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New Brunswick Innovation Hub
Smart Mobility Testing Ground (SMTG)

FINAL REPORT

July 2024

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16. Abstract

In this project, the team led by Rutgers University's Center for Advanced Infrastructure and Transportation (CAIT), in collaboration with Iteris, Econsult Solutions, Gannett Fleming, and MBO Engineering, completed the construction and application deployment of the New Brunswick Innovation Hub Smart Mobility Testing Ground (SMTG), now named DataCity SMTG. The project instrumented 12 roadside locations along the Route 27 and Route 18 corridors to provide complete coverage of the 2.1-mile testing ground with self-driving grade sensing, computing, and Cellular Vehicle-to-Everything (C-V2X) technologies. The DataCity testing ground created a living laboratory environment to promote the research, development, and testing of smart mobility, Connected and Automated Vehicle technologies. DataCity provides four major services, including a technology proving ground for transportation agencies, a high-resolution smart mobility data hub, a digital twin platform to support early-stage research and development, open-road technology testing facilities, and community mobility applications for traffic safety application deployment and testing. DataCity is expected to promote the NJDOT's "Commitment to Communities" initiative and the FHWA's accelerated testing and deployment of V2X technologies.

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EXECUTIVE SUMMARY

Background

The New Brunswick Innovation Hub Smart Mobility Testing Ground (SMTG), now renamed as DataCity Smart Mobility Testing Ground (DataCity SMTG), as proposed by Rutgers University's Center for Advanced Infrastructure and Transportation (CAIT), established a living laboratory for smart mobility and smart city technology research and development (R&D) in downtown New Brunswick, New Jersey. The testing ground will serve as the foundational element of the New Brunswick Innovation Hub that will attract public and private sector researchers testing advanced driving system applications in real-world conditions while also serving as a source of high-resolution transportation data.

Echoing New Jersey Department of Transportation (NJDOT) Commissioner Diane Gutierrez-Scaccetti's vision on "Commitment to Communities," the DataCity SMTG team, consists of Rutgers CAIT, Middlesex County, City of New Brunswick, Iteris, Econsult Solutions, Gannett Fleming, and MBO Engineering, focuses on deploying equitable sensor-enriched Cellular Vehicle-to-Everything (C-V2X) safety applications (e.g., requiring no more than a cell phone). The SMTG created a dedicated open-road testing ground and data infrastructure on 2.1 miles of multi-modal corridor in downtown, supporting New Jersey Governor Phil Murphy's vision towards building a New Brunswick Innovation Hub to promote the innovative economy.

The DataCity SMTG corridor is equipped with Self-Driving-Grade, high-resolution roadside sensors and computing devices to enable smart mobility services to all travelers on the corridor without the need for expensive on-board units or high-end vehicles. A living laboratory with data computing, modeling, data sharing interfaces, and application testing interfaces will be implemented to provide operational data support for NJDOT and local agencies as well as high-resolution datasets for private sector R&D.

Concepts and Technologies

As illustrated in figure 1, the key concepts and technologies of the testing ground consists of the following.

- **Self-Driving-Grade Roadside Sensing and Computing Infrastructure:** The SMTG corridors are equipped with self-driving-grade, high-resolution roadside sensors, and computing devices. This setup enables smart mobility services for all travelers along the corridor, eliminating the need for expensive on-board units or high-end vehicles. It ensures precise real-time data acquisition and processing.
- **Smart Mobility Management Center:** At the heart of the testing ground is the Smart Mobility Management Center. It oversees all operations, hosts applications, and manages the traffic data processing and analytics flow. The Smart Mobility Management Center will be integrated with Middlesex County Traffic Operations Center.
- **Digital Twin 3D Data Modeling and Visualization Platform:** Leveraging the high-resolution data and comprehensive coverage of the corridor, a virtual digital twin of

the SMTG has been developed. This platform facilitates early-stage R&D activities by converting field-collected trajectory and geometry data into moving three-dimensional (3D) objects against a static, full-colored infrastructure background, as generated in Task 4. Users can view, interact with, and export visual data from any perspective in the model, and create their own smart mobility test datasets.

- **C-V2X Smartphone-based Community Mobility Applications:** This component includes the development of cellular-network-based community mobility applications. These applications display geo-fenced safety and mobility messages or guidance signals for testing purposes, enhancing community engagement, accessibility, and user experience.
- **Industrial-Grade Smart Mobility Data Hub:** A data portal has been established for sharing smart mobility data collected from the SMTG and other corridors, integrating datasets from local agencies and the private sector. The portal offers interfaces for public, private, and academic sectors, accommodating various data exporting formats and needs, including enhanced data privacy/security for private sector clients.
- **Technology Testing and Certification Center:** This center is designed to establish a pipeline for technology testing, evaluation, transfer, and training, aiming to promote smart mobility technology deployment in New Jersey. The SMTG can test various sensors, controllers, and communication configurations, suitable for deployment across different corridors. Even without the full SMTG configuration, these technologies can be assessed for cost-effectiveness and scalability and can be certified for large-scale deployment.

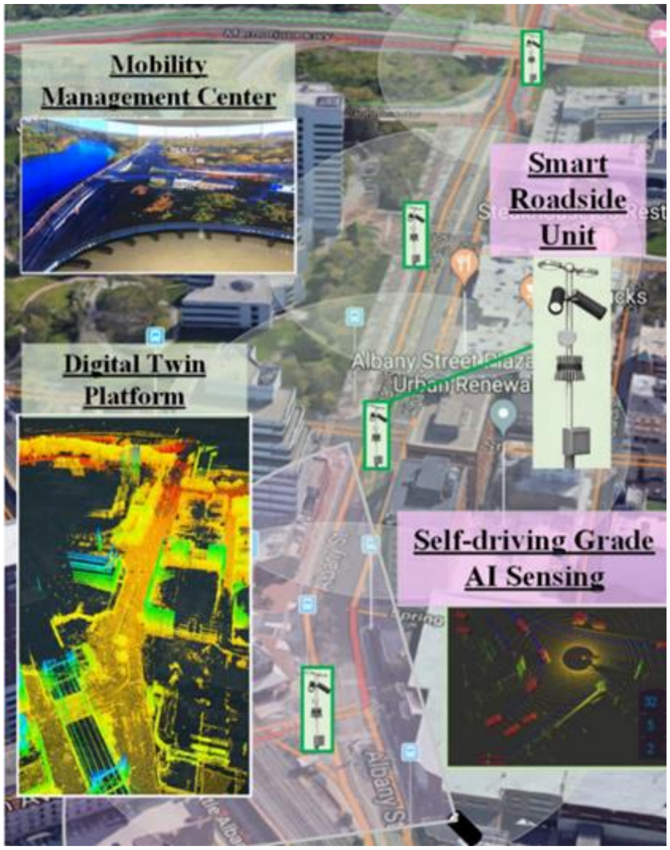


Figure 1. Concepts and Technologies

DataCity Smart Mobility Testing Ground Corridors

The SMTG will be deployed in a multi-jurisdiction, 2.1 miles, multi-modal corridor in the City of New Brunswick on Route 27 from Hardenberg Street (Robert Wood Johnson Hospital, Mile Marker (MM) 15.92) to River Road (MM16.65) and on Route 18 from Route 27 (MM42.29) to US 1 (MM40.61) as shown in figure 2. The New Brunswick Innovation Hub is located in the Albany Street corridor. Five Rutgers campuses are located along this corridor. The project corridor offers a diverse transportation testing environment for users ranging from universities to Departments of Transportation (DOT) to automotive Original Equipment Manufacturers (OEMs) and technology firms. The corridor has key congestion and safety challenges that provide opportunities for SMTG to make an impact on community travel experiences.

Phase 1 is within the scope of this project. Phase 2 is the complementary corridors to be funded by Middlesex County in a separate project. Middlesex will also fund the establishment of the Smart Mobility Management Center for the testing ground. The **Smart Mobility Management Center** is housed in a 1200-square-foot facility located on Hose Lane within the Old Ericsson Building as part of the Middlesex County Traffic Operations Center. This facility is central to support the data and application testing platforms.

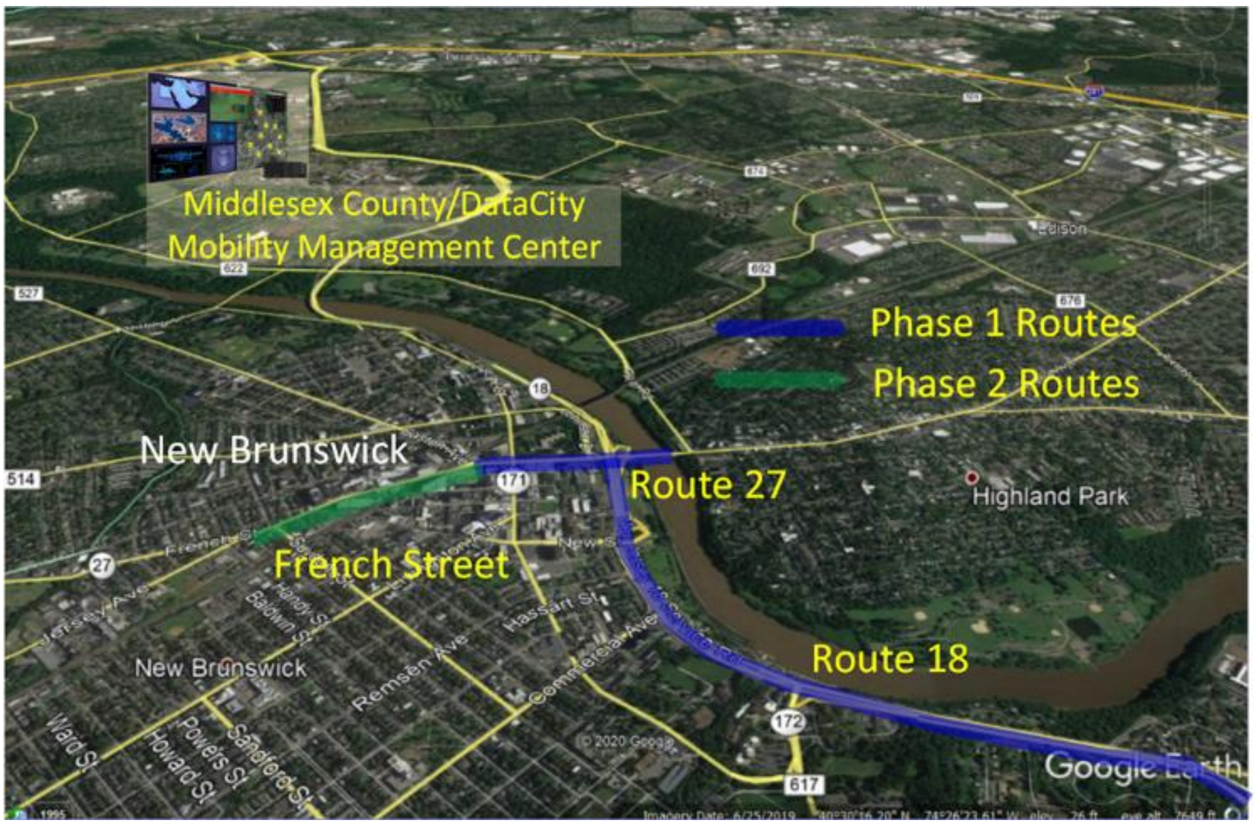


Figure 2. DataCity Smart Mobility Testing Ground Corridors

DataCity Roadside Unit and Central Instrumentation

Sensors:

- HD Cameras (2K/1080p 60fps/720p 30fps)
- Velodyne Alpha Prime LiDAR (128-Beam)

Edge Compute:

- NVIDIA Jetson Xavier: Dedicated LiDAR Analytics
- NVIDIA Jetson Orin: Data Transfer/Application Test

Connected Vehicle (CV):

- CV Roadside Unit
- Verizon Virtual RSU, VZMode

Communication:

- Gigabit Switch/Router
- Verizon Fios Fiber Nodes/P2P
- Verizon Cellular

Control Center:

- Videowalls (Flat and CAVE)
- Servers: Local 1.5 PB DELL PowerScale Storage Node, Analytics/Application, Work stations

Cloud:

- AWS Video Analytics / Rutgers HPC (Nvidia Tesla)
- AWS Glacier or other Storage Lake Solutions

Figure 3. DataCity Smart Roadside Unit

An array of advanced sensors that collect high resolution data form the foundation of the STMG. Sensors range from autonomous-grade Light Detection and Ranging (LiDAR) sensors to differential Global Positioning System (GPS) base stations to High-Definition (HD) surveillance cameras. An initial data capture using LiDAR has been used to capture roadway, transportation facilities, exterior, and in some cases, interior building infrastructure is collected to serve as a “base map” of the SMTG.

As depicted in figure 3, the multi-resolution sensors include LiDAR and HD cameras.

- **LiDAR sensors** utilize lasers to create 3D images of the surrounding area within 100 – 240m depending on the type of sensor. High-angle, building mounted LiDAR sensors are used to collect high resolution vehicle trajectory and velocity information to support a variety of Connected Vehicle (CV) and other applications. They are also used at intersections to support smart intersection applications.
- **HD cameras** that can capture 2K resolution are used in tandem with LiDAR sensors to collect information regarding vehicle operations and pedestrian/cyclist behavior and interaction at smart intersections. HD cameras are supplemented with network cameras at locations where HD resolution is not required.

The roadside computing layer supports application delivery for test ground users and travelers in the project corridor. Given the low latency required to support connected and advanced driving system applications, data processing takes place at the roadside level near drivers, pedestrians, and bicyclists. Key roadside computing technologies for use at SMTG include the following:

- **Edge Processors -** LiDAR and other sensors generate significant amounts of data; pushing this data to a central location/back office would introduce significant latency into application processing. In addition, the large amounts of data generated by LiDAR or camera systems would require significant bandwidth for the communications network. Edge processing can alleviate much of this challenge by performing the processing locally via direct connections to the sensors. Data that will be used locally is immediately available; data to be aggregated with other data for use nearby can be pushed to a roadside “Fog” (Fog is the term used to refer to intermediate data processing before the cloud) processor nodes. Ouster’s BlueCity Solution provides edge computing service through Nvidia Jetson AGX Xavier.

- **Fog Processor Node -** Fog Processor Node serves as an intermediary server at the roadside. Nvidia Jetson AGX Orin is used as a fog processor node. It aggregates data from edge processors and sends the data to servers found in the Central Data Management Environment for storage and further processing/computing. These nodes can also disseminate real-time local traffic and infrastructure information to test vehicles and pedestrians/bicyclists.
- **Roadside Unit (RSU) -** The RSU is the fixed Dedicated Short-Range Communication (DSRC) unit which serves as a main application platform. These units are highly capable Linux computers with radios enabling low latency communications which enable CV applications over distances of 400 – 500 meters with clear line of sight.
- **Network Security Appliance -** Network security is enhanced using industrial-grade security appliances that are installed at nodes with public-facing communications as well as any traffic signal controllers that should be involved in testing or equipped with public-facing applications.
- **Fiber/Cellular Connectivity -** Local wired and wireless connectivity are provided via fiber and cellular nodes to minimize processing times and as an element of potential pedestrian/cyclist applications. Fiber/Point-to-Point (P2P) connectivity is used for connections to the Central Data Management Environment and between Fog Nodes for certain types of data, and cellular connectivity is used for connections to VZMode for real-time Basic Safety Message (BSM), Personal Safety Message (PSM), Signal Phase and Timing (SPaT), Traveler Information Message (TIM), MAP, etc.

The Central Data Management Environment layer represents the storage and application servers that are housed at the Traffic System Lab at Rutgers University for initial processing and later migrated to the Middlesex County Network Operational Center.

- **Central Computing Node –** The Traffic System Lab at Rutgers provides initial processing to create the system-wide vehicle and object trajectories, consolidate, and reconcile overlapping objects from different sensors and apply anonymization algorithms to mask personal identification information (PII) for pedestrians and other in the test ground.
- **Smart Mobility Data Portal –** Researchers and practitioners can access the high-resolution mobility data collected by test ground sensors and any applications developed by Rutgers researchers. The team acquired approval from the Institutional Review Board (IRB) of Rutgers University for data processing and protection protocols.

DataCity Smart Mobility Testing Ground Deployment Status

Figure 4. DataCity Roadside Instrumentation Deployment Status as of 12/15/2023

Figure 4 shows that as of December 15, 2023, eight sites have been constructed with full sensing and connectivity capabilities along Route 27 and Route 18.

- **Sensing –** Every site collects data from two HD cameras and one 128-beam Ouster VLS-128 LiDAR.
- **Connectivity -** All eight sites have direct or indirect (P2P) access to the fiber network provided by Verizon Fiber Optic Service (FiOS) and are streaming data back to Rutgers' central server.
- **Edge Processor -** At each site, one Nvidia Jetson Xavier (BlueCity Edge Processor) and one Nvidia Jetson Orin (Rutgers Edge Processor) serve as the edge processors and are positioned in separate cabinets for maintenance.
- **Trajectory -** LiDAR trajectory data is available on BlueCity IndiGo Intelligence for all eight sites, processed and broadcast by Ouster's BlueCity Solution. Camera trajectory data is available on VZMode for Albany Street & George Street, processed and broadcast by Verizon.
- **SPaT -** The SPaT messages are available for Albany Street & George Street and French Street & Paterson Street, broadcast through RSU.
- **Trailer Sites -** Four more trailer sites (MM42.3: Route 18 Northbound (NB) Off-ramp to Highland Park, MM42.1: Route 18 NB Ramp from New Street, MM41.5: Route 18 Southbound (SB) On-ramp, MM41.2: Route 18 SB Next to Remote Traffic Microwave Sensor (RTMS) Pole) are coming upon approval with solar power, cellular network, and camera and LiDAR sensors, to fill the coverage gap between the existing sites.

TASK 1: STAKEHOLDER OUTREACHING AND ENGAGEMENT

In Task 1, the team conducted significant outreach efforts to public agencies, private sector R&D companies, and peer academic institutions towards establishing a Public-Private-and-Academic Partnership (PPAP).

Project Timeline and Major Milestones

The DataCity project embarked on its journey in May 2019. Since then, it has unfolded a succession of consequential milestones and outreaching activities. The milestones and outreaching activities include meetings with stakeholders, conceptual development, technology acquisition, field construction, field testing, and the establishment of major systems. Figure 5 shows the DataCity timeline and milestones from 2019 to 2020.

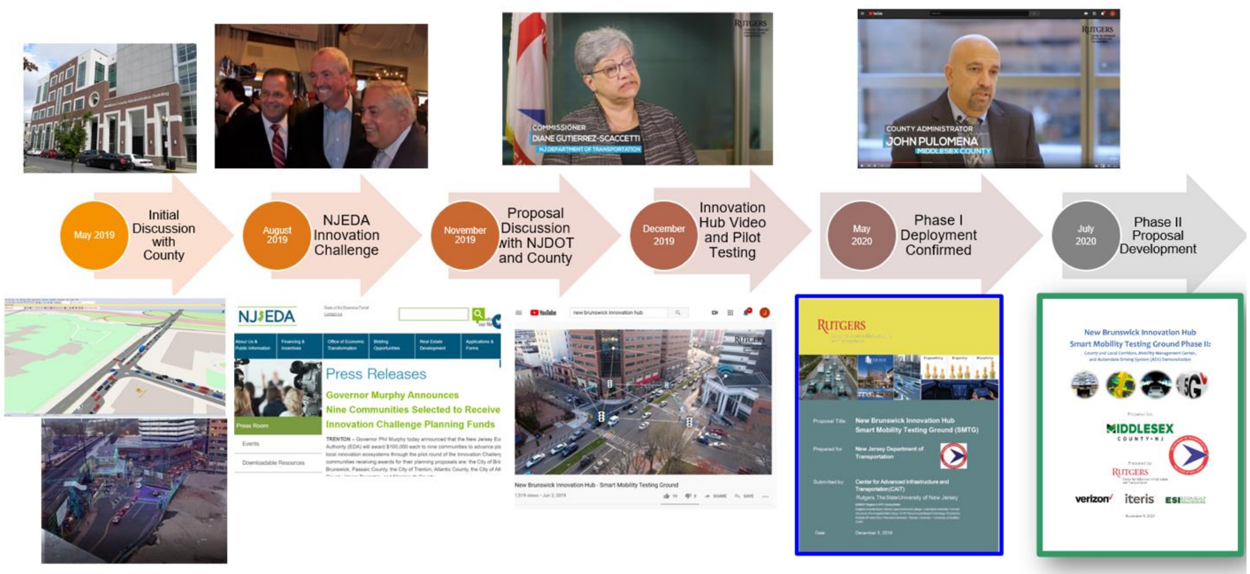


Figure 5. DataCity Timeline and Milestones (2019-2020)

- **May 2019: Initial Discussion with Middlesex County**
  In May 2019, the project was inaugurated with a series of preliminary discussions with the County, marking the foundational phase for subsequent collaborative efforts. These initial dialogues laid the groundwork for the project's overarching objectives and collaborative strategies.
- **August 2019: New Jersey Economic Development Authority (NJEDA) Innovation Challenge**
  In August 2019, the project participated in the inaugural NJEDA Innovation Challenge, showcasing the project's innovative aspects and potential. This engagement served as a platform to demonstrate the project's technological advancement and alignment with innovative practices.
- **November 2019: Proposal Discussion with NJDOT and Middlesex County**
  In November 2019, the team engaged in detailed discussion with NJDOT and Middlesex County regarding the project proposal. The conversations centered around

the formulation and refinement of the project proposal, reflecting a collaborative effort to address logistical and strategic considerations.

- **December 2019: Innovation Hub Video and Pilot Testing**
  In December 2019, the team created an innovation hub conceptual video and conducted pilot testing to demonstrate the feasibility and functionality of DataCity project. The visualization explicitly conveyed the innovative concepts by employing multimedia resources and the pilot testing provided a validation of the project's operational capabilities.
- **May 2020: Phase I Deployment Confirmed**
  In May 2020, Phase I deployment of the project was confirmed. This milestone signifies the progress of the project's development, indicating the approval and support from relevant stakeholders for the initiation of the first implementation phase.
- **July 2020: Phase II Proposal Development**
  In July 2020, the team initiated the development of the Phase II proposal, indicating a strategic move towards advancing and expanding the project.

Figure 6. DataCity Timeline and Milestones (2021)

Figure 6 shows the DataCity timeline and milestones in 2021.

- **May 2021: Project Kickoff**
  In May 2021, the NJDOT Phase I kickoff symbolized the transition from planning to active implementation. DataCity project has been moving towards achieving the outlined goals since then.
- **July 2021: LiDAR Acquisition Completed**
  A critical technological milestone was the completion of 128-beam Ouster VLS-128 LiDAR acquisition in July 2021. Since LiDAR sensing technology is one of the major components of the DataCity project, this completion represented a cornerstone in the project's technological infrastructure.

- **August 2021： Middlesex County Phase II Started**
  In August 2021, the Middlesex County Phase II kickoff indicated a strategic scaling of the project and extended its reach and impact within the designated region.
- **September 2021: Hub Breaking Ground (First Intersection: Albany & George site)**
  In September 2021, tangible progress was realized as the innovation hub broke ground with the construction of the first site at Albany Street and George Street intersection. Technological infrastructures including LiDAR sensors, cameras, and edge computing devices have been installed at this site.
- **February 2022: Four Sites Completed**
  The installation of technological infrastructures on four designated sites was completed in February 2022. This progress demonstrated the capacity of DataCity project to progress systematically, with each site serving as a significant part of the project.

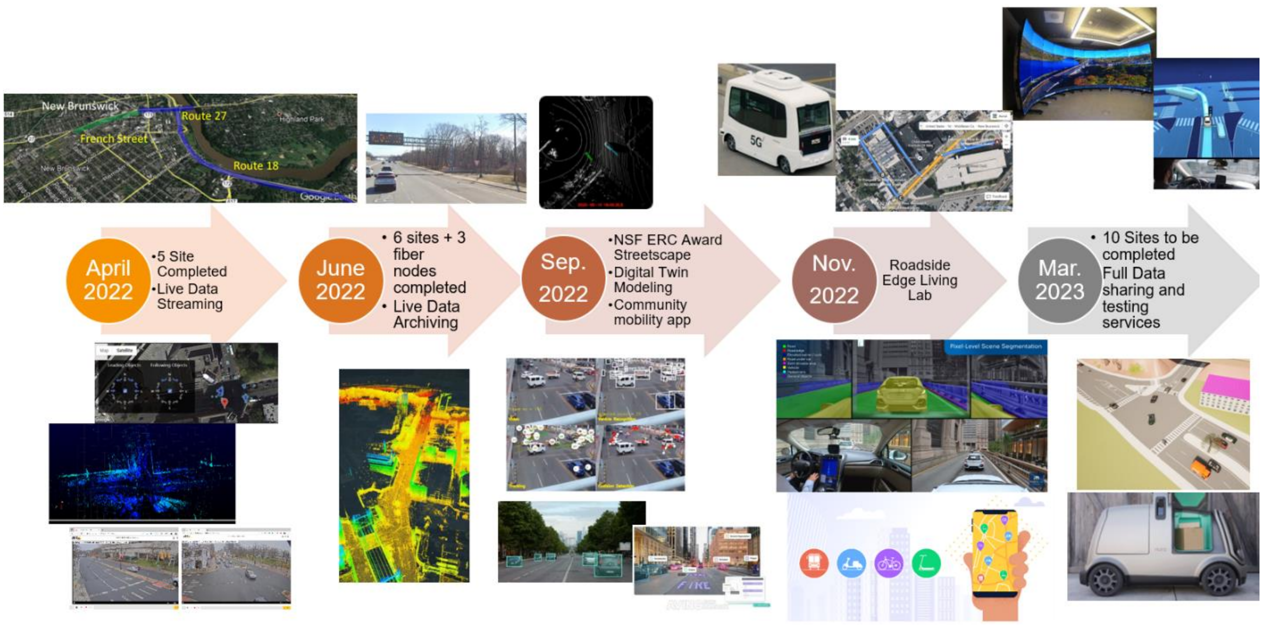


Figure 7. DataCity Timeline and Milestones-Ongoing/Planned (2022)

Figure 7 shows the DataCity timeline and milestones from 2022 to 2023.

- **April 2022: Five Sites Completed and Live Data Streaming**
  The initiation of live data streaming enhanced the project's real-time data monitoring capabilities, providing valuable insights into the traffic conditions across the project sites, and generating rich live data for the development of more efficient traffic operation and management.
- **September 2022: National Science Foundation (NSF) Engineering Research Center (ERC) Award Streetscape, Digital Twin Modeling, Community Mobility App**
  In September 2022, the project team became part of the University consortium of the NSF ERC Award. The digital twin model to mirror the real-world traffic conditions within the project scope was developed. A mobile application to provide users with real-time traffic information was developed as well.

- **October 2022: Control Center and Autonomous Vehicle (AV) Shuttle Feasibility Studies**
  In October 2022, the establishment of a control center was completed, representing a milestone of the traffic management system for this project. An AV Shuttle Demo feasibility study was also conducted but the planning results indicate that the proposed low-speed autonomous shuttle technologies are not a good fit for the testing ground corridor.

DataCity Products and Services

The DataCity Smart Mobility Testing Ground will provide several key products and services including the DataCity smart mobility data hub, digital twin virtual application testing platform, open-road field application testing platforms, and agency and community support.

Product 1. Smart Mobility Data Hub

The DataCity Testing Ground generates smart mobility data with high resolution (1ft x 0.1s) full-corridor coverage, and full vehicle and pedestrian penetration. The high-resolution data comes from both LiDAR and computer vision datasets, and HD map and infrastructure data. Along with the traffic, signal, and Closed-Circuit Television (CCTV) video datasets provided by the city, county, and NJDOT agency, it provides industrial data exchange and support for not only driving and navigation but also safety-critical applications.

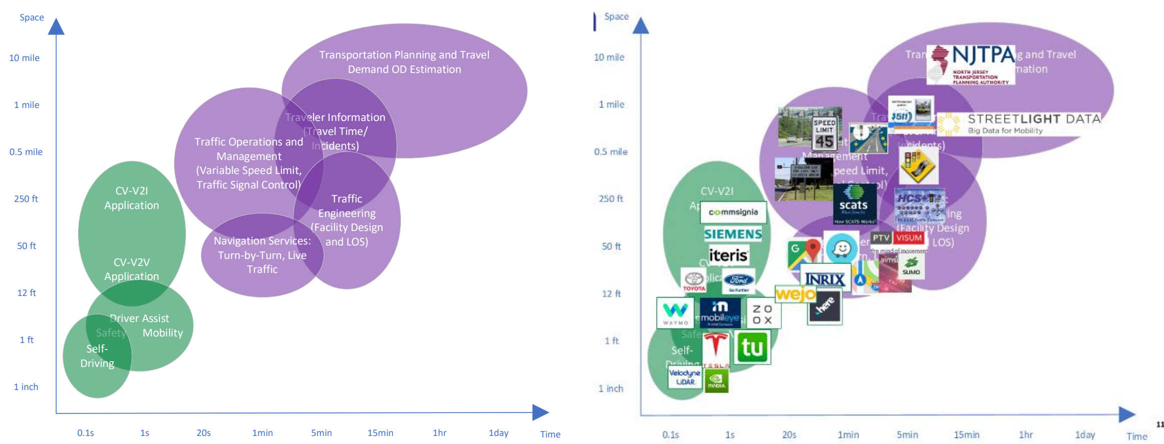


Figure 8. DataCity Data Resolution

The resolution limitations of traditional datasets have generally confined applications to areas such as Transportation Planning and Travel Demand Origin-Destination (OD) Estimation (examples include North Jersey Transportation Planning Authority (NJTPA), STREETLIGHT DATA), Traveler Information (Travel Time/Incidents, such as 511 New Jersey (511NJ))., Traffic Engineering, (Facility Design and Level of Service, for instance, Highway Capacity Software plus (HCS+)) Traffic Operations and Management (including Variable Speed Limit, Traffic Signal Control, e.g., Sydney Coordinated Adaptive Traffic

System (SCATS)) and Navigation Services (Turn-by-Turn, Live Traffic, represented by platforms like Waze, Google Maps, Apple Maps, INRIX, etc.).

DataCity, in contrast, offers datasets with a significantly higher resolution of 1ft×0.1s, compared to the 0.5 mile×5 min resolution typical of traditional datasets. This enhanced resolution facilitates applications with high-resolution requirements, including Self-Driving (e.g., Ouster LiDAR), Driver Assist systems focusing on both Safety and Mobility (examples are Waymo, Mobileye, Tesla, Nvidia, etc.), and Connected Vehicle Vehicle-to-Infrastructure (CV-V2I) and Connected Vehicle Vehicle-to-Vehicle (CV-V2V). Figure 8 illustrates the potential applications that can be enabled by the DataCity capabilities.

Moreover, the DataCity datasets offer extensive coverage that encompasses the entire corridor, as opposed to datasets that are limited to intersections. This full-corridor coverage allows for the continuous capture of trajectories across a wider range of scenarios, enabling large-scale traffic simulation and virtual training. Furthermore, unlike datasets reliant on self-reporting from vehicles, DataCity employs full penetration sensors, ensuring comprehensive dataset completeness irrespective of the penetration rate of connected vehicles.

Product 2. CAV Application Testing Platform

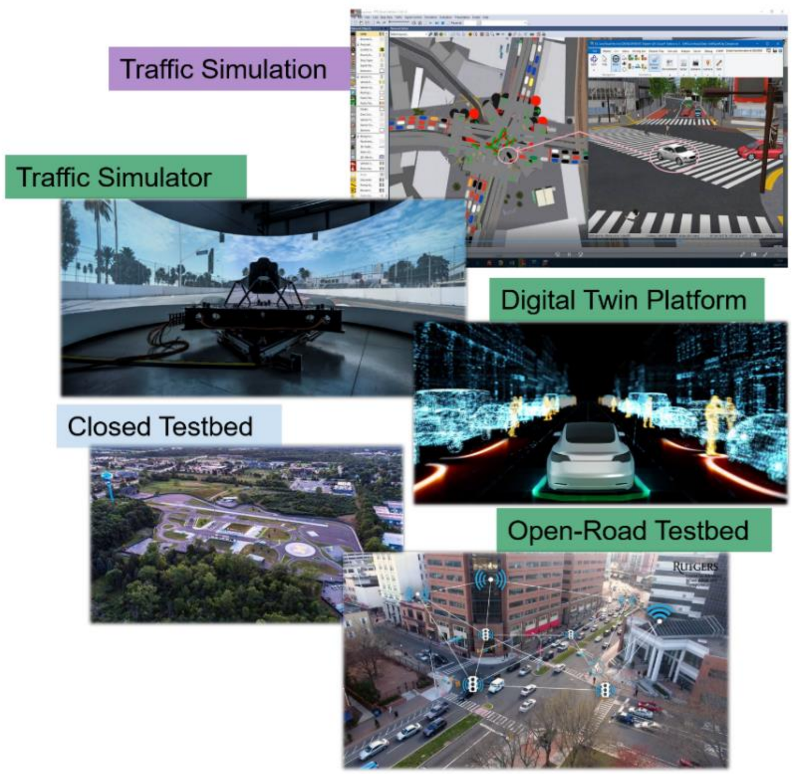


Figure 9. DataCity-Supported Testing Environments

The Connected and Automated Vehicle (CAV) testing environment that can be supported by the DataCity testing ground consists of several major components: Traffic Simulation Tools, Digital Twin Platform, Closed Testbed, and Open-Road Testbed. Aside from a conventional traffic simulation platform, the DataCity testing ground will create a living laboratory based on the real-time object and infrastructure data collected to support a traffic simulator, a digital twin platform to test out what-if scenarios, and early-stage technological innovations, as shown in figure 9. Our open-road testbed will be able to host the testing of different smart mobility, CAVs, and intelligent transportation system (ITS) technologies in real-world environments. Some of the living lab testing scenarios can also serve as the virtual background to be used in closed testbeds.

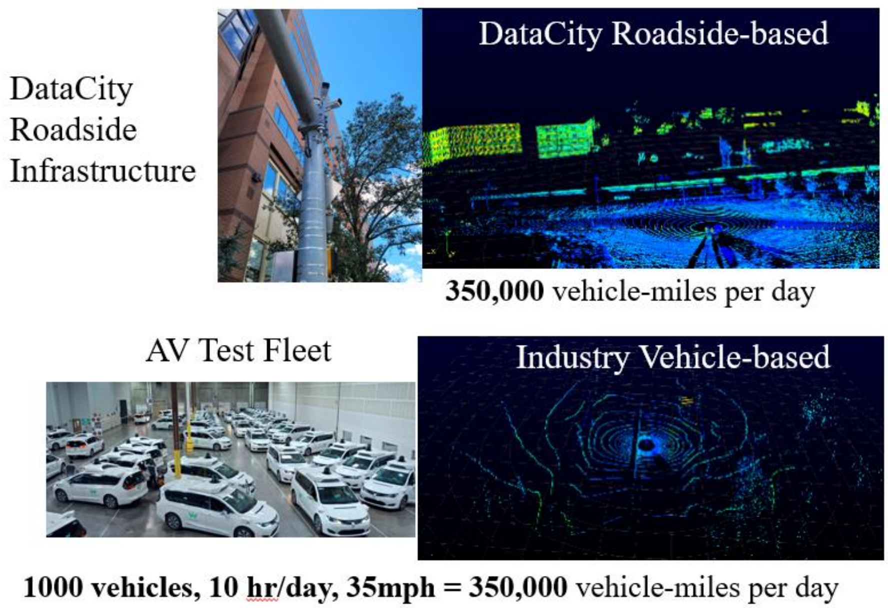


Figure 10. DataCity Roadside Data Collection Capability versus Autonomous Vehicle Test Fleets

The Living Lab offers multifaceted virtual and physical testing services that are critical for the advancement of Smart Mobility and Smart City Technologies. These premier services are available to companies within the New Brunswick Innovation Hub, as well as those in Middlesex County, NJ—providing a substantial resource for high-resolution transportation data analytics and the testing of self-driving car technologies in a controlled environment. The DataCity Roadside-based data collection infrastructure as shown in figure 10 has the capability of collecting approximately 350,000 vehicle-miles of high-resolution object movement data per day. In parallel, the Industry Vehicle-based panel features a high-tech LiDAR imaging system, which tracks 1000 vehicles traveling 10 hours a day at 35 mph, translating to a significant data output of 350,000 vehicle miles per day along the testing corridor.

Product 3. Community Mobility Applications

The DataCity Community and agency impact through the PPAP represents a synergistic effort that integrates the collective expertise and resources of various stakeholders. Through the U.S. Department of Transportation's University Transportation Center Consortium, the alliance has a solid platform for research and development and attracting top-tier talent to Middlesex County's Innovation Hub, driving forward the agenda of smart city solutions.

Figure 11. Community Engagement through Artificial Intelligence Workforce Training

The focus on community engagement and workforce development also leads to job creation and skill enhancement in the local community. Additionally, community Artificial Intelligence (AI) degree programs focus on integrating AI into workforce training to enhance community engagement. (See figure 11.) These programs offer interdisciplinary curricula combining AI technology, data science, and ethical considerations. Technical training will include modules on developing and applying AI algorithms for detection and predictive analytics and autonomous systems, with an emphasis on cybersecurity to protect the integrity of smart city data. It will also cover cloud computing and Internet of Things (IoT) architectures, critical for deploying AI across distributed urban networks. The goal is to create a diverse, skilled workforce equipped to address both local and global challenges through AI solutions.

Product 4. Open-Road Testbed to Support Smart Mobility R&D and Training

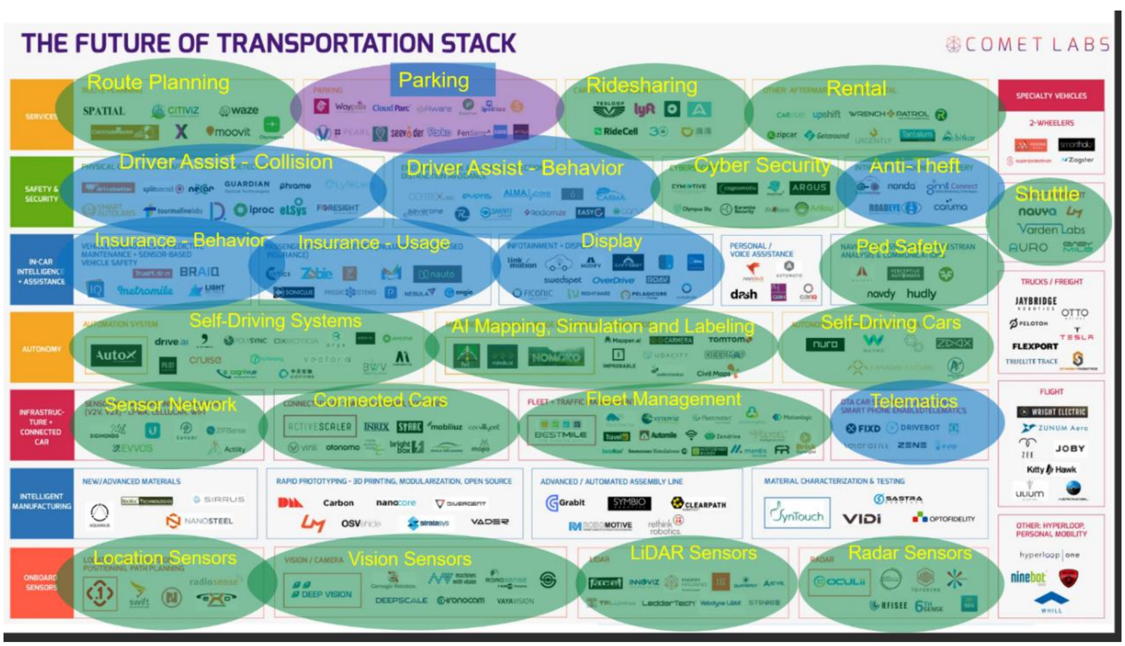


Figure 12. Technology Sectors Potentially Supported by DataCity

The DataCity project encompasses collaborations across various industrial sectors: sensor infrastructure, roadside computing, data management, transportation engineering, and public agencies, as shown in figure 12.

- **Sensor Infrastructure:** This sector is crucial to the project's technological framework. It involves deploying various types of sensors, including LiDAR, HD CCTV cameras, HD GPS base stations, Bluetooth beacons, traffic radar detectors, weather sensors, and parking sensors. This sector is essential for the project's data collection capabilities, serving as the primary source of data acquisition within the designated area.
- **Roadside Computing Sector:** This sector includes edge computing infrastructures deployed along roadways to process and analyze data collected by sensors. It is vital for enabling on-site data processing, supporting real-time decision-making, establishing C-V2X communication, and reducing reliance on centralized data processing.
- **Data Management Sector:** Responsible for the storage, organization, and analysis of the large volume of data generated by the project, this sector utilizes tools such as Amazon Web Services (AWS) cloud storage, Rutgers CAIT central computing node, and a smart mobility data portal. Effective data management is key to deriving meaningful insights from the collected data and supporting research, planning, and decision-making processes.
- **System Engineering Sector:** This sector handles the engineering and construction work involved in the project, including creating detailed drawings for construction and installation, installing sensors and roadside infrastructures, and constructing necessary infrastructures. It plays a critical role in translating concepts into real-world applications.
- **Public Agencies:** This sector involves public agencies to ensure the project's alignment with public policies, safety regulations, and community needs, fostering a conducive environment for project development and implementation. NJDOT contributes to operations on the public agency data portal, smart intersection assistance management, data visualization, and transportation infrastructure maintenance assistance systems. New Brunswick/Middlesex County and other agencies provide operations on emergency vehicle assistance, air quality monitoring, smart parking assistance, etc.

TASK 2: ROADSIDE INSTRUMENTATION

This section discusses the system approach and network architecture of the DataCity SMTG roadside instrumentation.

System Overview

The DataCity SMTG establishes a living laboratory for smart mobility and smart city technology R&D in downtown New Brunswick, New Jersey, and nearby roadways. The SMTG will serve as the foundational element of an innovation hub that will attract public and private sector researchers testing advanced driving system applications in real-world conditions while also serving as a source of high-resolution transportation data.

The focal point of the system will be a multi-functional facility nearing completion at the old Ericsson building off Route 18. This facility will support Middlesex County traffic operations, provide a hub for information sharing with NJDOT, support Rutgers' university research as well as support research by other academic institutions and the private sector.

The system consists of advanced ITS and CV sensor stations located along intersections and Route 18 in New Brunswick.

The SMTG system architecture was designed to address the following needs.

- Rutgers University researchers require a flexible system that can be easily reconfigured to meet evolving research needs.
- Middlesex County traffic engineers require a stable platform for operational support, data collection, and application development.
- NJDOT traffic engineers for data collection and potential application development.
- The needs of the academic and private sector research and development.

As indicated later in this document, a key requirement of the system network architecture is the ability for Rutgers researchers to be able to easily access the network to make configuration changes to meet data and sensor connectivity changes. For this reason, SMTG elements at the roadside (and cloud elements) are completely independent of the NJDOT network – connectivity with roadside sensors and processors utilizes commercial or private data links. No data is moved on NJDOT fiber or networks. This provides Rutgers with the ability to make quick configuration changes without interfering with NJ Office of Information Technology (NJOIT).

Roadside connectivity with Middlesex County traffic elements was designed in cooperation with and in conformance with existing security protocols; the Rutgers team configuration was reviewed by Middlesex County traffic engineering staff and tested by the County's traffic signal contractor.

At the highest level, the system consists of the three elements as shown in figure 13:

- Roadside & Cloud Elements
- DataCity Control Center
- Internet Users

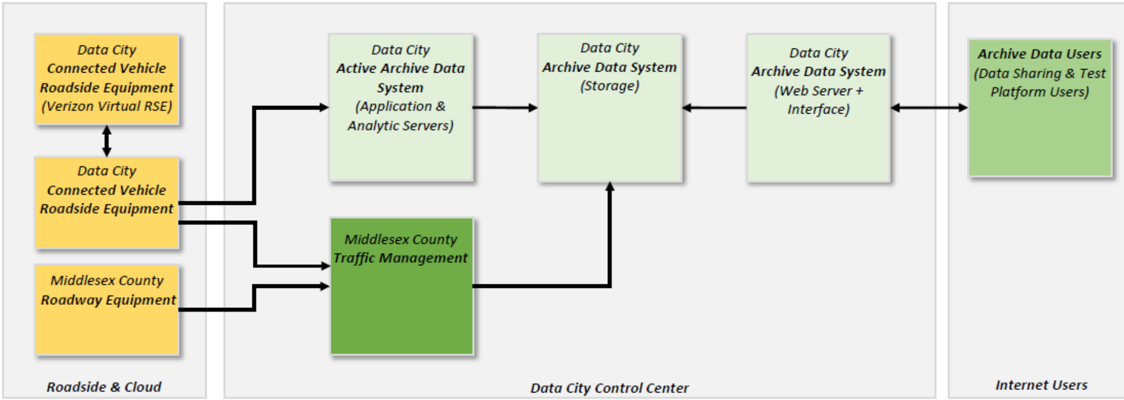


Figure 13. System Architecture Overview (Highest Level)

A more detailed description of the system from a National ITS Architecture perspective (Layer-1, Physical Architecture) showing data flows among key SMTG system elements is shown in figure 14.

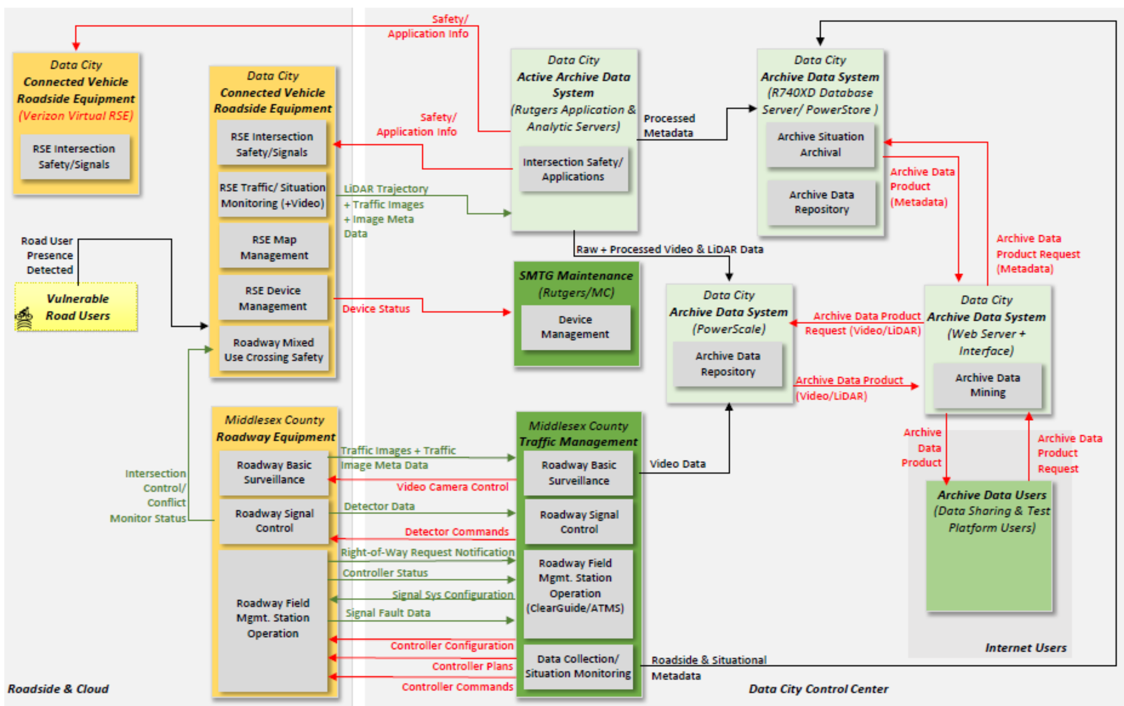


Figure 14. SMTG ITS Physical Architecture

SMTG Network Architecture

The architecture of the SMTG is designed to provide the needed capabilities to support the operation of research devices and concepts on operational roadways in the vicinity of New Brunswick, NJ. Support for the needs of the project includes providing high-availability access to the devices and enabling the collection of extensive quantities of data while protecting the security of device access and interacting with peer organizations interested in the accumulated data.

The field components of the SMTG are located at signalized intersections and freeway segments. The devices deployed at these locations include LiDAR sensors, CV RSU, and fixed cameras. Supporting these devices are processing and communication equipment including edge processors integrated with the LiDAR sensors, additional field computers, Ethernet switches, private wireless radios to interconnect field locations, wireless routers connected to the Verizon Wireless network, and fiber routers connected to the Verizon FiOS network. At a subset of the intersection locations, the SMTG devices can receive CV-related data from the operational traffic signal controller.

The Smart Mobility center serves as the location for operation, monitoring, and data collection for the SMTG. Communication among the locations of the SMTG is achieved using Internet connectivity for all sites except the Verizon Multi-access Edge Computing (MEC), which is accessed using the Verizon Wireless network. The Verizon Wireless network also serves as an Internet service provider for locations without fiber access. Internet communication is also used to provide remote monitoring and configuration access from support contractors and data exchange among centers and partners. An overview of the involved devices is shown in figure 15.

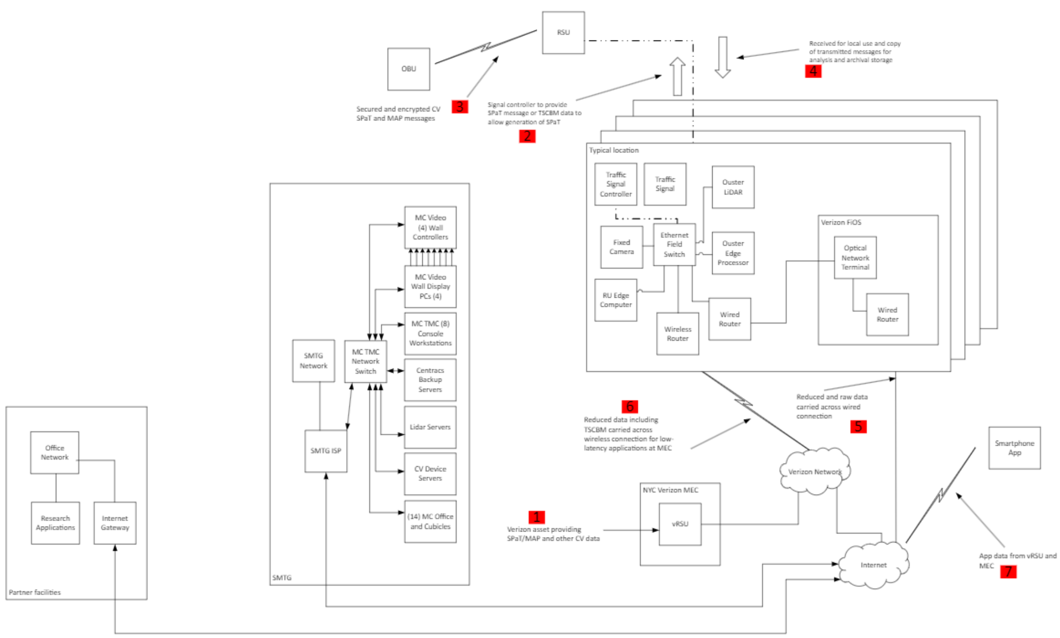


Figure 15. SMTG Network Overview

Typical Location

Communication to each site is achieved using Internet connectivity provided by Verizon. Each site is configured as a local area network using a single subnet and no Virtual Local Area Network (VLANs). All location Local Area Networks (LANs) are configured consistently behind the gateway, with the site Internet Protocol (IP) address assigned by the Internet provider distinguishing locations. Incoming data traffic destined for SMTG devices is forwarded to the designated IP addresses with specific ports assigned.

Security is provided to the locations using an access control list consisting of static IP addresses authorizing traffic for trusted partners. At intersection locations accessing the traffic signal controller, Virtual Private Network (VPN) restrictions are established for an additional layer of security. All locations are equipped with wireless routers.

Additionally, five locations have gigabit connections served by Verizon FiOS that provide the primary path to Internet access. At locations with access to fiber, the wireless connection is used as a pathway to Verizon services requiring low latency and as a backup communication path. All communication within each site is achieved using wire Ethernet of Category 5 or Category 6 copper cables.

Each site is powered from a nearby power source and can be unpowered by use of a single breaker near the source. Where possible, power is acquired through a nearby power cabinet or traffic signal cabinet. For trailer locations, power is acquired from a battery pack recharged through a solar panel array. The solar array is sized to operate the devices at least 16 hours per day, with 24-hour operation feasible frequently. A typical intersection with grid power and only wireless Internet access is shown in figure 16.

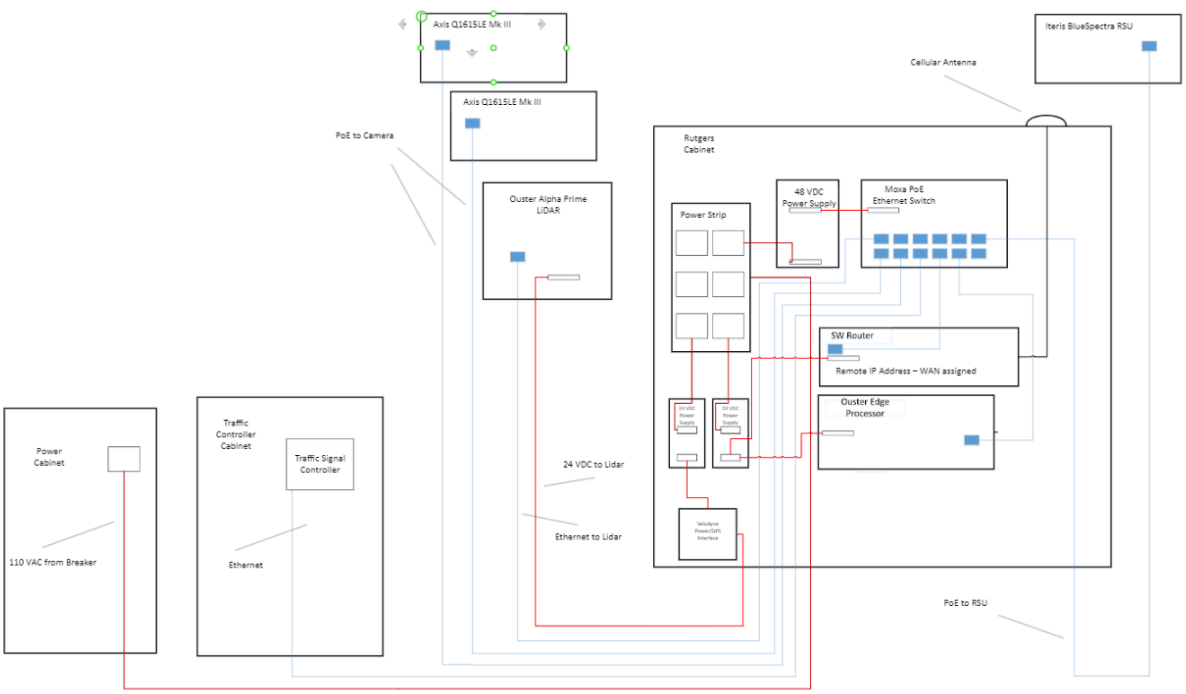


Figure 16. Typical Sensor Site

Private Wireless Sites

At two of the fiber locations, adjacent sites are connected to the site LAN using a private wireless radio. These locations leverage the investment in wired installations to access high-bandwidth Internet service. To accommodate the presence of multiple copies of each device on field LAN, the IP addresses of the second or third copy of the devices are modified. The configuration of such locations is shown in figure 17.

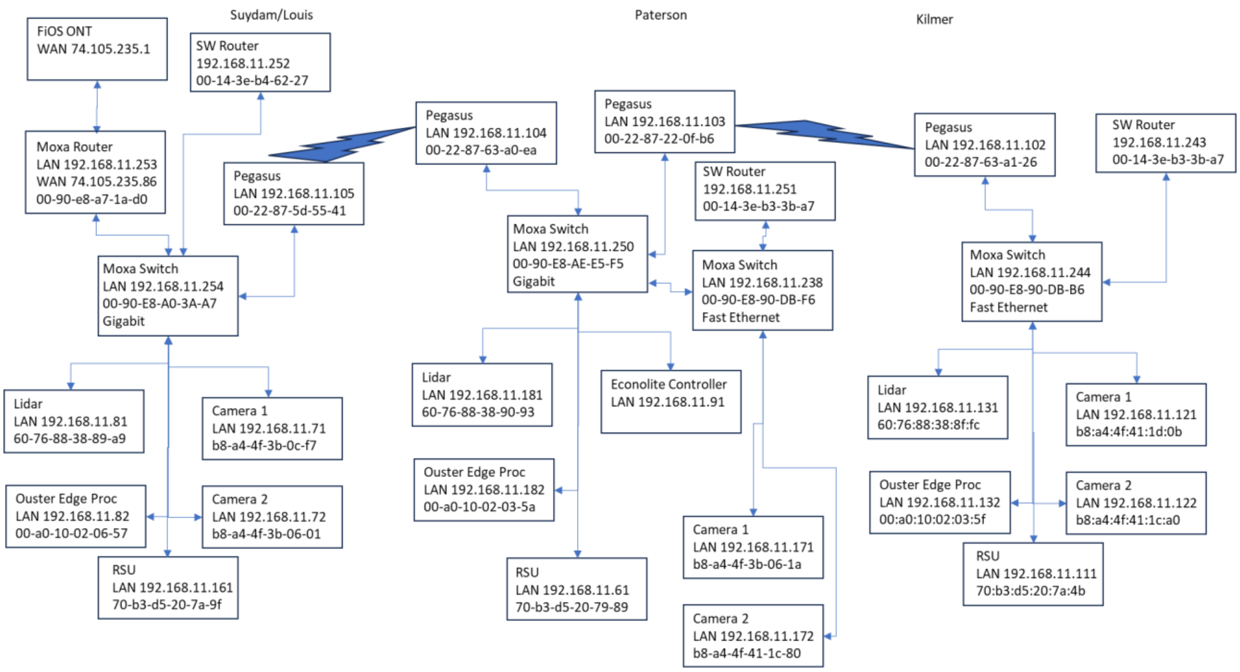


Figure 17. Private Wireless Site Configuration

Private Wireless Sites – French & Suydam

The specific sensor devices and IP address configuration for the intersection of French Street and Suydam Street are shown in figure 18.

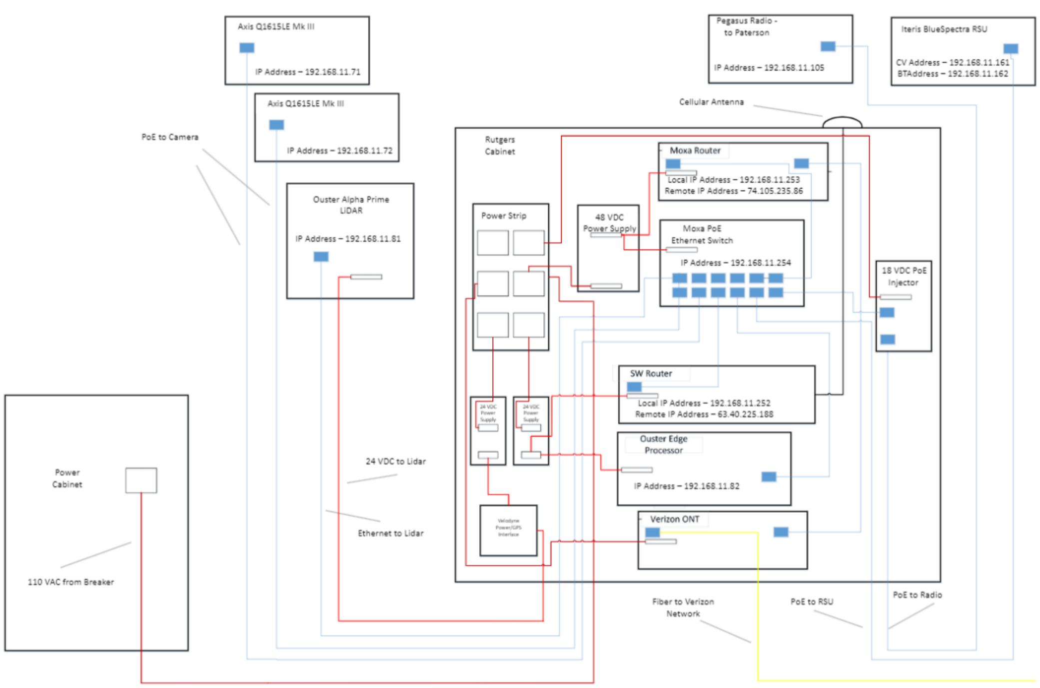


Figure 18. French & Suydam Wireless Network Diagram

Private Wireless Sites – French & Paterson

The specific sensor devices and IP address configuration for the intersection of French Street and Paterson Street are shown in figure 19.

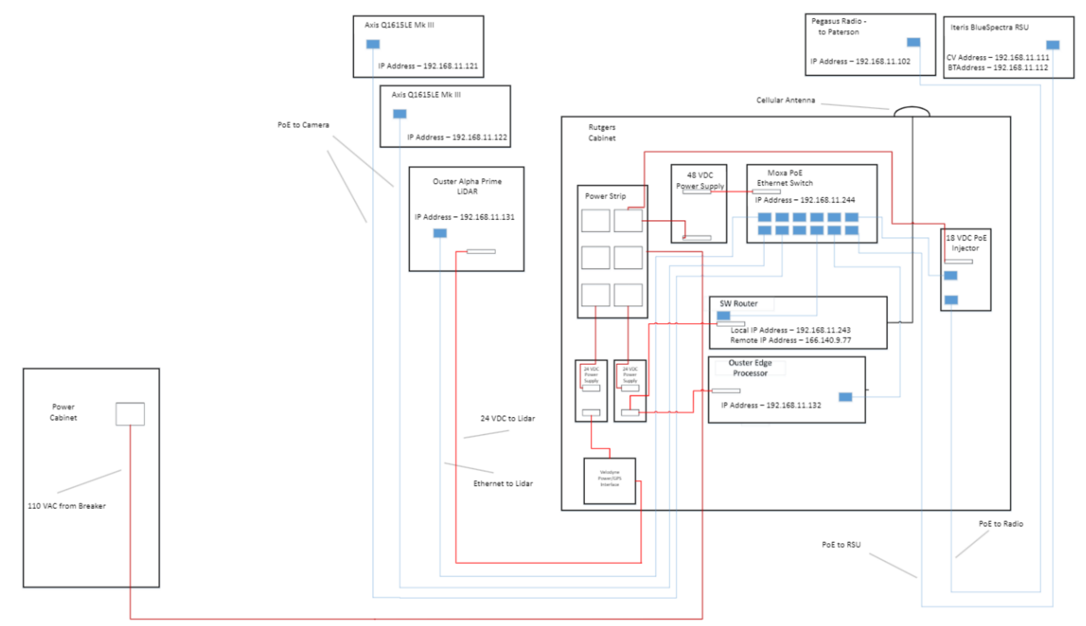


Figure 19. French & Paterson Wireless Network Diagram

Private Wireless Sites – French & Joyce Kilmer

The specific sensor devices and IP address configuration for the intersection of French Street and Joyce Kilmer Street are shown in figure 20.

