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REAL-TIME TRAFFIC SIGNAL SYSTEM PERFORMANCE MEASUREMENT
PHASE II: DATA AND FUNCTIONALITY ENHANCEMENT, LARGE SCALE DEPLOYMENT, CONNECTED AND AUTONOMOUS VEHICLES INTEGRATION
FINAL REPORT

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Submitted by

Peter J. Jin, Ph.D.
Associate Professor
Department of Civil and Environmental Engineering
Rutgers, The State University of New Jersey

Tianya Zhang,
Graduate Research Assistant,
Department of Civil and Environmental Engineering
Rutgers, The State University of New Jersey

Thomas M. Brennan JR., Ph.D., P.E.
Professor
Department of Civil Engineering
The College of New Jersey

Mohammad Jalayer, Ph.D.
Associate Professor
Department of Civil and Environmental Engineering
Rowan University

NJDOT Research Project Manager –
Priscilla Ukpah

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16. Abstract

Traffic signal performance measurement and visualization provide insights as operational tools to help traffic management centers (TMC) get more paybacks from infrastructure investment. However, evaluating and monitoring signal performance is challenging in real-time, which requires immediate data collection and analysis capability. As part of the implementation of the FHWA EDC (Every Day Counts) 2.0 toolboxes, NJDOT is working the research team consisting of Rutgers University, The College of New Jersey, and Rowan University to explore the deployment strategies and conduct pilot deployment of the Automated Traffic Signal Performance Measure (ATSPM) system with existing and planned NJDOT arterial management resources. 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 PCDs (Purdue Coordination Diagrams), 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 (real-time traffic signal performance measure) with Connected and Automated Vehicle technologies at intersections in collaboration with NJCTII (New Jersey Connected Technology Integration and Implementation) program.

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EXECUTIVE SUMMARY

Background

Traffic signal performance measurement and visualization provide insights as operational tools to help traffic management centers (TMC) get more paybacks from infrastructure investment. However, evaluating and monitoring signal performance is challenging in real-time, which requires immediate data collection and analysis capability. As part of the implementation of the FHWA EDC (Every Day Counts) 2.0 toolboxes, NJDOT is working with the research team consisting of Rutgers University, The College of New Jersey, and Rowan University to explore the deployment strategies and conduct pilot deployment of the Automated Traffic Signal Performance Measure (ATSPM) system with existing and planned NJDOT arterial management resources. Furthermore, with the development of Connected Vehicle (CV) technology and its nationwide piloting and deployment, opportunities emerge for potentially improving real-time arterial operations through the generation, delivery, and application support by using SAE (Society of Automotive Engineers), J3524 SPaT (Signal Phase and Timing), MAP, BSM (Basic Safety Message), PSM (Pedestrian Safety Message), and TIM (Traffic Information Messages).

In the project's first phase, the team successfully developed a software toolbox, NJDOT ATSPM 1.0, that converts the event output data from SCATS and InSync ATSC (Adaptive Traffic Signal Control) Systems into event data. The generated event data are consistent with the input data needed by the FHWA Automated Traffic Signal Performance Measures (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 ATSPM performance metrics. Those new performance metrics include PCDs (Purdue Coordination Diagrams), 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 (real-time traffic signal performance measure) with Connected and Automated Vehicle technologies at intersections.

Research Objectives

NJDOT arterial management operators can then 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:

1. Review the state-of-the-art practice of RT-SPM (real-time signal performance measurement): Conduct a comprehensive nationwide review of existing national guidelines and recommendations on SPM systems and identify existing public and commercial SPM platforms.
2. Review the state-of-the-art practice of Roadside Units (RSU)/ On-board Units (OBU) enabled Connected Automated Vehicle technology: A review of existing CAV (Connected and Autonomous Vehicles) pilots and test sites on V2X(Vehicle-to-

Everything)-based intersection safety and mobility applications to learn their success stories and lessons.

3. Obtain feedback from NJDOT regarding needs and challenges in implementing SPM Systems: Organize stakeholder meetings to identify the needs and challenges of deploying ATSPM and V2X applications with the considerations for NJDOT arterial signal operations, evaluation, and maintenance.
4. Review the existing data sources, API integration requirements, and potentials to develop more signal performance metrics in RT-SPM systems for NJDOT: The project's outcome is used to develop an actionable implementation plan for NJDOT to deploy the developed RT-SPM systems and CAV applications with ATSC controllers.
5. Pilot testing and deployment of a prototype of RT-SPM on a statewide scale and different types of controllers: Testing the prototype RT-SPM toolboxes with NJDOT to develop an actionable implementation plan so that the system can be deployed based on existing data sources and extendible with future and planned data sources.
6. Conduct ATSC Connected and Autonomous Vehicle (CAV) application development and pilot testing: Evaluating and pilot-testing the integration of the CV RSUs and OBUs with the existing ATSC systems (SCATS and InSync), which are currently deployed on New Jersey arterial corridors.

The outcome of this project can 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 2.0 overcomes the challenge of evaluating and monitoring signal performance in real-time through immediate data collection and analysis capability. During the second phase of the RT-SPM project, the designed system was tested on a large scale. It enabled more intersection-specific performance to identify deficiencies, support decision-making proactively, and efficiently manage the tuning process of the signal timing plan. Another critical research outcome of the deployment of CAV technologies at NJDOT arterial intersections is to improve safety and efficiency at signalized intersections. The following is a detailed description of those benefits.

1. ***Traffic Operations and Maintenance***
    a. NJDOT ATSPM 2.0 provides extended arterial performance metrics for large-scale arterial signal system management. During Phase 2, the team utilizes multiple sources of traffic data to show additional performance metrics, such as Arriving On Green (AoG) in PCD, speed, volume, Purdue Link Pivot, and Purdue Split Failure. In addition, the testing scale extends to all existing ATSC signal-controlled corridors with both InSync and SCATS, such as NJ-18, US1, US-130, and NJ168.
    b. CAV-enabled Intersection allows real-time high-resolution vehicle data collection and signals control feedback. CV technology can potentially report real-time vehicle presence and their trajectories for signal performance assessment and feedback control. Those CV trajectory data can be used to assess vehicle delay and arrival patterns using PCDs, build arrival flow profiles, and estimate queue lengths. In addition, CAV-enabled intersection control will allow microscopic coordination and feedback between vehicles and enabled intersections.

2. ***Traffic Safety and Mobility***

a. NJDOT ATSPM 2.0 provides NJDOT with more performance metrics for arterial traffic signals with improved integration with SCATS's APIs and sensors data. NJDOT ATSPM 2.0 allows the NJDOT to conduct comprehensive assessment and monitoring of their arterial corridors and further accelerate identifying, assessing, and addressing signal control and maintenance problems.
b. CAV-enabled intersections will facilitate personalized intersection driving assistance and smart intersection applications to enhance arterial operations, safety, and mobility which can also be applied to pedestrian movements. Using CV technology such as Left Turn Assist (LTA) and Intersection Movement Assist (IMA), more than 90% of crash types can be avoided with CV applications. Connected Automated Vehicles can better understand surrounding objects, terrain, and the environment through real-time traffic information communication.

3. Strategic Planning

a. The development of RT-SPM and the adapting and deploying of ATSPM with existing NJ ATSC systems follows the FHWA EDC (Every Day Counts) Initiative to promote the rapid deployment of proven innovations. NJDOT ATSPM 2.0 helps meet the strategic EDC goal to accelerate the deployment of ATSPM on existing and planned arterial corridors to reduce crashes, injuries, and fatalities, optimize mobility and enhance the quality of life.
b. Data support state initiatives on policy preparation and testing of CAV technologies. The project's outcome is 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: Literature Review: The research team reviewed the state-of-the-art-and-practice review on the latest development in integrating ATSC and ATSPM systems and prevailing intersection CV applications.

Task 2: Stakeholder Meeting/Synthesis: To best align this project team's effort with actionable research outcomes for NJDOT, the research conducted this project with a stakeholder and expert panel of public, private, and academic sectors. The best practices identified and the deployment plan and strategies developed throughout this research project are packaged and disseminated to decision-makers at the technical level (operations and maintenance) and the policy level (decision making regarding future system improvement projects and resource optimization). This project also developed a standalone synthesis report to document and communicated the research outcome. In addition to the technical deliverables, it is envisioned that the stakeholder panel can work with NJDOT towards the deployment of CV systems and ATSPM well after completing the study.

Task 3: ATSPM Multi-source Data and API Integration: The research team explored additional data sources, including Inrix and TRANSCOM travel time data, Wavetronics detector data, Autoscope stopbar detector data, and other video analytic tools to detect vehicles and pedestrians. These additional data sources enable further development of additional performance metrics that cannot be generated using only signal event data without detector data. Mobility and safety performance metrics are explored, such as pedestrian delay times (directly measured in ATSPM), green time extensions (holding green until peds are cleared), and near-misses. The team eventually chose the Autoscope data to develop the traffic sensing models and archiving tools to provide detector data inputs in ATSPM.

Task 4: ATSPM Enhanced Functionality Development: The team extended the performance metrics that can be enabled in ATSPM with the detector data sources used in Task 3. Furthermore, the pedestrian detector data collected from Task 2-3 is used to enable more performance measures related to PED calls and explore the impact on intersection performance (AOG (Arrival on Green), Delay, Travel time), as well as safety performance (close calls, ped extension time, extended green times), and corridor coordination (e.g., link pivot).

Task 5: CAV RSU Integration Experimentation: Collaborating with Jacobs and NJDOT Mobility Engineering team. The research team completed experimentation and documentation of controller-RSU communication at TCNJ laboratories. The team secured necessary hardware systems, including RSU, NJDOT Signal Controllers, project-specific routers or switches, and a controller/RSU testing platform. The team also evaluated controllers' data input/output/login capabilities and the feasibility of Detector Information based on controller/ATC system data output. Testing software such as virtual controller, virtual RSU messaging generation (e.g., SPaT, MAP, RTCM, etc.) applications was acquired. Existing adaptive RSU testing procedures on manuals were validated to ensure the system's wiring, connectivity, and communication were running correctly.

Task 6: NJ DOT ATSPM 2.0 Pilot Testing and Deployment: More sophisticated testing were conducted at a large scale according to the deployment strategy developed in phase one. The pilot testing and deployment consider existing infrastructure and planned infrastructure. Different implementation scenarios are recommended at different stages, including pilot site deployment, corridor deployment, network deployment, and upgrading and maintenance.

Task 7: ATSC CAV Pedestrian Application Deployment and Pilot Testing: In the field experiment, the team worked with NJDOT to deploy and implement the simulated CAV application at US1 at Bakers Basin Road. The team deployed the roadside application at RSUs connecting to the signal controllers. The team used testing vehicles equipped with OBUs to test the vehicle-side CAV applications. An existing in-vehicle data collection application collected dashcam videos, real-time vehicle status, and driver operational data. Corresponding data from the RSU side includes the sensor and signal controller data and RSU SPaT messages. The team also developed performance metrics to evaluate the reliability of communication (e.g., data drops), the efficiency and accuracy of CAV messages, and application functionalities. Comprehensive analysis to make recommendations on feeding CAV applications for NJDOT to deploy.

Task 8: Quarterly and Final Reporting: The team provided technical memos and reports Bi-monthly. The bimonthly report included the latest deliverables, documentation, and tech memo on task results.

Acronyms and Abbreviations

AI	Artificial Intelligence	**OIT**	Office of Information Technology
AMC	Arterial Management Center	**PCD**	Purdue Coordination Diagram
AoG	Arriving On Green	**PPD**	Purdue Phase Diagram
ATCS	Adaptive Traffic Control System	**PSM**	Pedestrian Safety Message
ATMS	Arterial Traffic Management System	**QOD**	Queue-Over-Detector
ATSC	Adaptive Traffic Signal Control	**RCD**	Rutgers Coordination Diagram
ATSPM	Automated Traffic Signal Performance Measures	**ROS**	Robot Operating System
BSM	Basic Safety Message	**RSE**	Roadside Equipment
CAV	Connected and Autonomous Vehicle	**RSU**	Roadside Unit
CCTV	Closed-circuit Television	**RT-SPM**	Real-time Signal Performance Measurement
CV	Connected Vehicle	**SAE**	Society of Automotive Engineers
CV2X	Cellular Vehicle-to-Everythin	**SCMS**	Security Credential Management System
CVPD	Connected Vehicle Pilot Deployment	**SPM**	Signal Performance Measurement
DMS	Dynamic Message Sign	**SPaT**	Signal Phase and Timing
DSRC	Dedicated Short-Range Communications	**STMap**	Spatial Temporal Map
FHWA	Federal Highway Administration	**TIM**	Traffic Information Messages
GOR	Green Occupancy Ratio	**TMC**	Traffic Management Center
INDOT	Indiana Department of Transportation	**TOD**	Time-Of-Day
ISS	Integrity Security Services	**TR**	Traffic Responsive
ITS	Intelligent Transportation Systems	**TRL**	Technology Readiness Level
MSE	Mobility and Systems Engineering	**TTG**	Time To Gap Out
NCDOT	North Carolina Department of Transportation	**TTI**	Texas A&M Transportation Institute
NJDOT	New Jersey Department of Transportation	**UDOT**	Utah Department of Transportation
NPRM	Notice of Proposed Rulemaking	**v/c**	Volume to Capacity
NYCDOT	Newyork City Department of Transportation	**V2I**	Vehicle-to-Infrastructure
OBU	On-board Unit	**V2X**	Vehicle-to-Everything

TASK 1: LITERATURE REVIEW

NJDOT ATSPM 1.0 Summary

ATSPM has many advantages over traditional traffic signal monitoring and management processes. When implementing ATSPM, it is essential to consider those existing, forthcoming, and planned infrastructures. NJDOT is actively deploying adaptive signal control technology on major NJ corridors. Incorporating various adaptive traffic control systems (ATCS) such as InSync and SCATS systems has created a foundation for building real-time performance measures. To implement an ATSPM system successfully in NJ, the research team has accomplished the prototype for the first phase. In Phase 1, the following critical research problems have been investigated:

1. **Create Inventory of Existing NJDOT Arterial Management System**: The team investigated several signal performance systems, including InSync, SCATS, and TRANSCOM fusion application interfaces, and different types of detectors and their availability. The team also conducted an intensive review of the state-of-the-art practice of the ATSPM system and identified ways of migrating the system to NJ.
2. **Identify Performance Metrics and Measurement Methods for NJDOT ATSPM System**: The team has conducted a comprehensive review of SPMs built in the ATSPM system. The team has also investigated customized SPMs generated by the NJDOT detector and travel time data.
3. **Develop System Architecture and Concept of Operations for NJDOT ATSPM System and established a bench test of ATSPM located on TCNJ's campus**. To leverage the existing ATCS system, the team has developed a signal event conversion program to translate SCATS and InSync history log files to event code that ATSPM can recognize.
4. **Real-Time Traffic Signal Data Management Guidelines**. In this project, the research team created a data management manual for the data process. Then, the team validated the outputs through a comprehensive process. The team also completed the test to automatically connect to the ATSPM database using VPN and MSSQL database management system.
5. **Develop Deployment Strategies Considering Existing, Planned, and Future Systems/ Conduct Case Studies of System Deployment**. The team has started pulling one-month data into their platform of ATSPM. Large-scale deployment of this system will be conducted in phase two.

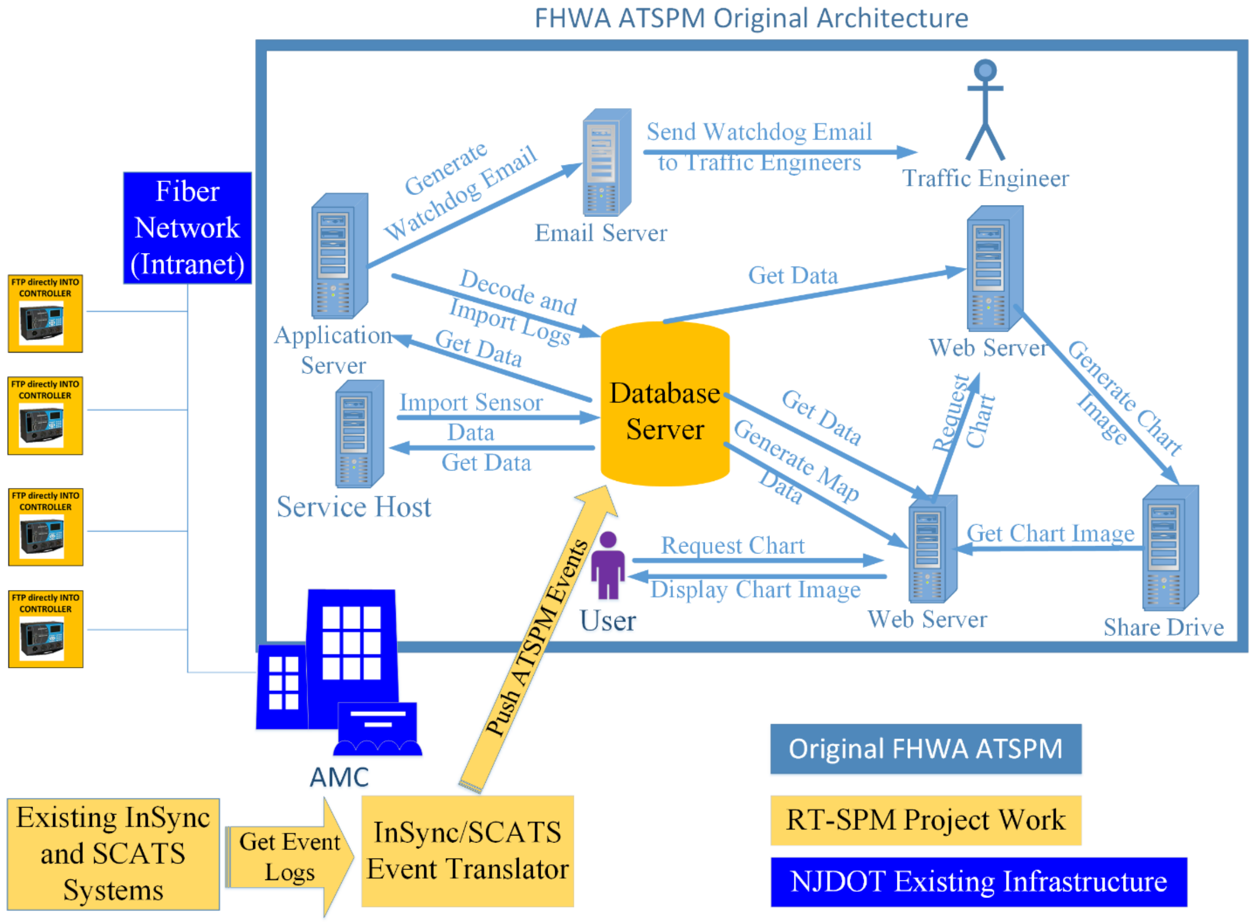


Figure 1. Proposed ATSPM Architecture

The original ATSPMs framework relies on point-to-center communication and a high-resolution controller. In this project, the newly developed ATSPM program can automatically retrieve the controller's logfiles and translate records into standard ATSPM event code. This method is agnostic to the controller type.

The State of Practice of ATSPM in the US

Table 1 lists the ATSPM practices for different states in the US, with information on controller types, event data, detectors, number of signals, and applications.

Table 1. List of ATSPM practices in the US

Agency	Year	Controller	Signal Event Data	Detectors	Number of Signals	Applications
Utah DOT	2012	High-res. controllers	Active Phase, Pedestrian, Phase Control, Detector Events, Preemption Events	Wavetronix SmartSensor Matrix	2178	Signal QA/QC, Optimization/ Retiming
Georgia DOT	2017	High-res. controllers	Active Phase, Pedestrian, Phase Control, Detector Events, Preemption Events	Midblock, Probe data	7812	Signal QA/QC, Optimization/ Retiming, Remote troubleshooting
New Jersey DOT	2017	Low-res. controllers	Active Phase, Pedestrian, Phase Control, Detector* and Preemption* Events	Autoscope Video Detector	122 InSync and SCATS Signals	Signal QA/QC, Optimization/ Retiming, Arterial Operations, Pedestrian Safety
Florida DOT	2018	High-res. Controllers	Active Phase Event, Active Pedestrian Events, Phase Control Events, Detector Events, Preemption Events	Midblock/ Radar	393	Signal QA/QC, Optimization/Retiming, Arterial Operations
Michigan DOT	2017	High-res. controllers	Active Phase, Pedestrian, Phase Control, Detector Events, Preemption Events	Midblock/ Radar	Initially, 22 signals, expand to 40	Signal QA/QC, Optimization/Retiming, Arterial Operations

The traditional signal timing practices that employ modeling software (Highway Capacity Software (HCS) or Synchro software) are time-consuming and labor-intensive because they require a variety of input parameters such as volumes, speeds, and roadway characteristics (Gordon, 2010). These signal timing plans do not incorporate unpredicted traffic events. They are usually retimed at an interval of 30 to 36 months, resulting in outdated timing plans that can increase road user complaints.

In 2005, the Indiana Department of Transportation (INDOT) researched to develop new traffic signal system performance measurements using logged timestamped vehicle detectors and traffic signal controller events, otherwise known as high-resolution data. Day et al. (2008) proposed PCD as a tool for visualizing and evaluating signal performances on a cycle-by-cycle basis, enabling the visual inspection of the concurrence of vehicle platoons within green bands. Day et al. (2012) built a system-in-the-loop simulation to test the effectiveness of performance measures for adaptive signal control. The two objectives of signal control, which include allocating capacity to competing movements and traffic progression along corridors, are examined using two performance measurements created from high-resolution controller events. Four performance measurements were fully explored as follows under five operational strategies: free operation; time-of-day (TOD) operation; TOD operation with ACS-Lite enabled (TOD + ACS); traffic responsive (TR) operation; TR operation with ACS-Lite enabled (TR + ACS).

- The green to cycle (g/C) ratio illustrates changes in how green time was allocated.
- The volume to capacity (v/c) ratio demonstrates whether the degree to which the phase was utilized changed.
- The average delay shows whether this impacted the delay, which provides the system's overall performance.
- The percentage of vehicles AoG shows the progression quality of corridors.

Day et al. (2014) delivered a report for transportation agencies to assist with establishing an active traffic management program to advance the use and implementation of performance measures to manage traffic signal systems. The performance measures presented in this report include metrics for assessing detector health in traffic signal systems and assessing local/system signal control. Remias et al. (2018) examined the benefit-cost ratio of ATSPMs through pilot testing in Michigan. The estimated benefit to the cost ratio of statewide implementing ATSPMs on a centralized system is approximately 25:1, considering travel time reduction, emission reduction, safety benefits, maintenance, and operational benefits. The Michigan DOT pilot implementation report shows that upgrading equipment and installing required components is $4,612.5 per intersection per year (Remias et al., 2018). The NCDOT (North Carolina Department of Transportation) created an implementation matrix to prioritize corridors to implement ATSPM, considering the potential levels of ATSPM implementation. Four factors affecting the readiness to deploy ATSPMs include Central Signal Control, Field Hardware, ATSPM software, and Detection (NCDOT, 2020). Traffic operators are familiar with systems that employ ATSPMs, having identified several shortcomings, such as a lack of data quality control and the intensive resources needed for system-wide management. Huang et al. (2018) created a new tool called intelligent traffic signal performance measurements (ITSPMs) to provide data quality control for ATSPMs and support data-driven traffic monitoring. The proposed ITSPMs employ machine learning methods, traffic flow theory, and visualization to improve state-of-the-art ATSPMs.

Utah DOT, Georgia DOT, and Florida DOT are national leaders deploying ATSPM systems. Many other state or local agencies, including Pennsylvania DOT, Michigan DOT, New Jersey DOT, California DOT, Lake County (Illinois), and Maricopa County (Arizona), are active in including ATSPMs in their traffic management and operation strategies (Atlanta DOT 2019; Gault 2018; Iteris 2020). Implementation lessons learned from different agencies reveal that ATSPM, and its suite of performance metrics and analysis tools, are critical to the adaptive signal control system. Lake County (Illinois) DOT used ATSPM to evaluate and monitor its adaptive traffic controllers. The Lake County DOT found several advantages of evaluating Adaptive Signal Control Systems (InSync and

SCATS) with ATSPMs, including quick response to customer concerns and initial evaluation of new adaptive systems. Many companies also developed their ATSPMs interfaces (e.g., Iteris 2020 and Parsons 2020), promoting multiple applications for traffic operation and intersection-as-a-service. However, the ATSPMs and adaptive signal controllers did not communicate with each other in their process (Grossman, 2013). Chan (2018) conducted a case study in Irvine, California, to test ATSPMs and ATSC. The two systems share many similarities but also differentiate in multiple ways. Combing the ATSPMs with ATSC is still relatively new but shows promise. One big challenge for two signal management systems is the timing and funding incurred by infrastructure upgrades. ATSPMs and adaptive traffic control are increasingly being integrated. Stevanovic (2019) compared ATSPMs and ATSC comprehensively, suggesting that ATSPMs would evolve towards adaptive signal control. Integrating ATSPMs and ASCT with CV technology would fundamentally change information distribution and reshape future traffic control.

Connected Vehicle Equipment and Application Review

FHWA-Sponsored CV Applications Review

CV application prototyping and assessment have focused on FHWA CV research and development activity. As a result of these efforts, more than three dozen CV applications concepts have been developed, many through prototyping and demonstration. The USDOT has published documentation from the more advanced application development efforts, including concepts of operations, system requirements, design documents, algorithms, and source code associated with these prototypes. As a result, CV offers a wide range of applications that can be implemented with crucial vehicle and infrastructure components installed. Table 2 lists the CV applications the USDOT has sponsored. Table 2 also sets forth each CV application's Technology Readiness Level (TRL). The Volpe Center developed the TRL to measure the progress of highway-related technology toward maturity. It is based on a scale originally developed by the National Aeronautics and Space Administration and later adapted by other Federal agencies, notably the Department of Defense. The original TRL scale measured the position of a technology (1 being the lowest score, 9 being the highest score) on a path that starts with basic scientific principles and ends with a mission-deployed system or piece of hardware.

The applications described in Table 2 vary in maturity. The applications with a TRL score of seven (7) are being deployed as part of pilot demonstration projects in Columbus, New York City, Tampa, and Wyoming.

Table 2. FHWA-Sponsored CV Applications

V2I Safety	**TRL**	**Environmental**	**TRL**
Red Light Violation Warning (RLVW)	7	Eco-Approach and Departure at Signalized Intersections	2
Curve Speed Warning (CSW)	7	Eco-Traffic Signal Timing	2
Stop Sign Gap Assist (SSGA)	5	Eco-Traffic Signal Priority	2
Spot Weather Impact Warning (SWIW)	7	Connected Eco-Driving	2
Reduced Speed/Work Zone Warning (RSWZ)	7	Wireless Inductive/Resonance Charging	2
Pedestrian in Signalized Crosswalk Warning (PCWALK)	7	Eco-Lanes Management	2
V2V Safety	**TRL**	Eco-Speed Harmonization	2
Emergency Electronic Brake Lights (EEBL)	7	Eco-Cooperative Adaptive Cruise Control	2
Forward Collision Warning (FCW)	7	Eco-Traveler Information Applications	2
Intersection Movement Assist (IMA)	7	Eco-Ramp Metering	2
Left Turn Assist (LTA)	7	Low Emissions Zone Management	2
Blind Spot/Lane Change Warning (BSW/LCW)	7	AFV Charging / Fueling Information	2
Do Not Pass Warning (DNPW)	6	Eco-Smart Parking	2
Vehicle Turning Right in Front of Bus Warning	7	Dynamic Eco-Routing (Light Vehicle, Transit, Freight)	2
Mobility	TRL	Eco-ICM Decision Support System	2
ATIS (Advanced Traveler Information System 2.0)	2	**Agency Data**	
Intelligent Traffic Signal System (I-SIG)	7	Probe-based Pavement Maintenance	3
Transit Signal Priority (TSP) and Freight Signal Priority (FSP)	7	Probe-enabled Traffic Monitoring	7
Mobile Accessible Pedestrian Signal System (PED-SIG)		Vehicle Classification-based Traffic Studies	3
Emergency Vehicle Preemption (PREEMPT)	7	CV-enabled Turning Movement & Intersection Analysis	3
Dynamic Speed Harmonization (SPD-HARM)	6	CV-enabled Origin-Destination Studies	3
Queue Warning (Q-WARN)	6	Work Zone Traveler Information	3
Cooperative Adaptive Cruise Control (CACC)	6	**Road Weather**	
Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)	6	Motorist Advisories and Warnings (MAW)	3
Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)	6	Enhanced MDSS	3
Emergency Communications and Evacuation (EVAC)	7	Vehicle Data Translator (VDT)	3
Connection Protection (T-CONNECT)	3	Weather Response Traffic Information (WxTINFO)	3
Dynamic Transit Operations (T-DISP)	3	**Smart Roadside**	
Dynamic Ridesharing (D-RIDE)	3	Wireless Inspection	3
		Smart Truck Parking	3

Connectivity project stakeholders prioritized several of these applications. Safety followed by mobility were identified as the top priorities by the Connectivity Project stakeholders. Prioritization was also performed, bearing in mind software and hardware constraints. Stakeholder input was sought to discuss their operational needs and desired CV applications. The meeting with these stakeholders was realized early on to identify all needs of the stakeholders and gain a greater understanding of what CV could do for them. The 15 CV applications chosen below were prioritized based on stakeholder desire and the TRL rating. In certain instances, engineering judgment was used because an application has a significant perceived benefit in safety or mobility to the motorist (i.e., Red-Light Violation Warning). Constraints associated with CV applications, policies, processes, and strategic implementation of Connectivity, were also discussed with the stakeholders. Table 3 describes the CV applications desired to be deployed to support a statewide CV system.

Table 3. Desired CV Applications as part of Statewide Connectivity

No.	Type	Name	Description	TRL
1	V2I Safety	Red Light Violation Warning (RLVW)	An application that broadcasts signal phase and timing (SPaT) and other data to the in-vehicle device, allowing warnings for impending red-light violations. RLVW is unrelated to ticketing or violations. It simply provides advance notification to motorists.	7
2		Curve Speed Warning (CSW)	An application where alerts are provided to the driver who is approaching a curve at a speed that may be too high for safe travel through that curve.	7
3		Spot Weather Impact Warning (SWIW)	An application that warns drivers of local hazardous weather conditions by relaying management center and other weather data to roadside equipment (RSE) and re-broadcasts to nearby vehicles.	7
4		Reduced Speed/Work Zone Warning (RSWZ)	An application that utilizes RSE to broadcast alerts to drivers warning them to reduce speed, change lanes, or come to a stop within work zones.	7
5		Pedestrian in Signalized Crosswalk Warning (PCWALK)	An application that warns motorists when pedestrians within the crosswalk of a signalized intersection are in the vehicle's intended path.	7
6	Mobility	Transit Signal Priority (TSP) and Freight Signal Priority (FSP)	Two applications provide signal priority to transit at intersections and along arterial corridors and signal priority to freight vehicles along an arterial corridor near a freight facility.	7
7		Dynamic Speed Harmonization (SPD-HARM)	An application that aims to recommend target speeds in response to congestion, incidents, and road conditions to maximize throughput and reduce crashes.	6
8		Queue Warning (Q-WARN)	An application that aims to provide drivers timely warnings of existing and impending queues. Q-WARN was thought to be helpful at toll plazas where approach sight distance was limited.	6
9		Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)	An application that warns on-scene workers of vehicles with trajectories or speeds poses a high risk to their safety.	6
10		Emergency Vehicle Preemption (PREEMPT)	An application that provides signal preemption to emergency vehicles and accommodates multiple emergency requests	7
11		Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)	An application that provides input to responder vehicle routing, staging, and secondary dispatch decisions	6
12		Emergency Communications and Evacuation (EVAC)	An application that addresses the needs of evacuees with and without special needs or their transportation	7
13	Agency Data	Probe-enabled Traffic Monitoring	An application that utilizes communication technology to transmit real-time traffic data between vehicles.	7
14		Work Zone Traveler Information	An application that monitors and aggregates work zone traffic data.	3
15	Smart Roadside	Smart Truck Parking	An application to provide information such as hours of service constraints, location and supply of parking, travel conditions, and loading/unloading schedule to allow commercial drivers to make advanced route planning decisions. This application will also address the parking needs of NJ TRANSIT and the City of Newark.	3

These applications are supported by the regions' long-range transportation plans. Two of the 12 NJTPA regional capital investment strategy principles outlined in the Draft Plan 2045 Connecting North Jersey will move freight more efficiently because of its importance to the region's economy and quality of life and the management of incidents through technology deployment. The DVRPCs' Connections 2045 plan calls for facilitating goods movement and moving towards zero transportation deaths, which is the basis for the NYC CV Pilot Deployment project (which is implementing some of the same CV applications planned for statewide connectivity in New Jersey).

RSU/OBU Equipment

V2X technology enables the communication between a vehicle and the surrounding environment, which includes other vehicles (V2V), infrastructure (V2I), and people (V2P). V2X systems collect real-time driving information to generate predictive insights, providing situational information for enhanced safety and mobility. Hardware used in V2X includes Dedicated Short-Range Communications (DSRC) software protocol stack, OBUs, RSUs, and through-glass antennas. CAVs can transmit their own and surrounding information using wireless communication. Thus, CAV applications have been developed and well-discussed to integrate with traffic signals. According to Chang's research (Chang 2017), components in V2I hubs may also consist of Traffic Signal Controller, RSU, Global Positioning System (GPS), Signal Phase and Timing (SPaT), Transportation Management Center (TMC), Map Message, Curve Speed Warning (CSW), and the other sensors for position correction and weather detection.

<u>Roadside Unit</u>

CAVs rely on traffic signal controllers that generate Signal Phase and Timing (SPaT) messages, including green, yellow, red, and the amount of time left until the next phase. Research has been accomplished on Signal Timing Optimization (Li, Elefteriadou, et al. 2014, Zheng, Lin, et al. 2017, Ng, Vasudha, et al. 2018), Vehicle-at-Intersection Trajectory Control (Ioris, Pedarsani, et al. 2017), and Safe Warnings (Sukuvaara and Nurmi 2012, Genders and Razavi 2016, Townsend 2018).

<u>On-Board Unit</u>

In 2015, the NYC Department of Transportation (NYCDOT) established its CV project with USDOT. AutoLink ASD was selected as the OBU in this project due to its interoperability with all vehicle types and existing infrastructure. The AutoLink ASD can also manage NYC's urban environment, where GPS accuracy is limited (Frost 2019). Chang et al. (2019) designed an OBU for a driving simulator, which consists of 1) a sensor unit collecting distance gap data; 2) a module judging the vehicle states; 3) A voice-based warning unit. The OBU connects the server through a Wi-Fi hotspot and transmits the data through TCP/IP protocol.

Currently, communication among RSUs and OBUs can be enabled by DSRC or Cellular Network. Specifically, DSRC uses radio frequencies in the 5.9 GHz band range, which is controlled and allocated by the Federal Communications Commission (FCC). DSRC is a vital component in CAV safety and data transfer environment. A constant and dependable wireless signal extends past findings of 500 feet (Lee and Lim 2013). An alternative to

DSRC is the cellular network, e.g., 4G LTE network. Vinel (2012) compared the performance of DSRC and 3GPP LTE and concluded that LTE is worse than DSRC in transferring data, which is already below the safety requirements for his application. However, 5G is promisingly providing outstanding performance on V2X communication. 5G-based V2X has much higher throughput and reliability (99.999%), more extended range (443m line of sight and 107m none line of sight), and significantly lower latency (10ms end-to-end and 1 MS over-the-air) (Americas 2018).

Existing CV-based Practices on RSU/OBU Deployment

USDOT's Connected Vehicle Pilot (Thompson 2018)

According to the FHWA, CV equipment should be collocated at closed-circuit television (CCTV), dynamic message sign (DMS), or traffic signal locations sites to take advantage of the existing roadside infrastructure, power, and communications equipment. RSU mounting locations should also be optimized to achieve a clear line of sight free of radio frequency (RF) signal path interference from trees, bridges, overpasses, and other structures. All RSUs and OBUs used for USDOT CV Pilot deployment should conform to USDOT specifications as closely as possible; all messages should conform to the latest versions of SCMS, SAE J2735, SAE 2945/x, IEEE 802.11p, IEEE 1609.x, NTCIP 1202, NTCIP 1103, ISO 19091, and related standards.

Wyoming DOT's Connected Vehicle Pilot

Wyoming DOT deployed 75 RSUs along 400 miles of I-80 and developed an open-source application that allows authorized Transportation Management Center (TMC) operators to monitor and manage each RSU on the road. The WYDOT team found that the same application can also be leveraged as a public-facing tool showing the CV Pilot's high-level status (WYDOT, 2020).

New York City's Connected Vehicle Pilot

In New York City, many signal poles and mast arms lay behind the building face line so they could limit the line-of-site. Field inventories identified 15% of the installations require additional infrastructure changes (e.g., additional communications gear, new mast/luminaire arms, controller relocation) to place the RSU with adequate line-of-site. For the New York City pilot project, the RSU installations were performed by the New York City Department of Transportation (NYCDOT) field crews at a rate of about two per day per crew, a slower rate than what the NYC team had anticipated. The NYC Pilot vendors introduced a combination of supporting techniques to improve GPS location accuracy, including 1. A dead reckoning; 2. CAN bus integration for speed information; 3. Inertial Measurement Unit (IMU) integration; 4. RSU time-of-flight feature.

Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Pilot

THEA connected vehicle pilot was deployed on TH-55 between downtown Minneapolis and I-494 to the West. This corridor will be implemented with CV communications infrastructure, including DSRC, 4G LTE, and longer-term cellular V2X (Hallmark, Veneziano, et al., 2019). The DSRC uses a 5.9 GHz broadcast radio infrastructure to transmit SPaT messages to vehicles in real-time. During testing of THEA Pedestrian Crossing (PED-X) smartphone application, it was found that the position accuracy through the mobile devices is not precise enough to determine if pedestrians are on the street or sidewalk. Thus, TEHA used LIDAR sensors installed near the crosswalk to locate pedestrians accurately.

Singapore: BESAFE

Ng et al. (2018) designed a system framework named BESAFE to support Singapore Autonomous Vehicle Trials, which fully complies with international standards of DSRC/WAVE, IEEE 1609. x, and SAE J2735, to ensure interoperability between AVs and infrastructure. The RSUs and OBUs are equipped with Cohda Wireless 5.9 GHz DSRC MK5 modem.

RSU/OBU Devices in Reviewed Testbeds

As of January 2019, the THEA Pilot project has installed 1,580 Vehicle OBUs, 20 Bus OBUs, and 4,800 Antennas (3 per vehicle). The RSUs include SIEMENS RSU, SIEMENS Pedestrian Detector, WAVETRONIX Vehicle Detector, and MsSedco Wrong Way Detector (USDOT, 2019). NYC Pilot has deployed up to 8,000 fleet vehicles with OBUS, 100 Physical Interface Device (PID) units, and RSUs at 353 locations (USDOT 2019). Wyoming Pilot has deployed 400 OBUs and 78 RSUs (USDOT, 2019).

Table 4. RSUs and OBUs Suppliers

Testbed	**RSU**	**OBU**
THEA Pilot	Metortech[1], Quanergy[1], Siemens[2], Wavetronix[2], Iteris[3], Econolite[3], Flir[3], Gridsmart3, MsSedco4	Savari[5], SiriusXM, Commsignia, Harada[5]
NYC Pilot	Siemens[2], Flir[3]	Savari[5], Danlaw[5]
Wyoming Pilot	Lear	Lear, Sirius XM

1: LiDAR Supplier; 2: Radar Supplier; 3: Video Sensor Supplier; 4: Microwave; 5: Antenna Supplier

Review of RSU/OBU Devices

According to the reviewed existing practices on Testbeds, several types of RSUs and OBUs are further investigated (Tables 5 through 7).

Table 5. V2X Devices from DANLAW (Adapted from DANLAW's website)

DANLAW V2X devices	**Functionality**
RouteLink, V2X Roadside Unit 	RouteLink alerts drivers to adverse driving conditions, enables pre-emption for first responders, and grants signal priority to buses and service vehicles. RouteLink can be configured to utilize either C-V2X or Dedicated Short-Range Communications (DSRC) radios to maximize compatibility with global intelligent transportation systems (ITS).
Through-Glass Integrated V2X Antenna 	Danlaw's dual-radio, glass-mounted antenna passes DSRC or C-V2X RF signals from the interior to the vehicle's exterior, enabling aftermarket CV applications. The antenna's glass coupler is adjustable to any windshield angle and can be installed on the vehicle's rear, front, or side. The antenna uses automotive-grade glass adhesive, eliminating the need to drill holes through the vehicle or run cables through window openings.
AutoLink – V2X Onboard Unit 	Danlaw's AutoLink OBU can be easily installed in any vehicle. AutoLink is built to provide a variety of connected vehicle functions and seamlessly integrate into V2X pilot programs using C-V2X or DSRC radios.

Cohda Wireless's MK5 (Wireless 2020) is a widely used OBU that enables fast-morning data exchanges over extended distances and provides class-leading reaction times to potential hazards and safety-critical scenarios.

Table 6. COHDA MK5 RSU/OBU (Adapted from COHDA's website)

Brand	**Features**
MK5 RSU meets NEMA 4 requirements for indoor and outdoor use, offering exceptional range and coverage, and a single, inexpensive, self-contained unit can cover all approaches to an intersection 	Dual IEEE 802.11p radio; Powerful processor running Cohda software applications. Global Navigation Satellite System (GNSS) that delivers lane-level accuracy. Integrated security. Hardware acceleration. Tamper-proof key storage. NXP chips with Cohda firmware. Supports G5, DSRC (IEEE 802.11p)
MK5 OBU is a small, low-cost, rugged module that can be retrofitted to vehicles for aftermarket deployment or field trials, serving as a reference design for automotive production 	Dual IEEE 802.11p radio; Powerful processor running Cohda software applications. Global Navigation Satellite System (GNSS) that delivers lane-level accuracy. Integrated security. Hardware acceleration. Tamper-proof key storage. NXP chips with Cohda firmware. Support DSRC (IEEE 802.11p), Ethernet 100 Base-T

Table 7. OmniAIR-Certified CV RSU/OBU Devices

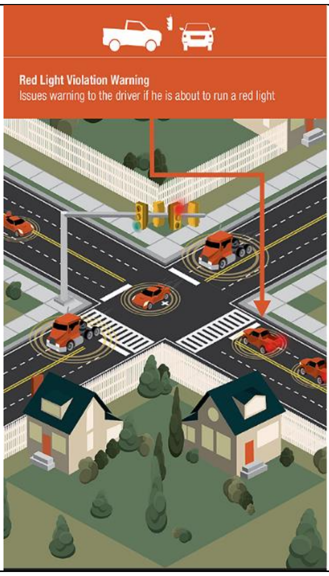
Brand	**Info**
Intersect RSU	Model: Intersect-ECO/ ISECT-ECO-A RSU RSU Version: HW 1.0A SW v1.3.0-ARMv7 Connected Vehicle: DSRC – V2X (RSU) v1.0 Conformance / Interoperability OmniAir Authorized Test Laboratory: Dekra – Malaga (OATL DSRC-V2X 2018101901) Certificate: 2019050602
SIEMENS (RSU)	SITRAFFIC ESCOS ROADSIDE UNIT RSU Sittraffic ESCoS Roadside Unit RSU Version: HW 1.0 SW 01.01 Connected Vehicle: DSRC – V2X v1.0 Conformance
COMMSIGNIA (OBU)	Model: ITS-OB4 OBU Version: v1.17.45-b186782 Connected Vehicle: DSRC – V2X v1.0 Conformance Certificate 2018050801
LEAR (OBU)	Certificate Date/Number: 2019010201 Company Name: Lear Corporation Product Name/Model: Locomote Roadstar OBU Firmware/Software Version: PR12.06

CAV Applications

The following section summarizes some CV Applications at Signalized Intersection.

<u>V2I Safety</u>

- Red Light Running Warning (RLVW):

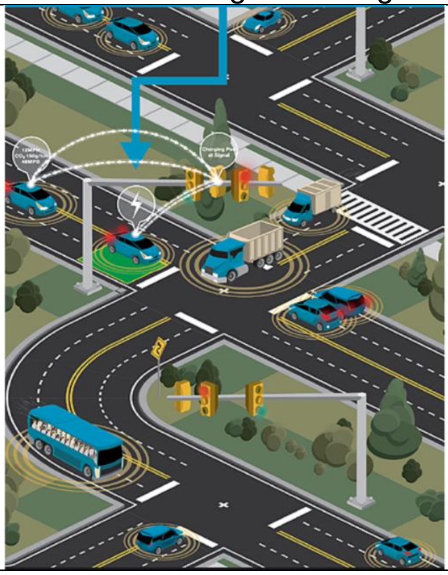


It is a V2I application that the signal phase, timing (SPat), intersection geometry, and position correction information will communicate with the onboard unit, broadcasting warnings for impending red-light violations. RLVW aims to establish a cooperative V2I communication system that prevents drivers from potential crashes at signalized intersections by warning the equipped vehicle if the vehicle is predicted to violate the red light according to current speed and distance.

Figure 2. Red Light Violation Warning

Environment

- Eco-Traffic Signal Timing:



Eco-Traffic Signal Timing is a V2I application to decrease fuel consumption and decrease air pollutant emissions on arterials by optimizing the performance of traffic signals. Vehicle location, speed, and emissions data will be collected to develop adaptive signal timing strategies to reduce idling stops, unnecessary accelerations, and decelerations and improve traffic flow in real-time at intersections, along a corridor, or for a region.

Figure 3. Eco-Traffic Signal Timing

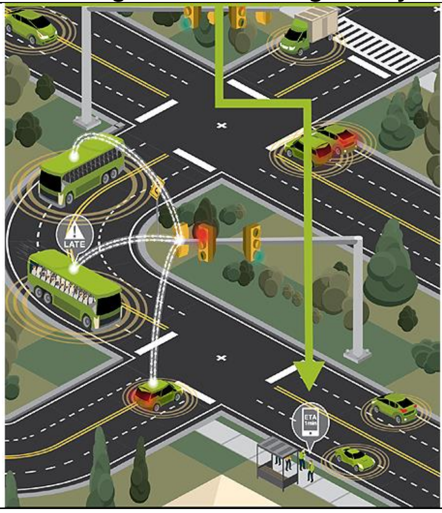
- Eco-Approach and Departure at Signalized Intersections:

This is an application as the equipped vehicle approaches the traffic signal intersection. Its OBU receives the SPaT message. The vehicle's OBU calculates whether the vehicle can pass through the intersection within the speed limit before the traffic light turns red. The vehicle's OBU calculates an eco-approach to the intersection, considering prevailing traffic conditions and other vehicles' trajectories, then recommends the driver's optimal speed to decelerate at the signalized intersection. Following the recommendations from the OBU, the trajectory reduced fuel consumption and vehicle emissions.

Figure 4. Eco-Approach and Departure at Signalized Intersections

Mobility

- Intelligent Traffic Signal System (I-SIG)



I-SIG is an application that accommodates signal priority, preemption, and pedestrian movements based on high-fidelity real-time data collected from vehicles through wireless communications. Real-time data availability will facilitate accurate measurements and predictions of lane-specific platoon flow, platoon size, and other driving characteristics. This V2V and V2I application have the potential to develop new systems to improve traffic conditions significantly and transform how traffic signal systems are designed, implemented, operated, and monitored.

Figure 5. Intelligent Traffic Signal System

Agency Data

- CV-enabled Turning Movement & Intersection Analysis

This CV-enabled traffic study application uses paths self-reported by vehicles to track turning ratios, delay, and other intersection metrics. This application does not provide data for real-time optimization of traffic flows and feedback to vehicles. However, system operators, including transportation planning agencies, public transportation providers, and port and terminal operators, have actionable information and the tools to affect the transportation system's performance.

Connected Vehicle Reference Implementation Architecture (CVRIA) for Signalized Intersection Application

CVRIA is a user-friendly online resource for CV technical standards, applications, and web-based training designed for technical and non-technical audiences. CVRIA uses multiple viewpoints to capture stakeholders' concerns and international applications, including Enterprises to carry out applications, Functions to satisfy requirements, Physical objects to implement that functionality, and Communications protocols necessary. In June 2017, the US DOT released the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT), a significant upgrade to the National ITS Architecture that covers all the scope and content from CVRIA Version 2.2 and the National ITS Architecture Version 7.1.

Application 1: Eco-Approach and Departure at Signalized Intersections

Eco-Approach and Departure at Signalized Intersections aim to protect and enhance the environment, promote energy conservation, improve the quality of life, and promote consistency between transportation improvements and State and local planned growth and economic development patterns.

Table 8. Physical Components of Eco-Approach and Departure at Signalized Intersections

Physical Object	**Class**	**Functional Module**
Connected Vehicle Roadside Equipment	Field	RSE Intersection Management/ RSE Traffic Monitoring
Driver	Vehicle	
ITS Roadway Equipment	Field	Roadway Signal Control
Other Vehicle OBEs	Vehicle	
Traffic Management Center	Center	TMC Signal Control
Vehicle OBE	Vehicle	Vehicle Basic Safety Communication/ Vehicle Eco-Driving Assist

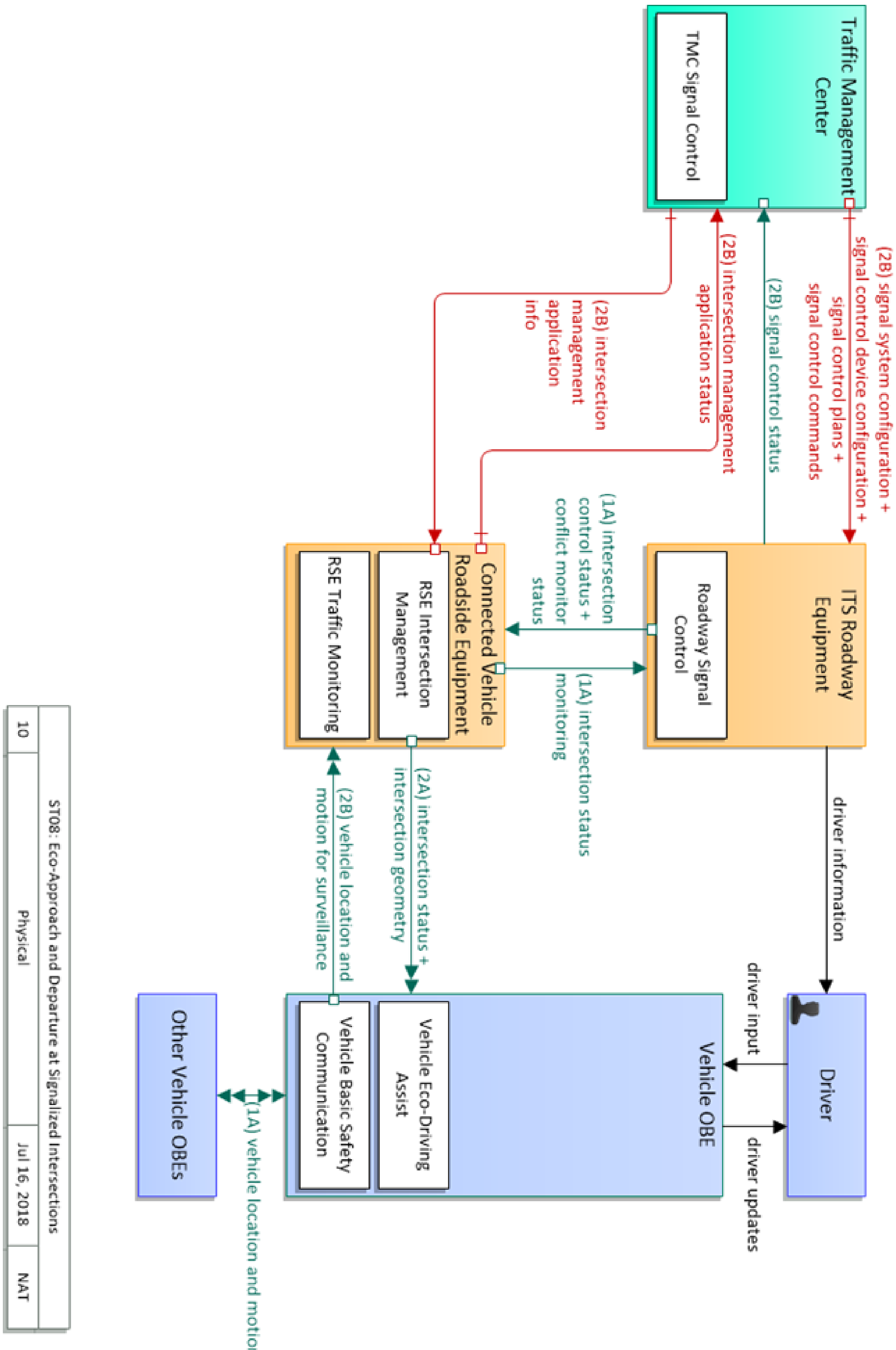


Figure 6. The architecture of Eco-Approach and Departure at Signalized Intersections

Application 2: Eco-Traffic Signal Timing

The Eco-Traffic Signal Timing service package is similar to current ATSC systems. However, the application's objective is explicitly to optimize traffic signals for the environment rather than the current adaptive systems' objective, which is to enhance the intersection level of service or throughput, which might improve the intersection's environmental performance. The Eco-Traffic Signal Timing service package processes real-time and historical CV data at signalized intersections to reduce fuel consumption and overall emissions at intersections, along corridors, or for a region. It evaluates traffic and environmental parameters at each intersection in real-time. The traffic network is optimized using the available green time to serve the actual traffic demands while minimizing the environmental impact.

