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# REAL-TIME TRAFFIC SIGNAL SYSTEM PERFORMANCE MEASUREMENT (PROJECT NO. 2016-14)
# Phase III: System Integration, Intersection Deployment, and Control Center Dashboard Development

## Final Report

June 2024

Submitted by

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**16. Abstract**
In the proposed third phase of the NJDOT Automated Traffic Signal Performance Measures (ATSPM) project, the research team 1) evaluated Roadside Unit (RSU) /Onboard Unit (OBU) data with ground truth data, 2) validated physical and virtual RSU deployment scenarios for pedestrian safety applications, 3) studied the boundary conditions of Light Detection and Ranging (LiDAR) and Closed-circuit television (CCTV) sensors for traffic and pedestrian sensing, and 4) developed a dashboard application for visualizing and Quality Assess and Quality Control (QA/QC) of the real-time traffic signal performance metrics and Connected Vehicle (CV) messages from the ATSPM and deployment sites.

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## EXECUTIVE SUMMARY

### Background

Traffic signal performance measurement and visualization serve as critical operational tools to assist traffic management centers (TMC) in maximizing the benefits of infrastructure investments. Nonetheless, real-time evaluation and monitoring of signal performance present challenges that necessitate immediate data collection and analysis capabilities. As part of the implementation of the FHWA Every Day Counts (EDC) 2.0 toolboxes, New Jersey Department of Transportation (NJDOT) collaborates with a research team from Rutgers University, The College of New Jersey (TCNJ), and Rowan University to explore deployment strategies and pilot the Automated Traffic Signal Performance Measure (ATSPM) system using NJDOT's current and planned arterial management resources. Additionally, the advancement of Connected Vehicle (CV) technology and its nationwide piloting and deployment create new opportunities to enhance real-time arterial operations through the generation, delivery, and application of support using SAE (Society of Automotive Engineers) J2735 Signal Phase and Timing (SPaT), MAP, Basic Safety Message (BSM), Personal Safety Message (PSM), and Traveler Information Message (TIM).

In the first phase of the project, the team successfully developed software toolbox, NJDOT ATSPM 1.0 that converts the event output data from SCATS and InSync Adaptive Traffic Signal Control (ATSC) Systems into event data that can be processed by the FHWA ATSPM platform.

In the second phase, the team integrated multiple sensor data sources such as Wavetronix, Autoscope computer vision sensor, and Probe travel time data to enable several critical performance metrics including Purdue Coordination Diagrams (PCDs), Link Pivot diagrams and other metrics relying on vehicle occurrence, volume, or speed data. The team also completed the full deployment of the developed ATSPM 2.0 platform on NJDOT servers. The team further initiated the pilot experiment and integration of real-time traffic signal performance measure (RT-SPM) with Connected and Automated Vehicle technologies at intersections.

In the third phase of this project, the research team extended the deployment of the ATSPM platform from limited intersections at two corridors to all SCATS signals on Routes 1, 18, 73, and 130, utilizing an extensive AutoGUI-based interface to automate the detection data extraction process. The team, in collaboration with industrial partners, conducted and deployed CV physical and virtual roadside unit technologies both in the TCNJ lab and at the NJDOT Bordentown training facility. They experimented with the generation and reception of key SAE J2735 messaging, including TIM, MAP, SPaT, BSM, and PSM to support pedestrian safety applications. Specifically, the team explored Verizon’s VZMode technologies for converting and receiving TIM, MAP, and SPaT messages, as well as converting pedestrian detection data inputs from Bosch cameras and Ouster LiDAR sensors into virtual PSM messages. The boundary conditions for using LiDAR and computer vision sensors to support CV applications were explored. The Neaera team developed a comprehensive Operational Data Management (ODM) and data Quality Assessment and Quality Control (QA/QC) platform for the health monitoring and visualization of physical and virtual CV datasets.

## Research Objectives

NJDOT arterial management operators can use the ATSPM platform to generate key performance metrics and conduct system analysis for NJDOT's ATSC corridors. The research team achieves these goals by considering the following individual objectives:

- **Update the state-of-the-art and practice of RT-SPM and CV Virtual RSU Technologies**: In phase three, the team expand the literature review to include prevailing technologies and existing or planned systems on ATSPM based on intersection sensors and CV virtual Roadside Unit (RSU) systems and identify existing public and commercial SPM and CV Virtual RSU platforms. The team also review CV basic and pedestrian safety message protocols and review the message standards, architecture, software and hardware implementation, and related applications. The team conduct literature review on prevailing visualization, map, and dashboard applications for ATSPM metrics and CV RSU and OBU messages.
- **Obtain feedback from NJDOT regarding needs and challenges in implementing RT-SPM and CV Virtual RSU technologies**: Organize stakeholder meetings to identify the needs and challenges of deploying ATSPM with roadside sensors and CV vehicle basic and personal safety message (BSM and PSM) broadcastings from both physical and virtual RSU technologies.
- **Review, evaluate, and propose configuration optimization methods on the existing data sources for BSM and PSM Message generation for NJDOT**: The team review existing roadside sensor technologies such as video, LiDAR, radar, and other sensor data sources that can be used to support the generation of BSM and PSM data. The team also evaluate the operating limitations and conditions of different sensors and develop optimization tools to help maximize the performance for pedestrian safety applications. The review and evaluation studies focus more on the existing and planned sensor technologies of NJDOT.
- **Pilot testing and deployment of a prototype of CV-enabled RT-SPM on different types of controllers**: Testing the prototype ATSPM toolboxes with NJDOT based on potential pedestrian and vehicle data to be collected in Phase 3. In prior phases, a database system has been established to store signal controller event and Autoscope detector data for ATSPM system. However, the CV messages generated by pilot RSU sites and testing OBUs have not yet been effectively processed and archived. The team build data management systems that can transfer the real-time data from the site to Arterial Management Center (AMC), process and denoise the raw data, and efficiently archive and query historical data.
- **Conduct CV pedestrian safety message validation and performance evaluation and impact assessment on intersection safety performance measures**: In this project, the research teamwork with NJDOT to validate and evaluate the pedestrian safety messages with safety RT-SPM obtained through CV virtual RSU technologies. The team identify visualization technologies that can create map-based and graph-based visualization of NJDOT arterial corridors and intersections deployed with the ATSPM and CV technologies through the first three phases of the project. The goal is to create a visualization platform to support NJDOT arterial traffic operators and

decision makers on monitoring the health and conditions of arterial traffic signals, RSUs, and CV applications.

- **Establish QA/QC procedures and develop dashboard application for ATSPM Platform and CV Roadside Units**: Develop a QA/QC procedure with NJDOT to monitor and maintain the performance of the deployed ATSPM and CV RSU platforms and applications in previous three phases. The dashboard application should be able to create QA/QC reports periodically and generate alerts regarding significant performance issues and system failures.
- **Conduct testing and deployment of the developed data archiving, visualization and QA/QC platforms**: Based on the developed platforms, the final objective is to conduct pilot deployment and fine-tuning to provide NJDOT with an operational application platform at the end of the project.

The outcome of this project will enable safety and mobility applications that can be used to improve intersection safety, reduce congestion and environmental impact, and improve the performance of New Jersey arterial corridors. The NJDOT ATSPM 3.0 will overcome the challenge to evaluate and monitor signal performance in real time, reduce the heavy data collection load at servers of AMC, through intersection-based distributed data collection and analytics. During Phase III of the RT-SPM project, the designed system will be tested on intersections instrumented with connected vehicle technologies to enable more intersection specific applications and performance monitoring capabilities to improve safety and efficiency at NJDOT signalized intersections. The followings are the detailed description of those benefits.

- Traffic Operations and Maintenance
  - NJDOT ATSPM 3.0 will provide extended arterial performance metrics for arterial intersections instrumented with CV RSU technologies. During phase III, the team will utilize data sources from computer vision and other vehicle and pedestrian detection sensors to for generating ATSPM performance metrics, such as Arriving on Green (AoG) in PCD, speed, volume, Purdue Link Pivot, Purdue Split Failure with low computational cost at AMC servers. The testing scale will focus on intersections instrumented with RSU technologies on US-1.
  - Connected and Autonomous Vehicles (CAV)-enabled Intersection will allow real-time high-resolution vehicle data collection and signal control feedback. Connected vehicle technology can potentially report real-time vehicle presence and potentially their trajectories for signal performance assessment and feedback control. Those CV trajectory data can be used to assess vehicle delay, vehicle arrival pattern using PCDs, build arrival flow profiles, and estimate queue lengths. CAV-enabled intersection control will allow microscopic coordination and feedback between vehicles and enabled intersections.
  - Data archiving, visualization, and QA/QC dashboard application to be developed in this project will provide NJDOT arterial management center with valuable tools to monitor their intersections in near real-time. If successful, the developed platform will reduce the operator loads and hours spent on conducting manual data processes for periodic monitoring of the deployed ATSPM and CV RSU systems.

    - The proposed platform will also serve as an evaluation platform for NJDOT to explore, test, and evaluate a wide range of CV applications for their accuracy, coverage, functionalities, and real-time capabilities.
- Traffic Safety and Mobility
    - NJDOT ATSPM 3.0 will provide NJDOT with more efficient and cost-effective performance monitoring solutions for arterial traffic signals with the improved integration of Verizon and Cisco CV applications. NJDOT ATSPM 3.0 will allow the NJDOT to be able to conduct comprehensive assessment and monitoring of their arterial corridors and further accelerate the process of identifying, assessing, and addressing signal control and maintenance problems.
    - CV-enabled intersections will facilitate personalized intersection driving assistance, smart intersection applications to enhance arterial operations, safety, and mobility which can also be applied to pedestrian movements. Successful implementation of BSM and PSM broadcasting will enable a wide range of CV safety applications that have the potentials of significantly reducing the number of pedestrian crashes at NJDOT intersections.
    - The proposed dashboard will contribute to the 24x7 operations of the NJDOT ATSPM 3.0, and CV RSUs deployed through Phase I to III. Long-term operations of NJDOT ATSPM 3.0 and Arterial Intersection RSUs will allow the NJDOT to be able to conduct comprehensive assessment, monitoring, and control of their arterial corridors and further accelerate the process of identifying, assessing, and addressing signal control and maintenance problems.
    - The dashboard application will also help maintain the functionalities of CV applications to be tested and deployed at NJDOT CV pilot sites. CV-enabled intersections will facilitate personalized intersection driving assistance, smart intersection applications to enhance arterial operations, safety, and mobility which can also be applied to pedestrian movements. Successful implementation of BSM and PSM broadcasting will enable a wide range of CV safety applications that have the potential of significantly reducing the number of pedestrian crashes at NJDOT intersections.
- Strategic Planning
    - The development of RT-SPM and the adapting and deployment of ATSPM with existing NJ ATSC systems follows the FHWA EDC Initiative to promote the rapid deployment of proven innovations. NJDOT ATSPM 3.0 will help to meet and exceed the strategic EDC goal to accelerate the deployment of ATSPM on existing and planned arterial corridor to reduce crashes, injuries, and fatalities, optimize mobility and enhance the quality of life.
    - The development of the data management, visualization, and QA/QC platform will ensure the performance of ATSPM and CV pilot sites on existing and planned arterial corridors to reduce crashes, injuries, and fatalities, optimize mobility and enhance the quality of life.
    - Data will support state initiatives on policy preparation and testing of CAV technologies and create a scalable application that can support the further expansion of the CV pilot deployment. The outcome of the project will be reported to NJDOT which is part of the New Jersey Advanced Autonomous Vehicle Task Force to make recommendations on laws, rules, and regulations, to safely

integrate advanced autonomous vehicles on the State's highways, streets, and roads.

**Research Tasks**

**Task 1: The State of the art-and-Practice Update:** The research team conduct a review of the state-of-the-art-and-practice review on the integration of ATSPM and CV systems and dissemination of the Video Analytics of Pedestrian Tracking and CAV warning systems, the state of the art and practice in traffic conflict analysis, and the latest development of ODE and Dashboard application for data visualization and QA/QC platforms. The list of data types to be considered are as follows:

- SCATS Traffic signal controller event data
- Traffic detection data from video cameras (Autoscope and Bosch cameras)
- CV BSM and PSM Messages from LiDAR sensor detection
- CV SPaT Messages
- Vehicle and pedestrian trajectory data
- Other datasets and messages used or generated in CV Applications

**Task 2: Stakeholder Outreaching and Engagement:** To ensure this project's efforts result in actionable outcomes for NJDOT, the research was conducted with a stakeholder and expert panel comprising members from public, private, and academic sectors. The identified best practices, along with the deployment plans and strategies developed during this project, have been compiled and disseminated to decision-makers at both the technical and policy levels. Additionally, the research team actively promotes in-depth presentations and discussions of the research topics at academic conferences and forums.

**Task 3: Pedestrian and Vehicle Sensor Performance Evaluation and Boundary Condition Analysis:** The research team will conduct an analysis based on field data to determine the boundary and optimal conditions for video sensors used in pedestrian safety applications. This involves collecting detailed vehicle and pedestrian data from pilot site to establish baseline conditions for evaluating the impacting factors and understanding effects on the sensing performance for both pedestrians and vehicles.

**Task 4: BSM and PSM Messaging Pilot Validation and Evaluation and Operational Data Environment Establishment for ATSPM, SAE J2735 Message Processing and Archiving:** At one or two pilot sites, the team will compare physical or virtual RSU-broadcasted BSMs and PSMs with the actual signal changes, pedestrian and vehicle object trajectories collected from roadside sensors. The team will validate pedestrian safety message logic on the following aspects: 1) Alerts generated versus actual push-button status or timestamp, 2) Time gaps from users receiving alerts to the minimum response time, and 3) Pedestrian-vehicle conflict time versus the actual conditions collected from sensors. The team will further evaluate the accuracy, coverage rate, and latency metrics to be evaluated to provide on-time safety alerts. A NJDOT CV lab setup for ODE, database, and website for visualization in support of the proof of concept will be deployed. It will include the receipt of SAE J2735 message, with decoding and archiving capabilities of JSON formatted messages. Additionally, a website will be configured to visualize the location of the RSUs, and to show message counts in tabular and heat map format.

The team will work with NJDOT and collaborators to identify all data silos and links currently deployed through the first three phases of the project. The team will design the ODE for NJDOT's pilot intersections based on existing ODE architecture. A prototype ODE implementation will be developed during the project period to support subsequent dashboard development for the pilot CV test sites. The team will streamline and consolidate the software and hardware components of the system to allow potential scaling up of the deployment at key arterial corridors.

**Task 5: RSU Integration and Visualization Dashboard:** The team will conduct experimentation and documentation on the connection of Pedestrian Video Analytics and RSU devices. Integration with NJDOT ATSC controllers will be explored once PED – RSU – CONTROLLER (PRC) communication is established. The team will complete experimentation and documentation of PRC communication at The College of New Jersey (TCNJ) laboratories. The team will conduct in lab testing of the PRC systems, including the following:
1. Setup PRC bench on TCNJ Campus
2. Obtain 'vehicle/ped' type data from PRC to integrate into ATSPM where possible.
3. OBU input from RSU will be evaluated.

With the ODE developed in Task 4, the research team will further develop a pilot dashboard application that can fulfill some of the following proposed functionalities:
1. Map-based Visualization of the BSM and PSM data.
2. Monitoring and visualization of RSU SPaT and MAP messages.
3. Map-based Visualization of ATSPM performance.
4. ATSPM system performance and intersection health reports

The team will work closely with NJDOT on determining a prioritized list of functionalities for implementation based on NJDOT arterial management and CV pilot needs. Detailed system documentation and training materials will be developed along with the software and hardware systems.

**Task 6: NJDOT ATSPM 3.0 Pilot Testing and Deployment:** The team will develop the prototype CAV-enabled RT-SPM and pedestrian SPMs developed in Task 3 and 4 will be further tested in the field. The team will install and configure ATSPM modules on the Application Test Server for comprehensive testing. A semi-automatic configuration program will be developed to efficiently configure ATSPM signals and detectors. The team will also configure SCATS events data and a GUI-based archiving efforts for live data automation and manual processes for historical data. The team will collaborate with NJDOT Office of Information Technology (OIT) to consolidate the software and hardware components of the system to allow potential scaling up of the deployment.

**Task 7: CAV BSM and PSM pilot deployment and evaluation and Dashboard Supported CV Application Testing Procedure and Tools Development and Pilots** The team will conduct a field test in coordination with HNTB, Cisco, Verizon, and NJDOT for CAV messages reception and analysis to assess the safety improvements such as the vehicle and pedestrian conflict data. The team will demonstrate the potentials based on SAE J2735 messages, such as red-light running signal, smart departure/approach, signal priority, wrong-way driving, and emergency vehicle preemption in the context of pedestrian detection. OBUs and smartphones will be used to analyze and document the RSU messaging quality and performance. The team will work with NJDOT on the development of testing procedure and tools by using functionalities of the develop ODE and dashboard platform to visualize the messages, data, and intersection performances during the tests.

**Task 8: Quarterly and final Reporting:** The team provide technical memos and quarterly report. The quarterly report will include the latest deliverables, documentation, and tech memo on task results.

## Acronyms and Abbreviations

| | | | |
|---|---|---|---|
| **ADAS** | Advanced Driver Assistance Systems | **NHTSA** | National Highway Traffic Safety Administration |
| **AMC** | Arterial Management Center | **NJDOT** | New Jersey Department of Transportation |
| **AoG** | Arriving On Green | **OBU** | On-board Unit |
| **ATSC** | Adaptive Traffic Signal Control | **ODE** | Operational Data Environment |
| **ATSPM** | Automated Traffic Signal Performance Measures | **OIT** | Office of Information Technology |
| **AV TEST** | Automated Vehicle Transparency and Engagement for Safe Testing | **OTA** | over-the-air |
| **BSM** | Basic Safety Message | **PCD** | Purdue Coordination Diagram |
| **CAV** | Connected and Autonomous Vehicle | **PET** | Post Encroachment Time |
| **CCTV** | Closed-circuit Television | **PRC** | Pedestrian-RSU-Controller |
| **CPI** | Crash Potential Index | **PSD** | Proportion of Stopping Distance |
| **CTI** | Connected Transportation Interoperability | **PSM** | Personal Safety Message |
| **CV** | Connected Vehicle | **QA/QC** | Quality Assessment and Quality Control |
| **CV2X** | Cellular Vehicle-to-Everything | **RLVW** | Red-Light Violation Warning |
| **DSRC** | Dedicated Short-Range Communications | **ROS** | Robot Operating System |
| **DRAC** | Deceleration Rate to Avoid a Crash | **RSU** | Roadside Unit |
| **DNN** | Deep Neural Network | **RTTC** | Relative Time to Collision |
| **EDC** | Every Day Counts | **RT-SPM** | Real-time Signal Performance Measurement |
| **FHWA** | Federal Highway Administration | **SAE** | Society of Automotive Engineers |
| **FOV** | Field of View | **SDP** | Speed Distance Profile |
| **GOR** | Green Occupancy Ratio | **SPM** | Signal Performance Measurement |
| **HMMs** | Hidden Markov models | **SPaT** | Signal Phase and Timing |
| **ISS** | Integrity Security Services | **SPMD** | Safety Pilot Model Deployment |
| **ITS** | Intelligent Transportation Systems | **SSM** | Surrogate Safety Measures |
| **ITS JPO** | Intelligent Transportation Systems Joint Program Office | **TCNJ** | The College of New Jersey |
| **MTTC** | Modified Time to Collision | **TFHRC** | Turner Fairbank Highway Research Center |
| **TIM** | Traveler Information Messages | **UDOT** | Utah Department of Transportation |
| **TMC** | Traffic Management Center | **USDOT** | U.S. Department of Transportation |
| **TSC** | Traffic Signal Controller | **V2I** | Vehicle-to-Infrastructure |
| **TTC** | Time-To-Collision | **V2X** | Vehicle-to-Everything |

## TASK 1: THE STATE OF THE ART-AND-PRACTICE UPDATE

### NJDOT CAV-ATSPM 2.0 Summary

In the second phase of NJDOT CAV-ATSPM project, the team integrated multiple sensor data sources such as Wavetronix, Autoscope computer vision sensor, and Probe travel time data to enable several critical performance metrics including PCDs Link Pivot diagrams and other metrics relying on vehicle occurrence, volume, or speed data. The team also completed the full deployment of the developed ATSPM 2.0 platform on NJDOT servers. The team further initiated the pilot experiment and integration of RT-SPM with CAV technologies at intersections.

### State of the Practice of Connected and Automated Vehicle Technology

#### *Connected Vehicle Technology*

CV application prototyping and assessment have been a collaborative effort involving public, private, and academic stakeholders. The Federal Highway Administration (FHWA) played a crucial role by providing federal funding and maintaining a repository of developed technology documentation and application codes. The research and development activities saw contributions from various entities, resulting in the development of over 30 CV application concepts, many of which have advanced through prototyping and demonstration phases. To ensure comprehensive information availability, the USDOT has published extensive documentation, including concepts of operations, system requirements, design documents, algorithms, and source code for these prototypes. This collaborative approach facilitates the effective implementation of a diverse range of CV applications by seamlessly integrating essential vehicle and infrastructure components.

### Connected and Automated Vehicle Test Sites in the US

In 2017, The USDOT designated ten automated vehicle proving grounds to encourage testing advanced autonomous vehicles technologies. The location of these testing activities is shown in the following figure 1.

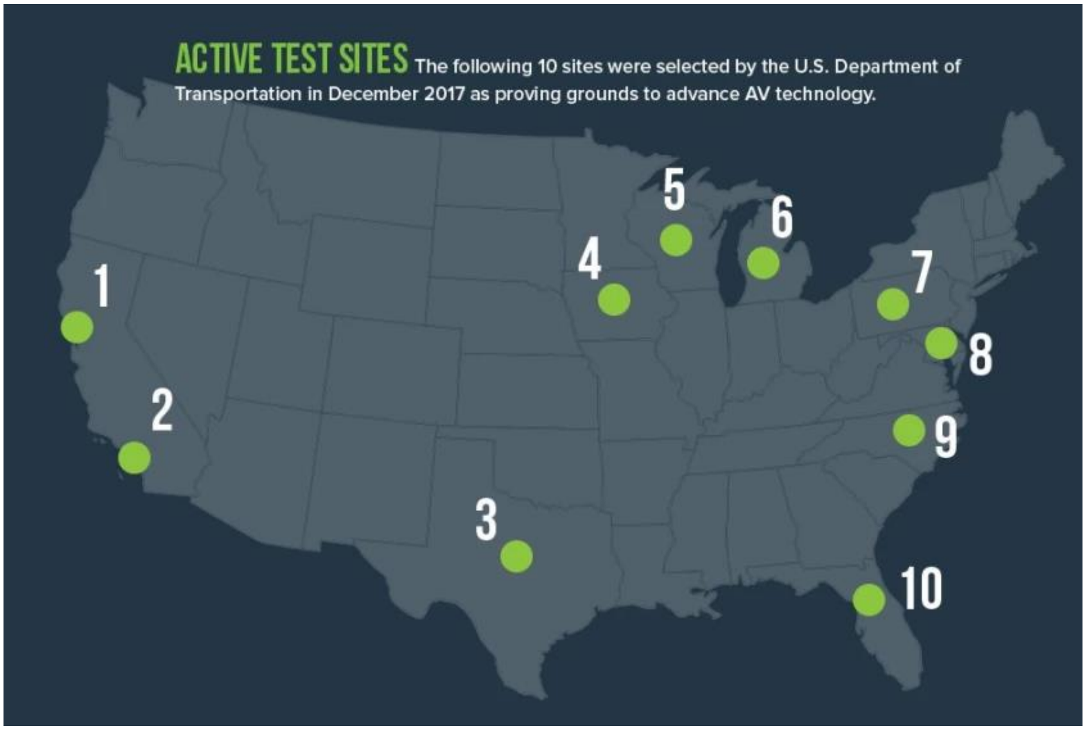


Figure 1. Locations of Autonomous Vehicle (AV) Proving Grounds (1)

In Concord, California, Contra Costa Transportation Authority GoMentum Station offers 5,000 acres of varied terrain with 20 miles of paved roadway focused on testing connected and autonomous vehicle technology. (2) The connected and automated vehicle Vehicle-to-everything (V2X) Lab at GoMentum Station includes advanced traffic signal controllers, video vehicle detectors, advanced IP switches, traffic signal cabinets, and dedicated short-range communication (DSRC), Cellular Vehicle-to-Everything (C-V2X), and 5G equipment. The lab is well suited for cities and transit agencies to test applications to enhance safety and reduce street congestion. Currently, the lab has equipment from the following vendors:

- Traffic Signal Controllers: Trafficware, Siemens, Intelight
- OBU/RSU: Commsignia, Savari, TraffficCast, Siemens
- Detection: Iteris, BlueCity Technology
- Switches: Cisco with edge computing capabilities

In San Diego, CA, the San Diego Association of Governments has three different environments: the express lanes on Interstate 15, city streets in Chula Vista, and part of the South Bay Expressway. These sites offer real-world conditions for AVs and CVs and their associated technology. (1)

In Texas, several sites compose the Texas AV Proving Grounds Partnership taps into existing transit testing facilities, many of which have been engaged in AV projects for several years. Each Texas AV Proving Grounds Partnership research agency conducts CAV research and has proving grounds for development and testing on their campuses. (3)

In Iowa City, Iowa Home to the National Advanced Driving Simulator at the University of Iowa, the Iowa City Area Development Group site offers both on-road and closed-course testing and simulated transportation environments. AVs can test in different kinds of weather and on various road surfaces. [4]

In Madison, Wisconsin, the Wisconsin AV Proving Grounds' mission is to provide a path to public road evaluation by contributing to the safe and rapid advancement of automated vehicle development and deployment and providing a full suite of test environments, coupled with research, open data, and stakeholder communication. [5] In May 2017, Governor Walker issued an executive order to create a committee on connected and automated vehicles, with the mission to coordinate among agencies and identify “laws or rules that impede the testing and deployment of CV/AVs.

In Michigan, American Center for Mobility at Willow Run powered by Intertek and Humanetics have partnered together to help your test team learn how to achieve higher test results in complex scenarios with integrated CAV test equipment. [6]

- Constructing Test Scenarios: Building and testing against the operational domain using test rigging/fabrication, interaction vehicles, unique surfaces/track features
- Repeatability & Reliability with ITS Integration: Traffic lights, DSRC, cell network, data management, software-in-loop/hardware-in-the-loop, cloud-based programmable infrastructure
- Support Services: Testing services/support, data processing, field operational tests

University of Michigan’s Mcity operates the world’s first purpose-built proving ground for testing the performance and safety of CAV technologies under controlled and realistic conditions. [7] The Mcity Test Facility sits on a 32-acre site on UM’s North Campus, with more than 16 acres of roads and traffic infrastructure. The full-scale outdoor laboratory simulates the broad range of complexities vehicles encounter in urban and suburban environments. It provides the connected infrastructure and operating system as a smart city test bed. Features include:

- State-of-the-art instrumentation and sensors throughout the facility include a control network to collect data about traffic activity using wireless, fiber optics, ethernet, and a highly accurate real-time kinematic positioning system,
- Patent-pending augmented reality testing technology allows physical test vehicles to interact with virtually connected vehicles in real-time inside the facility,
- Fully connected 5G network and V2X communication throughout the facility,
- Facility infrastructure and testing conditions can be controlled with our Mcity OS cloud-based software,
- Multiple road surfaces, a variety of road markings, and crossing types (e.g., pedestrian, railroad),
- 1,000-foot straightaway, plus access ramps, curves, roundabouts, traffic circles, and urban streets,
- Traffic signals and traffic signs, plus building facades and simulated tree cover,
- House and garage exterior with accessibility ramp for first mile/last mile testing, deliveries, and ride-hailing,
- The bridge deck, underpass, guardrails, barriers, and crash attenuators,
- Onsite workstation and configurable open test areas,

- Test vehicles and support available.

In Pennsylvania, Penn State researchers aim to develop a driver-in-the-loop vehicle simulator tool to better understand the effects of CAV technology on commuting behavior, thanks to a $60,000 Multidisciplinary Research Seed Grant. [1]

In Maryland, U.S. Army Aberdeen Test Center is currently engaged with Maryland DOT and exploring collaboration on CAV development opportunities. [8] Maryland DOT is coordinating the possible use of several different transportation facilities for testing highly automated and connected vehicles, providing for various scenarios and conditions. Maryland DOT Motor Vehicle Administration has established an online permitting system to accept and review expressions of interest and applications, and issue permits for testing.

In North Carolina, the North Carolina Turnpike Authority provides around 20 miles of expressway to multiple research universities for CAV testing. They also provide 19 miles of fiber optics, enabling electronic tolling, live feeds, and pavement sensors. These features will help identify necessary changes to CAV road signs and markings for CAVs. [1]

In Florida, the Central Florida Automated Vehicle Partners are implementing a three-phase testing plan for the Regional Advanced Mobility Elements project. These phases include signal shop lab testing, Traffic Engineering Research Laboratory testing, and on-site testing. District Five has recently completed the lab testing phase. This phase aimed to evaluate communication between devices, focusing on converting the National Transportation Communications for Intelligent Transportation System Protocol to SAE J3725 and ensuring compatibility with existing infrastructure to maintain interoperability across the district. In the lab environment, various RSUs and OBUs were tested to determine if end-to-end communication, such as BSM, MAP, and SPaT, was successfully transmitted and received. The lab setup included devices from four controller manufacturers, seven RSU manufacturers, and five OBU manufacturers. [1]

In New Jersey, in partnership with NJDOT and Middlesex County, The City of New Brunswick, and additional private companies, the DataCity Smart Mobility Testing Ground is an investment in innovative CAV technology and a source of high-resolution transportation data designed to attract leading public and private sector companies interested in testing advanced driving system applications in real-world conditions. The DataCity Smart Mobility Testing Ground provides a 2.4-mile multi-modal corridor in downtown New Brunswick, NJ, for collecting multi-modal smart-mobility data. It will help the region improve safety, congestion, and equity in its transportation systems while establishing NJ as a hub for research and development in the growing CAV industry. [9]

### *CV Deployment Sites in the US*

USDOT provides a map of the distribution of connected vehicle deployment locations in the U.S [10] which is shown in figure 2. The operational CV deployment is in yellow, and the planned CV deployment is in green. As of June 30, 2022, there are currently 70 deployment sites spread across 27 states, and there are plans for an additional 101 deployment sites in 31 states.