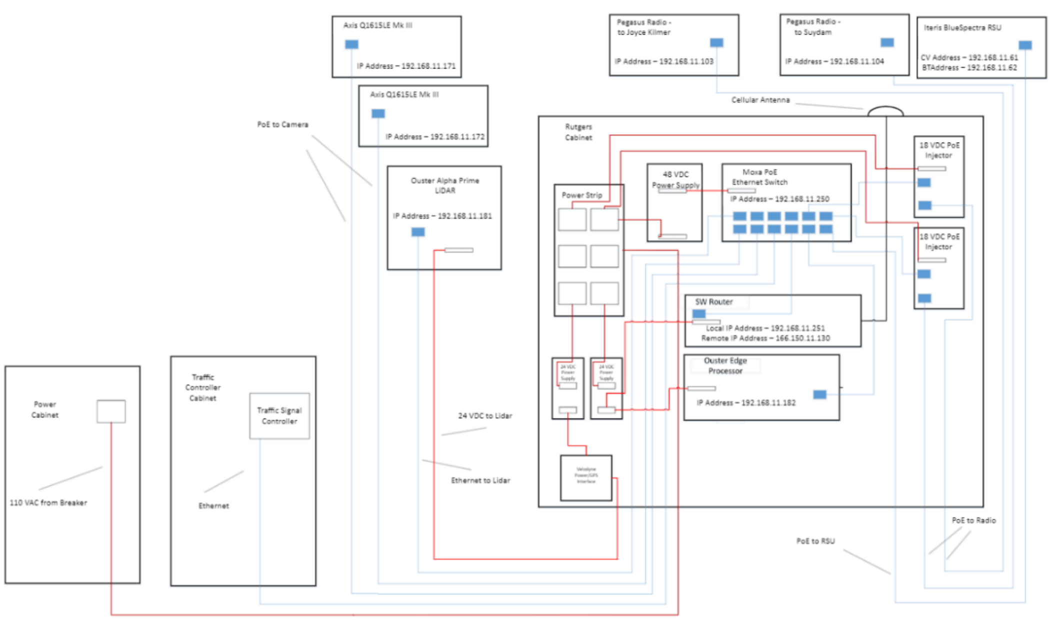


Figure 20. French & Joyce Kilmer Wireless Network Diagram

Private Wireless Sites – Albany & Neilson

In addition to the private wireless along French Street, the sensor site at Albany Street and Neilson Street utilizes private wireless to provide high bandwidth connectivity via its connection to the fiber site at Albany Street and George Street. The specific sensor devices and IP address configuration for the intersection of Albany and Neilson are shown in figure 21.

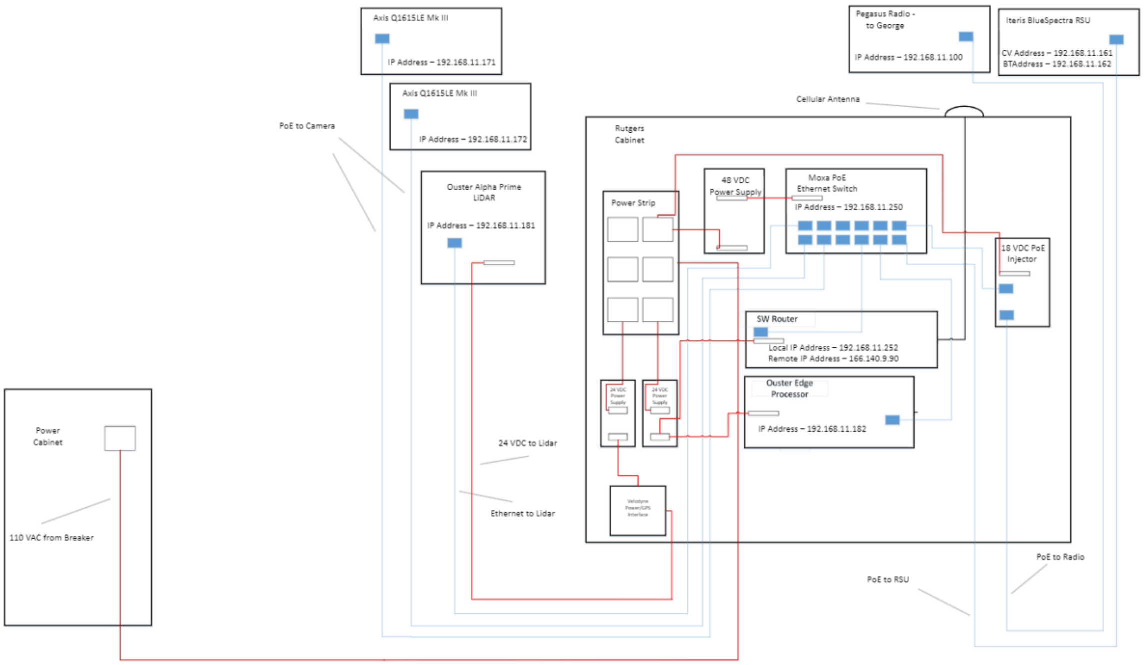


Figure 21. Albany & Neilson Wireless Network Diagram

Fiber Sites

As noted above, five locations have gigabit connections served by Verizon FiOS that provide the primary path to Internet access. At locations with access to fiber, the wireless connection is used as a pathway to Verizon services requiring low latency and as a backup communication path. The details of network and device information for five fiber sites are provided:

Fiber Site – Albany & Easton

The specific sensor devices and IP address configuration for the intersection of Albany Street and Easton Street are shown in figure 22.

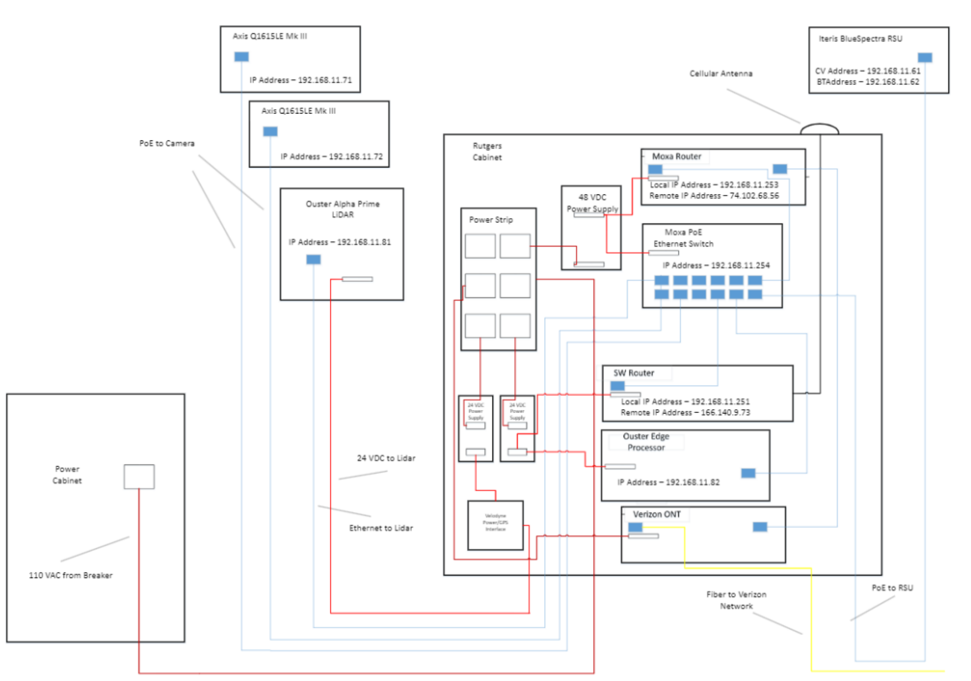


Figure 22. Albany & Easton Wireless Network Diagram

Fiber Site – Albany & George

The specific sensor devices and IP address configuration for the intersection of Albany Street and Easton Street are shown in figure 23. Please note that this site also serves as the private wireless connection hub to the site at Albany and Neilson Streets.

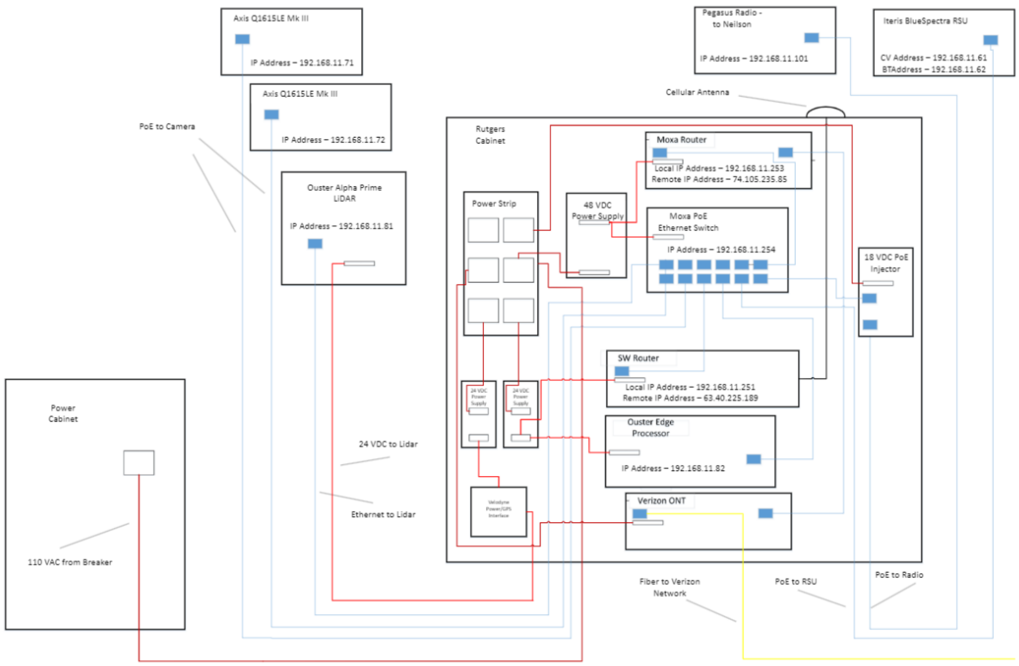


Figure 23. Albany & George Wireless Network Diagram

Fiber Site – Route 18 VMS Sign Bridge at MM 41.2

This site is located along southbound Route 18 at MM 41.2. Sensors are mounted on a vertical sign bridge supporting a walk-in Variable Message Sign (VMS) operated by NJDOT. Verizon Fiber is provided to the site via a direct connection to the Rutgers sensor enclosure – there is no physical (or logical) connection to the NJDOT network. The specific sensor devices and IP address configuration for this site are shown in figure 24.

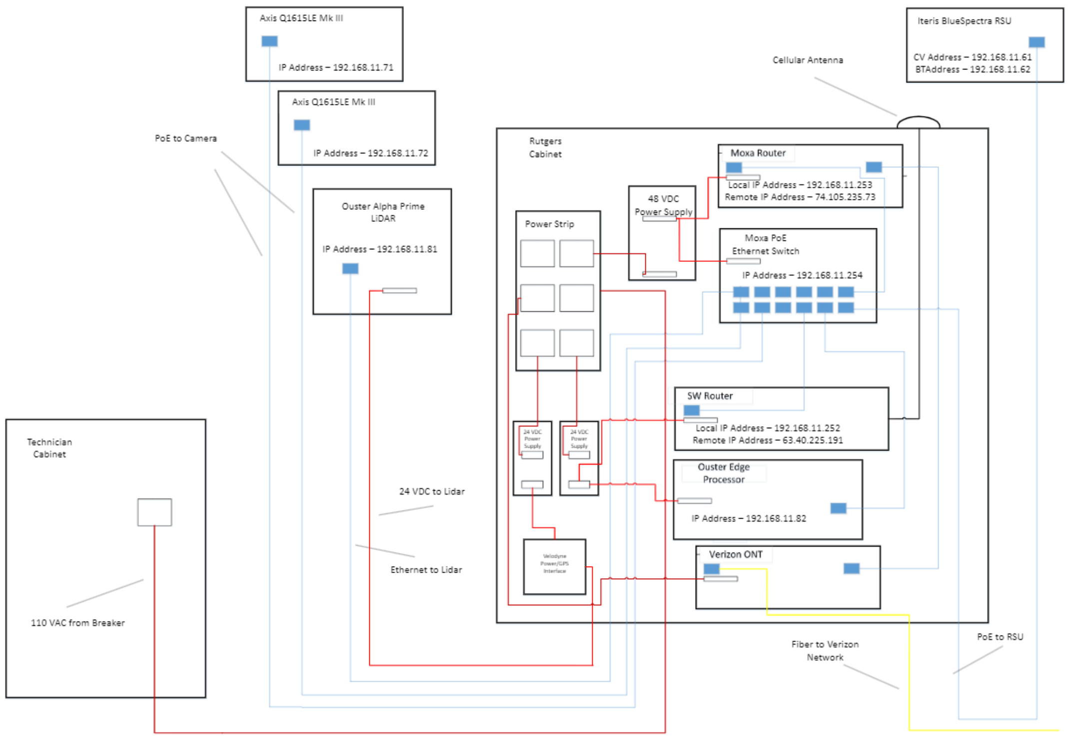


Figure 24. Southbound Route 18 at MM 41.2 (VMS Sign Bridge) Fiber Network Diagram

Fiber Site – Route 18 "Boathouse" in Boyd Park

This site is located on the roof of a city-owned building in Boyd Park along northbound Route 18 near MM 41.2. The city provided access to the roof as well as dedicated power. Verizon Fiber is provided to the site via a direct connection to the Rutgers sensor enclosure, which is located on the outside of the building to facilitate access by Rutgers team staff. There is no physical (or logical) connection to the NJDOT network. The specific sensor devices and IP address configuration for this site are shown in figure 25.

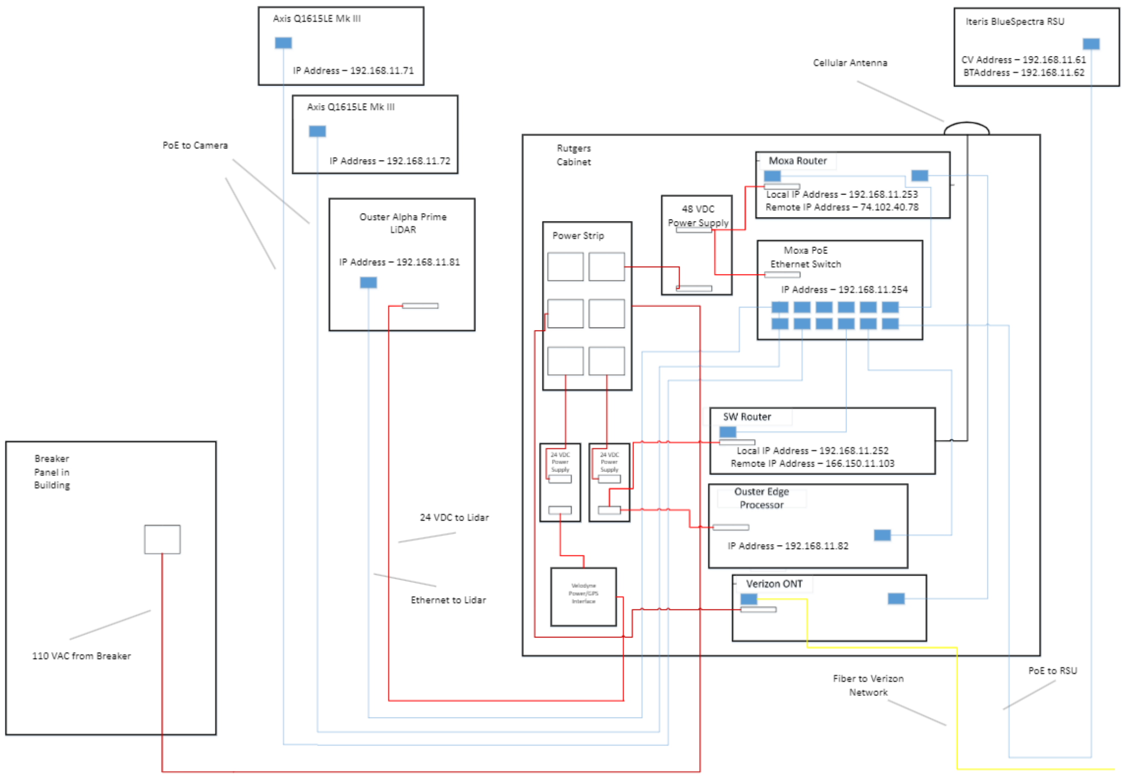


Figure 25. Northbound Route 18 (Boyd Park "Boathouse") Fiber Network Diagram

Fiber Site – French & Suydam

The specific sensor devices and IP address configuration for the intersection of French Street and Suydam Street are shown in figure 26. Please note that this site also serves as the private wireless connection hub to the site at French and Paterson Street described in the previous section.

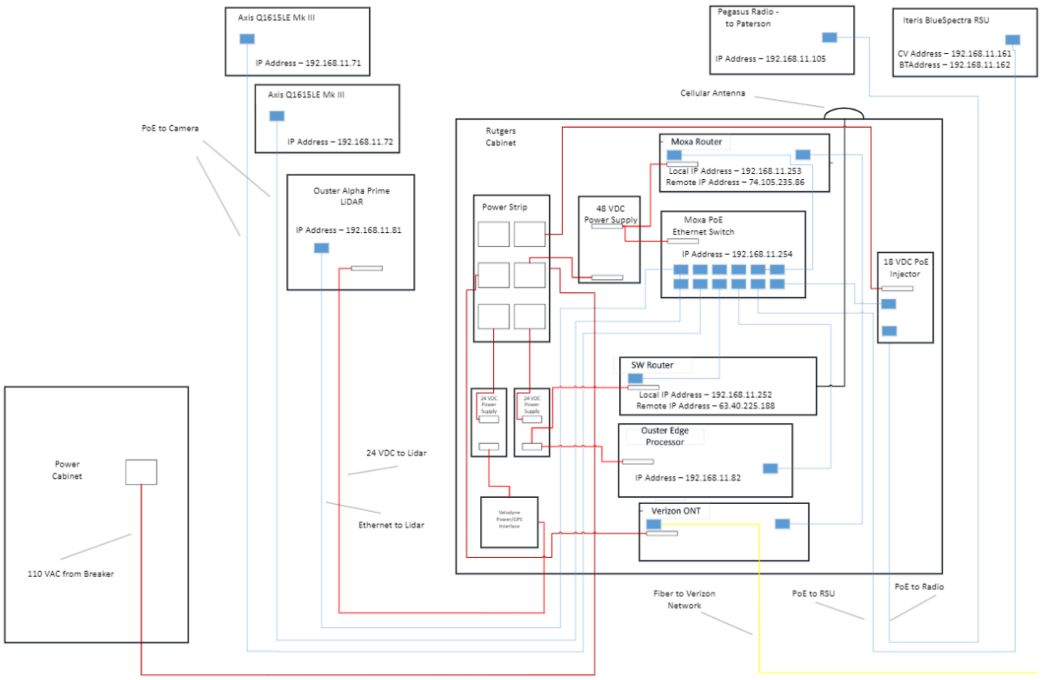


Figure 26. French Street and Suydam Fiber Network Diagram

Trailer Sites

The SMTG includes four sensor sites mounted on trailers. The trailers provide sensor gap coverage for areas lacking supporting utilities or areas that otherwise were not conducive to permanent installations. In addition, the trailers provide a flexible means of providing SMTG coverage to support special research projects or, in case of emergencies, provide highly detailed data collection capabilities. The trailers, as currently configured, will not support live streaming of LiDAR data as they utilize wireless modems over commercial internet connectivity. Should the Rutgers team choose, the sites will support the use of private wireless communications such as those used along French Street to support high bandwidth connectivity. The specific sensor devices and typical IP address configuration of the trailers are shown in figure 27.

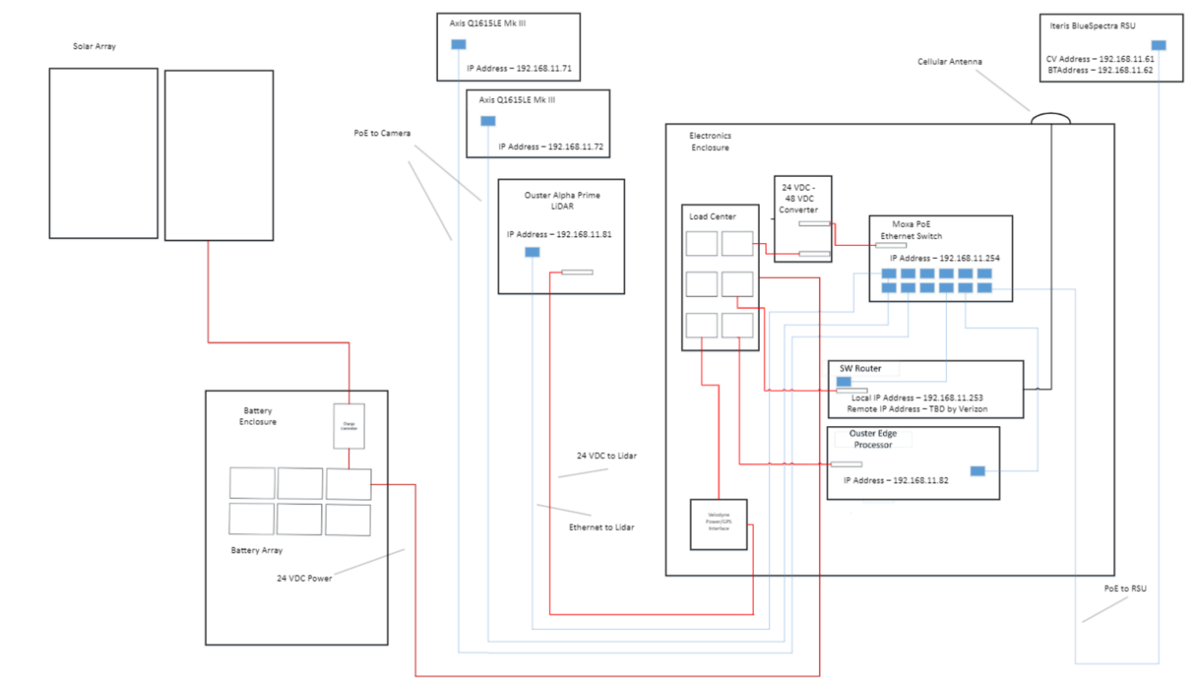


Figure 27. Trailer Site Configuration

TASK 3: TESTING GROUND MOBILITY MANAGEMENT CENTER

The Smart Mobility Management Center serves as the brain of the DataCity Smart Mobility Testing Ground, it provides the functionalities of controlling and managing the mobility network within the range of the testing ground area by receiving, storing, processing, and visualizing the LiDAR and video data generated on-site. It was established in collaboration with Middlesex County and the City of New Brunswick to support county-wide Transportation System Management and Operations (TSMO) and further extend the functionalities of Living Laboratory functionalities to support extended Middlesex DataCity data and testing capabilities and provide high-resolution datasets for private and academic sector research and development. The major functionalities and tasks to be performed in the establishment of the Smart Mobility Management Center include central computing, data sharing, and application testing. To meet the requirement of performing intensive data processing tasks and preparing a user-friendly working environment, the Smart Mobility Management Center is equipped with state-of-the-art workstations, video wall systems, and associated communicating & server systems. It can perform intensive computation, and create an ease-of-use, high-resolution, immersive, configurable environment for operators to manage and monitor both county and Middlesex DataCity facilities and infrastructure. The backend applications will ingest and visualize all connected county intersections, 511 video feeds, and Middlesex DataCity roadside units' video and data feeds. In addition to the functionalities, the data sharing and data market services will also be housed at the smart mobility center servers to distribute the data and models to public, private, and academic sector users.

The Smart Mobility Management Center is located at the west wing of the south side of the Ericsson Building at 1 Ericsson Dr, Piscataway, NJ 08854.

Floor Plan

The Smart Mobility Management Center aims to provide full functionalities of SMTG traffic operation and management, as well as a comfortable workspace. It consists of fully equipped office rooms, cubicles, an IT room, a storage room, a server room, and a large space area. The design of the floor plan was performed by Ep Design Service LLC. The total area of the Smart Mobility Management Center is 7,585 SF, sharing the same building with public health and dedicated county amenities, and taking up to 18% of the total lease area inside the building. Figure 28 demonstrates the floor plan of the Smart Mobility Management Center. (See red-shaded area on figure 28.)

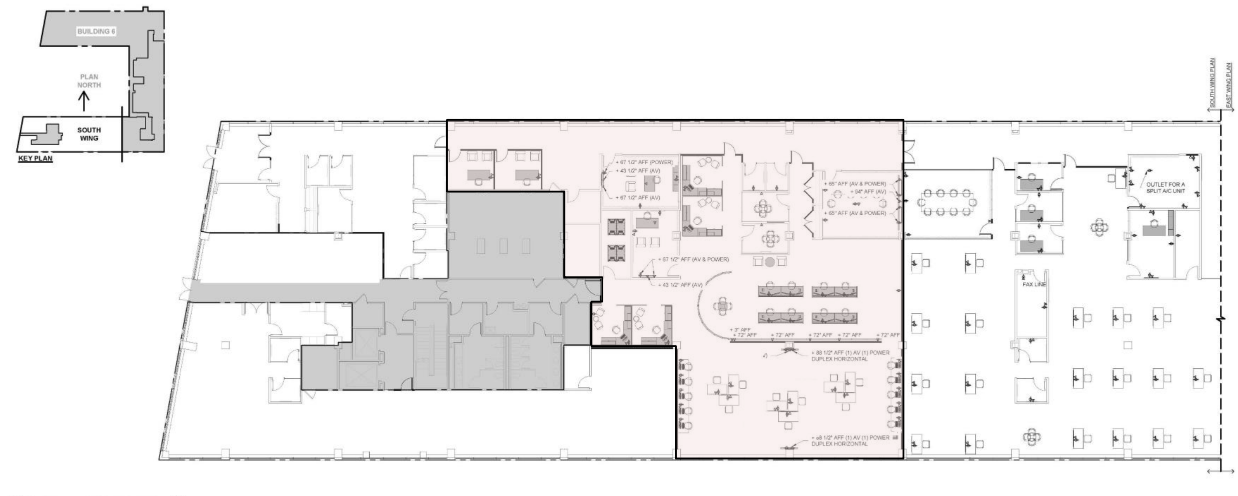


Figure 28. Mobility Management Center Floor Plan

Center Layout

The furniture layout supports a streamline to provide a better working environment. Since the devices including servers, video walls, and video controllers have specific heat and environment requirements, the furniture is arranged to associate all the equipment with the electrical, network, and heating, ventilation, and air conditioning (HVAC) system of the building, as well as to meet the Americans with Disabilities Act (ADA) requirements and produce better office activities. Figure 29 demonstrates the furniture layout of the Smart Mobility Management Center.

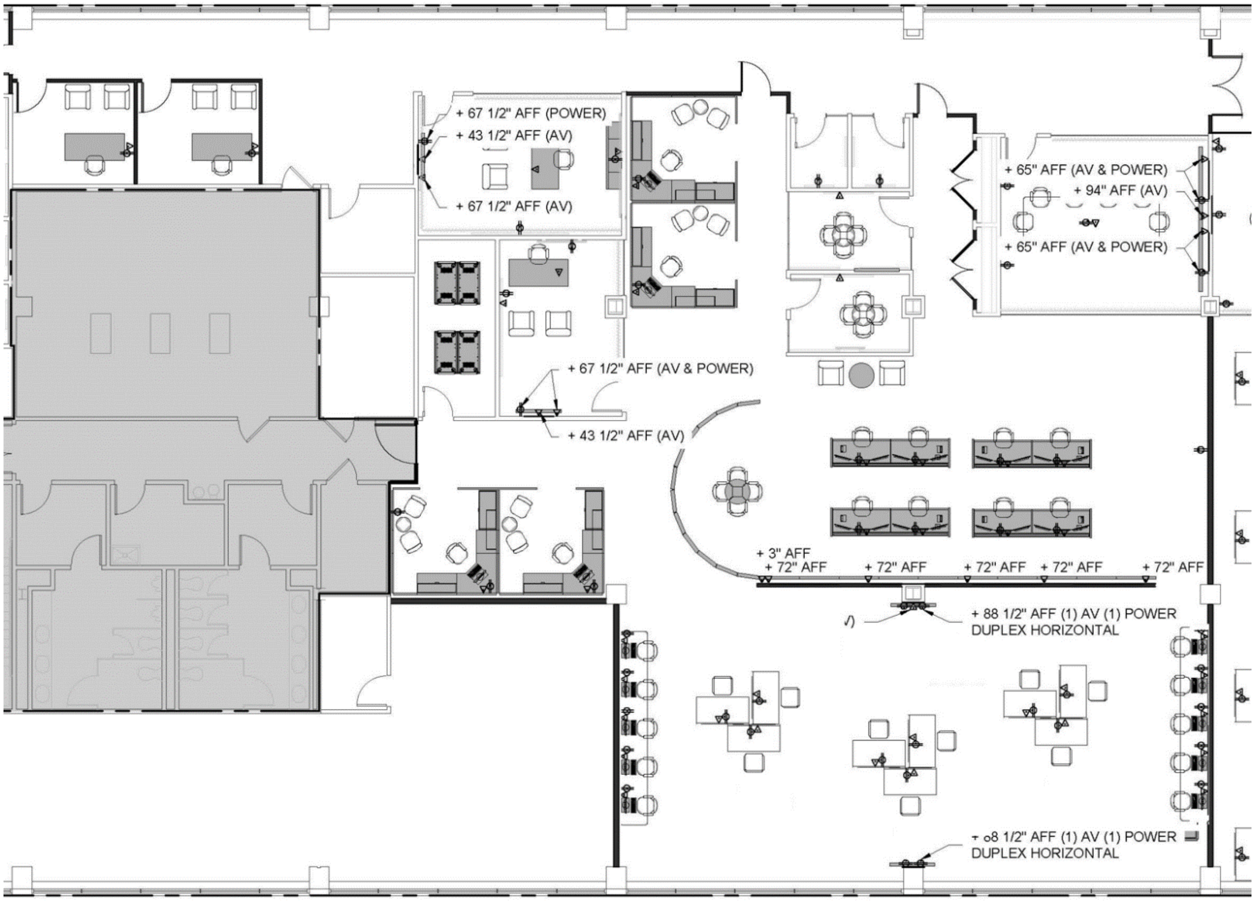


Figure 29. Mobility Management Center Layout Plan

System Diagrams and Devices

To ensure the full functionality of traffic data processing, modeling, visualization, and producing precise real-time traffic monitoring for operation and management, a system with three major components was designed and implemented in the Smart Mobility Management Center: video walls, servers, and connectivity. In general, video walls provide support for high-resolution real-time traffic monitoring and presentation, servers provide support to high-performance computing and storage, and connectivity provides support for data feeds and data transmission. Each of the three components is composed of integrated state-of-art technologies and devices to achieve the functionalities. Figure 30 indicates the system diagram in the Smart Mobility Management Center and table 1 displays the detailed description and functionalities of each component in the system.

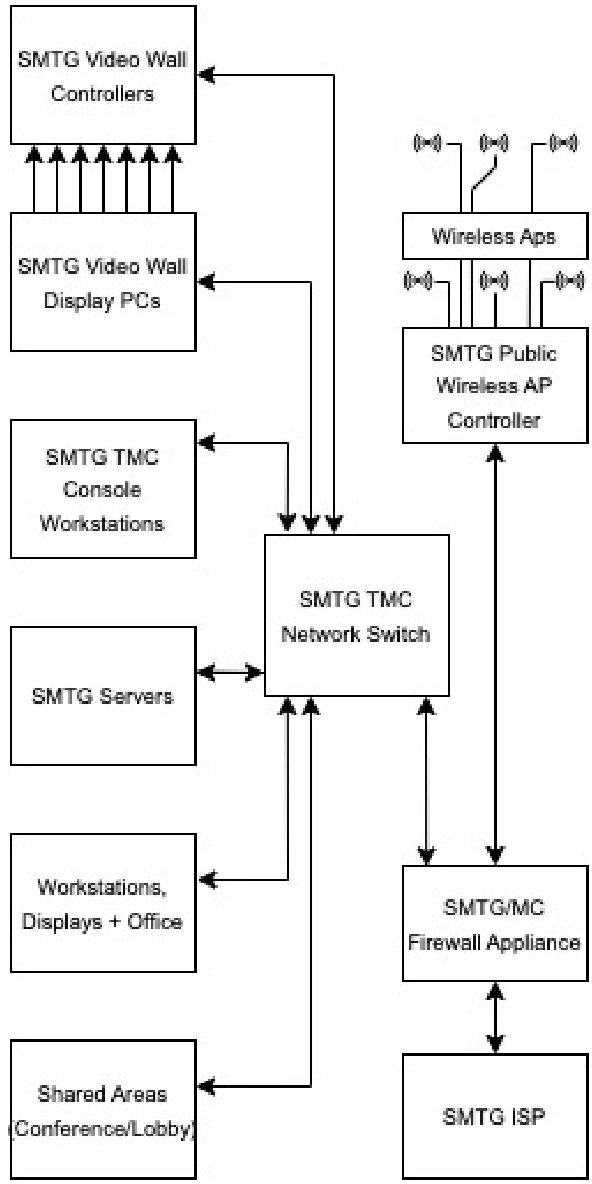


Figure 30. The Smart Mobility Management Center System

Table 1 - Control Center System Component and Functionalities

System Component	Functionalities
SMTG Video Wall Controllers	A video wall controller is a device that splits a single image into parts to be displayed on individual screens.
SMTG Video Wall Display PCs	Video walls display personal computers (PCs) are connected to the video wall to provide signal inputs.
SMTG TMC Console Workstation	Transportation Management Center (TMC) console workstations will be used to perform traffic operations & management in the traffic management center.
SMTG Servers	A server stores, sends, and receives data. It can be acted by a computer, software program, or even a storage device.
Workstations, Displays + Office	Workstation displays + provide basic and daily office usage and construct a connected, user-friendly working environment.
Shared Areas (Conference/Lobby)	Shared areas provide space for conferences.
SMTG TMC Network Switch	A network switch (also called switching hub, bridging hub, and bridge) is networking hardware that connects devices on a computer network by using packet switching to receive and forward data to the destination device.
Wireless APs	Wireless AP (Access Point) allows other Wi-Fi devices to connect to a wired network. It may have a wired connection to a router or be an integral component of the router itself.
Switch Public Wireless AP Controller	Switch Public Wireless AP Controller provides support for controlling and managing Wireless APs.
SMTG/MC Firewall Appliance	A firewall is a network security system that monitors and controls incoming and outgoing network traffic based on predetermined security rules. It establishes a barrier between a trusted network and an untrusted network. The firewall appliance is set up by both hardware and software.
SMTG ISP	An Internet server provider is an organization that provides services for accessing, using, or participating on the Internet.

High-Performance Computing and Storage

The Mobility Management Center is equipped with a high-performance computing and storage system to meet the requirements of processing and storage of a large volume of data. The system is powered by Dell Technologies and the major components are listed as follows:

- Precision Workstation
  - 8 Tower and 8 Rack-mounted
- PowerEdge Servers
  - Web Server, Application Server, Database Server, Video and 3D Analytics Server
- PowerSwitch Top of Rack Switches
  - S5248-ON and Cables
- PowerStore SANs for Databases
  - 2x PowerStore 1000T with Asynchronous Replication
- PowerScale (Isilon) NAS for Unstructured data and Veeam backup target
  - 6x Isilon A2000 nodes with backend switches and Titan XL rack

All the devices are equipped with associated software to support the full functionalities.

Video Wall and Video Controllers

A video wall is a special multi-monitor setup that consists of multiple computer monitors, video projectors, or television sets tiled together contiguously to form one large screen. In the Smart Mobility Management Center, two video walls are installed in the largest open space area to provide a high-resolution presentation of real-time traffic conditions to support the operation and management of the SMTG testing ground. The video wall system can be divided into two different components based on the functionality: video wall and video wall controller. The details of the video wall and video wall controller will be demonstrated in the following sections.

Video Wall

The location of the video walls is selected to provide the best display and presentation, as well as to associate with electrical and network systems in the building. Figure 31 and figure 32 indicate two options for the location of video wall installation, which either is arranged in the large free space area.

The entire video wall consists of a 4x2 flat landscape video wall and an 8x2 round portrait video wall, with every 4 monitors connected with a daisy chain in each. Peerless FPZ-600 floor stands are used to support the video wall. Two PCs are used to handle the signal input for the two video walls respectively. With all the equipment setup, the video wall has the capability of providing 3840 x 2160 (4K) displays across all the monitors.

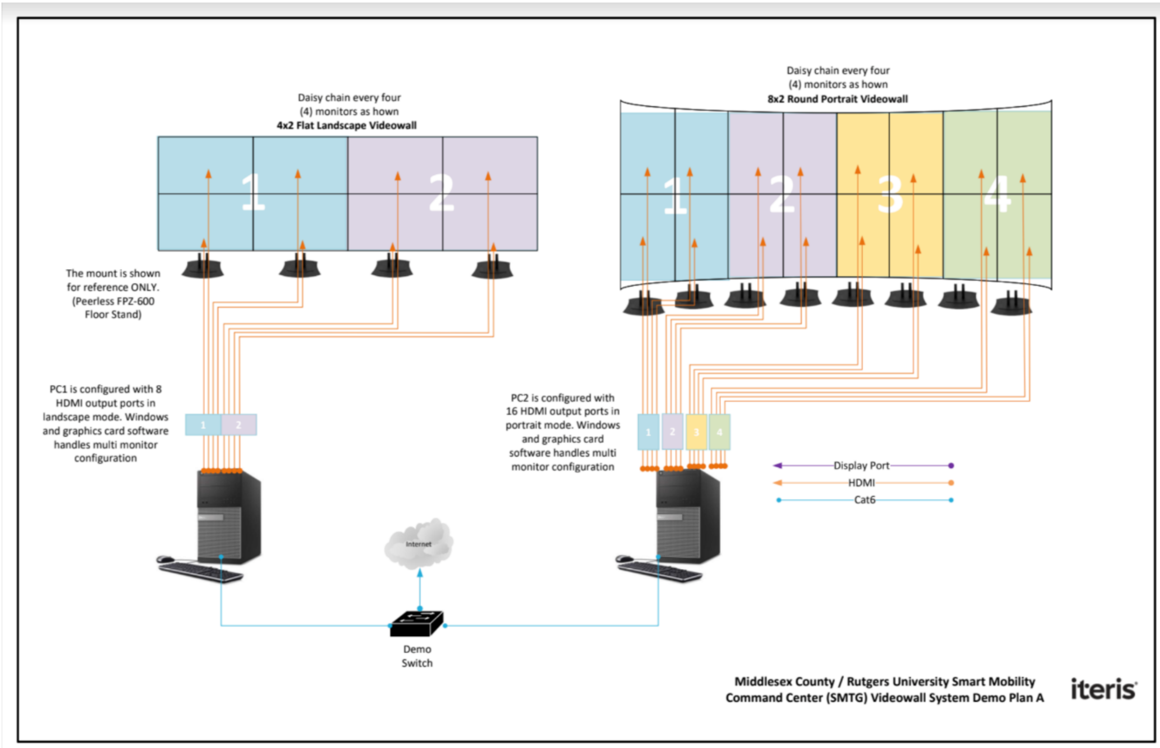


Figure 31. Video Wall System Plan A

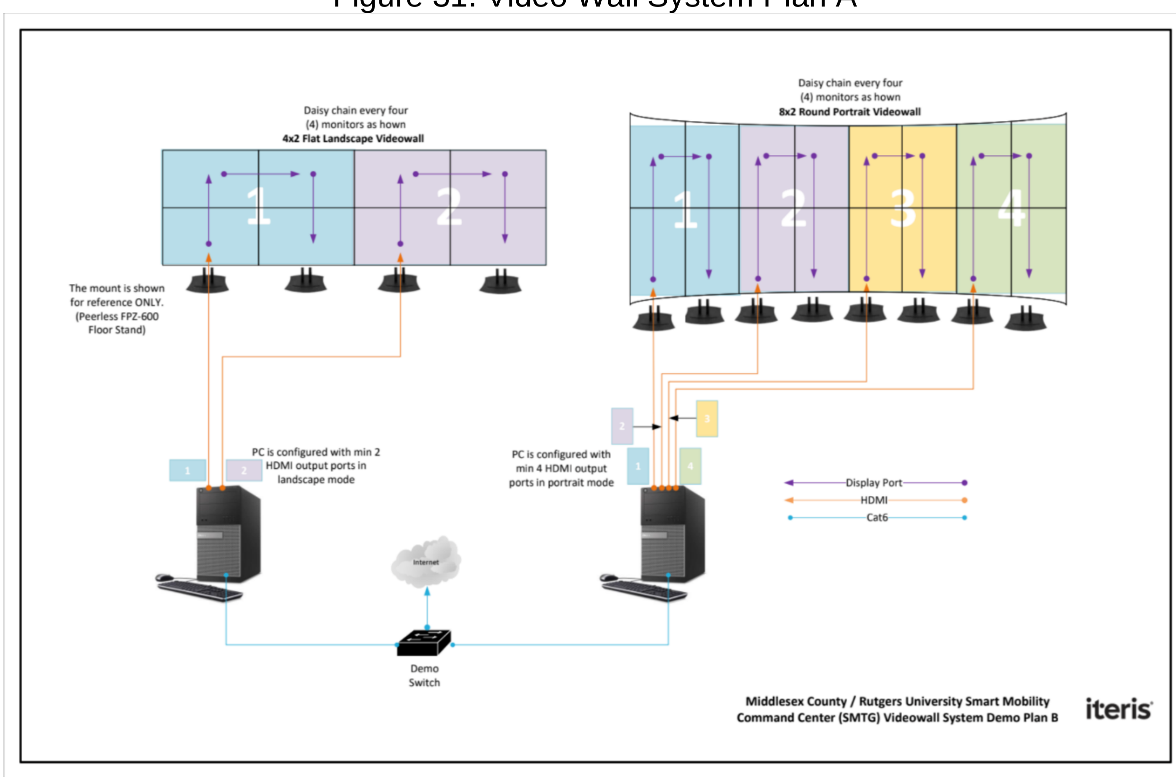


Figure 32. Video Wall System Plan B

Video Controller

A video wall controller (also called “processor”) is a device to splits a single image into parts to be displayed on individual screens. To provide high-quality video display support, a video controller with favorable features such as high-performance video windowing, compatible input/output, easy display control, and simplified setup is required. The Smart Mobility Management Center used Crestron HD-WP-4K-401-C to achieve all the desired functionalities. It is a 4K multi-window video processor with HDBaseT & HDMI outputs. It enables the display of up to four video sources simultaneously on a single HD, Ultra HD, or 4K display. Parallel HDMI® and HDBaseT® outputs provide flexible connectivity for the display device and other equipment. Input sources up to 4K are supported via four HDMI inputs. Fully automatic operation enables use without a control system, while enhanced operation and custom functionality can be attained through integration with a Crestron® control system. Additionally, video windowing enhances the presentation and collaboration capabilities of any meeting space, allowing multiple presentation sources to be connected and displayed together on screen. The Smart Mobility Management Center can benefit from the use of video windowing, expanding the facility’s display capabilities while saving costs by allowing more video sources to be viewed on fewer display devices. The look of Crestron HD-WP-4K-401-C Video Processor is displayed in figure 33.

HD-WP-4K-401-C front view

HD-WP-4K-401-C rear view

Figure 33. Crestron HD-WP-4K-401-C Video Processor

CCTV Traffic Monitoring and Living Lab Capabilities

With all devices and functionalities, the Mobility Management Center provides the capability of CCTV traffic monitoring to be used by Middlesex County representatives to perform traffic monitoring, operation, and management. Figure 34 demonstrates the traffic monitoring functionalities demo with the Living Lab application.

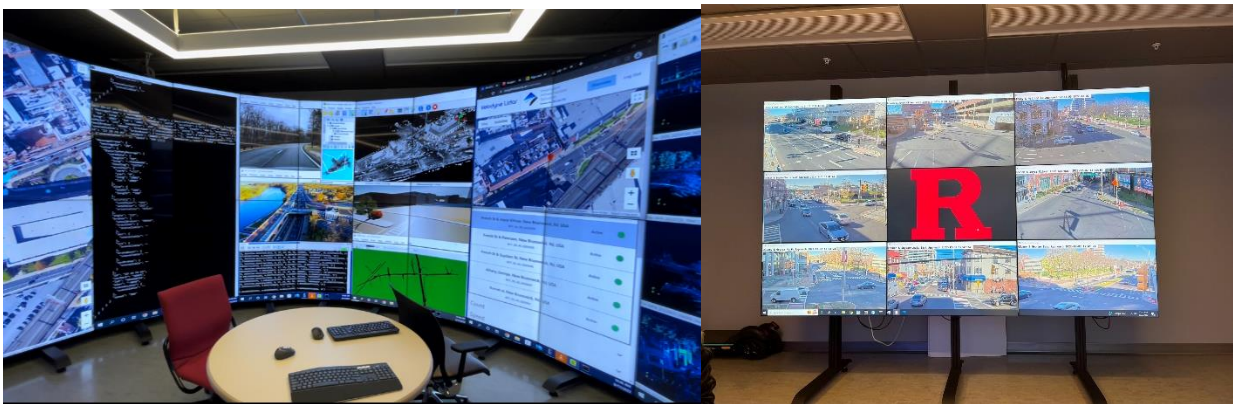


Figure 34. Real-Time Traffic Monitoring in Living Lab

TASK 4: TESTING VEHICLE AND INFRASTRUCTURE DATA COLLECTION AND MODELING

Building Information Modeling (BIM) involves not only 3D virtual design but also the integration of embedded information and data throughout the project lifecycle. With BIM to Extended Reality (XR) workflow, can interactively visualize the proposed design with human scale and immersive experience. (1) Users can interact with the 3D information model on top of the physical space by either superimposing the different design options within the existing job site condition or reading additional information that does not exist in the real world. The BIM-to-XR process requires a platform/system for sharing data and collaboration information and enabling real-time communication among different stakeholders/users. The most popular and easy-to-use systems are cloud-based systems such as Autodesk BIM360 and Autodesk Viewer. These systems combine data in a BIM model according to categories such as model, schedule, sheets, text, and so on, and indifferent exchange format. Files can be communicated and shared through these main databases.

Workflow for Infrastructure Data Collection

To support BIM-to-VR research, a workflow is first needed to build digital models of the real world. In this project, we build the digital infrastructure world following the steps of workflow shown in figure 35.

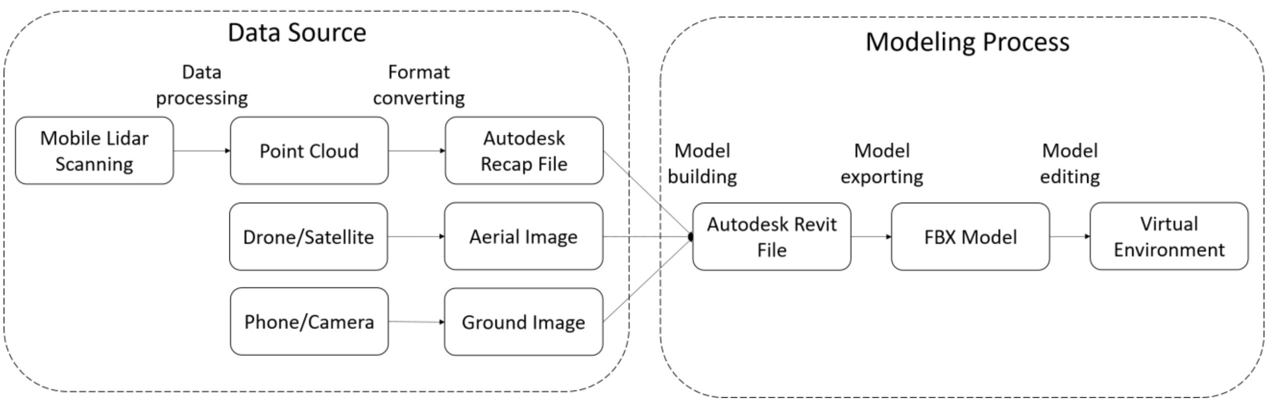


Figure 35. Scan-to-Model Workflow for Infrastructure Data

In this project, the "scan-to-model" workflow initiates with mobile LiDAR scanning. This scanning process yields point cloud data encompassing all collected infrastructure details. Additional public resources will be leveraged to support infrastructure modeling, and the subsequent phase involves utilizing Autodesk Revit Software to construct the infrastructure model for downtown New Brunswick. The output of the Revit is a Filmbox (FBX) model file, which can be easily edited and formatted for further development.

Mobile LiDAR Scanning of New Brunswick Downtown

The New Brunswick downtown section of New Jersey Route 27 was scanned by our mobile LiDAR scanning van, which was equipped with Zoller+Fröhlich (Z+F) Profiler LiDAR scanner, and Applanix POS LV Position and Orientation System.

The Z+F Profiler Lidar scanner (see figure 36) is a two-dimensional (2D) profile scanner that has a scan rate of more than 1 million points per second and a maximum scan speed of 200 profiles per second and is capable of scanning very short distances between profiles at high speed. It is a compact high-speed phase-based laser scanner with great precision, 119 meters range, and a 360° field of view/. Since the 2D profiler can only scan in the 2D plane of the laser head, to cover the 3D space, the scanning data needs to be combined with the trajectory data collected by the position and orientation system to produce a 3D point cloud.

Figure 36. Zoller+Fröhlich (Z+F) Profiler LiDAR

The Applanix POS LV (see figure 37) is a compact, fully integrated, turnkey Position and Orientation System, that utilizes integrated inertial technology to generate stable, reliable, and repeatable positioning solutions for land-based vehicle applications. It mainly relies on the Global Navigation Satellite System (GNSS) satellite signals of GPS + GLObalnaya NAvigatsionnaya Sputnikovaya Sistema in Russian (GLONASS) + Galileo + BeiDou + Quasi-Zenith Satellite System (QZSS) + Indian Regional Navigation Satellite System (IRNSS) + L-Band / mobile satellite service (MSS) / satellite-based augmentation system (SBAS) to locate the position and orientation of the Lidar sensor. When it encounters a GNSS signal outage such as when driving through dense buildings, overpasses, or tunnels, the system also uses external devices known as distance measurement instruments (DMI) and inertial measurement units (IMU) to continue the position and orientation recording.

Figure 37. Applanix Position and Orientation System Components

All equipment was installed on the same vehicle with fixed relative positions to ensure the accuracy of data collection and processing. During the mobile scanning in the field (driving in the target area), the Z+F profiler collects the 2D scan image, and the Applanix Position and Orientation System records the trajectory data. (See figure 38.) Both data are saved on the collecting devices respectively and are connected by the timestamp on the millisecond level. By revisiting the position on each timestamp, we can get the corresponding scanning images for the infrastructure and build them together for the entire infrastructure modeling. To achieve this, this part of Route 27 was modeled by tracing the building and road dimensions in the point cloud.

Figure 38. Exterior of Mobile Lidar Scanning Vehicle

Origin Collected Point Cloud Infrastructure Data

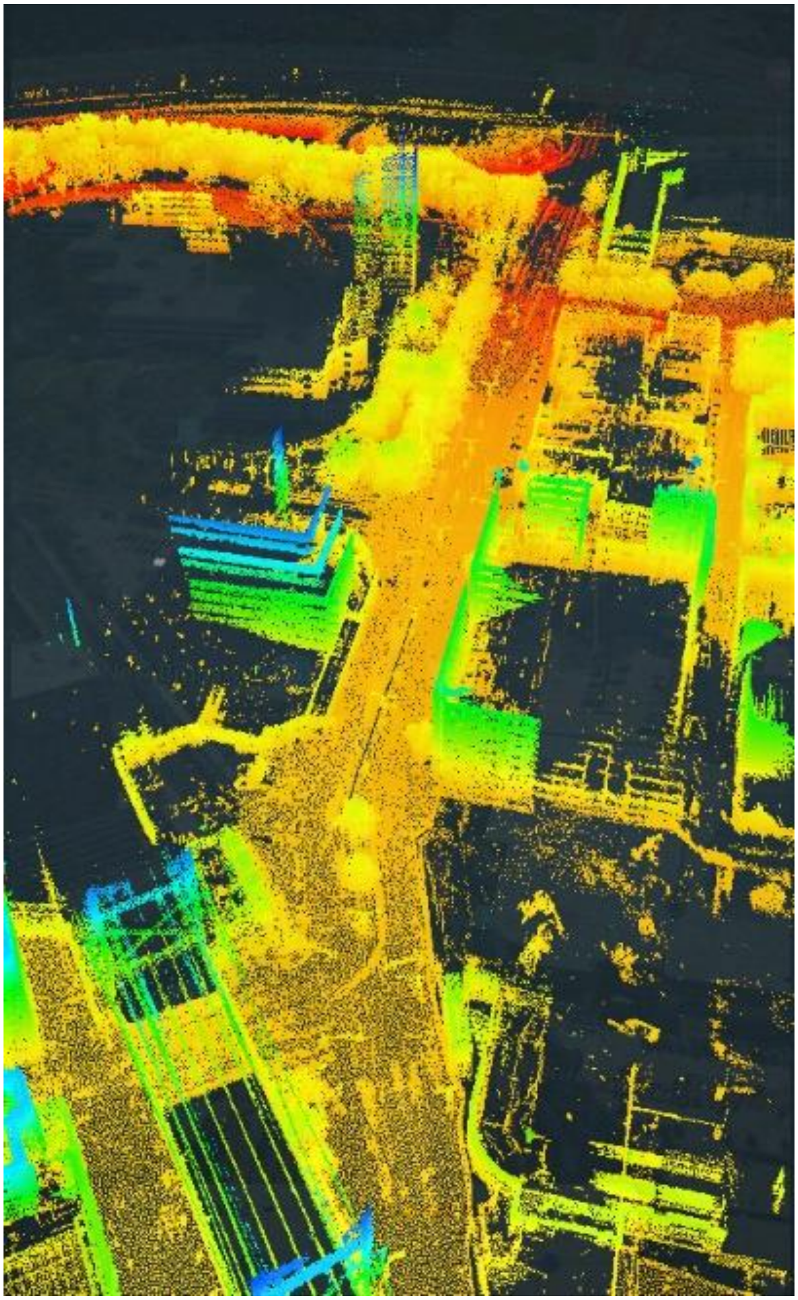


Figure 39. Raw Point Cloud Infrastructure Data of New Brunswick Downtown

The LiDAR data and trajectory of the scanning vehicle are uploaded to lab computers to be processed. After the data processing steps, the exported result is the point cloud file of the covered area in the format of ". las". The raw output of the Z+F profiler LiDAR is a kind of point cloud data set. A point cloud is a discrete set of data points in space. These points can represent 3D shapes or objects. Each point location has its own set of relatively Cartesian coordinates. It measures many points on the outer surface of surrounding objects. As an output from the 3D scanning process (see figure 39) even if it can roughly show the outline, shape, and other characteristics of the collected infrastructure, in many cases, it is still difficult to model buildings and environments solely based on point cloud data. First, the points in some places are relatively sparse, such as the top of the building, which is caused by the limitation of the scanning range. In addition, if the building is far away from the mobile scanning vehicle, such as the side and back of the building away from the road, it cannot be scanned. Also, the color of the point cloud is not related to the color of the real world. Therefore, we need to process the raw point cloud data into a good format that is more in line with the real world.

Additional Data Source for Infrastructure Modeling

As mentioned previously, the selected site's real-world buildings, roads, and scenery need to be reconstructed with real-world geometry information. Some additional data sources, most of them public, can be used as a reference to reconstruct the missing part of the infrastructure. Various images from satellites, drones, cameras, and mobile phones can be used as a reference for modeling. For example, the building address is 410 George St, New Brunswick, NJ 08901, since the building is right at the corner of the intersection, only two sides of the building can be scanned during mobile scanning. Therefore, the distance relationship between the satellite images and ground photos was used to approximate the background model to create a visually realistic background for this building. The images are shown in figure 40.

Figure 40. Aerial and Ground Image Reference Example

Autodesk Revit Software for Infrastructure Modeling

The modeling software Autodesk Revit is used to build the initial digital infrastructure. The Autodesk Revit needs the format of the Autodesk Recap (".rcp") as the input, thus we transfer the point cloud data needs into the ".rcp" data format. ".rcp" is a format used by Autodesk software to store spatially indexed point cloud data. When the point cloud in Recap format is imported into Revit, the 3D view of the point cloud is shown in figure 41. It is worth mentioning that in Revit, the model is only black and white, we will mention how to color the model later. Many details, such as building windows and plant outlines, can already be seen in the ".rcp" format.

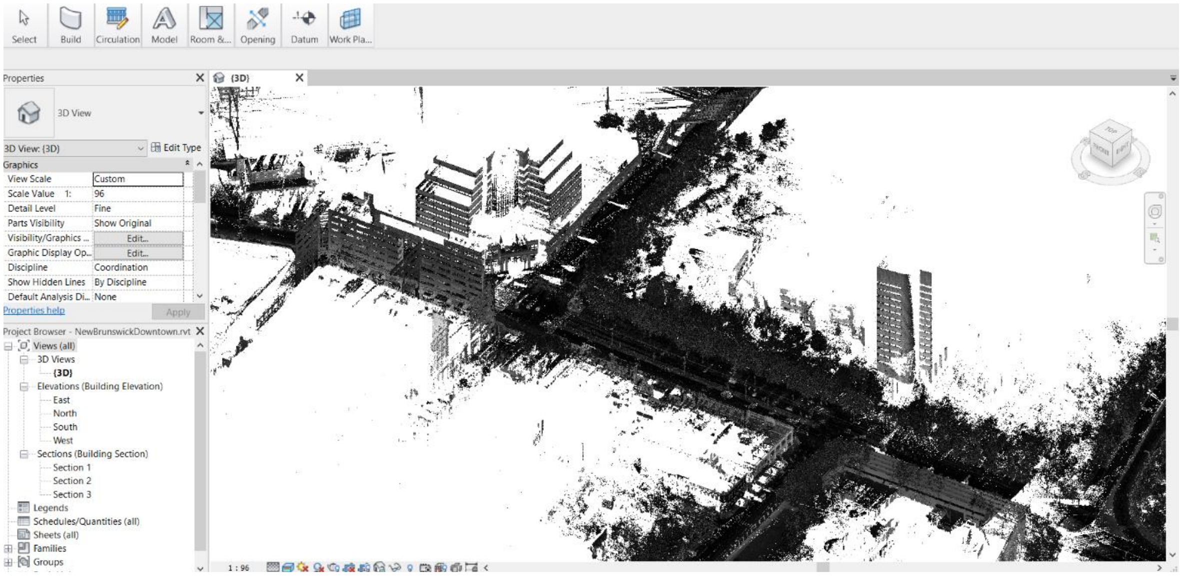


Figure 41. Autodesk Recap Format Point Cloud Loaded in Autodesk Revit

The recap data of the New Brunswick downtown still lacks so many features that are far away from the road or scanning shortage of the building. Therefore, we continue using the additional data resources to fill up the features in Revit manually.

There is another critical geometry issue that is difficult to find under the scanning. Route 27 road surface in New Brunswick downtown area is inclined, and the buildings have different first level and top-level heights, so we are required to create different height levels to match the points cloud data for each infrastructure. More than 30 height levels were created in the section view of this model to match the point cloud data. Figure 42 is the horizontal viewing which shows the different height levels for the building in the part of the digital twin world area along the road.

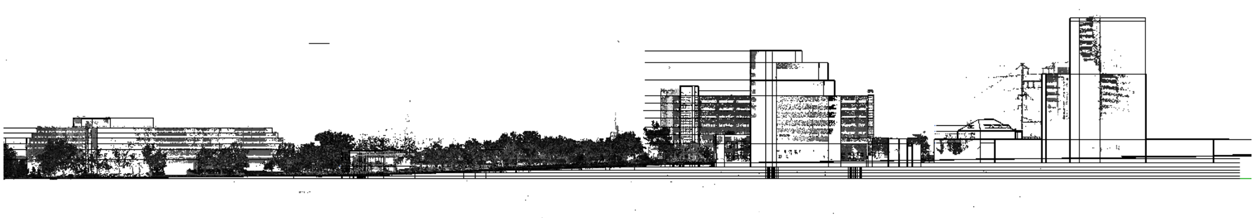


Figure 42. Side View of Created Height Levels in Autodesk Revit

To restore the real scene to the greatest extent, the inclined ground surfaces were divided into three main parts with different slopes that can be adjusted and fitted individually. Figure 43 shows that all ground surfaces were fitted to the point cloud in the side view.

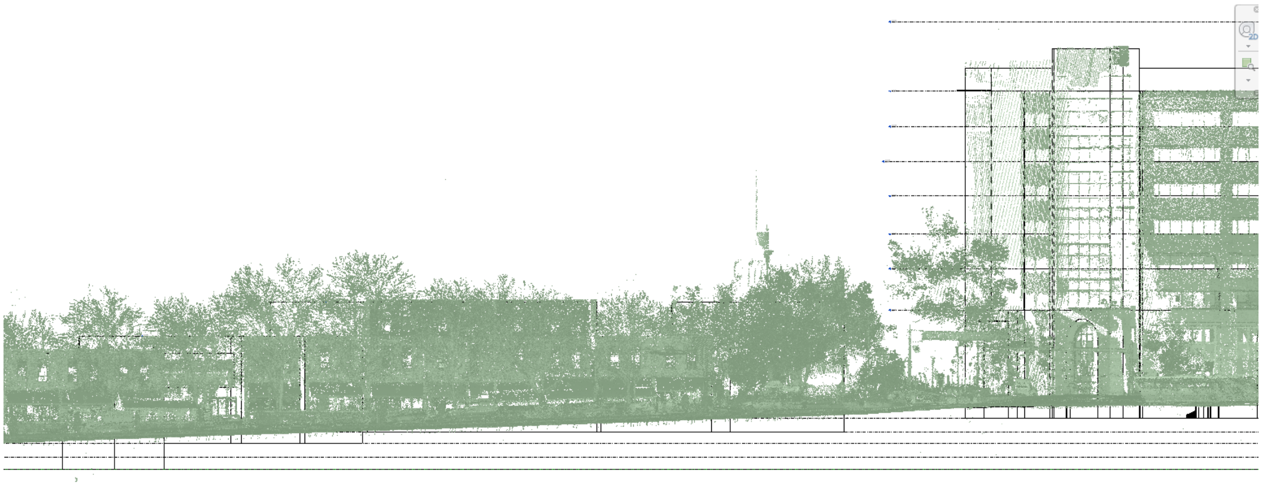


Figure 43. Adjusting Sloped Ground Surface According to Point Cloud

Finally, the facades of the buildings covered in the point cloud data are represented by models in Autodesk Revit. Figure 44 shows the parts of Route 27, and the buildings and landscapes along Route 27. The three main intersections are Easton Ave. & Albany Street, George Street & Albany Street, and Neilson Street & Albany Street. The outline and details of most of the buildings are completely consistent with the real world, there are only a few buildings that only have external outlines due to the lack of point cloud data, and their internal filling needs to be further added.

