Supporting the Safe Deployment of Connected and Automated Vehicles through Infrastructure Adaptation and Remote Monitoring

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Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, NY

Richard Mai
Senior Project Manager

New York State Department of Transportation

Albany, NY

Edward Mark
Project Manager

Prepared by:

State University of New York at Buffalo

Buffalo, NY

Department of Civil, Structural and Environmental Engineering
Adel W. Sadek, Ph.D.
Professor

Department of Computer Science and Engineering
Chunming Qiao, Ph.D.
SUNY Distinguished Professor and Chair

Foad Hajiaghajani Memar, Ph.D.
Graduate Research Assistant

Li Tang, Ph.D.
Postdoctoral Researcher

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16. **Abstract**

The goal of this project is to address the challenges that Connected and Automated Vehicles (CAVs) currently face, through infrastructure adaptation focusing on three key functionalities: (1) connectivity, (2) infrastructure sensing support, and (3) remote monitoring. The research encompasses multiple aspects to achieve these goals. First, the project investigates the feasibility of vehicle-to-infrastructure (V2I) communications between traffic control signals and approaching CAVs to control the approach speed of the CAVs. Second, the project investigates the feasibility of leveraging information sensed by infrastructure sensors to support CAV perception and operations. Third, the project explores the role of human supervision in challenging CAV driving scenarios by developing a platform for remote, human-supervised monitoring and control of CAVs. The research is conducted at the University at Buffalo's CAV proving ground, utilizing the Lincoln MKZ CAV controlled by the open-source automated driving software "Autoware." Through the installation of Road Weather Information Systems (RWIS) and light detection and ranging (LiDAR) light-poles as roadside units (RSUs), the project establishes the necessary infrastructure for data exchange and communication between RSUs, a centralized server (cloud services), and the CAV development platform.

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Abstract

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Keywords

connected autonomous vehicles, self-driving, connectivity, vehicle-to-everything, remote monitoring, vehicle-to-infrastructure, internet-of-things, light detection and ranging, intelligent transportation systems, smart intersections, efficiency

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Acronyms and Abbreviations

ADS	Automated Driving System
AI	Artificial Intelligence
API	Application programming Interface
AV	Autonomous Vehicle
BSM	Basic Safety Message
C2X	Cellular-to-Everything
CAV	Connected Autonomous Vehicle
CAVAS	Connected Autonomous Vehicle Applications and Systems
CPU	Central Processing Unit
CV	Connected Vehicle
DSRC	Dedicated Short Range Communication
ESS	Environmental Sensing Station
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HTTP	Hypertext Transfer Protocol
IEEE	The Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
IP	Internet Protocol
ITS	Intelligent Transportation System
JSON	JavaScript Object Notation
LAN	Local Area Network
LIDAR	Light Detection and Ranging
MH	Mega Hertz
OBU	Onboard Unit
OEM	Original Equipment Manufacturer
OS	Operating System
ROS	Robot Operating System
RSU	Roadside Unit
RWIS	Road Weather Information System

SAE	Society of Automotive Engineers
TCP	Transmission Control Protocol
UDP	Datagram Protocol
UKF	Unscented Kalman Filter
URL	Uniform Resource Locator
V2G	Vehicle-to-Grid
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad hoc Network
VPN	Virtual Private Network
WAVE	Wireless Access Vehicular Environments
WLAN	Wireless Local Area Network

Executive Summary

The project focuses on the integration of vehicle-to-infrastructure (V2I) communication in the context of autonomous vehicles (AVs) to enhance their capabilities and performance. This report explores the benefits and feasibility of V2I connectivity across various automated driving applications.

The first task investigates energy-efficient connected and automated vehicle (CAV) intersection crossing by leveraging V2I communication. Real-time data exchange between traffic lights and autonomous vehicles enables CAVs to optimize their energy consumption by adjusting their speed and trajectory based on signal phase and timing. The project deploys a portable traffic light and develops a cloud-based communication system to facilitate interaction between the traffic light and CAVs. It also explores the integration of an automated speed control algorithm into the open-source automated driving software "Autoware."

The second task focuses on V2I-enabled collaborative perception and road weather data dissemination for CAVs. By enabling collaborative perception between CAV sensors and roadside sensors, autonomous vehicles can gather more accurate and comprehensive information about obstacles, road conditions, and traffic situations. The project investigates light detection and ranging (LiDAR) point cloud fusion and the incorporation of road weather information into automated driving systems. Roadside units, including a LiDAR light-pole and a Road Weather Information System (RWIS), are installed on the UB CAV proving ground to demonstrate the feasibility and utility of collaborative perception.

The third task addresses remote monitoring and control of CAVs, also known as teleoperation. Remote monitoring allows for real-time observation and assessment of CAVs' performance, while remote control serves as a fail-safe mechanism. The project aims to research the feasibility of teleoperation by developing a cloud-assisted communication system between CAVs and a remote monitoring/control center on UB campus. It also investigates public trust and acceptance by administering a survey to gather insights on public opinions regarding self-driving cars and the potential impact of remote monitoring and control on trust and perceived safety.

The report concludes by highlighting the contributions of the project, including the development of energy-saving strategies for CAV intersection crossing, enhanced perception through collaborative sensing, and the exploration of teleoperation capabilities. It also emphasizes the importance of integrating AVs into V2I initiatives to assess the full potential of V2I technology in an autonomous driving context. The report suggests future work, such as traffic light timing adjustment based on traffic and the use of the existing connectivity framework to build an augmented reality environment for CAV testing and evaluation.

1 Introduction

Connected and Automated Vehicles (CAVs) can make roads safer, and add a new level of enhanced transportation mobility and efficiency, through the application of intelligent control algorithms that leverage vehicle-to-X (or V2X) communications [1]. V2X technology refers to an intelligent transportation system where all vehicles and infrastructure components are interconnected with each other, directly or indirectly. Such connectivity provides precise knowledge of the traffic situation across the entire road network, which in turn helps optimize traffic flows, enhance safety, reduce congestion, and minimize emissions. Connectivity in cars also offers opportunities for carmakers to enhance reliability, onboard diagnostics, telematics, and infotainment systems. In addition, connectivity supports predictive maintenance and repair, on-demand insights, usage-based insurance, and real-time navigation guidance [2]. In light of the long-term evolution (LTE) toward 5th-generation (5G) mobile data technology, it is becoming evident that vehicles connected to the cellular network will be given superior capabilities and possibilities, especially when considering the vehicle-to-network (V2N) architecture approach. In the near-future, 5G Cellular vehicle-to-everything (C-V2X) network can reach vehicles within a large region, allowing for increased range, and predictive measures toward safer traffic flow; this is thanks to higher capacity, ultra-low latency, ultra-high reliability, more extended range, and higher data rates.

1.1 Connectivity via Infrastructure

Controlling a vehicle to improve energy consumption has been studied extensively [3-6]. The energy impacts of connected autonomous vehicles may vary significantly along two pathways: (1) the level of automation (partial or full automation) and (2) whether there is a significant portion of shared autonomous vehicles versus personal autonomous vehicles. The behavior and decisions of fully autonomous vehicles heavily rely on their perception system. In fact, autonomous vehicles react to what they “see” in the surrounding environment. However, vehicles’ sensors do not allow the vehicle to perceive beyond their limited sensing range, which would allow them to plan more efficiently. This is exactly where intercommunication between autonomous vehicles and infrastructure through vehicle-to-infrastructure (V2I) communication becomes effective. Connectivity and intercommunication under such a paradigm would enable various benefits in different aspects of autonomous driving. Some of these benefits are summarized below with respect to different applications:

- V2I communication enables vehicles to receive real-time traffic information, including congestion, accidents, and road closures. By integrating this data into their decision-making algorithms, CAVs can dynamically adjust their routes and speeds to optimize traffic flow, reduce congestion, and minimize travel time.
- Through V2I communication, infrastructure components such as road sensors or cameras can provide CAVs with valuable information about hazards or obstacles on the road, such as potholes, debris, or construction zones. This information helps autonomous vehicles to anticipate and adapt their driving behavior accordingly, ensuring safer navigation.
- V2I communication allows infrastructure components, such as traffic lights or road signs, to communicate directly with CAVs. This enables infrastructure-initiated traffic control, where signals can be optimized based on traffic patterns, congestion levels, or specific events, enhancing overall traffic management and improving the efficiency of transportation systems.
- V2I communication enables CAVs to receive real-time updates on the presence and movements of pedestrians and cyclists near roadways. This information enhances the detection and prediction capabilities of autonomous vehicles, helping to ensure the safety of vulnerable road users and minimizing the risk of accidents.
- V2I communication facilitates remote monitoring and control of CAVs. Human operators can remotely assess the situation, provide guidance, and assume control if necessary.
- V2I communication can facilitate the exchange of data related to road conditions, including temperature, weather conditions, and surface quality. By incorporating this information, autonomous vehicles can adjust their driving behavior, adapt their control algorithms, and enhance safety and comfort in different weather and road conditions.
- V2I communication enables CAVs to access information about parking availability in real-time. By receiving data on parking space occupancy, autonomous vehicles can locate and navigate to available parking spots efficiently, minimizing the time spent searching for parking and reducing congestion around popular areas.
- V2I communication allows autonomous vehicles to be aware of priority vehicles, such as emergency service vehicles or public transportation. By receiving real-time updates on the presence and location of these vehicles, CAVs can yield right of way, adjust their driving behavior, and contribute to smoother traffic flow and emergency response.

1.2 V2I Connectivity in New York State

Connected vehicle initiatives, including V2I projects, have been gaining momentum globally to improve transportation efficiency, safety, and sustainability. Many regions and cities have been actively exploring and implementing V2I technologies to support connected autonomous vehicles. In the United States (U.S.), several states, including New York, have shown interest in deploying V2I infrastructure and testing its potential benefits. For example:

- **The New York City Connected Vehicle Pilot**: This pilot program, launched by the New York City Department of Transportation (NYCDOT), aims to improve safety and traffic efficiency. It includes V2I technology implemented at select intersections in Manhattan, Brooklyn, and the Bronx.
- **The Niagara International Transportation Technology Coalition (NITTEC)**: NITTEC, a partnership between the New York State Department of Transportation (NYSDOT) and various agencies, has been working on implementing V2I infrastructure along the I-190 corridor in Buffalo, enabling communication between vehicles and infrastructure to enhance safety and traffic management.

However, there are some limitations associated with these projects. For instance, they focus on a specific corridor or region. Another limitation of the aforementioned projects is that they may not directly involve autonomous vehicles (AVs) in their initial phases. While these projects focus on V2I technology, they may primarily concentrate on testing and implementing infrastructure and communication systems rather than involve autonomous vehicles. The absence of AV involvement can limit the ability to evaluate the full potential of V2I technology in an autonomous driving context. AVs have specific requirements and capabilities that can significantly benefit from V2I communication for enhanced navigation, traffic management, and safety. In fact, ignoring AV participation may restrict the ability to assess the overall effectiveness and interaction of V2I systems with autonomous vehicles.

This project aims to research benefits and feasibility of V2I technology with respect to various automated driving applications. Integrating AVs into V2I initiatives expands the potential benefits and paves the way for more advanced and efficient transportation systems. It enables a higher level of cooperation between vehicles and infrastructure, leading to improved safety, traffic management, and overall transportation ecosystem performance.

1.3 Purpose and Scope

The purpose of this project is to study Intelligent Transportation Systems (ITS) with a specific focus on vehicle-to-infrastructure (V2I) support for autonomous vehicles (AVs). It is essential to highlight that while ITS encompasses various applications and technologies to improve transportation, our project specifically emphasizes the integration of AVs and infrastructure elements to enhance their capabilities and performance. By leveraging V2I communication, we aim to facilitate real-time data exchange between AVs and infrastructure, enabling informed decision-making and enhanced traffic management. While V2I is a component of Intelligent Transportation Systems (ITS), it plays a crucial role in supporting autonomous vehicles.

This project aims to study the benefits, research the feasibility, and address the technological challenges of V2I connectivity for autonomous driving across different applications. In particular, we study the following tasks:

1. **Energy-efficient CAV intersection crossing**: Through V2I connectivity, traffic lights can transmit real-time data about their status, such as signal phase and timing, to approaching autonomous vehicles. This allows CAVs to anticipate changes in signal states and adjust their speed and trajectory accordingly to minimize unnecessary stops and accelerations. By leveraging this information, CAVs can plan their maneuvers more efficiently, optimizing their energy consumption by reducing idle time and optimizing acceleration and deceleration profiles. For example, if a CAV knows that a traffic light will turn green in a few seconds, it can adjust its speed to arrive at the intersection precisely when the light changes, minimizing energy waste and improving overall fuel efficiency.

   This energy-efficient intersection crossing is made possible through the utilization of cellular networks, such as 5G, which provide high-speed and reliable connectivity between the traffic infrastructure and autonomous vehicles over large regions. The low latency and high data rates of cellular networks enable real-time communication and precise coordination between traffic lights and CAVs, facilitating energy-saving strategies during intersection navigation. In this project, we explore the potential benefits of V2I-enabled autonomous driving by investigating the feasibility of integrating infrastructure communication into CAVs approaching signalized intersections. The project involves the deployment of a portable traffic light on UB North Campus CAV Proving Grounds and the development of a cloud-based communication system that facilitates interaction between the traffic light and CAVs. Furthermore, the project explores the integration of an automated speed control algorithm into the open-source automated driving software "Autoware."

2. **V2I-enabled collaborative perception and road weather data dissemination for CAVs**: Collaborative perception between CAV sensors and roadside sensors, enabled by V2I communication, allows autonomous vehicles to benefit from a wider and more comprehensive understanding of the surrounding environment. By fusing data from multiple sources CAVs can gather more accurate and complete information about obstacles, road conditions, and traffic situations. This enhanced perception enables CAVs to make more informed and efficient decisions, improving both safety and efficiency on the road. By leveraging V2I communication, this project investigates light detection and ranging (LiDAR) point cloud fusion and the incorporation of road weather information into automated driving systems.

   Similarly, by receiving real-time road weather information through V2I communication, CAVs can adapt their driving strategies based on current weather conditions including route selection, speed profile optimization, etc. Roadside units (RSUs), including a LiDAR light-pole and a Road Weather Information System (RWIS), are installed on UB CAV proving ground to demonstrate the feasibility and utility of collaborative perception.

3. **Remote monitoring and control of CAVs**: Remote monitoring and control, also known as teleoperation, enables the remote monitoring of CAVs, ensuring proper decision-making, and assuming control when necessary. CAV teleoperation offers several benefits and addresses critical needs in the realm of autonomous driving.

   Firstly, remote monitoring allows for real-time observation and assessment of CAVs' performance and behavior. By remotely monitoring the vehicles, operators can ensure that the systems are functioning properly, making the right decisions, and adhering to safety protocols. This monitoring capability enables the identification of potential issues or anomalies, allowing for immediate intervention and corrective actions, thereby enhancing the overall safety and reliability of autonomous vehicles on the road.

   Secondly, remote control or teleoperation serves as a crucial fail-safe mechanism. In complex and unpredictable situations where CAVs may encounter scenarios beyond their programming or perception capabilities, human intervention becomes essential. Remote control enables operators to assume control of the vehicle, providing an additional layer of decision-making and ensuring the safe navigation and maneuvering of the CAV. This capability bridges the gap between the current limitations of autonomous systems and the need for human oversight, leading to a gradual transition toward more advanced and reliable autonomous driving technologies.

   This project aims to research the feasibility of teleoperation by developing an end-to-end cloud-assisted communication system between CAVs and a remote monitoring/control center on UB campus. Additionally, a self-driving software interface for real-time data exchange and command execution is developed. Considering the societal impact of CAVs, this project also investigates public trust and acceptance. Public perception plays a vital role in the introduction and market adoption of AVs. To gauge public acceptance, a survey is administered to gather insights on public opinions regarding self-driving cars, perceived safety, and the potential impact of remote monitoring and control on trust and perceived safety.

1.4 Report Organization

This project report is structured into five sections. In section 2, we elaborate on the benefits and research regarding V2I communication for energy-efficient CAV intersection crossing. Section 3 focuses on addressing technical challenges of enabling collaborative sensing between CAV and infrastructure using roadside road weather and LiDAR infrastructure. In section 4, the benefits and feasibility of CAV remote monitoring and control are studied. Finally, section 5 summarizes and concludes the report.

2 Feasibility and Benefits of Connectivity

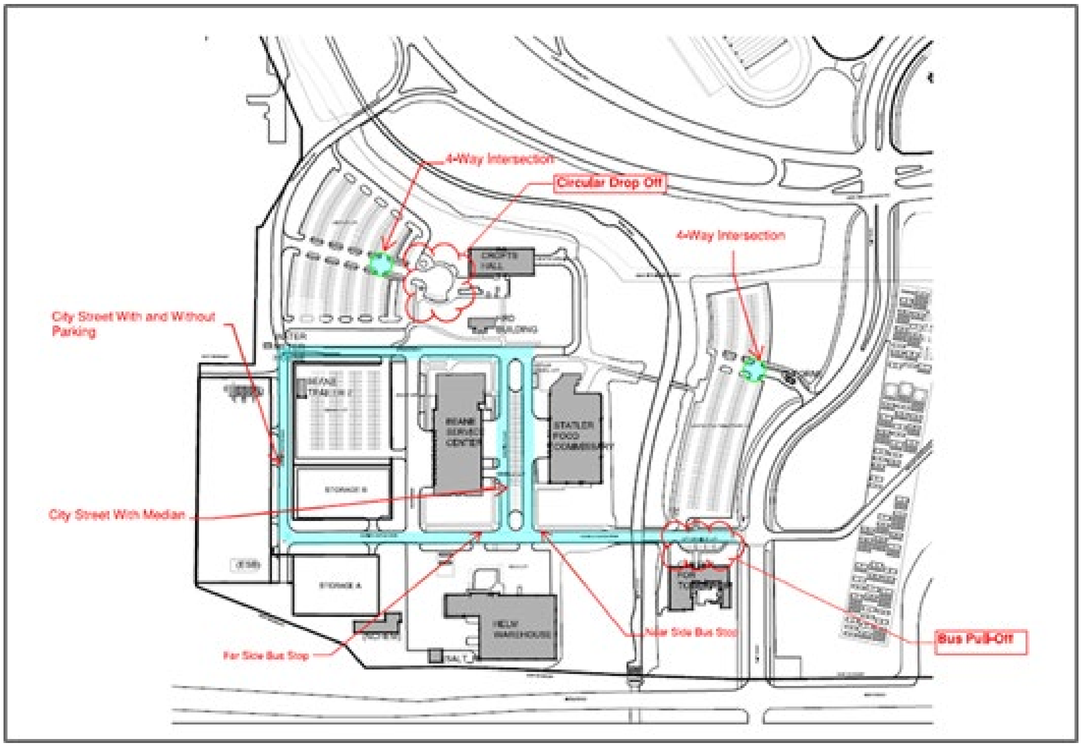
CAVs have the potential to revolutionize road safety, transportation mobility, and efficiency. By utilizing intelligent control algorithms and leveraging V2X communications [1], CAVs can enhance the overall transportation experience. V2X technology represents an intelligent transportation system where vehicles and infrastructure components are interconnected, creating a network that enables precise traffic monitoring across the entire road network. This interconnectedness optimizes traffic flow, improves safety, reduces congestion, and minimizes emissions. Moreover, the connectivity in vehicles offers car manufacturers opportunities to enhance reliability, onboard diagnostics, telematics, and infotainment systems. Additionally, connectivity enables predictive maintenance, on-demand insights, usage-based insurance, and real-time navigation guidance [2].