Table 9. Physical Components of Eco-Traffic Signal Timing

Physical Object	**Class**	**Functional Module**
Connected Vehicle Roadside Equipment	Field	RSE Emissions Monitoring/ RSE Environmental Monitoring/ RSE Intersection Management/ RSE Traffic Monitoring
Cyclist	Personal	
Driver	Vehicle	
Emissions Management Center	Center	Emissions Connected Vehicle Monitoring/ Emissions Data Management
ITS Roadway Equipment	Field	Roadway Basic Surveillance/ Roadway Emissions Monitoring/ Roadway Environmental Monitoring/ Roadway Field Management Station Operation/ Roadway Signal Control
Pedestrian	Personal	
Traffic Management Center	Center	TMC Basic Surveillance/ TMC Environmental Monitoring/ TMC Roadway Equipment Monitoring/ TMC Signal Control
Traffic Operations Personnel	Center	
Vehicle OBE	Vehicle	Vehicle Basic Safety Communication/ Vehicle Emissions Monitoring/ Vehicle Environmental Monitoring

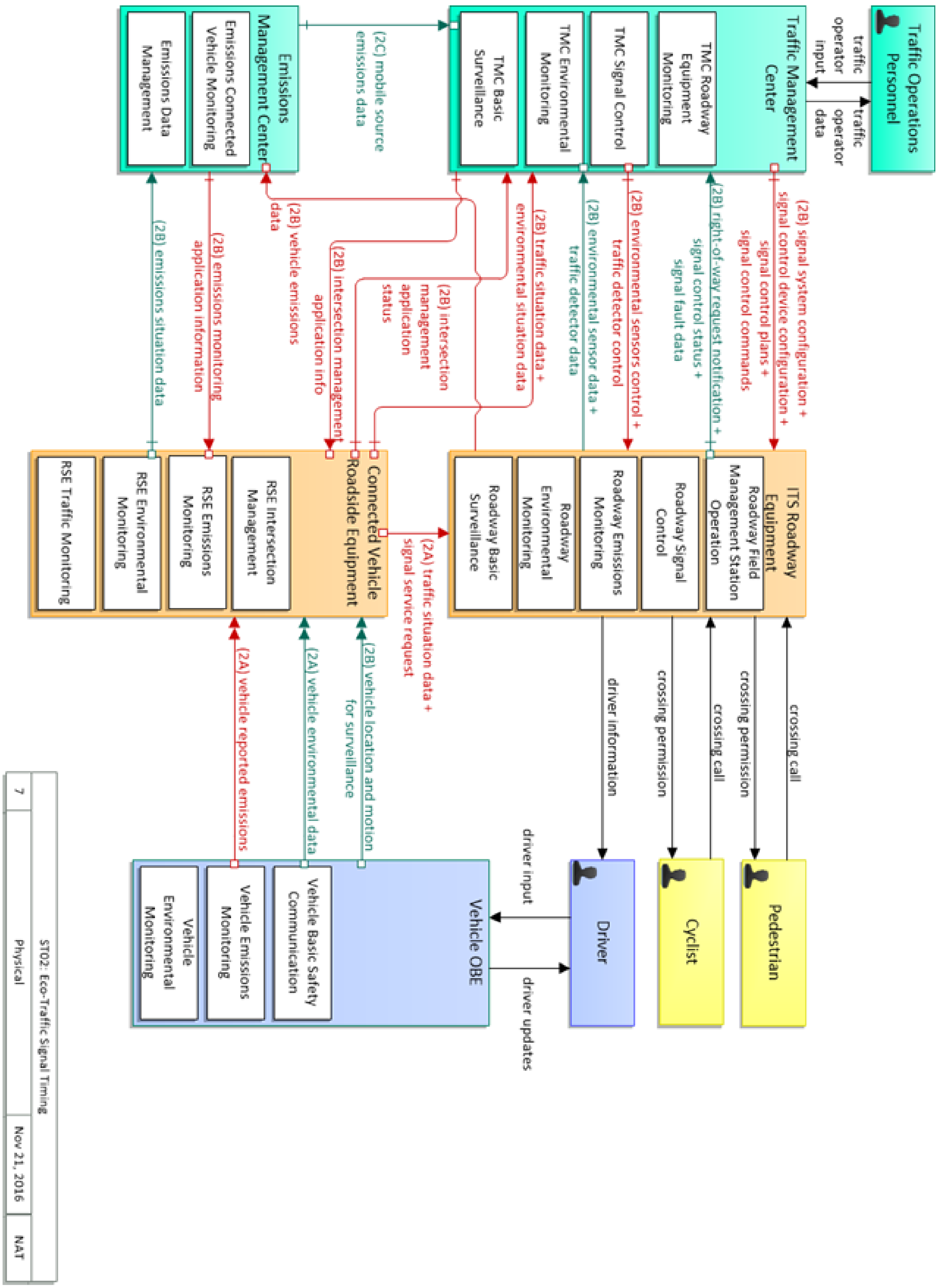


Figure 7. The architecture of Eco-Traffic Signal Timing

Application 3: Connected Eco-Driving

Connected Eco-Driving application protects and enhances the environment, promotes energy conservation, improves the quality of life, and promotes consistency between transportation improvements and State and local planned growth and economic development patterns. Table 10 summarizes the physical components of this Eco-Driving application.

Table 10. Physical Components of Eco-Driving Application

Physical Object	**Class**	**Functional Modules**
Connected Vehicle Roadside Equipment	Field	RSE Traffic Monitoring/_RSE Traveler Information Communications
Driver	Vehicle	
Other Vehicle OBEs	Vehicle	
Transportation Information Center	Center	TIC Connected Vehicle Traveler Info Distribution/_TIC Situation Data Management/_TIC Traveler Information Broadcast/
Vehicle OBE	Vehicle	Vehicle Basic Safety Communication/_Vehicle Eco-Driving Assist/_Vehicle Traveler Information Reception

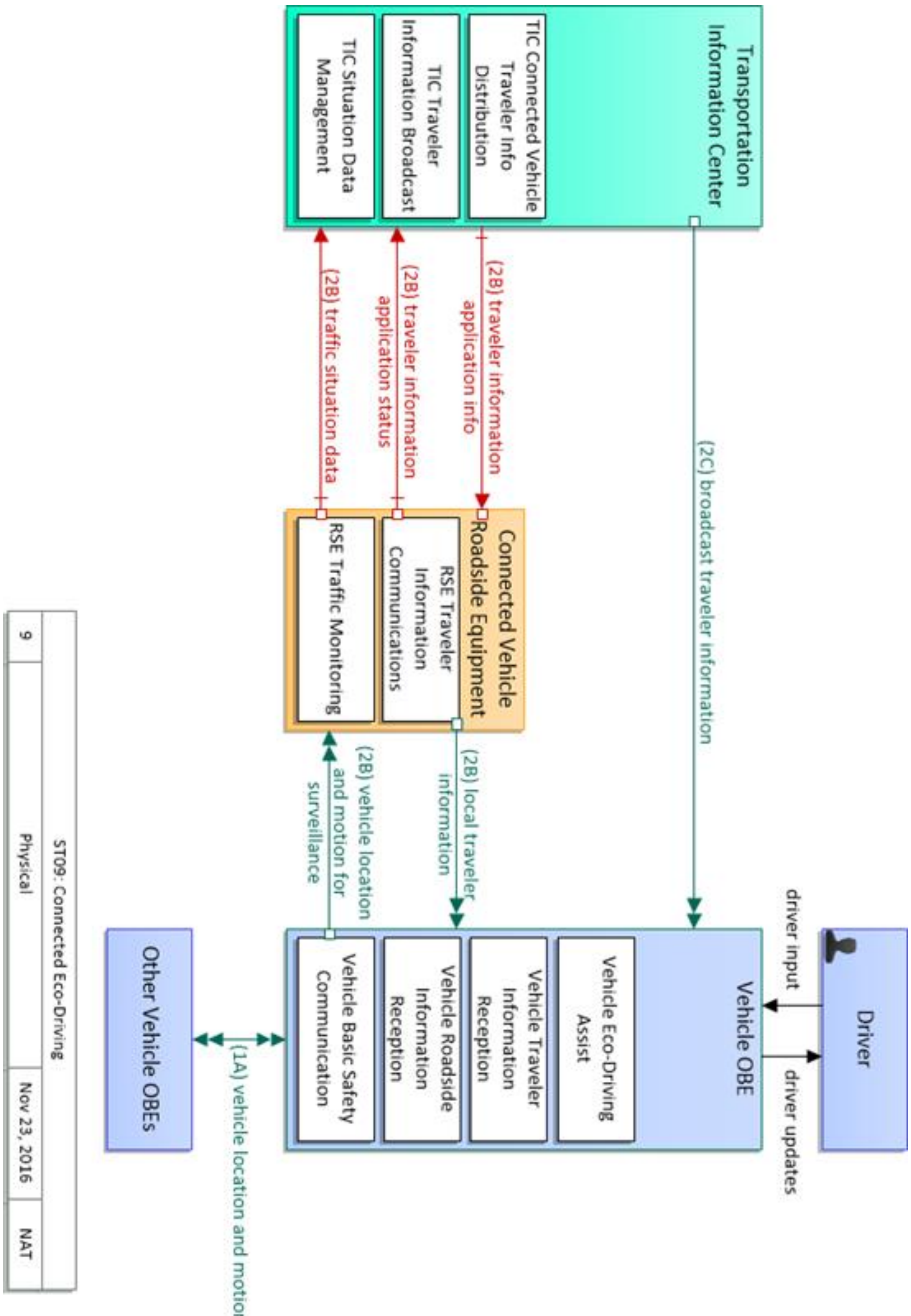


Figure 8. Eco-Driving Application Architecture

Application 4: Transit Signal Priority

The application of Transit Signal Priority uses transit vehicles for infrastructure communications to allow a transit vehicle to request priority at one or a series of intersections. The application provides feedback to the transit driver indicating whether the signal priority has been granted or not. This V2I application can contribute to the improved operating performance of the transit vehicles by reducing the time spent stopped at a red light.

Table 11. Physical Components of Transit Signal Priority

Physical Object	Class	Functional Module
Connected Vehicle Roadside Equipment	Field	RSE Intersection Management
ITS Roadway Equipment	Field	Roadway Signal Control
Traffic Management Center	Center	TMC Multi-Modal Coordination/ TMC Signal Control/ Transit Center Priority Management
Transit Management Center	Center	
Transit Operations Personnel	Center	
Transit Vehicle OBE	Vehicle	Transit Vehicle Signal Priority
Transit Vehicle Operator	Vehicle	

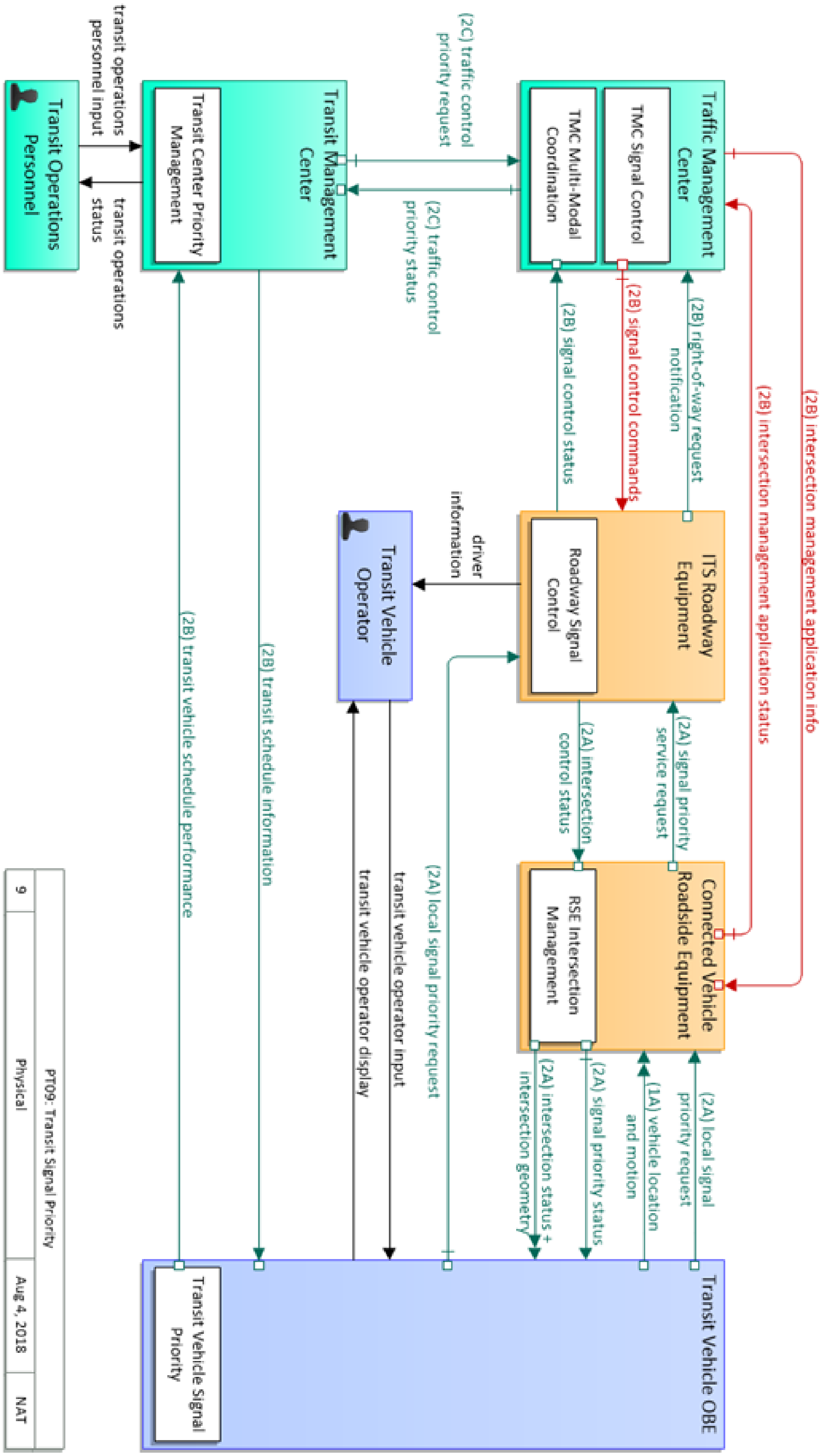


Figure 9. The architecture of Transit Signal Priority

Application 5: Connected Vehicle Traffic Signal System

Table 12. Physical Components of Connected Vehicle Traffic Signal System

Physical Object	**Class**	**Functional Module**
Connected Vehicle Roadside Equipment	Field	RSE Intersection Management/ RSE Situation Monitoring/ RSE Traffic Monitoring
Cyclist	Personal	
Driver	Vehicle	
ITS Roadway Equipment	Field	Roadway Basic Surveillance/ Roadway Field Management Station Operation/ Roadway Signal Control
Other ITS Roadway Equipment	Field	
Pedestrian	Personal	
Traffic Management Center	Center	TMC Basic Surveillance/ TMC Roadway Equipment Monitoring/ TMC Signal Control
Traffic Operations Personnel	Center	
Vehicle OBE	Vehicle	Vehicle Basic Safety Communication/ Vehicle Intersection Warning/ Vehicle Situation Data Monitoring

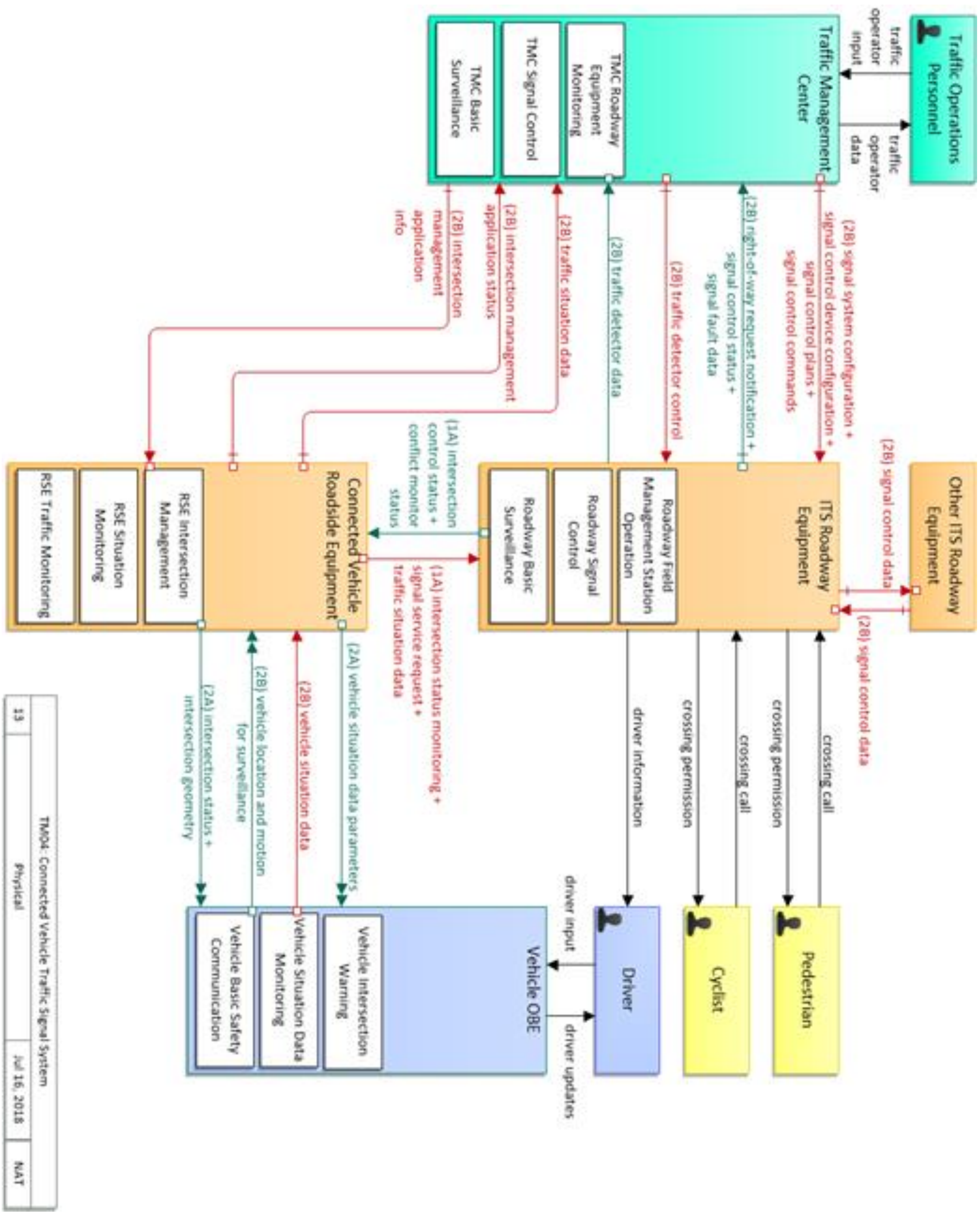


Figure 10. The architecture of the Connected Vehicle Traffic Signal System

Application 6: Intersection Safety Warning and Collision Avoidance

This application enables a CV approaching an instrumented signalized intersection to receive information from the infrastructure regarding the intersection's signal timing and geometry. The vehicle uses its speed and acceleration profile and the signal timing and geometry information to determine if it appears likely that the vehicle can pass safely through the intersection without violating the signal or colliding with other vehicles. Suppose the vehicle determines that proceeding through the intersection is unsafe. In that case, a warning is provided to the driver and /or collision avoidance actions are taken, depending on the automation level of the vehicle.

Table 13. Physical Objects of Intersection Safety Warning and Collision Avoidance

Physical Object	**Class**	**Functional Module**
Basic Vehicle	Vehicle	
Connected Vehicle Roadside Equipment	Field	RSE Intersection Safety
Driver	Vehicle	
ITS Roadway Equipment	Field	Roadway Signal Control
Other Vehicle OBEs	Vehicle	
Traffic Management Center	Center	TMC Intersection Safety/ TMC Signal Control
Vehicle OBE	Vehicle	Vehicle Control Automation/ Vehicle Control Warning/ Vehicle Intersection Warning

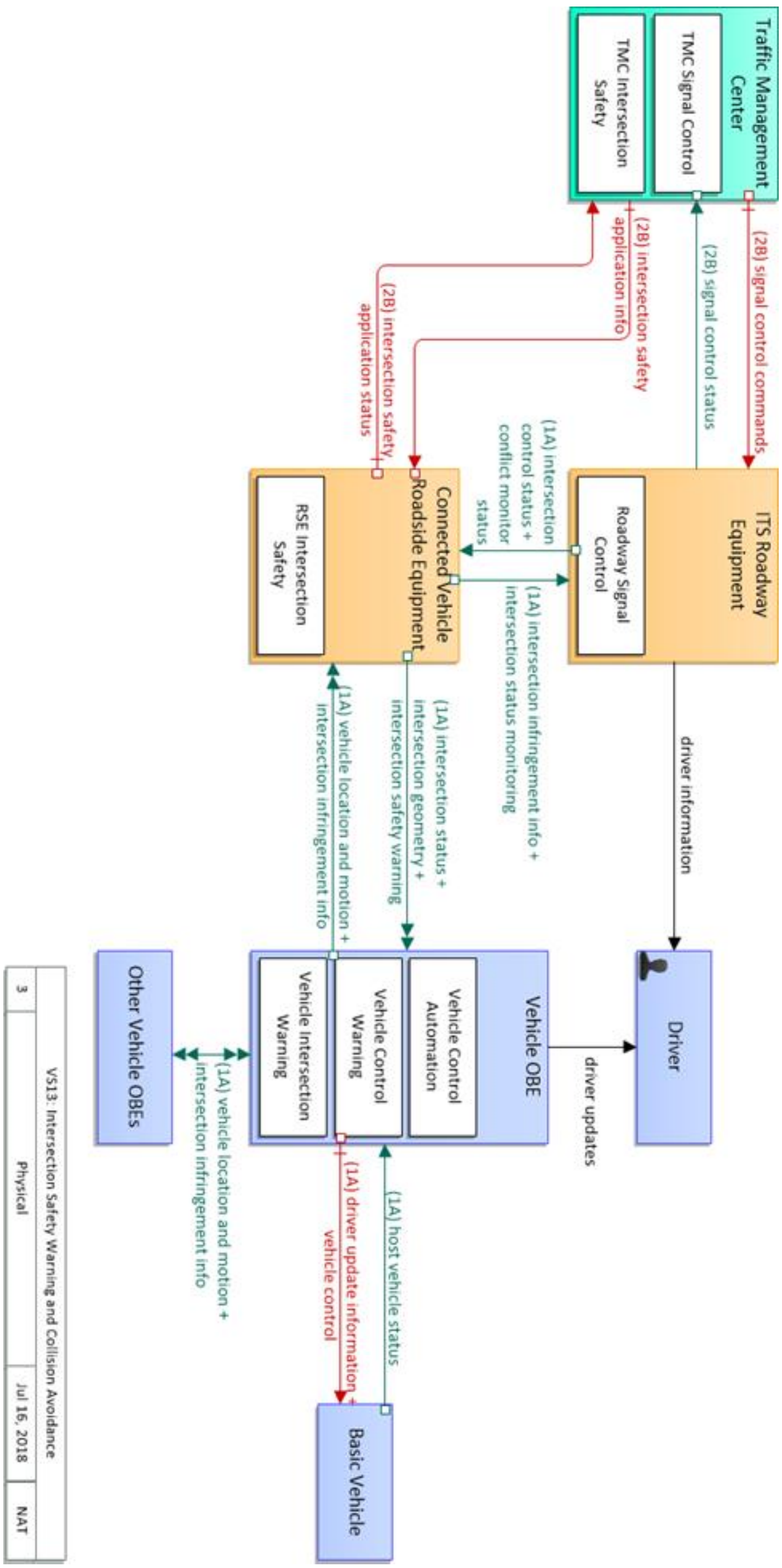


Figure 11. The architecture of Intersection Safety Warning and Collision Avoidance

Reports and Synthesis on Connected Vehicle

TTI (Texas A&M Transportation Institute) CVPD (Connected Vehicle Pilot Deployment) evaluation team conducted data analytic research to assess the mobility, environmental, and public agency efficiency (MEP), the cost-benefit impacts, user satisfaction, and stakeholder acceptance.

Key performance measures for each performance category are developed for the Tampa cases. (Balke et al., 2018)

- Safety: Crash reduction, crash rate, type of conflicts/near misses, the severity of conflicts/near misses, percent red-light violations, and approaching speed number/frequency of wrong-way entries.
- Mobility: Travel time, travel time reliability, queue length, vehicle delay, throughput, percent AoG, bus travel time, reliability of bus route travel time, percent arrival on schedule, and numbers of signal priority being granted/denied.
- Environmental: Emission reduction for idle speed and running.
- Public Agency Efficiency: Customer satisfaction

New York City site identified seven use cases for characterizing improvement in system performance. The seven cases include Manage Needs, Reduce Vehicle to Vehicle Crashes, Reduce Vehicle to Pedestrian Crashes, Reduce Vehicle to Infrastructure Crashes, Inform Drivers of Serious Incidents, Provide Mobility Information, and Manage System Operations. (Balke et al. 2018). For the Wyoming case, the evaluation plan identifies the critical mobility, environmental, and public agency efficiency hypotheses that TTI CVPD Evaluation Team uses in its independent evaluation to determine how the Wyoming CVPD achieved USDOT's overall goals and objectives. The TTI CVPD Evaluation Team uses these evaluation hypotheses to guide the development of the rest of the components of the independent evaluation plan. (Bennett et al., 2018)

The TTI CVPD Evaluation Team has identified the potential confounding factors and risks that may affect the pilot deployment evaluation. Some key risks and uncertainties that may impact the evaluation effort. Significant risks to the independent evaluation include lack of quality data to perform a valid evaluation of some deployments, data limitation for safety analysis, insufficient CV traveling in the downtown area to influence mobility, and participant attrition. Benefits from the CV environment are expected to accrue in several areas: Combined use of V2V and V2I communications has the potential to address 81 percent of unimpaired driver crashes in all vehicle types. CV systems have the potential to reduce urban traffic congestion, travel delays, and vehicle emissions, as well as improve vehicle fuel efficiency. The CV environment requires the deployment of technologies falling into six broad categories: In-vehicle or mobile equipment, RSE, Core systems, Support systems, Communications systems, and Applications-specific systems.

TASK 2: STAKEHOLDER MEETING AND SYNTHESIS

During the process of ATSPM system implementation, the transportation community is affected and involved, including users, operators, and managers of roads, devices, and vehicles. The significant users and stakeholders are:

- Transportation Users: People traveling on major arterial monitored by ATSPM can benefit from efficient and faster signal timing management.
- Transportation Planning Department: The ATSPM system can impact recurrent and non-recurrent congestion along major corridors, which may change the travel time. The traffic planning department can utilize this system to predict and evaluate travel time status to make better transportation plans.
- TMC: TMC directly receives actionable information needed to reduce congestion due to obsolete signal timing. High-quality mobility and safety service can be delivered to customers without significant investment in existing infrastructure.
- Signal Controller Vendors: A more advanced detector or adaptive system can be implemented with this system. Their users can easily assess the reliability and capacity of vendors' products.

The team hosted the stakeholder meeting on 12/14/2020.

Table 14. List of Stakeholder Meeting Participants

Attendees	**Department**
Peter Jin	Rutgers-CAIT
Tom Brennan	TCNJ
Kelly McVeigh	NJDOT MSE (Mobility and Systems Engineering)
Priscilla Ukpah	NJDOT Research
Mohammad Jalayer	Rowan
Deep Patel	Rowan
Terry Zhang	Rutgers
Ek Phomsavath	FHWA
Jason Simmons	SJTPO
Mark Taylor (Derrick)	UDOT
Amy Lopez	INRIX
Rick Schuman	INRIX
Mike Massaro	INRIX
Richard Cippoletti	NJTPA
Eddie Curtis	FHWA
Robert Meyer	Transcore
Mark Renner	NJDOT
LaDanya Friday	NJDOT
Virginia Todd	NJDOT
Steve Remias	Wayne State University
Christopher M. Day	Iowa State University
Katie Elliott	SJTPO
Allen Davis	Georgia DOT

NJDOT Perspectives

NJDOT provided some background about this research project and its significance in fulfilling the NJDOT requirements. An overview of the current NJDOT process for signal timing was covered:

- NJDOT has a management system, classification of arterial system technology, which was developed a couple of years that considers congestions and other factors. These results in traditional traffic signal optimization up to adaptive signal.
- NJDOT can get a prioritized list of corridors that would lead to project programming through system implementation.
- A consultant from NJDOT is on board to perform the necessary work. These works are done through traditional modeling, using synchro simulation traffic or other software.
- The project's output would essentially be updating timing plans in New Jersey.
- There are legal documents describing how a traffic signal is supposed to operate. If NJDOT received a complaint or someone observed an issue, NJDOT is responsible for making field observations to confirm the issues.
- A major issue would lead to a major project, then NJDOT would put that right into the project programming. It could lead to project delivery, which is a long process, or NJDOT might have some abbreviated project where minimal modeling was performed.

In addition, traditional modeling is required when NJDOT is updating timing plans, which would lead to an updated timing plan. These updated timing plans are the keys to unlocking how to update a single timing. Unlike a real-time traffic signal system, traditional methods cannot show if there is a need to update a gap time right if an issue with an approach is observed. A real-time traffic signal system is a quick feedback system in a real-time situation. Therefore, NJODT can adjust the system parameters and immediately start monitoring it and see how things change. NJDOT is investing a lot in existing adaptive signal systems. The goal of NJDOT is to make sure that proposed systems are using the unique signal control policy where a user can update gap time split-cycle and cycle length.

Discussion

Stakeholders discussed questions and critical points, and the records are as follows.

- FHWA asked if this project intends to overlay ATSPM on facilities equipped with adaptive control. And if ATSPM can be deployed on facilities not equipped with adaptive control. NJDOT responded that NJDOT wants a stand-alone ATSPM system so they can include non-adaptive signals. The translator would sit on the same server and run-on adaptive logs, and the end-users wouldn't know if the signal is adaptive or not. NJDOT does not want separate interfaces for adaptive SPMs vs. traditional ATSPMs.
- FHWA asked if the signals equipped with SCATS don't conform to the data enumerations. The Translator produces the information required to produce the measures and stores them in the database for retrieval, so no one knows the difference. NJDOT confirmed this question.
- FHWA asked if the process for updating timing directives will allow the flexibility to "tinker" with timings to discover solutions for problems, e.g., gap/extension times, detector delays, fixed/floating force offs. NJDOT answered that NJDOT has been able to update language in our adaptive timing directives.

- UDOT asked if SCATS data is 1/10th second resolution. Rutgers responded that it currently is at the second level, the same as detector data, and there can be multiple events in the exact second.
- NJDOT mentioned that a lot of the effort has been going into making available data and the most abundant available data through our adaptive systems and translating it to be provided in this format. Georgia DOT had done something towards the higher level of adaptive systems.
- UDOT mentioned that many jurisdictions with adaptive systems do not have an excellent way to measure what is happening. Most traffic signals in Utah are not fixed time, and in fact, they are activated systems except in Salt Lake City in the CBD area, where they have some fixed time in two sections. Around 2000 intersections are currently deployed in the ATSPM system.
- Iowa State University provided a few thoughts: since the team is looking at adaptive systems, that would be interesting if there was any way to extract any of its internal decision-making and apply it to some of the performance measure diagrams.
- Transcore mentioned that they forwarded some documentation to NJDOT regarding how the team could use it to go directly into those files. Still, a graphical user interface already shows the green times for each phase throughout the day.
- TCNJ mentioned that for an intersection, maybe even a movement, a higher resolution type of data, the team might be able to indicate better how vehicles are moving through the system. The one-minute increment gives us an idea of the location, the midpoint of a segment, but perhaps the team can start to outline a more specific type of spatial layout for intersections.
- UDOT mentioned that one of the first metrics they created on the ATSPM website was the cumulative frequency diagrams.
- TCNJ mentioned that those diagrams are compelling graphs showing users the before and after relatively quickly change.
- Rutgers stated that the team is looking to see how they can better integrate and enable some of the hidden treasure code. Most of the code is written in C sharp language, and some scripting language is used to create some results.
- UDOT mentioned that the ATSPM source code is open-source when others enhance the source code and get to it. UDOT hopes the team will push it back through GitHub through a pull request. If the coding is written in other languages, such as Python, that does not fit well with the ATSPM platform, and they cannot pull it unless there are links to it.
- Rutgers mentioned that the team would have a complete deployment and some of the added functionality to the ATSPM system by the next stakeholder meeting.

TASK 3: ATSPM MULTISOURCE DATA AND API INTEGRATION

TRANSCOM Travel Time and Event Data

Traveler information dissemination in NJ is primarily conducted through TRANSCOM. TRANSCOM collects and verifies work zone construction data from NJDOT via OpenReach and aggregates and fuses the data to create a regional view of near real-time transportation status. It includes a long-term planned or underway construction database to help build NJ work zone data streams. In general, TRANSCOM receives data from 1) TRANSCOM member agencies and centers in New Jersey, New York, and Connecticut; 2) Travel time data from E-ZPass electronic toll; 3) Third-party transportation Data Providers, including from INRIX and HERE (Nokia). TRANSCOM uses its Data Fusion Engine to validate and aggregate real-time and historical information (e.g., speed and travel time) referenced to a local transportation network. In addition, TRANSCOM converts these inputs to a geographically universal format.

The TRANSCOM system already has a complete data exchange process. TRANSCOM OpenReach is a network of terminals and servers installed in member agencies that ensures coordination and integration of advanced transportation management and information from agencies' sides. TRANSCOM Data Fusion Engine can collect real-time and historical information (work zone data) referenced to a local transportation network (links, nodes) and map the information to a regional reference system (links, nodes) to produce a normalized aggregated regional view of the information. TRANSCOM ITS Standards-based Center-to-Center (Middleware) provides an ITS standards-based interface for center-to-center communications. TRANSCOM Data Exchange is a secure API that allows agencies, including centers and devices, to access real-time transportation information gathered by TRANSCOM.
Furthermore, TRANSCOM also has public data exchange programs with WAZE and Google. Such a two-way exchange program can potentially bring the verified agency event and travel time to individual travelers efficiently and allow user-generated event and congestion data to be feedback to transportation agencies. TRANSCOM has developed a web-based data analysis tool (built around the DFE) called SPATEL that addresses the needs of member agencies to allow the analysis of transportation system performance (e.g., travel time and volume). The DFE/SPATEL tool consists of thirteen distinct tools/applications that provide utility to a cross-section of users within member agencies.

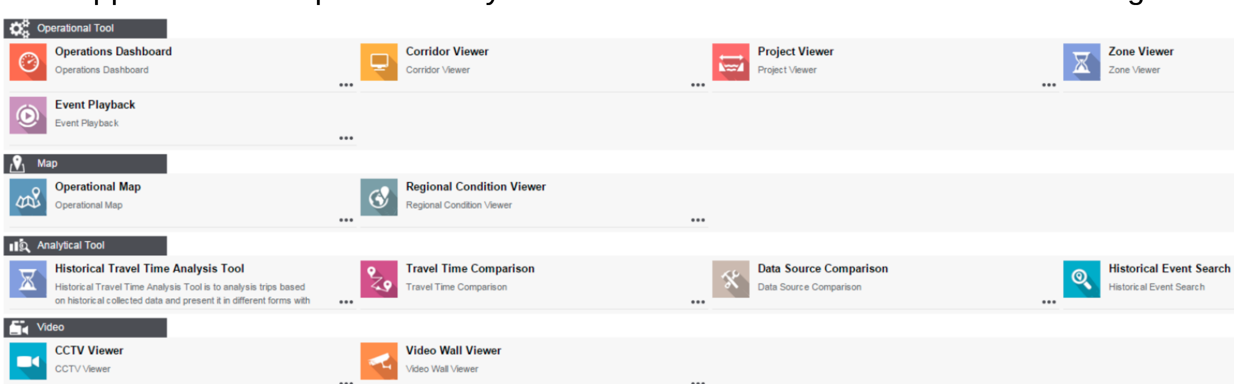


Figure 12. DFE/SPATEL Home Screen

The SPATEL tool returns a graph showing a comparison of travel time reliability, as shown in Figure 13. The graphs below show the number of occurrences of each measured travel time for 2015 and 2014. The average travel time and planning time are also shown.

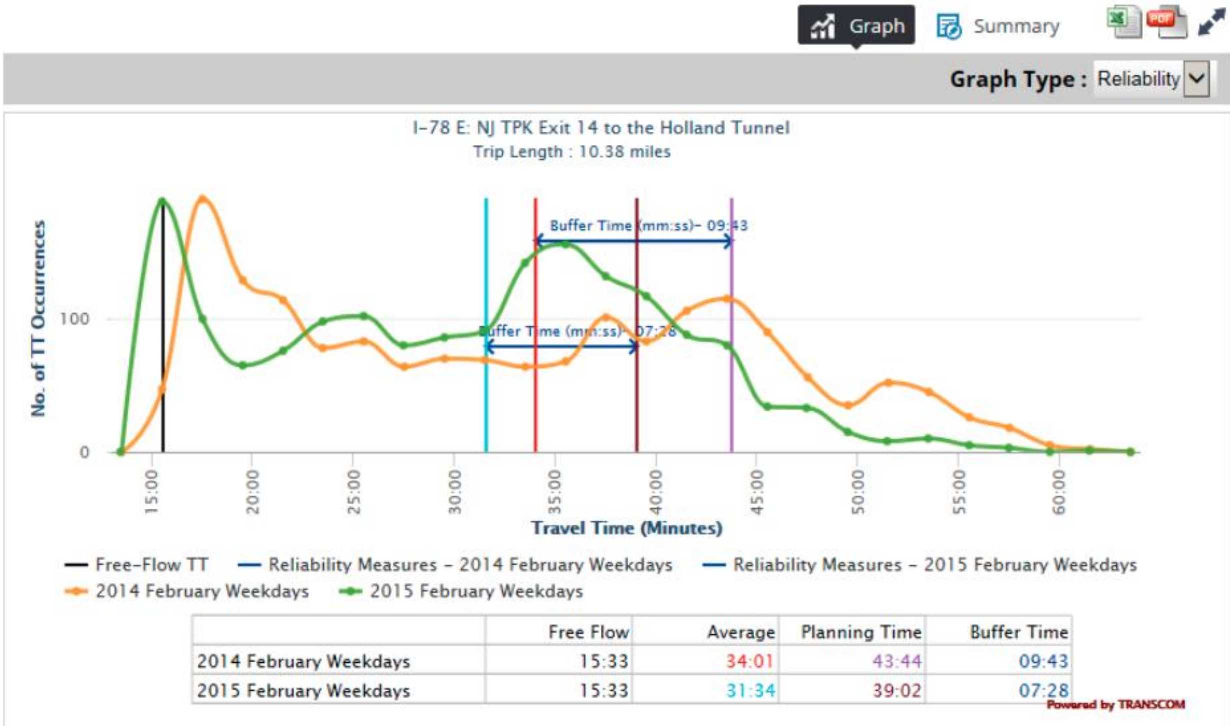


Figure 13. Travel Time Reliability

In Figure 14, the trip being analyzed on the map on the left is red color. The congestion graphs on the right show the average speed at each trip segment as time progresses through the morning peak hour. The congestion graphs are shown for 2014 and 2015.

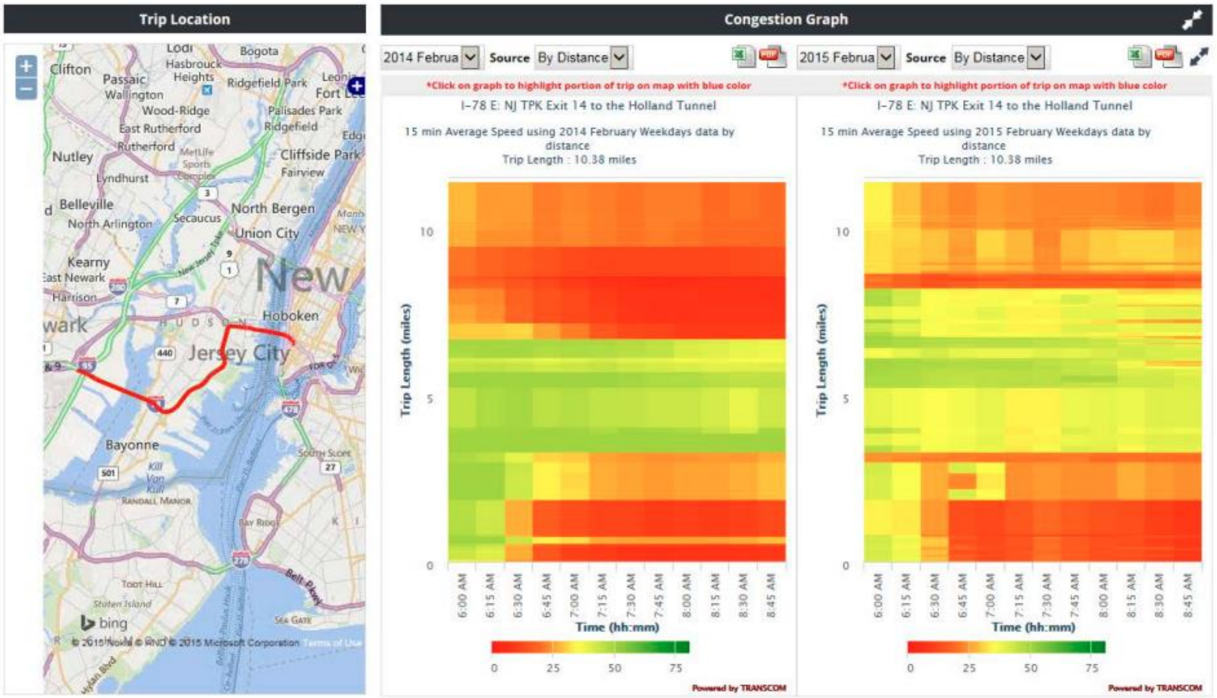


Figure 14. Trip Map and Congestion Graphs

Table 15 shows the sample data of SPATEL provided by TRANSCOM, including the detailed location and time information of road incidents.

Table 15. SPATEL Sample Data

Event ID	ORC25642301	ORI209302107	ORI207569110	ORI205389107
Facility	NJ 10	NY 32	NY 27	S15N
Event Type	drainage improvements	Construction	Construction	Roadwork
Direction	eastbound	both directions	both directions	northbound
Event Description	NJ DOT - STMC: drainage improvements on NJ 10 eastbound area of Algonquin Pkwy (Hanover Twp) Not currently scheduled	NYSDOT TMC - Albany: Construction, utility work on NY 32 in both directions between Clifton Street (Waterford) and Fulton Street (Waterford) alternate lanes closure until 3:00 P.M.	NYSDOT - Region 10: Construction, construction on NY 27 in both directions between Exit 38 - Little East Neck Road (Suffolk) and Exit 40 - NY 231; Babylon Northport Expressway (Suffolk) 1 lane closed until 3:00 P.M.	ConnDOT: Road Work on RT15 Northbound between Exits 59 and 60 (3.4 miles) today until 11:14 pm. The right lane is closed. Reported Monday, July 1 at 9:19 am.
State	NJ	NY	NY	CT
County	Morris	Saratoga	Suffolk	New Haven
From City	Hanover Twp	Waterford		New Haven
To City				Hamden
Start Date Time	08/20/2019 9:36:30 PM	08/22/2019 9:01:29 AM	07/31/2019 9:00:19 AM	07/01/2019 9:25:24 AM
Last Update Date	08/21/2019 3:00:14 PM	08/22/2019 9:01:29 AM	07/31/2019 9:00:19 AM	07/01/2019 9:25:24 AM
Close Date	08/21/2019 3:19:00 PM	08/22/2019 3:03:00 PM	07/31/2019 3:01:56 PM	07/01/2019 10:29:55 AM
Duration (Day-hh:mm)	0 - 17:43	0 - 06:02	0 - 06:01	0 - 01:04
Recovery Time (Day-hh:mm)		0 - 00:01	0 - 00:01	0 - 00:01
From Mile Marker	15.2			
To Mile Marker				
Latitude	40.81690732	42.78161804	40.7133	41.337866
Longitude	-74.40216047	-73.69593859	-73.3519	-72.978399

INRIX Travel Time Data

As shown in Figure 15, the team has developed a PHP script to ingest INRIX speed data to the ATSPM system. The scripts obtain data (with the appropriate API calls) through the Regionally Integrated Transportation Information System (RITIS), to which NJDOT subscribes. Historic data is also available through their website, but near real-time data, provided in 1-minute increments, was obtained. Within the ATSPM, there is an ability to set up the speed detection at the intersection, accepting speed data. However, travel time data cannot be directly input into the ATSPM at this time and would require a separate analysis outside the ATSPM to be connected.

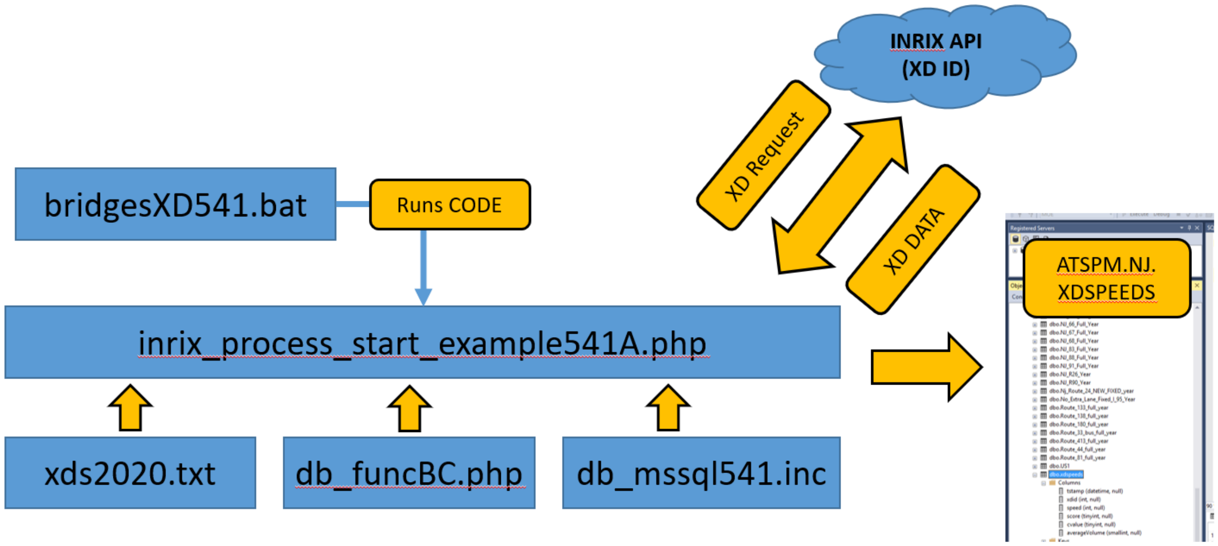
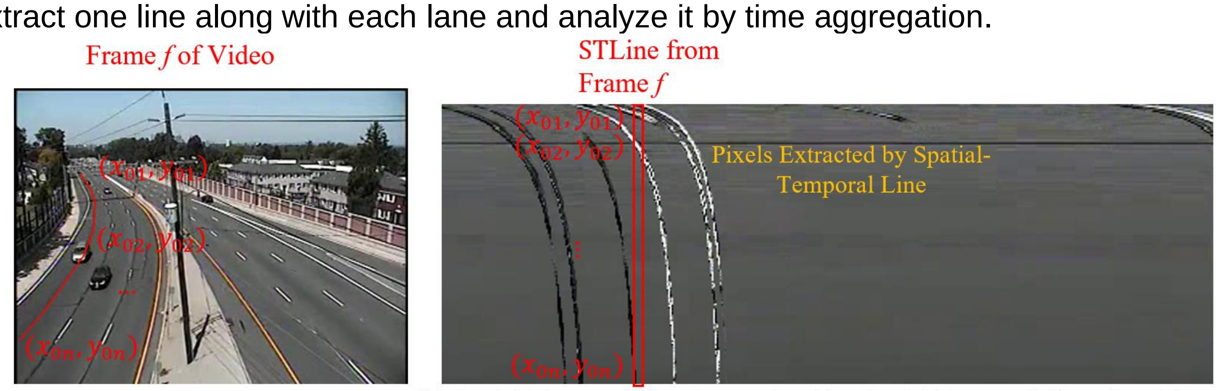


Figure 15. INRIX Data Ingestion to ATSPM

NJDOT CCTV Traffic Video Analytics

The 511NJ traffic video streams provide over 450 real-time CCTV traffic feeds to the motoring public and include video streams from NJDOT and the New Jersey Turnpike Authority. The videos have a low resolution of 320*240 and a frame rate of 8 frames per second (FPS). The video feeds can potentially be utilized to generate and publish travel time and event data with the proposed platform.

The project team has developed a STMap-based (Spatial-Temporal-Map) system to process large-scale traffic camera data efficiently. Unlike traditional video analytic systems, the STMap-based system will not process the whole video. Instead, it will only extract one line along with each lane and analyze it by time aggregation.



(a) Spatial-Temporal Line in Camera View (b) Spatial-Temporal Map Accumulated by Spatial-Temporal Lines Over Time

Figure 16. STLine-the Connection between Camera View and STMap

The system includes a video-analytic sensor to detect pedestrians and vehicles at the roadside. The performance of video-analytic sensors can be impacted by installation, maintenance, environmental, and traffic conditions, as summarized below.

Table 16. Performance Impacting Factors of Video Detection Sensors

Category	Factors	Boundary Conditions
Installation	• Location • Height • Tilting Angle	• Line of Sights (LOSs) • Field of Views (FOVs)
Configuration	• Detection zones, Scanlines • Detection Boundaries • Latency	• Object size, position, and color. • Video frame resolutions • Latency upper/lower bounds
Maintenance	• Video availability and quality • Lense cleanness (water, dust)	• Communication/Network/electricity • Lense maintenance triggers
Environmental	• Illumination (Nightime, exposure, contrast, etc.) • Weather • Shadow	• Brightness, operating hours, thermal/infrared needs • Feasible weather conditions • Missed/False detection
Traffic and Pedestrians	• Occlusions • Routing	• Vehicle and pedestrian density • Safety alert logics

The team has completed the algorithm to reconstruct vehicle arrivals from the Autoscope stop-bar video detector to build PCDs with vehicle arrivals. The model results were validated at both trajectory level and point levels. The method is comprised of traffic flow theory and scanline-based video detection.

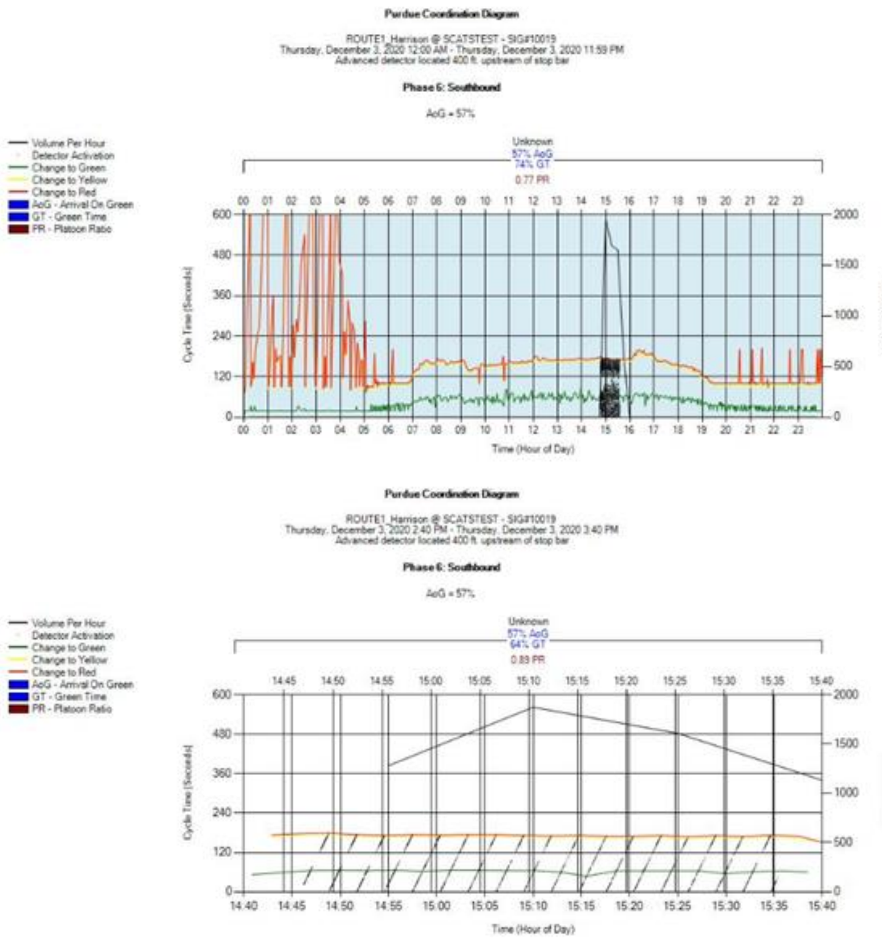


Figure 17. PCDs with Vehicle Arrivals Using Reconstructed Vehicle Trajectories

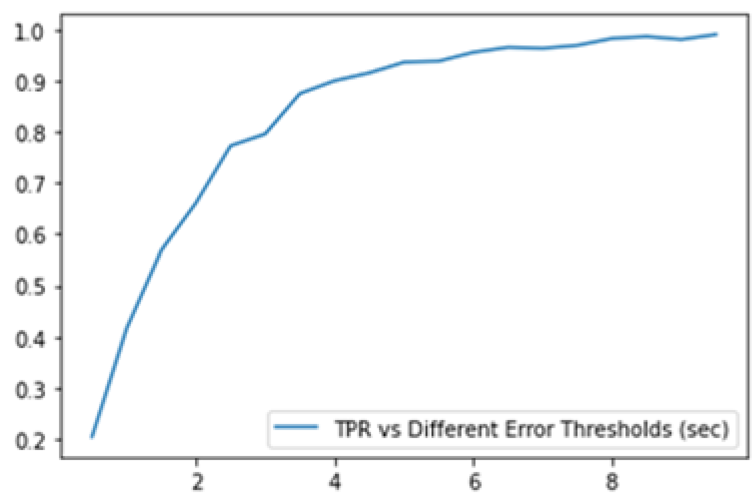


Figure 18. Point Level Evaluation at Advanced Detector Location

The project team has collected various data and investigated the stop bar video detector to verify our trajectory reconstruction method.

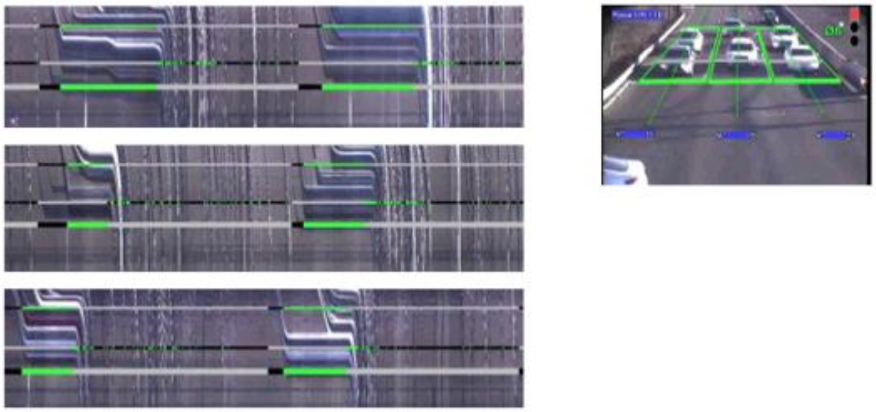


Figure 19. Collected and Investigated the Stop Bar Video Detector

The team also utilized the CCTV Camera to obtain vehicle trajectory using a deep learning model. The research team has designed a neural network to segment vehicle trajectory and understand vehicle movement from the roadside camera. The research team has also prepared and labeled training data to enhance the model performance further.

Figure 20. Developed Deep Learning Model for Traffic Detection

The team updated the SCATS translator program accordingly to reflect the SCATS version changes. The research team also conducted a before-after study using generated PCDs.

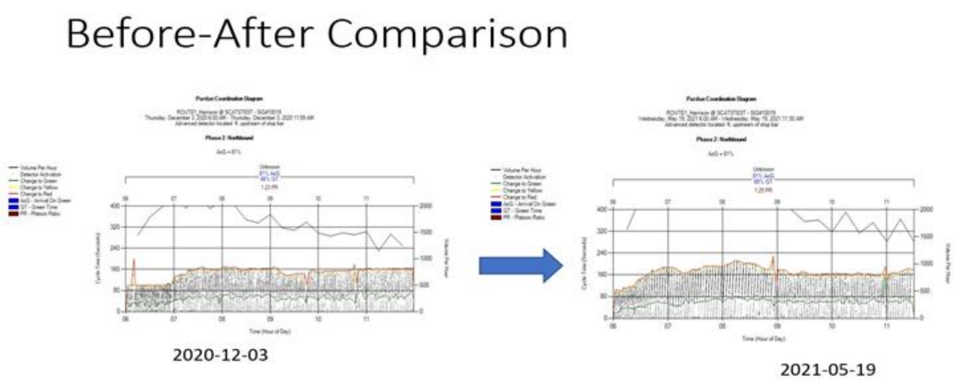


Figure 21. Before-After Study Using PCDs

The team also improved the longitudinal scanline-based vehicle detection method, a High-angle Spatial-Temporal Diagram Analysis (HASDA), for low- or medium-angle roadside CCTV Traffic video scenes. The ground truth and auto count results from the proposed algorithm and the HASDA model are as follows.