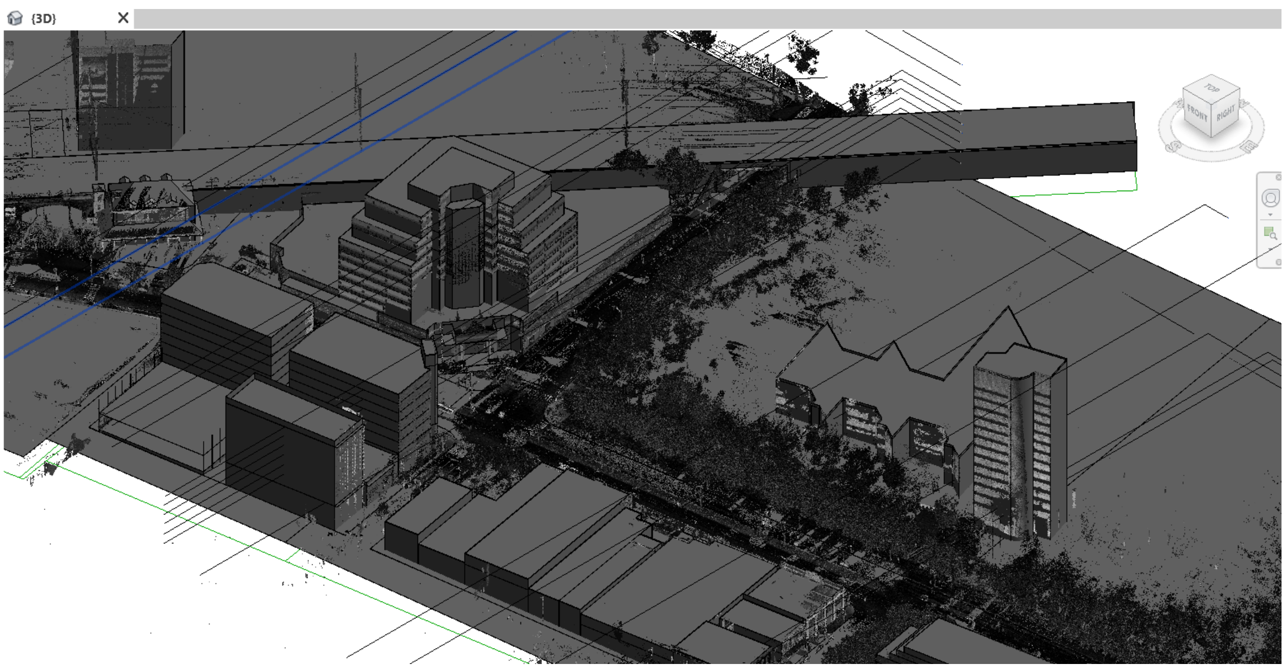


Figure 44. 3D View of Building and Road Surface Model in Autodesk Revit

Upon completing the basic building and ground geometry model, different ground types, such as asphalt roads and concrete sidewalks, are segmented. At this time, some detailed building components, such as windows, doors, chimneys, balconies, roof fascia, and external wall lights, can be added to match the real-world scene.

FBX File Format Output for Infrastructure Model

For the model exporting, the FBX file format, a proprietary file format was used to provide interoperability. Revit model was exported as an FBX file to be compatible with the Unity/Unreal game engine. The final FBX model visual effect is shown in figure 45.

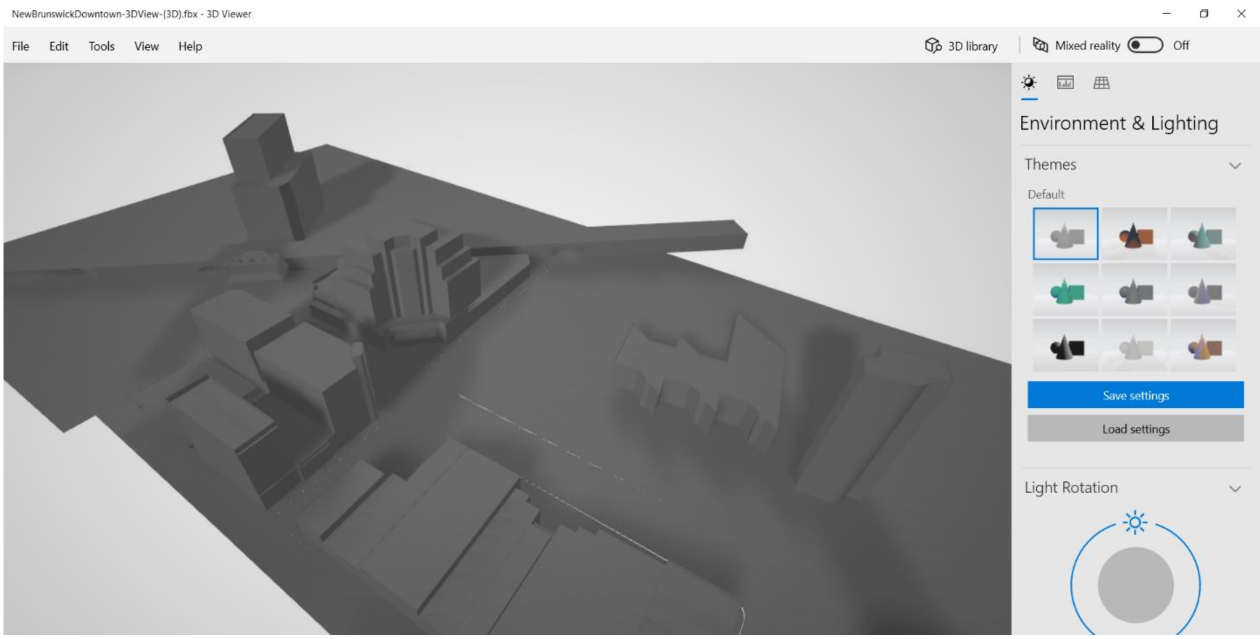


Figure 45. Example of FBX Format Infrastructure Model

Even though intuitively, the resolution or granularity of the infrastructure model is reduced, but the FBX format is a better form of interactive files, which can be called and processed by multiple engine software and can also be imported into most 3D visualization software. To obtain a better visual effect in a high-resolution tiles level, the material can be edited on different planes in the final editing environment. This model can then be used freely in a virtual environment for simulation or interactive research.

It can also be displayed as a wire frame in Autodesk Revit, but there are only black and white coloring and default textures. If you need to color and make real-world texture, such as asphalt for roads, or tiles for buildings, it is needed to import the FBX file to the Unity Engine for operation. Various images from open sources, such as satellites, drones, cameras, and mobile phones can be used as a reference for modeling in Unity. When we get the textures of these objects, we can import the textures into Unity, and then paste them on the surface of the object, so that these objects get the corresponding color and texture. (See figure 46.)

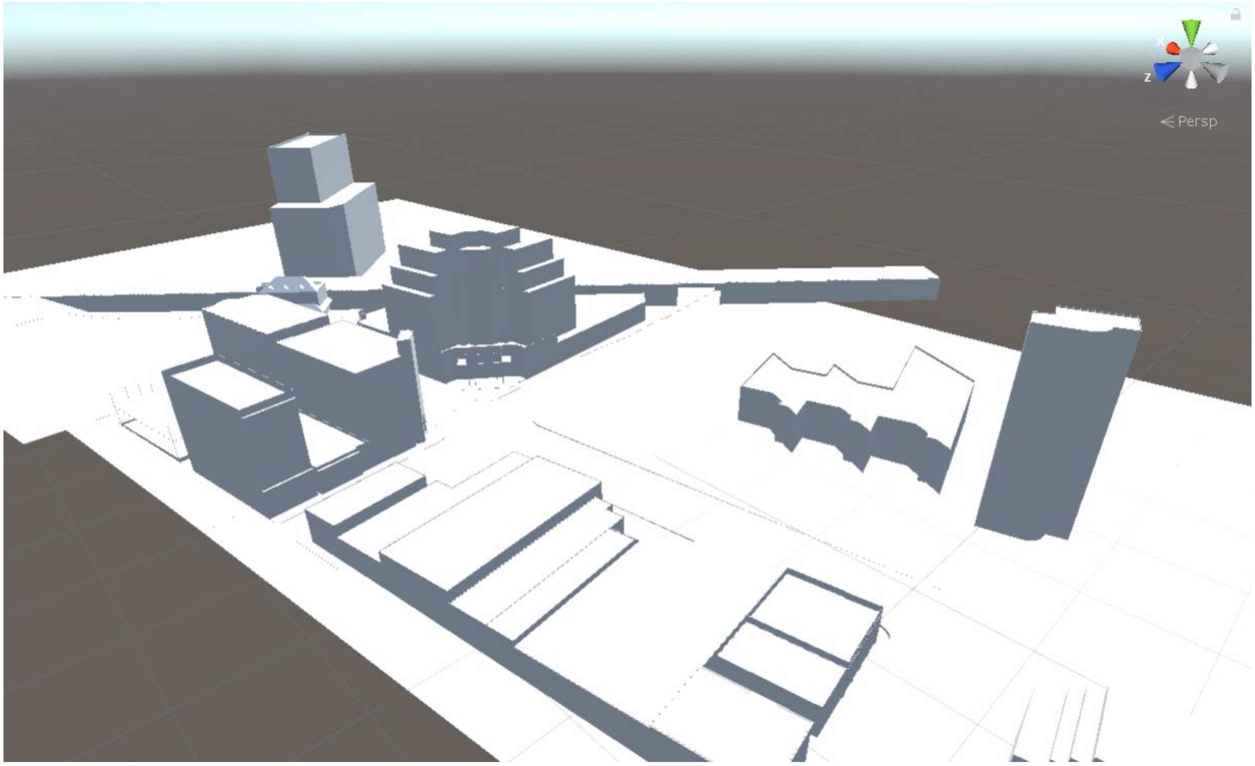


Figure 46. FBX Model in Unity (without Texture)

Depending on the specific usage, object textures were applied to the models in the Unity editor. (See figure 47 and figure 48.) Images from various sources were pasted on the building surface after editing steps such as cropping, stretching, and color adjustment. In the Unity editor, the operation process is to first import the picture into the asset library of the project and then drag the picture to the corresponding building component in the editor window, and the system will automatically generate the texture effect. Then the author manually adjusts the properties of the picture to obtain a suitable appearance.

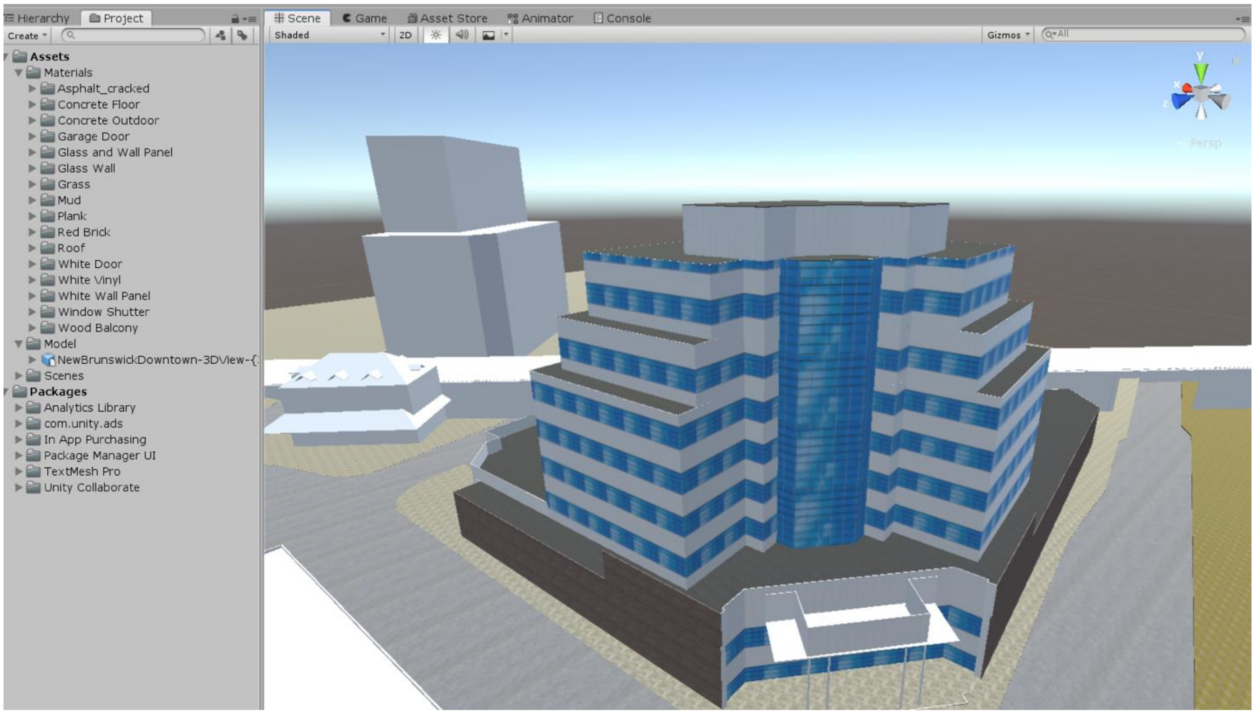


Figure 47. Import Texture Image for a Building into Unity and Apply to the Model

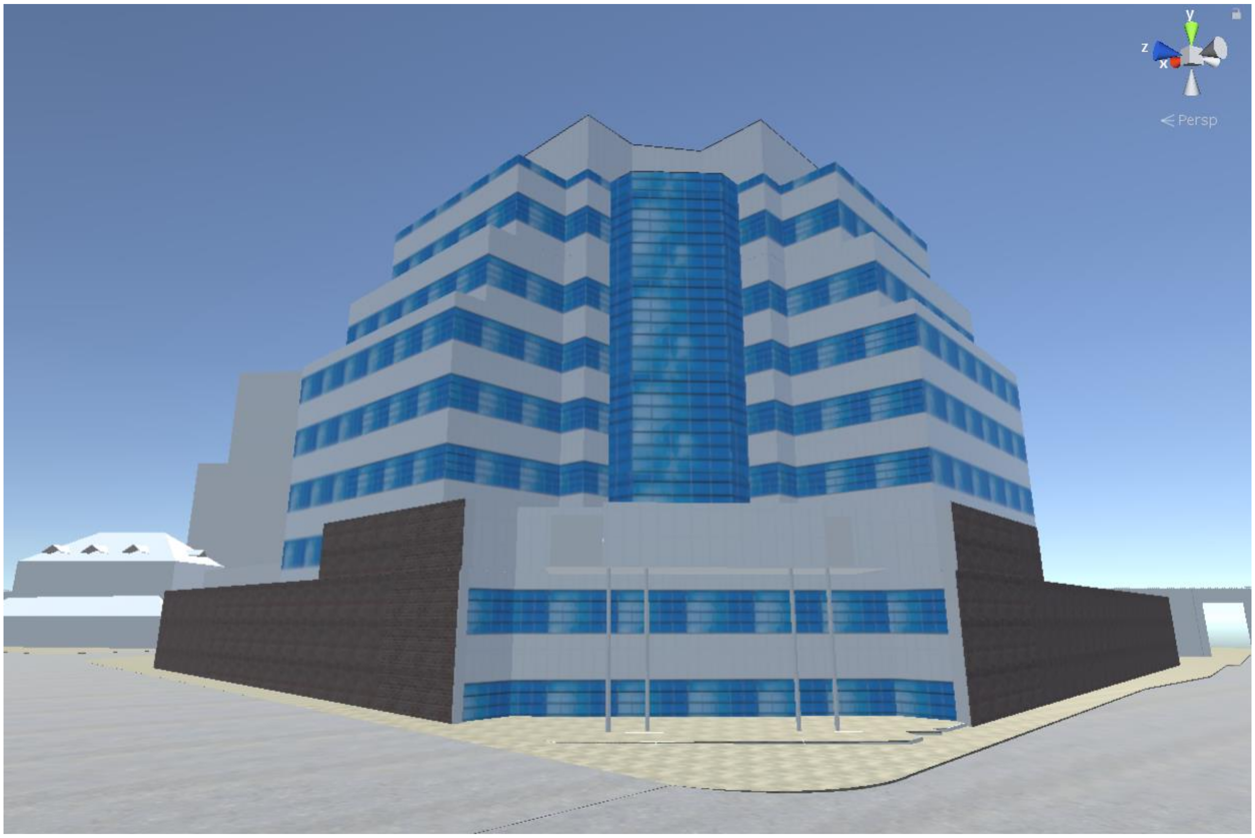


Figure 48. Example of Textured Building

On a larger scale, depending on the virtual environment's scenario setting, other environmental variables such as daylight, weather conditions, vegetation, and vehicles can also be added. The principle to follow is to make the virtual scene look realistic and not consume computer resources excessively.

TASK 5: CAV APPLICATIONS AND LEGISLATION

Connected Vehicle Reference Implementation Architecture (CVRIA) Architecture Diagram (Roadside Sensors to CAV Applications)

The Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) provides a common framework for planning, defining, and integrating intelligent transportation systems. (See figure 49.) It is a mature product that reflects the contributions of a broad cross-section of the ITS community (transportation practitioners, systems engineers, system developers, technology specialists, consultants, etc.).

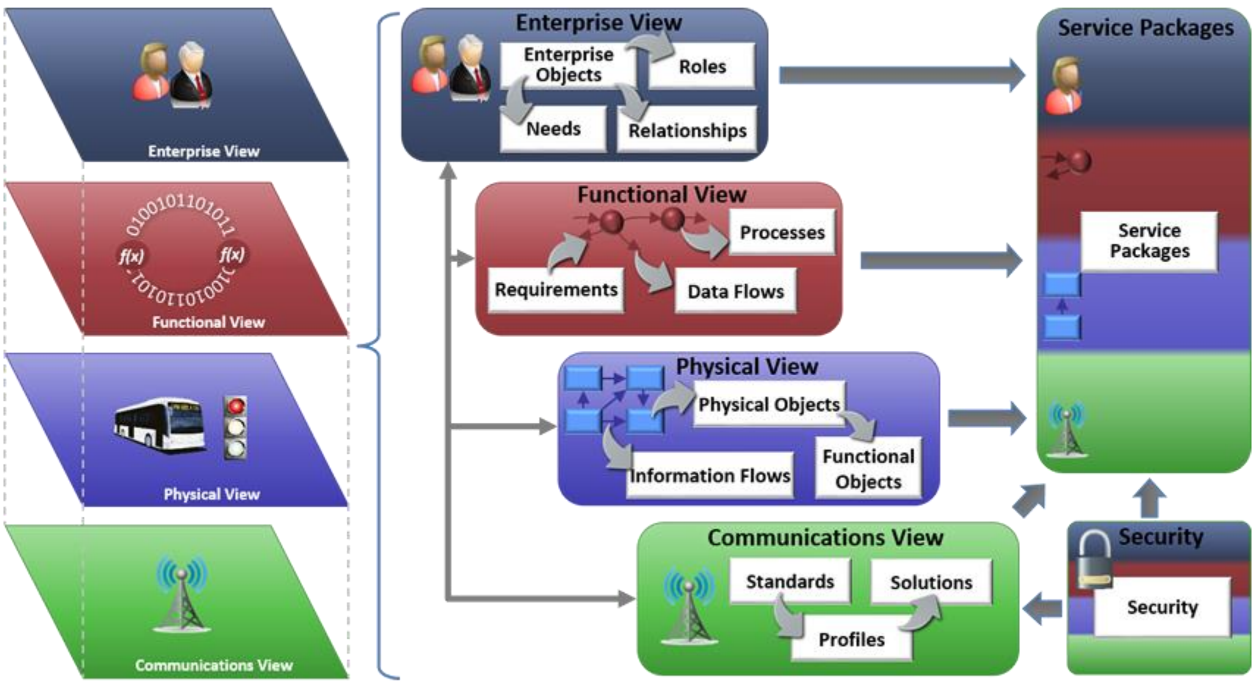


Figure 49. CVRIA Architecture Diagram

ARC-IT is a reference architecture, and it provides a common basis for planners and engineers with differing concerns to conceive, design, and implement systems using a common language as a basis for delivering ITS, but does not mandate any implementation. ARC-IT includes artifacts that answer concerns relevant to a large variety of stakeholders and provides tools intended for transportation planners, regional architects, and systems engineers to conceive of and develop regional architectures, and scope and develop projects.

Targeted CV Pilot Application Testing Capabilities

Table 2 - Targeted CV Pilot Application Testing Readiness Matrix

Metric	Application	RSU	OBU	MAP/TIM	BSM/PSM	SPaT*	Roadside App.	In-Vehicle Application
Safety	Pedestrian Crossing Assistance – Intersection	RSU/vRSU	SmartMobi/ Commsignia OBU	All intersections	LiDAR/ Dashcam	Route 27& Paterson	Iteris Vintage Edge Pedestrian signals	V2P conflict detection/alert
	Intersection Movement Assist – Near-miss	RSU/vRSU	SmartMobi/ Commsignia OBU	All intersections	LiDAR/ Dashcam	Route 27& Paterson	Left-turn/Right-turn/Pedestrian	V2V conflict detection/alert
	Collision Avoidance	vRSU	SmartMobi	All intersections	LiDAR/ Dashcam			V2V conflict detection/alert
	Forward Collision Warning (FCW)	vRSU	SmartMobi	All intersections	LiDAR/ Dashcam			V2V forward conflict detection/alert
	Blind Spot/Lane Change Warning (BSW/LCW)	vRSU	SmartMobi	All intersections	LiDAR			V2V multi-lane conflict detection/alert
	Cooperative Collision Avoidance	vRSU	SmartMobi	All intersections	LiDAR/ Dashcam			V2V platoon conflict detection/alert, CACC speed suggestion
	Pedestrian/Vehicle Alerts for Bus (Transit)	vRSU	Special Transit App	All intersections	LiDAR			B2V, B2P conflict detection/alert
Mobility	Emergency Vehicle Preemption	RSU	Commsignia OBU	All intersections	LiDAR		Preemption signal activation	Special Transit App
	Signal Priority (transit, freight)	RSU	Commsignia OBU	All intersections	LiDAR		Preemption signal activation	Special Transit App
	Dynamic Merge/Lane Change Assistance (DMA)	vRSU	SmartMobi	All intersections	LiDAR		Dynamic Merge Signs	Merging conflict detection/alert and merging planning
	Intelligent Traffic Signal System (I-SIG)	vRSU	SmartMobi	All intersections	LiDAR	Route 27& Paterson	ATSPM	MAP/TIM/SPaT reception and alerts
	Queue Warning (Q-WARN)	vRSU	SmartMobi	All intersections	LiDAR		Roadside queue warning sign	Queue estimation, Queue warning suggestion/display
	Dynamic Speed Harmonization (SPD-HARM)	vRSU	SmartMobi	All intersections	LiDAR		Dynamic speed limit sign	Dynamic speed limit suggestion/display
	Cooperative Adaptive Cruise Control (CACC)	vRSU	SmartMobi	All intersections	LiDAR/ Dashcam			CACC speed suggestion/display
Energy	Connected Eco-Driving	RSU/vRSU	SmartMobi/ Commsignia OBU	All intersections	LiDAR	Route 27& Paterson		Eco-driving speed suggestion/display

* Enabled at Albany & Paterson Intersection, blue-shared boxes require further development and coordination with application testing teams and agency teams.

Task 5 enhances the testing capabilities of the DataCity testing ground for current and emerging CAV applications. The readiness of the key components for various CAV applications at the testing ground is detailed in table 2. The team has successfully deployed both physical and virtual Roadside Unit (vRSU) systems and developed a prototype smartphone application, SmartMobi. This application can receive SAE J2735 messages, including MAP, TIM, SPaT, BSM, and PSM from both physical and virtual RSUs. Additionally, for targeted CV applications to be tested, the development of backend computing and analytical application interfaces is also necessary. The team has developed analytical interfaces for safety, near-miss analysis, and Automated Traffic Signal Performance Measures (ATSPM). To enable testing of all these applications, further on-demand development is required, along with coordination between application testing and agency teams for specific applications (as indicated by the blue-shaded cells in table 2).

Virtual RSU Implementation

At the instrument level, the sensors include two 2K Cameras and one 128-Beam LiDAR for both color and range data collection. As shown in figure 50, the two cameras and one LiDAR transfer the data for processing through the network switch device. The difference is that the video data are streamed to the Amazon Web Services cloud for Verizon to provide real-time Computer-Vision processing and generate and publish real-time BSM feed through VZMode. The LiDAR data is not streamed but processed through an edge computing device at the site. BlueCity Edge Processor (BCEP) receives and processes the raw LiDAR data and publishes the detection results in BSM format through both VZMode Virtual RSU and BlueCity API. Meanwhile, the Nvidia Jetson Orin archives raw LiDAR data for future analysis.

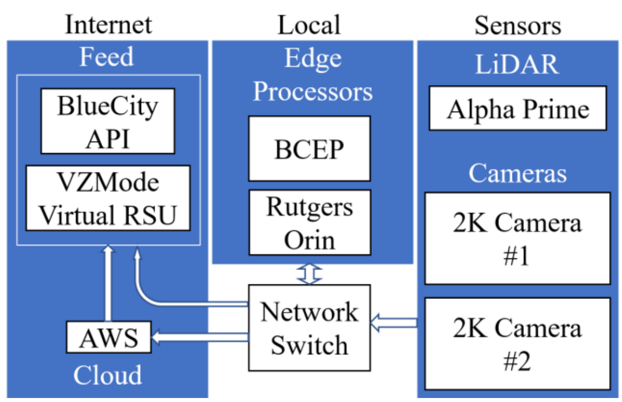


Figure 50. Diagram of System Components and Their Functionality

Data Flow and Sample Outputs

VZMode is a system for routing messages between clients, which targets messages to clients based on their geo-position instead of overloading them with extraneous messages. VZMode mainly serves three types of clients, entities on the road, infrastructure, and software-based clients. Each client will be assigned one unique ID and will be sending and receiving messages through MQ telemetry transport (MQTT), the standard for IoT messaging developed by IBM. In this project, the Verizon team has established a MQTT server to receive and publish BSM and both provided a demo BSM feed for real-time traffic video processing of the northbound camera located at Albany Street & George St and assisted BlueCity AI to publish their BSM feed through VZMode.

The following shows a received BSM message generated by Verizon and published through VZMode. The data source is the northbound camera located at Albany Street & George Street:

{"MessageFrame": {"messageId": "20", "value": {"BasicSafetyMessage": {"coreData": {"size": {"width": "120", "length": "300"}, "msgCnt": "32", "lat": "404966518", "long": "-744445028", "elev": "-4096", "speed": "0", "heading": "7200", "accelSet": {"long": "2001", "lat": "2001", "vert": "-127", "yaw": "0"}, "id": "24 59 8E 86", "secMark": "24819", "accuracy": {"orientation": "65535", "semiMajor": "255", "semiMinor": "255"}, "angle": "127", "transmission": {"unavailable": ""}, "brakes": {"traction": {"unavailable": ""}, "abs": {"unavailable": ""}, "scs": {"unavailable": ""}, "brakeBoost": {"unavailable": ""}, "auxBrakes": {"unavailable": ""}, "wheelBrakes": "00000"}}}}}}

Where "messageId" is the ID of the message, "width" and "length" are the vehicle/other road user's dimension, "msgCnt" is the count of the message, "lat", "long", "elev", "speed", and "heading" are the latitude, longitude, elevation, speed, and heading of the road user. In terms of the "accelSet", it contains a four-way acceleration set, including "long", "lat" for horizontal acceleration, "vert" for vertical acceleration, and "yaw" for yaw rate. "id" is the road user ID for tracking, "secMark" is the mark for second. In terms of "accuracy", it provides "orientation", "semiMajor", and "semiMinor" of the road user and there is an "angle" in addition to the orientation. If the roaduser supports, it may also report the status of "transmission", "brakes", "scs", "brakeBoost", "auxBrakes", and "wheelBrakes".

The following is an example of the MQTT BSM feed generated by BlueCity AI and published through VZMode. The data source is the LiDAR from Suydam Street & French Street:

{"MessageFrame": {"messageId": 715, "value": {"BasicSafetyMessage": {"coreData": {"msgCnt": 715, "id": "00 00 6b 72", "secMark": "57090", "lat": "404921584", "long": "-744531998", "speed": "87.0", "heading": "0", "angle": "3.0643554687499996", "size": {"width": 21.536458333333333, "length": 47.473958333333333}}}}}}

The Rutgers team worked closely with the Verizon team to subscribe to the real-time BSM feed from both the camera source from Albany Street & George Street provided by Verizon and the LiDAR source from French Street & Suydam Street provided by BlueCity AI. To locate the correct feed, a web address and port number are required to find the server of the MQTT broker, and then a topic is required to locate the specific feed. Meanwhile, to keep the feed secure, a user account and the corresponding password are used to authenticate the subscription of the feed. The feeds are being received and archived in the Rutgers server in real time and are ready for any safety analysis. There is also a mobile app that is being developed to receive and visualize the BSM nearby and potentially provide near-miss alerts.

Sensor Data Input and Processing (Video/LiDAR)

LiDAR is a modulated laser system that emits multiple laser beams and compares the time of return (TOF) or, frequency difference (Doppler frequency shift) of the signal, and then detects the position, velocity, and other measurements of surrounding targets. This technology can be utilized to extract high-resolution trajectories of moving pedestrians and vehicles on roads. Several studies on using LiDAR to analyze traffic conflicts corroborate the applicability of this method. The LiDAR deployed at the selected intersections helps to establish a 3D Digital Twin demonstration of the existing infrastructure and allows safety analysis to be conducted for varied conditions and scenarios. Moreover, real-time traffic count data, road user class, turning movement, and speed data are also made accessible. In the safety application testing program, LiDAR is utilized as a stationary observer to detect conflicts between vehicles and road users. For instance, LiDAR detection could identify near-miss situations at intersections and generate safety performances for signalized intersections. LiDAR sensor is not only an add-on to current detectors of signalized intersections but could also become an effective alternative to upgrade the legacy detection systems. Figure 51 shows that the LiDAR sensor is used to replace the traditional stop-bar detectors (video or induction loop) for lane-by-lane detections from all approaches. With the moving object trajectory and lane identification, we can properly draw stop-bar detection zones on a 2D bird-eye-view raster image and utilize LiDAR input as vehicle presence detection.

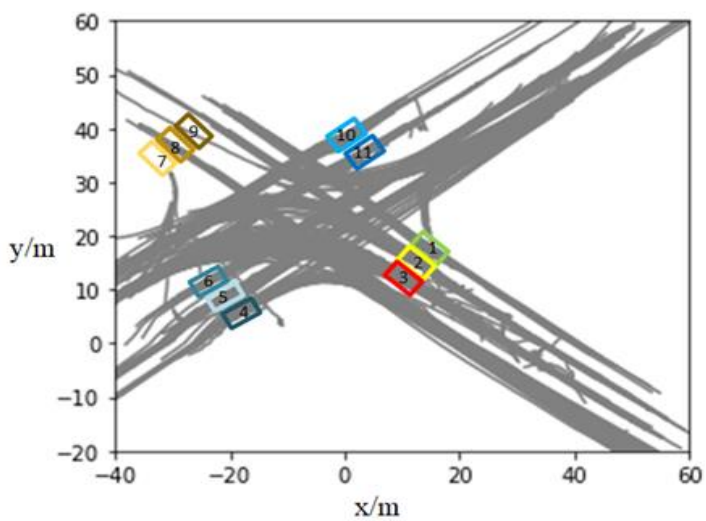


Figure 51. Using LiDAR as Stop-Bar Detectors for Signal Performance Metrics at a Signalized Intersection

Another advantage of using LiDAR as a stop-bar detector is that the LiDAR sensor has an accurate timestamp and does not have the latency issues found in traditional stop-bar detectors. Compared to video image processing, there is no significant distortion for the LiDAR sensor. The calibration process of the LiDAR-based stop-bar detector is much easier than the video image detector.

Traffic Conflict Detection and Metrics

Definition of Traffic Conflicts and Surrogate Safety Measures (SSMs)

The current practice of aggregate-level road safety analysis often fails to capture the actual crash causalities, and the safety impacts of time-dependent conditions at the operational level. Although advanced roadways and smarter vehicles would result in reduced crash occurrences, the severity of crashes are greater due to higher speeding tendencies by the drivers. The perceived enhanced sense of safety and comfort of driving encourage aggressive driving behavior, a primary factor in conflicts and accidents. With the abundance of high-quality real-time, high-resolution data, it has now become more feasible to understand road user behavior and identify fundamental defects in existing transportation infrastructure.

In response, a more proactive approach on safety improvement is gaining traction where road safety level is effectively assessed with surrogate safety measures (SSMs) used for identifying traffic conflicts, instead of actual crash events. In simple terms, a traffic conflict is "an observable event which would end in an accident unless one of the involved parties slows down, changes lanes, or accelerates to avoid collision".(2) Traffic conflicts are not crashes and can often be identified by evasive maneuvers of the road users. Each SSM is computed based on the occurrence of road user conflicts. Various surrogate measures of near-miss conflict events include time to collision (TTC), Instantaneous Time-To-Collision (ITTC), Post Encroachment Time (PET), Deceleration Rate to Avoid a Crash (DRAC), Maximum Speed and Speed Difference. (3, 4)

This serves as an intuitive, fast, and effective tool to assess the hazardousness of intersections under highly heterogeneous traffic conditions. Furthermore, traffic conflicts can be used to estimate the probability of crashes. Analysis of these conflict events aids in recommending effective countermeasures by evaluating their impact on safety.

Post Encroachment Time (PET) Definition and Calculation Methods

PET is an effective surrogate safety measure to understand the said traffic conflicts at intersections. It is described as "the time difference between the moment an "offending" vehicle passes out of the area of a potential collision and the moment of arrival at the potential collision point by the "conflicted" vehicle possessing the right-of-way". (5) (See figure 52.)

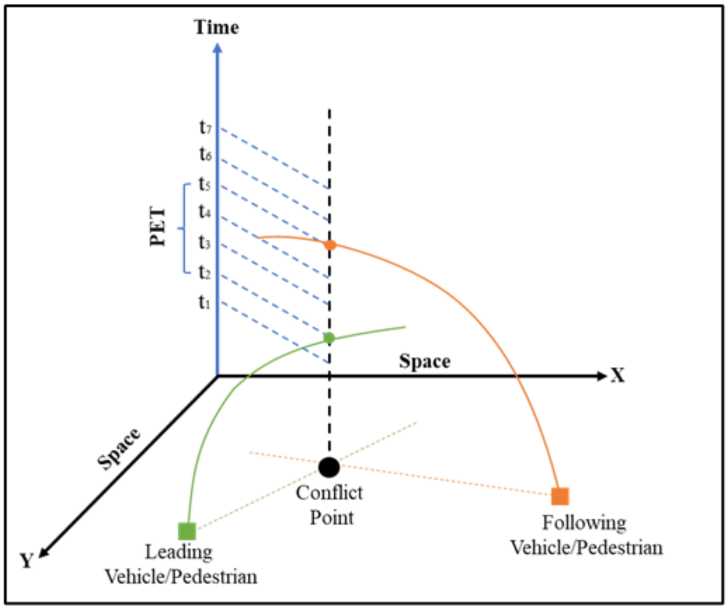


Figure 52. Time-Space Diagram to Calculate PET

PET applies only to moving, interacting vehicles or road users, and can be directly derived from their trajectories. It is more suitable for right-angle traffic interactions and can be related to the time gap between two consecutive vehicles in a car-following situation.

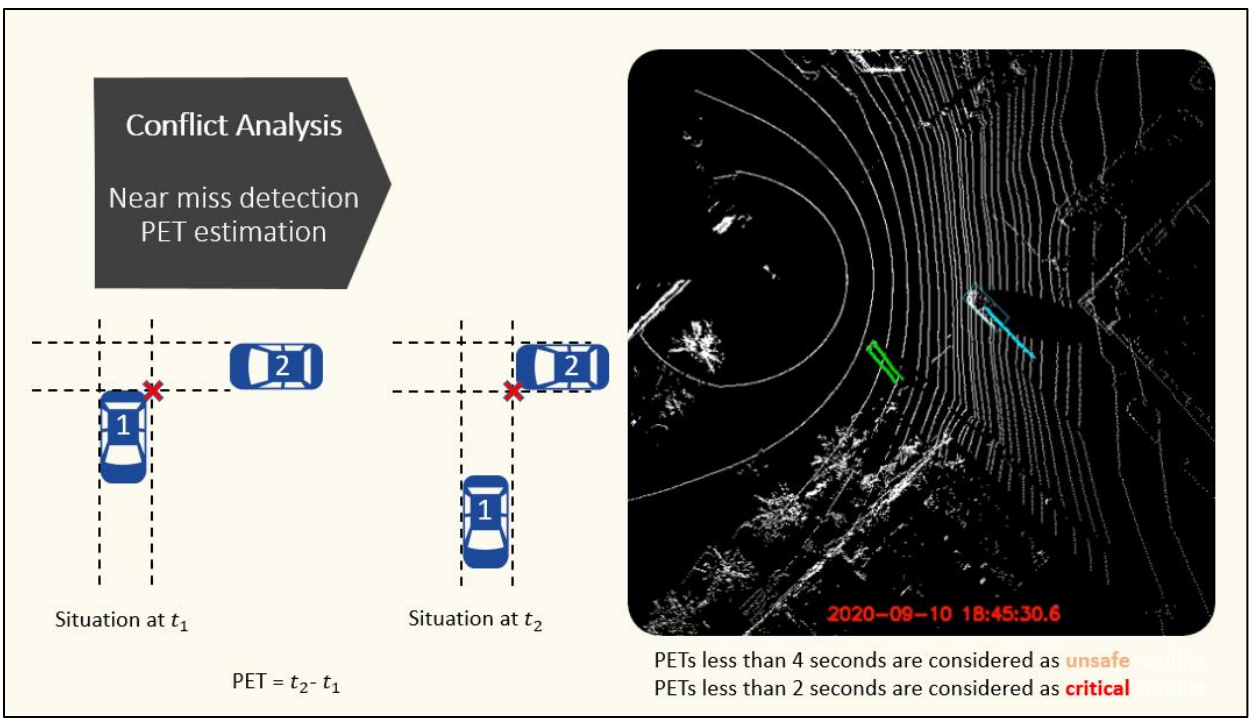


Figure 53. Estimating Post Encroachment Time (PET) for Near-Miss Detection

Figure 53 was generated from the extracted trajectory and object dimension data from roadside LiDAR. Here, Vehicle 1 is regarded as the leading vehicle, and Vehicle 2 is the following vehicle. The potential conflict point at this intersection is depicted with a red cross. The time headway between these two vehicles (e.g., $t_2 - t_1$) is defined as the PET.

As described in existing literature, PETs of less than 4 seconds are considered unsafe/possible conflict, and PETs of less than 2 seconds are considered critical or dangerous conflict. Critical conflicts demonstrate a higher probability of a crash occurrence and should be addressed accordingly.

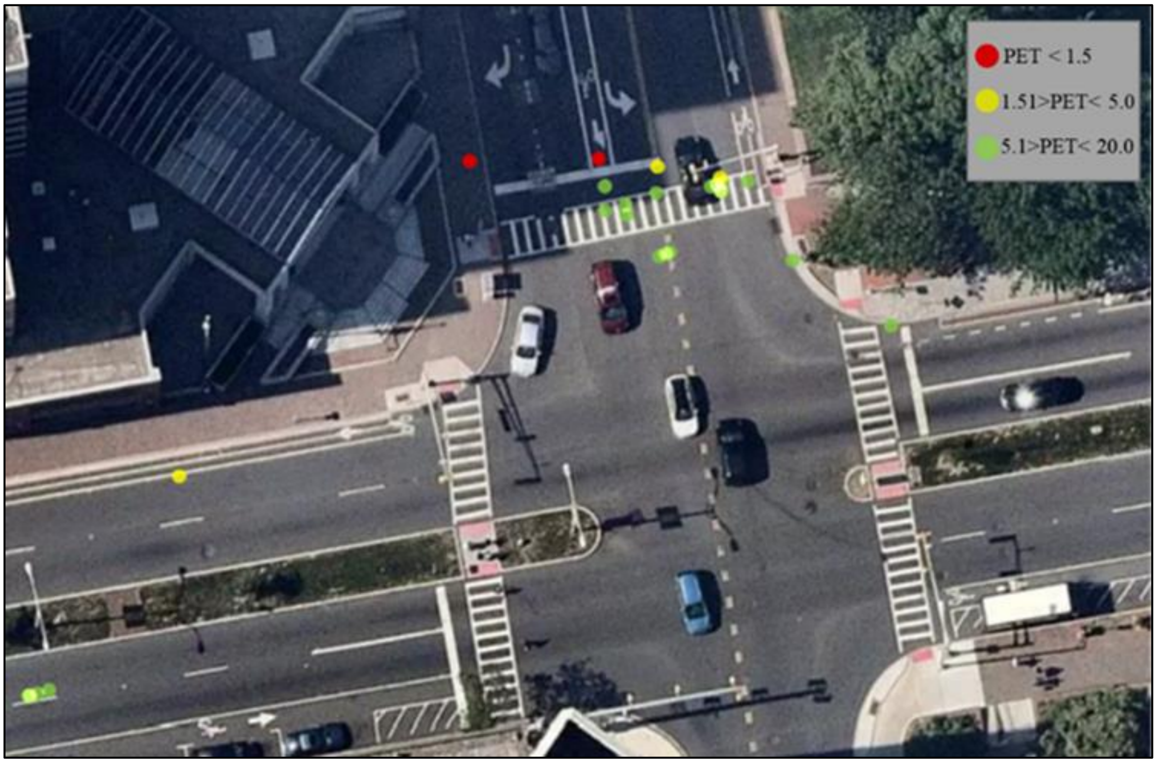


Figure 54. Spatial Distributions of Pedestrian-Vehicle Conflicts Points for Albany & George Street

Figure 54 shows the Spatial distributions of pedestrian-vehicle conflict points for Albany Street & George Street and table 3 lists the analyzed PET results for an hour of LiDAR data. Similar to the previous studies, PETs with less than 5 seconds and less than 1.5 seconds were regarded as potential conflict and dangerous conflict, respectively. [6, 7] The study also considered 20 seconds as the arbitrary threshold for identifying all potential risks for vehicle-to-pedestrian collisions at the intersection.

Table 3 - PET Results for Albany Street & George Street

PET Threshold (Seconds)	PET Events	Description
PET Events < 20	25	Arbitrary Count
PET Events < 5	5	Possible Conflict
PET Events < 1.5	2	Dangerous Conflict

The output from the LiDAR data was used to develop an interactive, user-friendly heatmap that can be modified to show the location of potential conflicts by selecting specific PET thresholds and speed values of vehicles. Moreover, details about conflicts can be retrieved by additional filtering of the type of road users (pedestrians, car, bus, bike, truck), turning movements, and time of conflicts.

BlueCity Platform Overview

Bluecity Analytics Platform is an easy-to-use and customizable analytics platform to monitor and visualize traffic data such as multimodal count data, speed and conflict analytics, automated traffic signal, performance measures at selected intersections in real-time. (8)

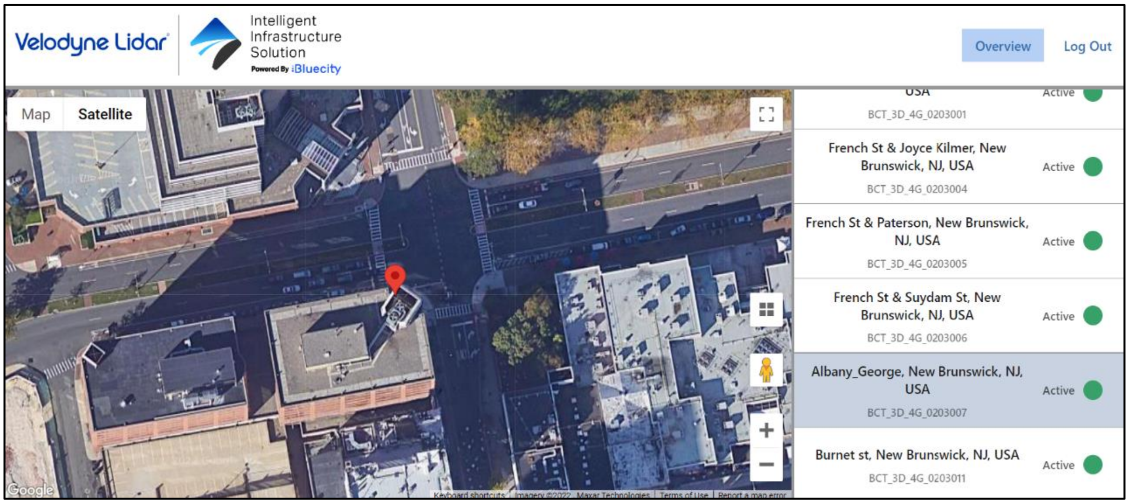


Figure 55. BlueCity Analytics Platform

The "Overview" page (see figure 55) presents various intersection options to select from and displays the corresponding analysis results. The satellite map view for a particular intersection can be displayed by clicking on it from the top right pane. The “green dot” next to the intersection name indicates whether the sensors are currently active at that location. Figure 56 and figure 57 illustrate the traffic data and performance measures that can be accessed and viewed by selecting the specific options. The tool is useful in viewing real-time classified traffic counts and speed data that are extremely critical for transportation planning purposes.

Count
Speed
Conflicts
PET Rate
Red Light Runner
Outside of Crosswalk Events (OCW)
Occupancy Ratio
Green Allocation
Phase Interval
Split Trends
Split Failure
Simple Approach Delay
Arrival Patterns

Figure 56. Different Performance Metrics

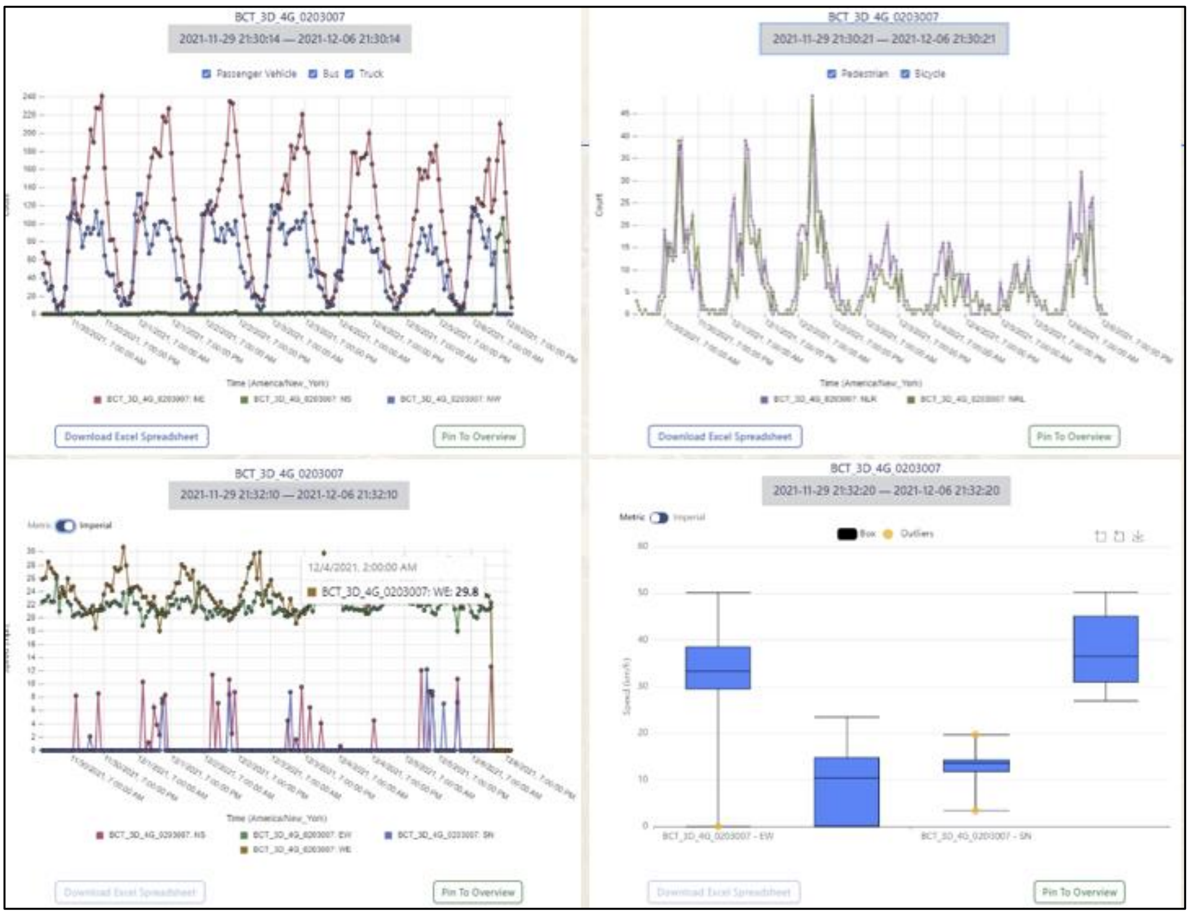


Figure 57. Real-Time Access to Traffic Count Data for Planning

Near-Miss Heatmap

An example of viewing the interactive near-miss heatmap is shown in figure 58. First, the Albany & George intersection was selected from the top-right pane, and then from the bottom pane “Conflicts” option was expanded to view the analytics. The analysis period can be tweaked by clicking on the dates at the top. The type of conflict can also be specified by toggling the sliders and checking the desired checkboxes. The dynamic sliders for “Speed” and “PET” can be altered to display the changes in conflict heatmaps.

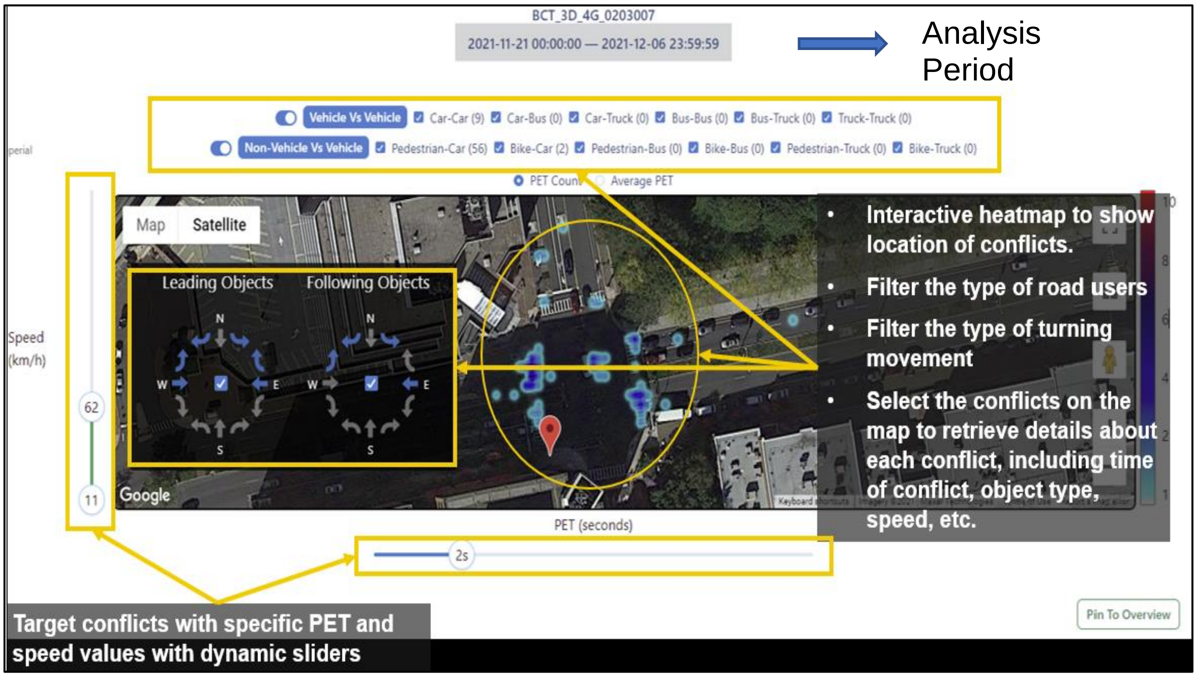


Figure 58. Interactive Heatmap for Potential Conflicts at Intersections

Near-Miss Playback

A real-life near-miss situation is illustrated in figure 59. In the left-most image, one vehicle is stopped at the stop bar and the other vehicle is maneuvering to take a left turn. In a near-miss scenario, the vehicles are at their closest point and finally, the right-most image shows the vehicles at a safe distance again. While near-misses are not crashes, they could escalate to crash events if any parameters change.

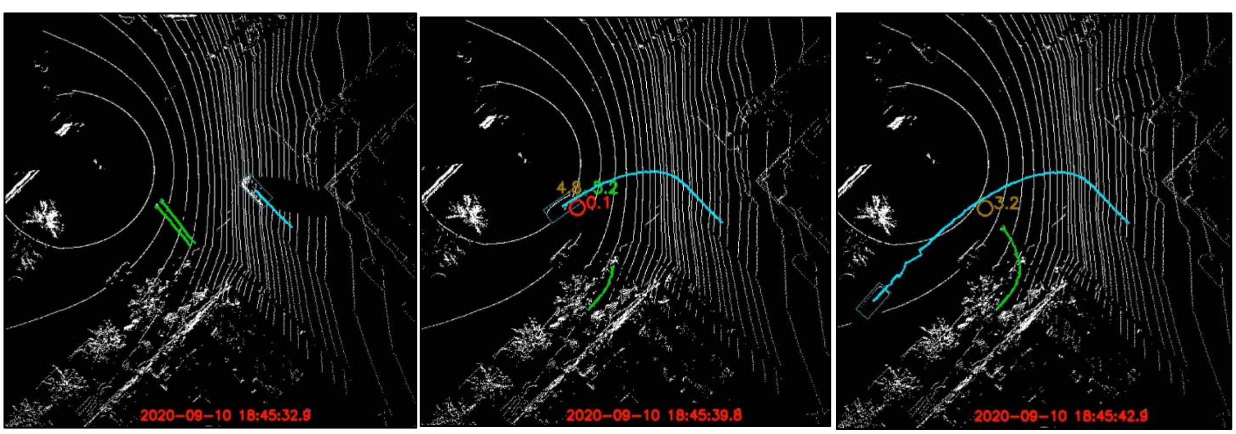


Figure 59. Near-miss Case: Before, at the Closest Point and After

Other Signal Performance Metrics

Apart from traffic count, speed, and conflict data, various signal performance measures such as green allocation, phase interval, split trends, split failure, simple approach delay, etc. can be viewed by clicking on the correct options. (See figure 60 to figure 63.)

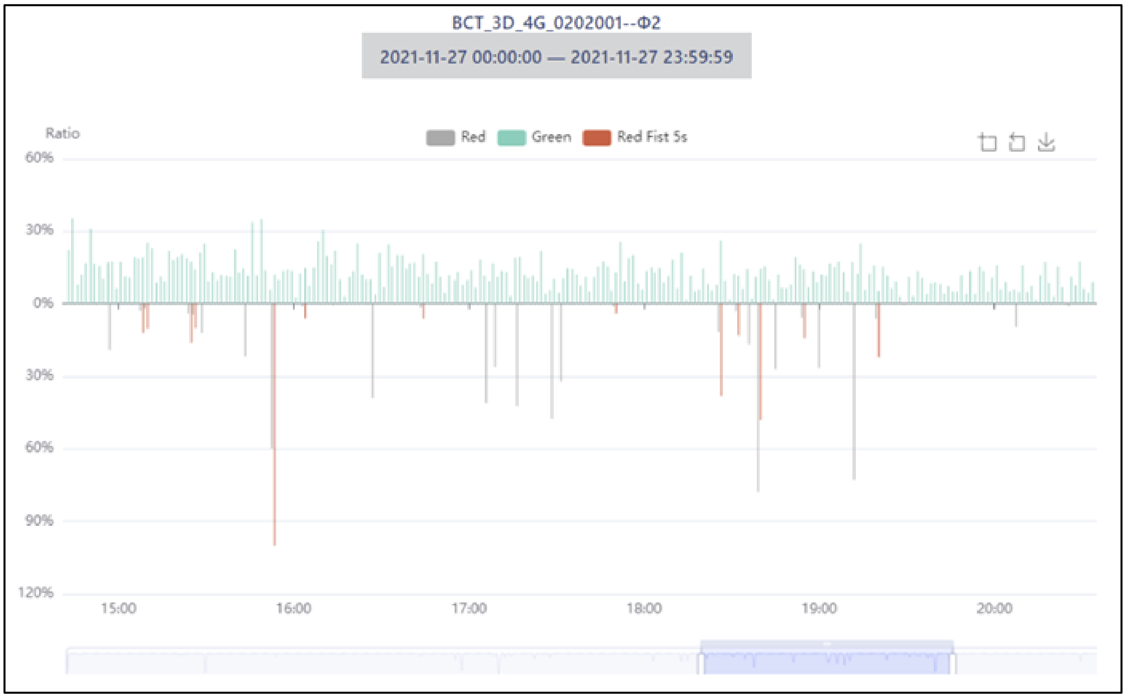


Figure 60. Occupancy Ratio

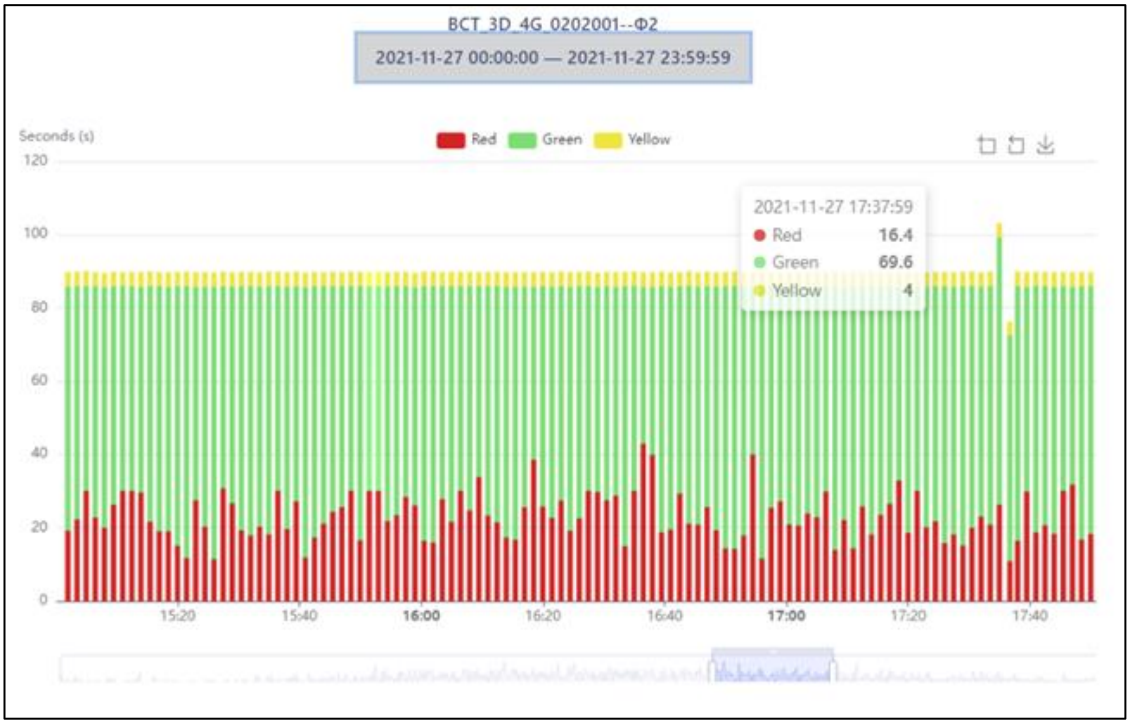


Figure 61. Phase Interval

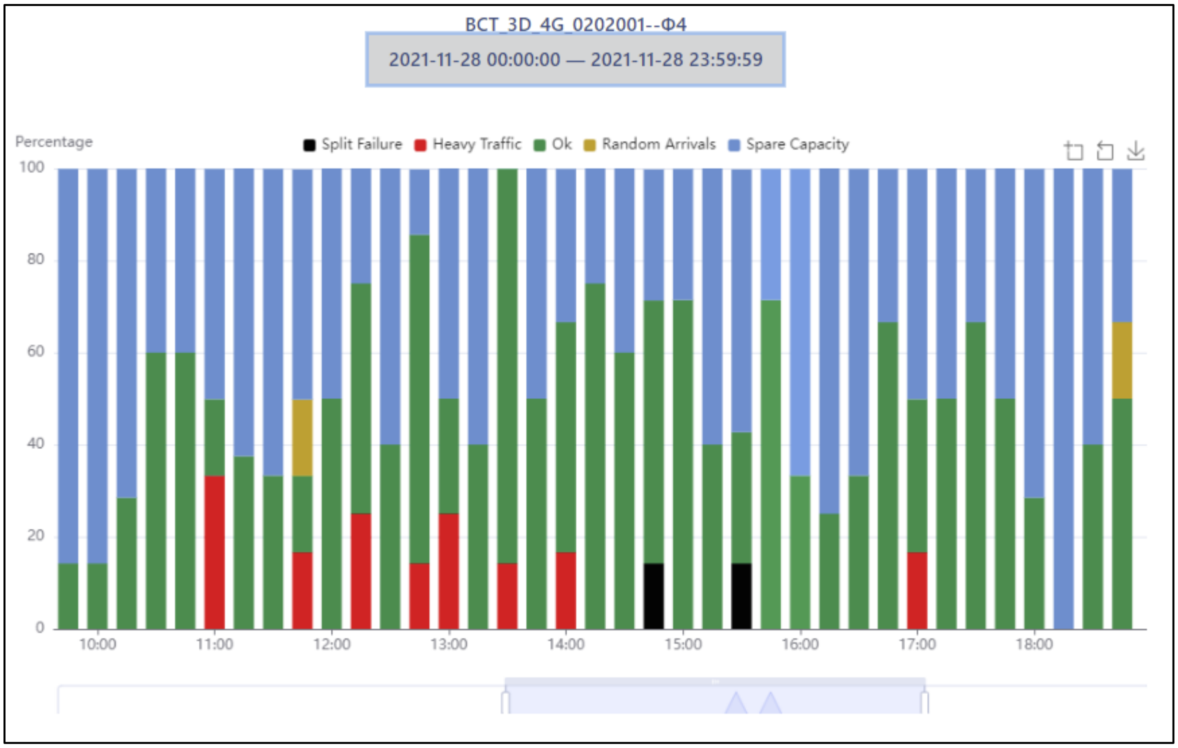


Figure 62. Split Trend

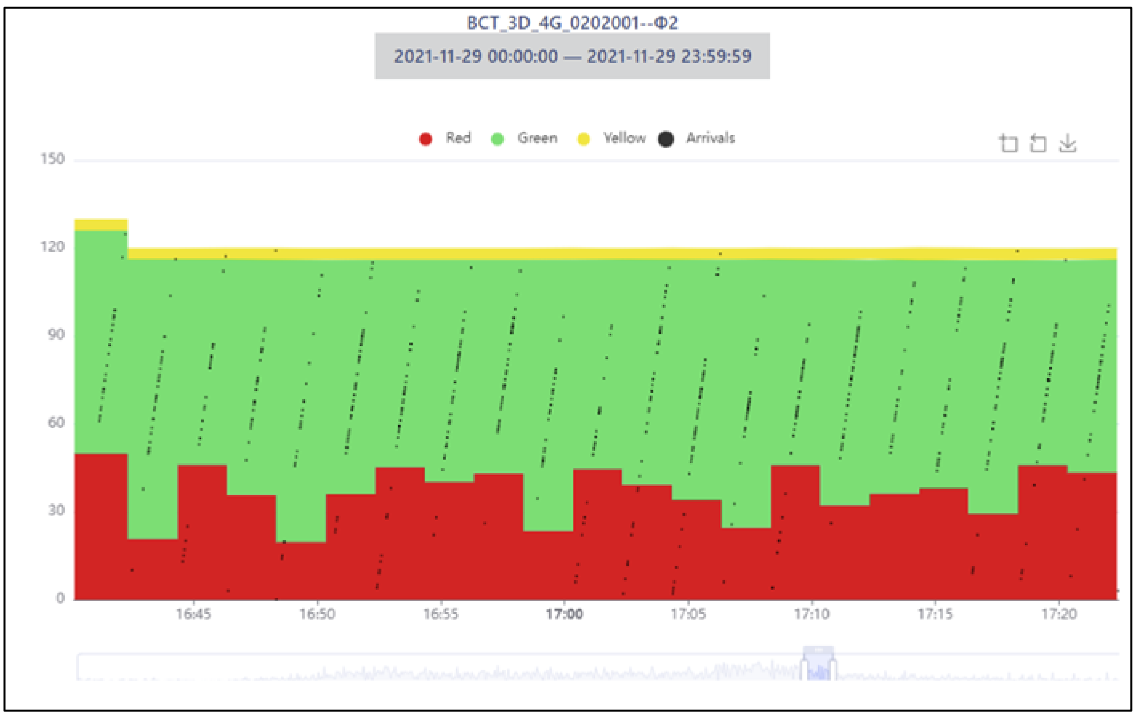


Figure 63. Purdue Coordination Diagram

BlueCity IndiGo Platform Near-miss Case Examples

This section presents illustrations of near-miss cases at various intersections, analyzed using the BlueCity IndiGo Platform.