With the evolution from long-term evolution (LTE) to fifth-generation (5G) mobile data technology, it is evident that cellular network-connected vehicles will gain superior capabilities, especially when adopting the vehicle-to-network (V2N) architecture approach. In the near future, the 5G Cellular vehicle-to-everything (C-V2X) network will extend its reach to cover a larger region, enabling increased range, predictive measures, and early interventions for safer traffic flow. This is made possible by the higher capacity, ultra-low latency, ultra-high reliability, extended range, and higher data rates provided by 5G technology.

The energy efficiency of connected autonomous vehicles has been extensively studied [3-6]. However, the energy impacts of these vehicles can vary depending on two key factors: (1) the degree of partial or full automation implemented in the autonomous vehicle technology and (2) the ratio of shared autonomous vehicles versus personal autonomous vehicles. Fully autonomous vehicles heavily rely on their perception systems and react based on their surroundings. Nevertheless, the limited sensing range of vehicle sensors restricts their perception capabilities, hindering efficient planning. This limitation highlights the significance of intercommunication between autonomous vehicles and infrastructure.

In this project, we aim to explore the benefits and assess the feasibility of V2I-enabled autonomous driving for vehicles approaching signalized intersections. To achieve this, we will construct and deploy a portable traffic light at UB North Campus CAV Proving Grounds, situated along the service road opposite the Center for Tomorrow (CFT) as depicted in Figure 1. Subsequently, we will develop a cloud-based end-to-end communication system that facilitates seamless interaction between the traffic light and CAVs. Additionally, we will investigate the feasibility of integrating an automated speed control algorithm into the open-source automated driving software, "Autoware."

Figure 1. The Test Environment at UB CAV Proving Grounds



2.1 Connectivity for CAVs

2.1.1 Communication Technologies and Standards

Vehicular connectivity which is basically characterized by vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) communications combines the inter-vehicle network and the mobile network. In the course of time and with the emergence of new technologies in automotive and Internet-of-Things (IoT) industries, additional forms of vehicular connectivity models have been introduced as well. They are vehicle-to-pedestrian (V2P), vehicle-to-network (V2N) and vehicle-to-grid (V2G) communications or in a broader form vehicle-to-everything (V2X) communications which construct the backbone of the Internet-of-Vehicles (IoV). Connectivity between CAVs and smart infrastructure is fundamental to realize intelligent traffic control, especially in the road transportation safety domain.

In the last decade, the development of sensors and machine-learning technologies has resulted in the increasing demand for bandwidth, connection reliability, and transmission delay of the vehicular networks. Moreover, various connected vehicle (CV) applications demand different network bandwidth and delay requirements. For instance, to avoid rear-end collisions, vehicles must make sure that the basic safety messages (BSM) can reach the surrounding vehicles in the matter of milliseconds, while dissemination of weather forecast information in weather advisory applications may tolerate a few seconds of delay. In addition, the message size for the latter is not as limited as the case in the former application. To exchange messages, connected vehicles and infrastructure, rely on different wireless technologies such as IEEE 802.11p—which is also known as dedicated short-range communication (DSRC) in the U.S.—as well as cellular (e.g., 4G/LTE, 5G, C-V2X) systems.

Existing 4G/LTE technology has great advantages; for example, it can support a large number of terminal access points at the same time. It has been applied in some vehicle networking projects, such as the European CoCar project. The feasibility of applying cellular mobile communication technology including LTE to the V2V and V2I scenarios has been studied. DhilipKumar et al. [7] applies 4G/LTE technology to the IoV. By analyzing data throughput, time delay, power consumption, and other indicators, it confirms that 4G/LTE can indeed improve the performance of the network. However, 4G/LTE technology introduces “indirect” communication wherein the network carrier or cellular-base station establishes the end-to-end connectivity.

In 2012, the United States Department of Transportation (US-DOT) led the Connected Vehicle Safety Pilot project, which mainly studied the influence of V2X applications based on DSRC technology, which is a form of point-to-point or “direct” communications, on vehicle driving safety. In Japan, the AHS project researched vehicle synergy technology impact on traffic safety. In Europe, the vehicle road coordination system (CVIS) project and the DRIVE C2X project realized vehicle communications and verified the improvements in the driving safety and transportation efficiency in collaborative environments. In what follows, we distinguish the main characteristics of both variants.

2.1.1.1 Dedicated Short-Range Communication (DSRC)

This technology comprises a transceiver or onboard unit (OBU) that can communicate directly with other OBUs for V2V communication or with roadside units (RSUs) for V2I communication. Dedicated short-range communication , also known as WAVE or IEEE 802.11p Wi-Fi, operates in the 5.850–5.925 GHz frequency range. It consists of seven 10 MHz channels with data rates available from 3–27 Mbps (also offered is the option of combining two sets of two 10 MHz channels (174/176 and

180/182) into two 20 MHz channels with data rates available from 6–54 Mbps), with the first channel (172) set aside strictly for vehicle safety. Data transmissions of DSRC typically take place up to 10 times per second with a latency in the millisecond range. When the transmitter is a vehicle, the data format for the messages may contain the vehicle's location, speed, direction, acceleration, or deceleration, turn status, and other such information. Likewise, when the transmitter is an infrastructure, the data may be related to traffic signal timing, congestion status, weather information, or a response to a prior computation request. The format of this data is defined by the Society of Automotive Engineers (SAE) in standards J2735 and J2945.

2.1.1.2 Cellular Communications

While DSRC provides a range of advantages, such as tolerance to high-velocity and message loss, security, and immunity to extreme weather conditions, it is generally geared for safety applications, has limited wireless range (typically about 1000 ft.) and suffers from channel congestion when too many OBUs and/or RSUs co-exist in the same area. Cellular communications can address some of these limitations in different ways. The major difference that sets cellular communications apart from DSRC is that it allows both direct and indirect communication. Traditional 4G/LTE can provide direct or indirect communication links between OBUs and RSUs. Indirect communication in which the data is relayed through the carrier's network could even overcome range limits that direct communications may have with the cost of additional communication latency. Indirect cellular communication is crucial as the cellular network can collect data from many vehicles, and therefore, can be more effective at managing traffic on a larger scale.

When compared to LTE, 5G communication technology offers significantly lower latency, higher data throughput, and greater capacity, enabling near real-time communication, faster data exchange, and support for a larger number of connected devices, making it a more suitable technology for future CAV applications. This low latency is crucial for CAVs to exchange vital information quickly, such as collision warnings or traffic updates. Moreover, 5G's higher data throughput and capacity allow for large amounts of data to be transmitted rapidly, supporting the exchange of high-resolution sensor data between vehicles and cloud-based systems. This data exchange facilitates advanced perception capabilities and enhanced decision-making in CAVs. Additionally, 5G's ability to handle a massive number of simultaneous connections ensures reliable and efficient communication among a dense network of vehicles, pedestrians, and roadside infrastructure. These advantages make 5G a promising technology for CAVs, improving their safety, responsiveness, and overall performance. It is worth noting that while 5G would be a key enabler for some advanced vehicle infrastructure integration (VII) such as collaborative sensing, it is not a strict prerequisite for other CAV applications such as coordinated traffic signals and CAV speed control such as eco-signals/eco-driving applications.

More recently, the idea of cellular vehicle-to-everything (C-V2X) has taken much attention in both academia and industry. Defined by the 3rd Generation Partnership Projects (3GPP), C-V2X utilizes cellular radio instead of WLAN, meaning that it utilizes the same set of cellular radio technology as cellphones. This standard is based on known LTE cell-phone technology. It's highly developed and widely implemented, plus proven reliable. It can achieve data speeds and a range much greater than WAVE, so it's attractive. Both technologies have been widely tested in V2V and V2I situations and are essentially equally effective. It is worth noting that direct C-V2X technology is not prevalent yet and existing OBUs/RSUs are much more expensive than DSRC units. However, since common cellular terminals can be used for indirect C-V2X, they are widely accessible from various providers. The choice of communication technology depends on various factors, including the specific use case, infrastructure availability, regulatory requirements, and technological advancements.

2.1.2 Benefits of Connectivity

V2I communication benefits other types of vehicular networking styles such as V2V communication by acting as an intermediary to facilitate information exchange between vehicles. It enables the sharing of real-time data on road conditions, traffic flow, and hazards collected by infrastructure elements. This information enhances situational awareness, enables cooperative maneuvers, and improves safety by allowing vehicles to make proactive decisions based on the shared information.

In terms of costs and maturity, V2V communication is theoretically more cost-effective, but it faces challenges in scaling due to the need for different Original Equipment Manufacturers (OEMs) to collaborate and develop compatible technologies. Additionally, V2V's effectiveness relies on a large initial adoption rate, as connected vehicles are most useful when there are other connected vehicles nearby. This can create a dilemma for potential buyers who may be hesitant to invest in a connected vehicle during its early stages. On the other hand, V2I communication offers more immediate benefits if infrastructure components such as roadside units are available. Consumers can experience the advantages of V2I right away without relying solely on the presence of other connected vehicles. Furthermore, V2I and V2V serve different purposes, with V2I's particular usefulness in applications such as electronic traffic signals that require direct communication with infrastructure elements.

In terms of application and information, V2I technology enables wireless exchange of various types of data between CAVs and roadside infrastructure, including but not limited to, traffic lights, traffic signs, sensors, lane markings, edge computing units, data aggregation units, etc. Different roadside infrastructure may be connected via a fiber-optic. The data that is exchanged between vehicles and infrastructure could be related to traffic congestion or hazards, weather advisories, construction zones, parking availability, signal phase and timing (SPaT) or the specific state of a vehicle. Basically, advantages of V2I connectivity can be categorized into three categories:

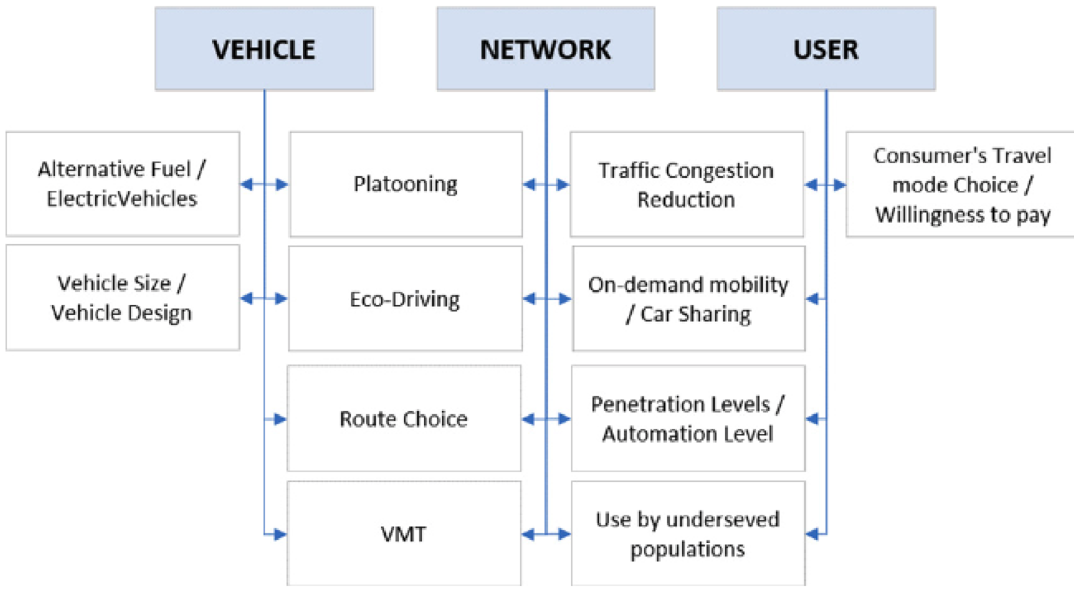
2.1.2.1 Environmental Benefits

The emergence and popularity of CAVs as well as vehicle electrification are supposed to have a positive impact on the amount of greenhouse gas (GHG) emissions originating from traffic. More than 6 billion gallons of diesel fuel and gas are wasted annually due to idling vehicles, according to the United States Department of Energy. Idling time is reduced with V2I. Since traffic flow will improve, fuel usage will be optimized. A reduction in idling is beneficial for electric cars for similar reasons. The energy will be used more efficiently, meaning less frequent charging and usage of the grid. The US-DOT notes: "When signal operations and freeway lane management applications are optimized for the environment, they could yield fuel savings of up to 22%." Idling a vehicle is also harmful to the engine. Excessive idling leads to increased maintenance needs and decreases an engine's lifespan, and naturally a shorter lifespan for the vehicles' engines would require increased vehicle production, and a corresponding increase in energy consumption.

It is also known that 22% of all wasted fuel is due to inefficient vehicle deceleration and/or lack of anticipation. AVs, without the added benefit of connectivity, have a limited range of sensing capabilities. For example, in many cases a vehicle which is about to go through an intersection applies hard brake because the perception system detects an unexpected obstacle (e.g., construction, incidents, etc.). Similarly lack of anticipation, for example about traffic signal timings, could result in wasted energy due to long idling times at intersections. Connectivity enables vehicles to receive signal status information along their trajectory in real-time; with this, control algorithms can be developed to adjust the speed profile of approaching vehicles to minimize stop-and-wait occurrences.

Kopelias et. al. [8] have identified twelve different impacts that connected autonomous vehicles could have on the environment. V2V and V2I connectivity, both play a critical role in realizing such impacts. As seen in Figure 2, platooning, eco-driving and ridesharing are some of the applications where environmental benefits of vehicular connectivity are significant.

Figure 2. Autonomous Vehicles Communication Structure



2.1.2.2 Safety Benefits

In the U.S., car crashes are the top reason for fatalities of people aged 54 and under. Worldwide, car crashes lead to 1.35 million fatalities a year. Therefore, transportation authorities are always looking for ways to improve vehicle safety, and experts say V2I can increase it in multiple ways. Accidents often happen because a driver does something that others on the road don't expect. Predictability and consistency lead to safety. Drivers changing lanes, for instance, have the potential to cause accidents. Therefore, even pavement markings that communicate with vehicles will lead to fewer accidents. Road markings and lane detection can enable vehicles to stay in their lanes rather than drift—due to driver distraction or poor visibility—into other lanes and potentially cause accidents. Changing lanes is safer when there is sufficient space and other vehicles are aware of the movement. Also, many accidents occur because drivers ignore a traffic sign, but V2I-enabled smart signs can help eliminate this problem.

Another scenario is a driver missing a highway sign indicating their desired exit. To not miss the exit, the driver abruptly brakes or changes lanes, leading to an accident. With smart signs connected to V2I, signs will always be visible to humans and machines, regardless of road condition. Improved readability will help drivers react more predictably and reasonably, enabling driverless vehicles to move appropriately and in a way that will not surprise other vehicles on the road.

Pedestrian and cyclist safety will also improve with V2I, proponents say. A smart intersection can cover blind spots of drivers' or autonomous vehicles and detect if someone is crossing. Vehicles approaching the intersection will be alerted to the pedestrian crossing and react appropriately. Smartphones could also be looped into the V2I technology network so pedestrians and cyclists could be alerted about traffic.

V2I technology can also help reduce tailgating accidents by providing real-time information about the distance between vehicles and promoting safe following distances. Infrastructure elements can communicate with vehicles, alerting drivers when they are following too closely and encouraging them to maintain a safe distance. By enhancing driver (or AV's) awareness and promoting safe driving behaviors, V2I technology can contribute to a reduction in tailgating-related accidents.

2.1.2.3 Mobility Benefits

V2I technology can also help improve mobility. While ground transportation is an inevitable part of every American's daily life, the top priority for most motorists when driving is getting from point A to point B as quickly and safely as possible. That's why one of the top priorities of nearly every infrastructure project is to improve mobility.

By communicating with drivers—or the car, in the case of autonomous vehicles—regarding the right speed to drive to avoid stopping at a red light, for example, V2I increases mobility. V2I connectivity can also improve traffic flow, through the use of traffic light cameras and sensors that sense traffic and communicate with one another to synchronize timing. By adjusting the timing of the traffic lights based on traffic flow, vehicles spend less time waiting at traffic lights. Autonomous vehicles approaching these intersections can constantly update their speed profile applying smooth acceleration or deceleration to arrive at intersections only when the signal is "GREEN." Without V2I technology, this would not be possible.

Vehicles will also be able to navigate roadways more efficiently with V2I technology, since data related to traffic congestion will be available. With this information, autonomous vehicles and human drivers can optimize route choice, allowing them to find the fastest route, thereby minimizing delay and congestion.

2.2 V2I-Enabled Eco-Drive System

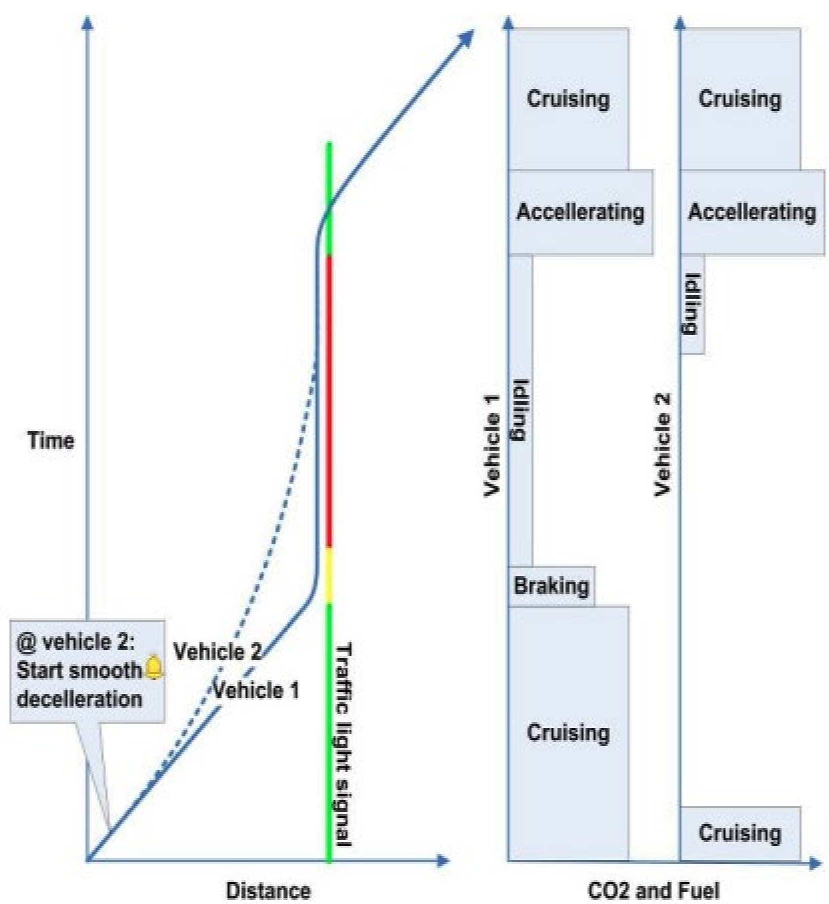
The combination of the route guidance and traffic light control has been studied before, mainly in a mathematical way, to quantify the likely traffic mobility and environmental benefits of such applications. Generally, the problem is treated as a bi-level equilibrium network design problem where the lower level refers to the traffic signal settings and vehicle queuing and the higher level refers to the network equilibrium and route choice behavior [6, 9]. A practical perspective is given[10] in a case study which shows that delays and travel times can be improved up to 64% and 40% respectively depending on the change of traffic controls and the availability of near-perfect information to make a route choice.

As mentioned before, 22% of all wasted fuel is caused by inefficient deceleration and/or lack of anticipation. Consequently, a reduction of fuel consumption can be obtained if drivers get information about the traffic light status and adapt their acceleration profile accordingly. The relayed information could help CAVs to optimize their driving behavior to save fuel. In most cases, when approaching intersections, human drivers accelerate hard to pass through the intersection before the end of the yellow light timeframe. However, due to wrong estimation, human drivers find that it is not possible to pass through the intersection and brake hard to stop at the stop line. This results in significant cumulative emissions and energy consumption.

