5.2.4 Testbed Integration Evaluation Criteria

All Hazmat placard reading tools analyzed for this project require customization and data integration into state and federal systems. The level of customization and integration varies among COTS tool providers but ranges from moderate to high:

Moderate integration assumes a modular COTS tool with a basic data format translator and established API connections. Will require a moderate level of cost to integrate into existing systems.

Moderate to high integration assumes multiple data translators and a third-party integration without full network definition to enable successful systems integration. Unknowns with moderate to high integration could create high costs to integrate.

High-level integration assumes that system design is required. No container exists, only a code sandbox. High-rated COTS tools require network and connectivity diagramming, resulting in a high cost to integrate into existing systems.

Table 8. Elements of a Testbed at a Weigh Station

Elements of Testbed	
Location of Testbed	Weigh station with heavy volume of Hazmat carriers (recommend locations along Interstate 5 for Washington State)
Infrastructure	• Foundational support next to traffic lane(s) for camera and light mounting • Exterior lights to illuminate truck lane(s) • Dedicated in-door workspace • Space for dedicated computer for each system under test (a 19-inch equipment rack could be used) • Ethernet/fiber-optic cables and internet connection • Connection to state database(s) • Utilities: 120VAC power supply
Interruption to Commerce	Testbed infrastructure and test personnel will work to minimize disruption to the flow of commerce
Safety	Location of the testbed equipment shall be sited such that test personnel will not be in harm's way

5.3 Testbed Protocol for Deployment

Statewide Deployment

Following the successful deployment of the Hazmat tracking system in a corridor, technology should be down selected based on performance. Statewide deployment will expand on the initial corridor deployment and necessitate similar capabilities. The selected technology will be ready for broader implementation across the state. Given the increased volume of data to be processed, the infrastructure will need to be carefully evaluated and appropriately scaled.

Centralizing the Hazmat detection system operator at a single, networked location connected to all deployment locations throughout the state should be considered.

Washington State Deployments

Deployments in Washington for phases one and two are recommended at weigh station(s) on the Seattle I-5 corridor. These locations provide several unique opportunities including detection of commercial traffic entering the state from seaports of entry as well as Canada and a series of weigh stations along the corridor. The weigh stations already have the necessary critical infrastructure. Figure 2 provides a map of Washington state e-weigh station locations. Coordination with stakeholders is required to select the weigh station location. Systems selected for testing should be procured and integrated at the testbed for verification and any required engineering development. Table 9. provides recommended locations within Washington State.

Table 10. Recommended Testbed Locations for Phases 1 and 2

Weigh Station Name	Direction
Stanwood Bryant (NB)	Northbound
Lake Stevens (SB)	Southbound
Everett (SB)	Southbound
Federal Way (NB & SB)	Northbound, Southbound
Dupont/Ft. Lewis (NB)	Northbound

6.0 Task 6 Create Testing Protocol

This section summarizes deliverables for Task 6: Create Testing Protocol. Pacific Northwest National Laboratory (PNNL) will develop testing protocols for an automated stand-off, maintaining a fixed distance, and non-invasive, to not obstruct flow of commerce, sensor system for Hazmat monitoring. Testing protocols will be generated for basic, intermediate, and advanced testbeds. The testing protocol includes:

- An **evaluation framework** to validate the performance and capabilities of the testbed
- An approach for **designing and implementing** a Washington state testbed plus a repeatable process for selecting and implementing testbeds across the United States
- **Functional criteria and requirements** for Hazmat monitoring systems and a protocol for establishing testbeds
- A plan to address potential **legal constraints** for capturing, analyzing, and storing relevant data and the ability to share information with a wide variety of stakeholders, as appropriate, including data aggregation and anonymization

6.1 Testbed Evaluation Framework

The primary purpose of a Testbed Evaluation Framework is to identify potential issues, validate performance, and ensure readiness for broader deployment. By using this framework, organizations can mitigate risks, reduce costs, and improve the reliability and effectiveness of the system being evaluated. This framework also allows for comparison of various testbeds and proposed testbeds.

The Testbed Evaluation Framework is outlined in Figure 1 and includes the following elements:

1. **Testbed Environment**: A controlled setting that simulates real-world conditions with a focus on specific test parameters.
2. **Functional Testing**: Defines the metrics and standards against which multiple technologies or systems will be assessed (e.g., performance, reliability, scalability).
   a. Detailed methodologies and protocols for conducting tests to ensure consistency and reproducibility
   b. Systematically gathering of data during testing to facilitate analysis and interpretation.
3. **Communication Testing**: Defines the methods to confirm communication protocols between system components; the LAN; and state, local, and federal databases and systems.
4. **Reporting**: Scientific techniques for analyzing test data, identifying strengths and weaknesses, and generating comprehensive reports.
   a. Processes for making iterative improvements based on test results to optimize the system or technology.
5. **Feedback and Testing Modification**: Request testing feedback from stakeholders, modify the testing methodology, and conduct additional testing as needed.

