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Understanding Connected and Automated Vehicles' Impacts on Utah Transportation Planning

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Keeping Utah Moving
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16. Abstract

With the rapid and continuous improvements in communication and detection technologies, connected and automated vehicles (CAVs) are being brought to the transportation network and various CAV applications have been developed rapidly in the past few years. Early implementations of CAV technology have shown great potential benefits in improving safety, enhancing mobility, and reducing emissions. To leverage CAV technology, UDOT deployed a full Dedicated Short-Range Communications (DSRC) corridor for supporting transit signal priority (TSP) controls. In this project, our research team aims to collect related bus data along the DSRC corridor to conduct benefit/cost analysis and to evaluate if this deployment is an efficient investment. Note that it is expected that the benefit of this CAV deployment will go beyond the initial application in a variety of ways, in the near future. Therefore, this project determines another application that integrates adaptive traffic signal control and signal coordination control into the system. This system contains two levels of optimization: signal timing optimization at the intersection level and offset optimization at the corridor level. A dynamic programming algorithm is applied to solve the two models. Then, a simulation environment based on the DSRC corridor is established. Several simulations are conducted in VISSIM and further benefit/cost analysis is conducted to evaluate the potential effects of the proposed signal control system.

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LIST OF ACRONYMS

AADT	Average Annual Daily Traffic
AASHTO	Association of State Highway Transportation Officials
ADOT	Arizona Department of Transportation
ATSPM	Automated Traffic Signal Performance Measures
BSM	Basic Safety Message
AV	Automated Vehicle
CV	Connected Vehicle
CAV	Connected and Automated Vehicle
DSRC	Dedicated Short-Range Communications
FCC	Federal Communications Commission
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GPS	Global Positioning System
MAP	MAP Message
MCDOT	Maricopa County Department of Transportation
MMITSS	Multi-Modal Intelligent Traffic Signal System
NCHPR	National Cooperative Highway Research Program
NHTSA	National Highway Transportation Safety Administration
NYCDOT	New York City Department of Transportation
OBU	Onboard Unit
PATH	Partners for Advanced Transportation Technology
PHT	Person Hours of Travel

PSM	Priority Status Message
RSU	Roadside Unit
SAE	Society of Automotive Engineers
SRM	Signal Request Message
SPaT	Signal Phase and Timing
SSM	Signal Status Message
TRB	Transportation Research Board
TSP	Transit Signal Priority
UDOT	Utah Department of Transportation
USEPA	U.S. Environment Protection Agency
UTA	Utah Transit Authority
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WFRC	Wasatch Front Regional Council
WYDOT	Wyoming Department of Transportation

Executive Summary

By exchanging real-time information between vehicles and infrastructures, connected vehicle (CV) technology shows great potential to improve traffic safety and mobility, reduce transportation emissions, and enhance energy consumption efficiencies. To leverage this new technology, the Utah Department of Transportation (UDOT) launched a project to build a full DSRC CV corridor starting in 2016. As an initial application, this CV deployment project equipped transit vehicles with onboard processors and the global positioning system (GPS) for vehicle-to-infrastructure (V2I) communications, which can provide transit signal priority (TSP) to buses that are behind schedule.

For evaluating this deployment, this project collects related bus data from UDOT and Utah Transit Authority (UTA) to conduct benefit/cost analysis. Based on the collected data, bus travel time saving is selected as the measurement to evaluate the benefits. Results showed that the B/C ratio for this deployment in 2018 is 0.71 which is less than 1.0. Therefore, the deployment for supporting the TSP application only seems to be an inefficient investment at the current stage.

However, it should be noted that investment in CV infrastructures can support other arterial applications in the near future, such as adaptive traffic signal control under the connected and automated vehicle (CAV) environment. To further predict the future benefits, this project develops a traffic signal control system. This system integrates adaptive traffic signal control at the intersection level and signal coordination control at the corridor level. At the intersection level, an optimization model is proposed to allocate optimal green times to each phase, as well as a method to estimate vehicle arrival information when the market penetration rate is low. At the corridor level, a model is formulated to optimize the coordination plan. These two models are solved by a dynamic programming algorithm.

With the developed signal control system, a simulation environment based on VISSIM is adopted to study the DSRC CV corridor. More specifically, simulation experiments with different market penetration rate (100%, 75%, 50%, 25%, 20%, 15%, 10%, and 5%) are conducted from 2018 to 2027. Based on the simulation results, this project conducts another benefit/cost analysis that fully accounts for the potential benefit when other CAV applications are placed on the corridor.

Some additional maintenance costs over each projected year are also considered. The new result shows that the B/C ratio is greater than 1.0 over the ten-year period, and it can be concluded that the CV deployment investment would become much more efficient with an increase in the CV and CAV penetration rate in the future.

1. INTRODUCTION

1.1 Problem Statement

In recent years, with the rapid increase in car ownership, current traffic control systems across the country are suffering from many issues, such as traffic congestion, air pollution, low travel reliability, etc. As presented in the 2019 Urban Mobility Report, 8.8 billion hours of extra time, and 3.3 billion gallons of fuel were wasted in 2017 (Schrank et al., 2019). Moreover, the U.S. Environmental Protection Agency (USEPA) estimated that about 34% of carbon dioxide emissions and about 28% of total greenhouse gas emissions were produced by daily transportation (Hockstad and Hanel, 2018). Hence, urban traffic conditions are critical to business, people's lives, and the economy, and it's important to take measures to address transportation problems. Today, with the rapid and continuous improvements in communication technologies and perception technologies, connected and automated vehicle (CAV) features are being introduced to the transportation community. They have also been developing and maturing rapidly in the past few years. With the applications of CAV, the outlook for resolving transportation issues is promising.

CAV is a combination of CV and automated vehicle (AV). With onboard units (OBUs), CVs can communicate with each other (V2V) and with infrastructure (V2I) in real time. Early implementations of CV technology have shown great potential in mitigating traffic congestion and improving the efficiency of transportation systems. Specifically, V2V technology allows CVs to exchange critical vehicle status data such as vehicle speeds, location, and acceleration, etc., and the V2I platform supports communications with infrastructure (e.g., receiving signal phase and timing - SPaT - data from the signal controller). On the other track, AV is operated with automation and self-driving functions, with the support of different types of sensors, e.g., LIDAR, Ultrasonic, radar, and camera. Sensor technologies allow vehicles to observe and analyze their surroundings and automatically make suitable driving maneuvers (e.g., deceleration, acceleration, lane-changing, etc.). When connectivity is added to the AV-based system, a CV would become a CAV which is equipped with both OBUs for communications and sensors for detections.

Although it is envisioned that full implementation of CAV will take a long period and the anticipated timeframe depends on many factors, a partial CAV implementation will still greatly impact infrastructure planning and transportation network performance. Therefore, to prepare for the appearance of CAV, it is critical to understand what infrastructure investments need to made today and how the investments could improve transportation service throughout the region. For example, UDOT is a leading state DOT on deploying CAV technology. Starting in 2016, UDOT launched a project to build a full DSRC corridor for CV technology testing. The CV deployment site is located along Redwood Road in Salt Lake City, and this UDOT-owned urban corridor stretches 11 miles long and includes 30 signalized intersections. As an initial application, onboard communication devices were installed on transit vehicles, and the corridor is operated with a TSP control system. In the near future, we envision CAV deployments in Utah going beyond the initial application in a variety of ways.

1.2 Objectives

The primary objective of this research project is to develop a microscopic simulation platform (in VISSIM) to test several types of CAV applications on local arterials (e.g., CAV-based adaptive signal control, speed harmonization, etc.), and to conduct corresponding benefit/cost (B/C) analysis on the current CV infrastructure investment.

The secondary objectives of this research project are to use the current Redwood Road CV corridor as a baseline to calibrate the simulation platform and discuss the possible benefit of implementing other CAV applications beyond the current TSP operations.

1.3 Scope

Task 1: Literature Review

Task 1 focuses on reviewing current CAV technology implementations across the U.S., including the Utah Redwood CV corridor.

Task 2: B/C analysis for TSP supported by CV on Redwood Road

In this task, related TSP data is collected from UDOT Automated Traffic Signal Performance Measures (ATSPM), DSRC records, and UTA. Then, the B/C analysis is conducted with the current TSP application. Using Redwood Road as the baseline, a simulation platform in VISSIM is developed and calibrated.

Task 3: Feasible applications identification and model development

This task aims to identify other possible CAV applications on local arterials (e.g., CAV speed harmonization, CAV-based adaptive signal control, etc.) and to develop simulation models using the VISSIM COM interface and VB.net.

Task 4: B/C analysis for identified applications

This task focuses on performing B/C analysis on implementing those additional CAV applications and making recommendations on future UDOT transportation planning.

1.4 Outline of Report

This report documents the findings of the research and proceeds with the following sections:

- Introduction
- Connected and automated vehicle technology
- Potential impacts of CAV on transportation planning
- Benefit/Cost analysis of Utah CV corridor with the current TSP application
- Benefit/Cost analysis with future CAV-based traffic signal control
- Conclusions and key findings

2. CONNECTED AND AUTOMATED VEHICLE TECHNOLOGY

2.1 Overview

This chapter introduces the current state-of-the art in CAV technology. We first present the current state of development for automated and connected vehicle technology, and then review the benefits of adopting CAV technologies. Finally, the current pilots or testbeds of CAV applications in the USA are summarized.

2.2 Automated Vehicles (AVs)

AVs refer to vehicles that can sense the surrounding environment and complete driving tasks independent of human involvement. This technology is assisted by advancements in automotive technologies and on-board computation, such as advanced sensors, processors, and complex algorithms. The advent and deployment of those advanced technologies enable AV to operate like human drivers.

Based on the operating features, automation levels of AVs range from the simplest automation, such as adaptive cruise control, which involves several driving behaviors, to completely automated driving, which means vehicles can operate themselves without the engagement of human drivers. Whether partly or fully automated, the achievement of automation relies on advanced technologies. For example, radar sensors monitor the surrounding environment, video cameras judge traffic lights and road signs. Table 2.1 summarizes the technologies leveraged to support automation and lists the limitations or opportunities (KPMG 2012, Wagner, 2014).

Table 2.1 Common AV technologies (KPMG 2012, Wagner, 2014)

Technology	Definition	Limitations or Opportunities
Radar	A system bounces radio waves around to see their surroundings; they are especially good at spotting big metallic objects.	Mature technology, cheap, reliable, and not influenced by fog, rain, or snow, etc.

LIDAR	An optical remote sensing technology that measures the distance to a target or other properties of the target by illuminating it with light.	LIDAR is expensive and is still trying to strike the right balance between range and resolution.
Camera	A device that spots things like speed signs and lane marks.	The camera can be used to identify things more accurately with a better machine version.
Computer Imaging	A process using a camera that captures images of the world and feeds the images into a computer program. The program analyzes the images to understand better.	Variation and diversity of environments can be challenging.
Ultrasonic Sensors	A system similar to radar that perceives the surrounding environment.	Better accuracy than radar with short-range detection.
Digital Mapping	A process by which a collection of data is compiled and formatted into a virtual image.	Only some parts of the world have been mapped (mainly urban areas), and there is a need for a critical mass of mappers to enter and cross-validate data to achieve a satisfactory degree of accuracy.
Global Positioning System (GPS)	GPS is a space-based satellite navigation system that provides location and time information anywhere on or near the earth.	The accuracy of a GPS receiver is about +/- 10 meters, not practical for locating an object the size of an automobile, which is about 3 meters long.
Differential Global Positioning	An enhancement to GPS that improves location accuracy from +/- 10 meters to about 10 cm.	The DGPS correction signal loses approximately 1 meter of accuracy for every 150 km. Shadowing from

System (DGPS)		buildings, underpasses, and foliage causes temporary losses of signal.
Real-Time Kinematic	Satellite navigation is based on the use of carrier phase measurements of the GPS, GLONASS, and/or Galileo signals where a single reference station provides real-time corrections.	The base station rebroadcasts the phase of the carrier that is measured; the mobile units compare their phase measurements with the ones received from the base station.

As described above, many technologies and functions are applied in AV. Variation in the maturity and complexity of these technologies results in different levels of automation from no automation to full automation. To make sense of the complexity of automotive features, several standardized terminology and classification systems have been developed by government and industry for the adoption of AV technology. Among those standards, the most widely accepted is the one defined by the National Highway Transportation Safety Administration (NHTSA), which includes five levels ranging from no automation (Level 0) to full automation (Level 4). A brief introduction of each level follows:

Level 0 – No Automation

As it sounds, vehicles at Level 0 have no automated functions. NHTSA describes it as "the driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for the safe operation of all vehicle controls" (NHTSA 2013). At this level, drivers must take full control and vehicles can only monitor the surrounding environment and provide certain warnings, such as blind-spot warnings.

Level 1 – Function – Specific Automation

According to NHTSA, at this level, one or more specific automations can be functioned with vehicles, but drivers still have "overall control". NHTSA stated that "the vehicle may have multiple capabilities combining individual driver support and crash avoidance technologies, but does not replace driver vigilance and does not assume driving responsibility from the driver. The vehicle's automated system may assist or augment the driver in operating one of the primary controls – either steering or braking/throttle controls (but not both)" (NHTSA 2013). That is to say, drivers must take control of one driving behavior. They cannot remove their hands from the steering wheel and their foot from the pedal simultaneously. Example applications at this level include adaptive cruise control and automatic braking.

Level 2 – Combined Function Automation

Drivers at this level can disengage at least two automation functions simultaneously. For example, vehicles can assist with accelerating and steering at the same time and relieve drivers from those tasks. However, drivers still need to monitor the surrounding environment and must be ready to take control of the vehicle in dangerous situations. An example of this level is adaptive cruise control with simultaneous lane-centering.

Level 3 – Limited Self-Driving Automation

At this level, drivers can disengage from "safety-critical" functions under certain traffic conditions. In those conditions, the vehicle can drive itself and monitor the surrounding environment, but the drivers' attention is still crucial. Drivers must control the vehicle when the system recognizes traffic changes. For example, the vehicle monitors an accident ahead it can't maneuver and sends messages to the driver to retake control of the vehicle.

Level 4 – Full Self-Driving Automation

As stated in NHTSA, "The vehicle at this level is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip." The only operation drivers need to do is to provide the direction and destination at the beginning of the trip. During this trip, vehicles can accelerate, brake, steer, monitor the environment, and respond to the changes on the roadway.

The aforementioned classification is from a governmental perspective. In 2014, another classification of AV was announced by the Society of Automotive Engineers (SAE) from the industry perspective. The SAE standard includes six levels, also ranging from no automation to full automation. SAE defined the levels based on the role of the human driver or the automated driving system in four aspects of the driving task— steering and acceleration, monitoring of the environment, fallback responsibility for the driving task, and driving mode. The specific SAE classification is described in Figure 2.1 (SAE J0316, 2014).

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 2.1 Classification of automation levels defined by SAE

2.3 Connected Vehicles

Connected vehicles can communicate with each other or with roadway infrastructure using a series of communication technologies. A CV environment includes vehicles, infrastructure, information service systems, etc. In a fully CV-deployed environment, vehicles can broadcast traffic information, including location, speed, acceleration, and speed, to infrastructure. At the same time, vehicles can also receive information transmitted by the infrastructure, such as the current traffic status. With the application of CV technology, travelers could make smarter decisions by receiving information from infrastructure, like a warning of a potential hazard and speed advice for entering and leaving intersections with minimal stops.

*CV communication technolog*y

The most substantial feature of CV is the application of wireless communication. Wireless communication is a method of transferring information between two or more points. Rather than using physical mediums like cables and wires, wireless communication leverages electromagnetic waves to transmit data. Nowadays, there are a variety of wireless technologies in the market. Different techniques have different operating characteristics. The primary features are communication range and latency. The communication range is the distance that the communication signal can travel. This range is influenced by several factors and may vary significantly from one point to another (Zeng et al., 2012). Communication latency is defined as the time interval between the stimulation and response. More specifically, it refers to the time that a communication signal takes from the starting transmission point to the ending transmission point.

In the transportation network, the degree of information connectivity is greatly affected by the communication range and communication latency. In general, longer range is better because longer-range communication has broader information coverage. Since communication latency represents how fast communication information is transmitted, it is desired when the latency is low. However, it should be noted that it’s impossible for long range and low latency to exist simultaneously. Communication range and communication latency are the most crucial criteria to consider when selecting wireless technologies for various transportation applications. Currently, a variety of wireless technologies highlight these two characteristics of application in the transportation system, and they are briefly introduced as follows:

- DSRC – This is a protocol for wireless communication which was dedicated by the Federal Communications Commission (FCC) in 2004 to utilize 75 MHz of bandwidth at 5.9 GHz spectrum to support communication between vehicles and infrastructure. DSRC has a low communication latency because it is intended for high-speed wireless communication. Therefore, the communication range of DSRC is relatively short. The range of DSRC is designed to be about 3000 feet (1000 meters), but this range in the real world is usually less than 1000 feet (300 meters) (Kandarpa et al., 2009).
- Cellular communication – This refers to mobile phone communication which leverages low-power wireless communication systems. The main problem with current cellular

communication technology is the big delay within the communication range. Moreover, the network will experience buffer-based delay if the cellular networks are busy. Therefore, current cellular technologies are considered suitable only for supplemental applications. However, cellular communication may surpass DSRC in the near future due to the rapid development of technology like 5G.

- Bluetooth communications – Bluetooth communication is another widely applied technology in the consumer market. The communication range varies with Bluetooth classes, ranging from 30 feet (10 meters) to 300 feet (100 meters). The communication latency of this technology is significantly higher than that of DSRC. Therefore, it is only suitable for communication between two relatively stationary objects.

- Satellite communications – This communication is achieved by the artificial satellite which creates a communication link between the transmitter and the receiver at different locations on Earth. Satellite communication consists of two main components: ground segment and space segment. The ground segment usually includes equipment for transmission and reception. The space segment is mainly the satellite itself. The satellite receives signals transmitted by equipment on earth, amplifies the signal, and then retransmits it back to Earth (Labrador, 2019). However, this technology is also not suitable for real-time safety-related applications because the capacity of this technology is limited and the communication latency is high.

Hardware

To achieve successful V2V communication and V2I communication, several devices need to be installed in vehicles and along roadways. According to the Federal Highway Administration (FHWA), those devices are defined as an on-board unit (OBU) and a roadside unit (RSU).

OBU is the equipment installed in the mobile applications that enables information to be exchanged between mobile users and other applications. For example, a CV system requires at least two DSRC radios installed in vehicles or on roadside infrastructure to support communication. Moreover, a device-based warning system should be installed to send warnings to drivers. Figure 2.2 shows a full picture of OBU in vehicles (Harding, 2014).