Similarly, autonomous vehicles cannot anticipate the status or timing of signals on the path ahead. Therefore, they apply sharp declarations to stop at the intersection as soon as their vision system detects a yellow or red signal. If these vehicles receive information, in advance, about remaining green signal time, they will start decelerating earlier and hence reduce idling time at an intersection. In an ideal case, a vehicle might even avoid stopping and return to normal accelerating when the signal switches to green. It is assumed that a CAV that receives information about the remaining green time information, knowing that it is not possible to pass through an intersection, will decelerate smoothly (using deceleration rate of -0.45 m/s2) until the stop line or end of the queue. A similar trajectory was applied[11], in which drivers are assumed to smoothly decelerate to a crawl speed (i.e., 10 km/h) and keep this speed until they apply maximum deceleration to stop. Figure 3 below shows the result of the experiment. It illustrates the two trajectories of a vehicle with and without information about the remaining GREEN time, together with a schematic diagram of expected CO_2 emissions and fuel consumption during cruising, decelerating, and idling. According to the powertrain of individual vehicles, the optimal trajectory for different vehicles can be determined. For a hybrid vehicle, for example, from an energy/emissions standpoint, one would prefer to let the vehicle drive normally because hard braking can be used to charge the vehicle's battery, and idling has zero emission (i.e., engine is shut down).

Figure 3. Trajectories and Relative CO_2 Emission and Fuel Consumption for a Vehicle Without (1) and with (2) Receiving Traffic Light Status Information.

Vehicle 2 Saves Fuel On: Cruising, Braking and Idling as Compared to Vehicle 1



In this section we describe how the project developed a physical testbed on UB CAV Proving Grounds (see Figure 1. above) for the physical testing, demonstration, and evaluation of V2I-enabled eco-driving applications. The intent is to demonstrate the feasibility of the approach and provide a physical testing environment for the evaluation, design, and optimization of V2I-enabled, eco-driving applications for

CAVs. The system developed contains (1) a portable connected traffic light system with cellular communication capability, (2) a cloud-based communication system that facilitates message passing between traffic light and CAV, and finally (3) an automated speed control algorithm that is integrated with “Autoware”—an open-source, self-driving software stack.

2.2.1 V2I-Enabled Eco-Drive System

There exist different types of traffic light systems in the market that are portable, rechargeable, and suitable for adverse weather conditions. Yet, there are major reasons that make them not a good fit for the purpose of this project. We summarize some of these reasons below:

- **TCP/IP and cellular networking**: most existing portable traffic light systems lack TCP/IP protocol, Wi-Fi, or cellular support. This feature is necessary for enabling V2I connectivity based on which traffic light can communicate with remote terminals and the world.
- **Built-in computing**: in order to be integrated into a robotic ecosystem, a built-in computer with an operating system is necessary. This module facilitates programming, controlling, and monitoring different functionalities of the system. While most existing portable traffic light systems lack any form of all-purpose computing modules, some come with closed-source single board processing modules.
- **Costs**: existing portable traffic light systems are quite costly (upfront and maintenance), which make them unsuitable for this project.

We built a three-phase portable traffic light system that perfectly fulfills the above requirements. The top compartment of our portable traffic light hosts a single-board, general-purpose computer with common input/output ports as one can find in desktop computers. The computer is interfaced with a cellular modem for communication and a relay module through which the three phases are controlled. To be effectively integrated into the robotic ecosystem, similar to typical autonomous vehicles, the built-in computer runs Robot Operating System (ROS) on top of Linux OS. This enables the system to be able to encode or decode messages in a standard form defined for ROS, known as “ROS messages.” The content and format of these messages will be described later in this report. The portable traffic light system as seen in Figure 4 is weatherproof and powered by a portable battery with a run-time over 12 hours per charge.

Figure 4. The Structure of a Portable Traffic Signal

Currently, Transit Signal Priority (TSP) technology is implemented in various cities worldwide as a means to optimize transit operations and improve the overall effectiveness of public transportation networks. TSP technology receives signals from equipped transit vehicles and adjusts the timing of traffic signals, such as extending the green phase to allow buses to pass through intersections more efficiently. However, the TSP system, as it currently exists, does not control the speed of the vehicles. In this project, the focus is on optimizing the CAV's speed profile based on the known traffic signal plan. While previous research has explored simultaneous control of both vehicle speed and signal timing in simulation, this study is implementing it in the real-world with an actual CAV, but without adjusting the timing of the signal.

2.2.2 System Design and Architecture

Autonomous vehicle software is typically trained to be capable of recognizing traffic lights much the same way they perceive presence and characteristics of other objects, e.g., traffic signs, motorists, pedestrians, etc. As soon as their onboard perception system detects or recognizes the situation, CAVs update their behavior accordingly. In many cases, however, this comes with sharp lateral or longitudinal motions such as a sudden deceleration. As mentioned earlier, the speed profile—which is referred to as distribution of velocity in time domain—of a vehicle traveling across roads with signalized intersections is directly related to its energy consumption. Frequent accelerations or decelerations contribute the most to the energy profile. Given that, CAVs could optimize their speed profile more efficiently when they know what they are going to encounter in advance. For example, if the vehicle, instead of onboard cameras, relies on wireless communication for receiving traffic signal information ahead, it would be able to optimize its velocity even before it is actually able to see the traffic light. This is advantageous in several ways. First, the stop time of CAV could be minimized. Second, sharp decelerations could be avoided, and third, the trip time could be reduced. To achieve this, we need to overcome challenges in both “communication” and “autonomous driving software”:

1. “Autoware,” the open-source, self-driving software stack that is used in this project, by default, is not capable of interacting with the world outside of the CAV. However, the autonomous speed control can be realized only when the CAV’s onboard software recognizes the information originated from a remote source, i.e., portable traffic light system. Therefore, we need to modify the software so that it receives, digests, and makes decisions in real-time as required.
2. New messaging protocols and high-level network interfaces are required to be defined and implemented so that every end of the connection can talk over the communication channels in a secure and reliable manner. It is worth noting that in this project, we use cellular links to realize unlimited range connectivity, which even introduces more challenges as every cellular terminal falls within a different network. Also, messaging takes place in a single direction from infrastructure to CAV as the traffic light system does not need to receive any information from the vehicle.

We aim to build a system in which (1) the traffic light system can transmit signal information to nearby (approaching) CAVs, (2) CAVs can receive traffic signal information when approaching an intersection, and, finally, (3) CAVs’ onboard automated driving software can allocate desired speed profiles to improve energy efficiency and riders’ comfort. In the following subsections, we will elaborate on different modules of the system.

2.2.2.1 Signal Phase and Timing (SPaT) Messages

A common speed profile optimization problem is characterized by three variables: speed, position, and time. In particular, to update speed v for time t, the CAV needs to know its current position p_{CAV} as well as the traffic light (or intersection) position p_{TL}. Moreover, to make a decision whether to “accelerate,” “decelerate,” or “maintain” the current speed, the CAV would require to know the current and near-future status of the traffic light, usually known as signal phase and timing (SPaT). Our autonomous speed control algorithm, which will be described later in this section, will require all of the aforementioned information in order to accomplish the speed control task. We therefore define a message structure under ROS which is filled and transmitted by the traffic light system periodically at a rate of 10 Hz. As shown in Figure 5, this ROS message provides information about the traffic light's ID, type, phase count, geo-location, current phase, next phase, and the remaining time to the next phase.

Figure 5. The SPaT Message Content Sent by the Portable Traffic Light System

```
Header header

uint8 infra_id               # unique ID representing publisher {0},{1},etc.
string infra_class           # Target class 'vehicle' or 'pedestrian'
uint8 total_phase            # Maximum number of phases {1},{2},{3} per infra_class

float64 latitude             # global coordinate of the infrastructure
float64 longitude            # global coordinate of the infrastructure

string phase                 # current phase string e.g., "r","g", etc.
string next_phase            # upcoming phase e.g., "r","g", etc.
float32 time_to_change       # time to next phase update (sec)
```

2.2.2.2 Cloud-Based V2I Connectivity

In general, V2I communication can be established through cellular or Wi-Fi links as seem in Figure 6. In this project we build a system where message passing takes place through the former, cellular links. Cellular communications could bring some advantages for us when compared to Wi-Fi communication. For instance, Wi-Fi is limited by communication range, while cellular communication could deliver messages beyond such distance limits. Also, cellular communication has proven to be more reliable than Wi-Fi when mobile terminals are moving at high speed close to the range that vehicles normally travel. Besides, we consider an "indirect" (equivalently centralized) message passing architecture with a message broker in between according to a number of advantages and/or limitations:

- System Scalability: considering a centralized message broker could expand the number of receivers while keeping the network load manageable. Particularly, a transmitter (e.g., traffic light) would transmit to one destination (centralized broker) at a time instead of separately transmitting the same message to every receiver (e.g., CAV) which further overloads the network resources and causes congestion. This would increase the number of connected terminals, whether they are vehicles or roadside infrastructure.

- Address Discovery: in order to establish a communication, two conditions must be met; i) transmitter needs to know the network address (IP) of the receiver to which the message is going to be delivered, and ii) both the transmitter and receiver must be in the same network (subnet). However, none of these two conditions hold when common LTE modems are used as transmitter/receiver terminals since network addresses in this case are managed by network service providers (e.g., AT&T, Verizon, etc.) and every terminal is protected by network address translation (NAT). Using a centralized message broker whose network address is known to both transmitter and receiver, establishing end-to-end communication would no longer be a problem.
- Organization: By definition, a message broker is a centralized server that relays messages in a passive manner. Under this paradigm, a CAV can query the broker by sending a small "request" and wait for "response" from the broker. This approach guarantees that each querying vehicle receives ONLY the messages they are interested in since queries can be distinguished by "transmitter" and "message format" of interest. Using Wi-Fi, however, all receivers in proximity of transmitters could receive broadcast messages even if they are not interested in those contents.

A centralized (indirect) architecture, by nature, comes with a few disadvantages such as posing slightly larger communication latency and more complexity in implementation.

Figure 6. The Difference between Wi-Fi and Cellular Communication Systems
Left: Direct Wi-Fi Communication. Right: Indirect Cellular Communication

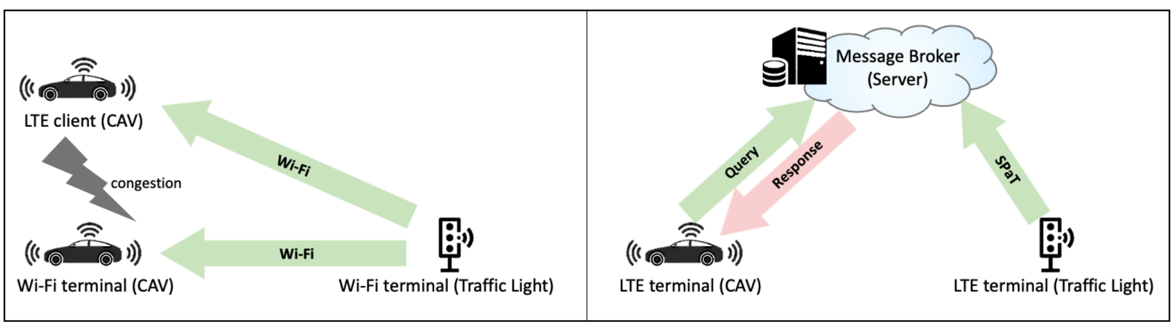
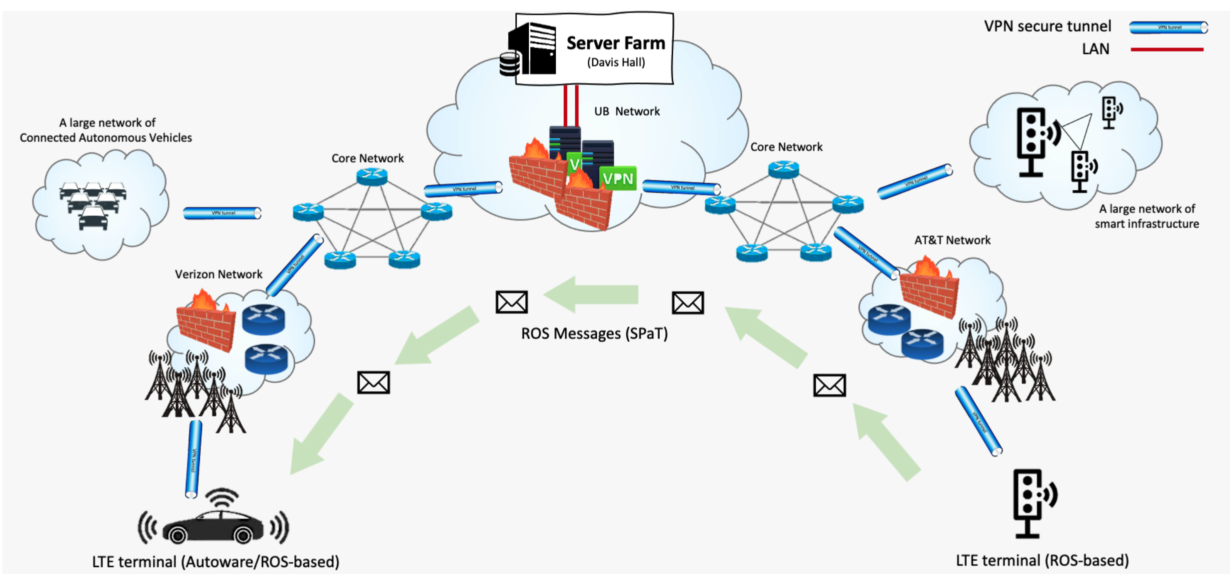


Figure 7 below shows the macroscopic view of our system architecture. In this architecture, the portable traffic light systems transmits SpaT information to a designated centralized server located in Davis Hall, University at Buffalo where we configured the message broker. The CAV, which in our case is a connected autonomous Lincoln MKZ, periodically queries the server to receive the SpaT information of the desired traffic light system. Please note that the traffic light and CAV might use different mobile carrier services, in our case AT&T and Verizon, and that they are not within protected or isolated networks. Instead, these network terminals are in public networks with Internet access and hence the communication links are prone to adversarial attacks or other security risks. As the autonomous speed control algorithm in this project is supposed to solely rely on SpaT information provided by the traffic light, any form of security attacks could lead the CAV to misconduct based on the manipulated, faulty, or incomplete information. The consequences could be catastrophic. To eliminate the chance of getting into such scenarios, we use virtual private networks (VPN), in which all information (either queries or responses) are encrypted and exchanged within secure channels also known as tunnels. This significantly reduces the exposure to malicious activities of attackers and therefore the vehicle makes decisions based on the actual data provided by the traffic light system.

Moreover, the architecture in Figure 7 below guarantees the scalability of the entire ecosystem where numerous terminals can plug into the system regardless of their type, physical location, whether they are stationary or mobile, and the time or duration of connectivity. It should be noted that the cloud (message broker) services run all the time, listen, and are ready to serve connections continuously. So, in contrast to direct communication models, in our model, transmitters or publishers such as roadside units, portable sensors or traffic lights can connect any time regardless of whether other terminals such as CAVs are there to receive those messages.

Figure 7. The Macroscopic Centralized Data Transfer Architecture through LTE Networks



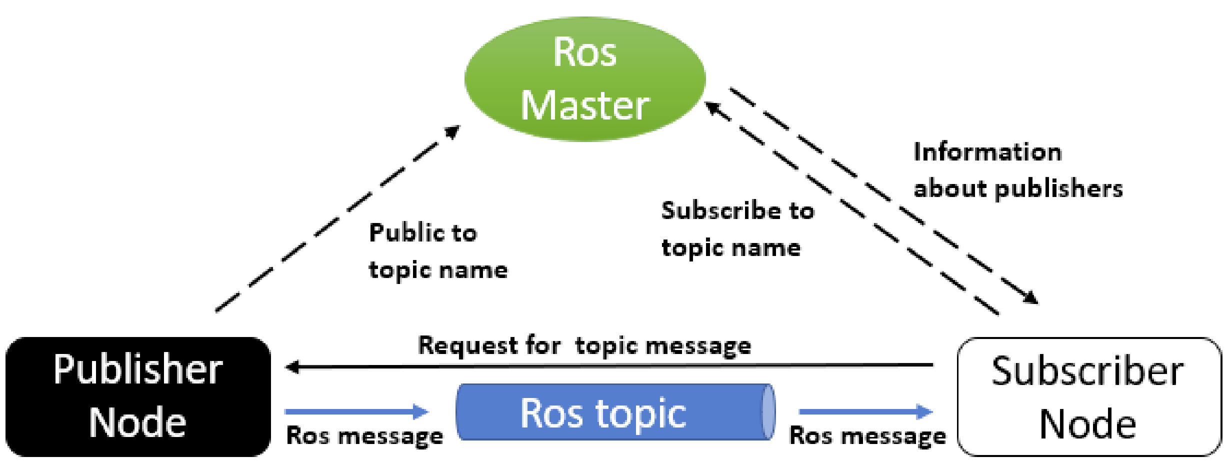
There are several services that run on the centralized server, we refer to it as cloud. To make those functions clear, we would like to elaborate on some of the major components inside the cloud and the way they interact with the remote OBUs and RSUs.

2.2.2.3 Robot Operating System

To understand why and how ROS could benefit our V2I communication model, we first need to understand what ROS stands for. Autoware, the self-driving software stack and our portable traffic light system are both ROS-based systems. ROS is a framework that works on top of Linux OS. It is called an operating system (OS) mainly because it provides all the services that other OS systems do—for instance, hardware abstraction, low-level device control, implementation of commonly-used functionality, or message-passing between internal processes. ROS is designed to be a loosely coupled framework where a process is called a node and every node should be responsible for certain tasks (see Figure 8).

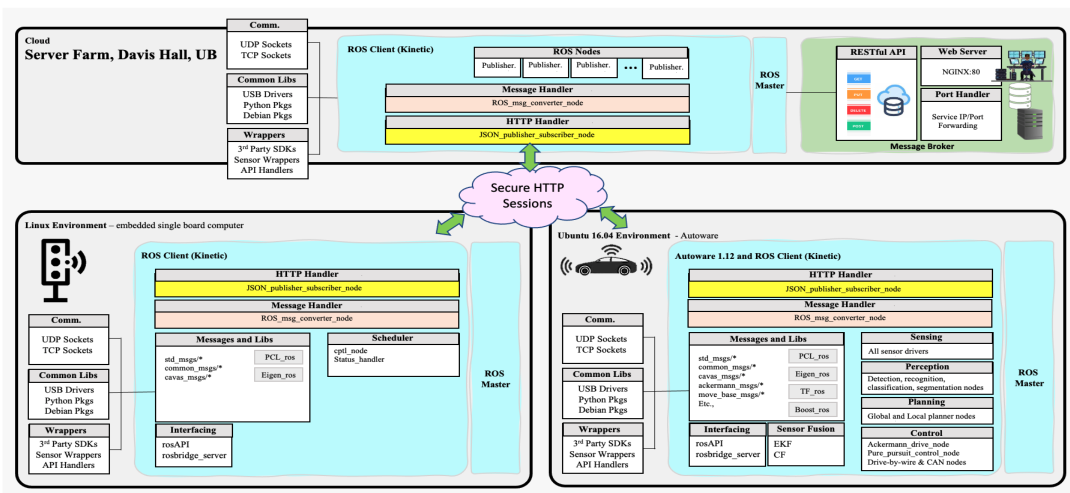
For example, in an autonomous vehicle, one ROS node could be responsible to calculate latitude and longitude from the raw signals received by onboard GNSS receiver while another could be responsible for fusing latitude and longitude into the raw measurements of the onboard accelerometer and gyroscope to improve localization accuracy. ROS nodes communicate with each other using messages passing via logical channels called topics. Each node can send or get data from the other node using the publish/subscribe model. Therefore, in our example, the first node publishes GPS coordinates in a message and the second node subscribes to that message so it can use the coordinates for fusion.
To efficiently build a distributed robotic ecosystem we configure a standalone ROS master and client on our cloud as well as the remote nodes.

