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Infrastructure Readiness for Electric, Connected and Automated Vehicles-Policies, Planning, and Pilot Testing on Infrastructure Readiness for Electrical, Connected, Automated, and Ridesharing Vehicles

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Connected and Autonomous Vehicles (CAVs) have gained huge expectations in improving safety, efficiency, and environmental friendliness for transportation. However, they are still at a relatively early stage of development, and little attention has been paid to the readiness of roadway infrastructure. The focus of this report will be on infrastructure readiness and will only focus on infrastructure issues and challenges for connected and electric vehicles. The report will deliver (I) A comprehensive review of the existing ITS system architecture and implementation in New Jersey; (II) Document the best practices in ITS system architecture practices in the country, which support transition to connected and electric vehicles; (III) Identify gaps in New Jersey compared to these best practices; (IV) Develop a preliminary system architecture for New Jersey that supports connected and electric vehicle technologies; and (V) Identify critical infrastructure barriers and challenges in New Jersey to make the transition. A preliminary plan will be developed for a test bed. This will include preliminary experimentation of collecting field data and the use of this data to validate the proposed architecture. Based on the conceptual plan, a test case for Adaptive Signal Control application and the simulation results are presented in the report.</td></tr>
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1. Problem statement

Connected and Autonomous Vehicles (CAVs) appear to have reached – or be near – the peak of inflated expectations but very little work has been done on the difficult questions relating to the readiness of the road infrastructure. Connectivity is most fundamental and common denominator to all stages of vehicle automation and can be achieved through a number of technologies (wireless, the Internet, local area networks, GPS, etc.). It is expected that with CAV and ridesharing there will be substantial increase in miles traveled, hence, Electric CAVs (ECAVs) will be the only clean path forward. In all, ECAVs and road infrastructure exist in a reciprocal relationship and how this relationship will develop in the future is uncertain. To plan forward with the mass adoption of ECAVs the gaps between the current state of field practices and the state of technology must be clearly understood. This report attempts to provide some insightful look into various aspects of requirements for roadway connectivity to support ECAV.

2. Goals and objectives

There are many dimensions to ECAV ready infrastructure, physically and virtually. This report focuses on system architecture for Intelligent Transportation (ITS), communication, data and some physical aspects of roadways (i.e., roadway markings and signages). The report reviews the advanced state of technology that can support ECAV and briefly analyzes the technology gaps of the existing practices. The report ends with a demonstration of a preliminary simulation study that was carried out in New Brunswick, New Jersey for connected roadways. Finally, the report provides a preliminary conceptual design of a testbed for the second phase of this project. The following issues are tackled:

1) What is state of the ITS system architecture for connected roadways and how is different than the current ITS practices? How does ITS system architecture apply to various applications in congestion management, safety or EV charging? This discussion will help stakeholders with various stages of planning and implementing connected roadway infrastructure.
2) What is state of the advanced communication technology for connected roadways? The idea is to set the stage to plan communication infrastructure to support roadway connectivity.
3) What are the data requirements? This is extremely important topic; data from connected vehicles and roadways will be crucial to develop applications which are ultimately the main reasons for connectivity. These applications will serve to significantly improve roadway congestion, safety and prepare the roadways for upcoming electric vehicles.
4) How to quantify the impact on connected infrastructure on congestion management and safety? We will demonstrate some preliminary results using a digital simulation model developed for New Brunswick, New Jersey.
5) A preliminary conceptual design for the connected infrastructure for a roadway segment in New Brunswick will be presented for the purpose of setting stage for the next phase of this project.

3. ITS system architecture

This section covers a review of ITS system architecture for connected vehicles, some of the existing gaps between the traditional and connected architectures and example project level architectures for mobility, safety and EV charging applications. These applications are intended to provide insight to connected roadways operations

3.1. Connected Roadways ITS System Architecture

Currently, there are two well-developed ITS system architectures that are specially designed for connected vehicles. These are: ITS Station Architecture, which is an internationally driven architecture for C-ITS, and Connected Vehicle Reference Implementation Architecture (CVRIA), which is a U.S. based [1]. Figure 1 shows these together with two legacy architectures, namely, The U.S. National ITS Architecture and the FRAME. These standards are for road users, roadway facilities and traffic managers to share information and better coordinate their actions by communicating with each other.

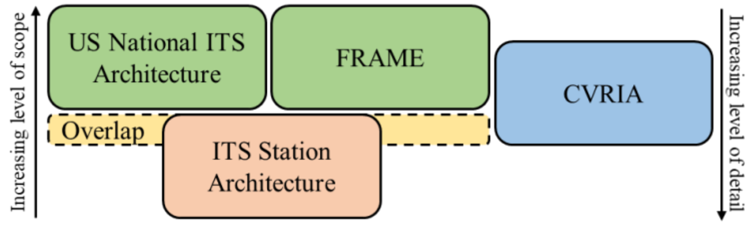


Figure 1 Difference between transportation architectures

The ITS Station Architecture provides a set of communication standards and series of requirements for different situations and actions. On the contrary, the CVRIA focuses more on physical objects, such as RSUs, CAVs, and the TMC. Therefore, the CVRIA is less detailed in functionality compared to ITS Station Architecture, but the CVRIA has a broader scope. The basic components of ITS Station Architecture are called ITS-Station Units, which are objects that contributes to C-ITS. Different from the ITS Station Architecture, the CVRIA uses physical objects to form applications, which are combinations of systems and software that provide transportation benefit. The CVRIA also considers supporting services and facilitating applications. There is also an overlap between the two architectures - The CVRIA defines the protocols necessary to realize a given application, which can be captured in the ITS Station Architecture. However, some standards (such as message set) referenced in the CVRIA cannot be found in the ITS Station Architecture [2].

ITS Station Architecture includes several layers. The top applications layer is designed to support multiple classes of ITS applications that rely on the communication services and vehicle operations. Based on the roadway inquiries to the system, the applications are initially grouped into “Road Safety”, “Traffic Efficiency”, and “Other Applications” [3]. The next layer of the ITS Station Architecture contains all blocks used to complete the communications. It provides the information standards for common V2V and V2I application scenarios. It also defines the communication security, connectivity, data exchange, and management functionality that implement transportation services. Finally, the security layer is in charge of authentication, authorization and profile management [4]. It applies firewall and hardware security modules to protect data collection, transmission and storage.

CVRIA “identifies the people and entities that have an interest in C-ITS (stakeholders), frames the concerns those stakeholders have as a series of questions, and then addresses those questions in series of views”. These views are then broken down to multiple applications, and each application is modelled in graphical language to facilitate stakeholder use [5]. CVRIA also defines a common framework for the implementation of connected vehicle functions and interfaces that is consistent with the National ITS architecture. It presents the connected vehicle environment’s functionality, and the information flows that enable applications and the physical devices to implement them. The applications can be classified into four types, which are “Environmental”, “Mobility”, “Safety”, and “Support”. Table 1 shows some examples of the applications in the CVRIA [6].

In this report, we will take the Queue Warning application as an application for demonstration as shown in Appendix Figure A1. The data links marked by green lines already exist, but the red ones are currently unavailable. The diagram formulates the information flows between CAVs, RSUs, and TMC to utilize connected vehicle technologies, including V2I and V2V communications. It enables connected vehicles within the queue event to automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to nearby upstream vehicles and to infrastructure-based central entities (such as the TMC) [7]. The infrastructure would then broadcast queue warnings to other vehicles to minimize or prevent rear-end or other secondary collisions. A vehicle’s OBE can retrieve queue status form its own Databus and receive other vehicles’ location and motion information from remote vehicle OBEs. It can also get driver inputs and warnings from roadside equipment. The Roadway and Roadside equipment communicate with Vehicle OBE and receive environmental sensor data. They report traffic data to the TMC and alert drivers. With data from Roadside equipment, TMC applies command and control to the ITS Roadway Equipment. It will also let other TMCs and TIC be aware of the existing congestion.

Table 1 Example of applications in the CVRIA

Type	**Group**	**Application Name**
Environmental	Sustainable travel	Dynamic eco-routing Eco-traffic signal timing Eco-smart parking Roadside lighting
	Road weather	Road weather motorist alert and warning Variable speed limits for weather-response traffic management
Mobility	E- payment	Electronic toll collection
	Public safety	Advanced automatic crash notification relay Incident scene work zone alerts
	Traffic network	Queue warning Intelligent traffic signal system Emergency vehicle pre-emption
Safety	Traffic signals	Stop sign gap assist
	V2I safety V2V safety	Reduced speed zone warnings Slow vehicle warning
Support	Core services	Core authorization

Figure 2 illustrates the ITS Station Architecture deployment, which shows how the conceptual view is mapped onto a physical structure [8]. The figure shows how vehicles, RSUs, and the service infrastructure are connected. The ITS Station Architecture focuses more on the standardized communication requirements, but less on physical information flows. Therefore, the ITS Station Architecture is less intuitive than CVRIA, but the two architectures complement each other. For instance, the physical objects in CVRIA could be implemented as an ITS-Station unit. Also, any ITS-Station Unit could be easily captured in CVRIA. The ITS Station Architecture provides a detailed logical framework for implementation, while CVRIA focuses on the realization of benefits through analysis of application concepts [1]. These two architectures can guide local transportation agencies to build their own standards for CAVs or update their existing ITS Architectures.

C-ITS architectures are specially designed to be adopted by organizations or transportation agencies to set up local C-ITS standards [8]. The process in which the C-ITS architectures can be used contains a series of systematic steps as shown in Figure 3. The process starts with the collection of stakeholder requirements and continues until the communication specifications have been produced.

Enterprise viewpoint expresses the expectations of the stakeholders for the services that the final C-ITS will provide. For example, travelers who would use the system require travel information and route planning to optimize their trips. The User Needs process aims at providing a set of clear user requirements whose properties are testable. The Function Viewpoint shows the functionality that is required to fulfil the users' needs. Function Viewpoints also illustrate how the functionality of the C-ITS communicate with outside entities. The Physical Viewpoint involves the allocation of functions and data to system components. The Communication Viewpoint clarifies which Function Data Flows lie within a component or pass between different sub-systems. The deployment plan, cost/ Benefit Analysis, Organization Issues, and Risk Analysis support detailed C-ITS design.

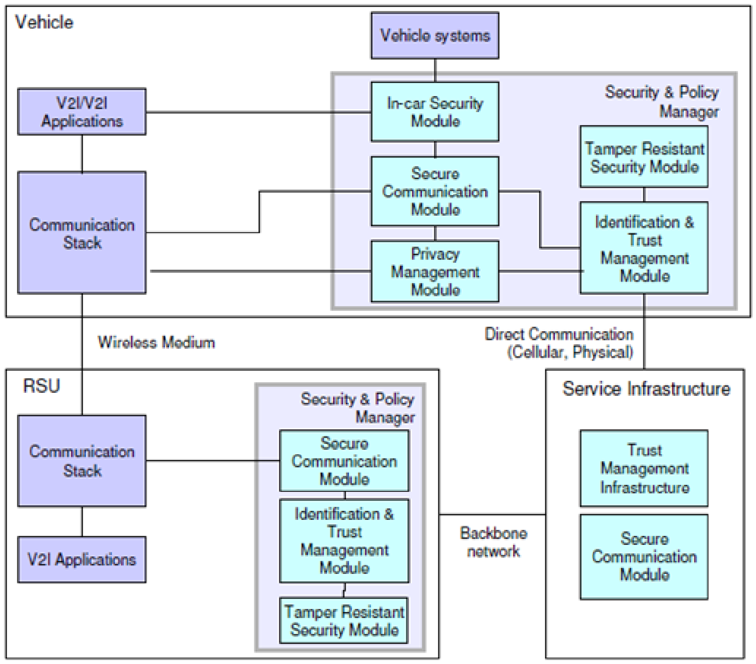


Figure 2 ITS Station Architecture deployment

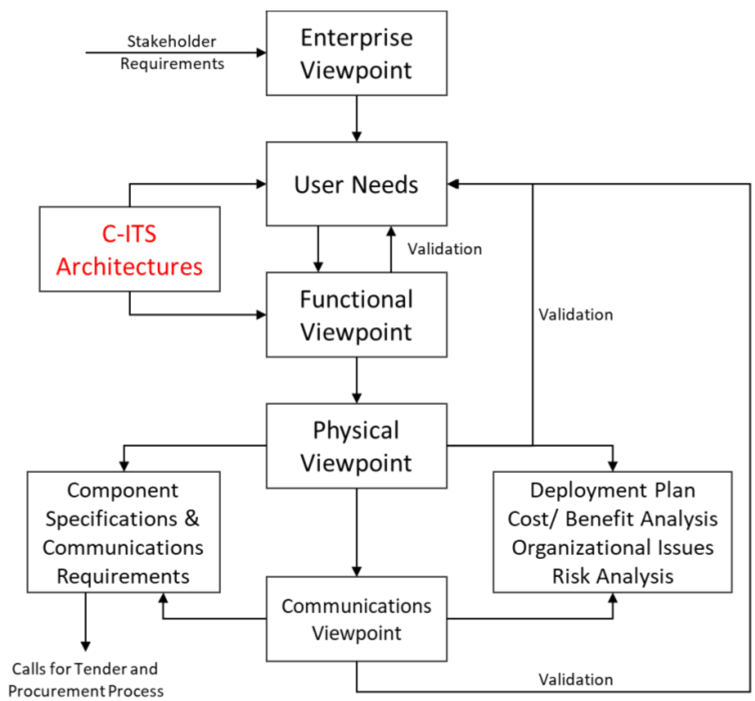


Figure 3 The process of C-ITS development

FRAME and the U.S. National ITS Architecture were developed to guide the development of regional architectures [9]. Figure A2 in the appendix shows the high-level physical architecture, where Travelers, vehicles, field, and centers are connected by fixed ways of communications. The information exchange is insufficient to support CAVs because vehicles cannot directly share information with roadway infrastructure, and hence useful data that support traffic control and decision-making might be wasted. The regular cellular network mentioned in the architecture is also unable to support the large volume of traffic data nowadays [10].