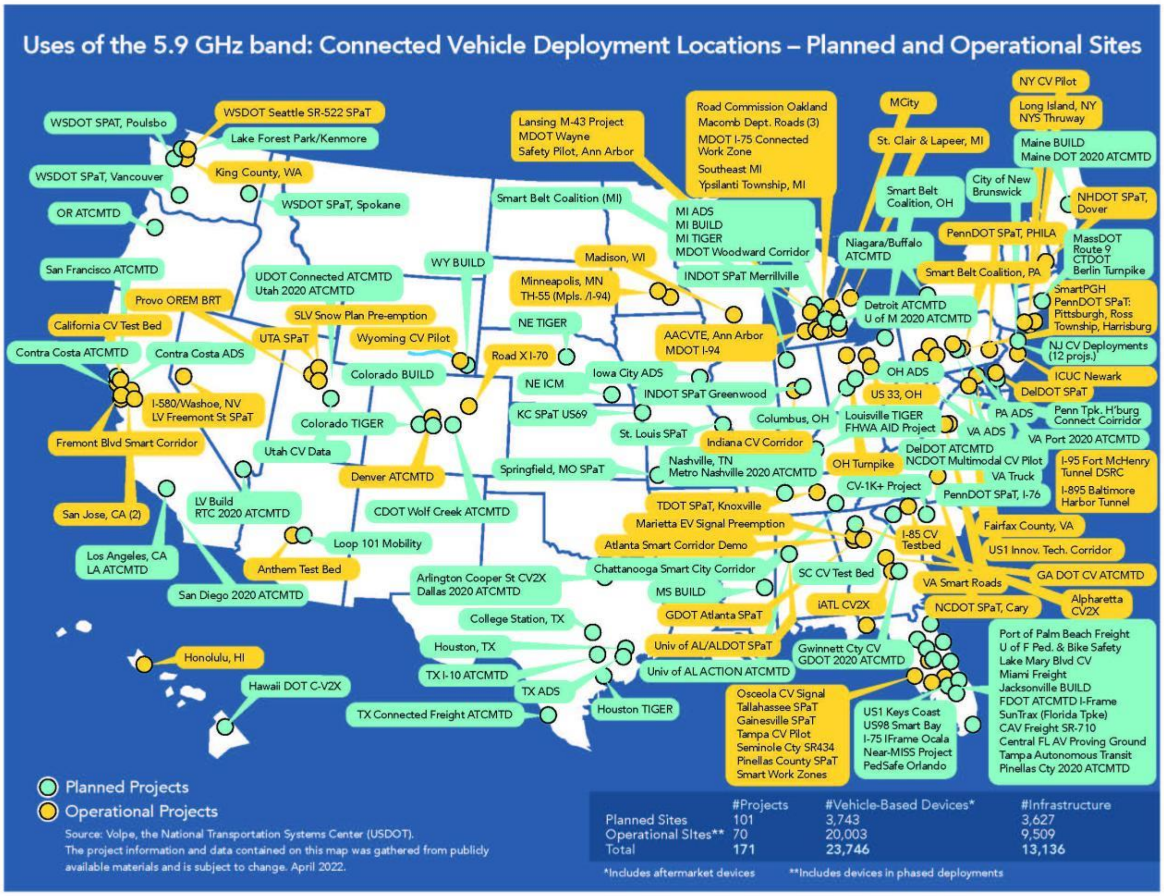



Figure 2. Distribution of CV Deployment Locations in the U.S [(10)]

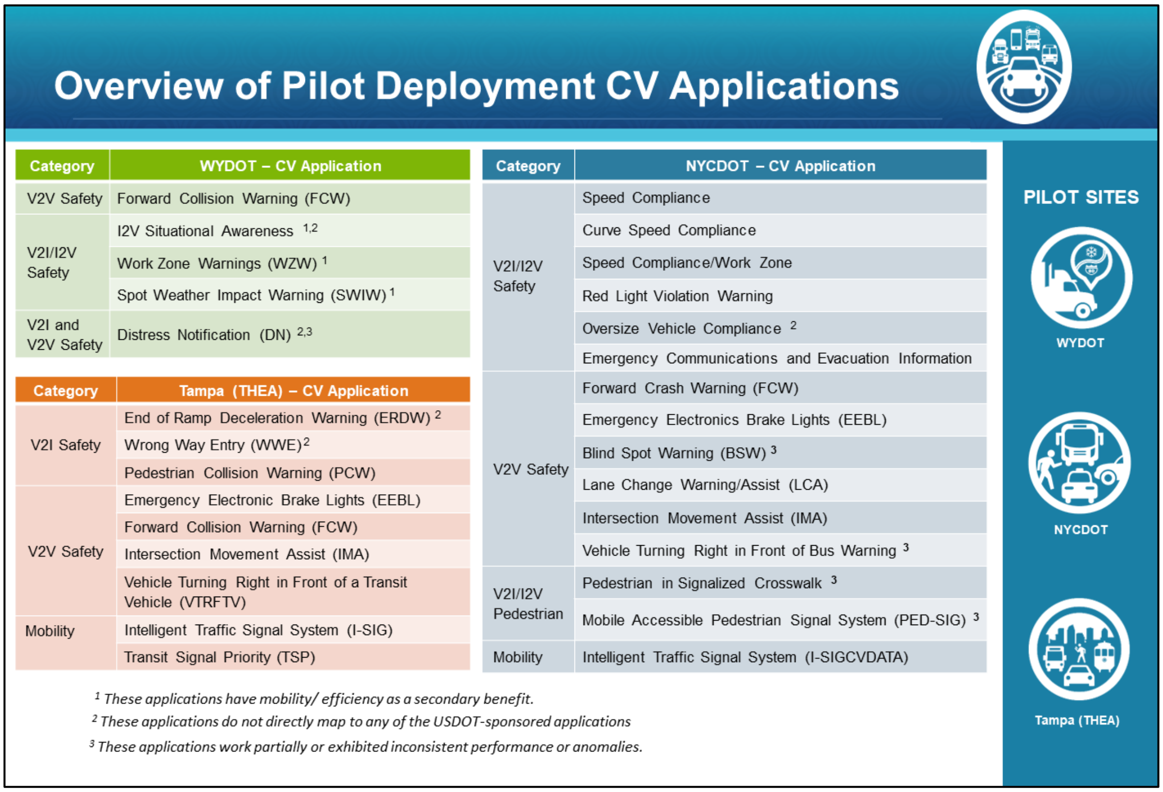
The CV Pilots intend to accelerate the deployment of interoperable connected vehicle technologies by: [(11)]

- Spurring innovation among early adopters of connected vehicle application concepts.
- Encouraging partnerships among multiple stakeholders.
- Demonstrating connected vehicle deployments' potential safety, mobility, and environmental benefits.
- Creating sustainable momentum for nationwide deployment of connected vehicle technologies

After a multi-year period of designing, testing, and integrating the components of their CV systems, the Wyoming Department of Transportation, New York City Department of Transportation, and Tampa Hillsborough Expressway Authority CV Pilot sites deployed the necessary equipment to support their operational concepts. Working in partnership with technicians from their respective City/State Department of Transportation staff, and in the case of THEA, technicians from the local community college, the CV Pilot sites completed the full installation RSUs and OBUs. These units enable the V2V and V2I communications required for the safety and mobility applications of their CV systems.

The Figure 3 and figure 4 below provide a summary of the following:

- The applications installed at each site
- The final number of installed devices by device/vehicle type




| Category | WYDOT – CV Application |
|---|---|
| V2V Safety | Forward Collision Warning (FCW) |
| V2I/I2V Safety | I2V Situational Awareness [1,2] |
| | Work Zone Warnings (WZW) [1] |
| | Spot Weather Impact Warning (SWIW) [1] |
| V2I and V2V Safety | Distress Notification (DN) [2,3] |

| Category | Tampa (THEA) – CV Application |
|---|---|
| V2I Safety | End of Ramp Deceleration Warning (ERDW) [2] |
| | Wrong Way Entry (WWE) [2] |
| | Pedestrian Collision Warning (PCW) |
| V2V Safety | Emergency Electronic Brake Lights (EEBL) |
| | Forward Collision Warning (FCW) |
| | Intersection Movement Assist (IMA) |
| | Vehicle Turning Right in Front of a Transit Vehicle (VTRFTV) |
| Mobility | Intelligent Traffic Signal System (I-SIG) |
| | Transit Signal Priority (TSP) |

| Category | NYCDOT – CV Application |
|---|---|
| V2I/I2V Safety | Speed Compliance |
| | Curve Speed Compliance |
| | Speed Compliance/Work Zone |
| | Red Light Violation Warning |
| | Oversize Vehicle Compliance [2] |
| | Emergency Communications and Evacuation Information |
| V2V Safety | Forward Crash Warning (FCW) |
| | Emergency Electronics Brake Lights (EEBL) |
| | Blind Spot Warning (BSW) [3] |
| | Lane Change Warning/Assist (LCA) |
| | Intersection Movement Assist (IMA) |
| | Vehicle Turning Right in Front of Bus Warning [3] |
| V2I/I2V Pedestrian | Pedestrian in Signalized Crosswalk [3] |
| | Mobile Accessible Pedestrian Signal System (PED-SIG) [3] |
| Mobility | Intelligent Traffic Signal System (I-SIGCVDATA) |

*[1] These applications have mobility/ efficiency as a secondary benefit.*
*[2] These applications do not directly map to any of the USDOT-sponsored applications*
*[3] These applications work partially or exhibited inconsistent performance or anomalies.*

Figure 3. Overview of Pilot Deployment of CV Applications [11]

## CV Device Deployment Dashboard

| Wyoming Pilot (WYDOT) | # Deployed |
|---|---|
| WYDOT Maintenance Fleet (Snow Plows) | 53 |
| WYDOT Highway Patrol | 66 |
| State Pool Fleet | 18 |
| Medium Duty Friendly Fleet | 21 |
| Heavy Duty / Commercial Fleet | 169 |
| **Total Equipped Vehicles** | **327** |
| **Roadside Units (RSU) along I-80** | **76** |

| Tampa Pilot (THEA) | # Deployed |
|---|---|
| **Phase 3**: Private Light-Duty Vehicles Equipped with On-Board Units (OBU) | 1,020 (Peak) |
| **Phase 3**: HART Transit Buses Equipped with OBUs | 7 |
| **Phase 3**: TECO Line Street Cars Equipped with OBUs | 8 |
| **Phase 4:** OEM Vehicles Equipped with OBUs and Upgrading of Existing OBUs | Upgraded OBUs: Wistron NeWeb Corp. (WNC): 103; OEM OBUs: 68 |
| **Total Equipped Vehicles** | **Phase 3: 1,035; Phase 4: 171** |
| **Roadside Units (RSU) at Downtown Intersections** | **47** |

| New York City Pilot (NYCDOT) | # Deployed |
|---|---|
| Department of Transportation (DOT) | 1,238 |
| Parks Dept. (Parks) | 511 |
| Dept. of Correction (DOC) | 293 |
| Dept. of Environmental Protection (DEP) | 159 |
| Dept. of Homeless Services (DHS) | 100 |
| TLC Fleet (DCAS) | 98 |
| Human Resources Administration (HRA) | 86 |
| DCAS Fleet Share | 78 |
| Dept. of Education (DOE) | 78 |
| Dept. of Buildings (DOB) | 69 |
| Administration for Children's Services (ACS) | 65 |
| Housing Preservation & Development (HPD) | 48 |
| Dept. of Health (DHMH) | 45 |
| Dept. of Design and Construction (DDC) | 38 |
| Office of Chief Medical Examiner (OCME) | 29 |
| MTA/New York City Transit | 14 |
| Office of Emergency Management (OEM) | 12 |
| Dept. of Consumer Affairs (DCA) | 12 |
| Anheuser Busch | 10 |
| Dept. of Info. Tech. & Telecom. (DOITT) | 9 |
| Department of Probation | 6 |
| TransCore | 1 |
| NYC TLC Taxis | 1 |
| MTA Bridges and Tunnels | |
| **Total Equipped Vehicles** | **3,000** |
| **Roadside Units (RSU) at Manhattan and Brooklyn Intersections and FDR Drive** | **470** |
| **Vulnerable Road User (Pedestrians/Bicyclists) Device** | **5** |
| **PED Detection System** | **10** |

**PILOT SITES**

WYDOT

NYCDOT

Tampa (THEA)

Figure 4. CV Device Deployment Dashboard [11]

### *Autonomous Bus and Shuttle Deployments in the US*

In 2020, the National Highway Traffic Safety Administration (NHTSA) launched Automated Vehicle Transparency and Engagement for Safe Testing (AV TEST). [12] As part of the AV TEST initiative, states and companies can voluntarily submit information about the testing of automated driving systems to NHTSA. The following map shows the NHTSA records on the automated bus and shuttle testing locations and information.

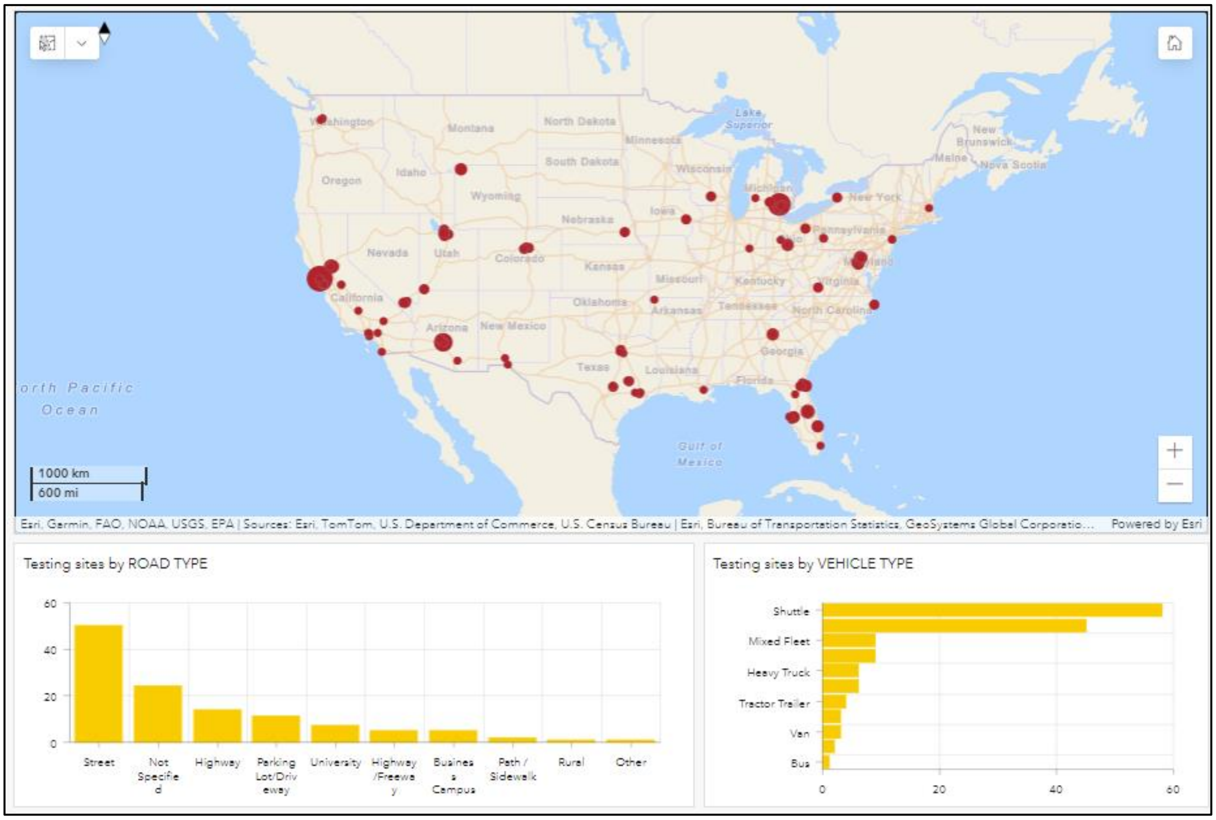



Figure 5. Distribution of the Autonomous Buses and Shuttles at the Testing Sites [12]

Figure 5 shows the distribution of autonomous bus and shuttle testing sites, with 50 currently in the open-road testing stages. The NHTSA will continue to gather information from states, local jurisdictions, and companies to share with the public. Furthermore, NHTSA is expanding this initiative to include more companies, states, and local jurisdictions.

## The State of the Art and Practice in Traffic Conflict Analysis

### *Traffic Conflict Measurement*

In traditional road safety practices, historical records of crash frequencies are utilized for safety analyses at intersections and road segments. However, due to challenges associated with the scarcity of accurate and reliable crash data, proper safety analyses often prove to be unfeasible. Crashes occurring within short intervals are indeed rare, yet the repercussions of such incidents are typically severe. In recent times, an alternative safety assessment method, the traffic conflict-based technique has gained recognition in the field as a proactive and effective measure for evaluating crash potentials at roadway segments and intersections, successfully addressing the limitations of the traditional approach. Again, the general practice of safety analysis based on long-term aggregation of crash data, over 3 or 5-year period, is suboptimal since it fails to identify the actual causes of crashes. Therefore, real-time, high-resolution information has become critical for understanding the behavior of road users and identifying geometric defects in the existing transportation infrastructure.

Traffic conflicts are described as "an observable event which would end in a crash unless one of the involved parties slows down, changes lanes, or accelerates to avoid collision". (13) By examining these near-miss events, it is possible to gain valuable insights into potential hazards and implement preventive measures before crashes occur. The high-risk locations where road users are more prone to experiencing near-misses can be shortlisted for safety audits, and proper improvements in road design, traffic signal timing, or other changes in the road infrastructure may be necessary to mitigate these risks. Currently, conflict studies are used to rank locations with respect to safety for construction improvements. (14) Moreover, traffic conflicts can be used to estimate the probability of crashes. Another important application of traffic conflict measures could be in understanding the safety impacts of various implemented countermeasures by comparing traffic conflict data before and after installing these certain interventions. This information is invaluable for transportation planners and engineers, as it enables them to make data-driven decisions when allocating resources and prioritizing safety improvements.

Various conflict measures, commonly referred to as surrogate safety measures (SSMs), such as Time-To-Collision (TTC), Post Encroachment Time (PET), Deceleration Rate to Avoid a Crash (DRAC), Crash Potential Index (CPI), etc. are continuing to be studied, developed, and implemented in the field. As the era of CAVs continues to rise and brings a wealth of real-time vehicle information since they are designed to communicate with each other and the surrounding infrastructure, conflict-based safety evaluations hold great potential to significantly influence safety operations, transportation planning, and design. Moreover, the interest in conflict-based safety analysis has grown, partly due to the development and deployment of active vehicle safety systems in new automobile models. These systems, such as collision avoidance, lane departure warnings, and adaptive cruise control, are designed to detect and respond to potential conflicts, and rely on accurate conflict data to function effectively. Also, while these newer and smarter vehicle technologies will undoubtedly reduce the crash risk on roads, when crashes do occur, they may be more severe due to increased speeds and the closer proximity of vehicles on the road.(15) By using insights from traffic conflict studies, strategies can be developed and implemented to reduce crash occurrence and severity, thereby, create a more efficient transportation network.

A summary of the reviewed studies is provided in table 1.

Table 1. Summary of Reviewed Literature

| Reference No. | Geographical Region | Data Collection Method | Observation Period | SSMs | Conflict Type | Real-time? |
|---|---|---|---|---|---|---|
| Xie et al. (16) | Brooklyn, NY | Computer Vision Techniques, Video-based Approach | 70 hrs | TTC | Vehicle-Vehicle | Yes |
| Chen et al. (17) | Beijing, China | Unmanned Aerial Vehicle Video | 1 hr | RTTC, PET | Vehicle-Vehicle Rear-end, Pedestrian-Vehicle | No |
| Xie et al. (18) | New York City | Automatic Vehicle Trajectory Extraction | 70 hrs | TTC | Vehicle-Vehicle | No |
| Yang et al. (19) | Ann Arbor, Michigan | Connected Vehicle Data | 1 month | RS | n/a | No |
| Ke et al. (20) | Seattle, Washington | Computer Vision Techniques | 30 hrs | TTC, DTS | Pedestrian-Vehicle | n/a |
| Hu et al. (21) | Cologne, Germany | HighD Trajectory Dataset | 1 min; 30 s interval | TTC | n/a | Yes |
| Katrakazas et al. (22) | UK | JTDB Dataset | 30 s; 1 min; 3 min; 5 min interval | TTC, PET, CPI | Lane-change; Rear-end | Yes |
| Wu et al. (23) | Reno, Nevada | Trajectory data extracted from LiDAR sensors | n/a | PET, PSD, CPI | Pedestrian-Vehicle | Yes |
| Lv et al. (24) | Sparks, Nevada | Trajectory data extracted from LiDAR sensors | 1 hr | SDP, TTC, DRAC | Pedestrian-Vehicle | Yes |
| Jiang et al. (25) | Shandong Province, China | Computer Vision Techniques | 80 hrs | Ti, TTC, PET, DRAC | Rear-end, Lane-change, Fixed objects | No |
| Zhang et al. (26) | Orlando, Florida | Traffic Flow Data from ATSPM; Computer Vision Techniques | n/a | TTC, PET | Pedestrian-Vehicle | Yes |
| Yuan et al. (27) | Cologne, Germany | HighD Trajectory Dataset | 16.5 hrs | TTC | n/a | Yes |
| Formosa et al. (28) | UK | Computer-Vision Techniques | 19 hrs | TTC, PET, MTTC, PSD, DRAC, CIF | Lane-change, Rear-end | Yes |
| Battiato et al. (29) | Catania, Italy | Computer-Vision Techniques | 16 hrs | TTC | Rear-end, Angle, Pedestrian-Vehicle | Yes |
| Ghoul et al. (30) | Athens, Greece | Drone Video and pNEUMA dataset | 10 hrs | TTC | Rear-end, Side-impact | Yes |
| Gore et al. (31) | India | Computer Vision Techniques | 10 hrs | PSD | Rear-end, Sideswipe | Yes |

- Xie et al. assessed safety conditions using TTC obtained from traffic video recordings of 70 hours at two intersections in Brooklyn, NY. Computer vision techniques were utilized to obtain the vehicle trajectories. A strong correlation between traffic conflicts and actual crashes was observed. (16)
- Chen et al. investigated the applicability of using Unmanned Aerial Vehicle (UAV) video recordings in safety analysis at intersections considering pedestrian-vehicle conflicts. The study was conducted at an urban intersection located in Beijing, China. As part of this study, 60 min of aerial video data along with two SSMs, including Relative Time to Collision (RTTC) and PET were analyzed. Results showed high exposure of pedestrians to traffic conflict outside and inside of the crosswalk. The results of the study predominantly proved the capability of UAV in assessing the safety of an intersection in an accurate and cost-effective way. (17)
- Xie et al. developed a framework to automatically mine massive vehicle trajectory data from video recordings using computer vision techniques. Traffic video data of 70 hours was collected from two intersections located in New York City. TTC was considered as the surrogate safety measure for rear-end conflict identification. Afterward, five-minute interval rear-end conflicts were modeled using Hidden Markov models (HMMs). Finally, HMMs are employed to determine the hidden states of traffic safety. Results revealed that the HMMs having four hidden states and zero covariates for Jay St. & Johnson St. as well as the HMMs having three hidden states and two covariates for Jay St. & Fulton St. perform the best in showing the conflict occurrence. (18)
- Yang et al. introduced a new safety performance measure named Risk Status (RS) which combines crash data and SSMs. Three SSMs (TTC, DRAC, and TTDC) were extracted from connected vehicle data collected in the Safety Pilot Model Deployment (SPMD) project in Ann Arbor, Michigan. The relationship between the crash frequency, RS, contributing factors, and risk determined by SSMs was modeled employing an equation having corridor-level random parameters and conditional autoregressive spatial effect. This study showed that RS is a reliable criterion for investigating safety conditions and identifying potential hotspot locations. (19)
- Ke et al. develop a framework to automatically detect, and extract vehicle-pedestrian near-misses through onboard monocular vision. The built camera model finds the correspondence between image coordinates and real-world coordinates of detected pedestrians in order to calculate the relative speed and position information of pedestrians. Video detection results are compared with events logged by the vision-based collision avoidance warning system, Rosco/MobilEye Shield+ with four camera sensors. The average overlap detection rate was 86.9% which indicates very good performance. (20)
- Katrakazas et al. in their paper demonstrate the feasibility of using traffic micro-simulation (VISSIM) along with the SSAM for real-time conflicts detection, and the superiority of random forest with 5-min temporal aggregation in the conflict classification results. (21)
- Wu et al. introduce an effective method for pedestrian-vehicle near-crash identification that extracts the high-resolution trajectory of each road user from roadside LiDAR data via several data processing algorithms: background filtering, lane identification, object clustering, object classification, and object tracking. In this study, PET, Proportion of

Stopping Distance (PSD), and Crash Potential Index (CPI) are used as SSMs for traffic conflicts. [23]

- Lv et al. also present an effective method to generate high-resolution traffic trajectories from the LiDAR sensor. The Speed Distance Profile (SDP) derived in this study is used to develop a rule-based method for vehicle-pedestrian conflict identification. [24]
- Zhang et al. use PET and TTC to identify pedestrian conflicts from closed-circuit television (CCTV) videos. Pedestrian exposure is estimated, and traffic flow-related variables are derived from the ATSPM system. Pedestrians' conflicts are predicted using multiple machine learning models with Extreme Gradient Boosting having the highest overall accuracy (0.841) and Logistic Regression. The proposed model can predict pedestrians' conflicts one cycle ahead, which can be 2-3 min. [26]
- Hu et al. present a methodology to evaluate real-time traffic safety at a lane level using the HighD trajectory dataset and traffic state data (volume and speed) from Germany based on TTC for conflict identification. The logistic regression model was used for relationship explanation and four other machine learning methods, including support vector machine, decision tree, random forest, and gradient boosting DT, are implemented for prediction modeling. Among these, the RF model achieved the best performance with an accuracy of 0.85. [21]
- When determining if a condition qualifies as a traffic conflict, the usual practice is to use a safety surrogate measure, such as TTC and compare it against a set threshold. However, this method fails to consider other relevant factors (traffic flow characteristics and weather conditions) that can impact traffic conflicts. Formosa et al. propose a digital architecture that is centralized and employs a Deep Learning technique to predict traffic conflicts more accurately in real time. The findings indicate that TTC values are influenced by speed, traffic density, and weather conditions, and that the best Deep Neural Network (DNN) model has a 94% accuracy, making it suitable for use in Advanced Driver Assistance Systems (ADAS) for proactive safety management. [28]
- Jiang et al. investigated which traffic conflict indicator was more suitable for traffic safety estimation based on conflict-crash Pearson Correlation Analysis. An improved indicator called Ti was proposed and also, and calculations for three types of traffic conflicts (rear-end, lane change, and with a fixed object) were included. The results show that the average value of the correlation coefficient for Ti indicator is higher than the other three conventional indicators. The findings also suggest that TTC often fails to identify lane change conflicts, PET indicator easily misjudges some rear-end conflicts when the speed of the following vehicle is slower than the leading vehicle, and PET is less informative than other indicators. At the same time, these conventional indicators do not consider the vehicle-fixed objects conflicts. The improved Ti is argued to overcome these shortcomings. [25]

The current research on real-time conflict detection is largely centered on SSMs such as TTC, PET, and DRAC. To enhance the precision of risk measurement, traffic flow features are also considered in traffic conflict analysis. On another note, the typical methods of data collection involved computer vision approaches and trajectory extraction utilizing LiDAR sensors. In addition, logistic regression, and machine learning techniques such as

Random Forest and Extreme Gradient Boosting have been regarded as benchmark models and demonstrated to be successful in conflict prediction modeling.

### *Review of Surrogate Safety Measures*

A proactive approach to enhancing safety is now gaining widespread acceptance where traffic safety is effectively estimated with a SSM for traffic conflict events, instead of relying solely on actual crash events. Traffic conflict measures or surrogate measures of safety, focus on near-miss events, where two or more road users come dangerously close to colliding but manage to avoid a collision through any evasive maneuver. Researchers can identify potential hazards, locate problematic sites, or design elements, and develop effective strategies to prevent crashes and enhance overall road safety by analyzing these near-miss incidents. Table 2 provides a summary of the most used SSMs in the literature. This table was prepared in conjunction with the papers reviewed in this study, and Arun et al.'s findings of the critical values of the SSMs. (32)

Table 2. Most-Commonly Used SSMs in Literature (33,34,35,36,37,38,39,40,41,42,43,44,45,46,47)

| Family of Conflict Measure | SSM | Definition | Conflict Type | Thresholds |
|---|---|---|---|---|
| **Temporal Proximity** | Time-To-Collision (TTC) | The time remaining until two vehicles collide, assuming they stay on their collision path and maintain their speed difference. | All types | 0.23 – 6 s |
| | Post Encroachment Time (PET) | The time difference between when a conflicting vehicle leaves the potential collision point and when the subject vehicle with the right-of-way reaches the potential collision point. | All types | 0.8 – 6 s |
| | Modified Time-To-Collision (MTTC) | A variation of TTC that calculates the time-to-collision by considering the relative speed and acceleration of the vehicles involved. | Rear-end | 0.88 – 3 s |
| | Gap | In a scenario where one vehicle is following another, it refers to the time difference between when the rear of the lead vehicle passes a certain point on the road and when the front of the following vehicle reaches the same point. | All types | 2 – 4 s |
| **Spatial Proximity** | Proportion of Stopping Distance (PSD) | The proportion of the remaining distance (RD) of the subject vehicle (to the potential collision point) to the minimum safe stopping distance (MSD) | Rear-end, Angle | 1 |

| Family of Conflict Measure | SSM | Definition | Conflict Type | Thresholds |
|---|---|---|---|---|
| **Kinematic** | Crash Potential Index (CPI) | The probability that the following vehicle's Deceleration Rate to Avoid Collision (DRAC) will exceed either the Maximum Available Deceleration Rate (MADR) or the vehicle's braking capacity. | All types | n/a |
| | Deceleration Rate to Avoid a Crash (DRAC) | The minimum deceleration rate required for a vehicle to prevent a possible collision | All types | 1.5-3.35 $m/s^2$ |
| | Longitudinal Deceleration | The instantaneous acceleration/deceleration of the vehicle in the longitudinal direction of motion. A hard braking/acceleration event is identified when this value is above a certain threshold. | All types | 2 -5 $m/s^2$ |
| **Crash Severity** | Delta-V | Change in the velocity of a vehicle because of a collision if both the vehicles continue to move at a constant velocity from the time of detection of conflict until the assumed collision. | All types | n/a |
| | Conflict Index/Safety Index | The released kinetic energy of a collision adjusted by the probability of occurrence of the collision based on post encroachment time (PET). | Angle | n/a |

Temporal proximity conflict measures include conflict indicators such as TTC and PET. Assuming two road users arrive at a collision point simultaneously, TTC estimates the closeness in time of two road users on a collision course to the point of collision. On the other hand, PET measures the proximity between two road users after one has just departed from the collision point. While TTC and PET are typically utilized to identify all kinds of conflicts, most researchers have adopted TTC for rear-end collisions. (32) In addition, a modified version of the TTC known as MTTC has been regarded as more effective than TTC in measuring safety conditions. (36) PETs are typically utilized as a feasible conflict metric when the trajectories of road users intersect. Spatial proximity measures are more suited to measuring conflicts over longer distances, such as those observed on a highway or arterial segments, as compared to the limited distances available between road users in an intersection area. (32) Another common measure, PSD is commonly used in conflicts involving vehicle-fixed objects or overturning. All conflict measures that depend on vehicle speed and acceleration data fall under the kinematic family of measures. For instance, DRAC considers the role of differential speeds and deceleration in traffic flow.

A brief description of the selected surrogate measures of safety with some representative equations is given below.

***Time-To-Collision (TTC)***

TTC is a surrogate measure of safety that calculates the remaining time before a possible collision between two road users, assuming they continue at their current speed and trajectory. The term was first introduced by Hayward. [33] This measure is also used in the development of ADAS and autonomous vehicles. TTC is relatively easy to calculate, as it only requires the distance between two road users and their relative speeds. According to Sayed et al. [38] TTC is expressed by the following Equation 1.

$$TTC = \frac{d}{\Delta v};\ \text{if v2} > \text{v1} \quad (1)$$

Other notable expressions include the following:

a) *Minderhoud and Bovy [48]:* The extended TTC measure of vehicle 1 at time t, with the leading vehicle of $i - 1$, is calculated as follows (Equation 2).

$$TTC_i = \frac{X_i(t) - X_i(t) - l_i}{x_i^0(t) - x_{(i-1)}^0(t)}\ \forall\ x_i^0(t) > x_{(i-1)}^0(t) \quad (2)$$

Where $X^O$ = speed; $X$ = position; and $l$ = vehicle length.

b) *Ke et al.[20]:* In this paper, the TTC is formulated using Equation 3.

$$TTC = \frac{y_1}{v_y} \quad (3)$$

Where $y_1$ is the y-coordinate of the detected pedestrian in the real-world coordinate. (See figure 6.)

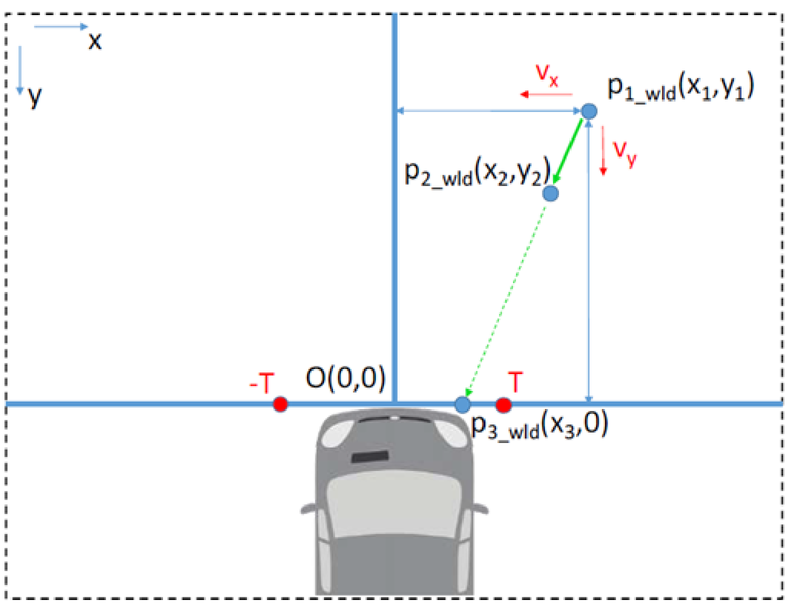



Figure 6. Vehicle-Pedestrian Interaction in Real-World Coordinate System

c) *Formosa et al.* [28]*:* This paper defines TTC using the Equation 4.

$$TTC = \frac{R-L}{V_F - V_L} \; \forall \; V_{FV} > V_{PV} \tag{4}$$

Where $R$ is the range of the two vehicles, $L$ is the length of the preceding vehicle, ΔX is $(R-L)$, $V_{FV}$ and $V_{PV}$ denote the speed of the following and preceding vehicle respectively.

d) *Jalayer et al.* [49] :For the turning movement conflicts, the TTC is illustrated using figure 7.

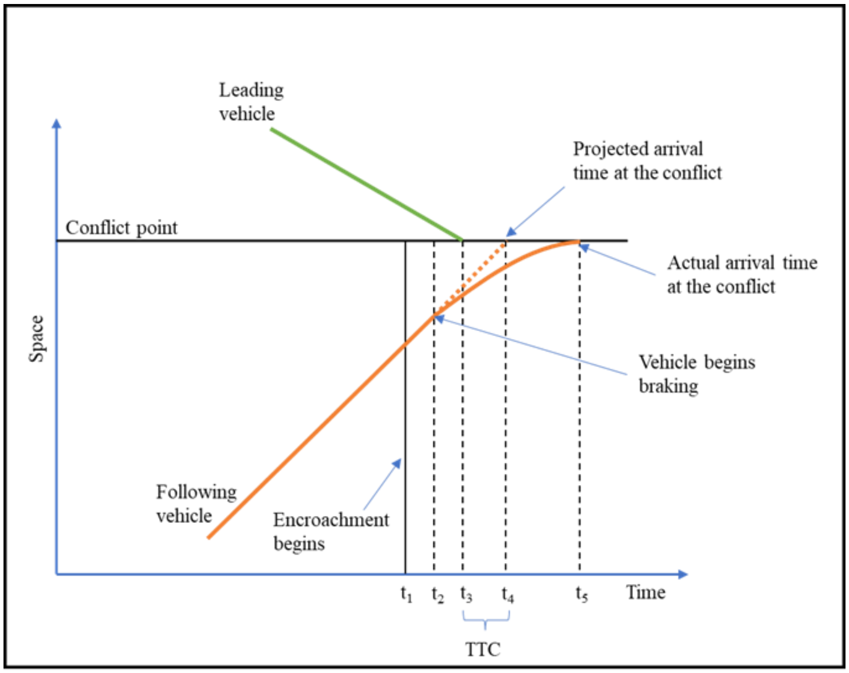



Figure 7. Time-Space Diagram for Identifying TTC

Based on the trajectory data TTC can be determined using the following Equation 5.

$$TTC_t = t_{F,t''} - t_{L,t} \tag{5}$$

Where:

$t_{F,t''}$ : the projected arrival time of the following vehicle at a conflict point after reconstructing the trajectory.