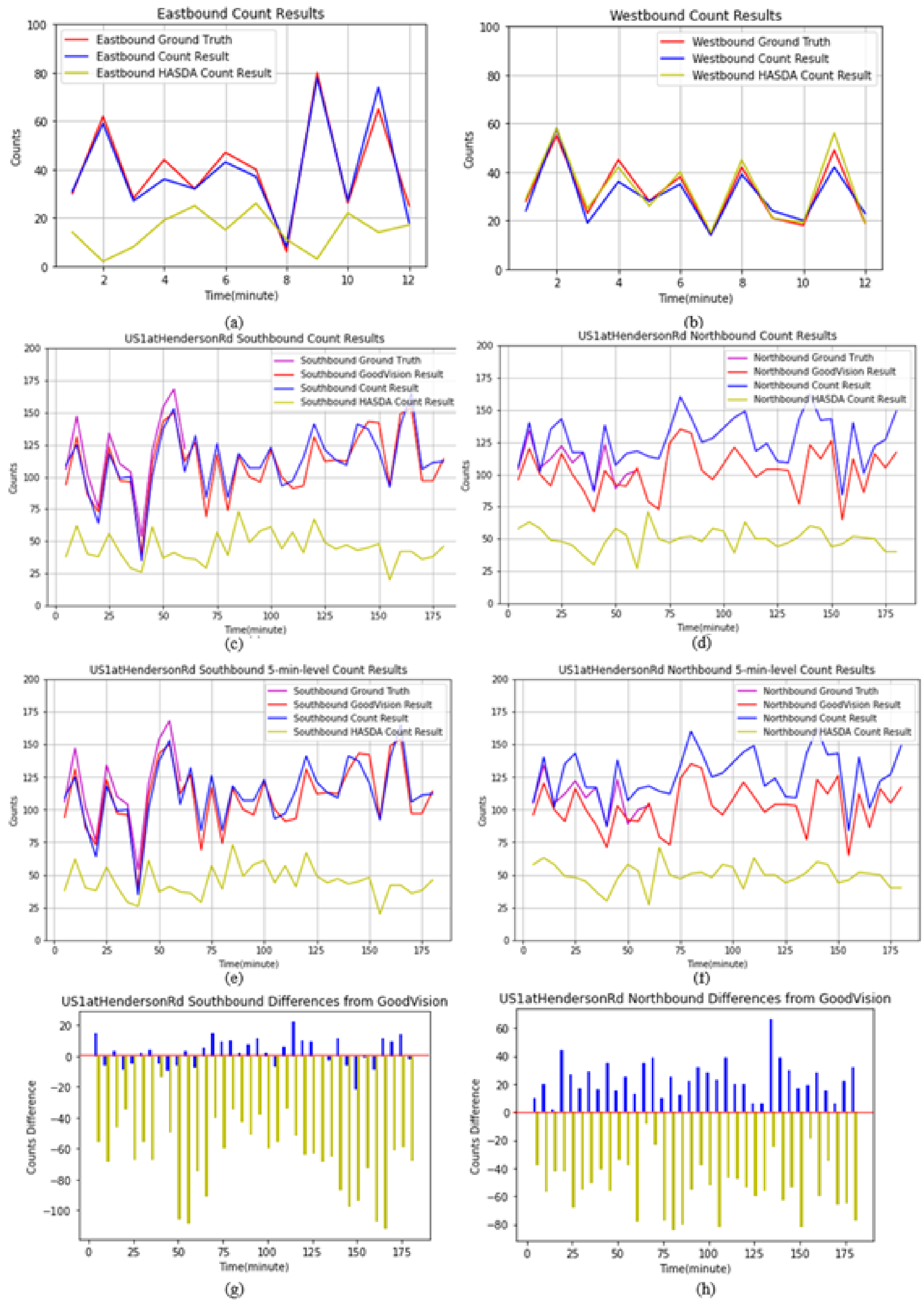


Figure 22. Performance Comparison of the Proposed Algorithm against HASDA, Manual Counting, and Commercial On-Demand Counting Service Results

Figure 22 depicts the temporal profiles of traffic counts generated by the proposed algorithm, the original HASDA algorithm, manual counting, and reference counting results by an on-demand commercial platform. The figures depict only approach-based results to avoid overcrowding the plots. In the following discussion, however, all the error measures are calculated based on lane-by-lane traffic counts, which are the original outputs of the proposed algorithm. Figure 22 (a) compares the count results on eastbound lanes. HASDA mostly undercounts the number of vehicles, which indicates its issue with occlusions. The proposed algorithm matches the manual counting results closely except for a slight error increase for the 4^{th} minute. The reason for undercounts may be the glitching in the video that left "ghost images" of vehicles to be discussed in the next section. The ME of the eastbound result generated by the proposed system is 1.25 vehicle/min indicating slight overcounting. The MAE and MAPE of the eastbound result are 3.4 and 10.62% significant improvement from the 26.6 vehicle/min and 59.06% of HASDA. In Figure 22 (b), HASDA has better performance on westbound than eastbound due to less traffic flow and higher separations among vehicles. The proposed algorithm still outperforms HASDA with MAE and MAPE at 2.1 and 5.91% for the proposed and 3.5 and 11.07% for HASDA.

Figure 22 (c) and (d) show the result for US-1 at Henderson Road. Significant undercounting can be observed with the HASDA algorithm due to the denser traffic flow with more than 61% MAPE on SB and 54% MAPE on NB. The proposed algorithm achieved a MAPE of 11.97% for SB and 11.92% for NB. Some undercounting is found on SB due to some turning vehicles missing the scanning range of the STLine. The static noise removal module causes the overcounting on NB. As expected, the static noise removal module removes most of the static noise and keeps the details from strands, which helps separate different strands. However, without a dynamic threshold for strand preserving, the static noise removal module leaves small blobs of static noise, which separates the strand and causes overcounting.

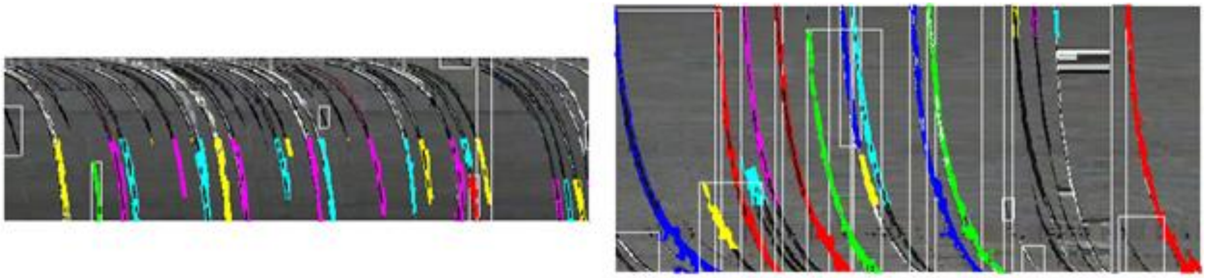
Figure 22 (e) and (f) show the 5-min-interval result of a three-hour video at the intersection of US-1 and Henderson Rd. Using GoodVision results as the reference data, the MAPE for the southbound results of the proposed system and HASDA is 5.68% and 53.45%, respectively. The proposed system can generate vehicle counts much more accurately than HASDA model. The proposed system has a MAPE of 25.2% for northbound direction compared to GoodVision. However, in the first hour with manual counting results, the proposed system produces counting results closer to the manual counting results than that of GoodVision. In summary, Figure 22 demonstrated that the proposed enhancement modules significantly improve the applicability of HASDA on CCTV traffic surveillance video. The results are primarily comparable to manual counting and commercial computer vision services.

Crossing Vehicle Removal Results
Among 212 crossing vehicles from 30 mins of Henderson Rd. video, 194 crossing vehicles were filtered successfully.

Figure 23. Crossing Vehicle Removal Sample

The 18 crossing vehicles that the module failed to filter can be divided into two groups. One group is the turning vehicles that come into the current counting lane later and cause a longer staying time. Limited by the lack of interaction from neighbor lanes, the proposed system cannot determine whether it's a lane-changing or turning vehicle. The other group is the occluded vehicles overlapping to form a consistent pattern. Figure 23 shows a truck overlapped with a sport utility vehicle (SUV), and the SUV was happening to make a left turn.

Occlusion Reduction Results
Much of the improvement of the proposed algorithm is attributed to the occlusion separations (Figure 24). In HASDA, without occlusion separation, many of the clustered vehicle strands will be considered one vehicle (one connected component area) rather than separate vehicles. The proposed algorithm effectively separated those vehicle strands as they traveled closer to the camera. Figure 24 (a) shows the vehicle traveling towards the camera, while Figure 24 (b) shows the vehicle traveling away from the camera. The proposed algorithm can separate the vehicle strands adaptively. For the "come to camera" view, among 24 severe occlusions in lane 1 (second lane from left to right) of Henderson Rd. happened in the first 20 mins, 132 strands were separated successfully, and 23 strands were not detected. Among 33 occlusions in lane 2 (third lane from left to right) that happened in the first 20 mins, 198 strands were successfully separated, and 13 strands were not detected. For the "away from camera" view, among 35 occlusions in lane 3 (fourth lane from left to right) in the first 20 mins, 228 strands were successfully separated, and 24 strands were not detected. Among 33 occlusions in lane 4 (fifth lane from left to right) in the first 20 mins, 172 strands were successfully separated, and 35 strands were not detected. The main reasons for the undetected strands were that the occlusion was mixed with slight noise that connected different strands. The occlusion was too severe that they never clearly separated in the STMap. In summary, 88.48% of the strands in occlusions have been detected.



(a) Come to camera (b) Away from camera

Figure 24. Occluded Vehicle Strand Detection Sample

The computer Vision vehicle detection and tracking model was built on instance segmentation network Mask R-CNN with a ResNeXt-101 feature pyramid network backbone. Five object classes of interest, including car, truck, person, bus, and bike, were used according to the Microsoft COCO dataset. A Weighted Inter-class Non-maximum Suppression (WINS) was applied to remove false interclass detections, as small trucks could result in car and truck double detections. The online association algorithm was employed to assign new frames to exist tracklets, considering feature similarity and spatial constraints. The outputs of computer vision algorithms were used to evaluate the detection results at the trajectory level. The detected objects and tracked trajectory points using benchmark computer vision algorithms are shown in Figure 25.

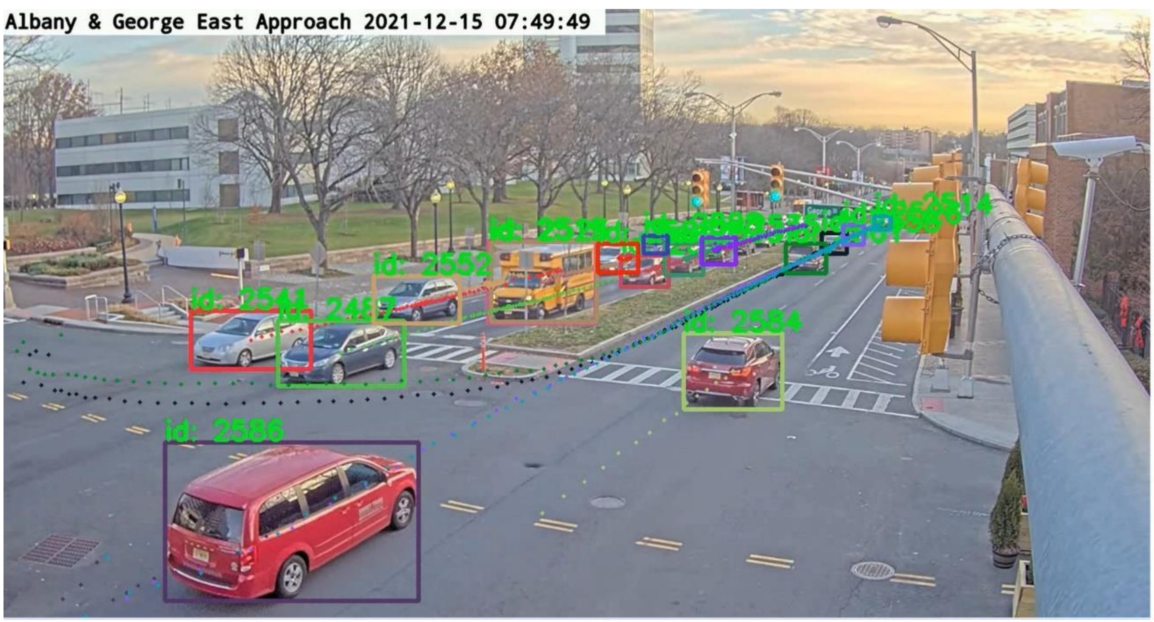


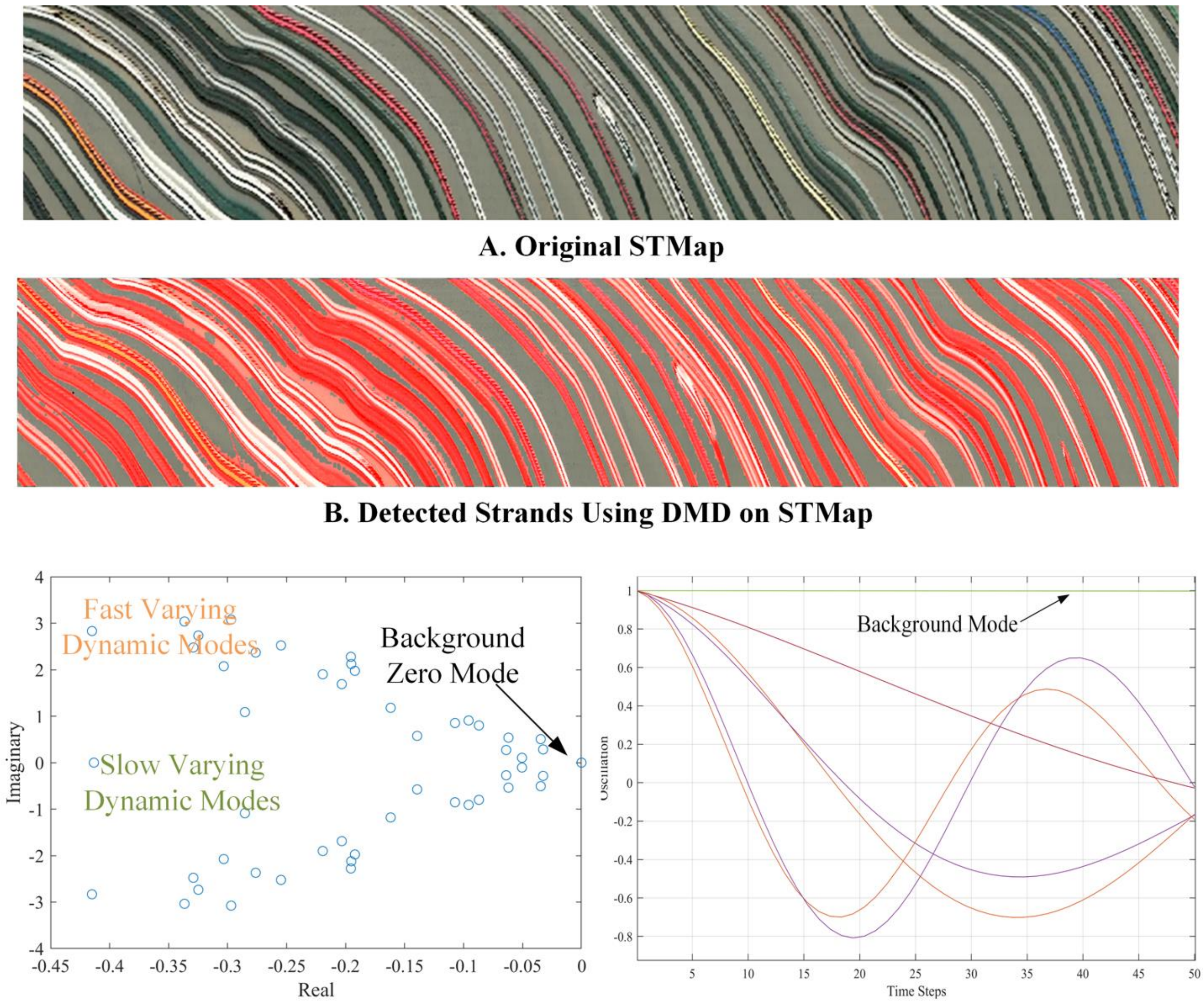
Figure 25. Computer Vision Benchmark Detection and Tracking

Baseline segmentation neural networks were trained and tested using the same STMaps dataset to evaluate the proposed model performance.

Table 17. Model Performance

		Lane 1	Lane 2	Lane 3	Lane 4	Lane 5
Res-UNet+	**Positive Detect Rate**	97.1%	98.9%	98.1%	98.0%	96.5%
	False Detect Rate	3.2%	2.7%	3.2%	4.2%	3.0%
HASDA Model	**Positive Detect Rate**	96.5%	96.9%	94.1%	89.58%	92.3%
	False Detect Rate	5.8%	6.9%	2.4%	9.5%	3.5%

Res-UNet+ was designed for the semantic segmentation task by adapting two prevalent deep learning architectures. The Res-UNet+ neural networks significantly improve the performance of the STMap-based vehicle detection. After a thorough evaluation, the model proved accurate and robust against many challenging factors. The data labeling process is semi-automated with the Dynamic Mode Decomposition (DMD) method. U-Shaped Dual Attention Inception (DAIU) Neural Networks were tested on NJ511 traffic cameras for different scenarios covering rainy, snowy, low- illumination, and signalized intersections from a key, strategic arterial in New Jersey. The DAIU net has improved performance than other mainstream neural networks based on segmentation model evaluation metrics.



A. Original STMap

B. Detected Strands Using DMD on STMap

C. DMD Eigenvalue Distributions

D. Decomposed-Mode Oscillations Over Time

Figure 26. STMap and Its Dynamic Modes

NJDOT Wavetronics Advanced Detection Data

The ingestion of speed data from Wavetronix and eventually connected vehicles into the ATSPM that reflects vehicle presence and provides a trajectory speed of the vehicle were evaluated as it relates to the time in the cycle for each approach. It builds on the current PCD, which can show vehicle presence. Figure 27 to Figure 29 show a lane-by-lane capture of vehicle presence with a speed vector. The longer the vector, the more the speed.

Southbound, Lane 1

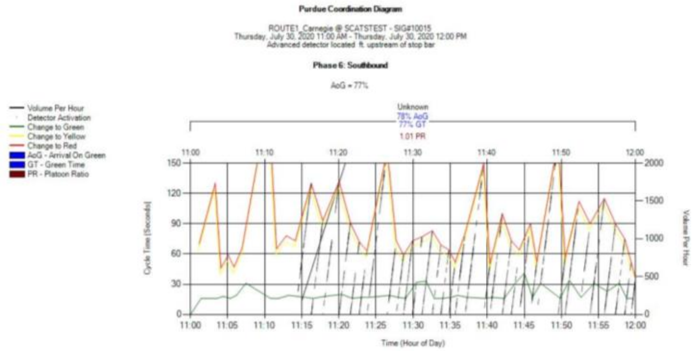


Figure 27. Actual Wavetronix data overlaid on PCD indicating a vector speed (1 hour) for southbound lane 1 at Carnegie and US 1.

Southbound, Lane 2

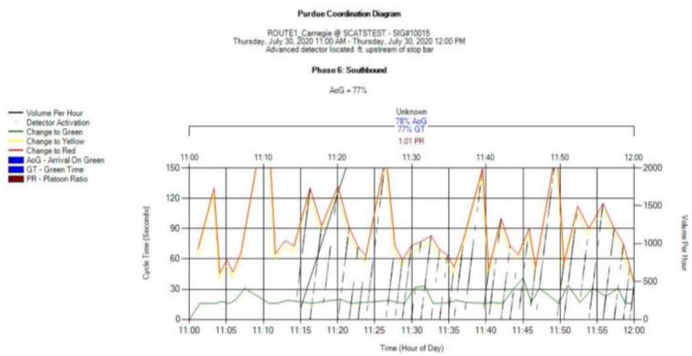


Figure 28. Actual Wavetronix data overlaid on PCD indicating a vector speed (1 hour) for southbound lane 2 at Carnegie and US 1

Southbound, Lane 3

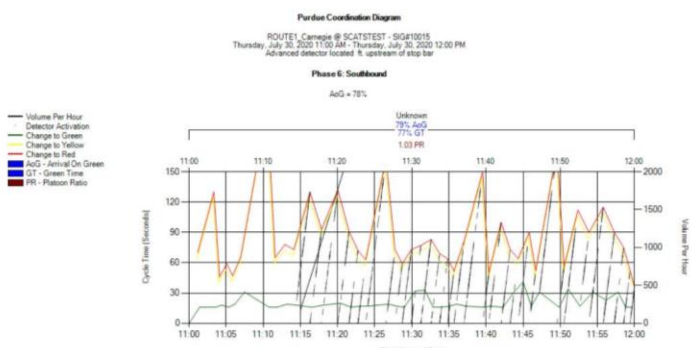


Figure 29. Actual Wavetronix data overlaid on PCD indicating a vector speed (1 hour) for southbound lane 3 at Carnegie and US 1

Autoscope Stop Bar Detection Analytics

The team developed a solution to reconstruct lane-by-lane vehicle trajectories using the prevailing stop-bar detector at an adaptively controlled intersection. The method is based on shockwave theory to estimate state-changing points of vehicle movements. This scanline method substantially reduces the complexity of obtaining macroscopic traffic parameters from roadside CCTV cameras. With the reconstructed vehicle trajectories, the stop-bar detection data can estimate the vehicle arrivals at the advanced locations, used to generate coordination diagrams in the ATSPMs system. A new coordination diagram is introduced by combing the stop-bar detector with signal phase and timing to enable traffic operators to monitor signal efficiency in real-time. The traffic flow condition from the reconstructed trajectory can be used for data-driven signal performance as live data to update models and predictions.

STMAP generation

The scanline method is a video analytic method in traffic-related research, which has been adopted broadly for traffic detection to address the vehicle tracking problem of the multi-camera network. The first step is defining the scanline on selected lanes and acquiring the pixel coordinates between each turning point. Next, the pixel value of the selected scanline will be accumulated, leading to the spatial-temporal map that shows the vehicle trajectories. The defined scanline and generated STMap is shown in Figure 30.

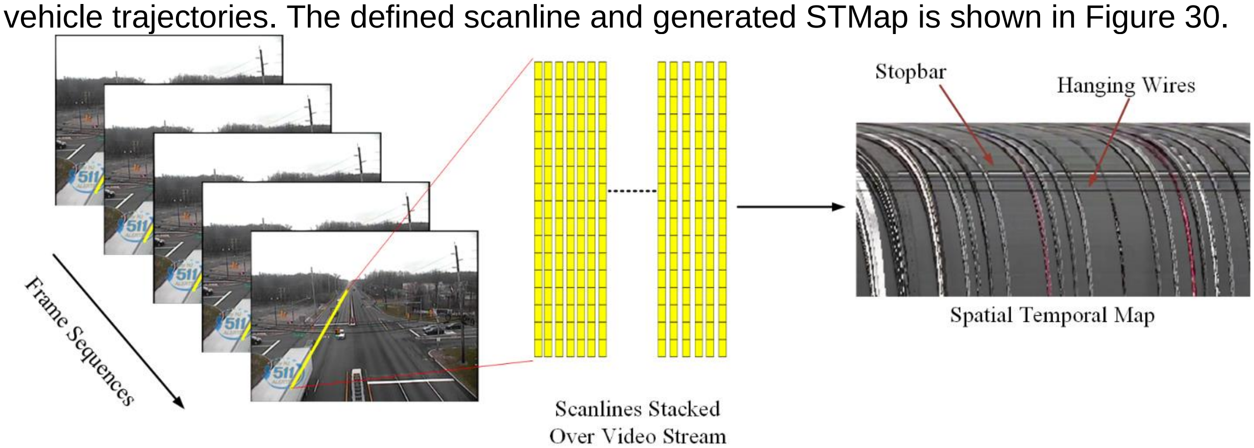


Figure 30. Scanline and STMap Generation (US1 at Henderson)

STMAP Coordinate Transformation

Due to the installation angle of the intersection CCTV camera, there is the perspective issue of raw STMap. As vehicles approached the intersection, the traveling trajectories in the farther location shown in STMap were distorted. In this step, we use perspective transformation to rectify STMap so that STMap can reflect the accurate traveling distance. We can obtain the homography transformation matrix by matching feature points between the video image and the google map. Next, the original STMap is converted to a real-world STMap. In Figure 2, the non-stopped vehicle trajectories from the original STMap are rectified as straight lines, in line with the intuition that the free flow speed should be constant. Finally, a scale factor is used to convert pixel distance on the undistorted STMap to physical distance. In the proposed model, the physical STMAP will be used to collect the observed shock wave patterns in traffic flow. Figure 31 Rectified STMap After Perspective Transformation Using Feature Matching US1 at Harrison (A. Feature Matching Between Google Map and CCTV Video; B. Original STMap; C. Transformed STMap without Perspective Distortion)

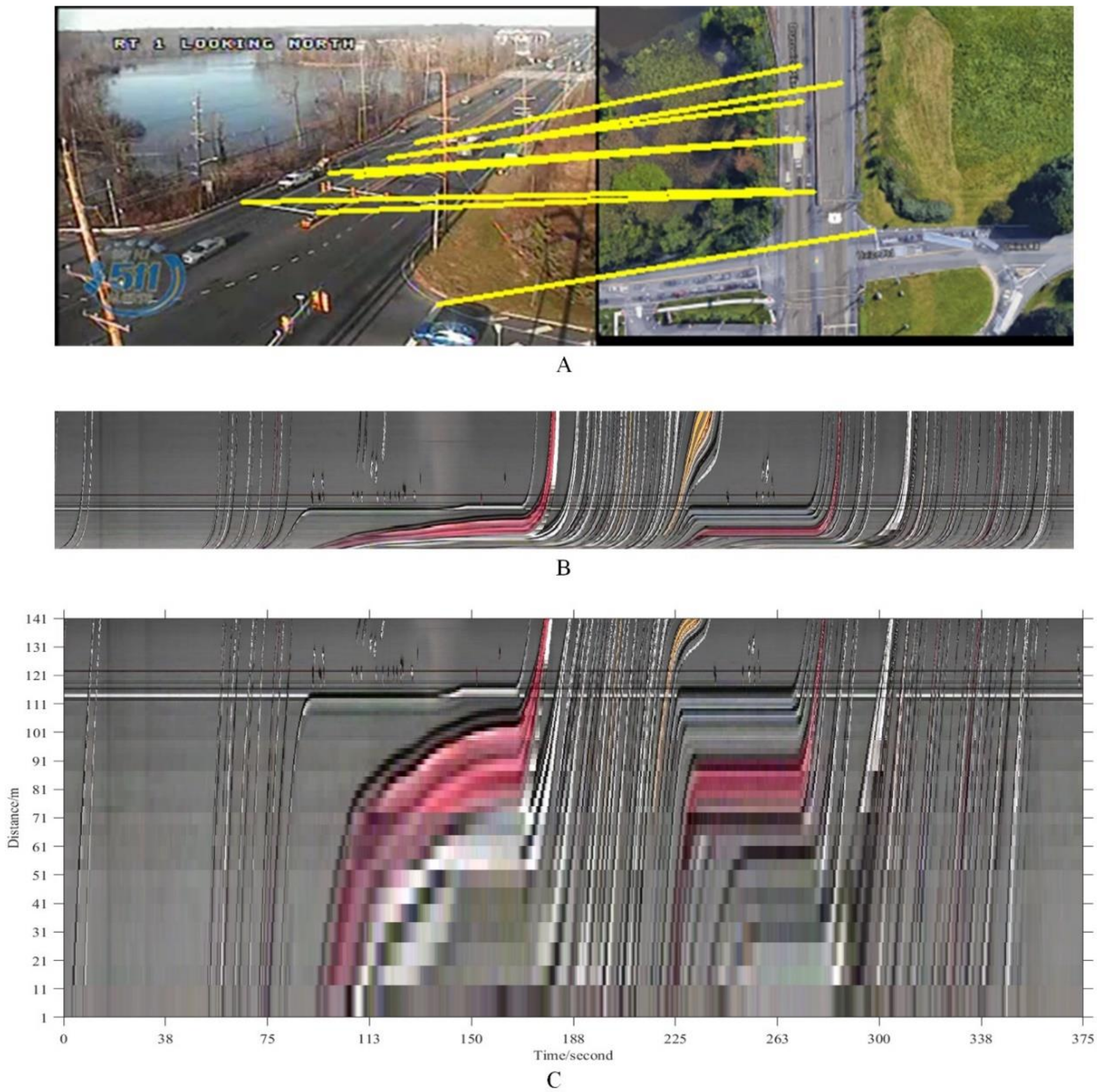


Figure 31. Rectified STMap After Perspective Transformation Using Feature Matching US1 at Harrison (A. Feature Matching Between Google Map and CCTV Video; B. Original STMap; C. Transformed STMap without Perspective Distortion)

The above session reviewed relevant studies regarding signal performance measures, shockwave theory, and stopbar detectors. Compared to existing research, the paper's contributions are summarized below:

1. Developed a Turning Point (TP) based trajectory algorithm to reconstruct traffic arrivals at the advanced location, which applies to the adaptive controller and fixed timing intersection, where only a stopbar detector is available.
2. It has proposed a dynamic queuing shockwave estimation model to update intersection queuing speed in real-time that can be used as input for queue length estimation and signal optimization.
3. Proposed new performance measures combine stopbar detection and signal phase and timing as a novel coordination diagram, which can be used for signal timing diagnosis.
4. Explored multiple data sources, including CCTV roadside camera, Autoscope Video detector, Wavetronix detector, and signal timing event log to compare multiple data sources of traffic signal systems.

Shockwave Speed Measurement Using STMap

Shockwave theory has been used widely to capture the change of traffic state, where the traffic state is described by density, flow, and density. According to Lighthill–Whitham–Richards (LWR) traffic flow model (Lighthill and Whitham,1955 and Richards, 1956), the shock wave speed is determined by the ratio of change in flow concerning the change in density between two traffic states. The shockwave speed is expressed as a ratio between the change of flow rate over the change of density, as shown in Eq. (1).

$$\omega = \frac{q_A - q_B}{k_A - k_B} = \frac{\Delta q}{\Delta k} \qquad (1)$$

Where q is the flow rate, and k is the density.

Figure 32 shows all types of shockwaves defining the boundaries of different traffic states, which include the queuing shockwave (ω_1), discharging shockwave (ω_2), departure flow (ω_3), and compression shockwave (ω_4).

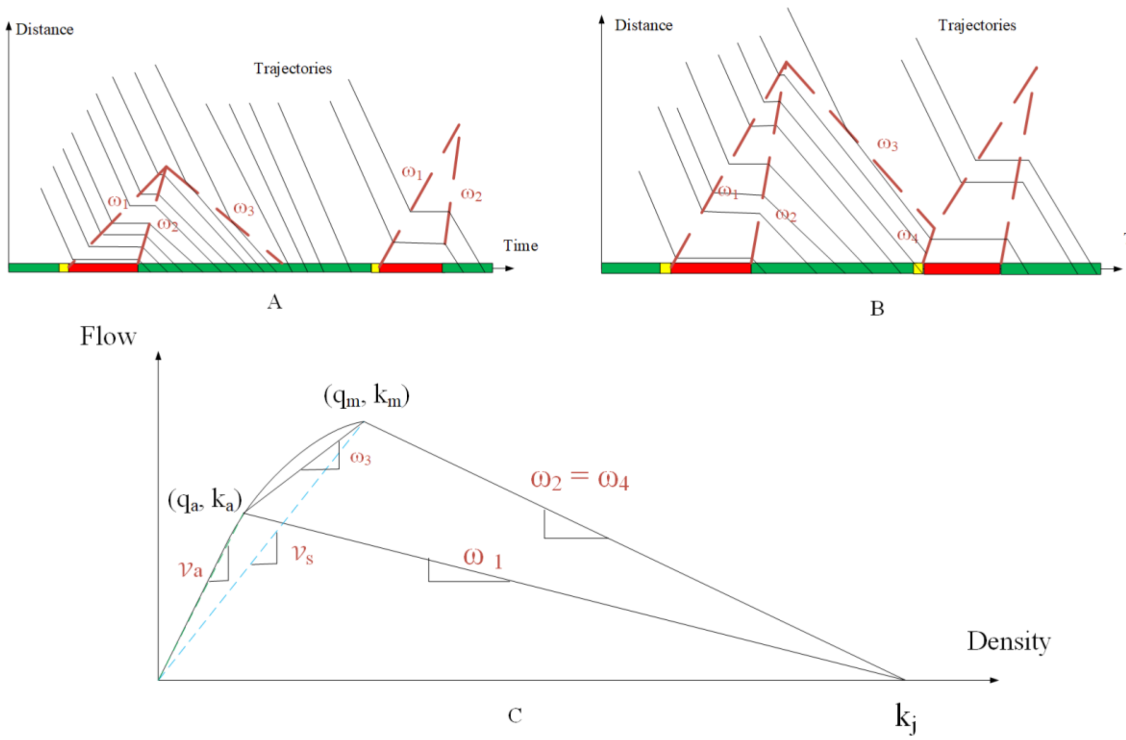


Figure 32. Shockwave and Fundamental Diagram (A. Under-Saturated Condition; B. Over-Queuing shockwave:

Queuing shockwave:

$$\omega_1 = \frac{q_a - 0}{k_a - k_j} \quad (2)$$

Discharging shockwave:

$$\omega_2 = \frac{0 - q^m}{k_j - k_m} \quad (3)$$

Propagating shockwave:

$$\omega_3 = \frac{q_a - q_m}{k_a - k_m} \quad (4)$$

Compression shockwave:

$$\omega_4 = \frac{q_m - 0}{k_m - k_j} \quad (5)$$

Where, q^a is arrival flow rate; q^m is maximum flow rate; k^m is the maximum density at maximum flow rate; k^j is jam density when vehicles are stopped. From the shockwave equations, we can find out that Discharging shockwave ω_2, saturation flow speed v_s and compression shockwave ω_4 are only impacted by the roadway design capacity and independent of arrival flows. Queuing shockwave is defined by traffic state changing from arrival speed v_a to jam condition. Discharging shockwave is defined by traffic state changing from jam condition to saturation flow. Propagating shockwave indicates that the arrival vehicles slow from arrival speed to saturation flow. Compression Shockwave is formed when queuing vehicles are not fully released during one cycle. The saturation flow rate is calculated by maximum flow divided by maximum density.

This methodology of trajectory reconstruction contains two parts. The first part uses the scanline method to measure shockwave speeds. Then, the stop-bar, signal phase, and timing data generate piece-wise linear trajectories for vehicles passing through the intersection area. Figure 33 illustrates the STMap with converted physical distances, and the shockwave patterns can then be observed for each signal cycle. ω_2 are stable because they are only related to lane characteristics. ω_1 can be impacted by arrival flows as shown in Eq. (2).

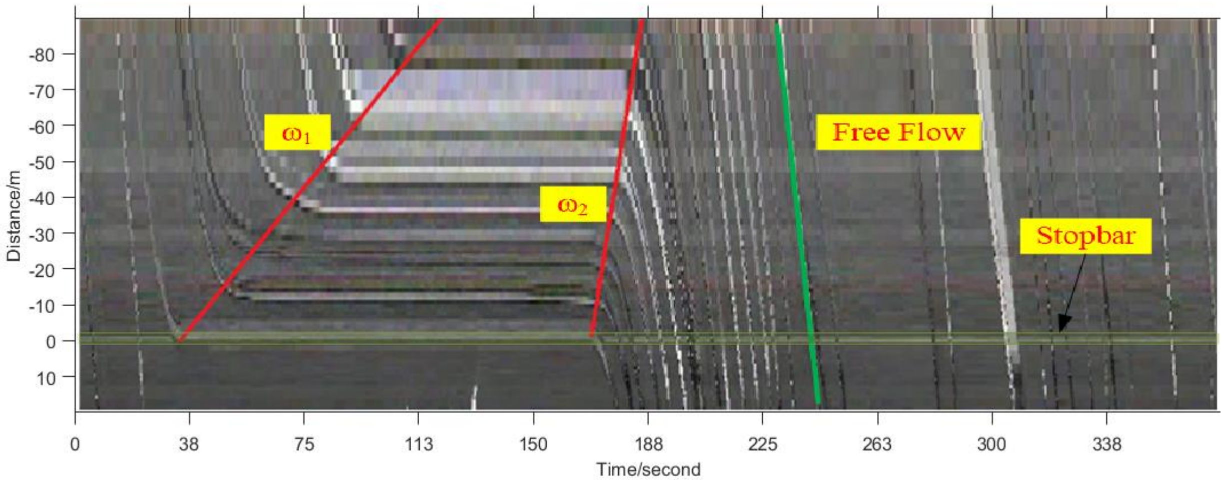


Figure 33. Shockwave Measurements from STMap ($\boldsymbol{\omega_1}$: Queuing Shockwave; $\boldsymbol{\omega_2}$: Discharging Shockwave)

Since the queuing shockwave often varies from different times of day and different cycle lengths, it is not sensible to use the same ω_1 all the time. To address the queuing shockwave speed (ω_1) estimation, a dynamic model, is created to account for the fluctuation of traffic volume. The model can update queuing shockwave speed based on stop bar presence detection in real-time. The complete derivation is as follows:
From Eq. (2), we can get:

$$\omega_1 = \frac{q-0}{k-k_j} = \frac{q}{k} * \left(\frac{1}{1-\frac{k_j}{k}}\right) \tag{6}$$

Given the speed-flow-density relationship,

$$q = \mu * k \tag{7}$$

We will obtain the following relationship by substituting the Eq. (7) into Eq. (6).

$$\omega_1 = \mu * \left(\frac{1}{1-\frac{k_j}{k}}\right) \tag{8}$$

Assuming the fundamental diagram is given by the speed-density relationship

$$\mu = \mu(k) \tag{9}$$

It follows that

$$\omega_1 = \mu(k) * \left(\frac{1}{1-\frac{k_j}{k}}\right) \tag{10}$$

Occupancy and density are almost constant multiples, assuming consistent average vehicle length. From the stop-bar detectors' occupancy measure, Occ for each lane. We can obtain Eq. (11), Eq. (12), and Eq. (13).

$$k = g * Occ \tag{11}$$

$$\frac{\mathrm{Occ}}{\mathrm{Occ_o}} = \frac{\mathrm{k}}{\mathrm{k_o}} \tag{12}$$

$$\frac{\mathrm{Occ_j}}{\mathrm{Occ}} = \frac{\mathrm{k_j}}{\mathrm{k}} \tag{13}$$

Where g is the factor that converts occupancy into density. Occ_o is the optimal stop-bar occupancy corresponding to maximum flow density. Occ_j is the jam occupancy.

ω_1 can be further written as:

$$\omega_1 = \mu(g * Occ)\left(\frac{1}{1-\frac{Occ_j}{Occ}}\right) \tag{14}$$

So, the team established a relationship between shockwave speed ω_1 with the occupancy observed at the stopbar detectors. By applying different speed-density relationships $u = \mu(k)$, we can then estimate the dynamic patterns of ω_1 shockwave in response to different queue spacing conditions in arterial streets.

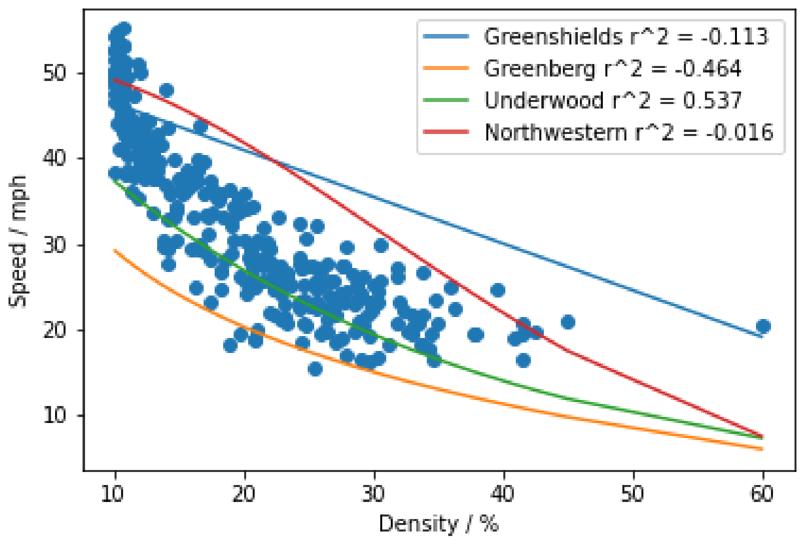


Figure 34. Comparison of Different Speed-Density Models with Field Data.

We conducted some preliminary analysis of several different speed-density relationships. Based on the model evaluation results with observed field data, the Underwood exponential model captures the trend better among all candidate models, including Greenshields linear model, Greenberg logarithmic, and Northwestern models.

The Underwood model is expressed as:

$$\mu = \mu_f * e^{-\frac{k}{k_o}} \tag{15}$$

Where, μ_f is free-flow speed, k_o is optimum density corresponding to the maximum flow. Given Eq. (12), we can substitute the ratio of density in Eq. (14) with Eq. (15). The following equation holds:

$$\omega_1 = \mu_f * e^{-\frac{Occ}{Occ_o}} * \left(\frac{1}{1-\frac{Occ_j}{Occ}}\right) \tag{16}$$

Where, ω_1 is real-time queuing shockwave to be determined; μ_f is the free-flow speed. Occ is stop-bar occupancy during the green phase; Occ_o is the occupancy under optimum flow; Occ_j is the occupancy under jam traffic.

The above derivation showed that we could estimate the queue forming speed with single detectors' occupancy for signalized intersection, QED.

Stop-bar Trajectory Reconstruction

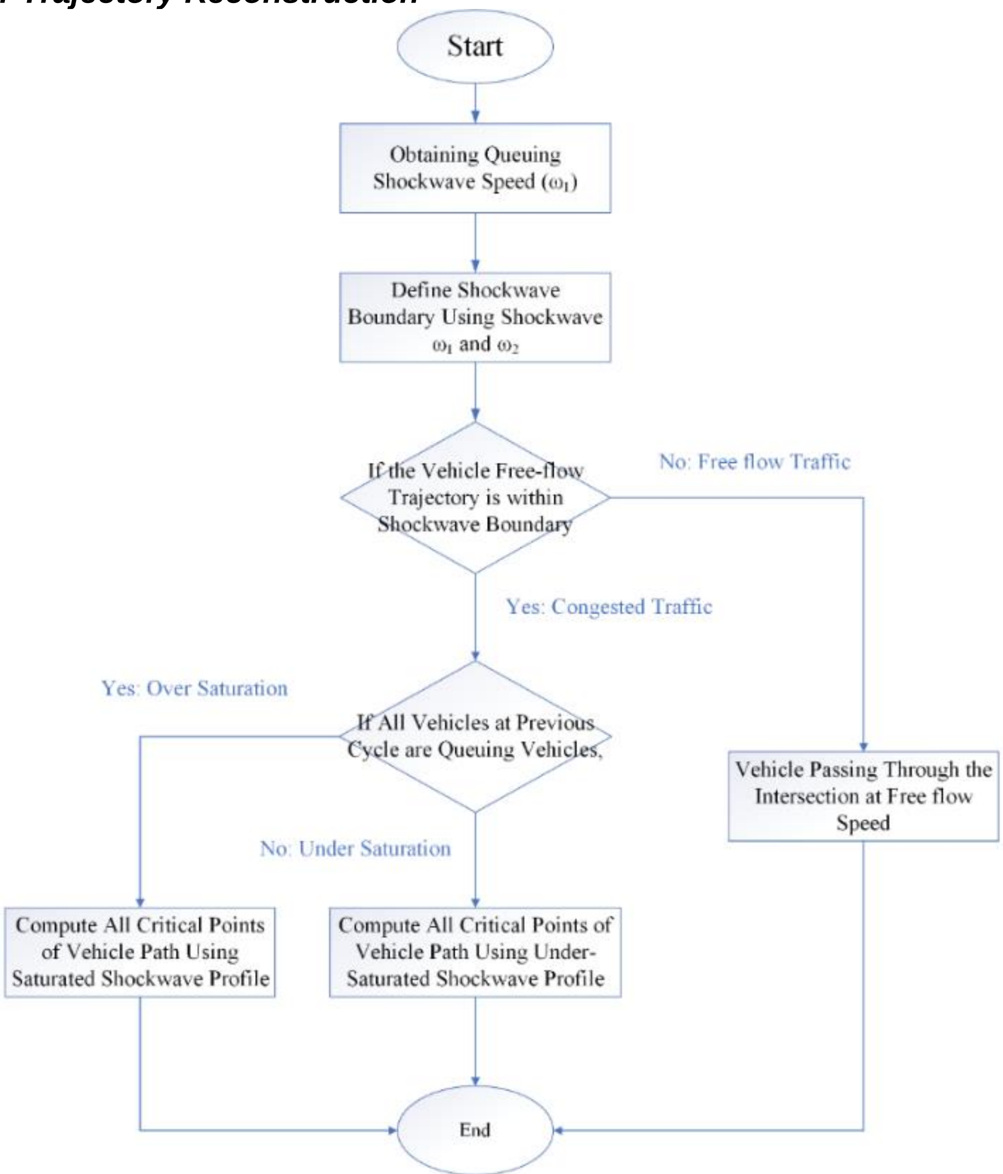


Figure 35. Workflow for Trajectory Reconstruction Based on Shockwave Profile

The key to reconstructing the vehicle trajectories is identifying all turning points of the piece-wise linear trajectory model. After obtaining ω_1 and ω_2, the queuing distance and shockwave boundary can be calculated, which are used to determine whether a vehicle is stopped or passing through at free-flow speed. The intersecting point of two shockwaves is calculated:

$$t_{boundary} = \frac{\omega_2 * t^1_{depart} - \omega_1 * t^1_{arrival}}{\omega_2 - \omega_1}$$
(17)

$$d_{boundary} = (t^1_{arrival} - t_{queue}) * \omega_1$$
(18)

Where $(t_{boundary}, d_{boundary})$ is the timestamp and location of the converging point between ω_1 and ω_2; ω_1, ω_2 are queuing and discharging shockwave; $t^1_{arrival}$ is the first vehicle arrival timestamp; t^1_{depart} is the first vehicle departing timestamp.

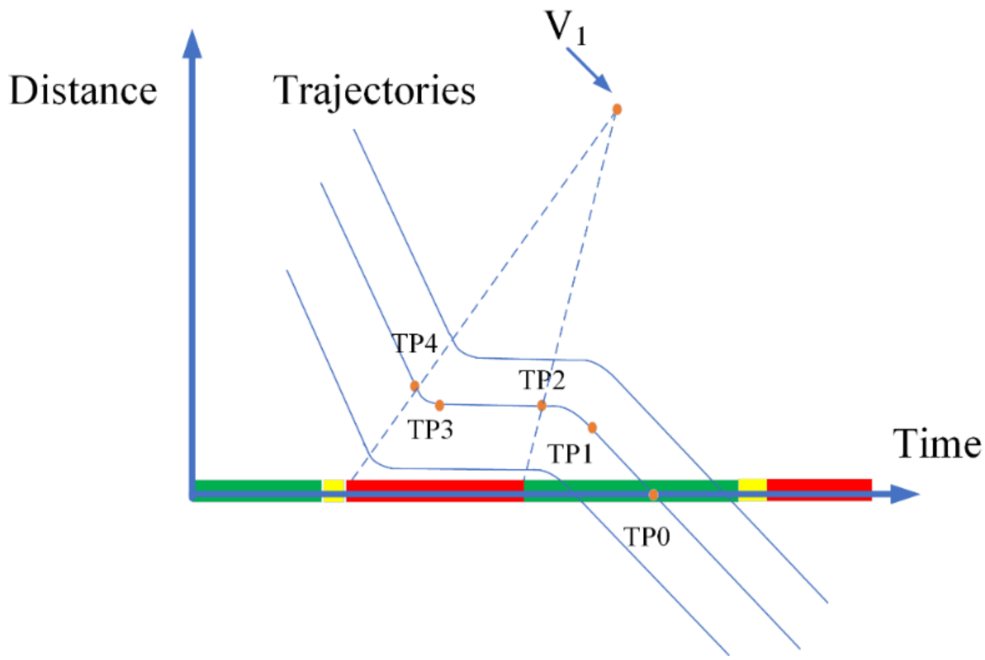


Figure 36. Under-Saturated: Turning Points used for Trajectory Reconstruction

Figure 36 shows the turning points of vehicle trajectories and shockwave triangles under saturated conditions. Turning Point $TP0$ is when a vehicle passed through the stop bar; Turning Point $TP1$ is when the car accelerated to the saturation flow speed; Turning Point $TP2$ is when the vehicle starts to move; Turning Point $TP3$ is when the car stopped; Turning Point $TP4$ is when the car begins to decelerate; $V1(t_{V_1}, d_{V_1})$ is the converging point between queuing and discharging shockwaves. The first step is to calculate each queuing vehicle's joining and departing point when the queuing and discharging shockwave propagates to the queued vehicle. It is a simplified macroscopic level model, which accounts for the inherent linear property of shockwave. First, the $TP0$ is computed, the timestamp of a vehicle passing the intersection.

$$t^i_{TP0} = t^i_{stopBar} \quad (19)$$

$$d^i_{TP0} = 0 \quad (20)$$

Second, the $TP2$ is computed when the vehicle starts to accelerate until its speed reaches the free-flow speed.

$$t_{TP2}^{i} = \frac{\frac{v_s^2}{\mathrm{acc}} - v_s * t_{stopBar}^{i} + w_2 * t_{green}^{begin} - \frac{1}{2} * acc * \left(\frac{v_s}{acc}\right)^2}{\omega_2 - v_s} \quad (21)$$

$$d_{TP2}^{i} = w_2 * (t_{TP2}^{i} - t_{green}^{begin}) \quad (22)$$

Upon obtaining turning point 2, critical point 1 is calculated once the vehicle reaches the saturation flow speed.

$$t_{TP1}^{i} = t_{TP2}^{i} + \frac{v_s}{acc} \quad (23)$$

$$d_{TP1}^{i} = v_s * \left(t_{TP1}^{i} - t_{stopBar}^{i}\right) \quad (24)$$

$TP3$ is determined when the queuing vehicle stops and joins the queue. To calculate $TP3$, the nonhomogeneous Poisson is used to capture the randomness of arrival patterns, as the vehicle arrival rates vary during different times of the day. While under certain heavy vehicle conditions, the normal distribution arrival model captures the high-volume vehicle arrival patterns. For a nonhomogeneous Poisson process with a rate $\lambda(t)$, the number of arrivals at any interval, at any point along the corridor, is a time-dependent random variable. The homogeneous or nonhomogeneous. The number of vehicle arrival between time interval s is expressed as:

$$N(t+s) - N(t) \sim Poisson\left(\int_t^{t+s} \lambda(\alpha) d\,\alpha\right) \quad (25)$$

The arrival headway Δ_i between consecutive two vehicles is defined as:

$$\Delta_i = t_1 - t_2, \; s.t. \; N(t_2) - N(t_1) = 1 \quad (26)$$

where $N(t), t \in [0, \infty]$ is the counted number of vehicles arrivals. For the Poisson process, it has to suffice two conditions: The time intervals between Poisson events that occur at the rate of λ per unit of time are: 1. mutually independent; and 2. described by an exponential distribution function with parameter λ. Given the segment between the testing location at Harrison (40.337361, -74.6310056) and the upstream SCATS intersection at Independence (40.3616489, -74.6014728) has a distance of over 2 miles. It is reasonable to consider the arrival of the vehicle is an uncoordinated Poisson process. For Platoon vehicles, a normal distribution is more realistic.

Therefore, $TP3$ is obtained with the following equations:

$$t_{TP3}^{i} = t_{arrival}^{1} + \sum_{\mathrm{k=2}}^{\mathrm{k=i}} \Delta_{\mathrm{k}} \quad (27)$$

$$\mathrm{d_{TP3}^{i}} = \mathrm{d_{TP2}^{i}} \quad (28)$$

$TP4$ is the vehicle starting to decelerate, which is considered the arrival of the red event.

$$t_{TP4}^{i} = t_{TP3}^{i} - v_f / dec \quad (29)$$

$$d_{TP4}^{i} = d_{TP3}^{i} - 0.5 * dec * \left(\frac{v_f}{dec}\right)^2 \quad (30)$$

Where, w_1 is queuing shockwave speed; w_2 is the discharging shockwave; v_f is free-flow speed; v_s is the saturation flow speed; acc is the acceleration rate $(\frac{ft}{s^2})$, dec is deceleration rate $(\frac{ft}{s^2})$;

$t_{stopBar}^{i}$ is the $timestamp\ of\ i^{th}\ vehicle\ passing\ the\ stopbar\ detector$;

t_{green}^{begin} is the green phase begin time;

$\left(t_{tp3}^{i}, d_{tp3}^{i}\right)$ is the joining point of the vehicle at maximum queue length.

Finally, all critical points are connected to reconstruct the vehicle trajectories. By obtaining vehicle trajectories from stop-bar detector data, the vehicle arrival timestamps can be inferred to create SPM such as Purdue Phase Diagrams (PPDs) even though there is no available advanced detector at the intersection.