Vehicle-to-Vehicle (V2V) Conflicts

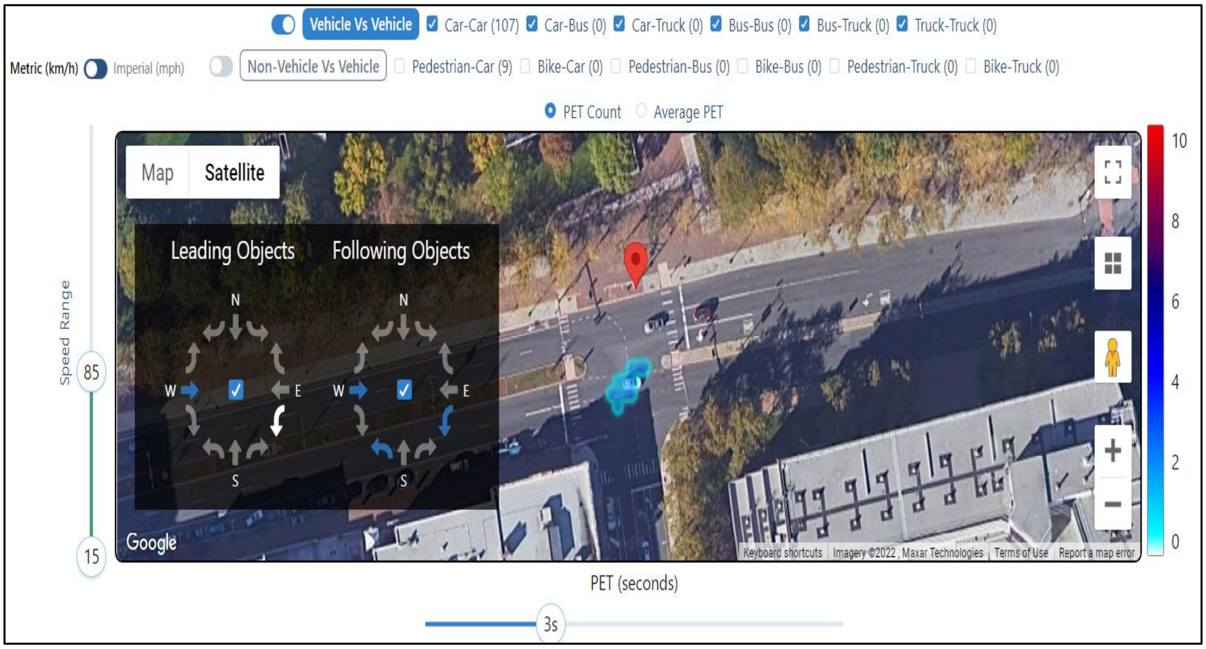


Figure 64. V2V Conflict Heatmap: Thru and Left Turn at Albany & Neilson Intersection

Figure 64 depicts the near-miss cases for V2V interactions (only for through and left-turn) for the Albany & Neilson intersection with a PET threshold of 3 seconds. The position and color of the heatmap denote the conflict locations and the conflict counts, respectively. Again, figure 65 shows the heatmap for right-angle near-miss events between two crossing vehicles. The potential conflict area can be further analyzed, and appropriate countermeasures can be implemented accordingly.

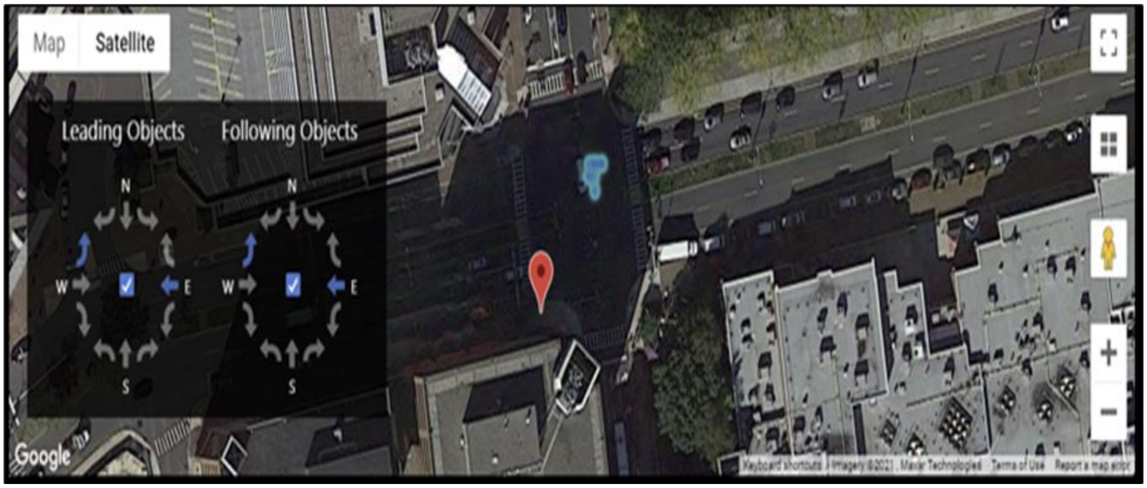


Figure 65. V2V Near-Miss Locations at Albany & George Intersection

In figure 66, for all through, turning, and merging vehicles, the near-miss cases at the French & Paterson intersection are illustrated using a heatmap.

Figure 66. V2V Conflict Heatmap: Thru, Left-Turn, Right-Turn, Merging French & Paterson Intersection

Vehicle-to-Pedestrian (V2P) Conflicts

Near-miss events in high-risk pedestrian-vehicle interactions, such as jaywalking or running red lights, are relatively common. Effectively addressing these traffic conflicts can reduce both the likelihood and severity of crash events.

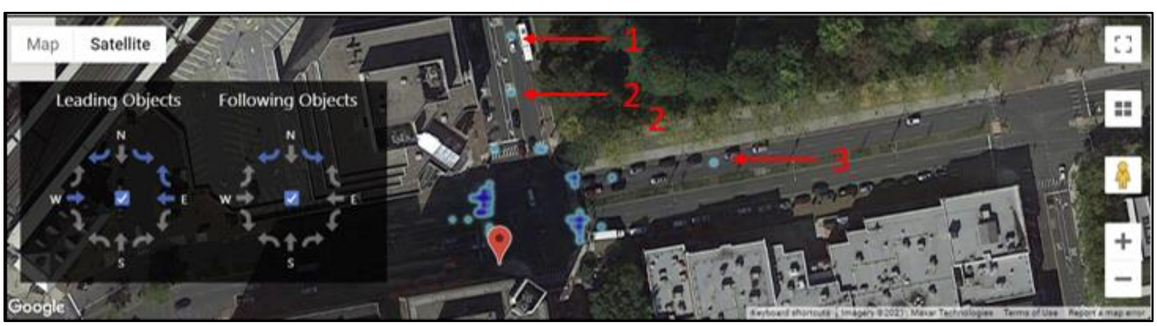


Figure 67. Conflict Points due to Jaywalking Located at Albany & George Intersection

Figure 67 depicts the conflict points arising from pedestrian jaywalking tendencies at the Albany & George intersection, as identified in the heatmap. This data is essential for optimizing signal timings, developing suitable pedestrian infrastructure, enforcing pedestrian laws, and formulating penalties for violations.

Figure 68. Location of Conflicts due to Redlight Running at Albany & George Intersection

Figure 68 shows the potential conflict points at the intersection where a pedestrian is more likely to be hit by an oncoming vehicle due to a motorist’s red-light violation. This information is critical in adjusting the signal timing, mounting proper traffic signs, and updating speed regulations. Highly visible traffic signals could warn drivers regarding the presence of intersections in advance, and the potential disruption in traffic flow caused by these signals. The primary challenge in addressing safety issues stems from the complex relationship between safety measures, road user behavior, and infrastructure, coupled with the challenges in accurate recording of crash data and measuring the frequency and severity of crash events. The analysis of traffic conflicts can aid in identifying safety deficiencies at specific locations, recommend suitable countermeasures, and thereby, ensure enhanced comfort and safety for all road users.

NJ Legislation Environment of Autonomous Vehicle

This task presents a comprehensive literature review of US-based and international legislations and regulations for AVs, and some interview studies from three states about the autonomous vehicle legislation environment and efforts.

Legislation and Regulations

The legislative landscape of AV technologies has been evolving rapidly over the last decade in the US:

- **Federal Framework: The** National Highway Traffic Safety Administration (NHTSA) published the Federal Automated Vehicles Policy (FAVP) in 2016 as a standard framework for building national and state-level legislation.
- **State Legislations or Executive Orders:** The number of states with either legislation or executive orders to allow testing or operation of AVs has increased from 15 in 2018 to 41 as of 2021. These legislations cover the definitions of AVs, performance, safety standards, and licensing, testing, and operations of AV technologies.
- **NJ Legislative Progress**: NJ is among the first states to introduce an AV bill in 2017. However, the legislative outcomes have been limited, and most of the introduced bills are pending at the congressional committees. The most successful legislation introduced is the formation of the "New Jersey Advanced Autonomous Vehicle Task Force". This task force completed a full recommendation report for NJ’s AV legislative

roadmap, presenting an oversight committee led by New Jersey Motor Vehicle Commission (NJMVC). There are some highlights from this task force:

- List detailed requirements of permit application form for prospective AV testers.
- List detailed certification process, insurance converge and license registration for AV testing.
- Specify a task force to study autonomous vehicles and recommend laws, rules and regulations.

Automated Transit System (ATS) Technologies

ATS technologies aim to implement transit services using shuttles/buses equipped with high-level ADS technology. ATS technologies can be classified into two generations of technologies:

- **Generation 1:** Electric autonomous shuttle technologies, which operate at Level 4 automation under specific routes and operational plans. These AV shuttles often operate under a limited speed range, passenger capacity, and mileage per charge. Their limitations usually make them challenging to operate under complex urban environments without significant route remedies. However, most AV shuttle manufacturers and operating companies have already conducted complete safety tests and obtained waivers from NHTSA and other state and local permits to operate their shuttle services. These representative manufacturers and companies include Navya, EasyMile, and Beep.
- **Generation 2:** Full-size autonomous bus with a similar passenger capacity as conventional buses. It can be seamlessly integrated into or replace existing buses on existing routes. However, few manufacturers and companies have thoroughly tested and obtained approvals to deploy full-size autonomous electric buses equipped with Level 4 automation systems, such as New Flyer. Volvo has started intensive testing of their full-size prototype autonomous electric buses in collaboration with academic and public agency partners. Most full-size autonomous buses are still in early closed-track testing and pilot stages, and the operational requirements are quite different from smaller vehicle autonomous bus technologies.

Automated Transit System Legislation, Regulations, and Policies

The legislative, regulatory, and policy environments are crucial to the public sector in supporting and developing automated transit system technologies. With the technologies rapidly advancing and evolving, an enabling environment is crucial in facilitating the research, development, testing, piloting, and deploying of new technologies while mitigating potential risks to the technology users, operators, and all the stakeholders involved. Many states in the US and countries around the world have been steadily introducing legislative, executive orders, and agency support for the testing and deployment of self-driving vehicles. The language employed in various state laws and executive orders also suggests legislative progress on what stages of AV testing and operations are allowed within a state.

National Legislation and Regulations

The legislative landscape for Avs in the US has been constantly evolving both at the federal and state levels. In 2016, National Highway Traffic Safety Administration (NHTSA) published the Federal Automated Vehicles Policy (FAVP) as a standard framework for building national and state-level legislation, the levels of autonomy, guidance for vehicle performance, a model state policy, and a discussion of current and future regulatory tools for AVs. [9,10,11,12] The key concept of vehicle safety assessment is shown in table 4.

- **Levels of Autonomy:** The FAVP provided a classification system of automation consistent with the SAE J3016 standards. A common terminology is also provided that is more consistent with the industry. The primary distinction between conventional vehicle operation (L0, L1, and L2) and a highly automated vehicle (HAV, including L3, L4, and L5) is the responsibility for monitoring the environment. It is likely that L4, which would include autonomous operation on a freeway during good weather, maybe realized before L5, which would be an autonomous operation on any public street in any weather condition.
- **Guidance for Vehicle Performance:** Vehicle safety standards are currently the responsibility of the federal government, and all vehicles sold in the US must meet Federal Motor Vehicle Safety Standards (FMVSS). A voluntary 15-point safety assessment is listed as an important factor that manufacturers should consider ensuring safety during testing and deployment. Manufacturers must obtain an exemption to FMVSS for testing purposes in some cases. For example, a vehicle without a steering wheel, accelerator, or brake pedal, like those vehicle models available from Navya and EasyMile, would require an exemption since it does not meet the FMVSS.
- **Model State Policy:** This part clarifies the federal and state responsibilities concerning AV and provides seamless operation of AV from one state to another. The Federal government regulates the safety standards for vehicles and equipment, enforces compliance, is responsible for vehicle recalls, communicates with the public regarding safety issues, and guides to support national safety goals. State responsibilities for AV include driver licensing and vehicle registration, traffic laws and enforcement, safety inspections, and motor vehicle insurance and liability. The states can also choose to regulate the testing and operation of AV based on the model state policy recommendations on the administrative structures and processes, testing and deployment on public roads, registration of vehicles and drivers, law enforcement, and liability and insurance consideration.

Table 4 - Vehicle Safety Assessment and Key Concept

Item	Concept and Details
1. Data Recording and Sharing	Process should be documented, and crash data should be available to NHTSA for crashes that result in fatalities or injuries or damage the vehicle such that it can't be driven.
2. Privacy	Consumer privacy should be ensured, and individual data should not be identifiable.
3. System Safety 4. Vehicle Cybersecurity	Process should include hazard analysis and safety risk assessment for HAV, overall vehicle design, and broader transportation system. There should be industry sharing.
5. Human Machine Interface	Design must consider need to convey information to driver as well as pedestrians and other drivers/vehicles.
6. Crashworthiness	Design must provide occupant protection (and potentially enhanced protection based on sensor.
7. Consumer Education and Training	Manufacturers must develop information for employees, dealers, distributors and consumers about system, operational intent, capabilities and limitations, and emergency operation and engagement/disengagement methods, etc.
8. Registration and Certification	Manufacturers must submit information about HAV components to NHTSA and vehicles must convey system capabilities and limitations. Information must be updated to reflect changes due to software updates or equipment modifications.
9. Post-Crash Behavior	Process should be documented for assessment after a crash and vehicle cannot operate in HAV mode until system and sensors are validated.
10. Federal, State and Local Laws	Plans for programming to assure compliance with all applicable traffic laws must be documented.
11. Ethical Considerations	There must be transparency regarding decision rules and programming to address conflict dilemmas on the road that affect objectives related to safety, mobility and legality.
12. Operational Design Domain (ODD)	Manufacturer must specify how and where the HAV system can operate, including roadway type, geographic area, speed, and environmental conditions.
13. Object and Event Detection and Response (OEDR)	There must be a documented process for assessment and validation of the capabilities of the HAV system, including the reception and response functions.
14. Fall Back (Minimal Risk Condition)	The response upon failure must be documented and may include transition of operation to a human driver or bringing the vehicle to a safe stop outside the traffic lanes.
15. Validation Methods	Performance of HAV components must be demonstrated with testing, validation, and verification. This may include testing via simulation, test track and on public roads.

NHTSA has been updating old regulations and has issued new regulations in recent years. In 2020, NHTSA launched Automated Vehicle Transparency and Engagement for Safe Testing (AV TEST). As part of the AV TEST initiative, states and companies can voluntarily submit information about the testing of automated driving systems to NHTSA; the document is the voluntary safety self-assessment. In 2021, NHTSA issued a standing general order that requires manufacturers and operators of automated driving systems and SAE Level 2 advanced driver assistance systems equipped vehicles to report crashes to the agency. Building on the prevailing policies and incorporating feedback received through public comments, stakeholder meetings, and Congressional hearings, NHTSA also issued a series of documents laying visions and guidelines titled Automated Driving System 2.0: A Vision for Safety (2016), Automated Vehicles 3.0: Preparing for the Future of Transportation 3.0 (2018), and Automated Vehicles 4.0: Ensuring American Leadership in Automated Vehicle Technologies (2020).

State Legislative Landscape

Different US States adopted different approaches towards setting up the legislative environment for the testing and deploying AVs. The most common approaches are through state legislation or executive orders from governors. According to the NCSL (National Conference of State Legislatures) database, as of August 2022, 25 states have enacted legislation to enable fully driverless operation, and 20 states got the permits testing and addressing AV policy. (See figure 69.) Successful legislation or executive order has been the key to authorizing and funding a lot of the AV testing activities around the country, which will, in turn, promote the private sector R&D activities in those states.

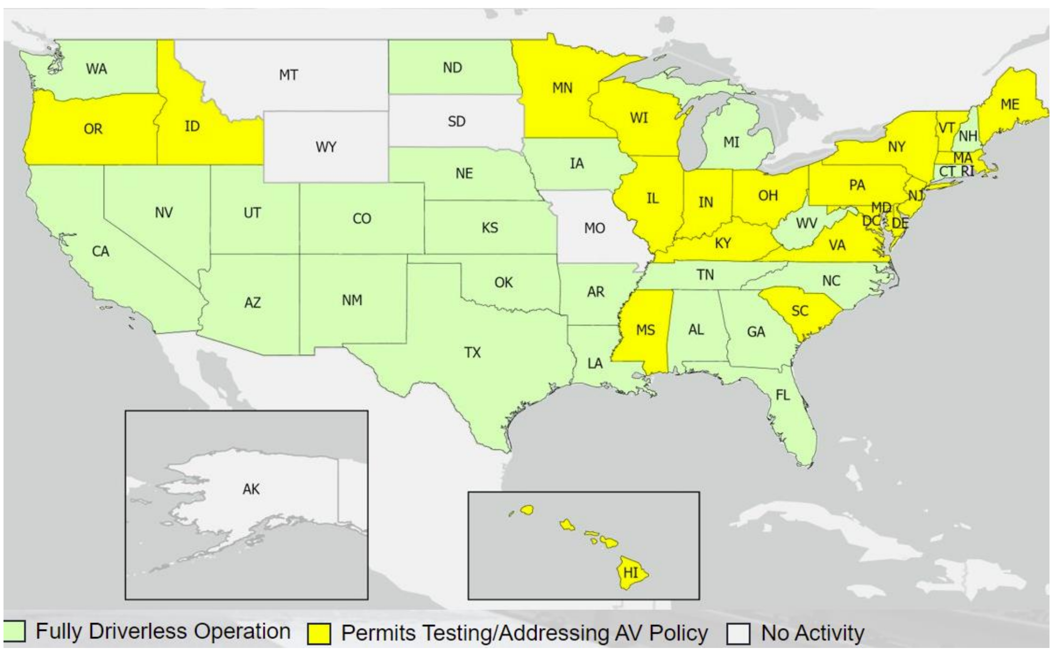


Figure 69. U. S. State Automated Vehicle Legislation Landscape: 2022

Different states have focused on different topics related to AVs. Here are the key topics addressed through state legislation.

- **Definitions.** Definitions are one of the most basic components of legislation and may stand alone or be part of more comprehensive legislation.
- **Study Request.** Existing agencies may be tasked with studies or committees of stakeholders may be responsible for studies of broad issues related to AV or specific functions; studies may require a single report to the legislature or have annual

reporting requirements. This is a topic addressed by all the executive orders and by most of the enacted legislation.

- **Licensing and Registration.** Machine driver licensing and autonomous vehicle registration programs are commonly addressed in legislation, reflecting traditional state responsibilities.
- **Insurance and Liability.** States have well-developed criteria for insurance and liability for AVs, although minimum requirements and allowable programs (e.g., no-fault insurance) may vary from state to state.
- **Vehicle Inspection Requirements.** Some states elect to conduct autonomous vehicle inspections to ensure minimum safety or emissions standards are met.
- Operator Requirements. The requirements for operators vary from state to state and, in some cases, for different levels of automation.
- **Infrastructure.** Infrastructure to support AV may include communications or signal systems equipment and CV technologies, as well as traditional components such as lane markings and signs.
- **Vehicle Testing on Public Roads.** The FAVP defines testing as the deployment of HAV by manufacturers or researchers to evaluate and analyze operations.
- **Operation on Public Roads.** The FAVP defines the operation as the use of HAV by members of the public who are not manufacturers or researchers.
- **Commercial Vehicle Operation (CVO).** CVO may have additional requirements such as commercial driver licensing, vehicle inspections, and permitting. Recent legislation in several states has addressed vehicle platooning targeted specifically to the CVO market.
- **Privacy.** Privacy concerns are an important consideration and include vehicle data that conveys vehicle location, as well as operational characteristics, particularly during or preceding an accident.

NJ AV Legislation Activities

Table 5 - NJ Legislative Activities Related to AVs

Bill No.	Year	Title	Status	Date of Last Action
NJ A 1810, NJ A 1607, NJ A 1853 (Failed), NJ A 3745	2017-2023	Testing and Use of Autonomous Vehicles on State Roadway	Pending - Assembly Transportation and Independent Authorities Committee	1/11/2022
NJ A 1812, NJ A 1859 (Failed)	2017-2023	Owners of Self Driving Motor Vehicles	Pending - Assembly Financial Institutions and Insurance Committee	1/11/2022
NJ S 343, NJ A 2030, NJ A 1187, NJ A 851, NJ A 4541 (Failed)	2016-2023	Driver License Endorsement	Pending - Senate Transportation Committee	1/12/2016
NJ A 2031, NJ A 1189, NJ A 3367 (Failed), NJ A 4573 (Failed)	2018-2023	Fully Autonomous Vehicle Pilot Program	Pending - Assembly Transportation and Independent Authorities Committee	1/11/2022
NJ A 2038	2023	Highly Automated Vehicles Process Test	Pending - Assembly Transportation and Independent Authorities Committee	1/11/2022
NJ S 3877	2021	Highly Automated Vehicles Testing	Pending - Senate Budget and Appropriations Committee	6/3/2021
NJ A 2495, NJ A 2807, NJ A 4977 (Failed), NJ S 3438 (Failed)	2019-2023	Autonomous Vehicles Interaction Training	Pending - Assembly Law and Public Safety Committee	2/14/2022
NJ S 2129, NJ A 4504, NJ A 554, NJ S 1530 (Failed), NJ S 2895	2017-2021	Self-Driving Motor Vehicle Insurance Requirements	Pending - Senate Commerce Committee	3/16/2020
NJ A 5681	2021	Testing Highly Automated Vehicles Process	Pending - ASSEMBLY	12/9/2021
NJ AJR 188 (Failed)	2019-2020	Advanced Autonomous Vehicle Insurance Task Force	Failed - Adjourned - Assembly Financial Institutions and Insurance Committee	2/7/2019
NJ SJR 105 (Failed)	2020	Advanced Autonomous Vehicle Task Force	Failed - Adjourned - SENATE	1/17/2019
NJ AJR 164 (Enacted), NJ SJR 105 (Failed)	2018-2020	Advanced Autonomous Vehicle Task Force	Enacted - Act No. 2019-2	03/18/2019 - Enacted
NJ S 2149 (Failed)	2018-2020	Autonomous Vehicles State Roadway Use	Failed - Adjourned - Senate Transportation Committee	3/5/2018
NJ S 3225	2017	Autonomous Vehicles Testing and Use	Pending - Senate Transportation Committee	5/18/2017

Table 5 summarizes the NJ AV legislation activities based on the NCSL records. [13] The state congress of New Jersey has been exploring AV-related legislation since 2016. More than 65 proposed laws have been reviewed. Only four bills reached a decision, with three failed and one being enacted. Other bills have been pending in related Senate and Assembly committees. Those bills focus on topics related to driver's licenses for AVs, AV testing and use, training programs, and assembling task forces to develop legislative and regulatory roadmaps for AV testing and pilots. The enacted bill NJ AJR 164 resulted in the assembling of the Technology Task Force. The full task force report was published in 2021. Several key 2023 legislations based on the Task Force recommendations have been pending in state congress, including designating MVC to establish an agency committee to review and regulate AV testing, especially the issuance of license plates.

Summary of Key Findings

This section conducts a detailed literature review of the current AV information and legislative environment. Here are some of the key findings:

- **Autonomous Vehicle Information:** ATS technologies currently consist of two generations of technologies. Generation 1 technologies are electric autonomous shuttles that operate at Level 4 Automation under specific routes and operational plans; however, are often low-speed (16-25 mph) and have significant limitations in complex urban environments. Those technologies have been operational in some routes at industrial parks. Generation 2 technologies are full-size autonomous buses that can be retrofitted from existing buses or fully manufactured new buses, often equipped with ADS technologies like the latest self-driving technologies and with the ability to travel on open roads. However, most of the Generation 2 technologies are still in their early testing and pilot stages.
- **AV Legislation:** The legislative and governance support of self-driving technologies has been evolving over the last decade. Many states in the US have legislation or executive orders to allow the testing and operations of self-driving vehicles to be conducted. However, related NJ legislation has been lagging behind the nationwide progress. Furthermore, there are limited legislations, guidelines, or policies specific to automated transit systems. Most are often languages covering transit vehicles as part of a broad legislation, policy, or guideline document.

TASK 6: LIVING LAB

Blind Zone Analysis

LiDAR Blind Zone Simulation and Evaluation

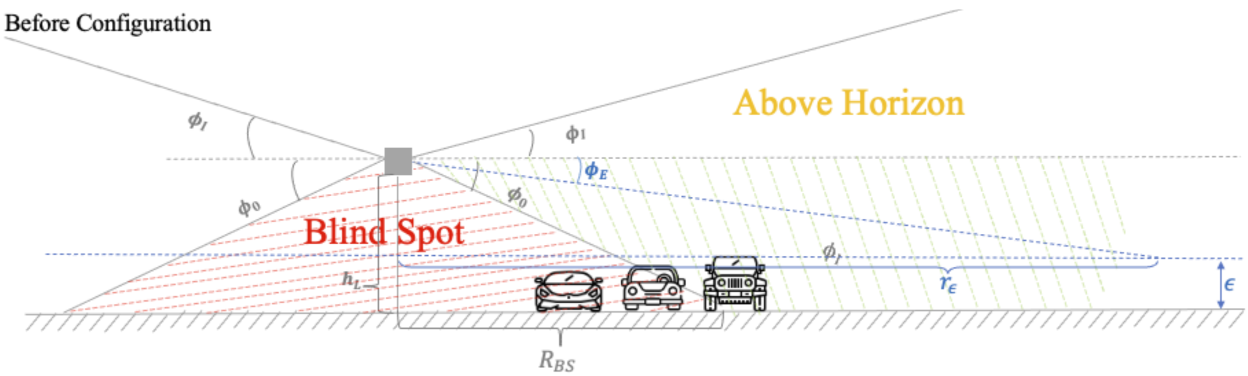
Unlike vehicle-based LiDAR, the installation scenarios of roadside LiDAR are more complicated, and it takes significant effort to find the optimal positions for all the different sites given different road geometry, grades, infrastructure layout, and other environmental factors. As table 6 shows, existing research has designed some generic metrics for evaluating the LiDAR sensor performance, e.g., accuracy, range, and data density. [14,15,16,17] But most of them focus on calibrating the LiDAR itself for high accuracy and long range instead of optimizing the sensor position and tilting parameters of the roadside LiDAR sensors for better coverage and objection detection performance. There are commercial simulation models with LiDAR simulation based on its manufacture configuration and preset effective range, e.g., Blensor, Ondulus LiDAR for ideal optical simulation. However, in-field deployment, LiDAR sensor performance can be affected by a lot of factors, such as weather, cleanness of the lenses, surface reflexibility, and other road geometry and infrastructure limitations. [18,19,20,21,22,23,24,25,26] Real-world traffic can also cause occlusions that temporarily block vehicle detection, especially towards the farther end of the detection ranges. The detection ranges of different LiDAR models are usually constrained by their power supply limitations that determine the longest reachable ranges by each laser beam. Manufacturers designed the power limits to reduce costs and avoid overheating and other risks. However, for some LiDAR models with dense enough laser beams, the effective range becomes the bottleneck of tracking and reconstructing vehicles and other objects at long ranges.

Table 6 - Literature on Roadside LiDAR Sensor Configuration and Data Quality Impacting Factors

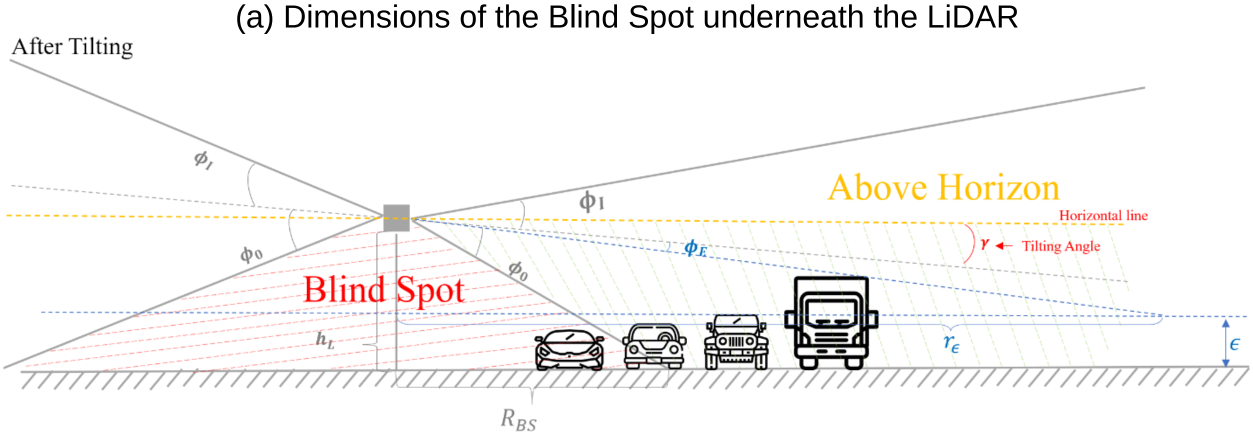
Type	Quality Concerns	Papers
Device Performance	Accuracy	Toth et al. (2007), ASPRS (2015)
	Range	Cooper et al. (2018), *
	Data Density	Heidemann (2012), *
Physical Factors	Weather	Wu et al. (2020a, 2020b), Rasshofer et al. (2011), Hasirlioglu et al. (2017a, 2017b)
	Cleanness of the Lenses	Toshniwal (2021)
Effective Coverage	Blind Zone and Blind Spot	*
	Dynamic Lane Coverage	
	Vehicle Detection Capability	

* The concerns that the topic in this project covers have been italicized.

Prevailing LiDAR sensors have built-in field-of-view (FOV) design both horizontally and vertically to ensure all laser beams go around vehicles thus creating a small blind zone underneath or behind the sensor but maximizing the density of the beams within meaningful detection sections (e.g., -45 to +30 degrees). [26] For roadside deployment, such vehicle-based FOV configurations are not ideal and can leave significant blind spots underneath the LiDAR sensors, therefore tilting is needed to reduce the blind spot and take advantage of the FOVs configured for vehicle-based mounting. Based on the specific layout of roads, intersections, and infrastructure, the LiDAR devices need to be tilted at a correct angle to focus the dense close-to-horizon laser beams for vehicle-mount positions onto the region of interest (ROI) for roadside sensing.



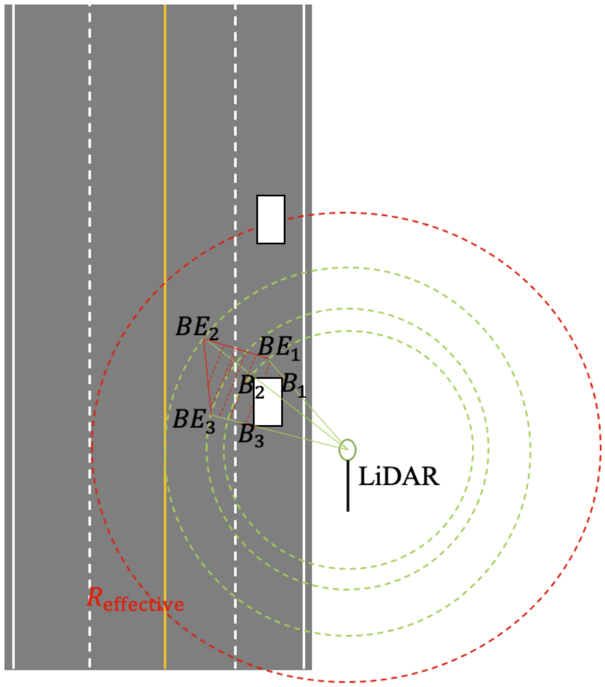
(a) Dimensions of the Blind Spot underneath the LiDAR



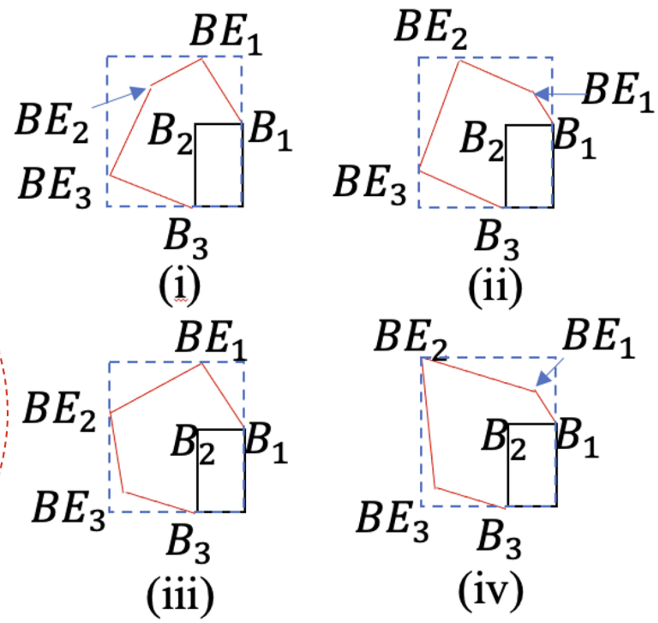
(b) Dimensions of the Blind Spot underneath Tilted LiDAR

Figure 70. LiDAR Coverage Blind Spot Schematics

To solve the above problems, the Rutgers team developed an assessment and optimization model for configuring roadside LiDAR installation. More specifically, an analytic and a simulation model have been developed to analyze the detection of blind zones and their impact on vehicle detection and tracking capabilities in CAV applications. The model can derive the area and height of the detection blind zones from a given roadside LiDAR location and road geometry. To facilitate further discussion, figure 70 depicts some of the key parameters of the LiDAR. The size of the blind spot on the roadway surface is determined by the height of the LiDAR origin h_L and the tilting or pitch angle γ, as figure 70 (a) (no tilting) and (b) (with tilting) show.

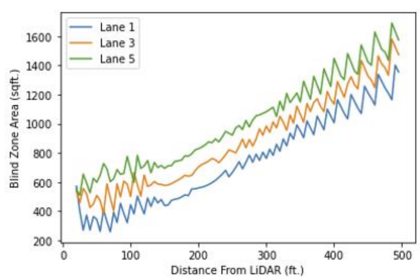


(a) Roadside LiDAR Blind Zone Calculation

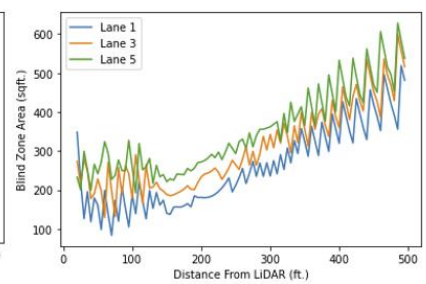


(b) Four Different Blind Zone Types

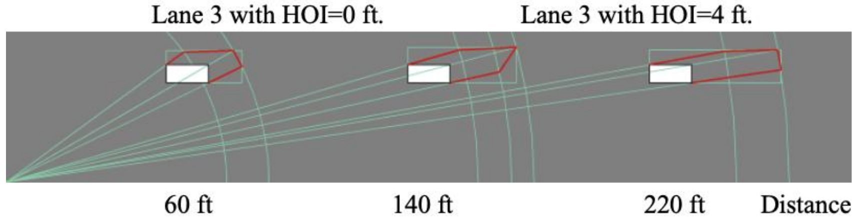
Figure 71. Illustrations of Roadside LiDAR Blind Zones Caused by Vehicle Occlusions



(a) Roadside LiDAR Blind Zone Area Lane 3 with HOI=0 ft.



(b) Roadside LiDAR Blind Zone Area Lane 3 with HOI=4 ft.



(c) Roadside LiDAR Blind Zone Lane 3 with HOI=4 ft.

Figure 72. Roadside LiDAR Blind Zone Area versus Distances from LiDAR Sensors

The blind zone area caused by each object can be calculated as figure 71 shows and the results are presented in figure 72. The results show that the blind zone area increases with the increase of the distance, and different heights of interest tend to have different blind zone areas. However, the horizontal blind zone area seems not straightforward enough, and the overlapping of other vehicles' blind zones will aggregately increase the computing complexity. Thus, the blind zone height is adopted for analysis of the blind zone impact. The blind zone height is determined by the lowest beam that is not blocked by any obstacles.

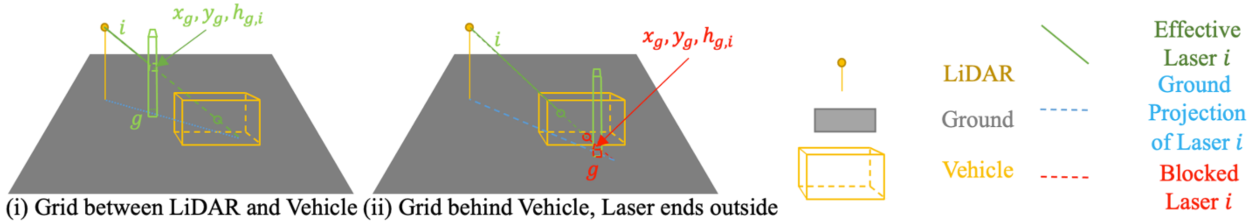


Figure 73. Occlusion Detection Scenarios

Figure 73 illustrates two different scenarios for occlusion detection. In scenario (a), the current grid is between the LiDAR and the vehicle. There is no vehicle between the LiDAR and the grid, therefore the laser is not blocked. In scenario (b), the grid is behind the vehicle, and the laser is blocked by the vehicle because the current laser height in the current grid is in the blind zone. Based on these two scenarios, it can be summarized that only if the laser goes through any of the vertical sides of the vehicle, while it does not end at the bottom of the vehicle, then it is blocked.

The blind zone height map is generated as figure 74 shows, the simulation covers 5 lanes of traffic plus a frontage road and ramps, with the vehicles marked by black bounding boxes. The LiDAR sensor is located at the bottom center, which creates the semicircle or half-eclipse blind spot underneath. The blind zone height measures in each grid are used to create the pseudo color map with blue for 0 ft and dark red for 14 ft.

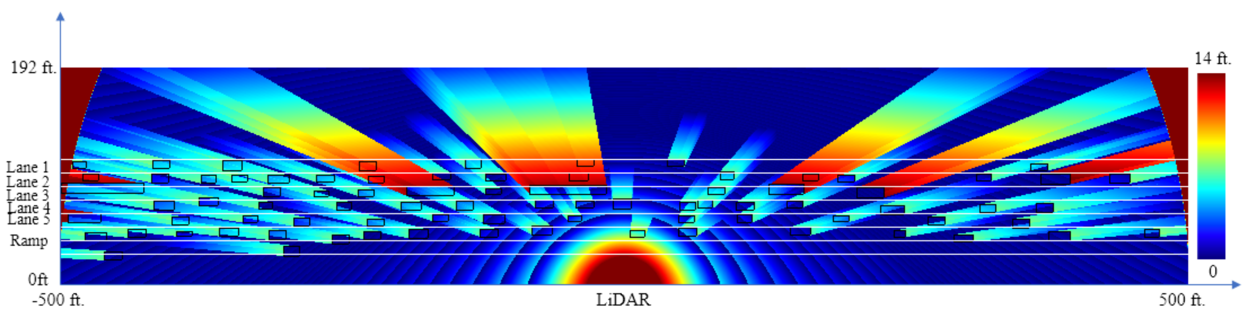


Figure 74. Blind Zone Height Map, 5 Degree at 23 ft., Right

Seven evaluation metrics have also been designed to assess the severity of the blind zone including laser density, blind zone height and duration, vehicle trajectory missing rate, and duration.

Numbers of Effective Lasers in Each Grid

For each frame f (0.1-second snapshots in the NGSIM dataset), the laser beam density map ρ_f is constructed by calculating the beam density in each grid g as follows:

$$\rho_{f,gx,gy} = \frac{\sum_i \left[h_{i,g,h_L} < \epsilon \text{ and beam } i \text{ is not occluded}\right]}{\epsilon} \quad (1)$$

Where the laser beam density map ρ_f is a 2D array to store the density data in frame f. gx and gy are the grid indices. $[C]$ is a counter function where if the clause C satisfies, $[C] = 1$, otherwise, $[C] = 0$. ϵ is the HOI. At this step, we focus on pedestrians and sedan/SUVs, the heights of interest were set to be between 1ft and 7ft, then the $HOI = 7 - 1 = 6ft$. Effective laser beams mean that the beams are not occluded.

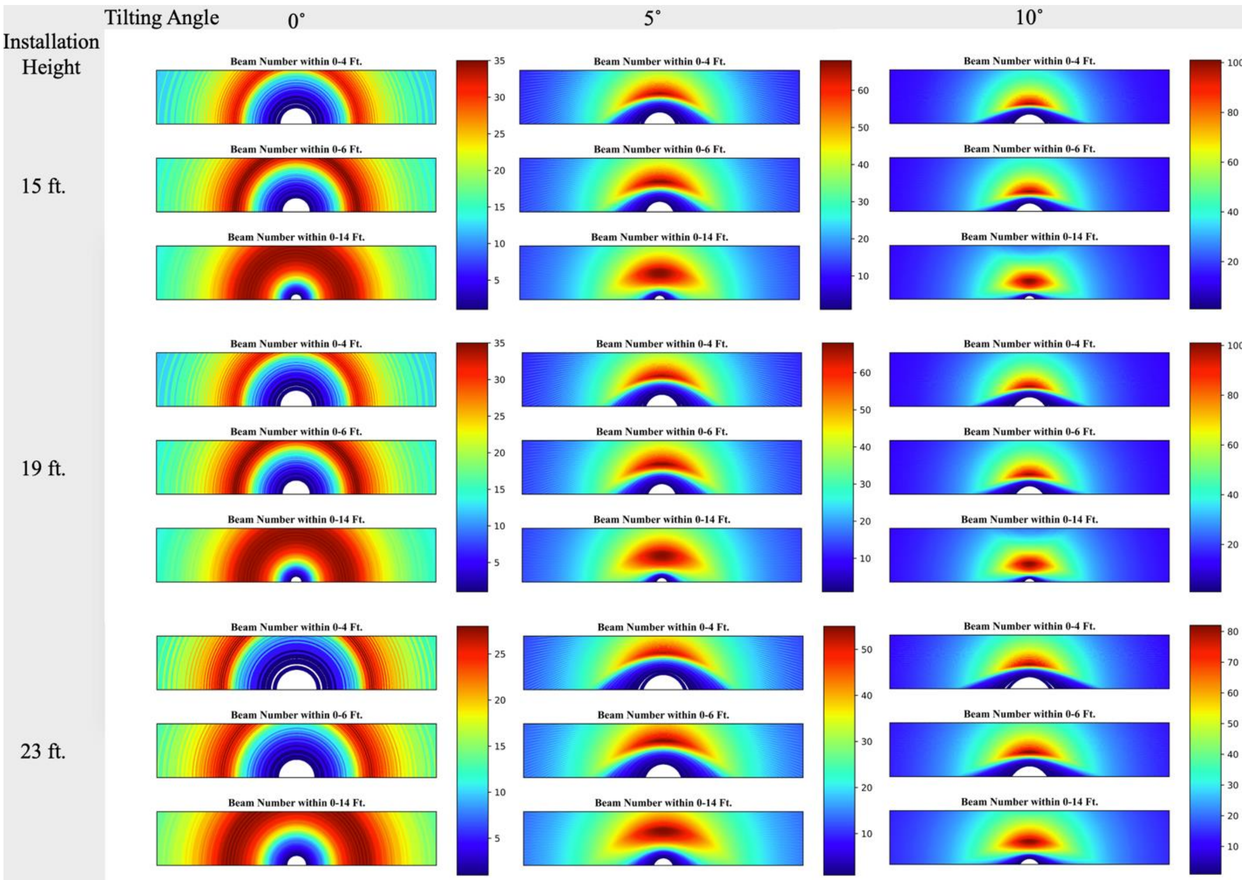


Figure 75. Laser Density Maps at Different Installation Height Levels and Tilting Angles

Figure 75 shows the maps of effective laser numbers that can inform the vehicle detection and reconstruction capabilities based on the grid positions. Jet colormap is used, in which the highest value is represented by dark red, and the lowest value, 1, is represented by dark blue. If there are no beams, it is white. We use 4 ft., 6ft., and 14 ft as the targeted HOIs. separately. As can be easily seen, there is always a blind spot under the LiDAR device (bottom center), without any laser beams. With more laser beams in the interested height range, the shape and model of the vehicles can be better recognized and reconstructed. Horizontally comparing figure 75, the tilting operation can significantly improve the laser density but will also shorten the vertical detection range. Vertically comparing figure 75, the increasing height of the LiDAR will slightly reduce the laser density and gradually increase the area of the blind spot.

Lowest Effective Laser Height in Each Grid

For each configuration, a lowest laser height map can be generated. Similar to the laser beam density map, the lowest laser height map μ_f can be defined as:

$$\mu_{f,gx,gy} = \min\left(H_{G_x \times G_y \times I}\right) \quad (2)$$

Where $\min\left(H_{G_x \times G_y \times I}\right)$ is the minimum laser height in each grid (gx, gy).

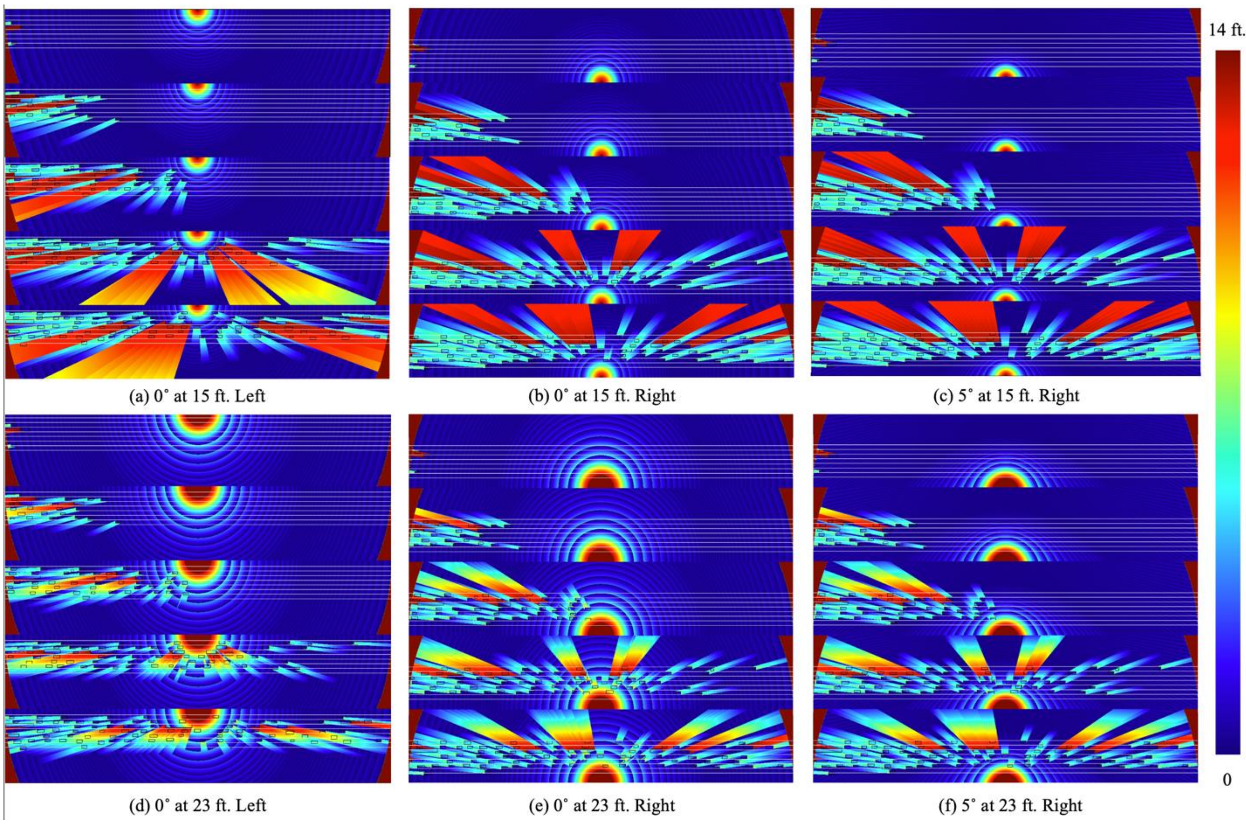


Figure 76. 10-Sec-Interval Simulation Blind Zone Map

Figure 76 provides the simulation results with six different configurations. Each configuration consists of five blind zone height maps, and the time interval between two consecutive blind zone maps is 10 seconds. The colors in the map, as the color bar shows, mean the blind zone height, from 0 (all clear) to 14 ft (4.37m, totally blocked). To be noted, the first and second lanes from the right in the dataset are frontage and ramps instead of lanes with light traffic, which has an impact on the blind zone pattern.

Figure 76 (a) shows the scenario where the LiDAR sensor is installed on the left side of the road, at the height of 15 ft. (4.57m) without tilting. Compared with figure 76 (b), the right-side installation, the maximum blind zone height from the left-side installation is lower. This is primarily due to the frequent occurrence of trucks on the second and third lanes from the left. Trucks blocked fewer beams in the left-side installation because of their proximity to the LiDAR sensor. It should be noted that the left-side installation of the

LiDAR sensor requires the installation of the LiDAR sensor at the medium or gantries, which makes the configuration unrealistic. Therefore, the analysis will only use the right-side installation as an example of tilting operations, though the simulation model has the ability for both right-side and left-side simulation and analysis.

Comparing figure 76 (a) with (d), the higher the installation, the less impact that the vehicle has on the LiDAR coverage, but the bigger the blind spot beneath the sensor. Comparing figure 76 (e) with (f), the 5° tilting operation slightly reduced the blind spot area underneath the LiDAR. Comparing figure 76 (b) & (c) vs. figure 76 (e) & (f), the tilting reduces the blind spot beneath the LiDAR sensor, and the higher installation reduces the blind zone caused by the vehicles.

Temporal Average of Grid-based Lowest Effective Laser Height

This is the time aggregation of the lowest height map, which shows the grid-based average blind zone height over time. It reflects the overall performance of the LiDAR covering the area and can be calculated as

$$TA_{f,gx,gy} = \frac{\sum_f \mu_f}{F_{Total}} \qquad (3)$$

Where F_{Total} is the total number of frames.

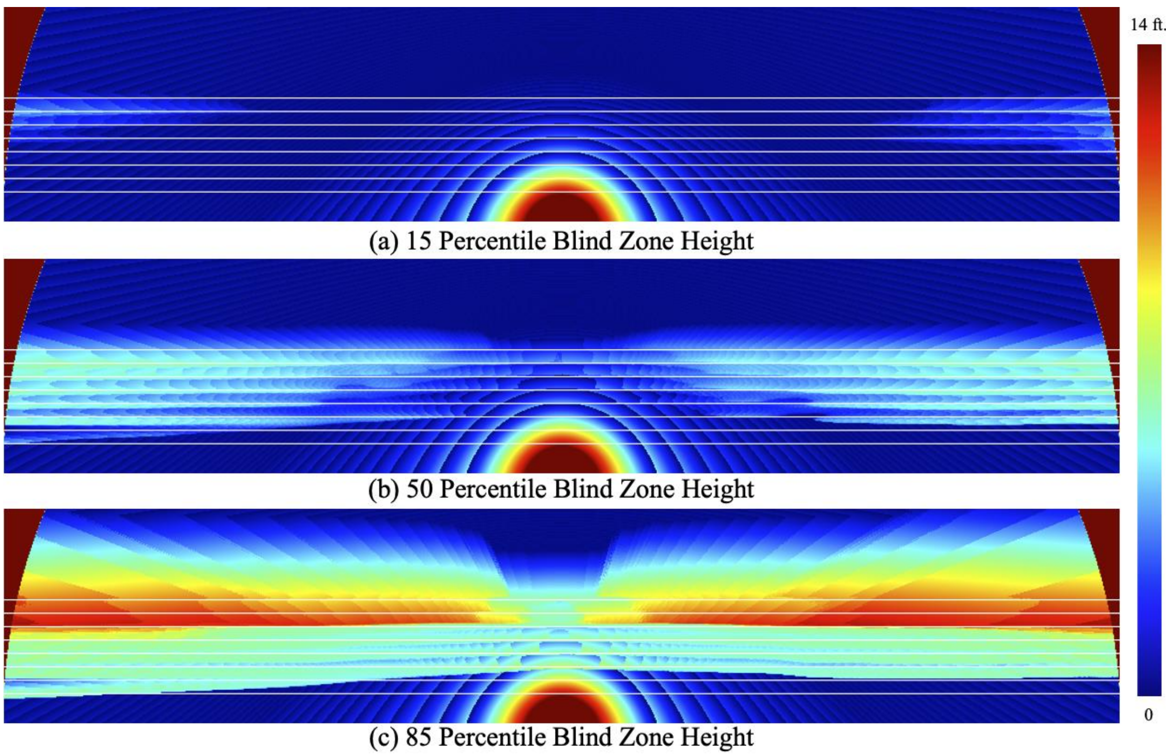


Figure 77. Duration Distribution of Blind Zone Height Map of 5 Degree at 23 Ft.

Figure 77 shows the histogram of the blind zone durations, with the white lines representing the lane markings. Jet colormap is applied to visualize the blind zone height, in which dark red is the highest value, 14 ft., and dark blue is the lowest value, 0 ft. Figure 77 (a) shows that light traffic does not have much influence on any lane as long as the LiDAR sensors are installed higher than the vehicles. Figure 77 (b) shows that, for half of the cases, the LiDAR may have trouble recognizing and reconstructing small vehicles beyond 200 ft, especially for the first two lanes from the left. Figure 77 (c) shows that for 15% of the cases, it will have trouble finding/tracking small and medium-size vehicles hidden behind trucks at or beyond 100 ft. The effective coverage may be significantly influenced. Although the laser beam may reach as far as 500 ft., the blind zone caused by heavy traffic can reduce it to a very short range. Therefore, it may be worth trying on installing the LiDAR at an appropriate height with tilting to gain better blind zone performance.

Lane-by-Lane Missing Trajectory Rate Histogram

This metric assesses the missing percentage of vehicle trajectories where they fall into blind-zone grids. Then the percentage is aggregated by frames and lanes. For each individual lane l, the aggregated missing trajectory rate is the following,

$$MT_l = \frac{\sum_v \frac{\sum_f P_{v,l,f}}{f_v}}{v_l} \tag{4}$$

Where f_v is the count of frames that vehicle v appears in the coverage area, $P_{v,l,f}$ is the percentage of vehicle v in lane l at frame f ,v_l is the count of vehicles that are in lane l, MT_l is the missing trajectory rate in lane l.

Lane-by-Lane Vehicle Missing Time Distribution

This metric assesses the percentage of time when a vehicle trajectory is traveling over blind-zone grids. Then the percentage is aggregated by frames and by lanes. The missing time distribution is calculated as follows,

$$VMTD_l = \frac{\sum_v \frac{sum(f_{vB})}{sum(f_v)}}{v_l} \tag{5}$$

Where f_{vB} is the count of the frames that vehicle v stays in the blind zone, f_v is the count of frames that vehicle v appears in the coverage area, and v_l is the count of vehicles that are in lane l. The percentage threshold P_{vm} for vehicle missing is set as 15, 50, and 85, separately.

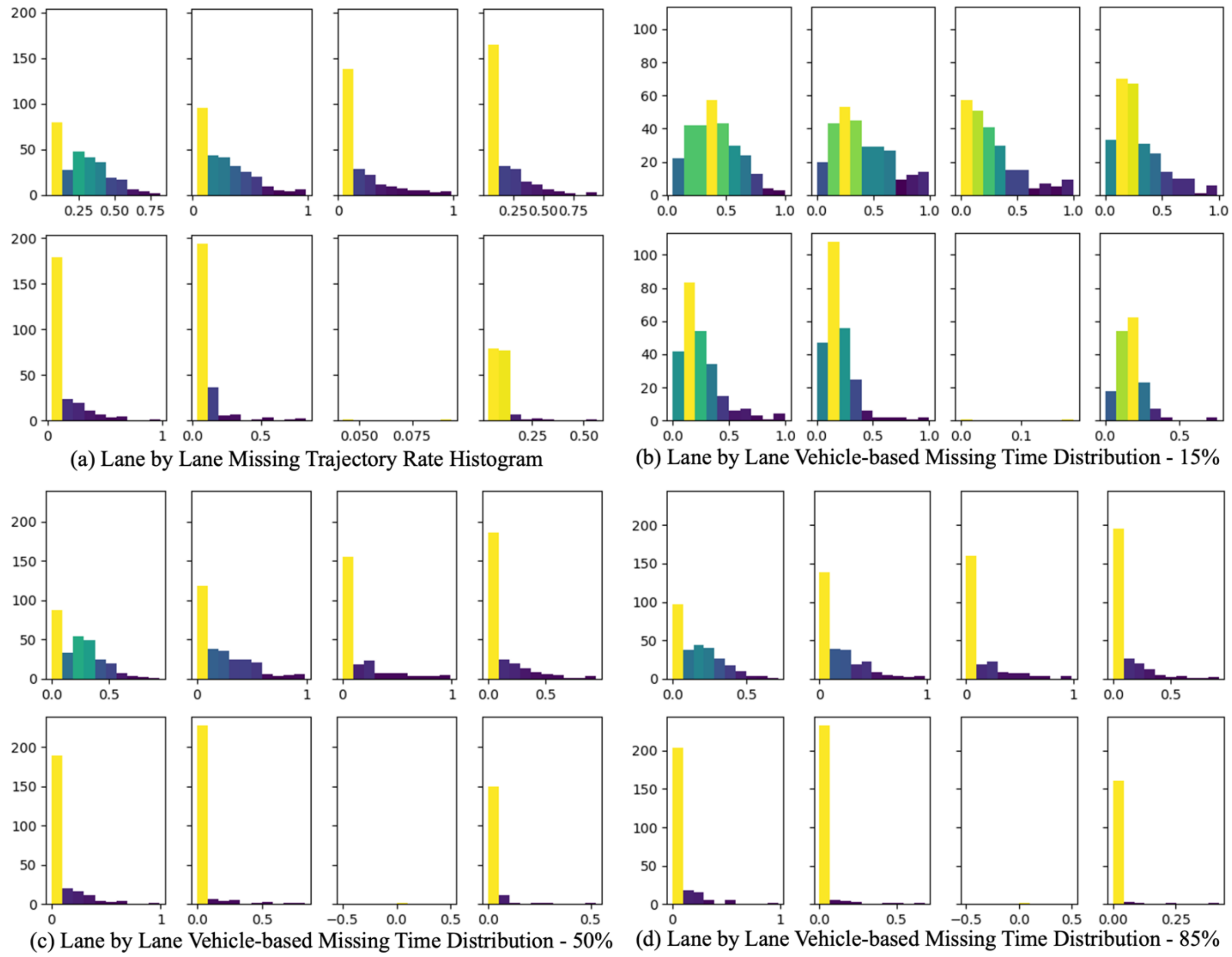


Figure 78. Lane-by-Lane Missing Trajectory and Lane-by-Lane Vehicle-based Missing Time of 5 Degree at 23 Ft.

Figure 78 (a) shows the histograms of the lane-by-lane missing trajectory rate. Figure 78 (b)(c)(d) shows the lane-by-lane vehicle-based missing time distribution with the threshold of missing areas at 15%, 50%, and 85%. All four figures consist of eight histograms, each histogram corresponds to one lane from the left lanes to the right lanes including frontage road, on and off ramps.

Figure 78 (a) shows that the first two lanes from the left have a bigger missing trajectory rate than the other lanes. Figure 78 (b) illustrates that most vehicles cannot meet the requirement of less than a 15% missing rate for most of the frames. Figure 78 (c) shows that most vehicles between the third lane and the sixth lane from the left can meet the requirement of having 50% of trajectories detected for most of the frames. Comparing figure 78 (c) with (d), not much improvement can be found for the first two lanes from the left.

The two metrics presented figure 78 can not only be used to find the optimal configuration of LiDAR installation through simulation but they can also be used as performance measurements in evaluating real-world LiDAR detection by lane-based missing trajectory rate and vehicle-based missing time.