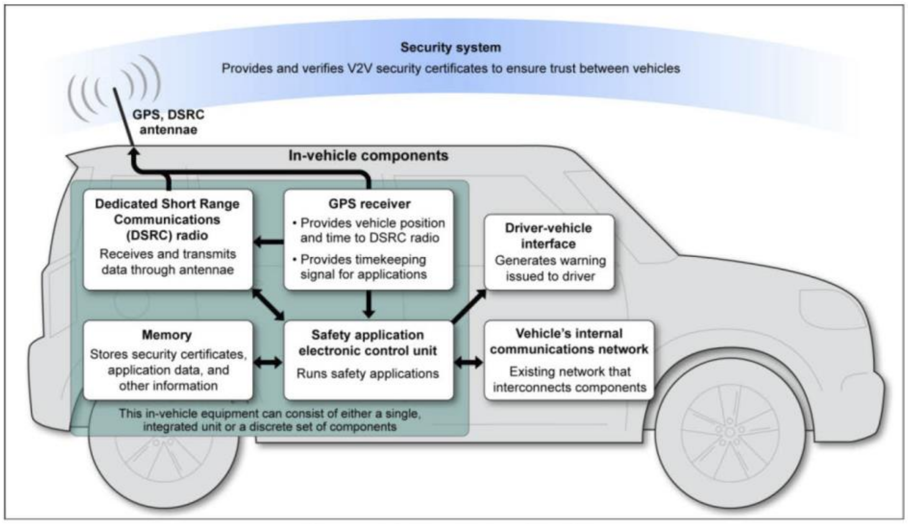

Figure 2.2 OBU of a CV system

In addition to OBUs, a fully-deployed CV environment requires a roadside unit (RSU) to support the communication between vehicles and infrastructure. RSU refers to the equipment that has been installed at the roadside and communicates with mobile devices via DSRC radio communications. RSE could employ DSRC, or could potentially use some other communications medium such as existing 3G/4G cellular networks or Wi-Fi.

2.4 CAV Benefits

To make the best use of the potential of CV and AV technologies, industry groups and researchers have dedicated themselves to developing a CAV system that combines CV technology and AV technology. The V2V communication and V2I communication provided by CV technology can provide useful traffic information to the AV system to improve operational performance and safety. With V2V communication and V2I communication added, traffic information can be provided to the vehicle ahead so that it can take self-control (e.g., brake and accelerate) in advance to enable smooth traffic flow. Therefore, when connectivity is added into the AV-based system, vehicles would become CAV which are equipped with both OBUs for communications and sensors for detections.

Due to the features of communication and automated driving of CAV, it can provide a wide range of benefits for the transportation system and its users, including drivers, passengers, pedestrians, etc. The benefits can be summarized in the aspects of safety, mobility, environment, and data, as follows:

- Safety: According to a survey by the USDOT, 94% of fatal vehicle crashes are caused by human error. Higher levels of automation can reduce dangerous driver behaviors, such as drugged driving, drunk driving, distraction, and speeding. If V2V communication and V2I communication are implemented, the number of traffic accidents can be significantly reduced because infrastructures like traffic signals and up-to-the-minute warning systems send real-time information about potential dangers, upcoming collisions, diversions, and terrible weather conditions. That information could be used to avoid hazards.
- Mobility: Several innovative mobility applications supported by CAV technology can increase the mobility of the transportation system. For example, cooperative adaptive cruise control, enabling vehicles to operate with small gaps and at the same speed as a platoon, is capable of increasing traffic throughput and alleviating congestion. With CAV technologies applied, vehicles can monitor the surrounding environment constantly and respond to changes by braking and accelerating quickly. CAV can then travel with a smaller headway and higher speed, and traffic throughput can be increased.
- Environment: Traffic congestion and bottlenecks are often caused by driver behavior such as changing lanes in the wrong place. With the application of CAV technology, such actions can be avoided and traffic congestion can be reduced. Higher emissions caused by frequent stop-and-go traffic can also be reduced. Moreover, traffic congestion caused by accidents can also decrease with the assistance of CAV technology, where vehicles and infrastructures can transmit real-time information to achieve coordination between vehicles and infrastructure. Then unnecessary braking and stopping can be avoided at some locations like intersections, resulting in lower emissions.

2.5 AV/CV Application and Pilots in the USA

AV application

Various automated features are available through the application of AV technology. Some features are developed to warn drivers of potential hazards. Some are designed to assist drivers with driving tasks in specific situations, such as parallel parking. Based on the function of AV technology, Table 2.2 summarizes the AV applications (Wagner, 2014).

Table 2.2 Applications of AV technology (Wagner, 2014)

Applications	Function
Antilock brakes	Prevent wheels from locking up and skidding when a driver brakes, particularly on wet or slippery roadway surfaces.
Blind-spot information system	Sensors monitor the sides of a vehicle for other vehicles approaching blind spots and transmit an alert to the driver. Typically, a visual alert appears on or near the side mirrors if a vehicle is detected.
Electronic stability control	A system that uses automatic computer-controlled braking to prevent loss of control if a vehicle loses directional stability or control during a skid.
Park assist	Cameras and sensors detect rear objects and available space when a vehicle is backing up, reducing the difficulty of parallel parking or in some cases enabling the vehicle to nearly park itself.
Adaptive cruise control	ACC allows the driver to set the desired speed the vehicle will maintain automatically. ACC uses sensors to track the distance from the vehicle ahead and maintains a safe gap by accelerating or braking to adjust to changes in traffic speed.
Forward collision prevention	Collision warning systems alert a driver if the vehicle is accelerating at a rate at which it would be likely to crash into a vehicle ahead.
Lane departure warning	A system using cameras to track vehicle position relative to a driving lane to provide feedback and/or steering assistance to help maintain the vehicle position in the lane.

Steering assist	A system uses all of its sensors and cameras to steer itself for a certain period of time.
Autopilot	Allows drivers to enable their cars to drive themselves on certain portions of the trip, like on freeways.

CV application

Over the past few years, scholars, industry groups, and other institutions made efforts to conduct research on CV deployments. As a result, a variety of CV application concepts have been developed. They can be categorized into six aspects of safety, mobility, environment, agency data, road weather, and smart roadside. The introduction of those applications in each category, by the UDSOT website, is shown in Table 2.3 – Table 2.8.

Table 2.3 Safety application of CV technology[1][2]

Safety Applications	Description
Red Light Violation Warning	An application that broadcasts signal phase and timing (SPaT) and other data to the in-vehicle device, allowing warnings for impending red-light violations.
Curve Speed Warning	An application that alerts drivers when they are approaching a curve at an unsafe speed for safe navigation.
Stop Sign Gap Assist	An application that utilizes traffic information broadcasting from roadside equipment to warn drivers of potential collisions at stop sign intersections.
Spot Weather Impact Warning (SWIW)	An application that warns drivers of local hazardous weather conditions by relaying management center and other weather data to roadside equipment, which then re-broadcasts to nearby vehicles.

[1] https://www.its.dot.gov/pilots/pilots_v2i.htm
[2] https://www.its.dot.gov/pilots/pilots_v2v.htm

Reduced Speed/Work Zone Warning	An application that utilizes roadside equipment to broadcast alerts to drivers warning them to reduce speed, change lanes, or come to a stop within work zones.
Pedestrian in Signalized Crosswalk Warning (Transit)	An application that warns transit bus operators when pedestrians within the crosswalk of a signalized intersection are in the intended path of the bus.
Emergency Electronic Brake Lights	An application where the driver is alerted to hard braking in the traffic stream ahead. This provides the driver with additional time to look for and assess situations developing ahead.
Forward Collision Warning	An application where alerts are presented to the driver to help avoid or mitigate the severity of crashes into the rear end of other vehicles on the road. Forward crash warning responds to a direct and imminent threat ahead of the host vehicle.
Intersection Movement Assist	An application that warns the driver when it is not safe to enter an intersection—for example, when something is blocking the driver's view of opposing or crossing traffic. This application only functions when the involved vehicles are each V2V-equipped.
Left Turn Assist	An application where alerts are given to the driver as they attempt an unprotected left turn across traffic, to help them avoid crashes with opposite-direction traffic.
Blind Spot/Lane Change Warning	An application where alerts are displayed to the driver that indicate the presence of same-direction traffic in an adjacent lane (Blind Spot Warning), or alerts given to drivers during host vehicle lane changes (Lane Change Warning) to help the driver avoid crashes associated with potentially unsafe lane changes.
Do-Not-Pass Warning	An application where alerts are given to drivers to help avoid a head-on crash resulting from passing maneuvers.
Vehicle Turning Right in Front of Bus Warning	An application that warns transit bus operators of the presence of vehicles attempting to go around the bus to make a right turn as the bus departs from a bus stop.

Table 2.4 Mobility application of CV technology[3]

Mobility Applications	Description
Advanced Traveler Information System	Enhanced traveler information services that record or infer user decisions and other contextual trip data that, when suitably processed, can improve or transform system management functions.
Intelligent Traffic Signal System	An overarching system optimization application accommodating signal priority, preemption, and pedestrian movements.
Transit Signal Priority and Freight Signal Priority	Two applications that provide signal priority to transit at intersections and along arterial corridors as well as signal priority to freight vehicles along an arterial corridor near a freight facility.
Mobile Accessible Pedestrian Signal System	An application that allows for an automated call from the smartphone of a visually impaired pedestrian to the traffic signal, as well as audio cues to safely navigate the crosswalk.
Emergency Vehicle Preemption	An application that provides signal preemption to emergency vehicles and accommodates multiple emergency requests.
Dynamic Speed Harmonization	An application that aims to recommend target speeds in response to congestion, incidents, and road conditions to maximize throughput and reduce crashes.
Queue Warning	An application that aims to provide drivers timely warnings of existing and impending queues.
Cooperative Adaptive Cruise Control	An application that aims to dynamically adjust and coordinate cruise control speeds among platooning vehicles to improve traffic flow stability and increase throughput.
Incident Scene Pre-Arrival Staging Guidance for	An application that provides input to responder vehicle routing, staging, and secondary dispatch decisions.

[3] https://www.its.dot.gov/pilots/pilots_mobility.htm

Emergency Responders	
Incident Scene Work Zone Alerts for Drivers and Workers	An application that warns on-scene workers of vehicles with trajectories or speeds that pose a high risk to their safety. It also warns drivers passing an incident zone if they need to slow down, stop, or change lanes.
Emergency Communications and Evacuation	An application that addresses the needs of evacuees with and without special needs for their transportation.
Connection Protection	An application that enables coordination among public transportation providers and travelers to improve the probability of successful transit transfers.
Dynamic Transit Operations	An application that links available transportation service resources with travelers through dynamic transit vehicle scheduling, dispatching, and routing capabilities.
Dynamic Ridesharing	An application that uses dynamic ridesharing technology, personal mobile devices, and voice-activated onboard equipment to match riders and drivers.
Freight-Specific Dynamic Travel Planning and Performance	An application that enhances traveler information systems to address specific freight needs. Provides information such as wait times at ports, road closures, work zones, and route restrictions.
Drayage Optimization	An application that optimizes truck/load movements between freight facilities, balancing early and late arrivals.

Table 2.5 Environment application of CV technology[4]

Environment Applications	Description

[4] https://www.its.dot.gov/pilots/pilots_environment.htm

Eco-Approach and Departure at Signalized Intersections	A V2I application where intersection traffic signals broadcast the current state of signal phasing (red, yellow, or green) and time remaining in that phase.
Eco-Traffic Signal Timing	An application that uses data collected wirelessly from vehicles (and other sources) to optimize the performance of traffic signals, thus reducing fuel consumption and emissions.
Eco-Traffic Signal Priority	An application that allows transit or freight vehicles approaching a signalized intersection to request signal priority, thereby adjusting the signal timing dynamically to improve service for the vehicle. Priority decisions are optimized for the environment by considering vehicle type, passenger count, or adherence to schedule.
Connected Eco-Driving	An application that uses V2I and V2V data to provide customized real-time driving advice to drivers, including recommended driving speeds and optimal acceleration/deceleration profiles, so that drivers can adjust their driving behavior to save fuel and reduce emissions.
Wireless Inductive/Resonance Charging	An infrastructure application that uses magnetic fields embedded in the pavement to wirelessly transmit electric currents between metal coils thus enabling the wireless charging of electric vehicles while the vehicle is stopped or in motion.
Eco-Lanes Management	An application that establishes parameters and defines the operations of eco-lanes. Eco-lanes are similar to existing managed lanes but optimized for the environment.
Eco-Speed Harmonization	An application that determines speed limits optimized for the environment based on traffic conditions, weather information, and GHG and criteria pollutant information, allowing for speed harmonization in appropriate areas.
Eco-Cooperative Adaptive Cruise Control	A V2V application that uses connected vehicle technologies to collect speed, acceleration, and location information of other vehicles and integrates these data into a vehicle's adaptive cruise

	control system, thus allowing for automated longitudinal control capabilities and vehicle platooning that seeks to reduce fuel consumption and emissions.
Eco-Traveler Information Applications	A group of applications that disseminate information to support transportation choices that reduce fuel consumption and emissions.
Eco-Ramp Metering	An application that collects traffic and environmental conditions data to determine the most environmentally efficient operation of traffic signals at freeway on-ramps and to manage the rate of entering vehicles.
Low Emissions Zone Management	An application that leverages connected vehicle technologies to enable the operation of Low Emissions Zones. Low Emissions Zones are geographic areas that seek to incentivize green transportation choices and deter high polluting vehicles from entering the zone.
AFV Charging / Fueling Information	An application that informs travelers of locations and availability of alternative fuel vehicle charging and fueling stations and inductive/resonance charging infrastructure, thereby alleviating "range anxiety."
Eco-Smart Parking	An application that provides users with real-time location, availability, type, and price of parking, resulting in reduced parking search times and emissions.
Dynamic Eco-Routing (Light Vehicle, Transit, Freight)	A navigation routing application that determines the most eco-friendly route in terms of minimizing fuel consumption or emissions for individual travelers.
Eco-ICM Decision Support System	An application that uses historical, real-time, and predictive traffic and environmental data on arterials, freeways, and transit systems to determine operational decisions by system operators that are environmentally beneficial to the corridor.

Table 2.6 Agency data application of CV technology[5]

Agency Data Application	Description
Probe-Based Pavement Maintenance	An application that allows the vehicle to automatically report potholes or other pavement anomalies.
Probe-Enabled Traffic Monitoring	An application that utilizes communication technology to transmit real-time traffic data between vehicles.
Vehicle Classification-Based Traffic Studies	An application that would allow sorting of vehicle behavior data by vehicle type.
CV-Enabled Turning Movement & Intersection Analysis	An application that uses paths self-reported by vehicles to track turning ratios, delay, and other intersection metrics.
CV-Enabled Origin-Destination Studies	An application that uses connected vehicle technology to monitor the beginning and endpoints of a vehicle's journey and extrapolate the route in between.
Work Zone Traveler Information	An application that monitors and aggregates work zone traffic data.

Table 2.7 Road weather application of CV technology[6]

Road Weather Application	Description
Motorist Advisories and Warnings	An application that will use road-weather data from connected vehicles to provide information to travelers about deteriorating road and weather conditions on specific roadway segments.
Enhanced MDSS	An application that will acquire road-weather data from connected and other general public vehicles to recommend treatment plans and

[5] https://www.its.dot.gov/pilots/pilots_agency_data.htm
[6] https://www.its.dot.gov/pilots/pilots_roadweather.htm

	weather response plans to snowplow operators and drivers of maintenance vehicles.
Vehicle Data Translator	A complementary application that, when installed on road service vehicles such as snowplows, collects road and atmospheric conditions data and transmits them to other portions of the road weather management network.
Weather Response Traffic Information	An application that will use connected vehicle data and communications systems to enhance the operation of variable speed limit systems and improve work zone safety during severe weather events.

Table 2.8 Smart roadside application of CV technology[7]

Smart Roadside Application	Description
Wireless Inspection	An application that will utilize roadside sensors to transmit identification, hours of service, and sensor data directly from trucks to carriers and government agencies.
Smart Truck Parking	An application that will provide information such as hours of service constraints, location and supply of parking, travel conditions, and loading/unloading schedule to allow commercial drivers to make advanced route planning decisions.

Current pilot in the USA

As described above, many concepts about CV and AV applications have been developed across the US. To test the effectiveness and feasibility of those applications, various institutes, including government, research organizations, and industries have deployed or have begun to

[7] https://www.its.dot.gov/pilots/pilots_smart_roadside.htm

deploy related pilots to do field tests of CV and AV technologies. The following part will briefly introduce those pilot tests.

(1) CV pilots

- New York

The New York City Department of Transportation (NYCDOT) intends to deploy a CV pilot to evaluate a series of CV applications on safety and mobility. The deployment site is located in tightly-spaced intersections in New York, as shown in Figure 2.3[8].

Figure 2.3 New York CV pilot

The CV pilot led by the New York City Department of Transportation (NYCDOT) includes three different areas in the boroughs of Manhattan and Brooklyn. As shown in the figure above, the first area consists of a four-mile segment of Franklin D. Roosevelt (FDR) Drive in the Upper East Side and East Harlem neighborhoods of Manhattan. The second area involves four one-way corridors in Manhattan, and the third area includes a 1.6-mile segment of Flatbush Avenue in Brooklyn. Using DSRC, V2I communication technology will be applied at selected intersections. Also, approximately 8 RSUs will be installed along the higher-speed FDR Drive to address issues such as short-radius curves and a weight limit, and 36 RSUs will be installed at other locations within the city to support traffic management.

- Florida

1) Tampa-Hillsborough Expressway Authority (THEA)

[8] https://www.its.dot.gov/pilots/pilots_nycdot.htm

To alleviate traffic congestion, reduce collisions, and prevent wrong-way entry at the Selmon Reversible Express Lanes (REL) exit, THEA plans to deploy a CV pilot that integrates a variety of CV applications. This deployment site is located in downtown Tampa, shown in Figure 2.4[9].

Figure 2.4 Connected Vehicle Pilot Deployment - Downtown Tampa

DSRC technology has been applied in the THEA CV pilot to enable transmissions among 10 buses, 8 trolleys, approximately 1,000 cars of individual volunteers, and approximately 47 roadside units along city streets. This deployment pilot is used to enhance pedestrian safety, improve transit operations, and reduce conflicts of mixed traffic. To support this initiative, THEA will be working with its primary partners, the City of Tampa, the Florida Department of Transportation (FDOT), and the Hillsborough Area Regional Transit Authority to create a region-wide Connected Vehicle Task Force.