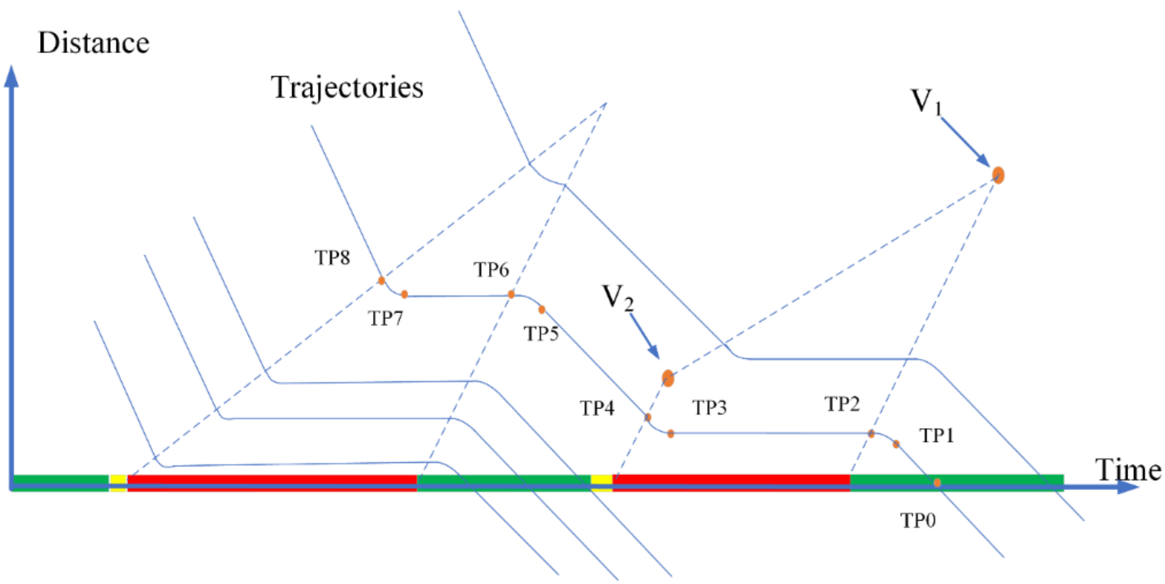


Figure 37. Saturated: Turning Points used for Trajectory Reconstruction

Figure 37 shows the turning points of vehicle trajectories and shockwave triangles at over-saturated conditions, meaning the queuing vehicles cannot be released from the previous green phase. $TP0, TP1, TP2, TP3$ are the same as under-saturated conditions. Turning Point $TP4$: is when the car begins to decelerate on compression shockwave; Turning Point $TP5$ is when vehicle reached the saturation flow speed at the previous cycle; Turning Point $TP6$ is when the car starts to move in previous cycle; Turning Point $TP7$ is when the car completely stopped in the previous cycle; Turning Point $TP8$ is when the car begins to slow down in the previous cycle; $V1(t_{V_1},\ d_{V_1})$ is the converging point between queuing and discharging shockwaves. $V2(t_{V_2},\ d_{V_2})$ is the converging point between compression and queuing shockwaves. Suppose the previous cycle is over-saturated, and the vehicle at free-flow speed will avoid the shockwave boundary. In that case, this vehicle is considered to pass the intersection at free-flow speed. Otherwise, using the following equations to calculate turning points (TP) $TP4$, $TP5$, $TP7$, and $TP8$.

If the previous cycle is over-saturated, and the calculated $TP2$ and $V2$ meet the condition $\left|d_{tp2}^{i}\right| \leq \left|d_{V_2}\right|$, which means this vehicle joined the compression shockwave during the current cycle, then the following equations are used to calculate $TP4$ to obtain its entire trajectory. If the vehicle does not join the compression shockwave, $TP4$ was calculated using Eq. (31) and Eq. (32).

$$t_{TP4}^{i} = t_{TP3}^{i} - v_s/dec \tag{31}$$

$$d_{TP4}^{i} = d_{TP3}^{i} - 0.5 * dec * \left(\frac{\mu_s}{dec}\right)^2 \quad (32)$$

The TP6 from the equation is computed when the vehicle starts to accelerate until its speed reaches the free-flow speed using the previous cycle's parameters.

$$t_{TP6}^{i} = \frac{\frac{v_s^2}{acc} - v_s * t_{TP4}^{i} + w_2 * t_{green}^{previous\ begin} - \frac{1}{2} * acc * \left(\frac{v_s}{acc}\right)^2}{\omega_2 - v_s} \quad (33)$$

$$d_{TP6}^{i} = w_2 * (t_{TP6}^{i} - t_{green}^{previous\ begin})$$

(34)

The $TP5$ is when the vehicle reaches the saturation flow speed obtained using the equations.

$$t_{TP5}^{i} = t_{TP6}^{i} + \frac{v_s}{acc}$$

(35)

$$d_{TP5}^{i} = v_s * \left(t_{TP5}^{i} - t_{TP4}^{i}\right) \quad (36)$$

Therefore, turning point 7 is obtained with the following equations based on Poisson Arrival Pattern and the first arrival vehicle's timestamp at the previous cycle. Note that, when an over-saturated condition, the current cycle i^{th} queuing vehicle is the j^{th} queuing vehicle in the previous cycle.

$$t_{TP7}^{i} = t_{arrival}^{previous\_1} + \sum_{k=2}^{k=previous\_j} \Delta_k \quad (37)$$

$$d_{TP7}^{i} = d_{TP6}^{i}$$

(38)

Turning point 8 is the vehicle starting to decelerate at the previous cycle.

$$t_{TP8}^{i} = t_{TP7}^{i} - v_f / dec \quad (39)$$

$$d_{TP8}^{i} = d_{TP7}^{i} - 0.5 * dec * \left(\frac{v_f}{dec}\right)^2 \quad (40)$$

Where, $t_{green}^{previous\ begin}$ is the green begin timestamp in the previous cycle.

$t_{arrival}^{previous\_1}$ is the first vehicle arrival timestamp in the previous cycle.

Spatial-Temporal Map with Stopbar Detector Data

We propose a trajectory comparison method to visually evaluate the reconstructed trajectory by plotting the estimated vehicle trajectory on STMap. This non-conventional way of model visualization significantly reduces the complexity of vehicle detection results. As shown in Figure 38, the grey strands are physical vehicle trajectories captured on STMap, which is used as ground-truth vehicle trajectories to evaluate the model results. The stop-bar detectors' on/off status is plotted on the STMap to show the duration of the vehicle passing by the Autoscope stopbar detection zone. The STMap can capture accurate spatial and temporal information and become an essential tool for traffic measurements.

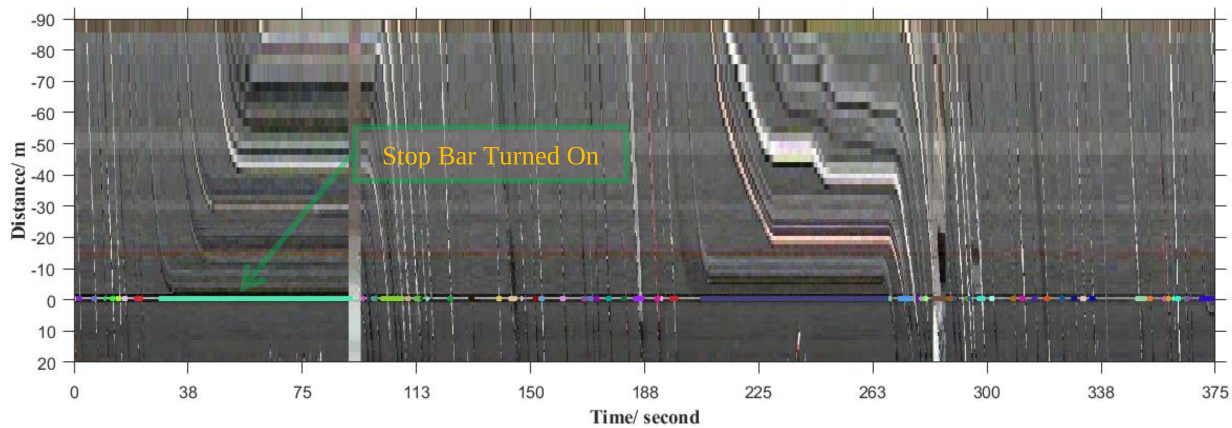


Figure 38. CCTV STMap Trajectory with Stop-bar on/offs.

In the project's first phase, the ATSPMs were successfully built on existing adaptive systems from the centralized management console instead of configuring at each controlled intersection on the field. The developed framework has been designed, implemented, and tested for two adaptive signal systems, SCATS and InSync. The effect of this research was validated on two selected corridors in New Jersey. The proposed method bridges the gap between the existing detection system and ATSPMs without investment in new controllers and detectors. Thus, the solution can help agencies focus on functionality in a legacy system instead of needed detectors/controller types.

Data Collection

The SCATS system featured two layers of control logic: strategic level and tactical level. The local controller is used to determine a single intersection phase and time, while the regional controller is used to adjust coordination between junctions. The SCATS can be used for data collection, control, and traffic modeling through its ITS interface with third-party applications. The collected data contains the signal controller event history file, Autoscope detector data, and roadside CCTV camera video, which can be accessed through TMC. The used data sources are shown in Figure 39.

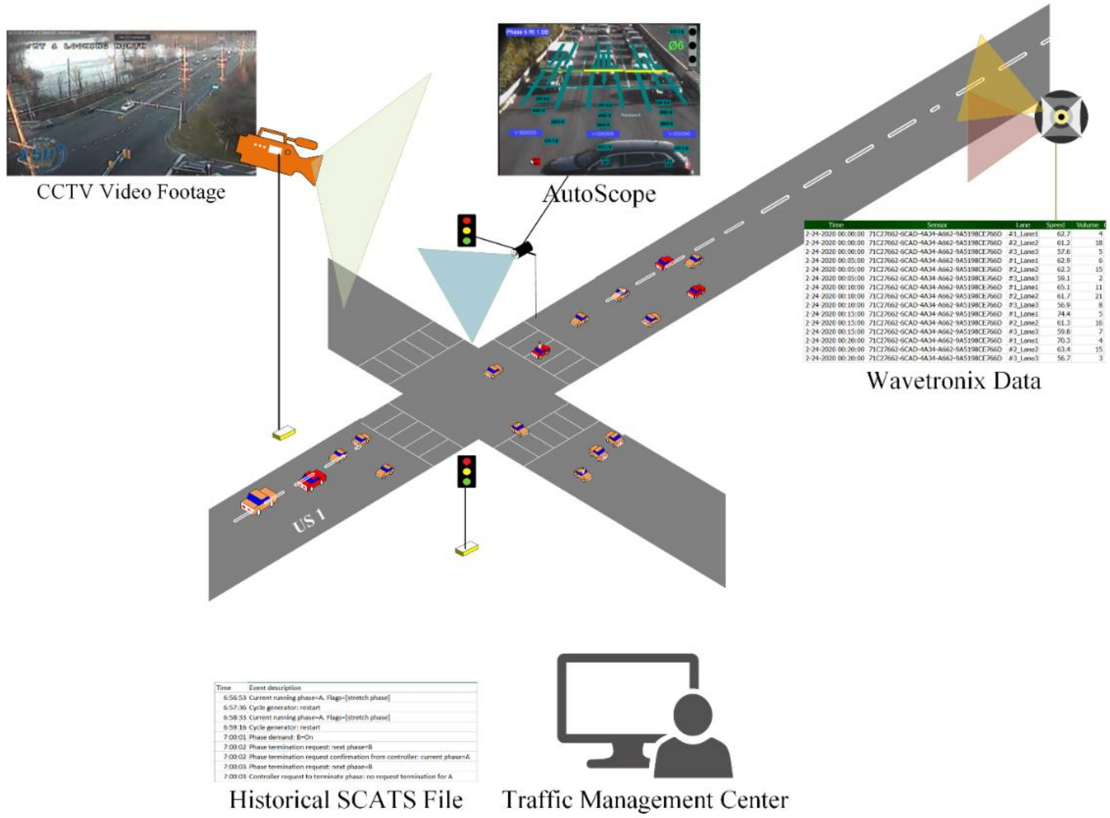


Figure 39. Multi-source Data Collected for Intersection Performance Measurement

- Signal Event History File:

The data are from a SCATS-controlled intersection on US-1 at Harrison in New Jersey. In addition, two days of SCATS Event data and Autoscope detector data were recorded, which span from December 02 to December 04, 2020.

- Autoscope Detector Data:

The Autoscope Vision detection system contains a high-definition (H.D.) camera-processor sensor that delivers reliable counting results for stop bar vehicle detection. The Autoscope stop-bar video detectors were recorded from the arterial TMC. The Autoscope detector data file contains the detector id for each lane, timestamps of detector state change, and metadata regarding the detector settings.

- CCTV Camera Recordings:

The 511 CCTV camera network is a critical ITS infrastructure for the advanced traveler information system. The CCTV video from the NJ511 camera network and CCTV data were recorded into several 1-hour clips to record real traffic situations. In addition, the CCTV video data were used to get initial measurements for shockwaves, free-flow speed, and other physical parameters.

- Wavetronix Detector Data:

Wavetronix detector is installed 1200 ft away from the intersection, providing lane-by-lane detection results at five-min intervals. From the Wavetronix detector data, three microscope traffic flow parameters were reported, including speed, volume, and occupancy. It also reported vehicle types, headway, and distance gaps at the microscopic level. From Wavetronix data, we can measure the optimal occupancy (Occ_o) and maximum occupancy (Occ_j). The Flow-Occupancy and Speed -Volume data are plotted in Figure 40.

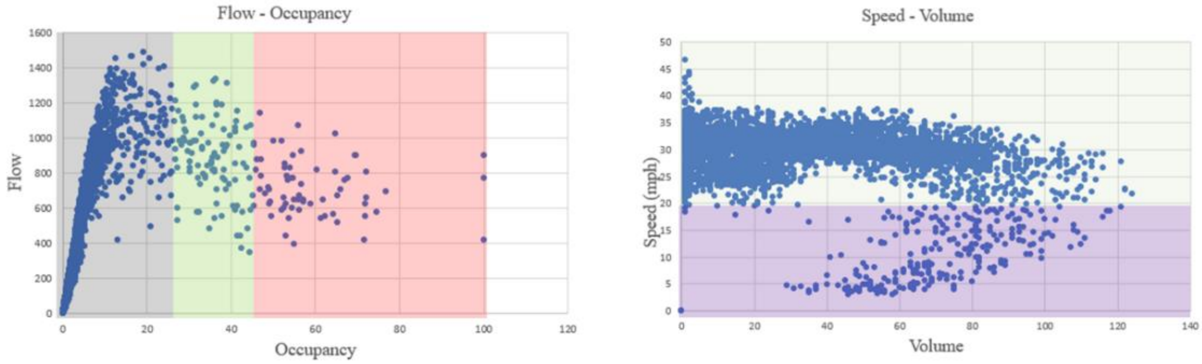
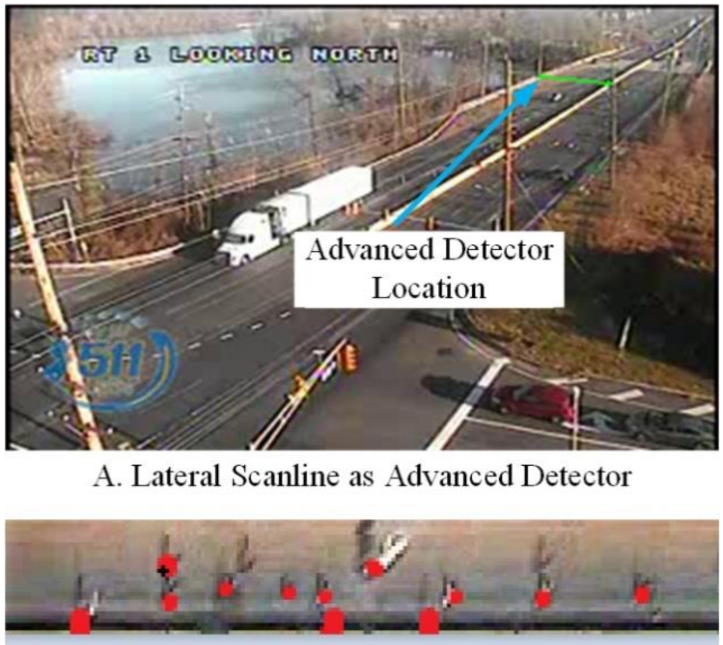


Figure 40. Flow-Occupancy and Speed-Volume Plot from Wavetronix Data

Following obtaining all the data from different sources, a preprocessing step is conducted to convert data into the standard format. For example, the SCATS history log files, which preserve the signal phase and timing information, were firstly converted into standard ATSPMs event code through an event translator program. After the data collection, wrangling, and projection, the data are then ready to be fed into our designed algorithm to generate performance measurements. Since the advanced detection system in this setting is not used for signal performance purposes, we will recover the vehicle arrivals through the proposed trajectory reconstruction method as inputs from an advanced location.

Parameter Optimization

As shown in Figure 41, a lateral scanline was placed in the video as an advanced detector to collect the actual vehicle arrivals from CCTV video footage. The timestamp of each passing vehicle was extracted after marking the passing cars from the lateral scanline. The collected vehicle arrivals were used as ground truth data to calibrate and evaluate our model performance.



A. Lateral Scanline as Advanced Detector

B. Manually Marked Passing Vehicles

Figure 41. Virtual Line Detection to Collect Vehicle Arrivals at Advanced Detector

Traffic parameters used in the model include three shockwave speeds, free-flow speed, acceleration rate, deceleration rate, and average vehicle arrival headway. Each parameter was first measured from a spatial-temporal map. Then the measured values of parameters were fed into our model and optimized using the Genetic Algorithm. The goal function of the Generic Algorithm is defined as follows:

$$f(X) = \frac{TPs}{TPs+FPs} \quad (41)$$

$$Z = argmax(f(X)) \quad (42)$$

The Genetic Algorithm is used to obtain the optimal parameter set Z by maximizing function $f(X)$.

$$T.P.(\tau_d) = \begin{cases} 1, & if\ \forall\bar{\tau}_d\ \ |\tau_d - \bar{\tau}_d| \le \varepsilon_r \\ 0, & otherwise \end{cases} \quad (43)$$

$$F.P.(\tau_d) = \begin{cases} 1, & if\ \forall\bar{\tau}_d\ \ |\tau_d - \bar{\tau}_d| \ge \varepsilon_r \\ 0, & otherwise \end{cases} \quad (44)$$

Where, ε_r is error threshold. T.P. is True Positive; F.P. is False Positive. The τ_d is the timestamp of the reconstructed trajectory at the advanced detector, $\bar{\tau}_d$ is the ground truth timestamp when a vehicle passes through the advanced detector from CCTV Video. The initial parameter values and calibrated parameter values are presented in the following table.

Table 18. Parameter Optimization Using Genetic Algorithm

Model Parameters	Initial Value	Calibrated Value
Discharging Shockwave w_2 (ft/s)	-25.54	-22.29
Optimal Occupancy (Occ^o)	30.5%	24.1%
Maximum Occupancy (Occ^j)	95%	90.4%
Saturation Flow Rate v_s (ft/s)	29.40	32.08
Free Flow Speed v_f (ft/s)	51.93	44.92
Acceleration Rate (ft/s^2)	13.12	12.39
Deceleration Rate (ft/s^2)	26.25	24.19
Mean Arrival Headway (seconds)	4.0	3.0

This research aims to obtain advanced detector data using reconstructed vehicle trajectories from stop-bar detector data. We calculated the distance error for model output trajectory with video recorded trajectory at the advanced detector in Figure 42. The developed algorithm has outstanding accuracy in that the majority of detected trajectories have distance error ≤ 5 ft compared to ground truth vehicle trajectory. The primary error source comes from the Autoscope video detector. According to our manual validation results using the raw Autoscope video, about 5 ~10% of vehicle detection errors exist in the stop-bar detection system.

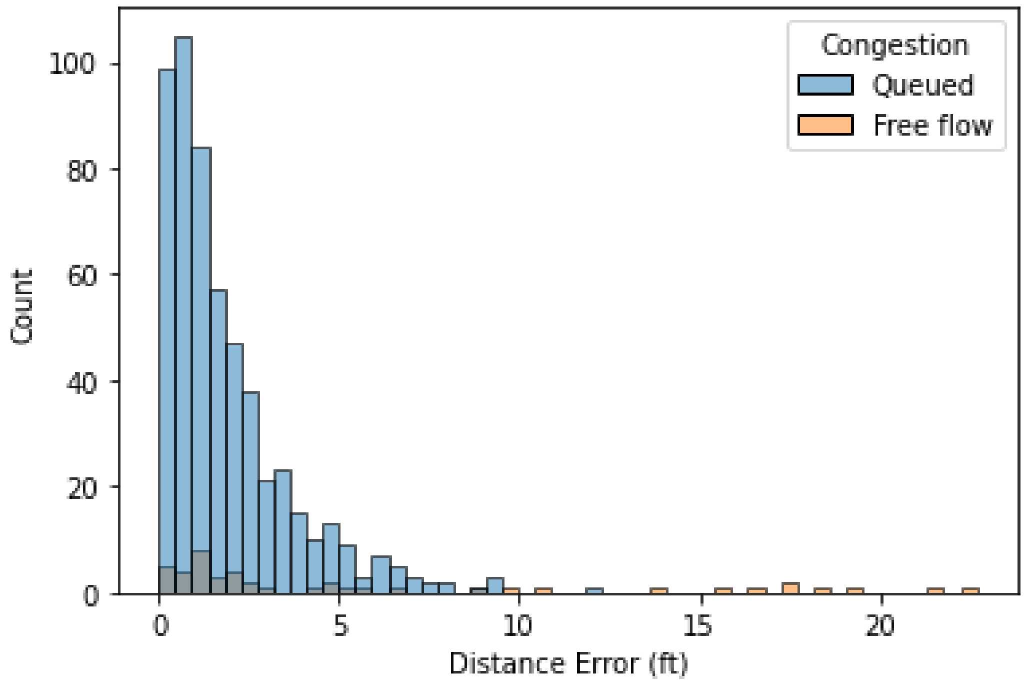


Figure 42. Trajectory Algorithm Distance Error for Congested Vehicles and Free Flow Vehicle

To illustrate how the detector errors would impact our model performance, we compared the model outputs results using manually collected stop-bar events and Autoscope stop-bar detector events, respectively. The figure of positive detection rates shows that manually counting vehicle stop-bar events has a lower trajectory detection error. Figure 43 presents positive detection rates for different error thresholds. The proposed model can accurately reconstruct about 90% of advanced detections with a 2-second discrepancy between ground-truth and reconstructed data. The model outputs can achieve about 95% at a 4-second error threshold.

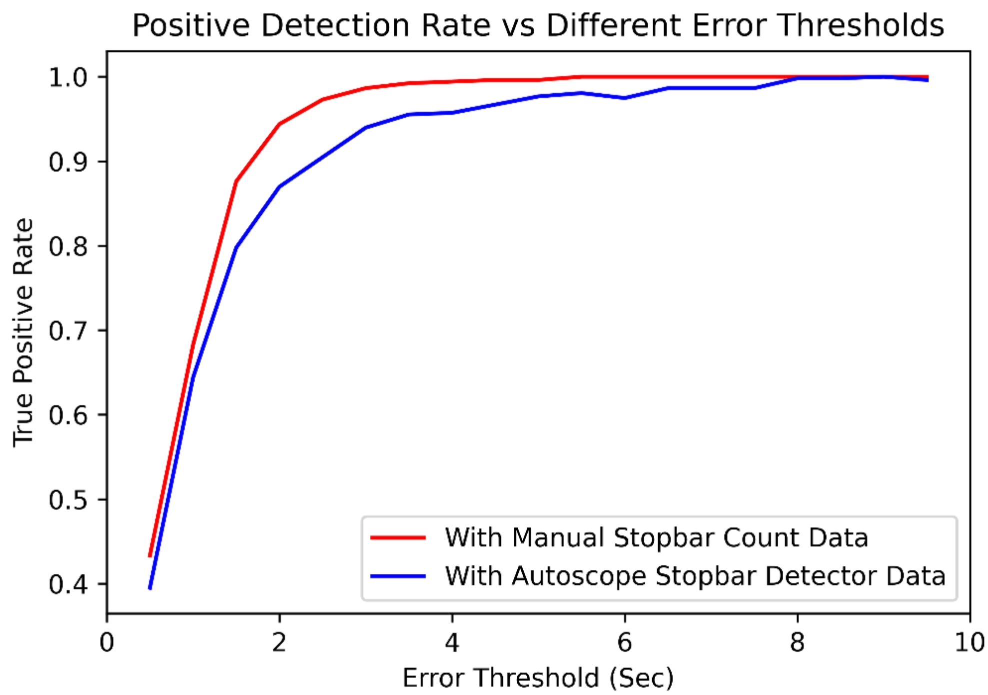


Figure 43. True Positive Rate Over Different Error Thresholds

As the legacy Autoscope video detector uses the traditional motion detection, it inevitably results in many false detections and missed detection issues. However, with the adoption of advanced computer vision algorithms, this error source is expected to be significantly reduced in the new video detection system. Figure 44 provides better visualization of model efficacy, including the reconstructed vehicle trajectories, stop-bar detector events, and advanced detector position on the STMap to demonstrate the accuracy of model results. For example, in the same figure, each color dot on the stop-bar represents the detection of one vehicle passing through the stop-bar detection zone. The purple line is placed at the advanced detector location, 400 feet away from the intersection. The trajectory diagram shows how well our estimated trajectories align with the actual vehicle movements in the STMap. The detailed TP-based vehicle trajectory plotting algorithm is shown in the following:

```
Algorithm: Drawing Trajectory on STMap
==========================================
Input: STMap, Turning Points of Trajectory
Outputs: Vehicle Trajectory Visualization on STMap
-----------------------------------------------------------------
Known Parameters:
FrameRate: frame/second
Scale-factor of each pixel: Scale (ft/pixel)
Video Start Time: Timestamp_video (0.1 second)
Stop Bar Row Number on STMap: R_stopbar

For Every Detected Vehicle
        For every turning point (Timestamp_tp, Distance_tp)
                Row_tp = Distance_tp/ Scale + R_stopbar
                Col_tp = (Timestamp_tp - Timestamp_video) /FrameRate
                turning_pts.append([Col_tp, Row_tp])
        End For
        Connect all Turning_pts on STMap
End For
==========================================
```

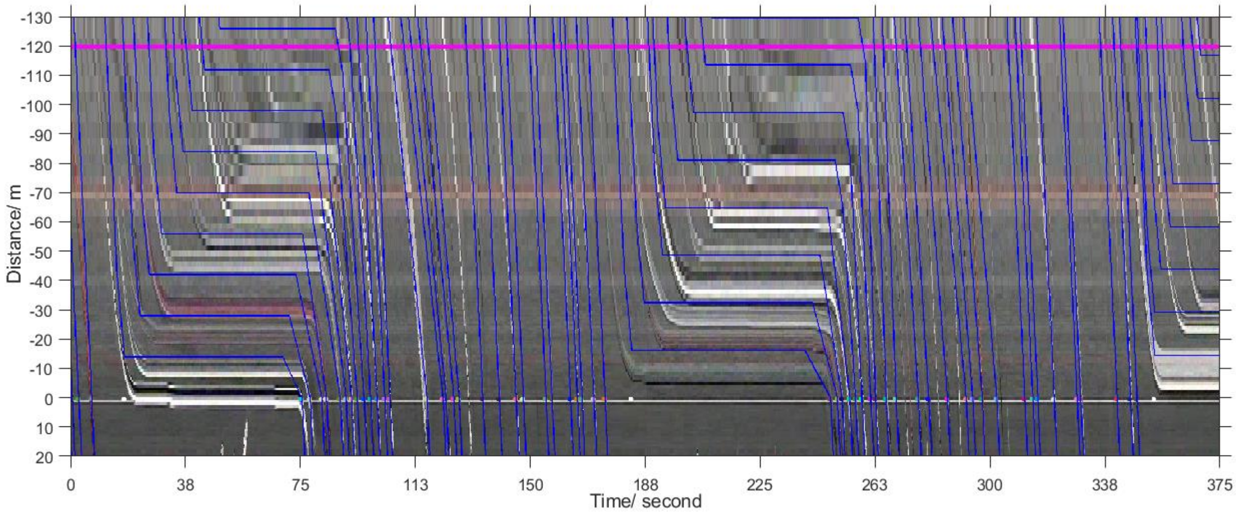


Figure 44. Reconstructed Trajectory and Stop-bar Detector Plotted on STMap

As this method tries to reconstruct vehicle trajectories from a macroscopic perspective, the randomness of driver behavior is not considered. For instance, the lane-changing event will be missed using this method. Future work will combine the GPS/CV trajectory data with fixed detector data to be more flexible and accurate in solving the randomness in vehicle trajectory.

Purdue Coordination Diagram from Reconstructed Trajectory

After obtaining the trajectories, an estimate of the vehicle arrivals was made to replicate an advanced detector to create the PCD. The first picture (Figure 45 A) shows CCTV video's manually collected vehicle arrivals. The second picture (Figure 45 B) is predicted detector data from the reconstructed trajectory. The high percentage of vehicle arrivals on green time implies fewer vehicle stops. Comparing the two results shows that the trajectory reconstruction method has the same AoG (arrival on green) value as vehicle arrivals recorded from CCTV cameras, indicating that the proposed method can efficiently recover upstream vehicle movements from the stop-bar detector actuation. Black dots are darker in the PCD with ground truth vehicle arrivals than algorithm-generated ones. Because the stop-bar detector tends to undercount, resulting in less vehicle counting due to occlusions in the Autoscope camera.

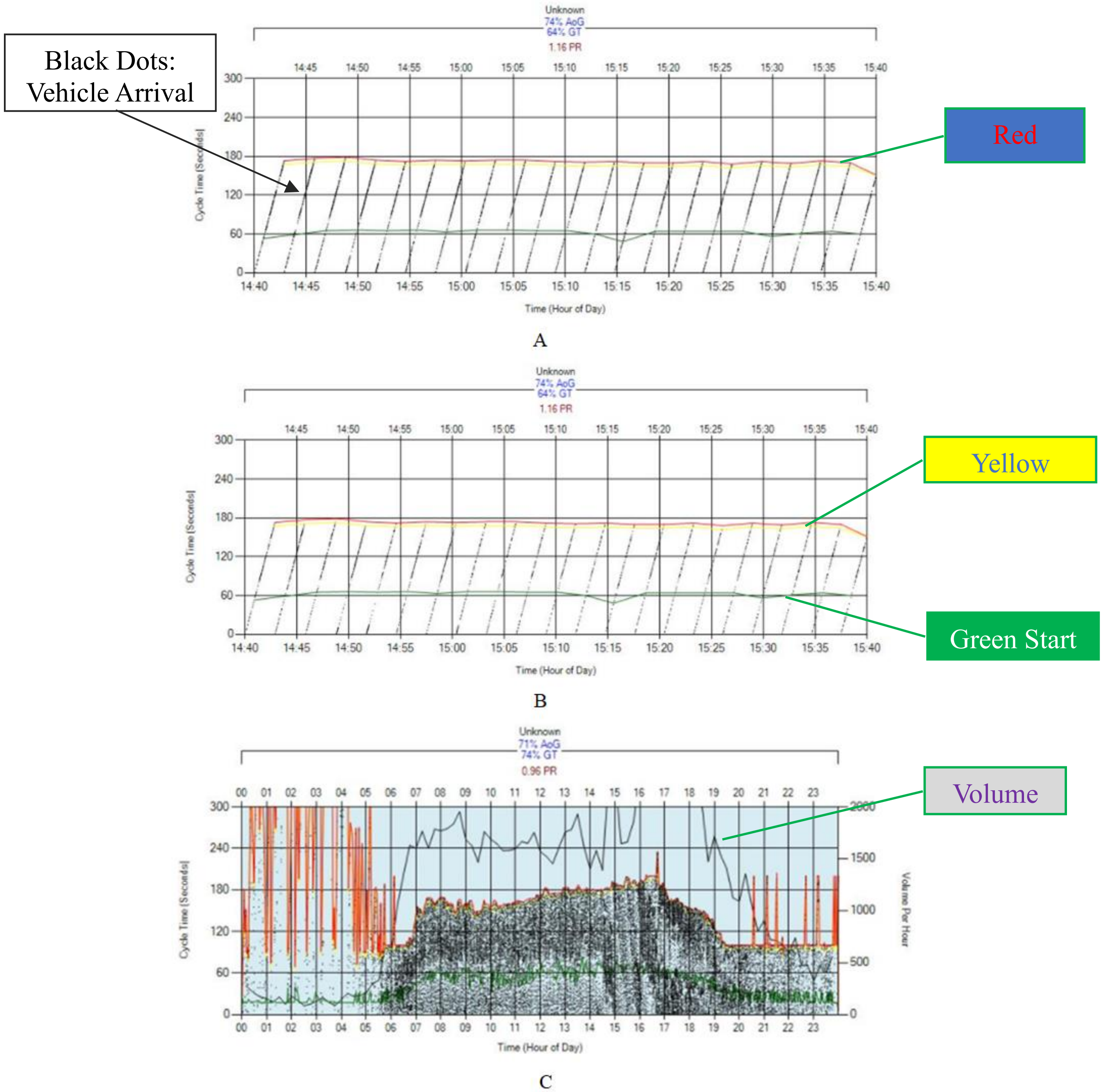


Figure 45. Purdue Coordination Diagram Using Reconstructed Trajectory. A. PCD with Ground Truth Advanced Detection. B. PCD with Algorithm Advanced Detection. C. 24-hour PCD with Algorithm Reconstructed Trajectory.

Stop-Bar Rutgers Coordination Diagram

The detector data tells the system when the vehicles arrive and leave the intersection, which is an essential part of adaptive signal control systems. The stop-bar detector data provides insight into how the signal controller functions to accommodate various traffic demands with high-resolution signal controller data. The stop-bar coordination diagram is a new SPM containing important information about vehicle departure headways, waiting time, delay, phase duration, volume, and occupancy. One advantage of the stop-bar coordination diagram compared to PCD is that it reflects how the vehicles accurately pass through the intersection instead of using projected vehicle arrivals from the advanced detector.

The stop-bar coordination diagram directly shows how traffic signals serve the traffic demands lane-by-lane and do not have the Queue-Over-Detector (QOD) issue. This new stop bar coordination diagram is named Rutgers Coordination Diagram (RCD). From the new coordination diagram, the effectiveness of the signal timing can be quickly recognized and diagnosed using the time headways. A significant time gap usually implies that the queuing vehicles were cleared. Therefore, vehicles AoG do not need to stop during that cycle. However, if all gaps within one cycle are minimal and almost constant, a split failure was considered as the queuing vehicles for that approach cannot be cleared. The stop-bar detector combined with signal timing data can also be archived for long-term purposes of traffic development.

Split failure can be identified using a combination of green occupancy ratio (GOR) and Red Occupancy Ratio for the first 5 sec of red (ROR5). Green Occupancy is the Percentage of green time for which the stop-bar sensor was switched on. Red Occupancy is defined as the ratio of the first 5 seconds of red time for which the stop-bar sensor was turned on. A high GOR and a high ROR5 value mean that the queue from the last cycle was not cleared, resulting in a split failure. Another way to detect the end of the queue using a stop bar detector is to find the large gap, which is greater than the site-specific threshold depending on road geometry and traffic composition. In many practices, the time to gap out (TTG) as a queue end indicator is 2 seconds.

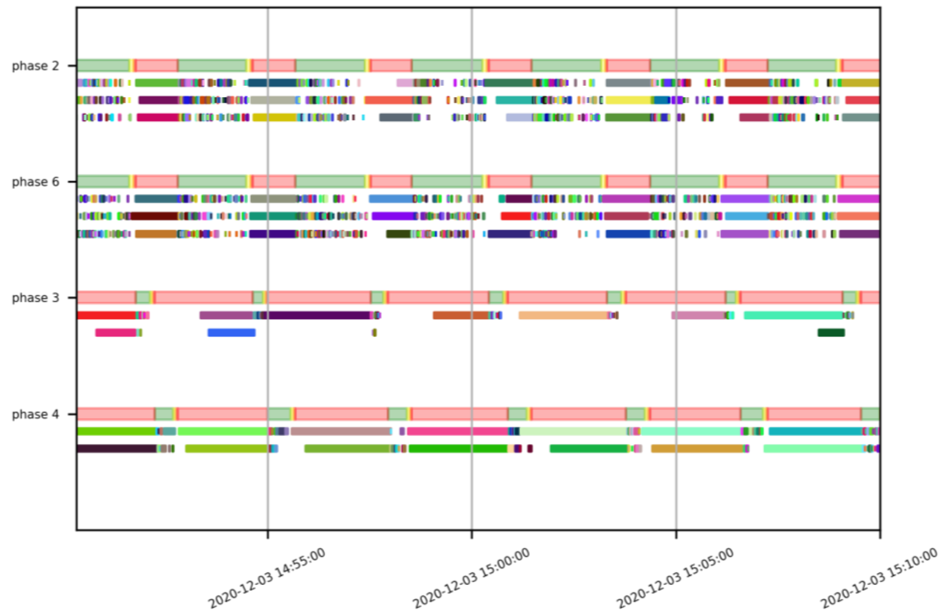


Figure 46. Rutgers Coordination Diagram

Some safety performance issues caused by signal timing can also be identified from this RCD. For example, the red-light-running event can quickly be flagged when vehicles pass through the intersection during the read phase on the coordination diagram (Figure 47). The two red-light running events happened during morning peak hours around 7:00 AM. Thus, the red-light violation is a significant threat to intersection safety caused by inefficient signal timing.

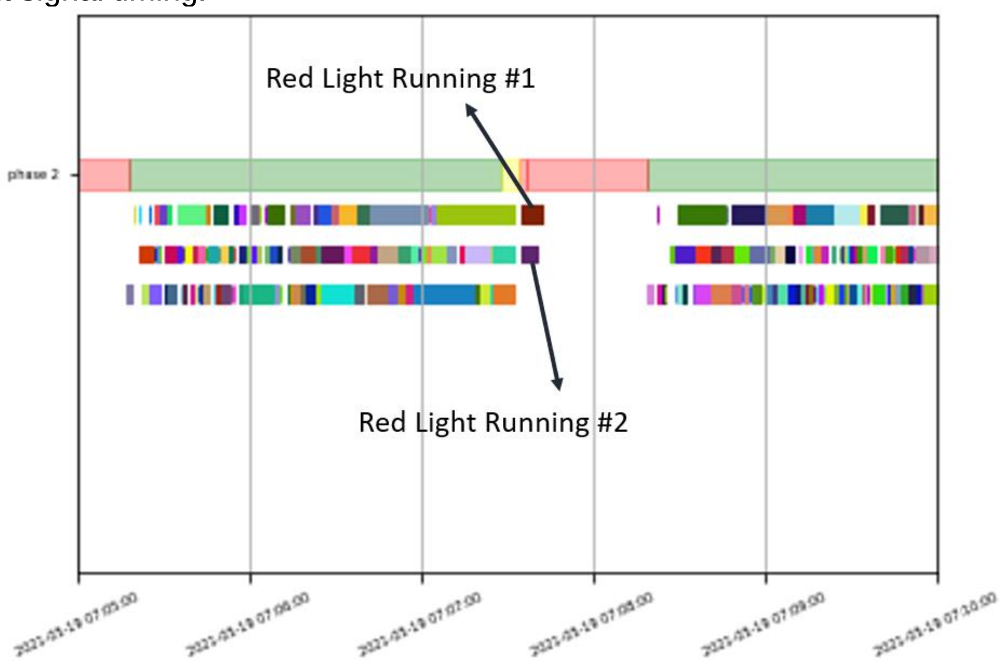


Figure 47. Red Light Running Captured by RCD

SUMMARY

The proposed trajectory reconstruction algorithm has been fully implemented in the current NJDOT ATSPM system that converts the stop-bar detection data from Autoscope in SCATS system into advanced detection data for ATSPM. The interpolated advanced detection data makes the PCD (Purdue Coordination Diagram) more accurate and informative. The following section provide a detailed description of the performance metrics enabled in ATSPM with the interpolated advanced detection data.

TASK 4: ATSPM ENHANCED FUNCTIONALITY DEVELOPMENT

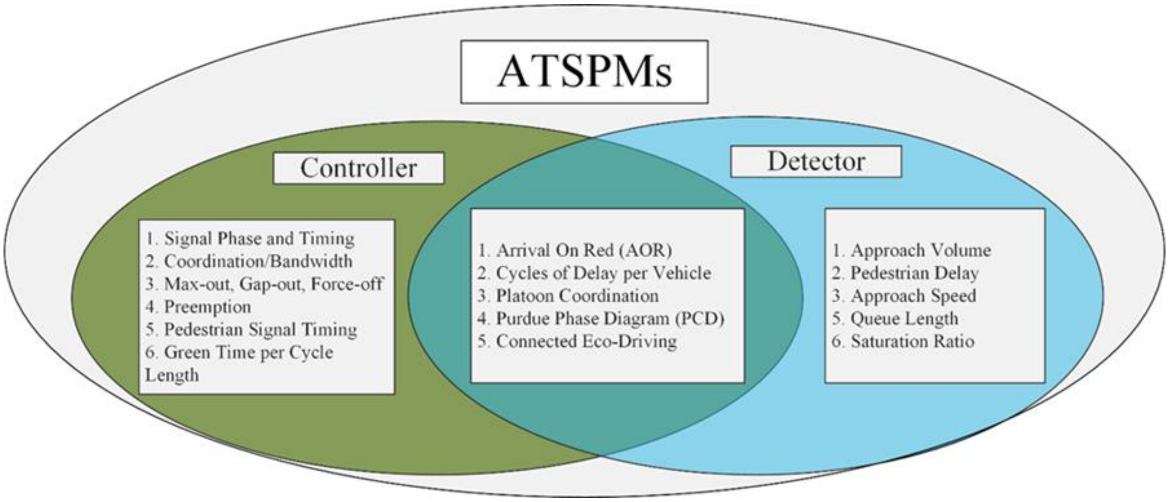


Figure 48. ATSPM Data Source and Performance Measurements

The project team improves the logic for Split Monitor and Phase Termination, considering the isolated master mode of SCATS status. Also, the project team links the real-time INRIX XD vehicle speed feed directly into ATSPM. Virtual Advance Detectors are used from XD Probe data. Wavetronix is used in the detector setup to get the software to process the data. All controllers in the system have some XD matched to an advanced virtual detector. For some intersections, only the mainline data is available. An example corridor layout with XD information is shown in Figure 49.

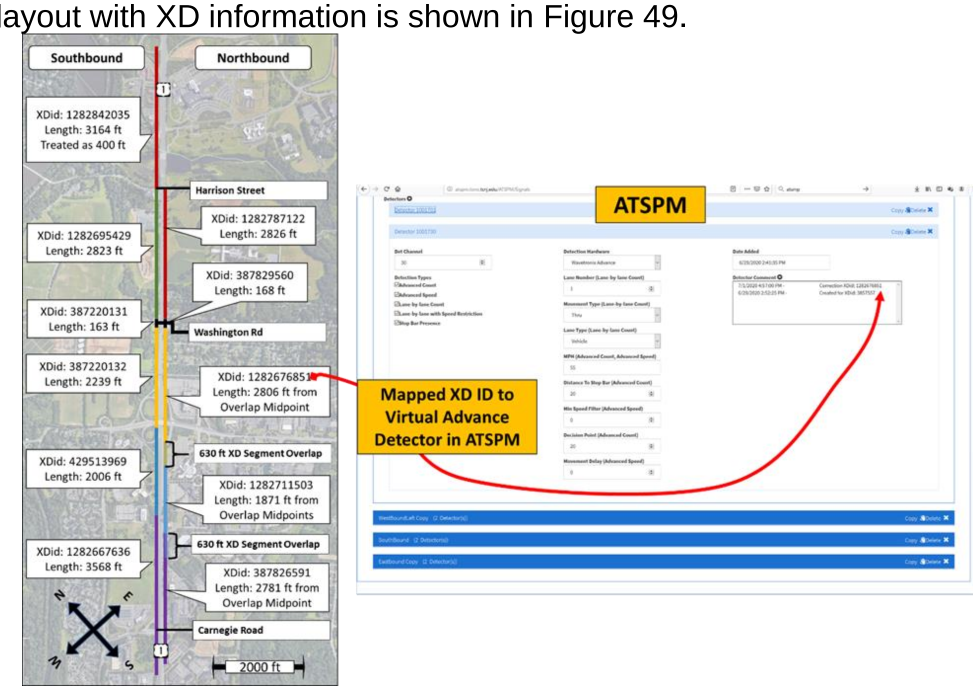


Figure 49. Virtual Advance Detector Layout (typical) for ATSPM Controllers

Purdue Phase Termination

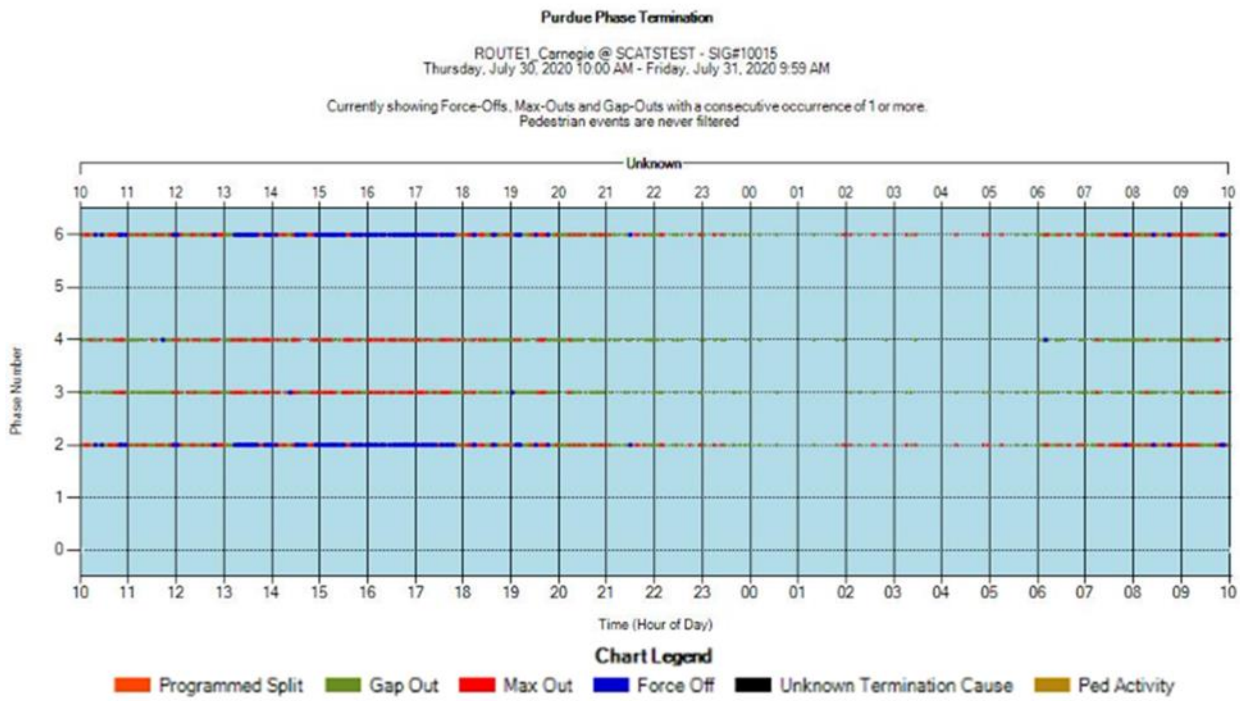


Figure 50. Phase Termination for SCATS System at US-1 & Carnegie Center Rd

Samples of data aggregation methods are shown in Figure 51. However, the raw data directly imported into the ATSPM seems to give the best results, where the southbound at Washington Road & US-1 has more variance in speed when compared to northbound. These speeds may be supplemented with CAV speeds. These speeds correlate to the PCD, where north and southbound have the same cycles, which appear to be driven by the southbound traffic.

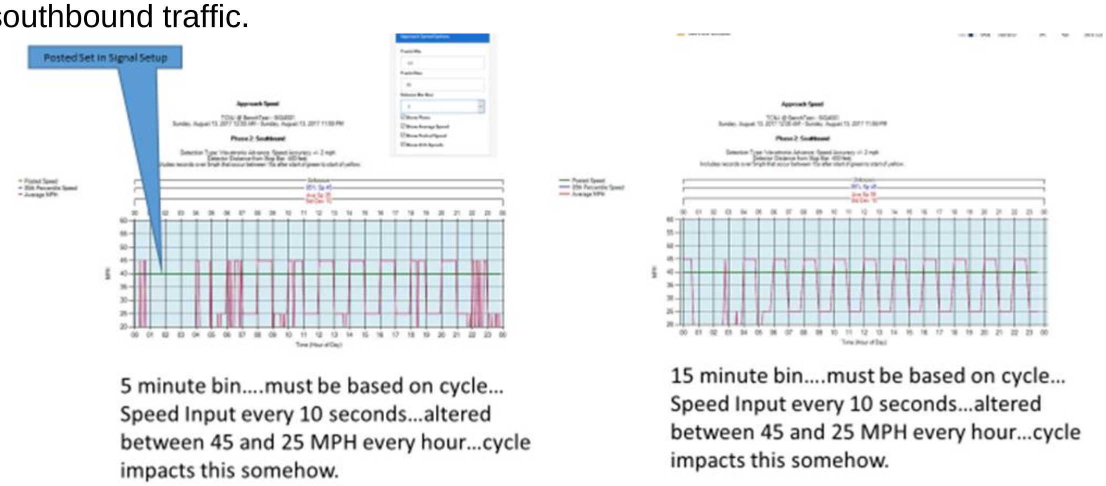
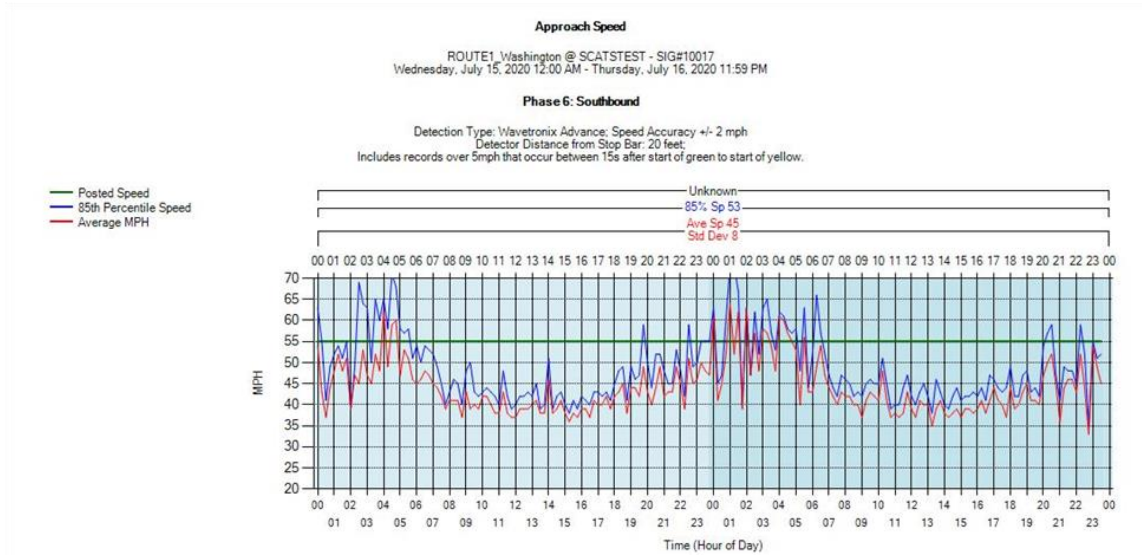
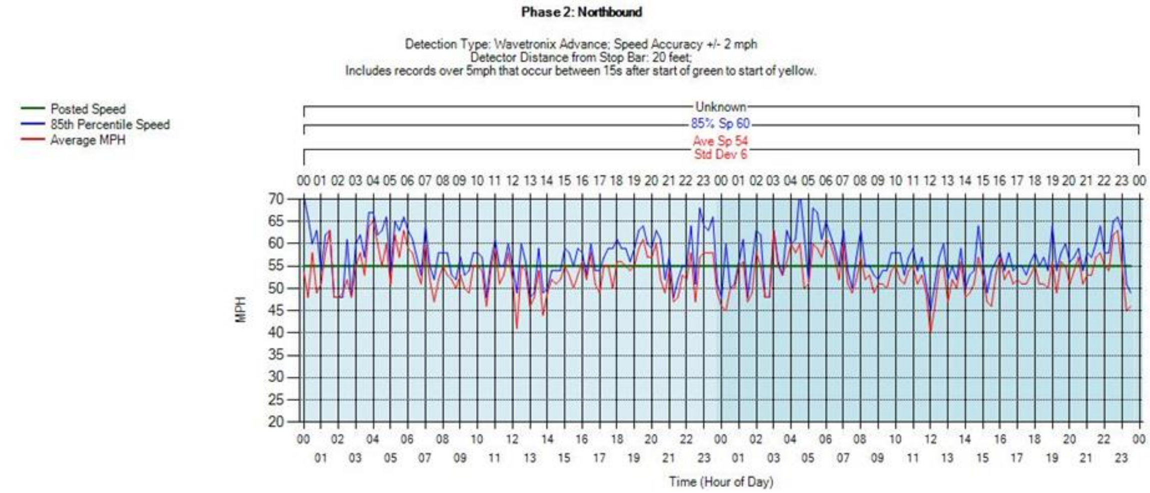


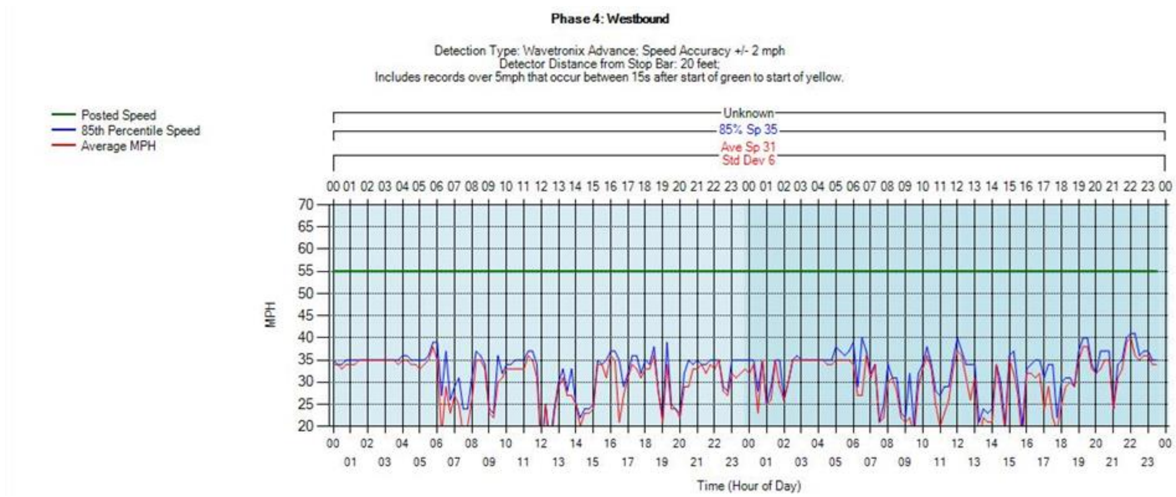
Figure 51. Speed Event Data



Southbound

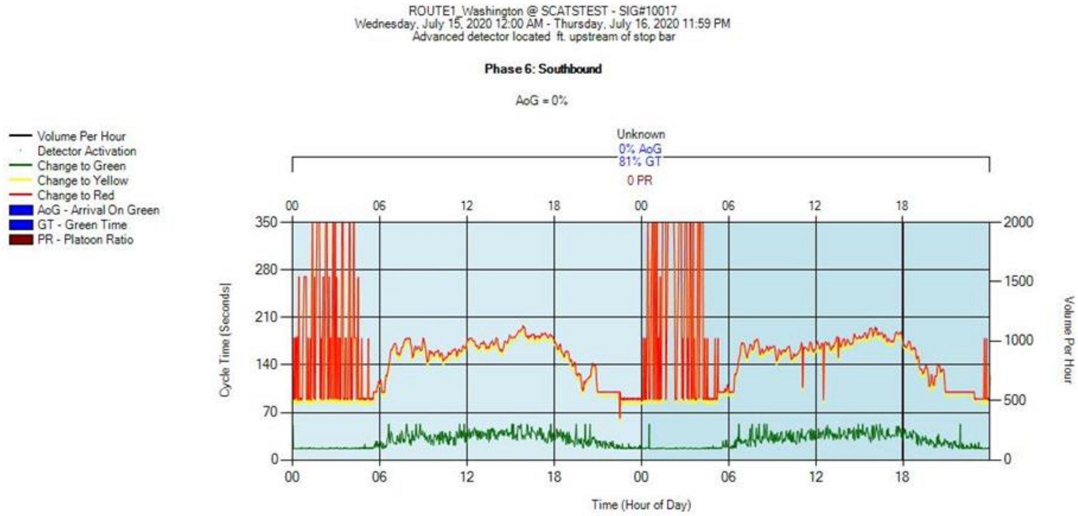


Northbound

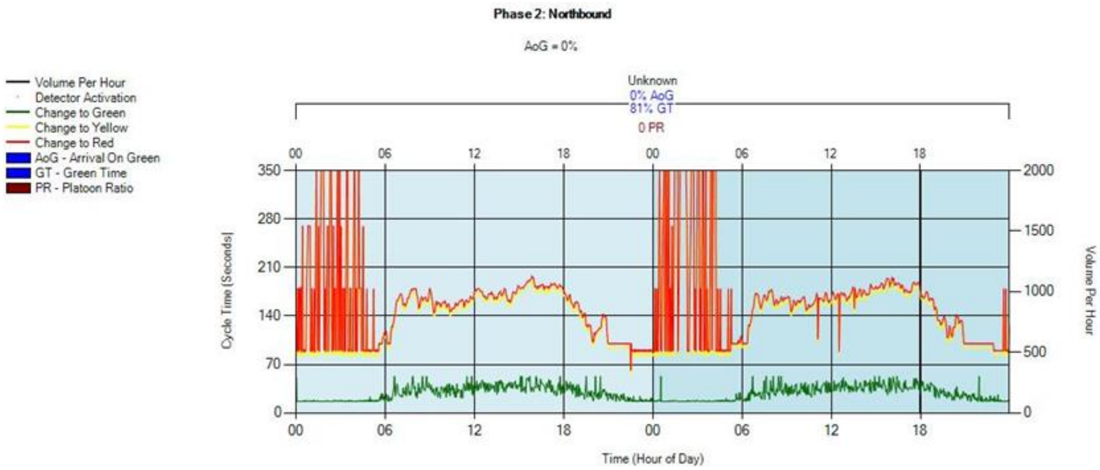


Westbound

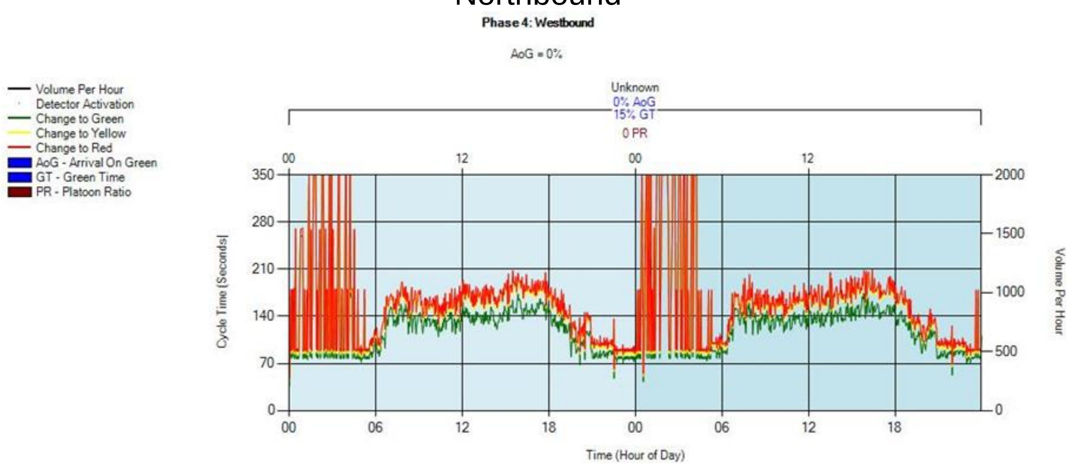
Figure 52. US-1 and Washington Road XD ingested ATSPM speed records July 15 – 16, 2020



Southbound



Northbound



Westbound

Figure 53. PCD of US-1 and Washington Road July 15-16, 2020

Split Monitor

The split monitor shows the amount of split time (green, yellow, and all-red) used by the various phases at the intersection. In addition, phase 2 has a high percentage of gap-outs caused by the pandemic social distancing policy. The Split monitor also shows that the mainline signal has many force-offs, indicating how the adaptive signal control system adjusts to the variation of traffic flow.