Grid-Based Blind Zone Duration Map

Different from the average lowest laser height map, the time in the blind zone map focuses on the time only when the height map exceeds a preset threshold for the height of the blind zone: h^B. It is calculated as the percentage of the total time that a grid is a blind zone. The grid is considered a blind zone when $h_{g,f} < h^B$, where $h_{g,f}$ is the lowest effective laser height in grid g at frame f, and h^B is the threshold value for the blind zone. 4 ft., 6 ft., and 14 ft were selected as h^B to represent typical vehicle heights. 4 ft. is the lowest height for most of the daily cars and most pedestrians over 8 years old. If the lowest laser height is within 4 ft., it means that almost all the vehicles and most of the pedestrians appearing in the coverage will be found in the LiDAR data. If the lowest laser height is over 6 ft., it means that the majority of the vehicles are missing except for some of the higher-than-average SUVs, pickups, and trucks. If the lowest laser height is over 14 ft., it means that the LiDAR can barely find any vehicles. Considering that the simulation scenario is on a highway, it is assumed that no children below 4 ft. will appear in the scenario alone. More heights will be considered in future work when performing the simulation for intersections.

$$TIBZ_{Gx,Gy} = \frac{\sum B_{Gx,Gy}}{F_{Total}} \quad (\mathbf{6})$$

Where $TIBZ_{Gx,Gy}$ is the time in the blind zone at grid $Gx, Gy, f_{B_{Gx,Gy}}$ is the frame at which grid Gx, Gy is in the blind zone.

Maximum Consecutive Blind Zone Duration Map

Similar to the Grid-based Time in Blind Zone Map, the Maximum Consecutive Blind Zone Duration Map focuses on the consecutive time instead of the total time. Consecutive loss of vehicle detection can have a significant impact on the detection and tracking capabilities of LiDAR sensing algorithms. This consecutive blind zone duration map can reveal whether acceptable consecutive vehicle missing time can be achieved to allow effective tracking and inferences of vehicle positions based on their prior driving behavior.

The simulation model can be used to evaluate and identify optimal configurations for different installation scenarios. To validate the model, the 15-min US101 Next Generation SIMulation (NGSIM) dataset was used for validating the model. Different configuration settings were simulated and compared. The evaluation results demonstrate the capabilities of the models in planning for optimal roadside LiDAR sensor installation for vehicle detection and tracking.

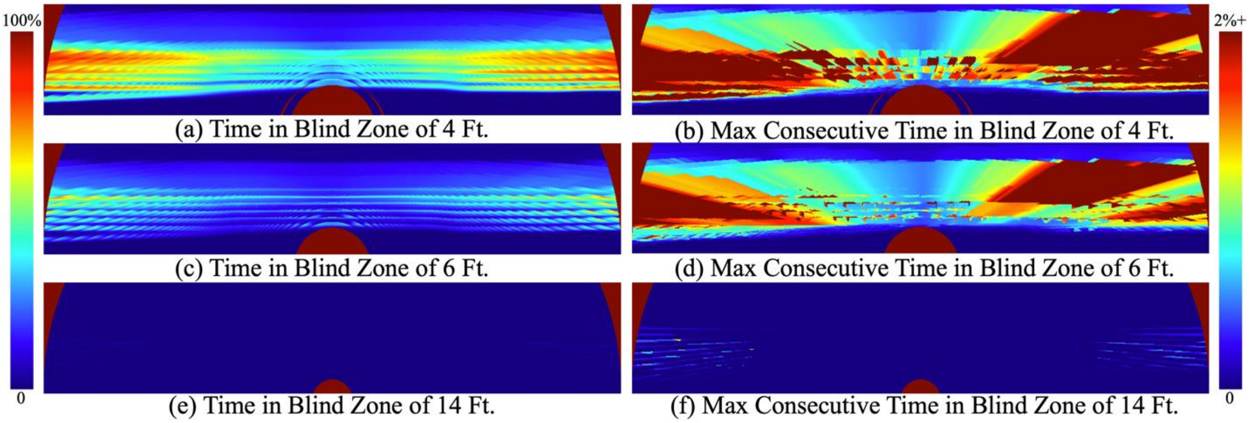


Figure 79. Time and Max Consecutive Time in Blind Zone of 5 Degree at 23 Ft.

Figure 79 shows the grid-based blind zone duration distribution and the maximum consecutive missing duration in the blind zone at HOI levels of 4 ft., 6 ft., and 14 ft. representing heights of sedans/coupes, SUVs/pickups, and trucks. Figure 79 (a)(c)(e) are the percentage of blind zone durations over the entire data period. Figure 79 (a) shows that under the 5˚ at 23 ft. configuration and the given traffic flow, if the vehicle is lower than 4 ft., then the vehicle can only be potentially detected within 200 ft. because there are blind zone durations over 50% starting from around 200 ft. Figure 79 (b) shows that when relaxed to 6 ft, the algorithm can most likely be detected and tracked within the coverage area, since most of the coverage area has less than 50% blind zone duration. Figure 79 (c) shows that if the vehicle is higher than 14 ft., then it can be detected and tracked easily, as overall the blind zone durations are less than 10%.

Figure 79 (b)(d)(f) are the maximum consecutive blind zone durations. It is proposed to evaluate the performance of object detection and tracking in LiDAR data analytic algorithms. Figure 79 (b) shows that, even if the vehicle height is within 4 ft., the vehicle will be detectable but hard to track because there is spatial-discrete temporal-consecutive missing even near the LiDAR. Figure 79 (d) shows that if the vehicle is around 6 ft., then the LiDAR can track it for around 300 ft. However, for the 300 ft. ~ 500 ft., the tracking capability may be influenced by the blind zone created by trucks/buses, because temporal-consecutive missing becomes denser beyond 3/5 of the covered 500 ft. Figure 79 (f) shows the same result as figure 79 (e) shows, that the vehicles higher than 14 ft. will always be detected and tracked within the coverage area.

Digital Twin

Digital twin (DT) models generate virtual entities in cyberspace that imitate the original physical entities, enabling monitoring, analysis, testing, and optimization of these physical entities. [28] DT model in traffic flow can replicate and model the interactions among individual vehicles, pedestrians, and other road users and their interaction with the infrastructure and environmental dynamics of real-world transportation systems. [29] DT models are different from conventional traffic simulation and simulator models since the goal is to reproduce and model the traffic flow dynamics with high fidelity at the object and trajectory level for dynamic vehicles and pedestrians with 3D or even photorealistic infrastructure backgrounds. [30] DT models aim to reproduce and model the movements of road users rather than the aggregated macroscopic traffic states (speed, flow, density) or driver behavioral characteristics in conventional traffic simulation models.

DT models have the potentials to provide diverse application scenarios that cannot be easily addressed with conventional traffic simulation and simulator models. It can provide the digital scene, enabling a high-precision traffic environment and using a highly realistic and scenario-rich simulation platform to test and train high-fidelity traffic flow dynamics. Analyzing the DT traffic data allows traffic administrators to optimize traffic scheduling and alleviate traffic conflicts. In the emerging Vehicle-to-Infrastructure (V2I) and Vehicle-to-Everything (V2X) technologies, the DT model can enable virtual BSM-dynamic conflict maps to broadcast collision avoidance messages. [31,32,33]

To meet the above application needs, DT models need high-resolution and high-quality object trajectory data inputs. More specifically, these requirements are reflected at three levels:

- Origin-Destination Level: All trajectories need to be continuous from their entry to exit points and should be between reasonable origin-destination pairs and lane changes. Any gaps or incomplete trajectories can lead to sudden vehicle disappearances and unexpected reappearances in the DT models.
- Trajectory Level: For each trajectory, the trajectory identification (ID) needs to be consistent throughout its movement in the DT models. Any ID switching for the same vehicle will result in noticeable changes to the vehicle's assigned 3D representation within the DT model.
- Behavioral Model Level: All traffic dynamic objects should exhibit realistic headings, kinematic motions, and microscopic traffic flow behavior (car-following and lane-changing) in the DT model. Authentic DTs should ensure correct, smooth, and uniform vehicle heading. Additionally, they should guarantee that turning movements mirror reality without displaying unnatural oscillations or gliding. In normal driving, vehicles should not go backward unless they are conducting street parking or yielding right-of-way for crossing traffic at a red light. Collisions should not appear unless there is a real-world accident captured.

Field trajectory data collected from high-resolution roadside sensors like CCTV, LiDAR are often processed by deep learning-based analytic models to derive vehicle or object trajectory data. However, the outcome from those analytic models has limitations. Vehicles can disappear in LiDAR's blind zones and can be mistraced between vehicle frames due to occlusions or video stream instability. Such problems result in raw trajectories having fluctuations, breaks, and discontinuities, causing vehicles in DT models to exhibit behaviors like shaking, disappearing, or ID switching. Moreover, depending on the underlying 3D visualization engine, such as Car Learning to Act (CARLA), it requires assigning vehicles to specific center lines of lanes. [34,35] The vehicle headings and movement can be affected by inaccuracy or unstable lane or approach assignment. Such an assignment is particularly challenging given that field data trajectories seldom stay precisely on a lane's centerline. Without appropriate corrections, the fidelity of DT models will be significantly compromised, adversely affecting their applicability.

We propose a vehicle trajectory stitching and reconstruction method to address and mitigate the data quality issues in raw vehicle trajectory data. First, a GPS waypoints-based lane-by-lane route centerline map is created as the reference to project and assign raw trajectory points onto individual lanes. Then, for the projected trajectories on each lane, a spatiotemporal-based stitching and reconstruction method are proposed to detect and fix anomalies or breakings among the trajectories. The broken trajectory fragments are detected and matched by conducting a spatiotemporal search around a trajectory terminated in the midblock of a roadway link for potential connecting trajectories based on the upstream-downstream and temporal relations. Once two trajectory fragments are matched, interpolation and smooth methods are implemented to fill the broken gaps. The proposed methods are evaluated with the trajectory data collection from roadside LiDAR sensors deployed at the DataCity Smart Mobility Testing Ground in New Brunswick, New Jersey. The point-level, trajectory-level, and general flow-level quality assessments are conducted to evaluate the data quality and performance of the proposed method. The resulting high-resolution (10 Hz) trajectories are used to build 3D DT models in the CARLA emulator. Camera visualization is used to compare the dynamics of DT model with the CCTV recordings from the same viewing angle to validate its fidelity.

Workflow for Digital Twin Modeling

The proposed method is one part of the overall flow to create a traffic DT, as shown in figure 80. The left branch is to build a static 3D real-world geometry and centerline map for the traffic network. The RoadRunner software is used to create a 3D virtual representation based on LiDAR point cloud data through vehicle-based or aerial scanning. [(36)] Aerial images are used to configure the road topology, building placement, and elevation data to ensure accurate positioning and alignment of infrastructure objects within the virtual environment. Furthermore, a high-resolution lane-by-lane map is created to incorporate geographic and topological information about the road network based on the OpenDrive standards. [(37)] Each link includes waypoints defined along the centerline of each lane and will be used for the map-matching process to determine the lane and approach assignment and regulate vehicle headings of raw vehicle trajectories. On the right branch, raw vehicle trajectories will be first projected vehicle trajectories onto the centerline of each lane in the high-resolution map created. A trajectory stitching method is proposed to detect and stitch disconnected trajectories on each lane in the space-time vehicle trajectory diagram. A multi-lane trajectory interpolation and reconstruction method then assesses the integrity of the vehicle trajectories across different lanes and conducts interpolation to prepare the vehicle trajectory data into the resolution and completeness needed for the CARLA simulator for building the 3D digital twin.

The proposed full 3D digital twin model will include real-world high-fidelity visualization and simulation of vehicle-by-vehicle traffic conditions and its feedback for microscopic vehicle control and macroscopic traffic operations. The current development is focusing on the "Dynamic Modeling" branch based on the HD maps created in static modeling and with results validated by the high-fidelity visualization module in the 3D traffic DT model.

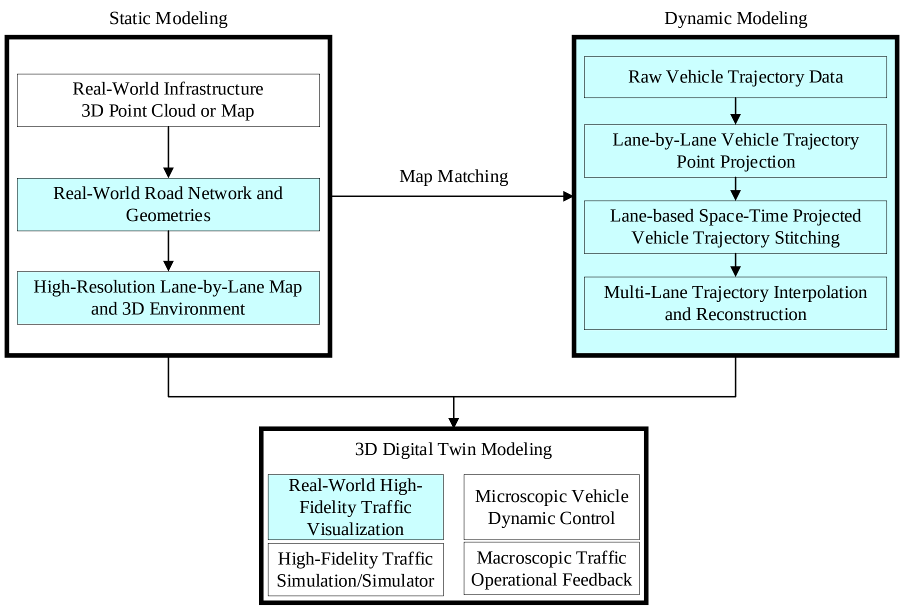


Figure 80. Overall Workflow of the Traffic Digital Twin Modeling Process

Digital Twin World Modeling

The first step to constructing a smart city with digital twin implementation is to create a digital world for the landscape and roadway system. We use the RoadRunner software to create the digital twin world as the real-world mirror with all the geofencing and traffic information. Therefore, the digital world can reflect all the real-world scenarios as our simulation background. As mentioned in Task 4, we already get the precise scanning points clouds of parts of New Brunswick downtown, which can be an input for the Roadrunner software. In addition, we can download the precision background aerial images from USGS website and use it as the reference for the location of the buildings and geographic information of roadways. The aerial images should be in ".JP2" format. The prototype map modeling includes two main routes: Route 27 from French & Easton intersection to Albany & Neilson intersection, and Route 18 from Albany ramps to intersection of Route 18 and US 1.

This also includes all major entrances and exits on Route 18. The geographic information features and traffic features of all roads, including slope, radian, number of lanes, and offset of the road, are produced in the RoadRunner software according to the real world to ensure the authenticity of the digital world. We used several tools in RoadRunner, such as the Road Build Tool for generating roads, the Lane Edit Tool for road offset, Lane Types, and the Junction Tool for intersection design. We can use specific road styles, materials, tiles, and textures provided by the RoadRunner software to match the real-world situation. Figure 81 shows the example of the Road Library in the RoadRunner software, we can select the Freeway style so that it will generate such as lane marks, surface textures automatically.

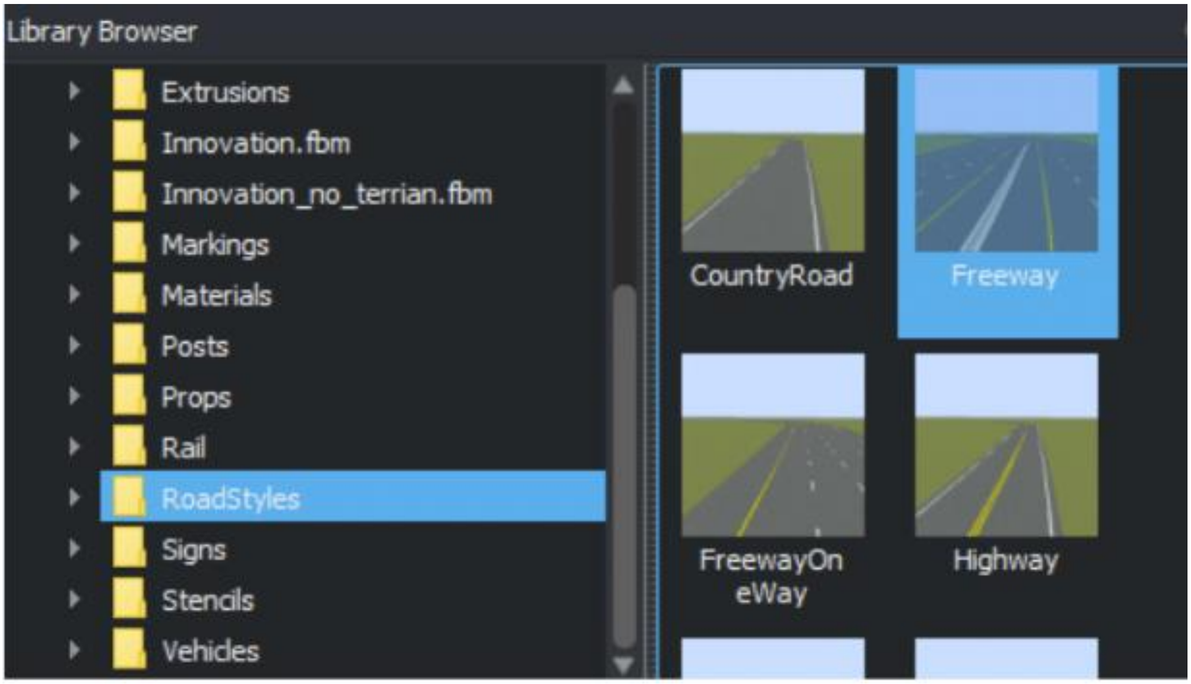


Figure 81. Road Designing Library in RoadRunner

The BIM modeling was also rendered based on the process and method mentioned in Task 4, and the digital world mainly showed the building layout and features along Route 27. Finally, the two-dimensional top view of the prototype digital twin world is shown in figure 82.

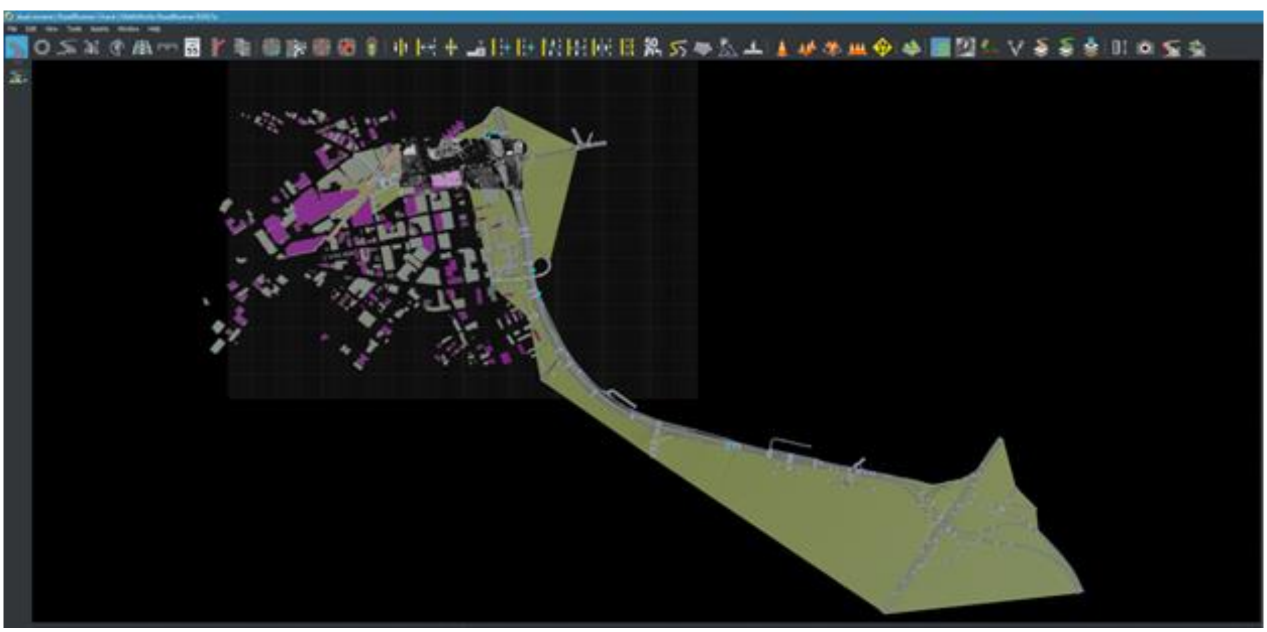


Figure 82. Top view of Digital Twin World in RoadRunner

For the dual intersection we focus on in the digital twin model, Albany & George intersection, and Albany & Neilson intersection, the Roadrunner software can build a detailed, colored 2D view, as shown in figure 83. The geographic location information is not only based on sparse point cloud data but also uses corresponding aerial pictures as a reference so that the details of buildings and roads can be obtained.

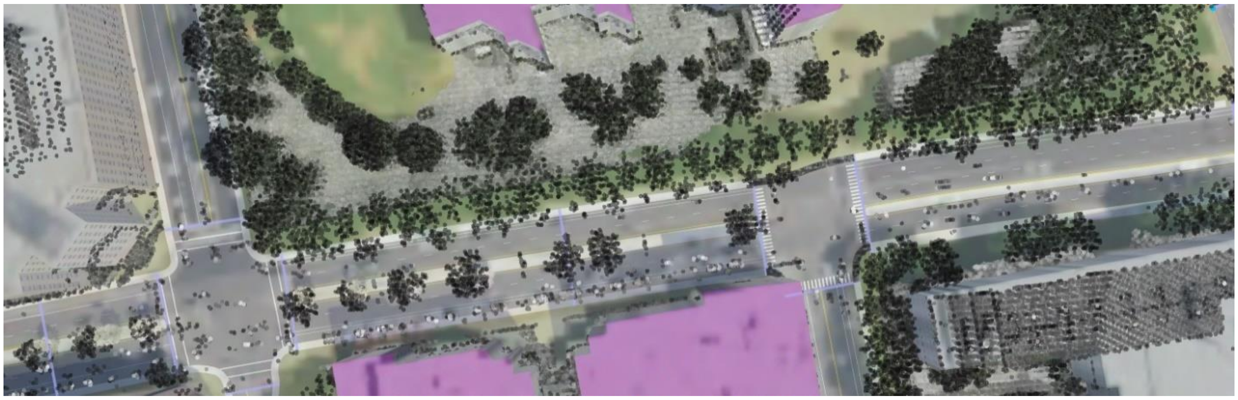


Figure 83. Details of Dual Intersection Digital Twin World in RoadRunner

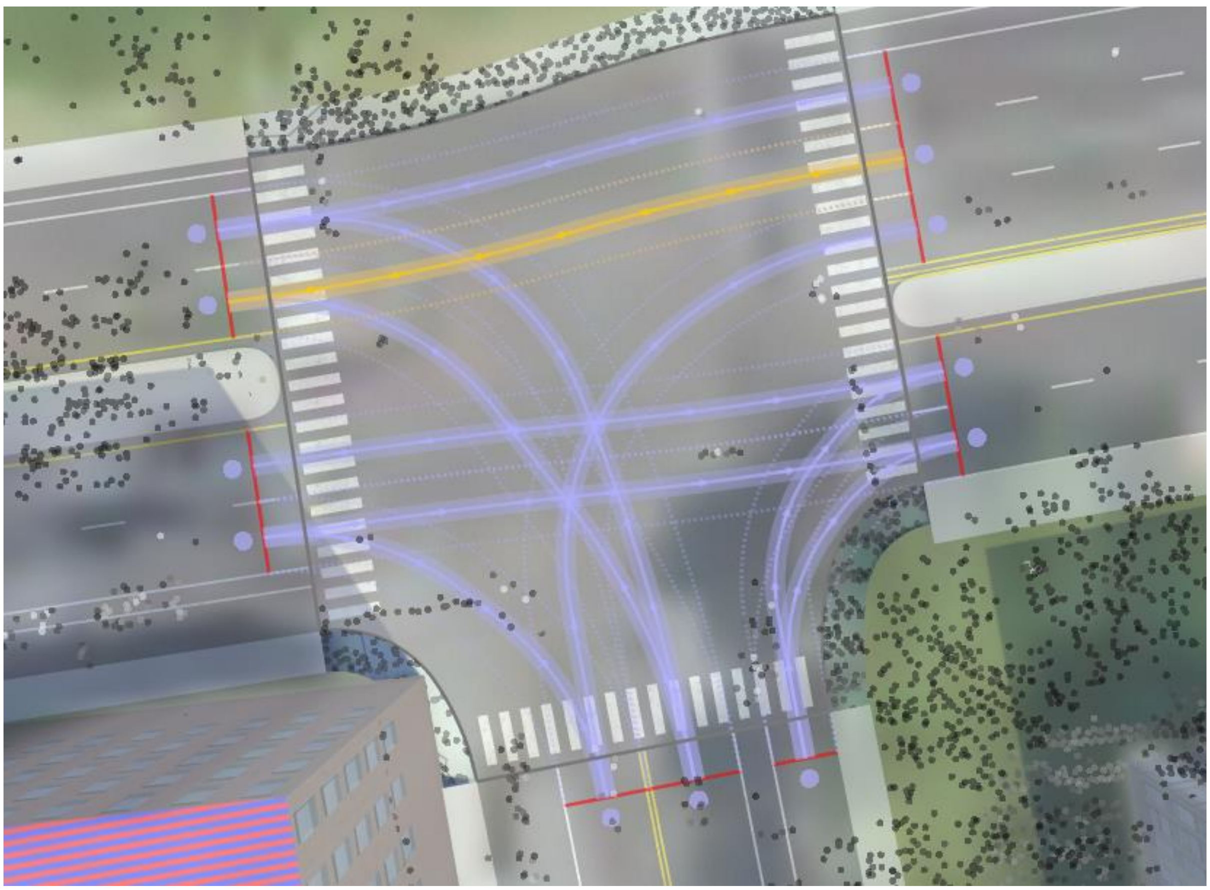


Figure 84. Road Connection Design at Albany & Neilson Street in RoadRunner

Each traffic lane and road in RoadRunner software has the basic geographic shape, we can preview and edit them to match the real-world road situations. Figure 84 shows the road connection design at the intersection of Albany & Neilson Street When the vehicle drives to the intersection, it can only follow the road form with connectivity, to ensure that the vehicle will not be confused about which way to go in the junction area. There are also arrows for each connected road, as shown by the yellow highlight of one of them, to ensure the correctness of the driving direction of the vehicle. In addition, the shape and radian of these connectivity roads are also fixed. In simulation, these lines will be replaced by dense waypoints.

For all the lanes, we can also set up the attributes for them. As figure 85 shows, there are three main attributes: Lane Type, such as Driving, Biking, Parking, Shoulder, Sidewalk, etc. Speed Limit: use the real-world rules for each road. Travel Direction: Set the direction that the corresponding lane can travel. Since some bicycle lanes or sidewalks are two-way, we should relax the travel direction limitation for those lanes. Both these attributes can be recognized by CARLA when importing the map into it. For example, if we assign the Biking type for a lane in RoadRunner, the simulation process cannot spawn any vehicles on that lane and only spawn bicyclists on this lane.

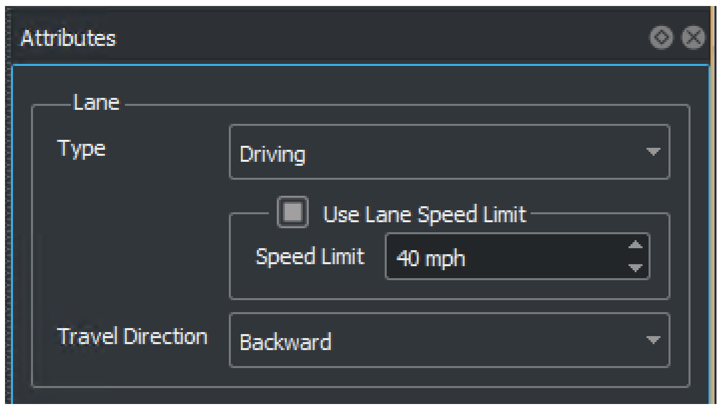


Figure 85. Lane Attributes in RoadRunner

Two useful output file formats can be generated by Roadrunner: ".fbx" file, which is mentioned in Task 4, provides texture files for digital twin world buildings, ground, natural environment, etc.; ".xdor" file, is a kind of the OpenDRIVE file, which provides the exchange format specification to describe static road networks for driving simulation applications. This file describes the geometry of roads as well as features along the roads that influence the logic, so that the emulator can get the correct road position to run the vehicle. When finished with the digital world-building, the RoadRunner software can easily export these two files separately. When exporting the files, we need some settings based on the version of the simulation software we used. Figure 86 shows an example of the settings for OpenDRIVE data format (".xdor" file).

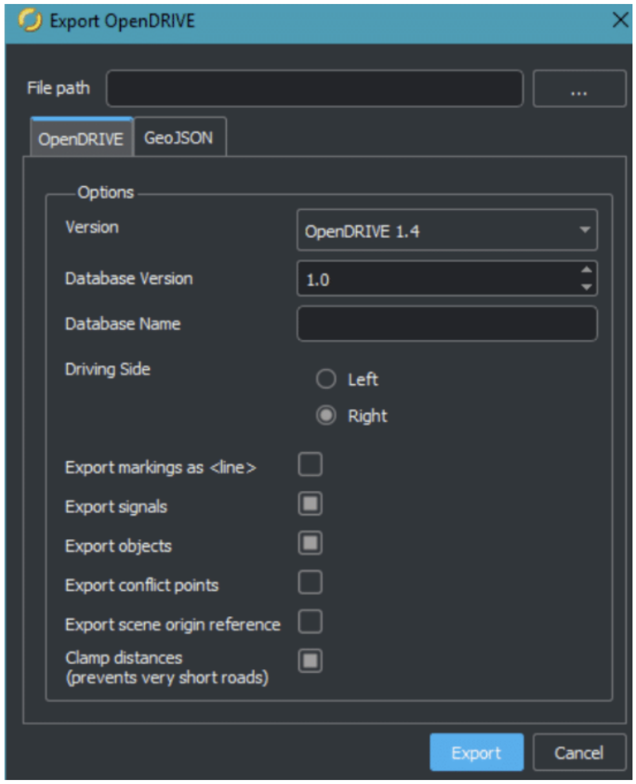


Figure 86. Settings for Exporting Format

CARLA Simulator for Digital Twin 3D Simulation

For the 3D simulation in the generated digital twin world, we use the open-source simulator CARLA. CARLA simulator has been developed to support the development, training, and validation of autonomous driving systems. CARLA provides open digital assets (urban layouts, buildings, vehicles) and supports flexible specification of sensor suites, environmental conditions, full control of all static and dynamic actors, map generation, and much more. Therefore, CARLA can be used as the tool to build up the digital twin model for the New Brunswick Smart Mobility Testing Ground from various sensor fusion feeds.

CARLA is mainly divided into two modules: Server and Client. The Server side is used to build the simulation world, while the Client side is controlled by the user to adjust and change the simulation digital twin world. The server side is responsible for everything related to the simulation itself: from vehicles, roads, buildings, and building sensor models, to physics calculations, and more. It is based on 3D rendering made by UnrealEngine software. [38] While the server constructs the entire world, how the world operates at different times (such as how many vehicles are running) is controlled by the client. The user sends instructions to the server to guide the changes in the world by writing Python scripts (the latest version of C++ is also available), and the server executes according to the user's instructions. In addition, the client side can also receive information from the server side, such as a road image captured by a camera. Figure 87 shows the relationship between Server and Client in CARLA simulator.

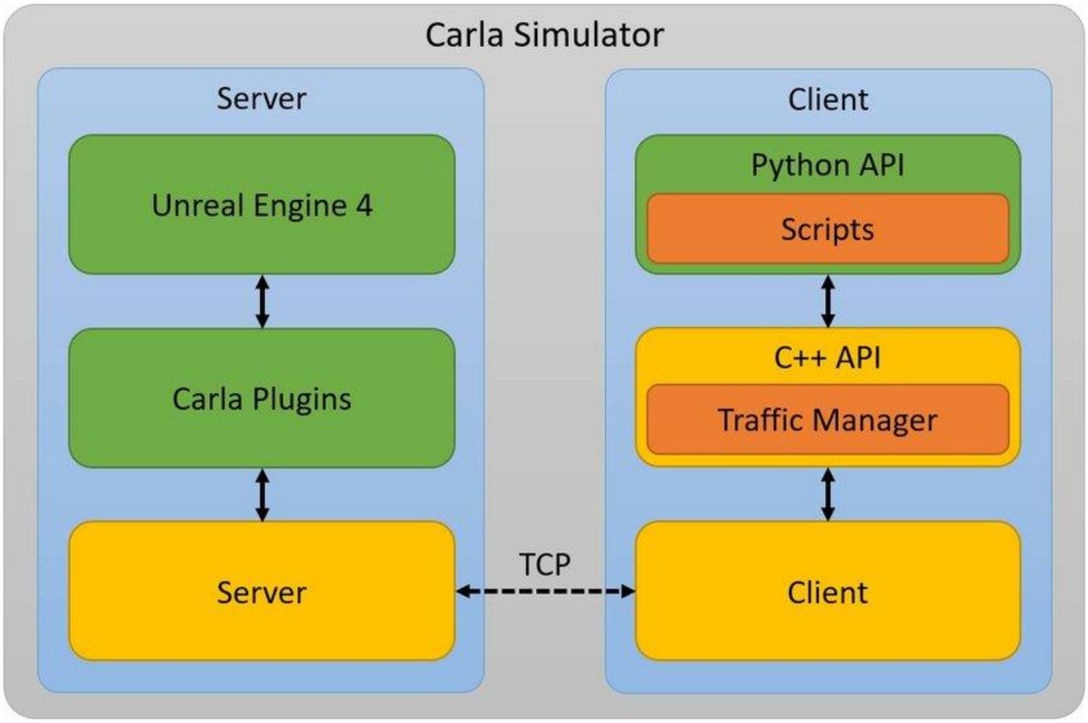


Figure 87. CARLA Simulator Structure

We mainly use the CARLA emulator configured on the Linux system to build and test the digital twin model. Although it is open-source software, the configuration of CARLA is complicated and requires the support of many other software, plug-ins, and hardware. The brief description is as follows: CARLA source version + Nvidia GPU Drvier + UnrealEngine + Clang environment for both CARLA and UnrealEngine + Ubuntu18.04 version with setup tools (recommend) + Github account for UnrealEngine private repo + PythonAPI configuration. The configuration process is basically as follows:

- Nvidia graphics card configuration and driver settings. Since the CARLA software has very strict requirements on the GPU, it is necessary to confirm the hardware configuration of the computer's graphics card before using it, and then select the appropriate CARLA version for installation.
- Configure the required environment and dependencies, including all software dependencies required by CARLA, and the environment software required by the Linux system itself.
- Download and install UnrealEngine from Github. Because the UnrealEngine repo in Github is private, if Github is not connected to the UnrealEngine account, it cannot be downloaded and used. Therefore, you need to create a private account for UnrealEngine before downloading.
- Install CARLA via Github. Set the environment variables of UnrealEngine so that CARLA can recognize UnrealEngine.
- Build the Python API required by CARLA and complete the launch. CARLA relies on UnrealEngine as a tool for GUI display and interaction.

The interface with the default simulated world and vehicle is shown in figure 88:

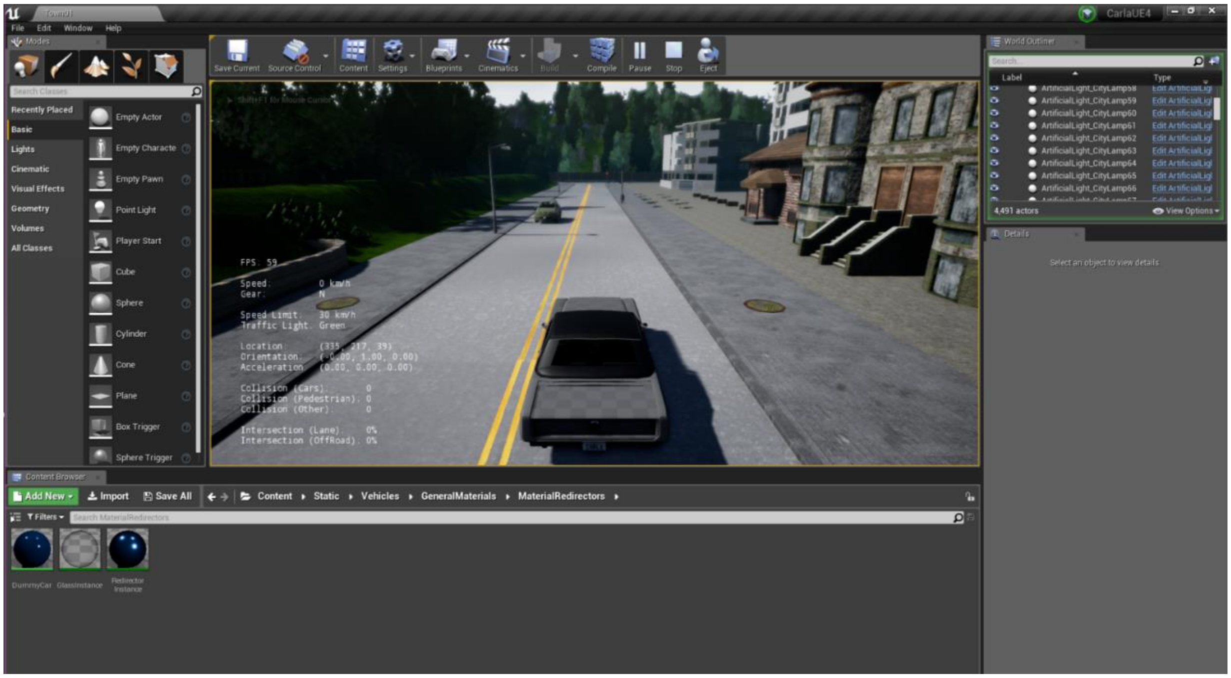


Figure 88. CARLA Simulator Scene Interface

CARLA software can build up the maps from both two files, ".fbx" file and ".xdor" file from RoadRunner, which unpack everything to the resources that can be used in UnrealEngine and called by the CARLA client. This process integrates the traffic geographic information files associated with the 2D map in RoadRunner into a 3D digital twin map, which can be displayed in UnrealEngine. The input process is generated by a port between CARLA and UnrealEngine, called the Python API. Every tile, texture, and road type provided in the RoadRunner will be detected by the CARLA, and UnrealEngine can find the corresponding 3D model for it, or create it based on the information provided by the ".fbx" file, which can ensure that the whole digital twin world is created correctly and completely. The sample maps of the dual intersection in this digital world are shown in figure 89, the position of the view is the LiDAR position at the intersection of Albany & Neilson in New Brunswick downtown.

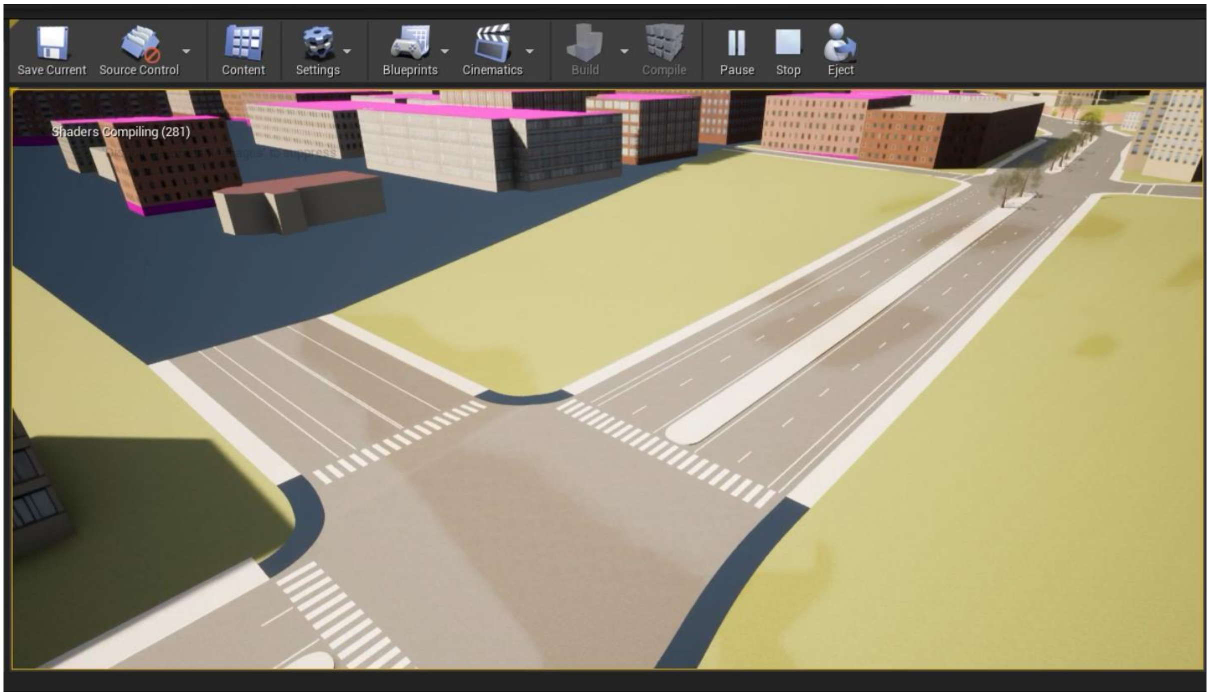


Figure 89. Digital Twin World for the Dual Intersection in New Brunswick Downtown

For each road user type, we can find the one-to-one correspondence of the blueprint in CARLA. Therefore, when CARLA recognizes the class type in data input, it will convert it to a 3D road user model, which will be displayed in the animation of UnrealEngine corresponding to CARLA. For example, if the input data says the object is a vehicle, the CARLA will select a blueprint as one of the vehicles, as shown in figure 90:

Figure 90. Vehicle Blueprint in CARLA

Also, the CARLA provides different blueprints for road users, figure 91 shows the blueprint library of pedestrians.

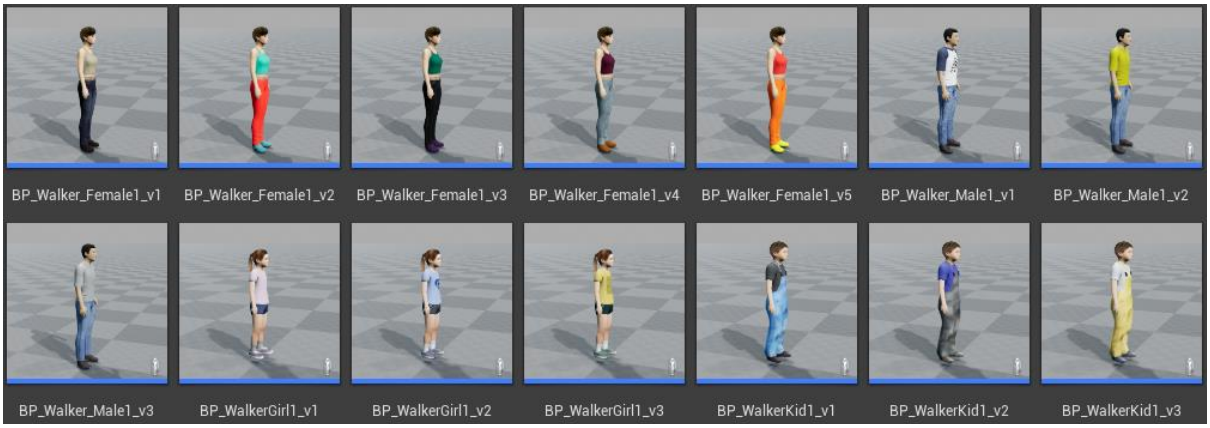


Figure 91. Pedestrian Blueprint in CARLA

SUMO Simulator for Digital Twin 2D Simulation

For the 2D digital twin simulation, and the co-simulation support in the future, we use the Simulation of Urban Mobility (SUMO) simulator. [39] SUMO is an open-source, highly portable, microscopic, and continuous multi-modal traffic simulation package designed to handle large networks. allows modeling of intermodal traffic systems including road vehicles, public transport, and pedestrians. Included with SUMO is a wealth of supporting tools that handle tasks such as route finding, visualization, network import, and emission calculation. SUMO can be enhanced with custom models and provides various APIs to remotely control the simulation. Unlike CARLA, the installation and configuration of SUMO is easy to follow, all the dependencies and packages are generated by the official website.

SUMO uses the Traffic Control Interface (TraCI) protocol for the simulation. The workflow of TraCI connect is shown in figure 92. Giving access to a running road traffic simulation allows for retrieval values of simulated objects and manipulates their behavior "online". TraCI uses a Transmission Control Protocol (TCP) based client/server architecture to provide access to SUMO. After starting sumo, clients connect to SUMO by setting up a TCP connection to the appointed route. TraCI supports multiple clients and executes all commands of a client in a sequence until it issues the TraCI/Control-related commands for simulation steps. To have a predefined execution order every client should issue a TraCI/Control-related command before the first simulation step. It assigns a number to the client and commands from different clients during the same simulation step will be executed in the order of that numbering which does not need to be consecutive nor positive but unique. Each simulation step in SUMO can be executed by the command line.

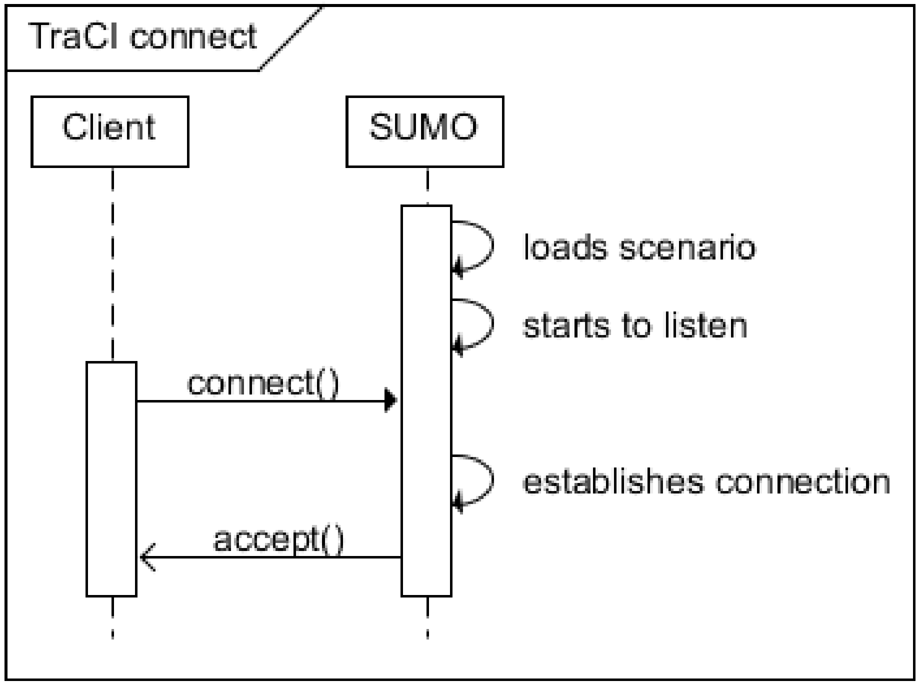


Figure 92. TraCI: Establishing a Connection to SUMO

Based on the workflow chart, the first is inputting the road system as the map to the SUMO. SUMO supports ".xdor" format file, which is already generated by the RoadRunner software, we can directly use it. The additional step called "netconvert" is we need to use the SUMO to convert the ".xdor" file to a traffic network ".xml" format file. This step can be finished by the following command line: "netconvert – sample. xodr -o sample.net.xml"

In addition, we also need to convert the input traffic data to the ".xml" format. The key features in this ".xml" traffic data are Vehicle Types (Needed, can be estimated). Vehicle Count (Needed). Vehicle Routes (Needed)

The recommended method to process the traffic data is using the turning count. It can be aggregated by 1 min or 15 min and needs whole coverage of all movements (straight, left, right, merge, etc.) of intersections, on-ramp and off-ramp, etc. Therefore, whatever data feed we use, we need to manually or with the help of other programming scripts to generate the input data into tunning count format and then use the command line to convert it into .xml format. The sample .xml format of the input traffic data is shown in figure 93. "<edgeRelation from="125.0.00" to="59.0.00" count="3"/>" depicts that three vehicles are moving from edge "125.0.00" to edge "59.0.00" during zero to 99 seconds. The edge ID is defined by the input map.

```xml
<!-- need to make sure edges are connected-->
<interval id="generated" begin="0.0" end="99.0">
    <edgeRelation from="125.0.00" to="59.0.00" count="3"/>
    <edgeRelation from="125.0.00" to="128.0.00" count="20"/>
    <edgeRelation from="-128.0.00" to="-125.0.00" count="15"/>
    <!-- not connected due to roadrunner error
    <edgeRelation from="-128.0.00" to="182.0.00" count="8"/>
    -->
    <edgeRelation from="-182.0.00" to="-11.0.00" count="5"/>'
    <edgeRelation from="-59.0.00" to="128.0.00" count="5"/>
</interval>
```

Figure 93. Sample Traffic Data Input in .xml Format of SUMO

The last step called "jtcrouter" uses a Python script to generate vehicle routes from turn-count data. It does so by converting the turn counts into flows and turn-ratio files that are suitable as "jtcrouter" input for the vehicle simulation in SUMO. When configured these steps. The SUMO can simulate the vehicles in the traffic input data on the roads from the input map.

Vehicle Trajectory Data Processing for Digital Twin Simulation

So far, we can start to use traffic flow data to simulate the digital twin world and build a digital twin model. Currently, the data we use is the BSM data stream obtained from the BlueCity Edge Computer. The data stream is obtained by BlueCity's real-time API from the vehicle data and trajectories identified in LiDAR. The real-time server sends data as a HyperParameter object. HyperParameter is a proto message designed as follows:

```
message HyperParameter{
   string timestamp= sample;
   Frame frame = sample;
   PhaseChange phaseChange = sample;
   OccupancyChange occupancyChange = sample;
}
```

For this digital twin model, we mainly use the frame data (location, class type and the tracking ID of each object within a frame). This API can be used to build more advanced applications on top of our traffic monitoring solution. Each Frame message contains a timestamp and a list of road users' information detected by the sensor called FrameObject as follows:

```
message Frame{
   string timestamp= sample;
   repeated FrameObject objects = sample;
}
```

Each FrameObject represents a road user detected in the frame. For each road user, it assigns a unique ID that is persistent in all the frames in which the object appears. It also sends the location of the object in meters concerning its distance to the sensor, width and length of the bounding box detected for the object, angle of the detected bounding box in radian, class type of the object. The FrameObject is as follows:

```
message FrameObject{
   string id= sample;
   float centerX = sample;
   float centerY = sample;
   float width = sample;
   float length = sample;
   float rotation = sample;
   string classType= sample;
```

Frame-Based Vehicle Trajectory Data Generation

Through these messages stream from BlueCity API, we combine them and transfer to framed-based vehicle trajectory data for both real-time and playback versions as the simulation input data to CARLA and SUMO. The format and attribute samples of the data stream are shown in table 7:

Table 7 - Sample Vehicle Trajectory Data Format from BlueCity BSM Data

Location ID	Measurement Tstamp	Object ID	Center_X	Center_Y	Width	Length	Rotation	Class Type
1	28-Jun-23 09.00.52.859147000 PM	8.03e+08	-26.5814	-9.54823	2.137249	4.728021	3.048343	2
1	28-Jun-23 09.00.52.959009000 PM	8.03e+08	-25.7455	-9.48938	2.126072	4.68666	3.070746	2
1	28-Jun-23 09.00.53.059003000 PM	8.03e+08	-25.0313	-9.46103	2.114668	4.64658	3.06649	2
1	28-Jun-23 09.00.53.158894000 PM	8.03e+08	-24.3855	-9.44633	2.105962	4.637128	3.071779	2
1	28-Jun-23 09.00.53.259556000 PM	8.03e+08	-23.7796	-9.45724	2.100414	4.619496	3.082983	2

Lane-Based Network Representation and Coordination Transformation

Waypoint Representation of the Centerline of Lanes

The raw coordinates of roadside sensors may come in the form of geographical coordinate systems in longitudes and latitudes or projected coordinated systems in x and y in distances. The trajectory stitching with the proposed algorithms requires the generation and analytics on the space-time vehicle trajectory diagrams along the directions of traffic on each lane. In this section, we discuss the network representation of the proposed algorithm and the projection and conversion algorithms from world coordinates into a relative coordinate system along the direction of traffic on each lane-based route.

Figure 94. Schematic Diagram of Lane-based Offset Coordinate System for Through Movements (Red Dots: Network Entry points, Arrows: Network Ending Points, Direction of Traffic, Yellow Squares: Waypoints of Major Road Geometry Changes, Yellow: Eastbound (EB), Green: Westbound (WB), Blue: Parking)

As shown in figure 94, the proposed method takes the input of a high-resolution lane-based map that contains the starting, ending, and turning points of each roadway link on each lane as shown in the squares. Due to the need to interact with RoadRunner's high-resolution waypoint system for simulation and simulator purposes, we further discretize each lane-based roadway link into dense intermediate waypoints based on the starting, ending, and turning points of each roadway link. The detailed discretization is as follows. For any set of edge and turning points of a lane $\boldsymbol{\beta}^r = \{(x_b^r, y_b^r)\}$, where $b = 1, \ldots, B$ for all the edge and turning points, then a set of interpolated waypoints $\boldsymbol{\gamma}_b^r$in between each pair of edge or turning points (x_b^r, y_b^r) and (x_{b+1}^r, y_{b+1}^r) can be calculated as follows:

$$\boldsymbol{\gamma}_b^r = \{(x_{c,\delta}^r, y_{c,\delta}^r) | \delta = 1, \ldots, C_b\} \tag{7}$$

Where:

$$\begin{bmatrix} x_{c,\delta}^r \\ y_{c,\delta}^r \end{bmatrix} = \begin{bmatrix} x_b^r \\ y_b^r \end{bmatrix} + \frac{\delta \Delta d_r}{d_b} \begin{bmatrix} x_{b+1}^r - x_b^r \\ y_{b+1}^r - y_b^r \end{bmatrix}$$

$$C_b = \left[\frac{d_b}{\Delta d_r}\right]_-$$

Where $[\cdot]_-$ is the floor function, d_b is the distance between (x_b^r, y_b^r) and (x_{b+1}^r, y_{b+1}^r), Δd_r is the assigned increments (e.g. 1 meter or 3 meters) for lane r. Then the full set of waypoints $\boldsymbol{\theta}^r$ can created as follows

$$\boldsymbol{\theta}^r = \boldsymbol{\beta}^r \cup \left(\bigcup_b \boldsymbol{\gamma}_b^r \right) \tag{8}$$

We denote each waypoint $Q_w^r = (x_w^r, y_w^r) \in \boldsymbol{\theta}^r$, where $w = 1, \ldots, W_r$, for all waypoints on a lane r in world geographic or projected coordinates. The waypoint resolution Δd_r for each lane r is one meter, so the offset calculation performance is still reasonably accurate with piece-wise linear approximation even for turns at intersections.

Vehicle Trajectory Projection to the Lane Centerline Map

This section proposes the methods to project a trajectory point $P_i(t) = \left(x_i(t), y_i(t)\right)$ of vehicle i at time t onto the centerline of a lane in the network. The projection is conducted by first searching around potential waypoint pairs on nearby lanes and then filtering the results by ensuring the projected points are within the line segments connecting the two waypoint pairs and following the same direction of travel of the vehicle. A closed-by waypoint pair $\{(Q_w^r, Q_{w+1}^r)\}$ is accepted if the following criterion is met. The dot product of the two vectors created by Q_w^r and $P_i(t)$ and Q_w^r and Q_{w+1}^r should be within the range of zero and the squares of the distance between Q_w^r and Q_{w+1}^r,

$$0 \le \overline{Q_w^r P_i(t)} \cdot \overline{Q_w^r Q_{w+1}^r} \le \left\|\overline{Q_w^r Q_{w+1}^r}\right\|^2 \tag{9}$$

That is,

$$\begin{aligned} 0 &\le (x_i(t) - x_{w-1}^r) * (x_w^r - x_{w-1}^r) + (y_i(t) - y_{w-1}^r) * (y_w^r - y_{w-1}^r) \\ &\le (x_w^r - x_{w-1}^r)^2 + (y_w^r - y_{w-1}^r)^2 \end{aligned} \tag{10}$$

onto the centerline map by searching for the centerline segment consisting of two waypoints (x_w^r, y_w^r) and (x_{w-1}^r, y_{w-1}^r). In most situations, a trajectory point will be matched with multiple centerline segments from multiple lanes. Two selection criteria are set for choosing the suited line segment consisting of a waypoint pair. The first rule is to ensure that the physical position of the trajectory point is within the range of the centerline segment, rather than being projected onto the extension line of any other vectors. The dot product C^r between the trajectory point and centerline, the segment will be considered as:

$$C^r = (x_i(t) - x_{w-1}^r) * (x_w^r - x_{w-1}^r) + (y_i(t) - y_{w-1}^r) * (y_w^r - y_{w-1}^r) \tag{11}$$

The second rule is to ensure that when the trajectory point is physically located in centerline segments of multiple lanes in the same travel direction, a lateral distance l_w^r between the trajectory point and centerline segment will be calculated:

$$l_w^r = \frac{\left|(x_w^r - x_{w-1}^r)\left(y_{w-1}^r - y_i(t)\right) - (y_w^r - y_{w-1}^r)\left(x_{w-1}^r - x_i(t)\right)\right|}{\sqrt{(x_w^r - x_{w-1}^r)^2 + (y_w^r - y_{w-1}^r)^2}} \tag{12}$$

Therefore, the projection of a trajectory points $P_i(t) = \left(x_i(t), y_i(t)\right)$ onto the centerline map is conducted a point-to-vector projection method when crossing the product $C^r$and the minimum lateral distance L^r both satisfy.

$$\left(\hat{x}_i^r(t), \hat{y}_i^r(t)\right) = (x_w^r, y_w^r) + (\vec{v} \cdot \hat{u}) \cdot \hat{u} \tag{13}$$

Subject to:

$$0 \leq C^r \leq (x_w^r - x_{w-1}^r)^2 + (y_w^r - y_{w-1}^r)^2$$

$$L^r = \min(l^1, \ldots, l^r)$$

Where:

$\vec{v}$ is the vector from (x_w^r, y_w^r) to $\left(x_i(t), y_i(t)\right)$ by subtracting the coordinates:

$$\vec{v} = (x_i(t) - x_w^r, y_i(t) - y_w^r) \tag{14}$$

û is the unit vector form of two waypoints (x_w^r, y_w^r) and (x_{w-1}^r, y_{w-1}^r):

$$\hat{u} = \frac{(x_{w-1}^r - x_w^r, y_{w-1}^r - y_w^r)}{\left|\left|(x_{w-1}^r - x_w^r, y_{w-1}^r - y_w^r)\right|\right|} \tag{15}$$

After getting the projected trajectory point $\left(\hat{x}_i^r(t), \hat{y}_i^r(t)\right)$, it will be used to calculate the offset of this trajectory point based on cumulative offsets from any waypoints.

Vehicle Trajectory Stitching and Reconstruction

Trajectory stitching starts from determining the traveling lanes of each trajectory point and then the stitching algorithm will be developed based on the spatial-temporal diagrams of the vehicle trajectories on each lane. In the proposed vehicle trajectory stitching and reconstruction algorithm, we assume that regardless of the driver behavior differences, the vehicle will travel through the direction of traffic unless there are street parking or other backward traveling scenarios. The vehicle trajectories should be continuous both in time and space but may not be continuous on each lane. Broken vehicle trajectories, if not merging onto a neighboring lane or exiting the network, will cause a vehicle to appear or disappear out of thin air, which is unrealistic, thus reducing the fidelity and reliability of the digital twin model.

Step 1: Trajectory Classification

Since the trajectory stitching and reconstruction method is to find two suitable objects from the existing trajectories, all trajectories are divided into four categories for searching purposes: complete trajectories as $T_{complete}$, upstream trajectories as T_{up}, midstream trajectories as T_{mid}, and downstream trajectories as T_{down}. The classification is based on the offset of the lane in the centerline map to which these vehicle trajectories are projected. A temporal threshold S^u is defined based on the offset s_1^r (the value is 0) of the starting waypoint and a temporal threshold S^d is defined based on the offset s_w^r of the end waypoint for each lane. The two thresholds will be calibrated in the experiment. The trajectories $\hat{P}_i(t)$ can be classified based on its offset $s_{\hat{P}_i(t_1)}^r$ of the first trajectory point $\hat{P}_i(t_1)$ and offset $s_{\hat{P}_i(t_N)}^r$of the last point $\hat{P}_i(t_N)$:

$$\hat{P}_i(t) \in \begin{cases} \mathrm{T_{complete}}, & if\ \ s^r_{\hat{P}_i(t_1)} < s^r_1 + S^u\ and\ s^r_{\hat{P}_i(t_N)} > s^r_w - S^d \\ T_{up}, & if\ \ s^r_{\hat{P}_i(t_1)} < s^r_1 + S^u\ and\ s^r_{\hat{P}_i(t_N)} < s^r_w - S^d \\ T_{mid}, & if\ \ s^r_{\hat{P}_i(t_1)} > s^r_1 + S^u\ and\ s^r_{\hat{P}_i(t_N)} < s^r_w - S^d \\ T_{down}, & if\ \ s^r_{\hat{P}_i(t_1)} > s^r_1 + S^u\ and\ s^r_{\hat{P}_i(t_N)} > s^r_w - S^d \end{cases} \qquad (\mathbf{16})$$

Where threshold $T^{u/d}$ is based on the geometry of the traffic network in the research area to exclude situations where the movement of vehicles entering or exiting the network may not be fully captured by the sensors since they are close to the range limit of the sensors.

Step 2: Upstream-Downstream Trajectory Pairing and Stitching Order Determination

This step determines the order of the stitching in the next steps to ensure the spatial-temporal integrity of the stitched trajectories, as illustrated in figure 95.

Each round of the algorithm needs to adopt a fixed search order to ensure that the search will not be repeated among the trajectory classifications. The upstream-downstream trajectory pairing focuses on matching potential spatial relationships between trajectories in different classification sets. First, all candidate midstream trajectories should be stitched to each other if possible. Then the stitching order will go from upstream to midstream to downstream to ensure the integrity of the trajectories if there are multiple segments. Additionally, separate upstream and downstream searches and stitches are used for trajectories with only a single large continuous break in midstream often associated with the blind zones of the LiDAR sensor.