3.2. Project level Architecture

The comprehensive physical architecture shown in Appendix Figure A3 illustrates the high-level planning for an example connectivity project. The architecture includes all the physical objects that take effect in all different kinds of applications and illustrates how they are connected with each other. The architecture also describes the domain, the priority and the security level for the information flows. For example, the information flow between Smart Mobility Roadside Equipment and Vehicle OBE requires real time information exchange using short range wireless communication. Also, it needs to be encrypted to protect privacy and for security reasons. Therefore, the link is marked in red and noted as "(1-2A-C) Short Range Wireless". Appendix Figure A4 describes the functionality of each physical object in Figure A3. Each physical object needs to fulfill these functions in order to support the whole system. For example, in order to get the system working, Smart Mobility detectors are designed to take charge of traffic speed monitoring and roadway basic surveillance. Next, we will discuss some project level applications for connected roadways. We like to stress the fact that these are sample conceptual designs intended to familiarize the stakeholders how technology can be implemented.

3.3. Applications

3.3.1. Adaptive Signal Control

Adaptive signal control application deals with the central control and monitoring equipment, communication links, and the signal control equipment that support traffic control at signalized intersections. [11] Adaptive signal control technology can adjust timing and sequence of red, yellow and green lights to accommodate changing traffic patterns and ease traffic congestion. Appendix A5 defines the application architecture for adaptive signal control. Figure 4 illustrates the logic flow of the architecture. The main functional steps are:

1) Smart Mobility Roadside Equipment detect real-time traffic situation
2) Dynamic 3D map is reconstructed in Smart Mobility Living Lab
3) Adaptive signal control strategy is calculated in the LAB
4) New strategy suggestion is sent to NJDOT Traffic Management Center
5) The strategy is applied to roadside equipment when approved
6) Vehicle OBE will receive new traffic signal instruction
7) Drivers and pedestrians are informed with the traffic light changes

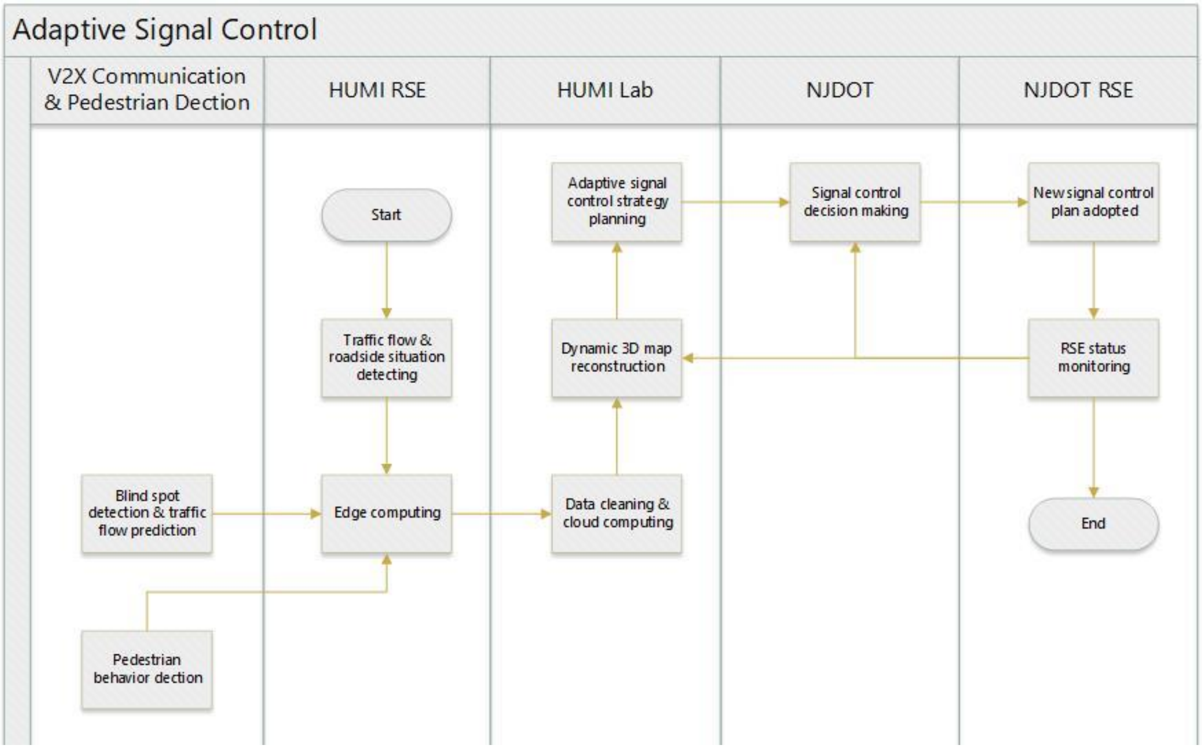


Figure 4 Logic flow of Adaptive Signal Control application

3.3.2. Electric Charging Station Management

The Electric Charging Station Management application provides an exchange of information between the electric vehicle and charging station to manage the charging operation. The agency or company operating the charging station can use vehicle information (e.g., operational status of the electrical system, how many amps can the vehicle handle, and % charge complete) to determine that charging is properly applied and estimate the time to completion. [12] The application architecture for Electric Charging Management can be found in Appendix A6. Figure 5 defines the steps of the management process.

1) Driver/vehicle OBE sends vehicle charging request.
2) Transportation information center provides available charging station location to the vehicle.
3) Vehicle arrives at the charging station and provide vehicle charging profile and payment information to the roadside equipment. Roadside equipment uploads vehicle payment information to the payment administration center.
4) Roadside equipment provides vehicle charging profile to the electric charging station and updates current charging status of the vehicle.
5) Roadside equipment keeps monitoring the vehicle charging status. Once the process has finished, the equipment updates all the files and uploads them to the transportation information center.

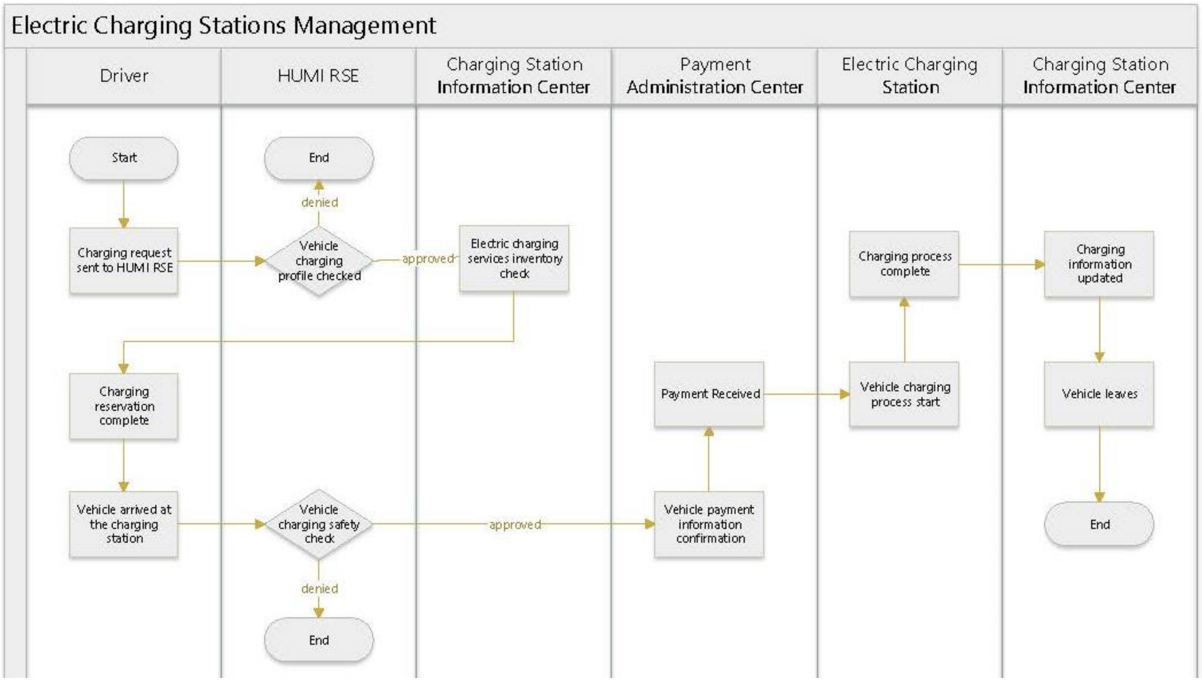


Figure 5 Logic flow of Electric Charging Management application

3.3.3. In-vehicle Signage

The In-vehicle Signage application delivers warnings, informational signs and signals by providing information directly to drivers through in-vehicle devices. The information provided would include static sign information (e.g., stop, curve warning, bus stops, service signs, and directional signs) and dynamic information (e.g., work zones, around incidents, current signal states). [13] Appendix A7 shows the application architecture for In-vehicle signage application. The logic flow diagram is shown in Figure 6.

1) Smart Mobility detectors captures traffic images and upload them to Smart Mobility Living Lab through Smart Mobility roadside equipment. The roadside equipment will also collect facility information data from roadside buildings and provide them to vehicle OBEs.
2) Smart Mobility Living Lab cleans the traffic data and uses them to reconstruct the real-time 3D map and transmit them to NJDOT Traffic Management Center.
3) TMC makes traffic control decisions and disseminate them through legacy dynamic message signs and send them to vehicle OBEs through Smart Mobility roadside equipment.
4) Also, vehicle OBEs will get information from remote vehicle OBEs directly.

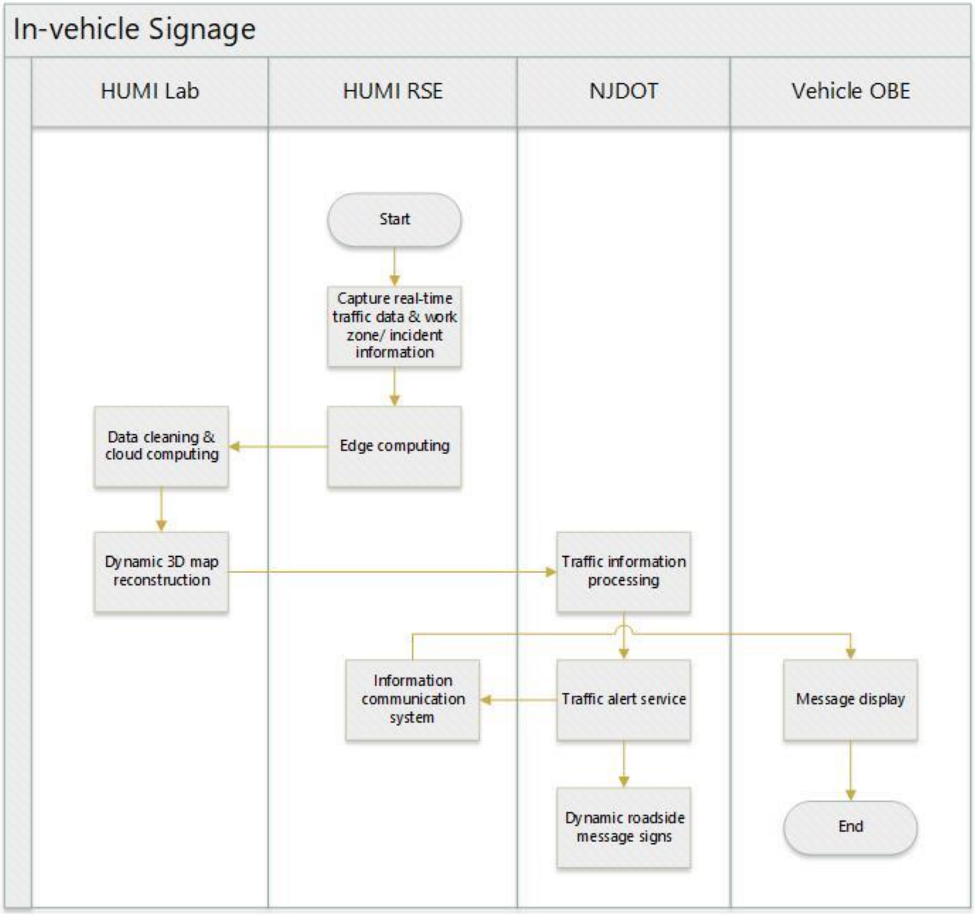


Figure 6 Logic flow of In-vehicle Signage application

3.3.4. Reduced speed zone warning

The reduced speed zone warning provides connected vehicles that are approaching a reduced speed zone with information on the zone's posted speed limit and/or if the configuration of the roadway is altered (e.g., lane closures, lane shifts). [14] Reduced speed zones include construction/ work zones, school zones, pedestrian crossing areas, and incorporated zones. The architecture is shown in Appendix A8, and the logic flow is given in Figure 7.

1) Smart Mobility detectors find emergent traffic conditions and send the warning information to Smart Mobility roadside equipment. It also informs NJDOT Traffic management center about the situation.
2) Smart Mobility Roadside equipment directly send reducing speed notification and lane closure information to vehicle OBEs.
3) The TMC will communicate with Smart Mobility roadside equipment to manually adjust the notification message and update dynamic message signs.
4) Vehicle OBEs will also get notifications from remote vehicle OBEs.