2) I-75 Florida's Regional Advanced Mobility Elements (FRAME)

The I-75 FRAME project is located on the I-75 and US 301/441 corridors, connecting east-west arterials between these two corridors, as shown in Figure 2.5[10]. The purpose of this project is to reroute the I-75 traffic in the case of emergencies and incident management, and to transfer real-time information to drivers when freeway incidents happen. The project impact area is comprised of FDOT Districts 2 and 5. Each District will lead the effort to leverage CV

[9] https://www.its.dot.gov/pilots/pilots_thea.htm
[10] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/i75-frame.shtm

technologies to better manage, operate, and maintain the multi-modal system while also generating an integrated corridor management solution.

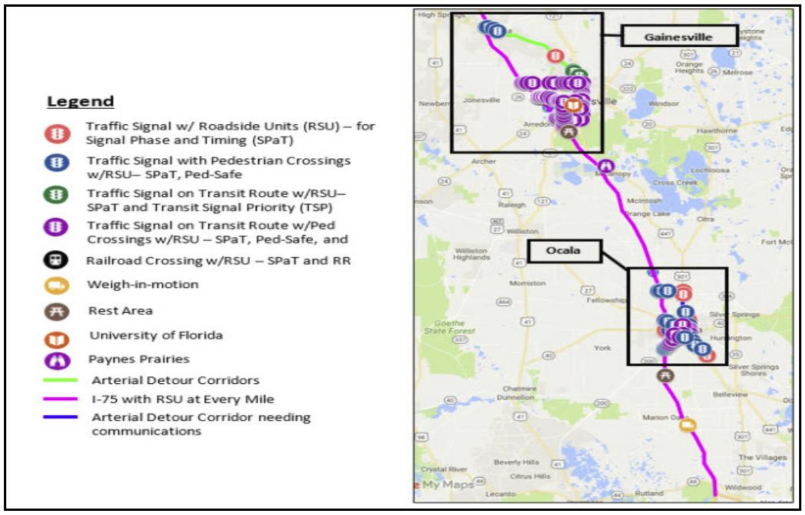

Figure 2.5 Exhibition of FRAME testbed

3) Lake Mary Boulevard CV Testbed

The Lake Mary Boulevard CV Testbed is located along seven signalized intersections from International Parkway to Rinehart Road in Lake Mary, Florida, as shown in Figure 2.6[11]. DSRC technology is deployed to evaluate many CV applications, including Red-Light Violation Warning, Signal Phase and Timing, Forward Collision Warning, Target Classification (identifying other OBUs), and Traffic Incident Messages.

[11] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/lake-mary-boulevard-cv

Figure 2.6 The Lake Mary Boulevard CV Testbed

4) Orlando Smart Community 2017 ATCMTD

Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) was announced by the Florida Department of Transportation, in partnership with MetroPlan Orlando, the University of Central Florida, the City of Orlando, and Orange County, FL, in 2017. This project consists of three components: PedSafe, GreenWay, and SmartCommunity.

PedSafe is a collision-avoidance system designed by FDOT for protecting pedestrians. The basic idea of PedSafe is to use CV technologies to connect the advanced signal controller to reduce the crash ratio of pedestrians and bicycles. The overview of the technical framework is shown in Figure 2.7[12]. The project designed 33 RSUs and is expected to be completed by the end of 2020.

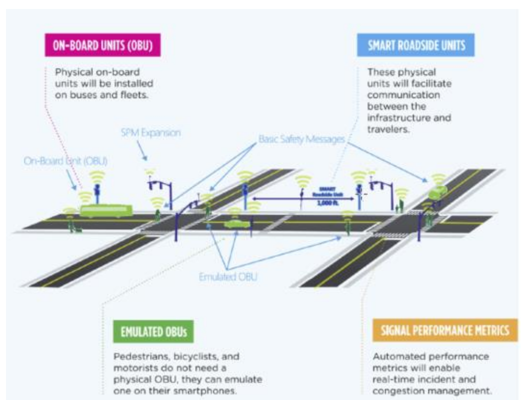

Figure 2.7 Overview of the technical framework of Pedsafe

Greenway was also developed by FDOT to dynamically manage over 1,000 traffic signals within the region by leveraging the multi-modal transportation system. Greenway aims to connect Advance Sensor Technology, Conditional TSP, Adaptive Deployment Traffic Signal Interface with Track Positive Train Control (SunRail), Smart Parking Technology with Signal Performance Metrics, Integrated Corridor Management, and Signal Control Analytics and Visualization. The control framework is shown in Figure 2.8[13]. This will allow strategic planning for special events

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[12] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/atcmtd-orlando.shtm

[13] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/atcmtd-orlando.shtm

considering all modes and users and will offer a unified strategy to system operations and management.

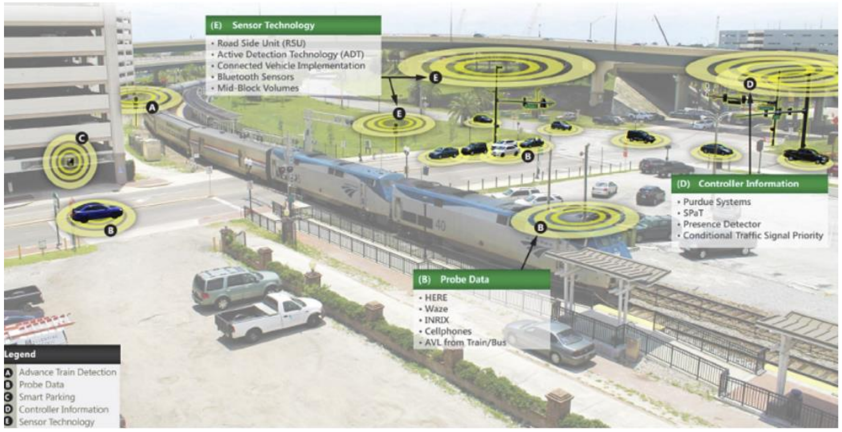


Figure 2.8 Control framework of Greenway

SmartCommunity is a program that integrates CAV technology, connected infrastructure, renewable energy, and a mobility-on-demand framework to alleviate day-to-day challenges, like traffic congestion. With this program applied, travelers can share information and then coordinate trips to the destination. Moreover, multimodal travel information integrating trip planning with modal choice options can be accessed by this program.

5) Gainesville Signal phase and Timing (SPaT) Trapezium

This deployment site is located along four roads: SR 121 (SW 34th St), SR 26 (W University Ave), US 441 (SW 13th St), and SR 24 (SW Archer Rd), surrounding the University of Florida main campus, as shown in Figure 2.9[14]. The four roads form a trapezium shape. This testbed consists of 27 traffic signals equipped with 27 Roadside Units. It aims to improve travel-time reliability, safety, and throughput, and provide traveler information with the application of CV technology.

[14] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/gains-trapezium.shtm

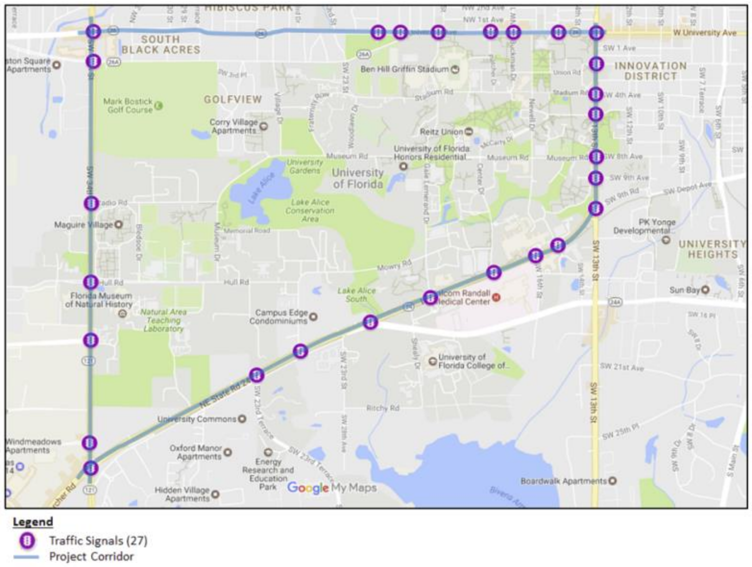


Figure 2.9 Gainesville SPaT Testbed

6)US 90 SPaT Tallahassee

The SPaT deployment site is located along the corridor from Duval Street in downtown Tallahassee to Walden Road, west of Interstate 10 (I-10), Florida, as shown in Figure 2.10[15]. SPaT equipment and CV-ready traffic signal controllers were integrated and installed at 22 signalized intersections along this corridor. The short-term goal is to confirm whether SPaT performs effectively in this hilly and forested region. The long-term goal is to assess DSRC effectiveness and safety for road users traveling along a signalized arterial corridor.

[15] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/us90-spat.shtm

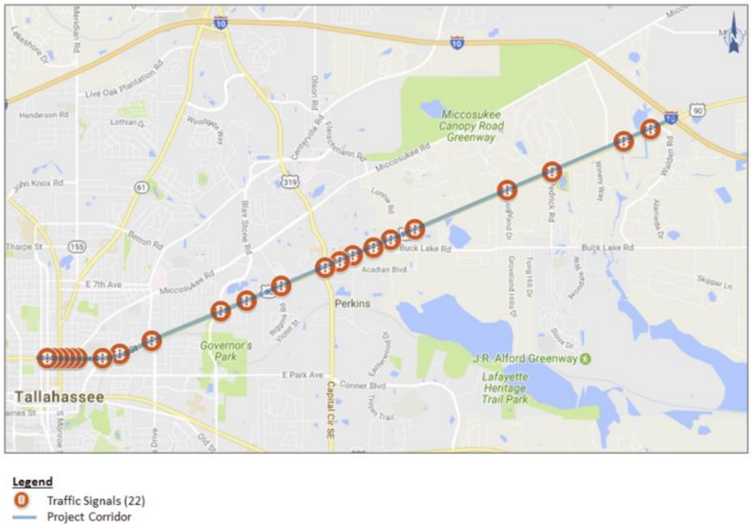


Figure 2.10 US 90 SPaT Tallahassee deployment

- Wyoming

Wyoming is critical for freight to transport across the country and between the United States, Canada, and Mexico, as shown in Figure 2.11[16]. Every year more than 32 million tons of freight are transported across this 6000-foot-long corridor, where the winter crash rate is three to five times higher than that in summer due to high wind speeds and wind gusts. Therefore, the Wyoming Department of Transportation (WYDOT) announced the deployment of a CV pilot to reduce the number of blow-over incidents and adverse weather-related incidents in the corridor. WYDOT will deploy approximately 75 roadside units (RSUs) along various sections of this corridor. Moreover, around 400 vehicles will be equipped. Of the 400 vehicles, at least 150 will be heavy trucks that are expected to be regular users of I-80. Also, 100 WYDOT fleet vehicles, snowplows, and highway patrol vehicles will be equipped with OBUs and mobile weather sensors.

[16] https://www.its.dot.gov/pilots/pilots_wydot.htm

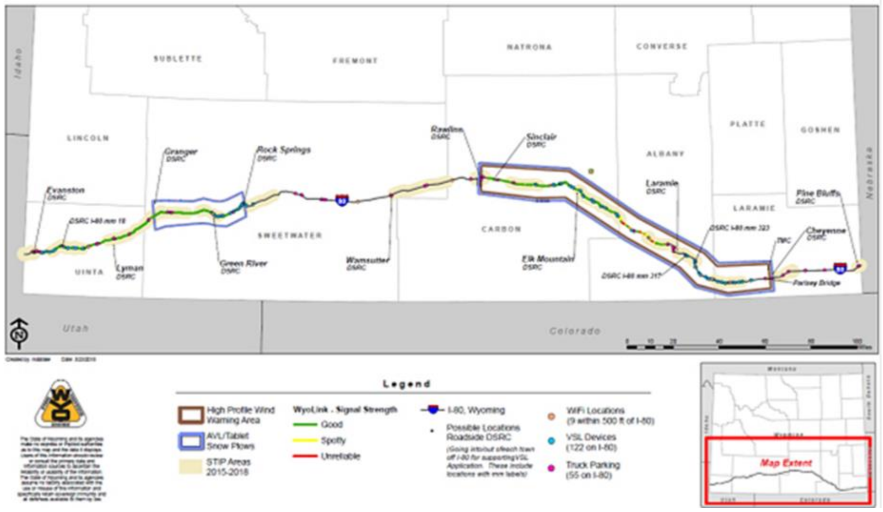


Figure 2.11 Wyoming CV deployment

- Michigan

1) M-City

M-City involves about 16 acres of roads and traffic infrastructure located on the 32-acre grounds of the North Campus Research Complex of the University of Michigan, as shown in Figure 2.12[17]. M-City is a full-scale laboratory that is able to provide traffic simulations involving various complex situations that vehicles may encounter in reality. This testbed can be used for a variety of CV and AV applications, such as driverless shuttle testing, accelerated evaluation of AVs in lane-change scenarios, and accelerated evaluation of AVs in car-following maneuvers.

[17] https://mcity.umich.edu/our-work/mcity-test-facility/

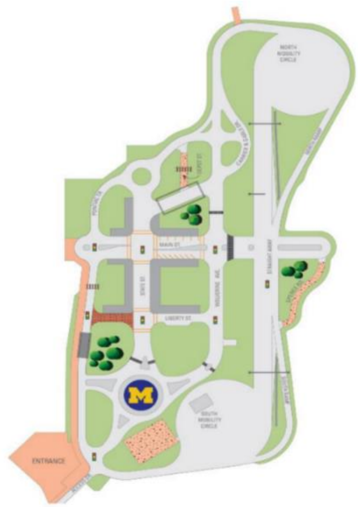


Figure 2.12 M-City CAV deployment

2) Southeast Michigan Connected Vehicle Testbed

This testbed is a roughly 125-mile-long road near General Motors' Milford Proving Grounds, along I-94 from Ann Arbor to metro Detroit, and U.S. 23 from Arbor to Brighton, as shown in Figure 2.13[18]. Approximately 115 sensors and other wireless equipment are installed on roadsides to broadcast signals to CVs to help alleviate traffic congestion.

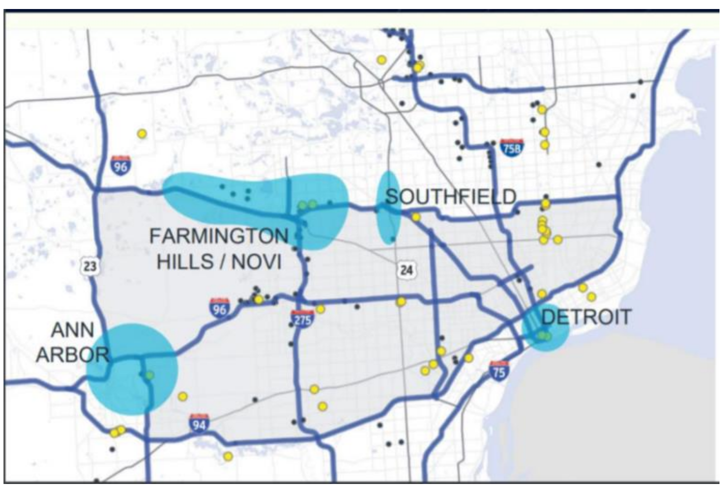


Figure 2.13 Southeast Michigan Connected Vehicle Testbed

[18] https://www.gomobilemichigan.org/planetm/southeast-michigan-connected-vehicle-test-bed.html

● California

In 2005, the nation’s first public CV testbed was developed by Caltrans, partnered with the Metropolitan Transportation Commission and the California Partners for Advanced Transportation Technology (PATH) program at UC Berkeley. This testbed is along El Camino Real (state route 82), a major arterial and state highway connecting South San Francisco to San Jose through the heart of Silicon Valley, as shown in Figure 2.14[19]. In 2018, to comply with the latest CV standards, technologies, and implementation architecture, Caltrans and PATH worked with USDOT to update this testbed. These improvements were successfully used to demonstrate the Multi-Modal Intelligent Traffic Signal System (MMITSS), including CV-based traffic signal control and signal priority for transit, freight, and pedestrians, and Environmentally Friendly Driving.

Figure 2.14 El Camino Real CV testbed

● Arizona

In 2007, the Maricopa County Department of Transportation (MCDOT), in partnership with the University of Arizona and the Arizona Department of Transportation (ADOT), deployed a testbed for connected vehicle (CV) technologies in Anthem, Arizona to field test DSRC deployments, as shown in Figure 2.15[20]. This testbed includes six intersections designated for the

[19] http://caconnectedvehicletestbed.org/index.php/about.php
[20] http://itswisconsin.org/wp-content/uploads/2017/07/2015-Forum-Khoshmagham.pdf

test of MMITSS with CV technology such as transit signal priority and emergency vehicle preemption.

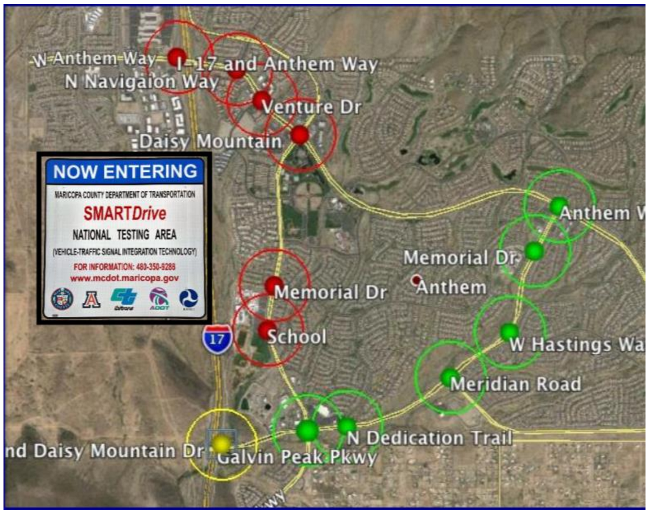


Figure 2.15 Arizona CV testbed

- Ohio

In 2014, Ohio State University launched its 33 Smart Mobility Corridor, and then the Ohio Smart Mobility Initiative quickly evolved to become a collaborative effort among several organizations who deploy this corridor. The corridor is centered around a 35-mile stretch of US-33 beginning in Dublin through Marysville, and continuing to East Liberty, Ohio, in the northwest portion of the Central Ohio region, as shown in Figure 2.16[21]. The corridor is serving as a testbed for real-world demonstrations of a range of CV technologies.

[21] https://drive.ohio.gov/wps/portal/gov/driveohio/know-our-projects/projects/03-33-smart-mobility-corridor

Figure 2.16 33 Smart Mobility Corridor in Ohio

- Utah

In 2016, UDOT built a full DSRC corridor for CV technology testing. The deployment site is located along Redwood Road in Salt Lake City, as shown in Figure 2.17[22]. This UDOT-owned urban corridor is eleven miles long and includes around 30 signalized intersections. As an initial application, this CV deployment project equipped transit vehicles with OBUs and the GPS for V2I communications, which can provide intelligent TSP to late buses. When a bus comes into the DSRC communication range of intersections, the V2I function will gather CV information and TSP control algorithms will be activated if the bus is behind schedule.