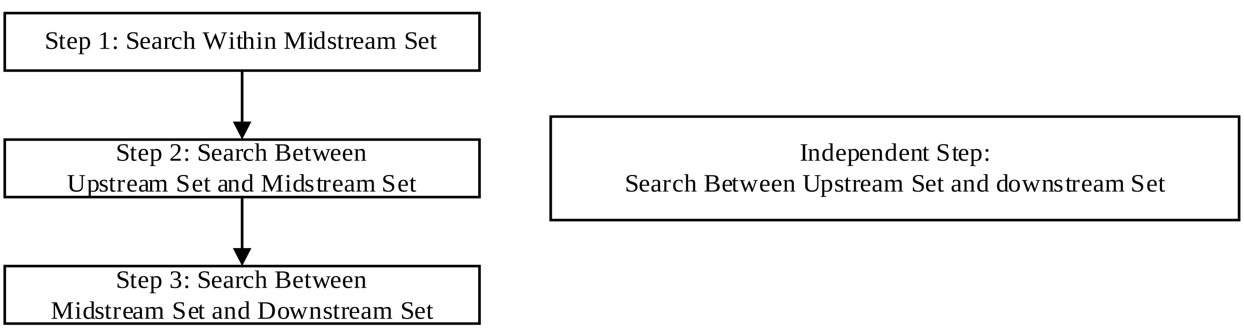


Figure 95. Stitching Order Determination Flowchart

Given the search order and four trajectory classification sets in Step 1, certain special scenarios may arise. It is imperative to define these situations, although they do not undermine the viability of the proposed trajectory stitching method. These scenarios can be delineated into several categories. Firstly, the most prevalent scenarios pertain to vehicles making turns at intersections and executing lane changes during their journey. In this framework, these trajectories are mapped onto different lanes. Despite this spatial shift, they maintain consistent vehicle identifications (IDs), thereby allowing them to be accurately classified into the four trajectory sets and subject to the subsequent search process. Even if the first point and last point belong to different lanes, the offset judgement will also use the corresponding projected lane to identify the classification. The second scenario encompasses vehicle trajectories associated with the enter and exit of street parking lots. Should their pre- or post-trajectories remain intact and complete, they are classified as either upstream or downstream trajectory data, contingent upon their ending or starting point aligning with the waypoint map and lying within the middle of the parking lane. These trajectories are subject to the search order but remain exempt from erroneous stitching, as the corresponding downstream or upstream trajectories cannot be located during the search. The specific trajectory matching methodology will be elucidated in Step 3. The third scenario pertains to vehicles positioned directly within traffic lanes, engaged in activities such as breakdowns or unloading. This classification is like that of the second scenario. It is noteworthy that this scenario may exert a broader influence on other vehicles within a defined temporal and spatial scope, precipitating forced deceleration and lane-changing behaviors. Nonetheless, these affected vehicles can once again be classified within the first scenario, with no discernible impact on the practical applicability of the proposed method.

Step 3: Trajectory Stitching and Reconstruction

With step 2 setting up the stitching order, for each endpoint of an upstream trajectory, the algorithm will search for the starting points of feasible downstream trajectories. Among the candidate downstream trajectories, we project the potential location of the upstream trajectory based on the smaller velocity of the upstream and downstream vehicles. Then, an optimal trajectory downstream will be selected if the projected location is matched for stitching. Let i indicate the upstream vehicle and i' indicate the downstream vehicle. The downstream trajectory $\hat{\mathbf{\Gamma}}_{\mathrm{i}'}$ matches (belongs to) the upstream trajectory $\hat{\mathbf{\Gamma}}_{\mathrm{i}}$, if the following condition holds.

$$\hat{\mathbf{\Gamma}}_{\mathrm{i}'} \in \hat{\mathbf{\Gamma}}_{\mathrm{i}} \quad if\ (s^{r}_{\hat{P}_{i'}(t_1)} - s^{r}_{\hat{P}_{i}(t_N)}) \leq \min\ (v_{i'}(t_1), v_i(t_N)) * \ (t_1^{i'} - t_N^{i}) \qquad \mathbf{(17)}$$

Where:
$\hat{\mathbf{\Gamma}}_{\mathrm{i}}$: upstream projected trajectory set vehicle i
$\hat{\mathbf{\Gamma}}_{\mathrm{i}'}$: downstream projected trajectory set vehicle i'
$v_{i'}(t_1)$: Instantaneous velocity of vehicle i' at the first timestamp t_1
$v_i(t_N)$: Instantaneous velocity of vehicle i at the last timestamp t_N
$s^{r}_{\hat{P}_{i'}(t_1)}$: Offset of vehicle i' at the first timestamp t_1.
$s^{r}_{\hat{P}_{i}(t_N)}$: Offset of vehicle i at the last timestamp t_N.
$t_1^{i'}$: First timestamp of vehicle i'
t_N^{i}: Last timestamp of vehicle i

The condition defined in Equation (17) can be applied to most matched trajectory cases. However, in some situations, the two vehicles can be in different traffic states caused by being located at different sides of the traffic shockwaves, e.g. queue ends or discharging vehicles from a red signal or bottleneck. Two partially captured vehicle trajectories, even with substantial variations in speed, may indeed represent the trajectory of the same vehicle, provided that specific spatial characteristics influenced by traffic shockwaves are satisfied. Within the vehicle trajectory acquisition area, three distinct types of shockwaves necessitate additional constraints during the trajectory stitching process:

- Given the LiDAR sensor's placement at an intersection, frequent speed variations arise from vehicle starts and stops primarily induced by traffic signals.
- During peak traffic hours, after traversing the initial intersection junction, vehicles become subject to the speed fluctuations of queuing vehicles at the downstream intersection.
- The lane proximate to street parking areas is susceptible to the influence of vehicles entering and exiting these parking spaces.

Therefore, for gaps between timestamps and gaps between offsets, the maximum threshold and the space-time relationship are set, respectively, to ensure the integrity of the judgment conditions.

$$\hat{\boldsymbol{\Gamma}}_{\mathrm{i}'} \in \hat{\boldsymbol{\Gamma}}_{\mathrm{i}} \quad if\ 0 < s^r_{\hat{P}_{i'}(t_1)} - s^r_{\hat{P}_i(t_N)} < s_{max}\ and\ 0 < t_1^{i'} - t_N^{i} < t_{max} \tag{18}$$

Next step is adding missing timestamps to the stitched trajectory for interpolation and corresponding offset information on the lane of the centerline map. It may be missing timestamps for complete trajectories, so interpolation methods are also required. For the gaps between the timestamp t_n and timestamp $t_{n'}$ on each trajectory, the interpolated timestamp $\bar{t}_{\bar{n}}$ and the corresponding offset $\bar{s}_i^r(\bar{t}_{\bar{n}})$ are:

$$\bar{t}_{\bar{n}} = t_n + (\bar{n} - n)$$

$$\bar{s}_i^r(\bar{t}_{\bar{n}}) = (\bar{n} - n) * \frac{v_i(t_n) + v_i(t_{n'})}{2} \tag{19}$$

The offsets for each vehicle trajectory point should be monotonically non-decreasing over time when the vehicle moves forward on the centerline map. It does not consider unusual behaviors such as reversing and turning around often seen around street parking lanes. Sometimes, trajectory detection has a back-and-forth jitter for a vehicle waiting for a signal light at the stop line. The smooth method proposed will solve this type of abnormal trajectory of back and forth to ensure that the vehicle's offset remains unchanged when it stops. In the DT model visualization, smooth operation ensures the vehicle will not move back and forth.

$$s^r_{\hat{P}_i(t_{n+1})} = s^r_{\hat{P}_i(t_n)} \quad if\ s^r_{\hat{P}_i(t_{n+1})} < s^r_{\hat{P}_i(t_n)} \tag{20}$$

3D Digital Twin Modeling in CARLA Emulator

The above steps will generate the cleaned and stitched trajectories ready for DT modeling. Additional trajectory data processing needs to be done as part of the modeling inside a digital twin platform such as CARLA. This is primarily due to how CARLA places and moves vehicles inside the platform. In CARLA, each vehicle has a unique ID, and its movements can be controlled individually and dynamically. The following is the proposed CARLA dynamic control algorithm to reconstruct vehicle movements.

The algorithm's core is to dynamically update the spatial information of each vehicle object in each timestamp instead of planning all the vehicles at all the timestamps. Giving the sets to classify the trajectories in the control algorithm as $g(\hat{P}_i(t))$ that control each point of vehicle trajectory for each timestamp, by comparing the vehicle object's status in the current and previous timestamp, three sets are obtained to store the vehicle ID that needs to be added, deleted, or updated.

$$\begin{cases} g_{add}(\hat{P}_i(t)) = \{\hat{P}_i(t_n) | \hat{P}_i(t_n) \in g(\hat{P}_i(t_n)) \text{and } \hat{P}_i(t_n) \notin g(\hat{P}_i(t_{n-1}))\} \\ g_{delete}(\hat{P}_i(t)) = \{\hat{P}_i(t_n) | \hat{P}_i(t_n) \notin g(\hat{P}_i(t_n)) \text{and } \hat{P}_i(t_n) \in g(\hat{P}_i(t_{n-1}))\} \\ g_{update}(\hat{P}_i(t)) = \{\hat{P}_i(t_n) | \hat{P}_i(t_n) \in g(\hat{P}_i(t_n)) \text{and } \hat{P}_i(t_n) \in g(\hat{P}_i(t_{n-1}))\} \end{cases} \quad (21)$$

When a unique ID always exists in the 3D digital twin model, the digital replica model of the vehicle shows the same shape and continuously completes the traffic operation without disappearing.

Digital Twin Modeling Demonstration

Experimental Design

The proposed raw trajectory stitching and reconstruction methods will be evaluated by roadside LiDAR data collected from two adjacent intersections: Albany & George intersection and Albany & Neilson intersection in New Brunswick, New Jersey. Both locations are equipped with one Ouster VLS-128 LiDAR and two 2K resolution cameras. These two intersection sites are part of the 2.1-mile DataCity SMTG corridor currently being constructed by CAIT at Rutgers to establish a living laboratory for smart city and CAV technologies in New Jersey. At this step, some prototype DT models are built for feasibility studies. Figure 96 shows the layouts and sensors at these two intersections:

Figure 96. Two Testing Intersection Sites at New Brunswick Smart Mobility Testing Ground

Demonstration Vehicle Trajectory Data Description

The raw vehicle trajectory data generated from the 128-beam Ouster LiDAR updated at 10 Hz at both intersections. The raw point cloud data are analyzed by edge compute services provided by Ouster's BlueCity engine. For each frame (0.1 seconds), LiDAR data analytics will run at the Nvidia Jetson Xavier box and generate the detected objects with their location and type information. The data archiving is done with a separate Nvidia Jetson Orin computing box and transmitted to the control center through fiber connection at Albany & George intersection and roadside hard drive storage (eventually through Point-to-Point communications) at Albany & Neilson intersection. The BlueCity engine provides consistent vehicle IDs if tracked and will switch IDs for any lapse in tracking. In addition to the vehicle location, it also provides its vehicle or object types including pedestrians, headings, length and width information. Data used in the experiment includes BlueCity LiDAR trajectory data obtained from 4-6 PM for five consecutive working days (June 26th – June 30th, 2023) at both intersections. A two-hour dataset on Monday, June 26th, 2023, is used for calibration and the model performance is evaluated across all five days.

Parameter Calibration

The proposed algorithm includes four parameters, $T^{u/d}$, S_{max} and t_{max} to calibrate. The actual number of vehicles is counted manually between 4-6 PM on June 26th, 2023, to serve as the ground truth data. Then the difference between the number of vehicle objects before and after stitching and the ground truth data is used as the objective function for parameter optimization. The calibration process then finds the optimal parameter values by enumerating the potential combinations of parameter settings. Table 8 shows the calibration results and test ranges of the parameters.

Table 8 - Calibrated Parameter of Proposed Method

Symbol	Definition	Optimal Value		Test Range
		Albany & George	Albany & Neilson	
T^u	Upstream threshold for trajectory classification	2.95 meters	1.75 meters	[0, 10] meters
T^d	Downstream threshold for trajectory classification	4.65 meters	4.45 meters	[0, 10] meters
t_{max}	Maximum timestamp gaps when searching for stitching candidates	±2.0 seconds	±2.3 seconds	[-5, 5] seconds
S_{max}	Maximum offsets gaps when searching for stitching candidates	±12.95 meters	±14.50 meters	[-30, 30] meters

Real World Map, Centerline Map, and 3D Digital Twin Map Generation

The two-intersection scenario is shown in figure 97. The images from top to bottom are:

- LiDAR scanning file of two intersections, the color represents the elevation.
- The scenario of the intersections in the RoadRunner software.
- Centerline waypoints on the satellite image of the two intersections.
- Static display of the virtual world in the CARLA emulator.

The research area of these two intersections is where the LiDAR is installed as the center and a radius of 200 meters based on the configuration of the LiDAR at the research location. The CARLA emulator uses the UnrealEngine to build up the dynamic 3D real-world environment with a static infrastructure background loaded from RoadRunner. The centerline waypoints are also imported through CARLA as the route waypoint reference for importing the projected, stitched, and reconstructed vehicle trajectories. The proposed dynamic control method selects a blueprint of a 3D vehicle model for each unique vehicle ID for vehicle dynamic reconstruction.

Figure 97. Birdseye View of Two Targeted Intersections at New Brunswick, NJ

Digital Twin Modeling Result Analysis

Trajectory Point Processing Percentage Analysis

The trajectory point level evaluation is conducted by using three indicators including the total number of trajectory points of the peak hour data, the number of all interpolated points, and the number of smoothed points. The number of interpolated points reflects the number of stitching conducted for broken trajectories, that is, the frequency of unreasonable appearing and disappearing. Smoothed points indicate the correction of vehicle movements that are the inverse of the direction of travel, smoothing is performed through Equations before. Figure 98 and figure 99 show the data quality evaluation of two intersections, respectively.

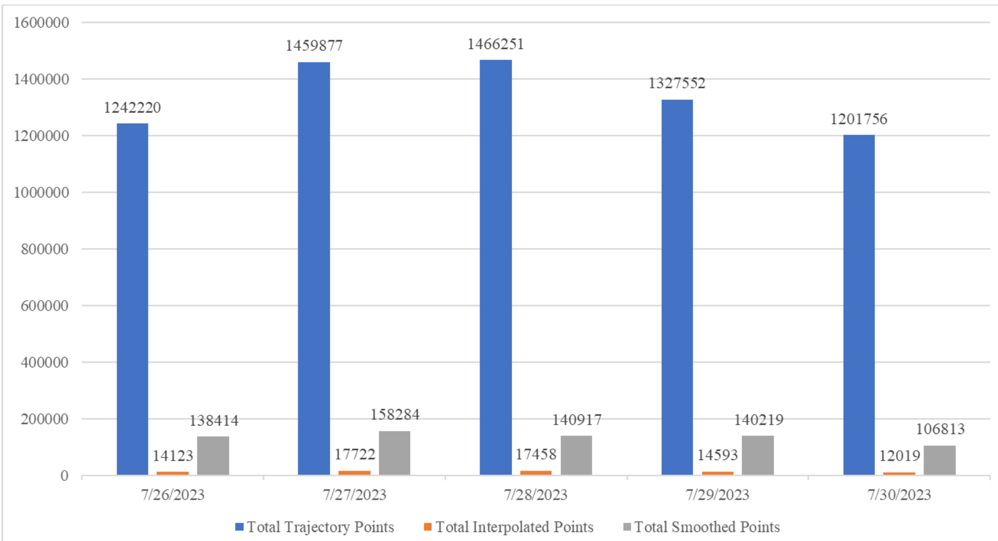


Figure 98. Data Quality of Albany & George Intersection

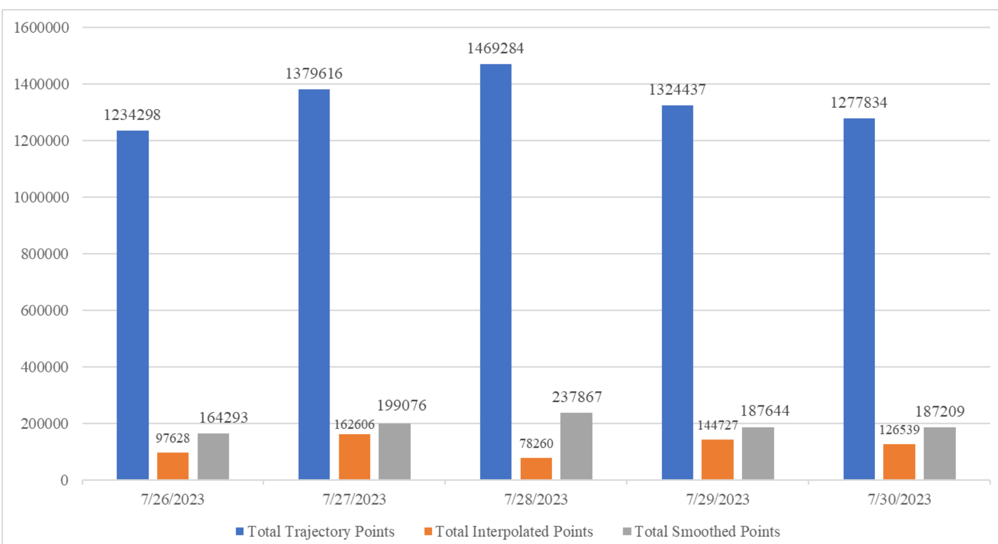


Figure 99. Data Quality of Albany & Neilson Intersection

The figures illustrate the range of trajectory points per intersection per day, which varies from 1,200,000 to 1,500,000. Specifically, the interpolated points at the Albany & Neilson intersection fall within 12,000 to 18,000, constituting less than 2% of the overall settlement count. Moreover, the number of smoothed points ranges from 100,000 to 160,000, accounting for approximately 10% of the total dataset. Even though the percentages are low for interpolated and smoothed points concerning overall situations, however, their occurrence is still very frequent and interruptive, especially at or near intersections where some of the blind spots of the LiDAR sensors are located. Albany & Neilson intersection requires more data interpolation and smoothing than Albany & George indicating worse data quality issues. Such results further validate the need for data cleaning and stitching methods to process the raw LiDAR trajectory data.

Trajectory Reconstruction Performance: ID Switching Measurements and Heatmaps

To gain a more comprehensive understanding of the overall stitching performance, we propose the Rapid ID switching count λ_{id} as an evaluation index for detecting broken trajectories. For any vehicle object $V_{t_n}^{id}(S'_{t_n})$, This index consists of two criteria:

$$\lambda_{id1} = \begin{cases} 1, \quad if \begin{cases} 0 < \mathrm{S}'^{\,\mathrm{id2}}_{\mathrm{t_1}} - \mathrm{S}'^{\,\mathrm{id1}}_{\mathrm{t_n}} < S_{max}, \\ and\ 0 < t_1^{id2} - t_n^{id1} < t_{max}, \\ and\ S_{\mathrm{t_1}}^{\mathrm{id1}} > S_1 + T^u, \\ and\ S'^{\,\mathrm{id1}}_{t_n} < \sum_1^i S_i - T^d \end{cases} \\ 0, \quad\quad Else \end{cases} \tag{22}$$

Vehicle trajectory data from 4 pm – 6 pm for five consecutive working days (June 26th – June 30th, 2023) are used to evaluate the rapid ID switching counts in both the original data and the processed data at the intersections as shown in table 9. The results show that the Albany & Neilson intersection had more rapid ID-switching occurrences in the original trajectories. After applying the proposed method, the number of rapid ID switching occurrences at both intersections decreased significantly by 94.0% for Albany & George intersection and 93.4% for Albany & Neilson intersection on average over the five days. Many of the broken trajectories were successfully repaired, contributing to the improved performance of the processed data.

Table 9 - Rapid ID Switching Count Before and After Processing at Two Intersections

Intersection	**Period**	**06/26/23**	**06/27/23**	**06/28/23**	**06/29/23**	**06/30/23**	**Average**
Albany& George	Before	2578	2804	3035	2916	2566	2780
	After	162	136	240	178	126	168
	Reduction	93.7%	95.1%	92.1%	93.9%	95.1%	94.0%
Albany& Neilson	Before	4129	4780	4547	4706	4729	4578
	After	266	324	327	312	320	310
	Reduction	93.6%	93.2%	92.8%	93.4%	93.2%	93.2%

The spatial-temporal pattern of the stitching performance is also mapped by using grid map diagrams as shown in figure 100. Each point is the value of the evaluation metrics within 5 meters of each location.

Figure 100. Grid Map of the Stitched Point Locations

For the grid-level number of stitched points in figure 100. The blue curved line represents the LiDAR laser beams, indicating the area within which the LiDAR can detect objects. Specifically, for the VLS-128 LiDAR system, the lower limit of the vertical field of view is set at -15-degree. Any vehicles traveling below this -15-degree angle line of sight will be rendered invisible within the system's blind zone. The unique shape of the blind spot beneath the LiDAR sensor, where laser beams do not reach, poses challenges for tracking nearby trajectories. In this region, vehicles will likely become untraceable, leading to trajectory disruptions. Additionally, at the corner of the intersection opposite the LiDAR, numerous trajectory points are stitched. This phenomenon is attributed to large vehicles making left turns at the intersection, particularly at the two target intersections. These turns can obstruct the path of vehicles waiting at the red light on the opposite side, resulting in sporadic breaks in their trajectories.

Lane-Based Detailed Trajectory Level Evaluation

This section selects several five-minute data from off-peak hours and peak hours to show the detailed trajectory stitching result. All trajectories projected on a straight lane traveling east on Albany Street's right lane before and after using the proposed method.

Figure 101 is the time-offset (spatial-temporal) diagram comparison of the raw and processed projected trajectories from a five-minute period during peak hours. The solid lines represent the projected points onto the current route, and the scatter points represent the scaled position of the points from the same vehicles on other lanes before or after lane changes. Area A exhibits trajectory breaks consistently occurring at the offset location approximately 100 meters from the state of the route. This location corresponds to the region directly beneath the LiDAR, commonly known as the LiDAR's blind zone. As a result, trajectories of vehicles passing through this region inevitably experience breaks, displaying similar fracture characteristics. It is shown that the proposed algorithm stitched all broken trajectories in this area. The trajectories in areas B and C also experience breaks. Moreover, due to their distance from the sensor and the impact of traffic signals at the downstream intersection, the vehicle trajectories show vehicle stoppage and queuing behavior. With the proposed method, the fragments in the vehicle trajectories are effectively repaired, preserving the complete movement characteristics of the vehicles.

The trajectory in area D presents a unique scenario where it comes to a halt near the middle of the road without matching downstream estimates, and no lane change is observed. Consequently, after applying the proposed method, the trajectory remains stationary at its original feature.

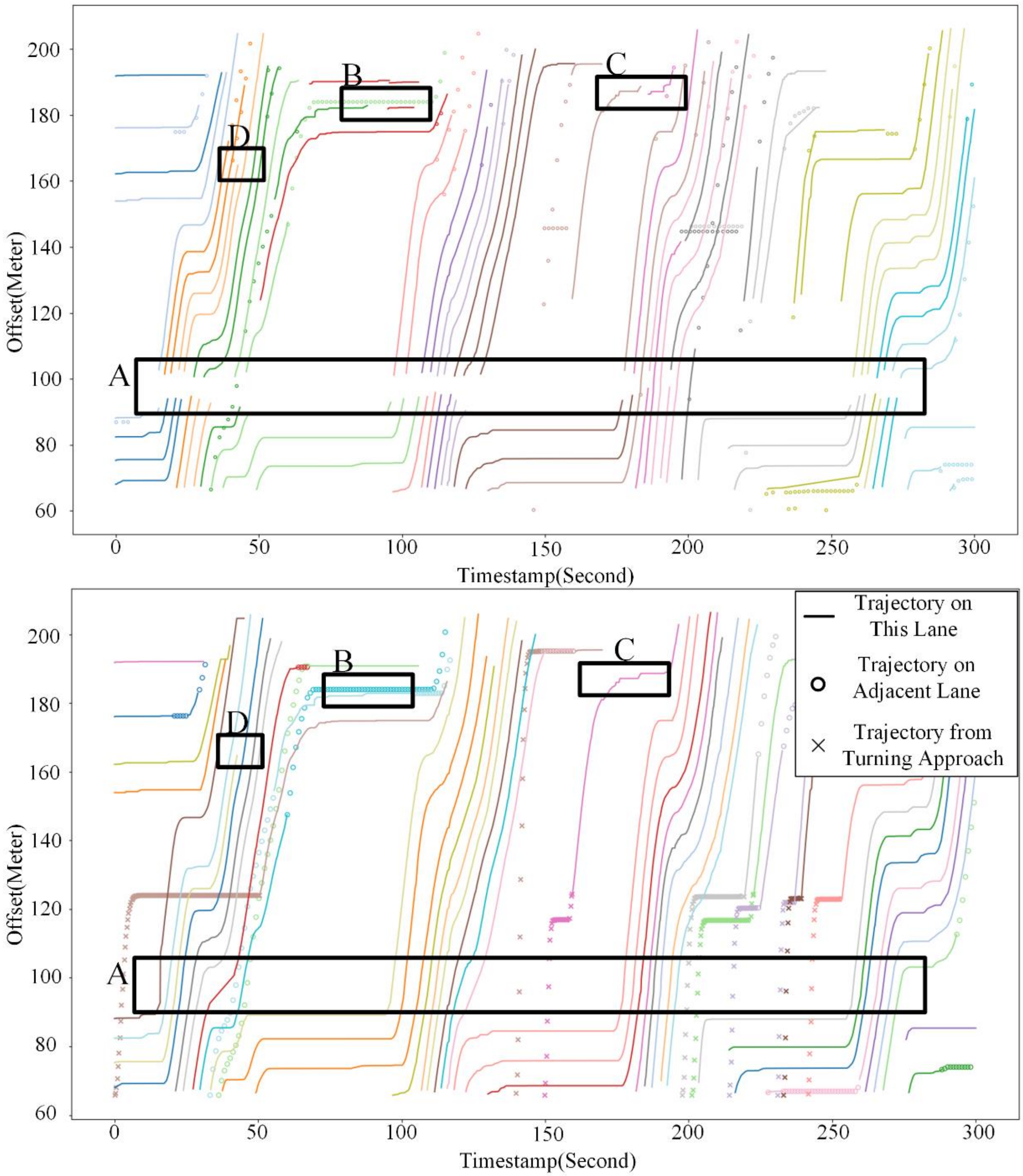


Figure 101. Projected Trajectory Before and After Stitching Case 1

Figure 102 is the space-time diagram comparison of the raw and processed trajectories from an off-peak hour period. The same blind zone area A has several broken trajectories, but the gaps are relatively small compared to the peak hour. Trajectories in these areas have been effectively stitched. In area B, although the trajectories appear connected and have overlapping sections, they are still identified as separate trajectories. The proposed method also performs well in reconstructing such trajectories. In area C, even if only a small portion of the vehicle trajectory appears on the corresponding lane due to lane-changing behavior, the proposed method can successfully stitch these segments together.

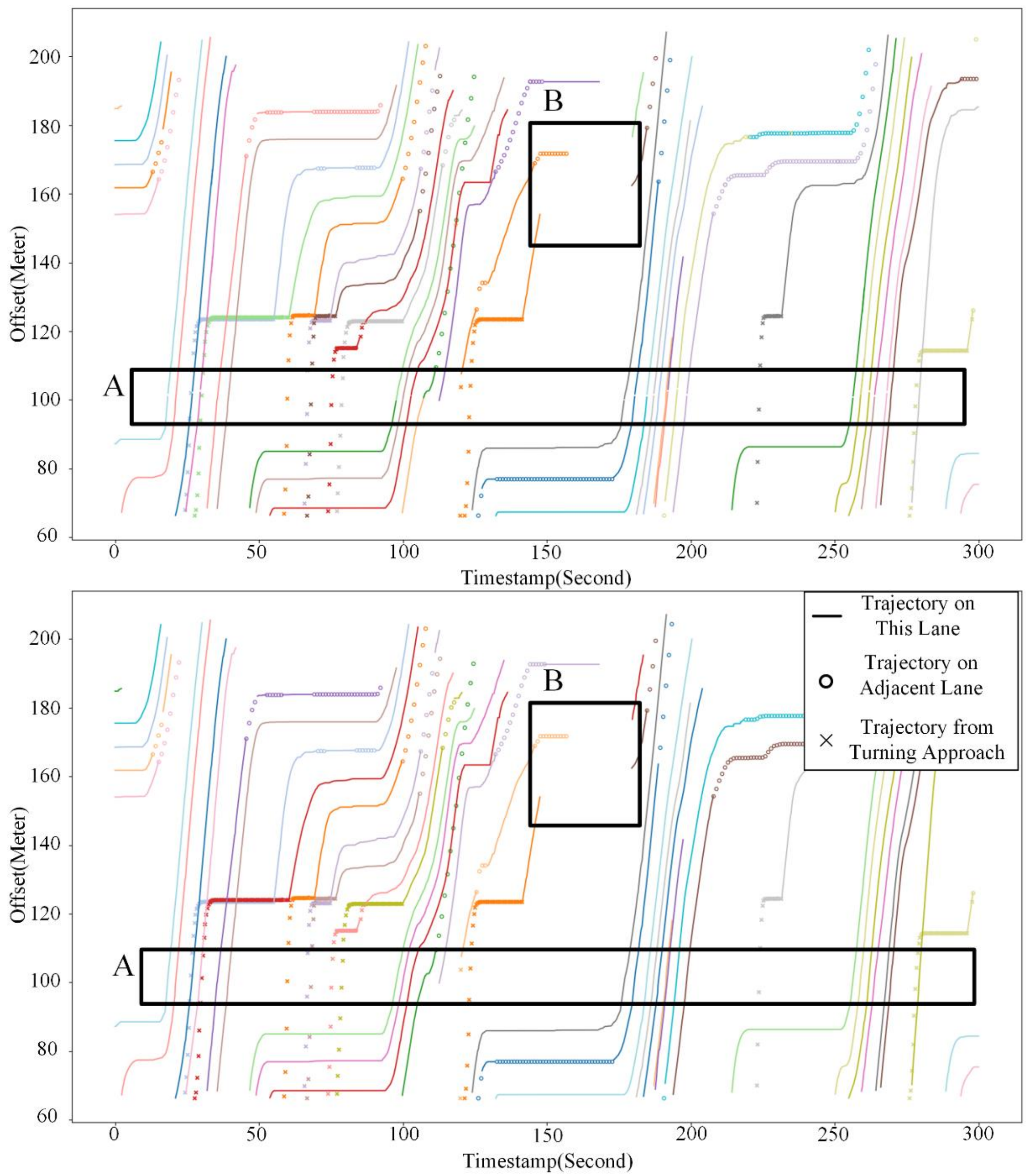


Figure 102. Projected Trajectory Before and After Reconstruction Case 2

Figure 103 shows some remaining issues of the proposed method. The trajectories are from the initial period of the peak hours. In area A, as the blind zone area, the trajectory stitching process shows good performance. However, in area B, none of the four displayed trajectories were successfully stitched together. It can be observed that the time interval between trajectory points in area B is as long as 30 seconds, and one of the trajectories still exhibits lane-changing behavior when it is interrupted. Additionally, for such long-interval trajectory breaks, it is challenging to determine with certainty whether the front and rear trajectories belong to the same vehicle, especially in areas with high trajectory density.

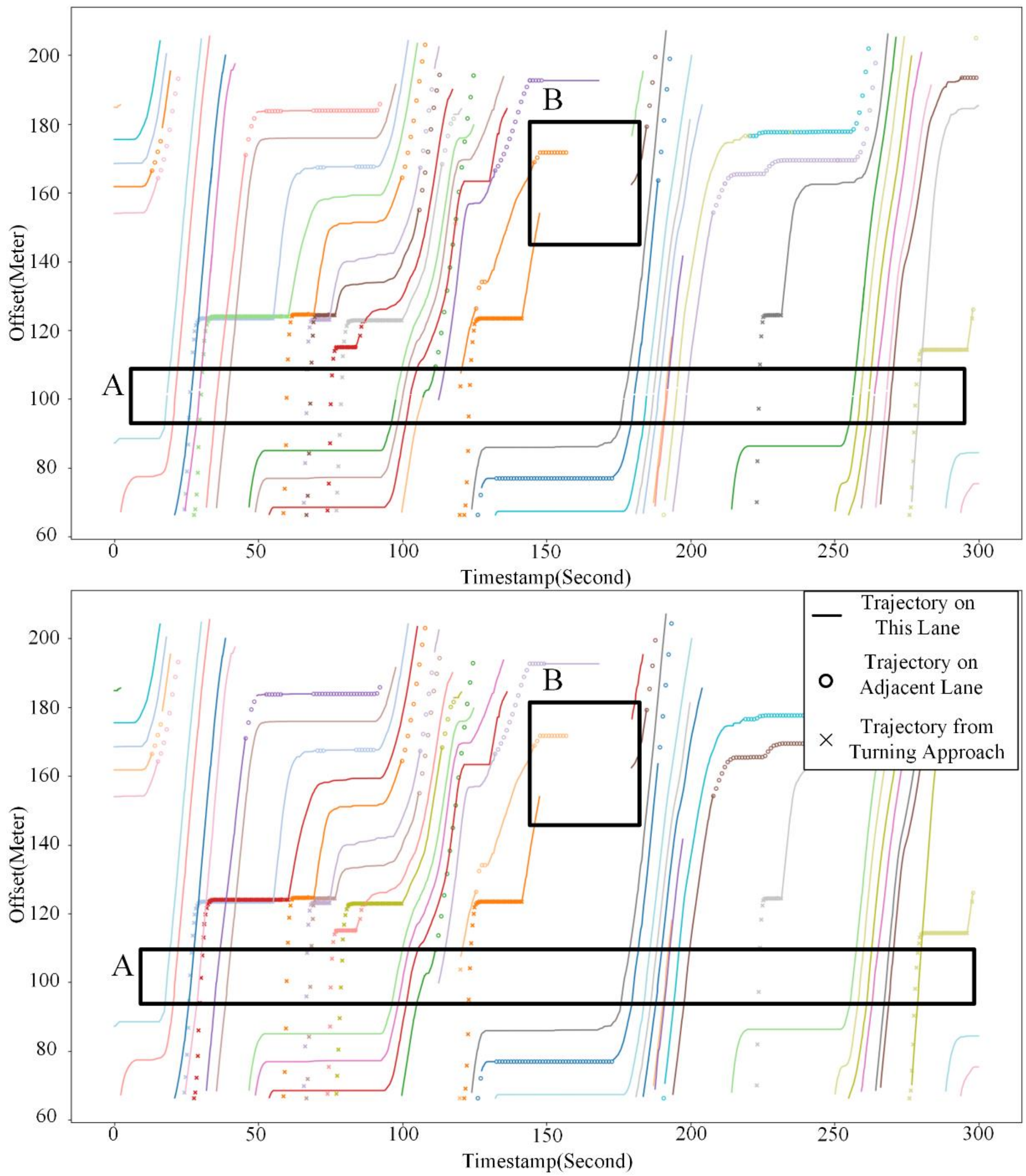


Figure 103. Projected Trajectory Before and After Reconstruction Case 3

Dual-Intersection Trajectory Analysis

This section discusses the combined dual-intersection traffic flow dynamics from the stitched space-time trajectories on the two mainline approaches across the two intersections. The trajectories are colored based on the velocity at each trajectory point. The red and green horizontal lines indicate the stop bar locations at each intersection with the red and green patterns indicating the duration of the red and green phases respectively. The solid black horizontal line indicates the location of the intersection exit. The gray dashed horizontal line represents the boundaries between two LiDAR sensor coverage areas. Both figure 104 and figure 105 are plotted with 15-minute vehicle trajectories processed for Albany Street at George Street and at Neilson Street intersections from 4:35 to 4:50 pm on Monday, June 26th, 2023. It should be noted that due to the limitations in the initial setup, there are minimal overlaps between the two sensor coverage areas.

Figure 104 shows the 15-minute vehicle trajectories for Albany Street eastbound with the upstream intersection at George Street and the downstream intersection at Neilson Street. Initially, the intersection queuing was normal. Many vehicles are traveling at free-flow speed across the intersections. Shockwaves are localized intersections queuing and discharging shockwaves due to signals. When entering the period as indicated in area A, congestion starts to build up between the two intersections, the congestion shockwaves propagated backward in time and space in-between the two intersections. Some queue spillbacks are observed as the congested queue grows into the upstream intersection.

In general, the left lane has more traffic than the right lane. The left lane is a dedicated through lane; while the right lane accommodates a combination of through and right-turn movements and is also adjacent to a street parking lane. At the downstream of Neilson Street, the left lane directly connects to the bridge across the Raritan River to the downtown area of the City of Highland Park. The right lane will lead to the on-ramp of Route 18 state highway. Extensive lane changes to realign towards the driver's direction of traveling often lead to spontaneous congestion as shown in area B of the left-lane trajectory diagram. In space-time area A, the right lane only has one congested cycle likely due to the pressures from the traffic on the right lane.

Figure 105 shows the 15-minute vehicle trajectories for Albany Street westbound with the reversed upstream and downstream intersections. In comparison to the eastbound direction, westbound traffic experiences lower volumes, leading to a sparse traffic flow and the absence of a congestion pattern. Vehicles that queuing at red lights in the westbound direction can be cleared smoothly. Within the space-time area B, a single shockwave pattern emerges, meaning a brief episode of congestion. This phenomenon may be attributed to factors such as the downstream section of the intersection being linked to the transit train station in downtown New Brunswick, NJ. Commercial vehicles picking up passengers might enter the road, or pedestrians crossing the street could lead to momentary delays for queued vehicles.

It is noteworthy that the trajectory data from the two intersections has not been stitched to each other. Consequently, vehicle trajectories may exhibit discontinuities, rendering them challenging to match near the boundary between LiDAR sensors. Despite this limitation, an examination of the spatiotemporal characteristics along the boundary, as indicated by the dashed line, shows two trajectory datasets from different LiDAR can effectively be encompassed for the entire road section. This capacity provides ample information for the subsequent task of trajectory repair. A forthcoming step in the research involves the integration and reconstruction of trajectory data across distinct roadside LiDAR.

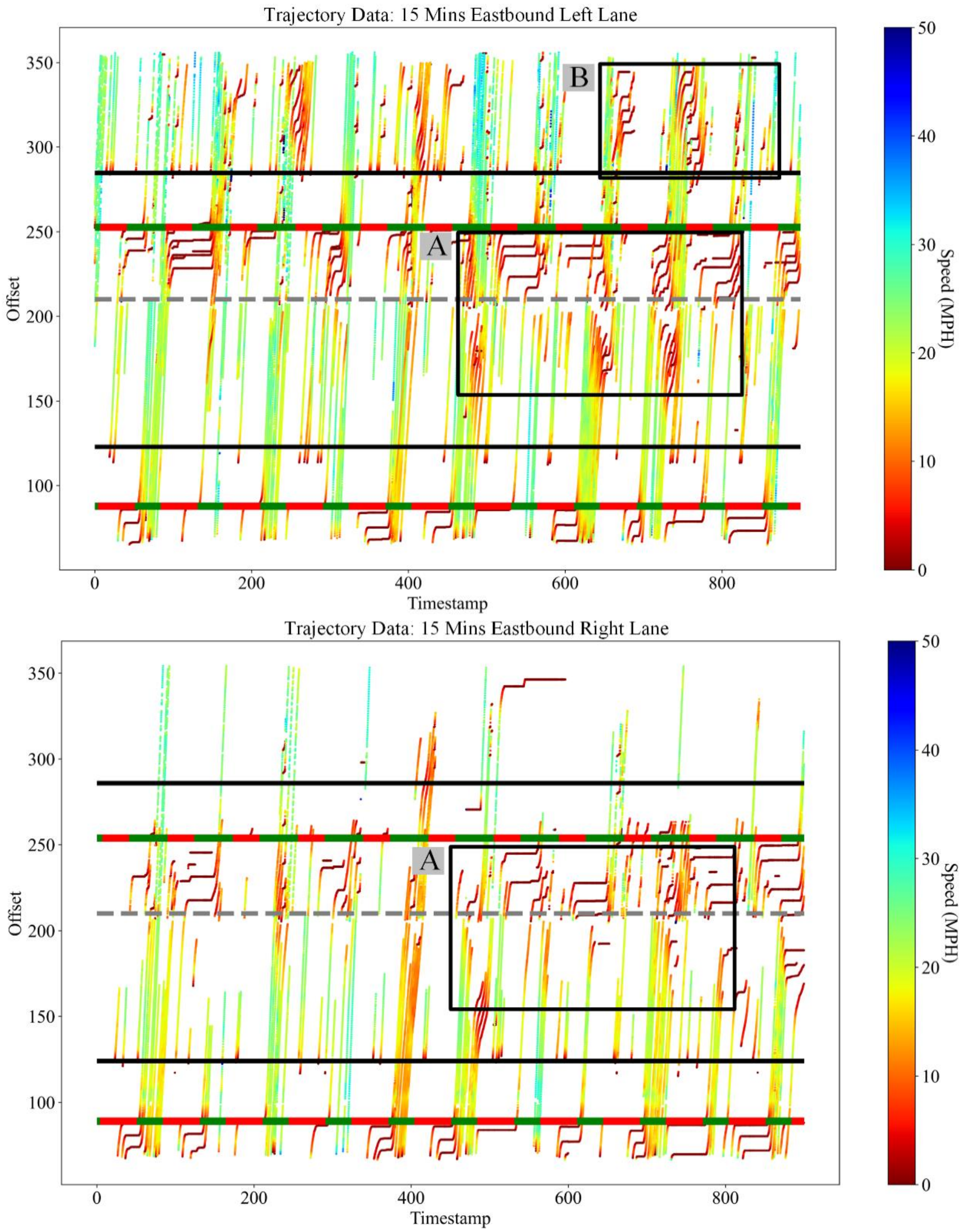


Figure 104. 15 Minutes Traffic Dynamics of Two Intersections, Albany Street Eastbound

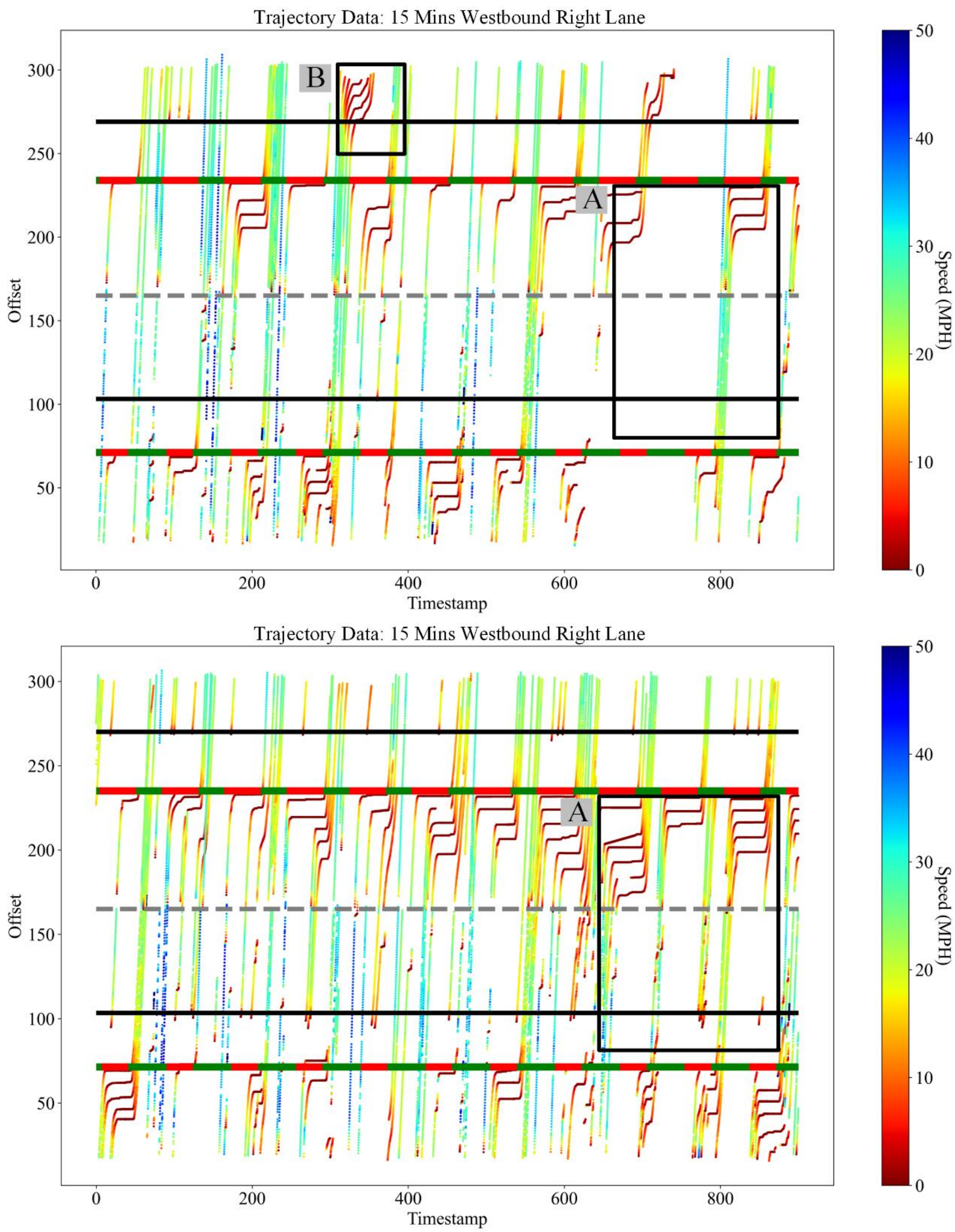


Figure 105. 15 Minutes Traffic Dynamics of Two Intersections, Albany Street Westbound

3D Traffic Digital Twin Model Improvement

This section evaluates how the proposed method can improve the quality of Digital Twin models. Figure 106 and figure 107 show the DT model visualization based on the raw and processed trajectory data at the Albany & George intersection, focusing on two specific cases within the continuous traffic flow on a through lane. The first case occurred near the eastbound intersection exit due to a fragmented vehicle trajectory. This fragmentation results in two significant issues: the switching to a different vehicle model, and upon re-detection, the interrupted trajectory temporality matched to a right-turn lane leading to the wrong vehicle heading as shown in the upper subplots of figure 106. The proposed method can address both errors by seamlessly stitching the trajectory at this problematic location as shown in the upper subplots in figure 107. In the second case, as shown in the lower subplots of figure 106, the problem occurs underneath the blind spot just below the LiDAR sensor. The vehicle trajectory experienced a temporary disruption, causing the vehicle to abruptly reappear in the middle of the road after 0.3 seconds. This is caused by vehicle ID switching and the CARLA reassigned a new vehicle model. As shown in the lower subplots of figure 107, the proposed method accurately maintained the vehicle tracking resulting in continuous appearance of the same vehicle model.

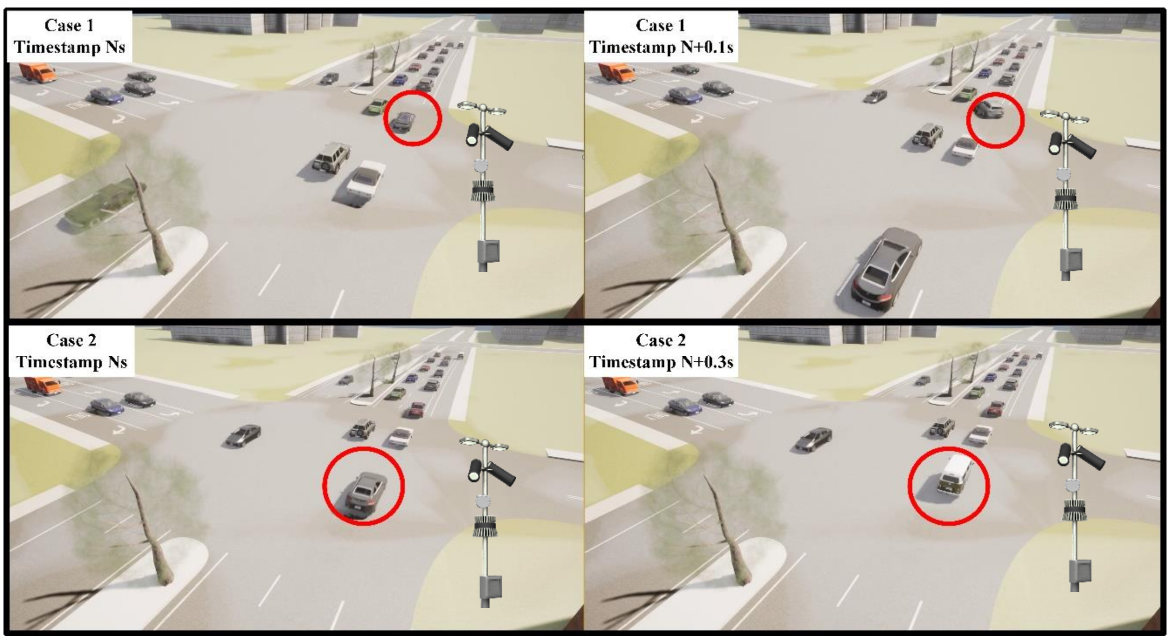


Figure 106. Vehicles in Digital Twin before Stitching

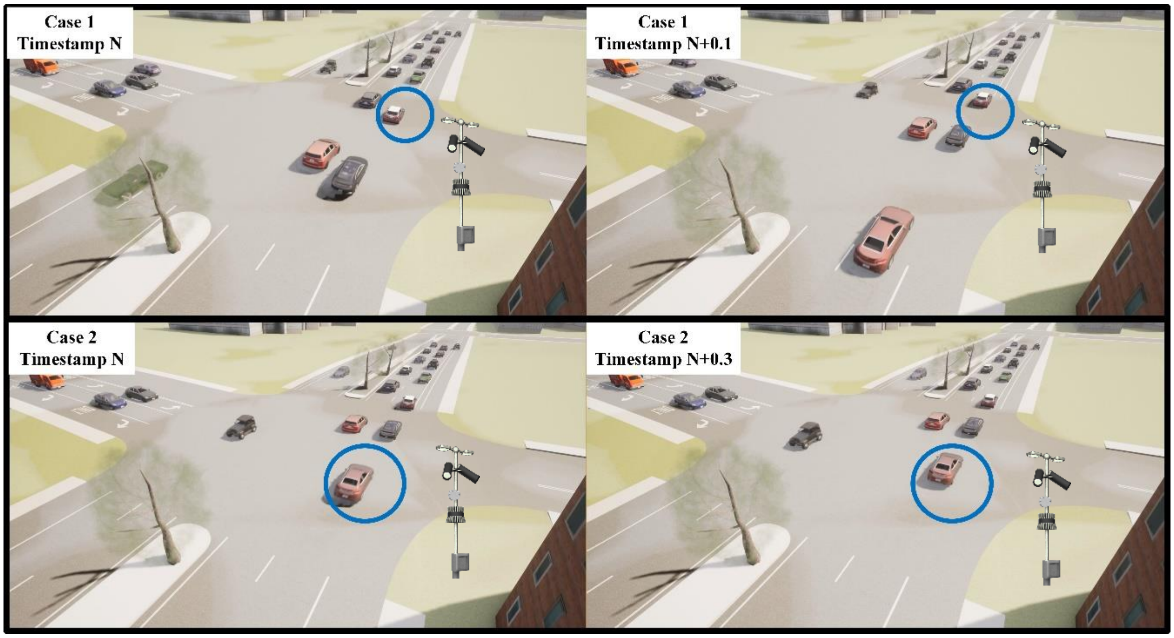


Figure 107. Vehicles in Digital Twin after Stitching

The resulting 3D DT visualization model is also evaluated by visually inspecting unreasonable vehicle “jittering” and “disappearing” instances while looking at how closely the vehicle movements replicate CCTV video footage. Figure 108 shows the screenshots of sample recordings from the 3D DT visualization tuned to the same camera angles as the CCTV cameras. Significant similarities can be observed. Meanwhile, the 3D DT model will allow more flexible tunning of camera angles, heights, or even movements for visualization.

Figure 108. Digital Twin Visualization versus CCTV View

We can not only use a fixed viewing angle from the perspective of LiDAR but also use a free viewing angle to look down on the entire digital twin world like from the eyes of a bird. In addition, we can also fix the viewing angle on a specified car, or simulate from the perspective of the driver, to observe the trajectory of a certain car or the driving behavior of a certain driver, and establish a more microscopic digital twin model, and can be locked in for future testing of proposed connected and autonomous vehicle observations. Figure 109 and figure 110 show the top view of a specific vehicle in traffic flow, and the driver view inside the same specific vehicle in traffic flow.

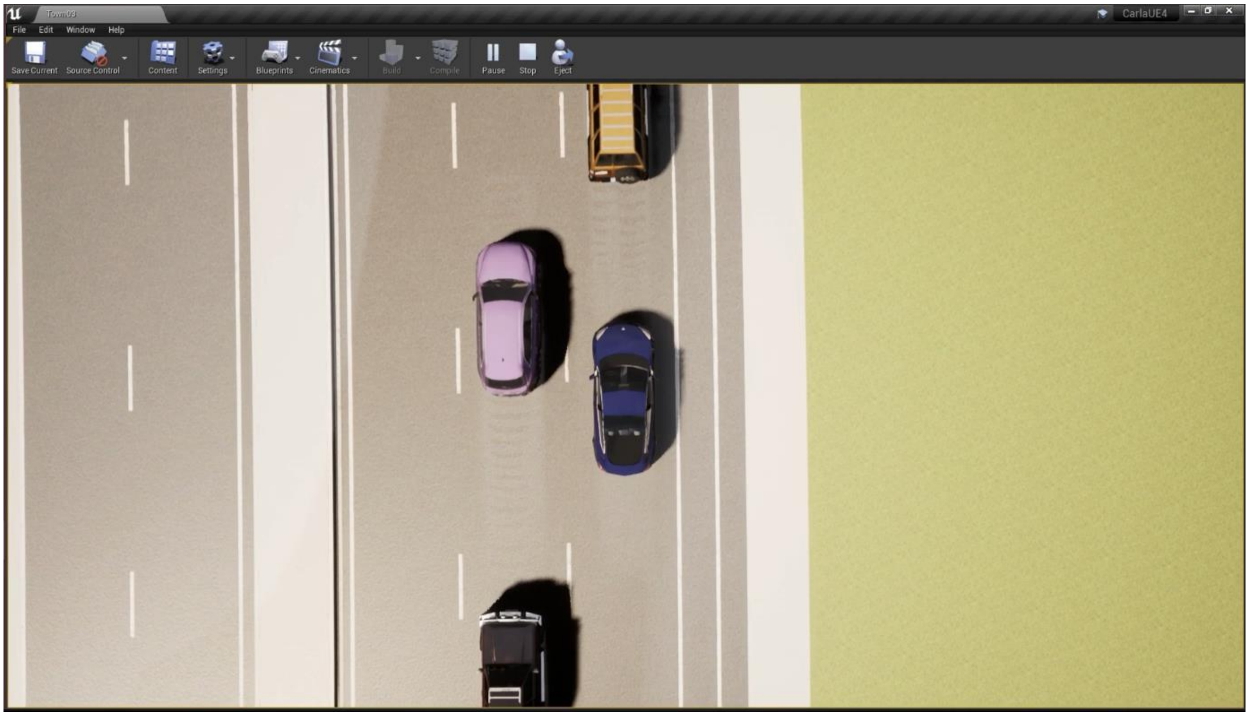


Figure 109. Top View of a Vehicle in the Digital Twin World in CARLA

Figure 110. Inside View of a Vehicle in the Digital Twin World in CARLA

SUMO Visualization Demonstration

In the SUMO, we generate data from a big traffic network, it is the whole prototype map area in the RoadRunner software: Route 27 includes three intersections: French & Easton intersection, Albany & George intersection, and Albany & Neilson intersection, and expands to the east that includes a part of the Raritan Ave.; Route 18 from Albany ramps to intersection of Route 18 and US 1. Due to the resource limitation, we didn't get the vehicle type as the input for the SUMO like we did for the CARLA. For the visualization in SUMO, now every vehicle is in the same icon. The one frame of the visualization animation in SUMO is shown in figure 111.

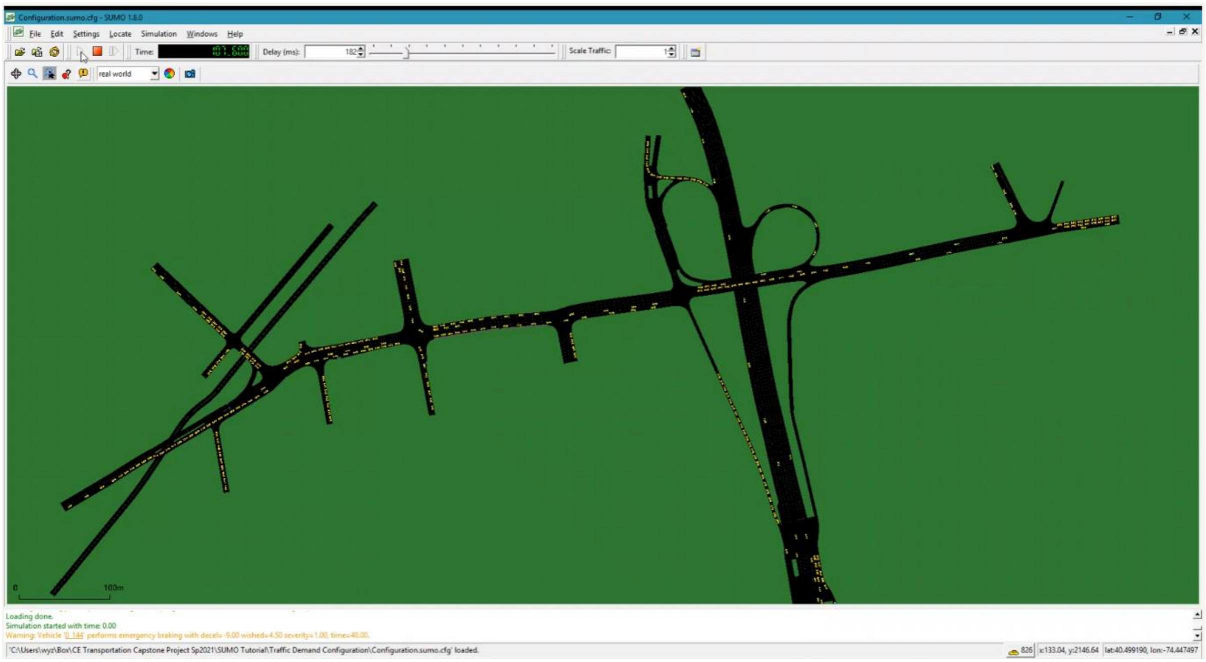


Figure 111. Simulation Animation on the Traffic Network in SUMO

In the animation, there is no background environment for the traffic road network due to the graphic limitation of the computer. In SUMO, we can add the background image directly from the Open Street Map (OSM). It is a free online resource, but sometimes it has detailed errors to be fixed when importing. Also, it is only the 2D base map image and has limited geometry information of the surrounding areas (New Brunswick Downtown). By importing the OSM, we first need to scale the map to the actual area that fits the traffic road network we generated from ".xdor" file. The infrastructure import from OSM into the SUMO simulation is affected by different Wizard options. By default, a road traffic simulation is generated but all types of roads and rails will be imported as well (cycle paths, footpaths, railways, etc.). if the demand checkbox "Pedestrians" is active, then sidewalks and pedestrian crossings will be generated. Therefore, we need to check Cars, Track, Bus, Motorcycles, Pedestrians, and Trains in the car panel to ensure the road user type. Then, a SUMO config file will automatically generate the OSM map. The OSM visualization is shown in figure 112.

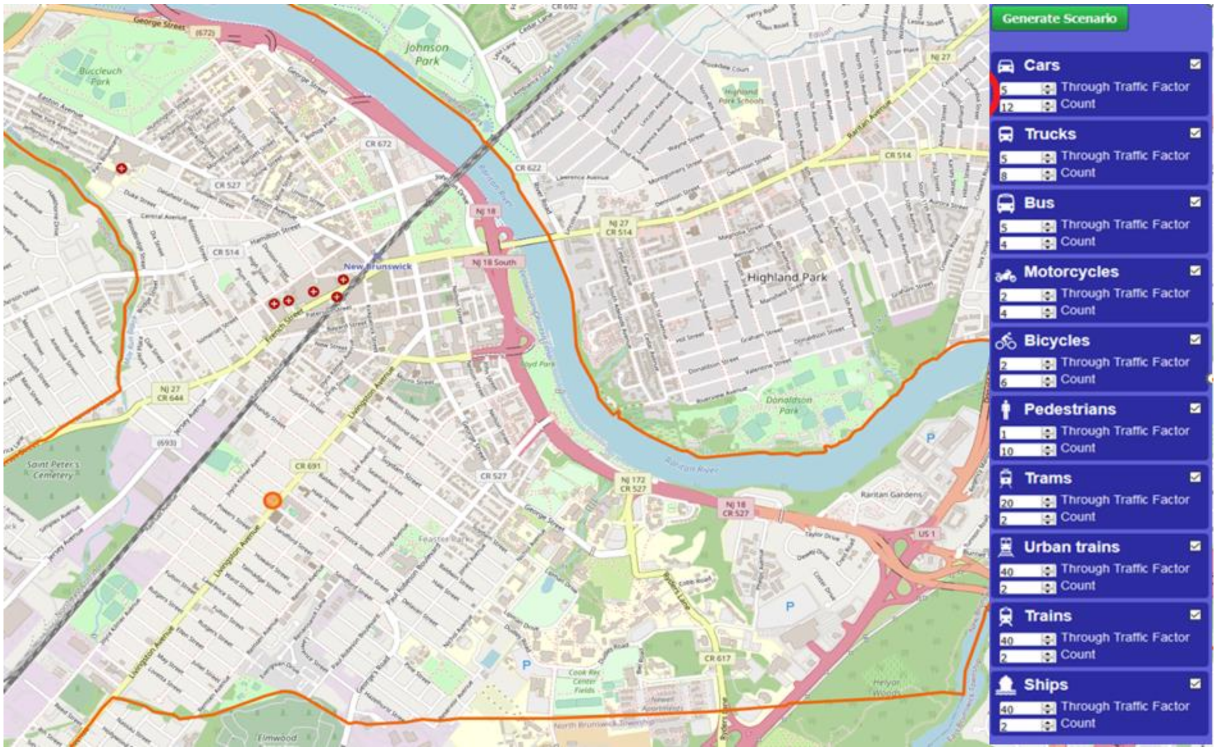


Figure 112. SUMO - OSM Layout with Scenario Panel

TASK 7: BUSINESS PLAN

DataCity will be a comprehensive smart-city project based in New Brunswick, New Jersey. The project's development is currently being led by the Rutgers University Center for Advanced Infrastructure and Transportation. The DataCity project includes the following products:

- **Data Hub**: The centerpiece of the project; using state-of-the-art sensing, communication, and computing technologies to develop real-time high-resolution smart mobility datasets based on traffic interactions in New Brunswick; engaging the community in data processing, labeling, and production; and enabling digital-twin based simulation and analytic modeling.
- **Innovative Ecosystem**: Members will gain access to virtual and physical testing services (with premier access available to New Brunswick Innovation Hub companies as well as those located in Middlesex County and the State of New Jersey); data and technology licensing/transferring services for early-stage companies; and live and historical data feed and modeling/labeling services for members and non-members alike.
- **Innovative Alliance**: DataCity will operate as a public-private-academic alliance, and Rutgers CAIT's status as a U.S. Department of Transportation University Transportation Center will be leveraged. The institute will help attract new businesses and researchers to Rutgers, the Innovation Hub, Middlesex County, and the State of New Jersey.