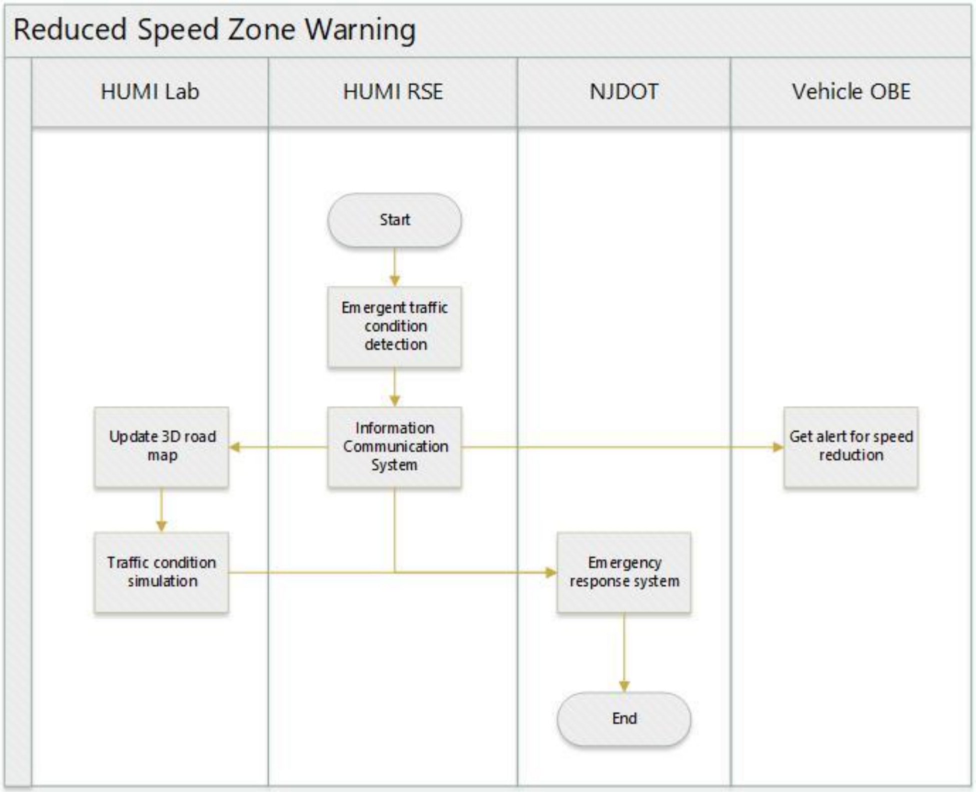


Figure 7 Logic flow of Reduced Speed Zone Warning application

3.3.5. 3D Map Management

Smart Mobility Living Lab is going to capture geographic map data and use real-time traffic data to reconstruct dynamic 3D maps for the testbed area. [15] The concept is bought up by Digital Twin, which refers to a digital replica of potential and actual physical assets physical twin. The application is used to optimize the transportation operations and management processes. The application architecture is given in Appendix A9. The logic flow is described in Figure 8.

1) Smart Mobility Living Lab gives Smart Mobility detectors commands to scan the environment.
2) Fixed location scanning results are uploaded to Smart Mobility Living Lab. Environment sensor data are transmitted to Smart Mobility roadside equipment for pre-processing. Vehicle OBEs will provide vehicle location and motion data to Smart Mobility roadside equipment and Smart Mobility Living Lab.
3) Smart Mobility Living lab receives traffic data and reconstruct or update 3D map.
4) The map will be provided to NJDOT Information system and TMC.
5) Updated map will also be provided to vehicle OBEs.

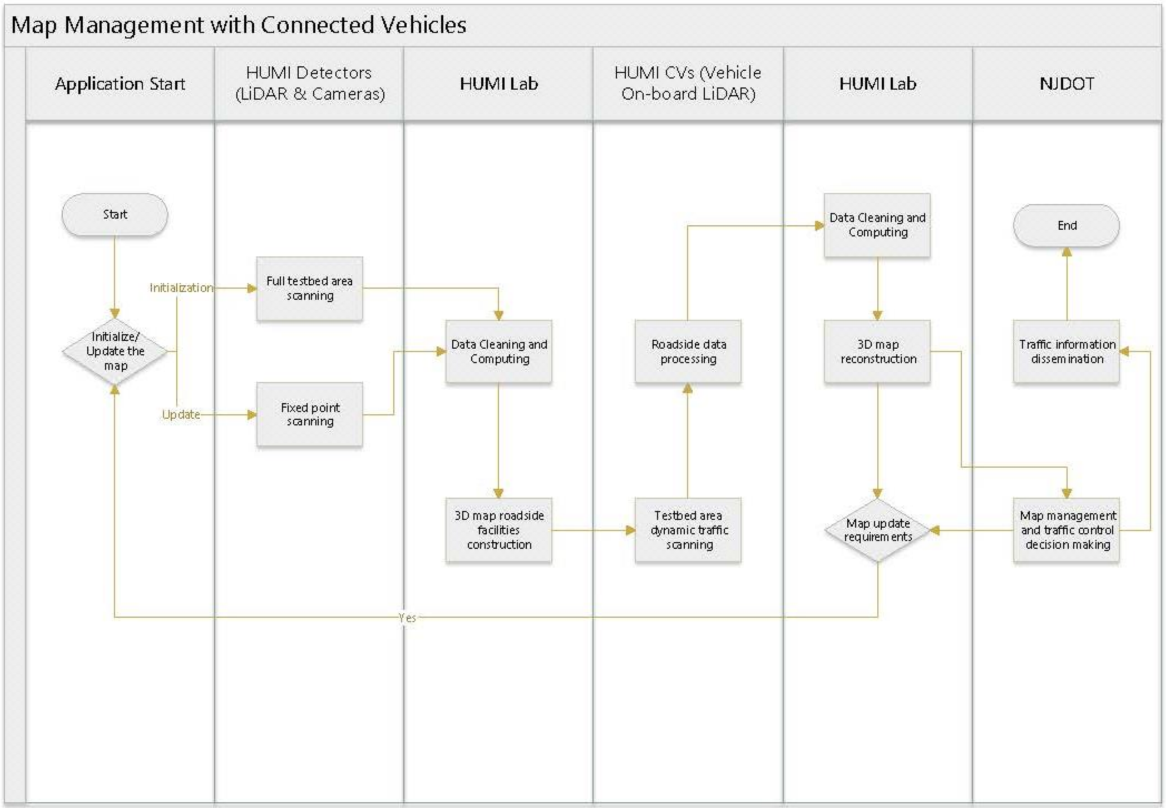


Figure 8 Logic flow of 3D Map Management application

4. Communication

Table 2 presents pros and cons of cutting edge technologies, namely, Direct Short Range Communication (DSRC), which is based on IEEE 802.11p, millimeter wave (mmWave), and cellular V2X (C-V2X), including both 4G LTE and 5G. DSRC is the incumbent technology and is able to address most of the V2X use cases, but its application is limited in some cases where long communication range and ultra-low latency is required, such as autonomous driving with high degree of automation. mmWave is attractive for its high data throughput, but it is only suitable for short range and point-to-point line of sight (LOS) communication [16]. 5G V2X is expected to outperform most of the current cutting edge technologies in almost all use cases sue to its ultra-low latency, ultra-high bandwidth, and high reliability.

Table 2 Pros and cons of current technologies

	Pros	Cons
DSRC	• Readiness IEEE 802.11p approved in 2010 [17] • Low latency, less than 5 ms [17]	• The system relies on RSUs, which are not currently deployed [18] • At the physical layer, several inefficiencies arise due to the asynchronous nature of the system, resulting in reduced performance such as range [1], ~300 meters [19] • There is currently no evolutionary path to allow for improvements in the

		DSRC physical/MAC layers with respect to range, robustness and reliability [18] ● Only V2V/V2I [17]
C-V2X (including LTE & 5G)	● Longer range and enhanced reliability, resulting in enhanced safety [19] ● More consistent performance under traffic congestions [19] ● Evolution path towards 5G for emerging applications [19] ● Better coexistence with other technologies [19] ● 5G specific: Ultra low latency (10 milliseconds latency end-to-end and 1 millisecond over-the-air) [19]; Reliability: targeting 99.999 percent for ultra-reliable transmissions [19]	a. Universal availability of V2X or other safety-related applications for vehicle owners that choose not to activate their mobile network [19] b. The current LTE standing is not capable of the low-latency and high-speed requirements for enhanced use applications [19], 4G at 50 ms [17] c. Cellular for V2X is still far out [20]
mmWave	● High data throughput [16]	d. Only suitable for mostly short range (a few hundred meters) and point-to-point Line of sight (LOS) communication [16]

Table 3 collects the performance requirement for advanced use cases of V2X. We mainly focused on four types of requirement, namely, end-to-end latency, reliability, data rate, and communication range. The requirement is further detailed under different degrees of automation of the vehicle. The description of the advanced use cases is listed below:

- Advanced driving with intent/trajectory sharing: Enables semi- or fully autonomous driving. Each vehicle and/or RSU shares data obtained from its local sensors with vehicles in proximity, thus allowing vehicles to coordinate their trajectories or maneuvers. In addition, each vehicle shares its driving intention with vehicles in proximity. The benefits of this use case group are safer traveling, collision avoidance and improved traffic efficiency [19].
- Extended sensors: Ability of vehicles to obtain information about objects around them located beyond the view of their own onboard sensors. Other nearby vehicles that can detect these objects process and broadcast them out to aid other nearby vehicles to build up a more complete picture of the road view. Overall, this provides vehicles in an area a more complete picture of the traffic environment. VIDEO involved here provide Non-Line-of-Sight (NLOS) awareness to other vehicles [19].
- Platooning: Platooning allows vehicles to form a tightly coordinated "train" with significantly reduced inter-vehicle distance, thus increasing road capacity and efficiency. It also improves fuel efficiency, reduces accident rate and enhances productivity by freeing up drivers to perform other tasks [19].
- Remote driving: Remote driving enables the remote control of a vehicle by a human operator or by a cloud-based application, via V2N communication. Examples of the application of remote driving: (1) Provide a backup solution for autonomous vehicles; (2) Provide remote driver services to youth, elderly and others who are not licensed or able to drive; (3) Enable fleet owners to remotely control their vehicles; (4) Enable cloud-driven public transportation and private shuttles [19].

- Cooperative awareness: warning and increase of environmental awareness (e.g., Emergency Vehicle Warning, emergency electronic brake light, etc.) [16].
- Cooperative sensing: exchange of sensor data (e.g., raw sensor data) and object information that increase vehicles environmental perception [16].
- Cooperative maneuver: includes use cases for the coordination of the trajectories among vehicles (e.g., lane change, platooning, and cooperative intersection control) [16].
- Vulnerable Road User (VRU): notification of pedestrians, cyclists, etc. [16].
- Traffic efficiency: update of routes and dynamic digital map update; for example, signal phase and timing (SPAT/MAP), green light optimal speed advisory (GLOSA), etc. [16].
- Tele-operated driving: enables operation of a vehicle by a remote driver [16].

Table 3 Advanced use cases and performance requirements

Use case	Degree of automation	End-to-end latency (msec)	Reliability (%)	Data rate	Communication range (meters)
Advanced driving [19] [21] [22] [23] ([21] includes both cooperative maneuver and perception)	Lower degree of automation	25 [21]	90 [21]		
	Higher degree of automation	10 [19] [21]	99.99 [19] [21]		
		3 – 100 [22]	90 – 99.999 [22]	10 – 50 Mbps [22]	360 – 500 [22]
		3 [23]	99.999 [23]	53 Mbps [23]	
Extended sensors [19] [21] [22] [23]	Lower degree of automation	100 [21]	99 [21]		1000 [21]
	Higher degree of automation	10 [19] [21]	95 [19] [21]	25 – 1000 Mbps [21]	
		3 – 100 [22]	90 – 99.999 [22]	10 – 1000 Mbps [22]	50 – 1000 [22]
		3 [23]	99.999 [23]	1000 Mbps [23]	
Cooperative awareness [16]		100-1000 [16]	90-95 [16]	5-96 Kbps [16]	<500 [16]
Cooperative sensing [16]		3-1000 [16]	>95 [16]	5-25000 Kbps [16]	<200 [16]
Vulnerable road user [16]		100-1000 [16]	95 [16]	5-10 Kbps [16]	<200 [16]
Platooning [19] [21] [22] [23] (Cooperative maneuver [16])	Lower degree of automation	25 [19] [21]	90 [19] [21]	10 Mbps [19]	
	Higher degree of automation	10 [19] [21]	99.99 [19] [21]		
		<3-100 [16]	>99 [16]	10-5000 Kbps [16]	<500 [16]
		10 – 500 [22]	90 – 99.99 [22]	50 – 65 Mbps [22]	80 – 350 [22]

		10 [23]	99.99 [23]	65 [23]	
Remote driving [19] [21] [22] [23] (Teleoperated driving [16])		5 [19] [21] [22] [23] 5 – 20 [16]	99.999 [19] [21] [22] [23] >99 [16]	1Mbps downlink and 25Mbps uplink [19] [21] [22] > 25 Mbps [16]	>500 [16]
Traffic efficiency [16] [24]		>1000 [16] < 100 [24]	<90 [16] 99.9 [24]	10-2000 Kbps [16]	>500 [16] 2000 [24]
Autonomous driving [24]		10 [24]	99.999 [24]		Urban-500, highway-2000 [24]
Collision warning [24]		10 – 100 [24]	99.9 – 99.999 [24]		Urban-500, highway-2000 [24]

Table 4 presents the applicability of each cutting edge technology to different types of use cases. Note that the applicability of 5G V2X to each use case is adapted from the applicability of the LTE-V2X based on pros and cons of the communication technology and the performance requirement of each use case. 5G-V2X outperforms other technologies in all use cases due to its ultra-low latency, ultra-high bandwidth, and high reliability.

- Cooperative awareness: warning and increase of environmental awareness (e.g., Emergency Vehicle Warning, emergency electronic brake light, etc.)
- Cooperative sensing: exchange of sensor data (e.g., raw sensor data) and object information that increase vehicles environmental perception.
- Cooperative maneuver: includes use cases for the coordination of the trajectories among vehicles (e.g., lane change, platooning, and cooperative intersection control).
- Vulnerable Road User (VRU): notification of pedestrians, cyclists, etc.
- Traffic efficiency: update of routes and dynamic digital map update; for example, signal phase and timing (SPAT/MAP), green light optimal speed advisory (GLOSA), etc.
- Teleoperated driving enables operation of a vehicle by a remote driver.

The NSF COSMOS advanced wireless testbed, which is being deployed in West Harlem, NYC, focuses on 5G and beyond technologies [10]. It targets the technology “sweet spot” of ultra-high bandwidth and ultra-low latency, a capability that will enable a broad new class of applications. Realization of such applications involves not only faster radio links, but also aspects such as spectrum use, networking, and edge computing. The testbed is designed to enable researchers to conduct accurate experiments over a broad range of new system designs, incorporating emerging techniques (such as mmWave, 100 Gbps+ optical backhaul, and software-defined networking). Edge cloud technology integrated into the COSMOS system, which is expected to support the low-latency applications, includes commodity CPU/GPU hardware. The testbed will incorporate sensors including cameras at intersections and within vehicles. The pilot phase (Apr. 2019) will include several cameras overlooking the intersection of Amsterdam Ave. and 120th St. as well as edge cloud and high speed (fiber) networking. Leveraging the ongoing COSMOS advanced wireless testbed in Harlem, NYC, the summarized advanced use cases can be realized and tested in a highly urbanized real-world area. In-depth research and practical tests of the advanced use cases can pave the way for the true realization of autonomous vehicle, smart city, etc.