Figure 2.17 Utah CV corridor

[22]https://transops.s3.amazonaws.com/uploaded_files/Utah%20DSRC%20MMITSS%20Project%20Overview%2002.14.18%20-%20NOCoE%20Peer%20Exchange.pdf

(2) AV Testbed

Two AV shuttles were operating in Lake Nona, Florida. The AV shuttles transported passengers along Tavistock Lake Boulevard from behind the Pixon Apartments outside the Lake Nona Town Center to Canvas Restaurant and Market in the Village Center, as shown in Figure 2.18[23]. The length of this route is 1.2 miles, and the shuttle frequency is 10 to 15 minutes. The AV shuttle service started in September 18, 2019.

Figure 2.18 AV testbeds in Lake Nona, Florida

An autonomous transit system, connecting the City of Gainesville Innovation District and downtown with the University of Florida campus, was deployed by Gainesville Autonomous Transit Shuttle. The goal of this shuttle is to guarantee a maximum headway of 10 minutes. The AV routes include SW 4th Avenue, SW 13th Street, SW 2nd Avenue, and S Main Street, as shown in Figure 2.19[24].

Figure 2.19 AV testbeds on the University of Florida campus, Florida

[23] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/LakeNonaAVshuttles
[24] https://www.fdot.gov/traffic/its/projectsdeploy/cv/maplocations/gainsav.shtm

Two fully automated, eleven-seat, all-electric shuttles manufactured by the French firm NAVYA operated in M-City from June 4, 2018, through December 19, 2019[25]. The goal of operating these two AVs is to have a better understanding of how passengers, pedestrians, bicyclists, and other drivers interact with the shuttle so the level of consumer acceptance of this technology can be evaluated.

Figure 2.20 Exhibition of AV shuttle in M-City

Waymo LLC is an American autonomous driving technology development company[26]. In April 2017, Waymo started a limited trial of a self-driving taxi service in Phoenix, Arizona. During recent years, Waymo has tested its autonomous vehicles in several cities, including Mountain View, Sunnyvale, Los Altos Hills, and Palo Alto in California, and in Phoenix, Arizona.

[25] https://mcity.umich.edu/shuttle/
[26] https://www.wired.com/story/waymo-self-driving-taxi-service-launch-chandler-arizona/

Figure 2.21 Exhibition of Waymo AV

3. POTENTIAL IMPACTS OF CAV ON TRANSPORTATION PLANNING

3.1 Overview

Transportation planning is a collaborative process to determine future goals, policies, investments, and designs for future events regarding traffic movement, facility usage, impact analysis, etc. In general, transportation planners conduct transportation planning by defining goals and objectives, identifying problems, generating and evaluating alternatives, and developing plans. This chapter will state the potential impacts of CAV technology on transportation planning in three aspects: transportation systems, land use patterns, and infrastructure investment decisions.

3.2 Impacts on the Transportation System

The impacts that CAV exerts on the transportation system are thorough and profound. Although the magnitude of the impacts depends on the market penetration rate of CAVs, management policy, and regulation, CAV will have different levels of impact on the following aspects.

Motorized traffic

When the market penetration of CAVs increases due to improvements in the maturity of the technology and a reduction in the economic burden, one of the most important things we will need to consider is how much and how often we drive. The most common measurements to evaluate are traffic demand and vehicle miles traveled (VMT), which FHWA defines as miles traveled by vehicles within a specified region for a specified period.

Recently, various research has been conducted to study the potential impact of CAV on VMT (Shladover et al., 2012; Cottam, 2018; Auld, et al., 2018; Taiebat et al., 2019). These studies show that VMT is influenced by various factors that are most likely to be affected by CAV technologies, which are summarized as follows:

- ***Travel demand***: With the application of CAV technology, citizens' travels become more convenient. CAVs will enable travelers to engage in other activities while traveling, such as reading, working, and playing. Thus, people will have fewer incentives to optimize or minimize their travel costs, and vehicle travel will potentially increase. Moreover, CAVs can reduce crash risk due to shorter reaction times and advanced warning systems. Therefore, vehicles can be operated more smoothly on the road network and vehicle travel will increase. Since CAV enables vehicles to drive in a platoon with a relatively short headway, the traffic throughput can also be generally boosted.

- ***Shift between traffic modes:*** Compared with transit, bicycle, and walking, CAV will be more attractive due to its increased convenience and affordability. Travelers are more likely to choose CAV. The shift from high-occupancy public transportation to low-occupancy CAV will increase travel demand. Besides, CAV is an optimal way to solve the problem of first-and-last mile. Therefore, travelers will select CAV even for a short trip that can be completed by walking or biking.
- ***Urban form:*** Since travelers are capable of doing other things when traveling by CAV, they may be more willing to accept a longer work commute to live in a more affordable home. This would give an incentive for urban sprawl, and in turn, would generate more miles of travel (Dennis, 2017).
- ***Increased mobility of nondrivers:*** CAV can enable people without driving abilities, such as the disabled, people under age 16, and senior citizens, to drive. Although this will benefit society, it will also increase travel demand.
- ***Increased vehicle occupancy:*** With CAV technology applied, several traffic modes like car-sharing will be more convenient and effective. CAV is capable of optimizing traffic routes in real-time, making sharing a ride with other passengers much cheaper and more convenient. Therefore, carpooling will be more attractive with CAV. If CAV car-sharing becomes prolific in the future, there will be fewer vehicles on the road.
- ***Less travel related to searching:*** CAV can search for a certain location or a parking site easily and quickly. This will reduce miles spent searching for desired locations.

Nonmotorized traffic

CAV applications will bring benefits and challenges to nonmotorized traffic (bicycle and pedestrian). Planners must understand those impacts so they can plan effectively for nonmotorized traffic.

Information provided by CAVs will change the nature of bicyclist and pedestrian experiences when they use transportation facilities. For example, the safety of bicyclists and pedestrians can be improved because CAV technology can send messages to warn vehicles of the presence of bicyclists and pedestrians. Bike-sharing stations can send information about their locations and availabilities in real-time. Bicyclists will then be less likely to arrive at a station where either all bikes have been taken or all spots are full (Krechmer, 2016).

Various information, such as bicycle travel times, bicycle occupancy, pavement conditions, and routing data, is expected to be available by application of CAV technologies. This information can enrich real-time data so the database can help identify system gaps and deficiencies. It can also assist with the development of bicycle and pedestrian plans (Krechmer, 2016).

Public transportation

CAV can have complex impacts on public transportation. Planners need to analyze those impacts and clearly present the investments necessary to meet future needs.

In the short term, the application of CAV technologies will provide plentiful traffic information which can improve the quality and timeliness of traveler information, resulting in the improvement of transit operations and higher ridership. In the medium term, since CAV is optimal to operate with car-sharing and ridesharing alternatives, ridership on traditional transit will decline. Planners need to consider potential trends when analyzing alternatives.

In the long term, with the development of CAV technology, travelers are increasingly connected to the transit system with smart devices, and transit can be more connected with road infrastructures. Therefore, dynamic operations and optimization can be achieved, such as intermittent bus lanes which enable transit to request exclusive bus lanes when required.

3.3 Impacts on Land Use

The study and deployment of CAV technologies rely on current land use. In the short term, the deployment of CAV technology could still be based on land use. However, in the medium to long term, planners need to make a thorough analysis of the impacts that CAV exerts on land use to provide crucial advice to policymakers and governments. Depending on the purpose of CAV utilization and how CAVs interact with others, CAV technology will result in a low or high density of land use.

One of the main benefits that CAV can provide is that it can relieve travelers from physically driving, giving them more time to engage in other tasks, such as work, meeting, relaxation, etc. Besides, CAV is capable of reducing travel time due to the reduction of traffic congestion and improving traffic safety. These aspects will increase people's willingness to travel long distances and make them more likely to search for lower-cost housing far away from urban centers. This creates an incentive for more sprawling, low-density urban development.

Apart from the low-density scenario, CAV can also produce high-density areas. For example, onsite parking needs, especially in urban cores, will be reduced with the assistance of CAV technology. Thus, valuable space can be freed and planned for other purposes, which will then increase density (Dennis, 2017).

3.4 Impacts on Infrastructure

The infrastructure on roadway networks is currently designed for the use of human-driven vehicles, which may not be suitable for CAVs. Therefore, the infrastructure needs of CAVs should be understood to make future investment decisions.

For many CAVs, their operations are achieved by identifying road marking with the assistance of vision systems such as cameras. In 2017, a research study funded by the Transportation Research Board was conducted to study the impacts that the characteristics of pavement markings exert on the ability of CAV's vision system. As reported in this research, it is not a feasible strategy to control CAVs by relying solely on lane marking recognition since it is unrealistic to expect that the lane markings on the road are always in perfect condition and several road markings cannot be identified by CAVs (TRB, 2017). Therefore, to better deploy CAV technology, government agencies require road markings to be maintained in good condition and those CAV can't identify are avoided.

Since CAV can communicate with RSU and 3D mapping inside the vehicle and can provide real-time traffic conditions and related information, several road signs and signals, such as speed limit signs, are no longer required.

In addition to infrastructures that need to be maintained, many new infrastructures must be deployed in developing CAV technology. For example, maps with higher resolution need to be provided to ensure a safe drive. New types of RSUs need to be installed to support communication with CAV.

4. BENEFIT/COST ANALYSIS OF THE REDWOOD CV CORRIDOR

4.1 Overview

Benefit/cost analysis is a crucial tool to evaluate a transportation project. This chapter will introduce the benefits and costs of UDOT's CV corridor deployment. Then a benefit/cost analysis for the initial TSP application along the corridor will be conducted to evaluate its efficiency at the current stage.

4.2 Introduction of Utah DSRC corridor

After participating in the Connected Vehicle Pooled Fund, UDOT started discussing the potential of deploying CV technology. In late 2014, UDOT began planning for the deployment of a V2I system. The goals of the initial deployment include 1) obtaining experience in purchasing and installing DSRC equipment, 2) deploying a program which could generate a tangible benefit and identify the installation cost, and 3) building a CV corridor (Leonard et al., 2019). For the initial application, UDOT decided to deploy the MMITSS in partnership with the Utah Transit Authority (UTA) to address the schedule reliability of transit vehicles. It plans to equip intersections with DSRC roadside radios and equip transit vehicles with DSRC on-board radios and GPS systems for V2I communications, which can provide intelligent TSP to buses. When a bus comes into the DSRC communication range of intersections, the V2I function will gather CV information and TSP control algorithms will be activated if the bus is behind schedule.

To make full use of CV technology and improve the operational reliability of buses, three standards were referenced when UDOT selected a site for installing a TSP system: a) an urban arterial traveled by a regular bus route which experienced challenges in complying with the published schedule, b) traffic signals are controlled by UDOT, and, c) traffic condition is diverse along the arterial (Leonard et al., 2019). Based on those standards, a segment of Redwood Road was selected as a CV corridor to deploy the TSP system.

Redwood Road is a south-north arterial located in Salt Lake City. The selected corridor stretches 11 miles long with 35 signalized intersections, extending from 400 South to 8040 South, as shown in Figure 2.17. This corridor includes a variety of land uses, such as commercial/retail establishments, residential areas, and educational institutions. Average annual daily traffic (AADT) ranges from 18,000 at the north end where it is less densely populated to 40,000 at the south end. The highest AADT is 60,000 at the I-215 interchange (Leonard, 2017).

Bus route 217 travels along this corridor and buses along this route operate with a 30-minute headway during the early morning hours and late evening hours, a 60-minute headway after 9:00 PM, and a 15-minute headway during the rest of the day.

Application Hardware

In the early stage of this application, among the 35 signalized intersections along Redwood Road, 30 intersections were selected to install DSRC radios. Several UTA buses were outfitted to install DSRC radios. Messages could be exchanged between radios and traffic signals with the application of DSRC wireless technology. The Society of Automotive Engineers (SAE) has defined these messages for both safety and mobility applications (SAE, 2016). The messages used in this deployment include the Basic Safety Message (BSM), Signal Phasing and Timing Message (SPaT), MAP Message (MAP), and Signal Request Message (SRM). For signal priority applications, the J2735 technical committee proposed a new type of message, Priority Status Message (PSM), and this has been integrated into the updated Signal Status Message (SSM) in the 2015 revision of the standard.

BSM is used for transmitting information related to the real-time operating status of vehicles. It is used in a variety of applications, especially in the safety application. BSM is transmitted 10 times per second. This message is referred to as the “here I am” message since it broadcasts vehicles’ real-time status. BSM includes two parts. Part I contains the mandatory data to broadcast, including vehicle positions, speed, heading, brake status, and steering wheel angle. Part II contains optional data that supplements part I data, such as windshield wiper status and headlight status.

The SPaT message is leveraged to send the current status of traffic signals. With this message and others, the receiver is capable of knowing the current signal status, remaining phase time, etc. The contents contained in this message are 1) Intersection ID – the identification number of an intersection; 2) LanesCnt. - the number of movement states to follow; 3) MovementState - information about the current signal status; 4) Active priority and preemption state data.

The MAP message describes the geometric information of the intersection defined at the lane level. This message is transmitted 1 time per second. It includes 1) Intersection ID; 2) Refpoint. The GPS reference point from which other lane nodes are offset. 3) Approaches. Information to express the approach; 4) Lanes. Data to describe the lane information, including lane number, lane width, etc.

The SRM message is sent by several types of vehicles (e.g., transit) to request signal priority. SRM contains not only the information regarding the specific request, such as vehicle type, time of service, and type of request but also the BSM data.

The SSM message is used to reply to a service request sent by the SRM message. The generation of SSM is transmitted only when there are active events or pending requests. This message contains all active priority and preemption states, all pending requests, and the signal state.

The DSRC hardware in this deployment project was from four different vendors, including Savari, Arada, Cohda, and Lear. Those vendors managed the broadcasted messages in different ways and handled message headers differently so that each device is not incompatible with other devices. To solve those issues, developers had to find workarounds in the software. In this deployment project, small stand-alone Linux computers were installed at the intersections to operate the application software. Considering the excellent performance and processing capability, UDOT selected BeagleBone Black industrial-grade Linux boards with 1GHz CPU with 4GB of flash memory to process messages (Leonard, 2019).

Application software

UDOT selected MMITSS as the TSP application software. MMITSS was developed for the Connected Vehicle Pooled Fund Study by the University of Arizona and the University of California PATH program. The MMITSS application allows agencies to manage bus service by granting bus priority based on several factors using V2I communication. The factors considered for the Utah deployment were bus arrival time and occupancy. If the bus is behind its schedule time for certain criteria and meets minimum occupancy criteria, this CV deployment will help the bus get back on schedule by granting priority. Various modifications were made for the original MMITSS software to enable those two criteria. The modified version applied in this deployment is called MMITSS-Utah.

Operation of hardware and software

In this CV application, transits are allowed to request signal priority when specific criteria are met. More specifically, when a bus arrives at a stop more than five minutes behind schedule and the occupancy of the bus is more than twenty percent, this bus can request a signal priority. The “five minutes” standard was made by UTA and the “twenty percent” standard was selected by UDOT. These figures correspond to nine or more passengers on the bus.

Buses in Utah are connected with a software called Service Interface for Real-Time Information (SIRI) operated by UTA. The SIRI system records the time that buses arrive at stops along their planned route, and then compare that time with their scheduled time. If the actual arrival time is later than the scheduled time for more than five minutes, this system designates the bus as “late”. The bus occupancy is recorded by the optical sensors installed in the doorways. The on-board SIRI system connects to the MMITSS software to broadcast the real-time status message of the bus. When the bus enters a limit range of an intersection, usually defined as 20 seconds or about 1000 feet ahead of the stop bar, the MAP message and BSM message are leveraged to determine which lane the bus is in and how far it is from the stop bar. If the “late” and occupancy standards are satisfied, the OBU will send the SRM message to request signal priority. The signal controller then receives this message passed by the Linux computer and determines whether to grant this message. Then the RSU sends the SSM message to the OBU to notify if the priority request is active. The framework of the operation process is shown in Figure 4.1 (Leonard, 2019).

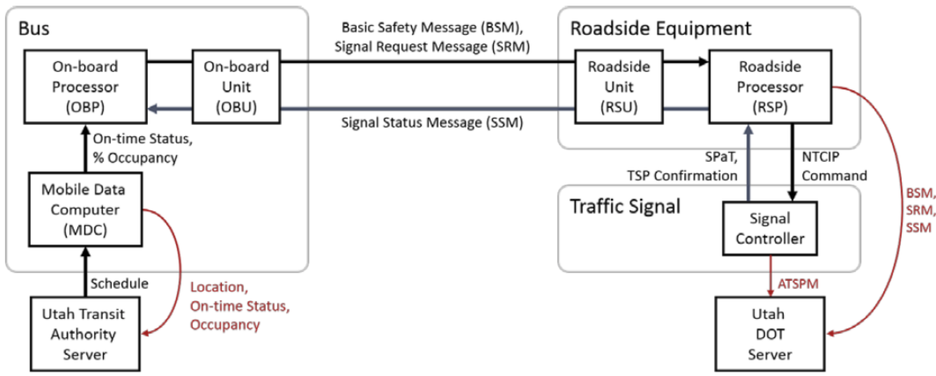


Figure 4.1 Operation process of MMITSS-Utah

4.3 Overview of Benefit/Cost Analysis

A benefit/cost analysis, or B/C analysis, attempts to capture all benefits and costs to society from a project or series of activities. In general, a B/C analysis has two purposes: 1) to evaluate if it is a sound investment, and 2) to compare it with alternative projects (Sallman, 2012).

The core of BCA is that one or more alternatives are compared with a base case, and then the difference between the alternatives and base case will be evaluated. In other words, BCA tries to evaluate what benefits will be obtained if an alternative is taken and what costs will be requested. Therefore, it is critical and helpful to understand the costs and benefits of the transportation project.

Benefits

The benefits of a transportation project refer to the improvement in some measurements by implementing this project, such as a reduction in crashes and an increase in travel-time reliability. In B/C analysis, benefits are usually first estimated by physical terms and then valued by economic terms. In reality, physical terms can include a wide range of measurements, depending on what changes we desire by investing in a project. The commonly used measurements in B/C analysis are as follows:

- ***User travel time***. User travel time is the most commonly used measurement to do B/C analysis related to a project. Changes in the user travel time refer to differences in the sum of all person-hours of travel (PHT), resulting from the implementation of a course of strategies (Sallman, 2012). User travel time is integrated by in-vehicle travel time and out-of-vehicle travel time. In-vehicle travel time represents PHT incurred in a traffic mode. Out-of-vehicle travel time represents PHT to get access to the traffic mode.

