MOUNTAIN-PLAINS CONSORTIUM

MPC 22-470 | M. Zlatkovic, M. Ahmed, Z. Cvijovic and S. Bashir

CONNECTED-AUTONOMOUS TRAFFIC CONTROL ALGORITHMS FOR TRUCKS AND FLEET VEHICLES

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Technical Report Documentation Page

1. Report No. MPC-599	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Connected-Autonomous Traffic Control Algorithms for Trucks and Fleet Vehicles		5. Report Date July 2022
		6. Performing Organization Code
7. Author(s) Dr. Milan Zlatkovic, Dr. Mohamed Ahmed, Dr. Zorica Cvijovic, Sara Bashir		8. Performing Organization Report No. MPC 22-470
9. Performing Organization Name and Address University of Wyoming, 1000 E. University Ave., Laramie, WY 82071		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Mountain-Plains Consortium, North Dakota State University, PO Box 6050, Fargo, ND 58108		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes Supported by a grant from the US DOT, University Transportation Centers Program		

16. Abstract

Connected and Autonomous Vehicle (CAV) technologies enable communication among vehicles, and vehicles and infrastructure, paving the way for multiple safety and operational applications. This research developed and tested traffic signal control algorithms and control programs, which utilized CAV-equipped heavy trucks and traffic signals. The focus of the study was on Intelligent Traffic Signals (ISIG), Freight Signal Priority (FSP), Transit Signal Priority (TSP), Queue Warning (Q-WARN), Speed Harmonization (SPD-HARM) and Emergency Preemption (PREEMPT) applications. The application, testing and analysis were performed through Traffic In Cities Simulation Model (VISSIM) microsimulation software, coupled with real-world traffic control software (Econolite ASC/3). The test-case networks included six signalized intersections adjacent to I-80 in Wyoming, and a busy urban corridor along State Street in Salt Lake City, Utah. The results showed significant improvements in operations and safety for CV-equipped vehicles. FSP can reduce intersection truck delays up to 70 percent, TSP can reduce transit delays six percent on average, SPD-HARM can reduce truck delays in excess of 80 percent, Q-WARN can significantly improve safety without impacts on operations and PREEMPT can reduce the intersection delay of emergency vehicles up to 35 percent and increase their speeds in excess of 50 percent.

17. Key Word	18. Distribution Statement
algorithms, autonomous vehicles, connected vehicles, driving simulators, emergency vehicles, freight traffic, microsimulation, optimization, signalized intersections, traffic signal control systems, truck traffic, vehicle fleets	Public distribution

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	69	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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July 2022

Acknowledgements

The authors thank the Wyoming Department of Transportation (WYDOT) and the Mountain-Plains Consortium (MPC) for funding this research, and the following individuals for their help and guidance in this research: Christina Spindler, P.E., Assistant State Traffic Engineer, WYDOT; Dr. Aleksandar Stevanovic, Associate Professor, University of Pittsburgh; and Dr. Yu Song, Postdoctoral Research Associate, Connecticut Transportation Institute.

ABSTRACT

Connected and Autonomous Vehicle (CAV) technologies enable communication among vehicles, and vehicles and infrastructure, paving the way for multiple safety and operational applications. This research developed and tested traffic signal control algorithms and control programs, which utilized CAV-equipped heavy trucks and traffic signals. The focus of the study was on Intelligent Traffic Signals (ISIG), Freight Signal Priority (FSP), Transit Signal Priority (TSP), Queue Warning (Q-WARN), Speed Harmonization (SPD-HARM) and Emergency Preemption (PREEMPT) applications. The application, testing and analysis were performed through Traffic In Cities Simulation Model (VISSIM) microsimulation software, coupled with real-world traffic control software (Econolite ASC/3). The test-case networks included six signalized intersections adjacent to I-80 in Wyoming, and a busy urban corridor along State Street in Salt Lake City, Utah. The results showed significant improvements in operations and safety for CV-equipped vehicles. FSP can reduce intersection truck delays up to 70 percent, TSP can reduce transit delays six percent on average, SPD-HARM can reduce truck delays in excess of 80 percent, Q-WARN can significantly improve safety without impacts on operations and PREEMPT can reduce the intersection delay of emergency vehicles up to 35 percent and increase their speeds in excess of 50 percent.

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EXECUTIVE SUMMARY

The goal of this study is to develop and test traffic signal control algorithms which use Connected and Autonomous Vehicle (CAV) technologies to optimize signal operations, enable special signal control (such as priority and preemption) and CAV mobility and safety applications. Connected Vehicle (CV) technologies enable vehicles to exchange information with each other (vehicle-to-vehicle [V2V]) and with the roadside infrastructure (vehicle-to-infrastructure [V2I]) in real-time, using wireless-based communication technologies. The communication allows for sharing vital transportation information among the roadway users. The CV equipment continually transmits vehicle position, direction, speed, and other information, such as the status of vehicle's systems, to other vehicles in the vicinity. It also allows vehicles to communicate to equipment installed in the infrastructure, such as traffic signals, signs, work or school zones, railroad crossings, etc. Automated vehicles (AV) use various technologies to sense their surroundings and take driving functions from the driver at different levels. The connected-automated vehicles integrate the functions of CVs and AVs for a greater benefit. The US DOT recognizes several areas of CAV technology applications, such as V2I safety, V2V safety, road weather, environment, and mobility, among others.

CV technologies are gaining momentum in research and practice. The benefits of these technologies are just beginning to be recognized. The limited number of field tests have proven that they can be used for different adaptive traffic control programs. There are still many areas that must be covered through research. CV applications explored in this study, defined in the USDOT CV applications for mobility, include Intelligent Traffic Signal System (ISIG), Freight Signal Priority (FSP), Transit Signal Priority (TSP), Dynamic Speed Harmonization (SPD-HARM), and Emergency Vehicle Preemption (PREEMPT). The study developed and tested CAV-based traffic signal control algorithms and programs aimed at improving operations at signalized intersections, under the assumption that most fleet vehicles will be equipped with the new technologies in the near future. The test locations were intersections in Wyoming, adjacent to I-80 in Rock Springs, Rawlins, Evanston, Laramie and Cheyenne, and a multimodal corridor in Salt Lake City, Utah. The analysis was performed considering different model scenarios with different rates of CAV-equipped trucks, transit vehicles, emergency vehicles and cars.