Figure 8. The Framework of ROS Data Communication



While the aforementioned publish/subscribe model facilitates message passing between individual nodes (processes) that run on the same machine, it is not useful when nodes are running on different machines across the Internet. In other words, ROS nodes communicate with each other over reliable TCP connections that guarantee consistency and the order of every message. 23ith the Internet as the basis of connection between our centralized server and roadside traffic light system and CAVs, connection-oriented approaches like TCP would never be working reliably. To this end, we design and implement a high-level interface for exchanging ROS messages between remote nodes across the Internet. The interface exchanges messages in JSON format and through HTTP protocol. Accordingly, we developed a "message handler" node that converts messages between ROS and JSON formats, and an "HTTP handler" node that sends or receives JSON messages over the "to" or "from" on each side of communication, as shown in Figure 9.

Figure 9. The Microscopic V2I Communication Architecture between Portable Connected Traffic Light System and CAV



2.2.2.4 Message Broker API

The message broker API in our message passing model is a group of web-based services—consisting of RESTful API, web server and port handler—that registers published messages using unique identifiers. These identifiers are determined by the publisher node and the ROS topic name. These messages are then retrieved and relayed when the broker receives a request from a remote subscriber. When a particular CAV (subscriber) queries the server asking for SpaT messages of a particular traffic light, the API looks for a live message directory associated with that infrastructure. If that exists, it relays the most recent message received from the infrastructure. Since every message has a timestamp, the API can avoid relaying outdated messages based on user-defined criteria, in case the connection between broker and transmitter gets interrupted or lost.

Inside the TCP/IP protocol stack, ROS nodes and message broker API use services provided by transport and application layers, respectively. Our HTTP-based, message-passing framework encodes and carries ROS messages in chunks as needed. These messages are decoded and reshaped back into the original ROS message format when get delivered to a subscriber (e.g., CAV). Therefore, our model hides the complexity of the multilayer architecture from remote ROS nodes so that the publisher and subscriber may think they are both working on the same machine. We refer to this feature as the "rule of transparency" that is also held in modern distributed systems.

It is worth noting that the location of the message broker is not critical because its primary role is to relay messages between the traffic light infrastructure and the CAVs. However, having the message broker in the cloud (or remote server) offers scalability advantages. With a cloud-based message broker as implemented in this project, a single server can handle messages from multiple traffic signals, allowing for efficient management and coordination of a larger network of signals and CAVs. This centralized approach enables easy scalability as the number of connected devices and traffic signals increases. Additionally, the distance between the message broker and the traffic light/CAV does not significantly impact its performance. The propagation delay, which refers to the time it takes for a message to travel between the broker and CAVs, is typically very small due to the high-speed and low-latency nature of modern communication networks.

2.2.2.5 Automated Speed Control Algorithm

Smooth acceleration and deceleration, not only contributes to the total energy consumption of the autonomous vehicle, but also provides more comfort to the riders. A CAV approaching a signalized intersection can find itself within one of the following four scenarios (Figure 10):

1. Current signal is GREEN, but CAV would not make it at current speed, but would make it at some higher speed. In this scenario, CAV will need to accelerate and increase its "current speed" to some "target speed" to go through the intersection before the signal turns YELLOW/RED. The "target speed" must still be permissible based on traffic regulations (below posted speed limit).

2. Current signal is RED and stopping is unavoidable at current speed, but avoidable at a lower speed. In this case, CAV, if it continues at the current speed, would arrive at the intersection when the signal is RED. Therefore, in order to avoid stopping or waiting, CAV would need to decelerate and decrease its "current speed" to some "target speed". The "target speed" has still to permissible based on traffic regulations and drivers expectations (i.e., between a minimum and maximum speed limit).
3. Current signal is RED or GREEN and CAV will be able to legally go through the intersection at current speed. This condition states that no change in the current speed is required and CAV will avoid stop-and-wait anyway.
4. Current signal is RED or GREEN and stopping is unavoidable at any allowable speed. Under such conditions, CAV would maintain its current speed and normally, decelerate, stop and wait for the next GREEN signal. In other words, the "target speed" in this case would violate the minimum or maximum speed limit.

Mathematically, with t, d and $v_{current}$ denoting: the remaining time to the next phase, distance to intersection and CAV's current speed, respectively, the smoothest acceleration that is necessary to apply would be:

Equation 1.

$$\boldsymbol{a_{min} = \frac{2}{t^2}(d - tv_{current})}$$

here, a_{min} is valid if and only if the following condition holds.

Equation 2.

$$\boldsymbol{v_{max} \geq \sqrt{v_{current} + 2ad} \geq v_{min}}$$

where v_{max} and v_{min} are the maximum and minimum speed limits for a road. Otherwise, CAV would require a sharper pace in changing its current speed to satisfy the condition above. These four conditions are illustrated in Figure 10. Since the location of traffic light system, current and next signal phases, and the remaining time to the next phase, all are included in the SPaT messages transmitted by the traffic light, CAV would be able to perform these calculations and figure out the scenario. We propose a simple automated speed control algorithm. In this algorithm two regions are defined:

- Traffic Light Region (TLR): it is a range centered by traffic light (intersection) in which CAV constantly updates its speed profile based on the current scenario. It is assumed that CAVs located beyond this range are too far to the intersection, and therefore, they don't have to react to current SPaT information.
- Adaptive Deceleration Region (ADR): this is the range centered by traffic light in which CAV performs deceleration for a complete stop if acceleration or deceleration would not help the CAV to avoid a stop-and-wait (scenario 4). ADR is dynamic and is calculated based on CAV's current speed, distance to intersection, and a fixed deceleration rate.

Figure 10. The Four Scenarios of a CAV Approaching a Signalized Intersection

The algorithm pseudocode is summarized in Figure 11.

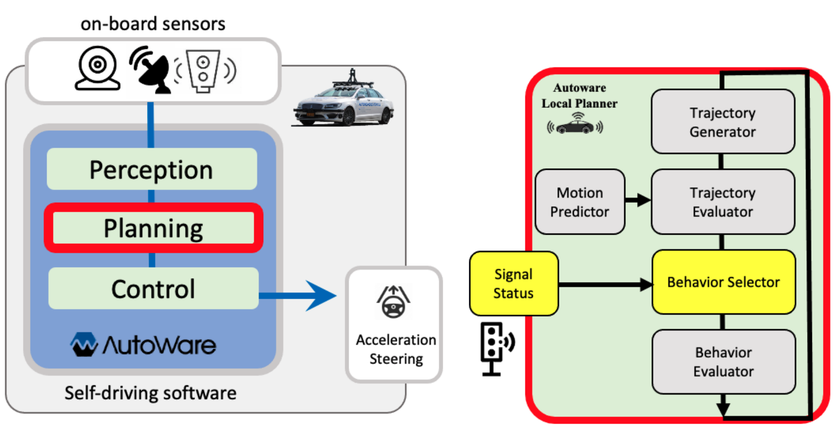
Figure 11. The CAV speed control algorithm (pseudocode)

```
if CAV is inside TLR:
        calculate current_arrival_time
        if signal is RED:
            if current_arrival_time < time_to_next_phase + guard_time:
                desired_speed = calc_speed_for_earliest_arrival_on_greeen()
                if desired_speed > MIN_SPEED_LIMIT: proceed at desired_speed
                else if inside ADR: prepare_to_stop()
            else: proceed at current_speed
        if signal is GREEN:
            if current_arrival_time > time_to_next_phase - gaurd_time:
                desired_speed = calc_speed_for_latest_arrival_on_greeen()
                if desired_speed < MAX_SPEED_LIMIT: proceed at desired_speed
                else if inside ADR: prepare_to_stop()
            else: proceed at current_speed
        else:
            if inside ADR: prepare_to_stop()
            else: proceed at current_speed
```

2.2.2.6 Self-Driving Software Integration

As mentioned before, we aim to conduct real-world experiments and assess the feasibility of deployment of portable traffic light systems and implementation of V2I-aided speed control on a CAV platform. The vehicle that we used for this purpose is a Lincoln MKZ that is outfitted with different sensors (LiDAR, cameras, radar), a computer and drive-by-wire interface. However, one of the challenges previously mentioned is that most open-source automated driving software stacks are not V2I-ready, which means that the software used does not have any form of internal routines to receive and process information from road infrastructures wirelessly. In this way, we need to further develop the vehicle's software to host our speed-control algorithm while interacting with the remote infrastructure and/or our cloud services (e.g., message broker). We have described how our nodes including the portable traffic light, CAV, and the cloud middleware interact with each other in subsection 3.2.2.2. In this subsection, we therefore focus on the Autoware self-driving software that is used on our development platform (Lincoln MKZ).

Figure 12. The Modular Structure of Self-Driving Software (Autoware) and Our Signal Communication



Autoware software stack consists of three major modules, they are the perception, planning, and control modules. Planning module is where the vehicle evaluates the driving environment and makes decisions accordingly. These decision-making tasks are informed by the perception module. The skeleton of "local planner"—which is the backbone of the planning pipeline—is depicted in Figure 12.

The pipeline consists of several nodes including trajectory generator, trajectory evaluator, behavior selector, behavior evaluator, and motion predictor. We have integrated our V2I-aided speed control algorithm into the behavior selector and defined new routines in which (1) CAV subscribes to SPaT messages, (2) evaluate the current scenario, and (3) calculate new speed profile and update the current behavior. These updates are further picked by the control modules where commands are generated for lateral and longitudinal motion of the vehicle. We have performed several tests on campus using a traffic light deployed on a road within UB's CAV proving ground and the Lincoln MKZ (CAV) through which we have successfully demonstrated the end-to-end V2I connectivity between CAV and portable traffic light. Figure 13 shows the experiment scenarios.

Figure 13. The Test Scenarios Using a CAV Platform (Lincoln MKZ) and Portable Traffic Light System

3 The Feasibility and Benefits of Infrastructure Sensing Support

Self-driving vehicles rely on sensors such as cameras, LiDARs, and radars to perceive the surrounding environment and navigate safely. These sensors suffer from some intrinsic limitations such as confined sensing range, occlusion (blockage of sensor's line of sight) and sensitivity to weather and/or lighting conditions. Currently, many connected autonomous vehicles (CAVs) primarily perceive the environment from a single perspective, i.e., using their onboard sensors only, and as a result are unable to leverage additional scene information from the viewpoint of other sources, such as other CAVs or the infrastructure. Obviously, data exchange and fusion would increase the situational awareness of autonomous driving systems, thereby improving both safety and comfort.

In this section, we research the feasibility of collaborative perception between the infrastructure and CAVs through vehicle-to-infrastructure (V2I) communication. In fact, we (1i) study LiDAR point cloud fusion between infrastructure and vehicle by developing 3D data processing and fusion algorithms, and (2) research the feasibility of incorporating road weather information into automated driving systems.

The objectives of the research are realized through the installation of a Road Weather Information System (RWIS) as well as a LiDAR light-pole as two different roadside units (RSUs) on UB Proving Grounds for CAVs, located along the service road, across from the Center for Tomorrow (CFT) on UB's north campus. To demonstrate the feasibility and the utility of collaborative perception, the research team build communication systems, including interfaces and message structures, that enable data exchange between RSUs, our centralized server (cloud services) as well as the AV development platform.

3.1 Roadside LiDAR Support for CAVs

The intrinsic limitations of CAV's onboard sensors such as LiDAR, radar, camera, in terms of field of view or sensing range, often result in inefficient planning and high-risk maneuvering. Sensory information exchange between CAVs (through vehicle-to-vehicle or V2V communications), or between a CAV and the infrastructure (vehicle-to-infrastructure or V2I communications), plays a crucial role in enabling efficient planning and safe maneuvering for CAV, by overcoming sensing limitations of onboard sensors. Each such cooperative CAV can then expand its perception capability, using all its sensing modalities, along with the sensory information it receives over wireless links from immediate neighbors or roadside infrastructure. Ultimately, the performance of any higher-level application using the augmented data (including long-term path planning, obstacle/crash avoidance strategy, and eventually autonomous driving) could be significantly enhanced through this cooperative dissemination of sensory information.

Navigating road junctions can be hazardous for CAV and humans alike. The perception sub-system that helps CAV to detect objects and accordingly adjust the velocity and steering angle through junctions requires direct visibility of the objects that the CAV must avoid. When the line-of-sight to such potential objects is obstructed by buildings, vegetation, other vehicles, or even by inclement weather, these systems may fail, resulting in an increase in risk for collision. Although there are several possible data types that can be exchanged between roadside infrastructure and CAV, the focus of this subtask is on 3D point cloud data generated by LiDAR.

The benefits and disadvantages of LiDAR are summarized in Table 1. 3D data obtained by LiDAR can provide abundant geometry, shape, and scale information about objects, and therefore, an opportunity to better understand the environment around CAV. Three-dimensional data can usually be expressed in different formats, including depth image, point cloud, and volume grid. As a common format, the point cloud retains the original geometric information in three-dimensional space without any discretization. Therefore, it is preferred in many scenarios and can be utilized by autonomous systems for detection, localization, and navigation. Moreover, automotive LiDAR sensors can sense a 360-degree, horizontal angle of view in most weather circumstances.

Table 1. Advantages and Disadvantage of LiDAR

Advantages	Disadvantages
Millions of points (accuracy)	Massive datasets
Day or night	Indiscriminate
360-degree, horizontal sensing	Output requires manipulation (processing)
Penetrating canopy gaps (open spaces between objects)	Occlusion (blockage of sensor’s line-of-sight)
Distance and size measurements	High price

A ***roadside*** LiDAR can be used to cover those areas of the road that are occluded from CAV's onboard LiDAR perspective. However, fusing point cloud from two different sources is challenging because of the following reasons:

- Point clouds can be very large. There could be thousands or millions of points that are measured by a single LiDAR in a second. Transmitting this huge amount of data wirelessly requires massive bandwidth which is not available today.
- Lengthy communication violates the real-time performance requirement of an autonomous system real-time safety critical tasks. It is worth noting that collaboration between different sources involves both computational and communication overhead. Given that in every second, a LiDAR could generate up to 30 frames of point cloud data, the data could easily become outdated if these two phases introduce large delays.
- 3D geometry and pre/post processing algorithms are necessary for fusion. Point cloud datasets are valid with respect to a particular coordinate system centered by the LiDAR. Also, point clouds vary strongly in their point densities and their accuracies. This is due to, e.g., the sensor size or the distance between sensor and object. Hence, fusion of heterogeneous multi-source 3D point clouds requires algorithms to handle such geometry discrepancies.

We will consider these challenges in our project and develop fusion algorithms to address some of the key challenges outlined above.

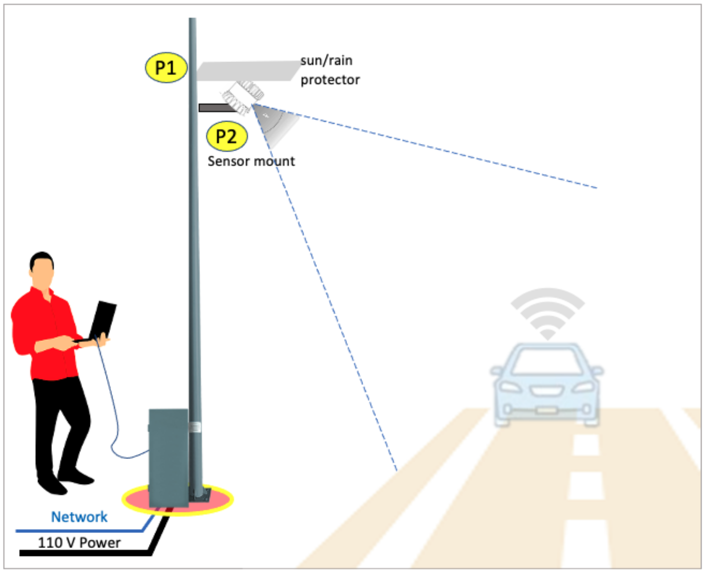
3.1.1 Roadside LiDAR Installation

To research the feasibility and demonstrate the benefits of collaborative testing, the project installed a 32 channel LiDAR on a lightpole located on Service Center Rd, UB north campus, (latitude 42.992749, longitude -78.795409). The location and effective road coverage of the roadside LiDAR are shown in Figure 14.

Figure 14. LIDAR Location on UB Proving Ground

The LiDAR used in the setup generates up to 86 Mb/s data and consumes between 14 to 20 Watts of power. The light pole hosting the LiDAR sensor is also equipped with a cabinet (for network and power support). Researchers can communicate with the sensor on site using portable computers and the provided network outlets or remotely from an on-campus server room, where the point cloud data is processed and relayed to CAVs. Figure 15 shows the light pole configuration model.

Figure 15. The Roadside LiDAR (light pole) Configuration



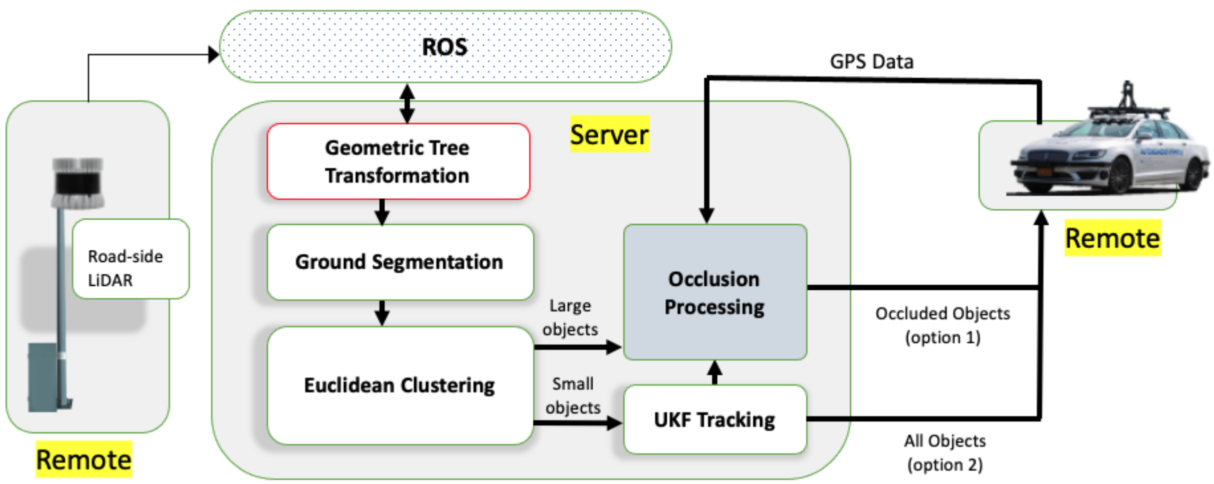
3.1.2 Data Accessibility

The LiDAR sensor is connected to UB's protected network and is allocated a fixed IP address. Therefore, designated servers on campus can find access to the data for processing. The processed data can then be relayed to remote CAVs or any other mobile node on campus that needs the data. Alternatively, researchers can adopt portable computers and wireless access points on site and create a wireless local area network (W-LAN), and then share data over wireless links to the connected nodes (e.g., CAVs, robots, etc.) in proximity. In order to access and process LiDAR data, all the machines including the server as well as CAVs' onboard computers are configured with Linux and Robot Operating Systems (ROS). Sensor drivers are also installed on these workstations.