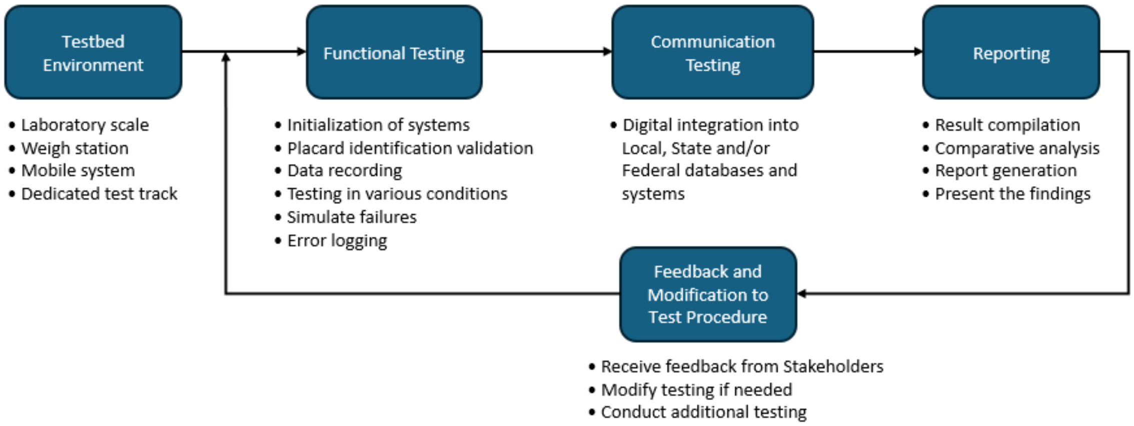

Figure 4. Framework Flowchart

6.2 Testbed environment design

Phase 0: Laboratory-Scale Testbed Framework

Laboratory-scale testbeds can be used to perform system engineering and integration of software and camera systems that have not been integrated into a state weigh station system. A laboratory-scale testbed can take the form of a benchtop or dedicated test track environment. These testbeds have the advantage of minimal infrastructure requirements, collocation with the engineering team, and low costs. Refer to section 5.1 for the limitations of a laboratory-scale testbed.

Location Selection:

- A laboratory space or existing test track
- Availability of 120VAC power supply, ethernet/fiber optic connections, an internet connection
- A secure connection to the state's digital network(s) (optional)
- Workbench and a standard 19-inch equipment rack
- Tripod or pole for mounted cameras and lights
- Sample Hazmat placards
- Computer system
- For a test track, semitrailer(s)

Equipment Setup:

- Place the workbench and 19-inch equipment rack in designated locations.
- Mount three cameras front, rear, and side views and lights for each system and position them relative to the workbench or lane.
- Connect each system to the computer system and ensure they have access to the LAN.

- For laboratory testing, configure adjustable lighting to simulate various conditions (daylight, artificial light, low light).
- Collect a variety of Hazmat placards (different classes, colors, and symbols). Standard placards can be purchased through a variety of vendors, including LabelMaster (https://www.labelmaster.com/shop/placards)

Safety Measures:

- Confirm external equipment is positioned to keep researchers clear of traffic and avoid interference.
- Establish safety protocols to prevent hindrance to the flow of traffic.

Phase 1 – Single-Point Roadside Testbed Framework

A single-point testbed configuration allows configuration, integration, and testing of multiple Hazmat placard reader systems in a controlled real-world environment. The single-point testbed allows researchers to validate and down-select systems under test to those that show promise for the phase two Highway Corridor-Scale Testbed.

Location Selection options:
Weigh station: Provides real-world scenarios and existing infrastructure. During installation, one lane of the weigh station may need to be closed. Most weigh stations are designed with a minimum of two lanes to facilitate maintenance of scales. Therefore, installation of the Hazmat tracking system would cause minimal commerce flow interruptions.
Mobile system deployment: A trailer-mounted Hazmat detection system to minimize construction at weigh stations, providing the same capability as a pole-mounted camera/light system. Trailers could be deployed at weigh stations, highway exits, or on-ramps.

Equipment Setup:

- Securely mount and calibrate all camera(s) with a clear view of the front, side, and rear of a commercial vehicle lane under test and lights for each system under test in an outdoor location. Ensure each camera is positioned for optimal placard visibility and minimal sun glare.
- If using a mobile unit, select a location that provides power and communication connectivity.
- A generator or solar power to provide power and a 5G cell modem if internet is not available at selected locations. Set up workstations with dedicated computer(s) and a 19-inch equipment rack in an indoor weigh station building, a temporary structure, or an equipped vehicle.
- Connect camera systems from each reader to the workstation using ethernet/fiber optic cables.
- Ensure 120VAC power supply at camera/light and workstation locations.
- Verify internet connectivity for data transmission and remote monitoring.
- Verify the connection to USDOT databases and that the systems under test APIs are communicating.

Safety Measures:

- Ensure all external equipment is positioned to keep clear of traffic and avoid interference.
- Establish safety protocols to prevent hindrance to the flow of traffic and commodities.

Single-Point, Low-Speed

A testbed location will require commercial vehicles to pass in a controlled manner so that cameras with associated lighting will illuminate Hazmat placards. For the low-speed testbed, vehicles should pass through the portal between 5 and 10 miles per hour.