$t_{L,t}$: the times the leading vehicle leaves at a conflict point.

e) *Ghoul et al.* [30]*:* For rear-end conflicts, the TTC is calculated using Equation 6.

$$TTC_t = \frac{X_L(t) - X_F(t) - D_L}{V_F(t) - V_L(t)} V_F(t) - V_L(t) > 0 \tag{6}$$

where $X_L(t)$ and $X_F(t)$ represent positions of the leading (L) and following (F) vehicles at time $t$, respectively; $V_F(t) - V_L(t)$ denotes the speed difference between the leading and following vehicles at time t; and $D_L$ represents the length of the leading vehicle. [50]

For side-impact conflicts, TTC is depicted using Equation 7.

$$TTC_t = \frac{E_1(t)}{V_1(t)} = \frac{E_2(t)}{V_2(t)} \tag{7}$$

Where $E_1(t)$ and $E_2(t)$ represent the distances of conflicting vehicles to the conflict point at time t; $V_1(t)$ and $V_2(t)$ represent their speeds at time t.

There are certain limitations to using TTC as a conflict measure. It does not account for potential conflicts arising from discrepancies in acceleration or deceleration, which may lead to an incomplete understanding of traffic conflicts. TTC calculations assume that road users maintain their current speed and trajectory, which may not always be the case in real-world traffic situations where drivers often react to potential conflicts by changing their speed or direction. Besides, scenarios involving multiple vehicles or complex interactions at intersections may require alternative measures.

### *Post Encroachment Time (PET)*

The time between the instant one road user (vehicle) exits the potential collision zone, and the other road user arrives at the collision area. PET is more appropriate for evaluating safety conditions at intersections. PET is sensitive to the severity of conflicts. Smaller PET values indicate higher conflict severity. According to a research, a time-space diagram to calculate the PET for vehicle-to-vehicle conflict is represented in figure 8.(49)

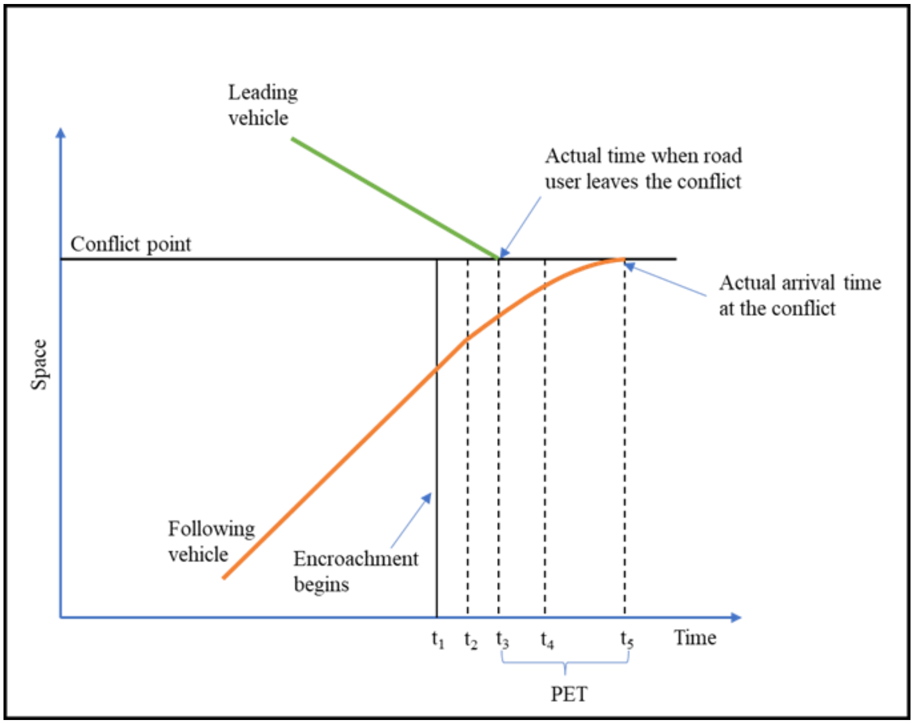



Figure 8. Time-Space Diagram for Identify PET

PET for paired vehicles at a conflict point is obtained using Equation 8.

$$PET_t = t_{F,t} - t_{L,t} \tag{8}$$

Where:
$t_{F,t}$ : the time when the following vehicle arrives at a conflict point.
$t_{L,t}$ : the times the leading vehicle leaves at a conflict point.
It should be noted that PET may not be as suitable for measuring conflicts that occur outside of intersections, such as highway or arterial segments. It also does not directly incorporate vehicle speed or acceleration, which can play a significant role in conflict severity and crash likelihood. Furthermore, the definition of a conflict area can be subjective and may vary across different studies or situations, which can affect PET calculations and the comparability of results.

### *Modified Time to Collision (MTTC)*

The definition of TTC overlooks many potential conflicts that may arise from acceleration or deceleration discrepancies. (36) As defined by Ozbay et al., and subsequently, in Essa and Sayed's paper, the Modified Time-to-Collision (MTTC) considers not only the relative speeds but also the relative accelerations of the involved vehicles, providing a more comprehensive understanding of potential conflicts compared to the original TTC measure. (36,37) The expression is depicted using the following Equation 9.

$$MTTC_t = \frac{\Delta V_t \pm \sqrt{\Delta V_t^2 + 2\Delta A_t(\Delta X_t - D_t)}}{\Delta A_t} \tag{9}$$

Where:
D = Vehicle length
ΔX = Relative position = $X_L - X_F$
ΔV = Relative speed = $V_F - V_L$
ΔA = Relative acceleration = $A_F - A_L$
Although MTTC has been shown to be more effective than TTC in some cases, there may be a need for further research and validation to fully understand its performance and applicability across various traffic scenarios and conditions.

### *Proportion of Stopping Distance (PSD)*

The proportion of Stopping Distance (PSD) is defined as the ratio of the available distance between two vehicles to the distance required for collision avoidance with respect to the maximum available deceleration rate (MADR). (41) With PSD, single-vehicle conflict with fixed or unfixed objects can be evaluated. It also takes into account the driver's reaction time, which is an important factor in real-world driving situations. It can be expressed as follows (see Equation 10). (42)

$$PSD = \frac{RD}{MSD} \tag{10}$$

where *RD* = remaining distance to the potential point of collision (m); and *MSD* = minimum acceptable stopping distance (m), which is defined as (Equation 11)

$$MSD = \frac{V^2}{2d} \tag{11}$$

where $V$ = approaching velocity (m/s); and $d$ = maximum acceptable deceleration rate ($m/s^2$).

One of the disadvantages of the PSD measure is that it is not applicable to all types of conflicts, as it mainly focuses on vehicle-fixed object conflicts and overturning incidents.

### *Deceleration Rate to Avoid a Crash (DRAC)*

DRAC considers the impact of speed differentials and deceleration in potential crash occurrences. It can be defined as the required deceleration rate for a vehicle to prevent a collision with another conflicting vehicle. [43] DRAC can be calculated continuously over time, allowing for real-time monitoring of potential conflicts and providing valuable information for proactive safety interventions. For each constituent vehicle trajectory within the same lane, DRAC can be continuously estimated over time (0.1 s) using the following Equation 12. [44]

$$DRAC_{FV,t+1} = \frac{\left(V_{FV,t} - V_{LV,t}\right)^2}{2[\left(X_{LV,t} - X_{FV,t)}\right) - L_{LV,t}]} \quad (12)$$

where $t$ = time interval (s); $X$ = position of the vehicle (m); $L$ = vehicle length (m); and $V$ = velocity (m/s).

There are various forms of expressions for this measure considering different cases and conditions. For example, Lv et al. calculated this measure using the following Equation 13. [24]

$$DRAC = \frac{V_t - V_{t+1}}{T} \quad (13)$$

where $V_t$ represents the vehicle speed at frame $t$. $T$ is the time interval between two adjacent frames.

One of the limitations of this measure is that DRAC assumes that deceleration is the primary means of avoiding a crash. However, in real-world scenarios, drivers may use other strategies, such as swerving or lane changing, to prevent collisions.

### ***Conflict Analysis Schematics***

Visual representations with the key elements involved in a typical traffic conflict situation at an intersection, and at a road segment are shown in this section.

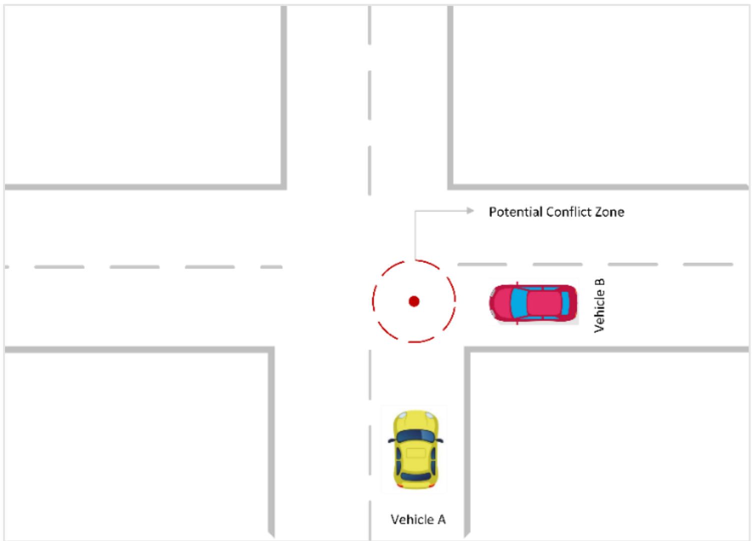



Figure 9. Conflicting Vehicles at an Intersection

Figure 9 demonstrates a situation where Vehicle A and Vehicle B approach an intersection at a right angle. Their projected paths are assumed to converge at the potential conflict point, marked by a red circle. To delineate the unsafe area surrounding this conflict point, a reasonable fixed radius can be considered, creating a potential "conflict zone". Any vehicles found within this zone are presumed to be on a collision course, and specific conflict measures will be calculated for the involved vehicle pair.

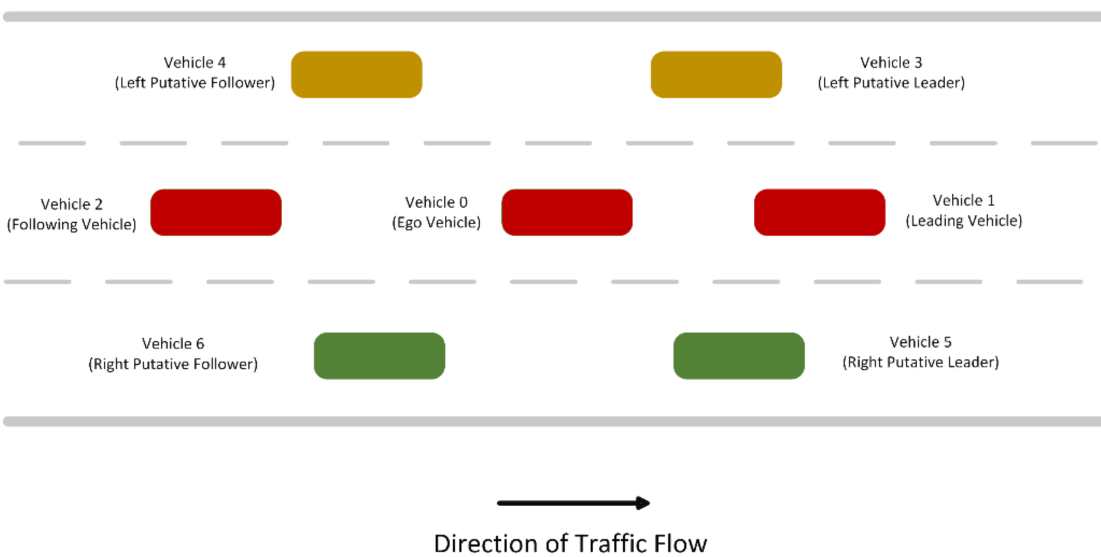



Figure 10. Traffic Flow at a Road Segment

In addition to intersections, road segments can also present traffic conflict situations. Visual representations of these scenarios may depict vehicles traveling in the same direction, vehicles merging or changing lanes, or vehicles encountering obstacles such as pedestrians or cyclists. In figure 10, a rear-end conflict scenario is depicted involving three vehicles: the ego vehicle (Vehicle 0), the leading vehicle (Vehicle 1), and the following vehicle (Vehicle 2) on the center lane. Again, vehicles in the neighboring lanes (Vehicles 3, 4, 5, and 6) present potential collision risks, such as sideswipes or lane-changing conflicts, if any hazardous maneuvers were to occur.

***One-Dimensional Formulation***

Time-to-Collison (TTC) Calculation

TTC is a critical measure in the field of road safety and autonomous driving systems. In essence, it quantifies 'how much time is left until a crash', giving valuable insights into the urgency of a potential collision situation. TTC is calculated as the ratio of the current distance to the relative speed between two objects. A smaller TTC value indicates a higher collision risk, assuming no changes in direction or speed. For self-driving cars, this measurement is paramount in providing an effective decision-making tool for avoidance maneuvers. In one-dimensional scenario, the calculation of TTC is quite straightforward and expressed using the following Equation 14.

$$TTC = \frac{x_2 - x_1 - \frac{1}{2} * v_{l_1} - \frac{1}{2} * v_{l_2}}{\sqrt{V_1^2 + V_2^2 - 2 * V_1 * V_2 * \cos(\theta_1 - \theta_2)}} \tag{14}$$

Where:
$x_1$ = x-coordinate of Vehicle A
$x_2$ = x-coordinate of Vehicle B
$v_{l_1}$= length of Vehicle A
$v_{l_2}$= length of Vehicle B
$V_1$ = velocity of Vehicle A
$V_2$ = velocity of Vehicle B
$\theta_1$ = heading angle of Vehicle A
$\theta_2$ = heading angle of Vehicle B

Post Encroachment Time (PET) Calculation

PET is a versatile conflict metric that can assess the level of safety in diverse collision situations, including right-angle collisions, lane-change incidents, and rear-end crashes. Nevertheless, it is particularly appropriate for assessing conflicts in angle collisions at intersections. If the timestamp information for pair of vehicles, Vehicle A and Vehicle B (see figure 10) is known, the PET can be determined as the time duration between the moment Vehicle B leaves the potential collision zone and the point when Vehicle A enters the crash area. This can be expressed with a straightforward Equation 15.

$$PET = t_2 - t_1 \tag{15}$$

Where:
$t_2$ = timestamp of Vehicle B
$t_1$ = timestamp of Vehicle A

***Two-Dimensional Formulation***

Time-to-Collison (TTC) Calculation

To compute TTC measures for both rear-end and angle conflicts, we assume a vector-based approach where their relative velocity vectors and their centroidal distance are taken into consideration. Figure 11 illustrates a pair of vehicles (e.g., Vehicle A and Vehicle B) within a potential conflict zone with their respective velocity vectors and heading angles onto a 2D plane.

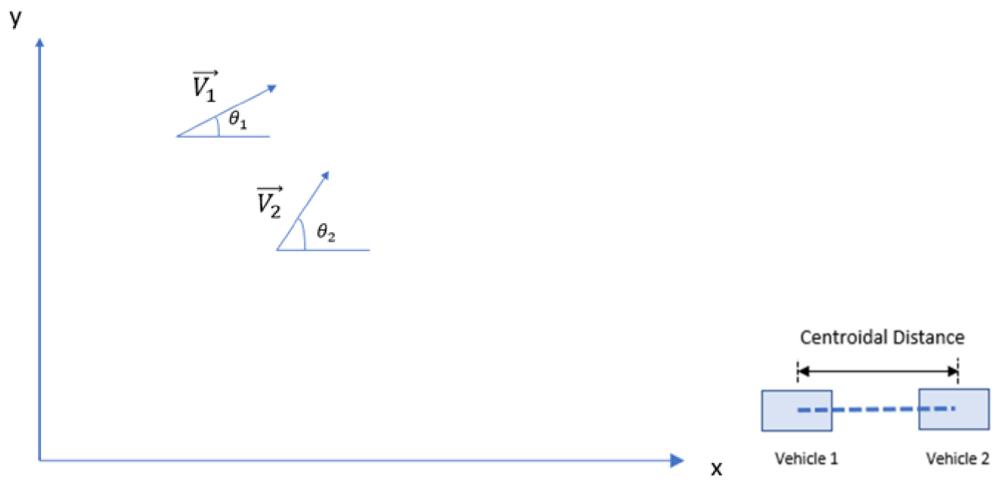



Figure 11. Vehicle 1 and Vehicle 2 within a Conflict Zone

Now, if we have the information on the horizontal (x-coordinate) and vertical (y-coordinate) axes of the vehicles, we can determine their centroidal distance (See figure 11.) Since in real-world situations, the end-to-end distance between two road users is more relevant when assessing conflicts, we also incorporate the vehicle lengths into the calculation of differential distance. It should be noted that the TTC calculation is only meaningful if the vehicles are on a collision course, i.e., if Vehicle B is getting closer to Vehicle A (ΔV > 0). If the vehicles are moving away from each other, the TTC may not provide useful information.

Equation 16 was derived to compute the TTC measure.

$$TTC = \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} - {}^1\!/_2\,(v_{l_1}) - {}^1\!/_2\,(v_{l_2})}{|\overrightarrow{V_1} - \overrightarrow{V_2}|}$$

$$= \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} - {}^1\!/_2(v_{l_1}) - {}^1\!/_2\,(v_{l_2})}{\sqrt{|V_1^2 + V_2^2 - 2 * V_1 * V_2 * \cos(\theta_1 - \theta_2)|}} \tag{16}$$

Where:
$x_1$ = x-coordinate of Vehicle A
$x_2$ = x-coordinate of Vehicle B
$y_1$= y-coordinate of Vehicle A
$y_2$ = y-coordinate of Vehicle B

$v_{l_1}$ = length of Vehicle A
$v_{l_2}$ = length of Vehicle B
$V_1$ = velocity of Vehicle A
$V_2$ = velocity of Vehicle B
$\theta_1$ = heading angle of Vehicle A
$\theta_2$ = heading angle of Vehicle B

### Deployment Updated on Automated Traffic Signal Performance Metrics

Over the past decade, there have been several states/counties across the United States who have been early adopters of ATSPM systems. A brief history of data required of the ATSPM systems and the respective performance metrics can be found at the Purdue University libraries. (51) For this review, the ATSPM systems are those related to the Utah Department of Transportation (UDOT) open-source code. (52) A map, derived from AASHTO (53) of agencies using, implementing, and interested in using SPM/ATSMPs is reflected in figure 12. Those eight agencies participating in FHWA studies are defined in figure 12 and are found under the case studies for FHWA. (54)

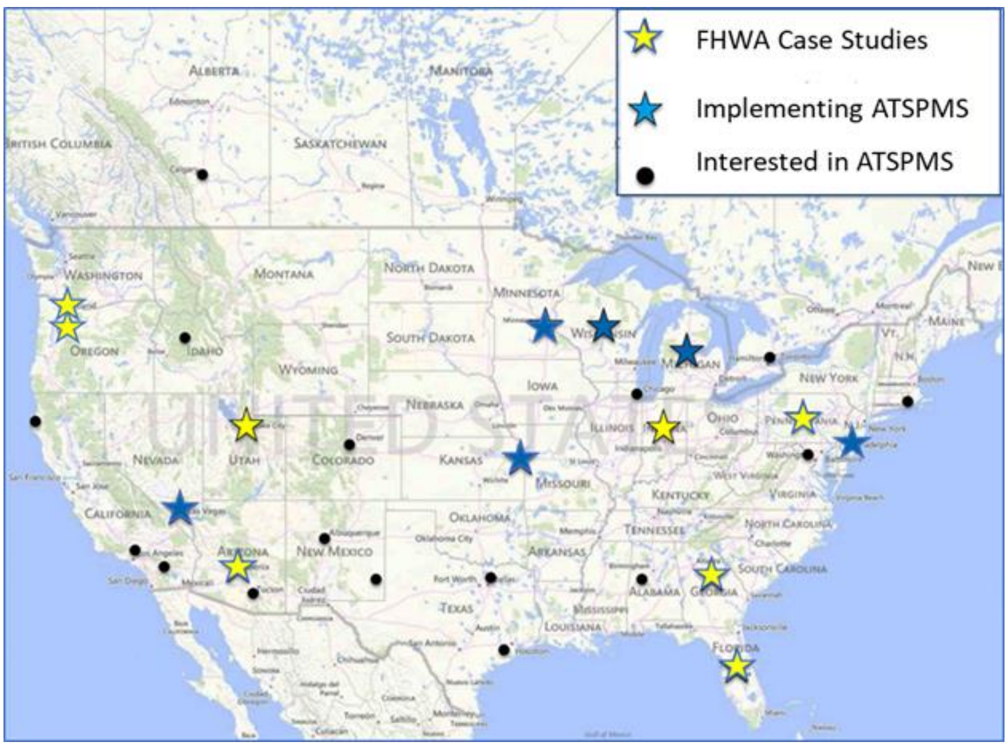



Figure 12. Signal Performance Metrics being Used or Considered in North America (53)

Of all the agencies using ATSPM, only seven have publicly accessible systems. New Jersey is currently in the process of implementing an ATSPM system, but it will be available only within the agency. Table 3 provides a list of the agencies with publicly accessible systems, along with the respective links to their ATSPM web servers.

Table 3. Summary Table of Deployed ATSPM Systems [55,56,57,58]

| Agency | Year | Location (State) | Link to ATSPM | Link to Study Data |
|---|---|---|---|---|
| UDOT | 2012 | Utah | https://udottraffic.utah.gov/atspm/ | UDOT AggregateDataExport |
| GDOT | 2017 | Georgia | https://traffic.dot.ga.gov/ATSPM/ | GDOT AggregateDataExport |
| FDOT | N/A | Florida | https://atspm.cflsmartroads.com/ATSPM/ | FDOT AggregateDataExport |
| ALDOT | N/A | Alabama | http://spm.ua.edu/ | ALDOT AggregateDataExport |
| NDDOT/NDSU | N/A | North Dakota | http://dotsc.ugpti.ndsu.nodak.edu/ATSPM/ | NDDOT AggregateDataExport |
| FAST/AASHTO | N/A | Nevada | https://challenger.nvfast.org/spm/ | FAST DataDownload |
| AZTECH/MCDOT | 2016 | Arizona | http://spmapp01.mcdot-its.com/ATSPM | AZTECH AggregateDataExport |

Of the vendors of high-resolution traffic signal controllers that can implement ATSPM systems, Econolite presented a summary of case studies across the United States. Although Centracs is not an open-source software but implements several performance metrics available in ATSPM. Additional studies have been conducted that have documented the deployment, concept of operations, and testing of ATSPM, SPM type systems to include NCHRP, [59] USDOT/FHWA, [60] and other user case examples. [61]

## Operational Data Environment (ODE) Overview

The Intelligent Transportation Systems Joint Program Office (ITS JPO) ODE is a real-time data acquisition and distribution software system that processes and routes data from Connected-X devices, such as connected vehicles, personal mobile devices, infrastructure components, and sensors, to subscribing applications. [62] The ODE complements connected vehicle infrastructure by brokering, processing, and routing data from various data sources, including connected vehicles, field devices, TMC applications, and other data users. Data users include transportation software applications, Public Data Hub, Secure Data Commons, and the Situation Data Exchange. The ODE performs necessary security/credential checks, data validation, and sanitization while provisioning data from data sources to data users.

The ODE's vision is not only to provide a scalable, data router software system to support ongoing connected vehicle research efforts but also to serve as an open-source, open-build system with an active group of collaborators who can define and develop its capabilities. This community of collaborators works with the ITS JPO to ensure the ODE continues to be maintained and that the contributions are of high quality and in alignment with software development best practices. The model ensures the long-term viability of the ODE and has benefits, including increased flexibility, performance, and enhanced customizability.

Using the JPO ODE within intelligent transportation deployments increases data fluidity and interoperability while meeting operational needs and protecting user privacy. The

ODE is an innovative solution that allows transportation stakeholders to leverage data to improve the safety, efficiency, and effectiveness of the transportation system.

### *ODE Vision*

The ODE is being developed under Agile development methodologies, using an open architecture approach in an open-source environment. As an open-source software application, the ODE enables data transfers between field devices and backend TMC systems for operational, monitoring, and research purposes. The system allows applications to submit data through various standard interfaces, supporting both the producers and consumers of connected vehicle data.

### *ODE Architecture*

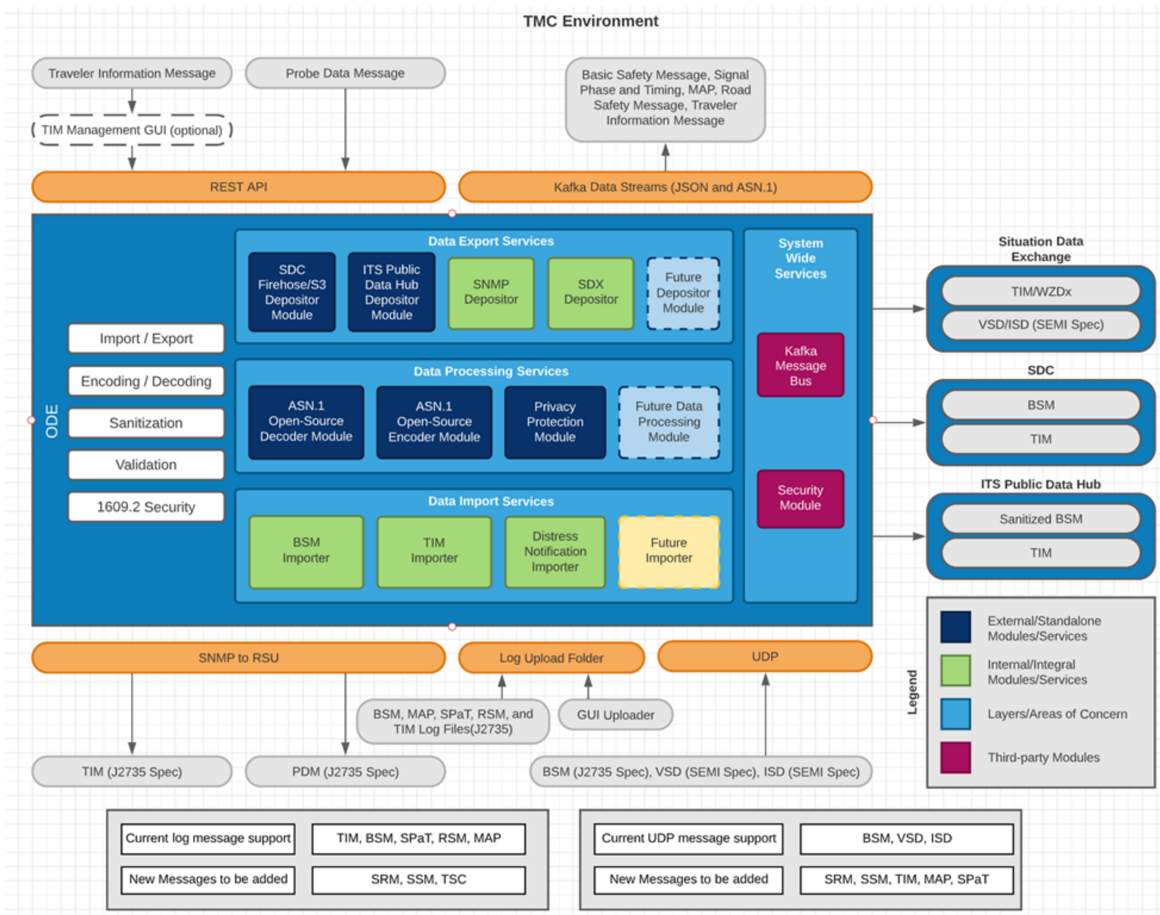



Figure 13. ODE Architecture [(63)]

The ODE's microservices architecture makes it easy to add new capabilities to meet local needs. The ODE is the backbone of connected vehicle data provisioning systems and is designed to be used as the information superhighway for connected vehicles. The system can provide data from different data sources to software applications that have subscribed to the ODE. In the other direction, the ODE can accept data from connected vehicle applications and broadcast them to field devices through roadside units. The ODE Architecture is shown in figure 13.

### *ODE Data Security and Integrity*

In addition to provisioning data, the ODE also performs necessary security/credential checks, data validation, and sanitization. Data validation involves making a judgment about the quality of the data and handling invalid data as prescribed by the system owners. Data sanitization involves modifying data as originally received to reduce or eliminate the possibility that the data can be used to compromise the privacy of the individual(s) that might be linked to the data.

### *ODE Deployments*

The following organizations have deployed the ITS ODE and rely on the ODE as a critical component of their Transportation Management capabilities:

- US Department of Transportation STOL at Turner Fairbank Highway Research Center (TFHRC)
- Colorado Department of Transportation
- Maricopa County, Arizona as part of the Connected Intersection Message Monitoring System
- New Jersey Department of Transportation
- Wyoming Department of Transportation [62]

## TASK 2: STAKEHOLDER OUTREACHING AND ENGAGEMENT

### AASHTO Research Advisory Committee's Supplemental High Value Research Award

At the 2024 TRB Annual Meeting, the Phase 2 portion of this project was honored with the AASHTO Research Advisory Committee's Supplemental High Value Research Award. This recognition highlights the significant contributions and advancements made during the second phase of the project. To showcase the project's achievements and findings, a detailed poster presentation includes enhanced functionality, CAV application integration and field corridor deployment were displayed at poster session. The poster attracted considerable attention, allowing attendees to engage with the project's innovative approaches and outcomes. This award and presentation underscore the project's impact and the value it brings to the field of transportation research. The poster is shown as figure 14.

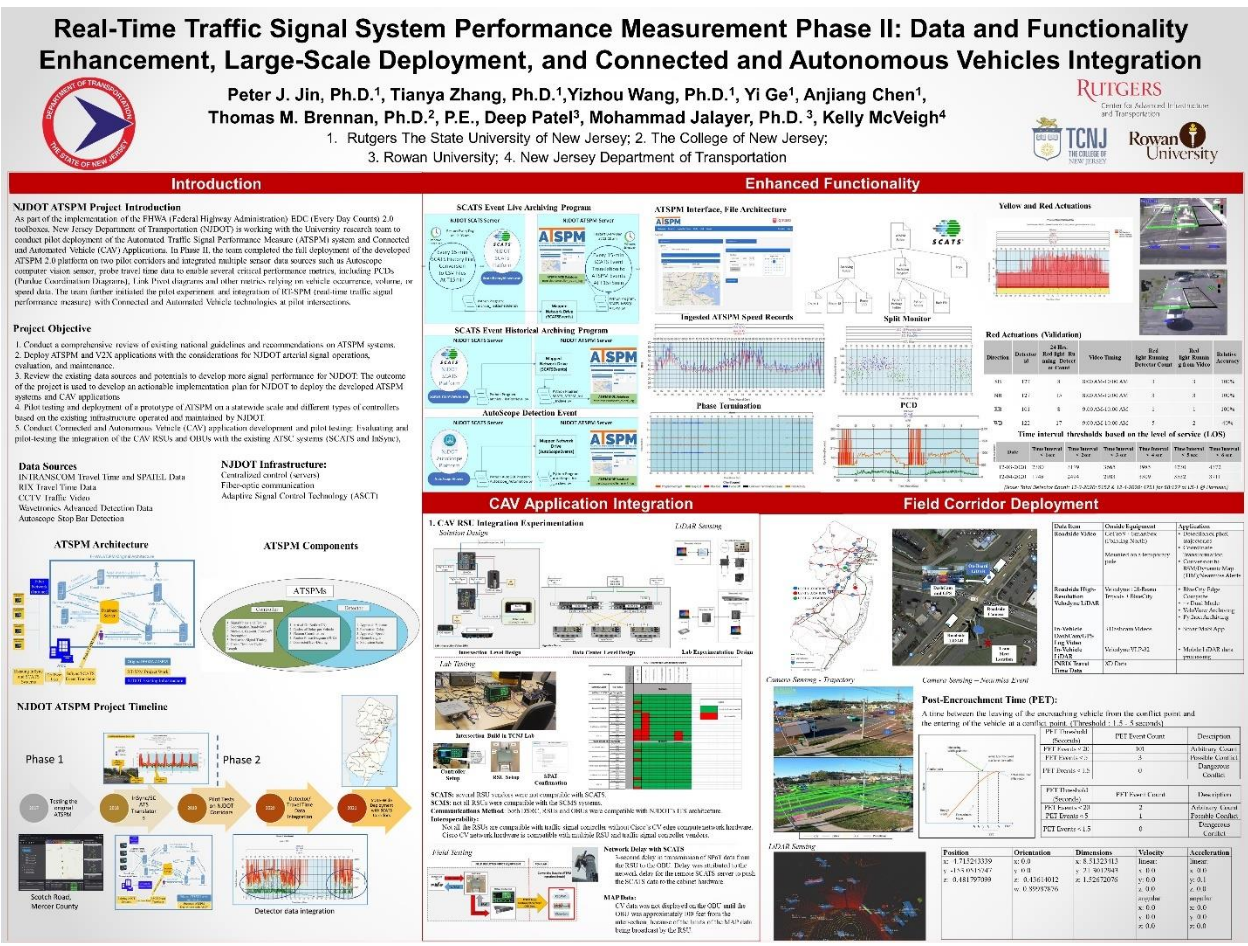



Figure 14. 2024 TRB Poster of this Project

## TASK 3: PEDESTRIAN AND VEHICLE SENSOR PERFORMANCE EVALUATION AND BOUNDARY CONDITION ANALYSIS

### Computer Vision Sensor Blind Zone Analytics

The CCTV traffic surveillance systems are widely used by TMCs to monitor congestion and incidents in daily operations. Over the past few decades, computer vision sensors based on CCTV traffic cameras have been extensively explored. Occlusion has been one of the key issues in traffic camera sensing. Most existing research focuses on designing camera installation for larger coverage in open area, while the occlusion has not been quantitively analyzed. The research team conducted virtual camera installation simulation with NGSIM trajectories to analyze the effective coverage by non-occluded vehicles in Field of View (FOV).