Table 4 Applicability of different technologies to advanced use case types

Use case type	DSRC	mmWave	5G-V2X
Cooperative Awareness			
Emergency vehicle warning	✓ ✓	-	✓ ✓
Forward collision warning	✓ ✓	✓	✓ ✓
Cooperative Sensing			
See-through	✓	✓ ✓	✓ ✓
Sensor sharing	✓	✓	✓ ✓
Cooperative Maneuver			
Platooning	✓	✓	✓ ✓
High density platooning	-	-	✓
Cooperative adaptive cruise control	✓	-	✓ ✓
Cooperative intersection control	✓	-	✓ ✓
Vulnerable Road User	✓	-	✓ ✓
Traffic Efficiency	✓	-	✓ ✓
Tele-operated Driving	-	-	✓ ✓

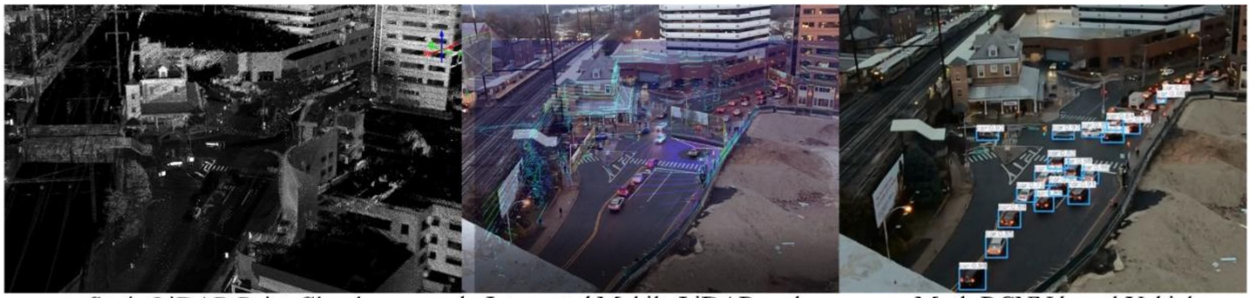
Note: "✓ ✓" suitable technology to support the use case and requirements under all circumstances with no (or with minor) configuration; "✓" suitable technology to support the use case and performance requirements under specific conditions (e.g. low congestion level); "-" not suitable technology because the specific use case or its performance requirements are not supported.

Applicability of DSRC and mm Wave to each use case is taken from [16], and the applicability of 5G-V2x to each use case is inferred based on the applicability of LTE-V2X to each use case from [16].

5. Data Requirements

5.1. Availability

Currently, the biggest difficulty we have is the lack of data. The team will conduct the initial assessment of the existing data sources available for the city of New Brunswick. Such data sources may include existing traffic simulation models, TRANSCOM travel time and event data, traffic video data from State-, County-, and City-operated CCTV traffic cameras, 3D LiDAR data of the street environment and major transportation hubs previously collected by CAIT, planning data from NJTPA, and other DOT design and infrastructure documentation. The team will review and create a traffic data and model inventory for the city to address some of the prevailing mobility issues in New Brunswick. The followings are some detailed description of the mobility data to be collected.



a. Static LiDAR Point Cloud b. Integrated Mobile LiDAR and Computer Vision Data c. Mask-RCNN based Vehicle Type/Trajectory Analysis

Figure 9 Sample High-Resolution Datasets to be Collected from the Testing Ground

- ***Rooftop High-resolution Sensors:***

Equipping buildings with high-angle fixed-mounted traffic camera or radar sensors to collect high-resolution vehicle trajectories to support connected and automated vehicles, incident, congestion, smart parking, and other urban mobility services.
Instrumentations/Software: 1) Wired 4K Surveillance Cameras (Purchase);
Deployment Environments: 1) Light Pole/Building Roof; 2) Roadside/Median; 3)Roadside/Median; 4) Roadside/Median;

- ***Smart Intersection and Roadside Infrastructure:***

Equipping intersection, light poles and other roadside infrastructures with smart sensing, control, and communication technologies. The sensors include AV-grade LiDAR (e.g. 128 beams with high scanning frequency), Bluetooth/Wi-Fi beacon network, radars, etc.
Instrumentations/Software: 1) Wired 4K Surveillance Cameras (Purchase); 2) Bluetooth positioning beacons (Purchase); 3) LiDAR (Purchase); 4) Wireless Router (Purchase).
Deployment Environments: 1) Light Pole/Building Roof; 2) Roadside/Median; 3) On-Vehicle; 4) Signal Box

- ***Vehicle and Pedestrian Positioning***:

Regular SLAM (Simultaneous Localization And Mapping), DGPS (Differential Global Positioning Systems), and beacon triangulation. SLAM interface will match the dashcam view with the pre-collected infrastructure and street view data. A differential GPS base station will be deployed near the test site and in-vehicle application will receive the correction data from the DGPS station to increase the accuracy levels of the GPS data. The last positioning data can also be generated by triangulating beacon signals around the corridor and infrastructure.
Instrumentations/Software: 1) Differential GPS Base Station (Purchase); 2) Bluetooth positioning beacons (Purchase);
Deployment Environments: 1) Roadside/Median; 2) Roadside/Median;

- ***Traffic Operations Data:*** We will work with the City and NJDOT to retrieve the existing traffic, video, probe travel time, signal, and incident data used in traffic operations. To address the needs of data synchronization, all high-resolution video, beacons, sensors except for LiDAR, which already has GPS timestamps will be marked with GPS timestamps with PPS systems. For traffic operations data, an NIST-synchronized timestamp will be added.

Instrumentations/Software: 1) GPS Time synchronization units (Purchase); 3) GPS Time triggers (Purchase);
Deployment Environments: 1) Around camera; 3) Around camera

- ***Static LiDAR Data:*** Static point cloud data of the roadway, transportation facilities, exterior and interior of building infrastructure will be pre-collected with mobile and static LiDAR in which Co-PI

Dr. Gongs group specializes in. The 3D point cloud data will be processed to extract 3D feature points for positioning and infrastructure objects (e.g. signals and signs).

Instrumentations/Software: 1) LiDAR (Purchase)

Deployment Environments: 1) Roadside/Median

5.2. Feasibility

This project will provide a data portal (cloud-based) for collection and sharing of real-time as well as archived data for sharing with university researchers and private companies. This would enable testing of in-vehicle signing, automated adjustment of vehicle operations in response to signal and roadside operations data and testing of other automated vehicle features with corresponding data collection activities. This portal would include the development of partnerships for getting operational data from Rutgers DOTS transit services, NJ Transit, Uber and Lyft, which would expose researchers as well as operations staff to travel patterns under different Travel Demand Management and Mobility-as-a-Service strategies, including various integrated payment options. Data portal data can also be made available to third party product and service developers to provide further application development and delivery within the Smart Hub environment.

To achieve connectivity between the infrastructure and transportation management, the team needs to develop specific datasets for analysis of traffic flow data and demand providing analytics on travel trends, as well as collection of data from vehicles for both operational purposes (using V2X communications to support signal timing and transit priority services), as well as studies related to route and mode choice along with naturalistic driving / human factors considerations. Examples are provided below.

- Reliability and Operational Datasets: Using infrastructure data from roadside and intersection traffic sensors, along with basic safety message (BSM) data from vehicles as obtained using V2I communications, comparisons between sensor and vehicle data will be made in order to assess accuracy, timeliness, and ability to more clearly identify changes in corridor flow characteristics. Data can be used to determine various reliability performance measures related to speed, volume and travel time over a route segment, and how those measures are impacted by specific operational strategies that are implemented. Performance management tools utilizing cloud processing (such as Iteris iPeMS), should be off-the-shelf products and services that can easily be configured and expanded
- Next Generation Simulation (NGSIM) Datasets: Four 15-min vehicle trajectory datasets collected in the NGSIM project in 2002 have been used in thousands of academic papers in the development of traffic flow theory, simulation models, and connected and automated vehicle control technologies. Those models have contributed to the generational evolution of transportation evaluation methods and software and vehicle control models
- NDS (Naturalistic Driving Study) Datasets: Directly and indirectly impacted the how computer-vision technologies are used in Connected and Automated Vehicle technologies. The data collection methods not only inspired new traffic safety analysis methodologies and models but also inspired an entire industry that uses computer-vision technologies for ADAS and AVs resulting in multiple billion-dollar startup companies, such as MobilEye, ZooX, Aurora, DriveAI etc. and the acceleration of automated vehicle research and development.

There are different types of sensors needed in this project. The captured data from sensors may include license plate number or biometric characteristics of pedestrians. These privacy issues will be addressed by developing anonymization software that will remove license plate number and biometric characteristics of pedestrians.

6. Road maintenance

The success of ECAV mass deployment will hinge upon roadways with clear markings, connected signage, smart traffic controls, easily accessible charging stations, and many other infrastructures related upgrades and changes.

6.1. Factors impeding the recognition of road markings

European Automobile Manufacturers' Association defined the factors that would affect the recognition of road markings as three levels: (1) High factors: Road surface condition (wet, ice etc.), worn out markings, multiple confusing road markings, old road markings not completely obscured even if blacked out, (2) Medium Factor: Road gradient, road curvature, boundaries between multiple lanes, and (3) Low Factor: Lane width, visibility (e.g. fog) [25].

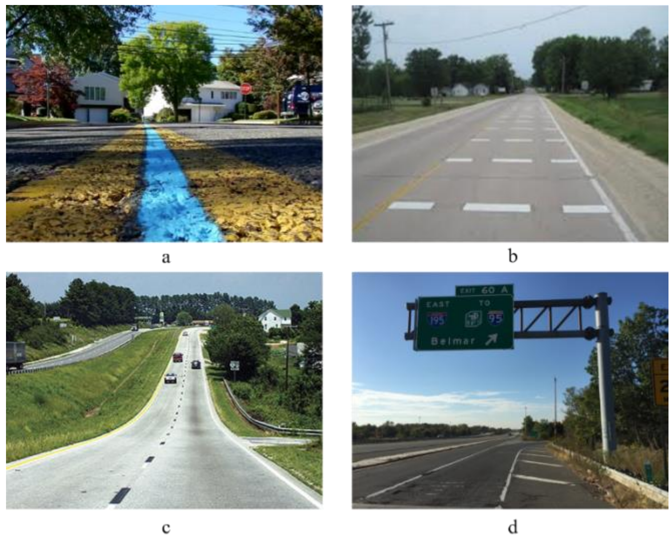


Figure 10 Different colors and shapes of road markings

After taking a survey of road markings in the U.S., we found server problems of the road markings that would make it hard for CAVs to operate properly. Figure 9 (a), (b), and (c) illustrate three kinds of road markings in the U.S. with different colors and dimensions. This would increase the difficulty for CAVs to recognize the lanes and take correct actions, which would bring safety problems. In Figure 4 (d), the road markings are nearly worn out at EXIT 60 A of I-195 in the U.S. The road markings need to be maintained so that it is clearly visible and not confusing [2].

Based on the experiment done by Texas A&M Transportation Institute, which is shown in Figure 10, retro-reflective markings should be used so that they are visible under all weather conditions [26].

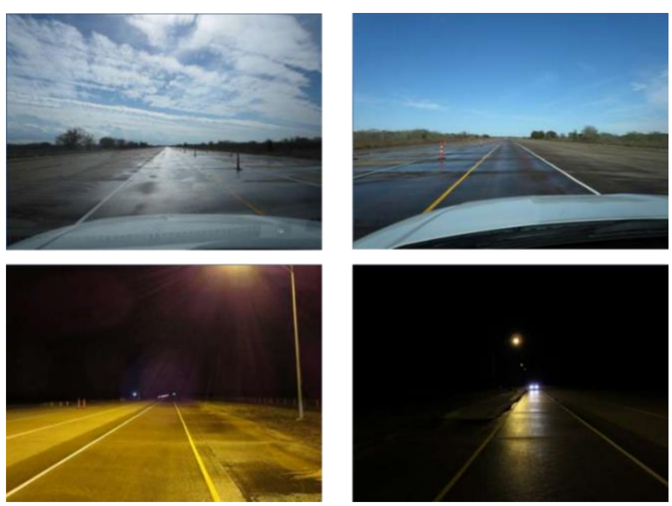


Figure 11 Road Markings under different time period and weather conditions

As a conclusion, following suggestions are provided in order to achieve improved performance of road markings: (1) road markings need to be a maintenance budget priority with all roads properly marked and maintained so they are clearly visible and not confusing, (2) use retro-reflective markings that are visible under all weather conditions, (3) harmonize across the U.S. the color and dimensions of lane and carriageway edge markings, and (4) install continuous lines to delineate the edge of the carriageway.

According to European Automobile Manufacturers' Association, factors that would affect the recognition of traffic signs can also be classified into three levels: (1) High Factor: Vandalism/graffiti, sign position, obscured signs (e.g. summer foliage), (2) Medium Factor: Confusion with traffic signs on immediately adjacent roads, signs wrongly positioned, sign angle to the driver, (3) Medium-low Factor: Confusion of multiple signs at the same location, ambient illumination [25]. The suggestions to improve the performance of traffic signs are as follows: (1) Standardize guidelines for the mounting positions, numbers of signs and, installation angle etc. (2) Systematic maintenance of signs that ensure they are clearly visible to all conditions. (3) Variable traffic signs must be developed so they can be read by cameras as well as the human eye. Figure 11 gives us an example of a new type of road signs that supports the environment detection of vehicles. The road signs are marked on the road so that they can be captured by the cameras embedded in the vehicles.

Figure 12 A new type of road signs being used in Dubai

7. Preliminary Testbed Design

Figure 13 shows the full system architecture of the proposed smart mobility testing ground. The full system consists of three major layers and two interfaces.