Single-Point, Highway-Speed

A single-point, highway-speed testbed configuration can be deployed to test systems with vehicles at high speeds. The framework of Phase 1 highway-speed single roadside testbed is the same as the slow-speed roadside testbed except for the locations of the cameras and associated lights to capture highway-speed traffic. Camera locations need to be positioned where traffic flows at normal highway speeds and where Hazmat carriers are not diverted from the highway (i.e., near weigh stations). Cameras should be located at a point along the highway that all commercial vehicles pass at standard highway speeds. A mobile detection system or co-locating the Hazmat tracking system with weigh-in-motion systems may be a solution for this phase of the testbed. If installed near an exit or on-ramp, vehicles using the ramps will not be traveling at highway speeds. If the cameras are located facing the highway, adjacent to a weigh station, the system would fail to see the vehicles passing through the weigh station. Additional unique items are listed below.

Testbed location should have commercial vehicles pass in a controlled manner so that cameras with associated lighting will illuminate the Hazmat placards. For the highway-speed testbed, vehicles should pass by the cameras at normal highway speeds. If detection of vehicles in multiple lanes is desired, dedicated cameras and lights for each lane will be required. Infrastructure listed below needs to be available.

Phase 2 – Highway Corridor-Scale Testbed Framework

Highway corridor-scale testbeds could process Hazmat-placarded vehicles at various regional highway corridor locations across the state. The testbed may be used to continue the down-selection of technology systems and will demonstrate the networked capability of the Hazmat placard readers and database. Data from the corridor-scale testbed will be used to test and refine the prediction ability of the highway corridor and state-wide Hazmat detection systems. Specifically, artificial intelligence will be developed and deployed to analyze patterns in Hazmat transportation and assist in several critical tasks including transportation volume prediction and planning enforcement activities.

This phase will employ multiple detection locations along a highway corridor. They will be networked together with the state networks, allowing the researcher to be located at any location with access to the network. The testbed will require access to a dedicated computer workstation and a co-located 19-inch equipment rack to house the systems under test. This could be an existing weigh station building, a temporary structure, or an equipped vehicle. Centralizing the Hazmat detection system operator at a single, networked location connected to the corridor locations may be a feasible approach.

The corridor-scale testbed could be deployed as either a low-speed or highway-speed testbed configuration contingent on the technical capabilities of the commercial Hazmat detection systems. The items listed below are like those in Phase 1. The differences are listed below.

Testbed Location Selection:

- Weigh stations: Two to four weigh stations along a regional highway corridor that allow safe and clear viewing of a commercial vehicle lane.
  - Use multiple weigh stations to allow for real-world scenarios and within existing infrastructure.
  - Can not cause commerce flow interruptions.
- Weigh-in-Motion locations: Co-locating the Hazmat tracking system with weigh-in-motion systems could capitalize on existing infrastructure.
- Mobile system deployment: A trailer-mounted Hazmat detection system to minimize construction at weigh stations, provide the same capability as a pole-mounted camera/light system.

Equipment Setup:

- If using a mobile unit, select a location that provides power and communication connectivity.
- A generator or solar power to provide power and a 5G cell modem if internet is not available.

Corridor-Scale, Multi-Point, Low-Speed

The framework of the corridor-scale, multi-point, low-speed roadside testbed is the same as Single Roadside Single-Point, low-speed testbed except that two to four additional locations are selected.

Corridor-Scale, Multi-Point, Highway-Speed

The framework of the highway-speed, multi-point roadside testbed is the same as Single Roadside Single-Point, Highway-Speed testbed except that two to four additional locations are selected.

Phase 3 – State-Wide Deployment Framework

State-wide deployment framework will be a replication of Phase 2 Highway Corridor-Scale technology across the state on major highways. The state-wide deployment could be a low-speed or highway-speed configuration contingent on the technical capabilities of the commercial Hazmat detection systems. Given the increased volume of data to be processed, the infrastructure will need to be carefully evaluated and appropriately scaled. A centralized Hazmat detection system officer would oversee the operation.

Designing and implementing a Washington State Testbed

An initial deployment in Washington state of Phase 1 and 2 testbeds at a weigh station on the Seattle Interstate-5 (I-5) corridor.

Table 1 provides recommended locations. These locations provide unique opportunities including detection of commercial traffic entering or exiting from the seaports, Canada, and a series of weigh stations along the corridor. Weigh stations already have the critical infrastructure required for testing. Coordination with stakeholders is required to select the weigh station location and obtain agreement from the state partners and stakeholders. Systems selected for testing should be procured and integrated at the testbed for verification and any required engineering development.

Table 11. Recommended Testbed Locations

Weigh Station Name	Direction
Stanwood Bryant (NB)	Northbound
Lake Stevens (SB)	Southbound
Everett (SB)	Southbound
Federal Way (NB & SB)	Northbound, Southbound
Dupont/Ft. Lewis (NB)	Northbound

Washington state stakeholders should identify the best Washington state testbed locations for Phase 1 and Phase 2.

