Preparing for Traffic Signal Operations in a Multi-Modal Connected and Autonomous Vehicle Environment

WA-RD 902.1

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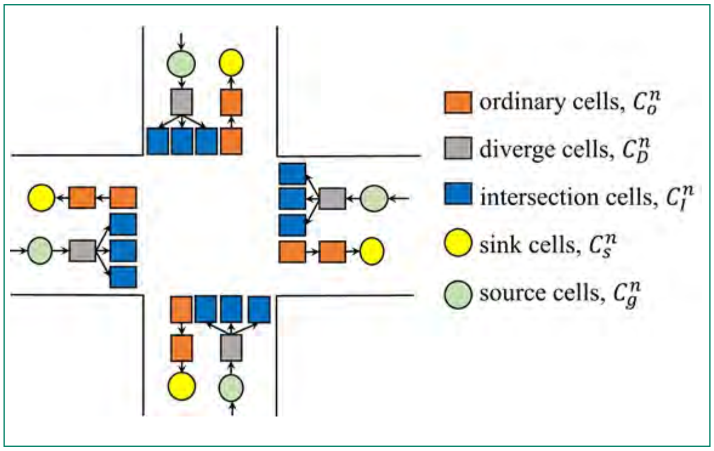

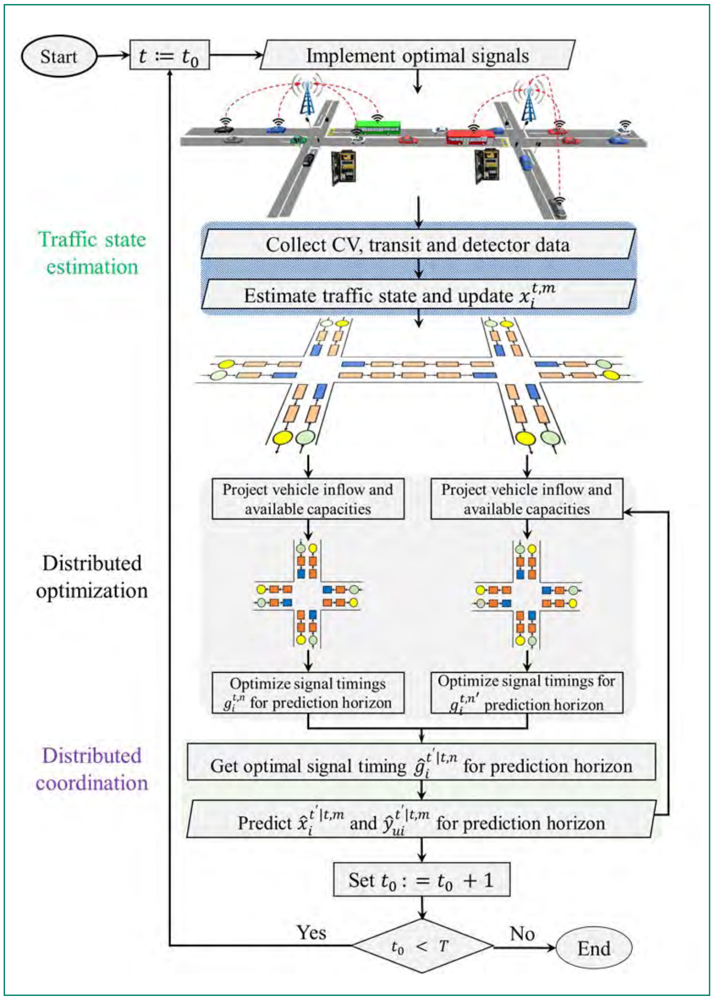

Above: Representation of a cell transmission model for an intersection.

Right: Flow chart of the signal control algorithm in a multi-modal environment.

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Preparing for Traffic Signal Operations in a Multi-Modal Connected and Autonomous Vehicle Environment

by

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16. Abstract

The objective of this research project is to help the Washington State Department of Transportation (WSDOT) identify the right time and location for selecting a corridor for Connected Vehicle (CV) implementation so that the technological needs and compatibilities are met and expected outcomes are significant.

This research team surveyed twenty-one state DOTs about their completed or ongoing CV projects. The results showed the following most common combinations of the signal controller and RSU types for broadcasting the Spat message: Econolite ACS3 controller and Savari RSU, SURTRAC controller and Arada RSU, Econolite Cobalt controller and Arada RSU, and McCain ATC eX controller and Arada RSU. Most state DOTs implemented SPaT broadcast with MAP and RTCM. The most common applications were Multi-Modal Intelligent Traffic Signal System, Transit Signal Priority, Freight Signal prioritization, and Eco-driving. Demographic characteristics, being a part of future development, and high traffic demand levels on a corridor were the most important criteria used by state DOTs for selecting a corridor for CV application.

This study also developed a methodology for multimodal signal control in urban streets with different CV market penetration rates. The research team used this methodology to evaluate mobility, progression quality, and system reliability at three corridors identified by WSDOT: SR-522 in Seattle, SR-503 in Vancouver, and SR-27 in Spokane using observed peak hour volumes and transit bus frequencies. Traffic operations improved with an increase in the CV market penetration rate. The research team found that 30%, 50%, and 70% CVs in traffic stream are required to outperform adaptive signals controlled using loop detector data respectively at SR-522, SR-503, and SR-27 corridors. The variation in the required connectivity showed that the percentage of CVs in the traffic stream is not enough to determine a critical CV market penetration rate. In addition to that, traffic volume and its distribution in the major and minor directions play an important role.

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List of Abbreviations

AASHTO	American Association of State Highway Transportation Officials
ADT	Average Daily Traffic
AKF	Adaptive Kalman Filter
BOG	Beginning of Green
BSM	Basic Safety Message
CDF	Cumulative Density Function
CICAS	Cooperative Intersection Collision Avoidance Systems
CO	Carbon Monoxide
COM	Component Object Model
CTM	Cell Transmission Model
CTR	Cumulative Travel-time Responsive
CTSP	Conventional Transit Signal Priority
CTT	Cumulative Travel Time
CV	Connected Vehicle
DOT	Department of Transportation
DP	Dynamic Programming
DSRC	Dedicated Short Range Communication
DVI	Driver Vehicle Interface
EOG	End of Green
FHWA	Federal Highway Administration
GPS	Global Positioning System
HOV	High Occupancy Vehicle
IMA	Intersection Management Agent

ISS	Intelligent Signal Systems
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation System
ITSA	ITS America
LOTTR	Level of Travel Time Reliability Index
MID	Mid-day
MILP	Mixed Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Program
MMITSS	Multi-Modal Intelligent Traffic Signal System
MMSC	Multi-Modal adaptive Signal Control
NCAR	National Center for Atmospheric Research
NOCoE	National Operations Center of Excellence
NTCIP	National Transportation Communications for Intelligent Transportation System Protocol
OBU	On-board unit
OCA	Oversaturated Condition Algorithm
OSADP	Open Source Application Development Portal
PAMSCOD	Platoon-based arterial multi-modal signal control with online data
PCD	Purdue Coordination Diagram
PMSA	Predictive Microscopic Simulation Algorithm
PTLM	Phase-to-Lane Movement
RLVW	Red Light Violation Warning
RSU	Road Side Unit
RTCM	Radio Technical Commission for Maritime services
SKF	Standard Kalman Filter

SLTA	Signalized Left Turn Assist
SPaT	Traffic Signal Phase and Timing
SR	State Route
SRM	Signal Request Message
SSA	Stop Sign Assist Status
SSM	Signal Status Message
TSA	Traffic Signal Adaptation
TSP	Transit Signal Priority
TSPCV	TSP with CV technology
TSPCV-C	Coordinated Transit Signal Priority with CV
TSPCVM	TSP with CV to accommodate Multiple transit vehicles
USA	United States of America
USDOT	United States Department of Transportation
UV	Unconnected Vehicle
VA	Vehicle Agent
V2I	Vehicle to Infrastructure
V2V	Vehicle to vehicle
VANET	Vehicular Ad-hoc NETwork
VCA	Vehicle Clustering Algorithm
VRU	Vulnerable Road User
WSDOT	Washington State Department of Transportation

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Executive Summary

As part of the Traffic Signal Phase and Timing (SPaT) Challenge, the American Association of State Highway Transportation Officials (AASHTO), the Institute of Transportation Engineers (ITE), and Intelligent Transportation Society of America (ITSA) challenged state and local public transportation agencies to work together to deploy Dedicated Short Range Communication (DSRC) infrastructure with SPaT broadcasts in corridors of 20 intersections by 2020 in each state.

The primary objective of this project was to help the Washington State Department of Transportation (WSDOT) identify the right time and location for selecting corridor(s) for the SPaT challenge and related deployments so that the technological needs and compatibilities are met and expected outcomes are significant. The secondary objective was to develop a real-time methodology to control the timing of signalized intersections in a multi-modal and connected transportation network. The approach not only can be used to control the signals in semi-connected and fully connected corridors, but it also determines the location, ideal implementation date (with respect to Connected Vehicle (CV) penetration rates), and expected benefits of connected corridors from both operational and technological standpoints.

To select the right corridor for studying the SPaT challenge in Washington State, the research team conducted a short survey among state transportation agencies that have either implemented or planned to implement DSRC in their traffic controllers. The research team contacted twenty-one State Departments of Transportation (DOTs) with a list of questions about the reasons for selecting a corridor for DSRC deployment, the type and brand of signal controllers used in the selected corridors, the software used in the signal controller, and CV applications deployed in the selected corridors. The survey and literature review results revealed the following CV applications: (1) Traffic signal phase and timing (SPaT) broadcast, (2) MAP broadcast, (3) Multi-modal

intelligent traffic signal system (MMITS), (4) Red-light violation warning, (5) Transit signal priority (TSP), (6) Freight signal prioritization, (7) Eco-driving, (8) pedestrian in crosswalk detection, and (9) Radio technical commission for maritime services (RTCM) broadcast.

The survey results also indicate that state DOTs mostly consider the following criteria to select the desired corridor for implementing the DSRC technology: (1) Need for transit signal priority, (2) Ease of access to the corridor, (3) Variation in land use, (4) Variation in traffic demand, (5) Being a part of an ongoing CV project, (6) Proximity to automotive R&D centers and Silicon Valley tech companies, (7) Being part of a fiber project, and (8) Favorable existing infrastructure.

WSDOT has selected three corridors to analyze the impacts of implementing CV technology on the mobility performance of transportation systems: SR-522 in Seattle, SR-503 in Vancouver, and SR-27 in Spokane. These corridors respectively have ten, four, and three intersections. Besides, several public transit routes pass through these corridors.

The research team developed an adaptive signal control methodology to control the timing of signalized intersections in a multi-class vehicle and connected transportation network. The methodology is used to analyze the impacts of CV on traffic operations in the three mentioned corridors under various CV market penetration rates. The methodology has the capability of controlling signals with (a) only detector data, (b) only CV data, or (c) integrated CV and loop detector data. In addition, the methodology is responsive to traffic demand and can prioritize the movement of transit vehicles.

The results show that traffic operations improved with the CV market penetration rate as expected. However, the improvement in mobility performance measures depends on the demography and traffic demand level in the corridor. For instance, the signal system that used only available CV data required 30%, 50%, and 70% CV market shares, respectively for SR-522, SR-

503, and SR-27 corridor to outperform the signal control system that uses only Loop Detector data. The integration of CV and Loop Detector data can help consistently outperform detector-based signals at a low CV penetration rate, even at 10%. The results showed that the integration of CV and loop detector data has positive impacts up to 60% market penetration rate. Beyond this point, CV data and integrated CV & Loop Detector yield similar traffic operations. Furthermore, increasing CV market share helps improve travel time reliability of both passenger cars and transit buses.

1. Introduction

Connected Vehicle (CV) technology is advancing rapidly, and many state and local agencies have taken initiatives to perform real-world testing and to deploy the technology. Effective communication with transportation infrastructure makes the CV technology more effective in improving traffic operations, environmental sustainability, and safety (Najm *et al.*, 2010; Goodall, Smith and Park, 2013; Feng *et al.*, 2015; Islam *et al.*, 2018, 2019). Improved communications between the infrastructure and vehicles can reduce travel time by up to 27% and carbon dioxide emission by 11% (Chang *et al.*, 2015). In terms of safety, CV applications can address about 80% of traffic crashes involving unimpaired drivers (Jadaan, Zeater and Abukhalil, 2017).

While there is a clear interest in CVs, most CV applications are not practice-ready yet. A promising application is providing Traffic Signal Phase and Timing (SPaT) information to vehicles approaching a signalized intersection. There is a need to explore the ability to take the basic traffic signal controller information, i.e. SPaT message and communicate it to CVs to allow them to respond and coordinate with ongoing signal operations directly. Besides, there is no real-time, reliable, and multimodal approach to control the timing of signalized intersections in a connected or semi-connected arterial street or urban street network to date. It is important to plan for this emerging and revolutionary technology and develop methodologies that can use additional information from CVs to improve traffic operations.

As the role of CV technology has continued to evolve, the American Association of State Highway Transportation Officials (AASHTO) came forward to encourage national-level deployment of the technology. To provide state and local departments of transportation with a tangible first step for deploying V2I technology, the AASHTO has set all the states a goal to achieve deployment of roadside Dedicated Short Range Communications (DSRC) in a corridor of twenty intersections by 2020.

1.1. Problem statement

WSDOT maintains approximately 1,000 signalized intersections throughout the state. These intersections handle a large volume of passenger cars and transit buses especially during the peak hours of the day. In 2017, traffic congestion yielded 167.4 million hours of delay in Seattle, the largest city in Washington State, which is 3% more than the total delay in 2015 (Lasley, 2019). On average, suboptimal traffic signals are responsible for 5 to 10 percent of all traffic delays (Denney Jr, Curtis and Olson, 2012). As such, the development of a real-time, reliable, and multimodal signal timing approach to use CV information offers great potential to reduce the congestion and its associated costs significantly, and also places WSDOT in a unique position to take on the SPaT challenge. WSDOT needs a strategic approach for how to prepare for the SPaT challenge and other opportunities that lead to the installation of CV equipments to connect real-time signal operations to surrounding CVs.

To deploy the CV technology, WSDOT needs to determine the time and place for implementing connected corridors from technological and traffic operational perspectives. Furthermore, the expected outcomes should be estimated more accurately to enhance the operations of signal systems in response to passenger cars and transit systems. Therefore, identifying the technological issues and requirements of integrating CV hardware in existing traffic signal systems would help WSDOT successfully apply the CV technology to corridors of intersections, where the highest improvements can be achieved.

A computationally efficient and scalable signal control methodology that works with various CV market penetration rates in a multi-vehicle class environment is needed to quantify the impacts of CV technology on traffic operations in arterial corridors.

1.2. Research objectives

This research project aims to address two main objectives. The primary objective is to help WSDOT with identifying the right time and location for selecting a corridor for CV technology implementation so that the technological needs and compatibilities are met and expected outcomes are significant. For this purpose, this research summarizes the outcomes of a short survey that was distributed to state transportation agencies who have either implemented or planning to implement DSRC in traffic controllers according to the National Operations Center of Excellence (NOCoE) website. The research team accessed this website, reviewed published reports, and contacted several State Departments of Transportation (DOTs) to collect information about (1) the reasons for selecting a corridor for DSRC deployment, (2) the type and brand of signal controllers used in the selected corridors, (3) the software used in the signal controller, and (4) CV applications deployed in the selected corridors. To quantify the expected outcomes of CV technology, a signal control methodology is needed.

The secondary objective is to develop a computationally efficient methodology to control the timing of signalized intersections in a multi-modal and connected transportation network. The proposed approach not only can be used to control the signals in semi-connected and fully connected corridors, but it also can be used to determine the location, ideal implementation date (with respect to CV penetration rates), and expected benefits of multimodal connected corridors.

1.3. Report layout

This report has seven chapters. Chapter 2 presents an extensive literature review on the SPaT challenge and its potential benefits to the transportation systems. It also discusses the guidelines for selecting a corridor for deploying CV technology. Several applications of the SPaT message in traffic operation, safety, and environmental sustainability are also presented. A review of recent CV-based traffic signal control systems is discussed as well.

Chapter 3 summarizes the outcome of the survey of the transportation agencies that have either deployed or planned to deploy CV corridors as a response to the SPaT challenge. The survey includes the reasons for selecting locations, technical challenges, and requirements for SPaT deployment in different states over the US.

Chapter 4 presents a methodology for multimodal signal control for corridors with a mixed traffic stream of connected and unconnected vehicles. The methodology prioritizes transit vehicles in signalized intersections. This chapter is intended only for readers that are interested in learning the fundamental of the developed signal control methodology.

Chapter 5 details the geometrical layout of three case study networks in Washington State. Furthermore, details on analysis scenarios, simulation setup, and transit bus operations are presented.

Chapter 6 provides numerical results in terms of mobility, progression quality, and travel time reliability measures for all three case studies. Chapter 7 presents the conclusion of this research.

2. Literature Review

This chapter presents a review of literature on the SPaT challenge and its potential benefits to the transportation systems. It also discusses the guidelines for selecting a corridor for deploying CV technology. Several applications of the SPaT message in traffic operation, safety, and environmental sustainability are also presented. A review of recent CV-based traffic signal control systems is discussed. Finally, a summary of all findings is presented.

2.1. SPaT challenge

AASHTO, the Institute of Transportation Engineers (ITE), and ITS America (ITSA) has challenged state and local public transportation agencies to work together to deploy DSRC infrastructure with SPaT broadcasts in corridors of 20 intersections by 2020 in each state. This is commonly called the 20/50/20 Challenge or, simply, the SPaT Challenge. In addition to the SPaT broadcast, V2I applications rely on the broadcast of a data file that defines the physical intersection geometry referred to as the MAP. In order to correctly specify vehicle location, Global Positioning System (GPS) position that is standardized by the Radio Technical Commission for Maritime (RTCM) services, will need to be sent in addition to SPaT and MAP messages. The AASHTO's SPaT challenge will include the following provisions and details:

- The primary goal is to achieve DSRC infrastructure deployment for SPaT, MAP, and RTCM broadcasts by January 2020, and to commit to operating the SPaT broadcasts for a minimum of 10 years. To this extent:
    - AASHTO has set the goal of deploying SPaT broadcasts in 20 intersections including either state, county, or local city intersections, as decided by each location. However, AASHTO still encourages the deployment to a smaller extent

when the local technical or financial environment can only support a smaller number of intersection deployment.

- In some situations, agencies may start with the SPaT broadcast alone and can add MAP and RTCM broadcasts later. This is recognized as a valid approach as long as the understanding is that MAP and RTCM will be required before vehicle equipped applications recognize the benefits of the broadcast.
- In order to maintain uniformity in the country, AASHTO mandated broadcasting the SPaT, MAP, and RTCM messages to be an element of every deployment as a base for broad-scale application deployment. However, AASHTO encourages agencies to deploy applications beyond these.

– State and local agencies responding to the challenge will have access to resources developed by the V2I Deployment Coalition and the AASHTO Connected and Automated Vehicle Working Group within the Subcommittee on Transportation Systems Management and Operations. Additional technology transfer is expected to include webinars.

2.2. Benefits of SPaT deployments

SPaT broadcast deployment is expected to have both immediate and long-term effects on the transportation systems. This section will briefly highlight some of them.

2.2.1. Immediate and short-term benefits of SPaT deployments

It is expected that SPaT broadcasts will largely benefit the transportation agencies by providing them with lessons learned from the experience. This will help the state and local public transportation agencies understand the DSRC licensing process, become familiar with the site selection process, and gain hands-on experience in DSRC deployment and operations. As such, the agencies will be ready to deploy more complex CV applications in the future. In addition to the increased knowledge about DSRC, agencies participating in the SPaT challenge will also be deploying the early stages of their eventual V2I applications. With SPaT broadcasts, as agencies deploy V2I applications at SPaT equipped intersections, the percentage of vehicles equipped with CV technology will increase and so do the financial, safety, and mobility benefits.

Finally, automakers will be able to see the progress on the CV technology deployment and use it in their consideration on when to install V2I applications in the manufactured vehicles. Private application developers will respond similarly (Abdirad, Krishnan and Gupta, 2020).

2.2.2. Long-term anticipated benefits of SPaT deployment and operation

Ultimately, the mobility and safety benefits of the SPaT broadcasts will be recognized as infrastructure owners and operators, public sector fleets (e.g. transit and emergency response), and Original Equipment Manufacturers deploy specific V2I applications (i.e. SPaT is a technology required to support multiple V2I applications) as CV market penetration rate increases. Some V2I applications supported by the SPaT broadcasts can be deployed in the field, and the anticipated benefits of these applications are summarized below:

- TSP applications operating in areas with SPaT broadcast-equipped intersections could be enhanced, allowing more sophisticated decisions regarding priority requests and ultimately reducing the delay of all vehicles at these intersections.
- Red Light Violation Warning (RLVW) applications could warn drivers approaching a signalized intersection when the potential of running the red light is determined based on the vehicle, SPaT, MAP, and RTCM data received from the infrastructure.
- Intelligent Signal Systems (ISS) applications would require DSRC broadcasts from the vehicles as well as the SPaT broadcasts from the infrastructure. However, when achieved,

the benefits would improve signal timings to reduce the congestion and delay for all vehicles traveling through SPaT equipped intersections.

- In-vehicle displays of countdowns describing green or red time remaining could be developed as in-vehicle or mobile hand-held applications informing the drivers approaching intersections of when the green light phase will end. Similarly, drivers stopped at intersections could see a countdown to the light change from red to green.

2.3. Implementation guidelines

2.3.1. Physical architecture drawing and summary

The process of broadcasting the SPaT messages can be described as follows (see Figure 2-1):

- Generate SPaT message output: The traffic signal controller will generate the current signal phase and timing parameters used to control the signal. NTCIP 1202 compliant traffic signal controllers are typically capable of generating the output of the SPaT parameters as 1202 SPaT messages.
- Conversion of 1202 SPaT Messages to J2735 SPaT Messages: The 1202 SPaT messages must be converted to J2735 formats prior to broadcast so that vehicle can interpret the message.
- Intersection MAP data: The MAP message is not created in real-time, but rather is a static description of the geometries of the intersection and vectors describing approaches. The vehicle systems will compare GPS location readings on the vehicle against the MAP message and determine the vehicle's approach.
- Generation of GPS Correction data: The GPS correction information standardized by the RTCM services is broadcasted to minimize the effects of GPS error caused by atmospheric conditions or reduced satellite access. The general concept is that a base station with a

known location (the location may be known either by surveying in the station location or operating a GPS receiver for a long continuous period of time) continuously receives satellite signals and determines a current latitude/longitude position given the current atmospheric conditions. The base station then compares the position determined with the current atmospheric conditions to the known location and computes an adjustment factor that corrects the current calculated position to the base position. This adjustment factor, or in other words the RTCM message is sent out to vehicles. Depending on the vehicle and the onboard GPS, the vehicle may or may not be able to apply the correction factor.

– Combining SPaT, MAP, and RTCM for broadcast: The SPaT, MAP, and RTCM messages are combined and sent to the DSRC antenna to broadcast.

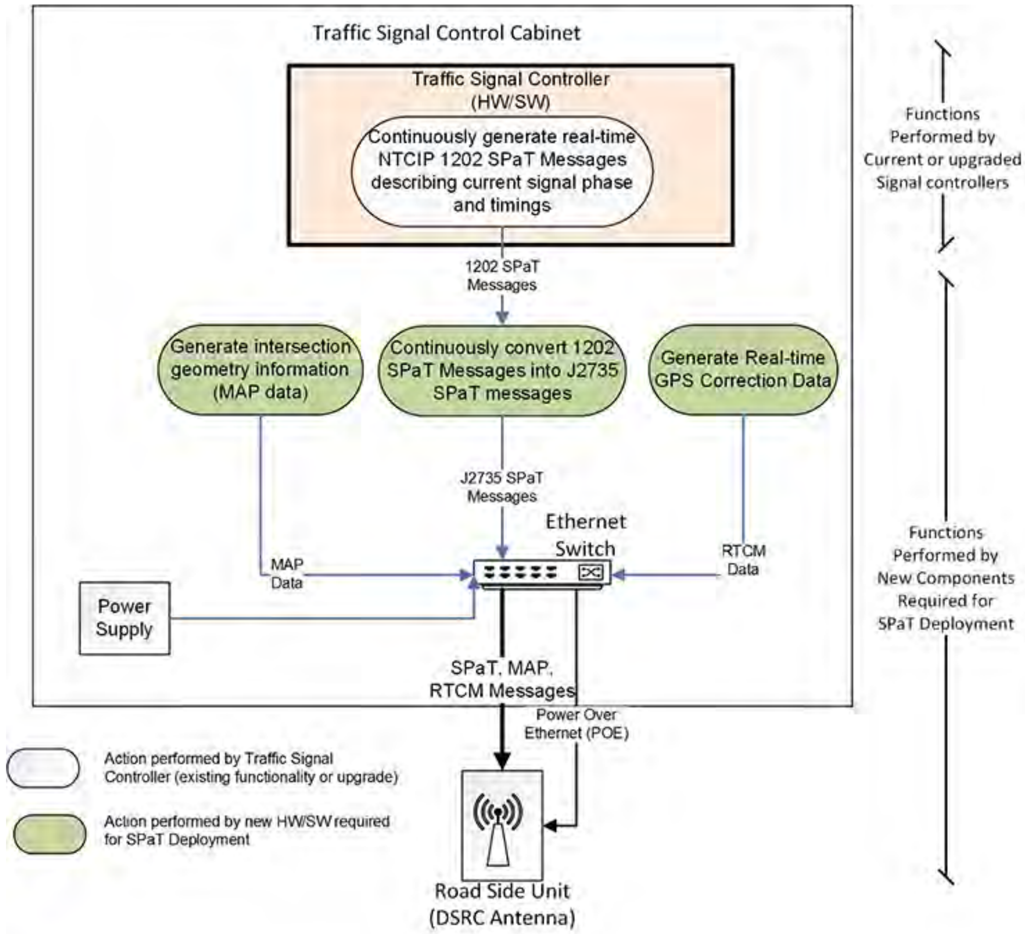


Figure 2-1: Functions to be performed to accomplish real-time DSRC broadcast of SPaT messages

Various approaches are possible to deploy SPaT broadcasts in a controller. The most commonly used approaches are:

1. Insert a SPaT control board into the controller,
2. Install a “black box” (such as an inexpensive Linux computer board) between the controller and the DSRC radio who translates the signal generated by the controller so it can be broadcasted. The “V2I Hub” software created by the FHWA will work well with this approach.
3. Use a DSRC radio which has a built-in SPaT data translation unit.

2.3.2. Installing new hardware/software to support SPaT

This section presents the minimum existing infrastructure and additional hardware/software needs to support SPaT broadcasts. Next, a brief description and resources for V2I-Hub will be discussed.

- Minimum existing field equipment to support SPaT:
  - A traffic signal controller with National Transportation Communications for ITS Protocol (NTCIP) 1202 SPaT message outputs via an open Ethernet port.
  - An Ethernet switch in the traffic signal controller cabinet that has at least three ports available. All of these ports need to be operated from the same subnet.
  - Possibility of mounting equipment inside the traffic signal controller cabinet.
- Minimum new hardware and software required to support SPaT:
  - Software to translate the NTCIP object-oriented SPaT data into J2735 SPaT messages to broadcast,
  - Software to create a MAP message to broadcast,
  - Hardware to acquire or create RTCM or GPS correction messages to broadcast,
  - The DSRC antenna to broadcast the SPaT, MAP, RTCM messages, and
  - Communication hardware and software to link existing and new components.
- The V2I Hub is an open-source software product developed by FHWA and a series of guidance documents to support the SPaT, MAP, and RTCM broadcasts. As illustrated in Figure 2-1, three high-level functions need to be performed to assemble the required information to be sent to the DSRC antenna. The V2I Hub offers solutions to accomplishing these functions as follow:

- The V2I Hub Software is available on the Open Source Application Development Portal (OSADP). Release notes, compilation and installation instructions, and supporting documentation are also provided on the OSADP website.
- In order to broadcast MAP Messages, the V2I Hub Map Plugin requires an XML input file with the infrastructure geometry of the deployment area. Guidance for developing this file is provided in the V2I Hub MAP XML Input File Instructions.
- The V2I Hub SPaT Plugin requires an XML input file to convert the NTCIP 1202 SPaT messages from the traffic signal controller to SAE J2735 SPaT messages to broadcast via the roadside unit (RSU). Guidance for developing this Phase-to-Lane Movement (PTLM) file is provided in the V2I PTLM XML Input File Instructions.
- V2I Hub, RSU, and Plugin configuration guidance are provided in the V2I Hub Sample Set-Up Guide.
- The V2I Hub Troubleshooting Guide provides information on potential issues and resolutions.

2.4. Guidelines for selecting corridors

NOCoE documented guidelines to assist agencies in accepting the SPaT challenge in selecting their corridors or network for the implementation. The selection of a corridor/network for an initial SPaT deployment involves at least two high-level criteria:

2.4.1. Corridor selection based on needs

Based on the agency, a formal user needs assessment accompanied by a system engineering analysis or a higher level preliminary sketch planning assessment of needs may be used in the corridor selection. The needs-based corridor selection criteria are given below:

- Corridors with operational TSP or being considered for future deployment
- A corridor or network of signalized intersections with operating traffic volumes at or near capacity during peak periods.
- A corridor, network, or isolated intersection that is near a freeway exchange, and therefore, might be considered for an Integrated Corridor Management approach soon.
- A corridor or network with frequent emergency vehicle traffic that currently utilizes emergency vehicle pre-emption.
- A corridor with higher than normal red-light violations and/or crashes related to red-light violations.
- A corridor with higher than normal commercial vehicles or freight traffic.
- A corridor with a major event venue that attracts major events.

2.4.2. Corridor selection based on existing infrastructure capabilities

In addition to the potential benefits of V2I applications, infrastructure capabilities should be considered in the site selection process. When the SPaT deployment is achieved in near future, there should be plans in place to upgrade the infrastructure to allow successful deployment. The following criteria are important to support the infrastructure compatibility with the SPaT broadcast:

- Traffic signal controller and software capable of broadcasting the SPaT message.
- The capability to accept input from vehicles by the traffic signal controller. The basic premise of a SPaT broadcast is a one-way communication describing the current signal phase and timing to the approaching vehicle, however, some of the CV applications may involve two-way communication between vehicle and infrastructure. In these scenarios, the traffic signal controller should be capable of accepting input from vehicles.

- Availability of a port to connect the DSRC antennae.
- Cabling capacity: The basic SPaT broadcast can be accomplished locally at the signal controller without requiring any feed-back from the vehicle. However, several CV applications may require two-way communications between the intersection and vehicle. Depending on the communications to/from the intersection, additional cables may be required.
- GPS coverage: Candidate location should have reliable GPS coverage. Locations in the vicinity of tall buildings on both sides could be affected. As a result, selecting these intersections are not encouraged. To locate SPaT broadcast sites, the agencies should consider RTCM broadcasts to enable vehicles to correct their GPS position for the locations with limited surroundings by buildings.
- Low latency in communications between traffic signal controllers and vehicles is favorable.

2.5. Application of SPaT message in traffic operation

There are several applications that use CV technology and data to improve traffic safety and operations in highway systems. In particular, Misener, Shladover and Dickey, (2010) identified some applications of real-time SPaT data that support improvements in both safety and mobility in arterial streets. Some of these applications are briefly described below:

2.5.1. Signal violation warning

The USDOT started a multi-year project titled “The Cooperative Intersection Collision Avoidance Systems (CICAS)” in 2003 with the objective of reducing the number of crashes at intersections (Maile *et al.*, 2008). The first segment aimed to address the problem of straight crossing path collisions, which tend to be the result of stop sign or stop light violations. The basic concept of CICAS-V (Violation) is illustrated in Figure 2-2. Some of the key features of CICAS-V are described below:

1. The traffic signal controller provides its phasing status to the RSU continuously, and the RSU broadcasts this information frequently as SPaT message (10 Hz update rate).
2. Intersections equipped with CICAS-V receive the position, speed, and acceleration rate of approaching CVs continuously.
3. The RSU predicts the probability of red light violations based on the signal status and the information received from approaching vehicles.
4. A warning message is issued if the driver is predicted to violate the signal and cause a crash.
5. Required hardware devices: DSRC radios on intersection and vehicles, vehicle positioning and heading sensors, interface from a traffic signal to RSU, in-vehicle computer to estimate violation status, and Human-Machine Interface to create audible alerts to drivers.

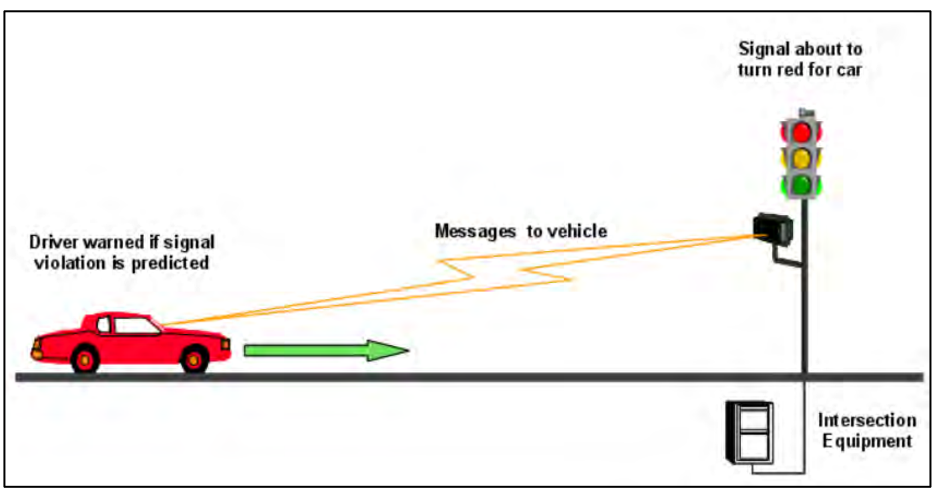


Figure 2-2: Basic Concept of the CICAS-V System at a Signalized Intersection (Maile *et al.*, 2008)

2.5.2. Stop sign assist

Minnesota Department of Transportation (MnDOT) led the second segment "CICAS – Stop Sign Assist Status (SSA)," which aimed to help the drivers in rural intersections identify unsafe gaps (Becic *et al.*, 2012). The system architecture consists of three distinct roadside detection subsystems: median presence detection system, minor road sensor, and mainline sensor system. These three subsystems work together to identify an unsafe condition as follow:

1. The system issues a warning to a driver on the minor road when the median presence detection system detects a vehicle on the crossroads.
2. The minor road sensor detects the presence, size, and position of vehicles in the minor direction. It determines the required time for the vehicle in the minor direction to cross the road safely and issues a warning if it is unsafe to cross.
3. The mainline sensor system continuously receives the presence, position, and speed of each vehicle within its coverage zone, and determines the time required for vehicles on the minor directions to cross safely.
4. The driver is warned via either the Driver Infrastructure Interface or Driver Vehicle Interface (DVI).