#### *Camera Field of View (FOV) Determination*

The FOV of the camera, as figure 15 (a) shows, determines the blind spot and the detection zone related to the camera characteristics. The proposed algorithm reproduces the camera coverage model by trimming the coverage based on the FOV, attitude, and installation position of the camera.

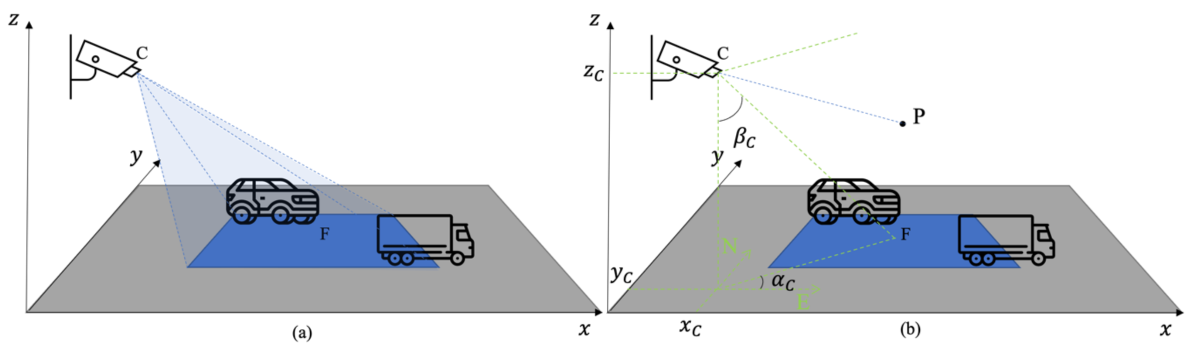



Figure 15. Camera FOV Demonstration

Figure 15 (b) shows the proposed algorithm first reads the position of the camera and attitude information of the camera and a given 3D model. We can use a transformation matrix $R^T$ to transform any line of sight (LOS) from world coordinate system to the camera's coordinate system for FOV determination.

#### *Vehicle Detection Capability*

The vehicle detection capability in Computer Vision mainly depends on the pixels available from the object(s). Here we define the pixel threshold to detect a vehicle as at least R pixels horizontally and at least C pixels vertically, no matter if the vehicle is too far or occluded by other objects.

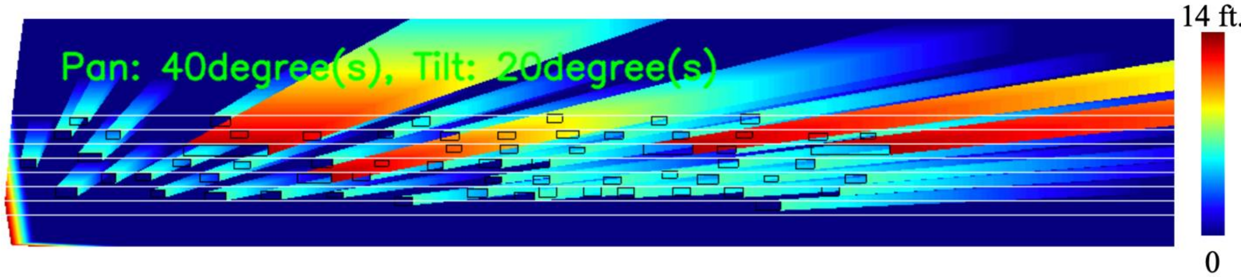



Figure 16. Camera Blind Zone Height Map at 20 Ft.

Figure 16 shows the blind zone height and the FOV of a camera installed at 20 ft high, 40 degrees from east (counterclockwise), and 20 degrees downwards. The input vehicle trajectory is from NGSIM. The vehicle heights are manipulated based on the vehicle class due to lack of direct height information. Higher, larger and closer vehicles tend to cause bigger blind zones, while lower, smaller and farther vehicles tend to cause smaller blind zones. With the distance increasing, the pixels become more sparsely distributed, and the vehicles will be captured by decreased pixels, which impairs the detection capability.

**Latency Analysis Testing (Lab-Generated Samples)**

An experimental procedure was devised, as outlined in the accompanying flowchart in figure 17, to assess the latency of messages from various devices. The messages, which include TIM, BSM, PSM, and MAP, are published using MQTT, a protocol tailored for high-latency networks. The process begins with the creation of different messages on the lab desktop. These messages then pass through VZMode - a component specifically designed for this test—before being received by the lab desktop again, thus closing the transmission loop.

This streamlined procedure allows for meticulous analysis of latency with VZMode devices, enhancing the understanding of message transmission times and system performance. The process also helps identify opportunities for communication optimization within a lab environment. Sample data for a 60-minute period was extracted for each type of message to ensure a comprehensive analysis. Furthermore, the start and end times of the messages are recorded, and the difference between them is calculated to determine the latencies of the data transmission.

To explore the outliers in the recorded latency data and observe any deviations from the expected timing for each message, an outlier analysis based on Interquartile Range (IQR) testing was conducted at a 75 percent quantile. This analysis helps in identifying significant variations and potential anomalies in message transmission times, providing insights for further optimization and refinement of the communication process. The flowchart in figure 17 visually represents the thorough processing of messages, illustrating each step from creation to analysis, thereby offering a clear understanding of the experimental workflow.

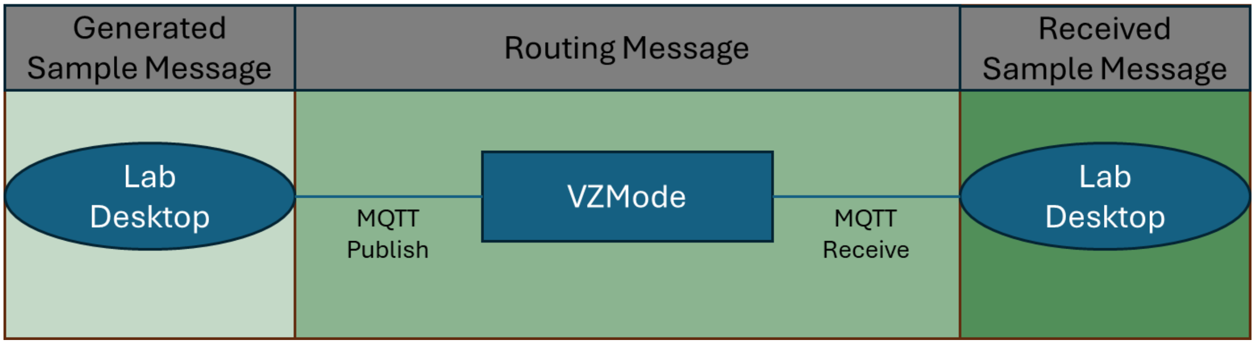



Figure 17. Experimental Workflow for Latency Evaluation of Different Messages Using MQTT and VZMode

Figure 18 presents the analysis of TIM message latency over a 60-minute period. The left plot displays the latency values with outliers highlighted in red and non-outliers in blue. The right plot shows the horizontal histogram of latency, which further quantifies the distribution of these values.

The analysis indicates that outliers constitute 7.98% of the total messages, with a mean latency of 0.02736 seconds. These outliers exhibit latency values significantly higher than most of the messages. The remaining 92.02% of the messages are non-outliers, with a mean latency of 0.02255 seconds, indicating latency values clustering around lower latency levels. The histogram shows a concentration of non-outlier messages with latencies around 0.022 seconds, highlighting the consistent performance for most messages within this range.

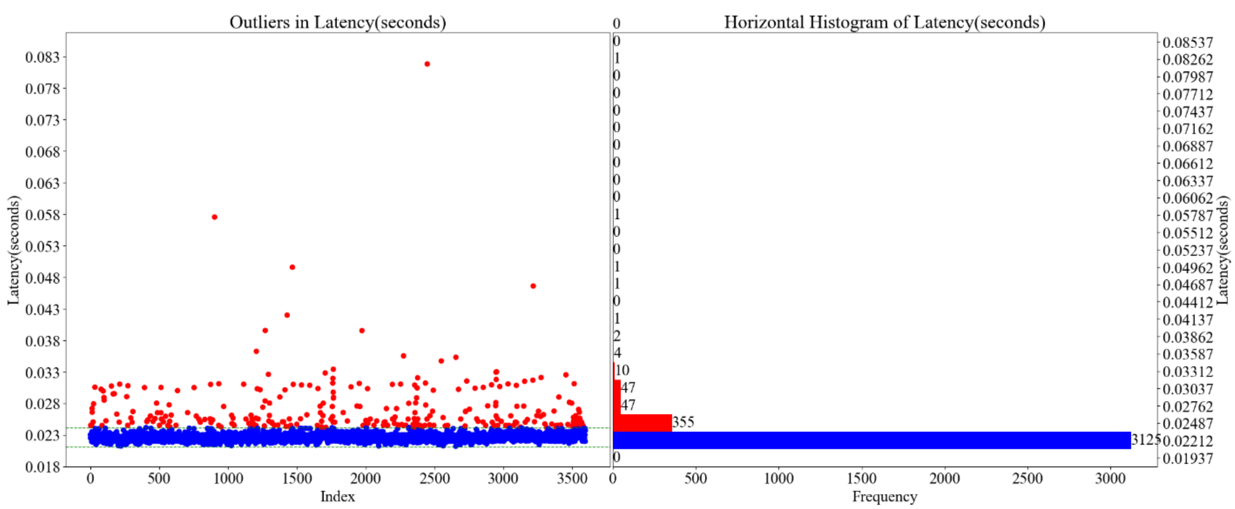



Figure 18. TIM Message Latency Analysis Results for 60 Minutes

Figure 19 analyzes SPAT message latency over a 60-minute duration. Outliers constitute 7.61% of the total messages, displaying a mean latency of 0.02897 seconds. These outliers have notably higher latency values compared to most of the messages. Conversely, 92.39% of the messages are non-outliers, with a mean latency of 0.02444 seconds. The latency values of non-outlier's cluster around lower levels, and the histogram shows a concentration of non-outlier messages with latencies around 0.025 seconds, underlining the reliable performance for most messages within this category.

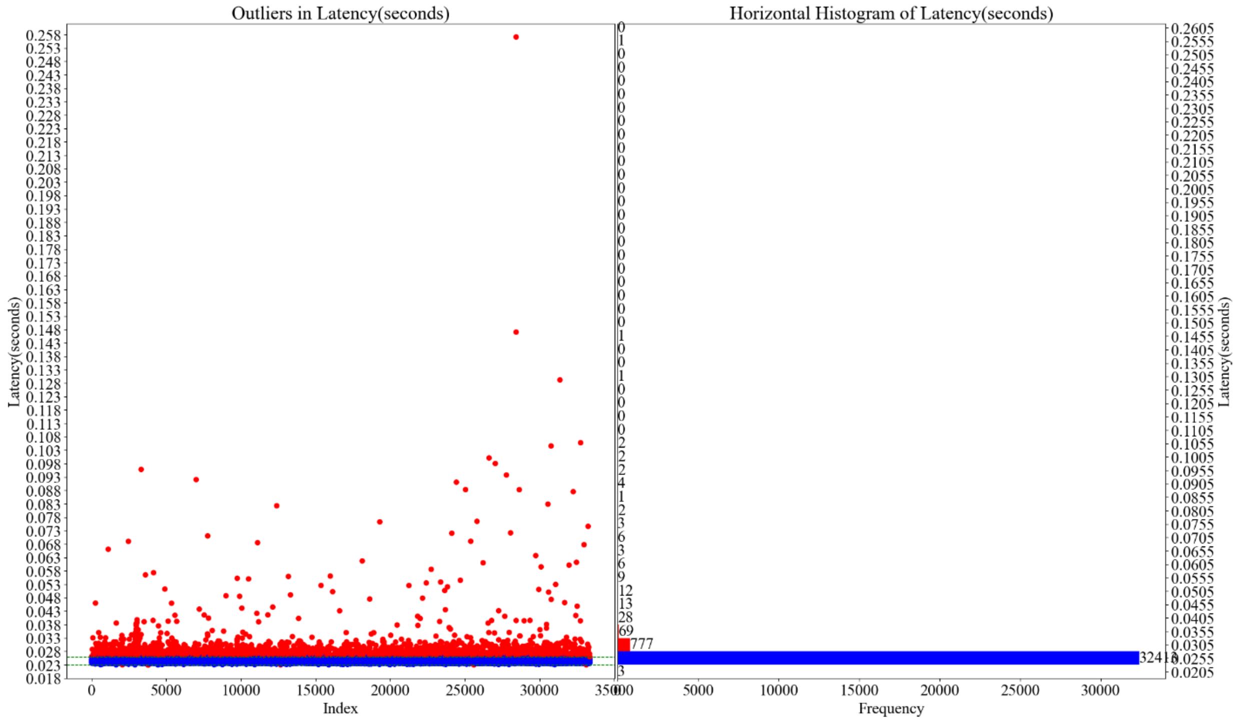



Figure 19. SPaT Message Latency Analysis Results for 60 Minutes

Figure 20 analyzes of PSM message latency over a 60-minute interval is depicted. Outliers account for 8.09% of the total messages, with a mean latency of 0.02550 seconds. These outliers have latency values that are considerably higher than most of the messages. The remaining 91.91% are non-outliers, with a mean latency of 0.02214 seconds, reflecting latency values clustering around lower levels. The histogram indicates a concentration of non-outlier messages with latencies around 0.022 seconds, demonstrating the consistent performance for most messages within this range.

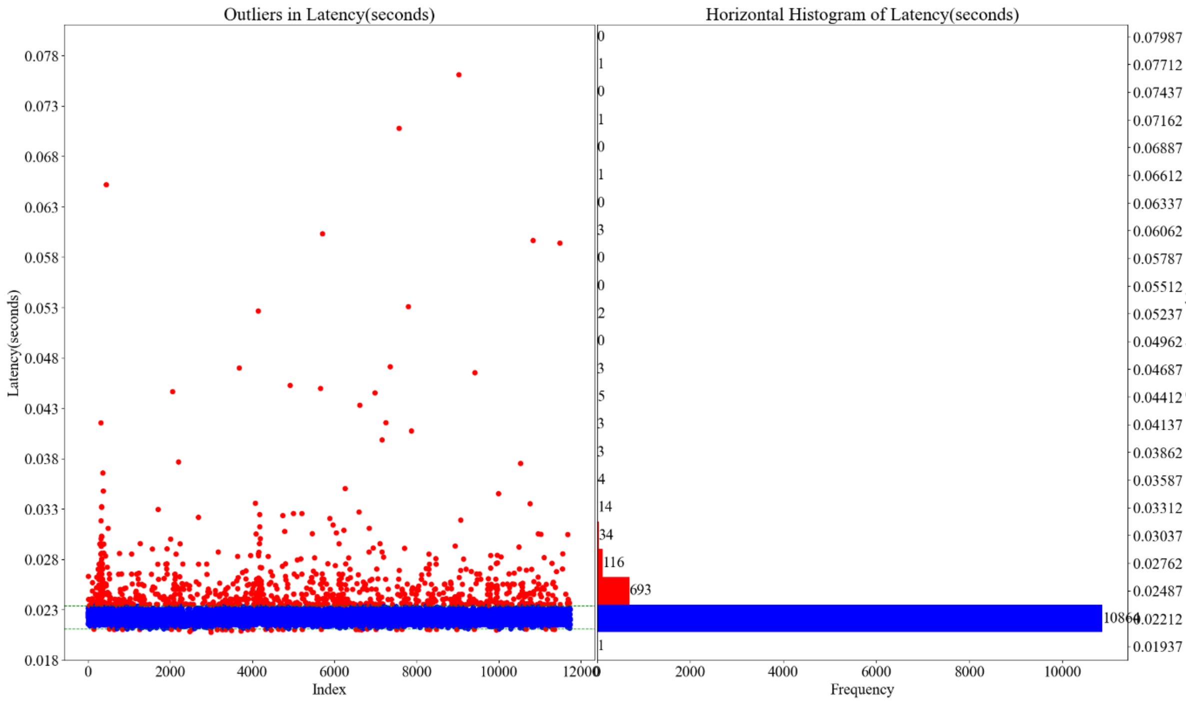



Figure 20. PSM Message Latency Analysis Results for 60 Minutes

Figure 21 illustrates the analysis of MAP message latency over a 60-minute period. Outliers represent 11.60% of the total messages, with a mean latency of 0.05917 seconds. These outliers have latency values significantly higher than most of the messages. The remaining 88.40% of the messages are non-outliers, with a mean latency of 0.05170 seconds, showing latency values clustering around lower levels. The histogram reveals a concentration of non-outlier messages with latencies around 0.052 seconds, highlighting the consistent performance for most messages within this range.

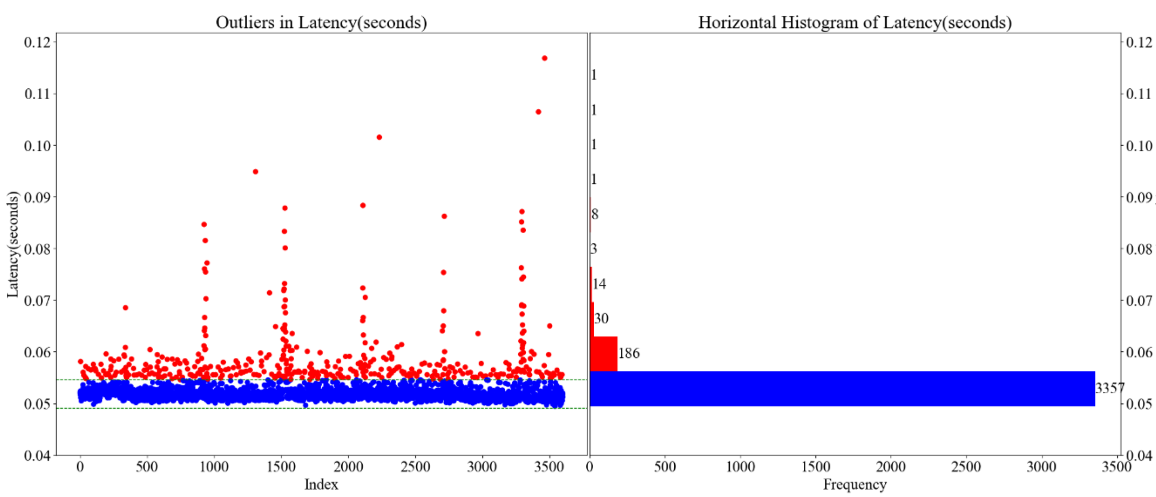



Figure 21. MAP Message Latency Analysis Results for 60 Minutes

In comparing the four types of messages (TIM, SPAT, PSM, and MAP), we observe that the percentage of outliers and their mean latency values vary. TIM messages have 7.98% outliers with a mean latency of 0.02736 seconds, while SPAT messages have 7.61%

outliers with a mean latency of 0.02897 seconds. PSM messages show a slightly higher percentage of outliers at 8.09% with a mean latency of 0.02550 seconds. MAP messages, however, have the highest percentage represent 11.60% of the total messages, with a mean latency of 0.05917 seconds. These outliers have latency values significantly higher than most of the messages. The remaining 88.40% of the messages are non-outliers, with a mean latency of 0.05170 seconds, showing latency values clustering around lower levels. The histogram reveals a concentration of non-outlier messages with latencies around 0.052 seconds, highlighting the consistent performance for most messages within this range.

***Pedestrian Safety Application***

The Red-Light Violation Warning (RLVW) application: In a non-connected environment, human drivers and highly automated vehicles depend on the displayed signal indications as the method of communication from the signal system. In a CI environment, however, information flow takes two different pathways to convey signal phase information to the driver. As shown in figure 22, a Traffic Signal Controller (TSC) generates new signal state information every tenth of a second (10 Hz Processing Loop). Pathway #1 illustrates TSC issuing commands over the field cabinet system's communications bus to activate the appropriate signal indications. Pathway #2 illustrates TSC transmitting the corresponding SPaT information through an Ethernet connection for processing and transmission (usually performed in a RSU over-the-air to CVs).

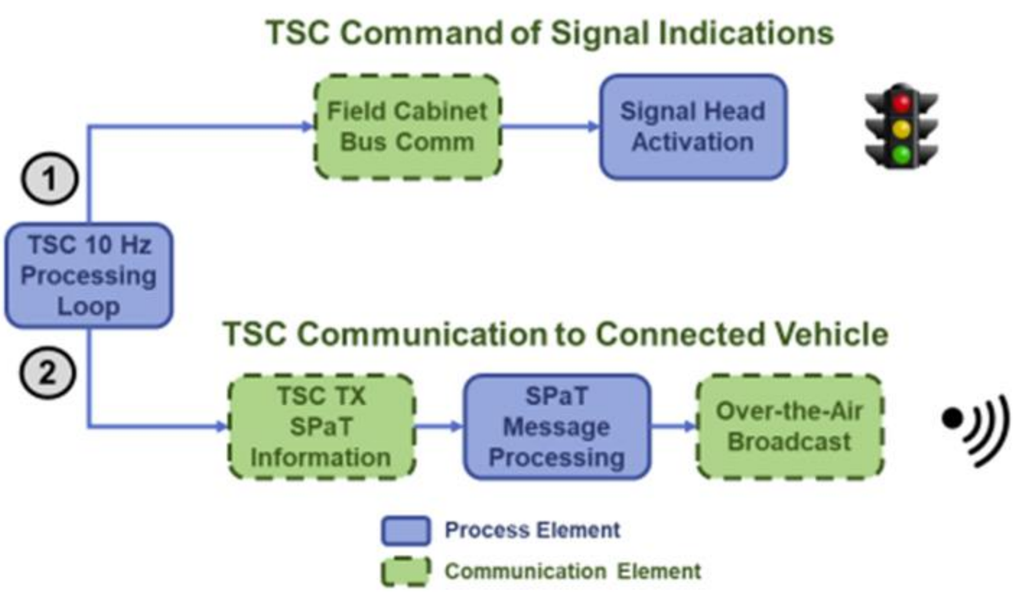



Figure 22. TSC [64]

The RLVW application in a CV system generates advisories, warnings, or alerts based on received SPaT information and vehicle dynamics, enabling the driver to take appropriate action. For safety and effectiveness, it is crucial that the visual indication provided in Pathway #1 and the SPaT information provided in Pathway #2 are synchronized in terms of information generation time interval, phase activation time, and signal state duration. Any delay in either pathway could lead to confusion or ambiguity for the driver, resulting in an unsafe driving condition. For example, a vehicle traveling at 45 mph (72.5 kph) covers 66 feet (20 meters) in one second. Latency factors include delays due to information processing (such as security signing and verification), V2X communication, Ethernet interface latency (medium access plus propagation delay), and Cabinet Data Bus latency.

Pathway #1 Latency = Information Processing Time + Cabinet Data Bus Communications Latency Pathway #2 Latency = Information Processing Time + V2X and Ethernet Interface Latency

***Example Calculation***

| Description | Time (milliseconds) |
|---|---|
| Field Cabinet Bus Communications | |
| • High-level Data Link Control (HDLC) using Serial Interface Units (SIUs) - or -<br>• Synchronous Data Link Control (SDLC) using Bus Interface Units (BIUs) | 220 |
| Signal Head Activation | |
| • Time to turn on the signal light (includes time taken by switch packs) | 30 |
| **Total** | **250** |

Figure 23. Example Maximum Latencies for Pathway #1 from the TSC to Signal activation

| Description | Time (milliseconds) |
|---|---|
| TSC Transmission of SPaT Information to RSU | |
| • Ethernet communication of NTCIP/TSCBM SPaT information | 10 |
| SPaT Message Processing | |
| • Generate UPER encoded SPaT message per SAE J2735 | 15 |
| • Process SPaT message for appropriate SCMS security for message broadcast | 30 |
| Over-the-Air Message Broadcast | 60 +/- 10[7] |
| **Total** | **115 ± 10** |

Figure 24. Example Maximum Latencies for Pathway #2 from the TSC to the OTA Broadcast of the SPaT Message

Figure 23 and figure 24 shows the information processing time which is the delay associated with generating SPaT. For example, the amount of processing time to generate the UPER-encoded SPaT message. This delay also includes security signing and verification.

V2X and Ethernet Interface Latency is the delay associated with communicating the intended information over the communication link using the specified protocol. This delay includes the amount of time waiting for a scheduled transmit opportunity over the Ethernet interface between the TSC and RSU, as well as the over-the-air (OTA) interface between RSU and vehicle.

Cabinet Data Bus Communications Latency is the delay associated with communicating the intended information over the field cabinet system’s serial data bus.

## TASK 4. BSM AND PSM MESSAGING PILOT VALIDATION AND EVALUATION AND OPERATIONAL DATA ENVIRONMENT ESTABLISHMENT

### V2X Message Processing & Validation

The V2X message processing and validation within NJDOT's CV lab environment is largely architected off of previous deployments with Colorado, Wyoming, and Utah DOT's. The deployment stack consists of several components that each perform different steps of the dataflow process. A top-level message dataflow pipeline is illustrated in Figure 25.

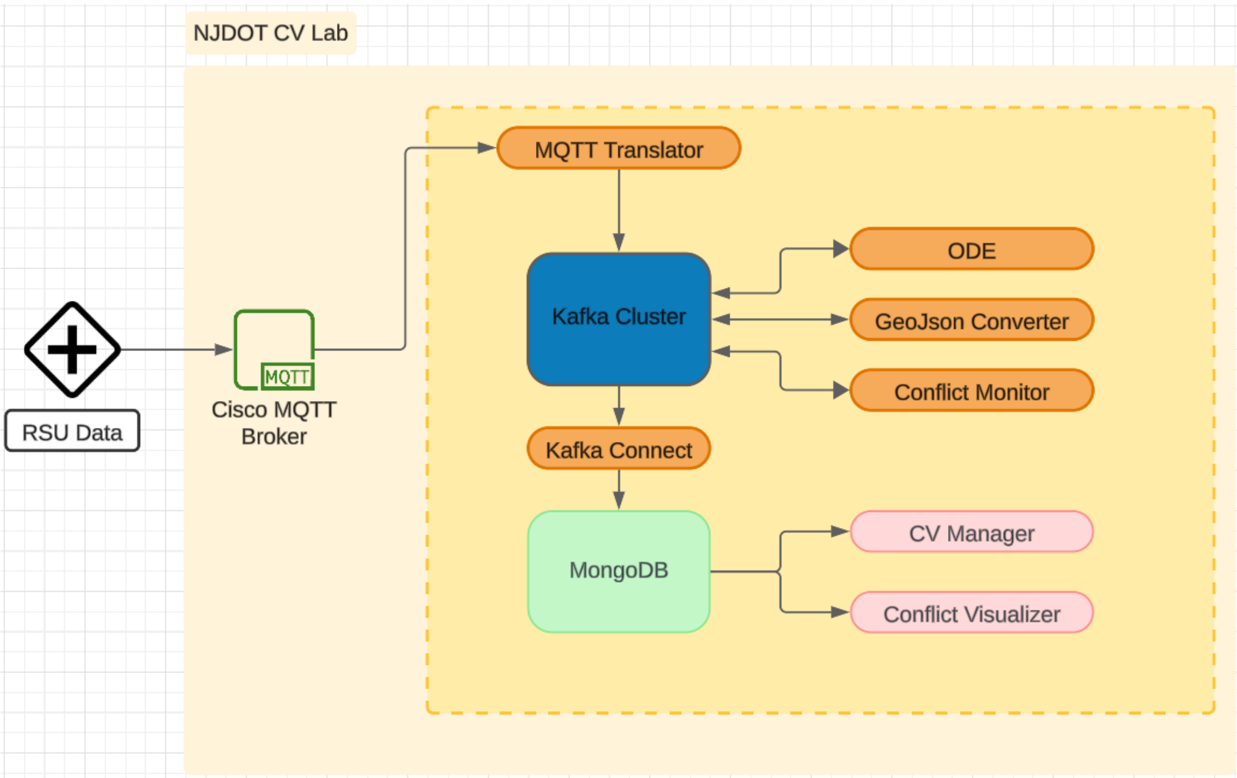



Figure 25. V2X Message Dataflow Diagram

In the above diagram, Cisco manages the data uplink from the intersection to a MQTT broker in the NJDOT CV lab environment. The MQTT translator forwards all V2X messages from Cisco's broker to an intermediate Kafka topic that then triggers the ODE, GeoJson converter, and conflict monitor applications to process the messages further. V2X message transformations are performed to allow for message validation and visualization.

Archiving of the data is performed by a MongoDB instance that is configured to keep several months of data. Certain message types that tend to stay the same (i.e. MAP and SPaT) have a deduplication system for archiving. The duplicator pipeline will store a message every hour or any messages that have been changed within the hour.

Visualization of the data is performed by the CV Manager and Conflict Visualizer applications. These tools are both useful but analyze different types of data. The CV manager provides message count statistics per RSU device and geospatial BSM/PSM message query tool. The Conflict Visualizer application serves to both visualize intersection data and analyze V2X messages for conflicts. It combines BSM, SPaT, and MAP message data for intersections and look for conflicts in each of the messages.

### *GeoJson Converter*

The JPO Intersection GeoJSON Converter is a real-time validator and data converter of JPO-ODE MAP and SPaT JSON based on the SAE J2735 message standard. Messages are consumed from Kafka and validated based on both the SAE J2735 standard and the more robust Connected Transportation Interoperability (CTI) Intersection Implementation Guide Message Requirements (Section 3.3.3 of SAE J2735). Message validation occurs simultaneously as the GeoJSON converter converts the JPO-ODE MAP and SPaT messages into mappable GeoJSON. The JPO Intersection GeoJSON Converter outputs the resulting GeoJSON onto Kafka topics. These messages contain validation information that identifies all issues encountered with validation. The architecture and data flow of GeoJson converter as shown in figure 26.

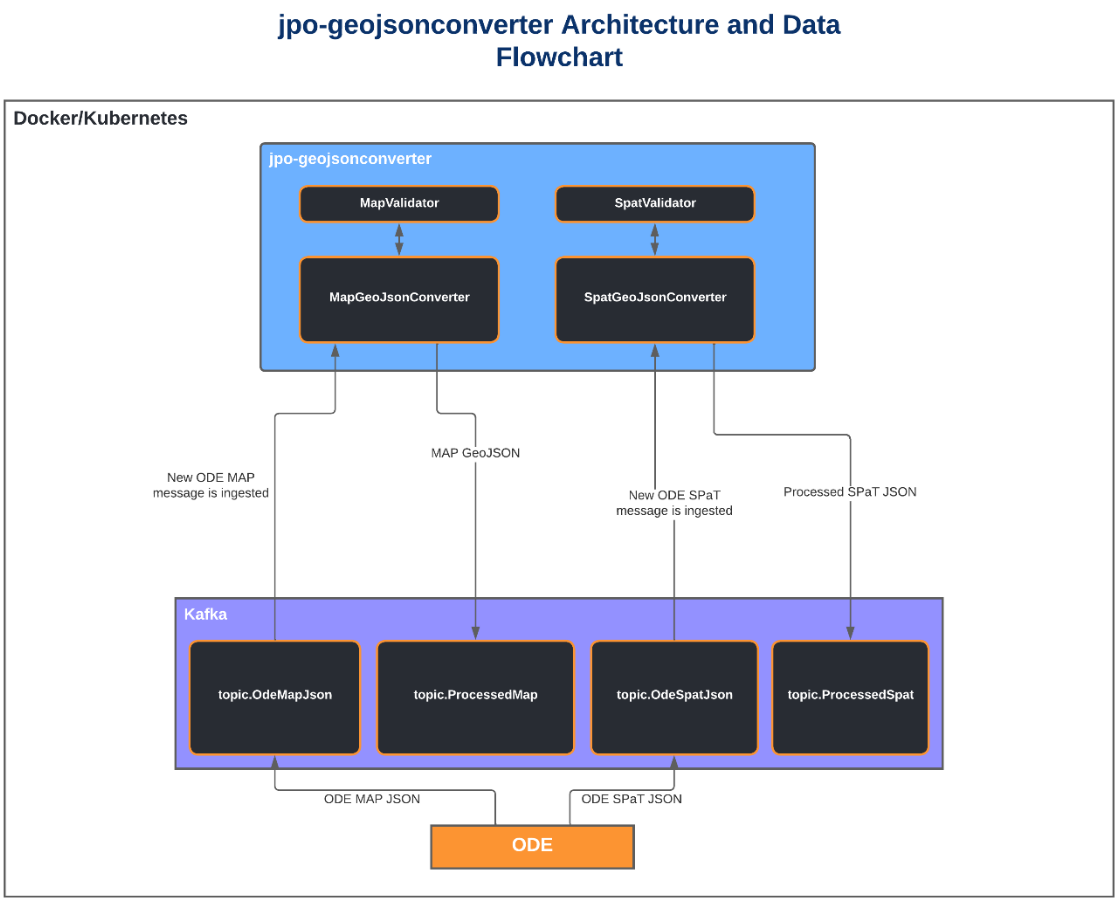



Figure 26. GeoJson Converter Architecture

### *Conflict Monitor*

The JPO Conflict Monitor is a real time validation system to verify corresponding SPAT, MAP and BSM messages. Validation is done by aggregating input messages, then performing appropriate analysis to establish and detect vehicle events for an intersection. Detected Events are published to Kafka Topics to be stored for further analysis. The workflow is shown in figure 27.