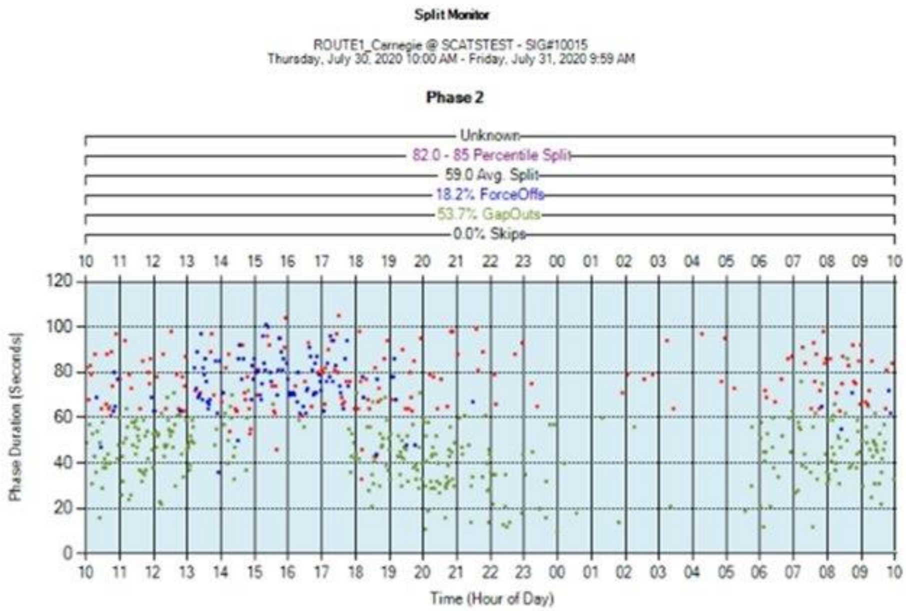


Figure 54. Split Monitor for SCATS System at US-1 & Carnegie Center Rd

Pedestrian Delay

Pedestrian Delay is a significant parameter to evaluate one perspective of the safety level for a signalized intersection. The longer the pedestrian waits, the more likely a pedestrian will violate traffic control at risk. Moderate waiting time for the pedestrian to cross the intersection has been observed in this Pedestrian Delay diagram.

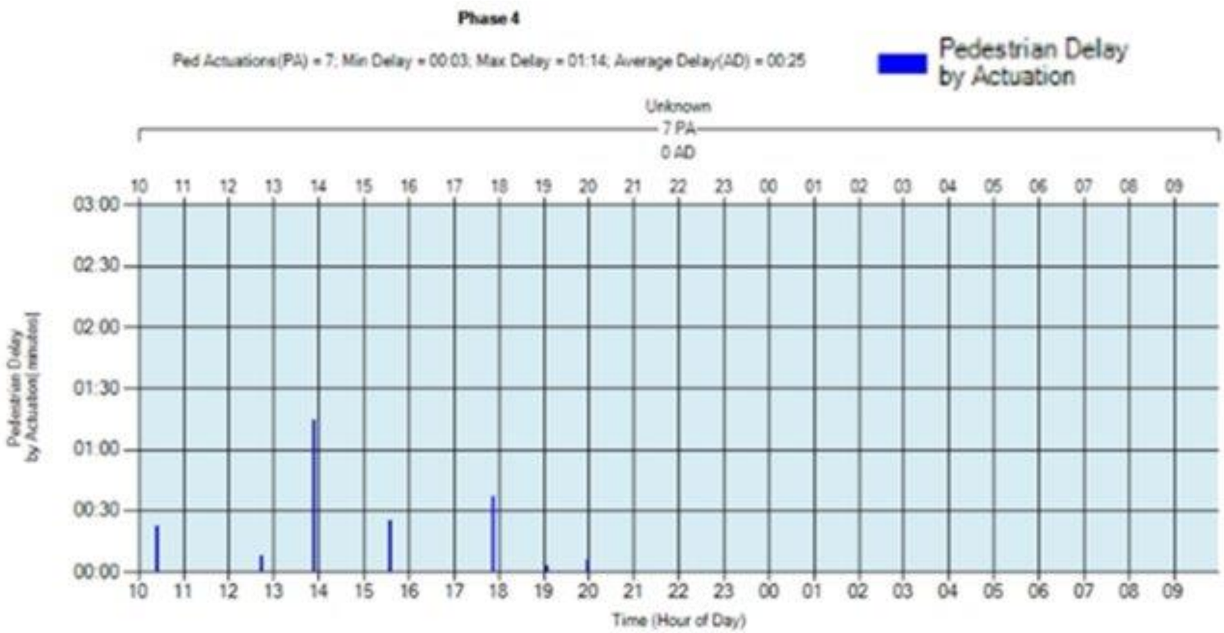


Figure 55. Pedestrian Delay for SCATS System at US-1 & Carnegie Center Rd

Yellow and Red Actuations

Yellow and Red actuations plots are vital in evaluating a signalized intersection's safety. This metric plots the vehicle arrivals during the yellow and red phases of the intersection. It provides a visual indication of violations, occurrences, and several other related statistics for the evaluation, assisting the professionals with information about the red-light running events and identifying engineering countermeasures. Figure 56 represents the detector activation during the yellow and red phases for the Northbound at Carnegie and US-1 intersection.

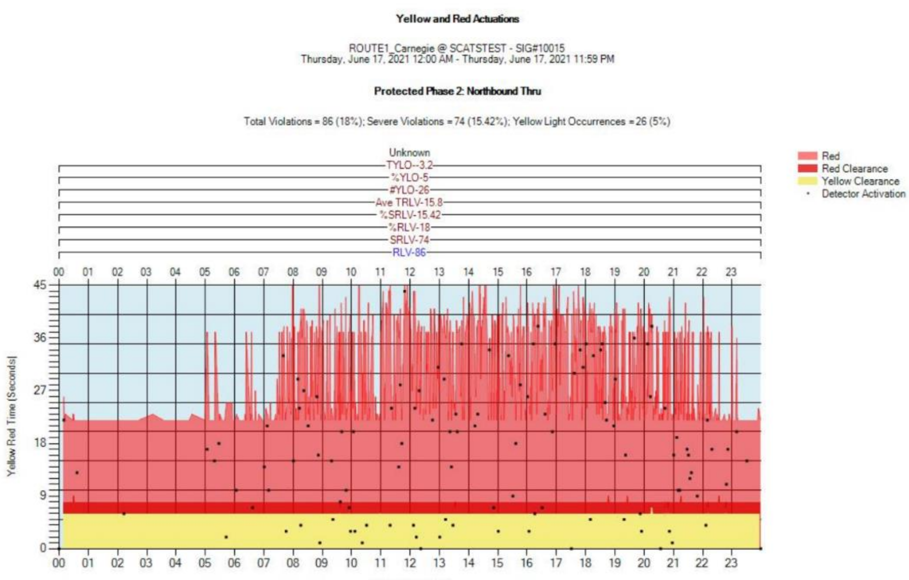


Figure 56. Northbound US-1 and Carnegie Red and Yellow Actuation June 17, 2021

Additionally, the team validated the detector activation by watching a few hours of video recordings for each intersection leg at US-1 and Harrison intersection. Results showed that the events that activated the detectors during the red phase (2 seconds from the start of the red phase) were the actual red light running events (Table 19). Figure 57 shows an example of a red-light running event.

Table 19. Validation results from the US-1 and Harrison, June 17th, 2021

Direction	Detector id	24 Hrs. Red light Running Detector Count	Video Timing	Red light Running Detector Count	Red light Running from Video	Accuracy
SB	127	8	8:00 AM-10:00 AM	3	3	100%
NB	127	15	8:00 AM-10:00 AM	3	3	100%
EB	101	8	9:00 AM-10:00 AM	1	1	100%
WB	122	17	9:00 AM-10:00 AM	5	2	40%

Figure 57. Example of Red Light Running Events

Time Interval Between Two Consecutive Vehicles

In addition to the listed ATSPM performance measures, the team also calculated the time interval between two consecutive vehicles, the difference between the time when the detector gets deactivated and activated again once another vehicle arrives. Table 20 provides a calculated time difference between two consecutive vehicles that activated and deactivated the southbound detector id 127 at US-1 and Harisson on March 8th, 2021.

Table 20. Calculated Time Interval of two consecutive vehicles at US-1 and Harisson, March 8th, 2021

Direction	Detector id	Time Difference ≤ 1sec	Time Difference ≤ 2sec	Time Difference ≤ 3 sec	Time Difference ≤ 4 sec	Time Difference ≤ 5 sec	Time Difference ≤ 6 sec
SB	127	4137	5795	6774	7390	7780	8082

Further, to evaluate the safe distance, the time interval thresholds were calculated by considering the Level of Service (LOS) of the road segment from the Highway Capacity Manual (2010). Table 21 provides the calculated thresholds for the 65 MPH, 60 MPH, and 55 MPH free-flow speeds.

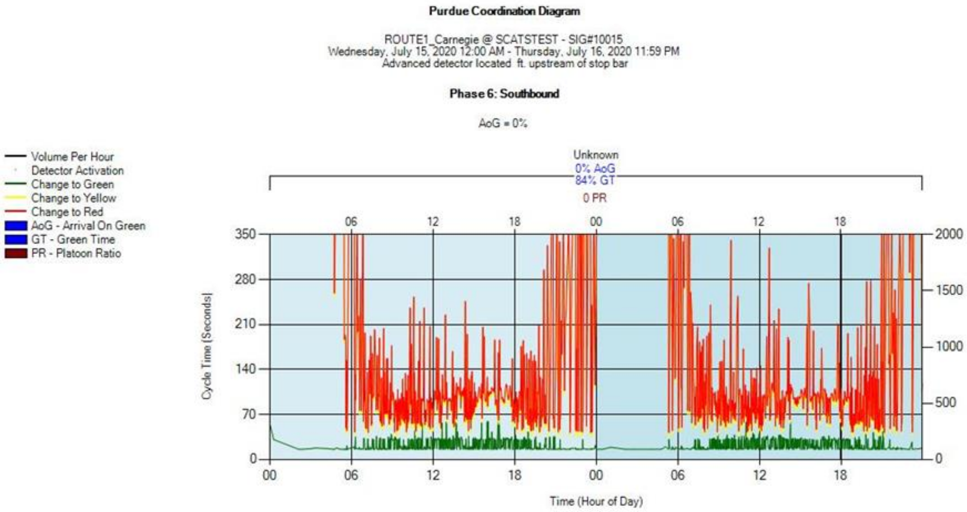
Table 21. Calculated Time Interval Thresholds for 65 MPH, 60 MPH, and 55 MPH Free-flow Speed

Level of Service (LOS)	**Time Interval Threshold (sec)**		
	FFS = 65mph	**FFS = 60mph**	**FFS = 55mph**
A	5.07	5.45	6.00
B	1.58	3.33	3.64
C	2.21	2.31	2.52
D	1.77	1.79	1.89
E	1.53	1.57	1.60

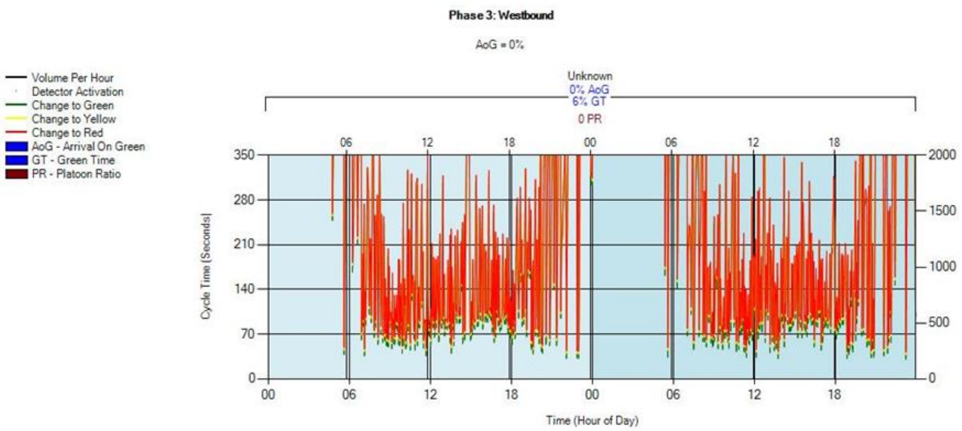
Based on the results, it can be noticed that many vehicles have not kept a safe distance in respect to time between each other, increasing the likelihood of rear-end crashes. Additionally, the New Jersey Division of Highway Traffic Safety (NJDHTS) recommends maintaining 2 seconds time interval between the two following vehicles during good weather conditions and 4 to 5 seconds during adverse weather conditions (NJSaferoads).

Intersection Carnegie @ US-1 PCD Evaluation

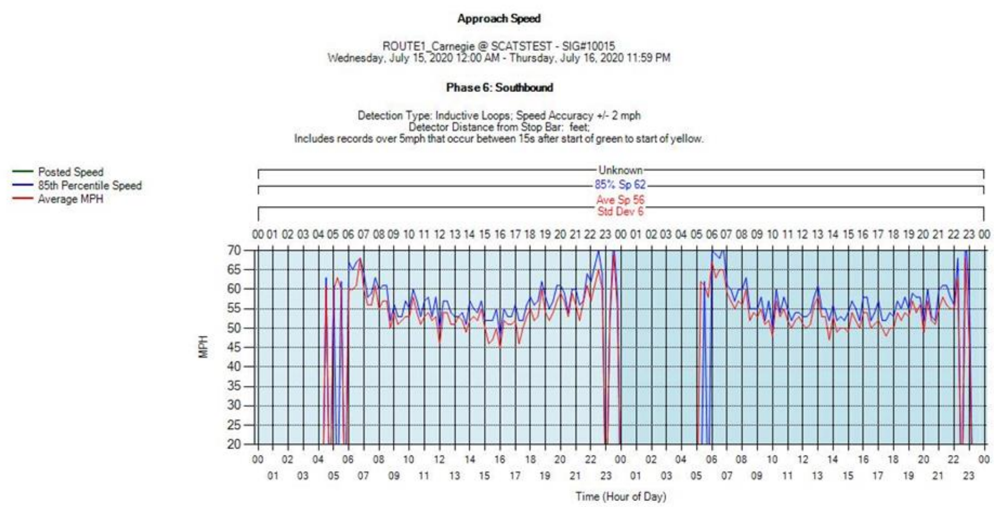
The project team evaluates the relationships between the speeds and the PCDs between the corridors. The PCDs for Carnegie is much more variable when compared to southbound at Carnegie. It results in the side street movements actuating the system and potential by the more variable speed coming from the southbound Washington, where speeds drop to around 40 MPH while remaining around 53 MPH on the Carnegie southbound approach. This difference in speeds is most likely due to the intersection of US-1 and Washington.



Southbound PCD



Westbound PCD



Southbound Speed

Figure 58. Southbound US-1 and Carnegie comparison of speeds and PCDs July 15 – 16, 2020

The team evaluated the ingestion of speed data from Wavetronix and eventually connected vehicles into the ATSPM that reflects vehicle presence and provides a trajectory speed of the vehicle with respect to the time in the cycle for each approach. It builds on the current PCD, which can show vehicle presence. Figure 61 shows a lane-by-lane capture of vehicle presence along with a speed vector. The longer the vector, the more the speed.

Southbound, Lane 1

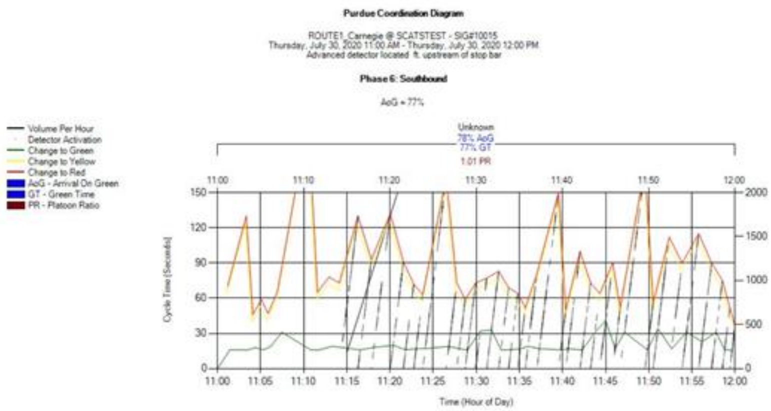


Figure 59. Actual Wavetronix data overlaid on PCD indicating a vector speed (1 hour) for southbound lane 1 at Carnegie and US 1

Southbound, Lane 2

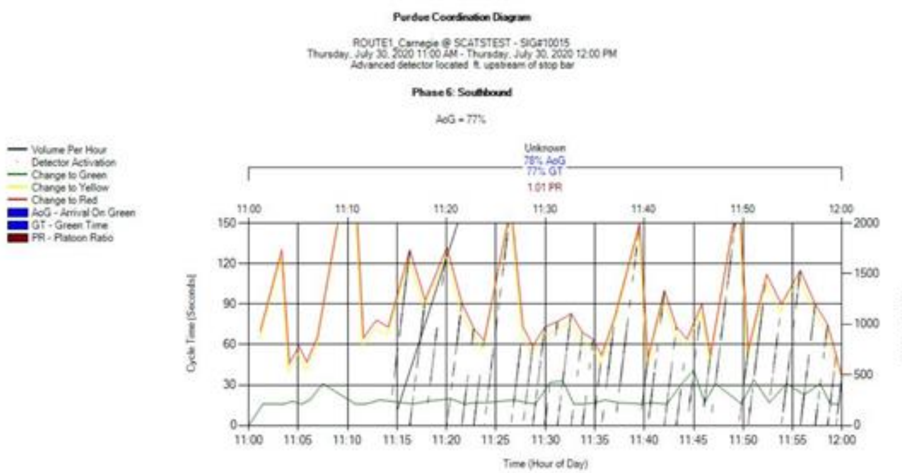


Figure 60. Actual Wavetronix data overlaid on PCD indicating a vector speed (1 hour) for southbound lane 2 at Carnegie and US 1

Southbound, Lane 3

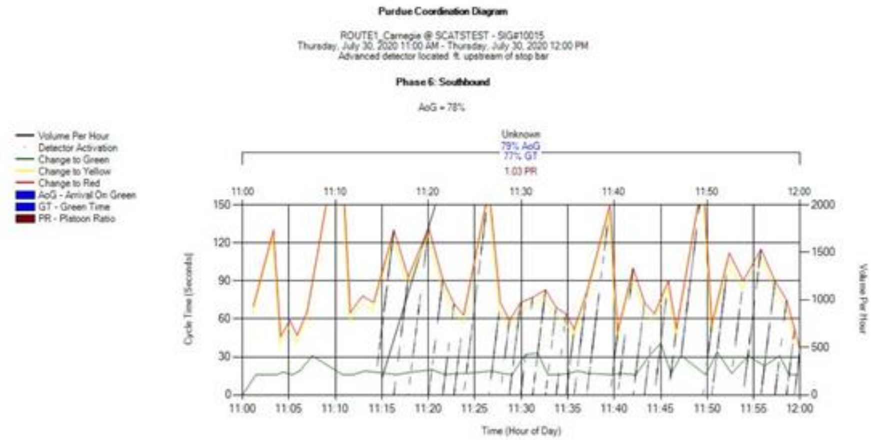
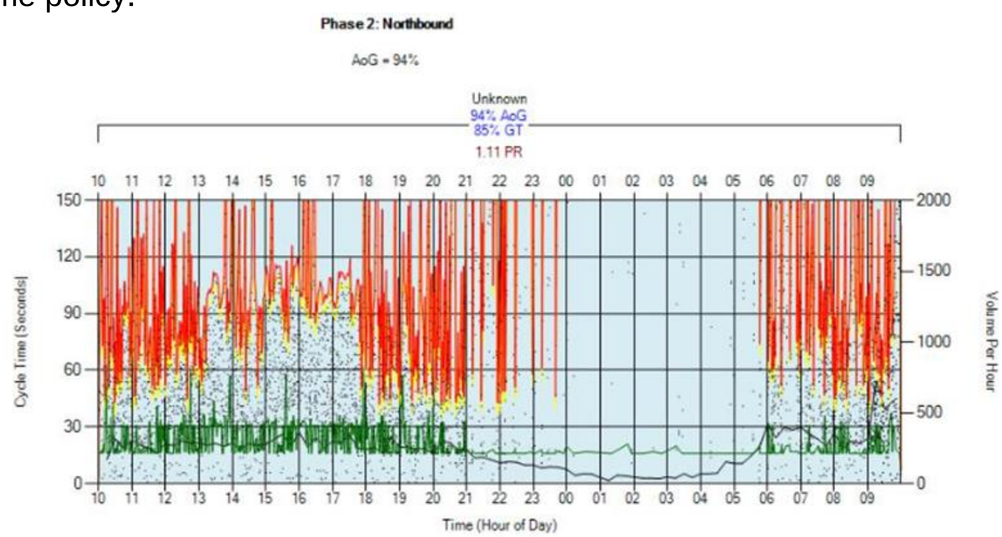
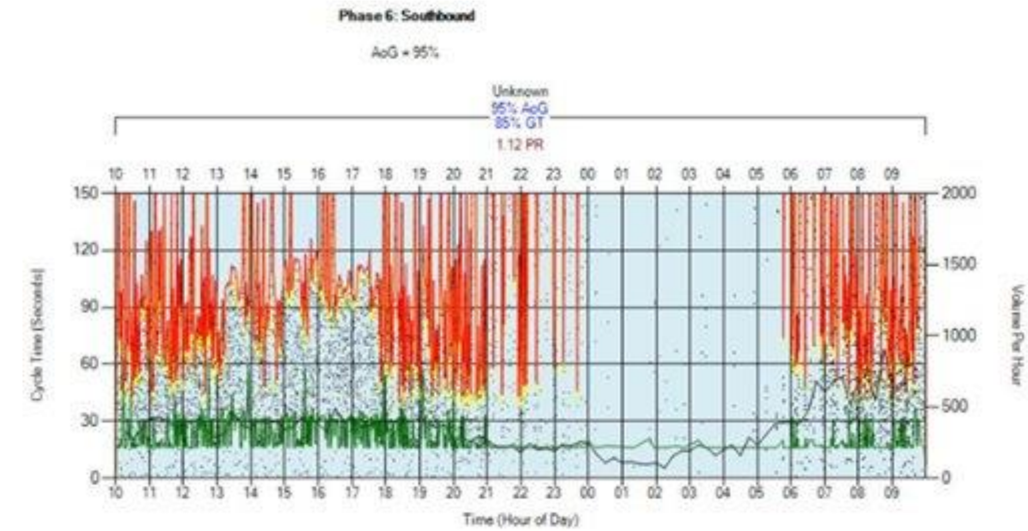


Figure 61. Actual Wavetronix data overlaid on PCD indicating a vector speed (1 hour) for southbound lane 3 at Carnegie and US 1

The project team ingests Detector Data into PCD to demonstrate the entire picture of vehicle arrivals and signal timing. For Figure 62, after 20:00, the SCATS server extends the cycle length to adjust to traffic reduction. From midnight to 6:00 A.M., the SCATS controller usually rests on the mainline. It is worth noting that the testing data is collected during the COVID-19 pandemic period; the vehicle volume is very light due to the work-from-home policy.



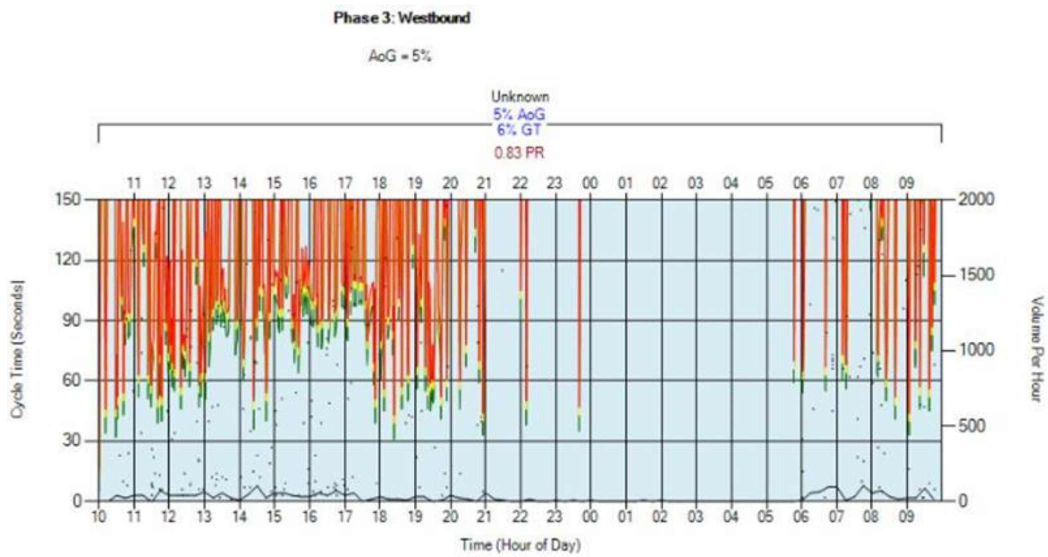
Northbound



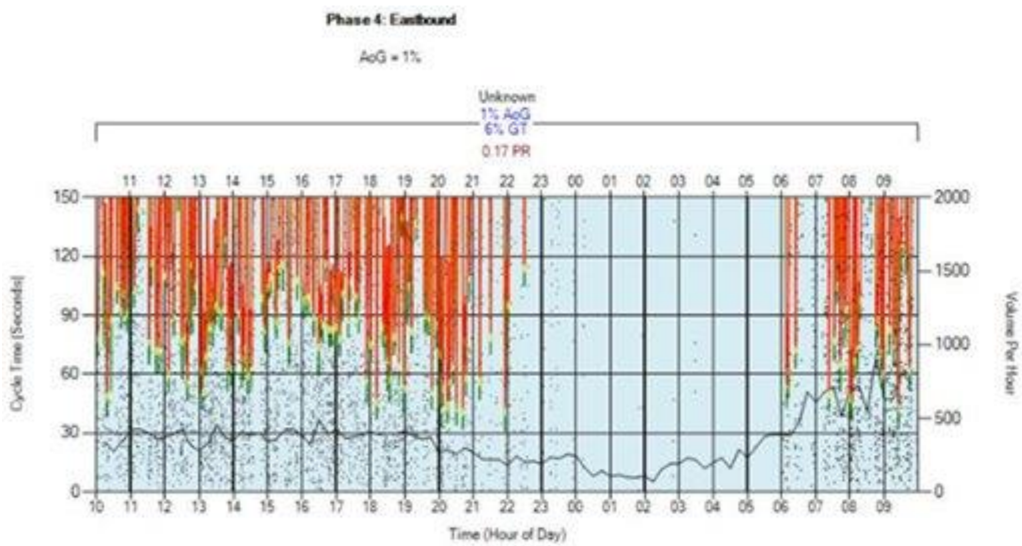
Southbound

Figure 62. PCDs with Detector Data-Part 1

The minor approach (Phase 3&4) PCD with 6% green time allocated to the minor approach for westbound and eastbound. And, Phase 4 has a higher volume than phase 3



Westbound



Eastbound

Figure 63. PCDs with Detector Data-Part 2

The team also conducts the ATSPM Functionality Enhancement with Roadside Sensor Data:

- External Sensor Data Input Process and Implementation to ATSPM
- Enabled ATSPM Functionalities
- Validation of Interpolated Advanced Detection Data from Autoscope

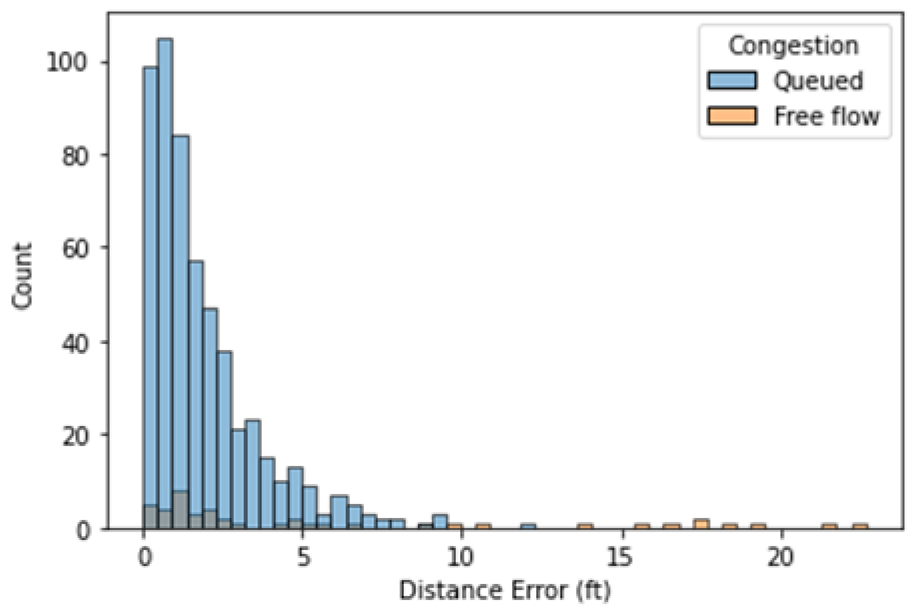


Figure 64. Trajectory Algorithm Distance Error for Congested Vehicles and Free Flow Vehicle

SCATS Signal Event Conversion

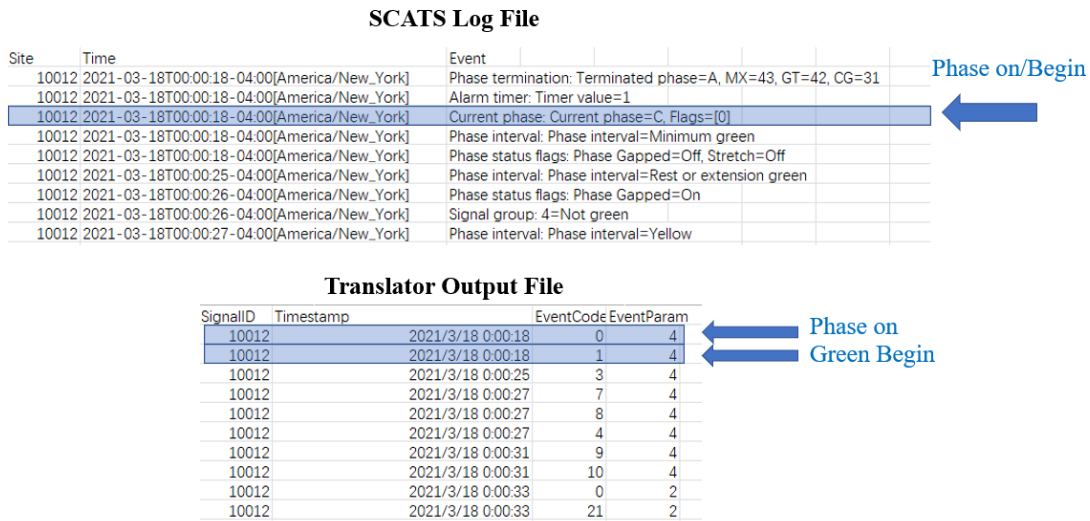
In the SCATS log files, all events have their unique identity code. The project team uses the SCATS message of events, phase status, and timestamps to build up a SCATS translator for archiving all the events in order. Table 22 shows the SCATS signal event and corresponding event code and Translator logic in the SCATS message. When looking for these events in the log file, the premise is that these events occur within the target phase time.

Table 22. Convertible SCATS Signal Event

Event Code	Event	SCATS Translator Logic
0	Phase On	"Current Phase" in SCATS message
1	Phase Begin Green	" Current Phase" in SCATS message
2	Phase Check	"Phase demand" in SCATS message
3	Phase Min Complete	calculate the phase min complete using the minimum green value from the metadata file
4	Phase Gap-Out	Green Duration < Maximum Green
5	Phase Max-Out	Green Duration > Maximum Green
7	Phase Green Termination	"Phase interval: Yellow" in SCATS message
8	Phase Begin Yellow Clearance	"Phase interval: Yellow" in SCATS message
9	Phase End Yellow Clearance	"Phase interval: All Red" in SCATS message
10	Phase Begin Red Clearance	"Phase interval: All Red" in SCATS message
11	Phase End Red Clearance	keyword: "Phase termination."
12	Phase Inactive	If a movement does not exist in a particular cycle, then create Phase Inactive
21	Pedestrian Begin Walk	keywords: "Walk" + "Active=On"
22	Pedestrian Begin Clearance	Keywords: "Walk" + "Active=Off"
45	Pedestrian Call Registered	keywords: "Walk" + "Demand=On"

Event #0: Phase On and #1: GreenBegin

For each phase in an intersection, the phase starts at the beginning of greenlight. Therefore, Event#0: Phase On and #1: GreenBegin has the same translator logic in the SCATS message, and they should appear simultaneously in the SCATS log files. The same message statement identifies their program logic: for event #0, 'If "Current Phase = X" is in the log event i, create event #0 for movement m that in the phase X in translator output'. $\mathrm{t}_{\mathrm{m,PhaseOn}} = \mathrm{t}_{\mathrm{i}}$; For event #1, that is 'If "Current Phase = X" is in the log event i, create event #1 for movement m that in the phase X in translator output'. $\mathrm{t}_{\mathrm{m,GreenBegin}} = \mathrm{t}_{\mathrm{i}}$.



SCATS Log File

Site	Time	Event
10012	2021-03-18T00:00:18-04:00[America/New_York]	Phase termination: Terminated phase=A, MX=43, GT=42, CG=31
10012	2021-03-18T00:00:18-04:00[America/New_York]	Alarm timer: Timer value=1
10012	2021-03-18T00:00:18-04:00[America/New_York]	Current phase: Current phase=C, Flags=[0]
10012	2021-03-18T00:00:18-04:00[America/New_York]	Phase interval: Phase interval=Minimum green
10012	2021-03-18T00:00:18-04:00[America/New_York]	Phase status flags: Phase Gapped=Off, Stretch=Off
10012	2021-03-18T00:00:25-04:00[America/New_York]	Phase interval: Phase interval=Rest or extension green
10012	2021-03-18T00:00:26-04:00[America/New_York]	Phase status flags: Phase Gapped=On
10012	2021-03-18T00:00:26-04:00[America/New_York]	Signal group: 4=Not green
10012	2021-03-18T00:00:27-04:00[America/New_York]	Phase interval: Phase interval=Yellow

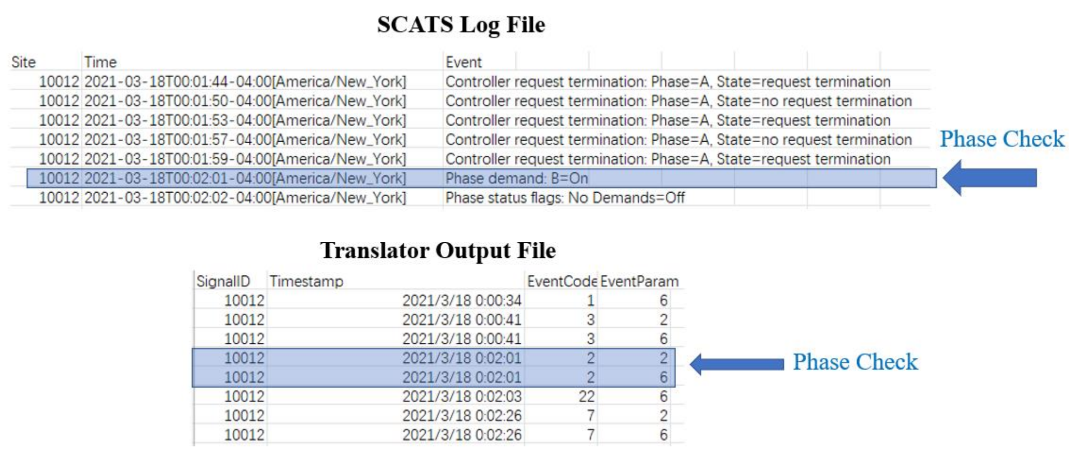
Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:00:18	0	4
10012	2021/3/18 0:00:18	1	4
10012	2021/3/18 0:00:25	3	4
10012	2021/3/18 0:00:27	7	4
10012	2021/3/18 0:00:27	8	4
10012	2021/3/18 0:00:27	4	4
10012	2021/3/18 0:00:31	9	4
10012	2021/3/18 0:00:31	10	4
10012	2021/3/18 0:00:33	0	2
10012	2021/3/18 0:00:33	21	2

Figure 65. SCATS Log File and Corresponding Event #0 and Event #1 in Translator Output

Event #2: PhaseCheck

PhaseCheck event is used to determine whether a phase is needed. We need to check the demand of a phase is 'On' while another phase is 'On.' Therefore, the program logic of event #2 is identified by: 'If phase $PhaseOn_{X,m} = True$, and log event i = "Phase demand: $X' = On$," then create PhaseCheck for movement m in translator output'. $t_{m,PhaseCheck} = t_i$



SCATS Log File

Site	Time	Event
10012	2021-03-18T00:01:44-04:00[America/New_York]	Controller request termination: Phase=A, State=request termination
10012	2021-03-18T00:01:50-04:00[America/New_York]	Controller request termination: Phase=A, State=no request termination
10012	2021-03-18T00:01:53-04:00[America/New_York]	Controller request termination: Phase=A, State=request termination
10012	2021-03-18T00:01:57-04:00[America/New_York]	Controller request termination: Phase=A, State=no request termination
10012	2021-03-18T00:01:59-04:00[America/New_York]	Controller request termination: Phase=A, State=request termination
10012	2021-03-18T00:02:01-04:00[America/New_York]	Phase demand: B=On
10012	2021-03-18T00:02:02-04:00[America/New_York]	Phase status flags: No Demands=Off

Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:00:34	1	6
10012	2021/3/18 0:00:41	3	2
10012	2021/3/18 0:00:41	3	6
10012	2021/3/18 0:02:01	2	2
10012	2021/3/18 0:02:01	2	6
10012	2021/3/18 0:02:03	22	6
10012	2021/3/18 0:02:26	7	2
10012	2021/3/18 0:02:26	7	6

Figure 66. SCATS Log File and Corresponding Event #2 in Translator Output

Event #3: Phase Min Complete

Event #3 is used to record the timestamp of minimum green time in the log file. We use this event to calculate the phase minimum green. First, compare the phase with minimum green by using timestamps in the log file. The duration is based on the time interval between the timestamp of Phase beginning and the timestamp of Phase turn to yellow.

Create the record if the duration is greater than the minimum green time. Therefore, the program logic of event #3 is identified by: If the duration $d_m = t_{m,\,PhaseGreenTerminate}$- $t_{m,\,PhaseOn} > m_{MinimumGreen}$, then create Phase Min Complete event for all movement m in translator output'. $t_{m,\,MinimumGreen} = t_i^{(SCATS)} + t_{m,MinimumGreen}$.

SCATS Log File

Site	Time	Event
10012	2021-03-18T00:00:34-04:00[America/New_York]	Phase interval: Phase interval=Minimum green
10012	2021-03-18T00:00:34-04:00[America/New_York]	Phase status flags: No Demands=On, Phase Gapped=Off, Stretch=On
10012	2021-03-18T00:00:40-04:00[America/New_York]	Controller request termination: Phase=A, State=request termination
10012	2021-03-18T00:00:41-04:00[America/New_York]	Phase interval: Phase interval=Rest or extension green
10012	2021-03-18T00:00:41-04:00[America/New_York]	Phase status flags: Request Termination=On
10012	2021-03-18T00:00:41-04:00[America/New_York]	Controller request termination: Phase=A, State=no request termination
10012	2021-03-18T00:00:42-04:00[America/New_York]	Phase status flags: Request Termination=Off
10012	2021-03-18T00:00:43-04:00[America/New_York]	Controller request termination: Phase=A, State=request termination
10012	2021-03-18T00:00:44-04:00[America/New_York]	Phase status flags: Request Termination=On

Phase Min Complete

Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:00:34	1	6
10012	2021/3/18 0:00:41	3	2
10012	2021/3/18 0:00:41	3	6
10012	2021/3/18 0:02:01	2	2
10012	2021/3/18 0:02:01	2	6
10012	2021/3/18 0:02:03	22	6
10012	2021/3/18 0:02:26	7	2
10012	2021/3/18 0:02:26	7	6

Phase Min Complete

Figure 67. SCATS Log File and Corresponding Event #3 in Translator Output

Event #4: Phase Gap-out and Event #5: Phase Max-out

Events #4 and #5 are used to evaluate the green time duration. We can create Phase gap-out, Phase max-out, and even Phase force-off entries by comparing actual green duration time to maximum phase green time. There are different event description messages in the original log file to indicate how the phase ends instead of calculating the actual duration of phase green. Therefore, we can search the SCATS message directly for the program logic of event #4 and event #5: 'If "Phase Gapped=On" or "No Demands=On" in the log file, create event #4 Phase Gap-out for movement m that in the phase X in translator output'; 'If "Mx Ack=Off" in or "Max Due=Off" in the log file, create event #4 Phase Gap-out for movement m that in the phase X in translator output.' $t_{m,\,GapOut} = t_i^{SCATS}$; 'If "Mx Ack=Off" in or "Max Due=Off" in the log file, create event #4 Phase Gap-out for movement m that in the phase X in translator output.' $t_{m,\,GapOut} = t_i^{SCATS}$; 'If "Cycle generator" in the log file, create Phase Force-off for movement m that in the phase X in translator output.' $t_{m,Forceoff} = t_i^{SCATS}$; If no corresponding messages appear, create event #5 Phase Max-out for movement m that in the phase X in translator output.' $t_{m,\,Maxout} = t_i^{SCATS}$;

SCATS Log File

Site	Time	Event
10012	2021-03-18T00:00:25-04:00[America/New_York]	Phase interval: Phase interval=Rest or extension green
10012	2021-03-18T00:00:26-04:00[America/New_York]	Phase status flags: Phase Gapped=On
10012	2021-03-18T00:00:26-04:00[America/New_York]	Signal group: 4=Not green
10012	2021-03-18T00:00:27-04:00[America/New_York]	Phase interval: Phase interval=Yellow
10012	2021-03-18T00:00:31-04:00[America/New_York]	Phase interval: Phase interval=All red
10012	2021-03-18T00:00:33-04:00[America/New_York]	Phase demand: A=Off
10012	2021-03-18T00:00:33-04:00[America/New_York]	Signal group: 2=Green, 6=Green, 18=Green
10012	2021-03-18T00:00:33-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Demand=Off, Interval=Walk]
10012	2021-03-18T00:00:34-04:00[America/New_York]	Phase termination: Terminated phase=C, MX=65, GT=16, CG=47

Phase Gap-out

Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:00:18	0	4
10012	2021/3/18 0:00:18	1	4
10012	2021/3/18 0:00:25	3	4
10012	2021/3/18 0:00:27	7	4
10012	2021/3/18 0:00:27	8	4
10012	2021/3/18 0:00:27	4	4
10012	2021/3/18 0:00:31	9	4
10012	2021/3/18 0:00:31	10	4
10012	2021/3/18 0:00:33	0	2

Phase Gap-out

Figure 68. SCATS Log File and Corresponding Event #4 in Translator Output

SCATS Log File

Site	Time	Event
10012	2021-03-18T00:02:25-04:00[America/New_York]	Signal group: 2=Not green, 6=Not green
10012	2021-03-18T00:02:26-04:00[America/New_York]	Phase interval: Phase interval=Yellow
10012	2021-03-18T00:02:31-04:00[America/New_York]	Phase demand: A=On
10012	2021-03-18T00:02:32-04:00[America/New_York]	Phase interval: Phase interval=All red
10012	2021-03-18T00:02:33-04:00[America/New_York]	Phase demand: B=Off
10012	2021-03-18T00:02:33-04:00[America/New_York]	Signal group: 3=Green
10012	2021-03-18T00:02:33-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Demand=On]
10012	2021-03-18T00:02:34-04:00[America/New_York]	Phase termination: Terminated phase=A, MX=-32, GT=120, CG=67
10012	2021-03-18T00:02:34-04:00[America/New_York]	Alarm timer: Timer value=1

Phase Max-out

Translator Output File

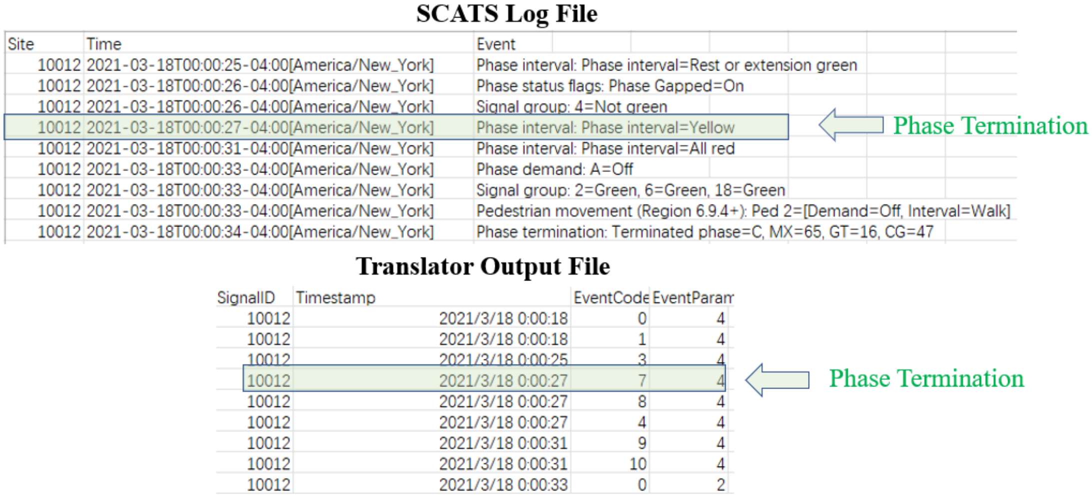
SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:02:26	8	2
10012	2021/3/18 0:02:26	8	6
10012	2021/3/18 0:02:26	5	2
10012	2021/3/18 0:02:26	5	6
10012	2021/3/18 0:02:31	2	2
10012	2021/3/18 0:02:31	2	6
10012	2021/3/18 0:02:32	9	2
10012	2021/3/18 0:02:32	9	6
10012	2021/3/18 0:02:32	10	2

Phase Max-out

Figure 69. SCATS Log File and Corresponding Event #5 in Translator Output

Event #7: Phase Green Termination

Event #7 is used to record the timestamp of the green light starts turning to yellow. That is, the termination of the green light occurs at the moment when the signal light turns yellow. Therefore, green termination is defined in the log file and occurs at the timestamp recorded by the 'Phase interval: Yellow' message. Program logic of event #7 is identified by: 'If log event i is "Phase interval=Yellow" and movement $PhaseOn_{X,m} = True$, Create Phase Green Termination in translator output'. $t_{m,\, PhaseGreenTermination} = t_i^{SCATS}$



SCATS Log File

Site	Time	Event
10012	2021-03-18T00:00:25-04:00[America/New_York]	Phase interval: Phase interval=Rest or extension green
10012	2021-03-18T00:00:26-04:00[America/New_York]	Phase status flags: Phase Gapped=On
10012	2021-03-18T00:00:26-04:00[America/New_York]	Signal group: 4=Not green
10012	2021-03-18T00:00:27-04:00[America/New_York]	Phase interval: Phase interval=Yellow
10012	2021-03-18T00:00:31-04:00[America/New_York]	Phase interval: Phase interval=All red
10012	2021-03-18T00:00:33-04:00[America/New_York]	Phase demand: A=Off
10012	2021-03-18T00:00:33-04:00[America/New_York]	Signal group: 2=Green, 6=Green, 18=Green
10012	2021-03-18T00:00:33-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Demand=Off, Interval=Walk]
10012	2021-03-18T00:00:34-04:00[America/New_York]	Phase termination: Terminated phase=C, MX=65, GT=16, CG=47

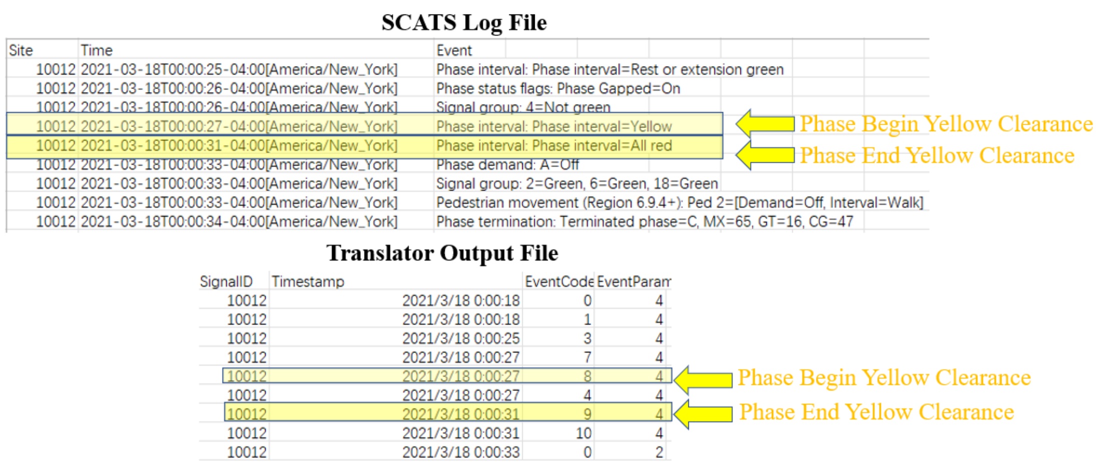
Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:00:18	0	4
10012	2021/3/18 0:00:18	1	4
10012	2021/3/18 0:00:25	3	4
10012	2021/3/18 0:00:27	7	4
10012	2021/3/18 0:00:27	8	4
10012	2021/3/18 0:00:27	4	4
10012	2021/3/18 0:00:31	9	4
10012	2021/3/18 0:00:31	10	4
10012	2021/3/18 0:00:33	0	2

Figure 70. SCATS Log File and Corresponding Event #7 in Translator Output

Event #8: Phase Begin Yellow Clearance and #9: Phase End Yellow Clearance

Events #8 and #9 identify the yellow time interval. The time point of Begin Yellow Clearance is the timestamp of phase interval: yellow in the SCATS log file. End Yellow Clearance's time point is when the yellow light turns red, the timestamp of Phase interval: All Red in the log file. The difference between them is the duration time of the yellow light. Therefore, for the program logic of events #8 and #9, we only need to search the corresponding SCATS message: 'If log event i is "Phase interval=Yellow," Create Phase Begin Yellow Clearance in translator output.' $t_{m,YellowBegin} = t_i^{(SCATS)}$; 'If log event i is "Phase interval=All Red," Create Phase End Yellow Clearance in translator output.' $t_{m,YellowEnd} = t_i^{(SCATS)}$



SCATS Log File

Site	Time	Event
10012	2021-03-18T00:00:25-04:00[America/New_York]	Phase interval: Phase interval=Rest or extension green
10012	2021-03-18T00:00:26-04:00[America/New_York]	Phase status flags: Phase Gapped=On
10012	2021-03-18T00:00:26-04:00[America/New_York]	Signal group: 4=Not green
10012	2021-03-18T00:00:27-04:00[America/New_York]	Phase interval: Phase interval=Yellow
10012	2021-03-18T00:00:31-04:00[America/New_York]	Phase interval: Phase interval=All red
10012	2021-03-18T00:00:33-04:00[America/New_York]	Phase demand: A=Off
10012	2021-03-18T00:00:33-04:00[America/New_York]	Signal group: 2=Green, 6=Green, 18=Green
10012	2021-03-18T00:00:33-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Demand=Off, Interval=Walk]
10012	2021-03-18T00:00:34-04:00[America/New_York]	Phase termination: Terminated phase=C, MX=65, GT=16, CG=47

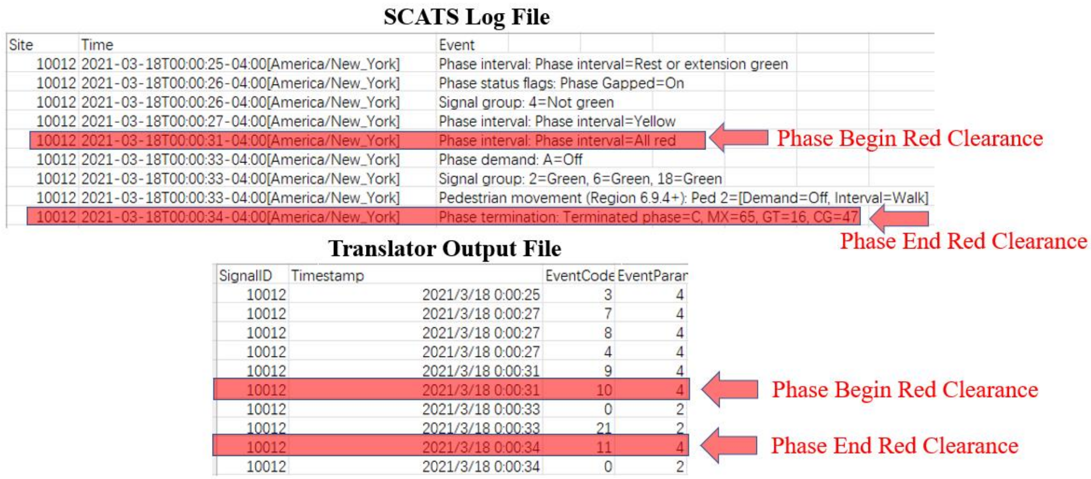
Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:00:18	0	4
10012	2021/3/18 0:00:18	1	4
10012	2021/3/18 0:00:25	3	4
10012	2021/3/18 0:00:27	7	4
10012	2021/3/18 0:00:27	8	4
10012	2021/3/18 0:00:27	4	4
10012	2021/3/18 0:00:31	9	4
10012	2021/3/18 0:00:31	10	4
10012	2021/3/18 0:00:33	0	2

Figure 71. SCATS Log File and Corresponding Event #8 and Event #9 in Translator Output

Event #10: Phase Begin End Clearance and #11: Phase End Red Clearance

Events #10 and #11 are used to identify the red time interval. The time point of Begin Red Clearance is the timestamp of phase interval: All Red in the SCATS log file. The time point of End Red Clearance is the end of a whole phase, which is the termination of a phase in a log file. The difference between them is the duration time of the red light. Therefore, for the program logic of events #10 and #11, we only need to search the corresponding SCATS message: 'If log event i is "Phase interval=All Red," Create Phase Begin Red Clearance in translator output.' $t_{m,RedBegin} = t_i^{(SCATS)}$; 'If log event i is "Phase termination," Create Phase End Red Clearance in translator output.' $t_{m,RedEnd} = t_i^{(SCATS)}$



SCATS Log File

Site	Time	Event
10012	2021-03-18T00:00:25-04:00[America/New_York]	Phase interval: Phase interval=Rest or extension green
10012	2021-03-18T00:00:26-04:00[America/New_York]	Phase status flags: Phase Gapped=On
10012	2021-03-18T00:00:26-04:00[America/New_York]	Signal group: 4=Not green
10012	2021-03-18T00:00:27-04:00[America/New_York]	Phase interval: Phase interval=Yellow
10012	2021-03-18T00:00:31-04:00[America/New_York]	Phase interval: Phase interval=All red
10012	2021-03-18T00:00:33-04:00[America/New_York]	Phase demand: A=Off
10012	2021-03-18T00:00:33-04:00[America/New_York]	Signal group: 2=Green, 6=Green, 18=Green
10012	2021-03-18T00:00:33-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Demand=Off, Interval=Walk]
10012	2021-03-18T00:00:34-04:00[America/New_York]	Phase termination: Terminated phase=C, MX=65, GT=16, CG=47

Translator Output File

SignalID	Timestamp	EventCode	EventParar
10012	2021/3/18 0:00:25	3	4
10012	2021/3/18 0:00:27	7	4
10012	2021/3/18 0:00:27	8	4
10012	2021/3/18 0:00:27	4	4
10012	2021/3/18 0:00:31	9	4
10012	2021/3/18 0:00:31	10	4
10012	2021/3/18 0:00:33	0	2
10012	2021/3/18 0:00:33	21	2
10012	2021/3/18 0:00:34	11	4
10012	2021/3/18 0:00:34	0	2

Figure 72. SCATS Log File and Corresponding Event #10 and Event #11 in Translator Output

Event #21: Pedestrian Begin Walk and #22: Pedestrian Begin Clearance

Events #21 and #22 identify whether pedestrians are crossing the road. A special message in the log file indicates the Pedestrian movement. In addition, the joint control of demand and walk parameters indicates whether pedestrians start to cross the road. Use clearance to mark whether pedestrians have completed crossing the road. Therefore, the program logic of events #21 and #22 are: Searching for the keyword "Pedestrian movement." Then, if "Demand = Off" and "Interval=Walk", Create Pedestrian Begin Walk-in translator output'. $t_{m,PedBeginWalk} = t_i^{(SCATS)}$; if "Interval=Clearance", Create Pedestrian Begin Clearance in translator output, including the number of pedestrians and the phase number'. $t_{m,PedBeginClearance} = t_i^{(SCATS)}, N_{m,ped} = n_i^{(SCATS)}$.