As a part of the ISIG applications, the study developed an approach that used the latitude and longitude (lat/long) coordinates of the CV-equipped vehicles and signalized intersections to establish communication, define the detection zone, update the position and speed of the vehicles, and the status of the current signal phase in each time step (taken as 0.1 seconds in this research). When this research was conducted, this study was the first of its kind to use actual latitude/longitude coordinates in traffic simulation of CVs. The study used the current vehicle routing, which can be communicated through the use of turn signals, to separate individual turning movements at intersections. All information shared among the vehicles and the infrastructure can be used to implement advanced traffic signal control programs.

The FSP application allows extra time for freight vehicles as they approach the signal, or wait for the signal to change, to minimize their delay. This also has safety benefits, as it reduces conflicts between heavy trucks and other vehicles, and non-motorized transportation. The algorithm developed in this study assessed the current vehicle position, speed, and signal timing state to optimize the FSP call and service. Results of the analyses showed that the FSP application has the ability to reduce the intersection delay of CV-equipped trucks between 10 and 70 percent, which, in most cases, is a statistically significant reduction. FSP also has some negative effects on other vehicles and non-FSP signal phases, which is shown on the network-wide level. However, in most cases the negative impacts are not significant.

The Q-WARN application alerts drivers of approaching vehicles that a queue exists downstream of their position. This is a common situation at approaches to signalized intersections. This application has the potential to improve safety by early alerting drivers, particularly in low-visibility conditions or where the geometry of the approach does not provide sufficient visibility. The Q-WARN application developed in this study used the position, speed, and heading of CV-equipped trucks and the current state of the signal phase on the vehicle approach to warn the truck drivers if there was, potentially, a queue at the intersection approach in their desired direction of travel, which gives them extra time to adjust their speeds as they approach the intersection. The results showed that the CV-based Q-WARN applications were effective in reducing truck delays by an average of two to five percent. The recorded vehicle spacing in the vicinity of the intersections were higher (up to 134 percent) in the CV Q-WARN models due to the earlier start of deceleration and lower lane speeds, which could be considered a safety benefit to prevent rear-end conflicts. The safety assessment of the Q-WARN algorithm showed significant safety benefits in preventing intersection-related crashes.

In addition to the control programs for heavy vehicles, this study developed, implemented, and tested priority control programs for both freight and transit vehicles. The test-case is a section of State Street, in Salt Lake City, Utah, which is a busy, transit-heavy multi-modal corridor. The implementation of unconditional signal control priority provided significant delay savings for trucks — up to 40 percent, but it also caused a significant increase in delays for other vehicles — in excess of 35 percent. Speeds for all vehicles would reduce, if unconditional Signal Control Priority (SCP) was provided to all target vehicles. The information that is sent from CV-equipped transit vehicles can be used to create different forms of conditional priority. This study used schedule adherence and real-time ridership to determine the level of granted Transit Signal Priority (TSP) for Bus Rapid Transit (BRT). Green extension, early green, and phase rotation were the strategies implemented for different combinations of vehicle lateness and ridership. The introduced TSP strategies in general reduced transit delays by about six percent, without significant impacts on other traffic and transit operations.

SPD-HARM application developed in this study applies communication between the vehicles on the same approach and heading, and between the vehicles and the traffic signal, to optimize the speed of the approaching vehicles, so they arrive at the intersection during the green interval. The application of this algorithm has the potential to significantly reduce truck delays, between four and 82 percent, depending on location.

The State Street corridor was also used to test and assess the performance of PREEMPT strategies for emergency vehicles (EV). The algorithm used the EV's location and speed to activate preemption strategies on intersection approaches and activate green light for the approaching EVs. The results showed that the implementation of CV-based PREEMPT strategies has the potential to reduce EV-signalized intersection delays up to 34 percent and increase their speeds in excess of 50 percent along busy urban corridors without impacts on other traffic.

Overall, this study shows the potential of CV technologies for the implementation of comprehensive and complex signal control programs, which can bring both operational and safety benefits. The developed algorithms and control programs are universal, meaning they can be applied to other locations and under different traffic conditions with minimum to no adjustments. The algorithms and control programs are using the existing information shared between the vehicles and the infrastructure through CV technologies.

1. INTRODUCTION

Connected vehicle (CV) technologies enable vehicles to exchange information with each other (vehicle-to-vehicle [V2V]), with the roadside infrastructure (vehicle-to-infrastructure [V2I]) and with other equipped transportation sytem users in real time, using wireless-based communication technologies (ITS JPO, 2018a). The CV systems combine different technologies, such as wireless communications, advanced vehicle sensors, advanced roadside infrastructure, and onboard computers/processing. Automated vehicles (AV) use various technologies (radar sensors, LiDar, GPS and similar) to sense their surroundings and take driving functions from the driver at different levels (ITS JPO, 2018b). The connected-automated vehicles (CAV) integrate the functions of CVs and AVs for a greater benefit. The US DOT recognizes several areas of CAV technology applications, such as V2I safety, V2V safety, road weather, environment and mobility, among others (ITS JPO, 2018c).

Traffic control signals assign the intersection right-of-way to various traffic movements and transportation modes, temporally separating the conflicting ones. Actuated traffic signal control applies vehicle detection and preset signal timing parameters to adjust the operation to varying traffic demand. Traffic signal controllers also have built-in functions to introduce special operations for emergency, transit, and freight vehicles, such as preemption and priority. The CAV technology offers new tools for detection, communication, and decision algorithms based on the wide array of information being shared among vehicles, infrastructure, and control devices. CV technologies are gaining momentum in research and practice. They can be used to implement various advanced traffic control programs aimed at improving mobility and safety at signalized intersections.

1.1 Traffic Signal Control Applications in CAV Environment

The USDOT has defined several CV applications for mobility improvements (ITS JPO, 2018c). The applications analyzed in this study include Intelligent Traffic Signal System (ISIG), Queue Warning (Q-WARN), Freight Signal Priority (FSP), Transit Signal Priority (TSP), Dynamic Speed Harmonization (SPD-HARM), and Emergency Vehicle Preemption (PREEMPT).