3.1.3 Collaborative Perception Algorithm

Generally, the fusion of two point clouds consists of three steps. First, both point clouds must be initially aligned to get a rough approximation for a common coordinate system and scale. Second, point-cloud registration is performed. In the third step, surfaces are smoothened, outliers are reduced, and artifacts are removed or highlighted. In our implementation, however, we add a few other steps to optimize the fusion process considering the constraints posed by wireless networking. In fact, we filter some part of the point cloud out before transmitting the point. This optimization involves ground segmentation, object detection (clustering) and occlusion discovery. Moreover, instead of raw points, we use a tree-data structure for representing 3D points which further helps to speed up embedded search algorithms as well as registration. Figure 16 depicts the flowchart of our collaborative perception software framework.

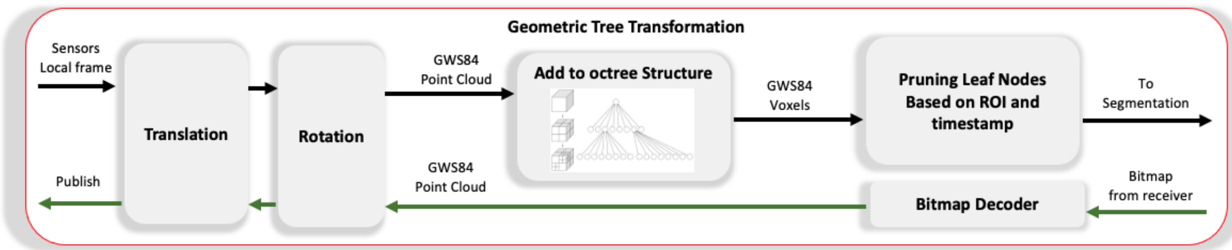
Figure 16. The Flow Chart of the Collaborative Perception Software Framework



We describe different elements and components of our collaborative perception pipeline below:

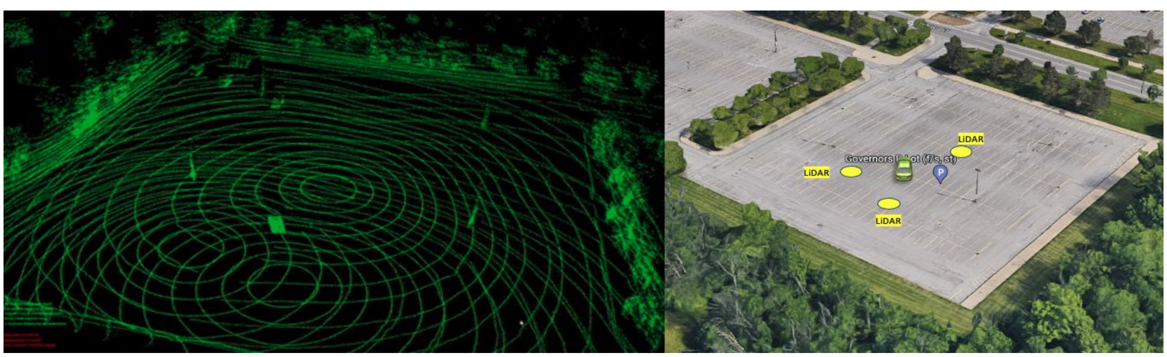
- **Geometric Tree Transformation:** At the first step, we convert the raw point cloud to an octree. An octree is a tree-data structure where each internal node has eight children. Non-empty leaf nodes of an octree contain one or more points that fall within the same spatial subdivision. The largest voxel is the world representing the entire point cloud. A tree-data structure facilitates occlusion discovery between the LiDAR and an object. It also encodes the large-point cloud into a smaller structure that can be compressed and exchanged more efficiently. This step is depicted in Figure 17.

Figure 17. Steps of Geometric Tree Transformation



It is worth noting that the tree constructed from a raw point cloud is built within the global coordinate system. In particular, we adopt the GWS84 world coordinate system and translate the LiDAR center coordinates into the earth coordinate center before we construct a tree. Conversion to/from a global coordinate system is necessary when two or more 3D data points are merged together. It is also worth noting that the translation and rotation of a 3D data, from source frame to frame, requires additional information such as source and destination precise location. While a roadside LiDAR's location can be surveyed, the precise coordinate of CAVs can be determined using real-time kinematic positioning (RTK) systems which provides cm-level accuracy. Figure 18 shows the result of merging three different LiDARs in the middle of Governors lot, UB north campus.

Figure 18. The Merging LiDAR Result in Test Field



- **Ground Segmentation:** The ground at the location where we install the roadside LiDAR is almost flat. Therefore, the points constructing the ground are not useful as all the road users including bikes, vehicles, and pedestrians are located or travel on the ground surface. Given this, a CAV is generally not interested in receiving such information about the ground. To remove ground points, we adopt planar segmentation algorithms.
- **Clustering:** Objects such as trees, buildings, traffic signs/lights are not of interest to a CAV. Given this, such information can be excluded from the point cloud data (octree) before transmission. However, large objects such as buildings and vegetation can potentially block CAV's line-of-sight and therefore hide smaller objects, e.g., cars, bikes, pedestrians which are of the greatest importance to CAVs perception system. We employ thus the euclidean clustering algorithm to partition the point cloud into sparse clusters (objects) based on their dimensions.

- **Object Tracking:** Object tracking allows us to estimate the trajectory of objects in a few seconds time frame. We use this estimation to compensate for the possible computational and communication delays. For example, if the point cloud data is going to be delivered to the CAV after 0.1 second, we can directly send a point cloud that describes 0.1 second in the future by incorporating the estimated non-linear trajectories of objects, their velocities and 3D point translation algorithm. Figure 19 illustrates the result of applying the unscented Kalman filter (UKF) tracking algorithm to time-series point cloud data. In this scenario two pedestrians are walking toward each other on a circular path around a vehicle.

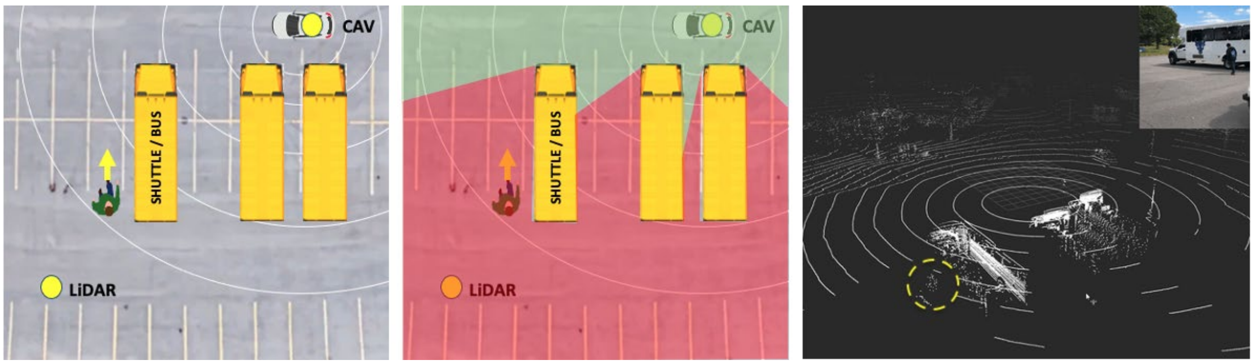
Figure 19. The LiDAR Point Cloud Data Using the Unscented Kalman Filter tracking Algorithm

- **Occlusion Discovery:** We further reduce the size of point cloud by filtering out the objects that the CAV can see without help, i.e., they are in the line-of-sight of CAV's LiDAR. To this end, we need to identify objects within the roadside LiDAR's point cloud that are occluded from CAV's perspective. Figure 20 illustrates an example scenario where the roadside LiDAR recognizes the occlusion between CAV and a cyclist. We carry out occlusion discovery using ray tracing algorithm wherein we look for voxels in the octree that are located in between CAV and every other object within roadside LiDAR's point cloud.

Figure 20. An Example Scenario for LiDAR to Recognize Occlusion

In an experiment we verified the proposed collaborative perception framework in which a large vehicle (shuttle) blocked the line-of-sight of CAV's LiDAR (see Figure 20). A pedestrian is walking behind this large vehicle toward the CAV's trajectory. In this experiment CAV is not moving. A second LiDAR (portable infrastructure sensing unit) is located behind the pedestrian so that this LiDAR can sense the pedestrian and collaborate with the CAV to cover the area due to occlusion. Figure 21 (middle) shows the occluded (red) and non-occluded (green) areas. Figure 21 (right-hand side) shows the result of point cloud fusion from the CAV's perspective. As it can be seen, the pedestrian is now visible to the CAV with the help of the second LiDAR.

Figure 21. Test Experiment Scenario for See-Through System Using Two LiDARs



3.2 Collaborative Weather Information Sensing

Inclement weather conditions, such as snowstorms, typically result in a significant reduction in visibility, reduced road friction and slippery roads. During such conditions, human drivers typically adapt their driving behavior, in an attempt to mitigate the increased risk for accidents that accompany inclement weather conditions. Specifically, drivers would tend to reduce their speeds, and leave longer headways between their own vehicle and the vehicles ahead.

Figure 22. The Impact of Sensors in Terms of Different Weather Conditions

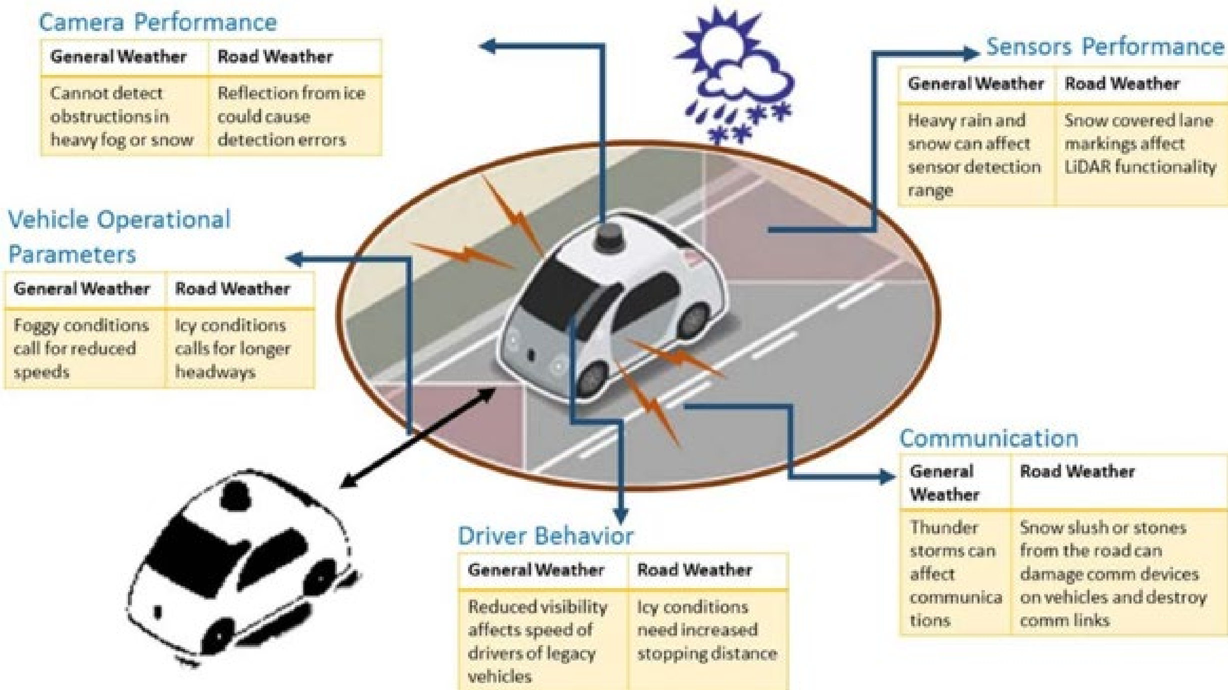
Modality	Light rain <4 mm/h	Heavy rain >25 mm/h	Dense smoke /Mist vis<0.1 km	Fog vis<0.5 km	Haze/Smog vis>2 km	Snow	Strong light	Contamination (over emitter)	Operating Temperature (°C)	Installation complexity	Cost
LiDAR (λ 850–950 nm and 1550 nm)	2	3	5	4	1	5	2	3	−20 to +60 (Velodyne, 2021d)	Easy	High
Radar (24, 77 and 122 GHz)	0	1	2	0	0	2	0	2	−40 to +125 (Texas Instruments, 2021)	Easy	Medium
Ground-Penetrating Radar (100–400 MHz)	0	0	0	0	0	1	0	2	−5 to +50 (Cornick et al., 2016)	Hardest	Medium to high
Camera	3	4	5	4	3	2 (dynamic) 3 (static)	5	5	−20 to +40 (Garmin Ltd., 2021)	Easiest	Lowest
Stereo camera	Almost same as regular camera								0 to +45 (Ricoh, 2021)	Easy	Low
Gated NIR camera (Bright Way Vision, 2021) (λ 800–950 nm)	2	3	2	1	0	2	4	3	Normally 0 to +65 (SenS HiPe, 2021) for InGaAs cameras	Easy	Low
Thermal FIR Camera[a] (λ 2–10 μm)	2	3	3	1	0	2	4	3	−40 to +60 (Axis Communications, 2021)	Easy	Low
Road-friction sensor[b] (Lufft, 2021) (infrared)	2	3	3	2	1	2	1	5	−40 to +60	Medium	Low

The effect level each phenomenon causes to sensors:
0 - negligible: influences that can almost be ignored.
1 - minor: influences that barely cause detection error.
2 - slight: influences that cause small errors on special occasions.
3 - moderate: influences that cause perception error up to 30% of the time.
4 - serious: influences that cause perception error more than 30% but lower than 50% of the time.
5 - severe: noise or blockage that causes false detection or detection failure.
[a]Thermal camera is considered to be installed outside of cabin and without glass housings.
[b]Road-friction sensor operating relative humidity is <95% but is able to measure 0~100% humidity.

Typically, CAVs navigate via the help of onboard cameras and radars, and LiDAR sensors. These high-resolution sensors help cars see everything from a traffic cone on the side of the road, and a bend in the road to a pedestrian crossing the street. However, sensing is also vulnerable to weather conditions. There are a number of additional risks posed by weather. For example, millimeter-wave radar's performance can be reduced by 55% during severe precipitation. Also, given that many CAVs are electric powered, their operation range could be significantly reduced in adverse weather, e.g., warm weather conditions decrease range by up to 17% and cold weather conditions decrease range by up to 41%. In a more comprehensive comparison [12], the impact of adverse weather conditions on a diverse variety of sensors is summarized in Figure 22.

Moreover, it is crucial to distinguish between *general weather* information and *road weather information* as each could impact autonomous driving in different ways. As shown in Figure 23, adverse weather conditions pose safety, mobility, and trip planning implications.

Figure 23. The Aspects of RWIS That Can Help CAVs



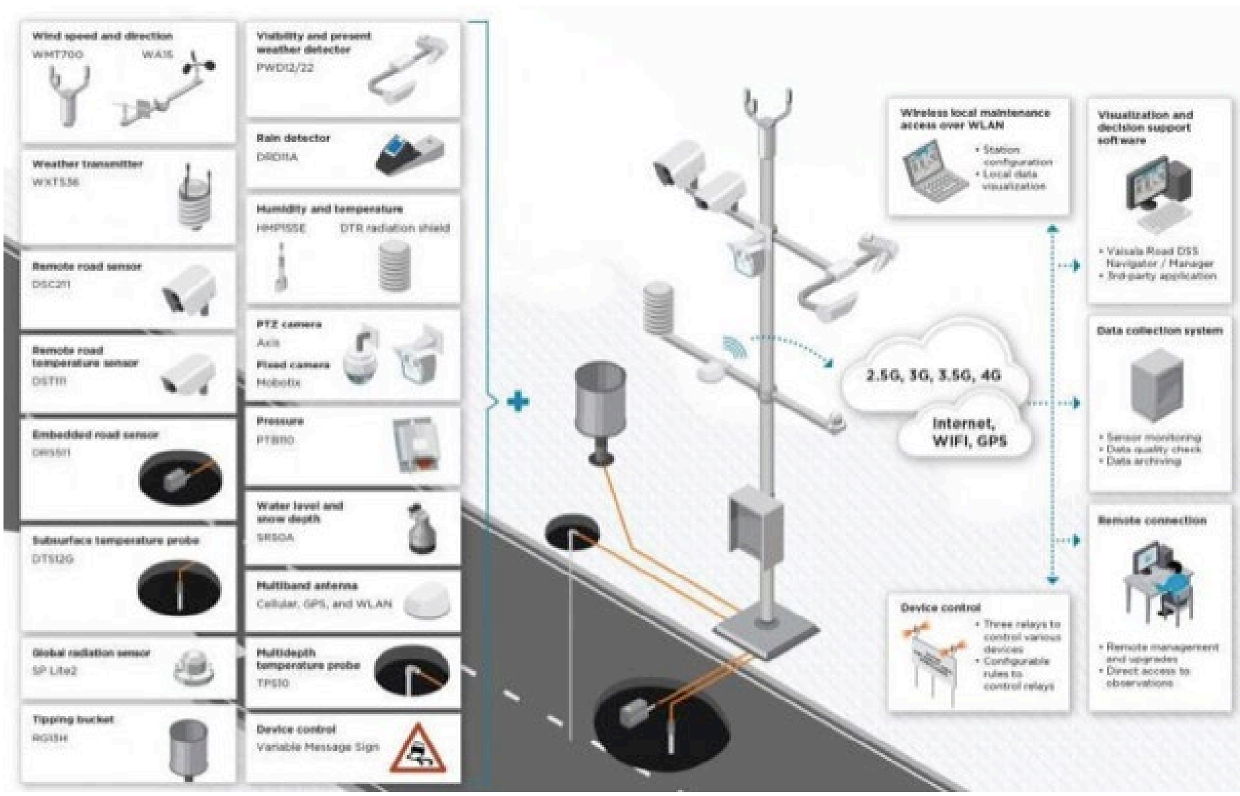
In this project, we research the feasibility of incorporating road-weather information into autonomous driving. In particular:

- We install a road-weather information system (RWIS) on UB Proving Grounds for CAV located along Service Center Rd on UB North Campus.
- We develop and build a system that enables communication between RWIS, cloud server and CAV.
- We study the feasibility of a sample application, i.e., road weather-aided autonomous speed control for CAVs, and conduct simulations.

3.2.1 Road Weather Information System

A Road Weather Information System (RWIS) consists of: (1) automatic weather stations in proximity of roadways, also known as environmental sensor stations (ESS), (2) a communication system for data transfer, and (3) central systems to collect field data from numerous ESS. These stations measure real-time atmospheric parameters, pavement conditions, water level conditions, visibility, and sometimes other variables. Central RWIS hardware and software are used to process observations from ESS to develop nowcasts or forecasts, and to display or disseminate road weather information in a format that can be easily interpreted by a manager. In particular, RWIS provides regional information including weather temperature, humidity, road surface temperature, ice/snow depth, and slipperiness rating. Figure 24 shows different sensor components of our RWIS.

Figure 24. The Sensors Contains in the RWIS



For the UB Proving Grounds, as mentioned earlier, the RWIS roadside unit was installed on Service Center Rd, UB North Campus, (i.e., R1, latitude 42.994116, longitude -78.797699). Figure 25 shows the exact location.