2.5.3. Signalized left turn assist

The final segment, CICAS- Signalized Left Turn Assist (SLTA) aims to address left-turn-related crashes, especially at signalized intersections with permissive left turns (Misener, 2010). CICAS-SLTA detects the presence of all approaching left turners and pedestrians within the intersection. The roadside unit processes the detection information, estimates vehicle trajectories, predicts the gap between two conflicting vehicles, and finally provides information to left-turning vehicles using the DVI. Figure 2-3 illustrates all steps that the system will process as a left-turning vehicle approaches the intersection. The CICAS SLTA information will be broadcasted through DSRC and displayed by a DVI.

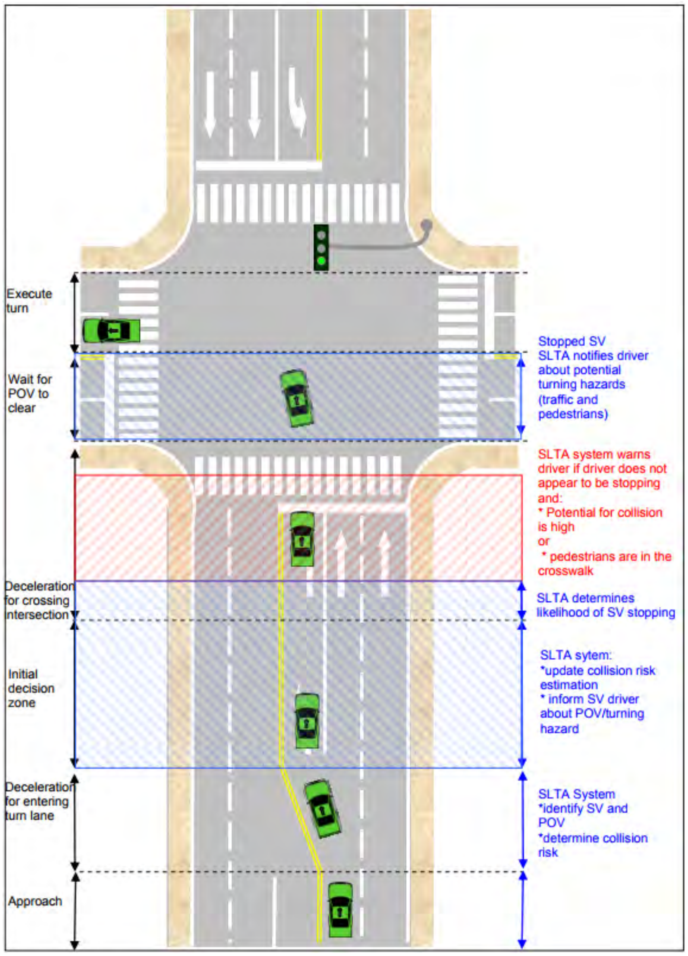


Figure 2-3: The SLTA Baseline Scenario (Misener, 2010)

2.5.4. Traffic signal adaptation

CICAS-Traffic Signal Adaptation (TSA) aims to adapt the traffic signal to reduce the probability of intersection crashes due to red light violations (Misener, 2010). The intersection controller equipped with RSU continuously broadcasts the SPaT message to all approaching vehicles within its communication range. The intersection signal controller receives the speed, acceleration, and location of vehicles in the form of a basic safety message (BSM) and combines the information with detector data to identify vehicles that may run a red light. To reduce the probability of a crash with conflicting direction, the signal controller will extend the all-red period and let vehicles to clear the intersection. Figure 2-4 illustrates the basic concept.

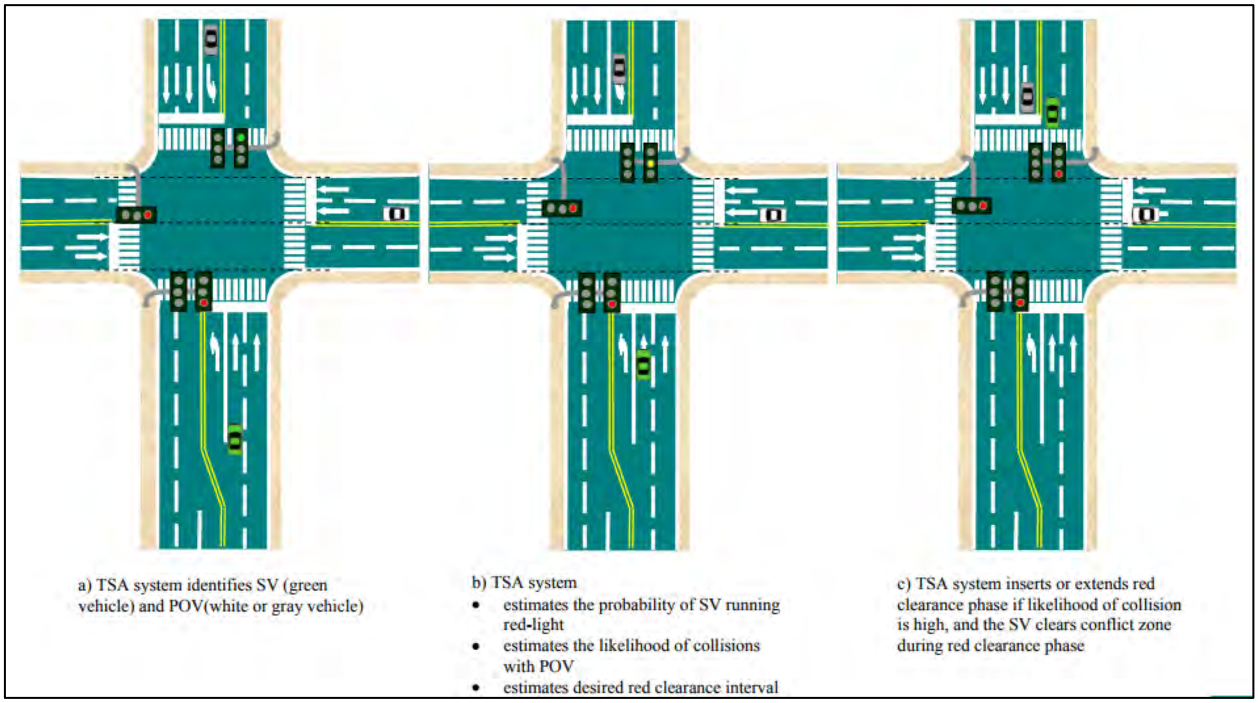


Figure 2-4: Basic concepts of CICAS-TSA (Misener, 2010)

2.5.5. Vulnerable Road User (VRU) warnings near intersections

The goal of this application is to warn the drivers about pedestrians and bicyclists who are close to vehicles to avoid possibly unsafe situations (Misener, Shladover and Dickey, 2010). RSU identifies pedestrians or bicyclists (who carry a communication device that can broadcast their location) who are currently violating or about to violate the signals based on the user's BSM and the SPaT message. The intersection controller broadcasts a VRU alert message to all approaching vehicles about the current or imminent violation. Each vehicle's on-board unit (OBU) compares its direction of travel with the direction of the violators and issues a VRU warning to the driver through the DVI.

2.5.6. Truck signal change warning

Heavy vehicles like trucks require a relatively long time to stop regardless of the capabilities of their driver. As a result, these vehicles require a longer yellow time to react to a sudden change in the traffic light. However, yellow intervals in a traffic signal are designed based on the expected braking response of passenger cars. As a result, the likelihood of crossing an intersection after the signal has turned red increases for heavy vehicles and so does the crash probability. This application estimates the required time to stop a heavy vehicle safely by using the BSM shared by their OBU and compares it with the remainder of the green signal based on the SPaT information broadcasted by the RSU. The system will alert the driver if the remainder of the green signal is smaller than the time required to stop the vehicle. The following devices are required to deploy this application:

1. RSU to broadcast the SPaT message.
2. Vehicles equipped with OBU.
3. Interface to truck data bus to obtain speed and other available information about truck loading, brake and tire conditions, and road surface friction.
4. DVI for displaying the emergency information.

2.5.7. EcoDriving

The EcoDriving application helps drivers navigate through the network with minimum fuel consumption (Misener, Shladover and Dickey, 2010). Each CV continuously calculates a smooth speed and acceleration rate to pass through intersections without a stop, using the SPaT message broadcasted from the RSU.

Kamalanathsharma and Rakha (2014) developed the Ecospeed control system. The Ecospeed optimizes vehicle trajectories to minimize fuel consumption by considering signal timing parameters, vehicular interactions, and other roadway constraints in a CV environment. The methodology was tested under various traffic volumes and market penetration rates in a simulated intersection. The control strategy reduced fuel consumption by 30% and increased average speed by 20%. Kamalanathsharma and Rakha (2016) extended this research and used a rolling horizon dynamic programming (DP) approach to find the optimal trajectories. In this study, they developed a modified A-star algorithm to reduce the computational complexity of solving the DP in real-time by utilizing SPaT data to predict future vehicle trajectories. The model was found to save fuel at signalized intersections by 5% to 30%.

Jung *et al.* (2016) applied a bi-level programming approach to minimize delay and fuel consumption by optimizing vehicle trajectories and signal timing parameters. They developed a genetic algorithm to solve the upper-level problem to find optimal signal timing parameters. They found the optimal vehicle trajectories at the lower level by exhaustive search. Fuel consumption was calculated by the VT-micro model (Rakha, Ahn and Trani, 2004) taking signal timing parameters, desired speeds, acceleration rates, and arrival times as input. Simulation runs showed that fuel consumption was reduced by 5-10% and travel time decreased by 12% compared to the existing control method.

Kamal, Taguchi and Yoshimura (2015) estimated the state of the followers using Gipps car following model (Gipps, 1981). They used SPaT data to find optimal acceleration rates of vehicles. The proposed algorithm dynamically tuned the speed of vehicles to avoid idling in red signals either by speeding up or slowing down. Simulation tests showed that the approach reduced fuel consumption by 4.5% and travel time by 2% compared to the traditional driving system.

2.5.8. Transit signal priority and multi-modal traffic signal control

TSP tools modify traffic signal timing or phasing to prioritize the movement of transit vehicles through intersections. TSP can be a powerful tool to improve both reliability and travel time, especially on corridors with long cycle times and long distances between intersections. According to Hu, Park and Parkany (2014), TSP applications using CV technology can reduce total bus travel times during peak hours between 4% and 15% in Minneapolis, MN. Applications in Portland, Seattle, and Los Angeles showed an 8% to 10% decrease in travel time.

Multi-Modal Intelligent Traffic Signal System (MMITSS) project conducted by University of Arizona (University of Arizona *et al.*, 2016) developed a comprehensive multimodal traffic signal control system and constructed the software and hardware systems required to support the developed method in a CV environment. The research team developed an analytical model and a flexible implementation algorithm that considers real-time vehicle actuations for controlling traffic signals in a multi-modal CV environment (Zamanipour *et al.*, 2016). A DP based two-level phase allocation algorithm takes the number of vehicles arriving, requests a phase as an input, and calculates optimal phasing sequences and timing. However, to accurately estimate the number of vehicles that arrive at the intersection at low CV market penetration rates, an algorithm based on the Wiedemann car following model (Higgs, Abbas and Medina, 2011) was used. This algorithm estimates the states (i.e. speed, acceleration, and position) of unconnected vehicles (UV) based on the information collected from CVs (Feng, Khoshmagham, and Zamanipour, 2015). The analytical model minimizes the total weighted priority request delay considering priority vehicle delay and coordination delay evaluation constraints. Finally, the implemented algorithm could guarantee the least negative impacts on regular vehicles.

Maricopa County, Arizona has tested MMITSS in a real-world field study. The framework of MMITSS is shown in Figure 2-5. Messages are received, processed, and broadcasted by the software components in the RSU and the OBU. RSU broadcasts MAP and SPaT messages to all CVs that are within the DSRC range. Then, signal request messages (SRM) are broadcasted through the priority request generator from all CVs and are processed in the priority request server by the RSU. An optimization model is solved, and a new schedule is implemented whenever a new priority request is added to the request table. Whenever a priority vehicle departs the intersection, or a vehicle changes its speed beyond the specified threshold, this process is bound to occur. The signal priority algorithm component gets the priority configuration and signal status message from the traffic configuration manager and the priority request server, respectively, and it also is connected to the signal priority control algorithm. A mathematical model is formulated by the signal priority algorithm using these inputs and the optimal signal timing schedule is acquired by solving it in real-time. Then, the critical points (that create a feasible region for the signal controller to serve priority request without any delay) are acquired by applying the flexible implementation algorithm to the optimal solution. A list of optimal signal control events is generated through critical points. The traffic controller interface implements the event list. NTCIP hold and force-off commands are sent to the traffic controller interface so that the optimal plan on the traffic controller can be implemented.

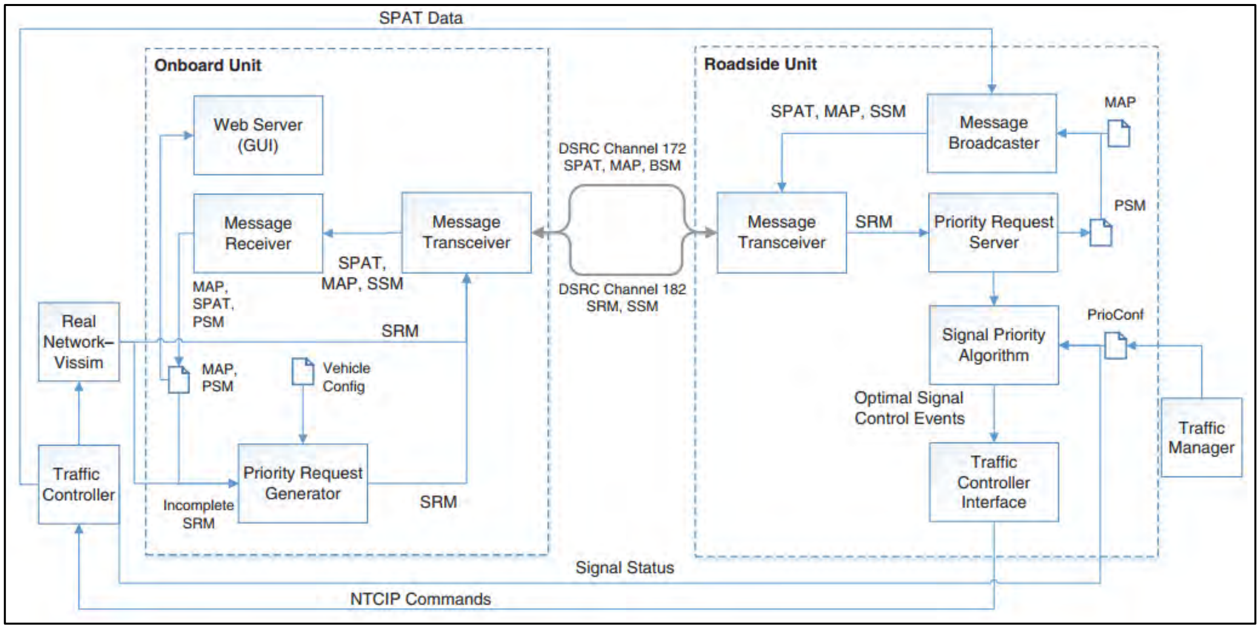


Figure 2-5: The basic concept of MMITSS priority control framework (Zamanipour *et al.*, 2016)**.**

Hu, Park, and Parkany (2014) proposed a different TSP logic in a CV environment. A transit vehicle will send a priority request while approaching an intersection. However, instead of adding additional green time to the original timing plan, the signal controller allocates part of the green to the requested phase of the transit vehicle so that it can travel through the intersection without impedance. However, the logic would account for delay per person as a conditional criterion to grant the TSP green time. Evaluation results from Vissim (PTV Group, 2013) simulations show that the proposed TSP logic reduces bus delay from 9% to 84% compared to conventional TSP and from 36% to 88% compared to a no-TSP condition in different congestion levels. Figure 2-6 presents the logic of the proposed TSP.

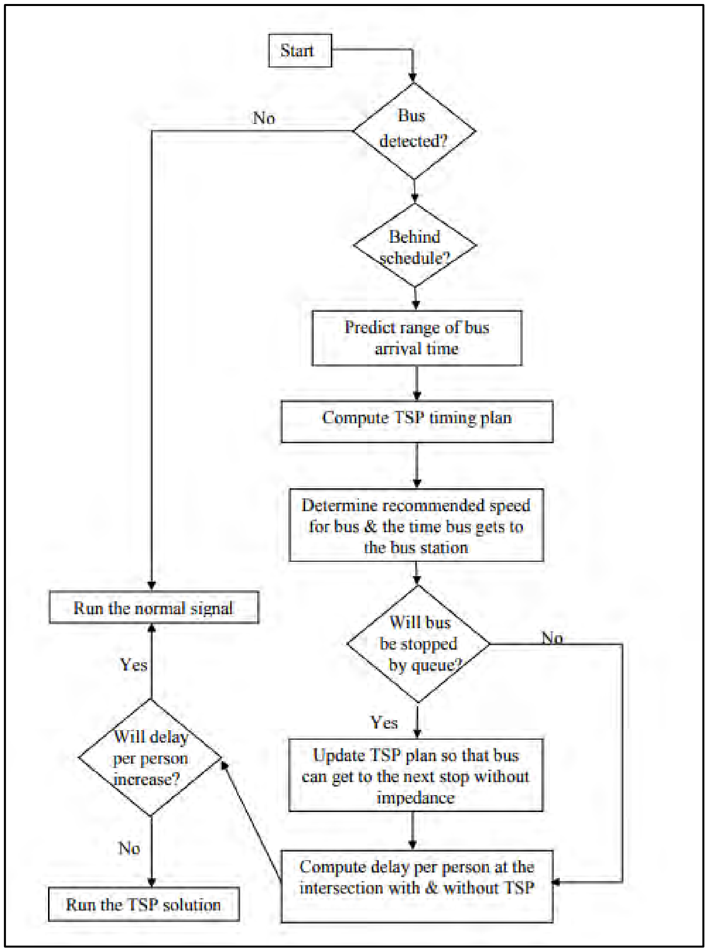


Figure 2-6: TSP logic proposed by Hu, Park, and Parkany (2014)

Hu *et al.* (2016) developed a TSP algorithm with the CV technology that can accommodate multiple transit vehicles (TSPCVM). The control logic is the extension of Hu, Park and Parkany (2014) to handle conflicting requests. TSPCVM can handle at most two TSP requests in a cycle using the logic presented in Figure 2-7. In the case of three or more conflicting TSP requests in one cycle, the algorithm identifies all possible bus pairs and accommodates the bus pair that is associated with the least travel time of all vehicles. TSPCVM prefers to serve two TSP requests from the opposite direction within the same green phase. Both analytical and simulation-based tests were performed to evaluate the TSPCVM logic. The results show that under moderate-volume conditions, the bus delay is reduced by approximately 40% to 50%. Furthermore, the performance of TSPCVM was compared with the Conventional TSP (CTSP) conditions under various congestion levels and various conflicting conditions. Results demonstrate that the TSPCVM logic reduces bus delay between 5% and 48% compared to CTSP.

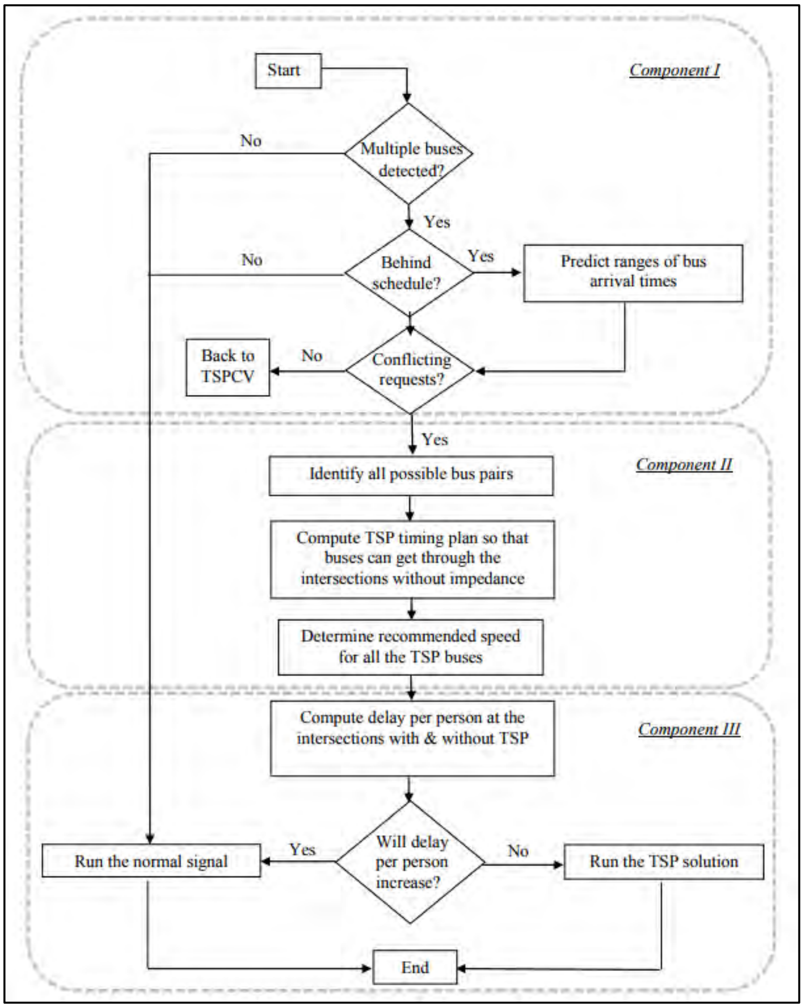


Figure 2-7: The structure of TSPCVM proposed in Hu et al. (2016)

The next phase of this research proposed Coordinated-TSPCV (TSPCV-C) to coordinate passage between intersections in a corridor (Hu *et al.*, 2016). The mechanism allows TSPCV-C to proceed to the next step for buses that are behind the schedule. As a result, the controller checks the state of a bus, every time it detects a bus crosses the activation point. Next, the proposed logic solves a Mixed Integer Linear Programming (MILP) model to compute the TSP timing plans of the closely spaced downstream intersections; however, implements the timings for the immediate intersection only. The algorithm assigns speed to the transit vehicle so that it can navigate through the intersections without impedance. Similar to TSPCV and TSPCVM, TSPCV-C only grants TSP signal plan if it reduces the per person delay. TSPCV-C reduces the bus delay by up to 75% compared to conventional TSP. Its performance is more efficient than any other TSP logic (TSPCV or CTSP) regardless of the intersection spacing. The logic ensures the optimal performance in terms of the total vehicle delay as long as the spacing between the signals is more than 0.24 miles. However, even with a spacing of fewer than 0.24 miles, it can reduce bus delay by about 59%. Figure 2-8 presents this TSP control logic in a flow chart.

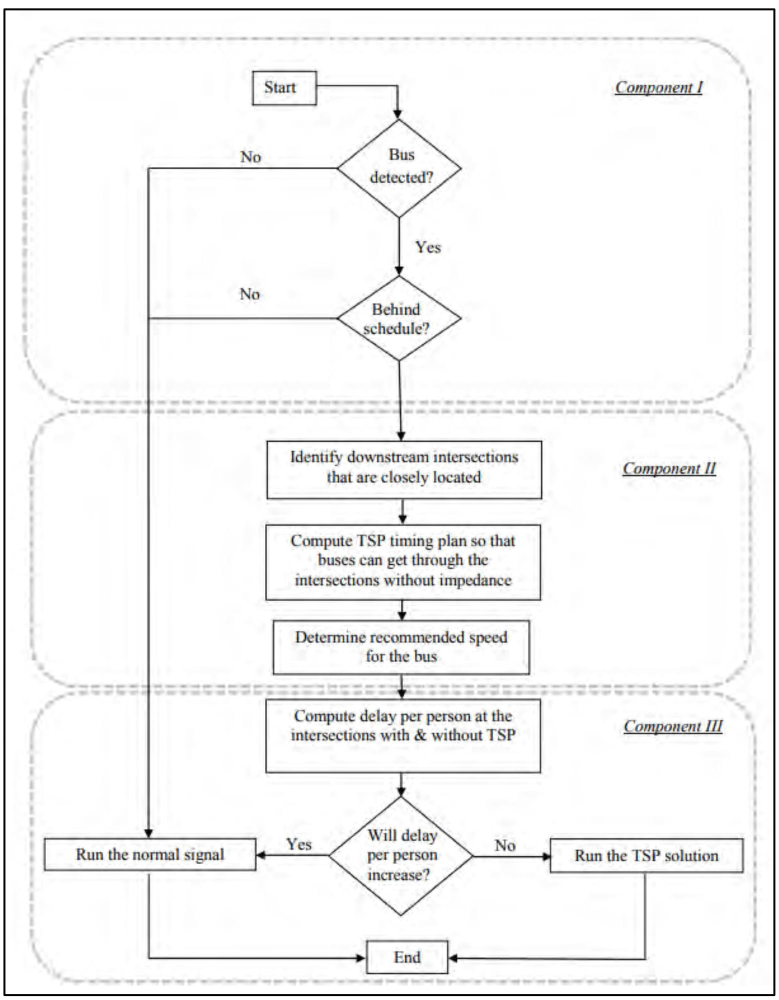


Figure 2-8: Basic concepts of TSPCV-C

Li *et al.* (2011) presented an adaptive TSP optimization model to optimize green splits in a horizon of three consecutive cycles. The dual-ring signal control strategy minimizes the weighted sum of transit vehicle delay and typical traffic delay while considering the safety constraints. They considered the queue and delay due to the TSP plan using deterministic queuing theory. Finally, they used a Mixed Integer Nonlinear Programming (MINLP) model to optimize the green splits. A field study showed that the proposed method reduced bus delay by 43%, although increased passenger car delay by 12%.

He, Head and Ding (2012) presented a Platoon-based Arterial Multi-modal Signal Control with Online Data (PAMSCOD) in a CV environment. First, a platoon recognition algorithm classified moving and queued vehicles in a platoon using CV data. Then, an MILP was formulated to determine phase sequence and timings for four cycles in the future based on the current traffic controller status, traffic conditions, platoon data, and priority requests. However, the signal controller only implemented the signal timing parameters for the first 30 seconds. PAMSCOD required at least a 40% penetration rate to outperform conventional multimodal signal control methods. PAMSCOD reduced the average vehicle and bus delay by 8% and 25%, respectively compared to coordinated-actuated signal timing parameters optimized by SYNCRO.

An integrated multi-modal priority control method was developed by He, Head, and Ding (2014) considering emergency vehicles, transit buses, commercial trucks, and pedestrians in an actuated-coordinated signal controller. An MILP formulation was developed to accommodate multiple priority requests from different modes of vehicles as well as pedestrians to optimize signal timing parameters. This control strategy also proposed a flexible implementation algorithm considering vehicle actuations and signal coordination in real-time. Integration of the MILP formulation with the actuation might result in early phase termination when no vehicle was detected, and extension or termination of a phase to serve a priority request. The proposed method reduced bus delay by 24.9% and pedestrian delay by 14%.

The TSP control framework in Ma, Liu and Yang (2013) used DP to explicitly model green extension, red truncation, and phase insertion with minimal bus delays. Each priority request was weighted by bus occupancy and deviations from the schedule while accommodating multiple requests. Although the model objective did not consider non-transit vehicle delay, the constraints were set to ensure minimal impact of the optimal plan on other vehicles. The formulation used a rolling horizon approach to adapt to the stochastic nature of traffic flow. This proposed method reduced bus delay by up to 30 % compared to fixed time control with no TSP implementations.

Zeng *et al.* (2014) proposed a stochastic mixed-integer TSP model to explicitly model randomness in bus arrival. The proposed model considered the impacts of the priority operation on other traffic streams considering the passenger car queue and minimized the delay to buses caused by signal timing and vehicle queue. The results showed that the proposed strategy reduced the bus delay by 30% compared with conventional ring barrier-controlled TSP in a single-bus case. The proposed method efficiently handled multiple priority requests under congested traffic conditions.

2.5.9. Traffic signal control algorithms

Wireless communication among vehicles and roadside infrastructure allows for more efficient traffic control strategies. High-resolution data from CVs allow traffic signal controllers to respond to changes in arrival rates and saturation flow and distribute green times accordingly. This section provides a brief description of recent studies that use V2I communication for traffic signal control.

As a part of a CV Pooled Fund Study, Smith *et al.* (2010) developed three traffic control strategies using CV data as their primary data source. The three algorithms were:

1- Oversaturated Condition Algorithm,
2- Vehicle Clustering Algorithm, and
3- Predictive Microscopic Simulation Algorithm.

In oversaturated flow conditions, queue spillback from an intersection may cause de-facto red at an upstream intersection. Oversaturated Condition Algorithm (OCA) controlled traffic to address the inefficiencies that result from queue spillbacks and helped the network's speedy return to manageable levels of traffic. This signal control system continuously monitored the queue length using location and speed data from CVs. The green phase of the coordinated approach is either delayed (i.e. late start of green on the main street) or cut short (early cut-off of green on the main street), as dictated by the real-time downstream queue. Available additional time is switched to the opposite direction (side street coordination). The algorithms were evaluated in a simulated network of 2-intersections with one-way streets. Figure 2-9 shows the layout of the OCA signal control strategy.

Secondly, a Vehicle Clustering Algorithm (VCA) was designed for high speed urban arterial streets with low-speed, low-volume side streets. The VCA ensured the clearance of leftover queues and prevented the breakup of vehicle platoons utilizing the shared data from CVs. VCA allocated green to a movement whenever the cumulative waiting time of that movement surpassed a predefined threshold. V2I communications ensured that there is no leftover queue at the end of the green phase. After obtaining the distances of all vehicles in the green-movement, the VCA clustered the vehicles to form a platoon. VCA utilized the speed of vehicles to compute the appropriate green-extension times so that the platoon can cross the intersection without any breakage. Figure 2-10 shows the signal control logic using VCA.

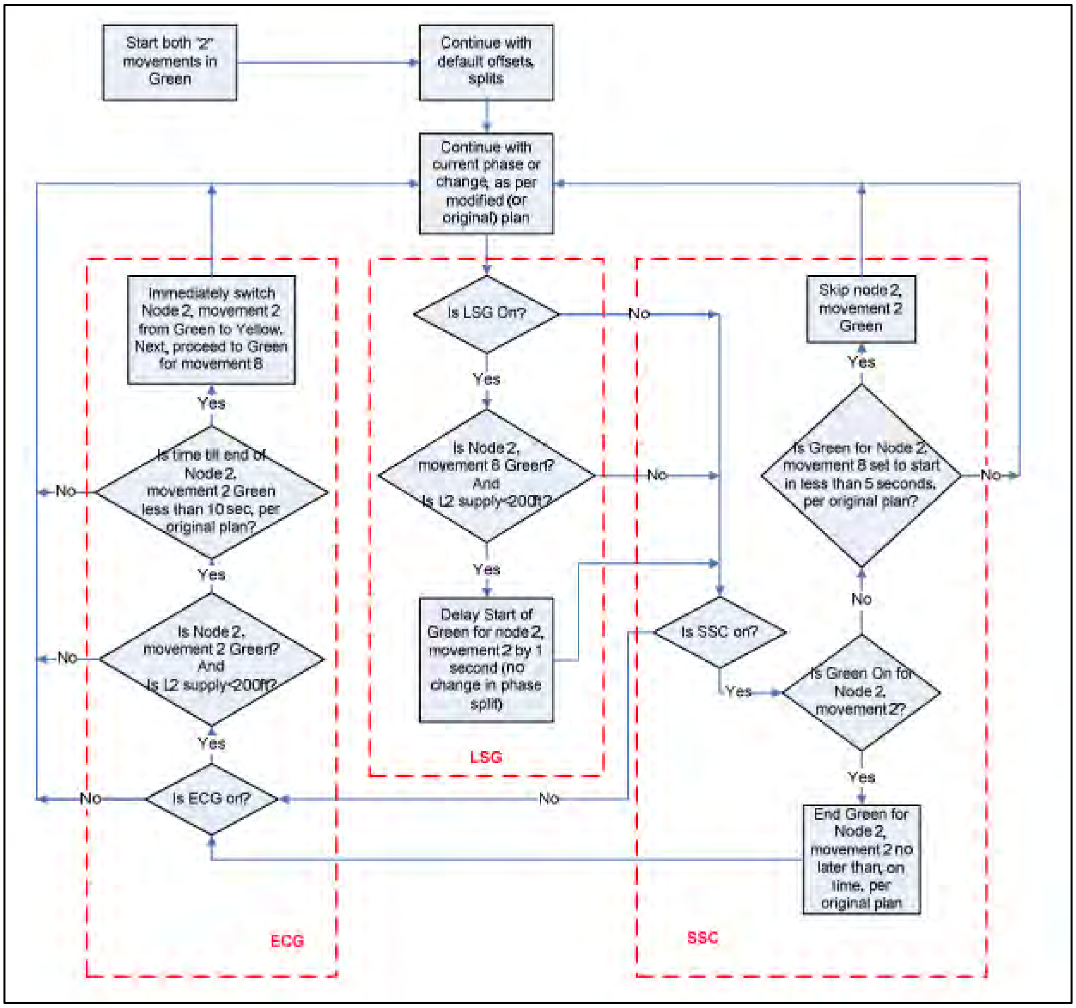


Figure 2-9: Oversaturated Condition Algorithm flow chart to control signal (Smith *et al.*, 2010)

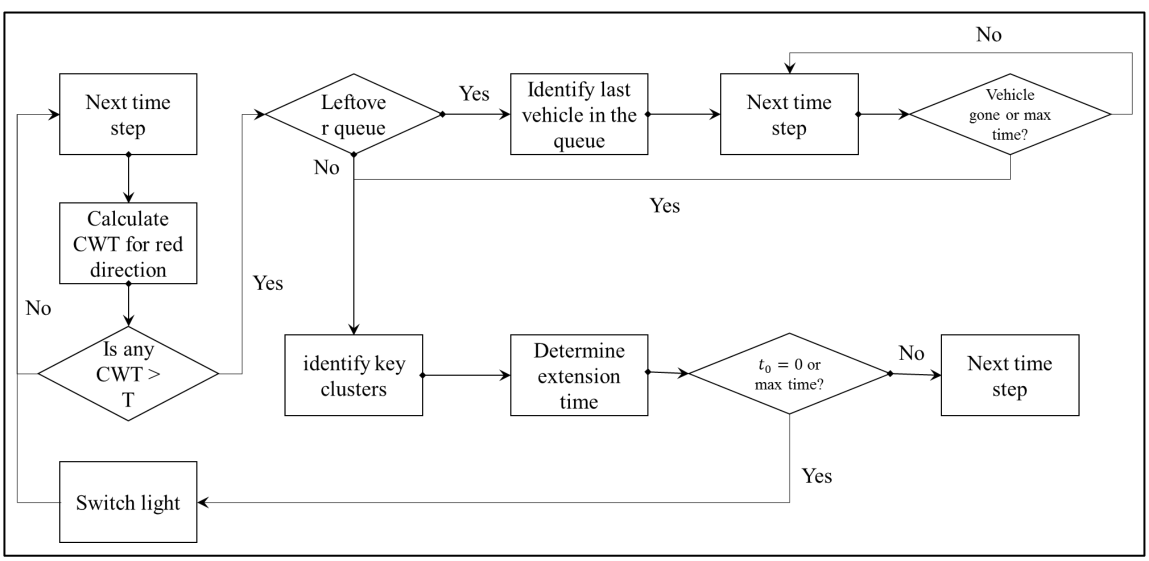


Figure 2-10: Vehicle Clustering Algorithm flowchart (Smith *et al.*, 2010)

Finally, they proposed a Predictive Microscopic Simulation Algorithm (PMSA). PMSA projected the forward movement of vehicles over a horizon in a simulated environment and recorded the cumulative delay of vehicles on each approach. PMSA continuously monitored the queue length in turning lanes to ensure no blockage in the movement of through vehicles occurred. Any movement with vehicles waiting over a certain threshold was given the highest priority to be served in the next phase. PMSA selected the phase sequence and length to minimize the predicted delays. The PMSA was tested using a microscopic simulation of a four-intersection corridor along US Route 50 in Northern Virginia. According to simulation analysis, the delay was reduced by more than 6% when the penetration rate reached 50%. However, to get the full benefit of PMSA, the network should have more than a 25% CV market penetration rate. Figure 2-11 shows an overview of the logic of the PMSA.