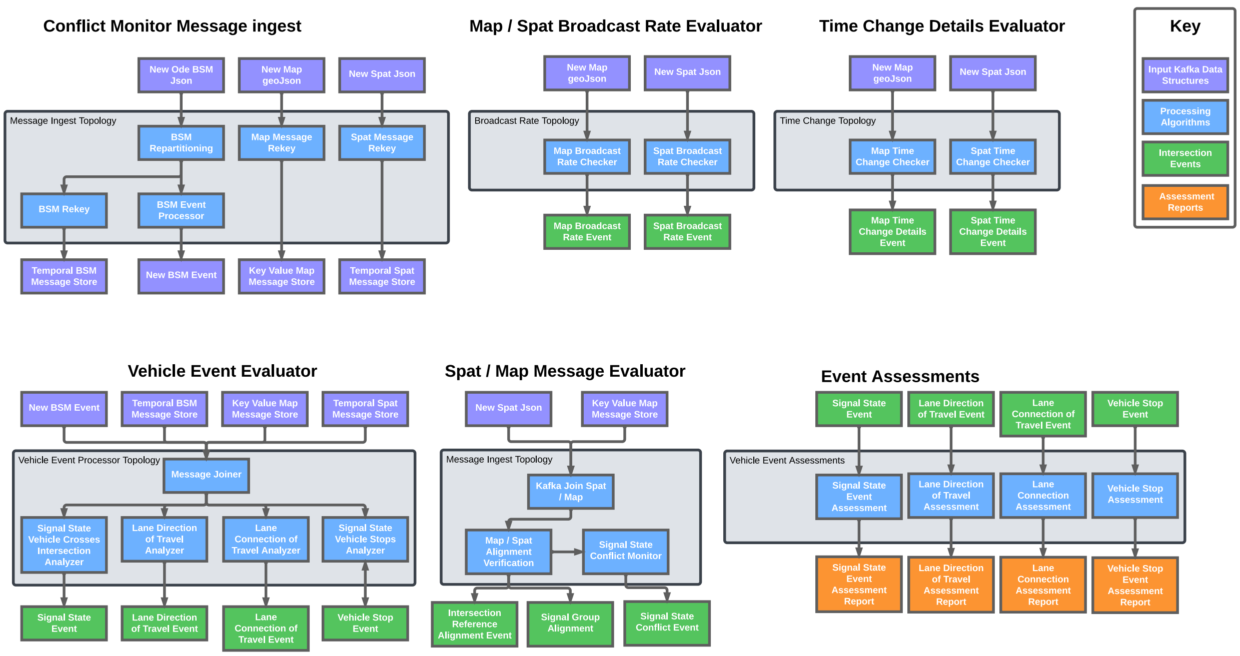



Figure 27. Conflict Monitor Architecture

The conflict monitor is focused on validating messages (SPaT, MAP and BSM) against one another to develop a picture of what is happening at a given intersection. In particular, the conflict monitor is looking for state information which is not self-consistent and is likely the function of incorrect message generation and broadcasting. The conflict monitor is not configured to validate message structure, as this functionality is performed by the jpo-geojsonconverter.

### *CV Manager – RSU Monitoring*

The JPO Connected Vehicle Manager is a web-based application that helps an organization manage their deployed CV devices (RSUs and OBUs) through an interactive, graphical user interface using Mapbox. This tool is used in conjunction with the previously mentioned ODE service to monitor message counts, geospatially query for BSM and PSM messages, and visually display RSU counts using a heatmap-based visualization. (65) This comprehensive management tool enhances the ability to maintain and optimize CV systems, ensuring efficient and effective communication between vehicles and infrastructure. An example visualization of received TIM messages by RSU along with the associated heatmap is shown below in figure 28.

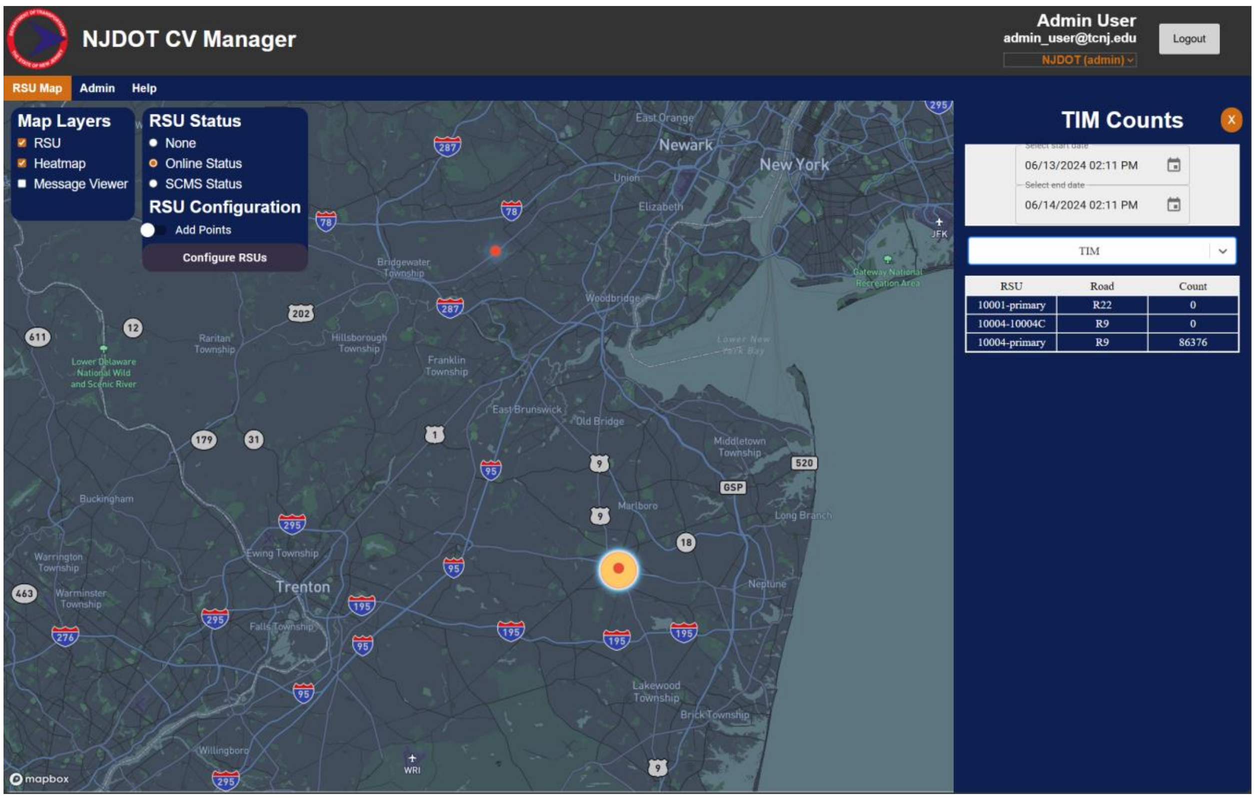



Figure 28. CV Manager V2X Counts & Heatmap Visualization

RSU status and uptime are additional statistics that the CV Manager website monitors and reports to the user. Each registered RSU is displayed on the map, and its online status is tracked based on the latest received message on Cisco's MQTT broker. An example view of this is shown in figure 29:

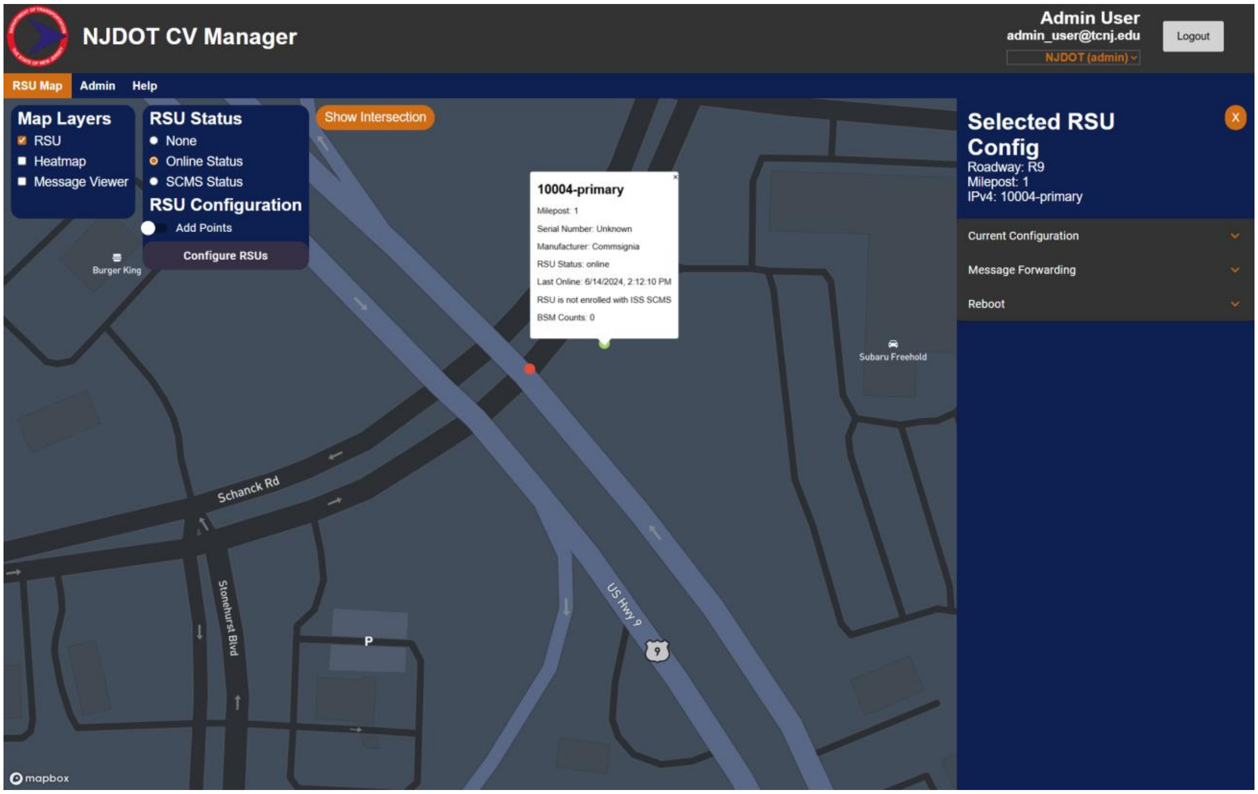



Figure 29. CV Manager RSU Status

## TASK 5. RSU INTEGRATION AND VISUALIZATION DASHBOARD

### Virtual RSU Setup at TCNJ Lab

The team deployed and tested C-V2X messages on both physical and virtual RSU systems in the TCNJ Laboratory Setup (see figure 30.) They completed a comprehensive engineering test for MAP, SPaT, TIM, and PSM data feeds, aiming to ensure reliable data transmission across the network. An engineering test document (see appendix a) was created to detail the testing process and results. This test is crucial for validating the efficiency and stability of real-time communication between RSUs and vehicles. Neaera has updated the RSU ID fields and is currently conducting tests on BSM, MAP, and PSM data. Figure 31 shows the MQTT message reception results, and figure 32 to figure 35 presents the visualized messages. All the tests have passed with anticipated results. These tests and updates are essential for advancing the deployment and functionality of CV systems, ensuring that all components work seamlessly together to provide accurate and timely information for vehicle and infrastructure interactions.

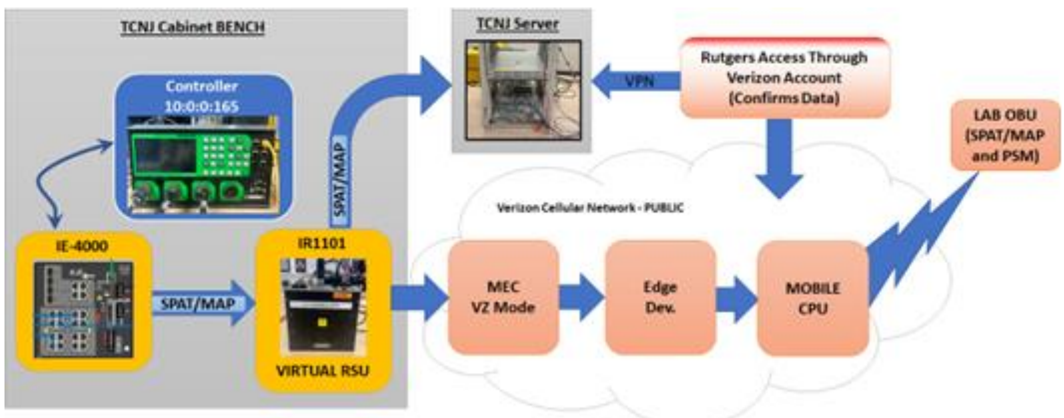



Figure 30. Illustration of Virtual RSU Lab Setup in TCNJ Lab

```
b'{"MessageFrame": {"value": {"MapData": {"intersections": {"IntersectionGeometry": {"id": {"id": "10004"}, "revision": "2", "refPoint": {"l
at": "402401042", "long": "-742755693"}, "laneWidth": "366", "laneSet": {"GenericLane": [{"nodeList": {"nodes": {"NodeXY": [{"delta": {"node
-LatLon": {"lon": "-742764239", "lat": "402400671"}}}, {"delta": {"node-LatLon": {"lon": "-742772467", "lat": "402407043"}}}]}}, "connectsTo
": {"Connection": [{"connectingLane": {"lane": "19", "maneuver": "100000000000"}, "signalGroup": "6"}, {"connectingLane": {"lane": "29", "ma
neuver": "001000000000"}, "signalGroup": "6"}]}, "laneID": "1", "ingressApproach": "1", "laneAttributes": {"directionalUse": "10", "sharedWi
th": "0000000000", "laneType": {"vehicle": "00000000"}}}, {"laneID": "2", "ingressApproach": "1", "laneAttributes": {"directionalUse": "10",
 "sharedWith": "0000000000", "laneType": {"vehicle": "00000000"}}, "nodeList": {"nodes": {"NodeXY": [{"delta": {"node-LatLon": {"lon": "-742
763917", "lat": "402400921"}}}, {"delta": {"node-LatLon": {"lat": "402407212", "lon": "-742772071"}}}]}}, "connectsTo": {"Connection": {"con
nectingLane": {"lane": "20", "maneuver": "100000000000"}, "signalGroup": "6"}}}, {"nodeList": {"nodes": {"NodeXY": [{"delta": {"node-LatLon"
: {"lon": "-742763622", "lat": "402401136"}}}, {"delta": {"node-LatLon": {"lon": "-742771696", "lat": "402407427"}}}]}}, "connectsTo": {"Con
nection": {"connectingLane": {"lane": "21"}, "signalGroup": "6"}}, "laneID": "3", "ingressApproach": "1", "laneAttributes": {"directionalUse
": "10", "sharedWith": "0000000000", "laneType": {"vehicle": "00000000"}}}, {"laneID": "4", "ingressApproach": "1", "laneAttributes": {"shar
edWith": "0000000000", "laneType": {"vehicle": "00000000"}, "directionalUse": "10"}, "nodeList": {"nodes": {"NodeXY": [{"delta": {"node-LatL
on": {"lon": "-742763294", "lat": "402401362"}}}, {"delta": {"node-LatLon": {"lon": "-742771327", "lat": "402407611"}}}]}}, "connectsTo": {"
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```

```
b'{"MessageFrame": {"messageId": "31", "value": {"TravelerInformation": {"msgCnt": "1", "timeStamp": "66780", "packetID": "00 00 00 00 00 21
 71 BE 75", "dataFrames": {"TravelerDataFrame": {"startTime": "66780", "duratonTime": "32000", "priority": "5", "regions": {"GeographicalPat
h": {"laneWidth": "5000", "directionality": {"both": ""}, "closedPath": {"false": ""}, "direction": "1111111000000000", "description": {"geo
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3"}}}}, "name": "NJDOTLAB", "id": {"region": "0", "id": "0"}, "anchor": {"lat": "402401042", "long": "-742755693"}}}, "sspMsgRights1": "0",
"content": {"advisory": {"SEQUENCE": [{"item": {"itis": "5906"}}, {"item": {"itis": "4868"}}]}}, "msgId": {"roadSignID": {"position": {"lat"
: "402401042", "long": "-742755693"}, "viewAngle": "1111111111111111", "mutcdCode": {"warning": ""}}}, "frameType": {"advisory": ""}, "start
Year": "2024", "sspLocationRights": "1", "sspMsgRights2": "0", "sspTimRights": "1"}}}}}}\n'
b'{"MessageFrame": {"messageId": "31", "value": {"TravelerInformation": {"msgCnt": "1", "timeStamp": "66780", "packetID": "00 00 00 00 00 21
 71 BE 75", "dataFrames": {"TravelerDataFrame": {"sspTimRights": "1", "startYear": "2024", "sspLocationRights": "1", "sspMsgRights1": "0", "
sspMsgRights2": "0", "content": {"advisory": {"SEQUENCE": [{"item": {"itis": "5906"}}, {"item": {"itis": "4868"}}]}}, "frameType": {"advisor
y": ""}, "msgId": {"roadSignID": {"position": {"long": "-742755693", "lat": "402401042"}, "viewAngle": "1111111111111111", "mutcdCode": {"wa
rning": ""}}}, "startTime": "66780", "duratonTime": "32000", "priority": "5", "regions": {"GeographicalPath": {"id": {"region": "0", "id": "
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 "direction": "1111111000000000", "description": {"geometry": {"direction": "1111111111111111", "circle": {"radius": "1", "units": {"mile":
""}, "center": {"lat": "402401042", "long": "-742755693"}}}}, "name": "NJDOTLAB"}}}}}}}}\n'
```

```
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"status": "0000001000000000", "moy": "114302", "timeStamp": "39110", "states": {"MovementState": [{"signalGroup": "1", "state-time-speed": {
"MovementEvent": {"timing": {"minEndTime": "1913", "maxEndTime": "2011"}, "eventState": {"stop-And-Remain": ""}}}}, {"state-time-speed": {"M
ovementEvent": {"eventState": {"stop-And-Remain": ""}, "timing": {"minEndTime": "2063", "maxEndTime": "2261"}}}, "signalGroup": "2"}, {"sign
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inEndTime": "1613"}}}}, {"signalGroup": "4", "state-time-speed": {"MovementEvent": {"eventState": {"stop-And-Remain": ""}, "timing": {"minEn
dTime": "1663", "maxEndTime": "1703"}}}}, {"signalGroup": "5", "state-time-speed": {"MovementEvent": {"eventState": {"stop-And-Remain": ""},
 "timing": {"minEndTime": "1913", "maxEndTime": "2011"}}}}, {"signalGroup": "6", "state-time-speed": {"MovementEvent": {"eventState": {"stop
-And-Remain": ""}, "timing": {"minEndTime": "2063", "maxEndTime": "2261"}}}}, {"signalGroup": "7", "state-time-speed": {"MovementEvent": {"e
ventState": {"permissive-Movement-Allowed": ""}, "timing": {"minEndTime": "1613", "maxEndTime": "1703"}}}}, {"state-time-speed": {"MovementE
vent": {"eventState": {"stop-And-Remain": ""}, "timing": {"minEndTime": "1663", "maxEndTime": "1753"}}}, "signalGroup": "8"}, {"signalGroup"
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nalGroup": "10", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timing": {"maxEndTime": "36001", "minEndTime": "36001"}
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"}, "eventState": {"dark": ""}}}}, {"signalGroup": "14", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timing": {"minE
ndTime": "36001", "maxEndTime": "36001"}}}}, {"signalGroup": "15", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timin
g": {"minEndTime": "36001", "maxEndTime": "36001"}}}}, {"signalGroup": "16", "state-time-speed": {"MovementEvent": {"eventState": {"dark": "
"}, "timing": {"minEndTime": "36001", "maxEndTime": "36001"}}}}]}}}}}}}\n'
```

```
Raw Message:  b'\n\x07\x08\x04\x12\x03CAM\x12\x0b\x08\xb2\xa1\x91\xb0\x06\x10\x80\x95\xf5*\x1a\x1f\x00 \x1c\x03\x00\x038\x00]%%UIM\xa5\xcd\xc3>\xb7\x1d\xc0\x10\
x00\xff\xff\xffK\x01\x10\t\x94'

Sliced Message: b'\x00 \x1c\x03\x00\x038\x00]%%UIM\xa5\xcd\xc3>\xb7\x1d\xc0\x10\x00\xff\xff\xffK\x01\x10\t\x94'