The Intelligent Traffic Signal System (ISIG) is using high-fidelity data collected from vehicles through V2V and V2I communications (and pedestrian and non-motorized travelers through mobile sensors) to control signals and maximize throughput in real time. The ISIG application also plays the role of an overarching system optimization application, accommodating transit or freight signal priority, preemption, and pedestrian movements to maximize the overall network performance (ITS JPO, 2018c; Yang, 2017). In a connected vehicle environment, Road Side Equipment (RSE) associated with an intersection signal controller broadcasts an intersection geometry (MAP) and signal phase and timing (SPaT) message. A vehicle with on-board equipment (OBE) that enters the range of the RSE will receive the MAP and SPaT data and will actively broadcast basic safety messages (BSMs) (Leonard, 2017; Cronin, 2012). The BSM contains static and dynamic elements of the vehicle, and the status of various vehicle systems (e.g. brakes, doors, windshield wipers etc.). Depending on the type of vehicle, it may send a signal request message (SRM) to request signal priority or preemption. In turn, the RSE sends a signal status message (SSM) with the acknowledgements of priority requests and the status of active priority/preemption request(s). This message exchange occurs in real time. This allows traffic signal control and signal priority for multiple modes to be managed within an integrated framework. Different levels of priority for eligible vehicles, whether multi-modal or within the same mode, can be assigned based on the local interpretation of signal priority importance and usefulness (Cronin, 2012; University of Arizona et al., 2016).

A majority of freight flows at their origins or destinations travel through urban areas. Certain parts of urban networks, such as industrial, warehouse or port areas, experience high volumes of truck traffic. Large trucks have significantly different physical characteristics from passenger cars, requiring more space and time for maneuvers. Therefore, the operation of traffic signals along truck routes can be modified to give certain priority for trucks, called Freight Signal Priority (FSP). This priority allows extra time for trucks to clear the intersection without stopping, or an earlier return to green phase if the truck is stopped, improving their travel time reliability and enhancing safety. Having trucks at the front of the queue is an undesirable scenario, since the start-up lost time for all vehicles is greater, and the vehicles behind have limited visibility of the traffic control devices. The benefits of FSP include, but are not limited to, reduced truck stops and delays, a reduction in truck red-light running, safer phase termination for trucks, higher capacity due to the reduced start-up lost time and similar benefits (Urbanik et al., 2015). Since more information is being transmitted through CAV communication channels, the signal controller receives more data, which can be used to adjust the operations. Therefore, additional strategies to FSP might include dynamic yellow/red clearance intervals (to allow more time for large vehicles or slow moving vehicles to clear the intersection before moving onto the next signal phase), adaptive left-turn treatments and operations (for example not allowing permitted a left-turn signal phase if large vehicles are present in the left-turn lane and the oncoming traffic volumes are high), or adaptive ring-barrier structure and sequence, that can change the order of phase sequences as needed. These additional strategies can have significant safety benefits and improve operations.

Transit Signal Priority (TSP) facilitates the movement of in-service transit vehicles through signalized intersections. Different strategies, such as green extension, early green, phase rotation, phase insertion and similar strategies are used for this purpose. The traditional TSP uses wireless communication (radar or infrared) between the transit vehicle and the traffic signal. However, the CAV technology will allow for sharing more information between the systems and providing opportunities for adaptive priority. This TSP can use the vehicles' position and speed, occupancy, schedule, door status and other information contained in the BSM to adjust the signal operation and select the optimal strategies that would benefit the transit vehicles, without impacting other traffic.

Dynamic Speed Harmonization (SPD-HARM) uses the communication among vehicles to control the speeds of clustered CAVs. The objective of this application is to dynamically adjust and coordinate maximum appropriate vehicle speeds in response to downstream congestion, incidents, and weather or road conditions to maximize traffic throughput and reduce crashes (ITS JPO, 2018c). Speed harmonization increases the capacity of traffic facilities and reduces congestions due to the phantom traffic jam effects. It also allows creating and maintaining vehicle platoons, increasing mobility through signalized intersections. The signals communicate their status (through SPaT) and the clustered vehicles will respond by adjusting and harmonizing their speeds, so the platoon reaches the signal during the green phase time.

The Queue Warning (Q-WARN) application uses CV technologies to enable vehicles within the queue to automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to upstream vehicles and to infrastructure. The queue warnings are sent to oncoming vehicles to prevent rear-end or other secondary collisions. The Q-WARN application performs two essential tasks: queue determination (detection and/or prediction) and queue information dissemination (ITS JPO, 2018c). In cases of limited visibility (either technical or environmental), the Q-WARN system can work in conjunction with the traffic controller to transmit the queue information to the vehicles approaching the intersection. This is of particular importance for heavy vehicles, due to their longer stopping distances.

Emergency Vehicle Preemption (PREEMPT) is a special signal control mode, which immediately alters traffic signal operation for the purpose of serving the approaching emergency vehicle (Urbanik et al., 2015). PREEMPT terminates the normal signal operation to perfom this task. Preemption can also be used for other purposes, such as railroad crossings or serving public transit vehicles. This study focuses only on emergency vehicles (EV), but the developed concept can also be applied in other cases. On-time detection and service request is critical in implementing preemption. Traditionally, radar of infrared communication has been used to establish a connection between the approaching EV and the traffic signal, and request preemption. With the implementation of CV technologies, preemption can be improved by utilizing the information sent by the EV.

1.2 Study Objectives and Methodology

The goal of this study is to develop and test traffic signal control algorithms which utilize CAV technologies to optimize signal operations, enable special signal control (such as priority and preemption) and CAV mobility and safety applications. The main research objectives of this study are:

- Synthesize the current state of research and practice related to signal control programs under the CAV environment.
- Recommend intersection communication protocols for CAV implementation suitable for Wyoming conditions, but transferable to other locations. The measure of success will be that the protocols can be incorporated in the current and standardized hardware and software for CAV implementation.
- Develop and test algorithms for ISIG, FSP, TSP, SPD-HARM, Q-WARN and PREEMPT. The measure of success will be that the algorithms can be implemented in traffic control programs and they are efficient: responding to dynamic inputs, changing operations and improving efficiency (delay reduction, speed increase, queue reduction) when compared to the base

The study tasks included a review of literature and practice, collection of the existing field data, and creation of traffic microsimulation models to develop, test, and select the most appropriate CAV control algorithms for ISIG, FSP, TSP, SPD-HARM, Q-WARN, and PREEMPT. Field data (geometries, traffic, and control) were collected from selected test-sites and used in the analysis and models development. The algorithms were developed according to the actual standards and protocols for CAV technologies. Traffic microsimulation software VISSIM was used extensively to develop and test actual control programs that are field-ready. The focus of the algorithms was to improve traffic operations and create traffic conditions that will benefit safety.