- **Sensor layer**: The integrated sensor layer includes high-resolution vehicle, pedestrian, and infrastructure data collected from roadside sensors to be deployed. The layer also integrated existing infrastructure point cloud data and transportation agency datasets such as travel time, signal, events, transit, planning, and other potential data sources.
- **Computing layer**: The computing layer includes the integrated edge computing directly connected to edge devices, fog computing nodes to coordinate the data and control signals with multiple edge nodes, center and cloud computing infrastructure for large-scale data processing.
- **Virtualization and modeling layer**: The virtualization/modeling layer will take the vehicle, pedestrian, infrastructure, and other data to build a digital sibling and system models of the testing ground. The digital sibling will allow simulated computer vision data to be collected by placing virtual cameras from any perspectives to support traffic operations, safety, mobility, and self-driving applications.
- **Application testing interface**: The application testing interface will be built by using an community mobility application. The application can potentially be used in the entire trip chain of travelers to provide door-to-door traveling assistance.

- **Data sharing interface**: The datasharing interface will be built to allow the sharing of the data collected from the testing ground to public, private, and academic sector users. Three different tiers will be provided including the free tier of typical traffic conditions, the on-demand tier to provide data playback for application testing, and the long-term tier for smart mobility company to request long-term datasets for analytics, model training and testing.

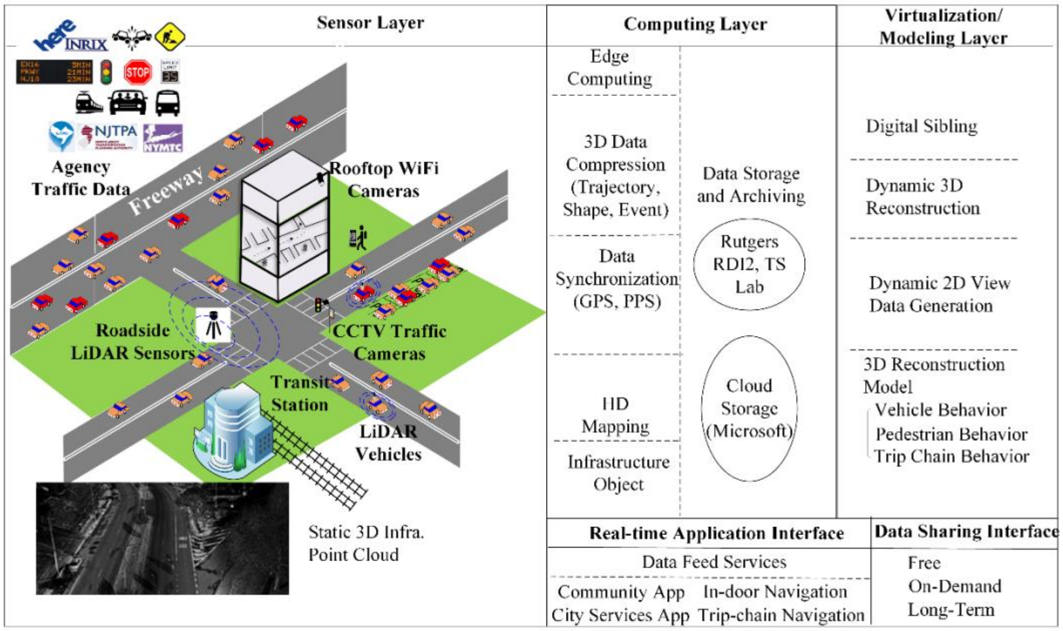


Figure 13 A new type of road signs being used in Dubai

As is shown in Figure 14, the testbed will be built on a 1-Mile Urban Arterial Road on Albany Street (State Route 27) in Downtown City of New Brunswick, NJ (Marked in red in the following graph, between Robert Wood Johnson Hospital and Memorial Parkway, in Parallel to NJ Transit Line around New Brunswick Station). The testbed area will also be extended to George Street and College Avenue, which are marked in orange.

The proposed testing ground will be equipped with multi-layer infrastructure-based sensor systems consists of 128-beam, 64-beam, 32-beam LiDAR sensors, synchronized high-resolution CCTV camera systems, other conventional traffic detectors, and Wi-Fi/Bluetooth beacons for parking and indoor activity sensing. Sensor and video data from the sensor network will be transmitted to roadside or cloud computing facilities through wired or wireless communication network. Community mobility service applications will be developed to allow the communication between vehicles and platform to enable the uploading of vehicle sensor data and the distribution of alert and traffic control signals to vehicles. Furthermore, for the first time, full high-resolution 3D point clouds and models will be established for the entire mobility chains from the highway to “door” including roadway infrastructure, roadside infrastructure and building exterior, and indoor facilities. Those datasets will be used as the high-resolution reference background for vehicle localization, traffic detection, and traffic congestion and event reconstructions and simulation.

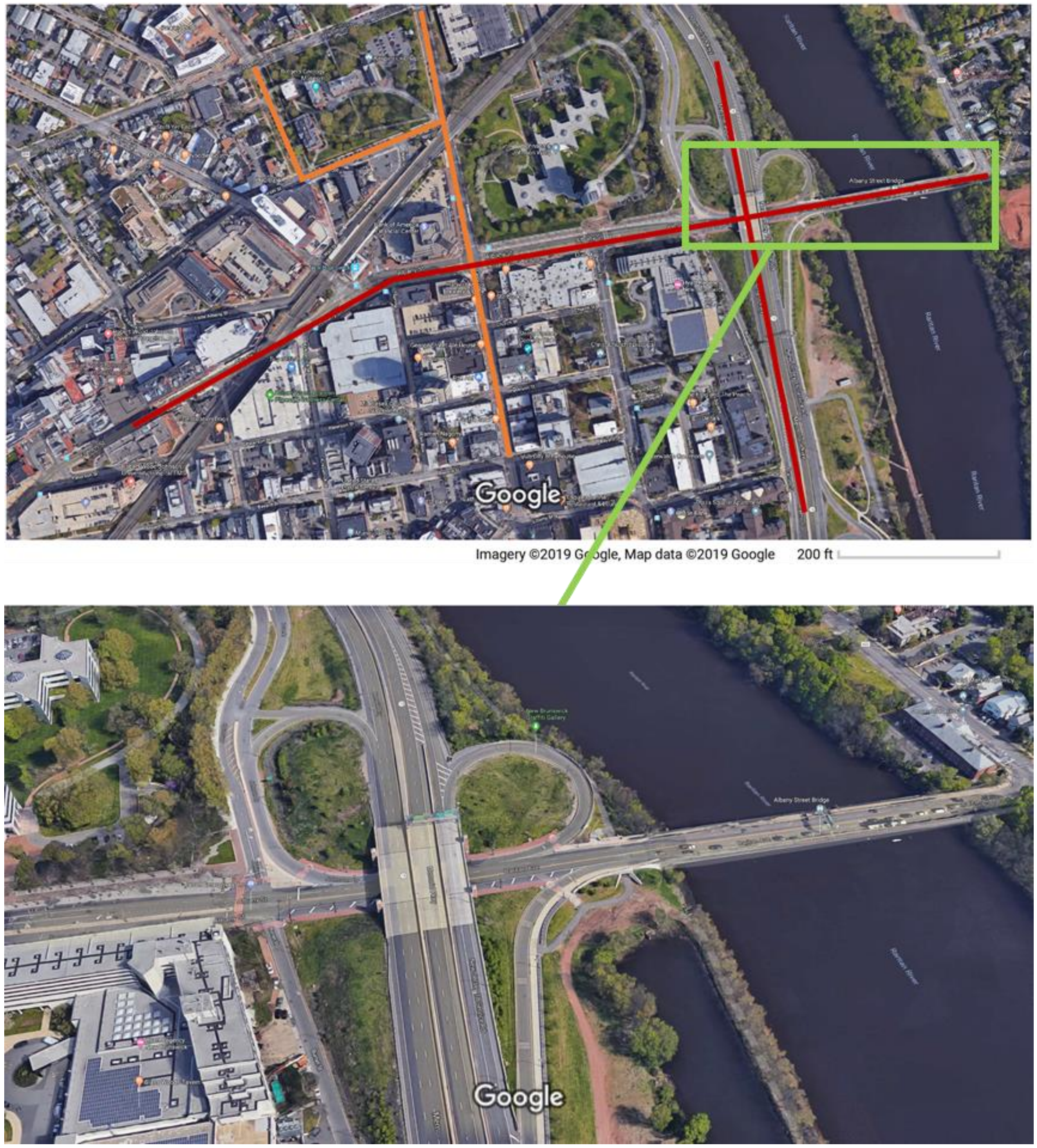


Figure 14 Scope of the case study

The implementation approach for unit installation is based on the team's experience working with DOTs in the installation of ITS and CV hardware at signalized intersections in urban settings and other environments (e.g., interstates, rural arterials, etc.). The process will include close coordination with NJDOT, City of New Brunswick, and Rutgers University staff to ensure safety and minimize disruptions to traffic operations. While not anticipated due to the nature of these installations, the team will also ensure that all proper permitting is addressed. All new electrical work will be coordinated with the appropriate jurisdiction; however, our installation approach utilizes Power Over Ethernet (PoE) solutions to simplify implementation and reduce costs. The team will work with NJDOT and the City regarding any planned improvements or roadwork and coordinate schedules as these types of activities may represent opportunities or potential conflicts for installation. See the conceptual deployment plan in the Figure 15. The team will prepare Maintenance of Traffic (MOT) plans for review and approval by NJDOT and the City.

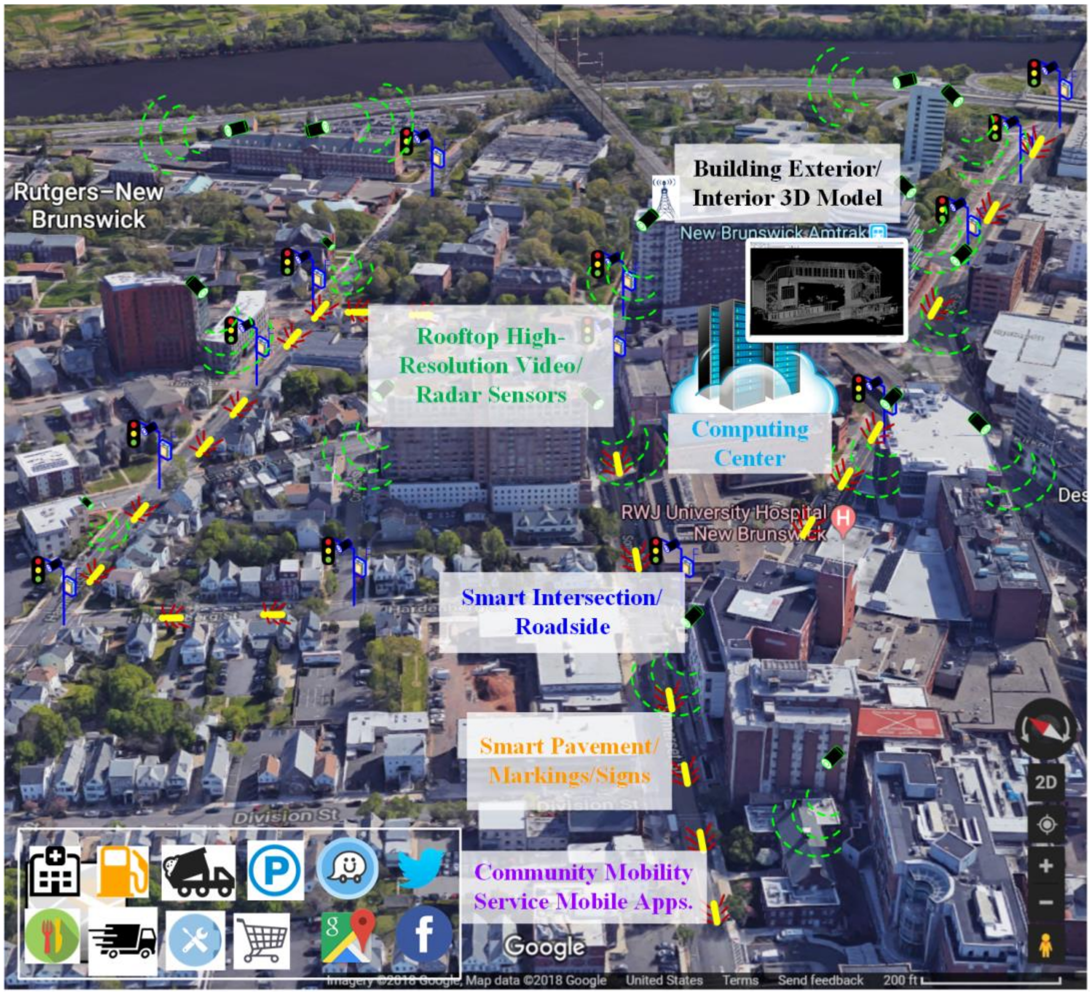


Figure 15 Hardware architecture

Table 5 summarized the list of required equipment for Queue Warning application (Appendix Figure A1). The required hardware can be classified into 4 parts:

1. Network connection includes wired or wireless network.
2. Surveillance 4K cameras used for computer vision-based vehicle detection to capture real-time traffic videos for traffic data analysis.
    a. Top of the street lights - The cameras placed on the top of the street lights can get an overview of the general traffic condition of the intersection.
    b. Roadside - Roadside cameras are used to cover some blind spots on the road, such as the roads under the freeway.
    c. In-Vehicle - Some CAVs are embedded with In-vehicle cameras. In-vehicle video will be transmitted to server through roadside Wi-Fi.
3. LiDAR system - 32-beam and 64-beam LiDAR sensors will be used at roadside for remote sensing of the traffic flow.
4. NJDOT roadside equipment and Smart Mobility roadside equipment includes Dynamic Message Signs and traveler information communications that are used to disseminate traffic information and guidance information to the drivers.

Table 5 Required equipment for Queue Warning application

	Item
Camera Systems	Wired 4K Surveillance Cameras: SDK Available
	360 Cameras Rylo
	GPS Time synchronization units, GPS Time triggers
LiDAR System	Velodyne LiDAR 32-Beam
	Velodyne LiDAR 64-Beam
Network	Wireless routers
	Local network switches
Solar Panels	Solar panel for edge units
Edge Computing	Local Server at the Intersections (GPUs)
Cloud Computing	300TB Cloud Storage

The LiDAR system and the camera system implemented in the intersection area keep capturing cloud point data and high-resolution video, and then transmit them to the local server for data pre-processing. The local server gathers the data collected by LiDAR and cameras, as well as GPS timestamps. After the edge computing is done, the raw data would be uploaded to the cloud server and be given to the Smart Mobility Lab. Data cleaning is been processed to clear the noise in the data set. Cloud point and video will be synthesized based on the GPS timestamps to visualize the dynamic 3D traffic situation. Smart Mobility Lab and the NJDOT TMC will monitor the real-time traffic situation of the intersection. When a queue is detected or predicted, Smart Mobility Lab will disseminate the information to CAV OBEs and the smartphone application. TMC will also inform the queue warning to legacy vehicles through roadside variable-message signs. Alternative routes will be suggested, and detour guidance will be delivered to the drivers who plans to enter the intersection. The above design will support many different application architectures.