SCATS Log File

Site	Time	Event
10012	2021-03-18T00:00:26-04:00[America/New_York]	Signal group: 4=Not green
10012	2021-03-18T00:00:27-04:00[America/New_York]	Phase interval: Phase interval=Yellow
10012	2021-03-18T00:00:31-04:00[America/New_York]	Phase interval: Phase interval=All red
10012	2021-03-18T00:00:33-04:00[America/New_York]	Phase demand: A=Off
10012	2021-03-18T00:00:33-04:00[America/New_York]	Signal group: 2=Green, 6=Green, 18=Green
10012	2021-03-18T00:00:33-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Demand=Off, Interval=Walk]
10012	2021-03-18T00:00:34-04:00[America/New_York]	Phase termination: Terminated phase=C, MX=65, GT=16, CG=47
10012	2021-03-18T00:00:34-04:00[America/New_York]	Alarm timer: Timer value=1
10012	2021-03-18T00:00:34-04:00[America/New_York]	Current phase: Current phase=A, Flags=[1]

Pedestrian Begin Walk

Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:00:31	10	4
10012	2021/3/18 0:00:33	0	2
10012	2021/3/18 0:00:33	21	2
10012	2021/3/18 0:00:34	11	4
10012	2021/3/18 0:00:34	0	2
10012	2021/3/18 0:00:34	0	6
10012	2021/3/18 0:00:34	1	2
10012	2021/3/18 0:00:34	1	6
10012	2021/3/18 0:00:41	3	2

Pedestrian Begin Walk

Figure 73. SCATS Log File and Corresponding Event #21 in Translator Output

SCATS Log File

Site	Time	Event
10012	2021-03-18T00:02:02-04:00[America/New_York]	Phase termination request: Current phase=B
10012	2021-03-18T00:02:02-04:00[America/New_York]	Phase termination request confirmation: Current phase=A
10012	2021-03-18T00:02:03-04:00[America/New_York]	Phase status flags: Mx Ack=On
10012	2021-03-18T00:02:03-04:00[America/New_York]	Phase termination request: Current phase=B
10012	2021-03-18T00:02:03-04:00[America/New_York]	Signal group: 18=Not green
10012	2021-03-18T00:02:03-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Interval=Clearance 2]
10012	2021-03-18T00:02:04-04:00[America/New_York]	Phase termination request: Current phase=B
10012	2021-03-18T00:02:05-04:00[America/New_York]	Phase termination request: Current phase=B
10012	2021-03-18T00:02:06-04:00[America/New_York]	Phase termination request: Current phase=B

Pedestrian Begin Clearance

Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:02:01	2	6
10012	2021/3/18 0:02:03	22	6
10012	2021/3/18 0:02:26	7	2
10012	2021/3/18 0:02:26	7	6
10012	2021/3/18 0:02:26	8	2
10012	2021/3/18 0:02:26	8	6
10012	2021/3/18 0:02:26	5	2
10012	2021/3/18 0:02:26	5	6
10012	2021/3/18 0:02:31	2	2

Pedestrian Begin Clearance

Figure 74. SCATS Log File and Corresponding Event #22 in Translator Output

Event #45: Pedestrian Call Registered

Event #45 is used to indicate if there is a need for pedestrians to cross the road. A special message in the log file indicates the Pedestrian movement. In addition, the control of the “Demand” parameter indicates whether pedestrians are waiting to cross the road. Therefore, the program logic of event #45 is: Searching for the keyword “Pedestrian movement.” Then, if “Demand = On,” Create Pedestrian Call Registered in translator output, including the number of pedestrians and the phase number.’ $t_{m,PedCall} = t_i^{(SCATS)}, N_{m,ped} = n_i^{(SCATS)}$

SCATS Log File

Site	Time	Event
10012	2021-03-18T00:02:26-04:00[America/New_York]	Phase interval: Phase interval=Yellow
10012	2021-03-18T00:02:31-04:00[America/New_York]	Phase demand: A=On
10012	2021-03-18T00:02:32-04:00[America/New_York]	Phase interval: Phase interval=All red
10012	2021-03-18T00:02:33-04:00[America/New_York]	Phase demand: B=Off
10012	2021-03-18T00:02:33-04:00[America/New_York]	Signal group: 3=Green
10012	2021-03-18T00:02:33-04:00[America/New_York]	Pedestrian movement (Region 6.9.4+): Ped 2=[Demand=On]
10012	2021-03-18T00:02:34-04:00[America/New_York]	Phase termination: Terminated phase=A, MX=-32, GT=120, CG=67
10012	2021-03-18T00:02:34-04:00[America/New_York]	Alarm timer: Timer value=1
10012	2021-03-18T00:02:34-04:00[America/New_York]	Current phase: Current phase=B, Flags=[0]

Pedestrian Call Registered

Translator Output File

SignalID	Timestamp	EventCode	EventParam
10012	2021/3/18 0:02:32	10	6
10012	2021/3/18 0:02:33	45	6
10012	2021/3/18 0:02:34	11	2
10012	2021/3/18 0:02:34	11	6
10012	2021/3/18 0:02:34	0	3
10012	2021/3/18 0:02:34	1	3
10012	2021/3/18 0:02:41	3	3
10012	2021/3/18 0:02:41	7	3
10012	2021/3/18 0:02:41	8	3

Pedestrian Call Registered

Figure 75. SCATS Log File and Corresponding Event #45 in Translator Output

TASK 5: CAV RSU INTEGRATION EXPERIMENT

At the beginning of the project, the team determined that the Systems Engineering “V” Model (Figure 76) approach, developed by the FHWA, would be used as the baseline for conducting the research. It was also determined that the Concept of Operations (ConOPs) would not be required for this effort since NJDOT had recently completed its Statewide Connectivity ConOPs, which included the deployment of CV hardware. Based on this, the project started in the Systems Requirements phase.

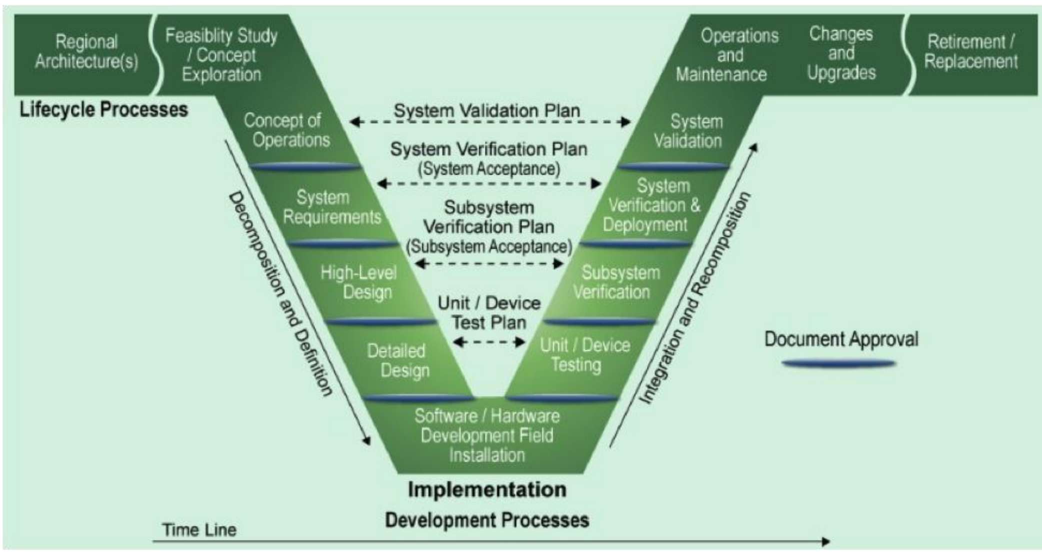


Figure 76. FHWA Systems Engineering “V” Model (https://ops.fhwa.dot.gov/plan4ops/sys_engineering.htm)

System Requirements

The subsequent sections describe the various requirements established and approved by NJDOT. It should be noted that the various steps of the systems requirements listed below occurred simultaneously, as all these essential elements had to be evaluated before the project could move forward to the solution design and testing phase.

Intersection Requirements

NJDOT initially wanted to ensure that there were field intersections that could support the deployment of the CV hardware. The Department expected that the design and lab experimentation should mimic the real-world conditions of the field intersections (IP addresses, traffic signal phasing, timing, corridor communications, etc.) to ensure success. NJDOT’s goal was to find “deployment-ready” intersections that would not require additional infrastructure upgrades to deploy the CV equipment. The project team developed criteria to evaluate and select signalized intersections along with NJDOT’s roadway network. The criteria that were utilized are listed below:

- Communications – NJDOT had previously determined that fiberoptic communications were required to deploy CV hardware. It is based on NJDOT’s need to have direct communications to the CV system and integrate/monitor the hardware through its CV data management platform.

- Cabinet Space –The existing traffic signal cabinet needed suitable space to house the CV hardware.
- Cabinet Accessibility – The existing traffic signal cabinet needed to be in a readily and safely accessible area to the project team to allow for installation and testing.
- Geometric Limitations – The field intersection needed to have no physical limitations that would impact the deployment of CV hardware. Limitations that were analyzed included Line of Sight (LOS) for RSU broadcasts and horizontal and vertical curvature of the road.
- Conduit Fill – The intersection was required to pass conduit fill calculations to ensure space for the CV cables within the existing conduit system.
- Structural Support/Approval – The intersection was required to pass a structural analysis, per NJDOT standards, to provide that the traffic signal pole and mast arms could support the additional CV hardware that would be mounted.

The project team completed field evaluations of intersections along various corridors in New Jersey to determine if there were intersections that met the requirements noted above. As a result of these field surveys, the project team was able to identify five intersections (Figure 77) that met all the criteria above. These intersections are noted below. It should be noted that the RT 1 intersection is currently using the SCATS adaptive traffic signal system.

1. US Route 1 at Bakers Basin Road
2. US Route 9 at Schank Road
3. Schank Rd at Stonehurst Road
4. US Route 22 at Rock Avenue
5. US Route 22 at West End Road

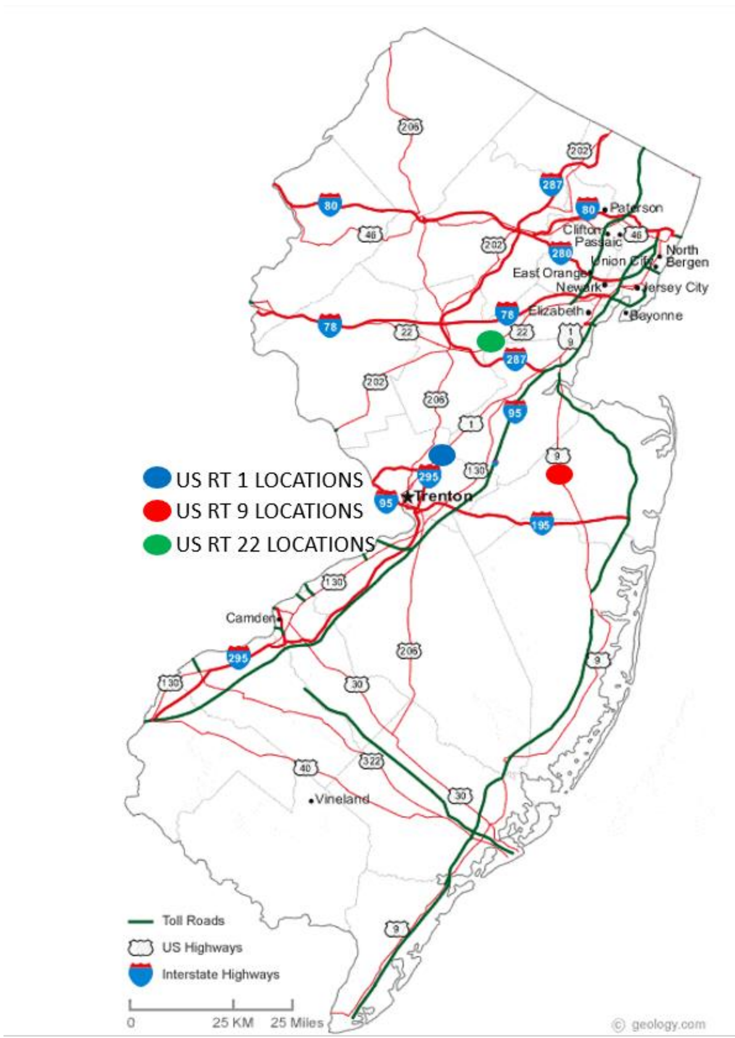


Figure 77. Pilot Intersection Locations

Hardware Requirements
The project team developed two sets of hardware requirements. One set of requirements for the CV/Signal hardware (RSUs, OBUs, Traffic Signal Controllers) and one for the networking hardware to integrate into the NJDOTs CV data management platform.

The following criteria were used for selecting the CV hardware.

- Communications – Based on the recent FCC Notice of Proposed Rulemaking (NPRM) associated with the 5.9 GHz spectrum, the project team that RSUs and OBUs would be tested using both DSRC and Cellular CV2X (Cellular Vehicle-to-Everything) communications
- Compatibility with Data Management Platform – The CV hardware had to be compatible with NJDOT's data management platform.
- Compatibility with NJDOT Traffic Signal Controllers – The CV hardware was required to work with traffic signal controllers that NJDOT had either already

deployed in the field or was planning to deploy soon. This requirement included compatibility with the SCATS adaptive system.

- Compatibility with Security Credentials Management System (SCMS) – The RSUs and OBUs had to be compatible with an SCMS to meet NJDOT security guidelines.

During the evaluation of the CV hardware, it was determined that the only way to evaluate some of the criteria noted above was to test the hardware in the lab. This determination was made based on the evolving technology associated with CV hardware. Ultimately, the following CV hardware was procured for the lab phase (Table 23).

Table 23. CV Hardware Procured

RSUs	o Blyncsy (DSRC)
	o Commsignia (DSRC and CV2X)
	o Danlaw (DSRC)
	o Siemens (DSRC and CV2X)
	o TrafficCast/Iteris (DSRC and CV2X)
OBUs	o Commsignia (DSRC and CV2X)
	o Danlaw (DSRC)
Traffic Signal Controllers	o Econolite ASC-3
	o Econolite Cobalt
	o Trafficware 2070LN
	o Trafficware Commander
	o SCATS Adaptive Traffic Signal System Software
Security Management System (SCMS)	o GHISS SCMS was procured, and test certificates were used for the project

The project team developed a Solution Requirements Document (SRD) that outlined all the network hardware needed to deploy and test the CV system through Edge Intelligence's CV data management platform. The document included all the hardware and virtual machines that Cisco Systems would provide to support the deployment of the CV solution at both the lab and the field levels.

Data Requirements

The SRD also outlined data requirements for the various CV use cases/data broadcasts and the required connectors to ensure the data could be transmitted from the data management platform to the CV hardware and vice versa.

As previously noted, the CV data broadcasts that were evaluated as a part of this project are noted as follows:

- Signal Phasing and Timing (SPaT) – This CV data broadcast transmits the traffic signal phasing and timing information. The transmission goes from the RSU to the OBU.

- Traveler Information Messages (TIM) – This CV data broadcasts various safety and mobility information. For the project, a Work Zone Ahead TIM message was tested. TIM data is transmitted from the RSU to the OBU.
- MAP – This CV data broadcast contains the geometric information of the roadway where the RSU is deployed. This data is transmitted from the RSU to the OBU. MAP information was generated using the USDOT ISD tool (https://webapp.connectedvcs.com/isd/).
- BSM – This CV data broadcast contains information associated with a vehicle, such as speed, position, and heading. This data is transmitted from the OBU to the RSU.
- Security Credential Management System (SCMS) – The SCMS is an encrypted certification included in the different types of CV data noted above. The SCMS intends to verify the CV hardware transmitting and receiving data from one piece of hardware to another is secure. When SCMS certificates are included in the data transmissions, only SCMS certificates can communicate with one another.

A summary of the data flow described above can be found below (Figure 78).

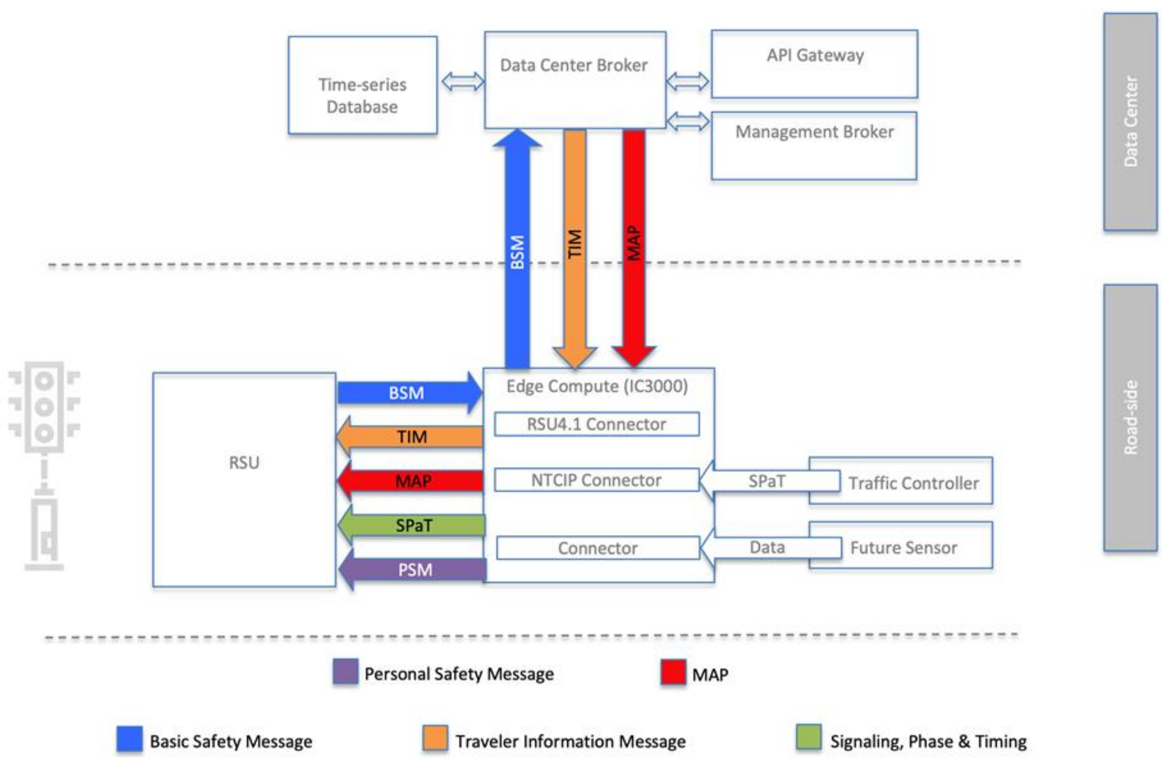


Figure 78. CV Data Flow Architecture

Testing Requirements

The project team developed testing protocols and procedures to ensure that all the functional requirements of the CV hardware, data and data management system would be verified. The test protocols developed provide steps for each CV data broadcast to validate that the data is transmitted and received for each piece of CV hardware.

Solution Design and Lab Testing

Once the system requirements were finalized, the project team completed a full system design and build-out in the TCNJ lab to begin verifying the CV system. The overall intent of the solution design was to create a "sandbox" testing environment at TCNJ that would mirror the actual field conditions of the five pilot intersections. It would ensure that the CV hardware deployed on the live intersection network would be functional within NJDOTs existing ITS architecture. The project team coordinated with all applicable stakeholders, such as the NJ Office of Information Technology (OIT), to get all the required information to build out a fully functional system in the lab.

Solution Design

The project team completed a design that included all the components at the intersection level (Figure 79) and the data center level (Figure 80) to ensure the system would be functional on NJDOT's existing network.

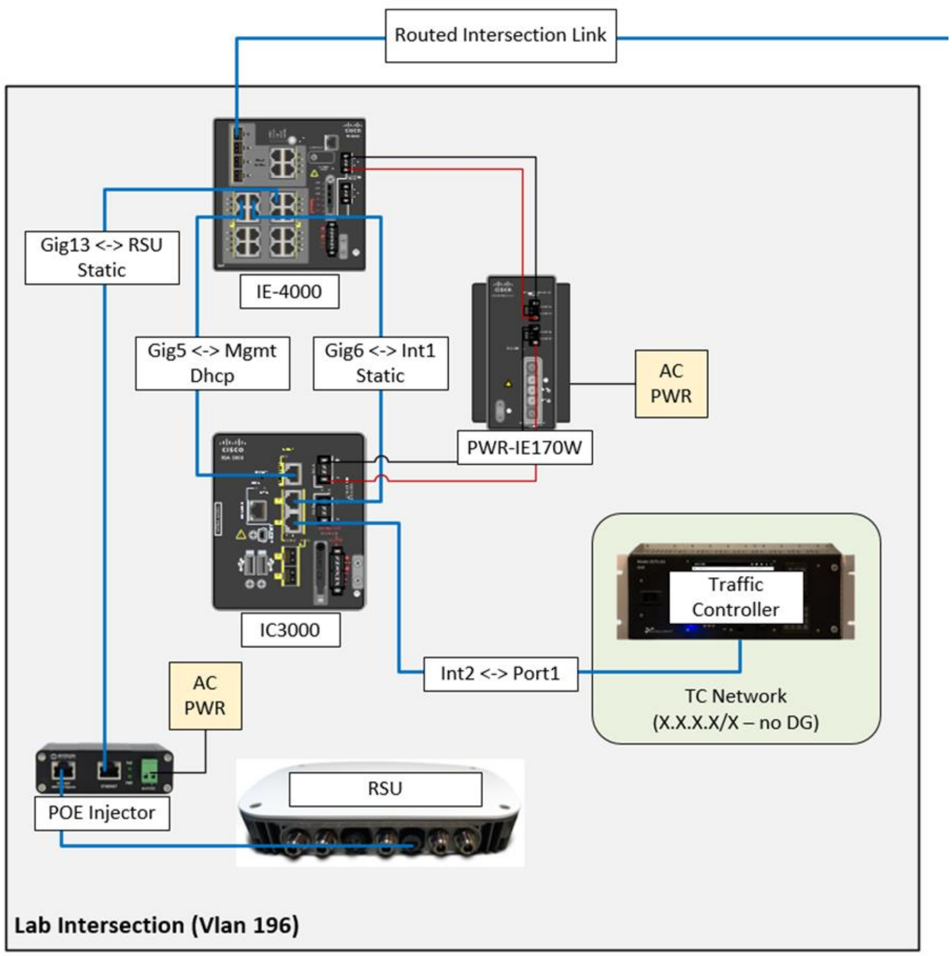


Figure 79. Intersection Level Design

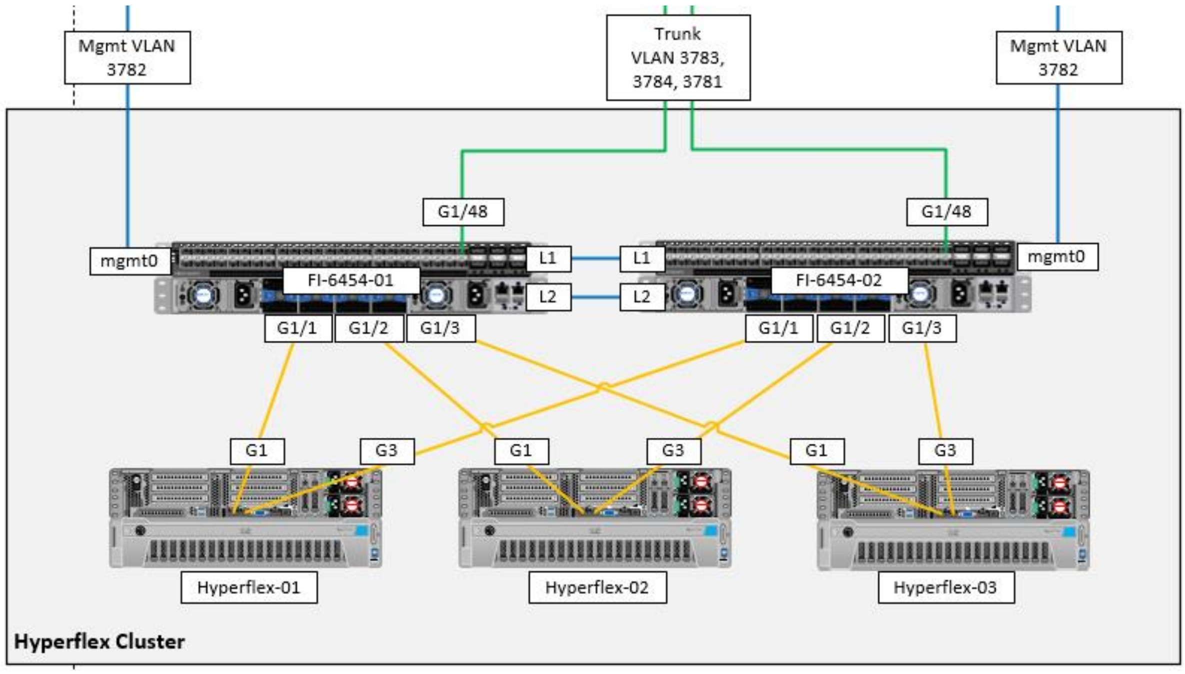


Figure 80. Data Center Level Design

Lab Testing

Once this design was approved, the project team built out each of the five pilot intersections in the lab environment (Figure 81). The project team tested each piece of CV hardware (RSUs, OBUs, and Signal Controllers) to determine the compatibility of the equipment.

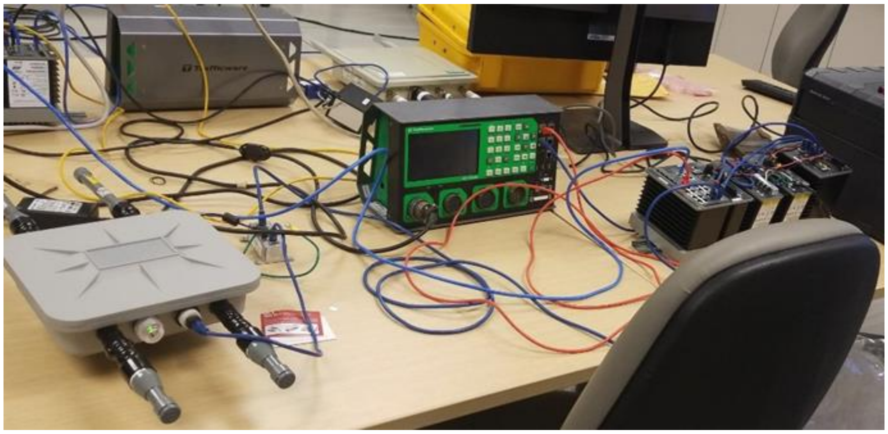


Figure 81. Intersection Build in TCNJ Lab

To complete the validation of the CV hardware and overall system, the project team used a spiral-based testing approach in the lab. The project team first tested all the CV hardware without the data management hardware or the SCMS. It allowed the project team to verify the interoperability of each piece of CV hardware with one another and pinpoint if any failures are related to the CV hardware or if updates need to be made to the data management platform. Once this first testing phase was completed, the project team incorporated the data management hardware and SCMS into the testing. A compatibility matrix (Table 24) was created to illustrate the lab testing results. The test protocols were conducted step-by-step and validated using the data management system and the OBUs in the lab. A Test was considered successful if the OBU and data management system could successfully broadcast CV data either to or from the OBU via the RSU.

Table 24. Lab Testing Compatibility Matrix

NJCTII Hardware Compatibility Matrix

Activity: CONTROLLERS	TEST CASE	RSU Manufacturer	Blyncsy DSRC	Danlaw DSRC	Siemens DSRC	TrafficCast DSRC	Siemens CV2X	Commsignia CV2X	TrafficCast CV2X
			RESULTS						
Without CISCO Edge Compute									
Econolite ASC-3	Communications		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
Econolite Cobalt	Communications		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
Trafficware Commander	Communications		Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
TrafficWare 2070LN	Communications		Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Not Compatible	Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
SCATS	Communications		Not Compatible	Not Compatible	Compatible	Compatible	Compatible	Not Compatible	Compatible
	MAP		Not Compatible	Not Compatible	Compatible	Compatible	Compatible	Not Compatible	Compatible
	SPaT		Not Compatible	Not Compatible	Compatible	Compatible	Compatible	Not Compatible	Compatible
	SCMS		Not Compatible	Not Compatible	Compatible	Compatible	Compatible	Not Compatible	Compatible
With CISCO Edge Compute			RESULTS						
Econolite ASC-3	Communications		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
Econolite Cobalt	Communications		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
Trafficware Commander	Communications		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
TrafficWare 2070LN	Communications		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
SCATS	Communications		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	MAP		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SPaT		Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	SCMS		Not Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible

LEGEND	
(green)	Tested, Confirmed Compatible
(red)	Not Compatible

Based on the testing completed in the lab, five decisions related to the field deployment were made.

1. Trafficware Commander – It was determined that a new Trafficware Commander Controller would be installed at each pilot intersection. At the same time, the project would keep the existing controller if a backup was needed and could be quickly installed. This decision was to have the existing

controller as a safety net if something went wrong with the deployment at a live intersection.

2. SCATS – It was determined that only RSUs compatible with SCATS with and without the data management hardware scenarios would be deployed on US Route 1 at Bakers Basin. It was decided to ensure compatibility with the SCATS adaptive signal system at this location.
3. Blyncsy RSU – Since the Blyncsy RSU was not compatible with SCMS, it was determined that these RSUs would not be deployed in the field.
4. Communications Method – It was determined that one DRSC and one CV2X RSU would be deployed at each pilot intersection for ten RSU deployments. It was determined to maximize the potential penetration (vehicle matching) at each pilot location. It was also done because of the FCC's NPRM (https://www.fcc.gov/document/fcc-modernizes-59-ghz-band-improve-wi-fi-and-automotive-safety).
5. OBU – It was determined that only the Commsignia OBUs would be used for field validation testing. It was based on the Commsignia OBUs, including a tablet that allowed for a more user-friendly experience.

System Deployment and Validation

Once all the testing was completed in the lab, the CV hardware was deployed, integrated, and testing at the five pilot intersections (Figure 82). The deployments were completed following the solution design and lessons learned from the lab testing. A summary of the success of the field deployment is covered in subsequent sections of this paper.

Figure 82. Field Deployed RSU

Test Results

The project team was the first in the country to successfully broadcast SPaT CV data on a SCATS adaptive traffic signal system. This project's crucial result is based on NJDOT's large deployment of SCATS on signalized corridors throughout New Jersey. Both the lab results and field validation are provided.

Lab Test Results

The validation testing results completed in the lab are provided in the compatibility matrix previously shown in Table 24. A summary of the key findings from the lab testing results is provided below:

1. SCATS – The lab testing revealed several RSU vendors were not compatible with SCATS adaptive traffic signal systems requiring Cisco's CV edge compute network hardware.
2. SCMS – The lab testing revealed that not all RSUs were compatible with the SCMS systems, requiring the team to eliminate some equipment.
3. Communications Method (DSRC v CV2X) – The lab testing verified that DSRC and CV2X RSUs and OBUs were compatible with NJDOT's ITS architecture, communications network, and CV data management platform. RSUs and OBUs using both methods of communication were able to transmit and receive CV data for each use case.
4. Interoperability –
    a. The lab test results revealed that not all the RSUs are compatible with every traffic signal controller without using Cisco's CV edge compute network hardware.
    b. The lab testing verified that the Cisco CV network hardware is compatible with multiple RSU and traffic signal controller vendors. It is critical as it will allow NJDOT to open CV hardware procurement.

Field Test Results

Once all the testing was completed in the lab, the same approved test protocols were completed. The field deployment used the lessons learned from the lab testing to avoid some of the observed issues during the lab testing. These lessons learned are summarized in this report's previous section(s). During the field testing, it was observed that all the CV hardware was able to successfully transmit and receive CV data through NJDOT's data management platform.

The key findings from the field testing are summarized below:

1. Network Delay with SCATS – During the field testing at the US Route 1 / Bakers Basin intersection, a 3-second delay in transmission of the SPaT data from the RSU to the OBU was observed. This delay was attributed to the network delay associated with the additional time for the remote SCATS server to push the SCATS data to the cabinet hardware. While a very slight delay was observed in the lab phase, it was not nearly as long. It is believed that this delay was not

observed in the lab phase because the field hardware was plugged directly into a SCATS server locally in the lab.

2. MAP Data – During the field testing, the CV data was not displayed on the OBU until the OBU was approximately 100 feet from the intersection. It is based on the limits of the MAP data being broadcast by the RSU. Subsequently, a file size restriction on MAP messages is further reduced when using SCMS credentials. It was not observed in the lab as all equipment was next to each other within the lab setting.

Discussion and Conclusions

Based on the project's findings, there are several items that NJDOT and the project team need to continue to evaluate and discuss potential resolutions. A summary of these items is provided below:

1. Network Delay – The project team is observing an approximate 3-second delay at locations using the SCATS adaptive traffic signal system. The team is currently coordinating with the SCATS local vendor to troubleshoot the problem and determine a solution. The delay will need to be reduced to avoid potential conflicts resulting in an OBU displaying incorrect traffic signal phasing and timing information to vehicles.
2. MAP Data – As previously noted, the current MAP data only broadcasts approximately 100' away from the intersection for all approaches. The team is currently evaluating potential solutions that would extend the MAP area. Potential updates could include extending the MAP data along with the main approaches and reducing it along the side streets. The expected solution will need to provide the CV data to motorists with enough time to evaluate the information before any driver decisions would need to be made.
3. Overlap Phasing – During the field testing, it was observed that the J2735 communications protocol does not support traffic signal overlap phasing for pedestrian signal phases and instead only supports vehicular phasing. This limitation only causes issues at locations where the signals are programmed with pedestrian overlap phasing. While coordinating with the CV hardware vendors throughout the project, it was discovered that specific proprietary vendor firmware would function with overlap phasing.

Based on the testing completed under the project, the project team successfully demonstrated that NJDOT could deploy CV hardware within its existing ITS Architecture. The project validated that NJDOT could meet its security regulations by securing its CV hardware with an SCMS system that could be operated through NJDOT's CV data management platform, Cisco *Edge Intelligence*. The project proved that NJDOT's ITS architecture could support the broadcast of SPaT, MAP, TIM, and BSM CV data. The research conducted as a part of this project has also resulted in NJDOT gaining hands-on experience with CV equipment.

The testing results also proved that SPaT CV data could be broadcast with a SCATS adaptive traffic signal system, the country's first successful validation of this functionality. The successful completion of this research has led NJDOT to move forward with the final design and deployment of CV hardware along various corridors within New Jersey. These deployments, along with the pilot deployments, will result in the motorists traveling within New Jersey realizing additional benefits related to safety and mobility. Further research will be conducted to better utilize the SCATS performance data with CV information, to manage better and reduce congestion along its connected corridors.

Lab Setup and Experiments

The project team built up an experiment lab environment to successfully develop a simulated field network to test RSUs, OBUs, and Signal Controllers. Figure 83 shows the lab setup system.

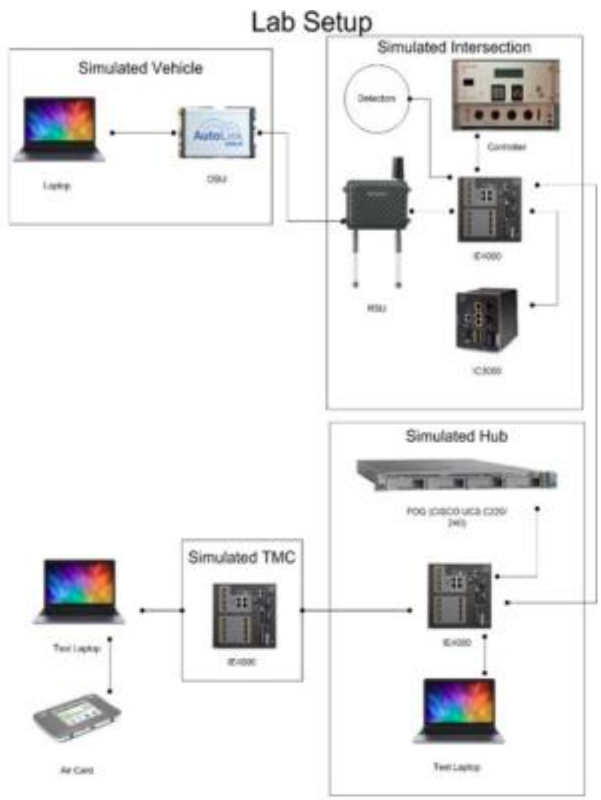


Figure 83. Lab Setup for Experiment

In addition, teams from NJDOT test the SPaT/MAP broadcasts on adaptive traffic signal systems. Figure 84 shows how the adaptive signal interacts with other vital systems.

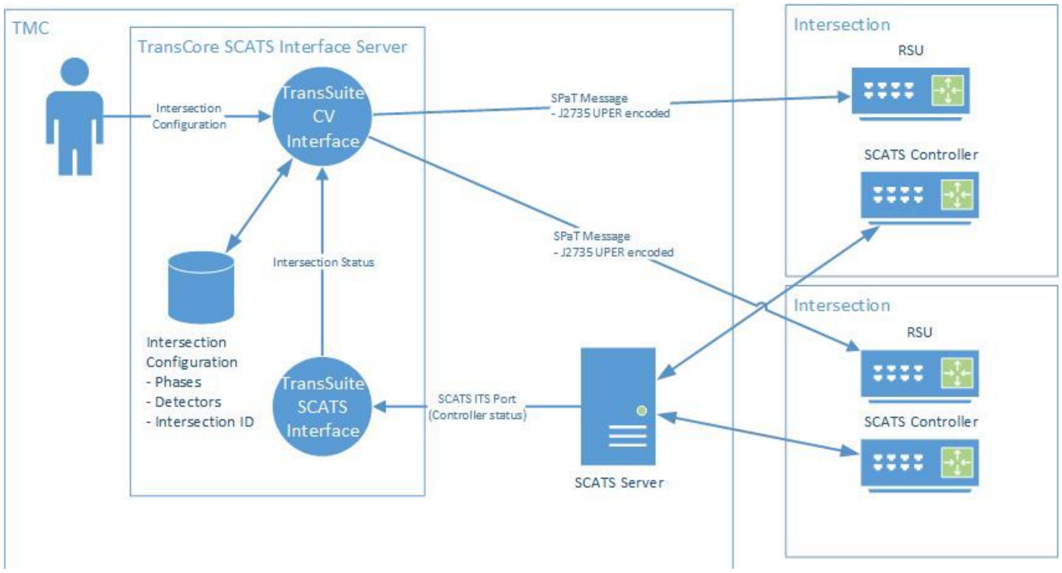


Figure 84. Adaptive Signal Intersection

The teams from NJDOT responded to coordinate with OIT to evaluate network requirements for integration. And OIT helps configure simulated field networks in the lab. All the current lab deployments will be on corridors with direct fiber connections. Figure 85 shows the framework of network connectivity.

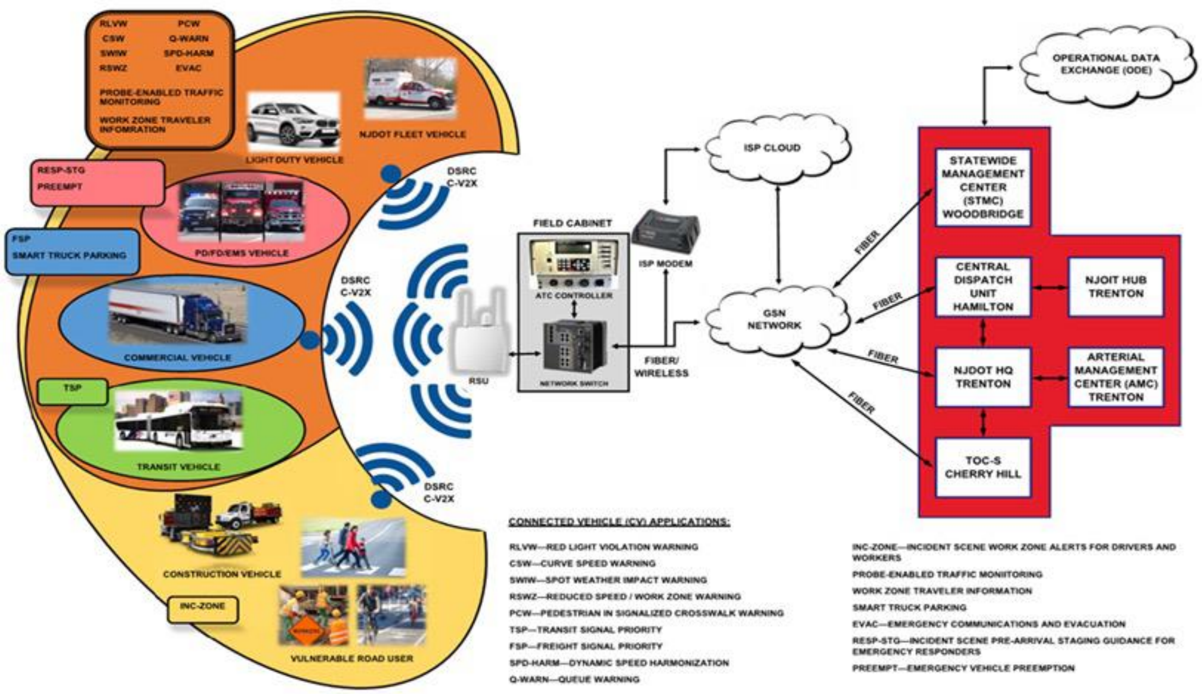


Figure 85. NJCTII Network Connectivity

RSU Configuration and Testing

Provided herein is a list of steps to set up an RSU-Controller Connection in a laboratory setting. This process will require basic changes (as noted) to conduct the same setup in the field. The Road Side Unit (RSU) provides a communication conduit between a traffic signal controller's Signal Phase and Timing Data (SPaT)/Pedestrian Data and a vehicle's

On-Board-Unit (OBU). In addition to some specific software, the network requirements to set up an RSU and controller are covered. Some RSU systems require a direct Ethernet connection to the RSU and may require the same connection to a controller requiring a static IP from a laptop. In addition, the RSU may already be connected to a controller or may require the controller to be set up before the RSU is connected. It is suggested that the latter be adhered to and the controller set up before the RSU to assure the RSU and controller communicate. A list of the general materials used for the laboratory setup is as follows:

- Items Necessary:
  - EtherWan or CISCO Switch (needed for the field, **CISCO SETUP TO BE DETERMINED**)
  - Assorted Ethernet cables
  - Siemens Sitraffic ESCoS RSU with POE injector
  - Commsignia ITS-OB4 OBU with associated Android tablet with Commsignia App (For testing OBU/RSU communication)
  - A controller:
    - Trafficware Commander ATC Controller
    - Econolite ASC/3-2100 Controller
    - Naztec 2070 LN Controller with 1C and 1B card
  - All available hardware manuals for the above items
  - Windows Laptop with Ethernet ports, **Admin access to Laptop**, Wifi internet access, Google Chrome browser (or Firefox) installed. Some RSU's only allow specific browsers.
  - !!! Note, you must ensure all antennas and wires are attached to the RSU unit before powering on. Failing to do so could damage the unit.

Controller Network and Communication Configuration

The recommendation is to have a controller set up before setting up an RSU. All controllers must have an IP established to communicate on the network before communicating with an RSU. The RSU will already be set up in some cases, and the controller is set up in others. In this way, the controllers can output SPaT messages that, once set up correctly, the RSU will be able to receive. Some controllers may require a direct connection via an Ethernet cable. If that is the case, go to *Initial Laptop Network Setup to communicate with RSU* and follow the same Laptop Network IP procedure required to establish a static IP on a local laptop. Other controllers may allow the IP addresses to be changed on the front panel. In both cases, they should be finished in a laboratory environment, and any changes in the field would need to follow standard protocol. This section assumes that any controller is set up for the standard 8 phase and properly configured to run a specific intersection. The following are some standard controller setup configurations:

Trafficware Commander ATC Controller: The Configuration for Network and Spat is through the Front Panel of this controller and should not require an Ethernet connection. The information is the recommended first step to pairing a Trafficware Commander ATC controller with a specific RSU. Any IP changes in the controller will require a reboot once the IP is changed.

To Initialize the controller for DSRC communication, follow this sequence. Hit Home à 8 'Login and Utilities' à 4 'Initialize' à 2 'Run Options'

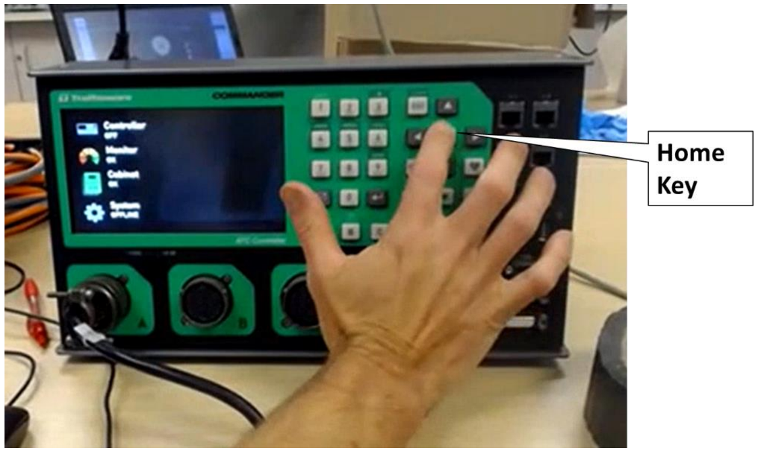


Figure 86. Trafficware Commander Initializing Controller ‘Home Key’

Figure 87. Trafficware Commander Initializing Controller ‘Home Key’ again if needed.

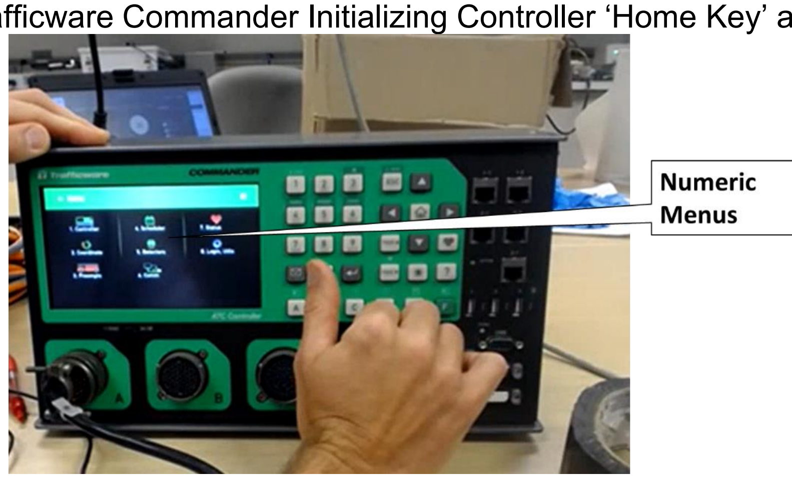


Figure 88. Trafficware Commander Initializing Controller-Numeric Menus

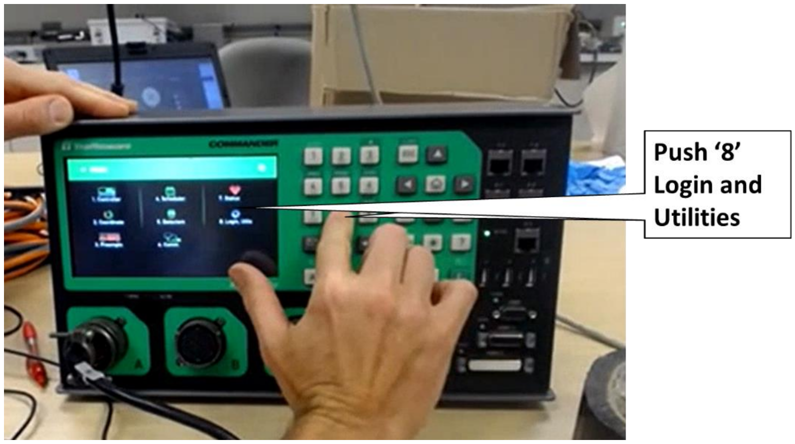


Figure 89. Trafficware Commander Initializing Controller-Utilities

Figure 90. Trafficware Commander Initializing Controller-Initialize

Figure 91. Trafficware Commander Initializing Controller-Run Options

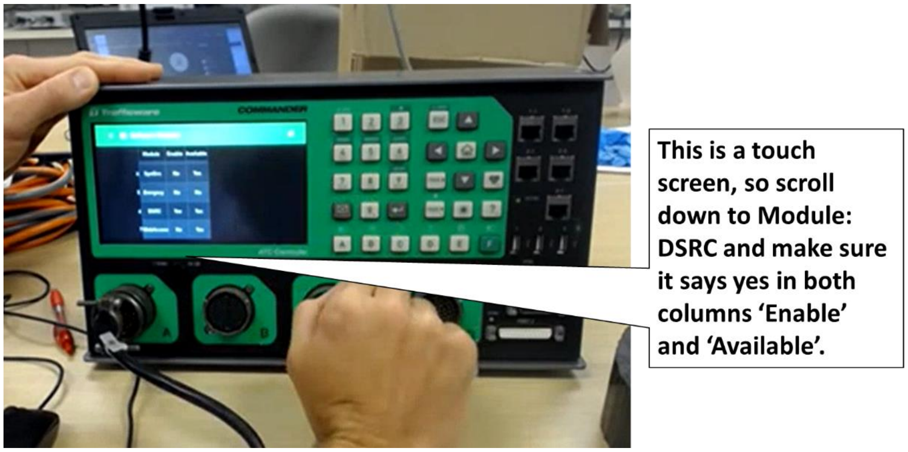


Figure 92. Trafficware Commander Initializing Controller- Scroll to DSRC

Figure 93. Trafficware Commander Initializing Controller – Assure setup

Once the initialization of the DSRC is completed, the controller's IP configuration needs to be set. The Controller will also have the RSU IP address placed in its configuration (Host 2), and the RSU will have the controller IP information. All the IPs must match.:

To change the IP follow this sequence. Hit Home à 6 'Comm' à 5 'IP Setup.'