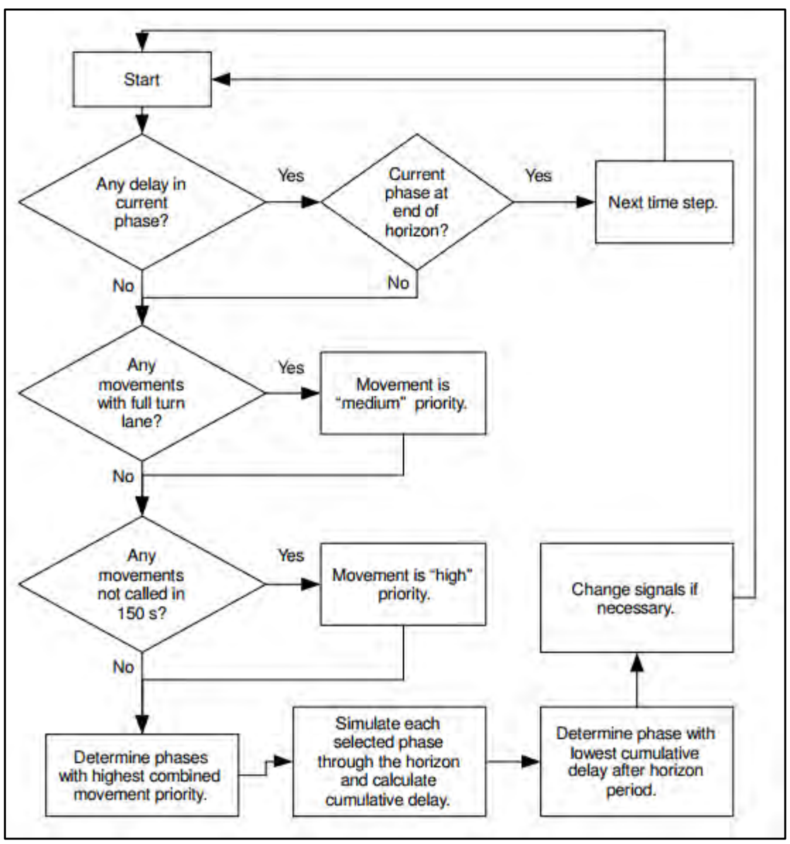


Figure 2-11: Predictive Microscopic Simulation Algorithm flow chart

Kari, Wu and Barth (2016) proposed an optimal signal control strategy considering two types of agents: Vehicle Agents (VA), and an Intersection Management Agent (IMA). The intersection management agent controlled the traffic signal based on received information from all VAs within the communication range of the intersection. The IMA made use of several signal timing constraints including minimum green time, maximum green time, yellow time, as well as the "all-red" duration to change the green phase. The decision-making flow chart of IMA is presented in Figure 2-12.

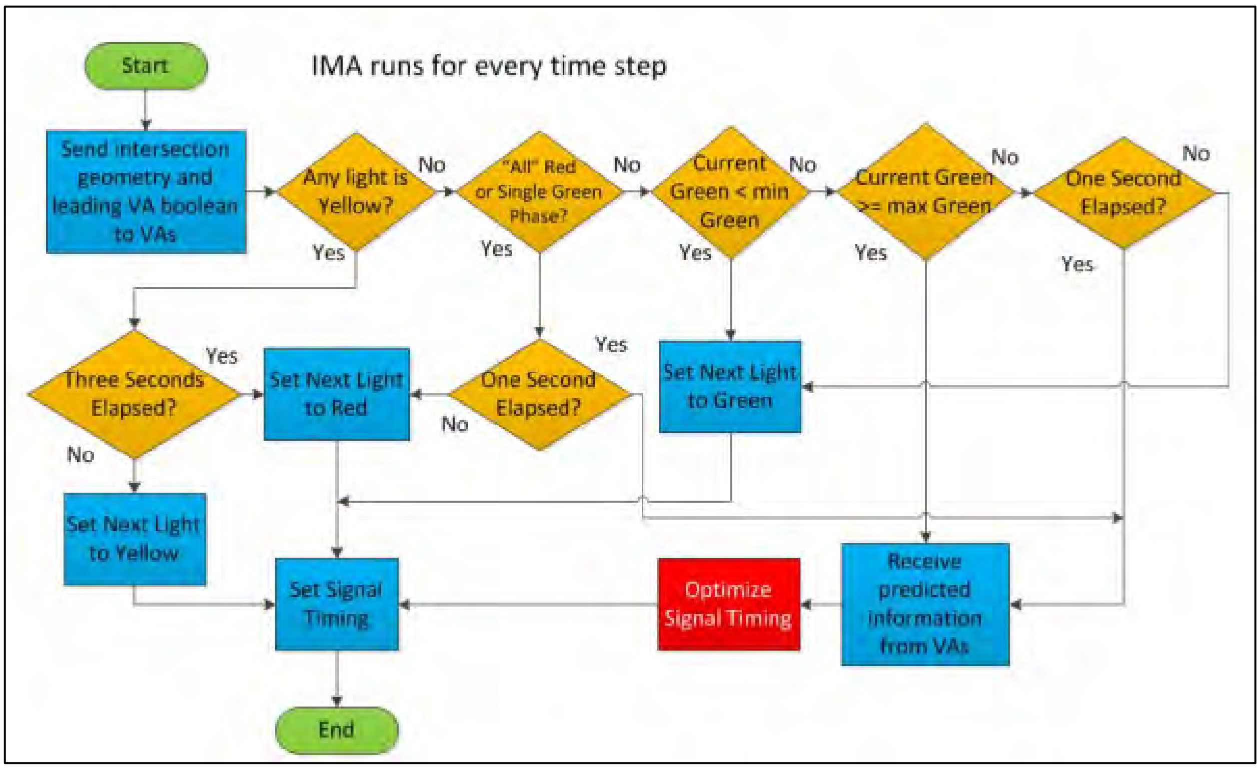


Figure 2-12: Decision-making flowchart of IMA (Kari, Wu and Barth, 2016)

The queue length optimizer of IMA determined the queue length for each movement and allocated the green signal to the phase with maximum combined queue length. The queue length optimizer maximized the number of processed vehicles within a green light at the intersection. The control logic is presented in Figure 2-13. For isolated intersections, the proposed algorithm reduced the average travel time up to 33%, and average energy consumption by 15% compared to a fixtimed signal control strategy. For a three-intersection corridor, the proposed methodology reduced the average travel time and average energy by 19% and 8%, respectively compared to the coordinated fixed-time signal timing strategy. However, this signal control system can only handle moderate demand levels.

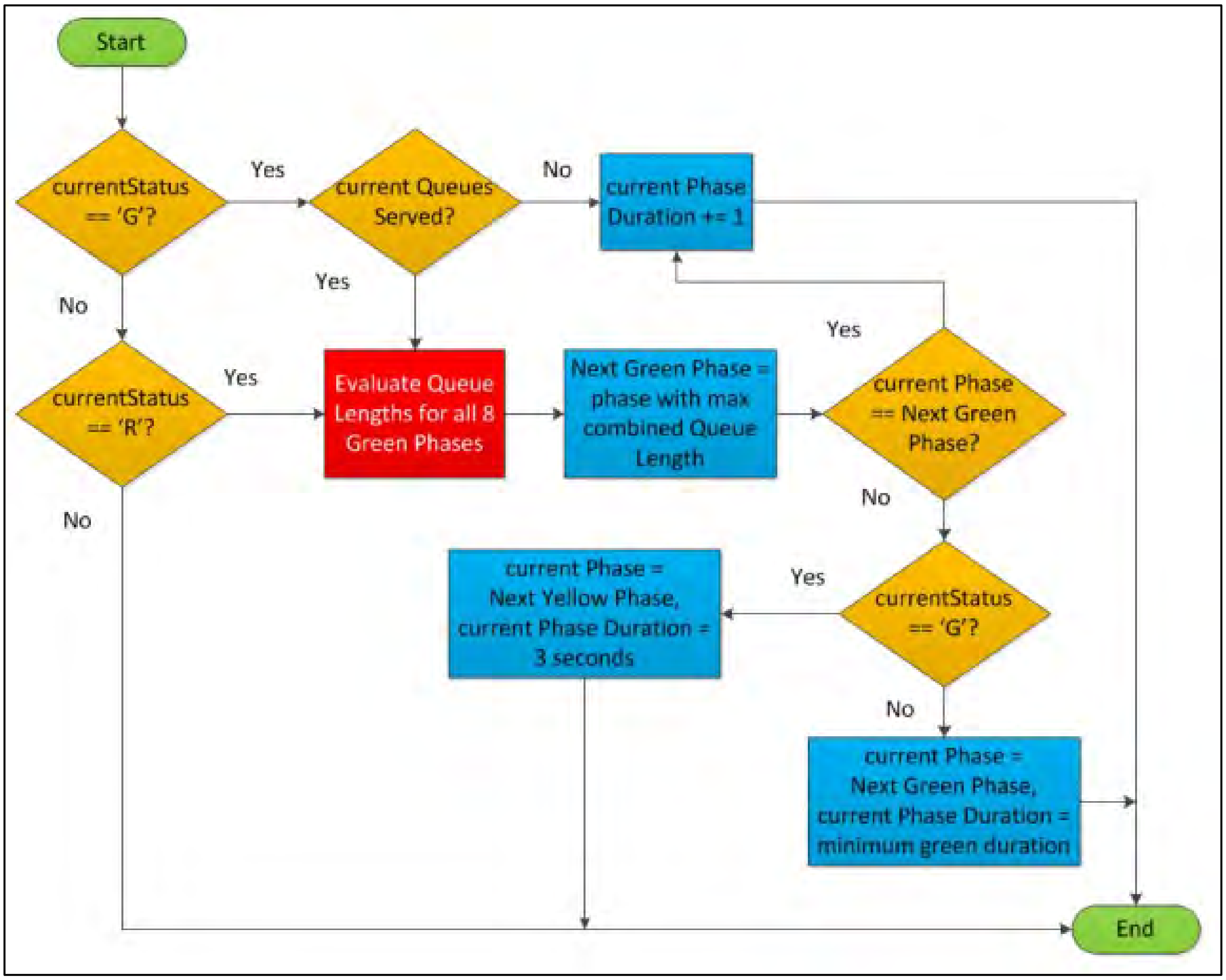


Figure 2-13: Queue Length Signal Optimizer (Kari, Wu and Barth, 2016)

The Cumulative Travel-time Responsive (CTR) control algorithm, proposed by Lee, Park and Yun (2013) determined the travel time of all the vehicles to the intersection from neighboring intersections. CTR allocated the green signal to the phase with the highest cumulative travel time (CTT). Besides, the CTR algorithm decided whether the current green time should be continued, and updated traffic signals every five seconds. At a low penetration rate, CTT for each phase was estimated based on a Standard Kalman Filter (SKF) and an Adaptive Kalman Filter (AKF) using available CVs, the number of vehicles approaching an intersection, signal status, and road geometry over time. The integration of the proposed algorithm in the traffic control system helped reduce the required CV market shares to outperform an actuated signal control from 70% to 30% for a CTR signal control system. Figure 2-14 shows the flow chart of the CTR algorithm.

An existing intersection with the CV testbed in Virginia, USA, was simulated in a microscopic traffic simulation model, under the current traffic signal timing plans and volumes of peak and off-peak hours using two CTT estimation techniques, SKF and AKF (Choi *et al.*, 2016). The CTR algorithm improved mobility in comparison with actuated traffic signal control when the CV market penetration rate exceeded 30% and 20% with the SKF and AKF methods, respectively. They recommended the use of CTR at high demand with 50% to 60% market penetration rates.

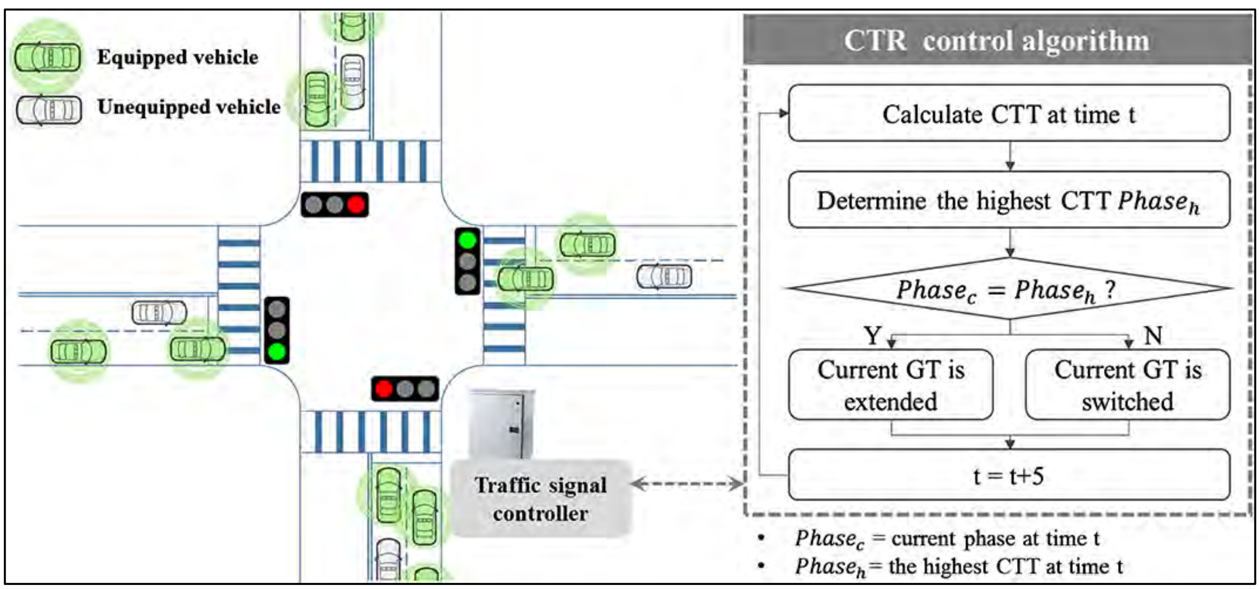


Figure 2-14: Concept of the cumulative travel-time responsive algorithm (Choi *et al.*, 2016)**.**

Priemer and Friedrich (2009) developed a decentralized adaptive traffic signal control algorithm in a CV environment. The algorithm minimized the total queue length in every five-second interval based on a simulated horizon of 20 seconds using DP and complete enumeration of all the possible states. The proposed algorithm required at least 33% CV market share to outperform signal control optimized in TRANSYT-7F (Wallace *et al.*, 1984). Furthermore, they integrated a queue length estimation algorithm developed in Priemer and Friedrich (2008) into the signal control systems in low CV penetration rates. As such, the required CV market penetration rate to outperform an actuated coordinated signal control system was reduced to 20% from 33%.

Goodall and Park (2013) proposed a rolling horizon based on PMSA based on cumulative vehicle delay. PMSA divided the network into individual intersections and controlled them separately in a CV environment. The algorithm collected CV data continuously from a real-world network and imported the information to a microscopic simulation. Next, the proposed solution technique predicted the future traffic conditions through simulation in a rolling horizon of 15 seconds and calculated the objective function value directly from the simulation results. The objective function could be either delay or a combination of delay, stops, and deceleration rates. At low and medium traffic volumes, PMSA performed better than the conventional system; however, it did not perform well in saturated and oversaturated conditions. To estimate traffic state in low CV market shares, Goodall, Smith and Park (2016) presented two algorithms (one for freeway facilities and the other for arterial streets) to estimate the positions of UVs based on the car-following model and CV data. This algorithm compared the expected driving behavior of a pair of CVs based on a Car-following model with the real-time CV data. The algorithm anticipated the presence of UVs between a pair of CVs based on the deviation of actual to estimation driving behavior. However, the integration of the proposed location estimation of UVs in signal control developed in Goodall, Smith, and Park (2013) showed poor performances at more than 50% CV market shares compared to the signal control without predicting UV locations.

Chang and Park (2013) proposed a real-time traffic control system based on inter-vehicle communications in Vehicular Ad-hoc NETworks (VANETs). At first, the platoon leader in a lane estimated the queue length using vehicle to vehicle (V2V) communication and transmitted it to the signal controller. Next, an algorithm was proposed to estimate cycle length based on the estimated queue length. Phase durations and green splits were assigned proportionally to the number of vehicles in each direction. The proposed algorithm showed improved performance compared to the random and best-first control methods.

The adaptive traffic signal control presented in Maslekar *et al.* (2013) utilized V2V and V2I communications. This paper proposed two algorithms to cluster the vehicles approaching an intersection. Based on the estimated density, the signal controller estimated an adaptive cycle time, green times, and inter-green intervals (i.e., yellow and red intervals between two consecutive green signals) for different phases using a modified Webster's model. The simulation results showed that the proposed control strategy improved the average waiting time and the number of stops at each road intersection.

Feng, Khoshmagham, and Zamanipour (2015) presented a real-time adaptive signal phase allocation algorithm in a CV environment. Next, they optimized signal phase sequences and timings using the estimated vehicle arrival time. Their algorithm applied a forward and a backward recursion. The forward recursion optimized the phase duration and calculated the value of the optimal function. Next, the backward recursion recovered the optimal signal policy starting from the result of forward recursion. They also minimized the total vehicle delay and queue length. The simulation results showed that the proposed algorithm reduced the total delay significantly under high penetration rates and was comparable to actuated control under low penetration rates.

To estimate the arrival time of UVs at low penetration rates based on CV data, Feng, Khoshmagham, and Zamanipour (2015) further modified the simulation-based approach presented in Goodall, Smith and Park (2016) by dividing the approaching link of an intersection into three regions: queuing region, slow-down region, and free-flow region. At the queue region, the position of the last stopped CV was used to estimate queue length, where the position of UVs in the slow-down region was estimated based on the same concept in Goodall, Smith and Park (2016). As such, the proposed algorithm outperformed current actuated coordinated signal control at 25% CV market share. Simulation-based estimation of vehicle location may not be real-time as it requires a parallel simulated network to be updated over time. Furthermore, it depends on the number of the vehicle in the system. Therefore, the simulation is computationally expensive, especially under high demand conditions.

Islam and Hajbabaie (2017) presented a distributed-coordinated methodology for signal timing optimization in connected urban street networks. They divided the network into intersections, where a mathematical program found the optimal timing by maximizing intersection throughput while penalizing for long queue length on different approaches. Furthermore, the distributed mathematical programs continuously coordinated with each other to avoid finding locally optimal solutions and to move towards global optimality. To account for unforeseen changes in traffic demand and capacity, the timing of signalized intersections was optimized for several time steps; however, only the decisions on terminating or extending green signals for the next time step were implemented. The proposed algorithm was real-time and scalable. The simulation demonstrates that the proposed algorithm could increase the intersection throughput between 1% and 5%, and decrease the travel time between 17% and 48%, compared to actuated-coordinated signals optimized by Vistro (PTV, 2014).

Mohebifard and Hajbabaie (2018) estimated the density of UVs over an approaching link considering a similar distribution of CVs to determine the traffic state at low CV market shares. They determined CV distributions from the shared information of CVs with a signal controller. They reduced delay in the network by 22% reduction while metering traffic at the gate of the network at 40% CV market shares, which may not be achievable in near future. Most importantly, the assumption of similar distribution could be misleading as the vehicle generation process is completely random. As such, Mohebifard, Islam, and Hajbabaie (2019) dynamically prioritize more on the distribution of CVs in high market share. The result showed that the required CV market penetration rate for cooperative signal timing and traffic metering in urban street networks was reduced to 20% from 40% to outperform conventional signal control systems.

Day and Bullock (2016) utilized vehicle arrival patterns by aggregating CV and detector data to optimize offsets for arterial signals in a CV environment. The results showed that accurate vehicle arrival patterns can be achievable for offline offset optimization at less than 1% CV market shares and real-time optimization within 15-minute periods at more than 5% CV penetration rates.

Tiaprasert *et al.* (2015) utilized historical data to estimate queue length for operating an adaptive signalized intersection under low CV market share. The CV market penetration rate was an input to the methodology based on which, queue length was estimated. Feng, Zheng, and Liu (2018) proposed several delay estimation models assuming a Poisson distribution of vehicle arrivals based on the information received from CVs. Comert (2016) estimated queue length analytically for a pre-timed signal control system using CV data. The proposed method could be used to evaluate the performance of the signal controller in real-time; however, it may not be applicable for optimizing signal timings. Beak, Head, and Feng, (2017); He, Head, and Ding, (2012); and

Tiaprasert, Zhang, and Ye (2019) detected incoming platoon, their size and arrival time using CV data to optimize the timings of an isolated intersection.

2.6. Safety-related applications of the CV technology

The outcomes of several research activities show that the CV technology can enhance safety as it offers drivers a 360-degree awareness around the vehicle. USDOT funded the CV Safety Pilot Research Program to test the safety effects of CVs (Schagrin, 2011). The goal of this project was to determine the efficiency of CV technology in reducing crashes and evaluate the effects of safety-related features on driving. The first phase of the project was a preparation for large scale field testing and carried out by Crash Avoidance Metrics Partnership in six locations in the US: Brooklyn, MI; Brainerd, MN; Orlando, FL; Blacksburg, VA; and Alameda, CA. More than 112 regular drivers and 24 CVs per location were tested over four days. Several safety-related applications of the CV technology including emergency electronic brake lights, forward collision warning, blind-spot warning/lane change warning, do not pass warning, intersection movement assist, and left turn assist were tested (Ahmed-Zaid *et al.*, 2011).

After the completion of the small scale test, the project began its second phase for a field test in Ann Arbor, MI (Bezzina and Sayer, 2014). Over 2,800 equipped vehicles were tested in a 73 lane-miles roadway with 29 equipped sites over one year. This was the first real-world large scale demonstration of CV. The data collected from this study have provided the factual evidence needed to support the efforts to further develop and deploy CV technologies. Throughout the project, the research team tested the effectiveness of different V2V and V2I related safety applications. In addition, the model deployment showcased some non-safety applications like the TSP, roadway maintenance application, and broadcasting the SPaT message. All the collected data are stored for further research in this field. After the successful completion of this project, state and federal level agencies have funded safety-related applications of CV technology. This section will briefly present some of the safety-related features of CVs.

2.6.1. Safety in snowplow operations

To increase the productivity of snowplow operations, several snow plow vehicles work side by side to clear the road at a time. This process is known as gang plow. However, the gang snow plow impairs visibility for other vehicles following the gang. As a result, it increases the probability of crashes. Alexander, Gorjestani and Shankwitz (2005) proposed the transmission of a warning message to the vehicles following the gang plow with the objective of making snow plowing safer. The leading snow plow continuously passes its position and speed to the following snow plows using V2V technology. The OBUs of the following snow plows determine the desired position of the snowplow. This information is then used to warn the following snowplow. Besides, for the smooth operation of snowplows, the gang requires an uninterrupted flow throughout the network. The snowplow can send a priority request to the signal controller for green extension or early green termination at the conflicting movements to navigate smoothly through the network.

2.6.2. Work zone safety

As a part of the Minnesota CV Pilot Deployment Project (Cregger, Brugeman and Wallace, 2013), MnDOT is expected to improve work zone safety by identifying and providing in-vehicle warnings to all approaching vehicles. This application will broadcast the position of active work zones using mobile applications. This project is expected to finish by 2018.

Stephens et al. (2013) described the concept of the Reduced Speed Zone Warning application. This system will alert high-speed vehicles to reduce their speed via V2I communications. Furthermore, the application broadcasts the configuration of the road to reduce the probability of crashes.

2.7. Transit vehicle operation

CV technology not only improves the transit vehicles operations using TSP but also enhances their safety. To reduce the probability of crashes with transit vehicles, under Minnesota CV Pilot Deployment Project (Cregger, Brugeman and Wallace, 2013), transit buses will warn the nearest vehicles when approaching them from behind and also at the moment of merging to other traffic lanes via DSRC. Another application will meter vehicles on ramps while a transit bus approaches the metering area. An RSU should be installed in the metering area to detect the approaching transit vehicles. The transit vehicles will request the controller to restrict the metering while they approach the ramp. This will reduce the probability of crashes between transit buses and vehicles entering the freeway from the entrance (Cregger, Brugeman and Wallace, 2013).

2.7.1. Curve speed warning application

The Curve Speed Warning safety application helps drivers navigate through horizontal curves using V2I communications. Based on the current road and weather conditions, the infrastructure estimates the safe speed (Stephens *et al.*, 2012; Christopher J. Hill, 2013) for the curve. This application issues a warning to the vehicle speeding over the safe speed. As a result, it will reduce the probability of losing vehicle control, run-off crashes, and roll-over events.

2.7.2. Oversize vehicle warning

Stephens *et al.* (2013) suggested this application to warn the drivers of oversized vehicles about the restricted clearances ahead. In a CV environment, an RSU detects the size of a vehicle based on the received BSM and compares it with the available clearance. The RSU will warn vehicles that do not meet the clearance needs.

2.7.3. Pedestrian in signalized crosswalk warning

This application alerts the drivers about pedestrians crossing a signalized intersection who are in the intended path of a vehicle (Stephens *et al.*, 2013; Burt *et al.*, 2014).

2.7.4. Railroad crossing warning application

About every three hours, a person or vehicle is hit by a train in the United States (Stephens *et al.*, 2013). As a result, the objective of this application is to reduce railroad crossing crashes (Stephens *et al.*, 2013). Using the V2I communication, the system helps the driver to navigate through the railroad. The system alerts the driver about a crash-imminent situation if the trajectory of any vehicle conflicts with the approaching train in the crossing.

2.7.5. Applications with V2V communications

CVs are designed to improve drivers' situational awareness as well as to reduce the probability of crashes in imminent situations. This section briefly describes some of the applications that improve safety using V2V communication.

1. Blind Spot/Lane Change Warning: this application warns the driver about the presence of any vehicle in the blind spot of the vehicle (Ahmed-Zaid *et al.*, 2011; National Highway Traffic Safety Administration, 2011; Sumner, Eisenhart and Baker, 2013).
2. Control Loss Warning: If an equipped vehicle losses its control, it will broadcast a self-generated message to warn all vehicles that are within the communication range (Ahmed-Zaid *et al.*, 2011).
3. Do Not Pass Warning: this application alerts the following vehicle before making a passing maneuver about the potential head-on collision situation (Ahmed-Zaid *et al.*, 2011; National Highway Traffic Safety Administration, 2011; Harding *et al.*, 2014).

4. Tailgating advisory: This application warns a driver if the vehicle follows` too closely (Sumner, Eisenhart and Baker, 2013).

2.8. Other applications of CV technology

2.8.1. Using the High Occupancy Vehicle (HOV) lane

MnDOT has implemented MnPass that allows single-occupant vehicles to use high occupancy lanes without turning entire roadways into toll roads. As the vehicle enters the HOV, RSU detects the vehicle and debits a fee from the driver's account depending on the current traffic flow condition. To receive the service, a transponder should be placed in the vehicle. After implementing MnPASS, single-occupant vehicles make up to 29% of the total vehicles in the HOV lane (Cregger, Brugeman and Wallace, 2013).

2.8.2. Weather-related application

The National Center for Atmospheric Research (NCAR) in Boulder, CO has been conducting research on using CV data to document real-time weather conditions (Synesis Partners LLC, 2015). The goal of this research is to utilize CV data to retrieve weather-related data. The projects at NCAR involves using collected data to determine the current road conditions as well as forecasting the future road conditions. After analyzing the weather data, the system will issue warnings to drivers about hazardous conditions.

2.9. Literature review summary

AASHTO have challenged all the state and local transportation agencies to deploy DSRC systems to broadcast SPaT message in a corridor of at least twenty intersections by 2020. Although AASHTO sets the minimum goal to broadcast SPaT message, it encourages State DOTs to deploy more complex CV applications. AASHTO predicts that all transportation agencies that participate in this challenge will gain hands-on experience, which will help them deploy more complex applications of CV in near future. In the long run, it is expected that this challenge will yield a national level uniformity in the deployment of CV infrastructure. To implement CV technology, traffic signal controllers require certain hardware and/or software to broadcast SPaT messages to approaching CV in a readable format with MAP and RTCM. The messages can be broadcasted either by installing DSRC with SPaT data translation facility or installing an open-source software in signal controllers.

The NOCoE provided initial site selection guidelines based on the (a) infrastructure requirements and (b) needs. Corridors with high traffic volume, frequent emergency vehicles, proximity to major business centers, and need for TSP are the preliminary selection criteria. The selected intersections should have good GPS coverage, available ports, and cabling capability in signal controllers.

Safety-related applications of SPaT message includes: stop violation warning, stop sign assist, signalized left turn assist, traffic signal adaptation, and VRU warning. These applications help reduce the likelihood of crashes by offering enhanced driver awareness about their surroundings. Similarly, traffic operation related applications that are presented in this report are eco-driving, intelligent traffic signal control, TSP, and multimodal signal control. These applications help improve network performances by reducing travel time, delay, emission, and fuel consumption.

3. Transportation Agency Survey

This chapter summarizes the outcomes of a short survey that was distributed between state transportation agencies that have either implemented or are planning to implement DSRC in traffic controllers according to the NOCoE website. The research team accessed this website in July 2018. Based on the available data, eleven cities (in nine states) had already deployed SPaT broadcasts in their corridors while the deployment in seventeen cities (in thirteen states) was underway. The research team contacted twenty-one DOTs with a list of seven questions as follows:

1. What are the reasons that led to selecting the corridor for DSRC deployment?
2. What type and brand of signal controller is used in the corridor?
3. What types of equipment and software are used in the signal controllers?
4. Is transit signal priority included?
5. Which connected vehicle applications will be included in the corridor?
6. What was the traffic demand level? High, moderate, or low?
7. Is there a map of the corridor that you can share?

The research team received responses from nine State DOTs and compiled them in this report. The research team reviewed published reports and websites that included some information about the other state DOTs that did not respond to the questions. In the remainder of this section, survey results for the operational SPaT deployment projects are summarized and are followed by presenting the results for the planned and ongoing projects.

3.1. Locations with operational SPaT deployment

SPaT message in addition to other CV applications has been operational as a part of the challenge in eleven cities in nine states: Arizona, California, Pennsylvania, Utah, Virginia, Georgia, Florida, North Carolina, and Michigan. Figure 3-1 illustrates the location of the corridors with completed deployment at that time. A summary of the survey findings in each state will follow.

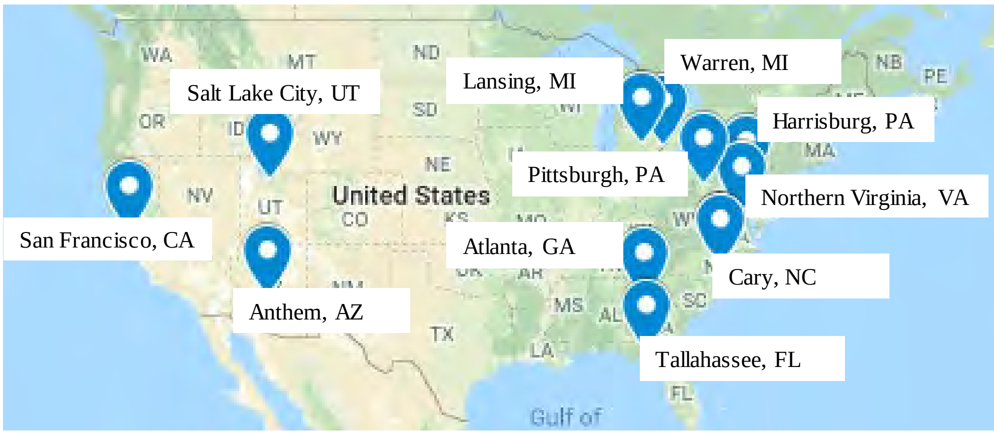


Figure 3-1: Location of the corridors with SPaT broadcast operations in 2018

3.1.1. Maricopa County, AZ

Eleven intersections are equipped with the CV technology to broadcast SPaT information in Maricopa County, AZ (see Figure 3-1). All eleven traffic signals are controlled by the MMITSS algorithm. All intersections utilize Econolite ACS3 signal controllers where a Savari RSU is directly connected to the controller and receives BSM from CVs. Table 3-1 describes the features of the SPaT deployment site and Figure 3-1 illustrates the locations of the intersections in the corridor. Besides, five other intersections are planned to be equipped with RSUs in the highway ramps.