The first outcome of the study is a synthesis of existing literature and practice on CAV technologies and algorithms, with a focus on traffic signal operation. The literature review recognized the current state of research and practice, technologies, implementations and potential gaps and problems that must be addressed. The second outcome is a set of microsimulation models for selected locations in Wyoming and Utah, which can also be used in future research. All models use state-of-the-art software and traffic control programs through software-in-the-loop (SIL) implementation. The most important outcome of the study is a set of field-ready traffic control algorithms and programs that use CAV technologies to improve operations of freight, transit and emergency vehicles through signalized intersections and urban arterials. This research is expected to be beneficial for WYDOT, UDOT and other state agencies in Wyoming and Utah, and for agencies across the United States that are preparing for the era of CAV technologies. This research also represents a good starting point for special signal operations using connectivity technologies.

2. LITERATURE REVIEW

Connected technologies are gaining momentum in transportation research and practice. The benefits of these technologies are just beginning to be recognized. The limited number of field tests have proven that they can be used for varous special traffic control programs. There are still many areas that must be covered through research. CV applications explored in this study, defined in the USDOT CV applications for mobility, include ISIG, FSP, TSP, SPD-HARM, Q-WARN and PREEMPT.

ISIG is the overarching application that combines high-fidelity data collected from vehicles through V2V, V2I, and Vehicles-to-Everything (V2X) communications to control signals and optimize their operation in real time. It also plays a role in the overall system optimization, special signal operations (such as preemption and priority), and the incorporation of pedestrian movements (ITS JPO, 2018c; Yang, 2017). In a CV environment, RSEs associated with an intersection signal controller broadcasts an intersection geometry and signal phase and timing message (MAP and SPaT). An equipped vehicle that enters the range of the RSE will receive the MAP and SPaT data and will activate BSMs, which contain static and dynamic elements of the vehicle, and the status of various vehicle systems (e.g. brakes, doors, windshield wipers etc.) (Leonard, 2017; Cronin, 2012). Depending on the type of the approaching vehicle (e.g. a heavy truck, a transit vehicle, or an emergency vehicle), it may send a signal request message to request signal priority or preemption. In turn, the RSE sends a signal status message with the acknowledgements of priority requests and the status of active priority/preemption request(s). This message exchange occurs in real time. This allows traffic signal control and signal priority for multiple modes to be managed within an integrated framework.

Different levels of priority for eligible vehicles, whether multi-modal or within the same mode, can be assigned based on the local interpretation of signal priority importance and usefulness (Cronin, 2012; University of Arizona et al., 2016). The infrastructure-based traffic signal control equipment consists of the traffic signal controller, field sensors/detectors, a roadside processor and the RSE. Communication between the signal controller RSE and vehicle OBE is performed through two dedicated DSRC channels. The vehicle OBE broadcasts BSMs, while the RSE broadcasts MAP and SPaT messages. This provides inputs for event-based traffic control algorithms. The New York City CV Pilot Deployment program includes intelligent signal system, where CV data serve as an input to the existing Adaptive Control Decision Support System (ACDSS), augmenting or replacing the existing sensor data (Galgano et al., 2016). Similarly, the Arizona CV testbed uses RSU and OBE information to optimize traffic control programs through microsimulation (University of Arizona et al., 2016). The simulation results showed an improvement in performance measures, which was significant for CV penetration rates of 50 percent or more. This experiment also successfully implemented CV-based priority for transit vehicles.

2.1 Freight Signal Priority

Freight signal priority allows extra time for trucks to clear the intersection without stopping (green extension, GE) or an earlier return to green if the truck is stopped (early green, EG), therefore facilitating the movement of the truck through the signalized intersection. Having trucks at the front of the queue is an undesirable scenario, since the start-up lost time for all vehicles is greater and the vehicles behind have limited visibility of the traffic control devices. The benefits of FSP include, but are not limited to, reduced truck stops and delays, a reduction in truck red-light running, safer phase termination for trucks, and higher capacity due to the reduced start-up lost time and similar benefits (Urbanik et al., 2015). Since more information is being transmitted through CAV communication channels, the signal controller receives more data that can be used to adjust the operations. Therefore, additional strategies to FSP might include dynamic yellow/red clearance intervals (to allow more time for large vehicles or slow moving vehicles to clear the intersection before moving onto the next signal phase), adaptive left-turn treatments and operations (for example, not allowing a permitted left-turn signal phase if large vehicles are present in the left-turn lane and the oncoming traffic volumes are high), or adaptive ring-barrier structure and sequence, which can change the order of phase sequences as needed. These additional strategies can have significant safety benefits and improve operations.

For FSP strategies to accomplish their goals, roadside infrastructure (traffic signals in this case) must receive accurate information about the arrival of the freight vehicle. After the vehicle is detected, the system extends or provides earlier green time. These systems could use historical or real-time data. Real-time data are collected by loop detectors, video-based systems, or radar-based systems. FSP can improve mobility in the range between 15 and 25 percent and reduce energy consumption five to 10 percent (National Center for Sustainable Transportation, 2016). A simulation study of a signalized intersection in Portland, OR, that experiences high-truck traffic evaluated the impacts of FSP on traffic performance, which included 11 seconds of green time extension (Mahmud, 2014). Results showed that the given FSP increased freight service reliability, reduced red-light running, improved safety, and smoother operations. Overall truck travel and stop delay reduced 13 and 20 percent, respectively, with minimum to no impact to other vehicles. The number of truck stops reduced nine to 16 percent in the major truck moving direction. A study Traffic Light Signal Control System with Truck Priority (Zhao and Ioannou, 2016) analyzed a co-simulation optimization control approach that determines the optimal signal timing with FSP. The control program was tested on a road network simulator adjacent to the twin ports of Long Beach /Los Angeles. The tests were performed with 3 and 20 percent of trucks in the traffic flow. The results showed that the FSP system can reduce truck delay 28 to 45 percent, with significant reductions in emissions, when the truck traffic is three percent. The savings were more significant for the 20 percent truck traffic. Another study (Kari et al., 2014) developed and tested an algorithm for eco-friendly FSP with the goal of reducing energy consumptions and emissions. The proposed algorithm was implemented and evaluated on an isolated intersection in microsimulation. The results indicated that the algorithm can improve system-wide fuel economy by five to 10 percent, and reduce freight vehicle travel time by up to 26 percent. Based on the simulation results, the eco-FSP algorithm provided fuel and time savings to both freight and non-freight vehicles.