Figure 94. Trafficware Commander Initializing Controller-IP Setup

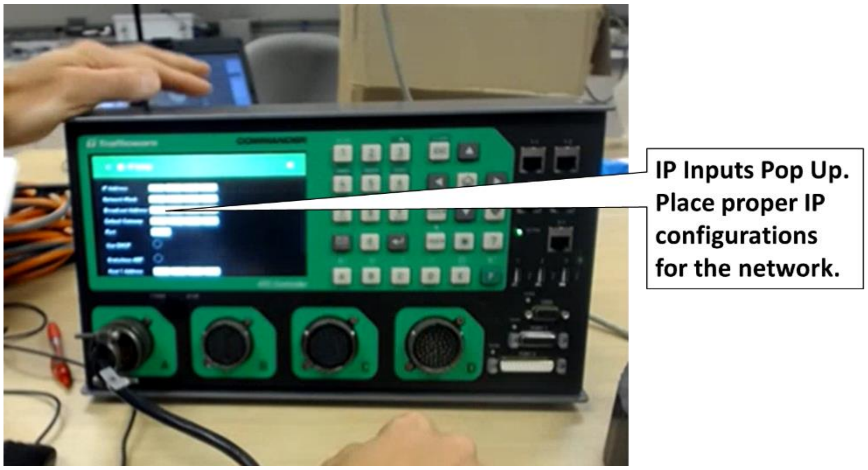


Figure 95. Trafficware Commander Initializing Controller –IPs need to be predetermined

IP, gateway, and subnet should already be set if a controller communicates over ATSM.now. This information would need to be obtained from OIT and placed in the controller if out of the box. NTCIP port for a lab is set to 501 and needs to match the RSU port. Some RSU's have a pre-set NTCIP 'Port,' but trafficware allows this to be set, but it needs to match RSU.

RSU Host Address 2 needs to be set to the RSU. In theory, the Host1 is the Arterial Traffic Management System (ATMS) now server.

PING address to match the RSU address (or planned RSU IP). Usually, this is the ATMS.now server. It should have defaulted to ATSM.now, but for testing of the future RSU setup, set up the PING to send to the RSU. Note that only one traffic controller can be paired with one RSU. The RSU will require the IP address of the controller. CISCO will resolve the pairing once the IPs are set up.

Once all set up, hit 'Home,' then save changes.

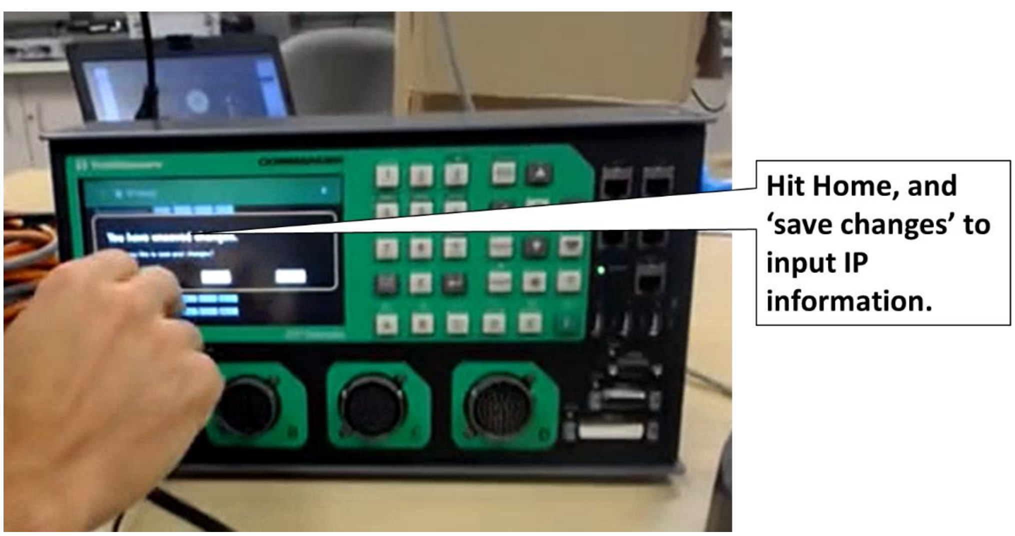


Figure 96. Trafficware Commander Initializing Controller- Saving IP data

Once the RSU is set up, a Ping Test can be performed to see if the controller can talk with the RSU over the network.
To ping the RSU, follow this sequence. Hit Home à 6 'Comm' à 8 'Ping'

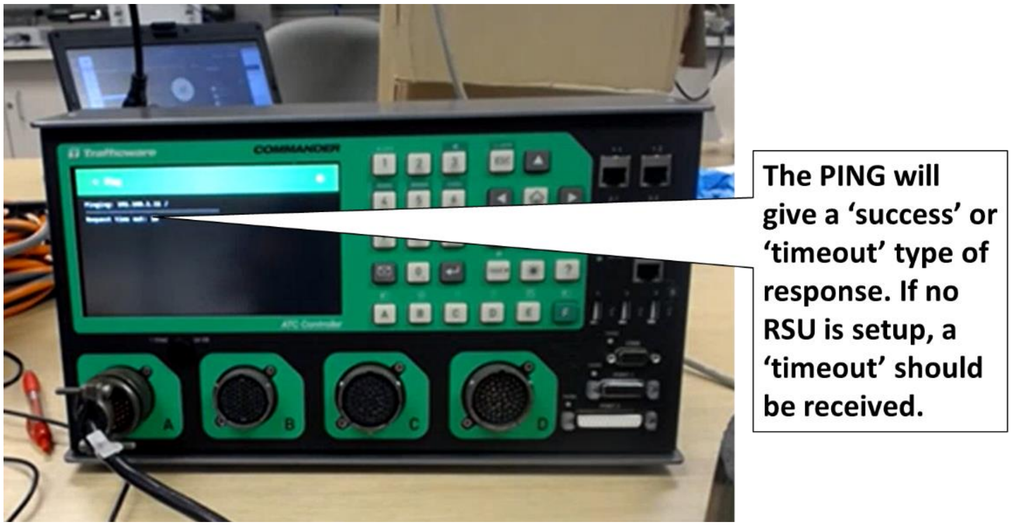


Figure 97. Trafficware Commander Initializing Controller –Ping Test

After initialization and all the IP addresses are established, the DSRC needs to be set up. **To set up, up the DSRC, follow this sequence: Home à 6 'Comm' à 9 DSRC Proprietary Setup**

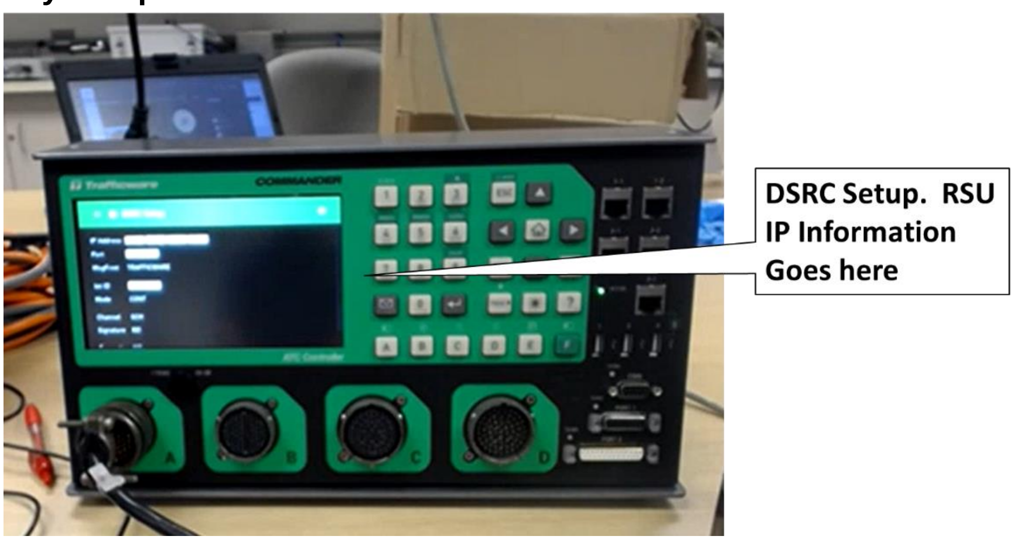


Figure 98. Trafficware Commander Initializing Controller –DSRC setup

The following need to be set:
PORT: Set to 6053, but can be changed in Trafficware and needs to match RSU. Message Format…no RSU will work on J2735 (Although this is the standard). All of the RSU's seem to prefer 'Trafficware Proprietary,' so leave this on default...
Intersection ID needs to match the MAP message being used for the intersection. It is super critical that the RSUs will emit a separate map and SPaT if the ID's are different, but the MAP MESSAGE (https://webapp.connectedvcs.com/isd/) and Intersection ID need to match.

MODE: Alternative 'ALT' or Continuous 'CONT.' Keep on Continuous.
Channel: Don't touch.
Signature: Don't touch.
Encryption: Don't touch for now.
The Trafficware Commander controller is now set up to communicate with an RSU,

Initial Laptop Network Setup to communicate with RSU:
The setup of an RSU is unit-specific; this section shows the primary method for setting up a laptop to communicate with an RSU. IPs are dependent on the unit type and configuration status. The same methodology for setting up a laptop to connect to an RSU can be done for a traffic signal controller. Some RSUs have a cellular connection (e.g., Blyncsy) and some do not (e.g., Siemens). For those RSUs that DO NOT have a cellular connection, a PC laptop (with admin writes) requires a static IP address setting to be adjusted to be able to communicate with the network (same first three octets of the connecting IP, different 4th octet set on the laptop that has Ethernet connectivity). There are two situations for non-cellular connections:

- The first is that the RSU needs to be reconfigured from its default IP settings, requiring a direct connection with a laptop via Ethernet cable.
- The second is that the **RSU is already set up** or had been set up and communicating with the existing network. In either case, the laptop used requires a new static IP, with the 4th octet being a high number in the range 0-255. (Suggested 251). To change the IP on a laptop, please follow Figure 99 to Figure 101, which starts by typing in 'Control Panel' in windows explorer and transitions through:
  Control Panel/ Network and Internet / Network and Sharing Center/

Once at the Network and Internet (Figure 99), Figure 100 pops up. Right-click active Ethernet connection and click on properties (Figure 101). Double Click Internet Protocol Version 4 in Figure 17. THE ADDRESS USED MUST BE UNIQUE AND OBTAINED FROM OIT…UNLESS IT IS A NEW RSU, then use the default manufacturer IP to change the IP. Ultimately this IP needs to be placed in a controller. The subnet mask should also match current network configurations. The necessary IP configurations placed in Figure 102 should be obtained from NJDOT.

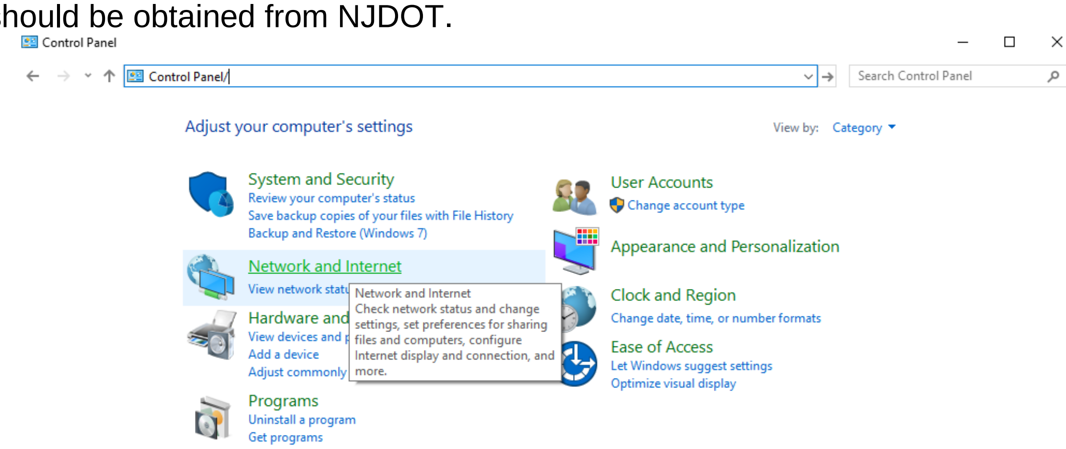


Figure 99. Control Panel/Network and Internet

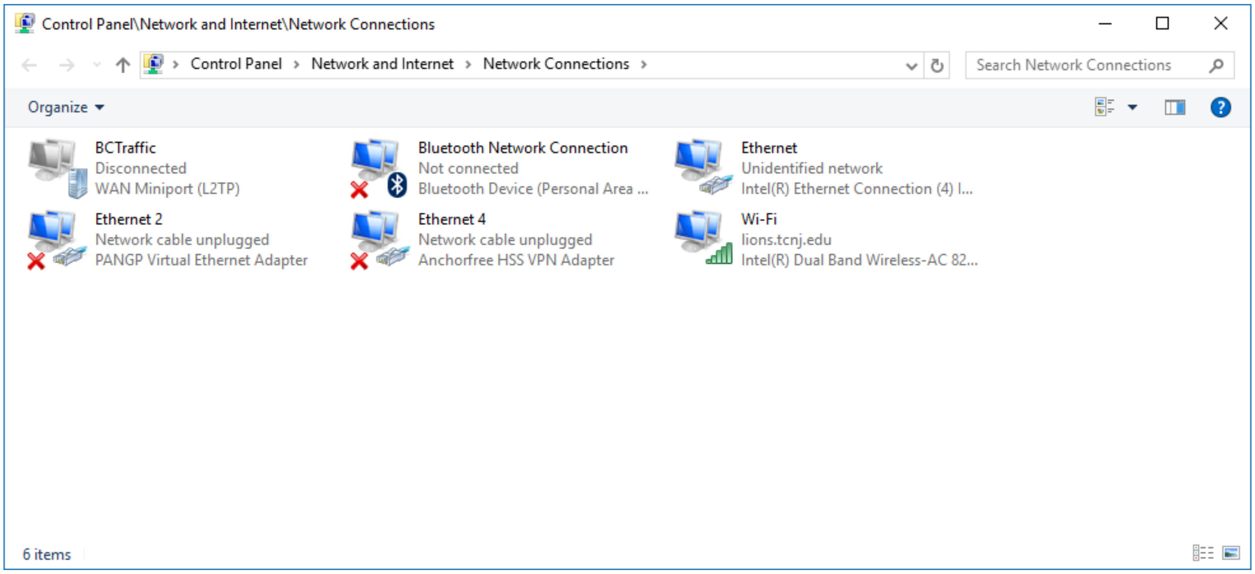


Figure 100. Ethernet Connection

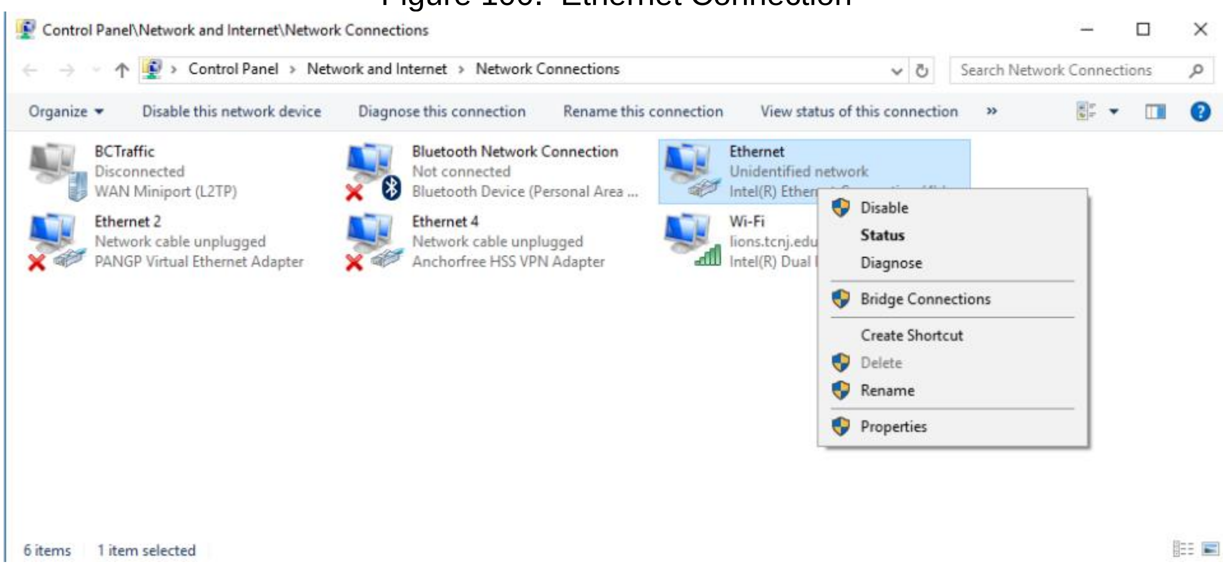


Figure 101. Adjust Properties

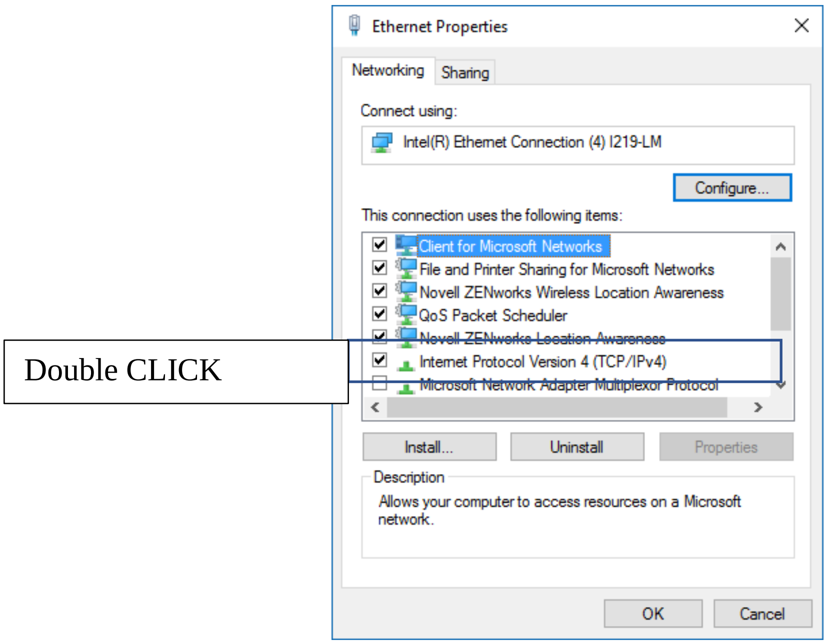


Figure 102. Select Properties for Internet Protocol Version 4 (TCP/IPv4)

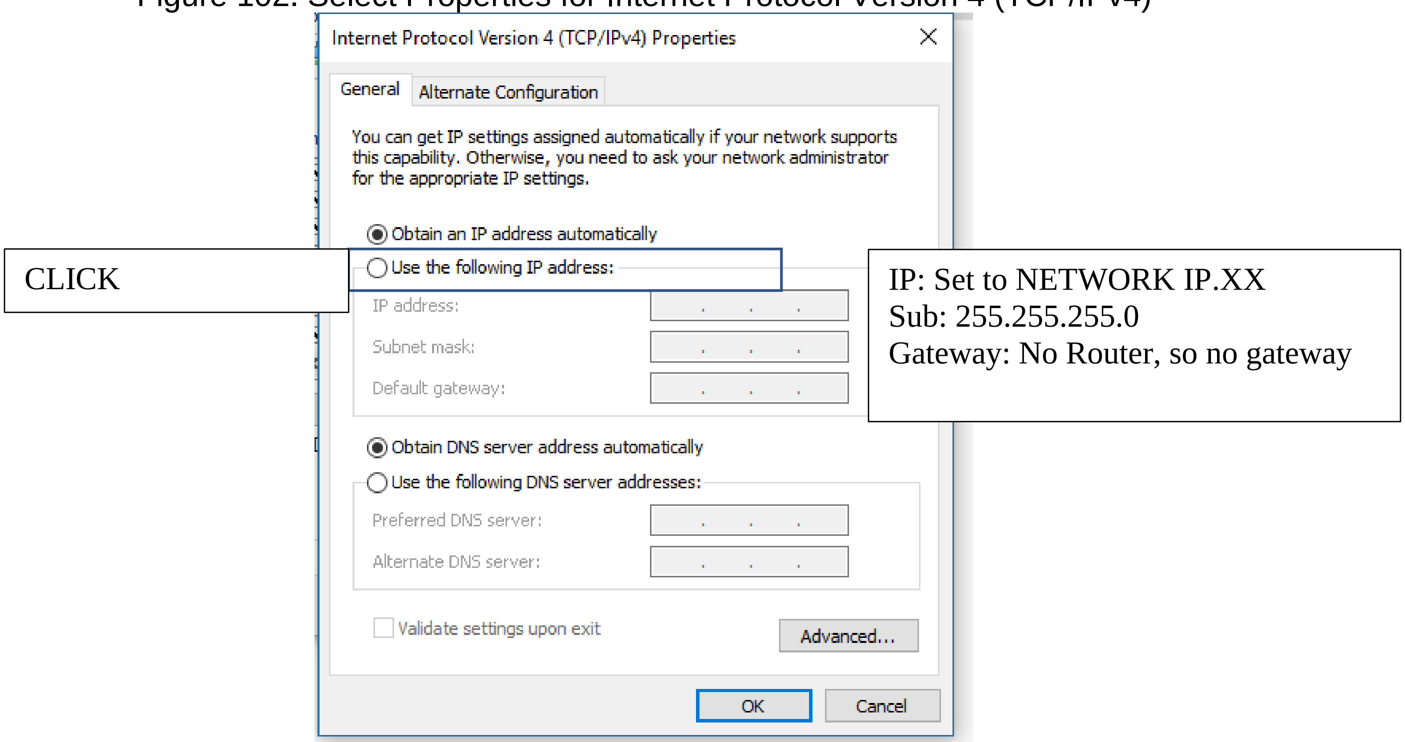


Figure 103. The IP address needs to be set for the laptop. 'Use the following IP Address.'

Once Internet Protocol Version 4 (TCP/IPv4) has the new IP address that matches either the default RSU or network IP, you **must hit okay** to set the laptop IP. Once this is completed, the laptop's initial network scheme has been configured. The RSU should be able to be 'pinged,' which can be done by opening up a DOS Command Prompt and typing the word PING followed by a space and the RSU's IP address, Figure 104.

Figure 104. Command Prompt to 'ping' RSU

The next step is to configure the controller and RSU's to the network. **<u>You must ensure all antennas and wires are attached to the unit before powering on an RSU unit.</u>** Each of these different pieces of hardware will have a unique process defined under the specific hardware direction. When connecting directly to the RSU, the default IP address will be needed (e.g., **Siemens's default IP is 172.24.4.254**). The RSU <u>can be reassigned to the appropriate network</u> (this is discussed in the RSU specific section. However, the laptop will need to be reset to match the network configurations (not the default RSU) to communicate with an RSU that is now configured for the network. In summary, you need to have your laptop talk with the RSU on the same IP network, reset the RSU IP to a new network, and reset the laptop to the new IP network. Go to the RSU setup for additional information:

RSU Network Configuration

- Trafficcast
  - Note, Trafficcast requires firefox for its interface.
- Siemens

Siemens <u>does not have a cellular connection</u> and therefore requires a direct connection to the RSU via CAT6/5 (See network setup). If out of the box, the RSU will have a pre-defined default address that needs to be changed to the new network. You must ensure all antennas and wires are attached to the unit before powering it on. The layout of the RSU unit from box to assembly is shown in Figure 105 - Figure 117.

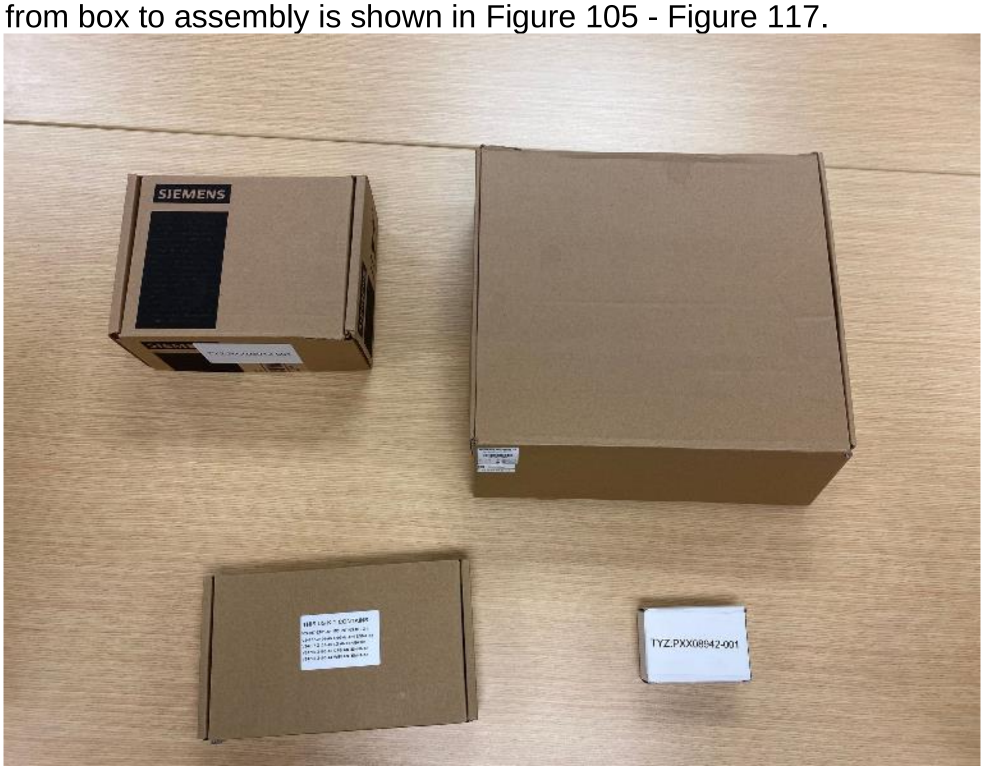


Figure 105. Siemens in the box

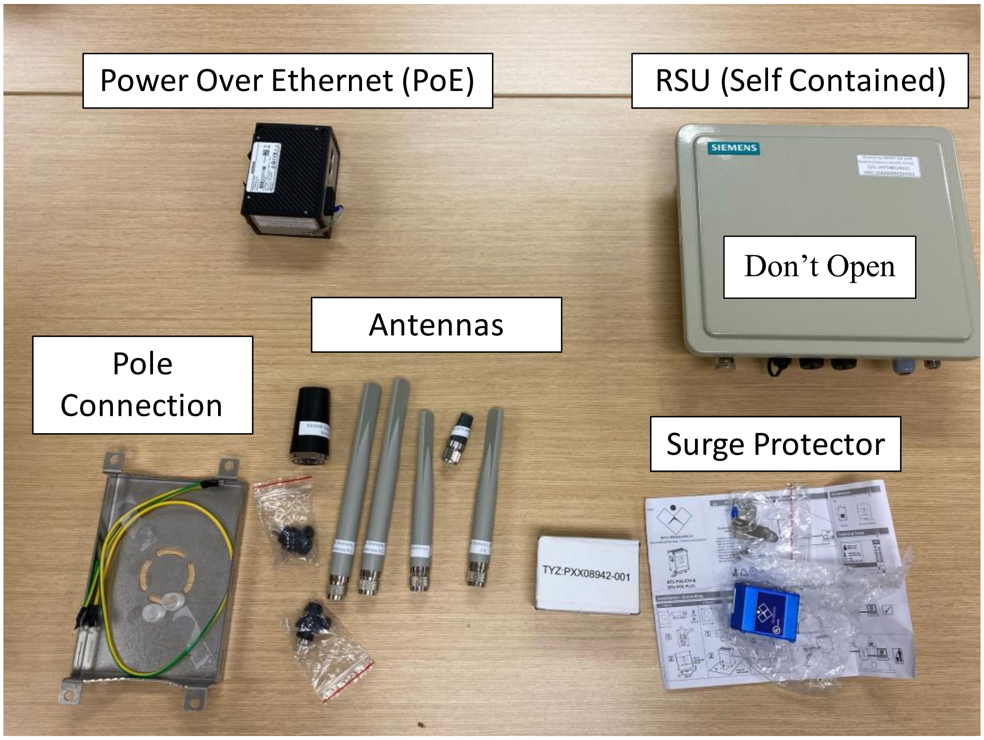


Figure 106. Siemens out of the box

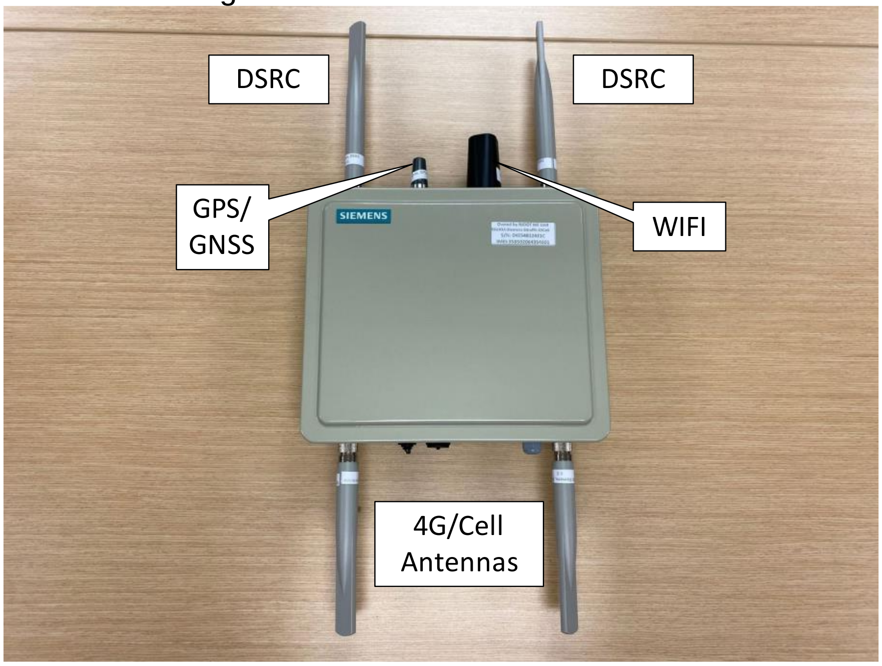


Figure 107. Assembled RSU

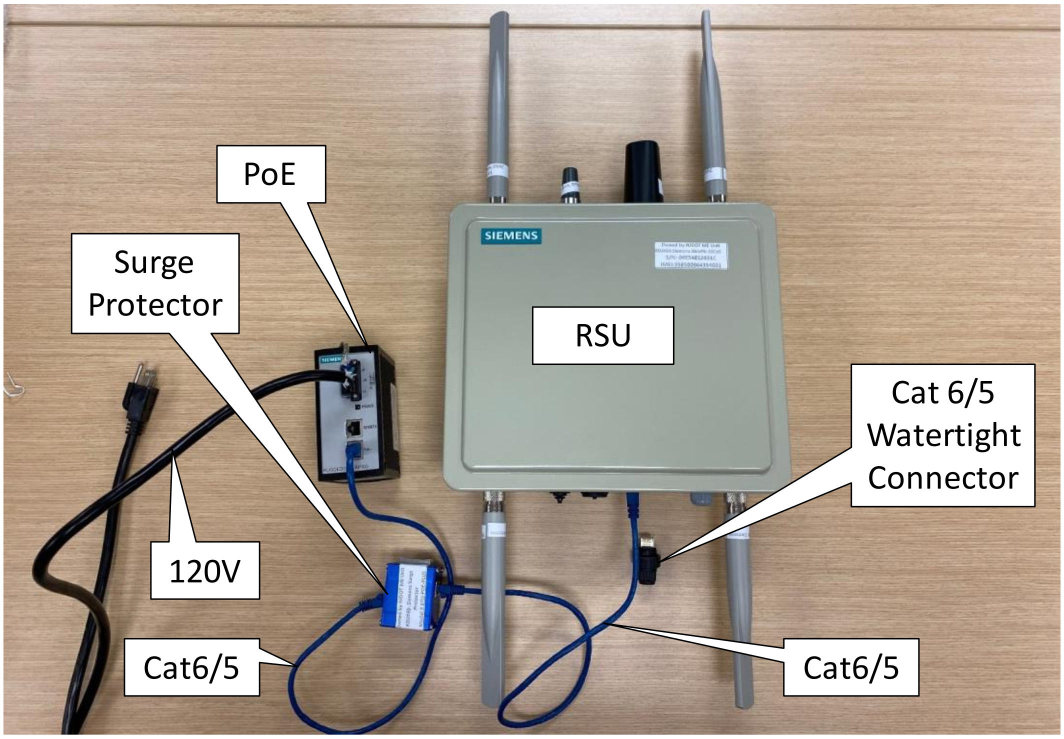


Figure 108. Setup of RSU connections

The Wire Power Supply is 120V to PoE. To power on the Siemens RSU, the connection for power is as follows:

Power (120V) à PoE Injector à Cat6/5 à Surge Protector à Cat6/5 à RSU

The Cat 6/5 connector to Siemens needs to be a watertight connector in the Field. A close-up picture of the connections and RSU on the button is shown in Figure 109.

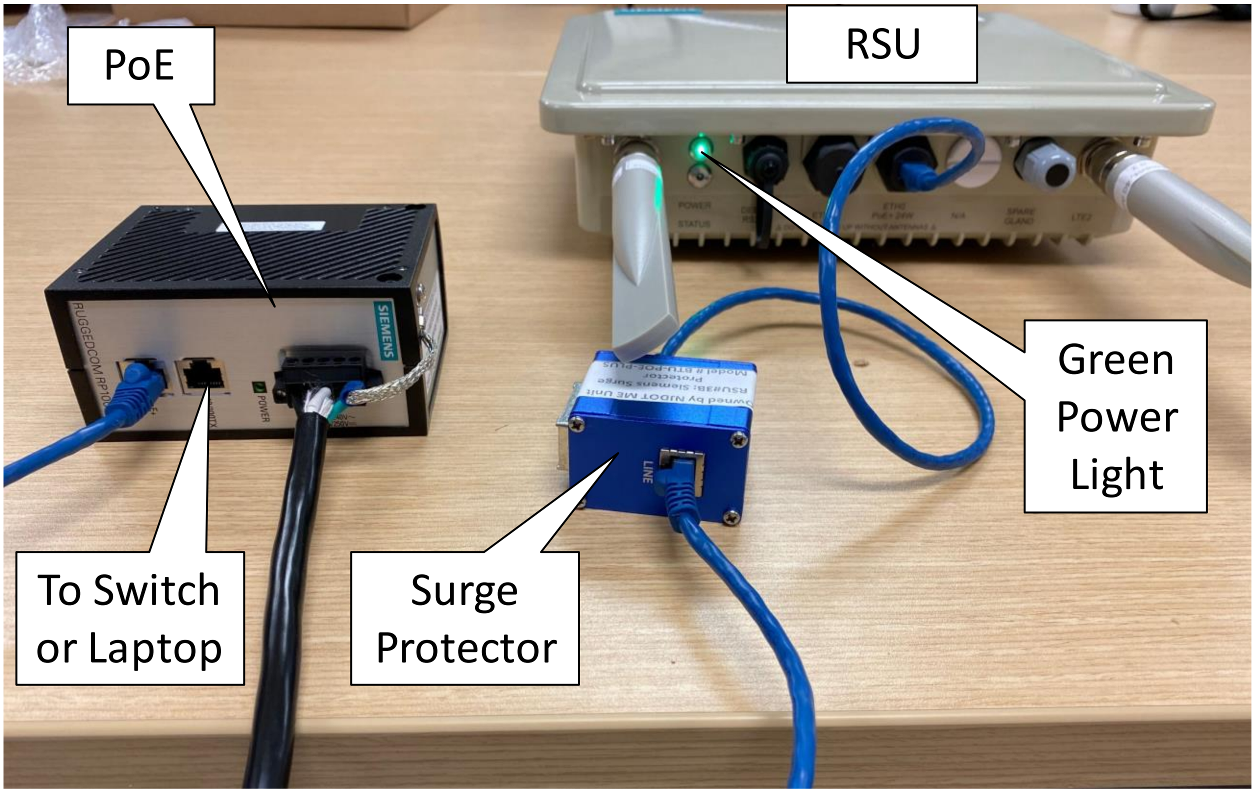


Figure 109. RSU powered up (Max 300’ Cat 6 in the field)

The Siemens unit is configured via web GUI, so all modifications must be done locally with CAT5/6 cable as outlined in the initial network setup. Connect the laptop via Ethernet to the POE OR network; again, make sure the laptop, with Ethernet port, is set to the appropriate address. Siemens does not have DHCP.

Use a browser (not internet explorer, preferred Chrome/Firefox) to access the RSU GUI by typing in the default Siemens IP address – 172.24.5.254 or 172.24.5.254: 4443. **(IF IT IS ALREADY SET FOR A NETWORK, THEN USE THAT NEW IP)** See Figure 110, which shows the Siemens GUI when first putting the IP address in the browser.

Default login credentials – Username “admin” Password – “**T_JKFM;5qH**”

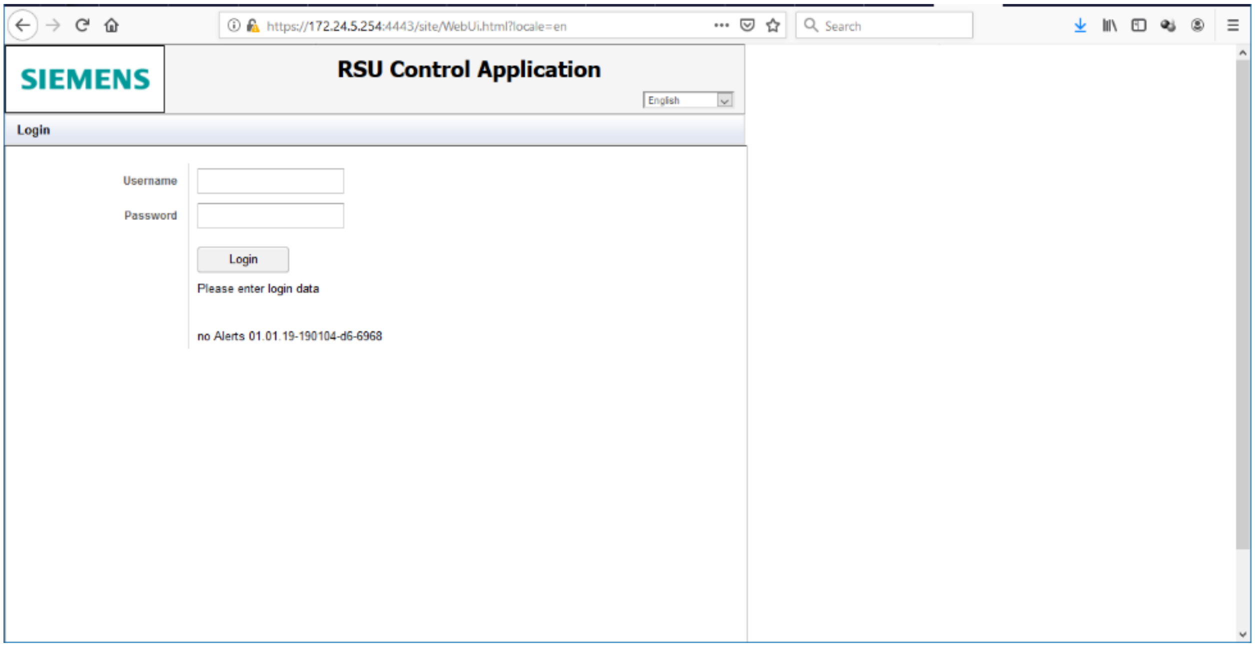


Figure 110. Siemens GUI

After successful login, the entire web GUI should be displayed (Figure 111). Make sure firmware is updated. Navigate to the "Network or Settings" tab and then "Wired Interface" (Figure 96). Input the IP address information for the configured local network (this may be defined for OIT). After inputting and applying these settings, reboot the unit. To confirm new settings, navigate back to the web GUI (Figure 97 with a new IP address) using the newly input IP address. (This would require the laptop to have its IP network reconfigured to regain access to RSU, re-do network settings)

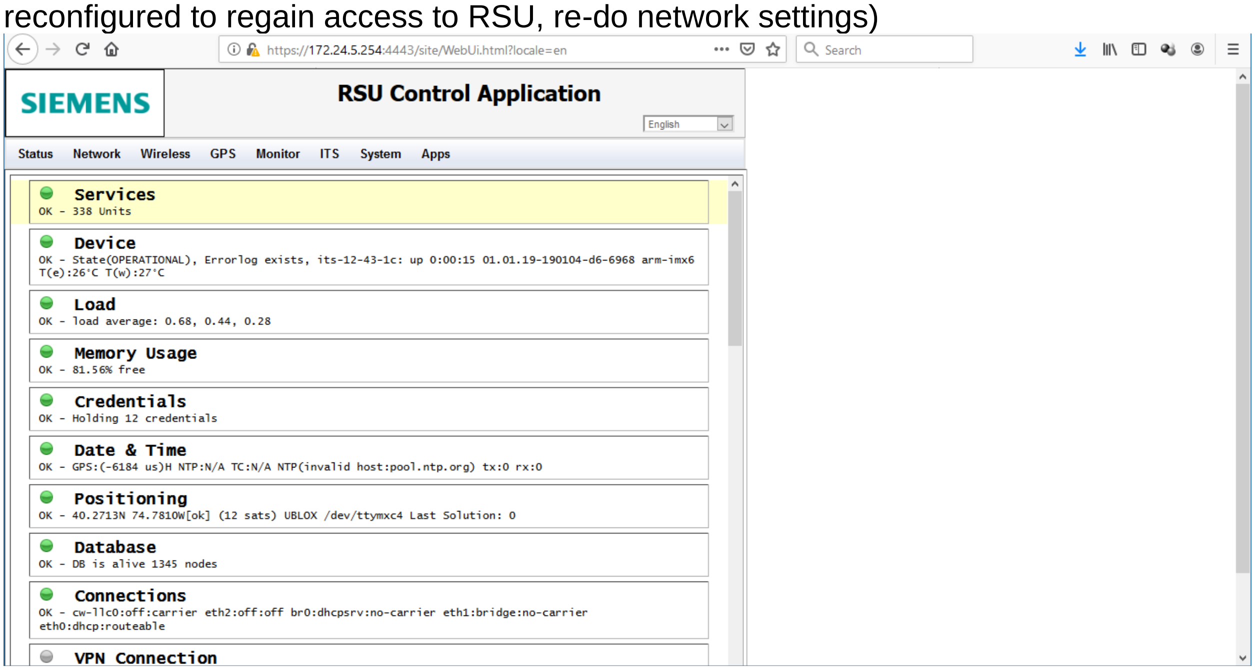


Figure 111. RSU services

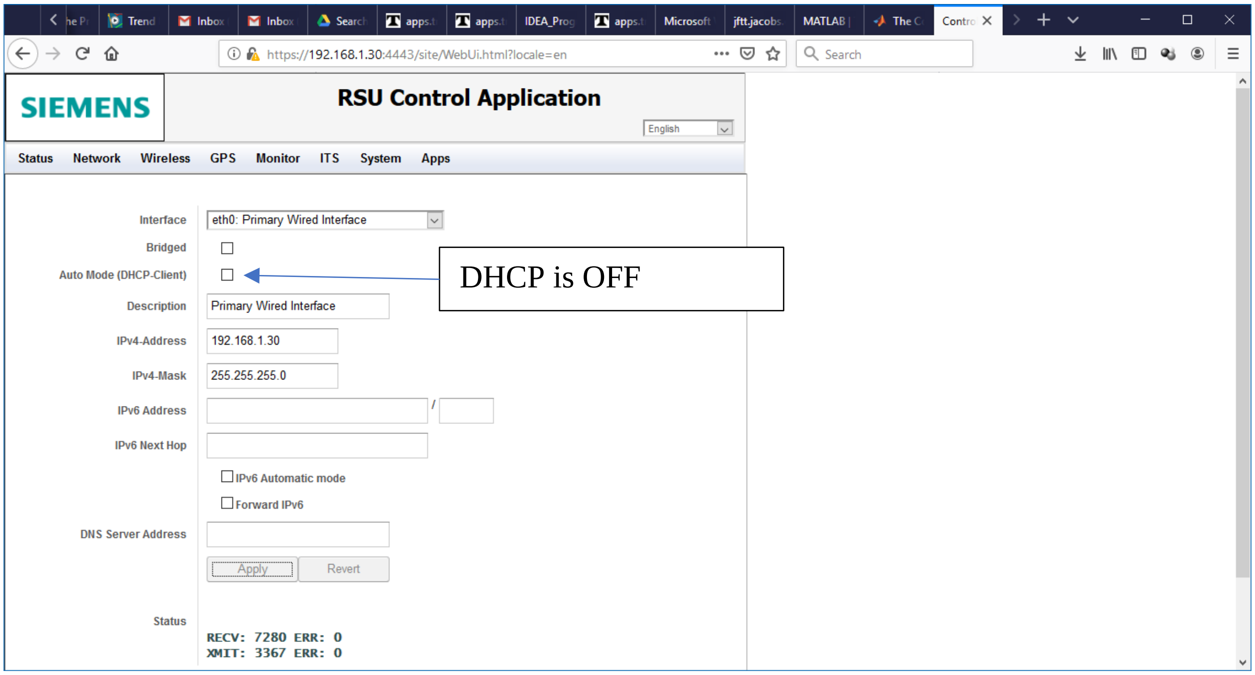


Figure 112. RSU IP Settings

In Figure 97, make sure Auto Mode **DHCP – CLIENT** is off:

After configuring network settings, configure to controller settings (Later on); for now, we are, and input desired settings. To activate MAP/SPaT output, a MAP message will need to be uploaded to the unit using the '**SPaT/MAP extension'** under the "APPS" tab. An XML file is required for the 'Map Upload' (contractor to make XML map message, from this site: https://webapp2.connectedvcs.com/). The files are shown in Figure 98. The GUI should say "MAP message okay" if this has been appropriately configured. Also, confirm under the "Status" tab that the MAP/SPaT indicator is green and active (Figure 99). It will only be green if connected to a controller via a switch. It will be yellow otherwise. In this case, the controller still needs to be set up. An Econolite COBALT controller was used for this example.

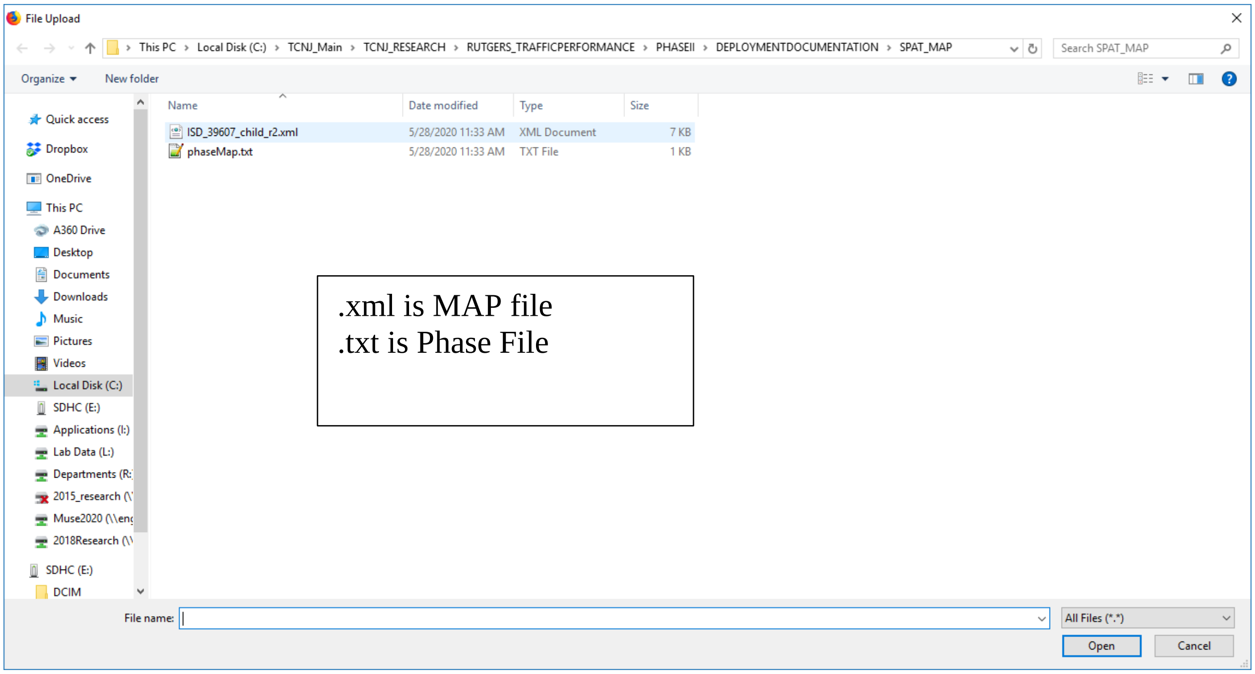


Figure 113. RSU XML

(txt is the translation between map message and timing, XML is map message)

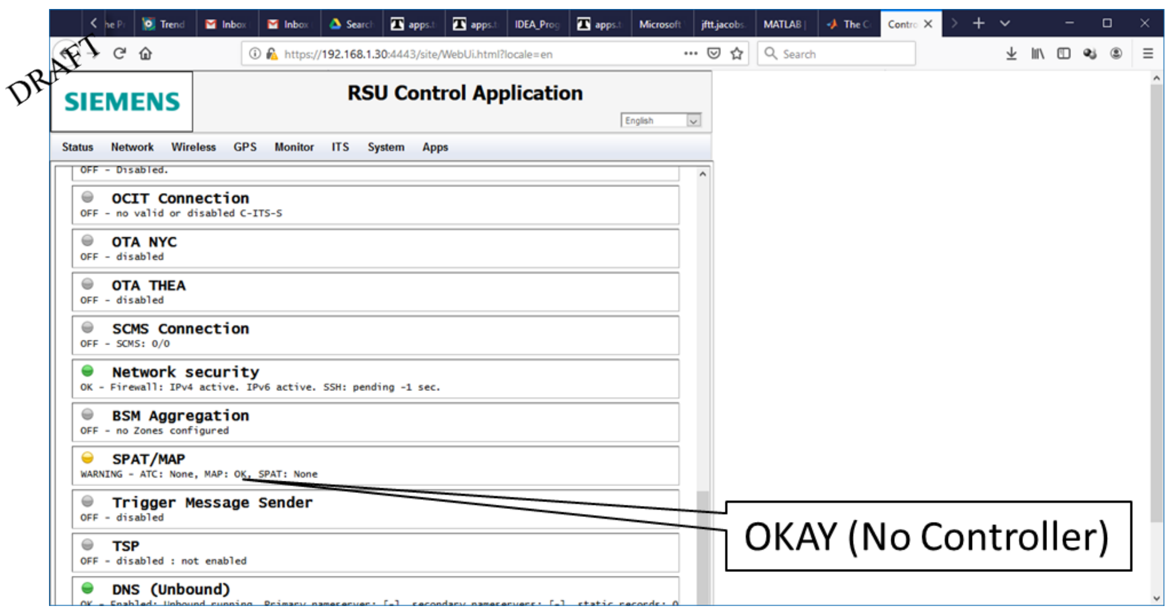


Figure 114. RSU setup, but no controller set with MAP message

The IF controller has not been set up. The controller needs to be paired with the RSU. It should have been completed, and the SPAT/MAP should be green. Make sure it is set to controller type (in Apps/ SPAT). It will communicate with the Controller on TCP Port 6053 in this example. The controller is set to 6053 by default for Cobalt; others may allow this to change (Figure 100). Note that Status will not show info w/o controller.

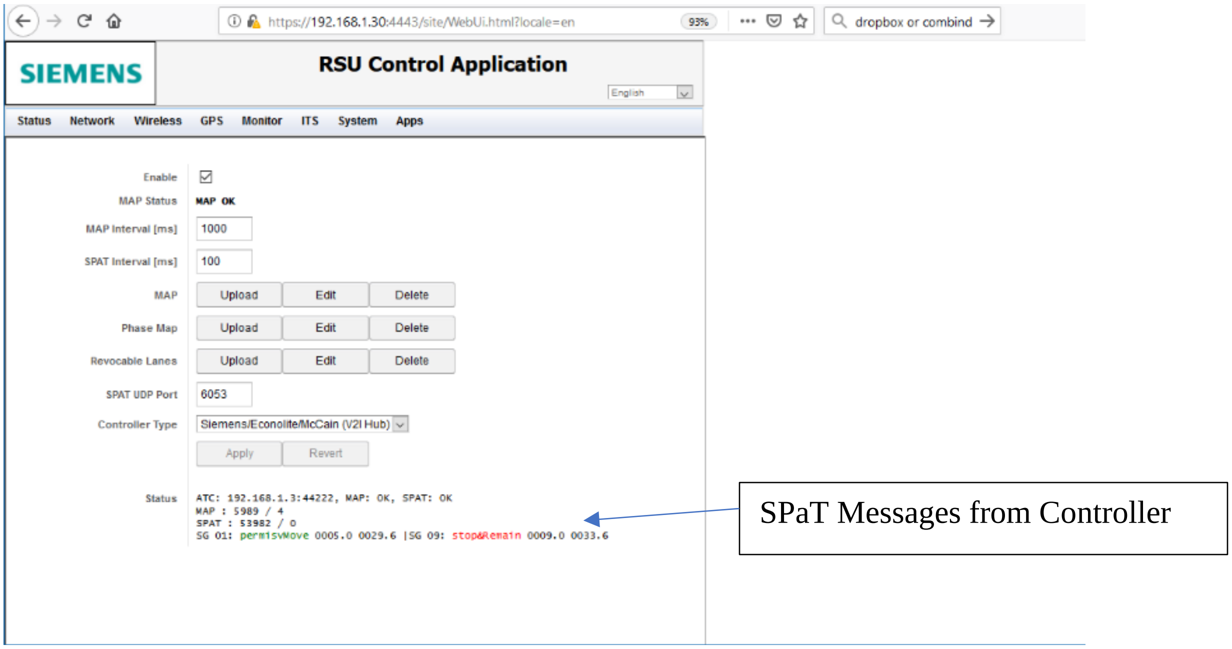


Figure 115. SPAT/MAP messages (MOVE IN ORDER)

Under APPs, the port needs to be set to the standard communication port under the controller. In the Cobalt controller being used, this port needs to be set to 501. The manufacturer's communication port would need to be known (Figure 101). Make sure the address on this screen matches the controller IP.