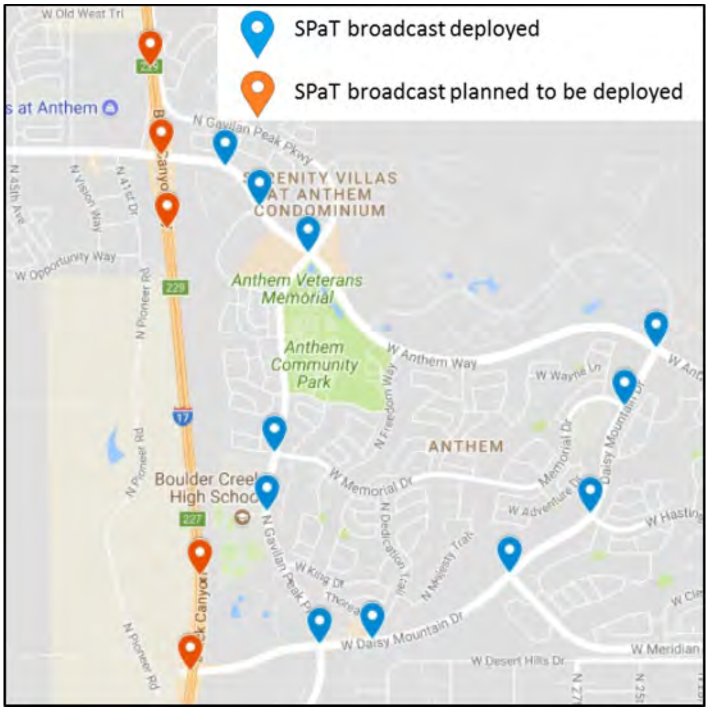


Figure 3-2 Intersections equipped with RSU in Anthem, AZ

Table 3-1: Description of the Anthem, AZ corridors with SPaT deployment

Location	Maricopa County, Arizona
Number of Intersections	11
Number of Corridors	2
Length	Corridor 1: 1.93 miles with six signalized intersections Corridor 2: 2.38 miles with five signalized intersections (planned)
Signal Controller Type	Econolite ACS3
RSU Type	Savari
System Architecture	Savari RSU is directly connected with Econolite controller
Signal Control System	MMITSS
CV Application	SPaT broadcast

3.1.2. Palo Alto, CA

Under a CV pooled funded study, eleven intersections along a 2.1-mile corridor in the city of Palo Alto, CA were equipped with RSUs. This corridor has an Average Daily Traffic (ADT) of more than 50,000 vehicles. All intersections are controlled using the MMITSS application and are equipped with Caltrans 2070 controllers with a Caltrans developed firmware called TSCP 2.10 that broadcasts SPaT message and receives BSM from CVs. Eco-driving application is planned to be included in the corridor. Table 3-2 describes the features of this site. In addition to the eleven signalized intersections that are already equipped with RSUs, five more intersections are planned to be equipped with RSUs on highway ramps.

Caltrans indicated that closeness to automotive research and development centers and Silicon Valley technology companies and high traffic volume on the corridors were the selection criteria.

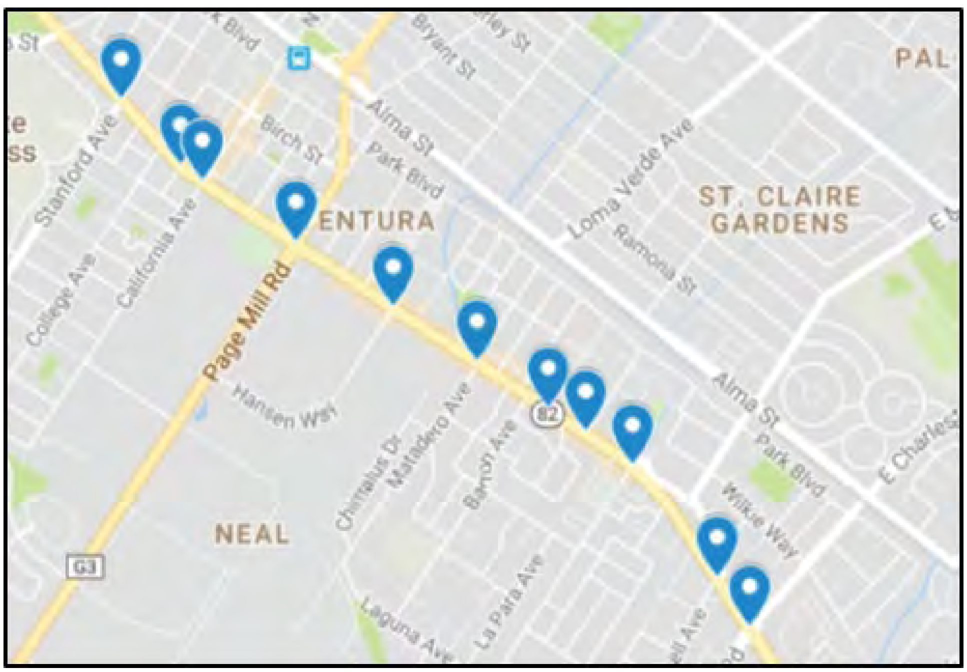


Figure 3-3 Intersections equipped with RSU in San Francisco, CA

Table 3-2: Description of the San Francisco, CA corridor with SPaT deployment

Location	The city of Palo Alto on State Highway 82, CA
Number of Intersections	11
Length	2.1 mile
Signal Controller Type	Caltrans 2070 controller
RSU Type	N/A
System Architecture	The controllers run a Caltrans developed firmware called TSCP 2.10 and they use the AB3418 protocol (not NTCIP)
Signal Control System	MMITSS traffic and priority control algorithm based on actuated traffic signals Transit signal control
CV Application	SPaT broadcast Eco-driving application will be deployed soon
Reasons for Selecting the Corridor	Closeness to Automotive R&D centers and Silicon Valley tech companies. Parallel to busy US-101 corridor.
Traffic Flow Level	High (ADT > 50000)
Pedestrian Flow	Moderate

3.1.3. Pennsylvania

Four corridors in Pennsylvania broadcast SPaT message, see Figure 3-4. There is no additional CV application; however, the TSP application will be deployed very soon in Pittsburgh. The corridor in Pittsburgh is 1.9 miles and has 24 signalized intersections. The intersections are equipped with SURTRAC signal controllers and Arada RSUs. The second corridor is 2.6 miles and consists of 11 signalized intersections. The intersections are equipped with Econolite Cobalt signal controllers and Arada RSUs. The third corridor is located in Cranberry Township and is 3 miles with 11 signalized intersections. SURTRAC signal controllers are used at each intersection with Arada RSUs. Finally, the last corridor is in Harrisburg with 8 signalized intersections. The number of signalized intersections was not available at this site. McCain ATC eX signal controllers are used at these intersections with Arada RSUs. The selection criteria for this site were not shared with the research team. Table 3-3 provides a summary of the gathered information in these four corridors.

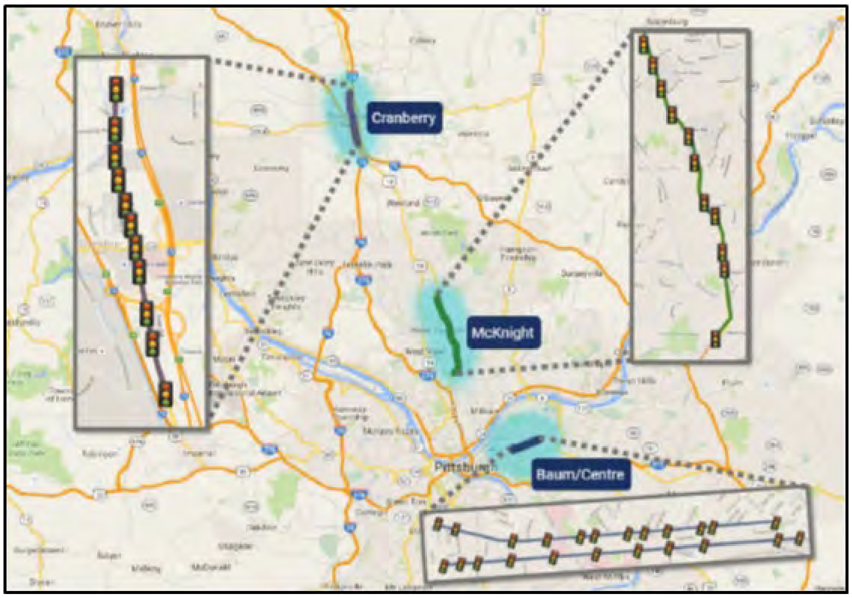


Figure 3-4 Intersections equipped with RSU in Pennsylvania

Table 3-3: Description of the corridors in Pennsylvania with SPaT deployment

Location	Pittsburgh	Ross Township	Cranberry Township	Harrisburg
Number of Intersections	24	11	11	8
Length	1.9	2.6	3	NA
Traffic Controller Type	SURTRAC software (Okonkwo and Gong, 2014)	Econolite Cobalt	SURTRAC software	McCain ATC eX
RSU Type	Arada RSU	Arada RSU	Arada RSU	Arada RSU
CV Application	SPaT broadcast	SPaT broadcast	SPaT broadcast	SPaT broadcast

3.1.4. Salt Lake City, UT

Utah Department of Transportation (UDOT) equipped 30 signalized intersections with DSRCs along the Redwood Road corridor. This corridor is 11 miles long and includes five intersections that are not equipped with DSRCs, see Figure 3-5. All signals are connected by fiber cables and managed using Intelight MaxView software at the Traffic Operations Center.

All these controllers continuously send high-resolution data to the traffic operations center for Automated Traffic Signal Performance Metrics System. The corridor is selected for CV project deployment because Utah Transit Authority has had difficulties in maintaining bus schedules and was interested in including the TSP application. All signal controllers are operated using MMITSS application with conditional TSP.

Among the thirty equipped intersections, 26 use Intelight, three use Econolite Cobalt, and one uses Econolite ASC/3 signal controller. Intersections are equipped with a variety of RSUs including Arada, Lear, Cohda, and Savari. The SPaT and MAP messages are broadcasted, and the TSP application is planned. A brief description of these sites is summarized in Table 3-4.

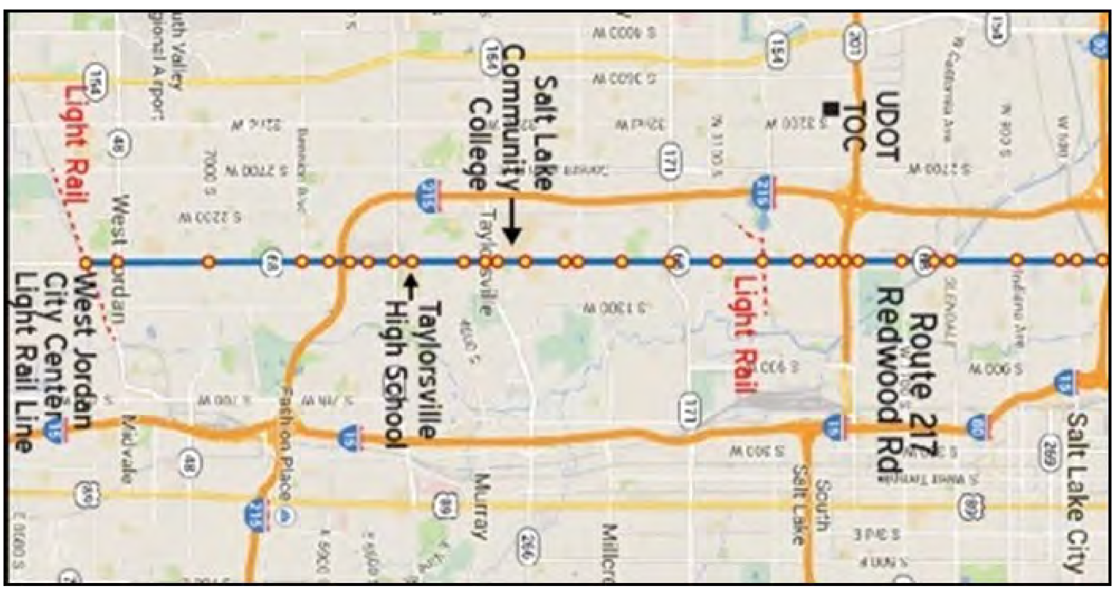


Figure 3-5 Redwood Road DSRC Corridor (Source: UDOT)

Table 3-4: Description of the Redwood Road Corridor, Salt Lake City, UT

Location	Redwood Road, a north-south arterial corridor in the Salt Lake Valley with 5 to 7 lanes.
Number of Intersections	30 signalized intersections out of 35 are equipped with DSRC in the corridor
Length	11 miles
Signal Controller Type	Three Econolite Cobalt One Econolite ASC/3 26 Intelight controllers
RSU Type	Arada (Lear purchased Arada in 2015) (USDOT RSU 3.0 specification) Lear (RSU 4.0/4/1 specification) Cohda (RSU 4.0/4/1 specification), and Savari (RSU 4.0/4/1 specification)
Signal Control System	Actuated coordinated signal control
CV Applications	Broadcasting SPaT and MAP messages A revised version of the MMITSS with conditional TSP Notes: The Utah Transit Authority is installing DSRC OBUs on their buses to request signal priority in case the bus is behind schedule. These buses can send BSM and SRM
Traffic Demand Level	ADT = 18,000 vehicles per day at the north end with mostly residential and light industrial area ADT = 40,000 vehicles per day at the south portion ADT = 60,000 vehicles per day at the point of intersection of Redwood Road with I-215, near the south end of the corridor
Pedestrian Volume	Light throughout the corridor
Land Use	Commercial/Retail Residential High school Community college
Reasons for Selecting the Corridor	The project started as a TSP project as UTA had difficulties in maintaining the bus schedule. The corridor is close to the office of maintenance, so easy to inspect. Good variety of demographics and traffic conditions

3.1.5. Northern Virginia, VA

Thirty intersections are equipped with RSUs in several congested corridors in Northern Virginia, see Figure 3-6. The initial goal is to broadcast the SPaT message. The initiative also broadcasts SPaT data for all signals that the Virginia Department of Transportation (VDOT) controls in Northern Virginia via a data interface to support SPaT data sharing in the absence of a DSRC radio. VDOT stores all the data collected from the corridor in a cloud database to allow further research through a website (URL: http://www.smarterroads.org/). A brief description of this site is presented in Table 3-5.

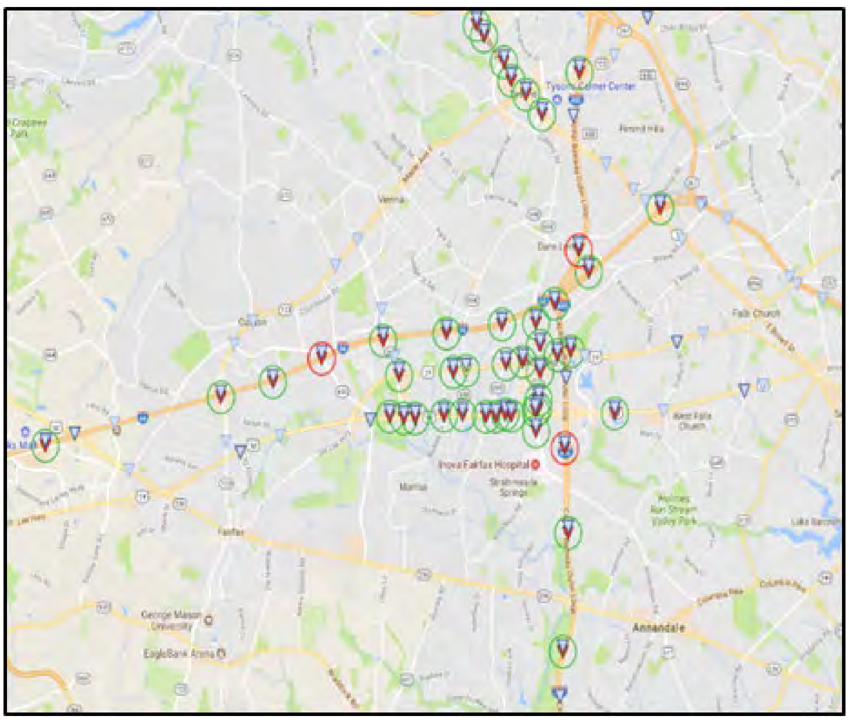


Figure 3-6 Northern Virginia DSRC corridor (source: VDOT)

Table 3-5: Description of Northern Virginia, VA corridor

Location	Northern Virginia - Routes 29, 50, and 7
Number of Intersections	30 intersections
Traffic Controller	MIST

Types of RSU	Cohda
CV Applications	The RSUs are broadcasting SPaT message currently The initial application focuses on demonstrating traffic signal assistance and red-light violation applications
Traffic Demand Level	Congested
Reasons to Select the Corridor	The selected corridor was a part of ongoing CV projects

3.1.6. Atlanta, GA

DSRCs are installed in 54 intersections and 12 freeway ramps along SR 141 from SR 9 to I-285, SR 8 from SR 9 to SR 42, and I-75/85 in downtown Atlanta, GA. Red-light violation warning, pedestrian in crosswalk detection, and eco-driving applications have been implemented initially in addition to SPaT and MAP messages broadcast. Intersections are equipped with CalTrans 2070 signal controllers with Lear RSUs. Favorable existing infrastructure and roadway characteristics were among the factors that led to the selection of the corridor. A brief description of the implementation site in Atlanta, GA is given in Table 3-6.

Table 3-6: Description of the corridors in Atlanta, GA.

Location	SR 141 from SR 9 to I-285, SR 8 from SR 9 to SR 42, I-75/85 in downtown Atlanta, GA.
Number of Intersections	54 signalized intersections and 12 freeway locations (ramp meter signals).
CV Applications	Broadcast SPaT and MAP message Red-light Violation warning Pedestrian in crosswalk, Eco-driving application.
Signal Controller Type	Caltrans 2070
RSU Type	Lear

Reasons for Selecting the Corridor	Favorable existing infrastructure Varied road characteristics for a wide variety of applications.
Traffic Demand Level	High (40-60k ADT)

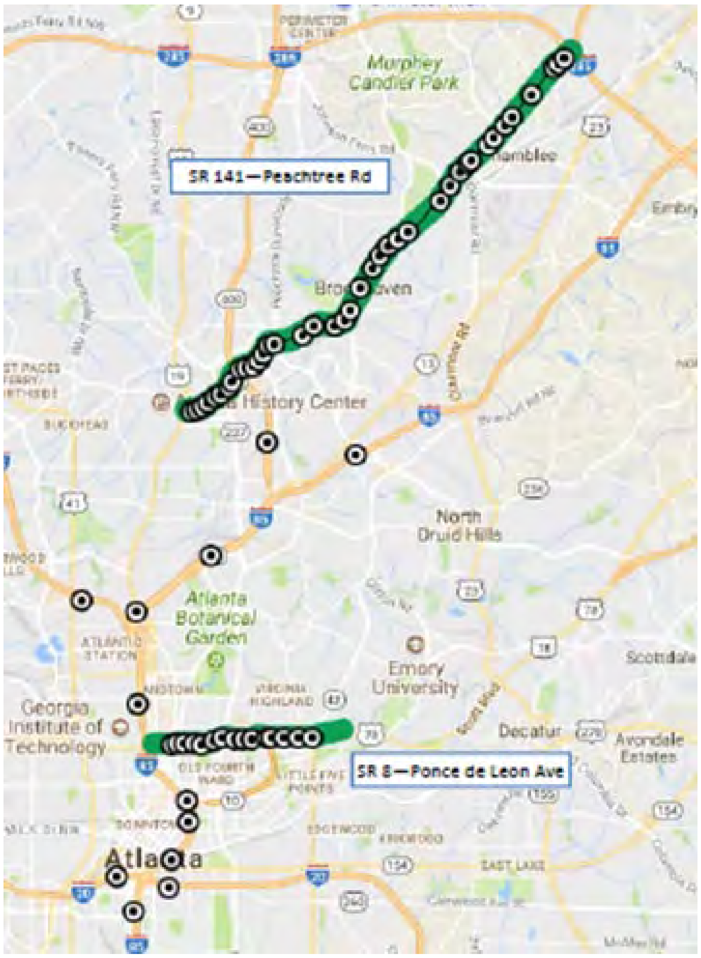


Figure 3-7 Location of Atlanta, GA corridor (Source: GDOT)

3.1.7. Tallahassee, FL

In Tallahassee, FL, 22 signalized intersections on US 90 are equipped with RSUs. Figure 3-8 shows the location of DSRC signalized intersections in the corridor. The RSUs broadcast SPaT messages in addition to MAP data for each individual location. The 5.9 GHz short-range communication is utilized. This project is planned to continue in the future for testing basic safety messages. Table 3-7 provides a summary of the available information at this site.

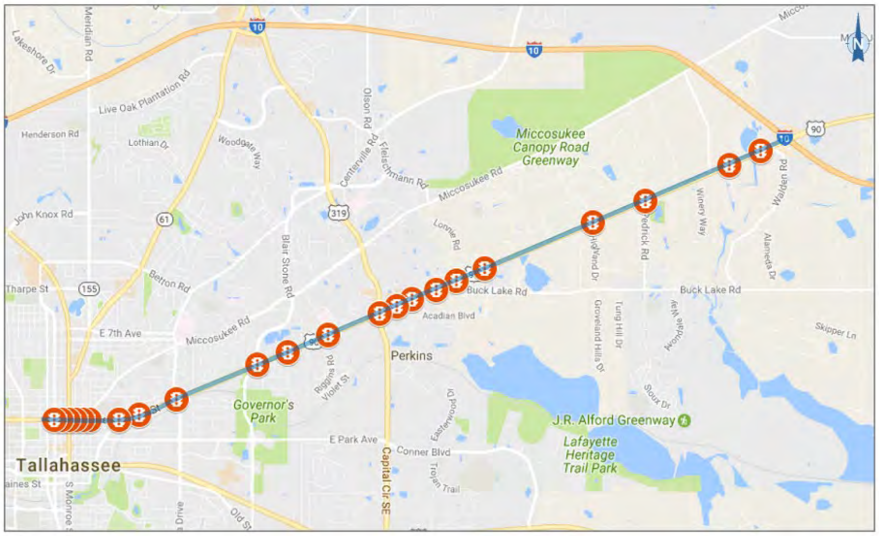


Figure 3-8: Location of equipped signalized intersections in Tallahassee, FL (Source: FDOT)

Table 3-7: Description of the corridors in Tallahassee, FL

Location	US 90 (Mahan Drive) from Duval Street to Interstate-10
Number of Intersections	22 intersections
CV Applications	Broadcast SPaT and MAP message and receive BSM

3.1.8. Cary, NC

More than 20 signalized intersections are equipped with RSUs to broadcast the SPaT message in Cary, NC. Among the selected intersections, 16 intersections are located along NC Highway 55 for the length of 6.6 miles in addition to 4 locations along High House Rd with a length of 1.6 miles. Figure 3-9 shows these sites. North Carolina Department of Transportation (NCDOT) selected this site due to the existing signal equipment, fiber optic communications infrastructure, and central management software. Aegis ITS (Econolite) is selected as the signal controller in this corridor. A brief description of this site is presented in Table 3-8.

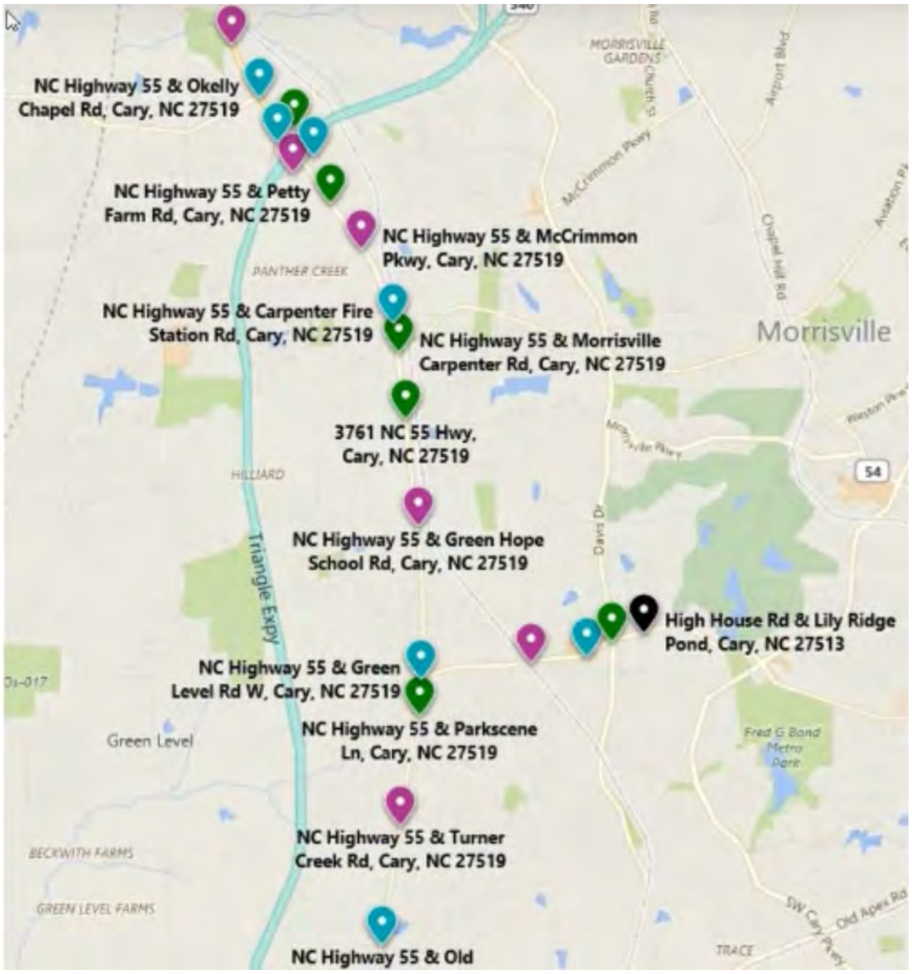


Figure 3-9: Location of equipped signalized intersections in Cary, NC (Source: https://transportationops.org/spatchallenge)

Table 3-8: Description of the corridors in Cary, NC

Location	NC55 Cary, NC
Number of Intersections	More than 20 intersections
CV Applications	Broadcast SPaT message
Traffic Controller	Aegis ITS (Econolite)
Signal Controller Type	Econolite ASC/3
Reasons to Select the Corridor	Existing infrastructure

3.1.9. Michigan

DSRC RSUs are deployed in two corridors in Warren and Lansing, MI. Mound Rd corridor in Warren has two intersections that broadcast SPaT and MAP messages. Besides, nine intersections along a 4.5 miles corridor on M 43 in Lansing broadcast SPAT, MAP, and BSM messages. Table 3-9 provides a brief description of selected sites in Michigan.

Table 3-9: Description of the corridors in Michigan

Location	Warren, MI, and Lansing, MI
Number of Intersections	2 intersections in Warren 9 intersections in Lansing
CV Applications	Broadcast SpaT, MAP, and BSM messages
Traffic Controller	Aegis ITS (Econolite)

3.2. Locations with SpaT Deployment Underway

Seventeen cities in thirteen states have started the SpaT challenge and the deployment is ongoing. Besides broadcasting the SPaT message, some of these corridors are planned to test additional CV applications. Figure 3-10 illustrates the locations of corridors with corresponding CV applications where SPaT deployment is underway in the following states: Ohio, Missouri, Wisconsin, North Carolina, Pennsylvania, New York, Idaho, Colorado, Tennessee, Indiana, Minnesota, New Hampshire, and Delaware. In the remainder of this section, a summary of the survey results for each location will be presented.

Figure 3-10: Location of the corridors with SPaT deployment underway (Source: SPaT challenge website, https://transportationops.org/spatchallenge)

3.2.1. Columbus and Marysville, OH

The SPaT challenge deployments in the City of Columbus and Marysville, OH have been started as an extension of an ongoing fiber cable installation project. There will be no signals along the corridor as it is a divided limited-access highway. There will be RSUs added to signals around Honda's manufacturing facility, to the 27 signals within the City of Marysville, and to several signals in the City of Dublin. This project was expected to be completed in 2018 or early 2019. A brief description of these sites is presented in Table 3-10.

Table 3-10: Description of the corridors in Ohio

Location	City of Columbus Cities of Marysville and Dublin, Union County
Number of Intersections	175 signals in the City of Columbus and intersections in US-33 smart corridors (https://www.33smartcorridor.com/).
CV Applications	City of Columbus: MMITSS, Transit Signal Priority (TSP), Freight Signal Prioritization, pre-emption for emergency vehicles, GPS correction, pedestrian detection Cities of Marysville and Dublin: Adaptive signal control with pre-emption for emergency vehicles
Reasons for Selecting the Corridor	Existing Fiber cables. However, with the Transportation Research Center plans for RSUs were added to improve mobility along the corridor.
Expected Completion	2018 and early 2019

3.2.2. Missouri

Under the SPaT challenge, three corridors in Missouri are considered for CV applications. Ten intersections on each corridor will be equipped with RSUs. The initial goal of the project is to broadcast the SPaT message with MAP and RTCM. A brief description of these sites is given in Table 3-11.

Table 3-11: Description of the corridors in Missouri

Location	Kansas City: US 69 from west of I-435 to Pleasant Valley Rd/Liberty Pkwy Springfield: The entire signalized portions of Sunshine Street and Campbell Avenue St. Louis: Manchester Rd between Lindbergh Blvd and Big Bend Blvd
Number of Intersections	10 intersections in each site
CV Applications	Broadcast SPaT, MAP and RTCM
Expected Completion	2019

3.2.3. Madison, WI

Under the SPaT challenge deployment project, 20 to 30 intersections are expected to be equipped with RSUs to broadcast the SPaT message. The primary purpose of this project is to provide transit signal priority and give priority to busses that are behind schedule. The project is also expected to provide priorities to fire trucks, ambulances, and taxi cabs that frequently use the route. Eventually, CV applications will be developed for vehicle-to-pedestrian and vehicle-to-bicycle communications. This project is expected to be completed by 2021. A brief description is given in Table 3-12.

Table 3-12: Description of the corridors in Madison, WI

Location	Park Street from University Avenue to Beltline Freeway
Number of Intersections	20-30 intersections
Signal Control System	MMITSS algorithm with TSP
CV Applications	SPaT broadcast, MMITSS, TSP, Firetrucks, ambulances, and taxi priorities. Vehicle-to-pedestrian and vehicle-to-bicycle communications
Expected Completion	2021

3.2.4. Philadelphia, PA

Under the SPaT challenge deployment project, 154 signalized intersections are expected to be equipped with RSUs to broadcast the SPaT message in Philadelphia by 2020. A brief description of this site is shown in Table 3-13.

Table 3-13: Description of the corridors in Philadelphia, PA

Location	I-76
Number of Intersections	154 intersections
CV Applications	Broadcast SPaT message
Expected Completion	2020

3.2.5. New York City, NY

Under the SPaT challenge project, 317 signalized intersections are expected to be equipped with RSUs in New York City by 2020. Pedestrian in crosswalk detection applications will be implemented initially in addition to broadcasting SPaT and MAP messages. A brief description of this project is given in Table 3-14.

Table 3-14: Description of the corridors in New York City, NY

Location	New York City, NY
Number of Intersections	317 intersections
CV Applications	317 intersections providing MAP, SPaT, and RTCM in New York City, including 10 that support pedestrian detection and notification to vehicles of pedestrians in walkways; 36 additional RSUs for operations and maintenance support
Expected Completion	2020

3.2.6. Idaho

Two locations in Idaho are planned to be equipped with DSRC equipment. The first place is an intersection on US 20 in Idaho Falls, ID, where the SPaT, MAP, and safety messages are going to be broadcasted. The second corridor contains four intersections that are planned to be equipped with RSUs for the test purposes in Boise, ID. These four intersections are located on Franklin Road. The initial phase of this project is to test various vendors and their corresponding range of DSRC for future deployment. It is expected to deploy more than twenty intersections with RSUs to broadcast the SPaT message by 2020 at Eagle road corridor. Eagle Road is selected as the main corridor because it has the highest traffic volume in Ada County, is a freight corridor, and has the highest crash rate among other corridors in Ada County. The pedestrian volumes on the selected corridors are moderate to low. Figure 3-11 shows the corresponding location of intersections on Franklin and Eagle Road in Boise, ID.