8. Quantifying Impacts of Connected Roadways

The purpose of this study is to demonstrate how connected roadways (in particular, adaptive traffic signal control) can mitigate traffic congestion. A case study on Adaptive Signal Control application will be presented. The project level architecture will be used as baseline for communication and coordination between vehicles and traffic signals.

The case study for the Adaptive Signal Control application is structured at the intersection of Raritan Avenue (Albany Street Bridge), Albany Street, and Memorial Pike Way as is shown in the above figure. The traffic condition of the area is complicated because it is the joint of a freeway, ramps, bridge, as well as a main street. Based on the traffic data provided by INRIX, the average passing time (Figure 16) of this intersection on weekdays is about 18 seconds during non-peak hours. However, the average passing time increases dramatically between 7:30 AM and 9:00 AM, as well as 3:00 PM and 7:30 PM. It would take people more than twice as much as the average time to pass this road segment. Queue Warning Application can be introduced in this intersection to help people avoid the congestion and provide suggestions for alternative routes.

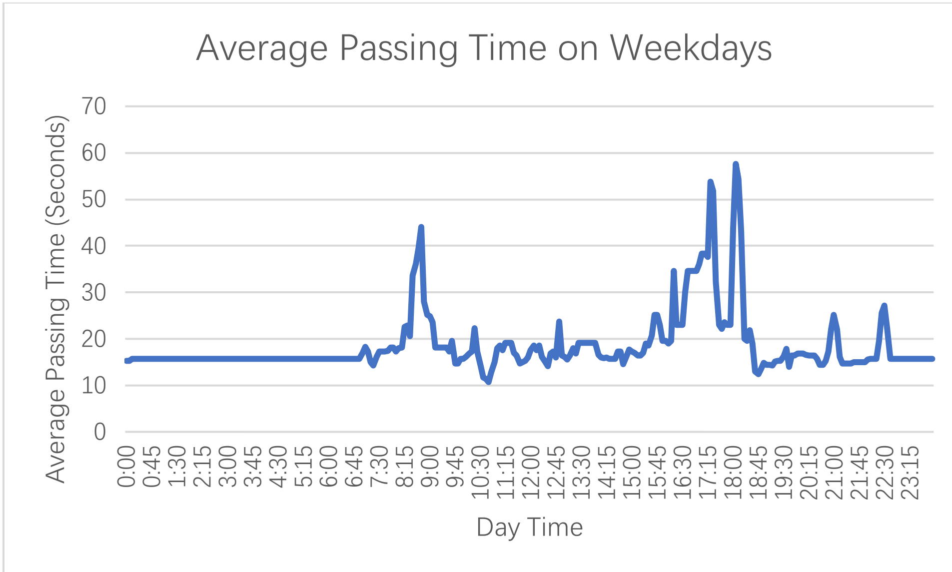


Figure 166 Average passing time on weekdays for the intersection

In order to make the simulation closer to real situation. We used hourly traffic volume provided by NJDOT. Also, we collect real time data at the intersections, including traffic volume, distribution of the numbers of cars in each lane, traffic light sequences, and traffic light timing.

a) Short term hourly traffic volume provided by NJDOT
Based on the traffic volume data provided by NJDOT, the rush hours during a day on Albany street is between 4:00 pm and 8:00 pm (Figure 17). However, the data is not precise enough. We can only get a brief concept of the total traffic situation. We cannot analyze real-time traffic flow and find out the traffic bottleneck. Also, the latest data we can get is from December 2018, which is out of date and cannot fully represent the current traffic condition.

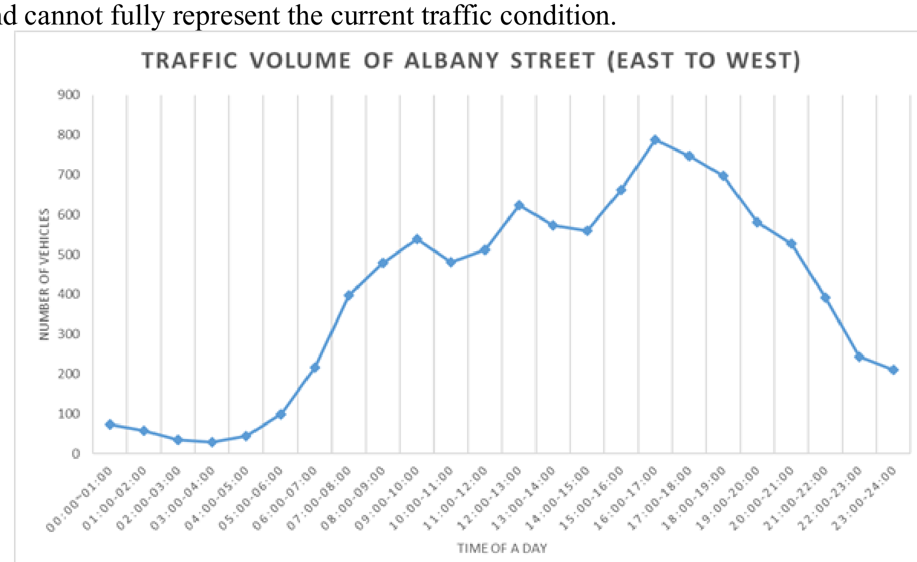


Figure 177 Average hourly traffic volume of Albany Street

b) Collected real time traffic volume and traffic distribution - In order to make the data more real, we collect real time traffic volume and traffic distribution at each intersection and fit the distribution of the provided traffic data. The traffic condition was captured by videos, and then we used computer vision to solve the raw data. We also manually calculate the distribution of the number of cars that take different directions at each intersection.

We used an economic-driven adaptive signal control (eATSC) policy for our Adaptive Signal Control application. The control strategy developed here uses some of the basic elements of Self-Organizing Traffic Lights (SOTL) algorithm and combines with the way interest rate and financial loans work in economics domain. In economy, interest rate defines the time value of money (loan) transacted between a borrower and a lender. It is an exogenous quantity, which is controlled by the market where the transaction takes place. In free market economies, a given interest rate is usually driven by the prime interest rate which is set by the government; and its value and variations are reflective of the current and future states of the local and global economies and major indices. The basic interest rate set at the government level trickles down differently to different parts of the economy depending on their own local conditions and global interactions.

We will use the same basic concepts in the formulation of our eATSC. Every time that a vehicle comes to stop at an intersection and waits for the green light, it engages in a virtual financial transaction with the intersection smart controller. Here, intersection controller is the debtor and vehicles waiting for traffic signal are the creditors. The time value of the initial virtual money compounded on a vehicle's waiting time is the payoff amount or the penalty that the intersection controller must pay to the stopped vehicle. The intersection control will want to minimize its total payoff amount over time. The prime interest rate used by the intersection is dictated by the roadway network and depends on how this intersection performs with respect to the overall network. The technical details of the model are not covered here for brevity reasons.

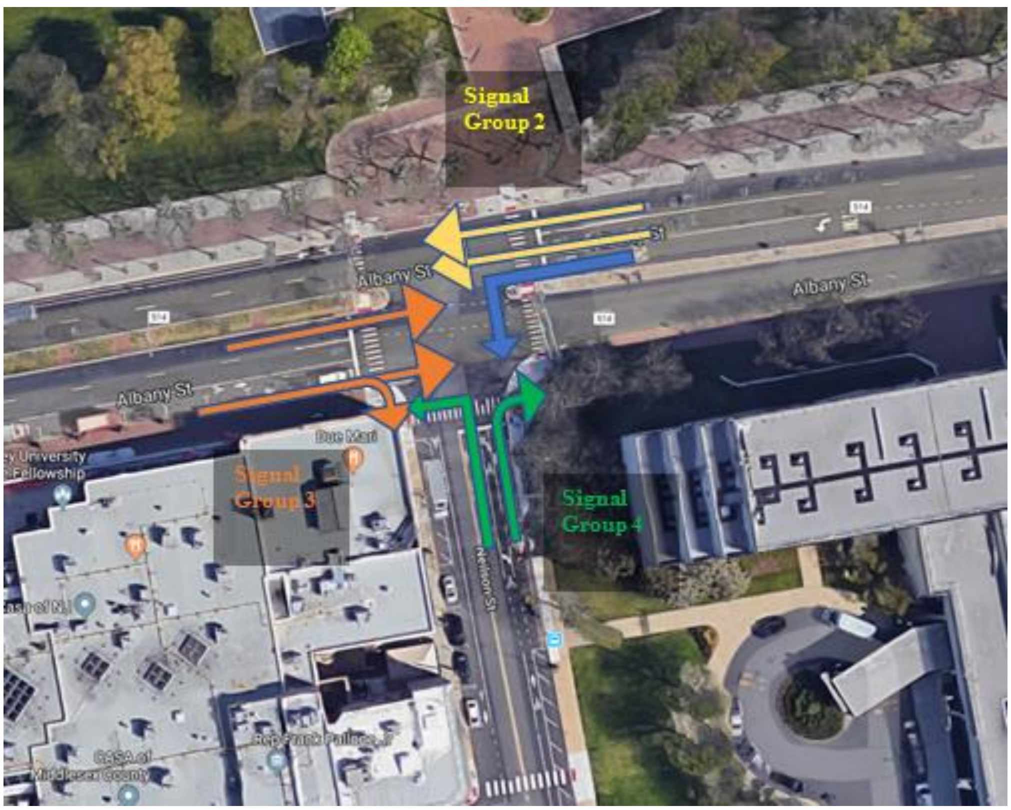


Figure 18 Grouping of directions at the intersection

In order to simply the problem, we divide the intersection into different signal groups. For example, Figure 18 shows us the intersection of Albany Street and Neilson Street. Four signal groups are marked in different colors and we made the following assumptions:

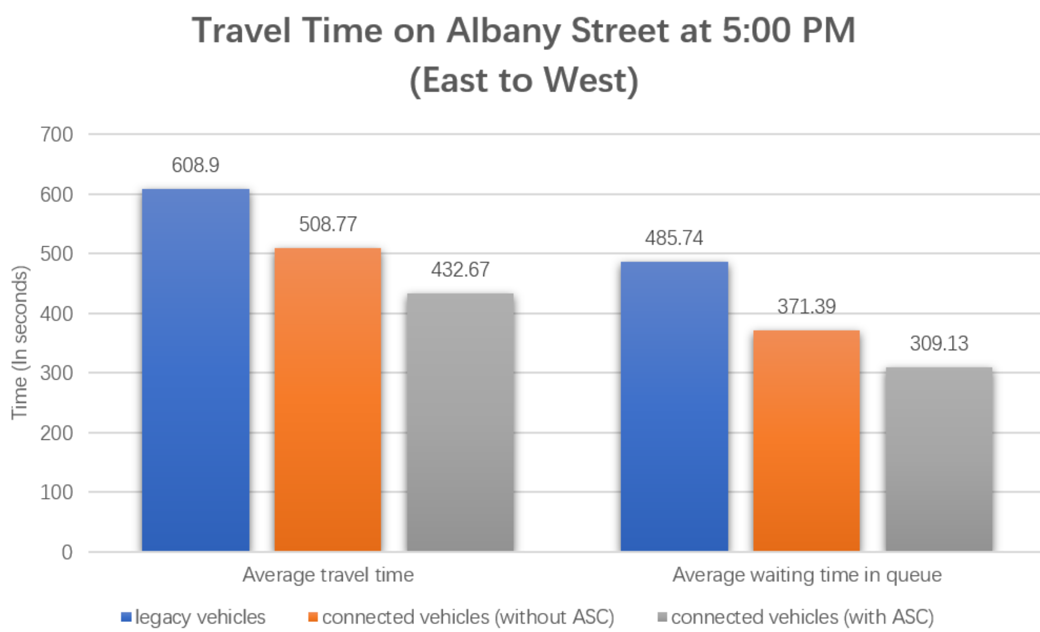
a) Signal group 2 and signal group 1 can be given green light signal together. Signal group 2 and signal group 3 can be given green light signal together.

b) Roadside LIDAR and cameras are able to capture the vehicles on the road and their driving behaviors.
c) The traffic light controllers can communicate with each other as well as the waiting vehicles at the intersection.

In our simulation, the following steps are applied for making traffic signal decisions:
a) Traffic signal decision is made every 15 seconds (for illustration purposes only).
b) The signal group with the maximum penalty will win the next green light cycle at the end of each decision period.
c) Each signal group cannot be given more than 4 consecutive green signal decisions.