A study by Park et al. (2019) evaluated the energy and environmental impacts of CV-based FSP. The study was performed in VISSIM microsimulation. The results showed that FSP has the potential to improve operations and significantly reduce fuel consumption and emissions. The fuel consumption was reduced by 11.8 percent, while analyzed emissions were reduced between 11.8 and 25.9 percent. A study by Murshed et al. (2021) found that the application of FSP can reduce fuel consumption and emissions by two percent and 20 percent, respectively. The FSP algorithms were tested on a two-mile section of San Pablo Avenue in Berkeley, CA. The study also revealed that the percentage of trucks in the vehicle composition affects the positive outcomes of the FSP. With the percentage of truck of two percent or less, the improvements in fuel consumption and emissions are complemented by improvements in system-wide delays and travel times. The increase in percentage of trucks was followed by further reduction in fuel consumption and emissions, but also with increases in system-wide delays and travel times.

FSP can be used effectively to reduce truck delay, but in most cases, it increases delays on side streets, especially for a high percentage of trucks in the traffic composition. A multimodal intelligent traffic signal (MMITSS) application developed in the CV environment by Ahn et al. (2016) optimizes different applications, such as signal priorities, to reduce network-wide delays. The simulation results showed a reduction in CV-truck delays by up to 48 percent but with a slight increase in travel time of buses. The travel time of unequipped vehicles and connected trucks was reduced by 40 percent and 42.4 percent, respectively.

Inaccurate data about the position, speed, and arrival time of incoming vehicles are a limitation for FSP performance. The development of new technologies, such as CAVs, is an opportunity for an upgrade of the existing FSP and introducing a performance-based evaluation. The accurate data provided by CV technologies ensures that precise information about the arrival of the priority is being sent to the signal controller. Based on the trajectory of the approaching vehicle, the controller can be programmed to implement the optimal FSP strategy.

Although FSP is not a new technology, it is not researched as much as TSP. Currently, available research is mostly based on microsimulation models, but they do not use the full capability of the CV technologies. This study developed CV-based FSP algorithms that rely on CV to alleviate shortages of conventional detection systems and optimize truck movements through the intersections. The algorithm defines a detection range for each transit vehicle independently based on the vehicle speed, distance from the intersection, and traffic condition on an approach. Using these criteria, it is possible to create an optimal position for the priority request for each vehicle, and this approach is suitable for field implementation.

2.2 Transit Signal Priority

TSP is an operational strategy that facilitates the movement of in-service transit vehicles through traffic-signal controlled intersections (Smith et al., 2005). It can be implemented as passive, active, or adaptive. Passive TSP does not require detection and is optimized based on the frequency of transit vehicles along a certain corridor. Active TSP is most common, and it requires detection of approaching transit vehicles. The detection can be achieved through loop, radar, video, infrared, or GPS, among other means. Active TSP can be unconditional (where every transit vehicle requests and is granted priority) or conditional (where priority is granted only to certain transit vehicles, such as those running behind schedule, or carrying more passengers on board). Adaptive TSP weighs the benefits and impacts of transit and vehicular traffic when determining the priority given to transit vehicles. TSP is mainly achieved through green extension (GE) and/or early green (EG), where the transit vehicle receives extra green time at the end or beginning of the green phase, respectively. Other strategies include phase rotation (PR), phase insertion, separate transit phase and similar. The benefits of TSP include reductions in bus delays, increase in operating speeds, improved schedule adherence, reduced bus bunching and increase in ridership, among others. However, it can have negative impacts on non-priority approaches and neighboring intersections (Park and Hu, 2014). Several studies used field data to estimate the effectiveness of TSP. In Tacoma, Washington, TSP (in combination with signal optimization) reduced traffic signal delays around 40 percent in two corridors. Powell Boulevard bus line in Portland, OR, recorded transit travel time improvements by up to eight percent and a reduction in travel time variability by 19 percent. In Chicago, the recorded reduction in bus running times was between seven and 20 percent, with a 44 percent reduction in bus intersection delays, depending on the time of day, which saved one bus weekly (Innovative Transportation Concepts, Inc., 2001). The bus travel time has reduced up to 25 percent in Los Angeles after TSP implementation (Smith et al., 2005).

As a more convenient approach, most studies have used simulation models to evaluate the effectiveness of the transit or freight signal priority, where field-collected data served to calibrate and validate the simulation models. An advantage of simulation studies is that they can develop and test new technologies in a virtual environment. Dion et al. (2004) used INTEGRATION traffic assignment and microsimulation software to evaluate TSP along transit corridors with different types of signals. VISSIM micro-simulation was applied by Chen et al. (2008), Ghanim et al. (2013), and Zlatkovic et al. (2013) in their evaluations of TSP on a BRT corridor in Beijing, a bus corridor in Michigan State University, and a BRT corridor in Salt Lake County, Utah, respectively. All studies showed significant reductions in transit travel times and delays. A study by Song et al. (2017) evaluated the effectiveness of conditional GPS-based TSP through microsimulation. The results showed that GPS-based TSP can reduce transit travel times by up to 13 percent, with a minimal negative impact on the side-street traffic (three percent delay increase). GPS-based TSP uses real-time vehicle location and wireless communication to transmit data. This system has shown a lot of advantages, such as low implementation cost, adjustability in detection distance, and huge capacity in data transmission.