- ***Vehicle operating costs***. This measurement can be categorized into fuel use costs and nonfuel use costs. Nonfuel costs typically include costs on maintenance, repair, insurance, and mileage-dependent depreciation. The estimation of vehicle operating cost is usually based on VMT. For simple analysis, changes in fuel use are achieved by multiplying a static rate of average fuel use (gallons per VMT) to the changes in VMT. Then the vehicle operating costs can be valued by multiplying changes in fuel use by a benefit value (cost per gallon).

- ***Safety***. Evaluating safety impacts is a critical part of any transportation B/C analysis. Safety impact analysis aims to evaluate how a project will affect crash frequency and severity. Various costs can be incurred by the crash. Thus, it plays a critical role in the evaluation of a project (FHWA, 2012). This benefit is often valued by a reduction in the number of crashes. As stated in the report (Sallman, 2012), "Crash reduction benefits are typically valued based on actual costs and costs to avoid. Actual costs aim to capture the actual accountable costs of the crash. For example, in the case of a fatality crash, those costs may include the costs of medical treatment of victims, the loss of the victim's wages for the family, and any property damage."

- ***Emissions***. Emissions are also a critical measure to conduct B/C analysis, especially for projects in the air quality and environmental area. Emissions considered in B/C analysis commonly include Nitrous Oxide (NO_x), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Sulfur Dioxide (SO_2), Particulate Matter (PM_{10}), and Fine Particulate Matter ($PM_{2.5}$). The common method to estimate emissions is based on the emission rate per VMT or vehicle hours. However, it is difficult to estimate emissions because emission rates are sensitive to various factors, such as vehicle speeds, the mix of gasoline, regional weather, etc.

- ***Travel-time reliability***. In recent years, travel-time reliability is increasingly applied by researchers and practitioners to assess transportation projects. Traditionally, average travel time was the primary indicator to conduct the B/C analysis of the transportation project. However, average travel time may not reflect the traveler's real experiences due to the nature of the measure and the methods applied to evaluate this measure. Unlike average travel time that only captures changes in recurring travel time, travel-time reliability can quantify the variability in travel times caused by nonrecurring travel time so the full distribution of travel times experienced by system users can be better estimated. Currently, a variety of performance metrics have been developed to quantify travel-time reliability, as shown in Table 4.1 (Lawrence, 2018).

Table 4.1 Performance measures of travel-time reliability (Lawrence, 2018)

Performance Metric	Definition	Units
Planning-Time index	95th percentile Travel-Time Index (95th percentile travel-time divided by the free-flow travel time), normalized by the average travel time	None
Buffer Index	(1) The difference between the 95th percentile travel time and the median travel time, normalized by the median travel time. (2) The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time	percent
Failure and On-Time Measures	(1) Percent of trips with travel times less than 1.1 $*$ Median Travel Time or 1.25 $*$ Median Travel Time (2) Percent of trips with mean speed less than 50 mph, 45 mph, or 30 mph	percent
80th Percentile Travel-Time Index	80th percentile travel time divided by the free-flow travel time	None
Skew Statistic	The ratio of (90th percentile travel time minus the median) divided by (the median minus the 10th percentile)	None
Misery Index (Modified)	The average of the highest five percent of travel times divided by the free-flow travel time	None

Costs

In the B/C analysis of a transportation project, the cost refers to the resources that must be consumed to support the project. The project cost is defined by FHWA as the lifecycle costs of implementing and operating project alternatives. It includes initial capital costs, maintenance costs, rehabilitation costs, and “end-of-project” costs.

- ***Initial capital costs*** are the total investment incurred to deploy and construct a project. The costs include planning, preliminary engineering and assessment, environmental impact reporting, final engineering, right-of-way acquisition, utility impacts, construction alternatives, construction engineering costs, equipment and vehicle purchases, and decommissioning costs for existing facilities impacted by the project (Lawrence, 2018).
- ***Maintenance costs*** are used for preventive activities and day-to-day routine maintenance. Typical examples of these costs include emergency repairs, labor, equipment maintenance, and utility costs.
- ***Rehabilitation costs*** refer to future costs beyond routine maintenance costs to maintain the serviceability of transportation facilities. For example, when the traffic signal reaches its service life, it needs to be replaced.
- ***“End-of-project” costs*** refer to the costs incurred at the end of a project. These mainly include three components: residual value, salvage value and close-out costs. (Lawrence, 2018).

The common measures to evaluate a project applying BCA are Benefit/Cost Ratio (or B/C Ratio) and Net Benefit. As the name implies, the B/C ratio is achieved by dividing the monetized benefits from a project by the cost spent on that project. If the B/C ratio of a project is determined to be greater than 1.0, it means the benefits created by the project are greater than the cost spent, and the project is considered an efficient investment. On the contrary, if the B/C ratio of a project is less than 1.0, it is considered an inefficient investment. Sometimes, a project has a 1.0 B/C. In that case, it is said to be at cost-efficiency. The net benefit is achieved by summing all benefits and then subtracting all costs of a project. This measure is an absolute index of benefits rather than the relative measures offered by the B/C ratio (Sallman, 2012).

4.4 B/C Analysis of Utah DSRC Corridor

This UDOT-owned CV corridor has been deployed and worked for about three years. The purpose of the B/C analysis at this stage is to check if this project is a sound investment. TSP is a set of technologies that could offer buses priority at signalized intersections. Based on the applied priority techniques, TSP can be categorized as passive TSP and active TSP. Passive TSP aims to optimize signal timing or coordinate successive signals to buses to pass through without stopping. Active TSP requires transit to communicate with traffic signals to dynamically adjust signal timing by either extending green time or shortening red time. Passive TSP and active TSP are both meant to improve transit operation performance. The most commonly used measurement of effectiveness is bus travel time and bus delay. Various research has been conducted to assess the effectiveness of implemented TSP systems, as shown in Table 4.2.

Table 4.2 Summary of the effectiveness of TSP applications

Scenario Selection	Method	Measurements and Results	Reference
Newark, New Jersey	Simulation	Bus travel time reduced by 12% to 21%	Muthuswamy et al.
Snohomish County, Washington	Simulation	Bus travel time reduced by 5% and average person delay decreased	Wang et al.
Jinan, China	Field test	Average bus delay decreased by 34.7% and average delay of motor vehicles increased by 8.9%	Ma et al.
Tucson, Arizona	Simulation	Average bus delay reduced by 50% in congestion conditions	He et al.
Arizona	Field test	Bus travel time reduced by 6.1%-8.2%	Ekeila et al.
Fairfax, Virginia	Simulation	Average bus delay reduced by 59%	Ahn et al.
Beijing, China	Simulation	Average person delay reduced by 10.41% to 12%	Kim et al.
King County, Washington	Field test	Total crashes reduced by 13%, property-damage-only crashes reduced by 16%, and fatal crashes reduced by 5%	Song et al.

The CV corridor supporting TSP along Redwood Road provides signal priority when buses behind the published schedule have reached the minimum criteria for threshold and bus occupancy. By granting signal priority with CV technology applied along this corridor, buses can reduce stopped time at signalized intersections so they can get back on schedule and travel time can be reduced. If transit travel time can be accessed, then the benefit can be estimated through economic impacts for travel-time savings.

Data collection

With the CV technology applied for TSP along the DSRC corridor, a quantity of data can be collected. The data can be categorized into three types based on the sources: DSRC data, ATSPM data, and UTA SIRI data. DSRC data is about the real-time vehicle information and the intersection information. ATSPM data records information about the signal status. UTA SIRI data records transit operation information.

At this stage of B/C analysis, since we decided to utilize bus travel time to evaluate the benefits, UTA SIRI data is selected to conduct the analysis. This dataset was requested from UTA. The UTA system provides two datasets. The first is the reliability dataset and the other is the occupancy dataset. Each record in the reliability dataset includes the timestamp, bus ID, driving direction, the actual and scheduled arrival time at bus stops, and the bus status ("Critical Early", "Early", "On Time", "Late", "Critical Late"). The occupancy database records the number of passengers on the bus, the number of passengers boarding and alighting at each bus station, and the dwell time at each bus station. In this project, four months of data, including May, June, July, and August of 2018, were selected to conduct the analysis.

Benefits

Based on the collected data, it was found that the bus schedule differs with direction and dates. Therefore, we selected six cases:

- Case 1: Southbound on workdays. Transits operate in a southbound direction along this corridor on workdays.
- Case 2: Northbound on workdays. Transits operate in a northbound direction along this corridor on workdays.
- Case 3: Southbound on Saturday. Transits operate in a southbound direction along this

corridor on Saturday.

- Case 4: Northbound on Saturday. Transits operate in a northbound direction along this corridor on Saturday.
- Case 5: Southbound on Sunday. Transits operate in a southbound direction along this corridor on Sunday.
- Case 6: Northbound on Sunday. Transits operate in a northbound direction along this corridor on Sunday.

Benefits for this year can be calculated by summing up the benefits of all cases. For each case, the benefit can be obtained by monetizing the travel-time savings, as shown in Eq. (4-1)

$$B = t_d * f * P_L * D * s \tag{4-1}$$

where, t_d represents the average travel-time savings of one trip by using CV technology; f represents bus frequency during a day; P_L represents average loading passengers on the transit on a trip; D represents the number of days in each case; and s represents the per capita income.

After processing UTA SIRI data, several indicators can be achieved for each case, including the average transit time with and without CV technology applied, average loading passengersw, and bus frequency. The results are shown in Table 4.3.

Table 4.3 Indicators of bus operation in various cases

Cases	Travel time of equipped bus (sec)	Travel time of non-equipped bus (sec)	Bus frequency	Loading passengers
Case 1	4128	4206	57	13
Case 2	3634	3664	55	13
Case 3	4058	4201	30	13
Case 4	3445	3569	30	12
Case 5	3758	4181	10	13
Case 6	3290	3575	10	14

According to the statistics, Utah per capita income in 2017 was $28,085/year. We define the average annual growth rate of income as 1.01% based on the historical data[27]. To monetize the benefits on weekends, this project assumes the salary is achieved on both weekdays and weekends rather than just workdays. Based on Eq. (1) and Table 4.3, the benefits of each case can be

[27] https://www.deptofnumbers.com/income/utah/

determined, as shown in Table 4.4.

Table 4.4 Benefits of DSRC corridor for supporting TSP in 2018

Cases	Benefits ($)
Case 1	40,711
Case 2	15,108
Case 3	7,826
Case 4	6,264
Case 5	7,717
Case 6	5,599

Costs

The cost analysis for this CV project captures the lifecycle costs associated with RSE deployment. These mainly include hardware costs, software costs, maintenance costs, and other costs such as project evaluation costs. They are summarized in Table 4.5.

Table 4.5 Costs of DSRC corridor

Category	Component	Costs ($)
Hardware costs	RSU	73,000
	OBU	22,000
	Beaglebone	3,700
	Misc. hardware (brackets, cables, SDK, shipping)	15,000
Software costs	Modifications of MMITSS	17,800
	Peer-to-peer feature	10,400
	Hardware interoperability	118,000
	User interface	59,000
Other costs	Installation/Integration/Coordination	153,600
	Project evaluation	104,000

According to the report presented by the National Cooperative Highway Research Program (NCHRP), the annual maintenance cost per unit is determined as $1,000.

B/C analysis

UDOT stated that the life expectancy of this CV deployment is estimated to be about ten years. Since we aim to conduct B/C analysis in 2018 in this part, the cost is averaged to each year.

Benefits and costs can then be calculated based on the above analysis. Moreover, the B/C ratio and net benefit can be calculated, as shown in Table 4.6.

Table 4.6 Results of B/C analysis of Utah CV deployment in 2018

Benefits ($)	Costs ($)	B/C ratio	Net Benefit ($)
83,225	1,180,300	0.71	-34,805

Table 4.6 shows that the B/C ratio and net benefits of Utah's CV deployment in 2018 are 0.71 and $-34,805, respectively. This is because the benefits from this deployment are lower than the costs spent. Therefore, this project is an inefficient investment at the current stage. However, it should be noted that the B/C analysis conducted in this chapter assumes that TSP is the only application in the ten-year period, while it is expected that the installed CV infrastructure would be able to support the functioning of many other CAV applications. In those cases, the B/C ratio may be greater than 1.0. Hence, in the next chapter, additional analysis based on a potential CV-based adaptive signal control will be further performed.

5. ADAPTIVE AND COORDINATION CONTROL

5.1 Overview

This chapter reviews the research conducted on traffic signal control in the CAV environment. Based on this review, a traffic signal control system integrating adaptive signal control and signal coordination control is proposed. To predict the potential benefits brought by this application, simulation experiments were conducted and B/C analysis was developed based on simulation results.

5.2 Literature Review

Traffic signal control is one of the most promising strategies to solve traffic problems such as congestion and air pollution. Up to now, three control strategies have been proposed and deployed widely all over the world: fixed-time control, actuated signal control, and adaptive traffic signal control.

In the case of fixed-time control, signal parameters, such as cycle length and splits, are pre-set based on the historical data. Actuated traffic signal control leverages real-time traffic information provided by infrastructure-based devices like loop detectors to control traffic signals. It usually maintains a green signal for traffic on the major street until pedestrians or vehicles are detected on the minor street. The performance of actuated signal control is better than fixed-time control in most situations. Adaptive traffic signal control is the most advanced and effective control strategy. This control strategy also relies on infrastructure-based devices. However, it develops models to predict various vehicle statuses such as vehicle arrival and queue length, leveraging the detected traffic information and then adjusts the signal timing plan.

Those strategies could improve the performance of some measurements of signalized intersections, such as reduction of vehicle delay and queue length. Nevertheless, there are some limitations of these strategies: (1) Fixed-time control assumes that the traffic demand remains similar during the control period. However, traffic demand may fluctuate in reality. (2) Current infrastructure-based devices are point detectors that can only provide instantaneous vehicle location when a vehicle is passing over the detector. Vehicle states at other locations need to be estimated. (3) The installation and maintenance cost of the detection system is considered high. If one or more loop detectors are malfunctioning, the performance of the adaptive signal control system can be degraded significantly (Feng et al., 2015).

Due to the above limitations, many researchers began to explore new strategies or technologies to improve the effectiveness of traffic signal control. Recently, the maturity in wireless communication has opened new doors for various new techniques applied in traffic control, among which CV is believed to be one of the promising technological advances. Different from loop detectors, trajectory data from CV can be tracked all the time and it can provide enriched real-time vehicle information, including vehicle location, speed, heading, etc. This information enables a direct measurement of queue length and travel time. Therefore, traffic signal control will be more effective and more dynamically responsive to real-time traffic conditions. Safety, mobility, and the environment of the transportation system can improve accordingly. For example, signal phase and timing can be broadcasted to determine speed advice for approaching vehicles so that they can pass the next intersection without stopping. Vehicle delay and fuel consumption can then be reduced.

Inspired by the benefits of CV technology, various research on traffic signal control under CV technology has been conducted. Goodall et al. (2013) proposed an algorithm called predictive microscopic simulation algorithm (PMSA) to control signals. The algorithm predicts future traffic conditions using the data collected from CV, including vehicle position and speed. Then a rolling horizon of 15s was selected to optimize either only delay or a combination of delay, stops, and decelerations. Priemer and Friedrich (2009) presented a decentralized adaptive traffic signal control algorithm with the assistance of CV technology. This algorithm optimizes the phase sequence every 5 seconds aiming to reduce the total queue length within a forecast horizon of 20 seconds. He et al. (2014) proposed a platoon-based multi-modal signal control system. They designed a mathematic formulation called PAMSCOD to update signal timing every 30 seconds. The MINLP model was developed to optimize the signal timing plan. The simulation experiment in VISSIM showed that the delays were reduced significantly compared with traditional coordinated actuated signal control. Lee et al. (2013) designed a cumulative travel-time responsive

(CTR) real-time traffic signal control algorithm leveraging CV technology. The core of this algorithm is that a stochastic estimation technique based on Kalman filtering was used to estimate cumulative travel times under different market penetration rates. They found that 30% of market penetration rates of CV were needed to achieve the benefits of the proposed algorithm. Feng et al. (2015) proposed a real-time adaptive traffic signal control in the CV environment. They developed a bi-level optimization model to optimize the phase sequence. Two objectives are considered in the model: minimization of total vehicle delay and minimization of queue length. They also proposed a method called EVLS to estimate the states of unequipped vehicles when the market penetration is low. Cai et al. (2013) developed a method consisting of travel-time estimation and adaptive traffic signal control in the V2I environment. This method is based on approximate dynamic programming (ADP), which allows the controller to learn from its performance progressively. Guler et al. (2014) presented an algorithm to control traffic signals using CV technology. The proposed algorithm optimized sequence of vehicles discharging from the intersection by incorporating information from equipped vehicles to minimize the total delay. Li and Ban proposed the MINLP model to optimize the signal timing plan. This MINLP model was formulated as a dynamic programming (DP) problem and a two-step method was proposed to solve this problem. Zhao et al. (2015) proposed a signal timing optimization strategy to minimize the vehicle's energy consumption and traffic delay. Vehicle trajectories were predicted second by second using the Nagel-Schreckenber model and an iterative grid search method was utilized to search for the optimized signal timing plan. Islam and Hajbabaie (2017) proposed a distributed-coordinated methodology to optimize signal timing in the CV environment. This method reformulated this optimization problem based on a central architecture. The complexity of a network-level decision problem was reduced to an isolated intersection-level problem by deciding the termination or continuation of green times. Li and Qiu (2017) proposed an adaptive signal control strategy to improve the intersection throughput relying on CV technology. This method incorporates a two-step centralized responsive control for moving vehicles and stopped vehicles. Datesch et al. (2011) developed a platoon-based signal control algorithm utilizing CV technology. This algorithm divided a phase into two stages, where the first stage served standing queue and the second stage served vehicles approaching the intersection.

The aforementioned studies were all about CV-based strategies to improve traffic signal control at the isolated intersection. Signal coordination between multiple intersections was seldom investigated. Signal coordination is a strategy of timing groups of traffic signals along an arterial to provide for the smooth movement of traffic with minimal stops. In a review of the existing studies, signal coordination can be divided into two categories: bandwidth-based coordination and delay-based coordination.