The following considerations should be made for each location:

- Ensure that the selected weigh stations for Phases 1 and 2 have the required footprint (inside and outside) and utilities for testing.
- Work with the chief of the weigh station and the WSDOT to design the infrastructure modifications to place systems, cameras, and lights.
- Outline requirements for construction (funding mechanism, architecture, detailed design, issuing construction drawings, hiring a contractor, developing a construction schedule, construction, and commissioning).
- Engage Information Technology (IT) subject matter expert(s) to validate the requirements and connectivity of an API interface with pre-determined databases.

Once the slow-speed and/or high-speed testbeds are constructed and systems under test are interfaced with databases, a series of commissioning tests for each system must be conducted. Tests will involve capturing and processing collected Hazmat placards, WSDOT numbers, and other information as directed, from commercial vehicles. Data can be added to each truck's data file as the stakeholders agree. Interface bugs in systems identified during commission testing will be resolved prior to operationalization.

6.2.2 Prediction and Analysis

A hazardous commodity flow testbed will allow for the development and testing of new capabilities, specifically around the utilization of algorithms that can be trained on historic data to inform real time considerations and even offer predictive capabilities to let stakeholders have situational awareness around what is likely to be seen on their roadways based on a number of factors including time of day, week, month, year and road conditions.

Database Integration:

- Ensure all data collected in the central database is securely stored and accessible.

- Ensure all data collected is correctly stored, with no unintended blank or null data fields.
- Integrate analytical tools to process and analyze the collected data.
- Verify data can be queried accurately from database with no errors.

Prediction Capability:

- Develop and/or deploy algorithms to predict the movement and flow of Hazmat-placarded vehicles based on collected data.
- Conduct leave-one-out analysis on collected data to test analytics and prediction algorithms.

System Monitoring:

- Continuously monitor system performance and prediction capabilities.
- Adjust and refine algorithms based on ongoing data collection and analysis.

6.3 Functional Criteria

Functional criteria and requirements for Hazmat monitoring systems and a protocol for establishing testbeds include functional testing, communication testing, and reporting. These criteria should be implemented on all testbed types and locations to verify systems perform and behave as expected within prescribed conditions. Each criterion is further outlined below and should be considered and implemented to the fullest extend for each testbed type.

Functional Testing

Functional testing verifies system features and functions work as intended and according to specified requires. Functional testing includes recommended processes and actions for each prescribed system and includes system(s) initialization, identification validation, data recording, failure simulation and error logging**.**

Initialization procedure:

- Power on computer systems and connected devices.
- Initialize the Hazmat detection software and calibrate cameras for each system.
- Establish connection with State Patrol and WSDOT networks. (optional)

Identification Validation:

- For laboratory testing, manually present Hazmat placards to each camera.
- For test track, mount Hazmat placards onto semitruck and drive truck around track at varying speeds.
    - approximately 3-5 miles per hour for single point, low speed testing.
- Ensure a varied sample of trucks, commodities and placards for comprehensive testing
- Confirm placards are captured at various angles and distances for each system.
- Test under varying lighting conditions.

Data Recording:

- Develop procedure for documenting test results, including type of placard, lighting condition, distance, and identification accuracy for each system.
- Design approaches for handling inaccurate data and rectifying incorrect predictions/classifications generated by the machine vision/AI component of the system.
- Ensure the data are properly recorded in the appropriate database, along with a structured schema for the types of data collected.

Simulate Failures:

- Simulate common failure scenarios (e.g., network disconnection, power supply interruption).
- Develop and document processes and procedures for handling common failure scenarios and troubleshooting.

Error Logging:

- Document any errors or discrepancies observed during testing. Note the system's behavior and any error messages received.

Communication Testing

Communication testing is a method of evaluating how effectively a system or systems can convey and interpret information. Communication testing includes initialization of system(s), verification of information transfer and reporting of data.

Initialization:

- Initialize communication protocol software on each system.
- Ensure data storage systems can connect on the same and/or separate LAN system, simulating cloud storage environment as the test environment dictates and ensuring that testing implementors can monitor the performance of each device in the system.
- Establish a secure connection to the US/WSDOT digital network(s) or other appropriate server/databases.

Verification:

- Send image and metadata packets from the computer vision system to the data storage system.
- Send test packet from computer vision system to State Patrol or US/WSDOT data storage system(s).
- Verify that the data packets are received without errors and are properly interpreted by each system.

Inter-device Communication:

- Validate communication between equipment (e.g., computer vision system to computer, computer to LAN, LAN to cloud).
- Validate the response time and reliability of data transmission for each system.

Reporting

Reporting is a critical tool for monitoring and managing the quality systems throughout the testbed process. Reporting includes detailed documents that summarize the results of testbed activities, highlighting identified defects, areas of improvement, and an overall quality assessment of a system, providing crucial insights to stakeholders to make informed decisions about the system's readiness for further deployment and ensuring it meets required standards and expectations.

Result Compilation:

- Develop test logging procedures and gather and record test data and test logs for each system.
- Analyze results for trends, accuracy rates, and failure points for each system.