A limited number of studies evaluated the effectiveness of CV systems for TSP implementation. CV technologies provide additional information on transit vehicles, such as speeds, arrival rates, position, acceleration, deceleration, stopped time, and the number of passengers on board, among other information contained in the BSM. However, the availability of CV technologies for this purpose depends on the market penetration rate of CV-equipped transit vehicles. A recent field implementation and study of CV-equipped buses along the Redwood Road corridor in Salt Lake County, UT, showed that the equipped buses that requested priority met their schedules two to six percent more frequently than other buses (Leonard et al., 2019). Other recent studies used traffic simulation to evaluate TSP effects in a CV environment. A study by Park and Hu (2014) developed a TSP logic that takes advantage of CV technologies, including two-way communication between the bus and the traffic signal controller, bus location detection and prediction, and the number of passengers on board to allow an accurate reallocation of the green time. Microsimulation was used to compare the developed TSP against scenarios with conventional TSP and without TSP. The results showed a reduction in bus delay from nine to 84 percent compared to conventional TSP, and from 36 percent to 88 percent compared to no-TSP.

A study by Head et al. used VISSIM microsimulation to estimate the benefits of the multimodal intelligent traffic signal (MMITS) in CV environment on two networks, in San Mateo, CA, and Maricopa County, AZ (University of Arizona et al., 2016). The study implemented MMITS strategies through ASC/3 SIL. The results showed a reduction in transit travel times of eight to 10 percent (San Mateo) and 11 to 15 percent (Maricopa), and a reduction in transit delays of 23 to 25 percent (San Mateo) and 32 to 43 percent (Maricopa). A study by Anh et al. (2016) used the same approach (VISSIM with ASC/3 SIL) to assess the potential effects of a broader MMITSS deployment. For TSP implementation with CVs, the results showed that travel time reduced for both transit and passenger vehicles by up to 29 percent and 28 percent, respectively. However, the study also found negative effects of TSP on system-wide delays because of the reduction of green times on side streets. With retiming of the traffic signals, performances of CV-based TSP could be additionally improved (Wang et al., 2020a). Transit priority in the CV environment still has room for improvement. By avoiding fixed positions from where transit vehicles request priority and consideration of traffic condition, occupancy, schedule adherence, and expected arrival time of vehicles to the stop line, CV-based TSP can provide high performances with minimal impact on side streets traffic (Cvijovic et al., 2021). CV environment has the potential to improve mobility of all vehicles, not only of buses.

2.3 Speed Harmonization

Dynamic Speed Harmonization (SPD-HARM) uses communication among vehicles to control the speeds of clustered CAVs. The objective of this application is to dynamically adjust and coordinate maximum appropriate vehicle speeds in response to downstream congestion, incidents, and weather or road conditions to maximize traffic throughput and reduce crashes. A dynamic SPD-HARM system will be successful at managing upstream traffic flow by: reliably detecting the location, type, and intensity of downstream congestion (or other relevant) conditions; formulating an appropriate response plan (i.e., vehicle speed and/or lane recommendations) for approaching vehicles; and disseminating such information to upstream vehicles readily and in a manner that achieves an effective rate of compliance (ITS JPO, 2018c; Mulligan et al., 2012). The fundamental idea of SPD-HARM is to mitigate the loss of highway performance by preventing traffic breakdowns and bottlenecks. This is represented in the fundamentals of traffic flow theory: a traffic breakdown at the bottleneck can be prevented by progressively guiding the upstream traffic to equal the downstream traffic flow, so the upstream traffic runs smoothly into the downstream traffic and can pass through the bottleneck without disruptions (Malikopoulos et al., 2018).

Talebpour et al. (2013) analyzed the impacts of early shockwave detection on breakdown formation and driving hazards, and the possible improvements through speed harmonization. An algorithm based on the detection of shockwave formation was combined with a speed limit selection algorithm to implement speed harmonization within traffic microsimulation. The results showed significant improvements in traffic flow characteristics with the implementation of speed harmonization. The analysis of traffic patterns in the traffic flow can also determine the optimal location to implement the speed limit changes upstream of the point of shockwave detection. The speed limit compliance is of a major importance for the success of a speed harmonization system.

A microsimulation and a limited field test study performed by Dowling et al. (2015) analyzed the effectiveness of a prototype SPD-HARM with Q-WARN algorithm. The assessment was performed through a VISSIM simulation model for the US 101 freeway corridor in San Mateo, CA, and evaluation of a small-scale demonstration that was conducted in segments of I-5, in Seattle, WA. Results from the simulation analysis found that the algorithm significantly reduces magnitudes of the speed drops (shockwaves) between vehicles even at low market penetration rates (about 10 percent). This reduces the probability of collisions where free-flowing traffic meets the back of a queue. The field tests included 21 CV-equipped vehicles. They showed that the quality of communications were high and that the Q-WARN and SPD-HARM algorithms could determine the best strategy in a short time interval (usually within 10 seconds) and send the information back to the vehicles.

FHWA (2014) developed VISSIM microsimulation models to evaluate the effects of a large-scale deployment of speed harmonization. For this assessment, portions of I-66 in northern Virginia were modeled during the evening rush hour. The results showed that speeds ranged from zerp to 44 mph approaching a congested location during a normal day. However, after the speed harmonization algorithm was implemented, the speeds ranged between 28 and 63 mph with only 20 percent of the cars traveling at recommended speeds. Based on these results, FHWA, in cooperation with the Virginia DOT, performed a real-world test of speed harmonization on I-66. During the test, three research vehicles equipped with V2I communications received recommended speeds in live traffic on I-66. Field data were sent to an external computer (located at FHWA), which performed the computations and sent back recommended speeds to the probe vehicles. The vehicles were equipped with cooperative adaptive cruise control to automatically adjust to the speeds recommended by the program. Although the speed harmonization was implemented successfully, numerical results were not obtained from this study, mainly because of the low number of CV vehicles.