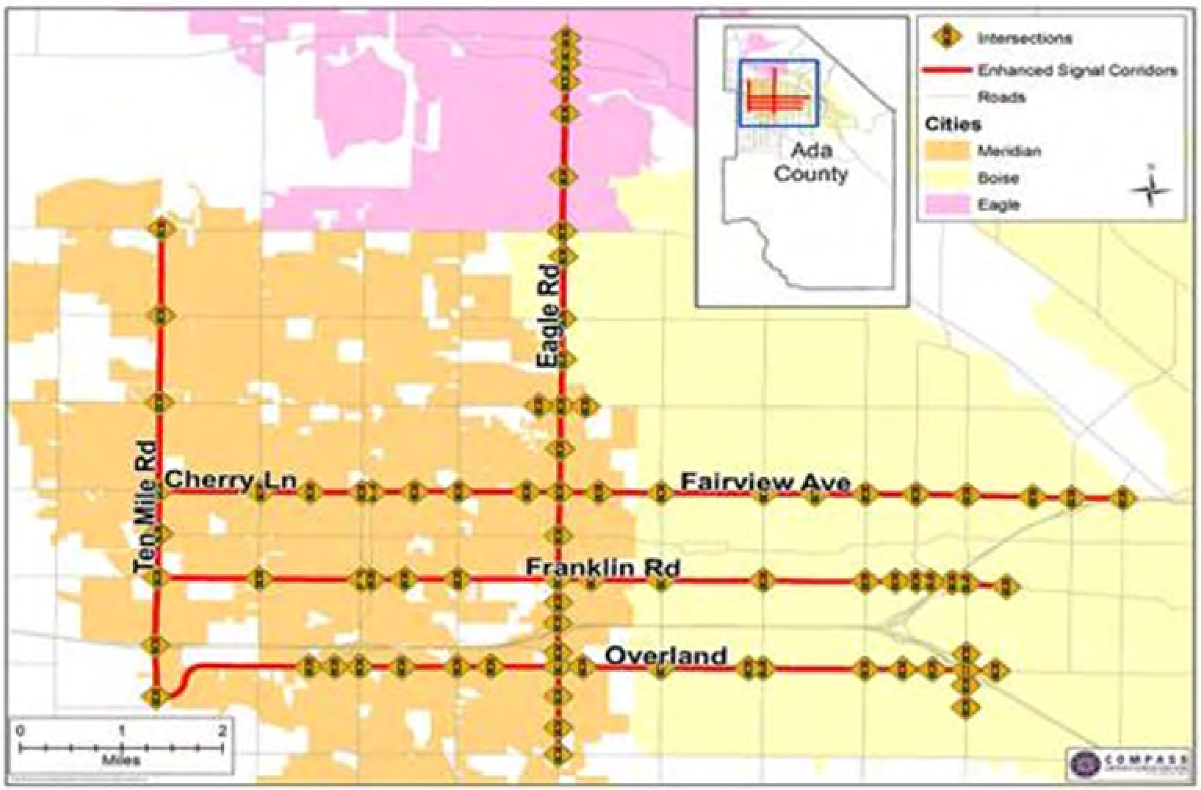


Figure 3-11: Location of Franklin Road and Eagle Road corridors in Boise, ID

Trafficware NEMA ATC controllers and Econolite NEMA Cobalt ATC controllers are already used on Franklin Road test corridor. However, only Trafficware NEMA controllers are used in Eagle Road corridor. It is expected to upgrade the controllers with a NEMA ATC controller in near future. Besides, it is planned to use the traffic vendor's central software. The ATMS.now software will be used for Trafficware, and the Centracs software will be used for Econolite. There is no transit priority on the corridors, but it is expected to test the freight priority on Franklin Road corridor. A brief description of the sites in Boise, ID is provided in Table 3-15.

Table 3-15: Description of the corridors in Boise, ID

Location	Franklin Road and Eagle Road in Boise, ID US 20, Idaho Falls, ID
Number of Intersections	4 signalized intersections in 2018 and 20 intersections in 2020.
CV Applications	Evaluate basic SPaT messages Test freight priority messaging
Traffic Controller	Trafficware NEMA ATC Econolite NEMA Cobalt ATC
Reasons for Selecting the Corridor	Selected corridors have high traffic volume with the highest crash rate in Ada County. They are freight corridors.
Traffic Flow Level	High vehicular volume, but moderate to low pedestrian volume
Expected Completion	2020

3.2.7. West Lafayette, IN

Ten signalized intersections on US 231 corridor in West Lafayette, IN in the vicinity of Purdue University are selected for the SPaT challenge project. This corridor is selected due to its "newness" of infrastructures, the relatively low volume for a 4-lane divided highway, and the proximity of the site to Purdue University since the Joint Transportation Research Program (JTRP) collaborates to support the research on the SPaT challenge. This project was expected to be completed by the end of 2017; however, it is still ongoing. Figure 3-12 shows the US 231 corridor and the location of selected intersections.

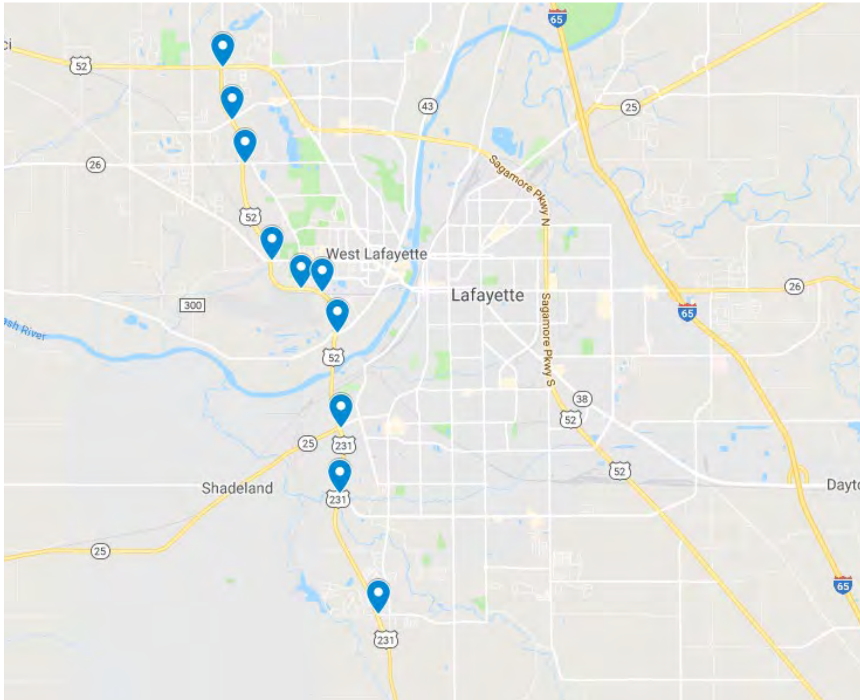


Figure 3-12: US 231 corridor, West Lafayette, IN

Econolite Cobalt devices were deployed along the US 231 corridor. Savari controller cards, RSUs, and recommended POE devices are procured. In this corridor, there is no transit signal priority. A brief description of the sites in West Lafayette, IN is provided in Table 3-16.

Table 3-16: Description of US 231 corridors in West Lafayette, IN

Location	US 231, West Lafayette, IN
Number of Intersections	10 signalized intersections
Traffic Controller	Econolite Cobalt
Reasons for Selecting the Corridor	The "newness" of infrastructures, the relatively low volume for a 4-lane divided highway, and the proximity of the site to Purdue University.
Traffic Flow Level	Low
Expected Completion	End of 2017 (not completed yet)

3.2.8. Dover, NH

Three intersections on Silver Street corridor in Dover, NH will be equipped with RSUs. The traffic volume in these intersections is low to moderate relative to other intersections in the city. The Silver street corridor was recently rebuilt as part of a capital improvement project with TS2 cabinets, fiber optic communications, and McCain ATC controllers. This project is expected to be finished by January 2020. Figure 3-13 shows the location of intersections on Silver Street.

Figure 3-13: Silver Street corridor, Dover, NH

In the selected intersections, McCain Omni eX version 1.10, which is an ATC controller is used. Version 1.10 of the Omni eX is compliant with the draft NTCIP 1202 V3 specification allowing it to produce the SPaT message. The signal cabinets are TS2 style cabinets utilizing SDLC connections. The detection at the intersections utilizes Gridsmart Bell cameras, which are used for both detection and traffic volume counting. The three intersections are interconnected using fiber optic communications and there is an existing 5.8 GHz wireless backhaul to a central server running advanced traffic management software.

There are several applications of connected vehicles in this project. The most important ones are providing red light violation warnings, exploring/developing a driver display focused on showing speed limit, lane use, and phase time to green. The V2I Hub software is utilized in the deployment and it is planned to explore other options available through the software once the radios are deployed in the field. A brief description of the sites in Dover, NH is provided in Table 3-17.

Table 3-17: Description of Silver Street corridors in Dover, NH

Location	Silver Street corridor in Dover, NH
Number of Intersections	3 signalized intersections
CV Applications	Red light violation warnings Driver display focusing on speed limit, lane use, and phase time to green
Traffic Controller	ATC controller
TSP	Not included
Reasons for Selecting the Corridor	The corridor infrastructures recently improved with TS2 cabinets, fiber optic communications, and McCain ATC controllers
Traffic Flow Level	Lower than other intersections in the city
Expected Completion	January 2020

3.2.9. Concord, NC

The City of Concord, NC plans to equip nine intersections with RSUs to broadcast SPaT and MAP messages in the first phase. Moreover, broadcasting RTCM is considered in the second phase of the project. The selected corridor is located on Concord Mills Blvd and Brutton Smith Blvd due to high traffic volumes. The signal controller is 2070C and ASC3-LX software is used to broadcast the messages. The connected vehicle applications in this project will be the TSP as well as fire truck preemption. This project is expected to be completed by summer 2019. Table 3-18 provides a brief description of the selected site in Concord, NC.

Table 3-18: Description of the selected corridor in Concord, NC

Location	Concord Mills Blvd and Brutton Smith Blvd, Concord, NC
Number of Intersections	9 signalized intersections
CV Applications	Transit Signal Priority (TSP) Firetruck preemption
Traffic Controller	2070C
Reasons for Selecting the Corridor	One of the busiest corridors in the state
Traffic Flow Level	Very high
Expected Completion	Summer 2019

3.2.10. Denver, CO

A corridor with more than ten signalized intersections is equipped with DSRC RSUs in Denver, CO. It is expected that RSUs broadcast SPaT and MAP data in each intersection. The connected vehicle application in this project also includes MMITSS and snowplow priority. The project is expected to be finished by summer 2019. Table 3-19 provides a brief description of Denver. CO SPaT challenge project.

Table 3-19: Description of the corridor in Denver, CO

Location	Denver, CO
Number of Intersections	More than 10
CV Applications	SPaT and MAP data broadcast MMITSS Snowplow priority

Expected Completion	Summer 2019

3.2.11. Knoxville, TN

It has been planned to deploy RSUs on 147 ATC signal controllers along two corridors on SR 1 and SR 71. The main purpose of the deployment is broadcasting the SPaT messages. The project was expected to be completed in fall 2018. However, it is still ongoing. Table 3-20 provides a brief description of the selected sites in Knoxville, TN.

Table 3-20: Description of the corridors in Knoxville, TN

Location	SR 1 and SR 71, Knoxville, TN
Number of Intersections	147 signal controllers
Traffic Controller	ATC
CV Applications	SPaT broadcast
Expected Completion	Fall 2018 (not completed yet)

3.2.12. Minneapolis, MN

Twenty intersections on State Highway 55 are planned for deployment of DSRC RSUs in Minneapolis, MN. It is expected that RSUs broadcast SPaT and MAP messages. Besides, the controllers need to send and receive BSM messages from a portion of agency fleets to measure the traffic performance. The connected vehicles application in this project will be the automatic dynamic message sign, warning of moving maintenance operations, and snowplow priority. The project is expected to be finished by December 2019. Table 3-21 shows a brief description of the deployed corridor in Minneapolis, MN.

Table 3-21: Description of the corridor in Minneapolis, MN

Location	State Highway 55, Minneapolis, MN.
Number of Intersections	20
CV Applications	Broadcast SPaT, MAP, and BSM. Measure the traffic performance, Dynamic message sign messages, snowplow priority
Expected Completion	December 2019

3.2.13. Smyrna, DE

RSUs are planned to be deployed at eleven signalized intersections in US 13 to broadcast SPaT and MAP data. The initial application will be a red-violation warning. The project was expected to be completed by the end of 2018. However, it is still ongoing.

3.3. Summary

There are eleven cities with operational SPaT deployments in nine states (i.e., Arizona, California, Pennsylvania, Utah, Virginia, Georgia, Florida, North Carolina, and Michigan) as of 2018. Combinations of Econolite ACS3 traffic controller and Savari RSU, SURTRAC controller and Arada RSU, Econolite Cobalt controller and Arada RSU, and McCain ATC eX controller and Arada RSU have already been successfully implemented.

At the time of this survey, several corridors are planned for SPaT deployment in Ohio, Missouri, Wisconsin, North Carolina, Pennsylvania, New York, Idaho, Colorado, Tennessee, Indiana, Minnesota, New Hampshire, and Delaware. Econolite ACS3, CalTrans 2070, SURTRAC, Econolite Cobalt, McCain ATC eX, Intelight, and MIST traffic controllers will be used in these corridors. In addition, Arada, Lear, Cohda, and Savari RSUs are planned to be used.

In both operational and planned projects, the following CV applications are deployed/planned:

1. SPaT broadcast,
2. MAP broadcast,
3. MMITSS,
4. Red-light violation,
5. TSP,
6. Freight signal prioritization,
7. Eco-driving,
8. pedestrian in crosswalk detection, and
9. RTCM.

State DOTs used the following criteria to select suitable corridors for SPaT deployment:

1. Need for TSP,
2. Ease of access to the corridor,
3. Variation in land use,
4. Variation in traffic demand,
5. Being a part of an ongoing CV project,
6. Proximity to automotive R&D centers and Silicon Valley tech companies
7. Being part of a fiber project, and
8. Favorable existing infrastructure.

4. Multi-modal Signal Control with Partial Network Observability

4.1. Introduction

This chapter presents a methodology for multi-modal signal control in urban streets with a mixed traffic stream of connected and unconnected vehicles. We first present a mathematical program that prioritizes the movement of transit vehicles based on their passenger occupancy and works with various levels of CV market penetration rates. Then, high-resolution CV data is used with point detector data to determine the vehicle density distribution over different network links. Finally, an algorithm is presented to solve the mathematical program and find the optimal signal timing parameters. Note that this chapter is intended only for readers interested in a deep understanding of the signal control strategy presented in this project.

4.2. The mathematical program for multi-modal signal control

4.2.1. Variables, parameters, and sets

We utilized the Cell Transmission Model (CTM) network loading concept to formulate the problem (Daganzo, 1994, 1995). The CTM divides a network into homogenous segments, i.e., cells, and discretizes the study period into a finite number of time steps. Figure 4-1 represents different types of cells in an intersection. We define $C^n, C_O^n, C_D^n, C_I^n, C_S^n$, and C_g^n as the set of all, ordinary, diverge, intersection, sink, and source cells, respectively corresponding to intersection $n \in N$. Furthermore, $\Gamma(i)$ and $\Gamma^{-1}(i)$ define the sets of all cells immediately downstream and upstream of cell $i \in C^n$, respectively. The movement of vehicles within the conflicting region of the intersection is controlled by a binary signal timing decision variable $g_i^{t,n}$ associated with each intersection cell $i \in C_I^n$ at time step $t \in T$, where T is the set of all time steps. Set M represents the set of all vehicle classes and the $x_i^{t,m}$ denotes the number of vehicles of class $m \in M$ in cell $i \in C^n$ at time step $t \in T$. Let B^n be the set of all buses and χ_b^t represents the position of bus $b \in B^n$ in intersection $n \in N$ along its path $P(b_i^n)$. Table 4-1 summarizes the definition of sets, variables, and parameters used in this report.

Table 4-1: Definition of sets, decision variables, and parameters

Sets	
T	Set of discrete-time intervals
T'	Set of prediction time intervals
N	Set of all intersections in the network
$\varsigma(n)$	Set of all intersections adjacent to intersection $n \in N$
P^n	Set of all phases in intersection $n \in N$
$\mathcal{L}^{nm}$	Set of all links between intersections $n \in N$ and $m \in \varsigma(n)$
$\acute{\mathcal{L}}^{nm}$	Set of all left turn links from intersection $n \in N$ to intersection $m \in \varsigma(n)$
D_n^ℓ	Set of stop-bar detectors at intersection $n \in N$ upstream of link $\ell \in \mathcal{L}^{nm}$ that connects intersection $n \in N$ to intersection $m \in \varsigma(n)$
${D'}_n^\ell$	Set of advanced detectors at intersection $m \in \varsigma(n)$ on left-turn link $\ell \in \acute{\mathcal{L}}^{nm}$
C	Set of all cells in the network
C^n	Set of all cells in intersection $n \in N$
C_o^n	Set of all ordinary cells in intersection $n \in N$
C_g^n	Set of all origin cells in intersection $n \in N$
C_s^n	Set of all destination cells in intersection $n \in N$
C_{gD}^n	Set of all dummy origin cells in intersection $n \in N$
C_{sD}^n	Set of all dummy destination cells in intersection $n \in N$
C_I^n	Set of all intersection cells in intersection $n \in N$ in the network
C_D^n	Set of all diverge cells in intersection $n \in N$
C_L^n	Set of all left-turn intersection cells in intersection $n \in N$
C_T^n	Set of all through movement intersection cells in intersection $n \in N$
M	Set of all classes of vehicle
B^n	Set of all buses in intersection $n \in N$
$J(i)$	Set of all cells with movements that conflict with the movement of cell $i \in C_I^n$
$A(i,n)$	Set of all cells immediately downstream of cell $i \in C^n$ at intersection $n \in N$
$B(i,n)$	Set of all cells immediately upstream of cell $i \in C^n$ at intersection $n \in N$
$V^t(\ell)$	Dynamic set of all vehicles on link $\ell \in \mathcal{L}^{nm}$ at time step $t \in T$
$UV^t(\ell)$	Dynamic set of all UVs on link $\ell \in \mathcal{L}^{nm}$ at time step $t \in T$
$P(b_i^n)$	Set of cells in the path of bus $b \in B^n$ in intersection $n \in N$
$\Gamma(i)$	Set of all cells immediately downstream of cell $i \in C^n$
$\Gamma^{-1}(i)$	Set of all cells immediately upstream of cell $i \in C^n$
Decision (Control) variables	
$g_i^{t,n}$	Signal state of intersection cell $i \in C_I^n$ at time step $t \in T$; 0 if red, 1 otherwise
Variables	
$x_i^{t,m}$	Number of vehicles of class $m \in M$ in cell $i \in C^n$ at time step $t \in T$
$y_{ij}^{t,m}$	Number of vehicles of class $m \in M$ advancing from cell $i \in C^n$ to downstream cell $j \in \Gamma(i)$ at time step $t \in T$
v_i^t	Space-mean speed in cell $i \in C^n$ at time step $t \in T$
w_i^t	Dummy variable; 1 if there is a bus in cell $i \in C^n$ at time step $t \in T$, 0 otherwise
$\varphi_{b,i}^t$	Dummy variable; 1 if bus $b \in B^n$ is in cell $i \in C^n$ at time step $t \in T$, 0 otherwise
χ_b^t	Position of bus $b \in B^n$ at time step $t \in T$
$u_{b,i}^t$	Speed of bus $b \in B^n$ at cell $i \in C^n$ at time step $t \in T$
Parameters	
$D_i^{t,m}$	Traffic demand for class $m \in M$ at gate cell $i \in C_g^n$ at time step $t \in T$
Q_i	Saturation flow rate in cell $i \in C^n$ at time step $t \in T$ in terms of the number of vehicles

$\underline{G}^i$	Minimum green time corresponding to intersection cell $i \in C_I^n$
N_i^t	Available capacity in cell $i \in C^n$ at time step $t \in T$ in terms of the number vehicles
N_i	Maximum capacity in cell $i \in C^n$ in terms of the number of vehicles
L_i	Starting coordinate of cell $i \in C^n$ in intersection $n \in N$
U_i	Ending coordinate of cell $i \in C^n$ in intersection $n \in N$
$\beta_i^{t,m}$	Portion vehicle class $m \in M$ flow entering intersection cell $i \in C_I^n$ from the total flow leaving its upstream cells $j \in \Gamma^{-1}(i)$ at time step $t \in T$
χ_b^0	Initial position of bus $b \in B^n$ at $t = 0$ relative to the reference point
VC	Free-flow speed of passenger cars
VB	Free-flow speed of buses
f	Fractional reduction of saturation flow rate to account for the start-up lost time
ρ_i	Percent reduction in saturation flow rate due to the presence of a bus in cell $i \in C^n$
ω	Ratio of the backward shockwave speed to the free flow speed
L^m	Length of a vehicle of class $m \in M$
α^m	Passenger occupancy of a vehicle of class $m \in M$
ψ^m	Occupancy ratio of vehicle class $m \in M$ relative to passenger car
$\mathcal{M}$	Big number
Δt	Duration of a time step in seconds
ΔX	Length of a cell that is the space traveled by a passenger car in free-flow speed VC within Δt
$\hat{g}_i^{t'\|t,n}$	The predicted state of signal serving cell $i \in C_I^n$ at prediction horizon $t' \in T'$ at the intersection $n \in N$
$\hat{x}_i^{t'\|t,m}$	Estimated number of vehicles of class $m \in M$ in cell $i \in C^n$ at prediction horizon $t' \in T'$ from CTM simulation based on the optimized signals at time step $t \in T$
$\hat{y}_{ij}^{t'\|t,m}$	Estimated number of vehicles advancing from cell $i \in C^n$ to downstream cell $j \in \Gamma(i)$ at prediction horizon $t' \in T'$ from CTM simulation based on the optimized signals at time step $t \in T$

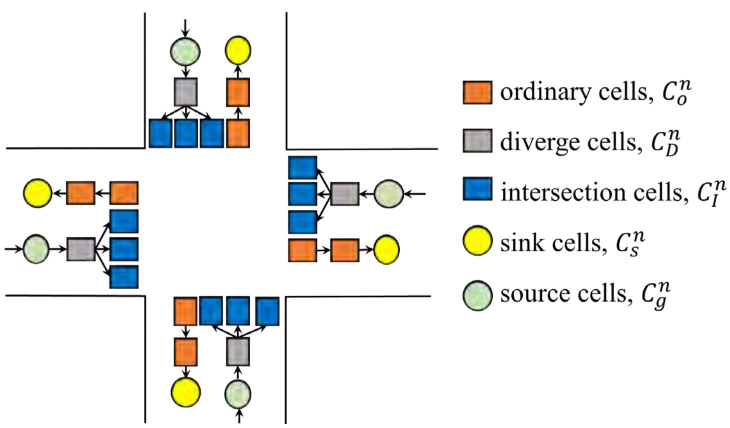


Figure 4-1 Cell representation of CTM for an intersection

4.2.2. Objective function

The proposed formulation aims at minimizing the total passenger travel time in an intersection. Prior research shows that this objective function works well in transportation networks (Hajbabaie, 2012; Hajbabaie and Benekohal, 2013, 2015; Islam, Aziz and Hajbabaie, 2020). Total vehicular travel time can be calculated from the summation of the number of vehicles $x_i^{t,m}$ over all classes $m \in M$, cells $i \in C^n \backslash C_s^n$, and time steps $t \in T$ multiplied by the duration of each time step. The time step duration is a fixed number that will not change the solutions and is not shown in the objective function. The number of vehicles $x_i^{t,m}$ is multiplied by passenger occupancy α^m to convert vehicular travel time to passenger travel time. However, Doan and Ukkusuri (2012) and Mohebifard and Hajbabaie (2019) showed that the minimization of total passenger travel time can cause some vehicles to be held-back when there is room available in the downstream cells. This holding back can be responsible for an unrealistic progression of vehicles in a multi-modal environment. To address the holding-back issue in the formulation, we added a positive penalty h_i corresponding to upstream cell i that is strictly greater than that of downstream cell $j \in \Gamma(i)$ according to Zhu and Ukkusuri (2013). The objective function and the penalty term are expresses as equations (1) and (2):

$$P1^n\text{: } \min Z^n = \sum_{\forall m \in M} \sum_{\forall t \in T} \sum_{\forall i \in C^n \setminus C_S^n} h_i \alpha^m x_i^{t,m} \quad (1)$$

$$0 < h_j < h_i \qquad \forall i \in C^n, j \in \Gamma(i) \quad (2)$$

4.2.3. Constraints

4.2.3.1. Signal control constraints

Constraints (3) to (5) ensure that no more than four (two from left-turning and through movements and two from right-turning movements) non-conflicting movements receive the right-of-way at the same time while satisfying the predefined minimum green duration threshold. We can modify set $J(i)$ to consider different phase combinations in an intersection. Constraints (4) guarantee the selection of non-conflicting movements.

$$\sum_{i \in C_I^n} g_i^{t,n} \leq 4 \qquad \forall t \in T \quad (3)$$

$$g_i^{t,n} + g_j^{t,n} \leq 1 \qquad \forall i \in C_I^n, \forall j \in J(i), \forall t \in T \quad (4)$$

$$\sum_{z=t}^{t+\underline{G}^i} g_i^{z,n} \geq (g_i^{t+1,n} - g_i^{t,n}) \times \underline{G}^i \qquad \forall i \in C_I^n,\ \forall t \in \{1,2,\ldots,|T| - \underline{G}^i\} \qquad (5)$$

4.2.3.2. Traffic state constraints

Constraints (6) to (8) ensure the conservation of flow in ordinary, source, and sink cells, respectively over the entire study period $t \in T$ for each vehicle class $m \in M$. According to the constraints, the number of vehicles of class $m \in M$ in a cell in the next time step $t+1$ is equal to the number of current vehicles $x_i^{t,m}$ plus the inflow $\sum_{k\in\Gamma^{-1}(i)} y_{ki}^{t,m}$ minus the outflow $\sum_{j\in\Gamma(i)} y_{ij}^{t,m}$ at time step t. Inflow of vehicles of class $m \in M$ in source cell $i \in C_g^n$ is equal to demand for the corresponding class, and the source cell does not have any outflow.

$$x_i^{t+1,m} = x_i^{t,m} + \sum_{k\in\Gamma^{-1}(i)} y_{ki}^{t,m} - \sum_{j\in\Gamma(i)} y_{ij}^{t,m} \qquad \forall t \in T, \forall i \in C_o^n, \forall m \in M \qquad (6)$$

$$x_i^{t+1,m} = x_i^{t,m} + D_i^{t,m} - \sum_{j\in\Gamma(i)} y_{ij}^{t,m} \qquad \forall t \in T, \forall i \in C_g^n, \forall m \in M \qquad (7)$$

$$x_j^{t+1,m} = x_j^{t,m} + \sum_{i\in\Gamma^{-1}(j)} y_{ij}^{t,m} \qquad \forall t \in T, \forall j \in C_s^n, \forall m \in M \qquad (8)$$

4.2.3.3. Flow propagation constraints

Constraints (9) to (12) ensure feasible traffic flow between two consecutive cells. Constraints (9) limit the number of processed vehicles of class $m \in M$ from cell i to downstream cells $j \in \Gamma(i)$ based on the number of class m vehicles $x_i^{t,m}$ that exists in that cell. Constraints (10) and (11) limit the total outflow and inflow between two adjacent cells based on the saturation flow rate of sending and receiving cells, respectively, at time step $t \in T$ when no bus is available in that cell $(w_i^t = 0)$. However, the outgoing and incoming saturation flow rates of a cell are reduced by a factor of ρ_i when at least one bus is present in that cell $(w_i^t = 1)$. Constraints (12) limit the total inflow to cell $j \in C^n \backslash C_g^n$ at time step $t \in T$ to the available capacity of the receiving cell in terms of passenger car. Therefore, vehicles of different classes are converted to the equivalent number of passenger cars by multiplying their cell occupancies $x_j^{t,m}$ with corresponding conversion factor ψ^m.

$$\sum_{j\in\Gamma(i)} y_{ij}^{t,m} \le x_i^{t,m} \qquad \forall t\in T, \forall i\in C^n\backslash C_s^n, \forall m\in M \tag{9}$$

$$\sum_{m\in M}\sum_{j\in\Gamma(i)} y_{ij}^{t,m} \le w_i^t\rho_i Q_i + (1-w_i^t)Q_i \qquad \forall t\in T, \forall i\in C^n\backslash C_s^n \tag{10}$$

$$\sum_{m\in M}\sum_{i\in\Gamma^{-1}(j)} y_{ij}^{t,m} \le w_i^t\rho_i Q_j + (1-w_i^t)Q_j \qquad \forall t\in T, \forall j\in C^n\backslash C_g^n \tag{11}$$

$$\sum_{m\in M}\sum_{i\in\Gamma^{-1}(j)} y_{ij}^{t,m} \le \omega\left[N_j - \sum_{m\in M}\psi^m \times x_j^{t,m}\right] \qquad \forall t\in T, \forall j\in C^n\backslash C_g^n \tag{12}$$

4.2.3.4. Bus position projection constraints

Constraints (13) to (17) project the position of bus $b \in B^n$ in intersection $n \in N$ over all time steps $t \in T$. Constraints (13) estimate the space-mean speed v_i^{t+1} in cell $i \in C^n$ based on its available space (Aziz, 2019). The available space is the difference between the cell length and the occupied length by vehicles. We estimated the occupied length in cell $i \in C^n$ by multiplying average length of vehicle L^m of class $m \in M$ by the number of vehicles that cannot be processed from that cell at a time step $t \in T$. Constraints (14) estimate the space-mean speed of a bus in all cells except for the intersection cells. Considering the slower speed of transit vehicles compared to passenger cars, the maximum achievable speed $u_{b,i}^t$ of a bus in cell $i \in C^n\backslash C_I^n$ is the minimum of space-mean speed v_i^t in that cell and the free flow speed VB of buses. On the other hand, the space-mean speed of a bus depends on the signal status $g_i^{t,n}$ in intersection cell $i \in C_I^n$ as shown by constraints (15).

Constraints (16) project the position χ_b^t of bus $b \in B^n$ at time step $t \in T$ based on its position χ_b^{t-1} and speed $u_{b,i}^{t-1}$ in the previous time step $t-1 \in T$. Note that when bus $b \in B^n$ is present in cell $i \in P(b_i^n)$ at time step t, $\varphi_{b,i}^t$ will be one and ensure that constraints (16) are active. Constraints (17) are used to set the initial position $\chi_b^{t=0}$ of all buses in the network.

$$v_i^{t+1} = \frac{\Delta X - \left[\sum_{m\in M}\left(x_i^{t,m} - \sum_{j\in\Gamma(i)} y_{ij}^{t,m}\right) \times L^m\right]}{\Delta t} \qquad \forall t \in T, \forall i \in C^n \qquad (13)$$

$$u_{b,i}^t = \min(v_i^t, VB) \qquad \forall t \in T, \forall i \in C^n \backslash C_I^n, \forall b \in B^n \qquad (14)$$

$$u_{b,i}^t = \min(g_i^{t,n} \times v_i^t, VB) \qquad \forall t \in T, \forall i \in C_I^n, \forall b \in B^n \qquad (15)$$

$$\chi_b^t = \chi_b^{t-1} + \sum\nolimits_{\forall i \in P(b_i^n)} \varphi_{b,i}^{t-1} \times u_{b,i}^{t-1} \times \Delta t \qquad \forall t \in T, \forall b \in B^n \qquad (16)$$

$$\chi_b^{t=0} = \chi_b^0 \qquad \forall b \in B^n \qquad (17)$$

4.2.3.5. Constraints on the number of buses in each cell

Constraints (18) to (26) map the projected position of all buses to the geometry of a cell and estimate cell occupancy of buses over time. Constraints (18) and (19) define the indicator variable w_i^t for cell $i \in C^n$ at time step $t \in T$. The value of w_i^t becomes one in presence of at least one bus in cell $i \in C^n$ at time step t. Constraints (20) determine the number of buses in cell $i \in C^n$ at time step $t \in T$. On other hand, constraints (21) to (26) ensure that the indicator variable $\varphi_{b,i}^t$ will take on the value of one when the position χ_b^t of bus $b \in B^n$ is within the boundary $[L_i, U_i]$ of cell $i \in P(b_i^n)$ at time step $t \in T$; otherwise, it will be zero. We defined additional binary variables $\eta_{1i,b}^t, \eta_{2i,b}^t$ corresponding to bus $b \in B^n$ in cell $i \in P(b_i^n)$ at time step $t \in T$ to linearize the conditional decision variable $\varphi_{b,i}^t$ following the approach presented by Mirheli *et al.* (2019).

$$w_i^t \le \sum\nolimits_{b\in B^n} \varphi_{b,i}^t \qquad \forall t \in T, \forall i \in C^n, m = \text{bus} \qquad (18)$$

$$w_i^t \ge \varphi_{b,i}^t \qquad \forall t \in T, \forall i \in C^n, \forall b \in B^n \qquad (19)$$

$$x_i^{t,m} = \sum\nolimits_{b\in B^n} \varphi_{b,i}^t \qquad \forall t \in T, \forall i \in C^n,\ m = \text{ bus} \qquad (20)$$

$$L_i \leq \chi_b^t + \mathcal{M}(1 - \varphi_{b,i}^t) \qquad \forall t \in T,\ \forall i \in P(b_i^n), \forall b \in B^n \qquad (21)$$

$$L_i \geq \chi_b^t - \mathcal{M}(\varphi_{b,i}^t + \eta_{1i,b}^t) \qquad \forall t \in T,\ \forall i \in P(b_i^n), \forall b \in B^n \qquad (22)$$

$$\chi_b^t < U_i + \mathcal{M}(1 - \varphi_{b,i}^t) \qquad \forall t \in T,\ \forall i \in P(b_i^n), \forall b \in B^n \qquad (23)$$

$$\chi_b^t > U_i - \mathcal{M}(\varphi_{b,i}^t + \eta_{2i,b}^t) \qquad \forall t \in T,\ \forall i \in P(b_i^n), \forall b \in B^n \qquad (24)$$

$$w_{b,i}^t + \eta_{1i,b}^t + \eta_{2i,b}^t = 1 \qquad \forall t \in T,\ \forall i \in P(b_i^n), \forall b \in B^n \qquad (25)$$

$$\eta_{1i,b}^t + \eta_{2i,b}^t \leq 1 \qquad \forall t \in T,\ \forall i \in P(b_i^n), \forall b \in B^n \qquad (26)$$

4.2.3.6. Intersection flow control constraints

Constraints (27) limit the total vehicles processed from intersection cell $i \in C_I^n$ at time step $t \in T$ considering the signal status of the cell. The intersection cell can process up to the saturation flow of Q_i when the signal is green; and zero otherwise. Constraints (28) account for the start-up lost time when the signal changes from red to green and the corresponding flows are reduced by a factor f. Constraints (29) maintain the predefined turning percentages $\beta_j^{t,m}$ at the intersection for all intersection cells $j \in C_I^n$ at time step $t \in T$.

$$\sum_{m \in M} \sum_{j \in \Gamma(i)} y_{ij}^{t,m} \leq g_i^{t,n} \times Q_i \qquad \forall t \in T, \forall i \in C_I^n \qquad (27)$$

$$\sum_{m \in M} \sum_{j \in \Gamma(i)} y_{ij}^{t,m} \leq g_i^{t,n} \times Q_i - f \times Q_i \times \left(g_i^{t,n} - g_i^{t-1,n}\right) \qquad \forall t \in T, \forall i \in C_I^n \qquad (28)$$

$$y_{ij}^{t,m} = \beta_j^{t,m} \times \sum_{k \in \Gamma(i)} y_{ik}^{t,m} \qquad \forall t \in T, \forall j \in C_I^n,\ \forall i \in \Gamma^{-1}(j), \forall m \in M \qquad (29)$$

4.2.3.7. Other constraints

Constraints (30) to (31) ensure that occupancies, flow, space mean speed, and the speed of a bus corresponding to a cell are non-negative variables. Constraints (32) to (35) ensure that $g_i^{t,n}$, $\varphi_{b,i}^t$, w_i^t, $\eta_{1i,b}^t$, and $\eta_{2i,b}^t$ are binary variables.

$$x_i^{t,m} \geq 0, y_{ij}^{t,m} \geq 0 \qquad \forall t \in T, \forall i \in C^n, \forall j \in A(i), \forall m \in M \quad (30)$$

$$v_i^t \geq 0, u_{b,i}^t \geq 0 \qquad \forall t \in T, \forall i \in C^n, \forall b \in B^n \quad (31)$$

$$g_i^{t,n} \in \{0,1\} \qquad \forall t \in T, \forall i \in C_I^n \quad (32)$$

$$\varphi_{b,i}^t \in \{0,1\} \qquad \forall t \in T, \forall i \in C^n, \forall b \in B^n \quad (33)$$

$$w_i^t \in \{0,1\} \qquad \forall t \in T, \forall i \in C^n \quad (34)$$

$$\eta_{1i,b}^t, \eta_{2i,b}^t \in \{0,1\} \qquad \forall t \in T,\ \forall i \in P(b_i^n), \forall b \in B^n \quad (35)$$

4.3. Accounting for different CV market penetration rates

Before optimizing the signal timing parameters, signal controllers in the network determine the state of the system around the intersection (i.e., the number of vehicles in each cell, and the initial position of transit vehicles) based on the position of CVs and transit buses. At a 100% CV market penetration rate, the position of CVs can be mapped to cell geometries to determine the number of vehicles in each cell. However, the point detector and CV data should be integrated to estimate the location of UVs when the CV market penetration rate is lower than 100%. The position estimation of UVs is based on the assumption that vehicles are distributed on a link following the actuation distribution following the approach presented in Islam, Hajbabaie and Aziz (2020). The entry time of UVs from the detection on loop detectors placed at the upstream of a link segment is recorded. Then, all the existing UVs on that link are allocated to a cell-based on their entrance times, and the initial input to the optimization program is estimated.