Decoded: {'messageId': 32, 'value': {'basicType': 'aPEDESTRIAN', 'secMark': 39936, 'msgCnt': 23, 'id': '49495552', 'position': {'lat': 402711747, 'long': -74781
1903, 'elevation': 0}, 'accuracy': {'semiMajor': 255, 'semiMinor': 255, 'orientation': 65355}, 'speed': 34, 'heading': 153, 'crossRequest': False, 'crossState':
 True}}
```


Figure 31. Sample MQTT Message Reception (MAP, TIM, SPaT, and PSM)

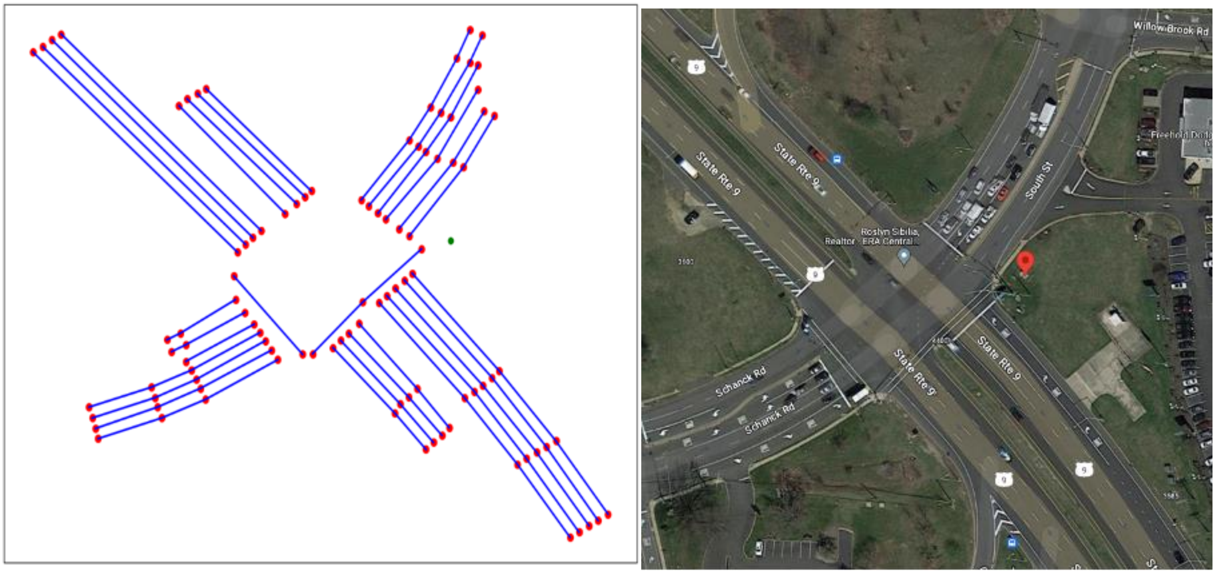



Figure 32. MAP message Visualization on Tested Intersection
(State Rt 9. @ Schanck Rd.)

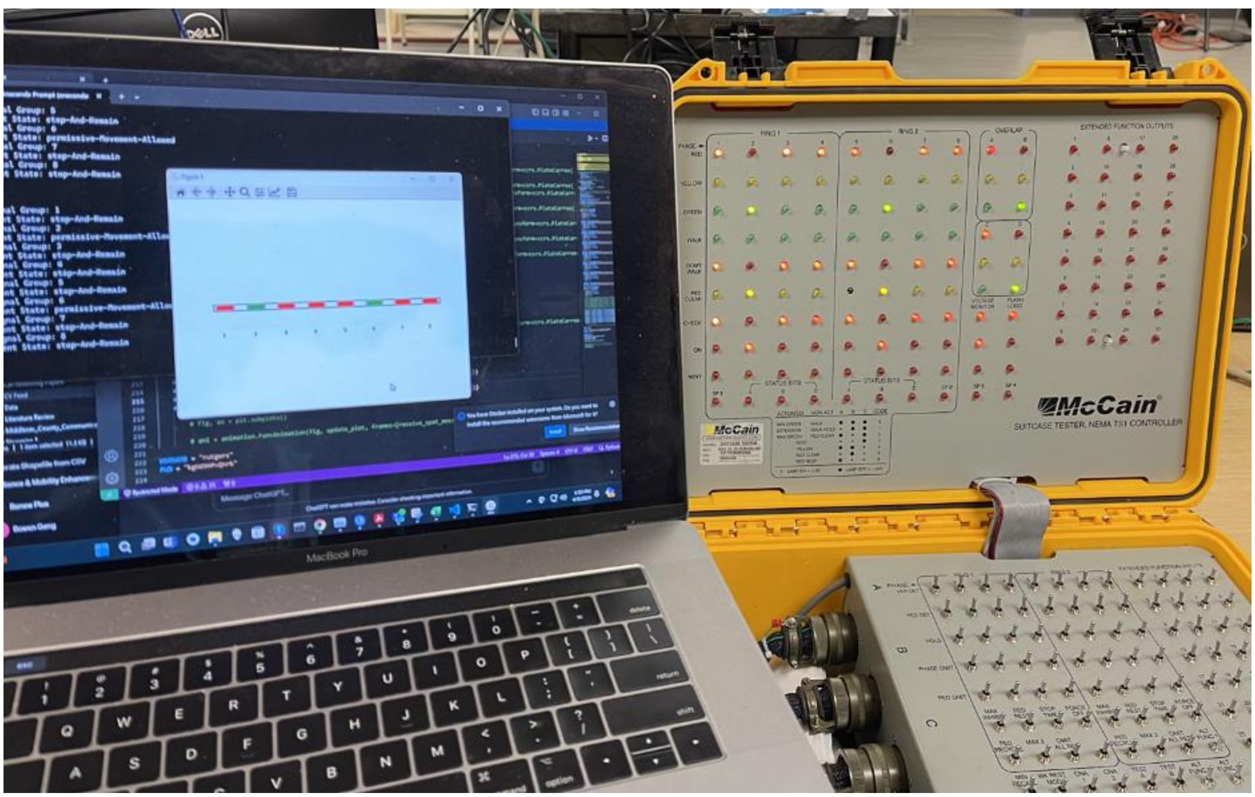



Figure 33. SPaT Message Reception and Visualization Results in the Lab

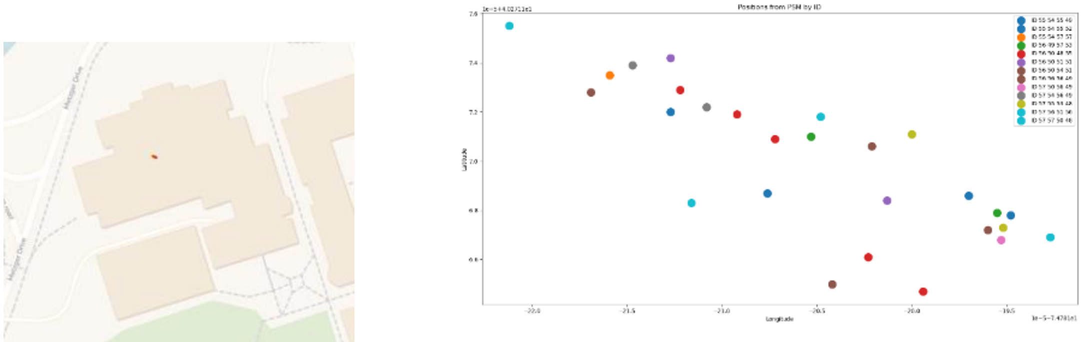



Figure 34. PSM Message Reception and Visualization Results (TCNJ Armstrong Hall)

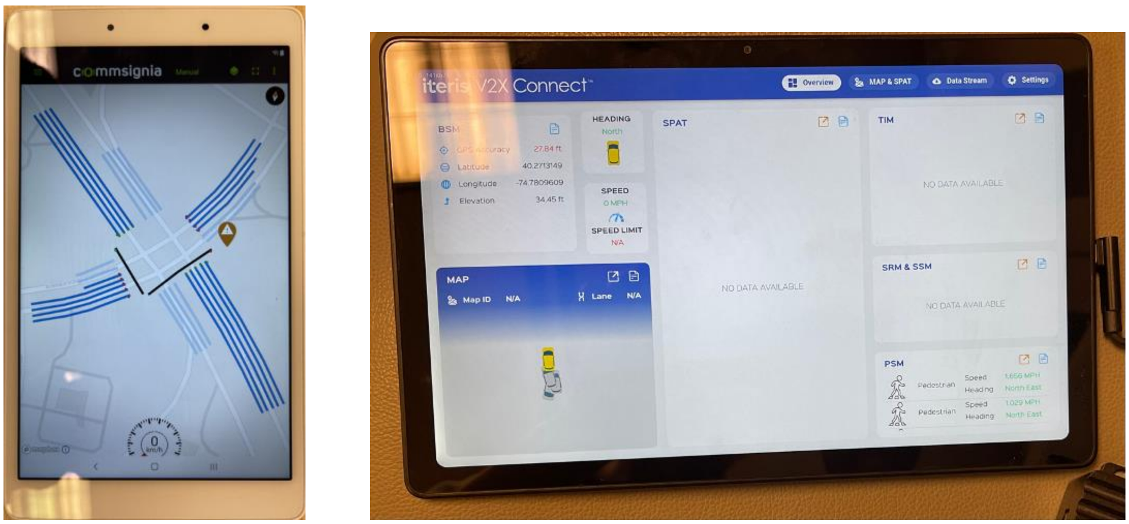



Figure 35. Message Reception and Visualization Results on Commsignia OBU
(Left: Data Reception from Virtual RSU, Right: Data Reception from Physical RSU)

### V2X Message Visualization Dashboard

The V2X message processing pipeline described in the V2X Message Processing & Validation section serves as the data source for the CV manager and conflict visualizer applications. To address BSM and PSM visualization, a geospatial message query utility is used within the CV manager. This tool allows the user to select a polygon, set a start date, end date, and message type to query on. The conflict visualizer addresses visualizing MAP and SPaT messages for intersection data.

#### *CV Manager – BSM & PSM*

V2X messages can be individually queried by message type using the drop-down menu, allowing users to access specific data from the counts database for a selected time interval. This feature enables precise monitoring and analysis of different types of V2X messages, such as BSM and PSM. The heatmap visualization uses the same data specified in the counts table but provides a visual representation of message distribution and density. This can be particularly useful for identifying outages or gaps in coverage within certain geographic areas. By offering both tabular and visual data analysis options, the system enhances the ability to diagnose issues, optimize network performance, and ensure reliable communication between vehicles and infrastructure. This dual approach supports comprehensive monitoring and management of V2X communication networks, facilitating the efficient deployment and operation of CV systems. The visualization platform is shown in figure 36.


Figure 36. CV Manager BSM & PSM Visualization

***Conflict Visualizer – MAP & SPaT***

The conflict visualizer website is a tool that allows users to see conflict events in BSM, MAP, and SPaT messages. It takes events generated from the Conflict Monitor application and allows the user to visualize them on a rendered map.

The website also has visualizations MAP, SPaT, and BSM messages in intersections queried based off historic data or a near real time (500 ms – 1000 ms) data viewer. An example visualization of an intersection with a MAP message and SPaT phases are shown below in figure 37.

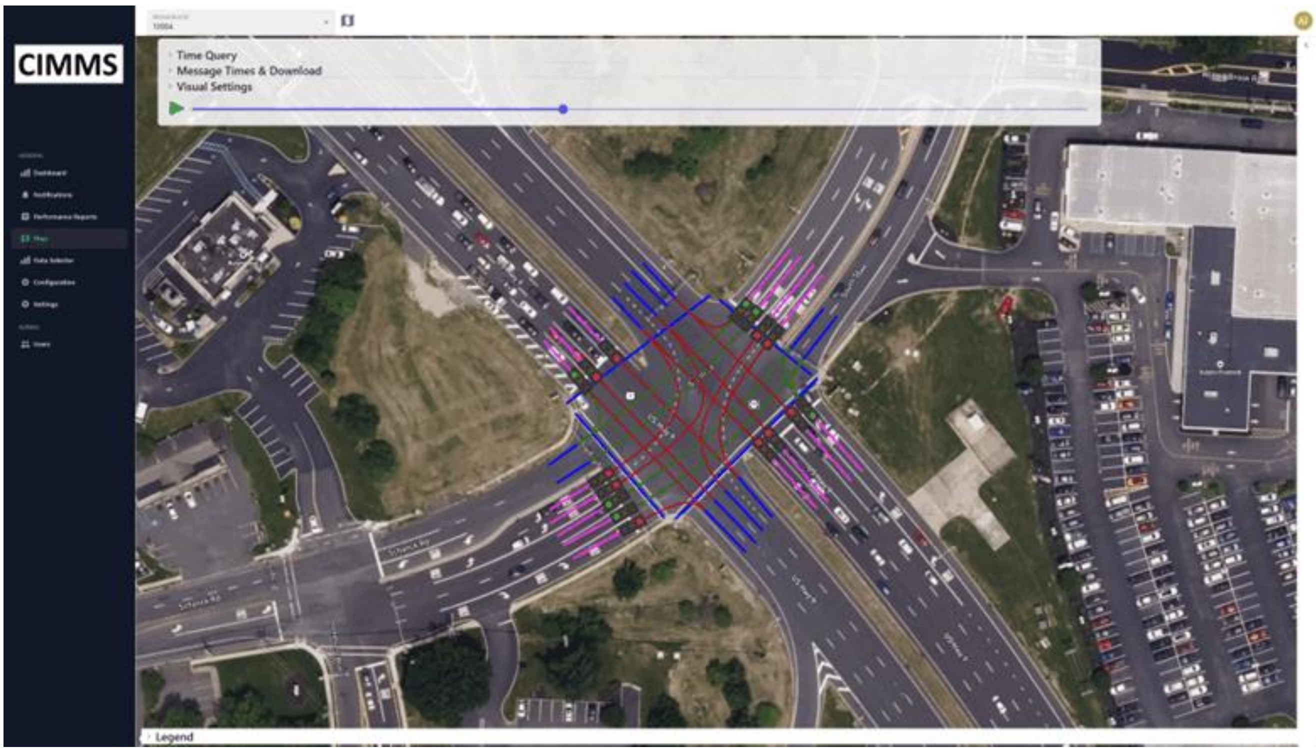



Figure 37. Conflict Visualizer SPaT and MAP Visualization

## TASK 6. NJDOT ATSPM 3.0 DEPLOYMENT

### ATSPM Modules

Table 4 shows the detailed installation status summary:

Table 4. ATSPM Installation and Configuration Status

| Package Name | Verizon | Status | Current Server | Target Server and Pending Issues |
|---|---|---|---|---|
| **SQL Server Database** | 1.1 | MOE Created | OIT Database Server | |
| **SQL Server Management Studio** | 1.1 | Pre-Installed | Application Test Server | To be installed on production application server, need account/password of OIT SQL Server database |
| **IIS 7** | 1.1 | Pre-installed | Application Test Server | To be installed on web server |
| **.NET 4.7.2** | 1.1 | Pre-installed | Application Test Server | To be installed on web server |
| **Website** | 2.1 | Pre-Installed | Application Test Server | To be installed on web server |
| **Launch website and populate database** | 2.2 | Pre-installed | Application Test Server/ OIT Database Server | To be set up on web server |
| **Database configuration** | 2.3-2.5 | Configured | OIT Database Server | |
| **"Generate Add Data Script" Component** | 2.6 | Pre-installed | Application Test Server | To be installed on web server |
| **Web Services** | 2.7 | Pre-installed | Application Test Server | |
| **GIS Services (Bing)** | | Pre-installed | Application Test Server | Need to purchase Bing Map Key |

All the ATSPM modules have been installed and configured on ATSPM Application Test Server for further testing.

### Route and Signal Configuration

A semi-automatic program, "ATSPM_Database_Auto_Configuration.py," has been developed to generate metadata and configure the ATSPM signals, detectors, and approaches for both SCATS and Autoscope systems. While the program handles most configurations, some special cases, such as irregular phase numbers or directions, still require human verification. By directly updating the MOE database, the program significantly reduces preprocessing time by avoiding the need to click through the web interface. This automation enhances efficiency and accuracy in managing and configuring ATSPM systems. With the prepared metadata and the script, the signals and detectors on four corridors, Route 1, 18, 73, and 130, have been configured, as figure 38 shows.

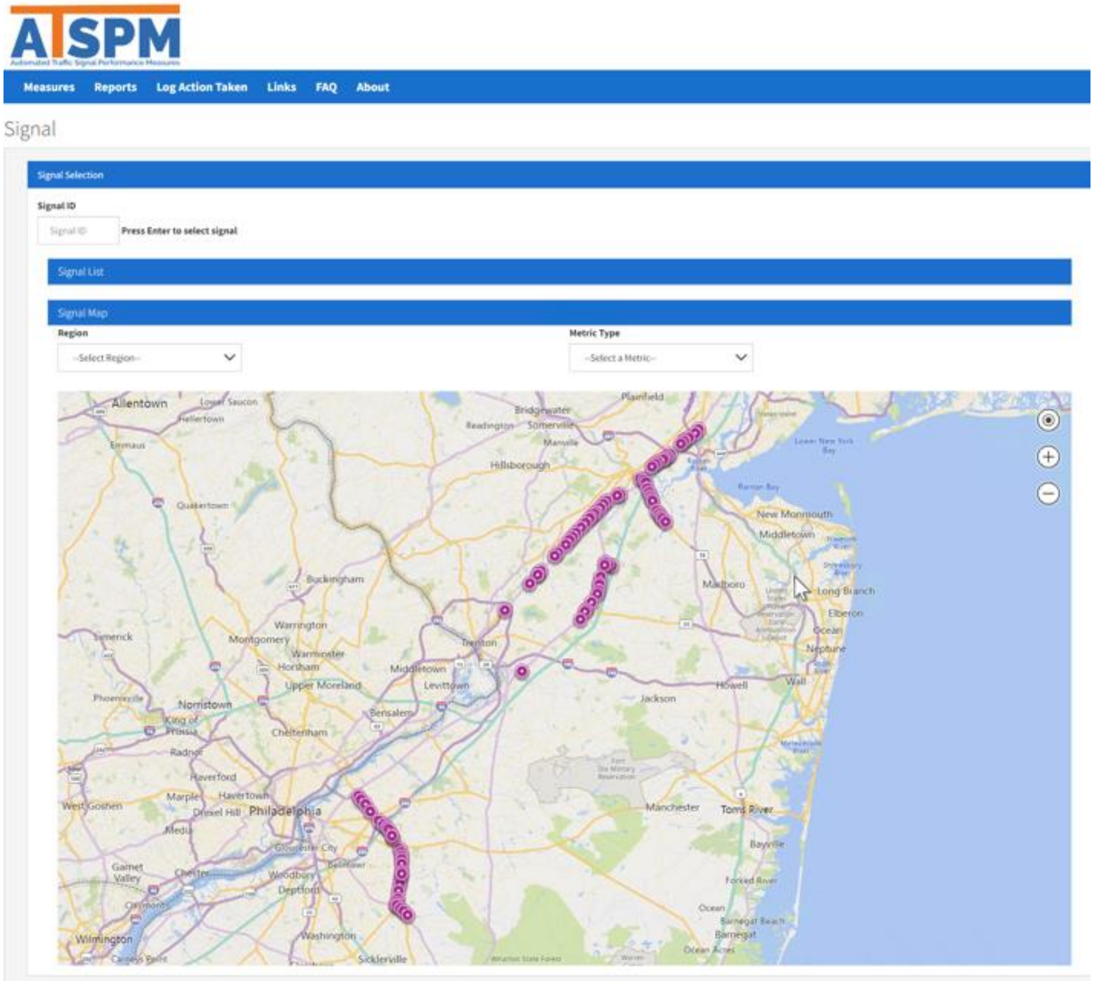



Figure 38. All Four SCATS Corridors with ATSPM Deployment

### SCATS Translator

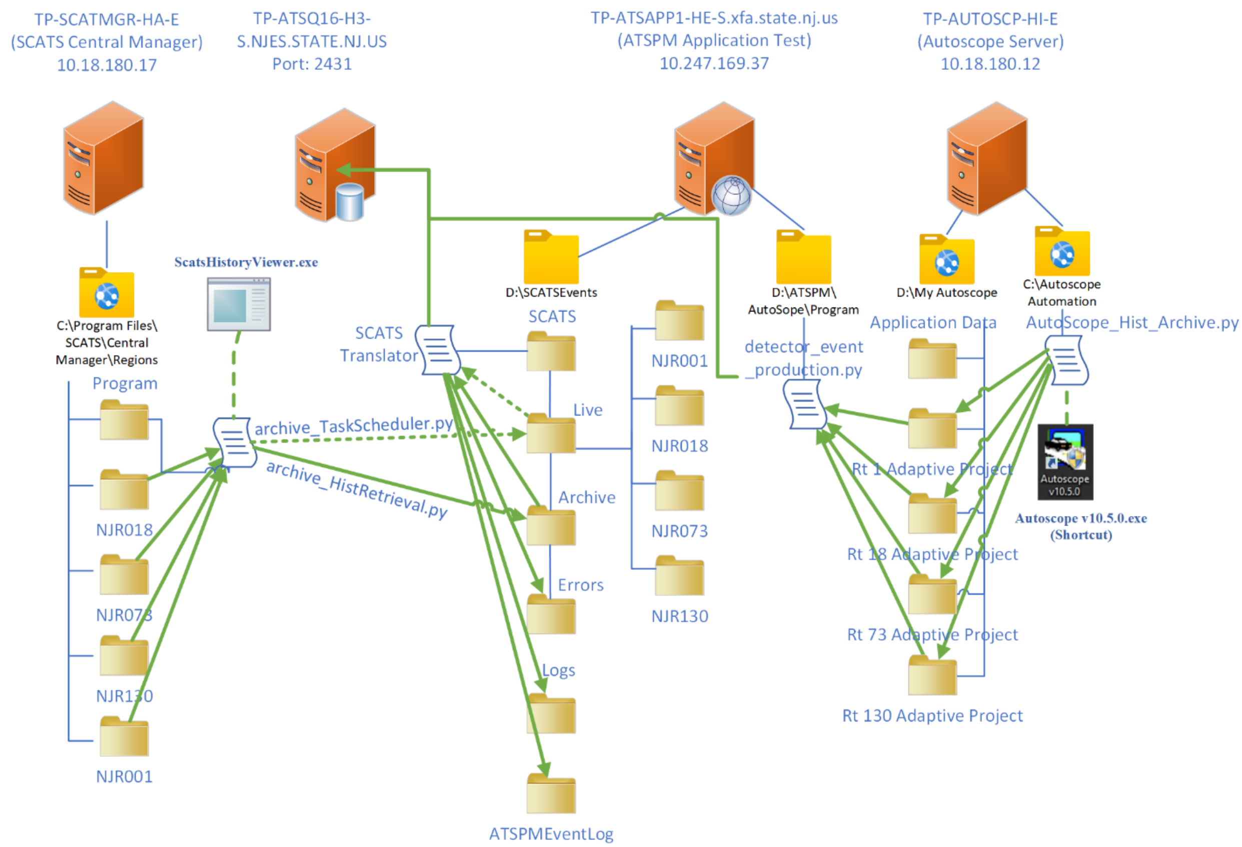



Figure 39. SCATS, Autoscope, and ATSPM Deployment Diagram

As figure 39 shows, the team finished SCATS archiving initiatives for both live event archiving and historical event archiving.

A Python script, along with associated metadata, has been developed for live archiving SCATS events on routes 1, 18, 73, and 130. The team's focus has been to verify this archiving process and extend it to include intersections without Autoscope detector data. Metadata for all four corridors has been prepared, and live event archiving has been tested across these corridors using “SCATS Server: archive_TaskScheduler.py” at 2-minute intervals and “ATSPM Application Test Server: SCATS_MSSQL_ATSPM.py” at 15-minute intervals. This ensures a comprehensive and reliable archiving process for SCATS events, even in locations lacking Autoscope data. Figure 40 shows the data from the extended two new routes, Route 73 and Route 130.

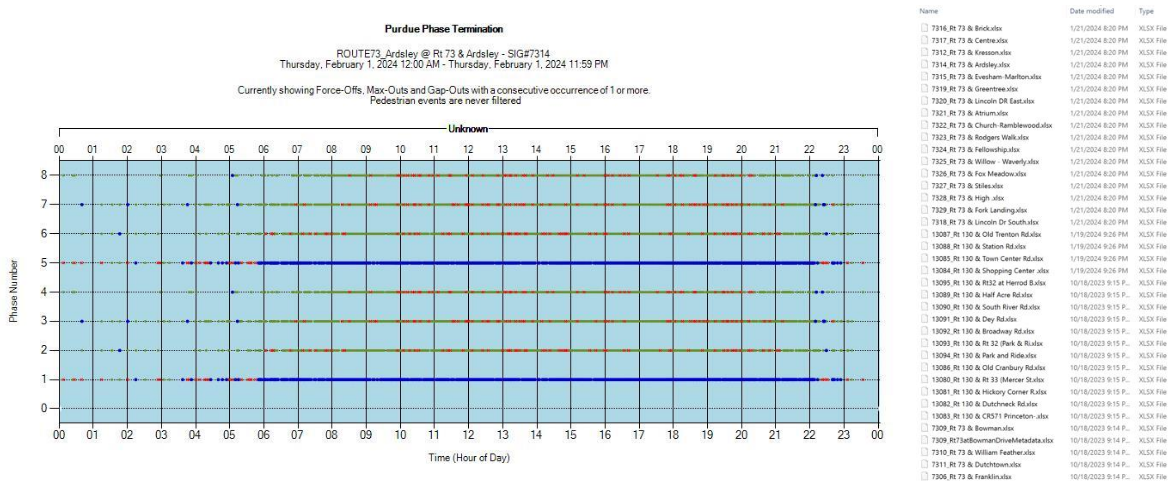



Figure 40. SCATS to Database for Route 73 and Route 130

As figure 40 shows, the historical event archiving involves both automated (via Python scripts) and manual processes. By manually providing the start and end dates, a Python script on the SCATS Server, “archive_HistRetrieval.py,” triggers the SCATSHistoryViewer.exe to translate SCATS “.hst” files to “.csv” files and forward the .csv files to ATSPM Application Test Server. Subsequently, a second script on the ATSPM App Test Server, “SCATS_MSSQL_ATSPM_hst_csv.py,” processes the records and inserts the results into the database, like the live event archiving process.

Due to a recent adjustment of user accounts for safety concerns, historical event archiving is now conducted weekly to transcribe the data into the database. To resume automatic live event archiving, a universal user account must exist on both the ATSPM App Test Server and the SCATS Server. This account is required by Task Scheduler to access the shared network drive. The team has been actively seeking solutions in collaboration with NJDOT OIT to resolve this issue and ensure seamless integration of the archiving processes.

### Autoscope GUI Automation

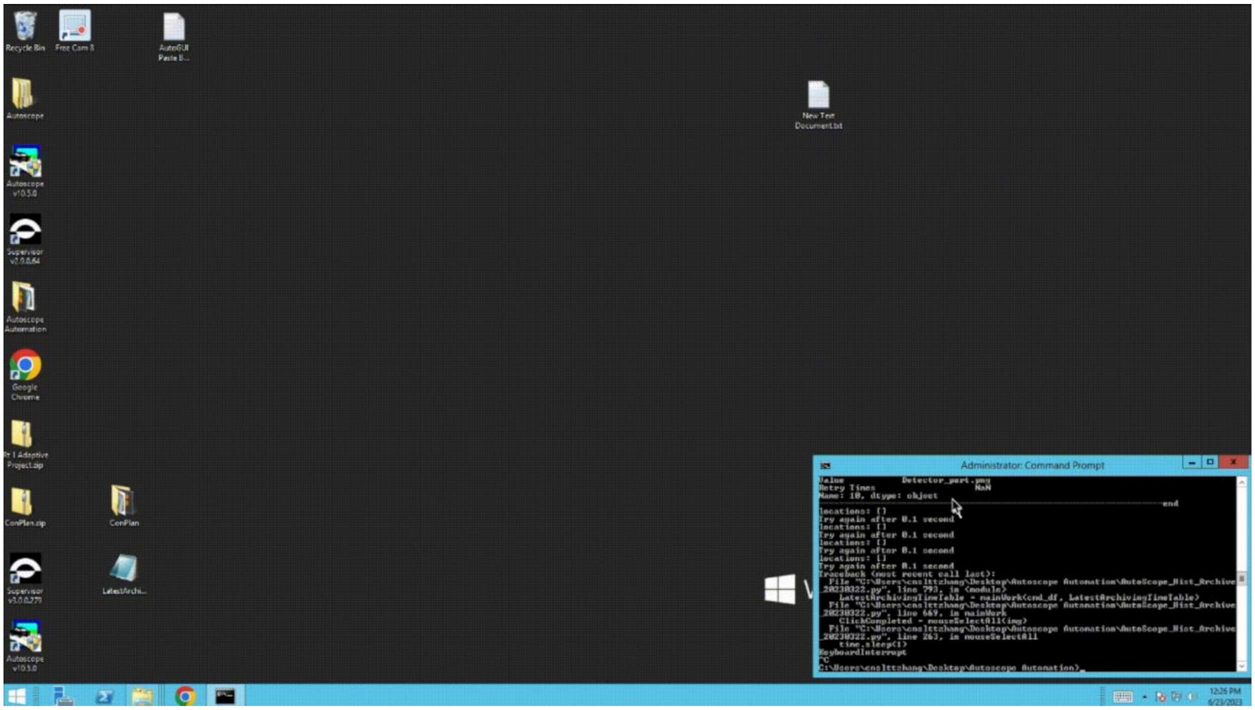



Figure 41. Snapshot of Autoscope GUI Automation Demo Video

The demo of Autoscope GUI automation is shown in figure 41. The team has also made progress on Autoscope Detector archiving efforts. For live archiving, the team continuously uses PyAutoGUI (Autoscope_Hist_Archive.py) for automating the time-consuming processes, with an initial manual run scheduled weekly, aiming for internal automation setup. Autoscope GUI automation has commenced with a weekly manual start-up at the Rutgers Lab.

For historical archiving, a comprehensive collection of existing event files is underway, with a strategy to manually archive all events and eliminate duplicate entries. Both live and historical data archiving for Autoscope detectors are currently in the debugging phase, indicating a commitment to refining these processes for optimal functionality.

## Autoscope Transcription to Database

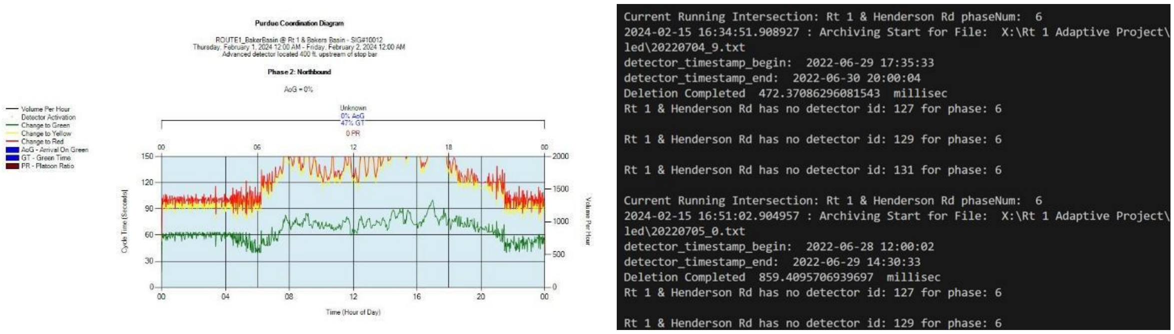



Figure 42. Autoscope Historical Data Archiving

The output of the Autoscope GUI Automation, ".txt" files, is being transcribed and loaded into the database, as shown in figure 42. The transcription program has been updated to be compatible with multi-phase detectors and can automatically locate the needed information from the .txt files.

For Route 1, 10,539 files were transcribed and loaded, 8,717 files were determined to be invalid due to no state change detected, and 496 files are yet to be processed. For Route 18, 1,917 files were transcribed and loaded, 2,043 files were determined to be invalid, and 878 files are yet to be processed. For Route 73, 18 files were inserted, 3,624 were determined to be invalid with no data, and 928 files are unprocessed. For Route 130, 1,853 files were determined to be invalid with no data, and 11 files are unprocessed.

The detectors at Route 73 & Jackson were reconfigured, and the files have been verified, transcribed, and loaded into the database. The team has also optimized the transcription logic for improved efficiency and better compatibility by only extracting the necessary information.

The Autoscope transcription is currently in the debugging phase, indicating a commitment to refining these processes for optimal functionality.

## TASK 7. BSM AND PSM PILOT DEPLOYMENT

### OBU Message Validation and Application Testing

In addition to lab testing and configuration, the team tested the connectivity of the OBU with the existing RSU at the US 1 and Bakers Basin Road intersection and collected field data. Over a 1-hour period, BSM, MAP, and SPaT logger data, as well as pcap files, were gathered by driving a car equipped with the OBU near the intersection. During data collection, the team validated the OBU's functionality by visualizing the vehicle's position on the Commsignia Foresight application on a tablet. Figure 43 shows the geo-position and the middle lane where the vehicle waits for the traffic light to turn green.

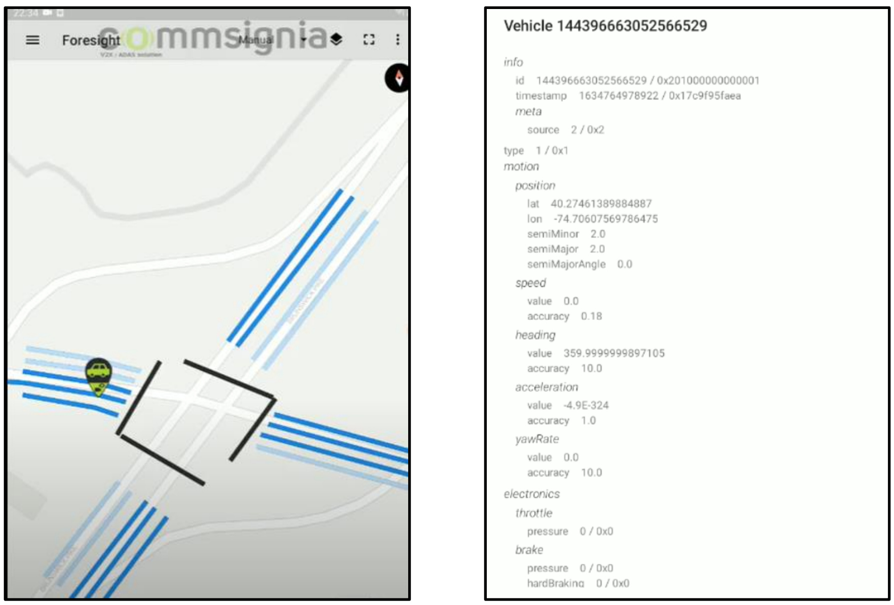


Figure 43. Validation Screenshots from the Commsignia Foresight Application

Furthermore, the team examined the BSM, MAP, and SPaT logger data and verified the recording process. It was identified that the logger files contained only communication logs, not the actual BSM, MAP, or SPaT data. Conversely, the pcap files recorded the data in an encrypted format. These files were later decrypted using Commsignia’s capture app, allowing the team to validate the geo-position of the vehicles. Figure 44 shows the encrypted and the decrypted information from the Commsignia’s capture app.

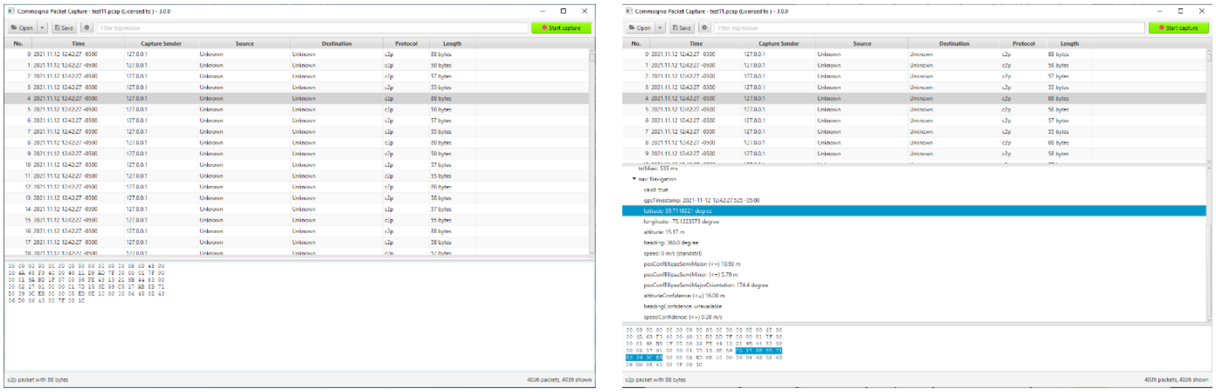
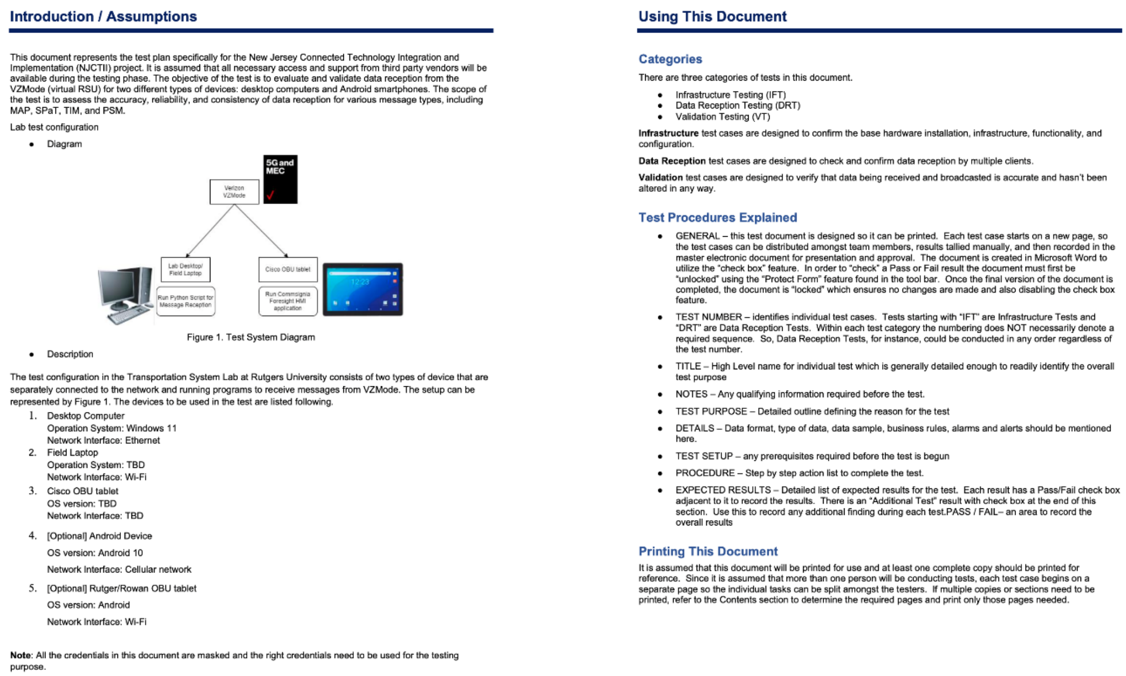


Figure 44. Validation Screenshots from the Commsignia Capture Application



### Introduction / Assumptions

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Lab test configuration

- Diagram

5G and MEC
Verizon VZMode
Lab Desktop/ Field Laptop
Run Python Script for Message Reception
Cisco OBU tablet
Run Commsignia Foresight HMI application
12:23

Figure 1. Test System Diagram

- Description

The test configuration in the Transportation System Lab at Rutgers University consists of two types of device that are separately connected to the network and running programs to receive messages from VZMode. The setup can be represented by Figure 1. The devices to be used in the test are listed following.

1. Desktop Computer
   Operation System: Windows 11
   Network Interface: Ethernet
2. Field Laptop
   Operation System: TBD
   Network Interface: Wi-Fi
3. Cisco OBU tablet
   OS version: TBD
   Network Interface: TBD
4. [Optional] Android Device
   OS version: Android 10
   Network Interface: Cellular network
5. [Optional] Rutger/Rowan OBU tablet
   OS version: Android
   Network Interface: Wi-Fi

**Note**: All the credentials in this document are masked and the right credentials need to be used for the testing purpose.

### Using This Document

#### Categories

There are three categories of tests in this document.

- Infrastructure Testing (IFT)
- Data Reception Testing (DRT)
- Validation Testing (VT)

**Infrastructure** test cases are designed to confirm the base hardware installation, infrastructure, functionality, and configuration.

**Data Reception** test cases are designed to check and confirm data reception by multiple clients.

**Validation** test cases are designed to verify that data being received and broadcasted is accurate and hasn't been altered in any way.

#### Test Procedures Explained

- GENERAL – this test document is designed so it can be printed. Each test case starts on a new page, so the test cases can be distributed amongst team members, results tallied manually, and then recorded in the master electronic document for presentation and approval. The document is created in Microsoft Word to utilize the "check box" feature. In order to "check" a Pass or Fail result the document must first be "unlocked" using the "Protect Form" feature found in the tool bar. Once the final version of the document is completed, the document is "locked" which ensures no changes are made and also disabling the check box feature.
- TEST NUMBER – identifies individual test cases. Tests starting with "IFT" are Infrastructure Tests and "DRT" are Data Reception Tests. Within each test category the numbering does NOT necessarily denote a required sequence. So, Data Reception Tests, for instance, could be conducted in any order regardless of the test number.
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- TEST PURPOSE – Detailed outline defining the reason for the test
- DETAILS – Data format, type of data, data sample, business rules, alarms and alerts should be mentioned here.
- TEST SETUP – any prerequisites required before the test is begun
- PROCEDURE – Step by step action list to complete the test.
- EXPECTED RESULTS – Detailed list of expected results for the test. Each result has a Pass/Fail check box adjacent to it to record the results. There is an "Additional Test" result with check box at the end of this section. Use this to record any additional finding during each test.PASS / FAIL– an area to record the overall results

#### Printing This Document

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Figure 45. Engineering Test Document Screenshot

A comprehensive engineering test was conducted at the Bordentown test intersection before field deployment to ensure C-V2X functionalities within the lab network configuration. The lab engineering test covered three major categories: infrastructure connectivity, C-V2X message reception, and C-V2X message validation. Infrastructure connectivity tests included verifying network connectivity between hardware and devices, ensuring the connection from the virtual RSU MQTT broker to multiple devices, including the server at Rutgers Traffic System Lab, a test desktop computer, an Android smartphone, and a Commsignia OBU. Data reception tests assessed the data reception functionalities on four devices (server, desktop, smartphone, and OBU) for four different types of C-V2X messages: MAP, SPaT, TIM, and PSM. Data validation tests involved visualizing C-V2X messages to confirm their accuracy. All tests were successful and yielded the anticipated results. A detailed engineering test document has been completed, outlining all test procedures and results. Figure 45 demonstrates the snapshot of the engineering test document.

**Bordentown vRSU Deployment**

The Bordentown system architecture is detailed in figure 46, which provides an overview of the virtual RSU layout, including the lidar detectors. The transition of the cabinet layout from the TCNJ lab to Bordentown is depicted in figure 47, while figure 48 illustrates the pole setup.

SPaT information is physically retrieved from the field using a thumb drive or hard drive and brought back to the TCNJ lab for further analysis. Figure 49 shows the overall field setup of the cabinet at Bordentown, and figure 50 displays the pole setup in the field.

These figures collectively outline the comprehensive infrastructure and setup necessary for ensuring the effective deployment and operation of the C-V2X system at the Bordentown test site.

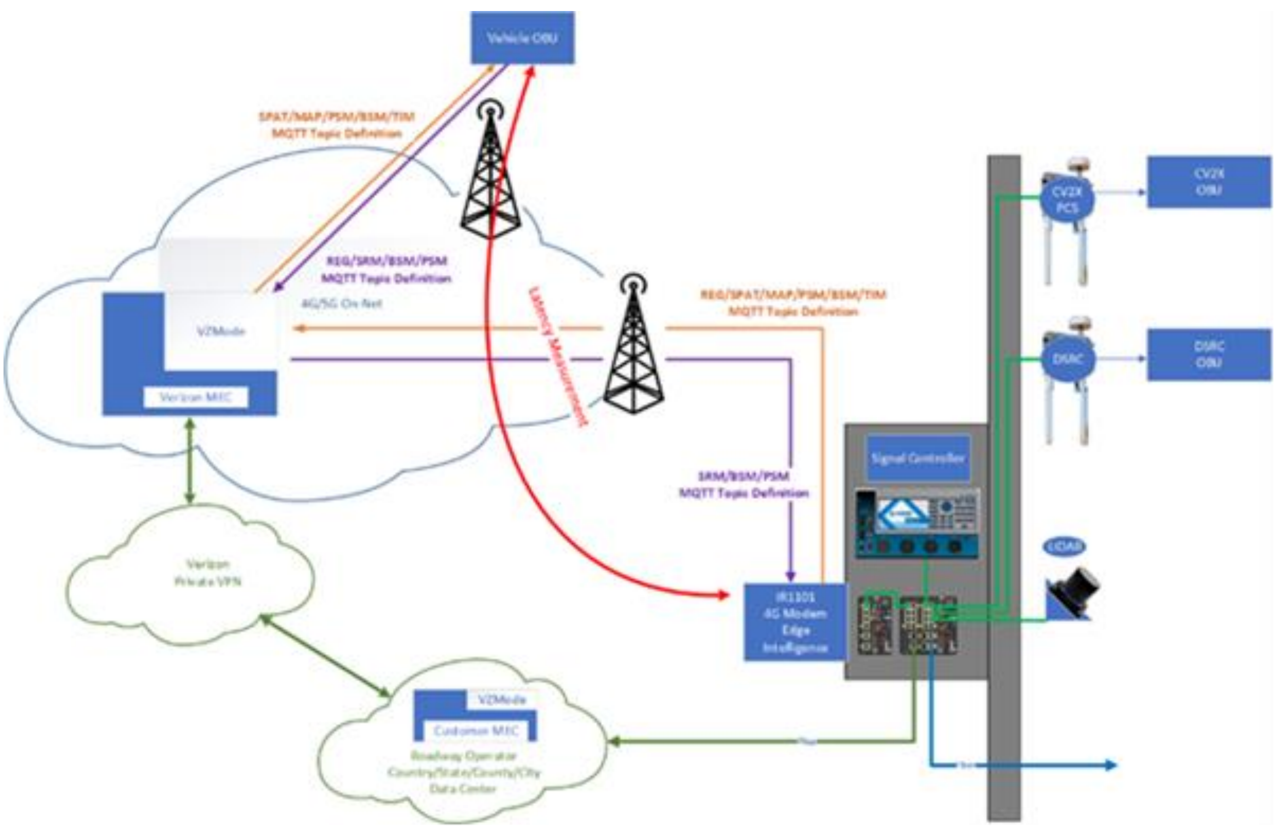


Figure 46. Illustration of Virtual RSU (vRSU) Deployment at NJDOT Test Site in Bordentown, NJ

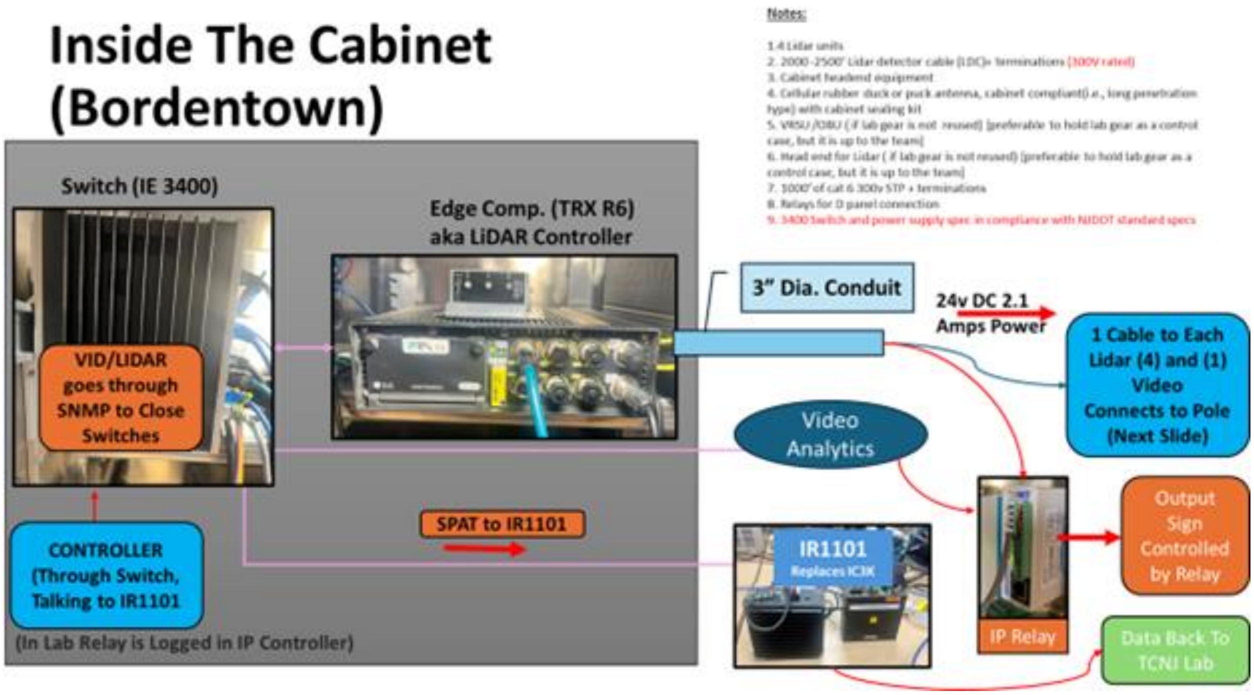


Figure 47. Illustration of Cabinet Setup at NJDOT Test Site in Bordentown, NJ

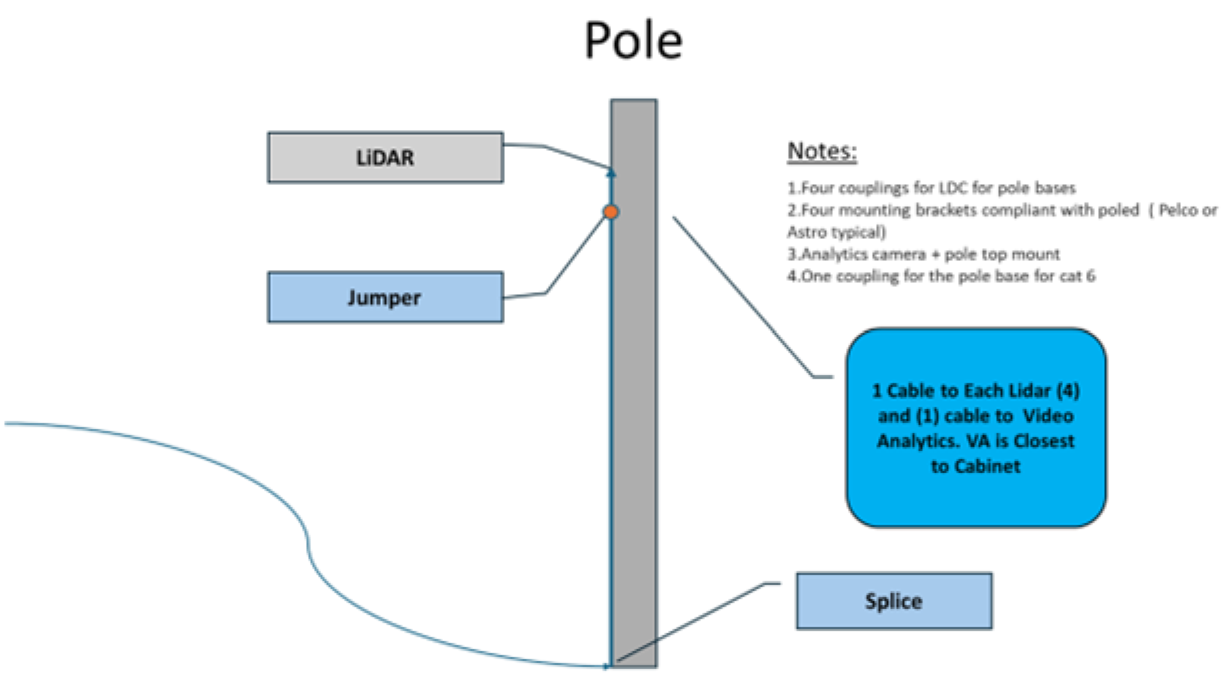


Figure 48. Illustration of Lidar Pole Mount Setup at NJDOT Test Site in Burlington, NJ

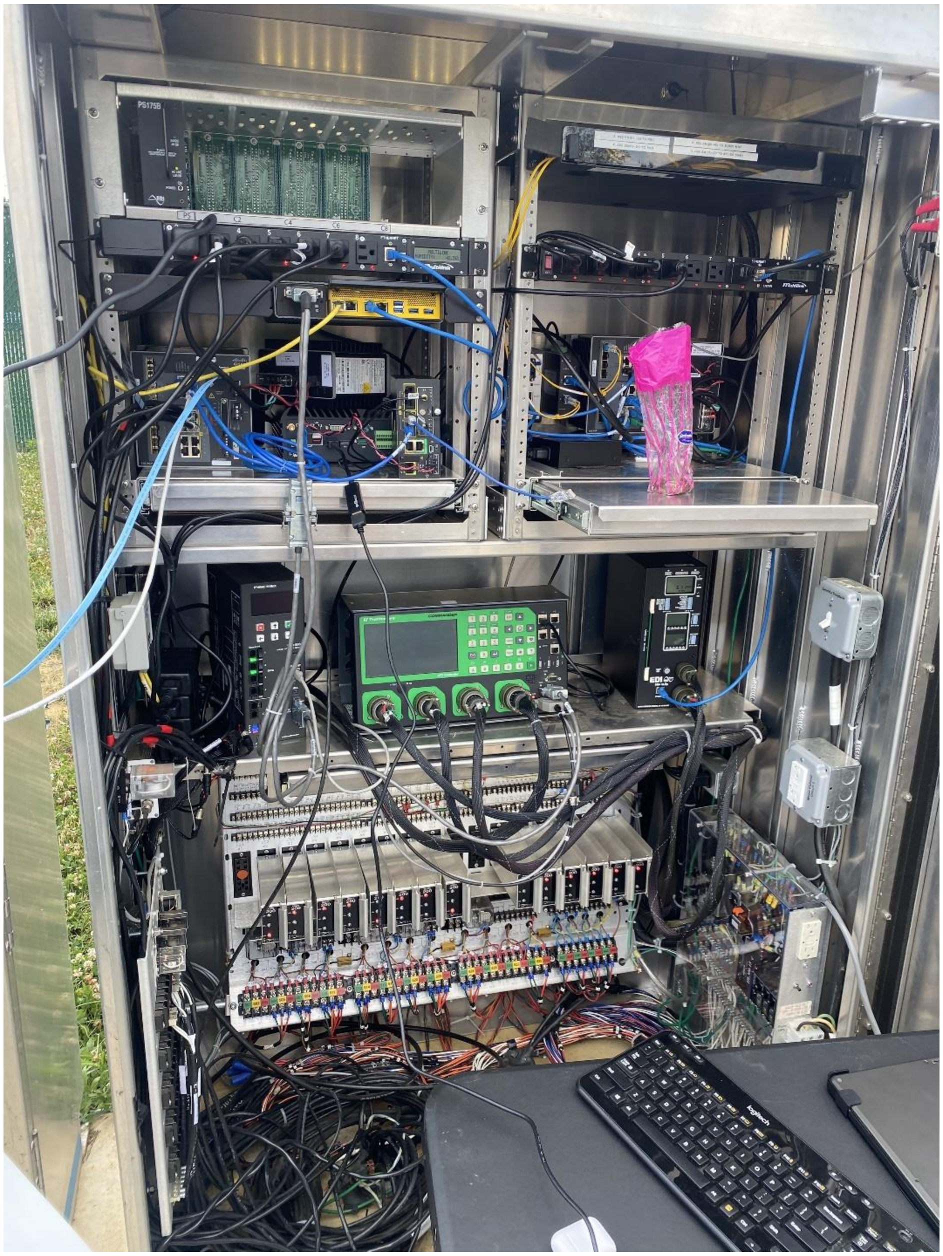

Figure 49. Bordentown, NJ Cabinet Setup for vRSU

Figure 50. Bordentown, NJ Pole Setup with LiDAR

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## APPENDIX A: CV-ATSPM PHASE III C-V2X MESSAGE DATA RECEPTION TEST PLAN

### Introduction and Assumptions

This document represents the test plan specifically for the New Jersey Connected Technology Integration and Implementation (NJCTII) project. It is assumed that all necessary access and support from third party vendors will be available during the testing phase. The objective of the test is to evaluate and validate data reception from the VZMode (virtual RSU) for two different types of devices: desktop computers and Android smartphones. The scope of the test is to assess the accuracy, reliability, and consistency of data reception for various message types, including MAP, SPaT, TIM, and PSM.

### Lab test configuration

- Diagram

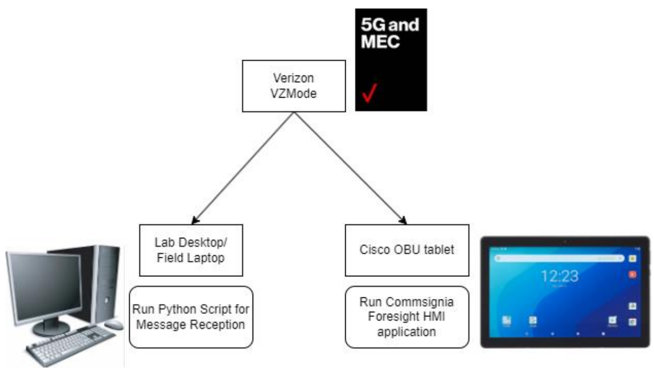


Figure 51. Test System Diagram

- Description

The test configuration in the Transportation System Lab at Rutgers University consists of two types of devices that are separately connected to the network and running programs to receive messages from VZMode virtual RSU. The setup can be represented by Figure A1. The devices to be used in the test are listed following.

a. Desktop Computer
    a. Operation System: Windows 11
    b. Network Interface: Ethernet
b. Field Laptop
    a. Operation System: TBD
    b. Network Interface: Wi-Fi
c. Cisco OBU tablet
    a. OS version: TBD
    b. Network Interface: TBD
d. [Optional] Android Device
    a. OS version: Android 10

    b. Network Interface: Cellular network

e. [Optional] Rutger/Rowan OBU tablet
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**Note**: All the credentials in this document are masked and the right credentials need to be used for the testing purpose.

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### *Categories*

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- Validation Testing (VT)

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### *Printing This Document*

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### *Infrastructure Details*

Infrastructure details below are for solution deployment.

**IP Address** needs to be filled as per the lab and production setups. Fill these details in the table given below, before executing any test case.

Table 5. Infrastructure Details

| IP Address | Description | Notes |
|---|---|---|
| **Data Reception Client** | | |
| 172.17.106.116 | Rutgers TSLab Desktop | |
| | Field Laptop | |
| | Cisco OBU tablet | |

***Test Case Results Summary***

This section summarizes the detailed tests. An overall PASS or FAIL is recorded here once the initial or subsequent detailed results are attained. This can be considered an “Executive Summary”.

Table 6. Test Case Summary Results

| **Solution Test Cases** | | |
|---|---|---|
| **Infrastructure Testing (IFT)** | | |
| **Test No.** | **Test Title** | **Pass/Fail Result** |
| IFT-001 | Network connectivity between hardware and devices | Pass ☒ Fail ☐ |
| IFT-002 | Connection from MQTT server to TSLab server | Pass ☒ Fail ☐ |
| IFT-003 | Connection from MQTT server to TSLab desktop | Pass ☒ Fail ☐ |
| IFT-004 | Connection from MQTT server to Android Smartphone | Pass ☒ Fail ☐ |
| IFT-005 | Connection from MQTT server to Field laptop | Pass ☒ Fail ☐ |
| IFT-006 | Connection from MQTT server to Cisco OBU tablet | Pass ☒ Fail ☐ |
| **Data Reception Testing (DFT) - Successful receiving of messages** | | |
| **Test No.** | **Test Title - ADD Description** | **Pass/Fail Result** |
| DRT-001 | Data Reception Test for MAP Messages | Pass ☒ Fail ☐ |
| DRT-002 | Data Reception Test for TIM Messages | Pass ☒ Fail ☐ |
| DRT-003 | Data Reception Test for SPaT Messages | Pass ☒ Fail ☐ |
| DRT-004 | Data Reception Test for PSM Messages | Pass ☒ Fail ☐ |
| DRT-005 | Data Reception Test on Cisco OBU tablet | Pass ☒ Fail ☐ |
| | | |

| **Validation Testing (VT) - Validate and visualize message content** | | |
|---|---|---|
| **Test No.** | **Test Title** | **Pass/Fail Result** |
| VT-001 | Validation Test for MAP Messages | Pass ☒ Fail ☐ |
| VT-002 | Validation Test for SPaT Messages | Pass ☒ Fail ☐ |
| VT-003 | Validation Test for PSM Messages | Pass ☒ Fail ☐ |

**Test Cases**

***Infrastructure Testing***

Table 7. IF-001: Network Connectivity between Hardware and Devices

<table>
<tr><td>Test No: IF-001</td><td>Revision: 1.0</td><td>Author:</td><td>Date:03/24/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Infrastructure Testing (IFT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details: IP addresses and device details are specified in Table 5 Infrastructure Details</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify the network connectivity of the following devices:<br>1. Rutgers TSLab server<br>2. Rutgers TSLab desktop<br>3. Field test laptop<br>4. Android smartphone<br>5. Cisco OBU tablet<br>6. Rutgers/Rowan tablet</td></tr>
<tr><td colspan="5">Test Setup: Ensure the devices are powered on and have required ethernet connection, cellular network, or Wi-Fi connection</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Ensure Rutgers TSLab server is connected to the internet<br>2. Ensure Rutgers TSLab desktop computer is connected to the internet<br>3. Ensure field test laptop is connected to Wi-Fi network<br>4. Ensure Android smartphone is connected to cellular network<br>5. Ensure Cisco OBU tablet is connected to Wi-Fi network<br>6. Ensure Rutgers/Rowan tablet is connected to Wi-Fi network</td></tr>
<tr><td colspan="3">Expected Results:<br>All the devices are connected to the internet through corresponding connection.</td><td colspan="2">Pass ☒ Fail ☐<br><br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

Table 8. IF-02: Connection from MQTT Server to TSLab Server

<table>
<tr><td>Test No: IF-002</td><td>Revision: 1.0</td><td>Author:</td><td>Date:03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Infrastructure Testing (IFT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details: IP addresses and device details are specified in Table 1 Infrastructure Details</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify the TSLab server can connect successfully to the MQTT server.</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the respective connectivity specified in Master Test No: IFT-001 has been established<br>2. Confirm the MQTT server is up and running.</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Open Anaconda Prompt<br>2. Go to the directory where the MQTT connection python code is located<br>3. Run “python <MQTT connection code>”</td></tr>
<tr><td colspan="2">Expected Results:<br>The returned result from Anaconda Prompt shows “connection OK”</td><td colspan="3">Pass ☒ Fail ☐<br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

Table 9. IF-003: Connection from MQTT Server to TSLab Desktop

<table>
<tr><td>Test No: IF-003</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td colspan="2">Tester: Bowen Geng</td></tr>
<tr><td colspan="6">Test Category: Infrastructure Testing (IFT)</td></tr>
<tr><td colspan="6">Notes:</td></tr>
<tr><td colspan="6">Details: IP addresses and device details are specified in Table 1 Infrastructure Details</td></tr>
<tr><td colspan="6">Test Purpose: The purpose of this test is to verify the TSLab desktop can connect successfully to the MQTT server.</td></tr>
<tr><td colspan="6">Test Setup:<br>1. Verify the respective connectivity specified in Master Test No: IFT-001 has been established<br>2. Confirm the MQTT server is up and running.</td></tr>
<tr><td colspan="6">Test Procedure:<br>3. Open Anaconda Prompt<br>4. Go to the directory where the MQTT connection python code is located<br>5. Run “python <MQTT connection code>”</td></tr>
<tr><td colspan="3">Expected Results:<br>The returned result from Anaconda Prompt shows “connection OK”</td><td colspan="3">Pass ☒ Fail ☐<br>Notes:</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
</table>

Table 10. IF-004: Connection from MQTT Server to Android Smartphone

<table>
<tr><td>Test No: IF-004</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Infrastructure Testing (IFT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details: IP addresses and device details are specified in Table 1 Infrastructure Details</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify the Android smartphone can connect successfully to the MQTT server.</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the respective connectivity specified in Master Test No: IFT-001 has been established<br>2. Confirm the MQTT server is up and running.</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Open SmartMobi mobile application<br>2. Click “start” button</td></tr>
<tr><td colspan="2">Expected Results:<br>The screen displayed “MQTT Connection OK”</td><td colspan="3">Pass ☒ Fail ☐<br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

Table 11. IF-005: Connection from MQTT Server to Field Laptop

<table>
<tr><td>Test No: IF-005</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Infrastructure Testing (IFT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details: IP addresses and device details are specified in Table 1 Infrastructure Details</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify the field laptop can connect successfully to the MQTT server.</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the respective connectivity specified in Master Test No: IFT-001 has been established<br>2. Confirm the MQTT server is up and running.</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Open Anaconda Prompt.<br>2. Go to the directory where <MQTT Connection Python Code> is located.<br>3. Run “python <MQTT Connection Python Code></td></tr>
<tr><td colspan="2">Expected Results:<br>The returned result from Anaconda Prompt shows “connection ok”</td><td colspan="3">Pass ☒ Fail ☐<br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

Table 12. IF-006: Connection from MQTT Server to Cisco OBU tablet

<table>
<tr><td>Test No: IF-006</td><td>Revision: 1.0</td><td>Author:</td><td>Date:03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Infrastructure Testing (IFT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details: IP addresses and device details are specified in Table 1 Infrastructure Details</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify the Cisco OBU tablet can connect successfully to the MQTT server.</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the respective connectivity specified in Master Test No: IFT-001 has been established<br>2. Confirm the MQTT server is up and running.</td></tr>
<tr><td colspan="5">Test Procedure:<br>Run Commsignia Foresight HMI application</td></tr>
<tr><td colspan="3">Expected Results:<br>The screen display test intersection with MAP, SPaT, and PSM information</td><td colspan="2">Pass ☒ Fail ☐<br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

***Data Reception Testing***

Table 13. DRT-001: Data Reception Test for MAP Data

<table>
<tr><td>Test No: DRT-1</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Data Reception Test (DRT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details:</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify that MAP messages are being received by both computer and mobile device, as the first step for further process and development.</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the following tests have passed successfully:<br>a. IFT 001<br>b. IFT 002<br>c. IFT 003<br>d. IFT 004<br>e. IFT 005<br>f. IFT 006<br>2. Ensure the MQTT server is up and running</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Run <MQTT_Receiver.py> on the computer devices.<br>2. Open the “SmartMobi” application on the mobile devices and press “start” button<br>Example message:<br>{"MessageFrame":{"value":{"MapData":{"msgIssueRevision":"2","layerType":{"intersectionData":""},"layerID":"0","intersections":{"IntersectionGeometry":{"id":{"id":"10004"},"revision":"2","refPoint":{"lat":"402401042","long":"-742755693"},"laneWidth":"366","laneSet":{"GenericLane":[{"laneAttributes":{"sharedWith":"0000000000","laneType":{"vehicle":"00000000"},"directionalUse":"10"},"nodeList":{"nodes":{"NodeXY":[{"delta":{"node-LatLon":{"lon":"-742764239","lat":"402400671"}}},{"delta":{"node-LatLon":{"lon":"-</td></tr>
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ver":"001000000000","lane":"29"},"signalGroup":"6"}]},"laneID":"1","ingressApproach":"
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ne":"20","maneuver":"100000000000"},"signalGroup":"6"}},"laneID":"2","ingressApproa
ch":"1"},{"connectsTo":{"Connection":{"connectingLane":{"lane":"21"},"signalGroup":"6"
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| | |
|---|---|
| Expected Results:<br>1. MAP messages are being displayed on command prompt panel, indicating that MAP messages are being received by desktop computer.<br>2. MAP messages are being displayed on Android phone | Pass ☒ Fail ☐<br><br>Notes: |

| | |
|---|---|
| screen, indicating that MAP messages are being received by the Android device. | |
| Remarks: | |