SPD-HARM increases the capacity of traffic facilities and reduces congestions due to the phantom traffic jam effects. It also allows for creating and maintaining vehicle platoons, increasing mobility through signalized intersections. The signals communicate their status (through SPaT) and the clustered vehicles will respond by adjusting and harmonizing their speeds so the platoon reaches the signal during the green phase time. A microsimulation study performed by Shams (2018) tested a speed control and platooning algorithm in an urban environment for different CV penetration rates. The results showed that over 20 percent of intersection delay reduction and more than six percent of speed increase can be achieved with a 25 percent CV penetration rate. Tajalli and Hajbabaie (2018) developed a speed harmonization algorithm for urban network considering traffic signals. The case study consisted of a portion of the downtown Springfield, IL, with 20 signalized intersection. The analysis was performed using cell-transmission models. Results indicated that the speed harmonization can reduce travel times and increase travel speeds close to six percent, significantly reduce speed variance (between 20 and 30 percent) and reduce the number of stops between eight and 19 percent.

Speed harmonization and signal priority treatments also can be granted to vehicles that are platooning. A platoon is a group of traveling vehicles separated by a short headway, applyiong the principles of dynamic speed harmonization. The length of the platoon usually includes a platoon leader who has a longer headway. The vehicles that follow the leader are known as bunched vehicles. Platoon generation and dispersion, and potential advantages of platoons on corridors, are researched through many studies. Most of the isolated intersections tends to carry more traffic on the major approaches than the minor approaches. This is particularly true on rural or suburban high-speed corridors. Calls for a green phase from side streets with low traffic often interrupt whole platoons on the major approaches and force them to stop or break down. This causes an increase in delays for the entire intersection, especially during peak hours. An integrated system that provides platoon progression and advance warning of the end of the green was studied by Liu and Bhimireddy (2009). The study used different parameters, such as platoon size, approach volumes and speeds, advance detector location, and the number of vehicles waiting on the minor approaches. This study showed a reduction in delays and stops by 50 percent on the major approaches with platoons, while the total intersection delay was reduced up to 20 percent. The model also was able to predict gap-outs by seven to eight seconds earlier. Due to closer headways and lower speed variations compared to conventional traffic flow, platooning in the CV environment has the potential to enhance traffic operations and safety concurrently (Rahman and Abdel-Aty, 2018).

A multi-objective CV platoon trajectory control method for isolated signalized intersections prioritizes the intersection throughput and traffic efficiency under a pre-defined signal cycle (C. Wang et al., 2020). The method was forming platoons that can pass through defined green time. Obtained results showed that the passing of CV vehicles in platoons could enhance throughput for one cycle, increase energy efficiency and longitude safety. The study was limited to simple scenarios and only on CV vehicles without interaction with human-operated vehicles (Wang et al., 2020b). Platoon priority could be affected by different CV penetration rates (Zlatkovic and Shams, 2019).

Another study used benefits of Green Light Speed Advisory (GLOSA) with CV to prioritize a specific category of vehicles. The study conducted a numerical test of transit priority at signals and speed advisory and simulation in SUMO. The algorithm developed by Colombaroni et al. (2020) first generates a platoon and then grants priority if the platoon reaches a maximum platoon length. The results showed that the proposed algorithm reduced delays, increased speeds, and reduced stops for MPR of 50 percent or higher. The information that could be exchanged between vehicles and infrastructure, such as the position and speed of individual vehicles, can significantly improve operation.

An algorithm developed by Guler et al. (2014) incorporated information from CV-equipped vehicles to determine the sequence of departures from an intersection, and to assess autonomous vehicle control and detailed vehicle information. The developed algorithm was beneficial in minimizing total delays and the total number of stops, and for car discharging in platoons. Results showed that MPR of CV-equipped vehicles could affect results. Up to 60 percent CV MPR, the average delay per car, can be decreased as much as 60 percent, while further increase in MPR did not show additional improvements.

To investigate platoon priority, another study (Li et al., 2019) developed a model with offset optimization for coordination in the CV environment that is an extension of the Purdue coordination diagram (PCD) (Day et al., 2008; Day et al., 2010). It is a probabilistic surrogate quantification model combined with offset optimization. The study was tested on a real arterial corridor in Edmonton, Alberta, Canada. Results from the study showed that the position of detectors and backward speed is essential for platoon recognition.

2.4 Queue Warning

The Q-WARN application uses CV technologies to enable vehicles within the queue to automatically broadcast their queued status information to upstream vehicles and to infrastructure. The queue warning is sent to oncoming vehicles to prevent rear-end or other secondary collisions. This application performs two essential tasks: queue determination and queue information dissemination (ITS JPO, 2018c). In cases of limited visibility, the Q-WARN system can work in conjunction with the traffic controller to transmit the queue information to the vehicles approaching the intersection. This is of particular importance for heavy vehicles due to their longer stopping distances. The application uses information from the roadways (freeway or arterial), traffic detection subsystems, weather information, available sign messages, OBE systems, driver interface, and CV broadcasting information. Significant roadway, environment, weather, and vehicle information must be exchanged for the application to work properly (Mulligan et al., 2012).

Q-WARN uses ITS technologies to enable vehicles within the queue to automatically broadcast their queued status information. If drivers have a 0.5-second additional warning time, about 60 percent of rear-end collisions can be prevented, while an extra second of warning time can prevent about 90 percent of rear-end collisions (Ankrum, 1992). The queue warnings are sent to oncoming vehicles to prevent rear-end or other secondary collisions. In cases of limited visibility (either technical or environmental), the Q-WARN system can work in conjunction with the traffic controller to transmit the queue information to the vehicles approaching the intersection. This is especially important for heavy vehicles, due to their longer stopping distances.

Q-WARN systems are effective in emergency braking and slowing down maneuvers and can reduce erratic behavior and queueing-related collisions. Q-WARN systems can reduce rear-end and other severe crashes by up to 45 percent (Neudorff and McCabe, 2015). Amini et al. (2019) have evaluated the safety aspect of the Q-WARN system throughout different studies. The studies showed that the number of rear-end collisions was reduced by 15 percent as a result of the queue warning message sent to the approaching vehicles. A study by Balke et al. (2014) developed a detailed description of the algorithm, which generates harmonized recommended speeds and queue warning information. This algorithm was extensively analyzed in another study conducted by Dowling et al. (2015). The speed harmonization and queue warning prototypes were written in the VISSIM COM interface. VISSIM microscopic simulation was used to test and model 8.5 miles of the US-101 freeway in San Mateo, CA. The authors concluded that the queue warning application could not be assessed in the microscopic simulation due to the lack of information on the drivers' expectancy and reaction to the queue warning messages.