Figure 25. The Location Where RWIS is Installed on Service Center Rd, UB North Campus

3.2.2 Communication System

Using CV terminology, communication between RWIS and CAV is classified as vehicle-to-infrastructure (V2I) communication. In the specific case of RWIS and CAV communications, the following challenges need to be addressed to enable CAVs to leverage road weather information:

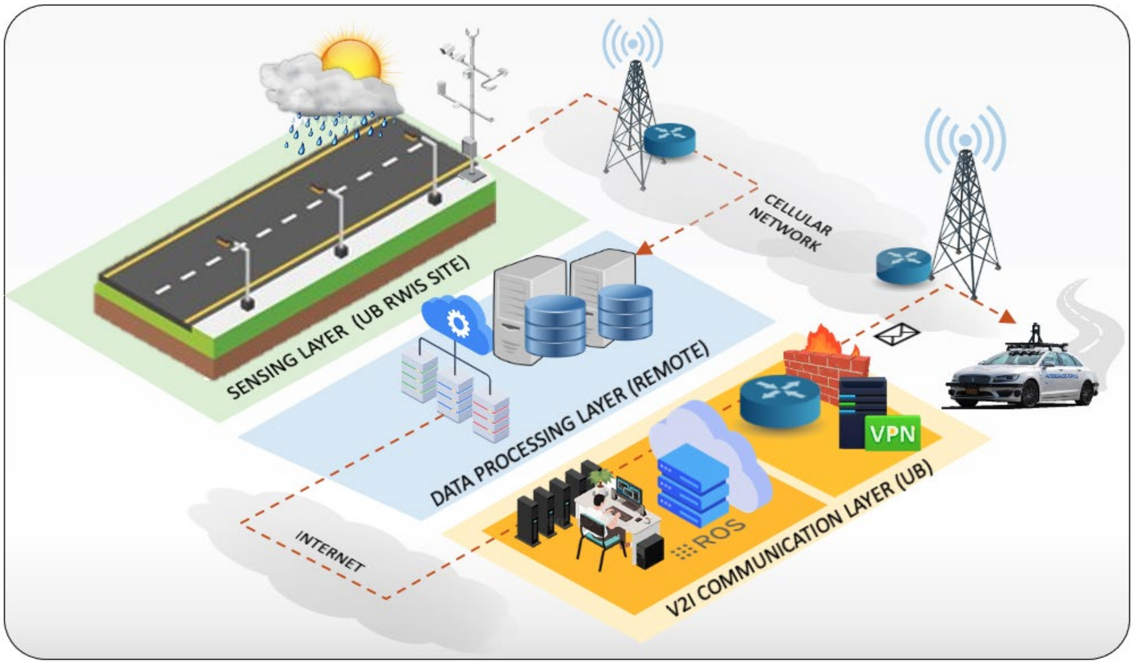
1. The RWIS is maintained by the vendor who provides specific methods for accessing and/or visualizing data e.g., website, weather portal. However, the autonomous driving system cannot directly use such methods to obtain information. Therefore, a secure V2I channel should be created through which CAV can access the data.
2. The RWIS data that is provided for the user through vendor's weather portal is not in the format that the automated driving system can use. In fact, CAVs rely on Robot Operating Systems (ROS) in which data between internal processes is shared through specific formats known as ROS messages. Moreover, not all the weather information provided by the RWIS is of interest to the autonomous driving system. Therefore, we need a different approach to preprocess this data before CAVs can utilize them.

In our project, the RWIS is configured to communicate with a server located in the control office (UB Davis Hall), which serves as a central point-of-contact. This server can receive and process data streams from various sources, including roadside LIDAR. Through this central server, RWIS can collaborate and communicate with any remote node, including connected autonomous vehicles (CAVs). Additionally, if necessary, the server can co-process roadside LiDAR and RWIS data before making it available for CAVs.

As shown in Figure 26, we develop a centralized communication system which comprises of the following three layers:

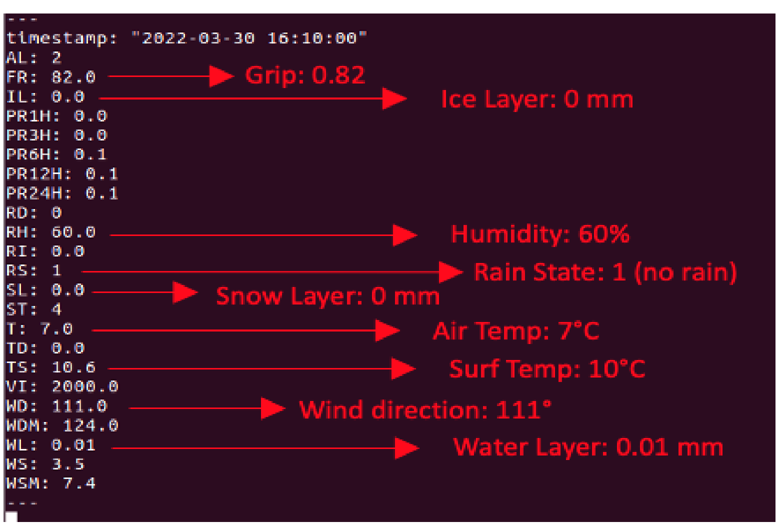
- **Sensing layer:** includes the road environment and ESS hardware.
- **Remote data processing layer:** The set of hardware/software systems (administered by vendor) that are responsible for converting the raw measurements into meaningful information for human understanding. The vendor processes RWIS sensory data once every 5 minutes and we have access to the processed road weather information through the vendor's API at any moment. The API returns data in the form of a response upon a request is sent. Every response is just a few kilobytes.
- **V2I communication layer:** The set of hardware/software systems on UB campus, including a locally defined API, that enables secure remote access to the processed road weather data for CAVs in the proper shape and format.

Figure 26. The Structure of Communication System between RWIS and CAVs



Based on the proposed communication system, the CAV does not need to communicate with untrusted sources outside of UB. Also, to further protect data from malicious activities, the communication between CAV and UB servers (third layer) are fully encrypted within a virtual private network (VPN). The vehicle periodically queries the centralized ROS API on our designated servers for updated road weather information as needed. The data is then transmitted to the CAV in a pre-defined ROS message format as shown in Figure 27.

Figure 27. Message Format for RWIS Information

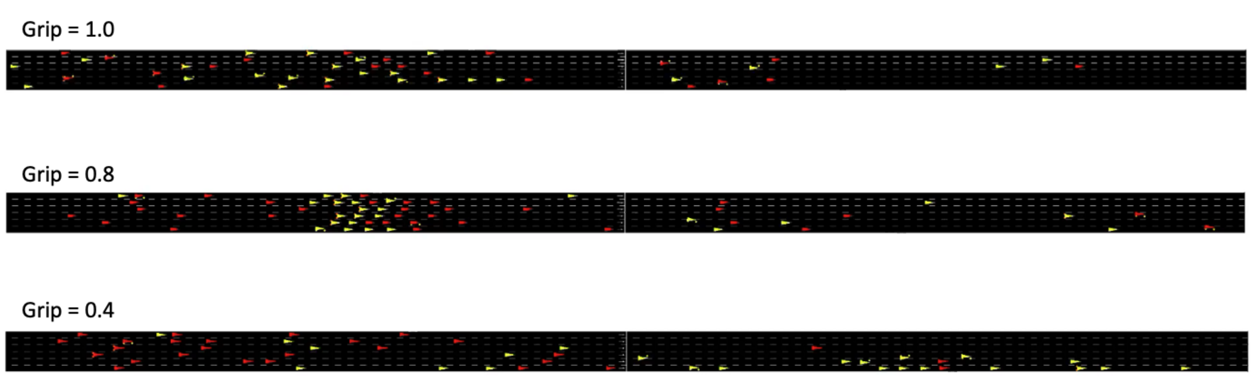


The onboard self-driving software of CAV (e.g., Autoware/ROS) can directly use the information provided at its different modules of perception, planning, and control. One application which this research project investigated is autonomous, weather-responsive speed control. In particular, based on the slipperiness or surface traction rating of the road surface (also known as grip in the ROS message), we can tune the maximum safe speed of the CAV while driving in the area. The lower the grip rating, the lower the top speed and hence the safer the maneuver.

3.2.3 RWIS-Aided Autonomous Speed Control

To analyze the performance of vehicles in different weather conditions, we choose one parameter in RWIS to simulate the traffic flow in SUMO, a microscope traffic simulator. In this simulation, the test scenario is a 0.31 miles road segment. There are two types of vehicles: normal vehicles (red) and autonomous vehicles (yellow). All normal vehicles have the same traffic behavior which is controlled by SUMO using the Gipps car-following model, and the autonomous vehicles are controlled by another car-following model (Intelligent Driving Model), and the simulation time is 600s. In this simulation, the index grip is introduced to change the drivers' driving velocity behavior. The definition of grip in RWIS is the vehicle's friction when driving. A higher value means the vehicles are easy to control and vice versa. In the Vaisala's system (our RWIS), the grip is in the range 0 to 1. Since grip is one index to show the road friction, we use grip as a velocity adjustment parameter in the car-following model. In this case, we test three different scenarios with 3 grips settings:1.0, 0.8, and 0.4 (Figure 28). Based on the test results, and as expected, when the grip parameter value gets smaller, the normal and autonomous vehicles show similar characteristics that will decrease the velocity significantly. However, autonomous vehicles can find a path to move to maintain their desired velocity if the road is not blocked by normal vehicles.

Figure 28. Case Study of the Impact of Using Different Grip (or Traction) Parameter Values



4 The Feasibility of Remote Monitoring of CAV and Impact on Public Trust

While Connected Autonomous Vehicles (CAVs) have learned how to recognize traffic lights, signs, moving pedestrians and vehicles while driving, they cannot yet adapt to all new situations, especially at high speeds and in complex urban environments. If they encounter a situation that they do not know how to handle, they are designed to prioritize safety, which means, in most cases, that they would pull over to the side of the road and stop. In other scenarios, the CAV might be stuck. Consider, for example, the case of a double-parked delivery vehicle. In that case, a CAV would not drive over a solid line of its own accord but would stay where it is until the delivery vehicle moves. Similar situations can arise at construction sites of which the autonomous system is not aware.

While CAVs can learn over time, as they continue to operate and encounter complex scenarios, thanks to advanced machine learning technologies. The idea of human supervision and intervention, when needed, could help these learning models not only learn at a faster pace, but also to gradually make decisions at a level comparable to humans. However, supporting the business case of CAVs would require these human supervisors to be able to *remotely* monitor and assume control of CAVs, when needed.

Remote monitoring and control, also referred to as teleoperation, is the technology that allows one to remotely monitor CAVs, make sure their systems are healthy, ensure that they are making the right decisions, and finally take control as needed. In the future, one may envision several teleoperators equipped with monitors, user interfaces and joysticks, sitting together in a remote-control center, monitoring and guiding a fleet of fully autonomous CAVs. However, realizing such a vision is still faced with several technical challenges, given the current state of technologies available today. In this project, we aim to research the feasibility of the concept of remote monitoring and control of CAVs. In particular, we develop a system comprised of (1) an end-to-end cloud-assisted communication system that facilitates data exchange between CAVs and a remote monitoring/control center on UB campus and (2) a self-driving software with an interface for sending sensory data, receiving control commands, and executing those commands in real-time.

We also focus on the public acceptance of the technology. CAVs are being researched by several major companies such as Waymo. Uber, Lyft, Ford, General Motors, Cruise, and Volvo. These companies are heavily researching and developing these technologies with the hopes of introducing them to the public market; some companies, such as Waymo and Lyft, have already started to provide rides for the public in the form of self-driving taxis (called Robotaxis). However, while automated driving is a rapidly developing technology that has the potential to substantially change the way society operates, not all technologies predicted by popular media are immediately welcomed into society—CAVs are one such technology. As is typical, new and emerging technologies are usually opposed by some. Opponents of self-driving vehicles argue over issues ranging from safety, personal comfort, privacy, freedom, technology dependence, and regulations. They see the introduction of CAVs as a threat to their safety on the roads and/or their jobs.

To research public trust and acceptance, this task developed and administered a short and small-scale, survey to gauge the level of public acceptance of CAVs. That survey sought to find answers to questions such as: (1) what the public thinks of self-driving cars, (2) individuals' perceived safety of the technology, (3) how would remote monitoring or teleoperation of CAVs improve perceived safety. The way the public perceives CAVs will naturally affect the way CAVs would be introduced to the market and how quickly we would be seeing them on the streets. It would also determine how car manufacturers develop and market them.

4.1 Background and Requirements

CAVs are expected to bring about many societal benefits, including reduced traffic and parking congestion, infrastructure savings, independent mobility for low-income or people with disabilities, increased safety, energy conservation and pollution reductions. However, these advantages will only be significant when CAVs become common and affordable. Currently, The Society of Automobile Engineers (SAE) defines six levels of autonomous driving, according to their relative extent of automation:

- Level 0 refers to the traditional vehicle, where the human driver is responsible for all aspects of the dynamic driving task. Driving support features, if present, are limited to providing warnings or momentary assistance.
- Level 1 refers to a vehicle with a driver assistance system that automates a single function (either braking/acceleration OR steering). The human driver must continuously supervise these support features.
- Level 2 defines a vehicle with driver assistance systems that automate both braking/accelerating AND steering. The human driver remains responsible for operating the vehicle.
- Level 3 refers to *conditional/partial driving automation,* or to a vehicle capable of self-driving, but *only under ideal conditions and with limitations*. The human driver should always be ready to take over, should road conditions fall below ideal.
- Level 4 refers to a *highly automated vehicle*, where the vehicle drives independently most of the time. Level 4 vehicles do not require human interaction in most circumstances. However, a human still has the option to manually override.

- Level 5 defines a *fully autonomous vehicle*, where the vehicle assumes all driving functions. Level 5 AVs are able to drive anywhere and do anything that an experienced human driver can do. There is currently some skepticism regarding whether Level 5 is technically attainable.

While full automation is the main goal of many self-driving companies, reports of recent crashes have made the general public skeptical about the achievability of such a goal [13, 4]. To help improve AV safety, and to determine what happened before, during, and after crashes, CAVs are required to be equipped with data recorders to collect information of driving behavior [15]. Such data are carefully analyzed, post-crashes, to help improve self-driving algorithms.

To better exploit the potential of today's CAVs without compromising driving safety, a promising interim solution is that of remote monitoring and control. Such an approach would allow an autonomous fleet administrator to audit the processes and see what exactly the CAV is doing. The monitoring can be combined with remote control (teleoperation), which complements autonomous driving systems through the involvement of human intelligence. As a result, it can make CAVs more capable and help them navigate in tricky situations that they cannot handle on their own. Under such a paradigm, a remote operator gathers information about the driving environment (e.g., live views fed by the vehicle's camera or other sensors, position, speed, direction, etc.) from a remote location. If the automated system requires human intervention, the remote operator can then provide timely advice or commands related to completing tasks that exceeds the capabilities of the decision-making software in the AV. The operator can ultimately take over the control of the vehicle when needed. In this project, we first focus on remote monitoring and its requirements, because monitoring is a prerequisite for commanding and teleoperation.

4.1.1 CAV Sensors

Before describing the remote monitoring framework implemented in this project, we summarize herein the types of data CAVs typically sense and collect, while operating on the road. Sensing is the first task in any automated driving system regardless of the autonomy level. Sensors onboard a CAV translate physical environmental attributes into signals to measure complex inputs for automated driving systems. Based on such an input, CAVs can recognize the size, location, and type/class of objects in their world. CAVs are typically equipped with two major classes of sensors, (1) exteroception and (2) proprioceptive sensors. While exteroception in ADS deals with information in the surroundings of CAV, proprioception, on the other hand, is related to the state of the CAV itself (e.g., position, velocity, yaw rate, accelerations, etc.).

4.2 Exteroception Sensors for CAVs

Exteroceptive sensors are used for the observation of the exterior environment. We summarize below the major characteristics of the most common exteroceptive sensors used in CAVs:

1. **Vision-based sensors:** Since texture and color vision is possible with a camera, it is often considered as the primary sensor for identifying road signs, traffic lights and lane markings. Cameras used on CAVs are either monocular, which transform the 3D environment into 2D, stereo cameras that can receive the world in 3D and provide an element of depth perception as a result of using dual lenses.
2. **LiDARs:** LiDAR (Light Detection and Ranging) operates by sending out a pulsed laser of light and measuring the time it takes for it to be reflected. Measurements are gathered and are used to generate a 3D map (point cloud) of the surrounding environment. Automotive LiDARs normally utilize 16 to 128 Lidar channels. In contrast to radars, ultrasonic and monocular cameras, LiDAR can be used to detect the shape and geometry of an object.
3. **Radar:** In self-driving vehicles, radar sensors use high frequency electromagnetic waves to measure the distance to nearby objects and traffic based on the round-trip time principle. 77GHz and 60GHz radar sensors are the most prevailing ones in the automotive market. In contrast to cameras or LiDAR, radar's performance is not limited by weather or light conditions (dark, snow, rain, fog, or dust).

4.2.1 Proprioceptive Sensors for CAVs

Proprioceptive sensors make measurements within the CAV system, e.g., speed, orientation, position, etc. These sensors do not directly interact with the world and objects beyond the CAV; however, they provide essential data that automated driving software would need to correlate from exteroception sensors with the world. The most common proprioceptive sensors in CAVs are listed below:

1. **GPS:** The Global Positioning System (GPS) is a system that uses signals from satellites to accurately determine CAVs location on Earth. This is also referred to as latitude and longitude coordinates.
2. **IMU:** Inertial Measurement Unit (IMU) is an electronic device that measures and reports acceleration, orientation, angular rates which together can determine the orientation of the vehicle. The positioning accuracy of a vehicle could also be increased if measurements from IMU devices are integrated, e.g., with GPS data and/or with vision odometry.

4.2.2 Remote Monitoring and Control Requirements

Different components are involved in any remote monitoring/control architecture. We list the key elements as follows:

- **Agents:** these are the players who are monitored. In this project, the fleet of connected autonomous vehicles are the agents.

- **Remote Center:** the remote center is a physical location where human operators and fleet administrators monitor and/or send commands to the agents, i.e., CAVs.
- **Data:** this is the information that is transmitted or shared between agents (CAVs) and the remote center. Data can be raw sensory data, processed abstract information, or a combination of both.
- **Medium:** includes the network infrastructure that facilitates data exchange between agents and the remote center.
- **Software/Hardware:** software is a set of programs and operating information used by a server at front and/or back ends. These programs and services constitute the networking, processing, and visualization software, and are typically hosted by, or used within, different machines or other physical components (e.g., routers, modems, computers, and servers).

Remote monitoring and control rely on V2I communications. CAVs may use different types of communication systems. Cellular systems, such as 4G/LTE, or 5G, are prevalent nowadays and are considered as one of the most effective ways of data exchange for CAVs. This is mainly because roads and neighborhoods are already under network coverage of one or several network service providers. Therefore, CAV developers and automotive companies do not need to dedicate extensive budgets to infrastructure. This is completely in contrast to Wi-Fi, DSRC, and mm-WAVE technologies which require installation of roadside access points. Using cellular networks would still pose some costs to CAV developers and automotive companies, in the form of a subscription fee.

A CAV fleet administrator needs to constantly monitor the autonomous vehicle during operation from the remote center. Monitoring could be as simple as receiving real-time behavior status (e.g., numerical codes) or receiving sensory information in the form of raw data. In the former case, the automated driving system informs the fleet administrator about what decisions it has been making, while in the latter, the fleet administrator can observe the surrounding environment in which the CAV is currently operating.. It is worth noting that lower-level automation requires fewer sensors, fewer network connections, and thus generates less data. On average, a Level 1 CAV utilizes a total of about 8 sensors, while a fully autonomous CAV (level 5) is expected to carry at least 32 sensors. Each of these sensor types generates data at different rates. The data rate for some of these sensors are summarized in Figure 29.