```
b'{"MessageFrame": {"value": {"MapData": {"intersections": {"IntersectionGeometry": {"id": {"id": "10004"}, "revision": "2", "refPoint": {"l
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edWith": "0000000000", "laneType": {"vehicle": "00000000"}, "directionalUse": "10"}, "nodeList": {"nodes": {"NodeXY": [{"delta": {"node-LatL
on": {"lon": "-742763294", "lat": "402401362"}}}, {"delta": {"node-LatLon": {"lon": "-742771327", "lat": "402407611"}}}]}}, "connectsTo": {"
Connection": {"connectingLane": {"lane": "22"}, "signalGroup": "6"}}}, {"laneID": "14", "ingressApproach": "3", "laneAttributes": {"sharedWi
th": "0000000000", "laneType": {"vehicle": "00000000"}, "directionalUse": "10"}, "nodeList": {"nodes": {"NodeXY": [{"delta": {"node-LatLon":
 {"lon": "-742763575", "lat": "402398388"}}}, {"delta": {"node-LatLon": {"lon": "-742766325", "lat": "402397205"}}}]}}, "connectsTo": {"Conn
ection": {"connectingLane": {"lane": "26", "maneuver": "010000000000"}, "signalGroup": "3"}}}, {"laneID": "13", "ingressApproach": "3", "lan
eAttributes": {"directionalUse": "10", "sharedWith": "0000000000", "laneType": {"vehicle": "00000000"}}, "nodeList": {"nodes": {"NodeXY": [{
"delta": {"node-LatLon": {"lon": "-742763347", "lat": "402398122"}}}, {"delta": {"node-LatLon": {"lon": "-742766090", "lat": "402396929"}}},
 {"delta": {"node-LatLon": {"lon": "-742767713", "lat": "402396381"}}}, {"delta": {"node-LatLon": {"lat": "402395752", "lon": "-742770207"}}
}]}}, "connectsTo": {"Connection": {"signalGroup": "3", "connectingLane": {"lane": "25", "maneuver": "010000000000"}}}}, {"laneID": "12", "i
ngressApproach": "3", "laneAttributes": {"directionalUse": "10", "sharedWith": "0000000000", "laneType": {"vehicle": "00000000"}}, "nodeList
": {"nodes": {"NodeXY": [{"delta": {"node-LatLon": {"lon": "-742763133", "lat": "402397861"}}}, {"delta": {"node-LatLon": {"lon": "-74276590
2", "lat": "402396632"}}}, {"delta": {"node-LatLon": {"lon": "-742767565", "lat": "402396049"}}}, {"delta": {"node-LatLon": {"lon": "-742770
080", "lat": "402395404"}}}]}}, "connectsTo": {"Connection": {"connectingLane": {"lane": "28", "maneuver": "100000000000"}, "signalGroup": "
8"}}}, {"laneAttributes": {"directionalUse": "10", "sharedWith": "0000000000", "laneType": {"vehicle": "00000000"}}, "nodeList": {"nodes": {
"NodeXY": [{"delta": {"node-LatLon": {"lon": "-742762878", "lat": "402397564"}}}, {"delta": {"node-LatLon": {"lon": "-742765728", "lat": "40
2396351"}}}, {"delta": {"node-LatLon": {"lon": "-742767458", "lat": "402395752"}}}, {"delta": {"node-LatLon": {"lon": "-742769952", "lat": "
```


Figure 52. MAP Message (JER) Reception Results


```
TEST: {'messageId': 18, 'value': {'msgIssueRevision': 2, 'layerType': 'intersectionData', 'layerID': 0, 'intersections': [{'id': {'id': 1000
4}, 'revision': 2, 'refPoint': {'lat': 402401042, 'long': -742755693}, 'laneWidth': 366, 'laneSet': [{'laneID': 1, 'ingressApproach': 1, 'la
neAttributes': {'directionalUse': {'length': 2, 'value': '80'}, 'sharedWith': {'length': 10, 'value': '0000'}, 'laneType': {'vehicle': '00'}
}, 'nodeList': {'nodes': [{'delta': {'node-LatLon': {'lon': -742764239, 'lat': 402400671}}}, {'delta': {'node-LatLon': {'lon': -742772467, '
lat': 402407043}}}]}, 'connectsTo': [{'connectingLane': {'lane': 19, 'maneuver': {'length': 12, 'value': '8000'}}, 'signalGroup': 6}, {'conn
ectingLane': {'lane': 29, 'maneuver': {'length': 12, 'value': '2000'}}, 'signalGroup': 6}]}, {'laneID': 2, 'ingressApproach': 1, 'laneAttrib
utes': {'directionalUse': {'length': 2, 'value': '80'}, 'sharedWith': {'length': 10, 'value': '0000'}, 'laneType': {'vehicle': '00'}}, 'node
List': {'nodes': [{'delta': {'node-LatLon': {'lon': -742763917, 'lat': 402400921}}}, {'delta': {'node-LatLon': {'lon': -742772071, 'lat': 40
2407212}}}]}, 'connectsTo': [{'connectingLane': {'lane': 20, 'maneuver': {'length': 12, 'value': '8000'}}, 'signalGroup': 6}]}, {'laneID': 3
, 'ingressApproach': 1, 'laneAttributes': {'directionalUse': {'length': 2, 'value': '80'}, 'sharedWith': {'length': 10, 'value': '0000'}, 'l
aneType': {'vehicle': '00'}}, 'nodeList': {'nodes': [{'delta': {'node-LatLon': {'lon': -742763622, 'lat': 402401136}}}, {'delta': {'node-Lat
Lon': {'lon': -742771696, 'lat': 402407427}}}]}, 'connectsTo': [{'connectingLane': {'lane': 21}, 'signalGroup': 6}]}, {'laneID': 4, 'ingress
Approach': 1, 'laneAttributes': {'directionalUse': {'length': 2, 'value': '80'}, 'sharedWith': {'length': 10, 'value': '0000'}, 'laneType':
{'vehicle': '00'}}, 'nodeList': {'nodes': [{'delta': {'node-LatLon': {'lon': -742763294, 'lat': 402401362}}}, {'delta': {'node-LatLon': {'lo
n': -742771327, 'lat': 402407611}}}]}, 'connectsTo': [{'connectingLane': {'lane': 22}, 'signalGroup': 6}]}, {'laneID': 14, 'ingressApproach'
: 3, 'laneAttributes': {'directionalUse': {'length': 2, 'value': '80'}, 'sharedWith': {'length': 10, 'value': '0000'}, 'laneType': {'vehicle
': '00'}}, 'nodeList': {'nodes': [{'delta': {'node-LatLon': {'lon': -742763575, 'lat': 402398388}}}, {'delta': {'node-LatLon': {'lon': -7427
66325, 'lat': 402397205}}}]}, 'connectsTo': [{'connectingLane': {'lane': 26, 'maneuver': {'length': 12, 'value': '4000'}}, 'signalGroup': 3}
]}, {'laneID': 13, 'ingressApproach': 3, 'laneAttributes': {'directionalUse': {'length': 2, 'value': '80'}, 'sharedWith': {'length': 10, 'va
lue': '0000'}, 'laneType': {'vehicle': '00'}}, 'nodeList': {'nodes': [{'delta': {'node-LatLon': {'lon': -742763347, 'lat': 402398122}}}, {'d
elta': {'node-LatLon': {'lon': -742766090, 'lat': 402396929}}}, {'delta': {'node-LatLon': {'lon': -742767713, 'lat': 402396381}}}, {'delta':
 {'node-LatLon': {'lon': -742770207, 'lat': 402395752}}}]}, 'connectsTo': [{'connectingLane': {'lane': 25, 'maneuver': {'length': 12, 'value
': '4000'}}, 'signalGroup': 3}]}, {'laneID': 12, 'ingressApproach': 3, 'laneAttributes': {'directionalUse': {'length': 2, 'value': '80'}, 's
haredWith': {'length': 10, 'value': '0000'}, 'laneType': {'vehicle': '00'}}, 'nodeList': {'nodes': [{'delta': {'node-LatLon': {'lon': -74276
3133, 'lat': 402397861}}}, {'delta': {'node-LatLon': {'lon': -742765902, 'lat': 402396632}}}, {'delta': {'node-LatLon': {'lon': -742767565,
'lat': 402396049}}}, {'delta': {'node-LatLon': {'lon': -742770080, 'lat': 402395404}}}]}, 'connectsTo': [{'connectingLane': {'lane': 28, 'ma
neuver': {'length': 12, 'value': '8000'}}, 'signalGroup': 8}]}, {'laneID': 11, 'ingressApproach': 3, 'laneAttributes': {'directionalUse': {'
length': 2, 'value': '80'}, 'sharedWith': {'length': 10, 'value': '0000'}, 'laneType': {'vehicle': '00'}}, 'nodeList': {'nodes': [{'delta':
```


Figure 53. MAP Message (UPER) Reception Results (Decoded)

Table 14. DRT-002: Data Reception Test for TIM Data

<table>
<tr><td>Test No: DRT-2</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Data Reception Test (DRT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details:</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify that TIM messages are being received by both computer and mobile device, as the first step for further process and development.</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the following tests have passed successfully:<br>a. IFT 001<br>b. IFT 002<br>c. IFT 003<br>d. IFT 004<br>e. IFT 005<br>f. IFT 006<br>2. Ensure the MQTT server is up and running</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Run <MQTT_Receiver.py> on the computer devices.<br>2. Open the “SmartMobi” application on the mobile devices and press “start” button<br>Example message:<br>{"MessageFrame":{"messageId":"31","value":{"TravelerInformation":{"msgCnt":"1","packetID":"00000000002171BE75","dataFrames":{"TravelerDataFrame":{"frameType":{"advisory":""},"startYear":"2023","startTime":"43200","duratonTime":"1","priority":"4","sspLocationRights":"0","sspMsgRights1":"0","sspTimRights":"0","content":{"workZone":{"SEQUENCE":{"item":{"itis":"7941"}}}},"sspMsgRights2":"0","regions":{"GeographicalPath":{"description":{"geometry":{"direction":"0000000000000000","circle":{"center":{"lat":"402401042","long":"-742755693"},"radius":"12","units":{"mile":""}}}}}},"msgId":{"roadSignID":{"position":{"lat"</td></tr>
</table>

| | |
|---|---|
| :"402401042","long":"-742755693"},"viewAngle":"0000000000000000"}}}}}}} | |
| Expected Results:<br>1. TIM messages are being displayed on command prompt panel, indicating that TIM messages are being received by desktop computer<br>2. TIM messages are being displayed on Android phone screen, indicating that TIM messages are being received by the Android device. | Pass ☒ Fail ☐<br><br>Notes: |
| Remarks: | |


```
b'{"MessageFrame": {"messageId": "31", "value": {"TravelerInformation": {"msgCnt": "1", "timeStamp": "66780", "packetID": "00 00 00 00 00 21
 71 BE 75", "dataFrames": {"TravelerDataFrame": {"startTime": "66780", "duratonTime": "32000", "priority": "5", "regions": {"GeographicalPat
h": {"laneWidth": "5000", "directionality": {"both": ""}, "closedPath": {"false": ""}, "direction": "1111111000000000", "description": {"geo
metry": {"direction": "1111111111111111", "circle": {"radius": "1", "units": {"mile": ""}, "center": {"lat": "402401042", "long": "-74275569
3"}}}}, "name": "NJDOTLAB", "id": {"region": "0", "id": "0"}, "anchor": {"lat": "402401042", "long": "-742755693"}}}, "sspMsgRights1": "0",
"content": {"advisory": {"SEQUENCE": [{"item": {"itis": "5906"}}, {"item": {"itis": "4868"}}]}}, "msgId": {"roadSignID": {"position": {"lat"
: "402401042", "long": "-742755693"}, "viewAngle": "1111111111111111", "mutcdCode": {"warning": ""}}}, "frameType": {"advisory": ""}, "start
Year": "2024", "sspLocationRights": "1", "sspMsgRights2": "0", "sspTimRights": "1"}}}}}}\n'
b'{"MessageFrame": {"messageId": "31", "value": {"TravelerInformation": {"msgCnt": "1", "timeStamp": "66780", "packetID": "00 00 00 00 00 21
 71 BE 75", "dataFrames": {"TravelerDataFrame": {"sspTimRights": "1", "startYear": "2024", "sspLocationRights": "1", "sspMsgRights1": "0", "
sspMsgRights2": "0", "content": {"advisory": {"SEQUENCE": [{"item": {"itis": "5906"}}, {"item": {"itis": "4868"}}]}}, "frameType": {"advisor
y": ""}, "msgId": {"roadSignID": {"position": {"long": "-742755693", "lat": "402401042"}, "viewAngle": "1111111111111111", "mutcdCode": {"wa
rning": ""}}}, "startTime": "66780", "duratonTime": "32000", "priority": "5", "regions": {"GeographicalPath": {"id": {"region": "0", "id": "
0"}, "anchor": {"lat": "402401042", "long": "-742755693"}, "laneWidth": "5000", "directionality": {"both": ""}, "closedPath": {"false": ""},
 "direction": "1111111000000000", "description": {"geometry": {"direction": "1111111111111111", "circle": {"radius": "1", "units": {"mile":
""}, "center": {"lat": "402401042", "long": "-742755693"}}}}, "name": "NJDOTLAB"}}}}}}}}\n'
```


Figure 54. TIM Message (JER) Reception Results