Organization and Management

Mission Statement

The mission of the DataCity SMTG project is to build America's transportation future through data and collaboration. DataCity is built around the Data Hub, a cutting-edge digital infrastructure allowing for the collection and analysis of real-time data on traffic interactions. The program is centered in a city with a dense college population featuring multimodal transportation and heavy pedestrian traffic - enabling data gathering on the sort of complex interactions that still present challenges for autonomous and connected vehicles. At full roll-out, DataCity will have three components:

Data Hub, the centerpiece of the project, features:

- **State-of-the-art sensing, computing, and communication technologies:** The rich datasets generated from smart roadside units at SMTG, will enable the development and testing of next-generation V2X technologies and applications not solely relying on in-vehicle technologies.
- **Real-time high-resolution smart mobility datasets:** The rich datasets generated from smart roadside units at SMTG, will enable the development and testing of next-generation V2X technologies and applications not solely relying on in-vehicle technologies.
- **Community-engaged data processing, labeling, and production:** The interoperability of SMTG mobility data with other smart city datasets such as

infrastructure, energy, utility, and service datasets will be capable of supporting the R&D of new smart city technologies.

- **Digital-twin-based simulation and analytic modeling.** Taking advantage of the high-resolution and full coverage of the corridor, a virtual digital twin mirroring of the SMTG will be created to reconstruct the full mobility systems on the corridor. This will allow R&D data to be exported from any data collection scenarios and any roadside or in-vehicle perspectives.

Innovative Ecosystem: there will be a network of services available to smart-city stakeholders from New Jersey and beyond across the public, private, and nonprofit sectors:

- The Living Laboratory will consist of four individual but related research, development, testing, and transfer (RDT2) labs, which will focus on Technology, Data, Applications, and Knowledge Transfer
    - The **Technology Testing** lab will focus on all the technology aspects that are (or will be in the future) part of the SMTG, including roadside, handheld, wearable, aerial, and in-vehicle sensors and equipment; wired and wireless communications, artificial intelligence and machine learning, cyber security, infrastructure resilience, and continuity of operations (COOP), etc.
    - The **Data Management** lab will focus on all things related to data, including innovative methods and approaches for data collection, processing, and distribution; data science, analytics, and visualization; integration of data sets from multiple agencies to support smart city-type applications; data privacy and protection of PII and SPII; and a virtual/digital twin of the real-world SMTG environment.
    - The **Applications Testing** lab will focus on modeling and simulation of transportation networks; development and testing of CAV-enabled safety, mobility, and environmental applications for deployment in the SMTG; advancement of traditional Active Traffic and Demand Management (ATDM) type applications; Advanced Driver Assistance Systems (ADAS) applications research that will enhance (but not compete with) industry solutions; and enabling and testing of smart city type applications developed by external 3rd party entities.
    - The **Knowledge and Technology Transfe**r lab plays a key role in taking the results and lessons learned from the SMTG field implementation, as well as the other three living labs described above, and develops a knowledge base that will be of immense benefit to the SMTG stakeholders and partners, as well as the transportation industry at large. The lab will also conduct analysis and evaluation of what works and what doesn’t work, and the levels of instrumentation that would be needed for real-world deployment and share this knowledge through multiple technology transfer channels that will be established as part of the lab.
- Premier data and testing services to New Brunswick Innovation Hub companies, Middlesex and NJ companies
- Data and technology licensing/transferring to support early-stage startup companies.

- Live and historical data feed and modeling/labeling services to members and non-member companies

Innovative Alliance: the initiative will be structured as a partnership that will help forge the intentional economic development of the smart-city-related innovation economy in New Brunswick.

- Public-private-academic alliance
- USDOT University Transportation Center Consortium
- Attract talent to Innovation Hub, Middlesex County, and New Jersey
- Regular Middlesex Innovation Challenges to cultivate new smart city startups in the area

Governance Structure

In the short-term, DataCity's development is being pioneered by Rutgers CAIT, an office of Rutgers University headquartered at Rutgers Busch Campus in suburban Piscataway, New Jersey. Its formation and early development will be led by CAIT staff (who are employees of Rutgers University). Table 10 shows the comparison of different governance structures.

As DataCity develops into a full-fledged organization, it is expected to become independent from CAIT and other Rutgers operations. For example, DataCity's offices are anticipated to be in the upcoming New Brunswick Innovation Hub building in downtown New Brunswick, rather than in Piscataway. This is like the structure used in another smart city initiative - the Smart Columbus initiative in Columbus, Ohio. That initiative was based in city government but ran semi-independently, including moving to an off-site location.

The public-private partnership would include CAIT, Rutgers administration, city, county, and state government, and the private sector. As recommended by the Deloitte Center for Government Insights, it is important to maintain a single locus of control over the partnership; the nonprofit organization would be that locus of control. Still, Rutgers and CAIT, Middlesex County, and other stakeholders would retain significant influence over the project.

The nonprofit organization would be an overarching structure over the program that would be able to collect donations and organize partnerships, membership, and networking opportunities. The partnership would be structured around a board of roughly 15-20 members, including representatives from CAIT, Rutgers University more broadly, various levels of government, and the private sector. Rutgers (alongside Middlesex County) could also maintain a significant level of influence over the 501c3 nonprofit through board appointments.

Table 10 - Comparison of Different Governance Structures

Comparison	Institute at Rutgers	For-Profit Company	Government-based	Public-Private Partnership (Non-Profit)
Strengths	Allows university researchers to maintain control of data and analysis	Allows raising of capital through equity investments	Prioritize economic development impacts	Combines strengths of all three other models, but revenue only needs to cover cost/expansion
Weaknesses	Can limit fundraising and partnership opportunities, as partners may prefer donations go directly to DataCity rather than through the university (e.g. overheads)	Requires profitability for continued operations; Could limit fundraising opportunities; Disqualified in leading public agency grants	Would complicate high-risk, high-reward data and technology innovation components and lead to increased bureaucratic requirements	Non-profit status places some constraints on potential activities

Recommended board structure: 15-25 board members in total.

- One-third of board members from Rutgers/CAIT
    - Including members from CAIT and members from the general university administration
        - Including both content/research-oriented and administrative-oriented university representatives
- One-third of board members from public sector/government
    - Including at least one representative from each of city, county, and state government
    - State government members could include representatives from NJDOT, NJEDA, and other relevant agencies.
- One-third of board members from the private sector
    - Including business partners and sponsors

Service or Product Line

Products and Services Offered

Smart Mobility Technology Testing, Certification, and Evaluation

The data hub will be instrumented with the latest sensors and technologies, including:

- Smart Roadside Units:
  - State-of-the-art sensing, computing, and C-V2X instruments.
- Vehicle-based technologies:
  - Provide full-scale assessment in real-world congested traffic flow.
  - Roadside sensors to monitor the full vehicle status and its interaction with traffic flow.
- V2I Integrated Technologies:
  - Smart roadside units for simulating different sensing and computing scenarios.
  - Cellular V2I or infrastructure-assisted CAV applications.

Smart Mobility Data Production and Sharing Platform

- Data Capability:
  - 250,000 vehicle miles traveled each day (AADT of over 100,000 vehicles/day)
  - Real-world driving scenarios: congestion, stop-and-go, merge-diverge, incidents, and inclement weather conditions.
  - Processing and labeling services with local and university community.
- Multi-tier data sharing and provision:
  - **Showcase Tier:** Free full datasets representing typical conditions.
  - **On-Demand Tier:** Free for companies conducting field tests.
  - **Deep Tier:** Long-term archiving and data provision.
  - **Live Tier:** Real-time streaming to enable live data application testing.

Premier Services

Services offered by DataCity will include:

- Fin-Tech solutions to fund, list, share, and sustain data production and reward all data contributors.
- Discounts and test slot rentals for New Brunswick Innovation Hub companies.
- Annual or Quarterly Innovation Challenges with testing ground data.
- Community Mobility applications including dashcam mode for drivers, pocket/handheld mode for pedestrians.
- Volunteer test fleets: retrofitted agency, university, and other local drivers/vehicles.

Pricing Structure

Partners can support the DataCity effort in a variety of ways:

- Annual subscribers
- Purchase subscriptions on an annual basis to support the DataCity testing ground operations, upgrades, and expansions.
    - Subscriptions available at four tiers: Bronze, Silver, Gold, and Platinum, each offering additional benefits (Academic tier also available, offering discounted price and benefits tailored for academic clients.)
- Benefits include for some, or all subscribers include:
    - Access to networking and collaborative opportunities
    - Engagement in Data Hub data processing, labeling, and production
    - Physical testing ground opportunities
    - Integrating physical technology into testing ground
    - Raw data access — available at various levels (with higher access levels requiring additional out-of-pocket fee)
- Subscribers at certain tiers are eligible to purchase additional data opportunities (at an additional out-of-pocket cost):
    - **Processed data packets** — pricing and number of packets permitted will vary depending on subscription level.
    - **Projects** — can purchase a package of processed data plus DataCity advising.
    - **Innovation Challenge sponsorship** — can pay small fee to sponsor and scout mobility startups.
- Accelerator companies
- Start-up support and access to DataCity
- Equity/Licensing agreements of data and technologies
- Innovation Challenge winners may be provided with space and start-up assistance

Product Life Cycle

DataCity is designed to be highly adaptable, ensuring that it remains at the forefront of technological advancements. Technologies or methods that become outdated in the future or are not working as planned will be able to be replaced. As smart city technologies continue to change, DataCity will adapt to changing methods of data collection and analysis. This commitment ensures that the platform remains agile and responsive to the evolving needs of the community. By embracing flexibility and adaptability, DataCity is poised to integrate the most effective and efficient technologies, promoting sustained performance in the long-term development.

Intellectual Property Rights/Technology Transfer

Econsult Solutions Inc. recommends that CAIT consult with legal experts regarding any potential intellectual property law concerns. Likewise, CAIT will need to coordinate with Rutgers Technology Commercialization.

Research and Development

DataCity will enable university researchers, including faculty and students, to use data collected on roadway interactions in New Brunswick, as well as any available simulation technologies, to develop new smart city technologies and conduct academic research. Access to this data for research purposes will be available to Rutgers University students with priority and may also be offered for a fee to students and faculty at other universities. Research and development conducted using DataCity technologies will not only benefit the body of academic knowledge regarding transportation; it will also enable the ongoing improvement of DataCity itself.

Rutgers Innovation Ventures and Rutgers Technology Commercialization Initiative will be engaged as active partners in this effort. Through Innovation Ventures, technology transfer agreements can be crafted with partners, allowing for mutually beneficial arrangements to license and commercialize research that emerges from DataCity and the SMTG. In addition, through a connection to the business school's Technology Commercialization Initiative, business partners and startups will have access to Rutgers innovation experts and students to assist in developing business plans, models and concepts for using the data.

Market Analysis

Industry

There are very few, if any, existing programs that mimic all three components of the DataCity project (data, networking, and economic development). Table 11 shows competitors that include one or more of DataCity's three core components.

Table 11 - Comparison to Peer Smart Mobility Testbeds

Testbed	Data	Networking	Economic Development
Intelligent Mobility Program – Nevada Center for Applied Research		**Multidisciplinary Team:** builds on the expertise of a multidisciplinary group of university researchers in advanced autonomous systems, computer science and information technology, synchronized transportation, robotics, geography, social psychology and judicial studies.	
Suntrax – Florida D.O.T.	Up to 70 MPH and incorporates varying driving speeds and potential weather conditions.		
Curiosity Lab at Peachtree Corners	Public sector cooperation enables greater data collection opportunities in a small suburban community.		
Sidewalk Labs — Google	Google's smart-city initiative; is best known for the high-profile initiative for a smart city experiment in Toronto that was eventually cancelled due to privacy and cost concerns. The cautionary tale of what can happen when a smart city data collection initiative ignores the question of privacy.		
Johns Hopkins University Technology Ventures		Offering various types + intensities of programming and support (from one-day bootcamp to six-month accelerator program) to suit different needs of different startups resulting in 170+ commercial startups.	

Testbed	Data	Networking	Economic Development
Michigan State University Innovation Center		Bridging gap between major public university located in college town and innovation capital often located in metropolitan centers. Results: 37 patents issued, $4 million in license royalties.	
SmartDeviceLink Consortium: Partnership between automakers and tech firms		Firms in two industries relevant to smart cities collaborate in partnership to develop open-source standards for in-vehicle entertainment, competing with the “walled gardens” of Apple CarPlay and Android Auto.	
Newark Smart City Program: City of Newark, MetroLab Network, New Jersey Innovation Institute, New Jersey Institute of Technology		City-University collaboration combines research with governance; and also incorporates communication with other cities via MetroLab Network.	
American Center for Mobility (Ypsilanti, MI)		**Special partnership model:** Allows members to serve on a topic-focused board of their choosing, giving them access to an issue-specific conversation with key stakeholders that may be hard to find elsewhere.	
MassChallenge Boston		**Expanded Access:** Innovation challenge supporting tech startups by expanding their access to resources and investors.	**Low-risk, high-reward:** Those who participate do so at zero cost, but winners get significant benefits, including four months of technical support.

Testbed	Data	Networking	Economic Development
Global Innovation Exchange Innovation Competition		Innovation challenge administered in collaboration with top U.S. and Chinese universities (University of Washington and Tsinghua University) brings together teams of undergrads and recent Bachelor's grads.	Finalists win mentorship from experts; winner gets a cash prize.
Pittsburgh, PA: Autonomous Vehicles + SmartPGH Initiative	**Topography:** Hilly topography presents unique challenges for autonomous cars.	**University research hub:** Location of two major research universities (Carnegie Mellon and Pitt); has attracted top autonomous vehicle talent to the Pittsburgh region based in part on proximity to university experts + resources. **Innovative Local Government:** City government enables legal accommodations for autonomous vehicle testing.	**Participation from Civic Community:** Community development organization in East Liberty encouraged early Surtrac testing.
Columbus, OH: "Smart Columbus" program	**Open Source:** Use of smart-city operating system for data management — primarily open-source, enabling use by other cities. Additionally, connected vehicle technology enables traffic management improvements.	**Giving back to community:** Focuses on connecting citizens with the outputs of smart city tech.	**Cross-sector partnership:** Public-Private Partnership led by City Government (including dedicated employees through city government) with support from a non-profit.
Ann Arbor, MI: Autonomous vehicle testing + real-time data	**University:** Location of premier large research university (University of Michigan) with strength in engineering.	**Connections to Industry:** Proximity to and collaboration with automakers based in Metro Detroit.	**Strong civic community:** Ann Arbor SPARK, an economic development organization, exemplifies the area's civic community.

Economic Development Case Statement

Competitive Advantages of DataCity: Why invest in DataCity instead of, or in combination with, other hubs?

- **University research foundation:** Proximity to Rutgers and CAIT:
    - **Access to the Resources of a Premier Public Research University:** DataCity offers participants access to the extensive resources of one of the nation's leading public research universities. This includes access to a vast pool of talent, with tens of thousands of undergraduate and graduate students, as well as thousands of dedicated faculty and staff members. Moreover, institutional partnerships are fostered, enabling collaboration with universities and research institutes both in New Jersey and beyond. Participants benefit from access to cutting-edge data and technology resources, further enhancing their research capabilities. Additionally, continuing education opportunities, such as professional development and certificate programs, are available to DataCity participants, ensuring that they have the opportunity for ongoing skills enhancement. Furthermore, event spaces located across the university campus are available for use as needed, facilitating gatherings and meetings.
    - **Crucial Resource for DataCity:** University Transportation Center Expertise: One of the most valuable resources available to DataCity is its access to the expertise and resources of a federal University Transportation Center. This affiliation brings specialized knowledge and capabilities in the field of transportation, providing DataCity with a significant advantage in addressing transportation-related challenges and opportunities.
    - **Potential Collaborations with Nearby Universities**: DataCity is strategically positioned to establish potential partnerships with several prominent nearby universities. These include Princeton University, Middlesex County College, Montclair State University, Saint Peter’s University, and the New Jersey Institute of Technology. Collaborations with these institutions offer a wealth of opportunities for knowledge exchange, joint research projects, and networking, further enriching the innovation ecosystem within DataCity.

- **Unique Location with Varied Transportation Patterns**:

New Brunswick boasts a truly unique location characterized by a blend of diverse transportation factors, offering exceptional opportunities for data collection and analysis. Situated at the heart of the Northeast Corridor, New Brunswick serves as a pivotal point where both shipping routes and private transportation routes converge. This convergence brings forth distinctive possibilities for gathering valuable transportation data. Moreover, being in the suburbs of the nation's largest metropolitan area, New Brunswick experiences a high volume of travelers, leading to a rich tapestry of potential traffic interactions. As a college town, it further stands out with a substantial influx of pedestrians, bicyclists, and users of alternative modes of transportation like scooters and skateboards. This dynamic mix of transportation patterns makes New Brunswick an ideal hub for exploring and studying various facets of mobility.

- **Abundant Pool of Highly Educated Workforce:**

New Brunswick and its surrounding areas in Central and Northern New Jersey are home to a highly educated local workforce. This region boasts a significant pool of well-educated individuals, offering a wealth of potential talent for various industries and projects. The availability of such a well-educated workforce provides a competitive advantage for businesses and organizations operating in the area, ensuring access to a skilled and knowledgeable labor force.

- **Convenient Transportation Access:**

New Brunswick enjoys excellent transportation access, making it an easily reachable destination for individuals from across the country and around the world. It is near one of the world's best-served airports, Newark Liberty International Airport (EWR), facilitating convenient air travel connections. Additionally, the area is accessible via major highways, an extensive public transportation network, and Amtrak Northeast Corridor service. This comprehensive accessibility ensures that New Brunswick is well-connected and easily accessible by various modes of transportation, promoting collaboration, commerce, and connectivity on a regional and global scale.

Business Model Example - American Center for Mobility (Ypsilanti, MI)

The primary business model would be based on a traditional partnership structure, as outlined in Section 3. Partners would pay for access to data and networking opportunities. This section summarizes one representative center, the American Center for Mobility (ACM). ACM is situated in Ypsilanti, Michigan, and operates within a structured organizational framework, serving as a critical hub for the advancement of smart mobility and innovation in the field of transportation.

- Organizational Structure:

ACM is formally established as a non-profit organization and is recognized as a "joint initiative" involving multiple stakeholders, each contributing to its overarching mission. Key partners in this collaborative endeavor encompass the state of Michigan, the Michigan Department of Transportation (MDOT), the Michigan Economic Development Association (MEDA), the University of Michigan (UMich), Business Leaders for Michigan, and Ann Arbor SPARK.

- Organization Functions:

ACM fulfills a multifaceted role within the domain of smart mobility and transportation innovation. Its operational functions encompass a comprehensive test track facility, a dedicated smart mobility innovation center, a versatile event center, and a collaborative platform for fostering networking partnerships. These functions collectively facilitate the development and testing of cutting-edge transportation technologies and solutions.

- Board Structure:

The governance of ACM is entrusted to a nine-member board, representing a diverse range of expertise and interests. The composition of the board comprises:

  - Three members from academia, including representatives from esteemed institutions such as the University of Michigan and Michigan State University. This academic representation includes both research-oriented experts and administrative leaders, ensuring a balanced approach to innovation.

- Two members from the state government, offered valuable insights and guidance from a governmental perspective.
- Two members from the economic development sector, with one operating at the state level and the other at the local level. Their involvement underscores the significance of economic growth and regional development in ACM's mission.
- Two members from the private sector, bring industry-specific knowledge and expertise to the board's deliberations.

- Partnership Structure:

ACM fosters a collaborative environment where partners actively engage in shaping its initiatives. Partners can serve on various advisory boards and committees, allowing them to contribute their expertise to specific areas of interest. These include:

- Industry Advisory Board, facilitating industry input and guidance.
- Testing Committee, overseeing the testing and evaluation processes.
- Standards Committee, focusing on the establishment of industry standards.
- Education Committee, promoting knowledge dissemination and educational initiatives.
- Smart Parking Standards Committee, addressing innovative parking solutions and standards.

ACM's partnership structure promotes inclusivity, ensuring that stakeholders across academia, government, economic development, and the private sector actively participate in advancing the future of smart mobility and transportation innovation within a collaborative academic research context.

Strategies for DataCity Growth and Sustainable Long-Term Operations

Growth Strategy

The growth strategy for DataCity encompasses a multi-pronged approach aimed at establishing it as a leading smart city initiative:

- Coordination with Local Government Authorities: Collaborative efforts with local government authorities, including the City of New Brunswick and Middlesex County, are pivotal in ensuring seamless integration and support for DataCity's objectives.
- Leveraging Existing CAIT Connections: Building upon CAIT's existing connections and infrastructure, including its involvement in DOT consortium partnerships, provides a strong foundation for DataCity's growth and innovation.
- Targeted Outreach and Stakeholder Engagement: DataCity will engage in targeted outreach with specific stakeholders who align with the project's vision and can potentially refer us to additional collaborators, thereby expanding its network.
- Data Monetization: DataCity intends to monetize its data by offering it to private, public, and institutional partners. Drawing inspiration from the high specificity and limited availability of healthcare data, smart city data is positioned as a valuable commodity.
- Corporate Partnerships: Building relationships with larger corporate partners, such as Verizon, serves a dual purpose: they can become customers and enhance the initiative's credibility.
- Collaborations with Universities: DataCity plans to establish data partnerships with smaller universities that may lack the capacity to create a similar testing ground. This

approach can also serve as a recruitment strategy, attracting graduate student interest to CAIT.

- Building a Reputation: DataCity aims to develop a reputation for smart city data and innovation, which can in turn attract further business opportunities and partnerships.
- Networking Opportunities: Attracting new partners is facilitated by the allure of networking opportunities, fostering an environment of collaboration and growth.
- Supporting Local Startups: DataCity will contribute to the development of local startups through its economic development component, potentially cultivating future customers and collaborators.

Communication Strategy

DataCity's communication strategy is integral to its success and comprises the following components:

- Early Branding and Messaging: The organization recognizes the importance of early branding efforts, including the creation of a distinct visual identity and messaging strategy. These efforts are vital for generating excitement and interest in DataCity, attracting potential partnerships, and positioning it as a leading smart city venture.
- Tailored Messaging: DataCity identifies key audiences and market segments, tailoring its messaging to resonate with each group. This includes end users/participants seeking comprehensive data on multimodal roadway interactions, community advocates and champions focused on traffic safety, reputation enhancement, and local economic development, as well as federal, state, and local government officials who can be informed about economic and traffic safety impacts.
- Leveraging Trusted Voices: The organization strategically leverages trusted voices, such as governments, universities, and non-profit entities, to effectively convey its message and enhance credibility.
- Key Messages: DataCity emphasizes key messages that underscore the alignment of its goals with the renewed focus on transportation infrastructure, as reflected in the Biden IIJA (Infrastructure Investment and Jobs Act). This highlights the potential for investments in smart city technology to enhance transportation performance.
- This strategic approach to growth and communication positions DataCity as a prominent player in the realm of smart city innovation and data-driven solutions.

Program Income Models

This section discusses proposed revenue and pricing models that can generate income for the sustainable operations of the DataCity program.

Revenues

DataCity envisions a multifaceted revenue generation approach, incorporating both initial revenue sources for the early years and long-term revenue streams designed to sustain the initiative's growth and impact.

Revenue Sources

In the initial years of operation, DataCity has devised a revenue projection model that outlines anticipated income sources as a percentage of overall revenues. These estimates are subject to adjustment and reflect the following:

- **Government Grants:** In the first year, DataCity's primary revenue source is anticipated to be government grants, representing 100% of overall revenues. As the initiative gains traction and demonstrates progress, the reliance on government grants is projected to decrease gradually to 75% in Year 2 and further to 50% in Years 3 and 4. Middlesex County, with a commitment of $2.2 million from mid-2021 through 2024, forms a significant portion of this support, while state, federal, and local-level assistance may also play a crucial role in funding. (See table 12.)
- **Sponsorship/Membership:** As DataCity evolves and establishes its presence, the revenue mix diversifies. Sponsorship and membership contributions are expected to increase from 0% in Year 1 to 20% in Year 2, and subsequently to 40% in both Years 3 and 4. This revenue source reflects the engagement of corporate partners, stakeholders, and members who see value in supporting DataCity's mission.
- **Data Purchase:** Data purchase, representing 0% of Year 1 revenues, is projected to increase gradually to 5% in Year 2 and 10% in both Years 3 and 4. This source signifies the sale of data generated by DataCity, which has become increasingly valuable and sought after by various entities over time.

Table 12 - Initial Revenue Source Estimates

Revenue Sources, as a Percentage of Overall Revenues	**Year 1**	**Year 2**	**Year 3**	**Year 4**
Government Grants*	100%	75%	50%	50%
Sponsorship/Membership	0%	20%	40%	40%
Data Purchase	0%	5%	10%	10%

* NJDOT and Middlesex County are contributing $3.5 million from mid-2021 through 2024. Federal, state, and local-level support may also be available.

Long-Term Revenue Sources

DataCity's sustainability plan encompasses a range of long-term revenue sources designed to ensure its financial viability and continued growth:

- **Proceeds from Equity Shares of Startups:** DataCity envisions generating revenue through the sale of equity shares in startup ventures that emerge from its ecosystem. This model involves investors becoming partial owners of startups, with the potential for returns on their investments as these startups grow and achieve success.
- **Licensing Fees (Tech Transfer & Commercialization):** DataCity anticipates earning revenue through licensing fees. This involves granting other entities the right to use, develop, or commercialize proprietary technologies, innovations, or solutions that originate from the DataCity project. Such licenses can encompass intellectual property, patented innovations, or technological solutions, exchanged for agreed-upon fees.

- **Fees/Grants for Innovation Challenges, Incubator Rental:** DataCity envisions generating revenue by hosting innovation challenges or competitions, where participants pay entry fees to showcase their ideas and solutions. Additionally, revenue can be generated by offering incubator rental services, and providing physical space and resources for startups and entrepreneurs to develop their projects. These initiatives promote creativity, collaboration, and entrepreneurship within the DataCity community, while also generating income.

These proposed revenue models demonstrate DataCity's commitment to financial sustainability and its vision for a diverse, resilient, and self-sustaining ecosystem that fosters innovation, entrepreneurship, and data-driven solutions within the smart city domain.

Pricing Model

DataCity is considering various pricing models to sustain its operations and support its mission of advancing smart mobility and innovation. These proposed pricing models are currently under consideration and subject to further refinement:

- **Annual Subscribers:** DataCity is exploring the possibility of offering an annual subscription model that would provide critical support for the ongoing operations, upgrades, and expansion of the DataCity testing ground. Under this proposed model, annual subscribers would have the opportunity to contribute to DataCity's sustainability while enjoying potential benefits such as reduced prices for data usage and the option to join the DataCity advisory board. This collaborative approach aims to engage stakeholders in the long-term success of DataCity.
- **Local Agency Support:** To enhance the partnership with local agencies, DataCity is considering a model where these agencies would provide essential services to support the initiative. Proposed services include traffic and video data processing, enabling the collection and analysis of vital transportation data. Additionally, local agencies may offer real-time online traffic monitoring interfaces and on-demand support for transportation system analysis and assessment.
- **Research and Data Access Partners:** DataCity is proposing a pricing structure for research and data access partners that includes long-term and live data tiers. These tiers are designed to cover data product acquisition costs. Research and data access partners would benefit from access to valuable data resources while contributing to the sustainability of DataCity. This proposed model aims to foster mutually beneficial collaborations within the smart city domain.
- **Accelerator Companies:** Start-ups seeking support and access to cutting-edge resources are encouraged to explore DataCity's proposed accelerator program. This program may offer start-up support and privileged access to DataCity's ecosystem. Potential equity and licensing agreements of data and technologies could provide a pathway for these companies to leverage DataCity's resources while promoting innovation within the smart city ecosystem.
- **Innovation Challenge Participants:** DataCity envisions hosting innovation challenges that provide participants with the opportunity to present their ideas and solutions. While the specific details of this model are being refined, winners of these challenges may be considered for additional support. Proposed incentives could

include access to dedicated space and start-up assistance. These incentives are designed to encourage innovation and provide practical resources to aspiring entrepreneurs and innovators, fostering a culture of creativity within the DataCity community.

CONCLUSION

This project deployed the DataCity Smart Mobility Testing Ground along Routes 27 and Route 18 in New Brunswick, NJ. The corridors of the testing ground are equipped with 12 smart roadside units, each featuring self-driving grade LiDAR and computer vision sensors, GPU-enabled edge computing devices, C-V2X technologies, and community mobility applications. A digital twin model was created to replicate the dynamic objects and infrastructure dynamics within these corridors, establishing a living laboratory environment. The project offers four key services: a technology-proving ground for transportation authorities, a comprehensive smart mobility data hub, a digital twin platform for early-stage research and development, open-road technology testing facilities, and community-focused mobility applications designed to enhance traffic safety. The accomplishments of the DataCity SMTG align with NJDOT's "Commitment to Communities" initiative and significantly contribute to the FHWA's objectives for the accelerated testing and deployment of V2X technologies. This report details the major outcomes of all research tasks.

In Task 1, the team conducted significant outreach efforts to public, private, and academic sectors, resulting in major awards that fund the full construction of the proposed DataCity testing ground. New technologies such as Verizon's virtual RSU technologies, Iteris' pedestrian safety technologies, and Ouster's LiDAR sensor and analytic technologies created state-of-the-art technological foundations for the testing ground.

In Task 2, Iteris led the effort to deploy eight permanent sites and four additional trailer sites along the testing ground corridors. Furthermore, five fiber nodes and three P2P sites were established to allow the transmission and archiving of valuable high-resolution mobility data collected from LiDAR and computer vision sensors. Connected Vehicle physical and virtual RSU technologies were also deployed at the testing ground locations, demonstrating the feasibility of both technologies in promoting C-V2X technology deployment.

In Task 3, a state-of-the-art Mobility Management Center was built with the financial, construction, and technical support of Middlesex County. The center features not only a conventional flat video wall surveillance system but also a curved-video-wall-based Cave Automatic Virtual Environment (CAVE). A large 1.5 PB storage and high-performance analytic center were established to support the archiving and processing of smart mobility data.

In Task 4, the Rutgers team collected a high-resolution point cloud of the DataCity testing ground corridors and developed high-fidelity 3D models to support the deployment of CAV applications and the digital twin model development.

In Task 5, the Rutgers team developed key analytic models and prototype CAV applications to demonstrate the capability of the proposed smart roadside units. Sensor data collected from roadside high-resolution sensors were converted into SAE J2735 messages that can be used to detect traffic conflicts and support CAV safety applications.

The team worked with Ouster's BlueCity team to deploy the InsightAI platform, providing key safety, mobility, and signal performance metrics for transportation agencies and supporting some of the safety improvements on Route 27 intersections.

In Task 6, the Rutgers team developed key digital twin platforms that can convert trajectory data from roadside instruments to CARLA-based visualization models that mimic real-world traffic dynamics. The digital twin model was also used to assess the boundary conditions of roadside LiDAR sensors.

In Task 7, the Econsult Solutions Inc. team worked with the Rutgers team to develop several strategies to support the formulation and long-term operations of the DataCity testing ground. Several key pricing, business, and marketing strategies were explored.

Through the execution of the above-summarized tasks, the project team was able to build a state-of-the-art smart mobility testing ground that will support local, regional, and nationwide pursuit of accelerated development and deployment of CAV technologies and build the foundations towards long-term sustainable operations of the DataCity Smart Mobility Testing Ground.

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APPENDIX A: AV REGULATIONS AND LEGISLATIONS

Table 13 - New Jersey AV Related Legislation Status
(White: Pending, Green: Enacted, Red: Failed) (13)

Legislation No.	Year	Title	Status	Date of Last Action	Author	Topic	Summary
NJ A 1810, NJ A 1607, NJ A 1853 (Failed), NJ A 3745	2017-2022	Testing and Use of Autonomous Vehicles on State Roadway	Pending - Assembly Transportation and Independent Authorities Committee	1/11/2022	Lampitt (D) Additional Conaway (D) Benson (D)	Definitions, Vehicle Testing, Operation on Public Roads	Permits testing and use of autonomous vehicles on state roadways under certain circumstances.
NJ A 1812, NJ A 1859 (Failed)	2017-2022	Owners of Self Driving Motor Vehicles	Pending - Assembly Financial Institutions and Insurance Committee	1/11/2022	Lampitt (D) Additional Benson (D) Mukherji (D) Chaparro (D)	Definitions, Insurance and Liability	Clarifies that owners of self-driving motor vehicles must comply with existing insurance requirements.
NJ S 343, NJ A 2030, NJ A 1187, NJ A 851, NJ A 4541 (Failed)	2016-2022	Driver License Endorsement	Pending - Senate Transportation Committee	1/12/2016	Kean T (R) Additional Kyrillos (R) Sacco (D) Stack (D) Beck (R)	Definitions, Licensing and Registration, Other	Directs MVC to establish driver's license endorsement for autonomous vehicles.
NJ A 2031, NJ A 1189, NJ A 3367 (Failed), NJ A 4573 (Failed)	2018-2022	Fully Autonomous Vehicle Pilot Program	Pending - Assembly Transportation and Independent Authorities Committee	1/11/2022	Benson (D) Additional Karabinchak (D) Calabrese (D)	Definitions, Operation on Public Roads, Licensing and Registration	Establishes a fully autonomous vehicle pilot program.
NJ A 2038	2022	Highly Automated Vehicles Process Test	Pending - Assembly Transportation and Independent Authorities Committee	1/11/2022	Benson (D) Additional Conaway (D) Mukherji (D) Calabrese (D) Stanley (D)	Definitions, Vehicle Testing, Request for Study	Establishes permitting process for testing highly automated vehicles in the State, establishes Highly Automated Vehicle Interagency Advisory Committee.
NJ S 3877	2021	Highly Automated Vehicles Testing	Pending - Senate Budget and Appropriations Committee	6/3/2021	Pou (D) Additional Kean T (R)	Definitions, Vehicle Testing, Operation on Public Roads, Request for Study	Establishes permitting process for testing highly automated vehicles, establishes Highly Automated Vehicle Interagency Advisory Committee.
NJ A 2495, NJ A 2807, NJ A 4977 (Failed), NJ S 3438 (Failed)	2019-2022	Autonomous Vehicles Interaction Training	Pending - Assembly Law and Public Safety Committee	2/14/2022	Murphy (D)		Requires Department of Law and Public Safety to establish training program to prepare law enforcement to interact with autonomous vehicles.

Legislation No.	Year	Title	Status	Date of Last Action	Author	Topic	Summary
NJ A 5681	2021	Testing Highly Automated Vehicles Process	Pending - ASSEMBLY	12/9/ 2021	Zwicker (D) Additional Conaway (D) Benson (D) Mukherji (D) Stanley (D)	Definitions, Vehicle Testing, Operation on Public Roads, Request for Study	Establishes permitting process for testing highly automated vehicles in NJ, establishes Highly Automated Vehicle Interagency Advisory Committee.
NJ AJR 188 (Failed)	2019-2020	Advanced Autonomous Vehicle Insurance Task Force	Failed - Adjourned - Assembly Financial Institutions and Insurance Committee	2/7/ 2019	DeCroce B (R)		Establishes State Advanced Autonomous Vehicle Insurance Task Force to investigate automobile insurance issues that may arise from use of autonomous vehicles.
NJ SJR 105 (Failed)	2020	Advanced Autonomous Vehicle Task Force	Failed - Adjourned - SENATE	1/17/ 2019	Diegnan (D) Additional Kean T (R) Greenstein (D)		Requires an evaluation of existing state laws that may unreasonably impede the testing and operation of AVs on public roads, licensing, registration, insurance, liability, and other issues.
NJ S 2129, NJ A 4504, NJ A 554, NJ S 1530 (Failed), NJ S 2895	2017-2021	Self Driving Motor Vehicle Insurance Requirements	Pending - Senate Commerce Committee	3/16/ 2020	Gill (D)	Insurance and Liability	Clarifies that owners of self-driving motor vehicles must comply with existing insurance requirements.
NJ AJR 164 (Enacted), NJ SJR 105 (Failed)	2018-2020	Advanced Autonomous Vehicle Task Force	Enacted - Act No. 2019-2	03/18/ 2019 - Enacted	Benson (D) Additional Conaway (D) Kean S (R Lampitt (D) Quijano (D) Pinkin (D) Houghtaling (D) Zwicker (D) Freiman (D)		Revises provisions relating to the Advanced Autonomous Vehicle Task Force.
NJ S 2149 (Failed)	2018-2020	Autonomous Vehicles State Roadway Use	Failed - Adjourned - Senate Transportation Committee	3/5/ 2018	Gordon (D)		Permits testing and use of autonomous vehicles on State roadways under certain circumstances.
NJ S 3225	2017	Autonomous Vehicles Testing and Use	Pending - Senate Transportation Committee	5/18/ 2017	Gordon (D)	Definitions, Vehicle Testing, Operation on Public Roads, Privacy of Collected Vehicle Data, Insurance and Liability, Operator Requirements	Permits testing and use of autonomous vehicles on state roadways under certain circumstances.

APPENDIX B: CONTROL CENTER DESKTOP AND SERVER CONFIGURATION

Computing Equipment

The compute nodes form a core of resources in the entire system. They supply the processing, memory, and network functionalities. In the Smart Mobility Management Center, the computing system consists of eight Precision 5820 workstations, five Precision 3930R Rack workstations, one Precision 7920 Rack, and two Power Switch. Figures 113-115 and tables 14-16 provide the detailed specifications of the servers.

Figure 113. Dell Precision 5820 Tower

Table 14 - Spec Sheet for Dell Precision 5820 Tower

Name	Precision 5820 Tower
Processor	Intel ® Core (™) i9-10989XE 3.0GHz, (4.8GHz Turbo, 18C, 24.75MB Cache, HT, (165W), DDR4-2933
Additional Processor	None
Memory Capacity	32GB, 2x16GB, DDR4 UDIMM non-ECC memory
Hard Drives	2.5" 512GB SATA Class 20 Solid State Drive
GPU	Nvidia RTX A4000, 16GB, 4DP
Dell Services: Hardware Support	ProSupport Plus: 7x24 Technical Support, 3 Years
Monitor (Qty: 3)	Dell UltraSharp 27 Monitor - U2722D
KB/Mouse (Qty: 8)	Wireless Keyboard and Mouse KM7321W

Figure 114. Dell Precision 3930R Rack Workstation

Table 15 - Spec Sheet for Dell Precision 3930R Rack Workstation

Name	Precision 3930 Rack
Processor	Intel ® Core (™) i9-9900K, (8 Core, 16MB Cache, 3.6 GHz, 5GHz Turbo w/UHD Graphics 630)
Additional Processor	None
Memory Capacity	128GB, 4x32GB, DDR4 UDIMM non-ECC memory
Hard Drives	2.5” 512GB SATA Class 20 Solid State Drive
GPU	Nvidia Quadro RTX4000, 8GB, 3DP, VirtualLink (3930R)
Dell Services: Hardware Support	ProSupport Plus: 7x24 Technical Support, 3 Years
KB/Mouse (Qty: 5)	Wireless Keyboard and Mouse KM7321W

Figure 115. Dell Precision 7920 Rack

Table 16 - Spec Sheet for Dell Precision 7920 Rack

Precision 7920 Rack	Precision 7920 Rack
Processor	Intel Xeon Gold 6226R 2.9GHz, (3.9GHz Turbo, 16C, 10.4GT/s 2UPI, 22MB Cache, HT (150W) DDR4-2933 1st)
Additional Processor	Intel Xeon Gold 6226R 2.9GHz, (3.9GHz Turbo, 16C, 10.4GT/s 2UPI, 22MB Cache, HT (150W) DDR4-2933 2nd)
Memory Capacity	192GB, 12x16GB, DDR4 2933MHz RDIMM ECC memory
Hard Drives	2.5” 2TB 7,200rpm SATA Hard Drive AG-Enterprise Class
GPU	Dual Nvidia Quadro RTX6000, 24GB, 4DP, VirtualLink (7920R)
Dell Services: Hardware Support	ProSupport Plus: 7x24 Technical Support, 3 Years

Storage Equipment

Storage systems are used to store the data and serve as storehouses for data and applications repositories. A typical storage node has two components: a physical server and its associated one or more hard drives. In the Smart Mobility Management Center, the storage system consists of one video & 3D data analytic server (DSS 8440), one web server (PowerEdge R440 Server), one application server (PowerEdge R740 Server), one database server (PowerEdge R740XD Server), one network attached storage (PowerScale A2000 NAS) and one storage area network (PowerStore 1000T SAN). Figures 116-121 and tables 17-22 provide the detailed specifications of the servers.

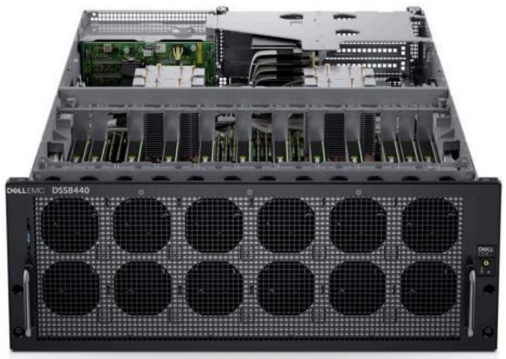

Figure 116. DSS 8440

Table 17 - Spec Sheet for DSS 8440

Name	DSS 8440 Cauldron	Quantity
Processor	Intel Xeon Gold 6248R 3.0G, 24C/48T, 10.4GT/s, 35.75M Cache, Turbo, HT (205W) DDR4-2933	1
Additional Processor	Intel Xeon Gold 6248R 3.0G, 24C/48T, 10.4GT/s, 35.75M Cache, Turbo, HT (205W) DDR4-2933	1
Memory Capacity	32GB RDIMM, 3200MT/s, Dual Rank, 16Gb BASE	8
Hard Drives	480GB SSD SATA Mix Use 6Gbps 512 2.5in Hot-plug AG Drive, 3 DWPD	2
Embedded Systems Management	iDRAC9, Enterprise	1
Network Daughter Card	Intel X710 Dual Port 10GbE SFP+ & i350 Dual Port 1Gbe, rNDC	1
Additional Network Cards	Intel XXV710 Dual Port 10/25GbE SFP28 Adapter, PCIe Low Profile	1
NVME and PCIe Storage Adapters	3.84TB Enterprise NVMe Mixed Use AG Drive, AIC, PCIe 4.0	1
GPU/FPGA/Acceleration Cards	Nvidia Ampere A100, PCIe, 250W, 40GB Passive, Double Wide, Full Height GPU	4
GPU/FPGA/Acceleration Cards	NVLink bridge A-Series Interconnect	6
Dell Services: Hardware Support	3 Years ProSupport Plus Mission Critical 4Hr Onsite Service	1
Deployment Services	ProDeploy Plus Dell Server R Series 1U/2U	1

Figure 117. Dell PowerEdge R440 Server

Table 18 - Spec Sheet for Dell PowerEdge R440 Server

Name	PowerEdge R440 Server	Quantity
Processor	Intel Xeon Silver 4215 2.5G, 8C/16T, 9.6GT/s, 11M Cache, Turbo, HT (85W) DDR4-2400	1
Additional Processor	Intel Xeon Silver 4215 2.5G, 8C/16T, 9.6GT/s, 11M Cache, Turbo, HT (85W) DDR4-2400	1
Memory Capacity	8GB RDIMM, 3200MT/s, Single Rank	4
Hard Drives	1.92TB SSD SATA Mix Use 6Gbps 512 2.5in Hot-plug AG Drive, 3 DWPD	3
Embedded Systems Management	iDRAC9, Enterprise	1
Network Card	On-Board Broadcom 5720 Dual Port 1Gb LOM	1
Additional Network Card	Broadcom 57414 Dual Port 25GbE OCP SFP28 LOM Mezz Card	1
Additional Network Card	Broadcom 57414 Dual Port 10GbE SFP+ Adapter, PCIe Low Profile	1
Dell Services: Hardware Support	3 Years ProSupport Plus Mission Critical 4Hr Onsite Service	1
Deployment Services	ProDeploy Plus Dell Server R Series 1U/2U	1

Figure 118. Dell PowerEdge R740

Table 19 - Spec Sheet for Dell PowerEdge R740

Name	PowerEdge R740 Server	Quantity
Processor	Intel Xeon Gold 6242 2.8G, 16C/32T, 10.4GT/s, 22M Cache, Turbo, HT (150W) DDR4-2933	1
Additional Processor	Intel Xeon Gold 6242 2.8G, 16C/32T, 10.4GT/s, 22M Cache, Turbo, HT (150W) DDR4-2933	1
Memory Capacity	16GB RDIMM, 3200MT/s, Dual Rank, 16Gb BASE	8
Hard Drives	960GB SSD SATA Mix Use 6Gbps 512 2.5in Hot-plug AG Drive, 3 DWPD	3
Embedded Systems Management	iDRAC9, Enterprise	1
Network Card	Riser Config 6, 5x8, 3x16 slots, Single-Wide GPU compatible	1
Additional Network Card	Broadcom 57412 Dual Port 10GbE SFP+ & 5720 Dual Port 1GbE BASE-T rNDC	1
Additional Network Card	Broadcom 57414 Dual Port 10/25GbE SFP28 Adapter, PCIe Full Height	1
GPU/FPGA/Acceleration Cards	Nvidia Tesla T4 16GB, Passive, Single Wide, Full Height GPU	1
Dell Services: Hardware Support	3 Years ProSupport Plus Mission Critical 4Hr Onsite Service	1
Deployment Services	ProDeploy Plus Dell Server R Series 1U/2U	1

Figure 119. Dell PowerEdge R740XD Server

Table 20 - Spec Sheet for Dell PowerEdge R740XD Server

Name	PowerEdge R740XD Server	Quantity
Processor	Intel Xeon Silver 4208 2.1G, 8C/16T, 9.6GT/s, 11M Cache, Turbo, HT (85W) DDR4-2400	1
Additional Processor	No Additional Processor	1
Memory Capacity	8GB RDIMM, 3200MT/s, Single Rank	4
Hard Drives	12TB 7.2K SAS 12Gbps 512e 3.5in Hard Drive	4
Embedded Systems Management	iDRAC9, Enterprise	1
Network Daughter Card	Broadcom 57412 Dual Port 10GbE SFP+ & 5720 Dual Port 1GbE BASE-T rNDC	1
Additional Network Card	Broadcom 57414 Dual Port 10/25GbE SFP28 Adapter, PCIe Lower Height	1
Dell Services: Hardware Support	3 Years ProSupport Plus Mission Critical 4Hr Onsite Service	1
Deployment Services	ProDeploy Plus Dell Server R Series 1U/2U	1

Figure 120. Dell PowerScale A2000

Table 21 - Spec Sheet for Dell PowerScale A2000

Name	PowerScale A2000 - 6 nodes
Backend Switches and Cables	2x S4112 - 10G Switches
Front End Network (per node)	2x 10G SFP+
Ram (per node)	64GB
SSD cache (per node)	1.6TB(2x800GB)
Drive Size	16TB drives
Raw Storage (cluster)	1920TB raw
Usable Storage	1585TB usable (at 100% utilization) 1347TB usable (at recommended 85% utilization)
Rack included	1 Titan XL deep rack - 42U
Read/Write Performance	3.77 GBytes/s, 2.25GBytes/s
Dell Services: Hardware Support	3 Years ProSupport Plus Mission Critical 4Hr Onsite Service
Deployment Services	ProDeploy Plus

Figure 121. Dell PowerStore Model 1000T

Table 22 - Spec Sheet for Dell PowerStore Model 1000T

Name	PowerStore Model 1000T
SSD cache	50TB usable on 7x3.84TB NVMe SSD drives
Dynamic Resiliency Engine	4+1 DRE with 1 Hot Spare
Data Reduction	Assuming DB Compression and 3:1 Data Reduction
Connectivity	25GBe Connectivity
Protection	Asynchronous Replication Architecture enables PRO = 5min
Appliance	2U Appliance

As-Builts Diagrams for Sensor Sites

As-built drawings for sensor sites are provided as follows:

- Albany & George (See figures 122-124)
- Albany & Neilson (See figures 125-127)
- French & Easton (See figures 128-129)
- French & Joyce Kilmer (See figures 130-131)
- French & Paterson (See figures 132-133)
- French & Suydam (See figures 134-135)
- Route 18 VMS Sign Bridge (See figures 136-138)
- Route 18 Boyd Park “Boathouse” (See figures 139-140)
- Trailers (See figure 141)

Albany & George

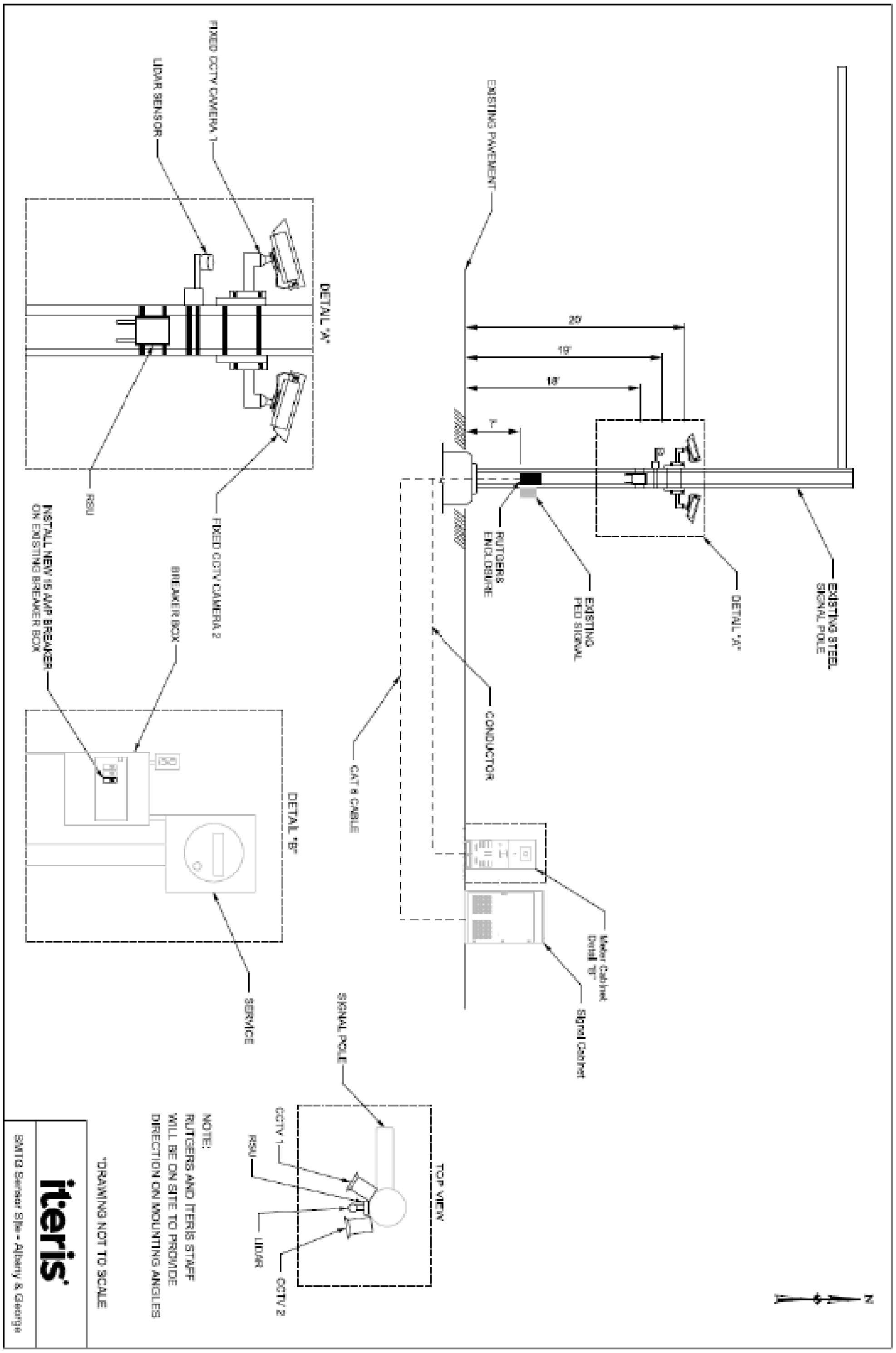

Figure 122. Instrumentation Detail at Albany & George

Cabinet Detail

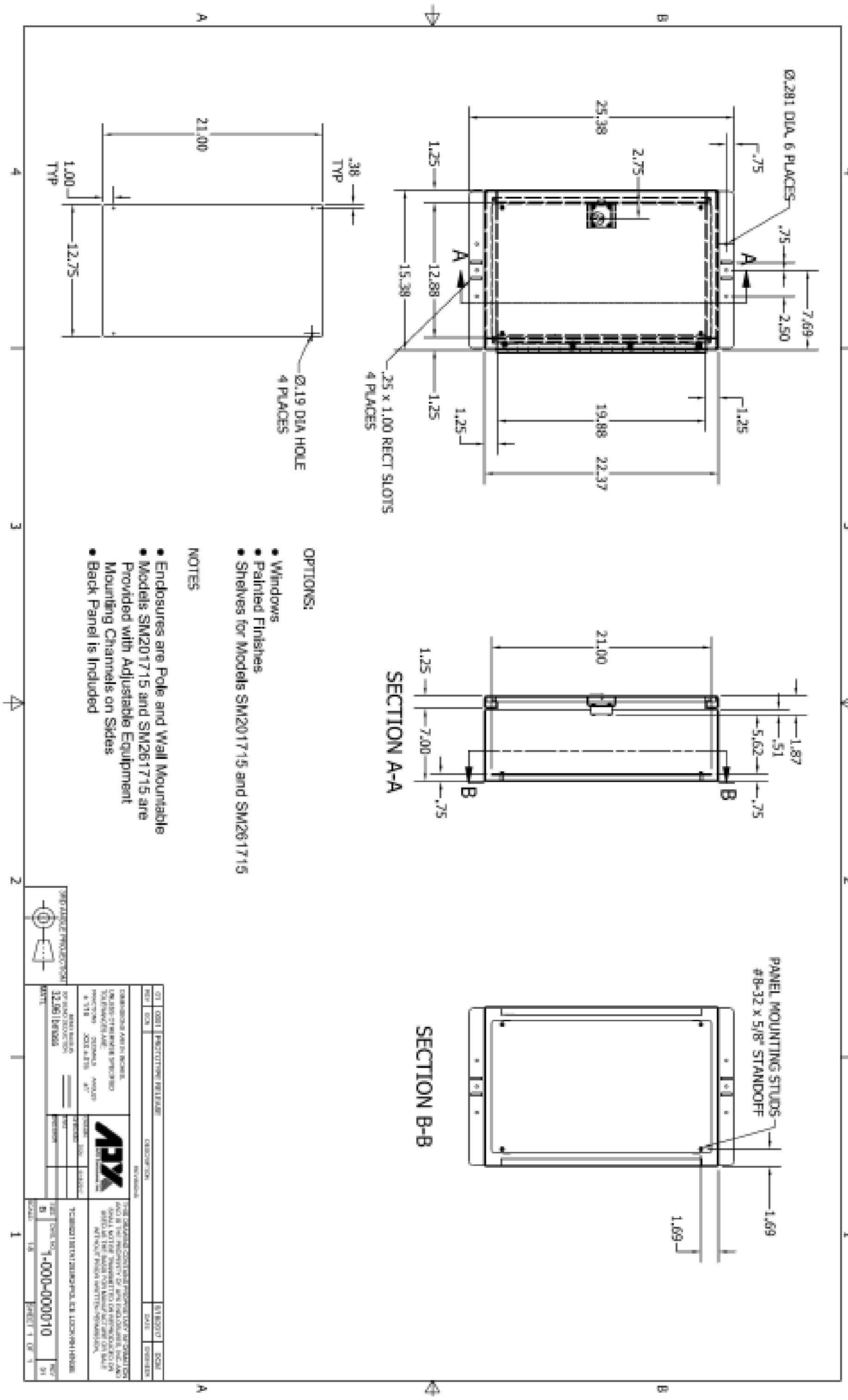

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Figure 123. Cabinet Detail at Albany & George