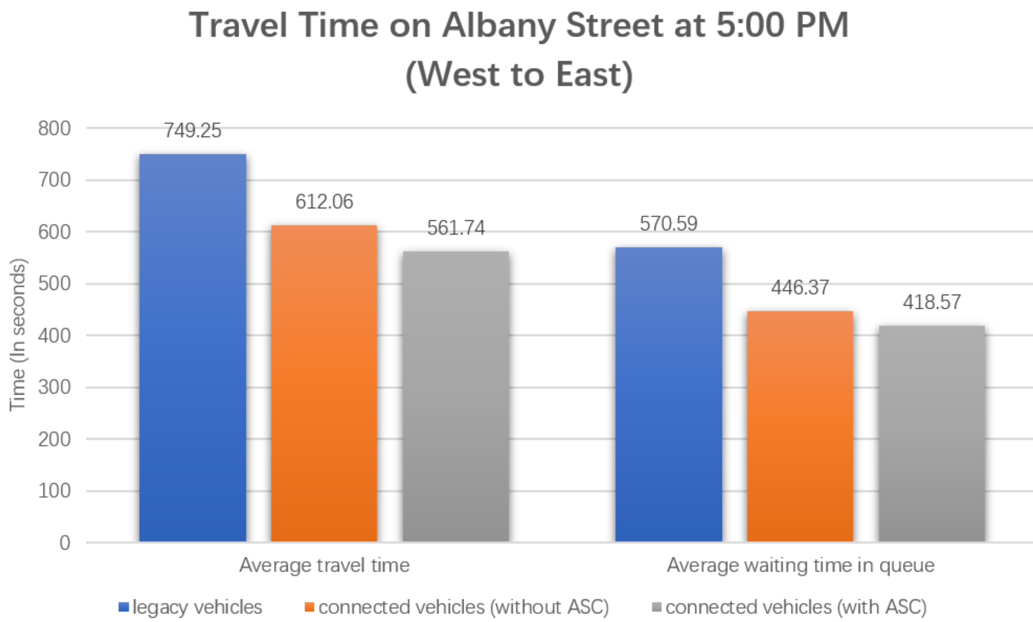
We designed three test cases in order to analyze the improvement made by using connected vehicles and applying Adaptive Signal Control algorithms. The three test cases are:
a) Legacy vehicles with current traffic light sequence and fixed durations
b) Connected vehicles with current traffic light sequence and fixed durations (without the support of roadside infrastructure)
c) Connected vehicles with the Adaptive Signal Control Application (with the support of roadside sensors, LIDAR and cameras)

We simulated the traffic conditions during rush hours on Albany Street and measured the average travel time along Albany Street under these three circumstances. And the results are shown as follows:



Improvement compared to legacy vehicles:		
	Average travel time	Average waiting time in queue
CVs without ASC	16.44%	23.54%
CVs with ASC	28.94%	36.36%

Figure 19 Comparison of road performance from East to West in terms of average travel time and waiting time in queue among legacy vehicles, connected vehicles (w/o ASC) and connected vehicles (with ASC)



Improvement compared to legacy vehicles:		
	Average travel time	Average waiting time in queue
CVs without ASC	18.31%	21.77%
CVs with ASC	25.03%	26.64%

Figure 20 Comparison of road performance from West to East in terms of average travel time and waiting time in queue among legacy vehicles, connected vehicles (w/o ASC) and connected vehicles (with ASC)

Figure 19 and Figure 20 shows us the average travel time and average waiting time in each test case. It is obvious that connected vehicles will reduce the traffic delays compared to legacy vehicles. After applying Adaptive Signal Control algorithm, the average travel time and average waiting time are further reduced.

9. Next phase recommendation

The next phase of this project will deploy the smart mobility testing ground in a combined state and local transportation network for the collection, processing, visualization, and application testing with the smart mobility sensor data. The proposed testbed will include the following key components.

1) Roadside sensors: LiDAR and computer vision sensors installed at the roadside infrastructure at or near the two intersections to collect real-time vehicle, pedestrian, and infrastructure data. LiDAR sensors will be mounted to the existing roadside infrastructure such as signal or light poles. Computer vision sensors consist of high-resolution video to be deployed on the top of buildings around the testbed sites.
2) Edge/Fog computing units: Edge/Fog computing units will be built to process the roadside sensor data in the field and transferring the processed data to the computing center at Rutgers Smart Mobility Lab to explore functionalities of next-generation traffic management centers (TMCs). If approved, the edge/fog computing units will also include the connectivity and data feed from the traffic signal controllers at the site.
3) Communication network: The communication architecture that realizes the two-way communication between sensing and edge computing units and the central computing units at the Rutgers Smart Mobility

Lab. This may include the combination of wired and wireless communication through cellular or University network infrastructure.

4) Cloud/Center Computing for 3D Data Processing and Modeling: The server or cloud based 3D data analytic platforms that will process, archive, and model the collected 3D LiDAR and Computer Vision data. The data will be denoised, anonymized, and mapped to the 3D space of the entire testbed. Object data such as vehicle, pedestrians, temporary road infrastructures (e.g. workzones), and infrastructure changes will be extracted and archived.
5) 3D Holistic-View Traffic Management Center (TMC): The 3D object data generated will be imported into 3D visualization and simulation models that will be displayed in a futuristic 360-view visualization theater for real-time inspection of traffic scenes from different viewing angles.
6) In-Vehicle Smart Mobility Service Applications: The in-vehicle test platform will be developed based on the research team's existing mobile applications. The research team has developed a naturalistic driving data collection mobile application and an user interface to receive adaptive traffic signal control guidance signals. The team will integrate both platforms and establish a cellular-based V2I (Vehicle-to-Infrastructure) and C2V (Center-to-Vehicle) smart mobility service application test platform.
7) Testing interfaces for mobility, safety, environment, and energy applications: The research team will build the prototype mobility, safety, environment, and energy application interfaces for testing different smart mobility solutions. The research team will design the workflow for both service/controller-end and user-end interfaces and will develop prototype interfaces for applications such as adaptive traffic signal control and intersection safety applications.

The actual deployment will take place in three stages.
Stage 1: On-Demand Platform and Application Development and Testing: At the first stage, the research team will focus on the development of the key sensing, computing, and communication systems while building all components on an on-demand platform that can be moved between roadside and the labs.
Stage 2: Roadside Instrumentation and Network Configuration: Once the full prototype system is developed. The research team will coordinate and work with Middlesex County, the City of New Brunswick, and NJDOT to fully deploy the proposed systems.
Stage 3: Computing, Analytic, and Visualization Platform Development: The research team will also develop prototype applications to process the collected real-time high-resolution smart mobility data and create the 3D model for in the proposed visualization theater for futuristic TMCs. This includes building both the static high-resolution environment of the test sites and mapping all dynamic 3D objects detected into the environment.
Stage 4: Data Sharing and Application Testing Platform Development: The data sharing platform will focus on the development of 3D high-resolution data packaging, archiving, and retrieval systems. Testing interfaces from both the user end and the service/controller end will also be developed for application testing.

10. Stakeholders

Table 6 List of Stakeholders

CATEGORY	DEPARTMENT/AGENCY/COMPANY	
1. PUBLIC AGENCY	NYC DOT	NJTPA
STAKEHOLDERS:	NJDOT Mobility Engineering	NJBUP
	Middlesex County Department of Infrastructure Management	RWJ Hospital
	Middlesex County Office of Engineering	City of New Brunswick
	NJEDA	NJ Office of the Governor
2. POTENTIAL	DEVCO	Iteris

PROJECT	NBPA (New Brunswick Parking Authority)	Siemens
PARTNERS:	NB Innovation Office	Verizon
	TRANSCOM	T-Mobile
	NJ Turnpike Authority	Utility Companies (e.g. PSE&G)
	NJ Transit	Navya
	ECONSULT	FristTransit
	Jacobs	CISCO
3. ACADEMIC	Rutgers Chancellor's office	Rowan
PARTNERS:	Rutgers VTC	TCNJ
	Rutgers WINLAB	NJIT
	Rutgers DIMACS	Princeton
	Columbia	Stevens
4. TESTBEDS/UTC	M-City	CMU
	Suntrax	NYC CV Testbed
5. POTENTIAL HUB	Toyota InfoTek	TRANSCORE (SCATS adaptive signal)
TESTING GROUND	Toyotao Research Institute	Rhythm Engineeering (InSync adaptive signal)
USERS	Volvo	Kimerley Horns
	BMW	Omni Air Alliance companies.
	Subaru	The Ray (NJDOT Research showcase 2018)
	Ford	Soliaris
	GM	Tesla
	Uber	PonyAI
	Lyft	AutoAI
	Tesla	ZooX
	Waymo	StreetLight
	MobiEye	TrafficCast International, Inc.
	PTV	Advanced Solar Products
	AIMSUN	Pennoni
	Optimus Ride	Dell

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Appendix

Figure A1 Queue warning application [27]

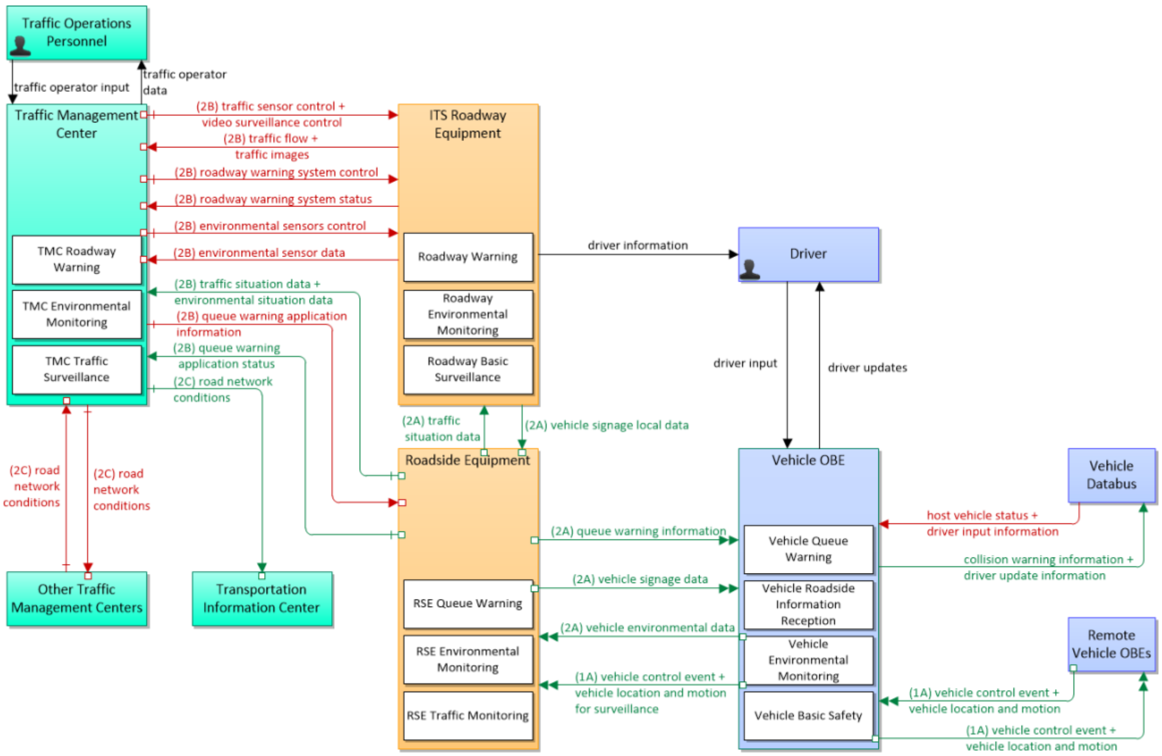

Figure A2 ITS system architecture [9]

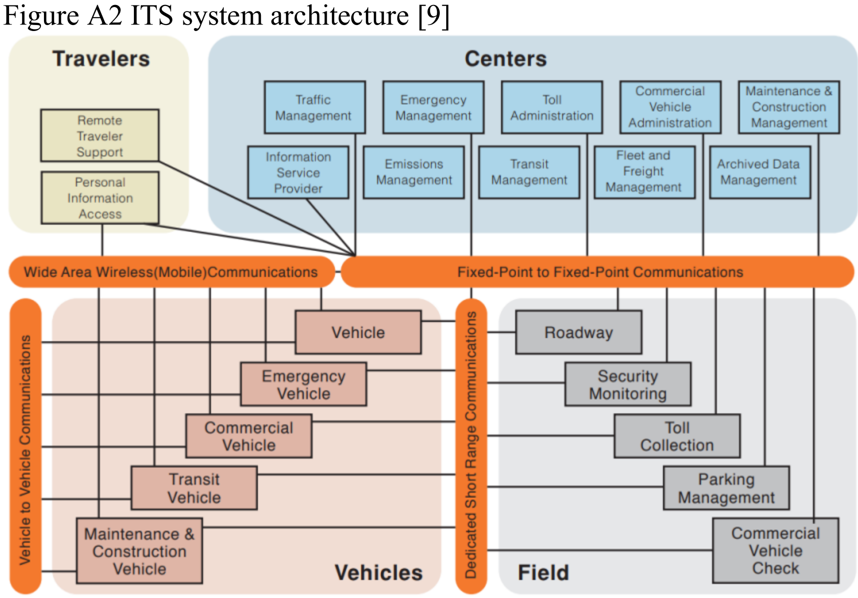

Figure A3 Comprehensive physical architecture [27]

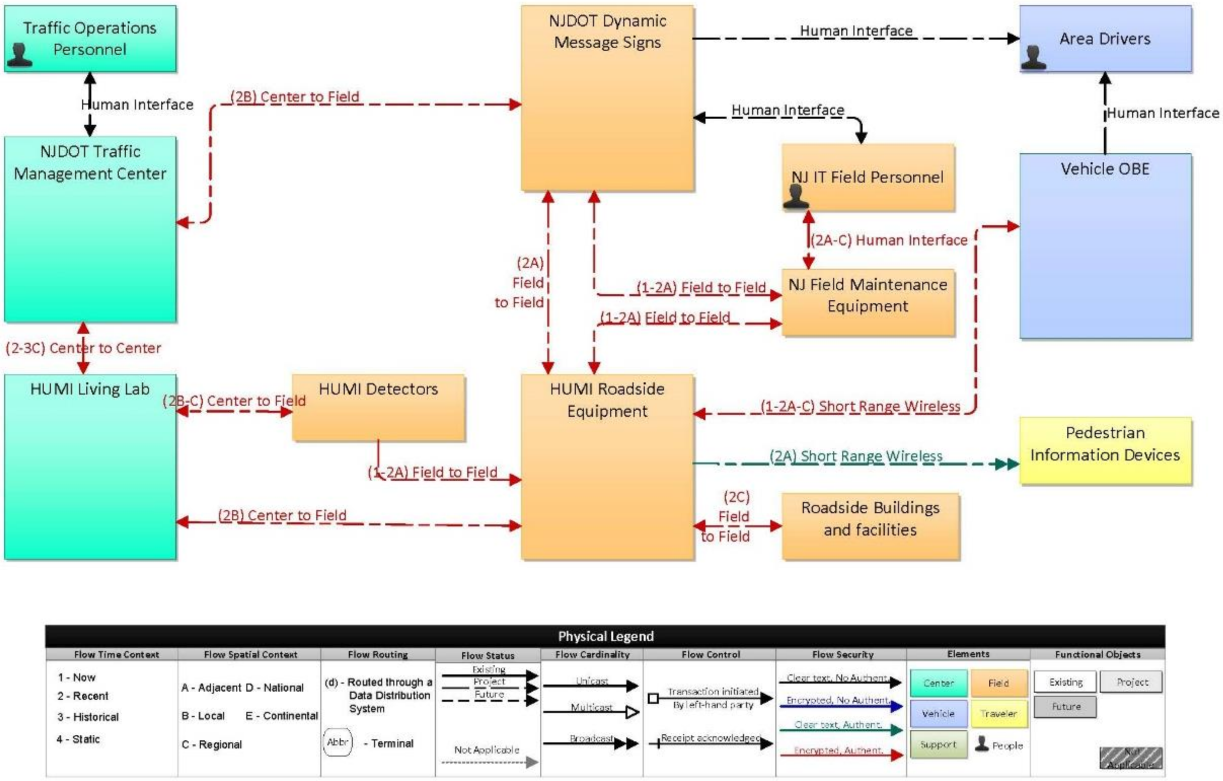

Figure A4 Function architecture [27]