Comparative Analysis:

- Compare the performance of systems under identical test conditions.
- Identify strengths and weaknesses unique to each system.

Report Generation:

- Create a comprehensive report detailing the test protocol, results, observations, and recommendations for each system.
- Include comparative analysis findings and possible improvements.

Feedback Loop:

- Present the findings to the engineering team to evaluate potential improvements or adjustments to each system based on test results.
- Modify testing procedures and conduct additional testing as needed.

6.4 Legal Constraints

PNNL will collaborate with the State Attorney General's office to determine the legal constraints related to the collection, analysis, and storage of video and photographic data for this project. These constraints may involve consideration of privacy, business confidentiality, and security sensitivities. Additionally, the project will adhere to the state's requirements regarding the sharing of collected and analyzed data with project stakeholders. Hazmat placards, USDOT numbers, and other information visible on the exterior of a vehicle are not likely to be considered personally identifiable information. Systems need to be validated to ensure compliance with the local, state, and federal regulations on the collection and storage of any Personally Identifiable Information.

The WSDOT currently owns truck-related data and images captured related to state weigh stations. The WSDOT partners with other state agencies as appropriate, (Washington State Patrol and the Washington State Department of Licensing for commercial vehicles) to support enforcement and records management. Sharing beyond State agencies will require the development of Data sharing agreements.

7.0 Outreach Materials

The following materials were developed in support of deploying a Hazmat monitoring system within a state or region initial outreach materials targeting technology providers, allowing deploying teams to gather current, up-to-date technologies. Follow on messages should target communications to state stakeholders, Hazmat carriers, and the public regarding upcoming testbed deployment and anticipated outcomes of a Hazmat monitoring system. Typical outreach communications include email notification, website announcements, social media posts, and information sessions.

Technology Providers:

Technology information request. _______ state is partnering with the Department of Transportation's Pipeline and Hazardous Materials Safety Administration to implement new technology to improve safety through the tracking and verification of hazardous material shipments. We would like to invite your organization to provide input to the attached USDOT and Hazard Placard Recognition System Information Gathering Form (Appendix A). This form will be used to evaluate technologies for addition into a testbed system. Inputs are confidential, with follow-up invitations forthcoming to demonstrate equipment based on technology capability and fit. We appreciate your time and look forward to learning more about your technology.

Technology demonstration request. Thank you for completing the Department of Transportation's Pipeline and Hazardous Materials Safety Administration USDOT and Hazard Placard Recognition System Information Gathering Form. This form was used to evaluate technologies as an addition into a _______ state testbed. We would like to invite you to participate in a demonstration of your technology. These demonstrations and subsequent discussions will inform technology selection for the _________ state testbed. We appreciate your time and look forward to learning more about your technology.

Technology testbed participation request. Thank you for completing the technology demonstration of your products and capabilities. The Department of Transportation's Pipeline and Hazardous Materials Safety Administration and the state of ______ would like to invite your organization to participate in the creation of a testbed. This testbed will provide a controlled environment to test and demonstrate the technology's capability. We look forward to further discussions around your participation.

State government agencies:

Technology testbed. _____ state is piloting camera systems powered by AI to identify commercial vehicles transporting hazardous material within the state. This system will track and verify that vehicles comply with state and U.S. Department of Transportation Hazardous Materials Regulations. Systems will be deployed at weigh stations and along the highways. As deployments are determined, we will inform your organization of the location and requirements for compliance. For additional information regarding how this deployment may affect your agency, please contact _____.

Stakeholders (state, local, tribal transportation partners and advocacy groups):

Kickoff Meeting, New Technology to Enable Safe Hazmat Transportation Safety. _______ state is partnering with the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration to better identify commercial vehicles transporting hazardous materials through the state. This technology system will allow ______ state to track and verify that hazardous material shipments comply with state, local and Federal Hazardous Materials Regulations, improve situational awareness related to hazardous materials, and improve the performance of those responsible for verifying and managing hazardous materials on the roadways through more constant and readily available engagement with these shipments. These requirements vary based on the type of material, quantity, packaging, mode of transportation, and transport route. The requirements include documentation, training, and acquiring an Environmental Protection Agency ID number. Please join us as a stakeholder in this new and exciting program to enable increased safety and compliance within the state. A kickoff meeting invitation is to follow.

Kickoff Meeting Request, New Technology to Enable Safe Hazmat Transportation Safety. _______ state is partnering with the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration to better identify commercial vehicles transporting hazardous materials through the state. This technology system will allow ______ state to track and verify that hazardous material shipments comply with state, local and Federal Hazardous Materials Regulations, improve situational awareness related to hazardous materials, and improve the performance of those responsible for verifying and managing hazardous materials on the roadways through more constant and readily available engagement with these shipments. These requirements vary based on the type of material, quantity, packaging, mode of transportation, and transport route. The requirements include documentation, training, and acquiring an Environmental Protection Agency ID number. Please join us as a stakeholder in this new and exciting program to enable increased safety and compliance within the state.