Figure 29. The Data Rate of Common CAV Sensors

	Data Rate	Network Overhead	Frontend	
			Raw	Visual
Radar	0.1-15 Mbit/s	moderate	✓	✓
IMU/GPS	<0.1 Mbit/s/sensor	low	✓	
LiDAR	20-100 Mbit/s	high	✓	✓
Camera	100-3500 Mbit/s	very high	✓	✓
Ultrasonic	<0.01 Mbit/s	very low	✓	

Based on these data rates, it can be estimated that a CAV at the lower end of the autonomous spectrum will produce about 3 Gbit/s of data, which amounts to about 1.4 terabytes every hour. At higher levels of autonomy, the total sensor bandwidth will be closer to 40 Gbit/s and approximately 19 terabytes per hour. This is clearly beyond the capacity of current 4G/LTE networks which can provide up to 1 Gbit data rate. Therefore, it is reasonable to say transmitting raw sensory data of CAVs would not truly take place before 5G wireless systems are prevalent. Nevertheless, 4G/LTE systems provide enough bandwidth for CAVs to send and receive data in the form of compressed, processed, or abstract data. In this project, we apply some of these techniques and demonstrate the feasibility of CAV's remote monitoring as well as control.

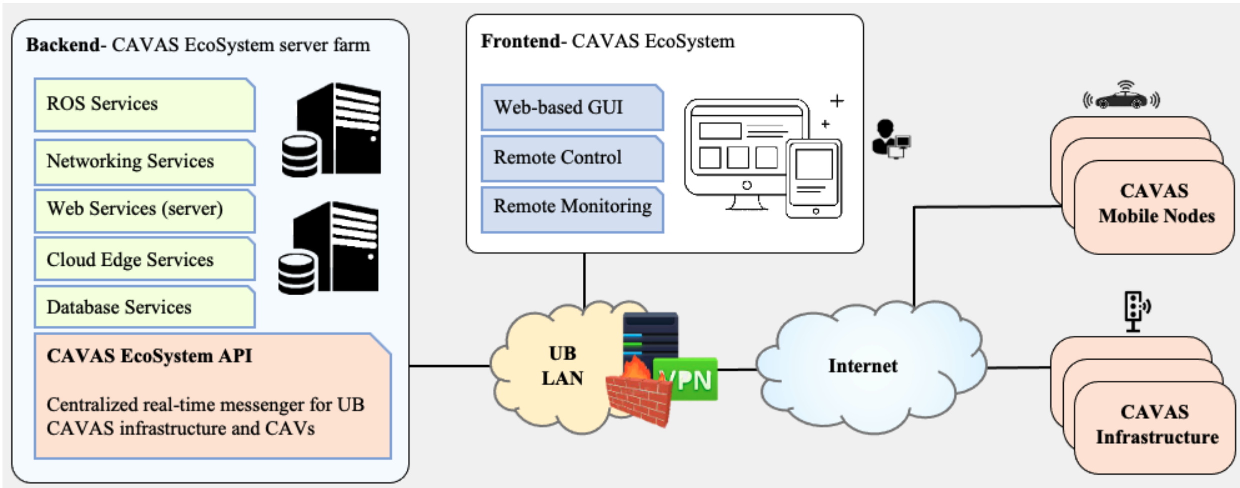
4.3 Remote Monitoring System

In this section, we describe the remote monitoring system architecture and its elements.

4.3.1 System Architecture

Figure 30 demonstrates the remote monitoring system architecture for UB's Connected and Autonomous Vehicle Applications and Systems (CAVAS) ecosystem. Mobile nodes, i.e., CAVs, and portable infrastructures together form the agents whose behavior and performance are supposed to be monitored. The software and hardware components consist of a web-based frontend as well as a set of servers and backend services. Finally, the connection between these two end points is based on cellular backhaul.

Figure 30. The Architecture of Remote Monitoring System



Below, we summarize the main functionalities of the system:

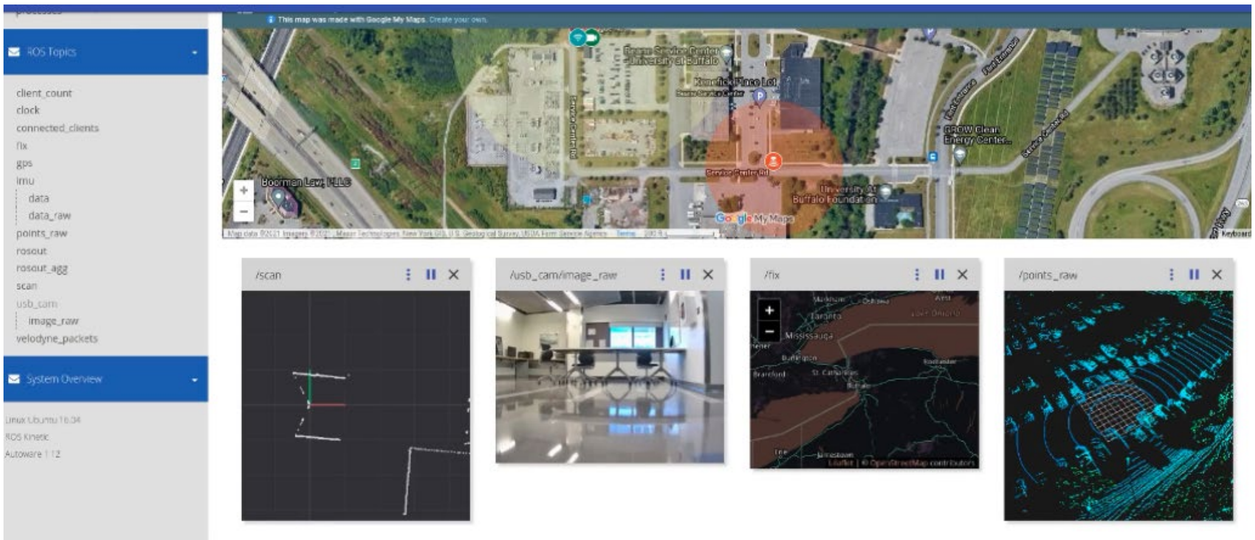
4.3.1.1 Web-based Frontend

The fleet administrator is responsible for monitoring the autonomous system from a physical location called remote center. We take advantage of web-based tools to provide a graphical user interface for the administrator. In fact, not only does the interface visualize the sensory data, but also can take user inputs and send them over the network to the autonomous systems as commands if required. The web-based user interface is developed using open-source tools and mechanisms that are available for robot operating system (ROS). Figure 31 (a) and (b) illustrate the graphical representation of the user interface. As it can be seen in Figure 31 (a), on the left panel, the administrator can select any ROS message or topic that is being published by mobile nodes and then have them visualized in the main panel, where camera, LiDAR and GPS data streams received from mobile nodes (agents) are rendered graphically. For example, GPS messages are generated using a predefined structure known as sensor_msgs/NavSatFix.msg. Upon receiving these messages, the software running on backend side uses OpenStreetMap API to visualize the coordinates of the agent on a vector map. Similarly, in Figure 31 (b) we see the list of all connected nodes across the ecosystem with their publishing messages, which is referred to as ROS Graph. This could be a useful administrative tool for users who would like to figure out if an agent is connected or disconnected and whether certain ROS services are available. Also, it provides user-friendly access to additional information associated with those messages such as time stamp, message type, publish rate, and so on. These are all crucial when it comes to troubleshooting a remote agent.

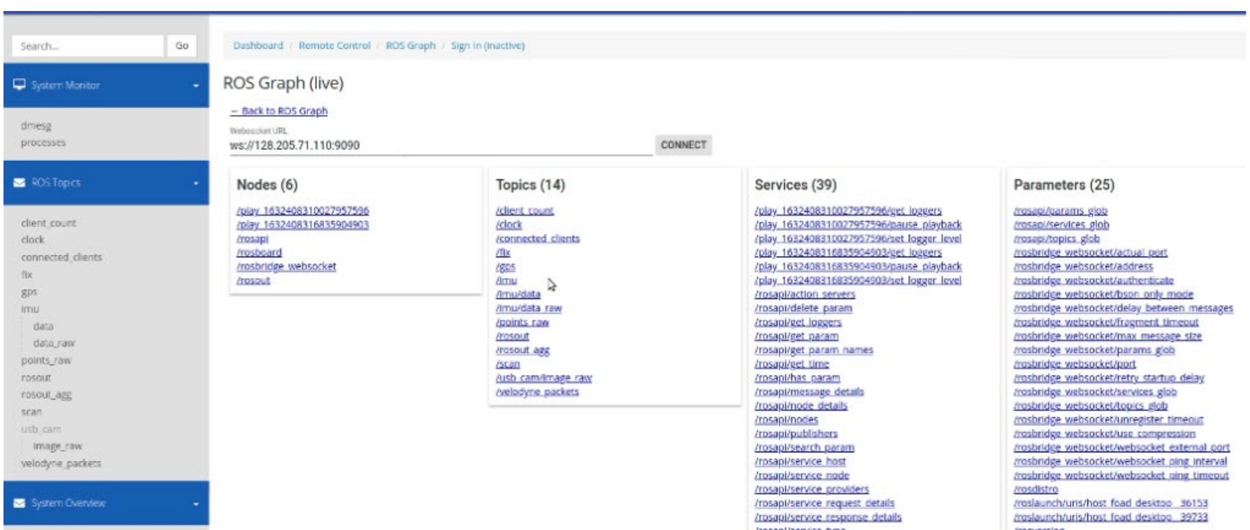
Figure 31. The Web Interface of Remote Monitoring System

Main panel (a), graph-based ROS on open-source material (b).

(a)



(b)



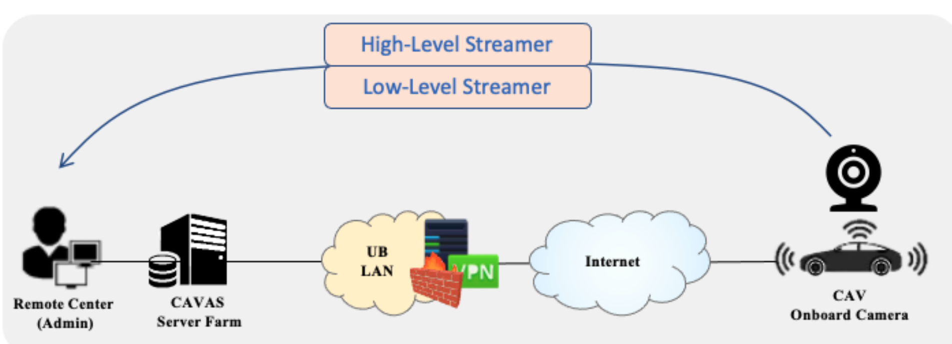
4.3.1.2 Backend Services

What the fleet administrator experiences on the frontend is powered by a set of services running on servers. These centralized services also empower communication between the remote office and CAVs (agents). We summarize the major components of the backend below:

- **Robot Operating System (ROS) services:** Similar to CAVs and robots, an instance of ROS is also available on a backend server that allows integration and smooth interaction between CAVs and the remote center.
- **Networking Services:** these services run in the background and facilitate IP address management and port forwarding, when required.
- **Web Services:** The web server is responsible for providing content in the context of the web and over a specific address/URL. The remote monitoring interface is then accessible through a specific IP address and port number such as http://192.168.100.1:4848.
- **Cloud Services:** These are software and programs that run on resource-rich hardware when GPU/CPU intensive tasks are delivered for processing, e.g., machine learning inference.
- **Database Services:** A database could be necessary for storing and retrieving data for the long term.
- **CAVAS API:** This is a ROS-based API responsible for establishing connections, data and message conversions, as well as message passing. This component acts like a message broker in the middle between remote agents and ROS services.

As previously mentioned, different data types demand different data rates and bandwidth. When it comes to CAV remote monitoring, it is crucial for the administrator to inspect the autonomous system with minimum latency. For example, imagine a scenario in which different video streams associated with CAV's onboard cameras are streamed over to the remote center for live monitoring purposes. A remote user would then be able to see the stream on the monitor screens to (1) ensure the system is working properly, and in some cases (2) correct the erroneous processes, address autonomous system confusions, or tele-operate the vehicle by sending commands to the CAV. The former is the prerequisite for the latter in the sense that the user must be able to see the *current status* of the vehicle before he/she can decide about the commands that are needed to be sent over. In case of experiencing large network delays, the user sees the outdated status of the vehicle and responds with commands. As a result, CAV receives commands with regard to some scenarios in the past and those may no longer be valid or safe to run.

Figure 32. The Structure of CAV Remote Monitoring System



As shown in Figure 32, we develop a CAV remote monitoring system with an API consisting of two different types of data streamers, namely “low-level” (LL) and “high-level” (HL) streamers. The main difference between these two data streamers is the layer they are implemented in the TCP/IP protocol stack. In particular, our HL data streamer relies on application layer protocols, i.e., HTTP, while our LL data streamer uses a transport layer protocol known as User Datagram Protocol (UDP). Exchanging information through HTTP requests and responses makes the use of HL streamer convenient for non-developers and end-users. For instance, using HL streamer, the data can be accessed through a web browser or software. However, the LL streamer does not provide access through the web, instead a developer is required to develop software in which sockets send and receive data. LL streamer handles larger data at faster transmission rate and was used for video streaming in our project. The HL streamer, however, works at slower data rate and can only handle small-sized information (such as odometry/position/GPS data). These two data streams are compared in Table 2. Through the HTTP protocol, data, and resources are exchanged between CAV and the remote monitoring center over the internet in a request-and-response fashion. In particular, CAV establishes HTTP sessions through which data (payload) is sent to a specific URL determined by the server (API) and in the form of “PUT request.” If any instance of the data exists from an older request, the new payload will overwrite the old data. Transmissions under high-level streamer take place regardless of the payload type and encoding, e.g., image, point cloud, etc., and therefore, is very user-friendly. However, due to the nature of the protocol, transmissions involve exchanging “request” and “response” which poses additional network overhead and latency.

On the other hand, UDP protocol is a connectionless protocol that is primarily used to establish low-latency and loss-tolerating connections between applications on the internet. Therefore, it potentially speeds up data streaming by enabling the transfer of data before an agreement is provided by the receiving end (server). However, further software development is required per data type. For instance, a low-level streamer that is developed for video streaming is not necessarily capable of streaming GPS or point cloud data. Therefore, we take advantage of both the protocols and build two different streamers to be used based on the context of data. Specifically, we use our low-level streamer for streaming videos and images where data rate is higher, while we adopt the high-level streamer for transmitting odometry, position and other small-size payloads in parallel.

Table 2. General Differences between the Proposed High- and the Low-Level Streamers

High-Level Streamer	Low-Level Streamer
Uses Application Layer protocols (http)	Uses Transport Layer protocols (UDP)
Generic for any data type	Data-specific
User-level	Developer-level
Supports Web and HTTP	No Web Support
Slow Streaming	Fast Streaming
Good for small data	Good for large data

To evaluate the performance of our high-level and low-level streamers in practice, we have conducted an experiment on UB campus. In this experiment, the goal is to transmit a camera stream which is installed inside our development AV, the Lincoln MKZ, to an office (monitoring center) inside Davis Hall, on UB campus. The vehicle is equipped with AT&T cellular modem for communication. The camera used in this experiment provides 30 frames per second images of 720p HD resolution. We used both streamers under the same constraints (60 Mbit/s uplink bandwidth) and measured average frame rate and latency. The results are shown in Table 3.

Based on the results, the high-level streamer delivers a stream of the images at rates 2 and 8 frame/sec when images are uncompressed and compressed, respectively. Compression in this case significantly reduces payload size with the cost of losing image quality/resolution up to some slight degree. Without adopting image compression techniques, the high-level streamer introduces very large latency, which makes the user experience unrealistic, in terms of monitoring of the environment inside/around CAV. On the other hand, using the low-level streamer and image compression results in the best performance, i.e., 26 frames/second and a delay of 0.2 seconds on average. It is worth mentioning that the performance of streaming approaches are supposed to vary depending on the quality of network coverage (agent location), timing on the day (network load), as well as the choice of network technology which is different among different networks. Therefore, this experiment evaluates the performance of one streamer compared to the other, regardless of the fact that the numbers alone may or may not be ideal for such applications.

Table 3. Comparison of Performance of the High- and Low- Level Streamers

	HL Streamer		LL Streamer
	Uncompressed	Compressed	Compressed
Average Frame Size	1.2 MB	70 KB	90 KB
Average Speed	2 fps	8 fps	26 fps
Average Latency	3.65 sec	0.23 sec	0.2 sec

4.4 Remote Control System

Remote control is also referred to as teleoperation. While remote monitoring can provide useful information about automated driving system status, it cannot protect the vehicle from doing wrong actions. Therefore, the question remains—what can be done if a CAV needs help to make a decision? Even though autonomous vehicle technology promises greater precision, the technology is still far away from matching human judgment, especially when it comes to responding to unfamiliar problems on the road such as confronting a fallen tree, complex work zones, etc.

As previously described, today’s CAVs are a complex combination of various pieces of sensors including cameras, GPS, LiDARs, and radar systems all of which work together with machine learning methods and algorithms to help navigate the vehicle on its way and anticipate unforeseen situations that may come up on the road. The problem here is that there is no mathematical model that can understand with absolute certainty situations that it hasn’t encountered before. In fact, CAVs are still not mature enough to adapt to every single scenario that may arise on the road in real life. Moreover, complex machine learning algorithms need a significant amount of data from driving scenarios and roads based on what they are trained and able to recognize, detect or classify objects, and estimate motion of these objects. It may take several decades to observe, collect, and use such data to train accurate machine learning models. Until then, a potential workaround could be “teleoperation.”

4.4.1 Definition and Requirements

CAV Remote control or teleoperation refers to the action of operating an autonomous vehicle from a distance via a wireless connection. Nowadays, teleoperation most commonly applies to autonomous vehicles and robots. These can range from delivery drones, robotaxis, rental cars, as well as equipment at shipping ports, mining, airports, and more.

In terms of logistics, teleoperation of CAVs requires a CAV outfitted with drive-by-wire interface and radio/communication device, and a human operator (teleoperator) who can be placed in a remote location (control center), to be able to have access to the CAV via network and to control it indirectly or directly. Under indirect control, the teleoperator does not control the acceleration or brakes, they merely assist in high-level commands, such as path choice or drawing a new path for the automated driving system to take. On the other hand, through direct control, the teleoperator fully takes over the control of the vehicle in the same way a driver would do in ordinary vehicles, but remotely.

The safety and efficiency of teleoperation depend on a few technical factors as well. First, a reliable communication channel is required. Given that the Internet is a best-effort service, i.e., the quality of service is not guaranteed, teleoperation will always involve some safety risks. Second, depending on what type of data is going to be transmitted by the vehicle to the control center and vise-versa, different data-rate, latency and bandwidth may be required. For example, transmitting 6 camera streams that are located around the body of the vehicle would provide a 360 view of the vehicle's surrounding environment and makes direct teleoperation feasible. However, it would require significant bandwidth. Network latency could also affect teleoperation safety as it results in delivering outdated data on either the monitoring or control channels.

While remotely operating a vehicle demands special permission from motor vehicle departments, the teleoperation itself is needed to get governments' approval in some countries/states, solve situations currently too complex for autonomy, and gain the general public's trust to enter a vehicle with no driver inside. In fact, the remote human operator is the missing link between testing and actually getting autonomous vehicles on the road.

4.4.2 Benefits of Remote Control

Teleoperation can be used on both public and private roads. It will ensure CAVs can complete their mission even when encountering new complex edge cases, they are unable solve on their own. This is much needed to boost public trust. We will further investigate this topic in the next section.