4.4. Solution algorithm for the mathematical program

The presented mathematical program has an excessive number of integer decision variables that grow exponentially with the size of the network. As such, traditional central approaches cannot find the optimal solutions in a reasonable amount of time even for a small network. As such, we utilized the receding horizon control technique that involves solving the proposed optimization problem over a moving planning horizon. Although the moving horizon technique helps reduce the complexity of the problem; optimization of signal timings of all intersections in a large-scale network remains very complex (Wünsch, 2008; Hajbabaie, Medina and Benekohal, 2011; Medina, Hajbabaie and Benekohal, 2011). As such, rather than making network-level decisions within a central architecture, each intersection optimizes its own signal plan through a distributed structure (Mehrabipour and Hajbabaie, 2017; Tajalli and Hajbabaie, 2018a; Mohebifard and Hajbabaie, 2019a; Tajalli, Mehrabipour and Hajbabaie, 2020) over a prediction horizon, i.e. several time steps in the future. Then, the signal controller implements the first decisions on terminating or extending the signals of the optimal control sequence for the next time step. This intersection level decision making in receding horizon control reduces the complexity of the optimization problem and accounts for the stochastic nature of traffic demand and capacity in a network. Furthermore, it helps make signal plans not only adaptive to the current condition of an intersection, but also the upcoming future condition. Furthermore, the intersection-level distribution of the network-wide signal control system facilitates the scalability of the optimization program. Finally, projected vehicle outflows are communicated among immediate intersections. As such, each intersection in the network has a broader overview of the network and ensure smooth traffic flow throughout the network. Therefore, the coordination among adjacent intersections pushes the locally optimal intersection-level solution towards global optimality and guarantees a high-quality network-wide performance. The main steps of the receding horizon control are:

1- Estimate the traffic state at a time step based on CV and detector data using a traffic state estimation algorithm,

2- Optimize the signal timing parameters over a prediction period (Distributed optimization), 3- Implement the optimal decisions for the current time step,

4- Communicate the signal timing parameters with neighboring intersections to project incoming flows, and available capacities (Distributed coordination), and

5- Check the termination criteria.

Figure 4-2 shows the algorithm flow. Each intersection controller estimates the initial traffic states based on the data from CVs and surrounding loop detectors. Then, the controller shares projected incoming flows and receiving capacities over the prediction horizon with adjacent intersections.

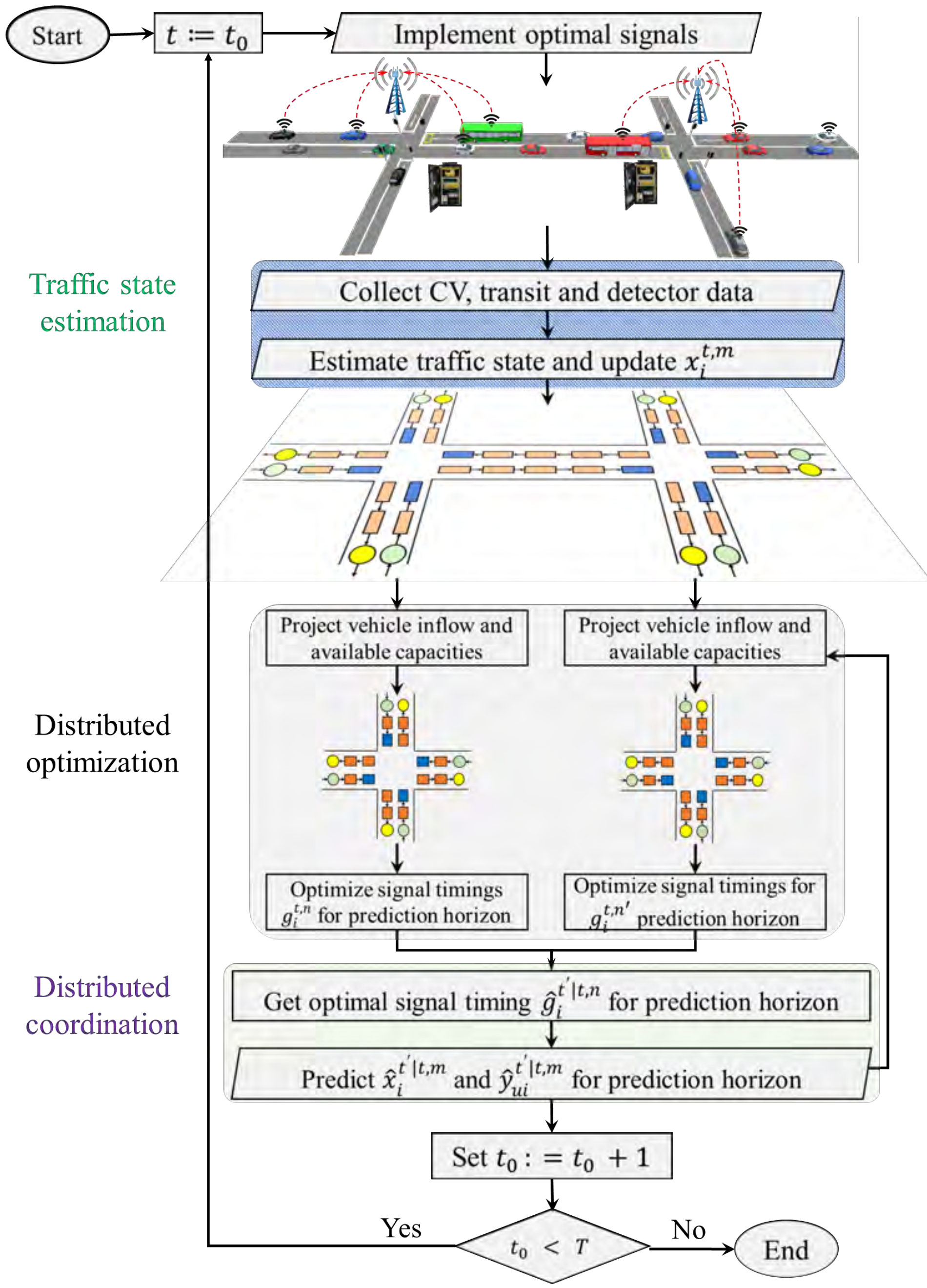


Figure 4-2 Flow chart of the signal control algorithm in a multi-modal environment.

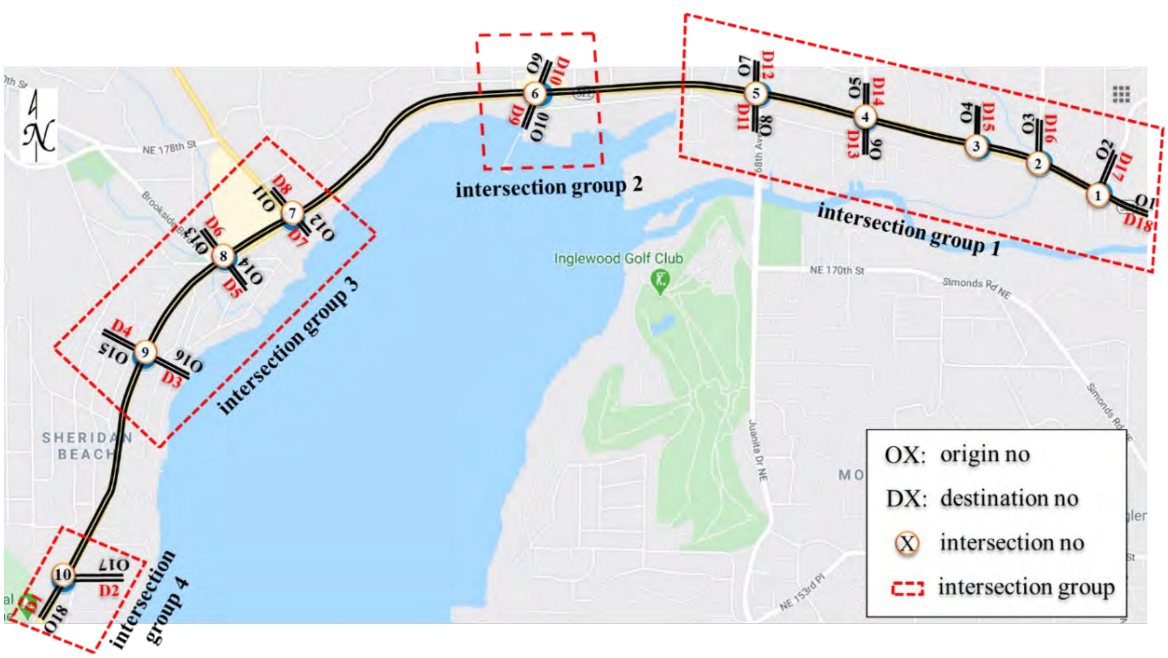
5. Case Study Details

5.1. Study Corridor and Traffic Conditions

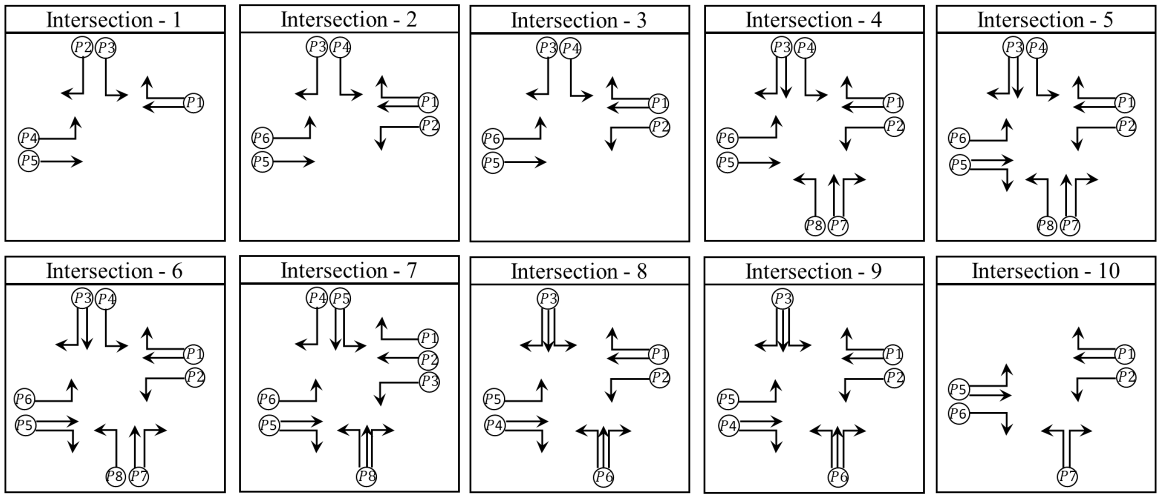
The proposed multi-modal signal control methodology was implemented in three case study networks in Washington State in a simulated environment in VISSIM. Traffic volumes that were provided by the WSDOT were used.

5.1.1. Case study-1: SR-522, Seattle, WA

The first case study is a portion of SR-522 corridor in Seattle, WA containing ten intersections as shown in Figure 5-1. The study corridor consists of bidirectional movements with one to three-lane segments and four intersection groups shown with rectangles. Figure 5-1(a) shows 18 origins and 18 destinations. All available movements corresponding to each intersection in the case study are presented in Figure 5-1(b). The arterial street is a heavily used commuter route that connects Seattle to Kenmore and Bothell.



(a) Network layout



(b) Available movements corresponding to each intersection

Figure 5-1 Case study network-1: SR-522, Seattle, WA

Figure 5-2 shows the volume at the origins in the case study area. We used AM and PM peak volumes. The network is loaded with 7,334 and 8,292 passenger cars for one hour in the AM and PM peak, respectively. As shown in Figure 5-2, two origins corresponding to the major direction have a higher volume. On the other hand, intersection-5 handles large traffic volumes from two major streets, i.e. SR-522 and 68th Ave NE. Furthermore, O-11 has high traffic volume during both AM and PM peak periods as it is directly connected to the off-ramp on I-5 via SR 104.

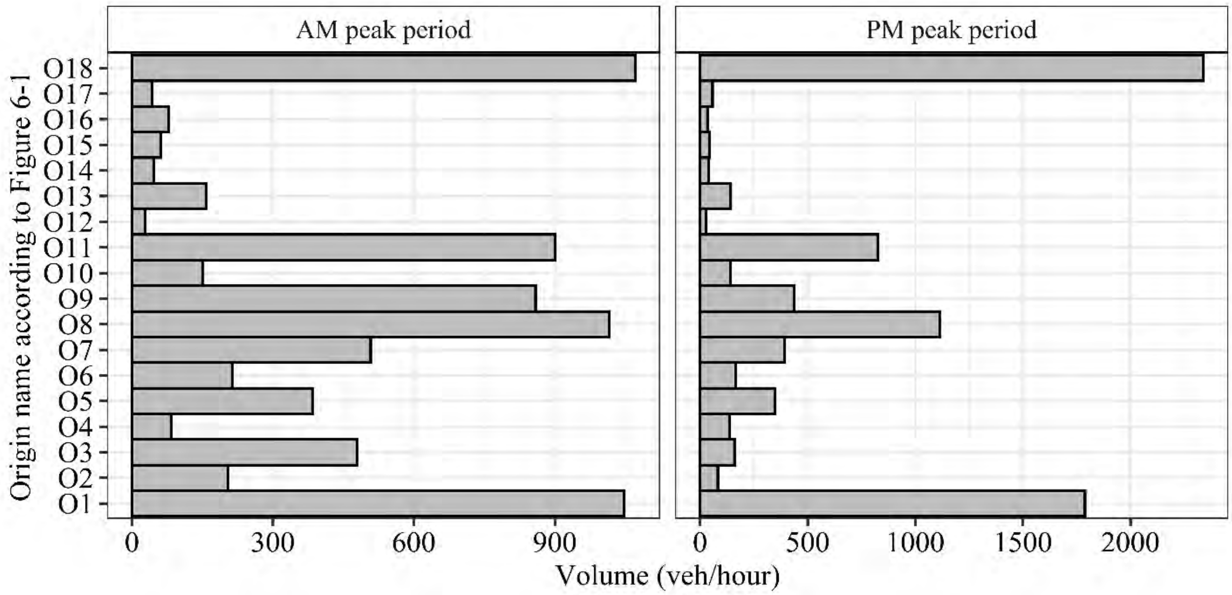


Figure 5-2 Volume at the origin of SR-522, Seattle, WA

Figure 5-3 shows the percentages of turning movements (left, through, and right) associated with all approaches (west, south, east, and northbound) for all intersections in the network. Eastbound and westbound approaches represent the major movement in the network and their corresponding through movement is higher compared to the left and right turn movements.

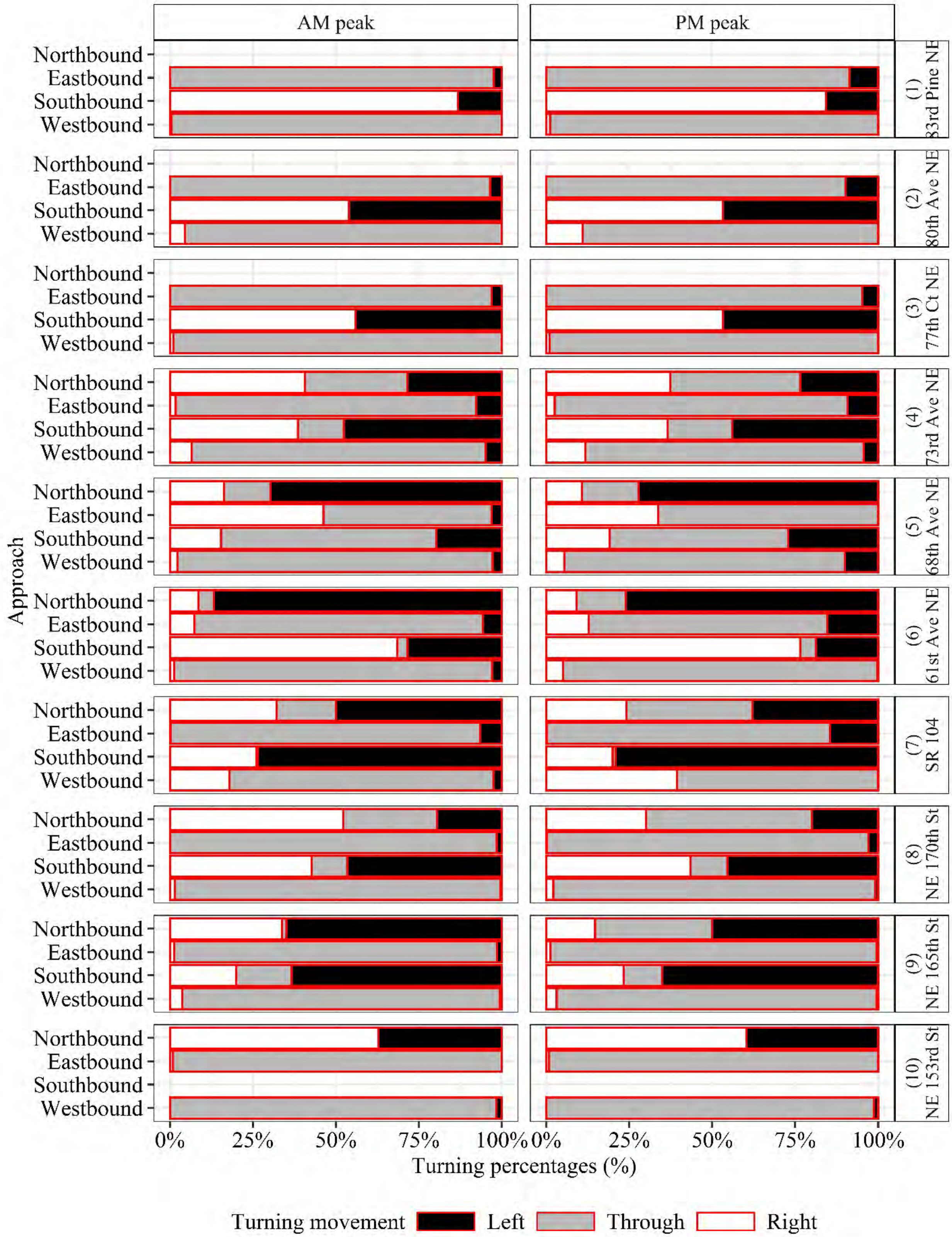
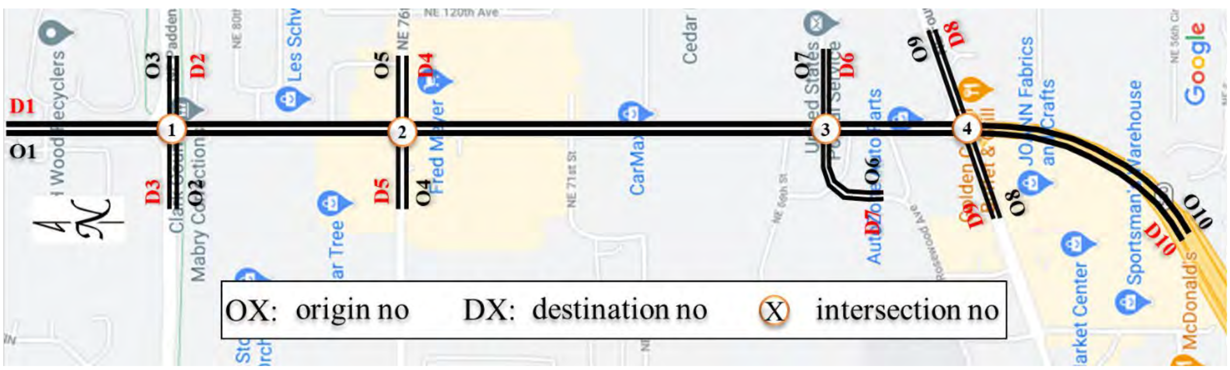


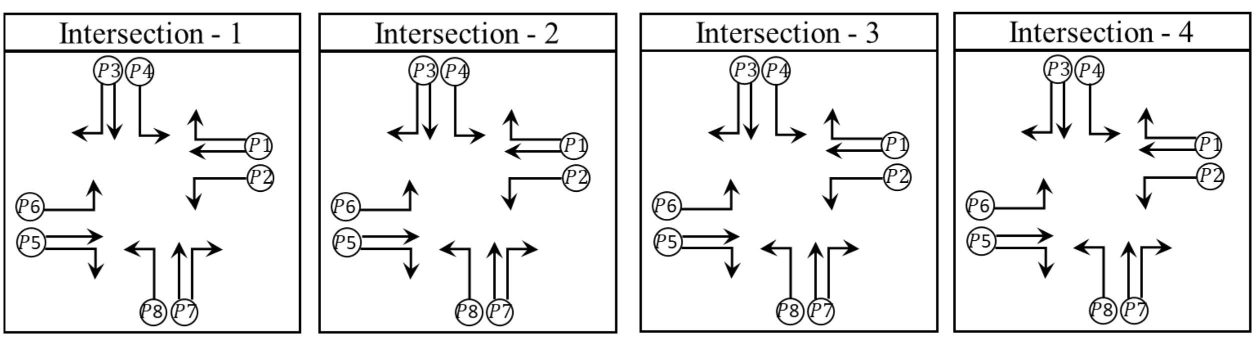
Figure 5-3 Turning percentages for all movements SR-522.

5.1.2. Case study-2: SR-503, Vancouver, WA

A 1.45-mile portion of SR-503 corridor in Vancouver, WA was considered as the second case study. The corridor is a heavily used commuter route that connects Battle Ground, WA to Interstate 5. The study area consists of four intersections, 10 origins, and 10 destinations as shown in Figure 5-4 (a). Figure 5-4 (b) shows the available movements corresponding to all the intersections in the network. Only one intersection group was considered within the case study area as the distances between adjacent intersections are less than the suggested coordination threshold of 2500 ft. The study corridor consists of bidirectional movements with one to two-lane segments.



(a) Network layout



(b) Available movements corresponding to each intersection

Figure 5-4 Case study network-2: SR-503, Vancouver, WA

Figure 5-5 shows the AM and PM peak volumes at the origins in the study area. The network is loaded with 8,190 and 11,326 passenger cars in the AM and PM peak hours, respectively. Figure 5-6 shows the turning percentages of all movements corresponding to all intersections. The figure shows a high percentage of through movement from north and southbound approaches in all intersections except intersection 4, where SR 500 crosses NE 4th Plain Blvd. Intersection 4 has high incoming traffic volumes from all the approaches.

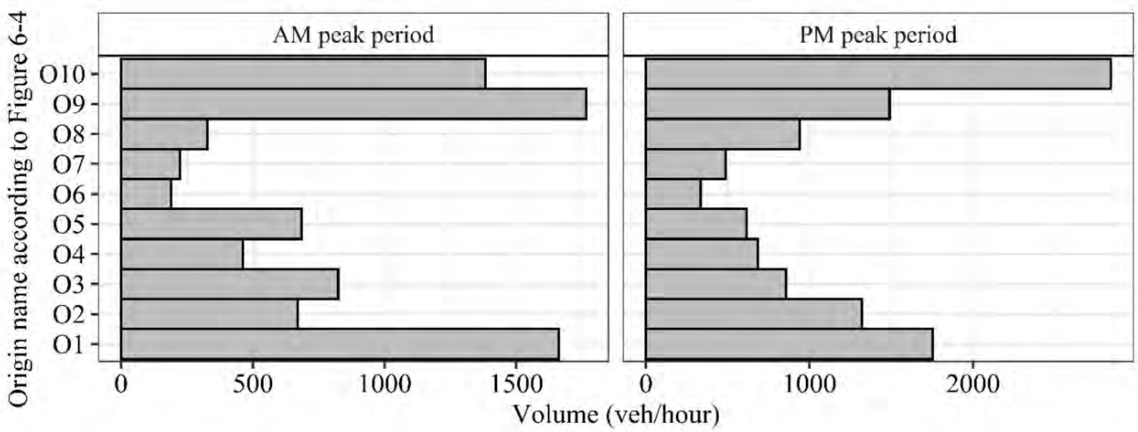


Figure 5-5 Volume at the origin of SR-503, Vancouver, WA

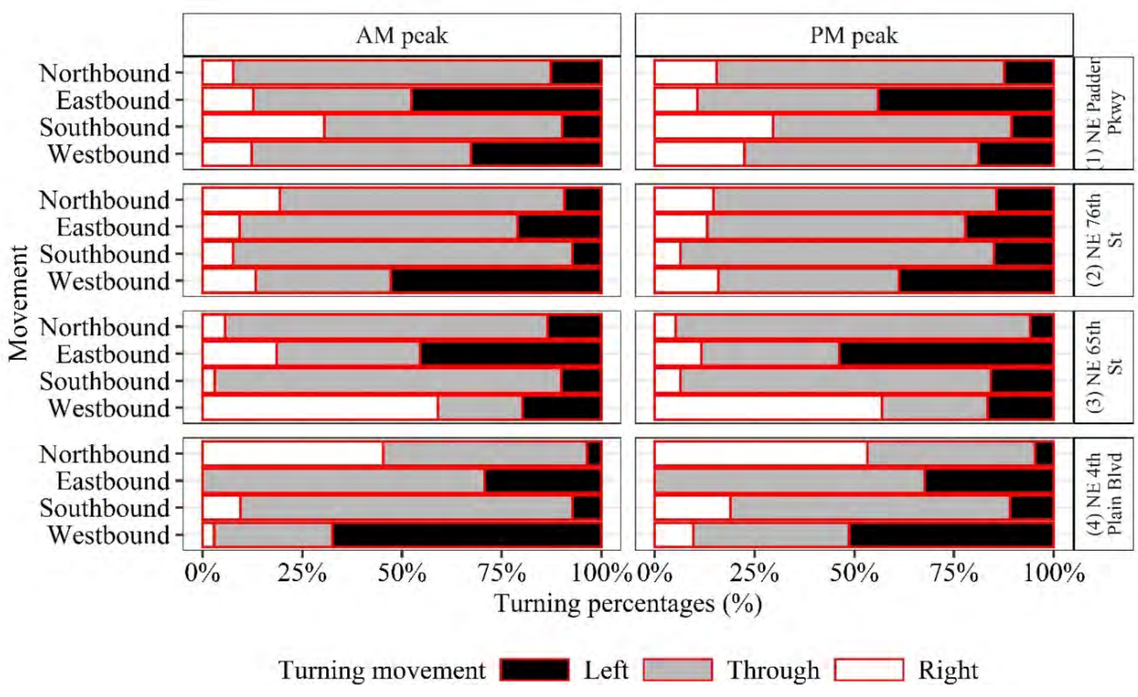
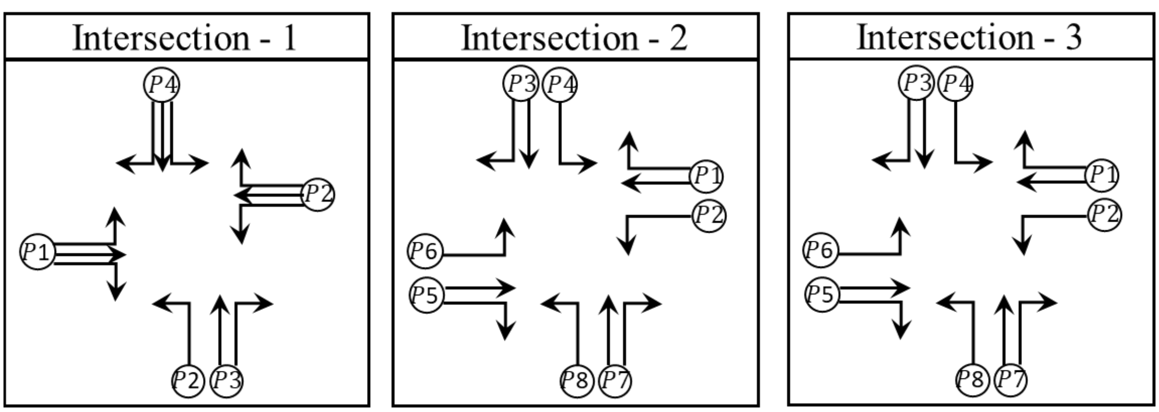


Figure 5-6 Turning percentages for all movements in SR-503.

5.1.3. Case study-3: SR-27, Spokane Valley, WA

The third case study arterial street is a portion of the SR-27 corridor in Spokane Valley, WA, as shown in Figure 5-7. The study area is a 1.38-mile corridor consisting of three signalized intersections. The arterial street is a commuter route with more than 5,000 hourly passenger cars. We used the AM peak, Mid-day (MID), and PM peak volume data that is shown in Figure 5-8. The arterial street consists of 8 origins and 8 destinations. Figure 5-9 shows the turning percentages of different movements from all approaches corresponding to all intersections in the network. As shown, intersection 3 handles high traffic volume from all approaches.

(a) Network layout



(b) Available movements corresponding to each intersection

Figure 5-7 Case study network-3: SR-27, Spokane Valley, WA

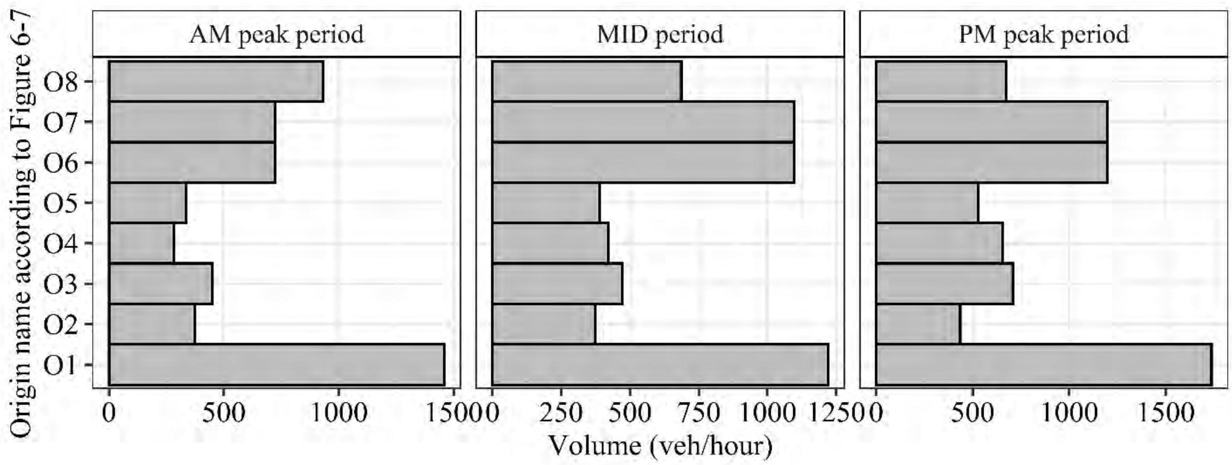


Figure 5-8 Volume at the origin of SR-27, Spokane Valley, WA

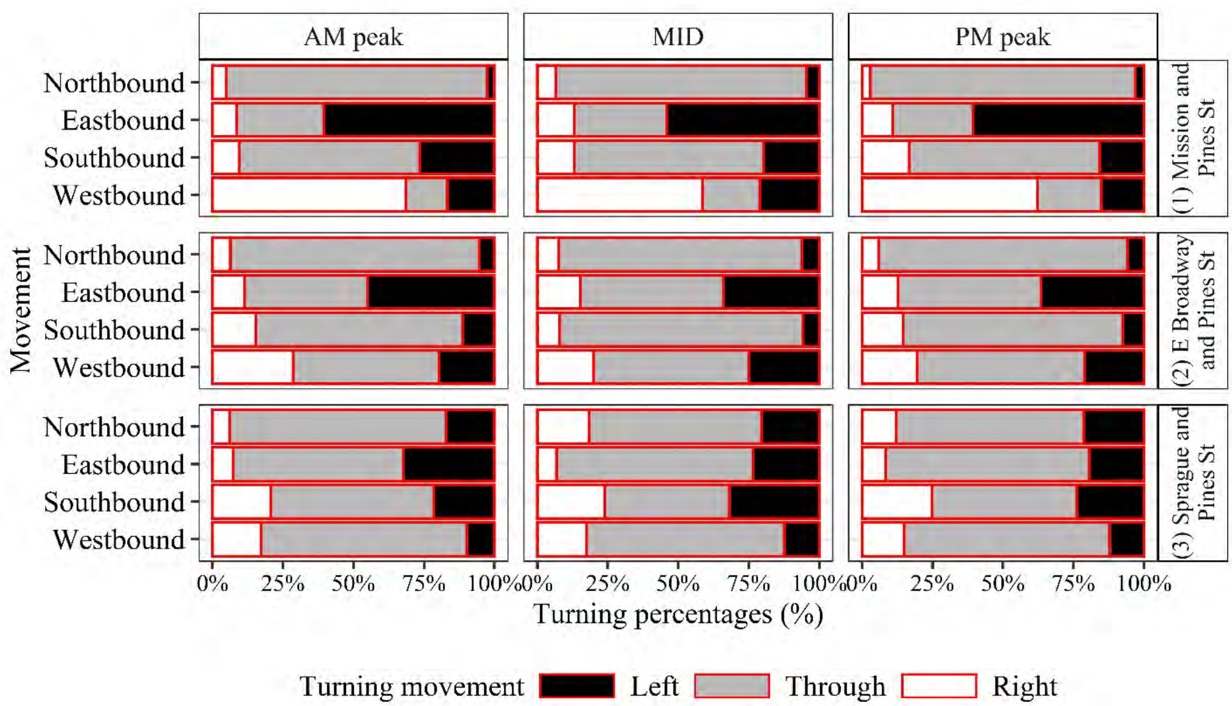


Figure 5-9 Turning percentages for all movements in SR-27, Spokane Valley, WA.