The core logic of bandwidth-based coordination is to synchronize signals of a common cycle length with optimized offsets to provide maximum green bandwidth to the traffic along an arterial. In this category, MAXBAND is one of the most typical models developed by Little. It was formulated as a mixed-integer linear programming problem (Little et al., 1966). In 1981, Little et al. (1981) enhanced MAXBAND by optimizing left-turn sequences, calculating green splits, and adding the queue clearance time. However, MAXBAND can only provide a uniform bandwidth along an arterial while the link volume may be various for different segments. To address this problem, Gartner et al. (1991) proposed a model called MULTIBAND to generate varying bandwidths. The basic idea of this model is to maximize the bandwidth of individual segments based on the traffic volume. Models proposed in later research are an extension of MAXBAND or MULTIBAND. Li (2014) directly extended the MAXBAND model to solve the dynamic progression time. Vasudevan and Chang (2006) proposed a signal control system consisting of the intersection control level and the progression control level. The progression control level aimed to maximize the bandwidth based on the MULTIBAND model. To relax the symmetrical progression band requirement in the MULTIBAND model, Zhang et al. (2015) constructed the Asymmetrical Multi-BAND model, which enables vehicles to use the available green times in each direction more efficiently. Considering through traffic may not always involve the highest volume, Yang et al. (2015) proposed three multi-path progression models to offer progression bands for multiple critical path-flows contributing to the high volume in each arterial link.

The objective of delay-based methods is to minimize the average traffic delay or total vehicle delay. TRANSYT is one of the most applied models and is usually used as the baseline to compare with other new proposed models. TRANSYT was originally developed by Dennis

Roberston in the 1960s (Robertson, 1969). Later, FHWA sponsored the development of TRANSYT and the new version was named TRANSYT-7F (Wallace et al., 1984). The objective of TRANSYT is to minimize the weighted sum of vehicle delay by optimizing signal timing plans. It combines a set of optimization algorithms (e.g., hill-climbing algorithm, genetic algorithm) with several macroscopic simulation models, such as platoon dispersion and queue spillback. With a similar simulation and optimization method, researchers developed various models to design arterial signal plans.

Recently, with the advent and deployment of CV technology, various studies on signal coordination in the CV environment have been conducted. Feng et al. (2016) proposed an adaptive control platform combining an integrated adaptive control algorithm with signal priority and coordination. The coordination was designed with fixed offsets by this system. However, a fixed coordinated signal plan does not always provide better performance due to fluctuating traffic conditions. Beak et al. (2017) extended this platform to enhance corridor-level performance by changing offsets along a corridor in a CV environment. The proposed optimization addresses problems at both the intersection level and the corridor level. At the intersection level, dynamic programming was adopted to allocate optimal green times to each phase. At the corridor level, the researchers formulated a mixed-integer linear model to optimize the offsets of all intersections along the corridor. Ban et al. (2018) proposed optimizing phase duration at the intersection level and offsets at the corridor level based on CV technology. Experimental results showed that their strategies maintain a better performance on several measurements (e.g., average vehicle delay, average vehicle stops). CV technology is also applied to provide signal coordination for buses. Hu et al. (2015) proposed a person-delay-based optimization approach that enables bus cooperation and coordination among consecutive signals in the CV environment. They formulated a Binary Mixed Integer Linear Program (BMILP) and adapted the branch-and-bound method to solve this problem.

In a review of the aforementioned literature, it was found that a number of benefits can be achieved from adaptive traffic signal control and signal coordination control with the application of CV technology. Therefore, we decided to design a traffic signal control system integrating adaptive traffic signal control at the intersection level and coordination control at the corridor level that can be deployed along the Redwood Road corridor.

5.3 Traffic Signal Control System Overview

This section introduces the structure of the proposed CV-based traffic signal control system. Leveraging the CV environment, the system integrates adaptive signal control at the intersection level and coordination control at the corridor level. Figure 5.1 shows the framework of the proposed control system. Note that this framework is compatible with not only simulated road networks but also actual road networks.

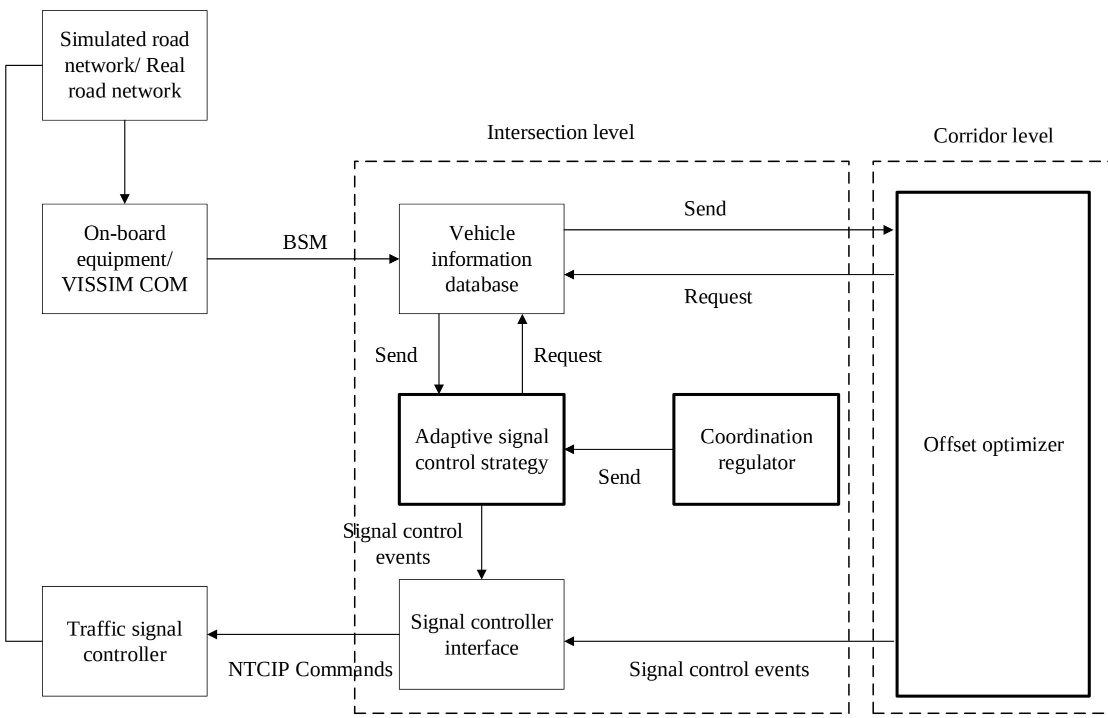


Figure 5.1 Overview of the proposed control system

CVs are equipped with OBU that can transmit and receive messages to and from roadside units (RSU) via wireless communication. The transmitted or received messages are classified into five types: (1) intersection geometry messages (MAP) providing road geometry; (2) signal phase and timing (SPaT) messages reporting real-time signal information; (3) basic safety messages (BSM) offering real-time vehicle trajectories; (4) signal request messages (SRM) indicating requested information; and (5) signal status messages (SSM) recording priority status information. In the proposed control system, only BSMs are broadcasted, and RSUs only receive BSMs when a vehicle is within the communication range. Each BSM records vehicle location, vehicle speed, vehicle heading, etc. This high-resolution data enables traffic signals to respond to real-time changes in traffic volume patterns. In the VISSIM simulator, the VISSIM COM API simulates the functions of OBUs.

At the intersection level, the RSUs include four main components: vehicle information database, adaptive signal control modules, traffic signal interface, and coordination regulator. The BSMs sent by the OBUs are decoded and recorded in the vehicle information database. Based on the stored vehicle data, the adaptive signal control strategy first estimates the detailed arrival information for each lane, which serves as the input of the signal timing optimization model. Then the adaptive signal control strategy uses a dynamic programming (DP) algorithm to optimize the signal timing plan. The optimization of the signal plan should comply with the coordination regulator which contains several constraints that ensure the coordination. For example, the cycle length of all coordinated intersections should be the same. At the corridor level, the offset optimizer optimizes the offset of each intersection along a corridor by solving a DP problem. In order to respond to the fluctuation of traffic demand, offsets are adjusted every time interval (e.g., 5 min).

5.4 Proposed Traffic Signal Control

5.4.1 Adaptive traffic signal control

Since adaptive traffic signal control leverages real-time traffic information to predict future traffic conditions, information about vehicle arrival and departure at intersections is of great importance. The estimation of this information has attracted much attention in previous studies. Chen and Sun (2016) developed a vehicle arrival estimation model based on tracking vehicle trajectory and variable queue length. The arrival time of each vehicle during the green time and red time could be obtained using that model. Feng et al. (2015) predicted the status of unequipped vehicles according to the information provided by equipped vehicles. Assuming that vehicle arrival is uniform, the vehicle arrival flow rate is calculated as in Eq. (5-1).

$$\mu_{l,i}(k,j) = \frac{1}{C} * q_{l,i}(j) \quad \forall l,j \tag{5-1}$$

where $\mu_{l,i}(k,j)$ represents the vehicle flow rate on lane l at intersection i within time interval k in the j^{th} cycle. C represents the cycle length of the j^{th} cycle. $q_{l,i}(j)$ represents the number of vehicles that passed the stop bar on lane l at intersection i in the j^{th} cycle. Based on CV technology, the intersection turning flows can be estimated by collecting real-time CV information. A simple but effective method is developed to estimate the intersection turning flow, which is shown in Eq. (5-2).

$$q_{l,i}(j) = \frac{1}{N}\sum_{n=1}^{N} q_{i,j}(j-n) \tag{5-2}$$

where N denotes the number of the previous cycles considered.

Since the trajectory of all vehicles can be tracked, lane flow is easy to observe when the market penetration rate of CVs reaches 100% (i.e., all vehicles on the road network are CVs). However, note that the market penetration rate of CVs will remain low for a long period due to technological and economic constraints. (Volpe National Transportation Systems Center, 2008). Getting lane flow in a low penetration rate remains a challenging task. Inspired by the idea that the traffic volume of an intersection can be easily estimated with the penetration rate of probe vehicles and traffic volume of probe vehicles (Wong and Wong, 2019; Zhao et al., 2019; Zhao et al., 2019), this project uses the following method to estimate the lane flow in Eq. (5-3)

$$q_{l,i}(j) = \frac{q_{l,i}^{c}(j)}{p_{l,i}(j)} \tag{5-3}$$

where $q_{l,i}^{c}(j)$ denotes the number of CVs that have passed the stop bar on lane l of intersection i during the j^{th} cycle. $p_{l,i}(j)$ denotes the real-time penetration rate of CVs on link l of intersection i during the j^{th} cycle. Since $q_{i,j}^{c}(k)$ can be easily obtained from the CV trajectory data, once $p_{l,i}(j)$ is known, $q_{l,i}(j)$ can be estimated. Note that the CV market penetration rate for each lane and during each cycle is a random variable rather than a constant since the distribution of CVs during the control period is stochastic.

This project uses the queue of each link at an intersection to get the market penetration rate of CVs. In the queue, several vehicles may be CVs while the others are non-CV. The CV data can be easily collected and information about non-CVs can be estimated. More specifically, since CVs transmit their location and speed with high frequency, it is simple to decide whether a CV is stopping in the queue or moving. Therefore, the last stopped CV in the queue on each lane can be determined, assuming that vehicles on the road network are identical. That is to say, all vehicles on the road network share the same effective vehicle length, which refers to the length from the front bumper of the preceding vehicle to the front bumper of its following vehicle. Then the number of vehicles between the last stopped CV and the stop line can be calculated. The number of vehicles behind the last stopped vehicle could be estimated utilizing the broadcasting speed of the queue. Specific details are illustrated in later parts. With knowledge of the number of CVs and all vehicles in the queue, the CV market penetration rate could be inferred. Denote the number of CVs and all vehicles in the queue on lane l by $N_{c,l}$ and $N_{all,l}$, respectively. The CV market penetration rate can be represented by ${N_{c,l}}/{N_{all,l}}$. Figure 5.2 shows a signalized intersection at which CVs are homogeneously mixed with non-CVs at each lane. In this example, on lane 2, the number of queued CVs is 3 (i.e. $N_{c,2} = 2$), the number of total vehicles in the queue is 6 (i.e. $N_{all,2} = 6$), then the CV market penetration rate of lane 2 is 0.333.

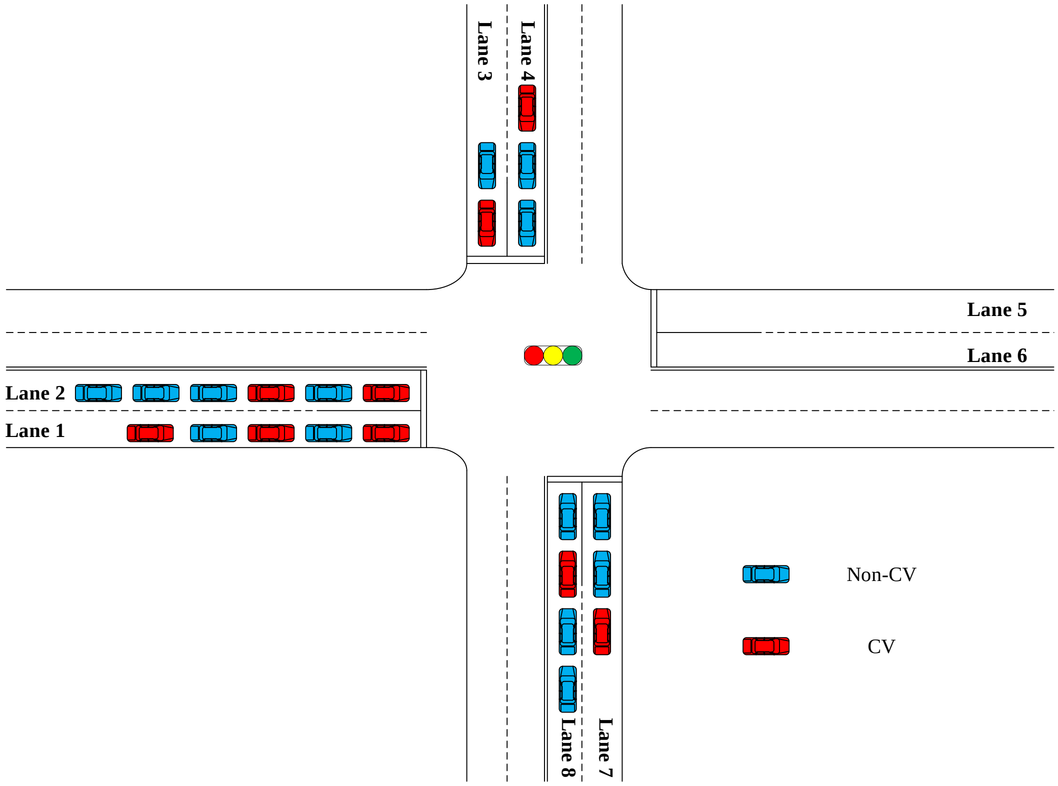
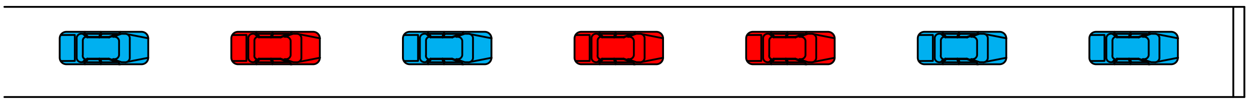


Figure 5.2 Example of a signalized intersection with CVs and non-CVs

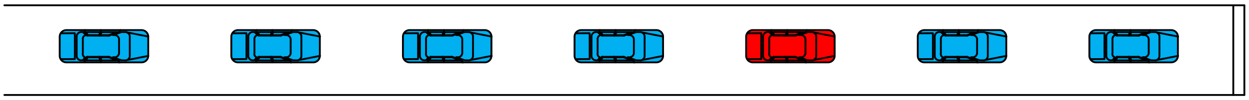
$N_{c,l}$ is obtainable according to the recorded vehicle trajectory data. To calculate the market penetration rate of CVs, the number of all vehicles stopped in the queue $N_{all,l}$ is obtained based on the length of the queue in Eq. (5-4)

$$N_{all,l} = \frac{L_{q,l}}{L_{eff}} \tag{5-4}$$

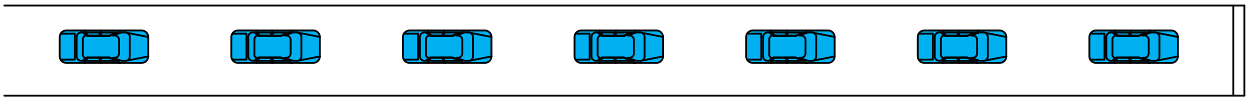
where $L_{q,l}$ is the queue length on lane l. L_{eff} is the effective length of each vehicle waiting in the queue. Figure 5.3 shows three cases that should be considered according to the distribution of CVs in the queue:



(a) More than one stopped CV



(b) one stopped CV



(c) no stopped CV

Figure 5.3 Snapshot of three queuing cases with CVs and non-CVs

Case a (More than one CV in the queue): In Figure 5.3 (a), more than one CV is waiting in the queue on lane j. Since CVs broadcast their speed, location, and heading frequently, it is simple to justify the last two stopped CVs in the queue according to the speed information and then get their stopped time and location. Denote $L_{c1,l}$, $L_{c2,l}$ as the stop location of the last stopped CV and its preceding stopped CV on lane l, respectively. Denote $t_{c1,l}$ and $t_{c2,l}$ as the stopped time of the last stopped CV and its preceding stopped CV on lane l, respectively. Therefore, the queue length before the last vehicle is $L_{c1,l}$. Note that the last stopped CV may not be the last vehicle in the queue since other vehicles may join the queue and stop at the back of the last stopped vehicle, as shown in Figure 5.3 (a). The queue length after the last stopped vehicle can be estimated on the condition that the transmission speed of the queue remains stable. The transmission speed of the queue is calculated in Eq. (5-5).

$$v_{q,l} = \frac{L_{c1,l} - L_{c2,l}}{t_{c1,l} - t_{c2,l}} \tag{5-5}$$

where $v_{q,l}$ denotes the transmission speed of the queue on lane l. Then the queue length at time t is calculated in Eq. (5-6).

$$L_{q,l} = L_{c1,l} + v_{q,l} * (t - t_{c1,l}) \tag{5-6}$$

Case b (Only one CV in the queue): In Figure 5.3 (b), only one CV is waiting in the queue. Similar to the situation in Case a, the CV in the queue is the last stopped CV and the queue length before this CV is also $L_{c1,j}$. In this case, the transmission speed of the queue is calculated in Eq. (5-7).

$$v_{q,l} = \frac{L_{c1,l}}{t_{c1,l} - t_{r,l}} \tag{5-7}$$

where $t_{r,l}$ denotes the start time point of red signal indication for lane l. Then the queue length for this case can be calculated by Eq. (5-6).