Teleoperation of CAVs will also be needed to help these vehicles handle unknown driving scenarios that they might encounter. For example, reinforcement learning algorithms are special machine learning techniques in which the agent (CAV) can learn more as it operates on its own and is involved in more scenarios. The remote operator, in such cases, can efficiently guide the vehicle through the best possible action and let the onboard software learn to judge, in a fashion like human judgment. In fact, data from teleoperation interventions may be instrumental in training future autonomous artificial intelligence (AI) software. But for now, remote human drivers will be better decision-makers for situations where the vehicle's algorithms are not properly trained for.

4.4.3 Teleoperation System Model

The autonomous driving software is typically fed by sensors and provides driving commands for the drive-by-wire interface. There are many different digital inputs that a vehicle can accept from a computer—such as wipers, headlights, and signals, gear shifter, brakes, etc. In an automated driving system, there are four major control commands that are associated with driving:

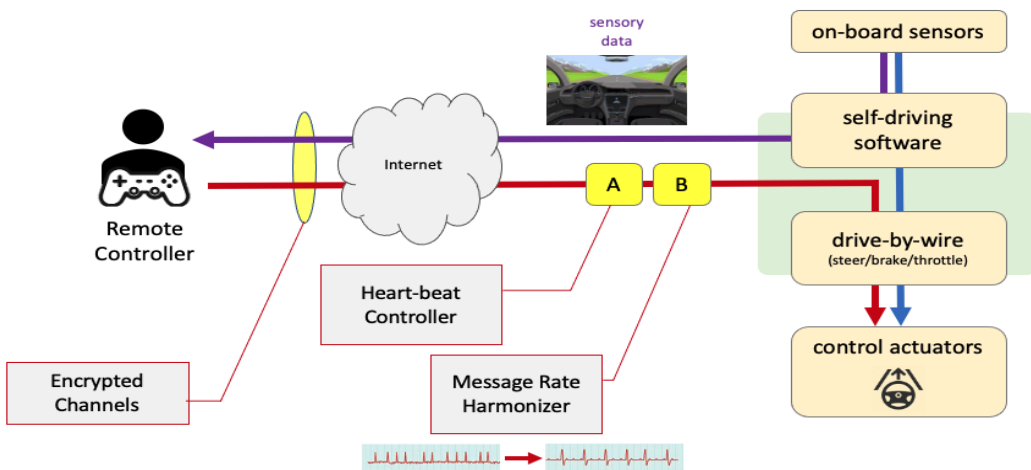
- **Acceleration cmd:** Linear acceleration in m/s^2 unit
- **Brake cmd:** the percentage of brake engagement
- **Steer cmd:** rotation degree of the steering wheel or front tires
- **Shift cmd:** the automatic gear identifier

The planning and control algorithms within self-driving software are responsible for calculating the control commands above during operation in a continuous manner. When teleoperation takes place indirectly, i.e., the remote human operator is only responsible for providing high-level commands such as path choice, the self-driving software takes input from both onboard sensors and the remote operator. In direct teleoperation, however, the aforementioned driving commands are provided by the human operator. Therefore, instead of the self-driving software, the remote operator directly talks to the drive-by-wire interface. This scenario is shown in Figure 33. The drive-by-wire interface mainly uses electrical/electronic components such as sensors and/or actuators to control vehicular systems. It is worth noting that a drive-by-wire system itself is divided into the following sub-systems which operate these systems:

- **Throttle-by-Wire:** Controls function of throttle
- **Brake-by-Wire:** Controls braking system
- **Steer-by-Wire:** Controls steering system
- **Shift-by-Wire:** Controls transmission system

As it can be seen, these four components match with the essential driving commands mentioned earlier. Hence, to control a vehicle, the remote operator needs to accurately generate and transmit these four commands to the vehicle where the drive-by-wire interface is waiting for input. It is worth noting that these commands should follow the same format as when they are generated by the self-driving software. To this end, in our teleoperation platform, we maintain a full instance of robot operating system (ROS) on the backend. The system is responsible for taking inputs from a joystick (gaming wheel/pedal), constructing the required ROS-messages, and sending them over to the vehicle through the Internet.

Figure 33. The Architecture of Remote Controlling System



To enhance security of communication and eliminate the risk of malicious activities in our teleoperation system model all the messages across monitoring and control channels are encrypted end-to-end. Due to the best-effort nature of the Internet, latency and payload delivery are not guaranteed. In other words, it is possible that some control commands sent through the network get delivered in different order and by inconsistent latency. However, since an autonomous vehicle is also a safety critical system, both the self-driving and drive-by-wire software components are normally optimized for a perfect environment and inconsistent inputs, and as such, could result in termination of the autonomous processes. We work around these issues by integrating two additional modules on the vehicle side:

- **Heart-beat Controller**: this module measures the consistency of incoming commands. In case of connection loss, it will put/maintain the vehicle in a safe mode.
- **Message Rate Harmonizer**: this component is responsible for recalibrating incoming messages which are out of sequence due to latency, corruption, or loss.

4.4.4 Real-World Experiments

We have implemented teleoperation based on the model described in the previous subsection. In this experiment, a remote operator, who is located in Davis Hall (remote control center) on UB north campus, remotely teleoperates a Lincoln MKZ (CAV) that is located in an isolated parking lot. A joystick set including wheel, gear and pedals is used for the purpose of commanding. A camera is installed inside the vehicle to provide a view similar to what a driver would normally see. The camera stream is transmitted to the remote center through AT&T cellular network where it is visualized on a display screen in front of the remote operator. Based on the experiment results, teleoperation has been successfully accomplished with an average network latency of 0.1 to 0.5 seconds for controlling and monitoring channels, respectively. Figure 341 (a) through (e) demonstrate the experiment setup.

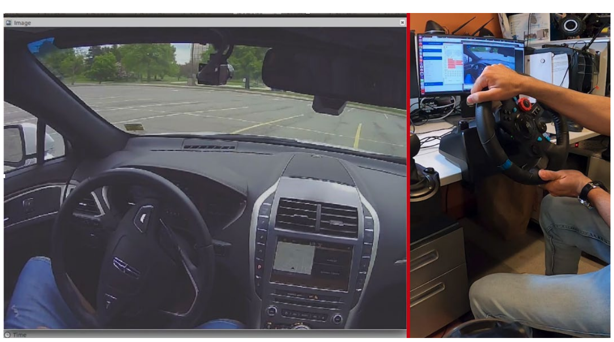
Figure 34. (a)–(e) The Experiment Setup for the Teleoperation of UB's Autonomous Lincoln MKZ

a.

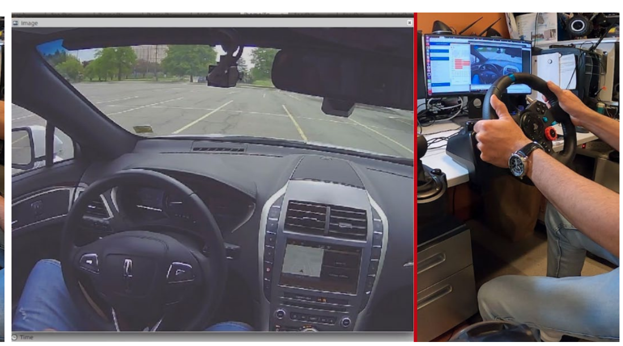
b.

c.

d.



e.



4.5 Public Trust and Acceptance

This task also conducted a small-scale public trust and acceptance survey, following the development of the remote monitoring and control framework previously describe. Specifically, this task developed a short questionnaire with questions about the public acceptance of AVs. The individuals surveyed were primarily UB faculty members, researchers, and students. Some highlights from this survey are described below. However, given the limited number of responders, and the fact that they were largely associated with the University, the findings from this survey should not be generalized.

In terms of perceived benefits of AVs (Question 8 on the survey), it was interesting to discover that all responders indicated that they thought AVs would reduce fuel cost (very likely or somewhat likely), as can be seen from Figure 35. At the same time, there was some doubt among responders that AVs would reduce traffic time and traffic congestion (Figure 35). The overall performance of the traffic stream is naturally going to be a function of the percentage of CAVs in the stream or their market penetration.

Figure 36 shows that 82.3% of respondents are willing to ride in an AV. However, all of them indicated their desire to have a human supervisor inside the CAVs. If remote monitoring and control is available, half the responders indicated that they would feel comfortable riding an AV (Figure 37). We also asked those surveyed to identify the driving scenarios which they thought would be of concern or risky, requiring human supervision.

Figure 35. Survey Responders' View of the Benefits from AVs

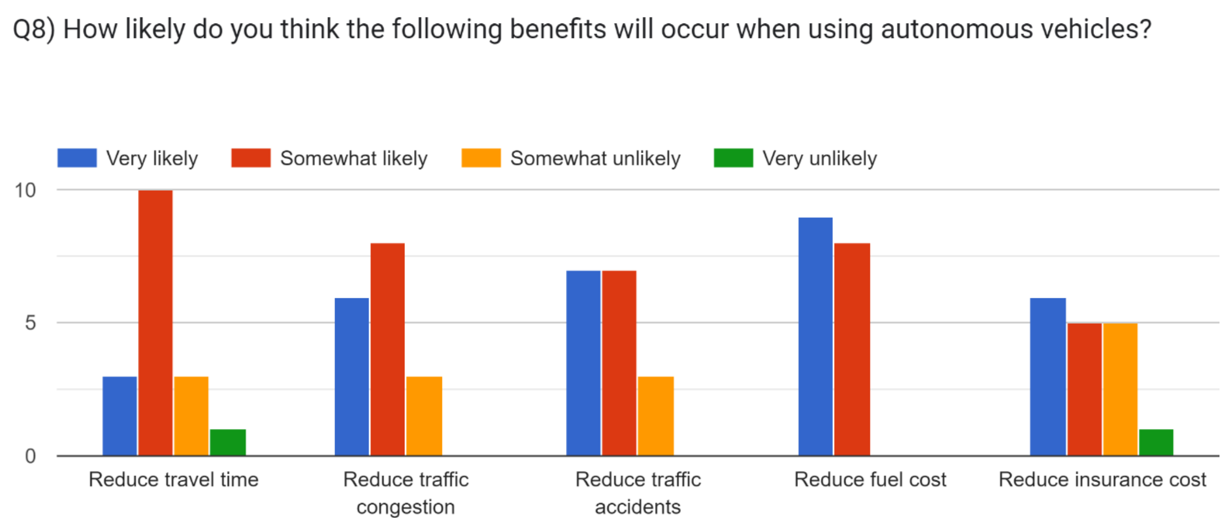


Figure 36. Responders' Willingness to Ride in an AV or a Robo-Taxi

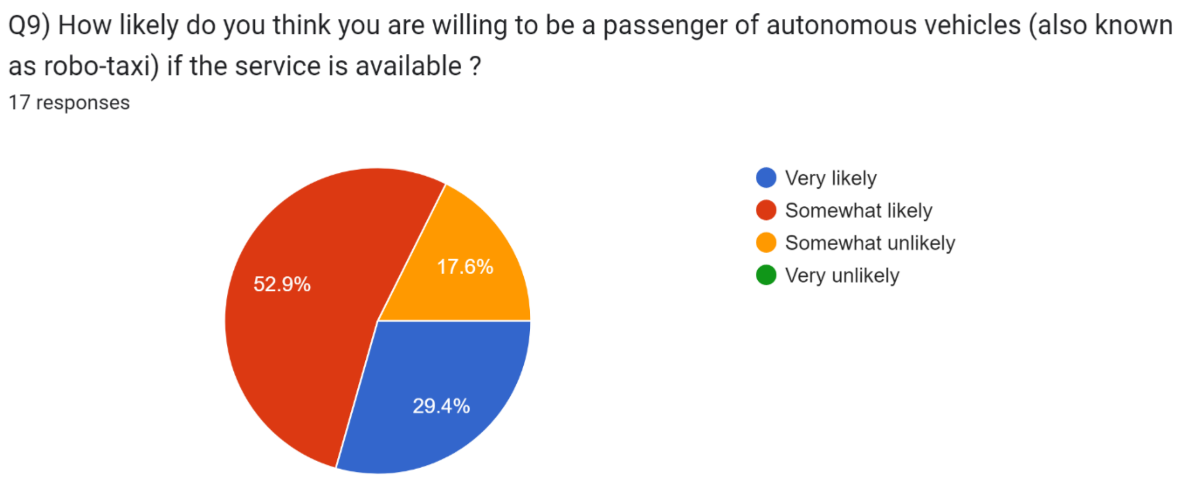
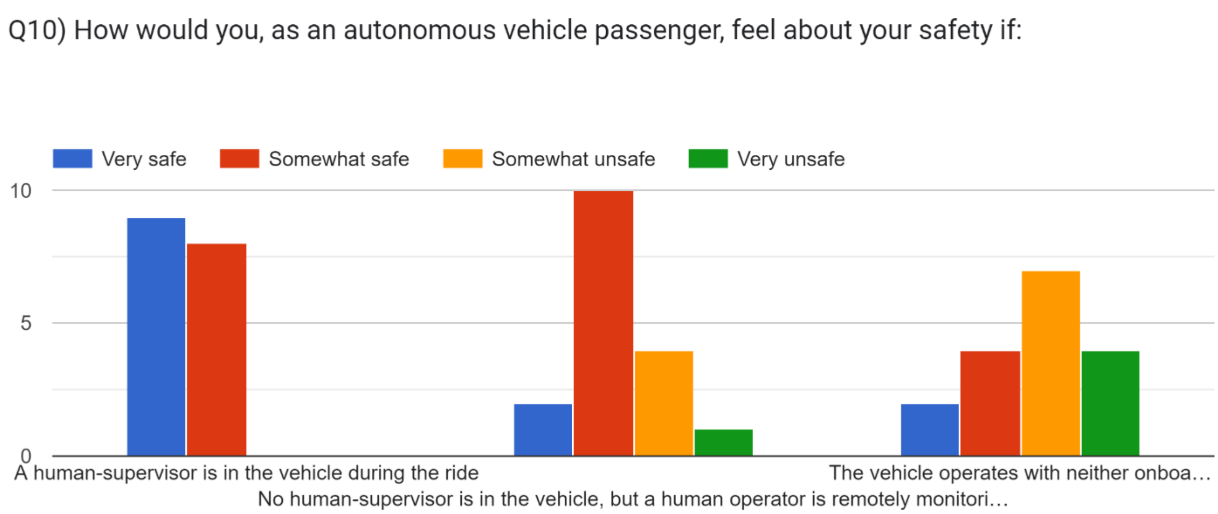


Figure 37. Responders' Attitudes toward AV Safety with and without Human Supervision



5 Conclusions

In this project, we have made significant contributions to the study of Intelligent Transportation Systems (ITS) with a specific focus on vehicle-to-infrastructure (V2I) support for autonomous vehicles (AVs). Our research aimed to enhance the safety, capabilities, and performance of automated driving by leveraging V2I communication, enabling informed decision-making and improved traffic management.

5.1 Research Contributions

We focused on three main tasks: energy-efficient CAV intersection crossing, V2I-enabled collaborative perception and road weather data dissemination for CAVs, and remote monitoring and control of CAVs. Through extensive experimentation and analysis, we have demonstrated the potential benefits and feasibility of V2I connectivity in these areas.

In the task of energy-efficient CAV intersection crossing, we successfully developed and deployed a portable traffic light on UB North Campus CAV Proving Grounds. By integrating this traffic light with a cloud-based communication system and the open-source automated driving software "Autoware," we were able to showcase how V2I connectivity can optimize energy consumption by allowing CAVs to anticipate changes in signal states and optimize their speed profile accordingly. Our results demonstrate the potential for significant fuel efficiency improvements and reduced traffic congestion.

In the task of V2I-enabled collaborative perception and road weather data dissemination for CAVs, we installed roadside units (RSUs) including a LiDAR light-pole and a Road Weather Information System (RWIS) on UB CAV proving ground. Through V2I communication, we enabled collaborative perception between CAV and roadside sensors, enabling a see-through framework for enhanced environmental understanding. Our findings highlight the enhanced safety and efficiency that can be achieved when CAVs can access accurate and real-time road condition and weather information, allowing for adaptive driving strategies.

In the task of remote monitoring and control of CAVs, we developed an end-to-end cloud-assisted communication system between CAVs and a remote monitoring/control center on the UB campus. This system enables real-time data exchange and command execution, facilitating remote monitoring and intervention when necessary. Our research emphasized the importance of human oversight and intervention in complex or unpredictable situations, bridging the gap between current limitations with autonomous systems and the need for safe navigation.

Our work builds upon existing research in the fields of autonomous vehicles and communication systems and contributes to advancing the knowledge and understanding of its potential benefits and feasibility. By addressing specific tasks and challenges, we have demonstrated the practical applications and positive impact of V2I technology on energy efficiency, collaborative perception, road safety, and traffic management.

Looking to the future, work should focus on addressing the limitations identified in this project. Efforts should be made to enhance the bandwidth and data rate of communication technologies to support more demanding applications such as remote monitoring and collaborative perception. Additionally, improvements in network access at the University at Buffalo would enable more seamless and real-time data exchange, facilitating advanced research and experimentation in the field of V2I connectivity for AVs.

Furthermore, expanding the scope of research to explore the integration of V2I connectivity with other emerging technologies is crucial. For example, the use of the existing connectivity framework to build an augmented reality environment for CAVs on the University at Buffalo campus could enable the testing and evaluation of different driving scenarios. This integration would contribute to the development and refinement of autonomous driving systems by simulating and analyzing complex real-world scenarios in a controlled environment.

5.2 Challenges and Limitations

However, our research has identified several limitations and challenges. One barrier is the limited bandwidth and data rate of existing communication technologies, which are data-intensive in some applications, such as remote monitoring and collaborative perception. The performance of these applications may be constrained by the data transfer capabilities of the communication infrastructure.

Furthermore, network access limitations at the University at Buffalo pose challenges for real-time video streaming and the transfer of information from inside to outside through network sockets. The current configuration of the school's VPN does not suit real-time video streaming and may limit the seamless exchange of data between CAVs and the infrastructure.

Additionally, given the limited budget for the project, we maximized the use of open-source materials, leveraged school resources, and even built hardware, such as the portable traffic light, to overcome resource limitations.

5.3 Future Works

Future work in this field holds great potential. For instance, further optimization of traffic management can be achieved by allowing the traffic light to adjust its timing based on real-time traffic conditions, ensuring smoother traffic flow and reduced congestion. Moreover, the existing connectivity framework can be utilized to build an augmented reality environment for CAVs on the University at Buffalo campus. This environment would allow for testing and evaluation of different driving scenarios, enhancing the development and refinement of autonomous driving systems.

In conclusion, while this project has shed light on the benefits and feasibility of V2I connectivity for autonomous driving, it has also identified limitations and challenges that need to be addressed. By overcoming these challenges and further exploring the potential of V2I technology, we can pave the way for a future of safer, more efficient, and sustainable transportation systems. By addressing specific tasks and challenges, we have showcased the benefits and feasibility of V2I technology in enhancing energy efficiency, collaborative perception, road safety, and traffic management. Despite limitations, our work lays the foundation for further advancements in this field, emphasizing the need for improved communication technologies, network access, and integration with emerging technologies. By continuing to explore and innovate, we can drive the future of transportation toward safer, more efficient, and sustainable systems.

6 References

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New York State Department of Transportation

50 Wolf Road
Albany, NY 12232

telephone: 518-457-6195

dot.ny.gov

New York State Energy Research and Development Authority

17 Columbia Circle
Albany, NY 12203-6399

toll free: 866-NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov

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