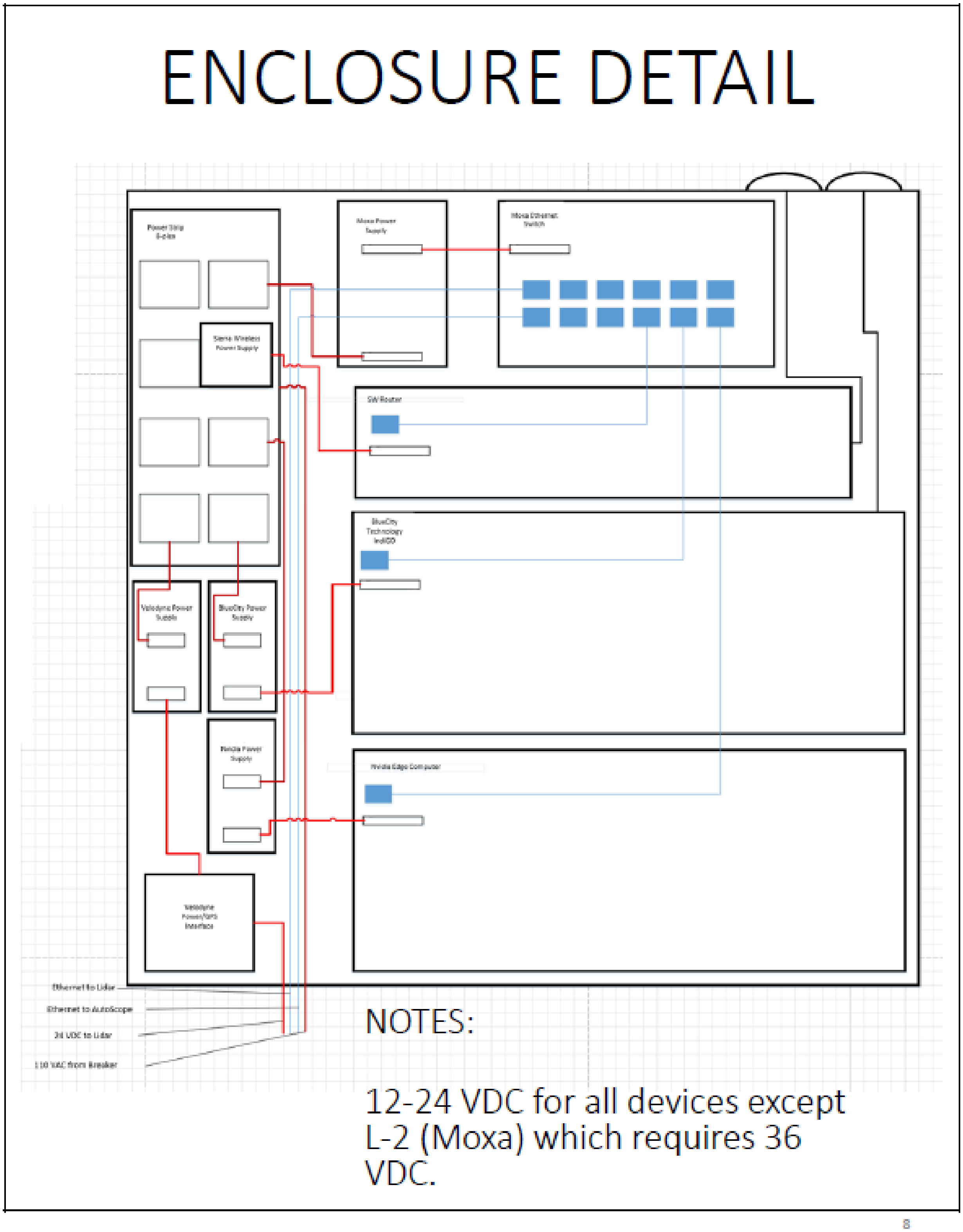


Figure 124. Cabinet Enclosure Detail at Albany & George

Albany & Neilson

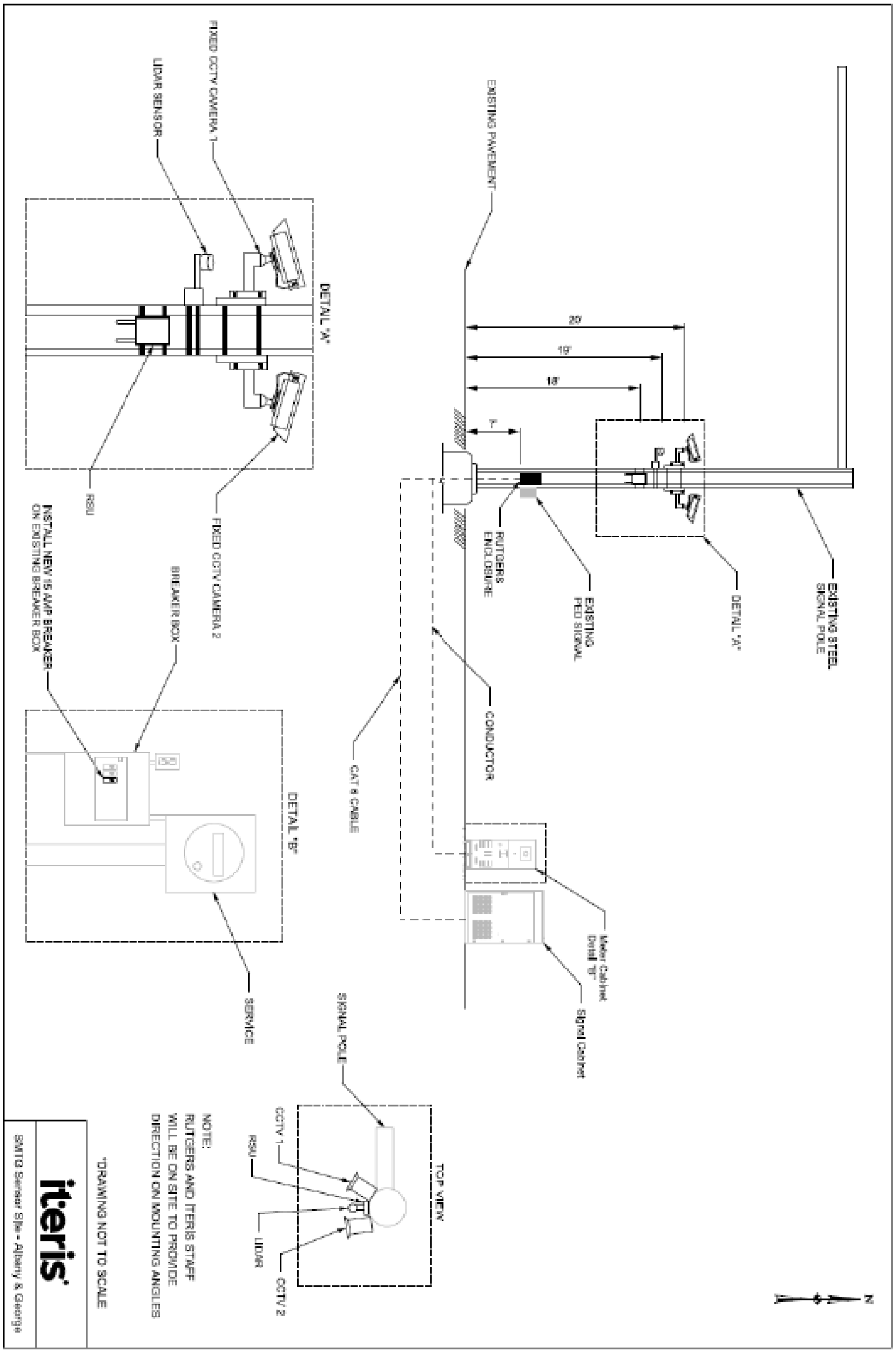


Figure 125. Instrumentation Drawing at Albany & Neilson

Cabinet Detail

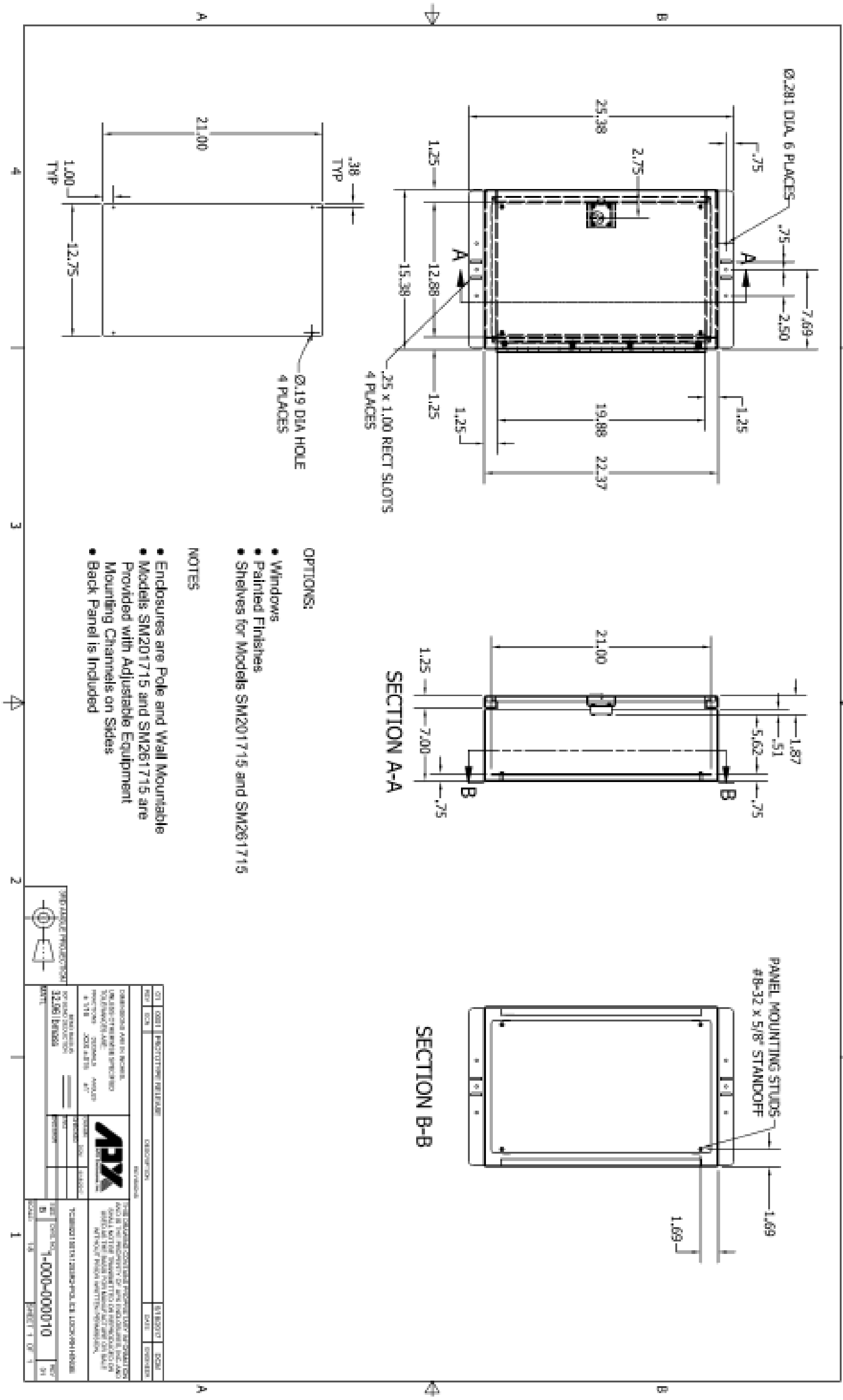


Figure 126. Cabinet Detail at Albany & Neilson

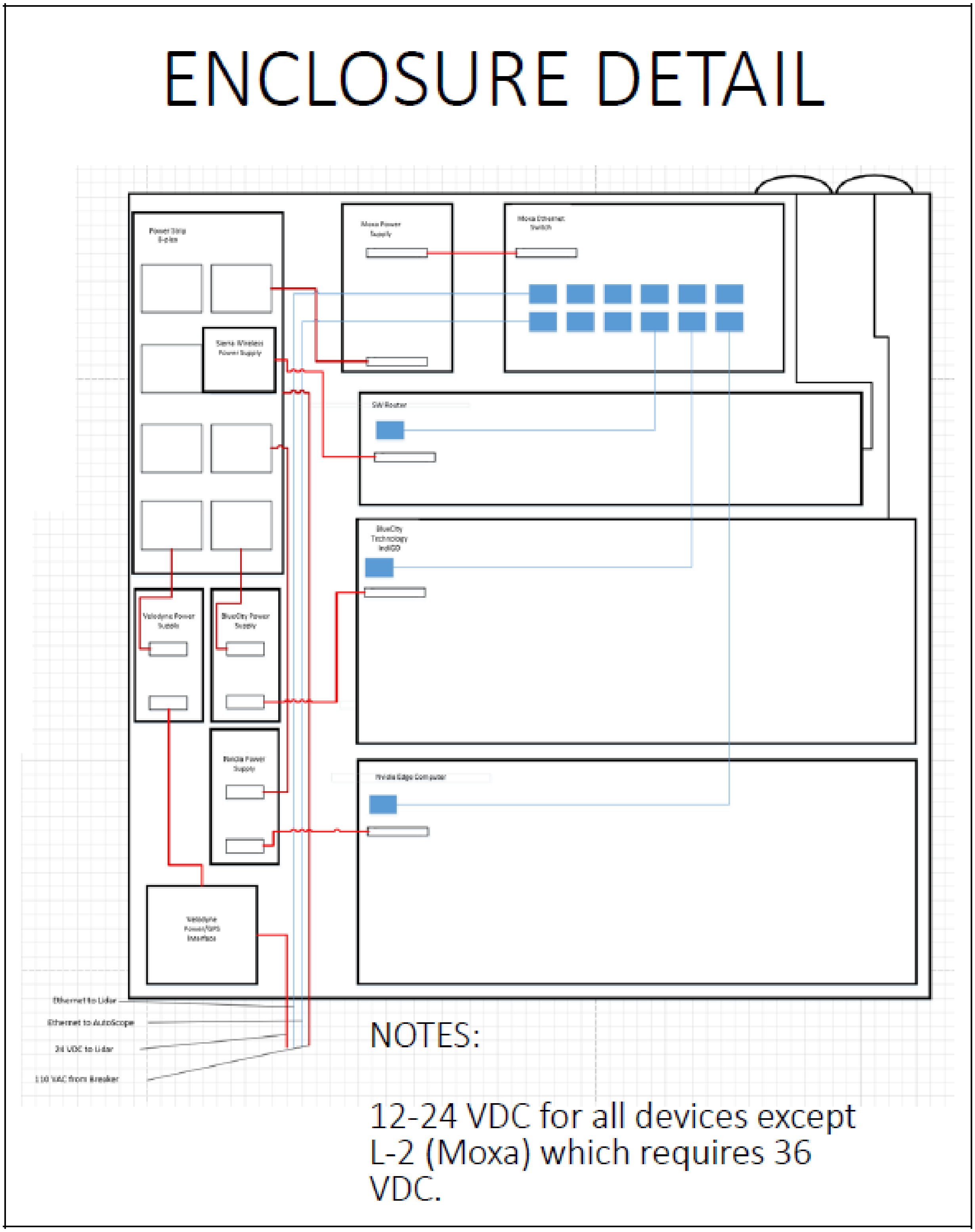
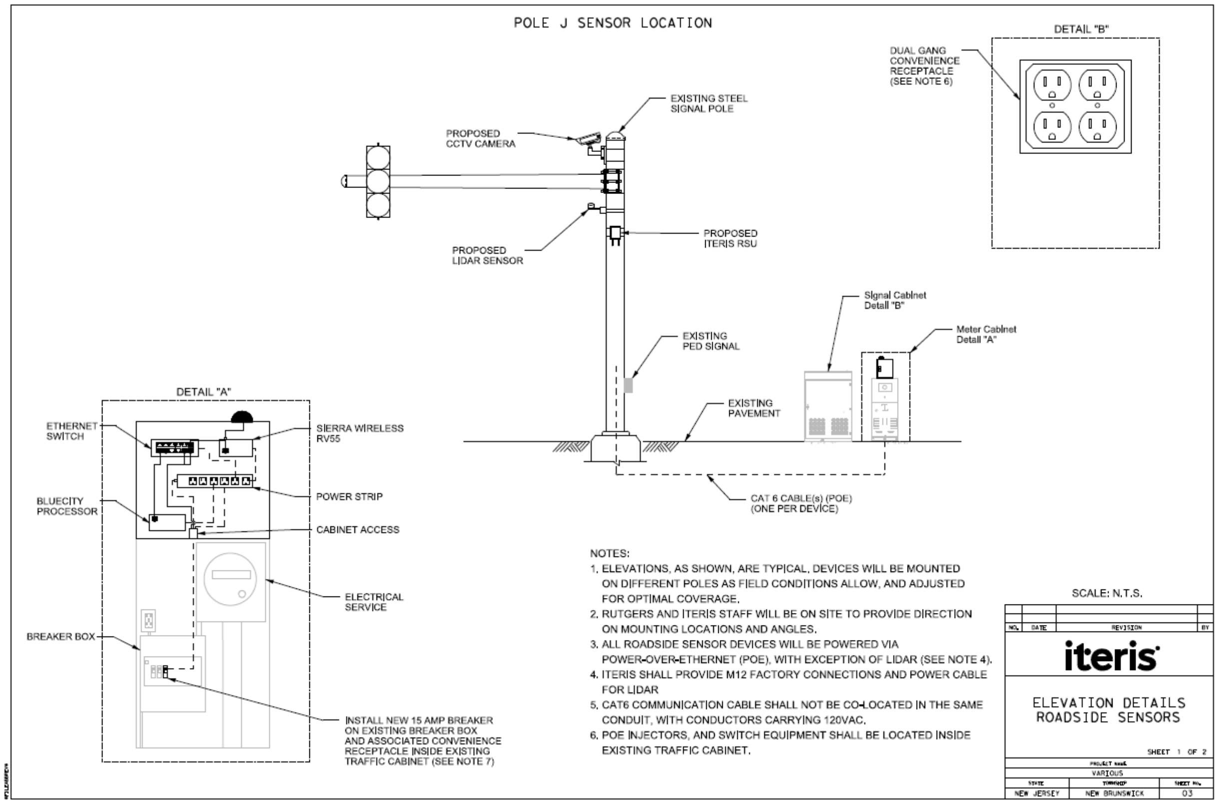


Figure 127. Cabinet Enclosure Detail at Albany & Neilson

French & Easton



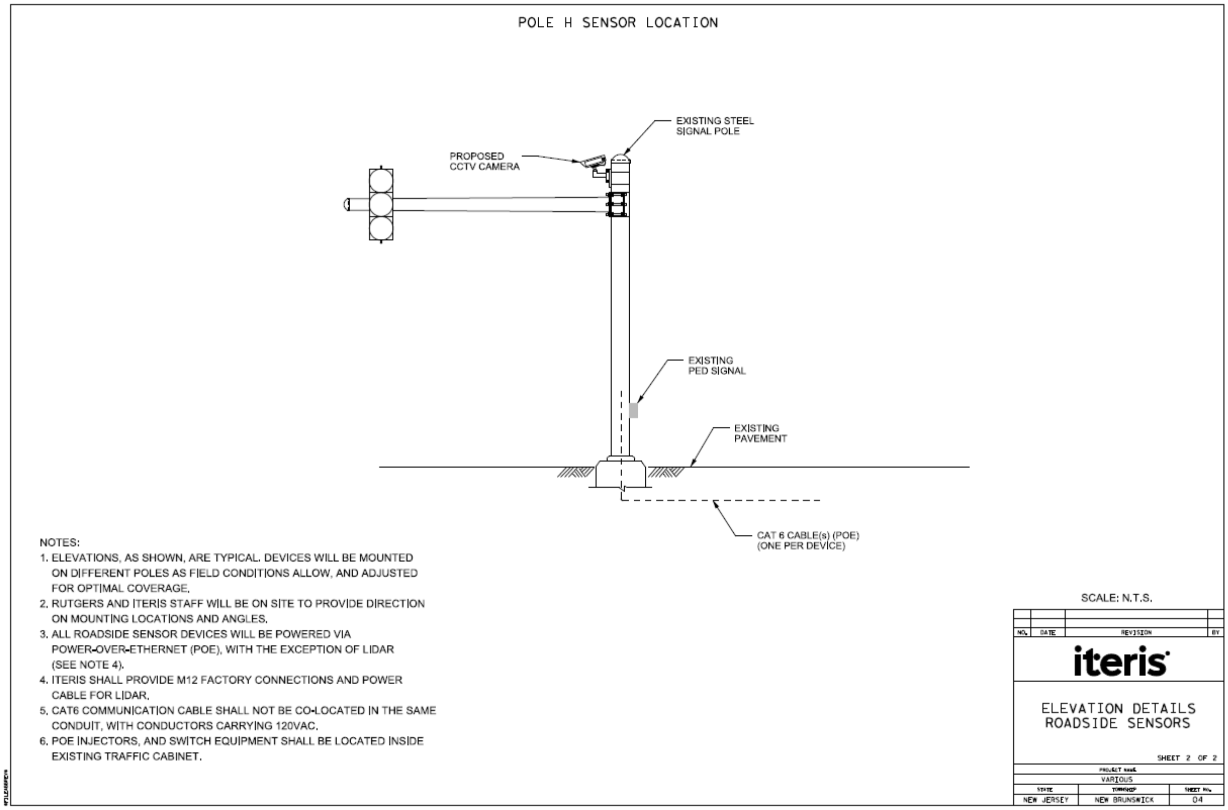


Figure 128. Instrumentation Drawing at French & Easton

DEVICE POWER LOAD				
DEVICE	**MANUFACTURER**	**MODEL #**	**AVERAGE WATTS**	**AVERAGE AMPS**
Router	Sierra Wireless	1104302	1,5	0,02
Switch	Moxa	EDS-P510A-8PoE-2GTXSFP	7	0,11
Camera	Axis	Q1615 LE mk III	6	0,08
Processor	Blue City	IndiGO IQ	10	0.13
Lidar	Velodyne	VLS-128-B422	30	0.37
RSU	Iteris	Spectra	7	0.1
		CALCULATED TOTAL	61.5	0.81

SCALE: N.T.S.

NO.	DATE	REVISION	BY

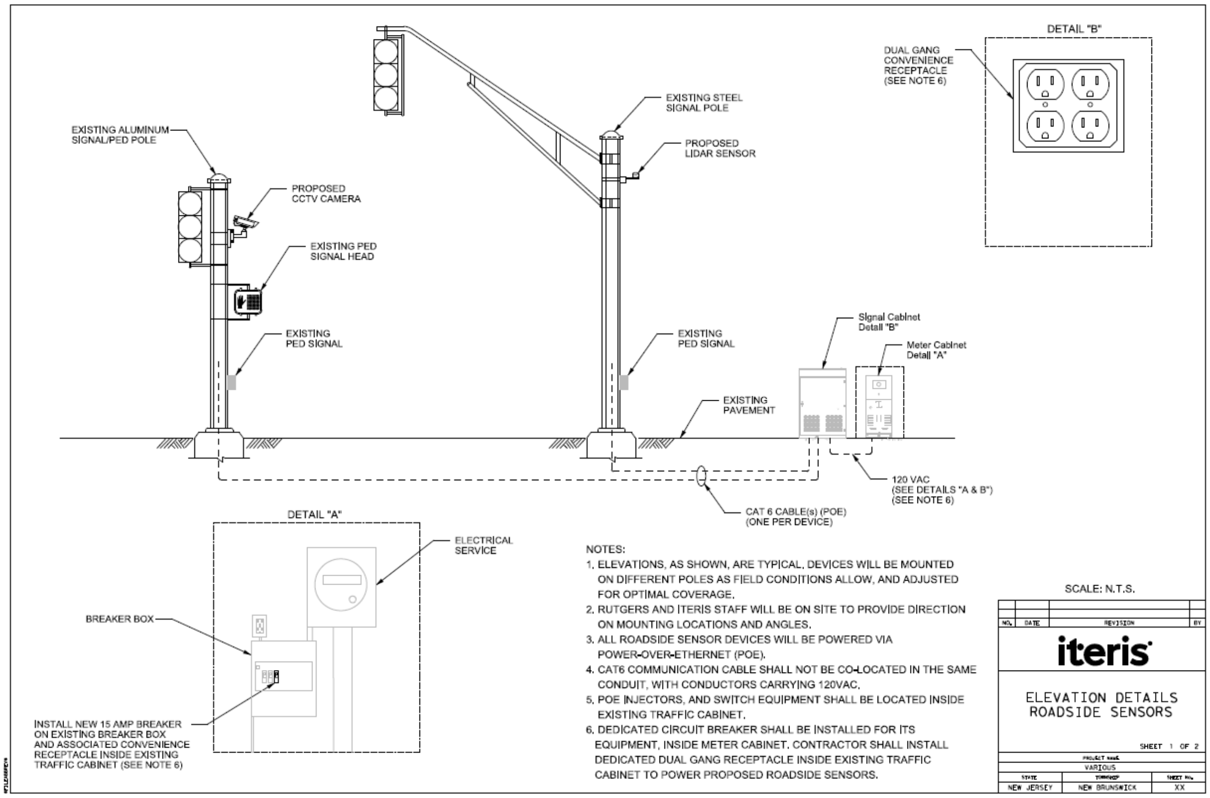
iteris

POWER CALCULATIONS TABLE

PROJECT NAME		
VARIOUS		
STATE	TOWNSHIP	SHEET NO.
NEW JERSEY	NEW BRUNSWICK	06

Figure 129. Device Power Load at French & Easton

French & Joyce Kilmer



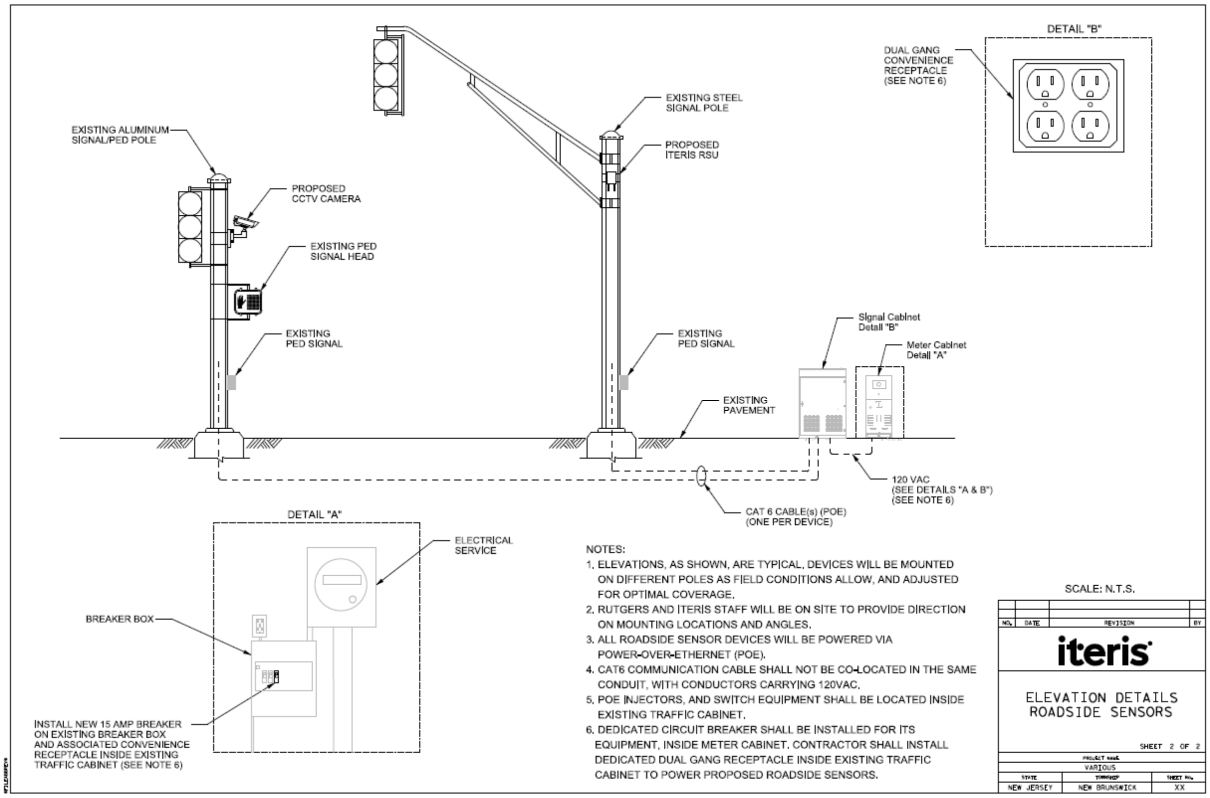


Figure 130. Instrumentation Drawing at French & Joyce Kilmer

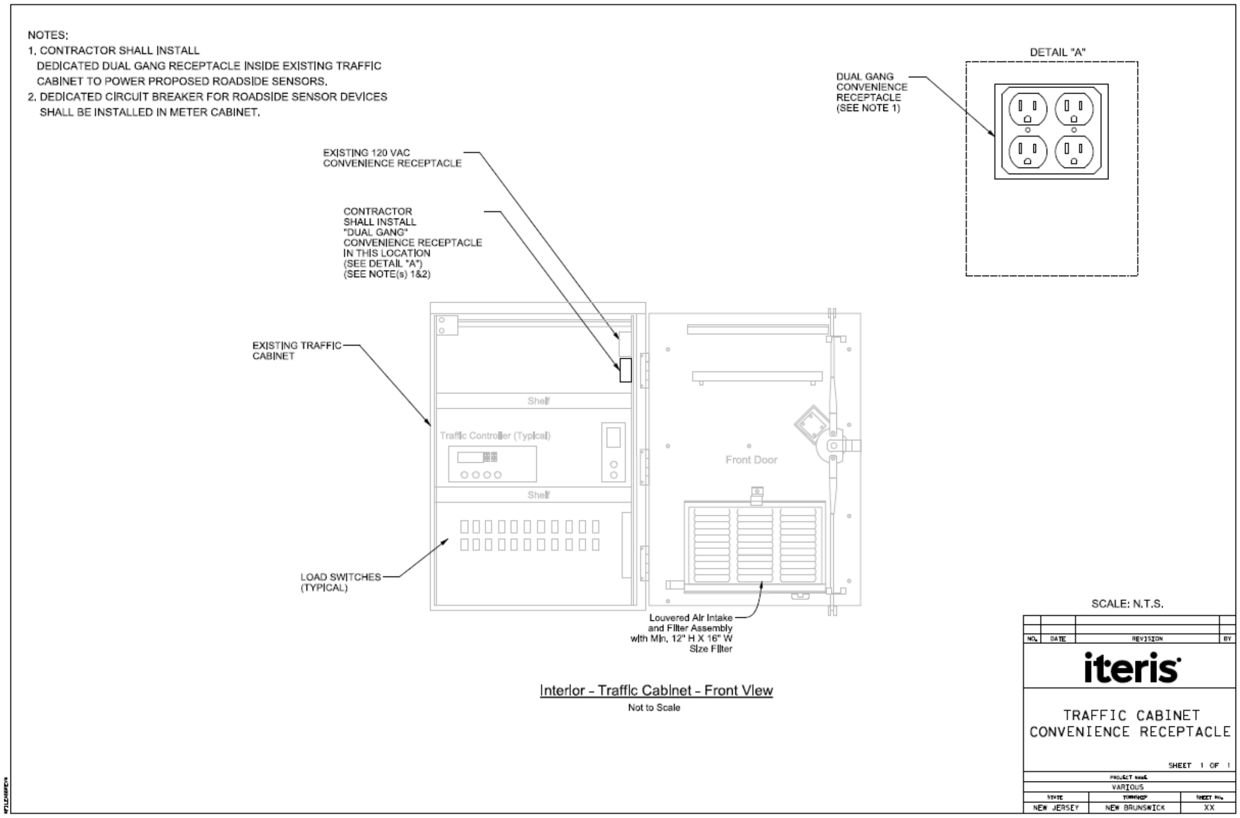
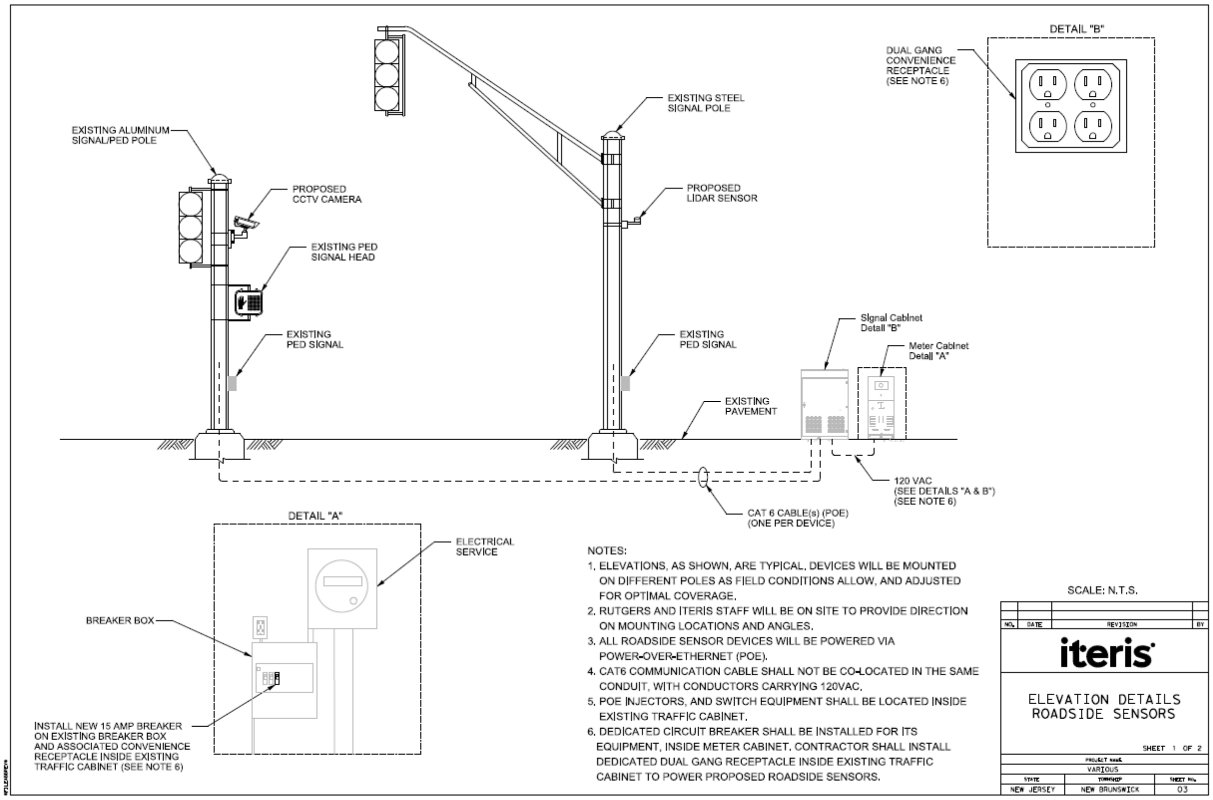


Figure 131. Cabinet Detail at French & Joyce Kilmer

French & Paterson



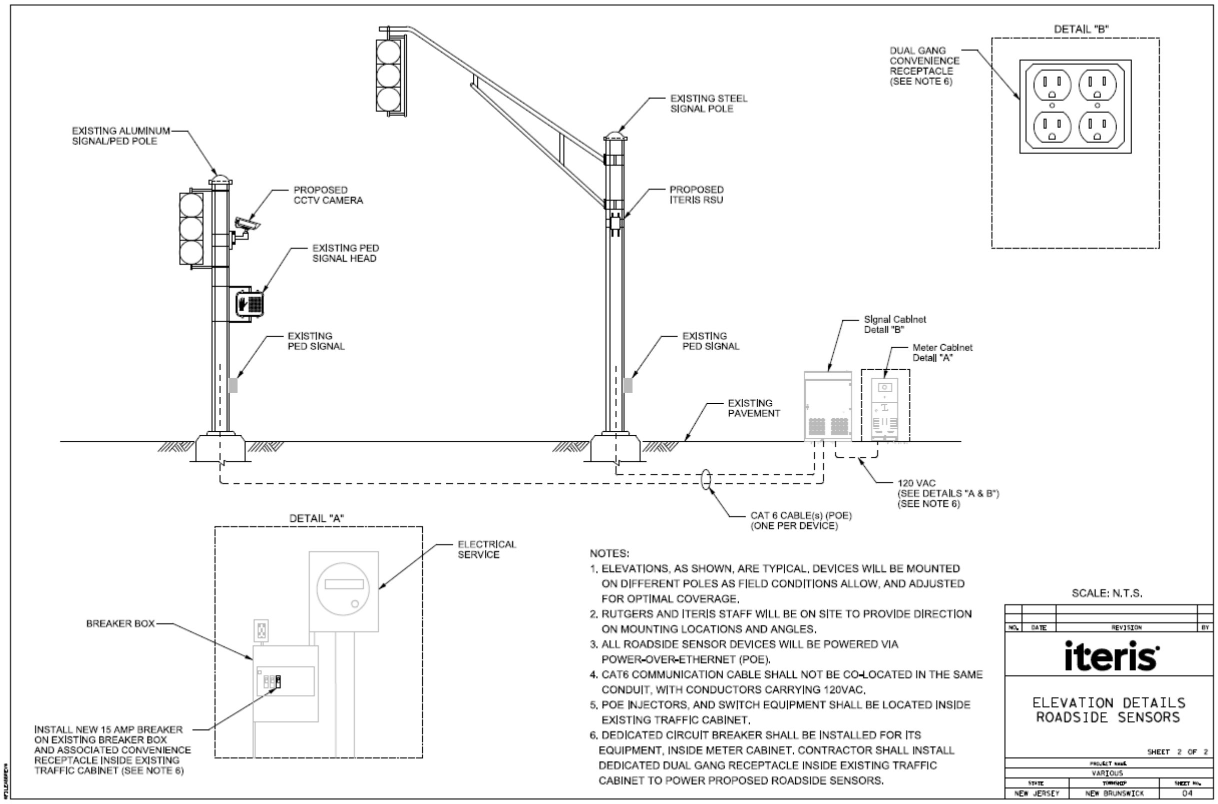


Figure 132. Instrumentation Detail at French & Paterson

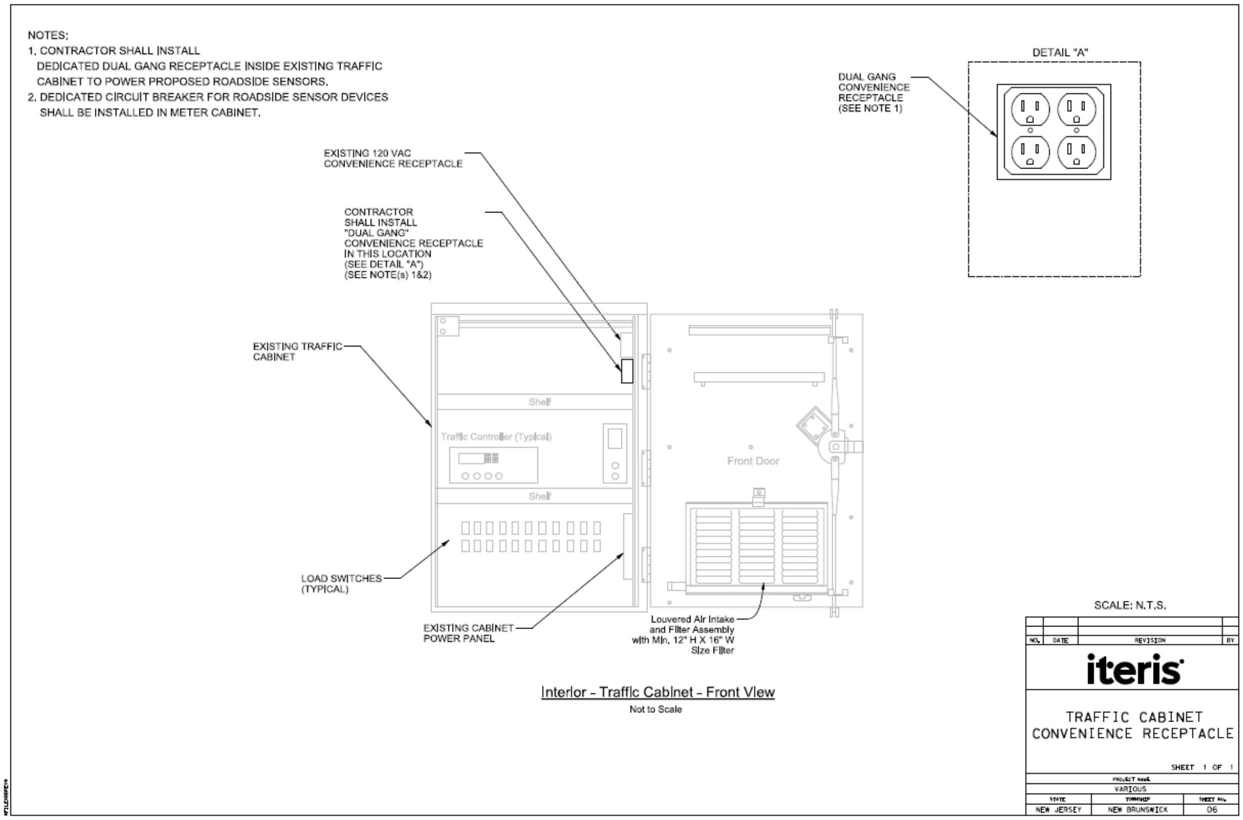
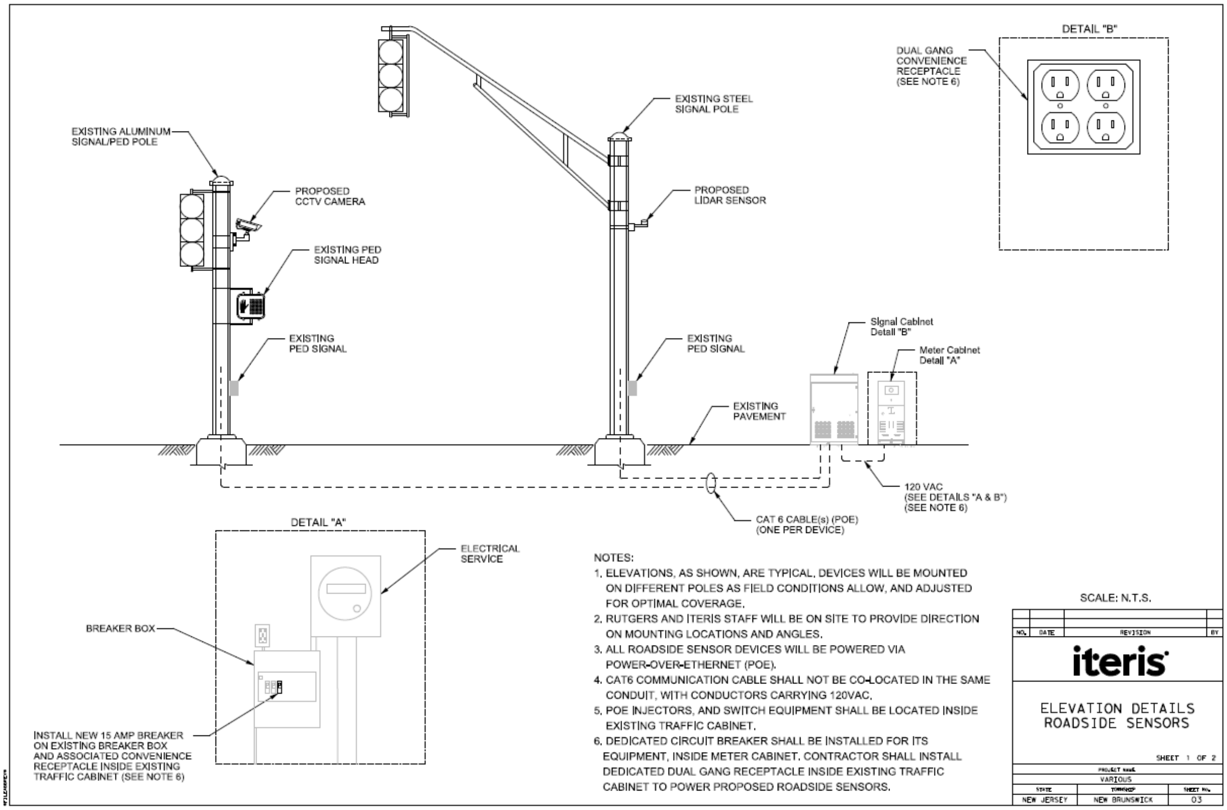


Figure 133. Cabinet Detail at French & Paterson

French & Suydam



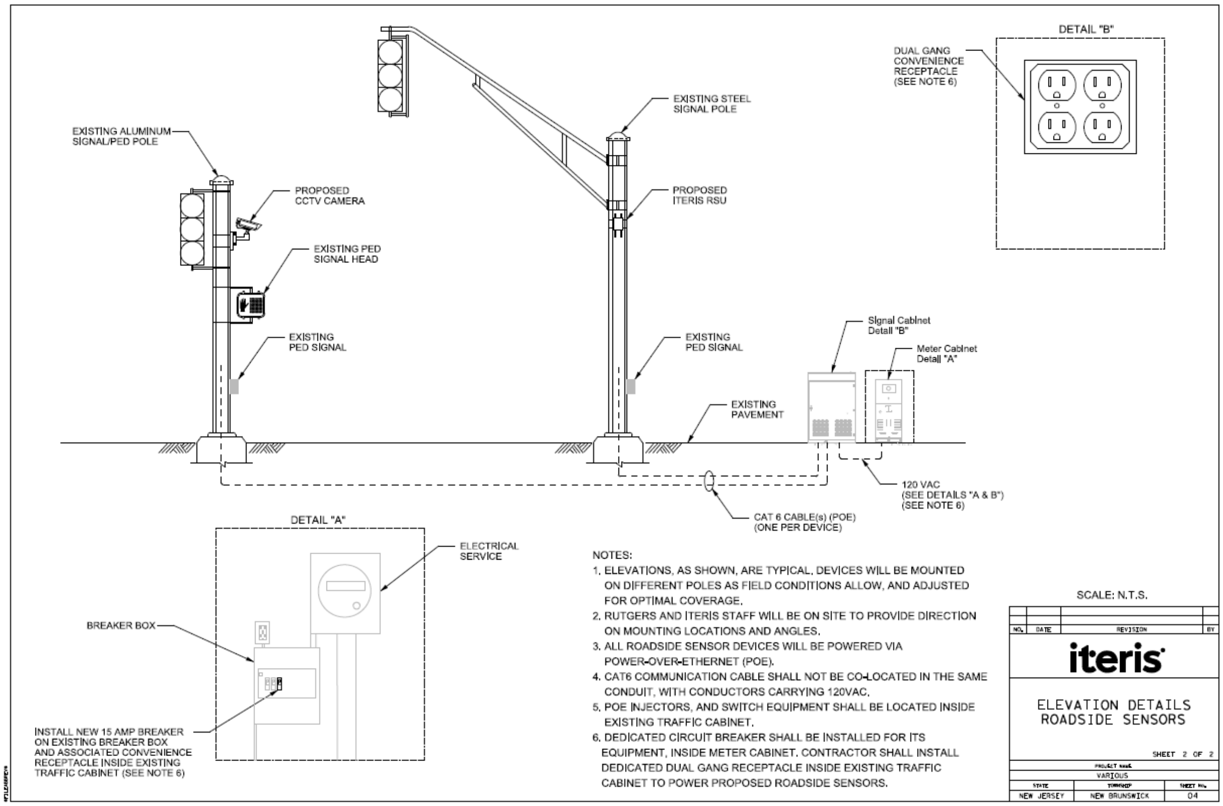


Figure 134. Instrumentation Drawing at French & Suydam

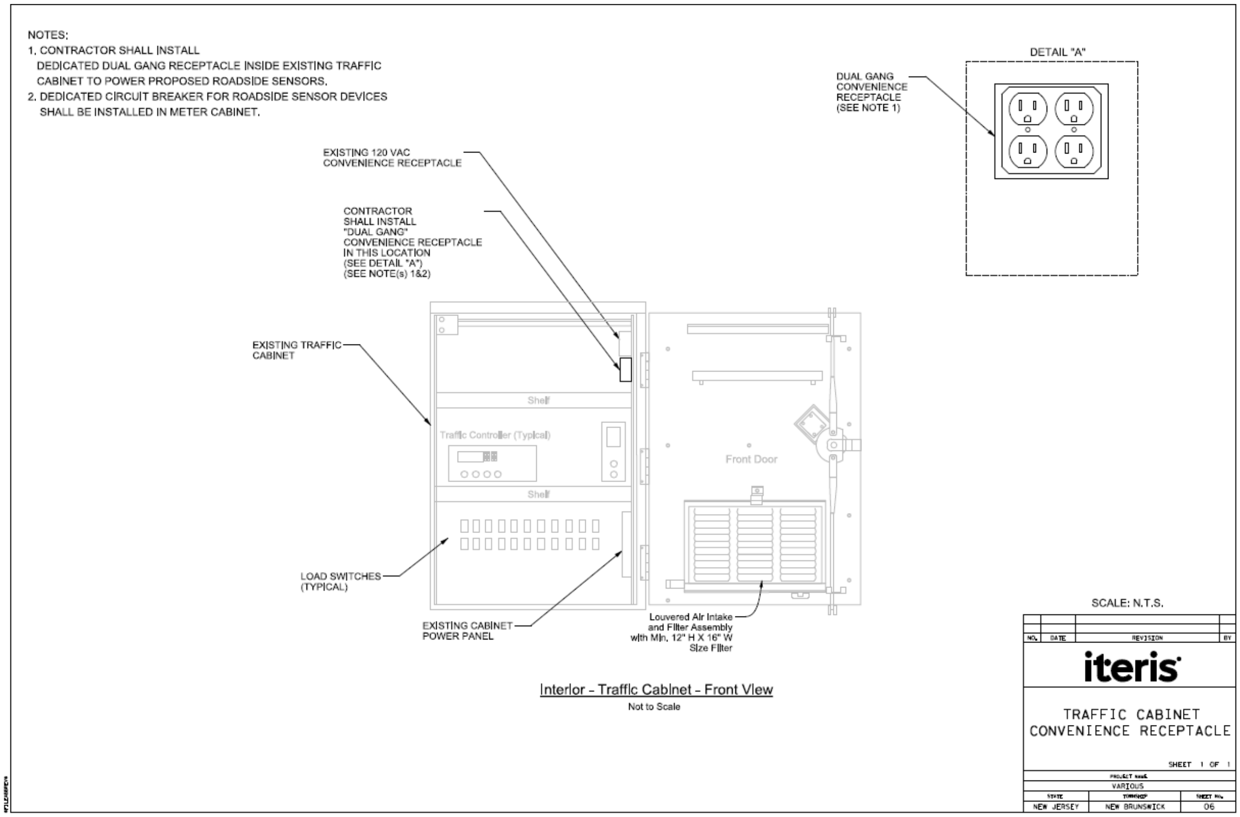


Figure 135. Cabinet Detail at French & Suydam

Route 18 - VMS Sign Bridge

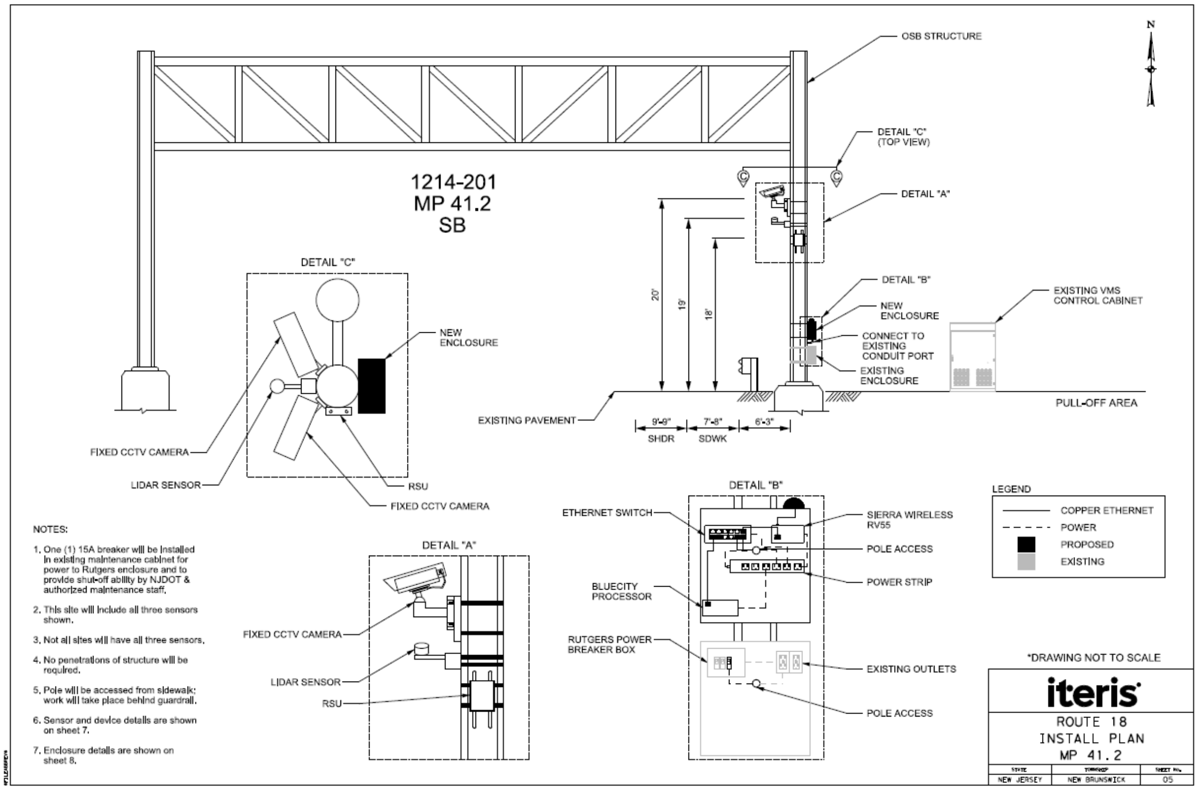
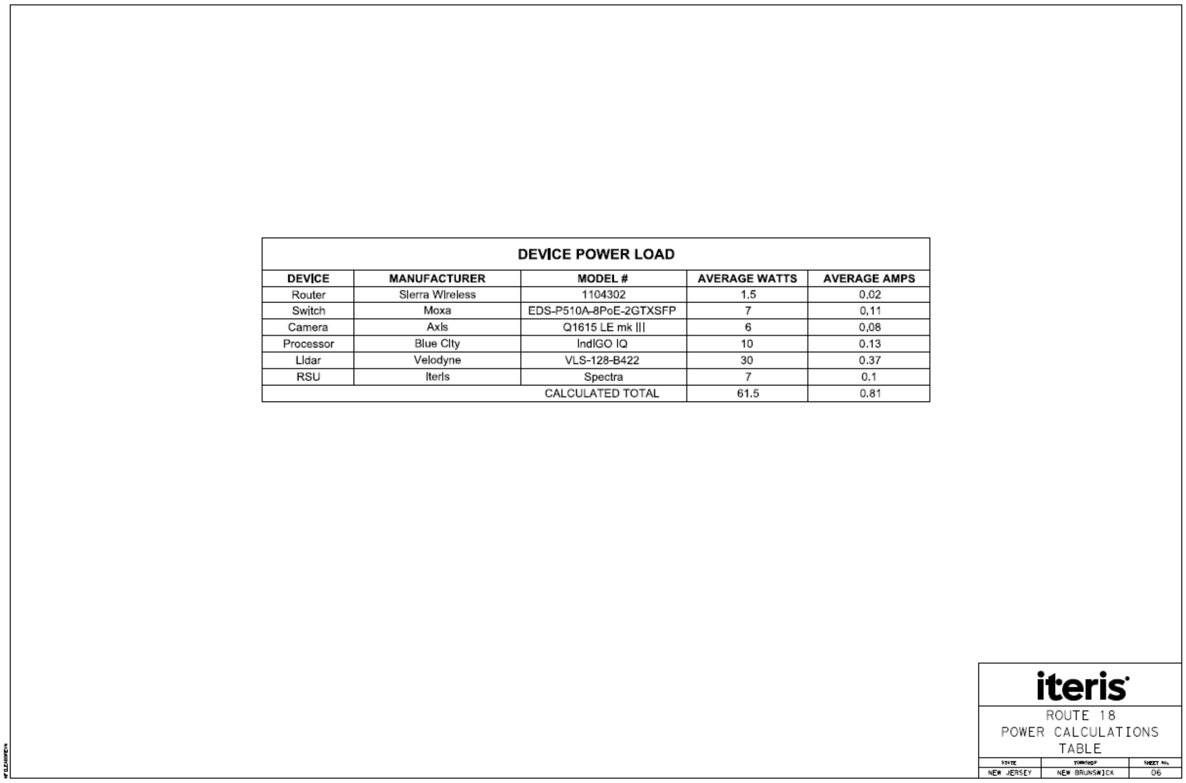


Figure 136. Instrumentation Drawing at Route 18 - VMS Sign Bridge



DEVICE POWER LOAD				
DEVICE	MANUFACTURER	MODEL #	AVERAGE WATTS	AVERAGE AMPS
Router	Sierra Wireless	1104302	1.5	0.02
Switch	Moxa	EDS-P510A-8PoE-2GTXSFP	7	0.11
Camera	Axis	Q1615 LE mk III	6	0.08
Processor	Blue City	IndiGO IQ	10	0.13
Lidar	Velodyne	VLS-128-B422	30	0.37
RSU	Iteris	Spectra	7	0.1
		CALCULATED TOTAL	61.5	0.81

Figure 137. Device Power Load at Route 18 - VMS Sign Bridge

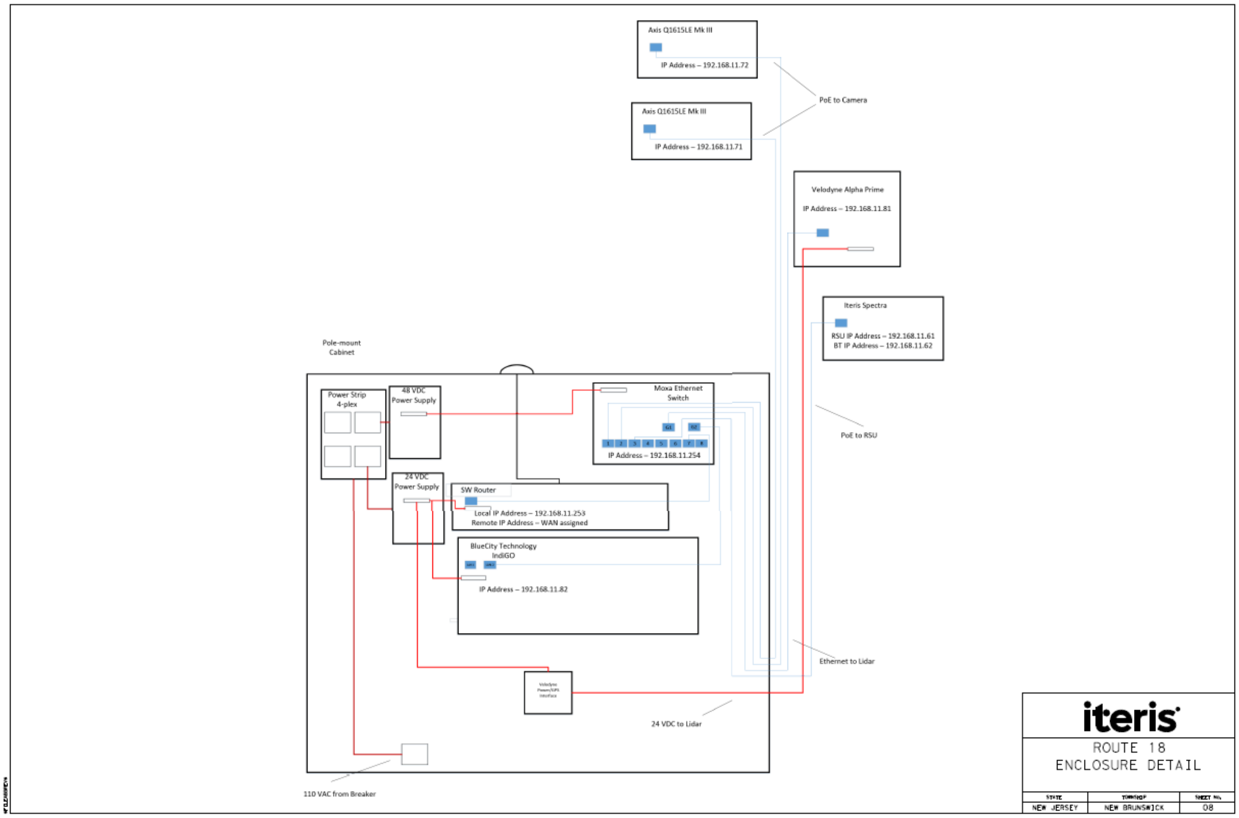


Figure 138. Cabinet Detail at Route 18 - VMS Sign Bridge

Route 18 - Boyd Park “Boathouse”

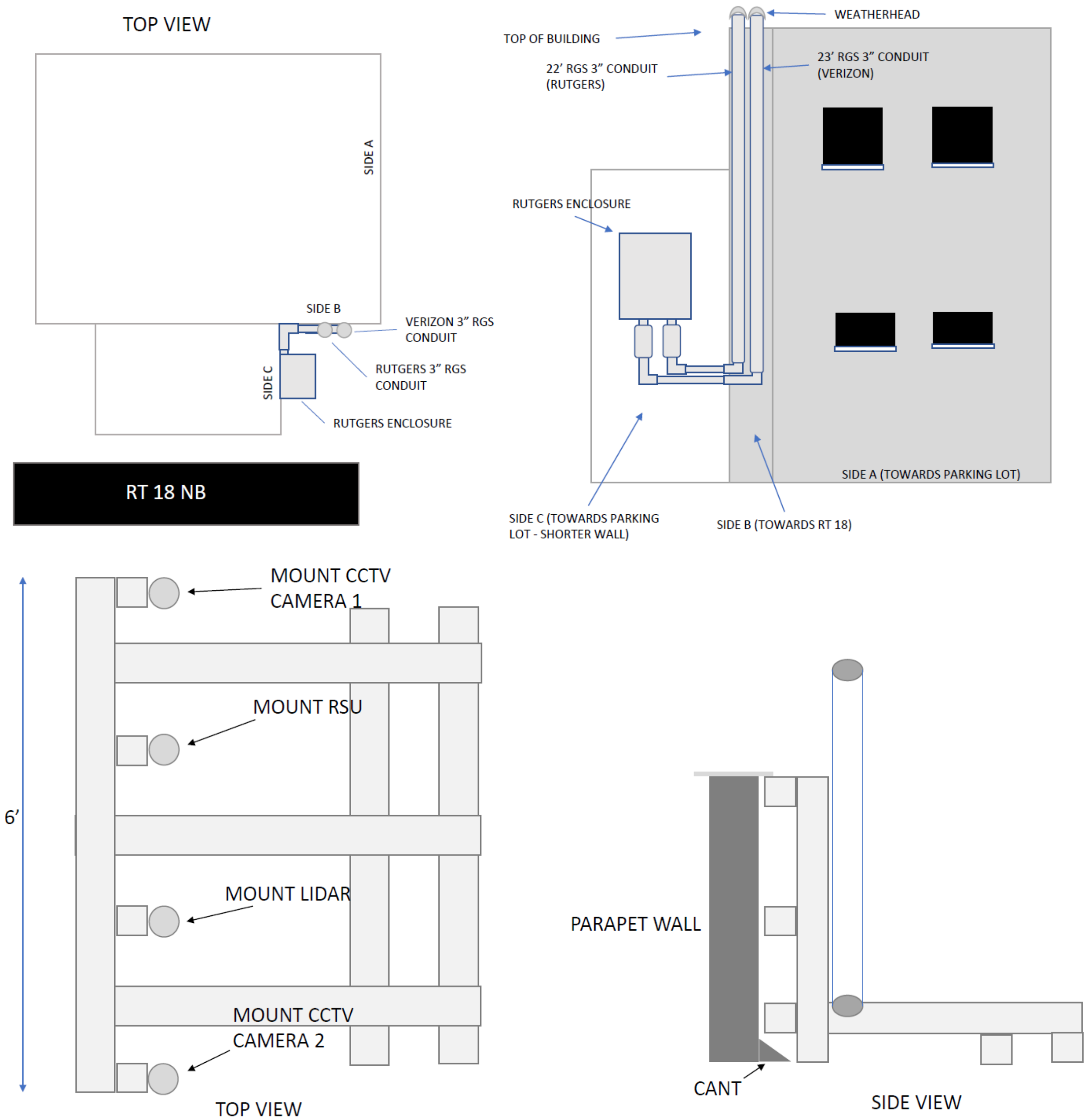


Figure 139. Instrumentation Drawing at Route 18 - Boyd Park “Boathouse”

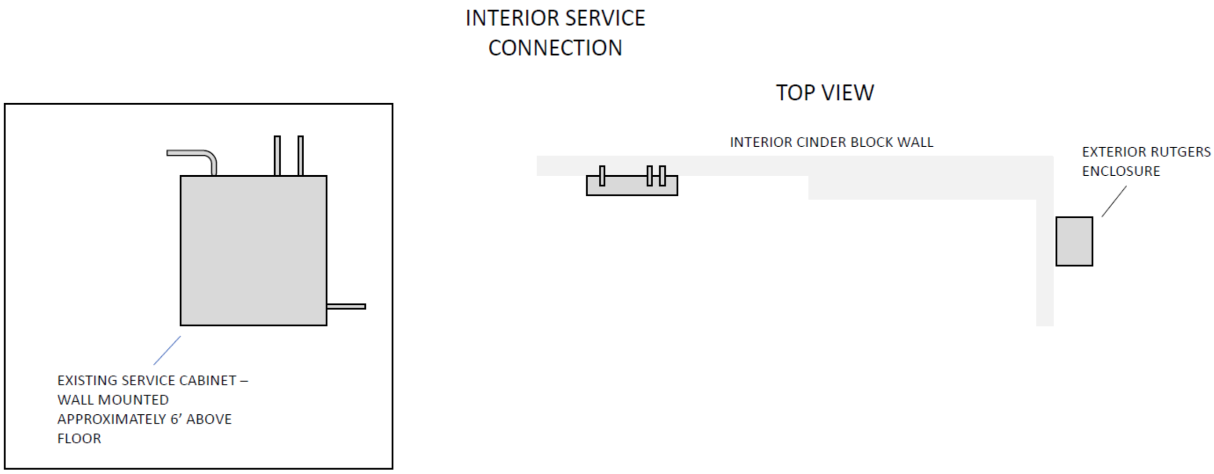


Figure 140. Interior Service Connection at Route 18 - Boyd Park “Boathouse”

Trailers

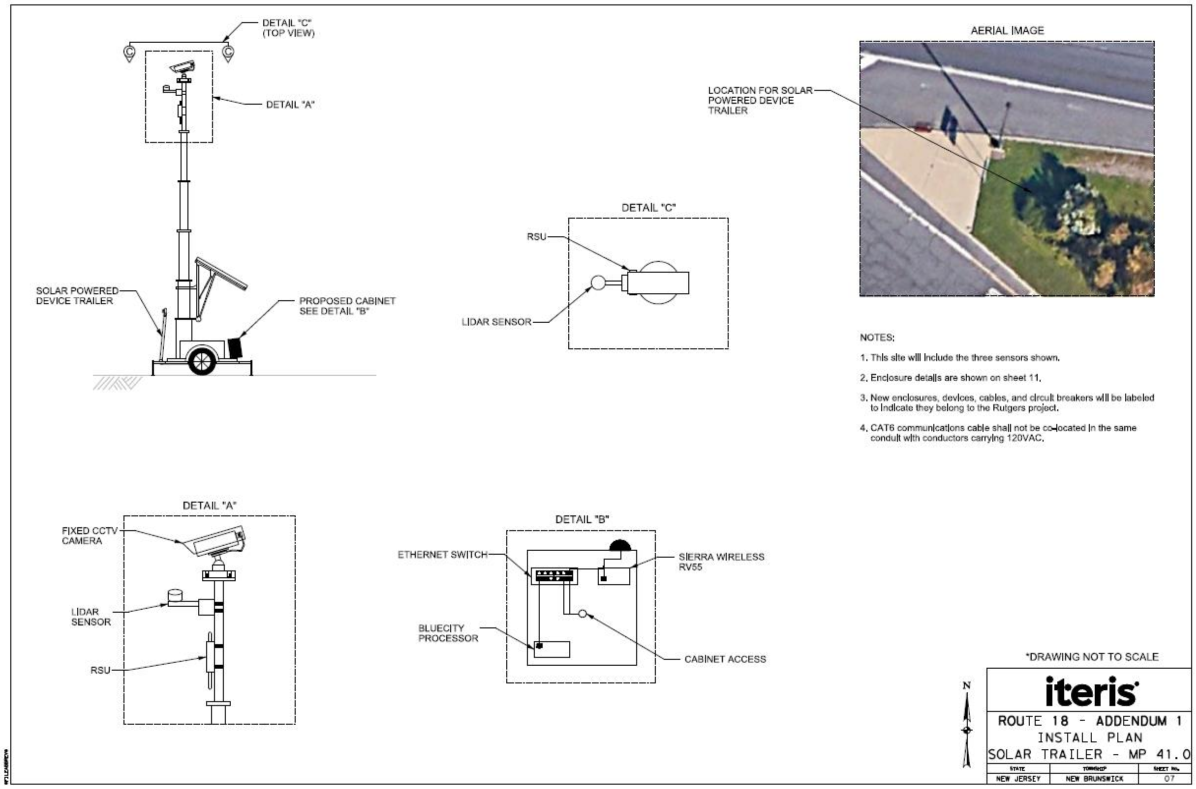


Figure 141. Instrumentation Drawing for Trailer Site