Case c (No CV in the queue): In Figure 5.3 (c). It is possible that no CV is waiting in the queue when the CV market penetration rate is quite low. In this case, the only information that can be used is the historical information. We simplify the lane flow of the current cycle under this condition by the average lane flow of the previous several cycles.

Giving the split plan and phasing plan, an optimization model is developed based on the predicted vehicle arrival during the whole control period. Thus, the signal timing plan of an intersection can be dynamically adjusted. (e.g., 1 hour). The formulation of the model for intersection i is shown as follows:

$$\min d_i(j) \tag{5-8}$$

s.t.

$$d_i(j) = \sum_{l=1}^{L} \sum_{k=1}^{c} Q_{l,i}(k,j) * \Delta t \qquad \forall l, j \tag{5-9}$$

$$Q_{l,i}(k,j) = \max\big(Q_{i,j}(k-1,j) + \mu_{l,i}(k,j) - r_{l,i}(k,j), 0\big) \quad \forall l, j \tag{5-10}$$

$$\mu_{l,i}(k,j) = \frac{1}{c} * q_{l,i}(j) \quad \forall l, j \tag{5-11}$$

$$r_{l,i}(k,j) = \begin{cases} s_{l,i} * \Delta t \\ 0 \end{cases} \quad \forall l, j \tag{5-12}$$

$$Q_{l,i}(0,j) = \tau_{l,i}(0, j-1) \quad \forall l, j \tag{5-13}$$

$$\sum_{p=1}^{p=N} \left(g_{i,p}(k) + l_{i,p}(k)\right) = c(k) \tag{5-14}$$

$$g_{min} \leq g_{i,m}(k) \leq g_{max} \tag{5-15}$$

$$g_{i,m}(k-1) - \Delta g_i \leq g_{i,m}(k) \leq g_{i,m}(k-1) + \Delta g_i \tag{5-16}$$

The objective is to minimize the total delay of intersection i in Eq. (5-8), where $d_i(j)$ denotes the total intersection delay in the j^{th} cycle. The total delay is calculated by the queue length in Eq. (5-9), where $Q_{l,i}(k,j)$ denotes the queue length on lane l at intersection i in the time interval k; L denotes the total number of lanes at intersection i. Δt denotes the length of the discrete-time interval. The queue length on lane l within time interval k is based on the queue length in the last time interval, vehicle arrival, and vehicle departure. The concrete calculation is represented by Eq. (5-10), where $Q_{i,j}(k-1,j)$ denotes the queue length of the last time interval; $\mu_{l,i}(k,j)$ is the arrival flow rate on lane l at intersection i within time interval k during the j^{th} cycle. $r_{l,i}(k,j)$ denotes the departure rate on lane l at intersection i within time interval t during the j^{th} cycle. $\mu_{l,i}(k,j)$ is obtained based on the estimated number of passing vehicles of each lane in Eq. (5-11). Eq. (5-12) calculates the departure rate, where $s_{l,j}$ is the saturation flow rate of lane l at intersection i. Eq. (5-13) indicates the initial queue length on lane l at intersection i at the start of j^{th} cycle. Eq. (5-14) ensures that the summation of effective green time and lost time equals to the cycle time, where p denotes the phase; N denotes the total number of phases; $g_{i,p}(k)$ denotes the effective green time of phase p in the j^{th} cycle at intersection i. Eq. (5-15) ensures that the green time of each phase is between the minimum green time and maximum green time, denoted by g_{min} and g_{max} respectively. Eq. (5-16) requires the adjustment of green time between two adjacent cycles is within an interval. This aims to ensure a stable transition of green time, where Δg_i denotes the maximum adjustment of green time between two consecutive cycles.

To solve the proposed model, an algorithm based on DP is proposed. The main idea of the DP algorithm is to decompose the decision problem into several manageable decision stages, then the optimal decisions can be determined recursively. The DP algorithm is composed of stage, control variable, state variable, performance measurement function, and value function. In this model, the stage indicates the phase, denoted by index p. The control variable is the green time allocated to each phase in the j^{th} cycle, denoted by $x_i(p,j)$. Then the set of feasible control variables at each stage should be:

$$X_i(p,j) = \{\max\left(g_{min}, g_{i,p}(j-1) - \Delta g_i\right), \dots \min\left(g_{max}, g_{i,p}(j-1) + \Delta g_i\right)\} \quad (5\text{-}17)$$

The state variable is the total allocated time when each stage is completed, denoted by $s_i(p,j)$. Then the set of the state variable, denoted by $S_i(p,j)$, is represented by Eq. (5-18).

$$S_i(p,j) = \{\max\left(g_{min}, g_{i,p}(j-1) - \Delta g_i\right) + l_{i,p}(j), \dots \min\left(g_{max}, g_{i,p}(j-1) + \Delta g_i\right) + l_{i,p}(j)\} \quad (5\text{-}18)$$

Performance measurement function is represented by the objective function of the proposed model, denoted by $d_i(x_i(p,j))$. The value function is the cumulative value of the prior performance measurement function, denoted by $s_i(p,j)$. Based on these defined elements, the algorithm can be summarized as follows:

Step 1: Set $p = 1$, and $v_i(0) = 0$;
Step 2: Let $p = p + 1$; update value function with the following equation
$v_i(s_i(p,j)) = \{v_{i-1}(s_i(p-1,j)) + d_i(x_i(p,j)) | x_i(p,j) \in X_i(p,j)\}$ and determine the optimal value function and then find the optimal solution which minimizes this equation at this stage, denoted as $x_i^*(j,k)$
Step 3: if $p < N_p$, go to step 2; otherwise, trace back to find the optimal solution for each stage.

5.4.2 Dynamic Signal Coordination Control

Given the intersection-level signal timing plan, the dynamic signal progression control model is formulated as follows:

$$max \sum_i \sum_p \omega_p(h) b_{p,i}(j) + \sum_i \sum_p \bar{\omega}_p(h) \bar{b}_{p,i}(h) \quad (5\text{-}19)$$

s.t.

$$b_{p,i}(h) = \max[b_{r,p,i}(h) - b_{l,p,i}(h), 0] \quad (5\text{-}20)$$

$$\bar{b}_{p,i}(h) = \max[\bar{b}_{r,p,i}(h) - \bar{b}_{l,p,i}(h), 0] \quad (5\text{-}21)$$

$$b_{r,p,i}(h) = \min[t_{r,p,i-1}(h) + t_{i-1,i}(h), t_{r,p,i}(h)] \quad (5\text{-}22)$$

$$b_{l,p,i}(h) = \max[t_{l,p,i-1}(h) + t_{i-1,i}(h), t_{l,p,i}(h)] \quad (5\text{-}23)$$

$$\bar{b}_{r,p,i}(h) = \min[t_{r,p,i}(h) + t_{i-1,i}(h), t_{r,p,i-1}(h)] \quad (5\text{-}24)$$

$$\bar{b}_{l,p,i}(h) = \max[t_{l,p,i}(h) + t_{i-1,i}(h), t_{l,p,i-1}(h)] \tag{5-25}$$

$$t_{l,p,i}(h) = \sum_m \sum_n \beta_{m,p,i} * \varphi_{m,n} * g_{i,m}(h) + \theta_i(h) \tag{5-26}$$

$$t_{r,p,i}(h) = \sum_m \sum_n \beta_{m,p,i} * \varphi_{m,n} * g_{i,m}(h) + \sum_m \beta_{m,p,i} * g_{i,m}(h) + \theta_i(h) \tag{5-27}$$

$$b_{l,p,i}(h) < b_{r,p,i+1}(h) - t_{i,i+1}(h) \tag{5-28}$$

$$b_{r,p,i}(h) > b_{l,p,i+1}(h) - t_{i,i+1}(h) \tag{5-29}$$

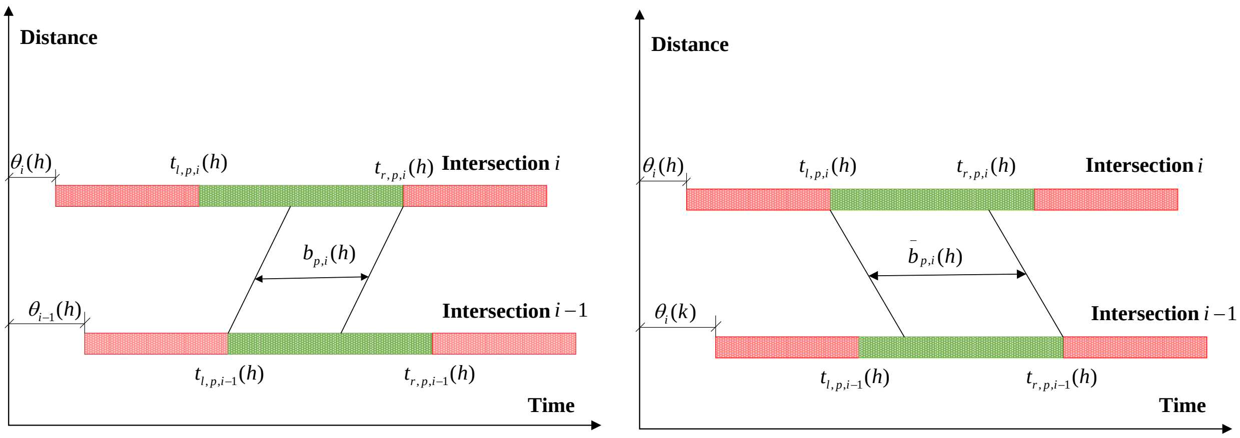
$$\bar{b}_{l,p,i+1}(h) < \bar{b}_{r,p,i}(h) - t_{i,i+1}(h) \tag{5-30}$$

$$\bar{b}_{r,p,i+1}(h) > \bar{b}_{l,p,i}(h) - t_{i,i+1}(h) \tag{5-31}$$

$$\theta_i(h-1) - \Delta\theta_i \le \theta_i(h) \le \theta_i(h-1) + \Delta\theta_i \tag{5-32}$$

The signal coordination model formulation is based on the bandwidth-based method. The objective function Eq. (5-19) is to maximize the green bandwidth of all through traffic along the arterial, as shown in the equation, where h denotes the control horizon index (e.g., number 1 represents the first control period); $b_{p,i}(h)$ and $\bar{b}_{p,i}(h)$ denote the green bandwidths of path p for outbound and inbound between intersection i and $i-1$ respectively, in seconds; $\omega_p(h)$ and $\bar{\omega}_p(h)$ denote the weighting factors for path p. Note that those factors are identified by traffic demands along various paths.

The green bandwidth of path p for outbound and inbound directions between two adjacent intersections could be obtained by Eq. (5-20) and Eq. (5-21), where $b_{r,p,i}(h)$ and $b_{l,p,i}(h)$ (also $\bar{b}_{r,p,i}(h)$ and $\bar{b}_{l,p,i}(h)$) denote the right bound and left bound of the green band of path p for outbound (inbound) in Eq. (5-22)-Eq. (5-25), respectively. $t_{l,p,i}(h)$ and $t_{r,p,i}(h)$ denotes the start and end of the green for path p at intersection i in Figure 5.4. $t_{i,i+1}(h)$ denotes the travel time from intersection i to intersection $i+1$.

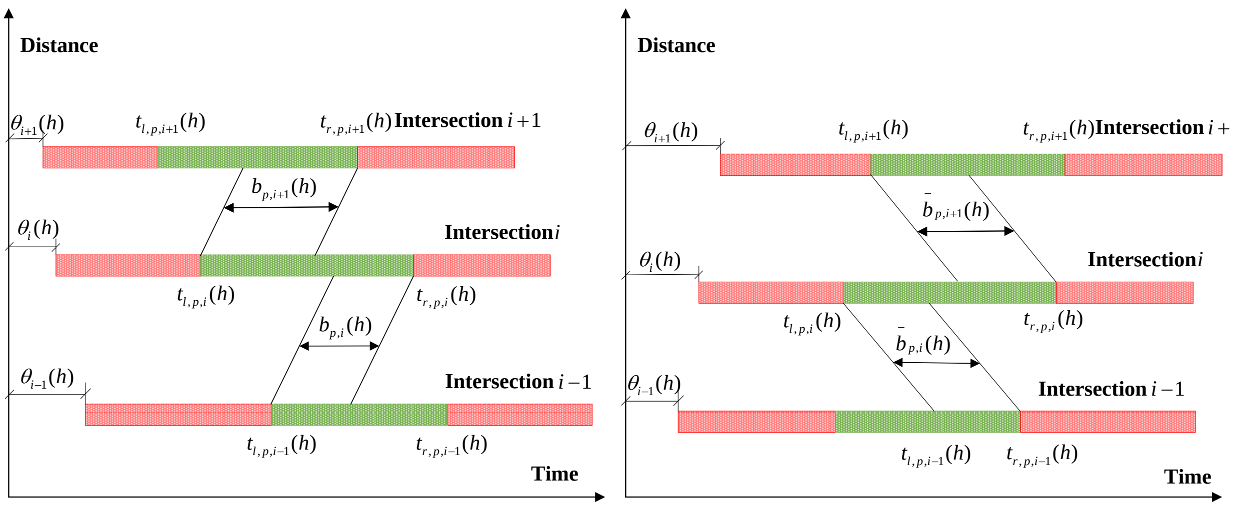


(a) Green band for outbound direction **(b) green band for inbound direction**

Figure 5.4 Variable definition of green bandwidth for two directions

Figure 5.4 shows that the start and end of the green band for each path can be computed given the signal phase plan, offsets, and green timings of intersections in Eq. (5-26) and Eq. (5-27). $\beta_{m,p,i}$ is a binary variable to indicate the phase allocated to path p at intersection i (it equals to 1 if path p receives green time in phase m at intersection i, and 0 otherwise); $\varphi_{m,n}$ is a binary variable to determine the sequence of phases (it equals to 1 if phase m is before phase n, and 0 otherwise); $g_{i,m}(h)$ indicates the green time allocated to phase m for intersection i; and $\theta_i(h)$ denotes the offset of intersection i at h^{th} control period.

Eq. (5-28) – Eq. (5-31) ensure the continuity of the green band for a path along multiple intersections. Note that if the green band for a path is not continuous between intersections along an arterial in Figure 5.5, vehicles may need to stop several times when traveling along this path, which will decrease the effectiveness of the coordination system.



(a) non-continuous green band for outbound direction. **(b) non-continuous green band for inbound direction**

Figure 5.5 Non-continuous green band in two directions between three adjacent intersections.

Eq. (5-32) ensures the offset difference between two consecutive control periods is within a range, where $\Delta\theta$ denotes the maximum offset difference of two consecutive control periods for intersection i, in seconds.

Using the DP-based algorithm, the proposed signal progression control model can be solved. The critical elements of DP in this algorithm are defined as follows:

The stage is defined as the index of intersections $\{1,2,3, \dots, N_i\}$; the state variable is defined as the feasible new offset of each control period at each intersection, the feasible solution is defined as follows:

$$S_i(h) = \{\theta_i(h-1) - \Delta\theta_i, \theta_i(h-1) - \Delta\theta_i + 1, \dots, \theta_i(h-1) + \Delta\theta_i\} \tag{5-33}$$

The value function $V_i(\theta_i)$ can be calculated in Eq. (5-34)

$$V_i(\theta_i) = V_{i-1}(\theta_{i-1}^*) + B_i(\theta_i) \tag{5-34}$$

where θ_{i-1}^* indicates the optimal offset determined at stage $i-1$; B(θ_i) denotes the total green bandwidth of all paths at stage i when the offset involves θ_i (i.e., the total green bandwidth between intersection $i-1$ and intersection i) in Eq. (5-35).

$$B_i(\theta_i) = \sum_p \delta_{p,i-1,,m}\,\delta_{i,p,m}\omega_p(j)b_{p,i}(j) + \sum_p \delta_{p,i-1,m}\,\delta_{p,i,m}\overline{\omega}_p(j)\bar{b}_{p,i}(j) \tag{5-35}$$

where $\delta_{p,i,m}$ is a binary variable to identify the green time for paths at each intersection (it equals to 1 if green time is allocated to path p in phase m at intersection i, and 0, otherwise).

Based on the defined elements for dynamic programming, the solution algorithm is summarized as follows:

Step 1: set $i = 1$, $\theta_1(h) = 0$, and $V_i(0) = 0$;
Step 2: $i = i + 1$; update value function with Eq. (33) determine the optimal value function
$V_i(\theta_i^*(h)) = max\{V_{i-1}(\theta_{i-1}^*(h)) + B_i(\theta_i(h))|\theta_i(h) \in S_i(h)\}$
find the optimal solution at this stage, denoted as $\theta_i^*(j)$
Step 3: if $i < N_i$, go to step 2; otherwise, trace back to find the optimal solution for each stage.

5.5 Simulation Study

5.5.1 Experiment designs

To predict the potential benefit of the proposed traffic system on the Redwood CV corridor, this project develops a simulation environment in VISSIM and conducts a new B/C analysis.

One basic requirement to do a B/C analysis is to determine the base case and proposed alternatives. In this project, the base case is determined as the current implemented actuated coordination plan for this corridor. The alternative is the proposed signal control strategy. Another requirement is to define the time-dependent elements, including the analysis timeframe and the number of days in a year. Since the life expectancy of this DSRC deployment is estimated at ten years and it was deployed in 2017, the timeframe is determined as ten years (2018-2027) for analysis in this project.

The traffic demand is collected from ATSPM which is managed by UDOT. ATSPM shows real-time and historical functionality at signalized intersections. Two types of ATSPM detectors, Wavetronix SmartSensor Advance detectors and Wavetronix SmartSensor Matrix detectors, are located approximately 300 feet upstream of signalized intersections and at signal stop-bar locations, respectively. Wavetronix SmartSensor Advance detectors can provide total through traffic and Wavetronix SmartSensor Matrix detectors can provide lane-by-lane counts. Based on the recorded events by the two types of detectors, the turning flow of each intersection can be determined. Note that ATSPM only provides real-time and historical information, so future traffic demand must be estimated. We determined that the average incremental ratio of traffic demand over ten years is 2.24%.[28,29,30]

The signal timing reference reported from UDOT's TOC shows that four actuated coordination schedules are implemented on weekdays and one actuated coordination plane is implemented on weekends, as shown in Table 5.1.