5.2. Transit bus operations

Table 5-1 summarizes the total number of buses generated in all bus routes over the case study corridors and their corresponding headways between consecutive buses. Three case study networks are loaded with 68, 75, and 75 transit buses with corresponding headways varying between 300 to 1000 seconds. Bus routes corresponding to each of the case study networks are available on Google maps. Furthermore, we assume that all transit buses are connected, and their passenger occupancy can be communicated with signal controllers.

Table 5-1. Summary of bus routes in all case study networks

Route no	Case study network								
	(1) SR-522, Seattle, WA			(2) SR-503, Vancouver, WA			(3) SR-27, Spokane Valley, WA		
	Path	Headway (sec)	Total buses	Path	Headway (sec)	Total buses	Path	Headway (sec)	Total buses
1	$O1 \Rightarrow D1$	300	13	$O2 \Rightarrow D9$	300	12	$O3 \Rightarrow D8$	300	13
2	$O18 \Rightarrow D18$	300	13	$O1 \Rightarrow D3$	300	13	$O8 \Rightarrow D2$	300	13
3	$O8 \Rightarrow D12$	300	13	$O4 \Rightarrow D1$	300	13	$O5 \Rightarrow D5$	300	12
4	$O7 \Rightarrow D11$	300	12	$O5 \Rightarrow D5$	300	12	$O4 \Rightarrow D4$	300	13
5	$O11 \Rightarrow D1$	600	7	$O6 \Rightarrow D1$	300	13	$O7 \Rightarrow D7$	300	12
6	$O11 \Rightarrow D18$	600	6	$O9 \Rightarrow D9$	300	12	$O6 \Rightarrow D6$	300	12
7	$O1 \Rightarrow D8$	1000	4	-	-		-	-	

5.3. Analysis scenarios

We use two sources of data in this report: CV and loop detector data to estimate the initial traffic state in the network. More details on three combinations of data sources are as follow:

1- Loop Detector data: The signal controllers receive vehicle actuation from stop-bar detectors placed at their upstream intersections. Then, the detection is transmitted between adjacent intersections using infrastructure-to-infrastructure communications. Then, the signal controllers estimate the position of vehicles over a link based on their actuation times on upstream detectors and optimize signal timing parameters. Note that, this approach only relies on the estimation algorithm for determining the initial traffic state for the optimization algorithm.

2- CV data: The signal controllers receive the speed and position of incoming CVs and transit vehicles through V2I communications. Then, the signal controllers estimate the cell occupancies by mapping the positions of CVs to cell geometry. The intersection controllers estimate the number of vehicles that are expected to arrive at the coordinated approaches based on the projected outflows from adjacent intersections using infrastructure-to-infrastructure communications.

3- CV & Loop Detector data: The signal controllers collect the detection times from detectors upstream of a link along with the speed and position of CVs and transit vehicles that are within the communication range. Then, the signal controllers use the estimation algorithm to determine the initial traffic state for the optimization program.

5.4. Simulation Setup

We implemented the proposed approach in a simulated environment in Vissim (PTV Group, 2013) using the Component Object Model (COM) interface. The COM interface allows collecting data from the simulated network and implementing the signal indications in it based on the output of the proposed methodology. We created a new vehicle type for CVs in Vissim and allowed these vehicles to share their speeds and position every 0.1 seconds (resolution of V2I communication) through the COM interface. We specified the percentage of CVs relative to other flow at each vehicle input location in the network to consider different CV market shares. Furthermore, loop detectors were placed on links, which allowed traffic signals to collect vehicle detections.

Therefore, CV and loop detector data are used to estimate traffic state over links via the COM interface. Furthermore, we created an information sharing environment following infrastructure-to-infrastructure communications where optimization programs of adjacent intersections in the same intersection group share information to estimate the number of vehicle arrivals on the coordinated approaches in the near future. Finally, the optimization program corresponding to each intersection is solved, and optimal signal timings are sent back to Vissim to be implemented in traffic lights. Figure 5-10 shows the flow of information in the signal control system. Note that the figure shows the flow of information based on the availability of both detector and CV data, but the algorithm still works if either of the data sources is unavailable. The signal controller only processes available data sources. We considered eleven CV market penetration rates (from 0% to 100% at 10% increments), and each simulation scenario was replicated three times with different random seeds.

Table 5-2 Case study information

Parameter	Case study		
	1	2	3
Free-flow speed (mph)	40	35	35
Free-flow speed of buses (mph)	20	20	20
Saturation headway (s)	2	2	2
Minimum green for through movements in major direction (s)	18	18	18
Minimum green for left-turning movements in major direction (s)	12	12	12
Minimum green for through movements in minor direction (s)	12	12	12
Minimum green for left-turning movements in minor direction (s)	6	6	6
Time interval for signal control (s)	6	6	6
Prediction horizon (s)	90	90	90
Study period (s)	3600	3600	3600

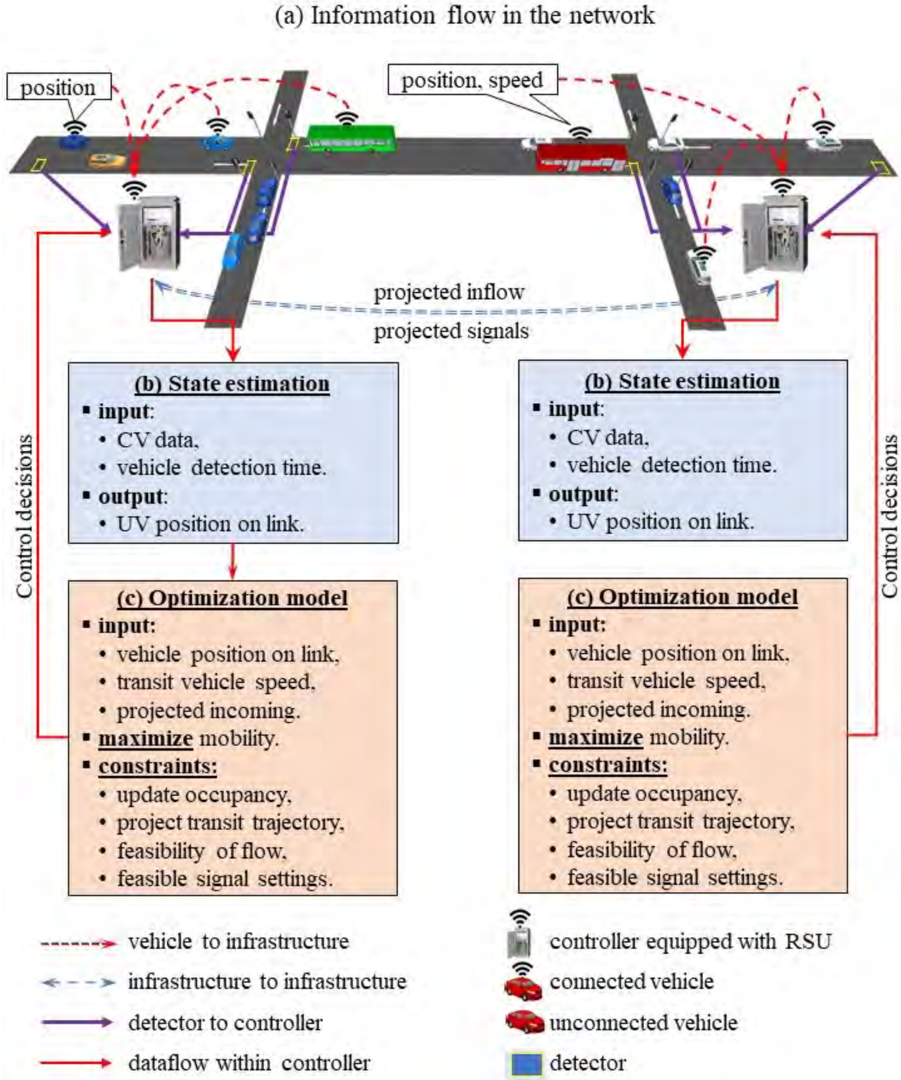


Figure 5-10 Control system for the proposed signal control system

5.5. Performance Measures

We have implemented the adaptive signal control strategies in Vissim to determine the mobility, progression quality, and travel time reliability measures in the system. We have used the travel time, delay, and number of completed trips for passenger cars and transit buses as three aggregate mobility performance measures. These performance measures have been used in prior research for the same purpose (e.g., Hajbabaie, Medina and Benekohal, 2010; Hajbabaie and R. Benekohal, 2011; Hajbabaie and Rahim Benekohal, 2011; Medina, Hajbabaie and Benekohal, 2013; Mohebifard and Hajbabaie, 2018a; Tajalli and Hajbabaie, 2018b).

Event-based measures allow assessing progression quality and capacity utilization of a signalized intersection (Day *et al.*, 2012). We use the Purdue Coordination Diagram (PCD) (Day *et al.*, 2008) to visualize and evaluate the progression quality. PCD illustrates vehicle arrivals relative to the green signal duration in a cycle against the study period. As the adaptive signal control system in this study does not follow a fixed sequence of phasing, we define cycle as the duration between two consecutive occurrences of green signals on the major phase. The Beginning-Of-Green (BOG) and End-Of-Green (EOG) times corresponding to each cycle show the signal status during vehicle arrivals. We further quantified the progression quality by two metrics: the green to cycle length ratio (g/C), and volume to capacity ratio (v/c). The g/C illustrates the percentage of green time allocated to a phase, and the v/c ratio shows the effectiveness of using the green times (Day *et al.*, 2012). The v/c ratios greater than 1.0 indicate an oversaturated condition with potential phase failure.

We assess the travel time reliability based on travel time Cumulative Distributed Functions (CDF) as suggested by Aghdashi, Rouphail and Hajbabaie (2013); Zegeer *et al.* (2014); Aghdashi *et al.* (2015); Hajbabaie, Aghdashi and Rouphail (2016). We also reported the level of travel time reliability (LOTTR) index, which is the ratio of the 80^{th} to the 50^{th} percentile of travel times. The LOTTR values less than 1.5, which is recommended by the National Performance Management Measures (Waddell, Remias and Kirsch, 2020), show a reliable travel time performance.

6. Results

This chapter discusses the performance of the MultiModal Signal Control (MMSC) methodology on mobility, progression quality, and travel time reliability in all three case study networks.

6.1. Mobility

Table 6-1 shows the number of completed trips and total delay for SR-522 arterial street obtained by the signal control systems using (a) Loop Detector data, (b) CV data, and (c) CV & Loop Detector data. The results show that during the PM peak hour, utilizing CV and Loop Detector data allowed the signal control system to reduce the total delay by 9% to 34% compared to utilizing only Loop Detector data. Moreover, the integration of CV and detector data let the signal controller consistently complete 2% to 3% more trips than the control strategy with only loop detector data. On the other hand, the control strategy with CV-only data required respectively 20% and 30% CV market penetration rate to have a lower network delay and a higher number of completed trips than Loop Detector data. These market penetration rates are shown with a star in the table and are called critical market penetration rates.

Similar trends were observed during the AM peak period. For instance, the signal control systems with CV & Loop Detector data reduced total delay by 24% to 55% and increased completed trips by 11% to 20%. The study network was more congested during PM peak compared to AM peak hours since the number of vehicles was increased by 13%. Using CV-only data for signal control yielded higher delays and lower completed trips than using only Loop Detector data at penetration rates up to 30% and 20%, respectively during the AM peak hours.

Table 6-1. Mobility performances in SR-522, Seattle, WA at different times of the day

Period	Measure	Penetration rate (%)	Data source			% Difference	
			Loop Detector (A)	CV-only (B)	CV & Loop (C)	(B) and (A)	(C) and (A)
PM peak	Total completed trips (count)	10	7600	6741	7727	-11.3	1.7
		20		6904	7751	-9.2	2.0
		30*		7609	7779	0.1	2.4
		40		7622	7800	0.3	2.6
		50		7626	7783	0.3	2.4
		60		7633	7797	0.4	2.6
		70		7797	7789	2.6	2.5
		80		7635	7812	0.5	2.8
		90		7794	7804	2.6	2.7
		100		7785	7785	2.4	2.4
	Total delay (hr)	10	179.4	213.4	162.6	19.0	-9.4
		20*		169.9	149.5	-5.3	-16.7
		30		147.7	135.1	-17.6	-24.7
		40		128.2	131.9	-28.5	-26.5
		50		124.8	127.9	-30.4	-28.7
		60		117.8	124.0	-34.3	-30.9
		70		117.8	123.1	-34.3	-31.4
		80		118.7	119.3	-33.8	-33.5
		90		117.7	118.7	-34.4	-33.8
		100		117.7	117.7	-34.4	-34.4
AM peak	Total completed trips (count)	10	5807	4462	6454	-23.2	11.1
		20		5322	6511	-8.4	12.1
		30*		5869	6710	1.1	15.5
		40		5962	6818	2.7	17.4
		50		5948	6828	2.4	17.6
		60		5999	6874	3.3	18.4
		70		6003	6870	3.4	18.3
		80		6455	6834	11.2	17.7
		90		6525	6573	12.4	13.2
		100		6957	6957	19.8	19.8
	Total delay (hr)	10	163.4	164.6	130.8	0.9	-24.5
		20*		148.8	121.0	-11.0	-31.8
		30		151.5	123.2	-9.0	-30.2
		40		144.6	118.1	-14.1	-34.0
		50		133.7	114.5	-22.3	-36.7
		60		119.0	94.2	-33.3	-51.9
		70		113.7	90.7	-37.3	-54.5
		80		124.2	99.4	-29.4	-48.0
		90		90.7	90.7	-54.5	-54.5
		100		90.7	90.7	-54.5	-54.5

* Critical CV penetration rate

Table 6-2 compares the number of completed trips and total delay in SR-503 arterial when different sources of data are used for signal control.

Table 6-2 Mobility performances in SR-503, Vancouver, WA at different time of the day

Period	Measure	Penetration rate (%)	Data source			% Difference	
			Loop Detector (A)	CV-only (B)	CV & Loop (C)	(B) and (A)	(C) and (A)
PM peak	Total completed trips (count)	10	11040	10827	11040	-1.9	0.0
		20		11019	11040	-0.2	0.0
		30		11039	11063	0.0	0.2
		40*		11048	11069	0.1	0.3
		50		11060	11062	0.2	0.2
		60		11072	11075	0.3	0.3
		70		11072	11060	0.3	0.2
		80		11065	11053	0.2	0.1
		90		11070	11073	0.3	0.3
		100		11067	11067	0.2	0.2
	Total delay (hr)	10	161.3	227.3	115.1	40.9	-28.7
		20*		141.9	107.4	-12.1	-33.4
		30		116.6	100.4	-27.7	-37.8
		40		105.8	97.8	-34.4	-39.4
		50		102.0	96.9	-36.8	-39.9
		60		98.2	95.0	-39.1	-41.1
		70		93.7	95.0	-42.0	-41.1
		80		91.0	91.4	-43.6	-43.3
		90		90.7	93.9	-43.8	-41.8
		100		90.1	90.1	-44.1	-44.1
AM peak	Total completed trips (count)	10	8010	7933	8017	-1.0	0.1
		20		7985	8016	-0.3	0.1
		30		8007	8013	0.0	0.0
		40		8008	8022	0.0	0.1
		50*		8011	8018	0.0	0.1
		60		8015	8020	0.1	0.1
		70		8020	8029	0.1	0.2
		80		8030	8014	0.2	0.0
		90		8021	8019	0.1	0.1
		100		8019	8019	0.1	0.1
	Total delay (hr)	10	68.8	144.7	64.3	110.4	-6.5
		20		92.3	61.6	34.3	-10.4
		30		74.5	59.7	8.3	-13.2
		40*		67.5	58.3	-1.8	-15.2
		50		63.1	56.5	-8.2	-17.8
		60		58.7	54.3	-14.6	-21.1
		70		56.4	54.5	-18.0	-20.8
		80		54.7	52.8	-20.5	-23.2
		90		53.4	53.1	-22.3	-22.8
		100		51.4	51.4	-25.3	-25.3

* Critical CV penetration rate

The signal control strategy with CV & Loop Detector data reduced total delay respectively by 28% to 44% and by 6% to 25% in the PM and AM peaks compared to using only Loop Detector data. The number of completed trips did not change considerably. Furthermore, the control system with CV-only data respectively required a 20% and 40% CV market penetration rate in the PM and AM peaks to yield lower total delay.

Table 6-3 shows the analysis results for the SR-27 arterial street. The integration of CV and Loop Detector data in the signal control strategy reduced total delay by 14% to 34% during the PM peak hour compared to utilizing Loop Detector data alone. On the other hand, the reduction of the delay was 0% to 22% and 12% to 32% during MID and AM peak hours, respectively. We observed a similar number of completed trips for the control strategy with CV & Loop Detector data over all CV market shares.

Table 6-3 Mobility performances in SR-27, Spokane Valley, WA at different time of the day

Period	Measure	Penetration rate (%)	Data source			% Difference	
			Loop Detector (A)	CV-only (B)	CV & Loop (C)	(B) and (A)	(C) and (A)
PM peak	Total completed trips (count)	10	7314	6762	7342	-7.5	0.4
		20		7092	7349	-3.0	0.5
		30		7298	7340	-0.2	0.4
		40		7300	7338	-0.2	0.3
		50*		7334	7343	0.3	0.4
		60		7335	7352	0.3	0.5
		70		7345	7341	0.4	0.4
		80		7345	7348	0.4	0.5
		90		7344	7345	0.4	0.4
		100		7344	7344	0.4	0.4
	Total delay (hr)	10	73.8	184.0	63.0	149.2	-14.6
		20		142.0	59.5	92.3	-19.5
		30		93.0	57.6	26.0	-21.9
		40		75.3	55.0	1.9	-25.5
		50*		61.4	52.1	-16.9	-29.4
		60		55.8	52.0	-24.4	-29.6
		70		55.3	52.0	-25.1	-29.6
		80		51.4	50.0	-30.4	-32.3
		90		50.0	49.3	-32.3	-33.3
		100		49.1	48.8	-33.5	-34.0

Period	Measure	Penetration rate (%)	Data source			% Difference	
			Loop Detector (A)	CV-only (B)	CV & Loop (C)	(B) and (A)	(C) and (A)
MID peak	Total completed trips (count)	10	5966	5741	5962	-3.8	-0.1
		20		5871	5968	-1.6	0.0
		30		5846	5971	-2.0	0.1
		40		5924	5971	-0.7	0.1
		50		5942	5971	-0.4	0.1
		60		5956	5973	-0.2	0.1
		70*		5970	5977	0.1	0.2
		80		5966	5974	0.0	0.1
		90		5976	5976	0.2	0.2
		100		5967	5973	0.0	0.1
	Total delay (hr)	10	47.7	191.1	47.7	300.6	0.1
		20		116.6	44.1	144.4	-7.5
		30		90.2	43.2	89.2	-9.4
		40		74.1	41.7	55.4	-12.6
		50		59.5	39.9	24.7	-16.4
		60		48.9	39.4	2.5	-17.4
		70*		43.7	39.6	-8.4	-17.0
		80		40.4	37.8	-15.2	-20.7
		90		38.9	37.6	-18.3	-21.2
		100		37.9	37.1	-20.6	-22.2
AM peak	Total completed trips (count)	10	5035	4584	5040	-9.0	0.1
		20		4966	5042	-1.4	0.1
		30		4976	5038	-1.2	0.1
		40		5011	5044	-0.5	0.2
		50		5015	5048	-0.4	0.3
		60		5028	5050	-0.1	0.3
		70*		5040	5047	0.1	0.2
		80		5036	5040	0.0	0.1
		90		5045	5046	0.2	0.2
		100		5047	5042	0.2	0.1
	Total delay (hr)	10	50.7	193.0	44.5	280.4	-12.2
		20		116.3	42.3	129.1	-16.7
		30		88.7	40.6	74.7	-20.1
		40		76.3	38.7	50.3	-23.8
		50		56.8	38.1	11.9	-24.8
		60*		49.1	36.8	-3.2	-27.5
		70		43.3	36.9	-14.6	-27.3
		80		39.5	35.5	-22.2	-30.1
		90		35.8	34.4	-29.4	-32.2
		100		34.5	34.3	-32.1	-32.4

* Critical CV penetration rate

The signal control strategy with CV-only data required 50%, 70%, and 60% CV market shares to reduce the travel delay below what was found by using only Loop Detector data during PM, MID, and AM peak hours, respectively.

Table 6-4 shows the critical CV market share for all the case studies. We defined the critical penetration rate as the required CV penetration rate for the signal control system with CV-only data to outperform the signal control system with Loop Detector data in both delay and the number of completed trips. A quick observation from this table is that the critical market penetration rates highly varies across sites and times of the day. The main reason is that the CV market share that is required to outperform existing adaptive signal controls based on Loop Detector data is not only a function of the percentage of CVs but also a function of the number of CVs present at the intersection vicinity, how traffic volume is distributed in the arterial street, and if any intersection has a high traffic volume in both major and minor directions. On SR-522 and SR-503, traffic volume is high and traffic volume on the arterial street is higher than the minor streets. On the other hand, traffic volume on SR-27 in major directions is lower than those on SR-522 and SR-503. In addition, there is a high traffic volume crossing the arterial street on the third intersection. Therefore, while a similar CV market shares of 30% to 40% on SR-522 and SR-503 is required to outperform Loop Detector based signals, the required percentage of CVs on SR-27 is higher than SR-522 and SR-503.

Table 6-4 Critical CV penetration rate for all case study networks

Study network	Period		
	PM peak	MID	AM peak
SR-522	30%	-	30%
SR-503	30%	-	50%
SR-27	50%	70%	70%

Figure 6-1 shows the average delays and travel times found by the adaptive signal control strategy for each vehicle class (i.e., passenger cars and transit buses), analysis scope (i.e., the entire network, major direction, and minor direction), data source (i.e., Loop Detector, CV-only, and CV & Loop Detector), and CV penetration rate (0% to 100%) on SR-522 corridor during the PM peak period.

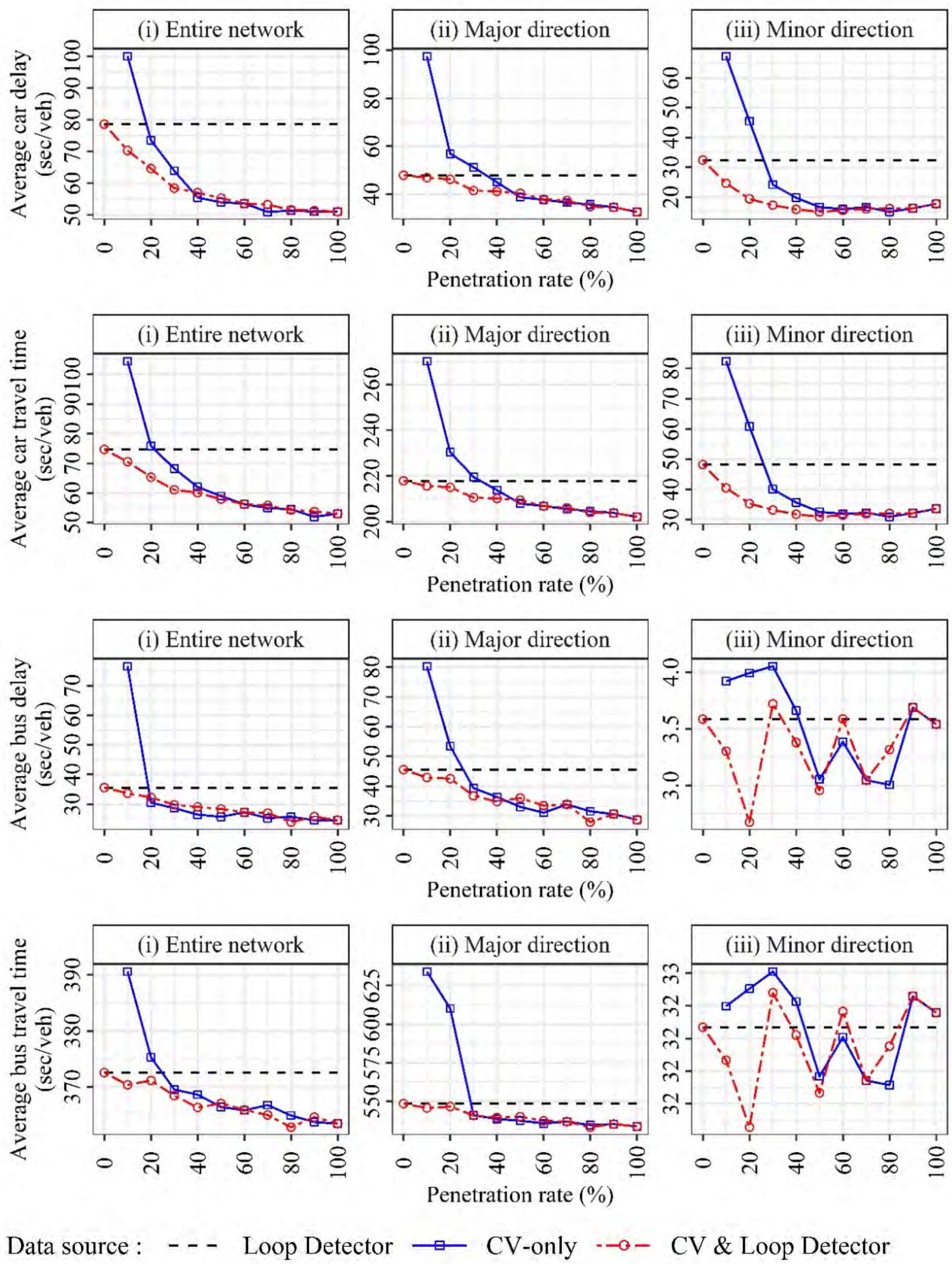


Figure 6-1 Average delays and travel times in SR-522 during the PM peak period.

The results indicate that the reduction of average car travel times in the minor streets were more significant than the major direction. For instance, integrating CV and Loop Detector data in the signal control system yielded between 2% and 32% reduction in the average car travel time in the major direction while reductions were between 24% to 54% in minor streets. In fact, while car travel time savings may seem negligible for up to 20% CV penetration rate in the major direction, even a 10% CV market share reduced average travel time by 24% on the minor streets. This saving is significant and is often ignored when a system-level analysis is considered without analyzing different directions separately. We observed similar trends on other corridors which indicates that even a low number of CVs can lead to significant reductions in car travel time on minor streets. The main findings of the direction-wise analysis of SR-522 during the PM peak hour follow:

a) Passenger cars: Integrating CV and detector data resulted in lower average travel times and delays compared to only using CV data in both major and minor directions up to 50% CV market share. Beyond this market share range, the average travel times and delays were similar. This observation was expected because integrating CV and detector data resulted in higher observability when there are not enough CVs in the traffic stream. The additional information provided by the detectors at CV penetration rates above 50% was marginal and did not yield significant changes in the average delays or travel times.

b) Transit buses: Integrating CV and detector data yielded lower average bus travel times and delays for CV market shares of up to 30% compared to using CV-only data. This trend is observed by looking at network-level and major-direction-level findings. The changes in travel times and delays in the minor directions did not show a consistent trend with the changes in the CV market share. The inconsistency may be due to a smaller hourly transit volume in the minor directions (24 transit buses/hour) compared to the major direction (40 transit buses/hour). Therefore, the signal controller prioritized the major direction where higher delays or travel times could be reduced. The discussion can be supported by the delay and travel time trends in the major direction where a more consistent decreasing trend was observed.

The adaptive signal controller used in this project allocated green times efficiently to each movement based on their approaching volume. In fact, while we integrate CV data with Loop Detector data, the allocated green times over different CV market shares became similar. In general, the signal controller gives priority to the major streets with higher demand. However, the control system allocated significant green times to movements from minor streets and left-turning movements from the major direction corresponding to their traffic volume level. As such, the signal controller can significantly improve mobility in major direction and minor streets. Note that most of the existing adaptive signal control systems mainly focus on major streets ignoring the opportunity of improving traffic operations on minor streets.

6.2. Travel time reliability

Figure 6-2 shows the Cumulative Distribution Functions (CDFs) of travel times for each vehicle class (i.e., passenger cars, transit buses, and all vehicles) in the major direction of SR-522 corridor during the PM peak period. The figure shows an overall improving trend in the travel time reliability as the CV market share increases. This is shown by CDFs following a more vertical shape at higher CV market shares. However, increasing the CV market share led to more significant changes in CDFs in the control strategy with CV-only data compared to integrated CV & Detector data. In fact, we observed a significant improvement in travel time reliability (i.e. reduction in standard deviations in travel times) as CV market share increased from 10% to 40% for the CV-only case.

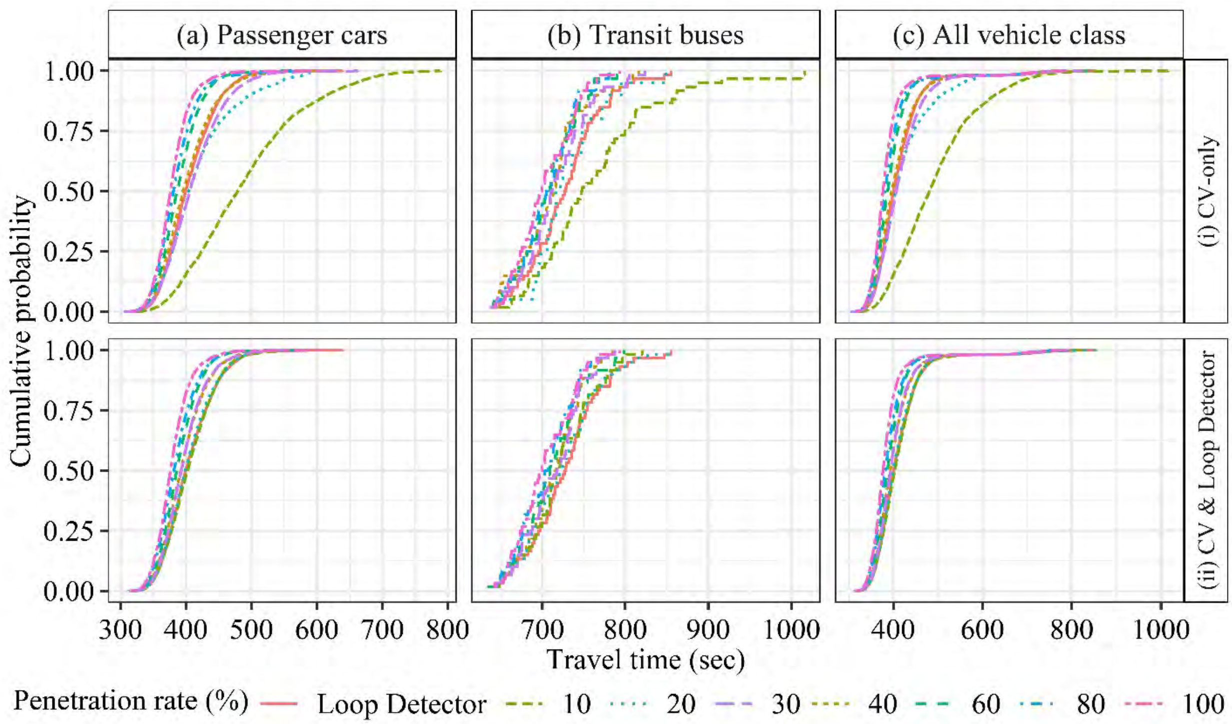


Figure 6-2 Travel time cumulative distribution functions in SR-522 during the PM peak.

Figure 6-3 shows the CDFs of travel times for all vehicles in SR-522 corridor during the AM peak period. The trends are similar to the cases that were discussed previously.