Public:

Stepping up our game – tracking Hazmat transportation. _____ state is working to better identify commercial vehicles transporting hazardous materials throughout the state. New camera systems powered by AI will be deployed to analyze hazardous materials transportation patterns with the goal of increasing safety across the state. Systems are safe and only track commercial vehicles on public roadways and state weigh stations and ports. Systems will provide a higher confidence level regarding the hazardous materials traveling throughout the state and will allow responders to take proactive actions if an accident occurs on our highways.

Technology testbed deployment. The Department of Transportation's Pipeline and Hazardous Materials Safety Administration and the state of ______ is deploying a Hazardous Material Commodity flow testbed {insert location}. This testbed will provide a controlled environment to test and demonstrate the technology capabilities, including camera systems powered by AI to monitor the flow of hazardous materials throughout the state/region. Systems are non-invasive and collect data from commercial carriers only, no information is gathered on citizens or their personal vehicles.

Hazmat commodity transportation tracking system deployment. The Department of Transportation's Pipeline and Hazardous Materials Safety Administration and the state of ______ has deployed a Hazardous Material Commodity system {insert location}. This system monitors the flow of hazardous materials throughout the state/region. Systems are non-invasive and monitor commercial carriers only, no information is gathered on citizens or their personal vehicles.

Carriers and Other Entities:

Technology testbed deployment. The U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration would like to request your participation in a pilot program to stand up a hazardous material commodity flow testbed within ____ state. This testbed will evaluate camera systems powered by AI for identifying, tracking, and analyzing the movement of hazardous materials on ___ state roadways. To better understand the types and amounts of hazardous materials that flow through the state, these systems will use camera feeds and artificial intelligence to identify commercial vehicles carrying hazardous materials and track the type of hazardous material transported. An invitation to participate in an informational meeting will follow and describe the impact and outcomes of the testbed pilot. Questions in advance of this meeting can be submitted to _______.

Technology deployment information session. _______ state is partnering with the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration to implement new technology to improve safety through the identification and verification of hazardous material shipments. Please join us for an industry awareness session as we begin this new and exciting program to enable increased safety and compliance within the state. A kickoff meeting invitation is to follow.

Technology deployment planned. _____ state is deploying camera systems powered by AI to identify commercial vehicles transporting hazardous material within the state. This new system will track and verify that vehicles are compliant with state and U.S. Department of Transportation's Hazardous Materials Regulations. Systems will be deployed at weigh stations, ports, and along the highways. As deployments are determined, we will inform your organization of the location and requirements for compliance. For additional information regarding how this deployment may affect your agency, please contact _____.

Technology deployment. _____ state has deployed camera systems powered by AI to identify commercial vehicles transporting hazardous material within the state. This new system will track and verify that vehicles comply with U.S. Department of Transportation Hazardous Materials Regulations. Systems are deployed at weigh stations and along the highways. For additional information regarding how this deployment may affect your company, please contact _____.

8.0 References

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2. Perceptics | *Summitt Software Hazmat* | https://perceptics.com/summitt-software-suite/#identification
3. PR Newswire | *International Road Dynamics Awarded $2.8 Million Contract for Caltrans Ramp E-Screening System* |https://www.prnewswire.com/news-releases/international-road-dynamics-awarded-2-8-million-contract-for-caltrans-ramp-e-screening-system-301966709.html
4. NASCENT | *NASCENT enVision®* | https://nascnt.com/products/envision/
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6. Rekor | *Rekor Discover* | https://www.rekor.ai/software/discover
7. Washington State Department of Transportation | *Map of weigh stations with bypass* | https://wsdot.wa.gov/travel/commercial-vehicles/maps-tools-commercial-vehicles/map-weigh-stations-bypass

Appendix A – Hazard Placard Recognition System Information Gathering Form

Company Information

Company: Click or tap here to enter text.

Point of Contact: Click or tap here to enter text.

Phone Number: Click or tap here to enter text.

Email: Click or tap here to enter text.

Company Web Site: Click or tap here to enter text.

Product Specific Web Sites:

Haz Rec System: Click or tap here to enter text.

Hazardous material codes: Click or tap here to enter text.

USDOT Number Reader: Click or tap here to enter text.

License Plate: Click or tap here to enter text.

Software Products: Click or tap here to enter text.

Software Products: Click or tap here to enter text.

Software Products: Click or tap here to enter text.

Software Products: Click or tap here to enter text.

Additional Products: Click or tap here to enter text.

System Specifications and Features:

Operating Systems (Windows / Linux): Click or tap here to enter text.

Mobile Apps (Android / iOS): Click or tap here to enter text.

Minimum system/hardware requirements:

Processor: Click or tap here to enter text.

RAM: Click or tap here to enter text.

Hard drive: Click or tap here to enter text.

Free slots for dedicated PCIe card(s) / USB drives: Click or tap here to enter text.

Licensing: Click or tap here to enter text.

Software update release schedule: Click or tap here to enter text.