```
TEST: {'messageId': 31, 'value': {'msgCnt': 1, 'timeStamp': 66780, 'packetID': '00000000002171BE75', 'dataFrames': [{'sspTimRights': 1, 'fra
meType': 'advisory', 'msgId': {'roadSignID': {'position': {'lat': 402401042, 'long': -742755693}, 'viewAngle': 'FFFF', 'mutcdCode': 'warning
'}}, 'startYear': 2024, 'startTime': 66780, 'duratonTime': 32000, 'priority': 5, 'sspLocationRights': 1, 'regions': [{'name': 'NJDOTLAB', 'i
d': {'region': 0, 'id': 0}, 'anchor': {'lat': 402401042, 'long': -742755693}, 'laneWidth': 5000, 'directionality': 'both', 'closedPath': Fal
se, 'direction': 'FE00', 'description': {'geometry': {'direction': 'FFFF', 'circle': {'center': {'lat': 402401042, 'long': -742755693}, 'rad
ius': 1, 'units': 'mile'}}}}], 'sspMsgRights1': 0, 'sspMsgRights2': 0, 'content': {'advisory': [{'item': {'itis': 5906}}, {'item': {'itis':
4868}}]}}]}}
TEST: {'messageId': 31, 'value': {'msgCnt': 1, 'timeStamp': 66780, 'packetID': '00000000002171BE75', 'dataFrames': [{'sspTimRights': 1, 'fra
meType': 'advisory', 'msgId': {'roadSignID': {'position': {'lat': 402401042, 'long': -742755693}, 'viewAngle': 'FFFF', 'mutcdCode': 'warning
'}}, 'startYear': 2024, 'startTime': 66780, 'duratonTime': 32000, 'priority': 5, 'sspLocationRights': 1, 'regions': [{'name': 'NJDOTLAB', 'i
d': {'region': 0, 'id': 0}, 'anchor': {'lat': 402401042, 'long': -742755693}, 'laneWidth': 5000, 'directionality': 'both', 'closedPath': Fal
se, 'direction': 'FE00', 'description': {'geometry': {'direction': 'FFFF', 'circle': {'center': {'lat': 402401042, 'long': -742755693}, 'rad
ius': 1, 'units': 'mile'}}}}], 'sspMsgRights1': 0, 'sspMsgRights2': 0, 'content': {'advisory': [{'item': {'itis': 5906}}, {'item': {'itis':
4868}}]}}]}}
TEST: {'messageId': 31, 'value': {'msgCnt': 1, 'timeStamp': 66780, 'packetID': '00000000002171BE75', 'dataFrames': [{'sspTimRights': 1, 'fra
meType': 'advisory', 'msgId': {'roadSignID': {'position': {'lat': 402401042, 'long': -742755693}, 'viewAngle': 'FFFF', 'mutcdCode': 'warning
'}}, 'startYear': 2024, 'startTime': 66780, 'duratonTime': 32000, 'priority': 5, 'sspLocationRights': 1, 'regions': [{'name': 'NJDOTLAB', 'i
d': {'region': 0, 'id': 0}, 'anchor': {'lat': 402401042, 'long': -742755693}, 'laneWidth': 5000, 'directionality': 'both', 'closedPath': Fal
se, 'direction': 'FE00', 'description': {'geometry': {'direction': 'FFFF', 'circle': {'center': {'lat': 402401042, 'long': -742755693}, 'rad
ius': 1, 'units': 'mile'}}}}], 'sspMsgRights1': 0, 'sspMsgRights2': 0, 'content': {'advisory': [{'item': {'itis': 5906}}, {'item': {'itis':
4868}}]}}]}}
```


Figure 55. TIM Message (UPER) Reception Results (Decoded)

Table 15. DRT-003: Data Reception Test for SPaT Data

<table>
<tr><td>Test No: DRT-3</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Data Reception Test (DRT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details:</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify that SPaT messages are being received by both computer and mobile device, as the first step for further process and development.</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the following tests have passed successfully:<br>a. IFT 001<br>b. IFT 002<br>c. IFT 003<br>d. IFT 004<br>e. IFT 005<br>f. IFT 006<br>2. Ensure the MQTT server is up and running</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Run <MQTT_Receiver.py> on the computer devices.<br>2. Open the “SmartMobi” application on the mobile devices and press “start” button<br>Example message:<br>{"MessageFrame":{"messageId":"19","value":{"SPAT":{"intersections":{"IntersectionState":{"status":"0000001000000000","moy":"25762","timeStamp":"32618","states":{"MovementState":[{"signalGroup":"1","state-time-speed":{"MovementEvent":{"eventState":{"stop-And-Remain":""},"timing":{"minEndTime":"13836","maxEndTime":"13895"}}}},{"state-time-speed":{"MovementEvent":{"eventState":{"stop-And-Remain":""},"timing":{"minEndTime":"13986","maxEndTime":"14145"}}},"signalGroup":"2"},{"signalGroup":"3","state-time-speed":{"MovementEvent":{"eventState":{"permissive-Movement-Allowed":""},"timing":{"minEndTime":"13536","maxEndTime":"13537"}}}},{"signalGroup":"4","state-time-speed":{"MovementEvent":{"eventState":{"stop-And-Remain":""},"timing":{"minEndTime":"13586","maxEndTime":"13587"}}}},{"state-time-speed":{"MovementEvent":{"eventState":{"stop-And-Remain":""},"timing":{"minEndTime":"13836","maxEndTime":"13895"}}},"signalGroup":"5"},{"state-time-speed":{"MovementEvent":{"eventState":{"stop-And-Remain":""},"timing":{"minEndTime":"13986","maxEndTime":"14145"}}},"signalGroup":"6"},{"signalGroup":"7","state-time-</td></tr>
</table>

<table>
<tr><td colspan="2">speed":{"MovementEvent":{"eventState":{"permissive-Movement-Allowed":""},"timing":{"minEndTime":"13536","maxEndTime":"13587"}}}},{"signalGroup":"8","state-time-speed":{"MovementEvent":{"eventState":{"stop-And-Remain":""},"timing":{"minEndTime":"13586","maxEndTime":"13637"}}}},{"signalGroup":"9","state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"minEndTime":"36001","maxEndTime":"36001"}}}},{"state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"minEndTime":"36001","maxEndTime":"36001"}}},"signalGroup":"10"},{"signalGroup":"11","state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"minEndTime":"36001","maxEndTime":"36001"}}}},{"state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"minEndTime":"36001","maxEndTime":"36001"}}},"signalGroup":"12"},{"signalGroup":"13","state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"minEndTime":"36001","maxEndTime":"36001"}}}},{"signalGroup":"14","state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"minEndTime":"36001","maxEndTime":"36001"}}}},{"signalGroup":"15","state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"maxEndTime":"36001","minEndTime":"36001"}}}},{"state-time-speed":{"MovementEvent":{"eventState":{"dark":""},"timing":{"minEndTime":"36001","maxEndTime":"36001"}}},"signalGroup":"16"}]},"id":{"id":"10004"},"revision":"77"}}}}}</td></tr>
<tr><td>Expected Results:<br>1. SPaT messages are being displayed on command prompt panel, indicating that SPaT messages are being received by desktop computer<br>2. SPaT messages are being displayed on Android phone screen, indicating that SPaT messages are being received by the Android device.</td><td>Pass ☒ Fail ☐<br><br>Notes:</td></tr>
<tr><td colspan="2">Remarks:</td></tr>
</table>

```
b'{"MessageFrame": {"messageId": "19", "value": {"SPAT": {"intersections": {"IntersectionState": {"id": {"id": "10004"}, "revision": "100",
"status": "0000001000000000", "moy": "114302", "timeStamp": "39110", "states": {"MovementState": [{"signalGroup": "1", "state-time-speed": {
"MovementEvent": {"timing": {"minEndTime": "1913", "maxEndTime": "2011"}, "eventState": {"stop-And-Remain": ""}}}}, {"state-time-speed": {"M
ovementEvent": {"eventState": {"stop-And-Remain": ""}, "timing": {"minEndTime": "2063", "maxEndTime": "2261"}}}, "signalGroup": "2"}, {"sign
alGroup": "3", "state-time-speed": {"MovementEvent": {"eventState": {"permissive-Movement-Allowed": ""}, "timing": {"maxEndTime": "1653", "m
inEndTime": "1613"}}}}, {"signalGroup": "4", "state-time-speed": {"MovementEvent": {"eventState": {"stop-And-Remain": ""}, "timing": {"minEn
dTime": "1663", "maxEndTime": "1703"}}}}, {"signalGroup": "5", "state-time-speed": {"MovementEvent": {"eventState": {"stop-And-Remain": ""},
 "timing": {"minEndTime": "1913", "maxEndTime": "2011"}}}}, {"signalGroup": "6", "state-time-speed": {"MovementEvent": {"eventState": {"stop
-And-Remain": ""}, "timing": {"minEndTime": "2063", "maxEndTime": "2261"}}}}, {"signalGroup": "7", "state-time-speed": {"MovementEvent": {"e
ventState": {"permissive-Movement-Allowed": ""}, "timing": {"minEndTime": "1613", "maxEndTime": "1703"}}}}, {"state-time-speed": {"MovementE
vent": {"eventState": {"stop-And-Remain": ""}, "timing": {"minEndTime": "1663", "maxEndTime": "1753"}}}, "signalGroup": "8"}, {"signalGroup"
: "9", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timing": {"minEndTime": "36001", "maxEndTime": "36001"}}}}, {"sig
nalGroup": "10", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timing": {"maxEndTime": "36001", "minEndTime": "36001"}
}}}, {"signalGroup": "11", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timing": {"minEndTime": "36001", "maxEndTime"
: "36001"}}}}, {"signalGroup": "12", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timing": {"maxEndTime": "36001", "m
inEndTime": "36001"}}}}, {"signalGroup": "13", "state-time-speed": {"MovementEvent": {"timing": {"minEndTime": "36001", "maxEndTime": "36001
"}, "eventState": {"dark": ""}}}}, {"signalGroup": "14", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timing": {"minE
ndTime": "36001", "maxEndTime": "36001"}}}}, {"signalGroup": "15", "state-time-speed": {"MovementEvent": {"eventState": {"dark": ""}, "timin
g": {"minEndTime": "36001", "maxEndTime": "36001"}}}}, {"signalGroup": "16", "state-time-speed": {"MovementEvent": {"eventState": {"dark": "
"}, "timing": {"minEndTime": "36001", "maxEndTime": "36001"}}}}]}}}}}}}}\n'
```


Figure 56. SPaT Message (JER) Reception Results


```
TEST: {'messageId': 19, 'value': {'intersections': [{'id': {'id': 10004}, 'revision': 37, 'status': '0200', 'moy': 114202, 'timeStamp': 3038
7, 'states': [{'signalGroup': 1, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13571, 'maxEndTime': 13575}
}]}, {'signalGroup': 2, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13721, 'maxEndTime': 13825}}]}, {'si
gnalGroup': 3, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13921, 'maxEndTime': 14075}}]}, {'signalGroup
': 4, 'state-time-speed': [{'eventState': 'permissive-Movement-Allowed', 'timing': {'minEndTime': 13521, 'maxEndTime': 13525}}]}, {'signalGr
oup': 5, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13571, 'maxEndTime': 13575}}]}, {'signalGroup': 6,
'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13721, 'maxEndTime': 13825}}]}, {'signalGroup': 7, 'state-ti
me-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13921, 'maxEndTime': 14075}}]}, {'signalGroup': 8, 'state-time-speed'
: [{'eventState': 'permissive-Movement-Allowed', 'timing': {'minEndTime': 13513, 'maxEndTime': 13517}}]}, {'signalGroup': 9, 'state-time-spe
ed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 10, 'state-time-speed': [{'eventState'
: 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 11, 'state-time-speed': [{'eventState': 'dark', 'timing':
 {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 12, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 360
01, 'maxEndTime': 36001}}]}, {'signalGroup': 13, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 3
6001}}]}, {'signalGroup': 14, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalG
roup': 15, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 16, 'state-t
ime-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}]}]}}
TEST: {'messageId': 19, 'value': {'intersections': [{'id': {'id': 10004}, 'revision': 38, 'status': '0200', 'moy': 114202, 'timeStamp': 3078
6, 'states': [{'signalGroup': 1, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13575, 'maxEndTime': 13575}
}]}, {'signalGroup': 2, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13725, 'maxEndTime': 13825}}]}, {'si
gnalGroup': 3, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13925, 'maxEndTime': 14075}}]}, {'signalGroup
': 4, 'state-time-speed': [{'eventState': 'permissive-Movement-Allowed', 'timing': {'minEndTime': 13525, 'maxEndTime': 13525}}]}, {'signalGr
oup': 5, 'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13575, 'maxEndTime': 13575}}]}, {'signalGroup': 6,
'state-time-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13725, 'maxEndTime': 13825}}]}, {'signalGroup': 7, 'state-ti
me-speed': [{'eventState': 'stop-And-Remain', 'timing': {'minEndTime': 13925, 'maxEndTime': 14075}}]}, {'signalGroup': 8, 'state-time-speed'
: [{'eventState': 'permissive-Movement-Allowed', 'timing': {'minEndTime': 13517, 'maxEndTime': 13517}}]}, {'signalGroup': 9, 'state-time-spe
ed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 10, 'state-time-speed': [{'eventState'
: 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 11, 'state-time-speed': [{'eventState': 'dark', 'timing':
 {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 12, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 360
01, 'maxEndTime': 36001}}]}, {'signalGroup': 13, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 3
6001}}]}, {'signalGroup': 14, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalG
roup': 15, 'state-time-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}, {'signalGroup': 16, 'state-t
ime-speed': [{'eventState': 'dark', 'timing': {'minEndTime': 36001, 'maxEndTime': 36001}}]}]}]}}
```


Figure 57. SPaT Message (UPER) Reception Results (Decoded)

Table 16. DRT-004: Data Reception Test for PSM Data

<table>
<tr><td>Test No: DRT-4</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td colspan="2">Tester: Bowen Geng</td></tr>
<tr><td colspan="6">Test Category: Data Reception Test (DRT)</td></tr>
<tr><td colspan="6">Notes:</td></tr>
<tr><td colspan="6">Details:</td></tr>
<tr><td colspan="6">Test Purpose: The purpose of this test is to verify that PSM messages are being received by both computer and mobile device, as the first step for further process and development.</td></tr>
<tr><td colspan="6">Test Setup:<br>1. Verify the following tests have passed successfully:<br>a. IFT 001<br>b. IFT 002<br>c. IFT 003<br>d. IFT 004<br>e. IFT 005<br>f. IFT 006<br>2. Ensure the MQTT server is up and running</td></tr>
<tr><td colspan="6">Test Procedure:<br>1. Run <MQTT_Receiver.py> on the computer devices.<br>2. Open the “SmartMobi” application on the mobile devices and press “start” button<br>Example message:<br>{"MessageFrame":{"messageId":"32","value":{"PersonalSafetyMessage":{"heading":"14320","crossState":{"true":""},"msgCnt":"92","id":"50485654","position":{"lat":"402401761","long":"-742755377","elevation":"0"},"accuracy":{"semiMajor":"255","semiMinor":"255","orientation":"65355"},"speed":"100","crossRequest":{"false":""},"basicType":{"aPEDESTRIAN":""},"secMark":"65355"}}}}</td></tr>
<tr><td colspan="5">Expected Results:</td><td>Pass ☒ Fail ☐</td></tr>
</table>

| | |
|---|---|
| 1. PSM messages are being displayed on command prompt panel, indicating that PSM messages are being received by desktop computer.<br>2. PSM messages are being displayed on Android phone screen, indicating that PSM messages are being received by the Android device. | Notes: |
| Remarks: | |


```
b'\n\x07\x08\x04\x12\x03CAM\x12\x0b\x08\xec\xac\xec\xaf\x06\x10\x80\xe8\x92&\x1a\x9a\x03{"MessageFrame": {"messageId": "32", "value": {"Pers
onalSafetyMessage": {"secMark": "5752", "msgCnt": "74", "id": "50 50 55 50", "position": {"lat": "402711685", "long": "-747811936", "elevati
on": "0"}, "basicType": {"aPEDESTRIAN": ""}, "speed": "49", "heading": "815", "crossRequest": {"false": ""}, "crossState": {"true": ""}, "ac
curacy": {"semiMajor": "255", "semiMinor": "255", "orientation": "65355"}}}}}\n'
b'\n\x07\x08\x04\x12\x03CAM\x12\x0b\x08\xee\xac\xec\xaf\x06\x10\x80\xd6\x9e$\x1a\x9b\x03{"MessageFrame": {"messageId": "32", "value": {"Pers
onalSafetyMessage": {"id": "50 50 55 50", "accuracy": {"orientation": "65355", "semiMajor": "255", "semiMinor": "255"}, "speed": "31", "cros
sRequest": {"false": ""}, "crossState": {"true": ""}, "msgCnt": "26", "secMark": "6087", "position": {"lat": "402711706", "long": "-74781196
5", "elevation": "0"}, "heading": "1040", "basicType": {"aPEDESTRIAN": ""}}}}}\n'
b'\n\x07\x08\x04\x12\x03CAM\x12\x0b\x08\xef\xac\xec\xaf\x06\x10\x80\xc4\xaa"\x1a\x9b\x03{"MessageFrame": {"messageId": "32", "value": {"Pers
onalSafetyMessage": {"basicType": {"aPEDESTRIAN": ""}, "crossRequest": {"false": ""}, "crossState": {"true": ""}, "heading": "515", "secMark
": "26164", "msgCnt": "74", "id": "50 50 55 50", "position": {"lat": "402711731", "long": "-747812014", "elevation": "0"}, "accuracy": {"sem
iMajor": "255", "semiMinor": "255", "orientation": "65355"}, "speed": "41"}}}}\n'
b'\n\x07\x08\x04\x12\x03CAM\x12\x0b\x08\xf6\xac\xec\xaf\x06\x10\x80\xc4\xaa"\x1a\x9b\x03{"MessageFrame": {"messageId": "32", "value": {"Pers
onalSafetyMessage": {"speed": "49", "heading": "518", "crossRequest": {"false": ""}, "msgCnt": "15", "position": {"lat": "402711706", "long"
: "-747811993", "elevation": "0"}, "accuracy": {"semiMajor": "255", "semiMinor": "255", "orientation": "65355"}, "crossState": {"true": ""},
 "basicType": {"aPEDESTRIAN": ""}, "secMark": "26011", "id": "50 50 55 50"}}}}\n'
```


Figure 58. PSM (JER) Reception Results


```
Raw Message:  b'\n\x07\x08\x04\x12\x03CAM\x12\x0b\x08\xb2\xa1\x91\xb0\x06\x10\x80\x95\xf5*\x1a\x1f\x00 \x1c\x03\x00\x038\x00]%%UIM\xa5\xcd\xc3>\xb7\x1d\xc0\x10\
x00\xff\xff\xffK\x01\x10\t\x94'

Sliced Message: b'\x00 \x1c\x03\x00\x038\x00]%%UIM\xa5\xcd\xc3>\xb7\x1d\xc0\x10\x00\xff\xff\xffK\x01\x10\t\x94'

Decoded: {'messageId': 32, 'value': {'basicType': 'aPEDESTRIAN', 'secMark': 39936, 'msgCnt': 23, 'id': '49495552', 'position': {'lat': 402711747, 'long': -74781
1903, 'elevation': 0}, 'accuracy': {'semiMajor': 255, 'semiMinor': 255, 'orientation': 65355}, 'speed': 34, 'heading': 153, 'crossRequest': False, 'crossState':
 True}}
```


Figure 59. PSM (UPER) Decoding Results (Decoded)

Table 17. DRT-005: Data Reception Test on Rutgers/Rowan OBU Tablet

<table>
<tr><td>Test No: DRT-5</td><td>Revision: 2.0</td><td>Author:</td><td>Date: 04/29/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Data Reception Test (DRT)</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details:</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify that messages are being received by V2X applications on tablet</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify the following tests have passed successfully:<br>a. IFT 001<br>b. IFT 002<br>c. IFT 003<br>d. IFT 004<br>e. IFT 005<br>f. IFT 006<br>2. Ensure the MQTT server is up and running<br>3. Ensure the lab physical RSU is running</td></tr>
<tr><td colspan="5">Test Procedure:<br>Run Commsignia Foresight HMI application on the tablet.<br>Run Iteris V2X Connect application on the tablet</td></tr>
<tr><td colspan="3">Expected Results:<br>MAP, SPaT, and PSM messages are being displayed on visualized intersection or other screen interface</td><td colspan="2">Pass ☒ Fail ☐<br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

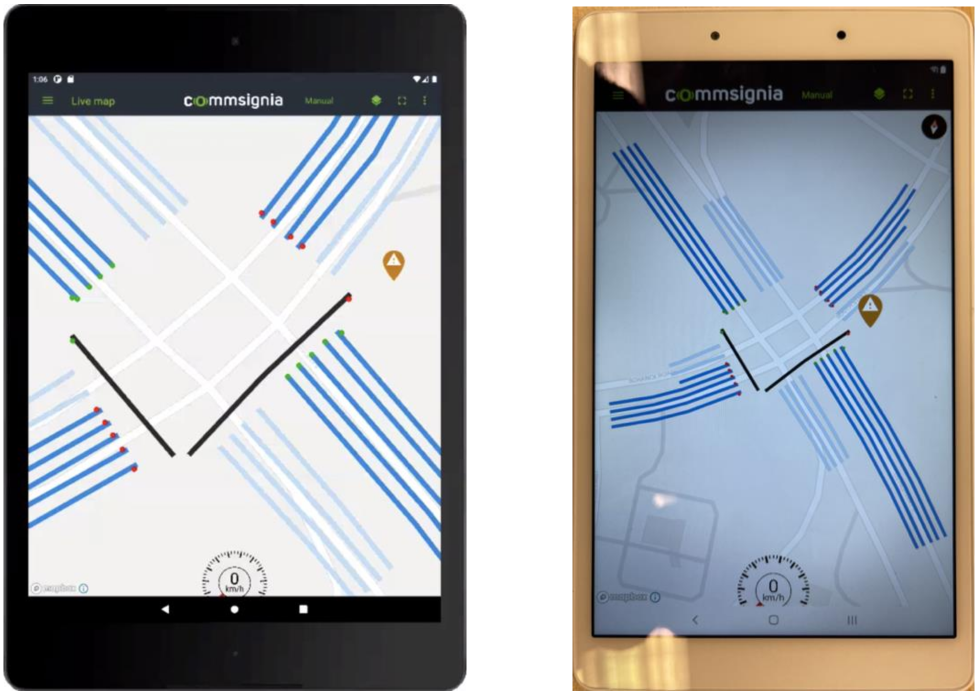


Figure 60. Commsignia Foresight HMI (MAP, SPaT, and TIM)

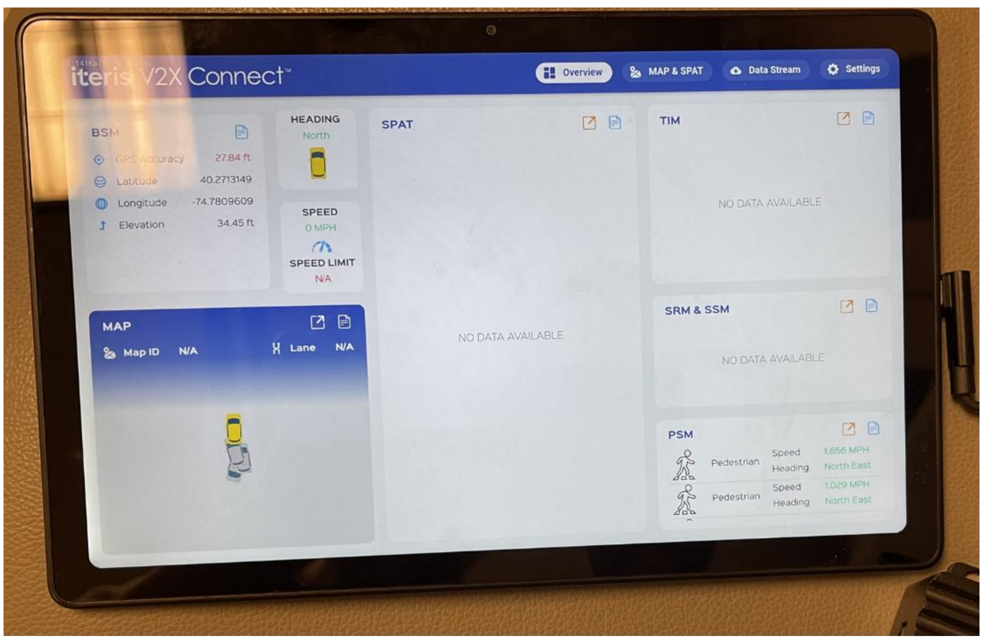


Figure 61. Iteris V2X Connect (PSM from LAB Physical RSU)

***Validation Testing***

Table 18. VT-001: Validation Test for MAP Data

<table>
<tr><td>Test No: VT-1</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Validation Test</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details:</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify that MAP messages are valid</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify DRT-1 has passed</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Run <MAP Visualization Python Code> on the tested computer devices.</td></tr>
<tr><td colspan="2">Expected Results:<br>1. MAP messages are being displayed on anaconda prompt panel, indicating that MAP messages are being received by computer devices<br>2. MAP messages are being visualized and plotted, showing the geometry and lane groups of the tested intersection</td><td colspan="3">Pass ☒ Fail ☐<br><br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

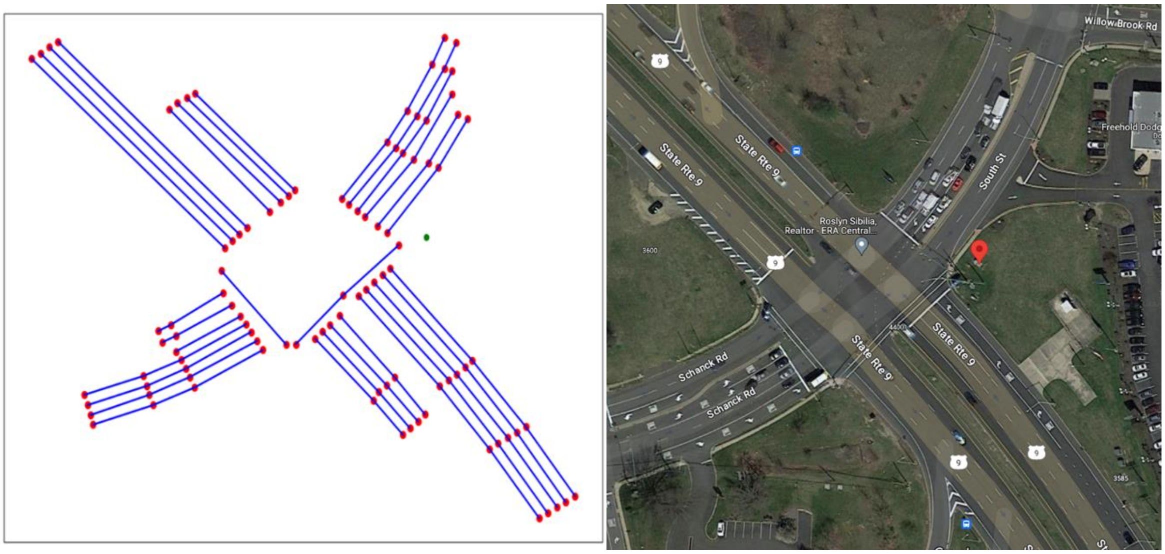


Figure 62. MAP Message Visualization Results (Rt. 9 @ Schanck Rd.)

Table 19. VT-002: Validation Test for SPaT Data

<table>
<tr><td>Test No: VT-2</td><td>Revision: 2.0</td><td>Author:</td><td>Date: 04/03/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Validation Test</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details:</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify that MAP messages are valid</td></tr>
<tr><td colspan="5">Test Setup:<br>1. Verify DRT-3 has passed</td></tr>
<tr><td colspan="5">Test Procedure:<br>1. Run <SPaT Visualization Python Code> on the tested computer devices.</td></tr>
<tr><td colspan="2">Expected Results:<br>1. SPaT messages are being displayed on anaconda prompt panel, indicating that SPaT messages are being received by computer devices.<br>2. SPaT messages are being visualized and plotted, showing the signal phase and timing of the tested intersection</td><td colspan="3">Pass ☒ Fail ☐<br><br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

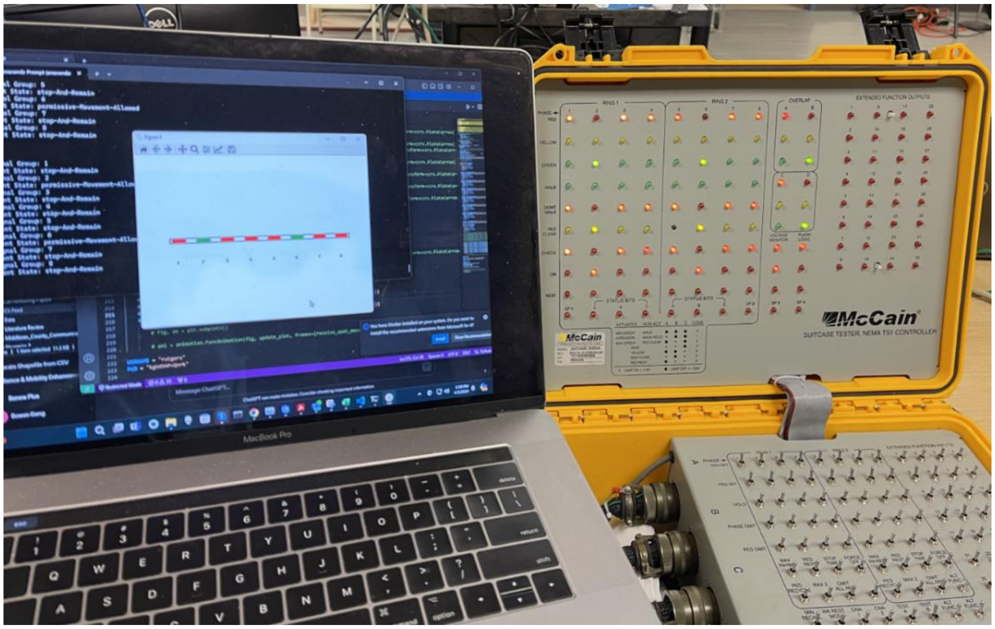


Figure 63. SPaT Message Visualization (Left: Received Message, Right: controller)

Table 20. VT-003: Validation Test for PSM Data

<table>
<tr><td>Test No: VT-3</td><td>Revision: 1.0</td><td>Author:</td><td>Date: 03/20/2024</td><td>Tester: Bowen Geng</td></tr>
<tr><td colspan="5">Test Category: Validation Test</td></tr>
<tr><td colspan="5">Notes:</td></tr>
<tr><td colspan="5">Details:</td></tr>
<tr><td colspan="5">Test Purpose: The purpose of this test is to verify that PSM messages are valid</td></tr>
<tr><td colspan="5">Test Setup:<br>2. Verify DRT-4 has passed</td></tr>
<tr><td colspan="5">Test Procedure:<br>2. Run <PSM Visualization Python Code> on the tested computer devices.</td></tr>
<tr><td colspan="2">Expected Results:<br>3. PSM messages are being displayed on anaconda prompt panel, indicating that PSM messages are being received by computer devices.<br>4. PSM messages are being visualized and plotted, showing the pedestrian positioning in the lab.</td><td colspan="3">Pass ☒ Fail ☐<br><br>Notes:</td></tr>
<tr><td colspan="5">Remarks:</td></tr>
</table>

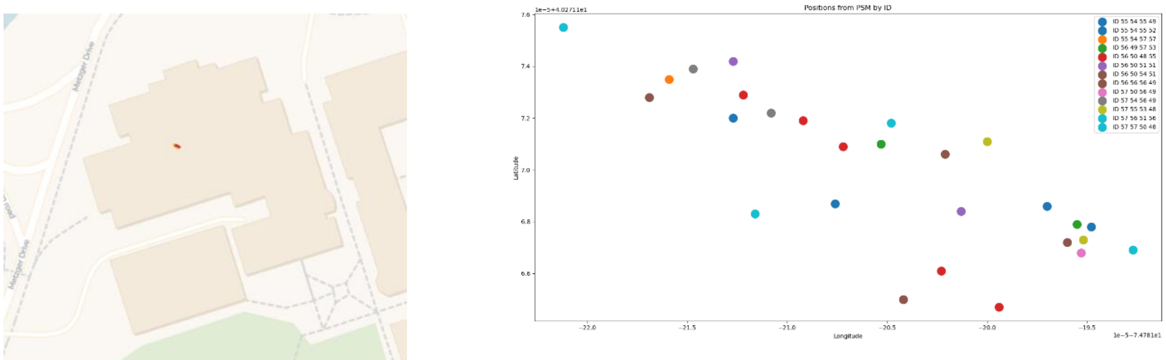


Figure 64. PSM Visualization (From TCNJ lab at Armstrong Hall)