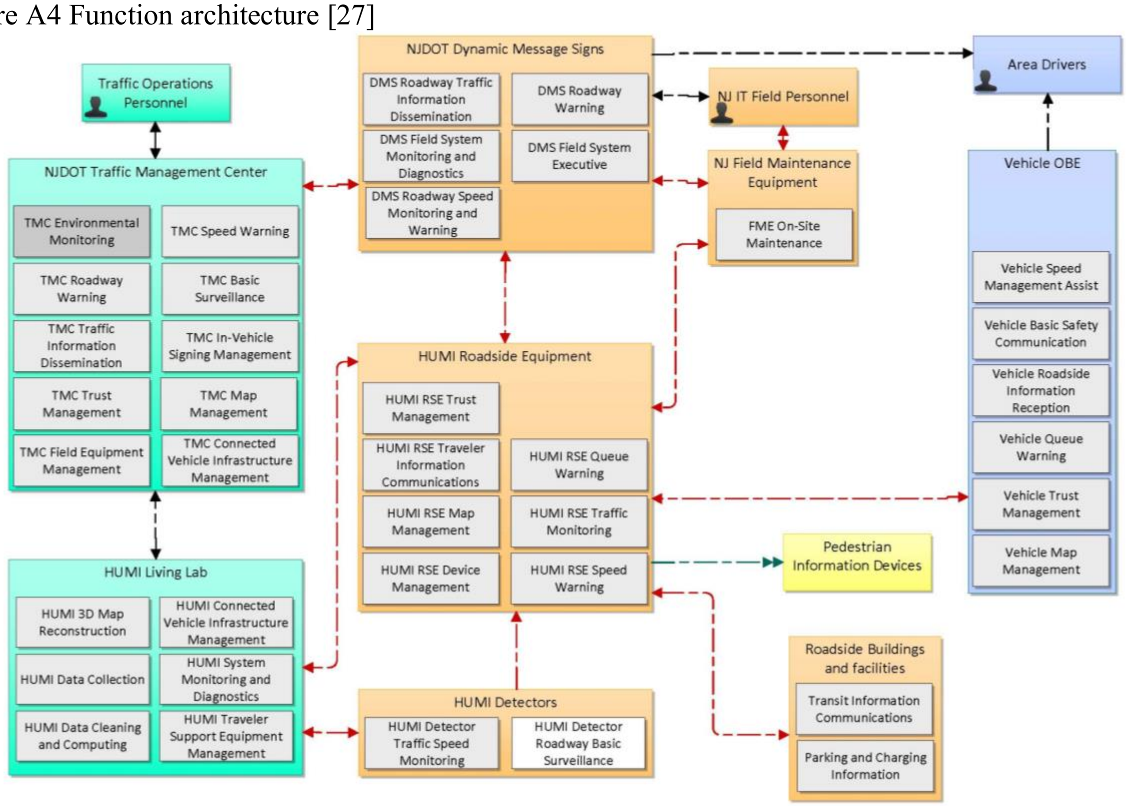

Figure A5 Adaptive Signal Control application architecture [27]

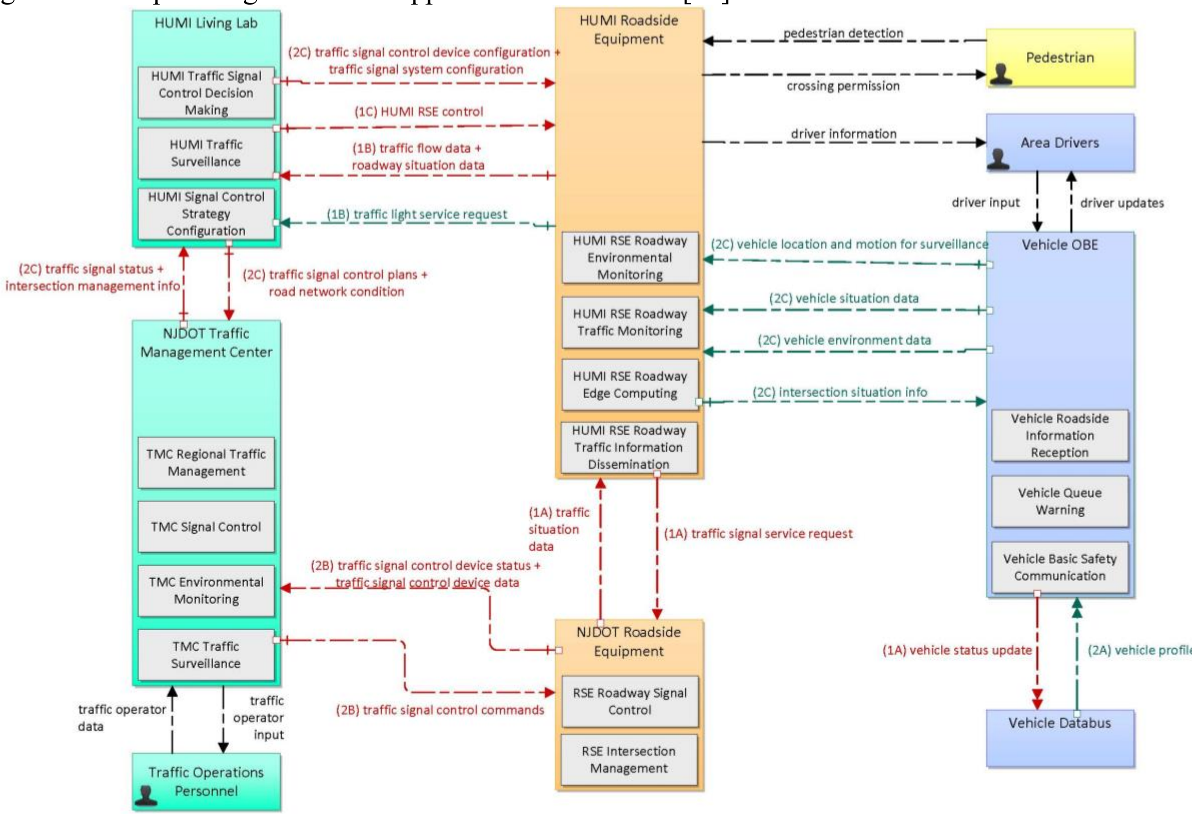

Figure A6 Electric Charging Management application architecutre [27]

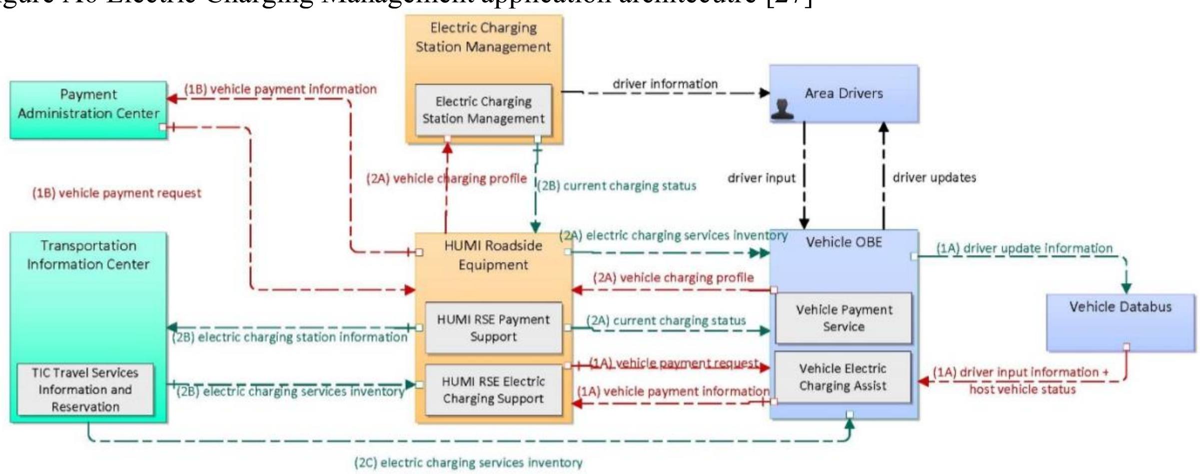

Figure A7 In Vehicle Signage application architecture [27]

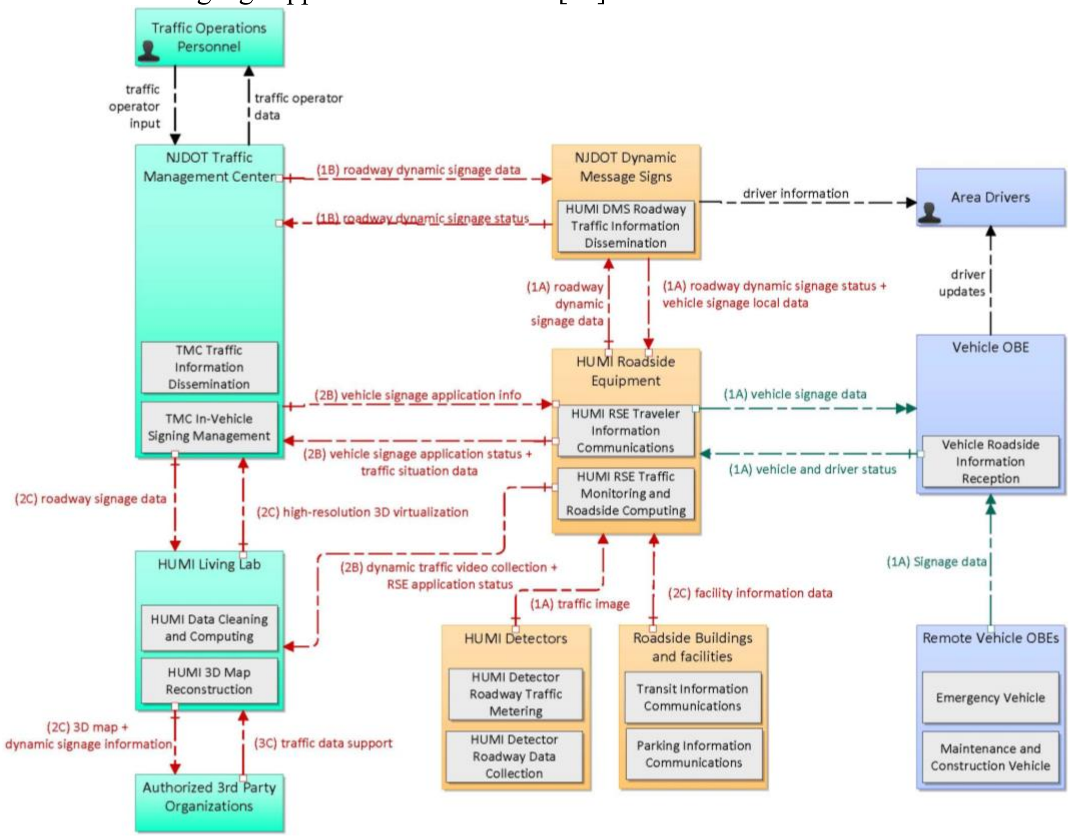

Figure A8 Reduced Speed Zone Warning application architecture [27]

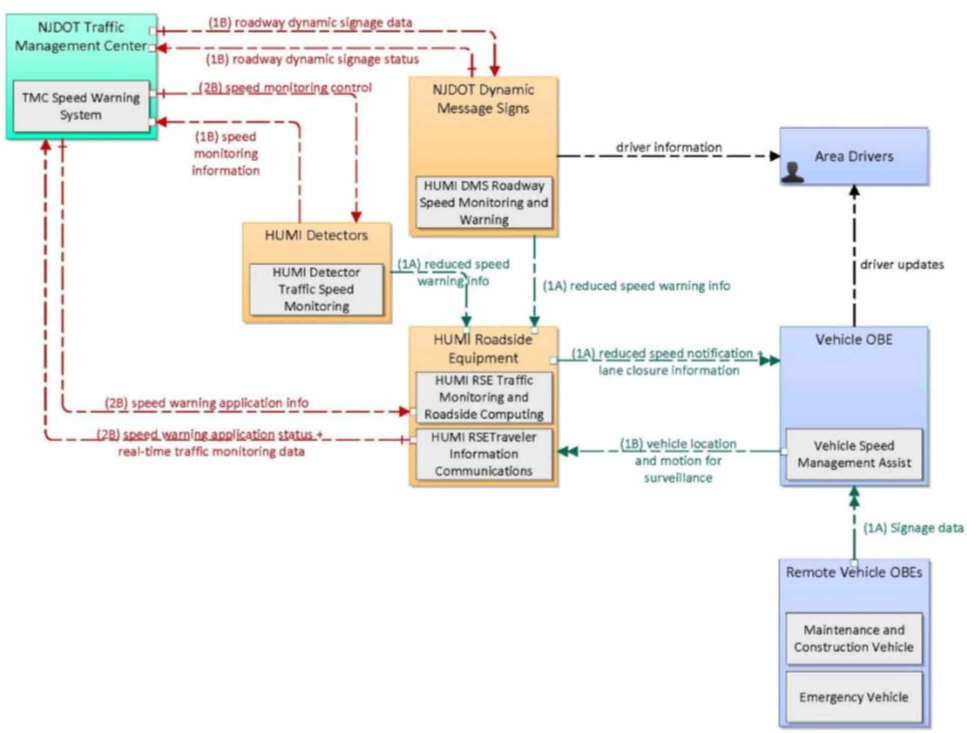

Figure A9 3D Map Management application architecture [27]