Supported codes:

ADR (Accord Dangerous Routier) ☐

The ADR Hazard Identification Number HIN, also known as the Kemler Code, is carried on road and rail vehicles with tanks etc. carrying bulk loads of dangerous substances. The ADR plate below shows the HI Number in the top section and the UN number (which identifies the substance) at the bottom.

eADR ☐

HIN (Hazard Identification Number) ☐

KEMLER ☐

IMO (Integrated Mobile Observation) /IMDG (International Maritime Dangerous Goods) ☐

SDK Options: Click or tap here to enter text.

Development tools for easy integration:

C ☐

C++ ☐

C# ☐

.NET ☐

Java ☐

Virtual Basic ☐

Development libraries ☐

Demo application ☐

Sample codes for each programming language

Neural network controller ☐

Comprehensive digital documentation ☐

Images/sec processing capacity: Click or tap here to enter text.

Interfaces:

Input: Still image format

- BMP ☐
- PNG ☐
- JPEG ☐
- RAW ☐
- Trigger device(s) for capturing images from a live video stream:

Output: Click or tap here to enter text.

- ARD imagery data ☐
- Hazard identification number in ASCII text ☐

- Confidence level in percentage ☐
- Confidence level for each character ☐
- List of further suggestions for each character ☐
- Location of each plate on one image ☐

Technical Questions:

What are the performance characteristics of the system under varying environmental conditions:

- What is the accuracy of the placard reader in correctly identifying and interpreting the information on Hazmat placards?
  Click or tap here to enter text.
- What is the sensitivity of the system in terms of its ability to detect true positives?
  Click or tap here to enter text.
- What is the specificity of the system in terms of its ability to avoid false positives?
  Click or tap here to enter text.
- At what range and angle is the system effective?
  Click or tap here to enter text.
- Night Operations
  Click or tap here to enter text.
- Rain / Snow Operations
  Click or tap here to enter text.
- Fog Operations
  Click or tap here to enter text.

How quickly can the system process images (i.e., frames per second)?
Click or tap here to enter text.

Which placard designs is the system capable of capturing and processing:

- UN placards ☐
- US/WSDOT placards ☐
- Others Click or tap here to enter text.

How does the system perform with placards that are faded or damaged?
Click or tap here to enter text.

Can data from the system be integrated / exported for use in other systems?
Click or tap here to enter text.

- Washington State Department of Transportation (WSDOT) software ☐
- USDOT Number Reader ☐
- Automated license plate recognition (ALPR) ☐
- WSDOT Commercial Vehicle Information Exchange Window (CVIEW) system ☐

- Commercial Vehicle Safety Alliance Decal Reader ☐
- Weigh in motion (WIM) ☐
- Smart roadside inspection system (SRIS) platform ☐
- Automated vehicle 915 MHz and 5.9GHz dedicated short range communication (DSRC) identification (AVI) ☐
- Over height detection system (OHD) ☐
- Thermal Brake Inspection System ☐
- Tire Anomaly and Classification System (TACS) ☐
- Weather data ☐
- Mapping ☐
- Other data/systems Click or tap here to enter text.

What analytics (i.e., reporting, predictions) can the system provide?
Click or tap here to enter text.

What is the data retention capability of the system?
Click or tap here to enter text.

Where is processing of data performed (i.e., at the edge, in the cloud, or on-premises)?
Click or tap here to enter text.

How scalable is the system?
Click or tap here to enter text.

Is the system current deployed and what examples in operation exist?
Click or tap here to enter text.

How reliable is the system?
Click or tap here to enter text.

What is the expected up-time of the system?
Click or tap here to enter text.

What are the maintenance and calibration need of the system?
Click or tap here to enter text.

What training and user support is available for the system?
Click or tap here to enter text.

Appendix B – Stakeholders

Primary Stakeholders		
Name	**Agency**	**Title**
Chris Caprio	Washington Emergency Management Division	Field Representative/Hazmat Subject Matter Expert
Jed Slagter	Seattle Department of Transportation (SDOT)	Enforcement Officer, Commercial Vehicle Enforcement
Mark Bernardo	SDOT	Safety and Health Specialist
Sean Farnand	SDOT	Spill response and Safety Manager
Angela Ranger	WSDOT	Commercial Vehicle Services Manager/Analyst
Flint Jackson	WSDOT	Traffic Electrical Systems Engineer, HQ Traffic Operations, ITS
Jonas Mast	WSDOT	Operations Manager, Weigh Station Systems
Matt Neeley	WSDOT	State Traffic Development Engineer, ITS/Commercial Vehicle Services
Sonja Clark	WSDOT	Operations Manager, Weigh Station Systems
Tony Leingang	WSDOT	Program Administrator, Transportation Division, Washington State ITS
Alex Hamby	WA State Patrol	Hazmat Specialist
Dave Coppinger	WA State Patrol	Eastern Washington Manager, Ports of Entries
Cpt. Dennis Bosman	WA State Patrol	Commercial Vehicle Enforcement
Cpt. Kyle Smith	WA State Patrol	Commercial Vehicle Enforcement