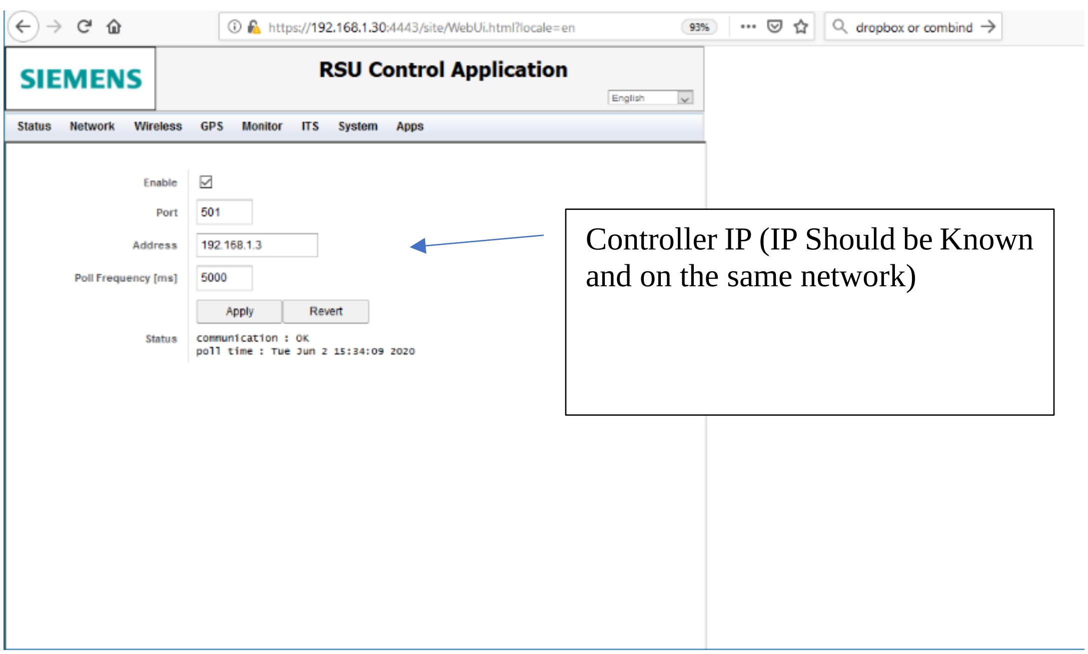


Figure 116. RSU Controller Configuration

If this has been appropriately configured, the RSU should now be outputting SPaT/MAP messages to any OBU in the area, and Figure 102 will show the green 'OK' under SPAT/MAP.

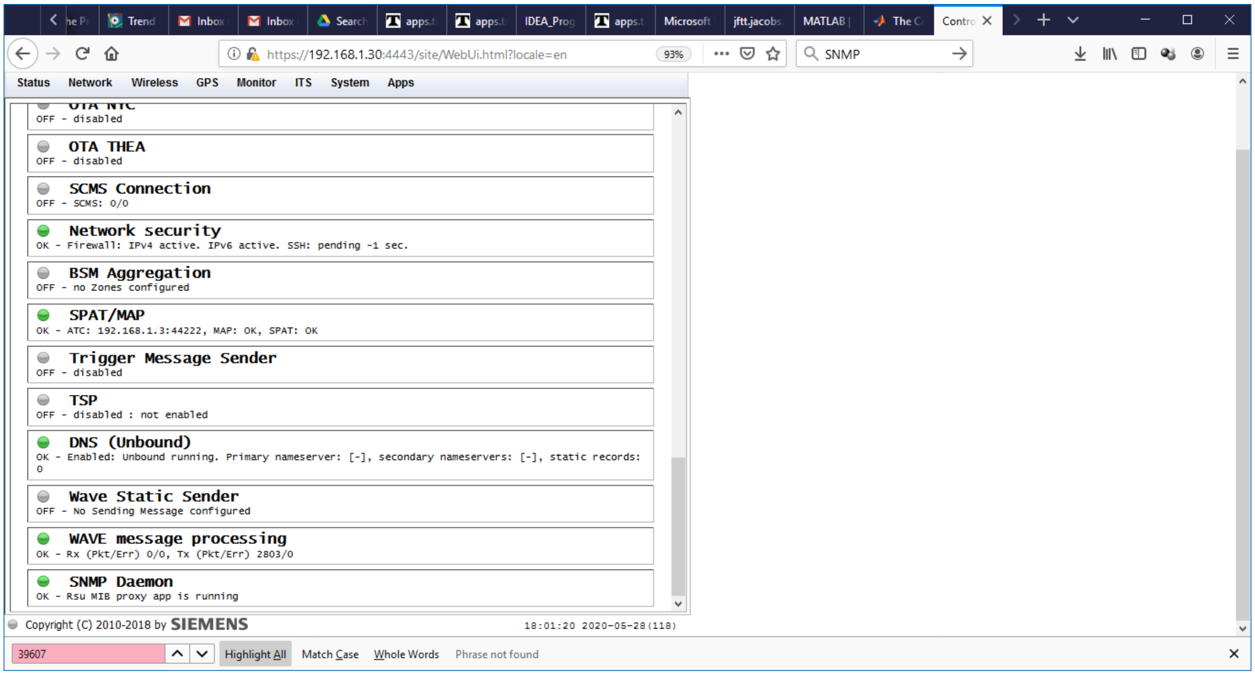


Figure 117. SPAT/MAP green, messages being sent

Please consult the hardware manual and contact the system administrator for additional support and/or support from Siemens directly. Reboot the RSU.

OBU Configuration and Testing

The team has extensively worked on OBU lab testing tasks. Over the past year, the team reviewed the functionalities of several OBU devices available in the market. Based on the functions, services, integrated V2X application, compatibility with V2X architecture standards, pricing, and flexibility of future application development and scope of the project, the team acquired the Commsignia OBU-Kit-D for both DSRC/5G and C-V2X for further field testing. To be specific, the team worked on the following tasks. The detailed information for each task is provided in the following sections:

- SCMS registration
- OBU configuration based on US region
- Establishing the connectivity between the OBU and foresight application on the tablet
- Establishing the connectivity between the OBU and laptop for visualizing and recording SPAT, MAP, and BSM data
- Installation of Commsignia capture-app-3.0.0, and replayapp- 1.6.2 application
- Preparing Python code to automated connectivity, record, and visualize the logger data from OBU in real-time.

SCMS Registration

V2X is a technology that permits vehicles to communicate with each other and their adjacent traffic infrastructure to transmit safety, positioning, and traffic efficiency associated information. This technology is established on dispersed communication

between OBU and RSU that communicate and receive standardized signals over IEEE 802.11p or Cellular V2X radio channels. As for the network security of the communication between OBU and RSU, the security module, certificate loader module, and pseudonymity module are the core process layers for securely transmitting the encrypted information between V2Xs. SCMS management is a prominent role in validating and generating pseudonym certificates over a secure interface.
As part of the SCMS registration, the team worked with NJDOT and Integrity Security Services (ISS) to register the OBU device and create the SignedEeEnrollmentCertRequest enrollment certificate. To create an enrollment certificate, the team generated several pieces of information using Python code to fulfill the requirements of creating an OER file, which is the significant component for generating the SignedEeEnrollmentCertRequest enrollment certificate. Volume II of this report provides all the step-by-step information for creating the OER file and the Python code to generate several pieces of information.

Configuration of OBU for the US Region
OBU devices are delivered with default configurations that are not compatible with any region. Additionally, devices require firmware updates periodically for better performance. In this task, the team used the Commsignia device manual and followed the steps to configure the devices for the US region and update their firmware. A step-by-step procedure followed by the team is provided in Volume II. These configurations steps give a default backup configuration set on the device that is fully compliant with US regional V2X standards. Usually, this configuration is a starting point for debugging purposes, and any custom changes planned to modify in future application development.

Established Connectivity Between the OBU and Tablet Foresight HMI Application
Along with the OBU and RSU devices, the kit-D also provides a tablet that can be used to access the live maps for the connected V2X devices and other transmitted information (e.g., speed, position, and elevation). As part of this task, the team installed the Commsignia Foresight HMI SDK on the tablet and connected the OBU device with the application. Foresight HMI provides essential information during the testing, but it has a limitation that requires extensive work for better performance. Figure 118 shows the connectivity process between OBU and Foresight HMI applications.

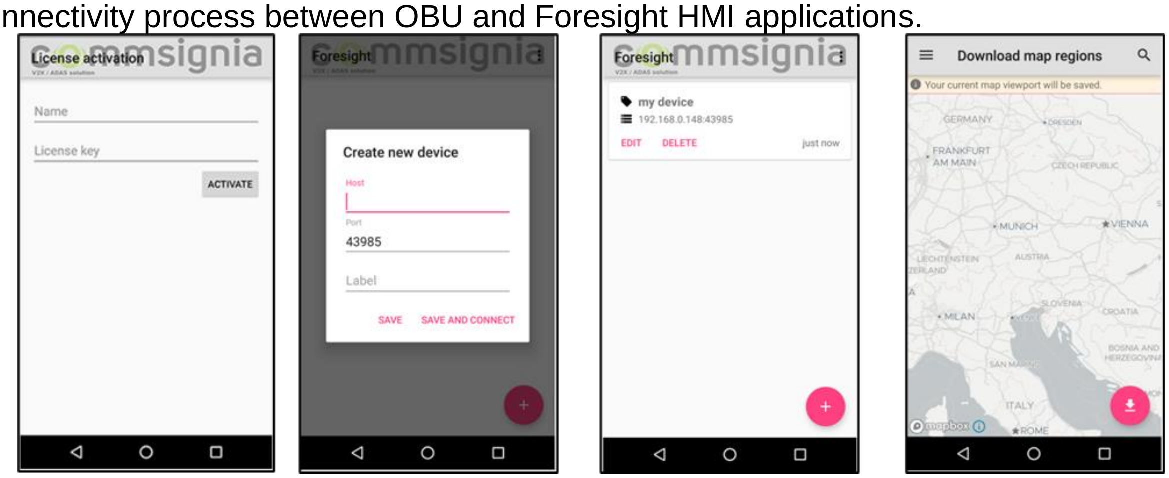


Figure 118. OBU and Foresight HMI application connectivity process

Established Connectivity Between the OBU and Laptop

Establishing connectivity between the OBU and a computational device is a core prerequisite based on the project's requirements. Connectivity with laptops provides several opportunities, including extracting logger data, customizing data requests, and validating with other data types, i.e., GPS or Mobiapp data. As part of this work, initially, the team used PuTTY to provide commands for configuring the data recoding framework and enabling the recording services for BSM, MAP and SPaT data. Please check the procedure in Volume II for details.

Installation and configuration of Commsignia Application

Once the recording is completed, and the data is stored locally, a couple of Commsignia applications, i.e., the Capture app and the Replay app., were used for visualizing and converting the data. In this task, the team installed both the applications, configured them based on the OBU specifications, and tested converting the recorded data. The procedure in Volume II was followed.

OBU and RSU Field Data Collection

The team has conducted data collection to test the applications of the NJDOT project to 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 data collation location is at US-1 at Bakers Basin Road.

Table 25. Data Collected from Existing ITS Infrastructure:

Data Item	**Live/Offline**	**Applications**
CCTV Traffic Video	Live/Offline 511NJ Website	Run real-time trajectory extraction. Plan A: Deep learning/YOLOV5 + Coordinate Transformation + BSM on-behalf (Ryhan) Plan B: Scanline extraction
SCATS Signal Event	Offline AMC	
Autoscope Data	Live/Online	Turn on detector status recording.
CV RSU MAP/SpaT/BSM Message - OBU	Live Roadside	Commsignia OBU-Tablet + Laptop application (Python access code)
ATSPM Data	Offline	Configure the intersection in ATSPM

Table 26. Data Collected with Additional Roadside/Onboard Instruments

Data Item	**Onside Equipment**	**Application**
Roadside Video	GoPro 9 + Smartbox (Pointing North) Mounted on a temporary pole	* Detection of pixel trajectories * Coordinate Transformation * Conversion to BSM/Dynamic Map (TIM)/Nearmiss Alerts
Roadside High-Resolution Velodyne LiDAR	Velodyne 128-Beam Tripods + BlueCity	* BlueCity Edge Compute => Dual Mode * VeloView Archiving

		* Python Archiving
In-Vehicle DashCam/GPS Log Video	3 Dashcam Videos	SmartMobi App
In-Vehicle LiDAR	Velodyne VLP-32 Terry	Mobile LiDAR data processing
Inrix Travel Time Data	XD Data	

With NJ DOT ATSPM 2.0 pilot testing and deployment now up and running, the data is obtained from the field-deployed intersection located within OIT. The setup is reflected in Figure 119, but the live feed is not active currently. Example/Field data from CISCO is obtained in the first few weeks of February to evaluate the existing ATSPM to use alternative detection data to identify vehicles, peds, etc., within the ATSPM performance metric suite. In addition, all intersections on the TCNJ bench (Figure 120) have been updated to include a virtual detector to monitor INRIX prove vehicle speed but still require SCATs data to run the performance metric on the ATSPM.

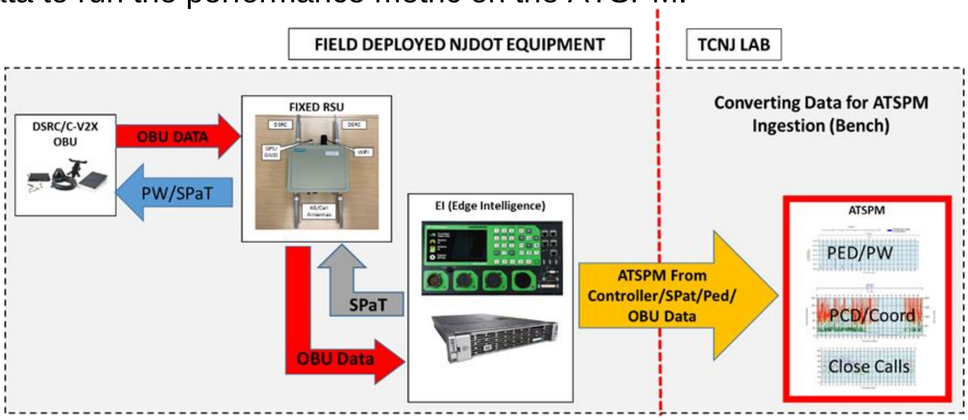


Figure 119. Field Data Collection Setup

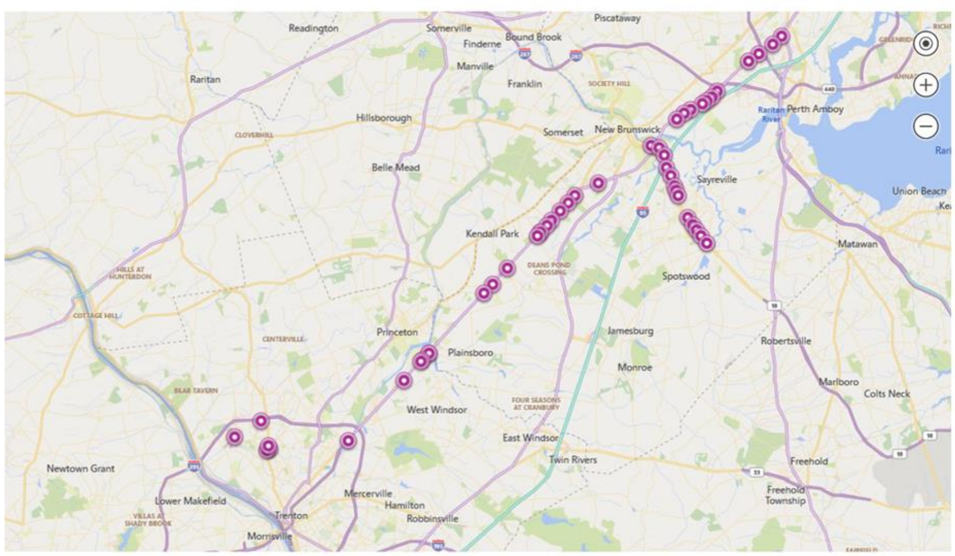


Figure 120. ATSPM Signals Set up at TCNJ

Automation for the Connectivity, Recoding, and Visualizing the Data transition in Real-time

Lastly, due to the complexity of the process of connectivity of OBU device to laptop and data recording and extracting, the team developed a Python script to automate the whole process, as shown in Volume II.

TASK 6: NJDOT ATSPM 2.0 PILOT TESTING AND DEPLOYMENT

Database and Interface Setup

The team has created a mirror system to test the C sharp (C#) configuration with SCATS data. The database connection between C# deployment and the pre-built ATSPM database server has been created. Python environment has been built to translate the SCATS data and import it to the SQL Server Database. The logo has been altered with Rutgers/NJDOT logo.

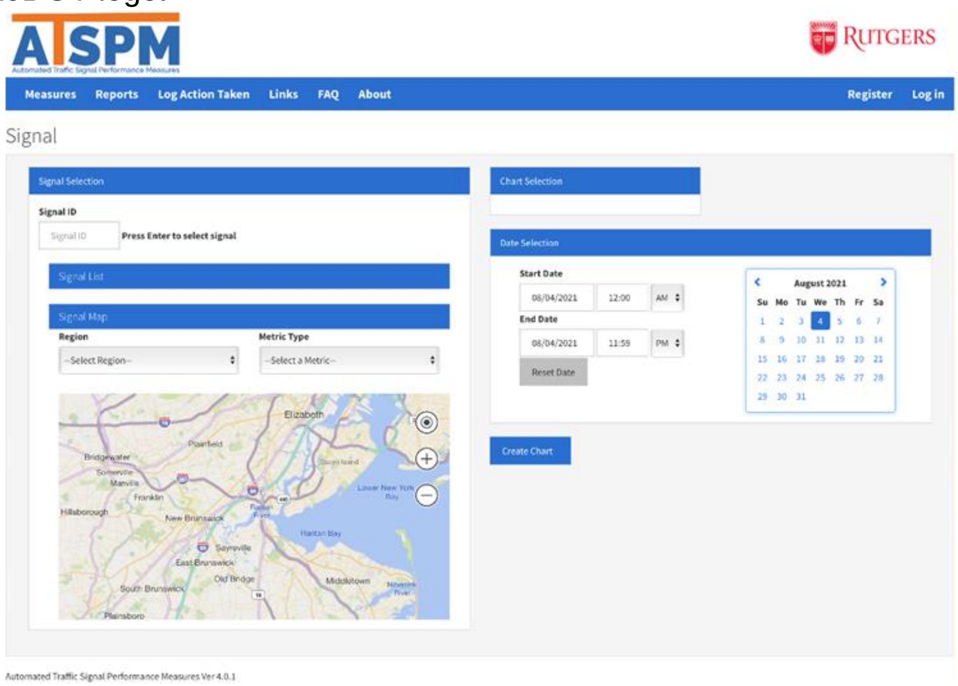


Figure 121. Screenshot of ATSPM interface

The project team successfully access the servers belonging to the NJDOT OIT that is ready to deploy ATSPMs. The team has deployed an automated archiving program to store SCATS history files every 15 minutes. Windows scheduler is used to start the automatic archiving program at midnight, and the python program then runs 24 hours till a new archiving session is started for the next day.

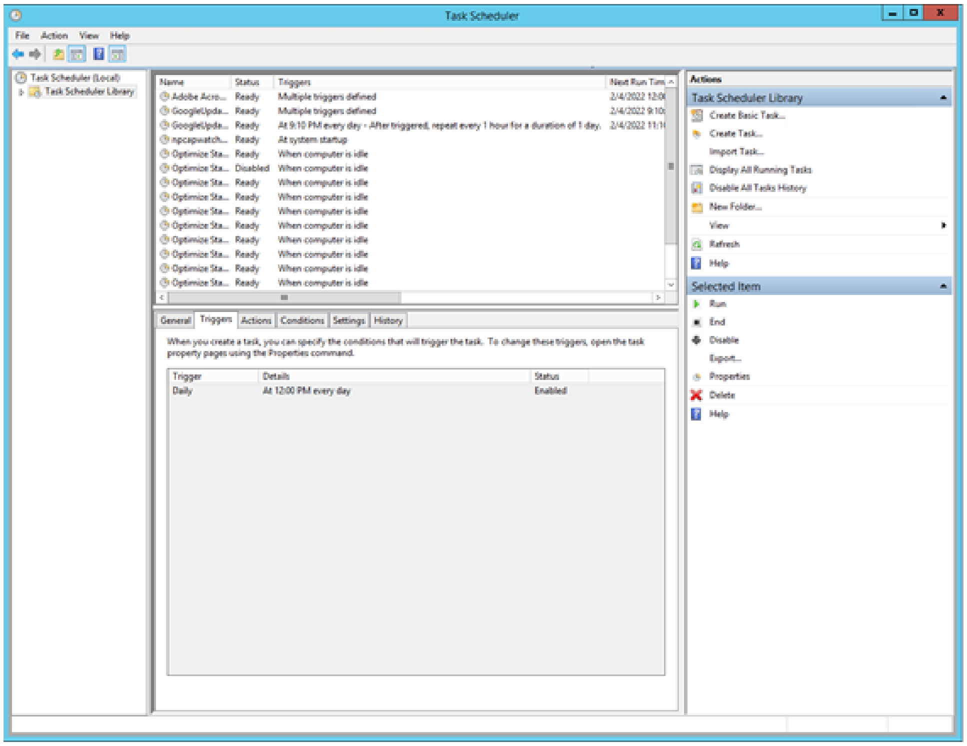


Figure 122. Screenshot of Task Scheduler for Archiving Data

In addition, the teams finished an auto Archiving tool for executing the command line. This program is executable using a batch file and triggered daily. Every 15 minutes, the program updates the history files with new data. A file structure system for the generated files was built on the SCATS server.

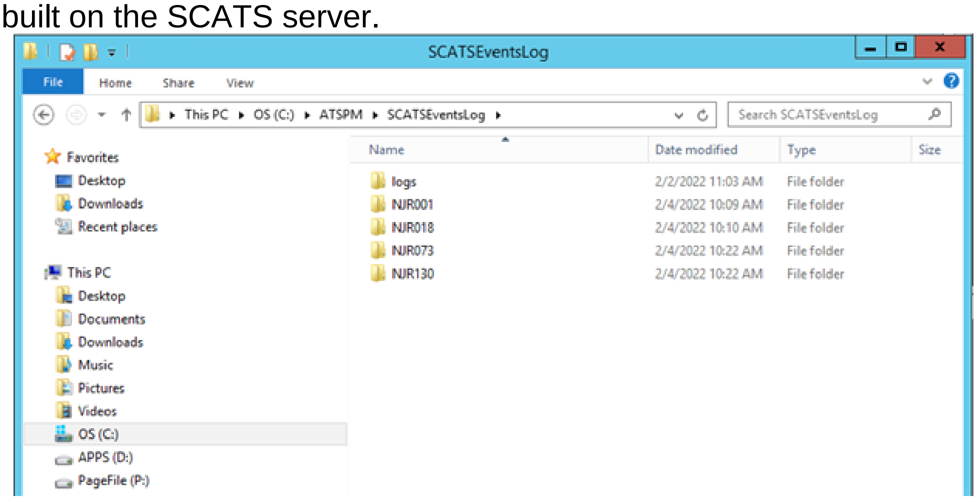


Figure 123. Screenshot of folder Containing Different Regions

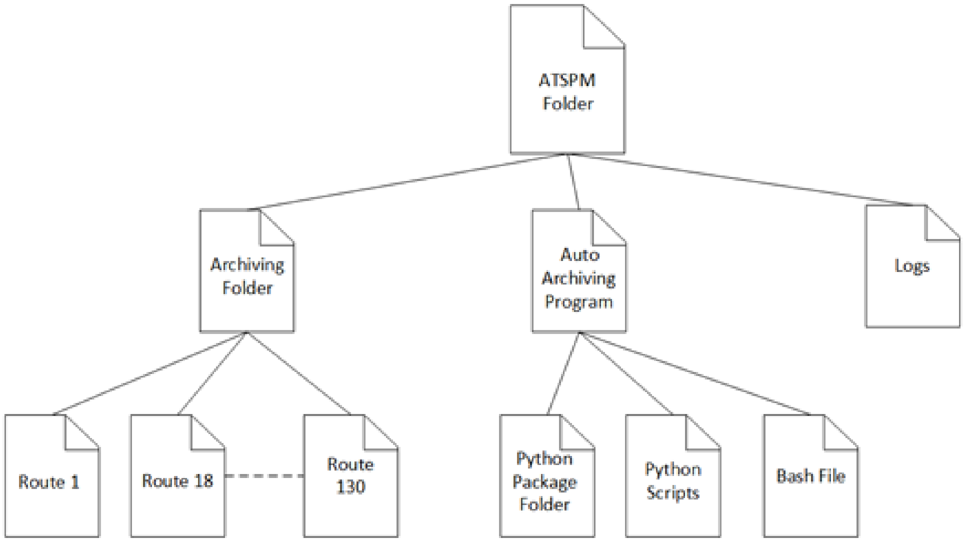


Figure 124. Conceptual ATSPM File Architecture on SCATS Server

All the ATSPMs installation packages were downloaded and stored on the application testing server.

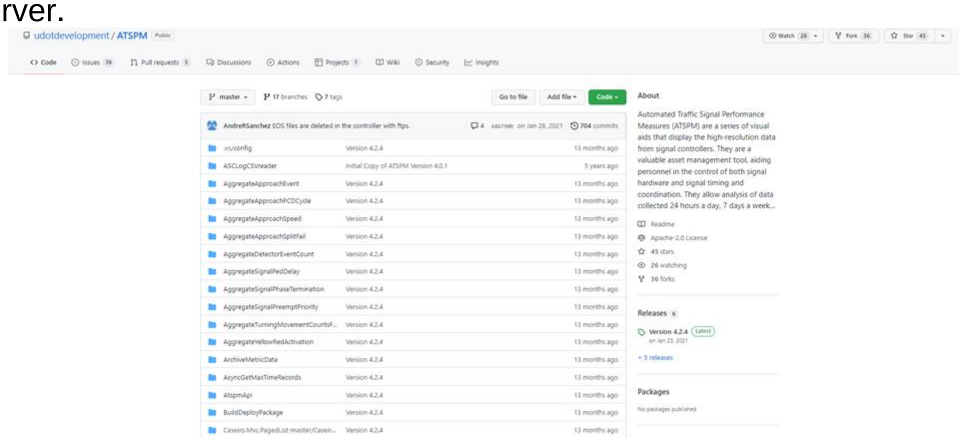


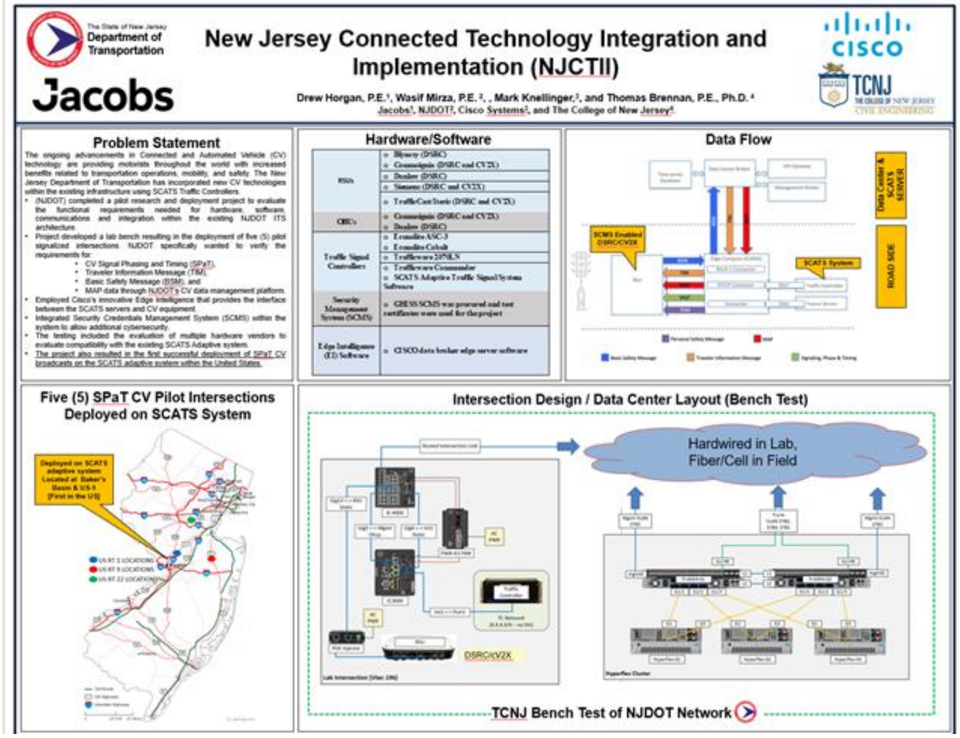
Figure 125. Github Utah DOT Package

Table 27 shows the detailed installation status summary

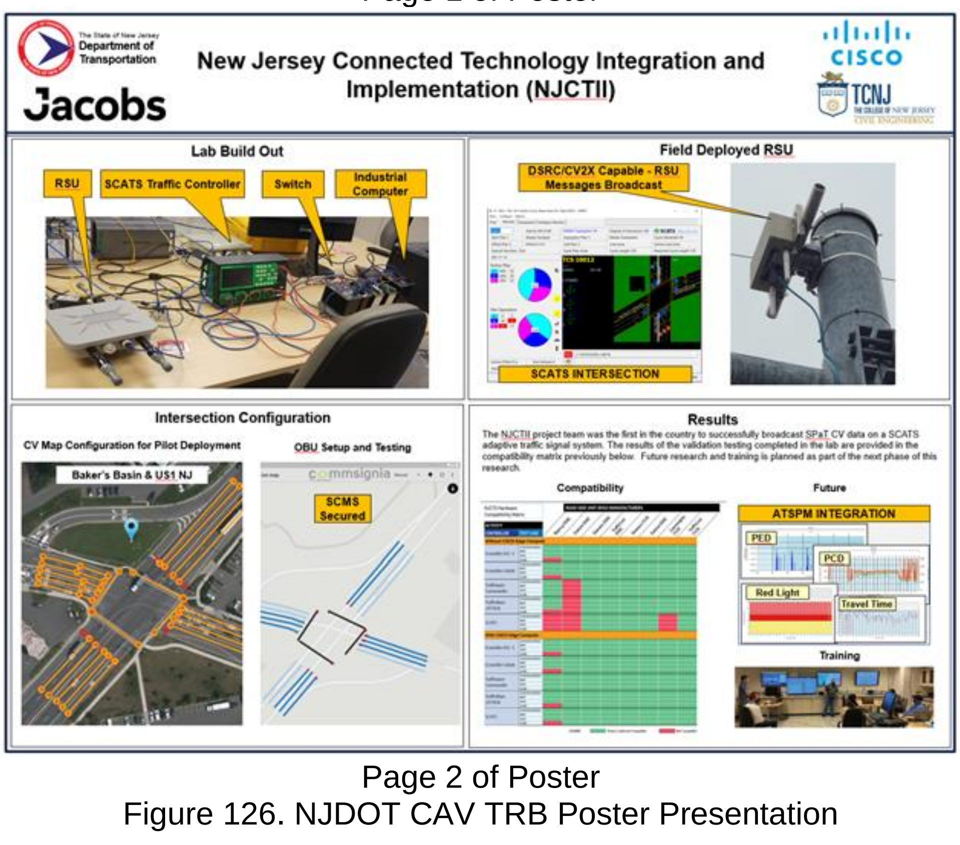
Table 27. ATSPM Installation and Configuration Status

Package Name	Verizon	Status	Current Server	Target Server and Pending Issues
SQL Server Database	1.1	Pre-Installed	Application Test Server/ OIT Database Server	To be installed directly on OIT Database Server, you need a user/password to login to the server or OIT SQL Server database.
SQL Server Management Studio	1.1	Pre-Installed	Application Test Server	To be installed on the production application server, you need the account/password of the OIT SQL Server database
IIS 7	1.1	Pre-installed	Application Test Server	To be installed on the webserver
.NET 4.7.2	1.1	Pre-installed	Application Test Server	To be installed on the webserver
Website	2.1	Pre-Installing	Application Test Server	SPMImage Folder not created yet To be installed on the webserver
Launch the website and populate the database	2.2	Not installed	Application Test Server	Unable to connect to Database
Database configuration	2.3-2.5	Not installed	Application Test Server	No usable database is available
"Generate Add Data Script" Component	2.6	Not installed	Application Test Server	
Web Services	2.7	Not installed	Application Test Server	
GIS Services (Bing)		Not installed	Application Test Server	

The pilot deployment of the CV technology was documented in a paper submitted to the Transportation Research Board Meeting on January 9 – 13, 2022. The poster presented is shown in Figure 126, and the paper can be provided as needed. That data from this intersection is being implemented in Task 4 to evaluate the captured data's ability in the ATSPM.



Page 1 of Poster



Page 2 of Poster

Figure 126. NJDOT CAV TRB Poster Presentation

TASK 7: ATSC CAV APPLICATION DEVELOPMENT AND PILOT TESTING

Vehicle and Pedestrian Sensing

Camera Video Object Sensing and Tracking

The team used Rowan's Safety Analytics tool to detect and track road users' trajectories in real-time from video data. Rowan's Safety Analytics tool is artificial intelligence (AI)-based video analytic tool that integrates a real-time AI detection model - YOLO-v5 with a tracking framework based on the DeepSORT algorithm. High-resolution video data was collected by mounting a GoPro Hero 9 at a US-1 and Bakers Basin Road intersection to extract and validate results from the tool. Table 28 provides a sample of the output file from Rowan's Safety Analytics tool.

Table 28. Sample Video Trajectory Data from the Rowan Safety Analytics tool.

Id	Frame Number	Speed (MPH)	Pixel-X	Pixel-Y	Class	Video Time	Start	End
48	9	6	2380	821	car	00:00:00:299	East	South
48	10	7	2361	820	car	00:00:00:333	East	South
48	11	7	2345	816	car	00:00:00:366	East	South
48	12	7	2327	813	car	00:00:00:399	East	South
48	13	8	2308	809	car	00:00:00:433	East	South
48	14	7	2292	805	car	00:00:00:466	East	South
48	15	7	2273	805	car	00:00:00:499	East	South
48	16	6	2257	803	car	00:00:00:533	East	South
402	375	20	2556	483	truck	00:00:12:12498	East	North
402	376	22	2557	483	truck	00:00:12:12532	East	North
402	377	23	2559	482	truck	00:00:12:12565	East	North
402	378	25	2560	482	truck	00:00:12:12598	East	North
402	379	26	2561	482	truck	00:00:12:12632	East	North
402	380	28	2562	482	truck	00:00:12:12665	East	North
402	381	29	2564	481	truck	00:00:12:12698	East	North
402	382	31	2565	481	truck	00:00:12:12732	East	North

Real-time AI detection model - YOLO-v5 is working with pre-trained COCO data that processes frame-by-frame analysis to detect the selected classes in the frame. After detecting the objects in the frame, the model creates a bounding box around the object. It passes the extracted information to the further algorithm pipeline, where DeepSORT compares the information obtained from the detected object with the previous frames and assigns ID accordingly. Figure 127 shows several detected and tracked road users from Rowan's Safety Analytics tool at the intersection.

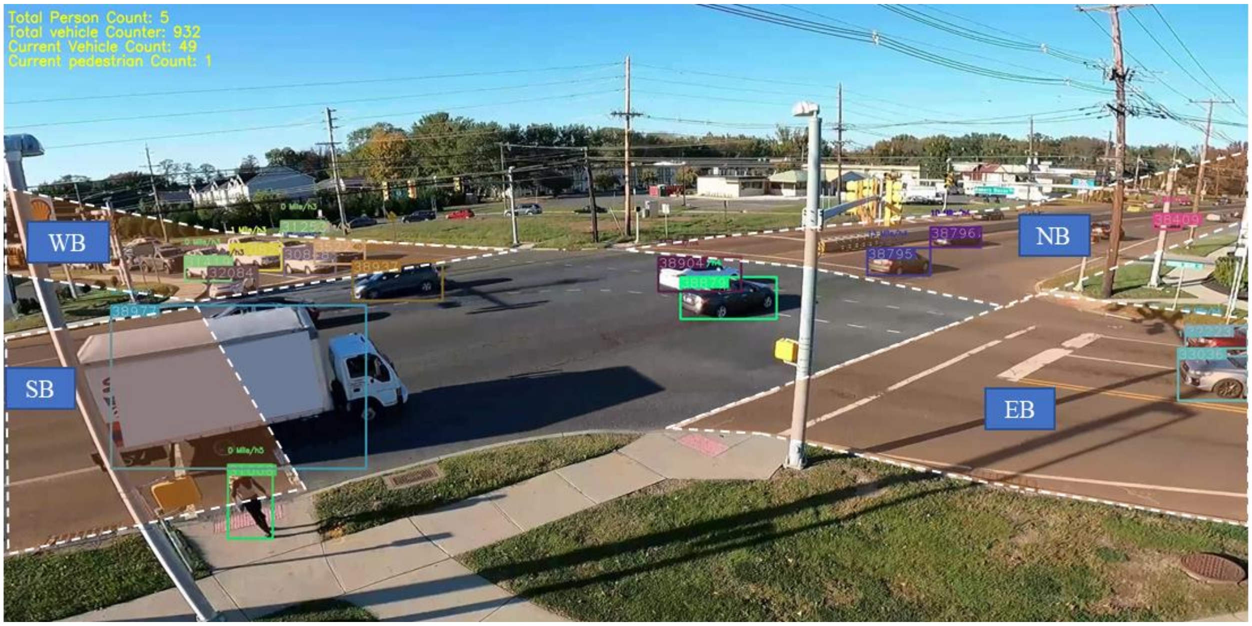


Figure 127. Sample of Road Users Detection Results

Figure 128 pictures the trajectories of all road users tracked from the 15 minutes of a video. Where green, blue, yellow, and pink lines represent cars, trucks, buses, and pedestrians, respectively.

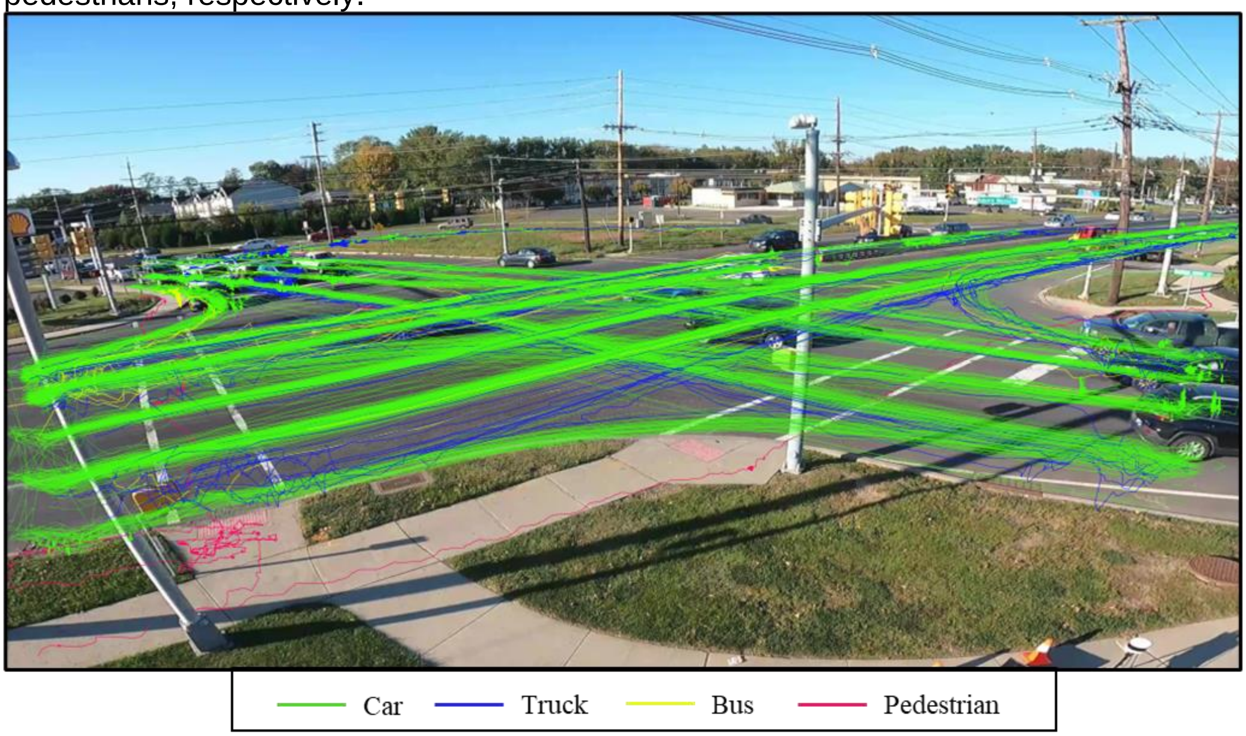


Figure 128. Sample of Road User's Trajectory Results

Furthermore, the team manually watched 15 minutes of the video and compared the results to evaluate the model's accuracy. Table 29 shows the relative accuracy and error by comparing the detected and manual counts values. Based on the result, the vehicles initially tracked in the West, East, and South showed more vehicles than the manual count, demonstrating an error of 0.07, 0.20, and 0.18, respectively. However, the North detected fewer vehicles than the manual count, showing an error of 0.07. Overall, it was observed that the detection and tracking algorithm used in the study showed an error of 0.09 percent.

Table 29. Detection and Tracking Accuracy Results

Start Direction	Detected Counts	Manual Count	Accuracy	Error
North	382	409	0.93	0.07
South	513	433	1.18	0.18
East	253	211	1.20	0.20
West	205	191	1.07	0.07
Total	1353	1244	1.09	0.09

LiDAR Object Detection and Tracking

The team investigated the Robot Operating System (ROS) platform and implemented the Object Detection and Tracking Algorithm to detect vehicles and pedestrians in real-time. Collected LiDAR Data at the US-1 and Bakers Basin Road intersection are tested with existing algorithms. The detection workflow includes the following steps referenced from the open-source autonomous vehicle project named Autoware:

1. Ground Removal: distinguish ground points from non-ground points in point clouds. It is meant to act as a filtering step for object detection algorithms (working on non-ground points). This method is speedy and allows the filtered point cloud to be exposed while the packets for a scan are still coming in.
2. Point Clustering: Euclidean Clustering method is used to group points into clusters. For any two points in a cluster, there is a chain of points within that cluster between both points such that the projected distance between subsequent points in the chain is less than some threshold. The clusters will then form a convex hull, deemed as objects, to be used for the object tracking module.
3. Object Tracking (Arya Senna Abdul Rachman, A.,2017): The tracker utilizes three combined Bayesian filters (IMM-UK-JPDAF) that simultaneously tackle association and motion uncertainties and estimate the non-linear stochastic motion model in real-time. Logic-based rule filters are also designed to augment the rest of the detection and tracking based on understanding LiDAR sensor limitation and occlusion characteristics.

Table 30 provides a sample result of an object detected through LiDAR data, with corresponding information in three dimensions x, y, and z.

Table 30. Sample Object Trajectory Results

Position	Orientation	Dimensions	Velocity	Acceleration
x: -4.71524333954 y: -153.051574707 z: -0.481797099113	x: 0.0 y: 0.0 z: -0.4361401220 w: 0.899878766251	x: 8.51323413849 y: 21.3012943268 z: 1.52672076225	linear: x: 0.0 y: 0.0 z: 0.0 angular: x: 0.0 y: 0.0 z: 0.0	linear: x: 0.0 y: 0.1 z: 0.0 angular: x: 0.0 y: 0.0 z: 0.0

Figure 129 visualizes the detection results from in the ROS platform, where red, yellow, and green points form concentric circles at the bottom. The LiDAR sensor uses the 128-beam Velodyne, located 3 meters away from the roadside of the intersection and around 1.5 meters in height from the ground. Blue bounding boxes detect dynamic objects such as vehicles and pedestrians and static objects such as trees and medians. The detection results also provide position, velocity, and acceleration for the sensor's coordinates in three dimensions.

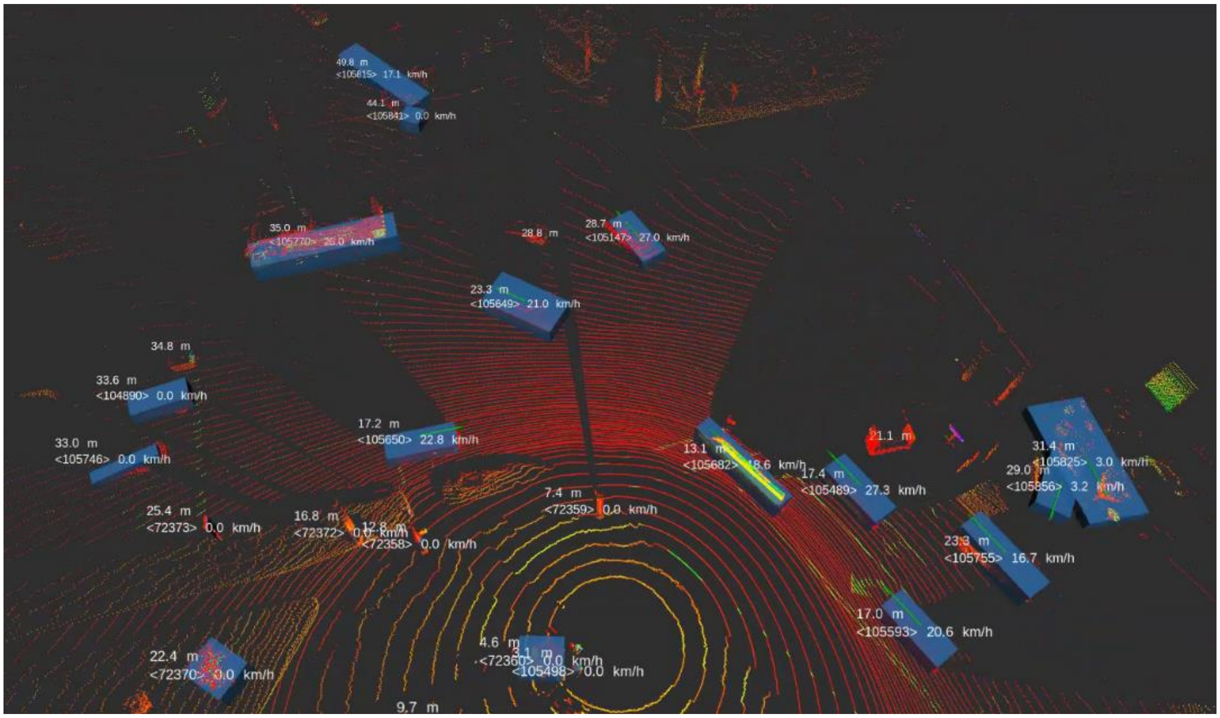


Figure 129. LiDAR Object Detection Results

From the vehicle moving trajectories quality perspective, the results provide position, vehicles, and acceleration of vehicles, yet the performances of Point Clustering highly impact it. The naïve Euclidean Clustering method can cluster two vehicles cling to each other as a single object or cluster a single tractor as two objects, which provides incorrect vehicle trajectories. Moreover, a single object in a particular frame can be split into multiple objects in the next few frames, creating a new object ID for those two split multiple objects.

The object detection accuracy closer to the LiDAR has much better accuracy as it provides a much denser point cloud, which is easier for the clustering method. For objects farther away from the sensor, their moving direction can be inaccurate because of the fluctuating bounding boxes caused by occlusions or sparse point clouds.

Three factors significantly impact detection accuracy: sensor height, object distance, and object types. Higher Sensor height and closer distance between object and sensor provide a more accurate detection accuracy with denser point cloud and fewer occlusions. As shown in Figure 130, occlusions from a large truck near the sensor lead to most vehicles in the intersection not being detected.

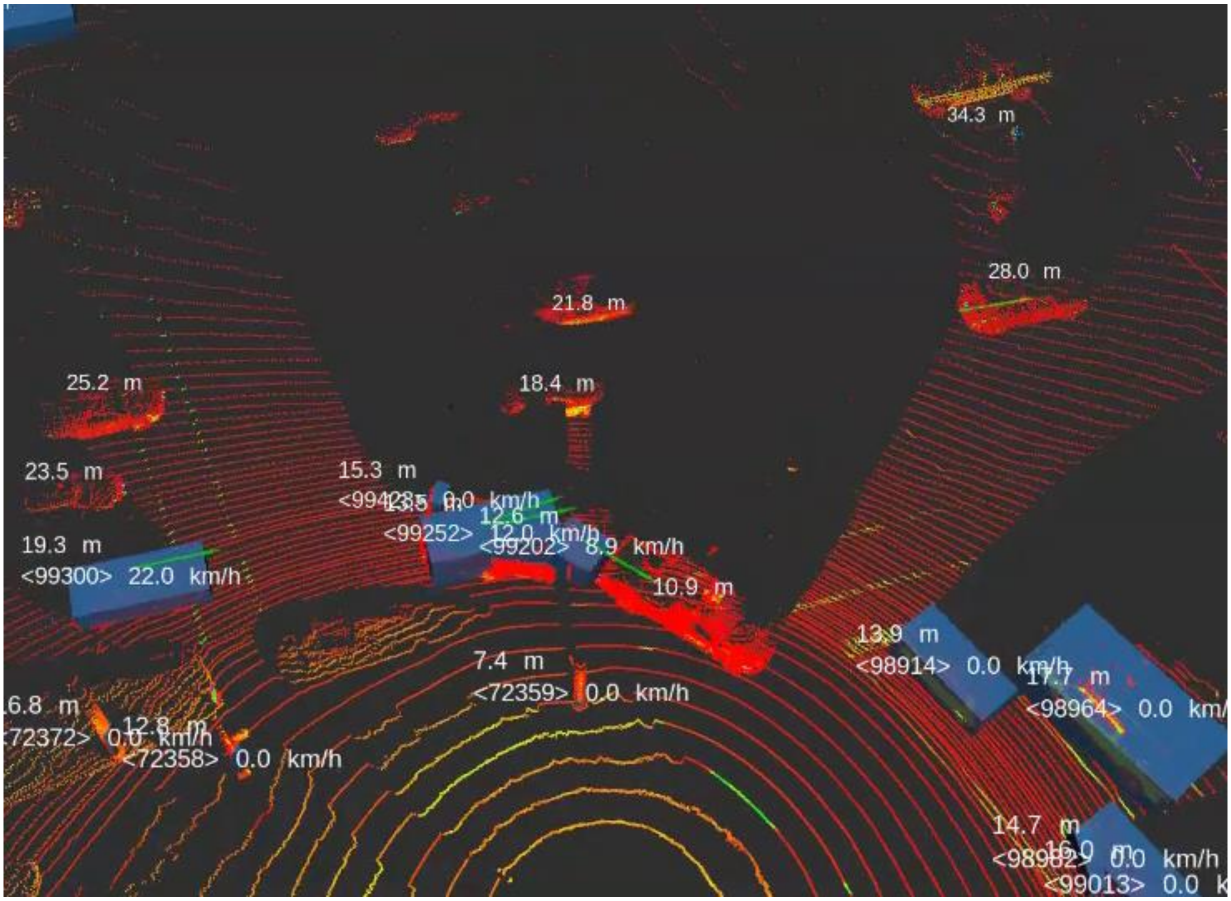


Figure 130. Object Detection Missing Caused by Occlusion

OBU Message Validation and Application Testing

Apart from the lab testing and the configuration, the team also tested the connectivity of the OBU with the existing RSU at US 1 and Bakers Basin Road intersection and collected filed data. BSM, MAP, and SPAT logger data and pcap data files were collected for 1-hour by driving the car with the installed OBU near the intersection. During the data collection, the team validated the functioning of the OBU by visualizing the vehicle's position on the Commsignia Foresight application on the tablet. Figure 131 shows the geo-position and the middle lane where the vehicle waits for the traffic light to turn green.

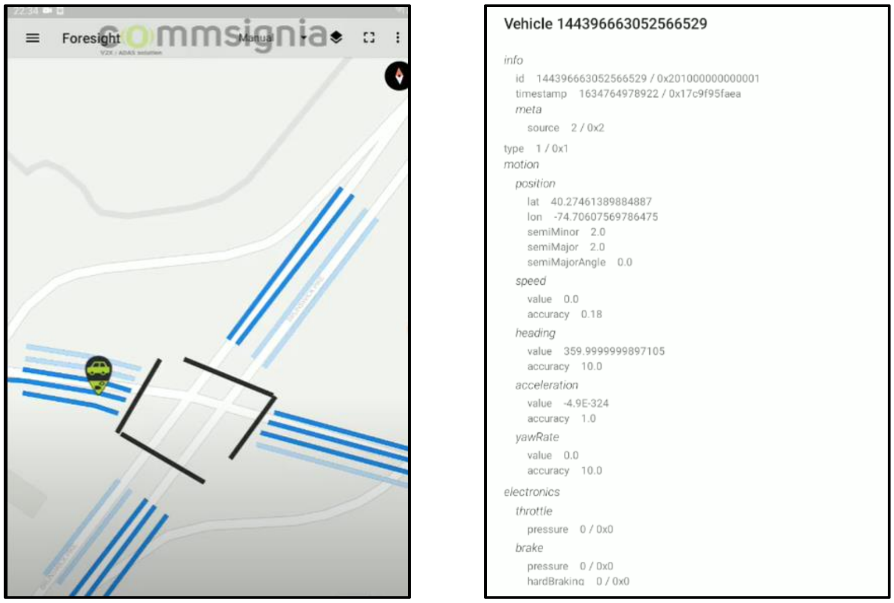


Figure 131.Validation Screenshots from the Commsignia Foresight application

Furthermore, the team also examined the BSM, MAP, and SPAT logger data and verified the recording process. It was identified that the logger files only provided the information about communication logs, not the actual BSM, MAP, or SPAT information. On the other hand, the pcap file enabled to be recorded data stored the encrypted files. Later, the files were decrypted using Commsignia’s capture app, and the geo-position of the vehicles was validated. Figure 132 shows the encrypted and the decrypted information from the Commsignias capture app.

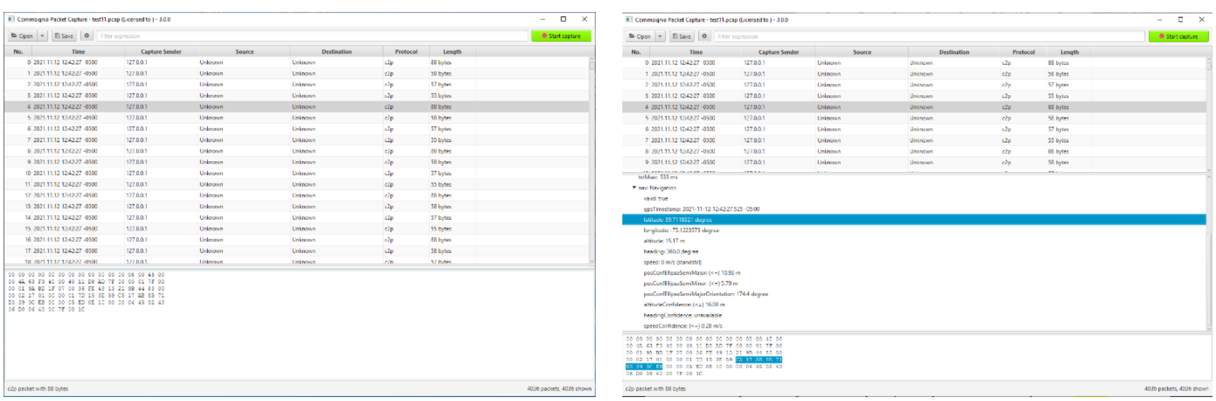


Figure 132. Validation Screenshots from the Commsignia Capture app

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