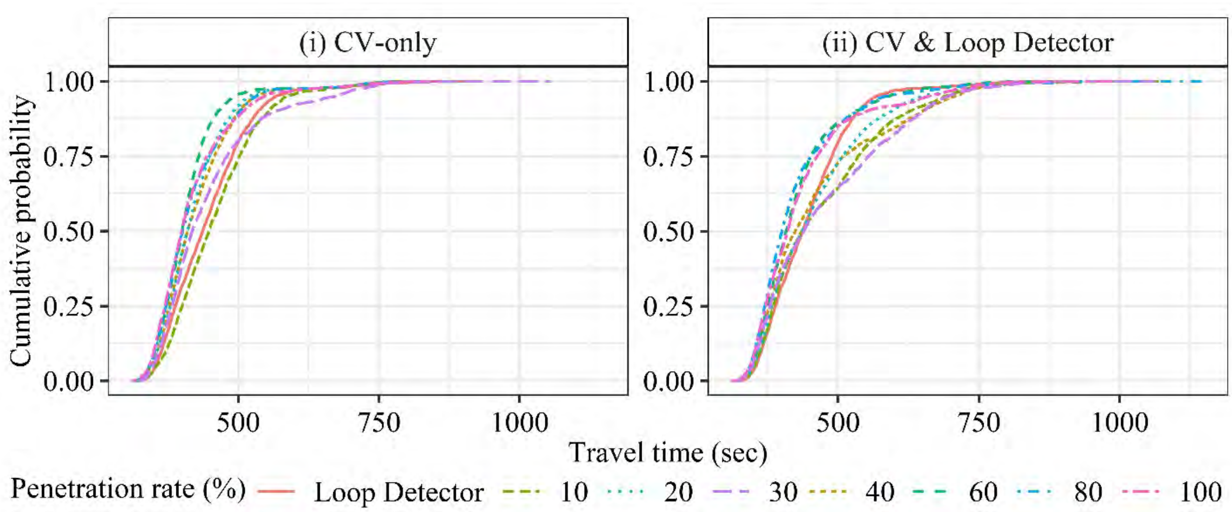
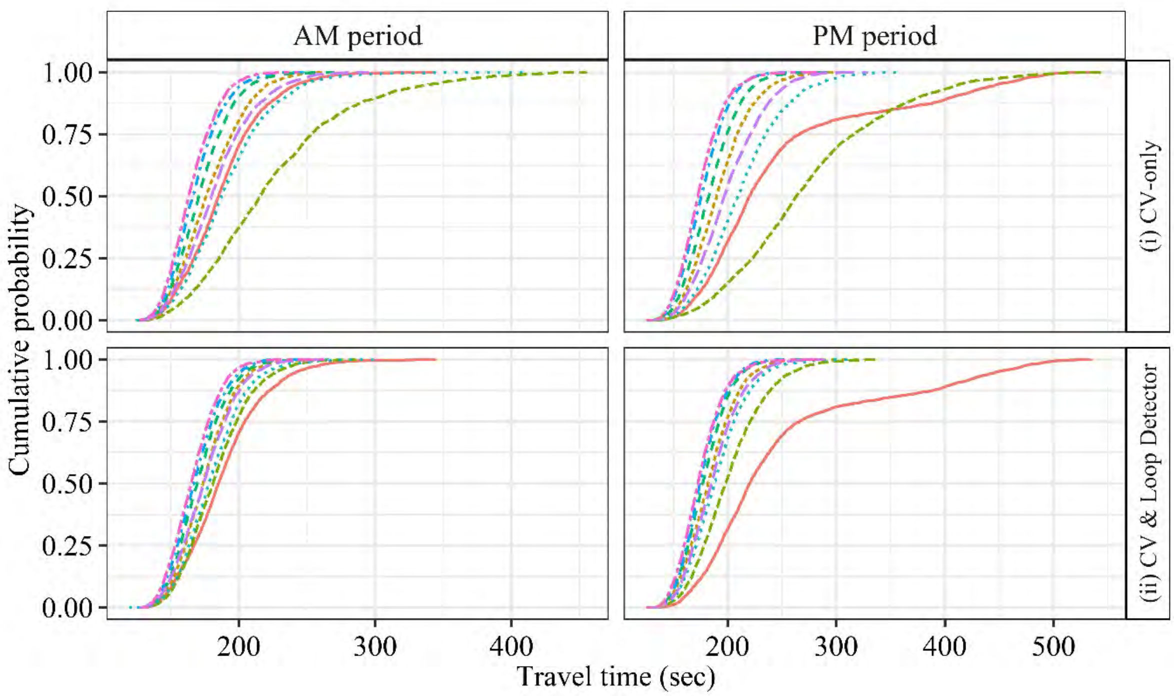


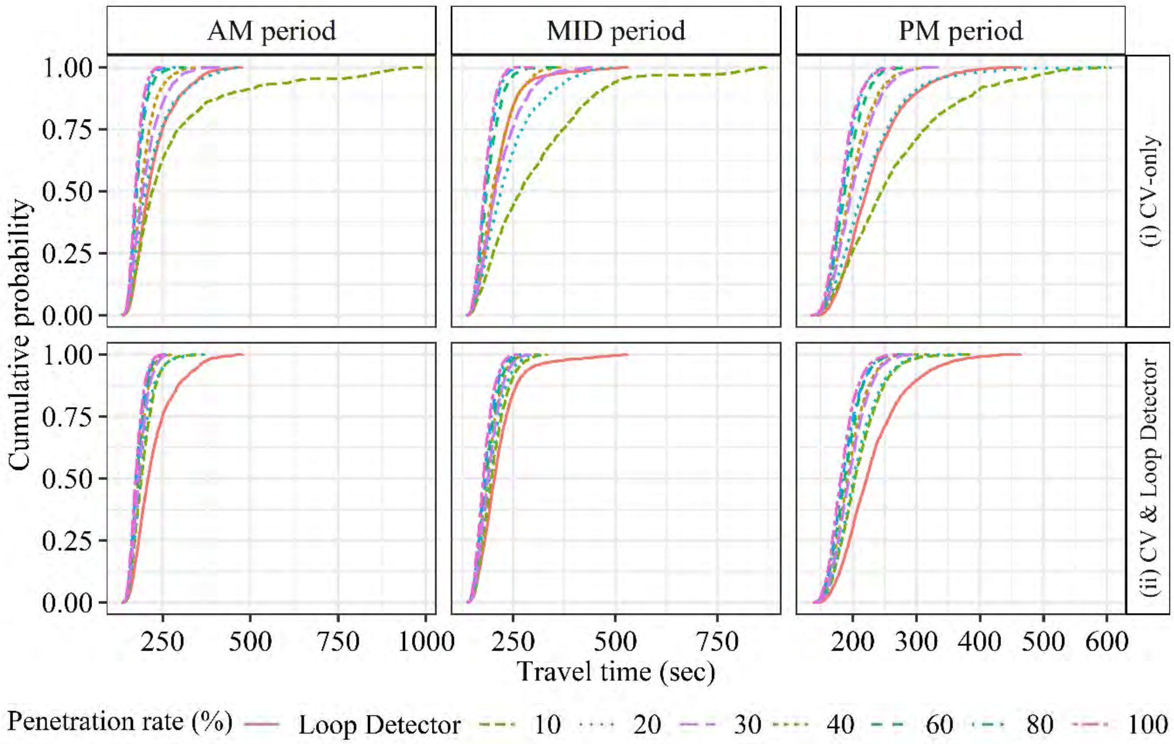
Figure 6-3 Travel time cumulative distribution functions in SR-522 during the AM peak.

Figure 6-4 shows CDFs of travel times for all vehicles during different times of the day on SR-503 and SR-27 corridors. As was expected, the signal control strategy with integrated data from

CVs and Loop Detectors yielded an improved distribution of travel time for both corridors. On the other hand, when only CV data was used, the improvement in travel time distribution largely depended on the corridor type, traffic volume, and CV penetration rate. For instance, the signal control strategy with CV-only data required a 20% CV market share to produce a better travel time distribution in the SR-503 corridor compared to using Loop Detector data. However, different market shares of CVs were required for the SR-27 corridor during different times of the day. For instance, the signal controller with only CV data required 20%, 30%, and 20% CV market shares in respectively AM, MID, and PM peak periods to outperform the signal controller with only Loop Detector data.



(a) SR-503, Vancouver, WA



(b) SR-27, Spokane Valley, WA

Figure 6-4 Travel time cumulative distribution functions during different times of the day.

Figure 6-5 provides further numerical analyses on travel times of vehicles in all corridors studied in this research. The Level of Travel Time Reliability (LOTTR) index in all evaluated scenarios was less than the suggested threshold by the National Performance Management Measures (Waddell, Remias and Kirsch, 2020). LOTTR shows a decreasing trend (i.e., improving travel time reliability) with the CV market shares. The adaptive signal controller with only CV data required a 30%, 0%, and 30% CV penetration rate to achieve the same reliability of Loop Detector data under the PM peak traffic for SR-522, SR-503, and SR-27 corridors, respectively.

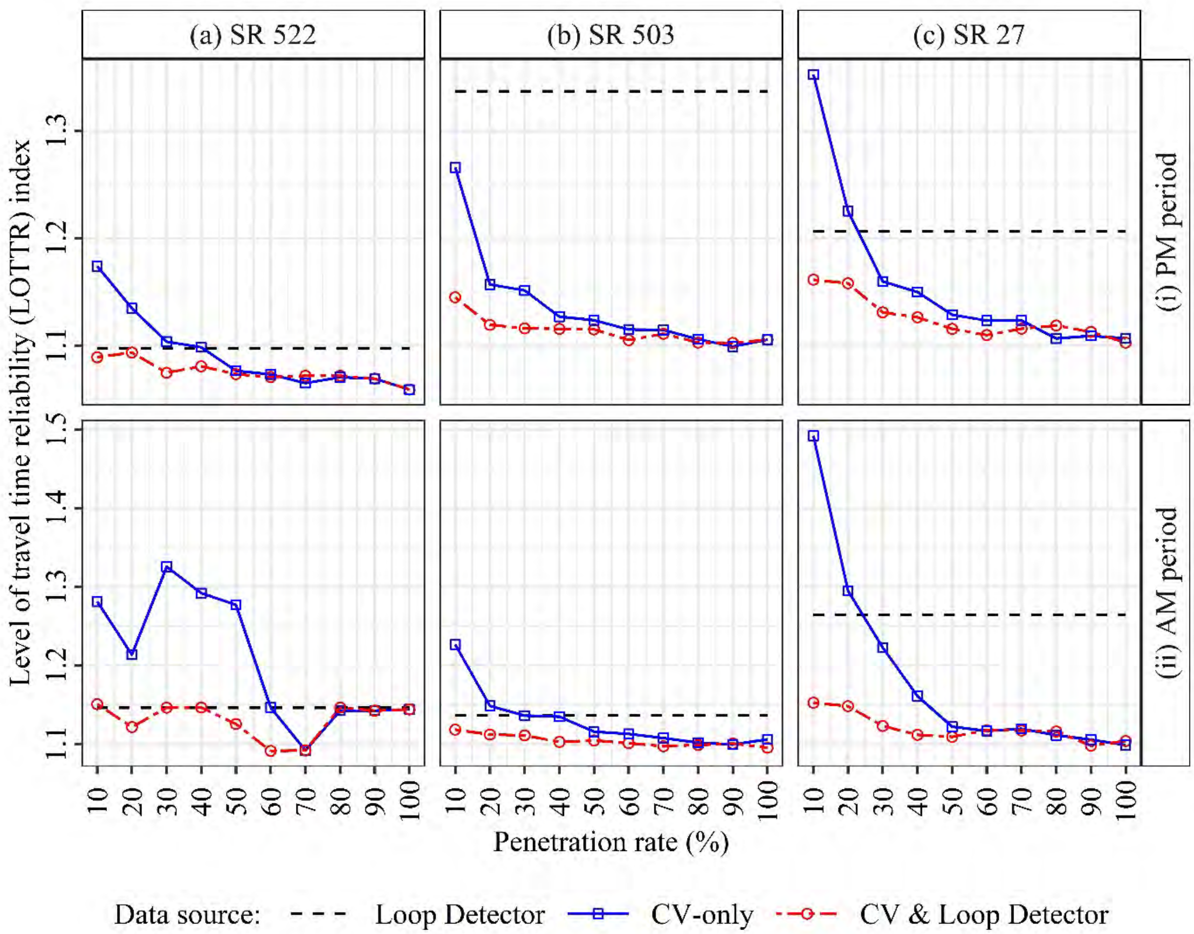


Figure 6-5 LOTTR Index for different CV penetration rates

Figure 6-6 shows LOTTR values for passenger cars and transit buses separately for the SR-522 corridor during the PM peak hour. The main findings follow:

a) The range of LOTTR variation for passenger cars was between 1.056 and 1.165 while this range was between 1.030 and 1.086 for transit buses. Therefore, transit buses had more reliable travel times compared to passenger cars across different CV penetration rates and data sources. The reason for this observation was that transit buses were all connected, as such signal timings could effectively accommodate them.

b) The adaptive signal control based on solely CV data required a 40% CV penetration rate to yield an LOTTR index lower than using only Loop Detector data for both passenger cars and transit buses.

c) The changes in LOTTR indices for transit buses did not show a consistent trend with the changes in the CV market share. In fact, the signal controller with CV & Loop Detector data performed poorly compared to Loop Detector data in high CV market shares. Since all transit buses are connected, the signal controllers are completely aware of the approaching buses, however; they receive limited information from the surrounding vehicles within the proximity of the intersection. The signal control system may overlook the impact of prioritizing buses on passenger cars due to the limited observability of the condition around the intersection.

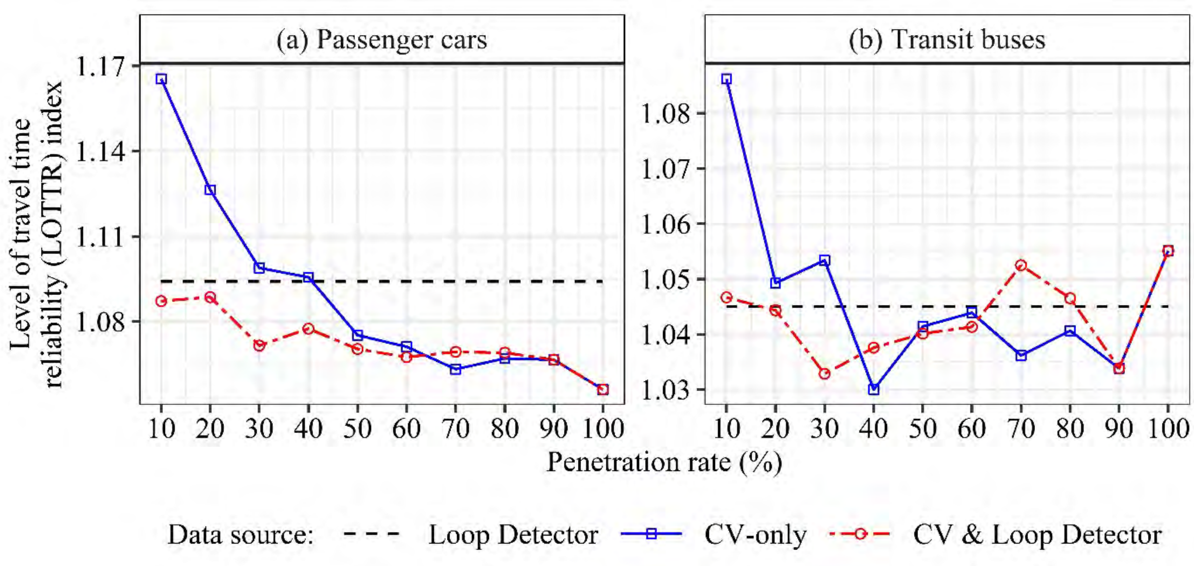


Figure 6-6 LOTTR Index for each vehicle class

6.3. Progression Quality

Figure 6-7 shows Purdue Coordination Diagrams (PCDs) for four sample intersections in the SR-522 corridor. The PCDs are drawn for both through movements (i.e., eastbound and westbound) in the major direction along the SR-522 corridor for the signal control strategy with only CV data at 30% market share in the under PM peak hour. This case represents the minimum penetration rate that provides a comparable mobility performance to signal control based on only

Loop Detector data. The four sample intersections presented in Figure 6-7 represent different types of movements in a corridor in terms of coordination (i.e., entry, coordinated, and non-coordinated movements). For instance, intersections 1 and 10 are located at the entry points of the arterial street. As such, we observed large gaps between vehicles entering the arterial street (see intersection 1 westbound and intersection 10 eastbound). These patterns are expected for entry movements with random vehicle arrivals. We observe good progression quality for coordinated movements at intersection 2 with more than 70% of vehicles arrived during the green times. PCDs corresponding to intersection 2 show the progression of tightly-clustered vehicles with no wasted green times. The presence of vehicle groups that progress through the intersection during the green interval of each cycle is an indication of good progression quality. Similarly, 80% of vehicles arrive on the green on eastbound through movement of intersection 1 and 82% on westbound through movement of intersection 10. It is worth mentioning that incoming volumes from minor streets in intersections 1, 2, and 10 constitute a small portion of the total volumes that each of these intersections handles. As such, the controller can focus on improving the progression quality of incoming platoons.

Note that the location of intersection 6 was more than 2500 feet away from the upstream and downstream intersections and was not coordinated. PCDs corresponding to intersection 6 confirm poor progression in both eastbound and westbound movements; two contributing factors include: 1) the controller had no information about the incoming platoons and operated the signal plans from a local perspective rather than improving the quality of progression, and 2) a high percentage of turning movements at southbound right and eastbound left movement left limited room for the controller to improve the progression quality. All PCDs in Figure 6-7 show a significant number of CVs and transit buses arrive at the intersections during the green signal. As CVs and buses continuously communicate with the controllers, the signal systems facilitate their smooth progressions throughout the corridor. This implies that increasing the CV market shares improves the quality of progression.

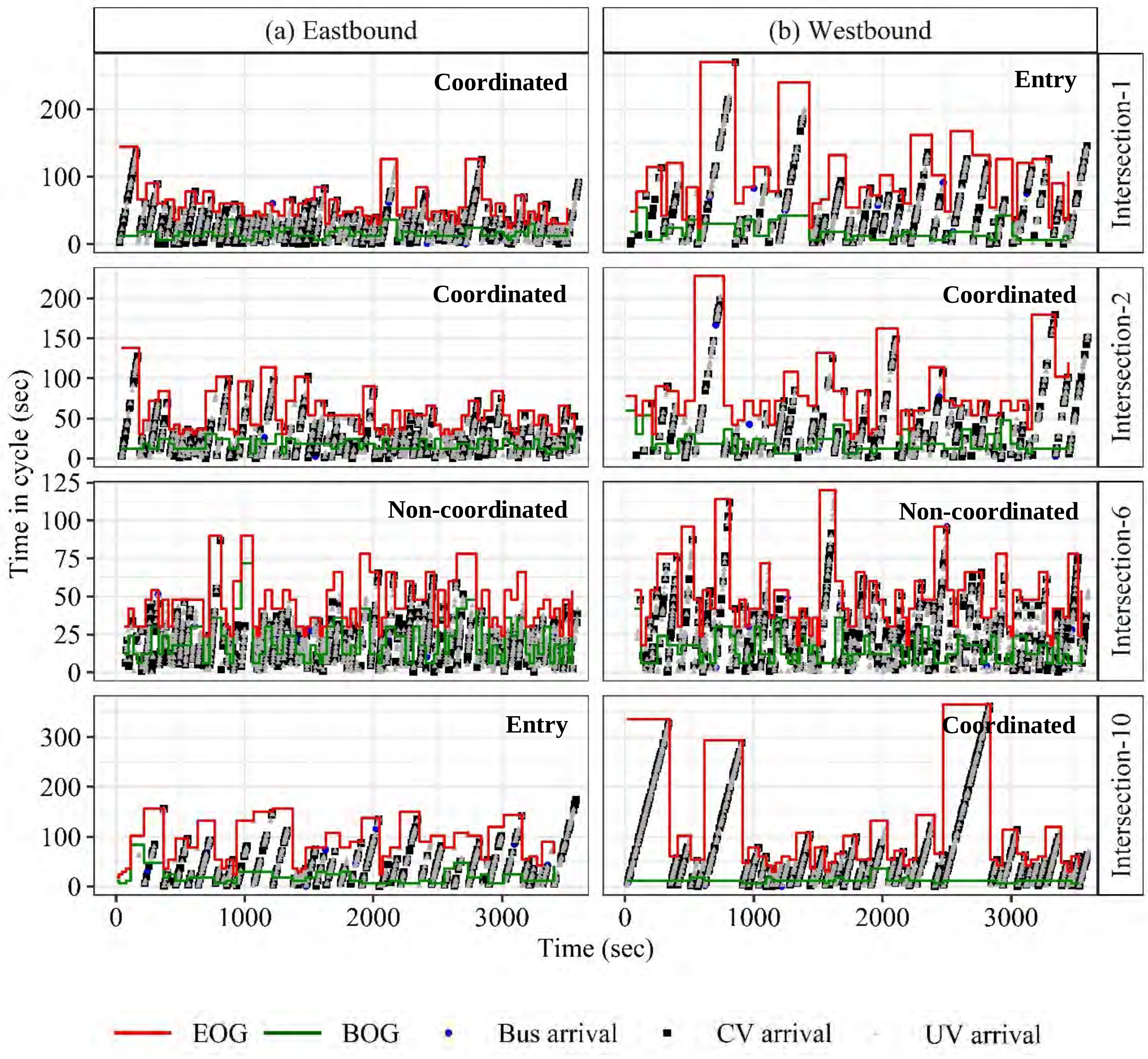
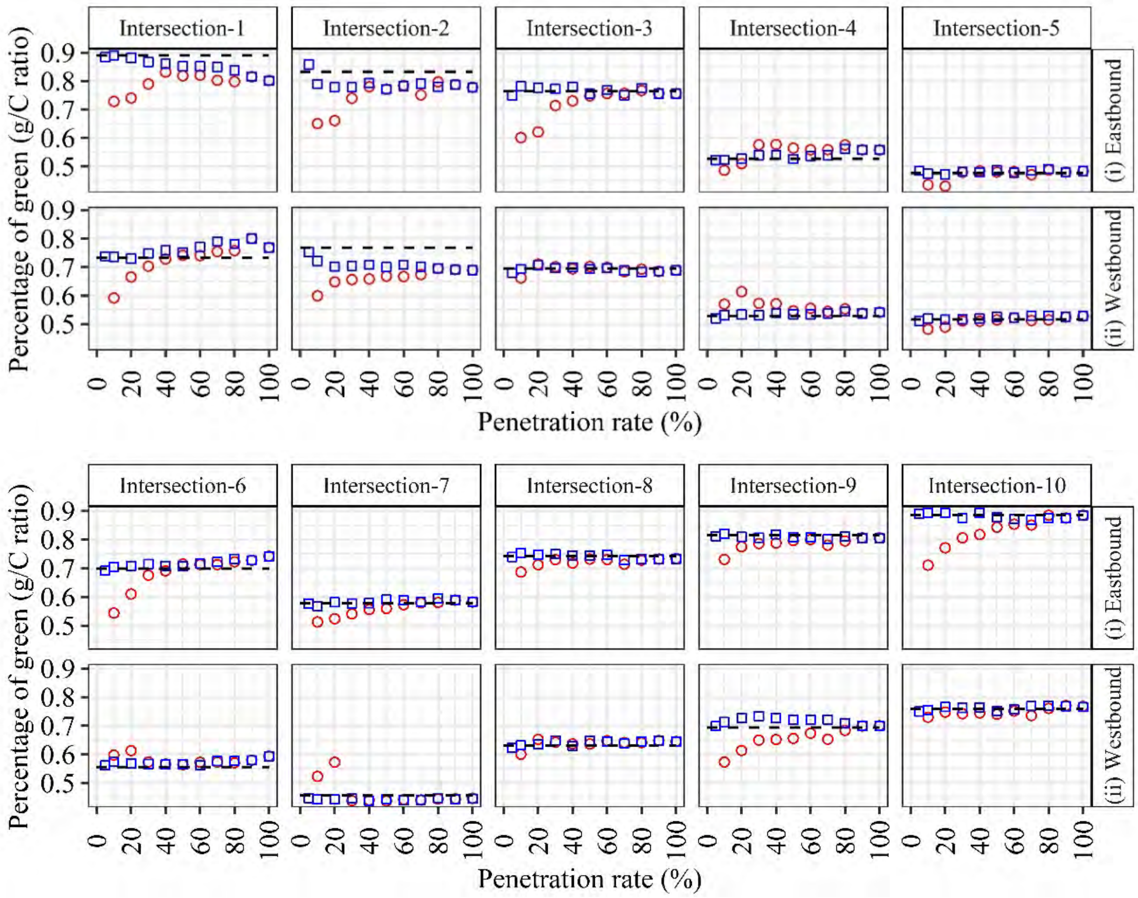
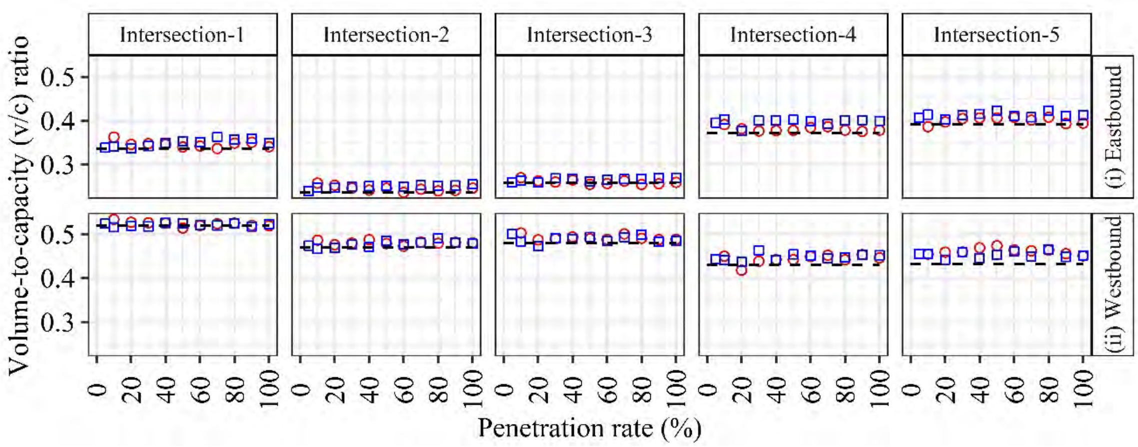


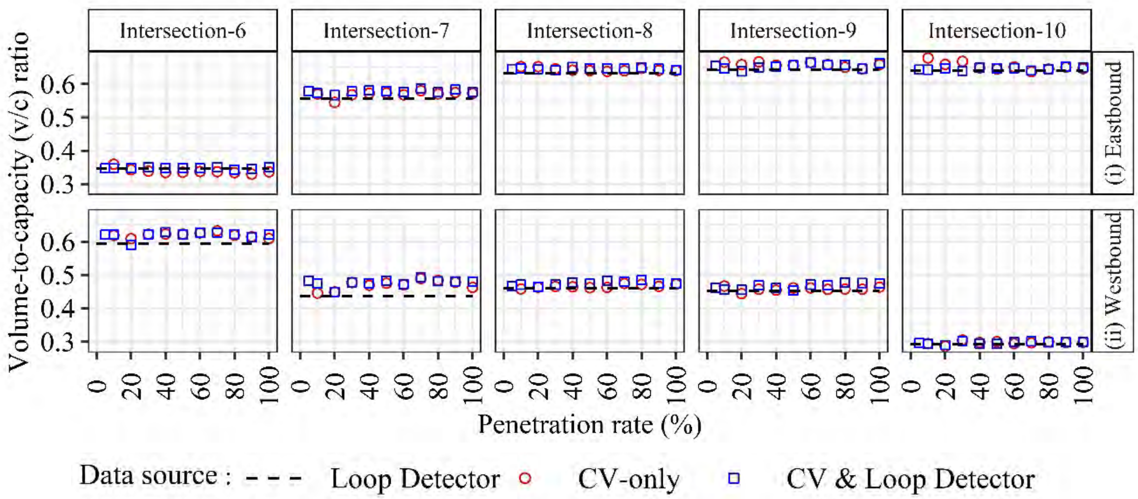
Figure 6-7 PCDs for the signal control with CV-only data and 30% penetration rate.

Figure 6-8 shows green-to-cycle length (g/C) and volume-to-capacity (v/c) ratios for the signal control strategy with all three data sources. The metrics are corresponding to major directions of all intersections in the SR-522 corridor during the PM peak period. Overall, Figure 6-8(a) indicates that the control strategy with CV and detector data yielded higher g/C ratios compared to using only Loop Detector data. This observation is an indication of an effective allocation of green times to major directions. Intersections 4, 5, and 7 had lower g/C ratios due to high volumes on the minor directions and greater turning ratios compared to other intersections. For instance, both eastbound and westbound movements in intersection-5 received the lowest g/C ratios as the incoming vehicles from the northbound direction were very high. A similar trend was observed at intersection-7 with high volume from the southbound direction. Furthermore, the westbound movement received slightly less green time (50% of the total study period) compared to the eastbound movement (54%) due to the high eastbound left-turning vehicles. Furthermore, Figure 6-8(b) shows that the v/c ratios corresponding to the major directions are less than 0.90. This indicates that the controllers managed to provide adequate capacity and vehicles did not experience significant queues and delays (Rodegerdts *et al.*, 2004). Moreover, with increasing CV market shares, the g/C ratio obtained by the signal control strategies with or without integrating Loop Detector data became stable. The g/C ratios of coordinated movements corresponding to both strategies become similar with more than 40% CVs. This implies that increasing the number of CVs enables the system to get a reliable estimation of traffic state around the intersections and thus, provides stable g/C ratios that resemble the approaching volume. Furthermore, non-coordinated phases as indicated in Figure 6-8(a) require CV penetration rates to be more than 60% to get stable g/C ratios.


Intersection-1
Intersection-2
Intersection-3
Intersection-4
Intersection-5
Intersection-6
Intersection-7
Intersection-8
Intersection-9
Intersection-10
(i) Eastbound
(ii) Westbound
Percentage of green (g/C ratio)
0.5 0.6 0.7 0.8 0.9
0 20 40 60 80 100
Penetration rate (%)

(a) g/C ratio


Intersection-1
Intersection-2
Intersection-3
Intersection-4
Intersection-5
(i) Eastbound
(ii) Westbound
Volume-to-capacity (v/c) ratio
0.3 0.4 0.5
0 20 40 60 80 100
Penetration rate (%)



(b) Volume to capacity (v/c) ratio

Figure 6-8 g/C and v/c ratios for SR-522 corridor during PM peak.

Similar trends were observed in other corridors. Overall, the g/C ratio became similar at high CV market shares for the control strategies that utilized CV data with or without integrating Loop Detector data. Most intersections had v/c ratios lower than 1.0 indicating that signal controllers managed to operate under capacity. However, we noticed some intersections had v/c ratios for more than 1 due to their high approaching volumes from minor directions and high left-turning traffic volume from major directions.

7. Conclusions and Recommendations

7.1. Results of survey state DOTs about their experience with DSRC implementation

The research team surveyed twenty-one state DOTs for their completed or ongoing projects on implementing DSRC enabled devices to broadcast SPaT messages. After analyzing the survey and available data on the National Operations Center of Excellence website, the research team found the following most common combinations of the signal controller and RSU types for broadcasting the SPaT message: Econolite ACS3 traffic controller and Savari RSU, SURTRAC controller and Arada RSU, Econolite Cobalt controller and Arada RSU, and McCain ATC eX controller and Arada RSU.

Most state DOTs implemented SPaT broadcast with MAP and RTCM. The most common applications are Multi-Modal Intelligent Traffic Signal System, Transit Signal Priority, Freight Signal prioritization, and Eco-driving. The research team also found that the Red-light violation warning and pedestrian detection in crosswalk applications were the most common safety-related applications. Demographic characteristics, being a part of future development, and high traffic demand levels on a corridor were the most important criteria used by state DOTs for selecting a corridor for CV application. Some other factors include variation in land use, easy access to the corridor, and favorable existing infrastructure.

7.2. Signal control in multi-modal CV environment

This project developed a Multi-modal adaptive Signal Control (MMSC) methodology for urban streets with various market penetration rates of CVs. The methodology prioritized the movement of transit buses in signalized intersections. This methodology was used to study the effects of the

CV market penetration rate on traffic operations in urban streets with different traffic demand levels and transit bus activities. The research team specifically studied the effects of using (1) CV-only data, and (2) integrated CV & Loop Detector data in comparison to using only Loop Detector data as the benchmark. The research team simulated three corridors identified by WSDOT under actual demand volumes in the AM and PM peak hours. These corridors were: SR-522 in Seattle, SR-503 in Vancouver, and SR-27 in Spokane. Key findings are:

1. The mobility performance measures in CV-based signal control strategies improved with penetration rates. However, the signal system with CV-only data requires 30%, 50%, and 70% CV market shares, respectively in SR-522, SR-503, and SR-27 corridors to outperform signal control with only Loop Detector data. However, the integration of CV and Loop Detector data can help consistently outperform Loop Detector-based signals at a low CV penetration rate, even at 10%.
2. The results showed that with 60% CV in the traffic stream, mobility performance measures for passenger cars under signal control strategies with or without integrating Loop Detector data became similar. On the other hand, similar mobility performance measures for transit buses can be achieved at 20% CVs.
3. With increasing CV penetration rates, the g/C ratios corresponding to coordinated phases in signal control strategies with CV-only and CV & Loop Detector data become similar at 40% CV market penetration rate. On the other hand, non-coordinated phases require CV penetration rates of more than 60%. The CV-based signal strategies provide a considerable portion of green times to movements on minor streets (when traffic volume is high), which may lead to a reduction in POG values; however, improve the overall operational performance measures.

4. LOTTR shows a decreasing trend (i.e. improving travel time reliability) with an increase in the CV market share. Combining detector data with CV data consistently provided better travel time reliability than detector-based signals. Transit buses experienced a more reliable travel time than passenger cars in low CV market penetration rates.

This research focused on signal control with CVs in corridors with passenger cars and transit buses. Further research is needed with more general settings with pedestrians, emergency vehicles, and freight trucks. The impacts of disruptions and delays in communications among vehicles and infrastructure should be further studied in the future. Finally, much research is devoted to controlling the flow of connected automated vehicles in intersections (e.g., Mirheli, Hajibabai and Hajbabaie, 2018; Mirheli *et al.*, 2019; Niroumand *et al.*, 2020a, 2020b; Tajalli and Hajbabaie, 2021). More research on traffic control on arterial corridors with connected automated vehicles is required.

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