Secondary Stakeholders		
Name	**Agency**	**Title**
Carter Danne	SDOT	Advanced Traffic Manager Supervisor, City of Seattle Enforcement Supervisor Commercial Vehicle Enforcement Unit Seattle Transportation Operations Center
Jill Macik	SDOT	Environmental Compliance Manager, Capital Projects
Ryan Holtz	SDOT	Environmental Construction Lead
Dudley Littleton	WSDOT	Advisor
Jeffrey Le Cates	WSDOT	Transportation Engineer 3, Olympic Region Traffic Management Center Supervisor
Scott Zeller	WSDOT	Deputy Director of Transportation Operations
Tim McCall	WSDOT	Olympic Region Freeway Operations Manager
Trett Sutter	WSDOT	Stormwater Specialist
Peter Hartman	WA Military	Eastside Field Representative, Emergency Management Division
Mark Francis	WA State Patrol	Lieutenant, WA State Patrol
Kevin Valentine	WA State Patrol	Commercial Vehicle Enforcement Officer
Deanna Brewer	WSDOT	Director, Virtual Coordination Center

Appendix C – Project Management Tools

RACI Matrix

A Responsible, Accountable, Consulted, Informed (RACI) Matrix has been developed for the project execution. The matrix is a project management tool that helps teams identify who is responsible for each task, milestone and project decision. The RACI Matrix below is a snapshot during the project execution.

RACI Matrix - (Responsible, Accountable, Consulted, Informed)
Hazardous Materials Commodity Flow Project

Roles and Responsibilities

R	**Responsible**: Assigned to complete the task.
A	**Accountable:** Has final decision-making authority and accountability for completion. (Only 1 per task)
C	**Consulted**: An advisor, stakeholder, or subject matter expert who is consulted before a decision of action.
I	**Informed**: Must be informed after a decision or action.

		Project Manger	Systems Engineer 1	Systems Engineer 2	Data Scientist 1	Data Scientist 2	Sponsor	WA DOT ITS Program Administrator	WA DOT Intelligent Transportation Systems	WA State Patrol Hazmat Specialist	WA DOT Hazmat Expert	WA DOT Commercial Vehicle Services Manager	WA State Patrol Commercial Vehicle Enforcement Officer
Task / Deliverable	**Status**	**Project Team**					**Sponsor**	**Key Stakeholders**					
Task 1: Project Management													
Project Management	In Progress	A					I						
Task 2: Conduct Technology and Data Scan													
Identify commercially available cameras, sensor technologies to identify and track hazardous materials.	Completed	A	C		R								
Review capabilities of existing roadside cameras, sensors, license plate readers	Completed	A	C		R								
Analytics software analysis	In Progress	A	C		R	C							
Deliverable: Report	In Progress	A	R	R	R	C	I	I	I	I	I	I	I
Task 3: Perform Capability Analysis													
Commercial system capability analysis	Completed	A	R	R	R	C							
Deliverable: Report	In Progress	A	R	R	R	C	I	I	I	I	I	I	I
Task 4: Identification of Stakeholders and User Engagement													
Identify government stakeholders who would likely be interested in adopting this technology.	Completed	A	R	R	C								
Formulate a stakeholder/user engagement plan	Completed	A	R	C									
Develop outreach materials	In Progress	A	C	R	C								
Deliverable: Report	In Progress	A	R	R			I	I	I	I	I	I	I
Task 5: Develop Testbed Selection Criteria													
Develop Testbed Selection Criteria	Completed	A	R	C									
Custom system functionality research items - Associate license plate with placard and DOT # - Functionality of commercial system and WA state databases	In Progress	A	R	C	C								
Integration Issues - Complexity of system to use / system overhead 'costs' - Initial and reoccurring system costs - Legacy issues - IT / technical support of products - Cross-platform sharing of hazardous traffic data	In Progress	A	C	C	C								
Deliverable: Report	Not Started	A	R	R	C		I	I	I	I	I	I	I
Task 6: Develop Testing Protocol													
Develop a testing protocol for one Hazmat portal	In Progress	A	R	C	C								
Develop a testing protocol for a highway corrodor Hazmat portals	In Progress	A	R	C	C								
Develop a testing protocol for state-wide Hazmat portals	In Progress	A	R	C	C								
Deliverable: Report	Not Started	A	R	C	C		I	I	I	I	I	I	I

Logic Model

A second management tool that was used in the project was a logic model. The logic model is a visual representation of the relationships between a program's resources, activities, outputs and outcomes.

Logic Model
Hazardous Materials Commodity Flow – TESTBED

Problem Statement: Develop an engineering development Hazmat identification testbed, deploy it at a WA State weigh station and integrate it into the WA State Patrol digital network.

Inputs / Resources:
- Funding
- PNNL staff
- Access to stakeholders
    - WS-DOT
    - WA State Patrol
    - Seattle DOT
- Access to weigh station facility and network

Activities:
- Meetings with stakeholders
- Selection of cameras, Hazmat placard, USDOT and license plate reader systems
- Integration equipment into testbed
- AI predictive modeling research

Outputs:
- Deployed single-node testbed
- Integrated AI predictive system into testbed
- Integrated testbed with State Patrol network

Outcomes:
- Acquire Hazmat detection data
- Determine the feasibility of deploying a multi-node, corridor testbed

Assumptions:
- Stakeholders support project

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