Table 5.1 Actuated coordination plan of traffic signals along DSRC corridor

Day of Week	Time Period	Coordination Plan
Weekdays	6:00 AM - 9:30 AM	plan 1
	9:30 AM -15:00 PM	plan 2
	15:00 PM - 19:00 PM	plan 3
	19:00 PM - 21:30 PM	plan 2
Weekends	6:00 AM – 21:30 PM	plan 2

The simulation scenario is defined based on the signal timing plan. Since the signal timing plans and traffic demands are similar during 9:30 AM – 3:00 PM and 7:00 PM – 9:30 PM on weekdays, we combined them into one scenario. The four scenarios are as follows:

- Scenario 1: 6:00 AM - 9:30 AM on weekdays
- Scenario 2: 9:30 AM -15:00 PM and 19:00 PM - 21:30 PM on weekdays
- Scenario 3: 15:00 PM - 19:00 PM on weekdays
- Scenario 4: 6:00 AM – 9:30 PM on weekends

[28] https://www.udot.utah.gov/main/uconowner.gf?n=10385322369402804
[29] https://www.udot.utah.gov/main/uconowner.gf?n=10399732437353573
[30] https://www.udot.utah.gov/main/uconowner.gf?n=23540107153558604

As it may take several years to achieve a high or full market penetration rate, each scenario is simulated under eight market penetration rates: 5%, 10%, 15%, 20%, 25%, 50%, 75%, and 100%.

Other values of the key parameters used in this simulation are listed as follows:

- Time is discretized to $1s$ during the simulation time (i.e. $\Delta t = 1\ s$).
- The lost time for each phase of all intersections is $5\ s$.
- The saturation flow rate of all approaches at all intersections is 1700 vehicles per hour.
- The maximum difference of green time between two consecutive signal cycles is $6\ s$.
- The maximum difference of offset between two consecutive control horizons is $4\ s$.
- The number of previous cycles selected for average flow prediction is 8.
- The dynamic progression model is performed to optimize offsets every five cycles.

5.5.2 Result analysis

Using the VISSIM-COM API, the CAV-based adaptive signal control application is simulated for each scenario by Python. The average delay of each scenario during the ten years with different market penetration rates and actuated coordination control is shown in Table 5.2-Table 5.5.

Table 5.2 Average vehicle delay under different situations in scenario 1

Year	Market Penetration Rate								
	100% (sec)	75% (sec)	50% (sec)	25% (sec)	20% (sec)	15% (sec)	10% (sec)	5% (sec)	Actuated (sec)
2018	87.45	87.08	87.7	89.54	95.78	101.95	108.34	111.3	112
2019	89.34	89.83	89.54	91.12	97.01	102.76	110.44	113.53	114.45
2020	88.03	91.15	91.02	91.78	97.53	103.26	110.24	113.27	115.06
2021	89.44	90.19	90.79	91.33	97.14	102.23	110.22	113.95	114.14

2022	92.46	93.59	93.78	93.99	99.34	106.1	113.31	116.67	117.98
2023	97.33	98.31	98.55	99.46	103.79	110.71	117.26	120.34	122.13
2024	100.15	101.35	101.31	101.79	106.89	114.01	121.38	124.37	125.36
2025	101.06	101.83	102.74	102.85	107.38	114.38	122.58	124.25	125.43
2026	102.02	103.5	104.69	104.98	108.43	115.61	123.24	125.35	126.24
2027	102.48	103.65	105	105.26	108.5	116.51	124.45	125.08	126.49

Table 5.3 Average vehicle delay under different situations in scenario 2

Year	Market Penetration Rate								
	100% (sec)	75% (sec)	50% (sec)	25% (sec)	20% (sec)	15% (sec)	10% (sec)	5% (sec)	Actuated (sec)
2018	81.99	81.75	82.41	82.27	89.97	100.56	107.78	111.67	112.63
2019	82.02	82.56	83.81	83.34	92.48	103.07	111.49	115.45	118.8
2020	83.64	83.25	84.25	84.59	93.19	106.14	115.42	119.81	123.1
2021	86.77	86.08	86.97	87.25	98.43	113.75	124.46	128.36	130.76
2022	87.03	87.12	86.98	86.73	100.81	115.87	126.99	130.58	132.97
2023	87.61	87.84	86.72	87.24	103.58	113.16	126.14	129.77	130.82
2024	90.03	89.38	90.68	90.12	107.72	119.04	130.85	134.54	138.75
2025	92.48	92.19	92.21	93.47	112.71	123.11	134.11	140.61	143.35
2026	94.25	93.16	93.85	93.86	115.83	128.58	141.28	143.62	145.14
2027	93.15	94.3	94.42	94.56	118.77	128.22	140.67	142.45	145.37

Table 5.4 Average vehicle delay under different situations in scenario 3

Year	Market Penetration Rate								
	100% (sec)	75% (sec)	50% (sec)	25% (sec)	20% (sec)	15% (sec)	10% (sec)	5% (sec)	Actuated (sec)
2018	106.45	105.88	107.01	107.23	113.92	118.73	124.11	125.04	126.15
2019	108.78	108.13	108.46	108.53	114.38	120.44	125.98	126.78	128.03
2020	109.7	109.66	110.52	110.77	115.16	121.33	126.44	127.24	130.9

2021	111.74	110.86	110.58	111.1	115.28	122.62	127.16	129.59	131.74
2022	112.56	112.69	112.94	113.78	117.08	123.52	128.97	132.68	133.78
2023	117.05	117.33	118.11	118.82	123.29	127.46	133.95	136.8	138.21
2024	118.41	118.58	118.66	119.19	124	128.72	133.89	136.86	138.91
2025	121.12	121.26	121.22	121.53	125.01	131.78	136.62	139.06	141.41
2026	123.55	124.27	124.3	124.69	128	133.09	138	141.04	143.54
2027	126.73	127.18	127.6	127.68	131.03	135.37	140.41	145.55	146.67

Table 5.5 Average vehicle delay under different situations in scenario 4

Year	Market Penetration Rate								
	100% (sec)	75% (sec)	50% (sec)	25% (sec)	20% (sec)	15% (sec)	10% (sec)	5% (sec)	Actuated (sec)
2018	80.06	79.18	80.92	81.51	88.55	95.33	103.42	104.87	106.71
2019	81.35	80.31	82.25	81.73	88.08	95.75	103.89	105.96	106.51
2020	81.98	82.67	83.62	84.13	90.89	97.21	103.52	105.22	106.45
2021	83.21	83.04	82.79	84.91	90.26	98.86	105.22	107.41	108.22
2022	86.01	86.28	86.25	87.11	95.58	101.47	106.66	109.59	111.1
2023	91.44	91.11	91.21	92.8	99.06	104.04	111.4	112.25	114.92
2024	93.8	93.03	93.27	94.69	102.62	107.59	112.69	114.32	116.34
2025	95.58	95.21	95.26	95.38	103.38	107.61	115.08	116.67	117
2026	99.59	100.36	100.81	101.1	108.24	112.56	120.09	121.61	122.51
2027	102.15	102.45	103.24	104.72	113.58	116.35	124.28	126.73	128.51

Table 5.2-Table 5.5 show that with an increase in traffic demand, the average vehicle delay increases. Moreover, the CAV-based adaptive coordination control outperforms actuated coordination control by reducing vehicle delay under all market penetration rates. To better exhibit the variation tendency, those results are shown in Figure 5.6 – Figure 5.9.

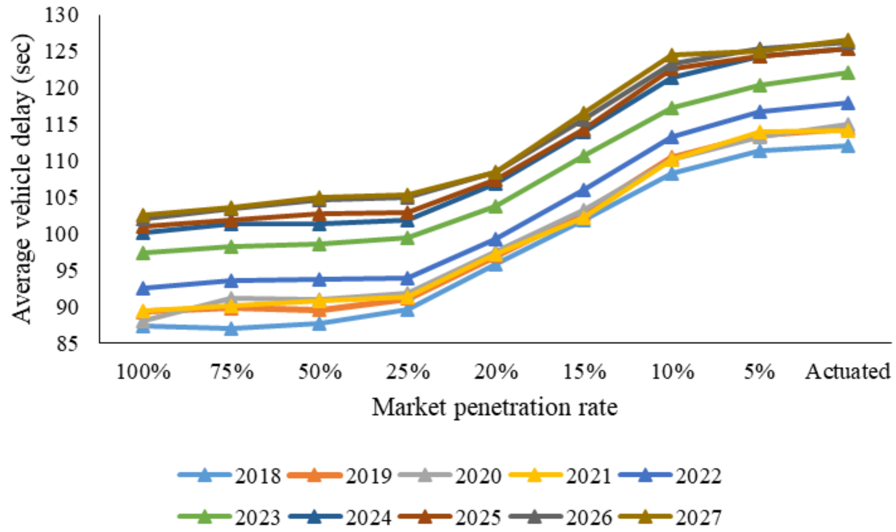


Figure 5.6 Average vehicle delay under different situations in scenario 1

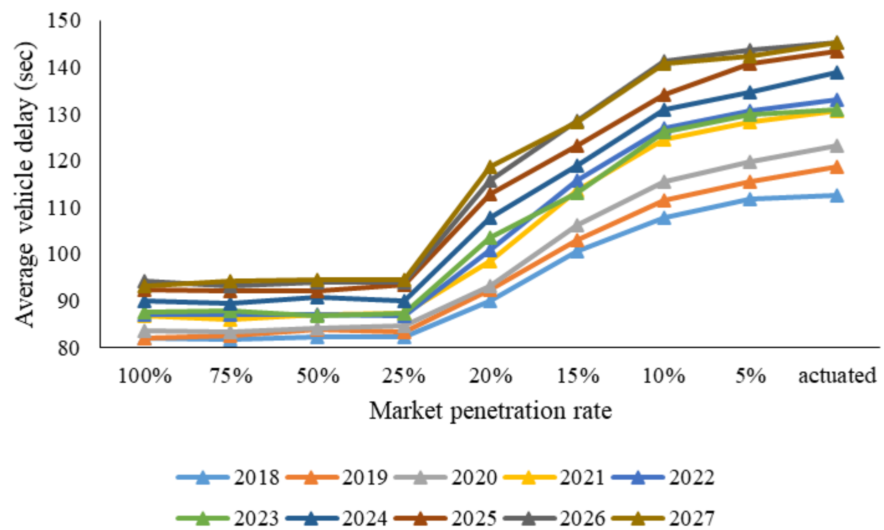


Figure 5.7 Average vehicle delay under different situations in scenario 2

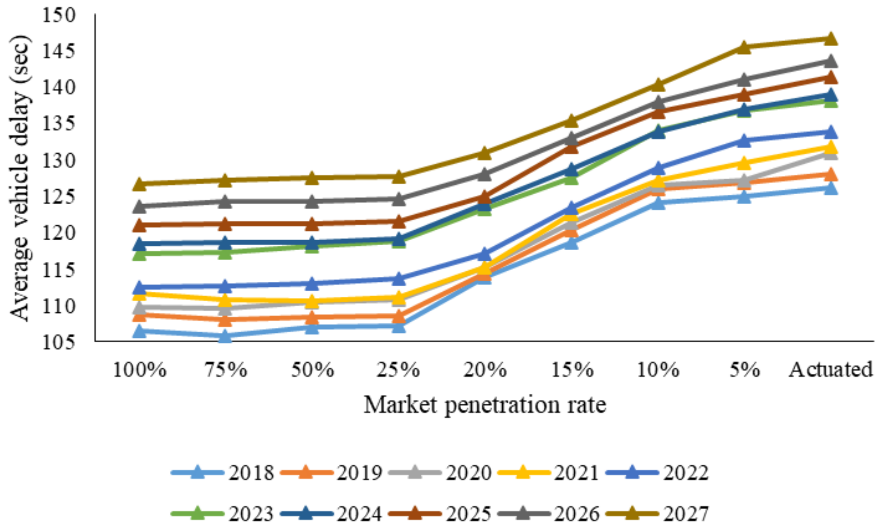


Figure 5.8 Average vehicle delay under different situations in scenario 3

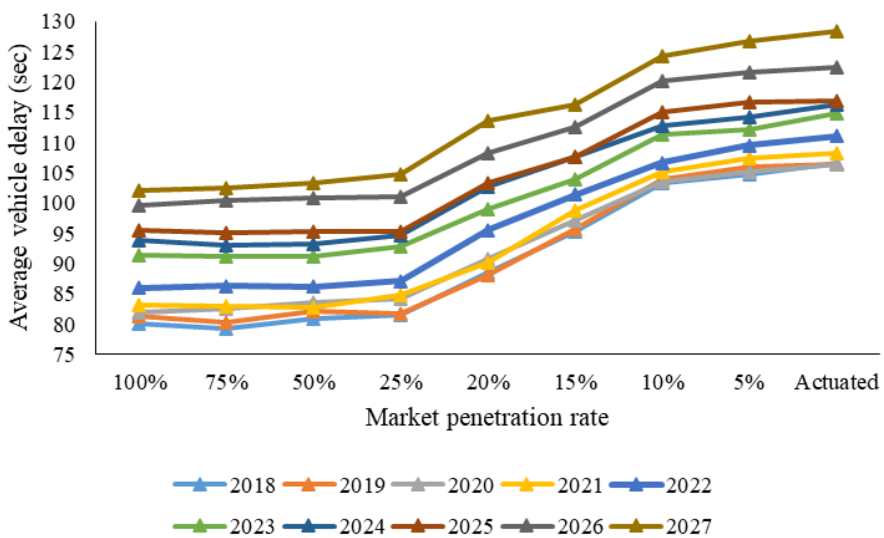


Figure 5.9 Average vehicle delay under different situations in scenario 4

When the market penetration rate is less than 10%, the variation tendency of average vehicle delay is slow. When the market penetration rate is more than 15%, the average vehicle delay reduces rapidly compared to the actuated coordination plan. Moreover, there is no big difference in the average vehicle delay when the market penetration rate is more than 25%. This is because when the market penetration is low, most vehicles on the road network are human driven, and the estimation accuracy of vehicle arrival information will be low. Therefore, the performance of signal control is poor in those cases. When the market penetration rate increases, signal control performance improves, resulting in a rapid reduction in average vehicle delay. Moreover, CAV are required to obey posted speed limits and operate with the same behavior on the road network, and human-driven vehicles behind them have to follow them. When the market penetration rate reaches 25%, it’s enough to enable all vehicles on the road network to operate with the same behaviors. Therefore, the average vehicle delay doesn’t change dramatically when the market penetration rate is more than 25%.

Based on the average vehicle delay, we can conduct a B/C analysis for the application of CAV-based adaptive control. The benefits are measured by the difference between it and the current actuated signal control.

Table 5.6 Benefits of the proposed control system under various market penetration rates

Year	Market Penetration Rate							
	100% ($)	75% ($)	50% ($)	25% ($)	20% ($)	15% ($)	10% ($)	5% ($)
2018	1291242	1316222	1264285	1276061	567630	524657	184023	64605
2019	1442338	1452047	1397915	1406570	1033598	616661	223940	89455
2020	1557456	1531483	1489202	1470476	1108104	655665	274695	134644
2021	1640803	1661655	1647824	1600852	1211271	661205	247663	84712
2022	1743784	1728116	1727097	1709249	1213725	698234	279969	93959
2023	1728470	1718174	1727703	1674092	1148693	764108	245312	98331
2024	1856658	1871772	1840127	1816237	1213752	777373	321040	155528

2025	1926619	1931042	1922412	1888814	1255509	813683	314757	103691
2026	1998701	1985511	1951376	1937695	1257629	772346	227050	90016
2027	2143890	2096013	2060525	2026014	1246400	853139	286964	126342

Table 5.6 summarizes the monetized benefits of various market penetration rate from 2018 to 2027. It can be observed that the benefits increase with the growth of the market penetration rate because a higher market penetration rate produces a larger reduction in average vehicle delay.

Based on the monetized benefits and costs, we summarize the benefits under different market penetration rates and costs of the ten years and then conduct B/C analysis. The result is shown in Table 5.7.

Table 5.7 Results of B/C analysis under various market penetration rates

Market Penetration Rate	Benefits ($)	Costs ($)	B/C Ratio	Net Benefit ($)
100%	17,329,961	1,180,300	14.68	16,149,661
75%	17,292,035	1,180,300	14.65	16,111,735
50%	17,028,466	1,180,300	14.43	15,848,166
25%	16,806,060	1,180,300	14.24	15,625,760
20%	11,256,311	1,180,300	9.54	10,076,011
15%	7,137,071	1,180,300	6.05	5,956,771
10%	2,605,413	1,180,300	2.21	1,425,113
5%	1,041,283	1,180,300	0.88	-139,017

Table 5.6 shows that when the market penetration rate is 5% within the ten years, the B/C ratio is 0.88 and the net benefit is $-139017. Therefore, this deployment for supporting adaptive coordination control under 5% of the market penetration rate within ten years is an inefficient investment because the benefit is lower than the cost. When the market penetration rate is larger

than 5%, this deployment for supporting the adaptive coordination control is an efficient investment.

Note that the market penetration rate may not remain stable within the ten years due to various factors such as technological improvements. Therefore, we define the market penetration rates for the ten years as: 5% from 2018 to 2023, 10% in 2025, 15% from 2026 to 2027 (Trommer et al., 2018; Talebian and Mishra, 2018; Peirce and Mauri, 2007). Then the benefits and costs can be calculated, as shown in Table 5.8.

Table 5.8 Result of B/C analysis of the proposed control system

Benefits ($)	Costs ($)	B/C Ratio	Net Benefit ($)
2,661,476	1,180,300	2.25	1,481,176

Table 5.8 shows that the B/C ratio is 2.25 and the net benefit is $1487717. Therefore, with the new application of CAV-based adaptive control, this DSRC corridor project is an efficient investment. The results also prove that additional CAV application in the near future will ensure the installed CV system is cost-effective.

6. CONCLUSION

6.1 Summary

In this project, our research team conducted a benefit/cost analysis for the TSP application along the Redwood DSRC corridor by collecting and analyzing data from UDOT and UTA. Despite the B/C ratio for this initial TSP being less than 1.0, it is expected that the installed infrastructure can be used to support many other CAV applications in the near future. Hence, to perform a more fair evaluation, this project further develops a CAV-based adpative traffic signal control system. Then several simulations were conducted in VISSIM with the CAV market penetration rate of 100%, 75%, 50%, 25%, 20%, 15%, 10%, and 5%. Based on the simulation results, new benefit/cost ratios with this additional application are obtained and this CV corridor project was proved to be efficient.

6.2 Findings

Our results revealed that if this DSRC corridor is only used for supporting TSP, this project is an inefficient investment because the B/C ratio is lower than 1. Therefore, other applications must be applied along this corridor. Adaptive and coordination control was determined to be another feasible application for this DSRC corridor. Simulation results showed that the proposed traffic signal control system would increase the benefits and thus the B/C ratio increases. It was found that the B/C ratio is greater than one even though the market penetration rate is low in recent years. Therefore, we recommend this proposed control system.

6.3 Limitations and Challenges

In the simulation experiments, the base signal plan is based on the signal timing plan implemented in 2018 during the ten years, which may be not reasonable, since UDOT may adjust the signal timing plan in the future. Therefore, the benefits will also change.

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