A field-based study was conducted by equipping 21 vehicles with CV technologies, traveling on a 23-mile corridor of I-5, in downtown Seattle, WA, in 2015, using a prototype of intelligent network flow optimization (INFLO) (Stephens et al., 2015). The CV data were transmitted and assembled using a cellular phone and dedicated short-range communications. The process of delivering the queue warning messages to drivers took less than 10 seconds. The queue warning algorithm was found to detect the back-end of the queue three minutes sooner and locate it 0.5 to 1.5 miles within upstream than the road loop detectors with 1-mile spacing would detect. Khan (2007) conducted a study on a queue-end warning system that predicts queue ends and notifies drivers of the predicted queue-end location using portable variable message signs. The system is a combination of traffic sensors and a queue-end prediction algorithm based on an artificial neural network model.

Another study analyzed a 20-mile segment on the I-95 southbound corridor in Broward County, Florida (Khazraeian et al., 2017). The study network was created and calibrated in VISSIM to test the end of the queue detection algorithms and queue warning system for four different market penetration rates (three, six, nine, and 15 percent) under the effect of CV-based Q-WARN. In a study by Gettman et al. (2008), the authors introduced a bottleneck location by incorporating a one-lane blockage incident into the traffic stream. This study concluded that CV data allow faster detection of the bottleneck and queue formation. The CV-based algorithm can detect the start of a queue four minutes sooner than the detector-based algorithm. Further, it is concluded that Q-WARN enhanced network safety conditions by reducing the number of rear-end conflicts.

2.5 Emergency Vehicle Preemption

Emergency Vehicle Preemption (PREEMPT) is a special signal control mode that immediately alters traffic signal operation for the purpose of serving the approaching emergency vehicle (Urbanik et al., 2015). PREEMPT terminates the normal signal operation to perfom this task. Preemption can also be used for other purposes, such as railroad crossings or serving public transit vehicles. Preemption systems are designed to give emergency response vehicles a green light on their approach to a signalized intersection while providing a red light to conflicting approaches. The most commonly reported benefits of using preemption include improved response time, improved safety, and cost savings (FHWA ITS JPO, 2006). Preemption can improve EV response times by reducing the probability that responding EVs will arrive at intersections during the red signal phase and encounter vehicle queues. An early green discharges the queue before the EV arrival, allowing the EV to maintain higher average speeds.

Malabanan et al. (2022) used VISSIM microsimulation to evaluate the delay reduction for emergency vehicles through signalized corridors, using a test-bed in Bangkok, Thailand, by applying different preferential treatments. They found that the preemption implementation has a potential to reduce emergency vehicle delays between 70 and 80 percent. Xie et al. (2017) used SMARTS traffic simulation software to assess the effectiveness of emergency vehicle preemption using three test-beds in Melbourne, Australia; Manhattan, New York; and London, England. The study results showed that preemption can result in EV travel time reduction close to 63 percent.

CV technologies have the potential to improve the priority operation through utilization of the information shared between the EVs and the traffic signals. Das et al. (2022) introduced MMITSS priority based on CV technologies. They developed a mixed integer programming model to consider the priority requests from multiple emergency vehicles and dilemma zone requests from freight vehicles. The study results show that the implemented algorithm has the potential to provide smooth progression of the emergency vehicles, without significant negative impacts on general purpose traffic. When compared to the traditional preemption, the MMITSS priority resulted in EV intersection delay reduction between 10 and 29 percent. Noori et al. (2016) developed a method that uses V2V and V2I communication to determine the number of vehicles in the queue ahead of the approaching EV, and provide early green to discharge the queue and clear out the route for the EV. The algorithm can look at all signals along the EV route and prepare a timely response. The method was tested in SUMO simulation using a real world network in Toronto, Canada. The results showed significant reduction in EV response times, ranging from 43 to 51 percent depending on the area density, when compared to no preemption.

Shaaban et al. (2019) developed and tested a joint strategy for optimal path selection and EV preemption using CV communication and tested it in VISSIM microsumulation. The developed method first finds the optimal route for EVs through the network and prepares intersection for preemption. One of the objectives of the research was to minimize negative impacts on other traffic. The results showed a decrease in the EV travel times ranging between 16 and 49 percent compared to no preemption. The vehicular traffic along the EV route also experienced a reduction in delays attributed to the EV preemption, while the increase in delays for the cross streets was not found to be significant. Obrusnik et al. (2020) developed a method for dynamic queue discharge in front of an oncoming EV, with the goal of providing preemption as short as possible to minimize negative impacts on other traffic. The method uses CV communication to determine the optimal preemption activation moment. It was tested in SUMO simulation and experimentally verified in the field. The results showed significant improvements in EV operations for low and medium congestion and queues; however, more improvements are needed for heavy congestion/long queues traffic states.

3. FREIGHT SIGNAL PRIORITY

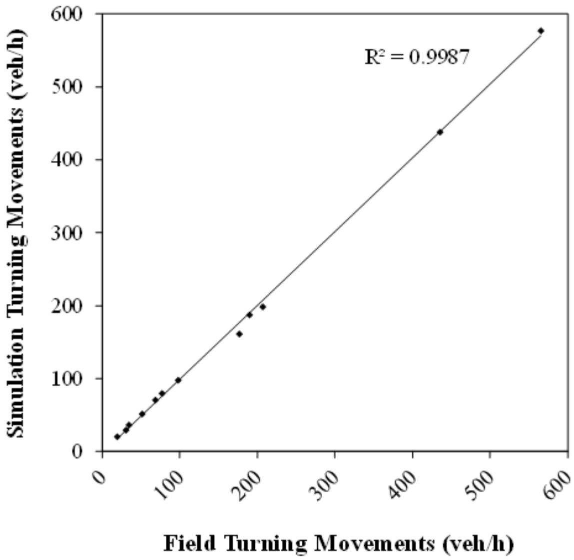
The CAV-based FSP algorithm was developed and tested in VISSIM microsimulation. FSP is based on the built-in signal control priority functions of the Econolite ASC/3 traffic controller software, implemented through the SIL application in VISSIM, and additional strategies achieved through the logic processor. With minor modifications, the algorithm can be implemented in various traffic controllers that support preemption.

3.1 Development of the VISSIM Microsimulation Models

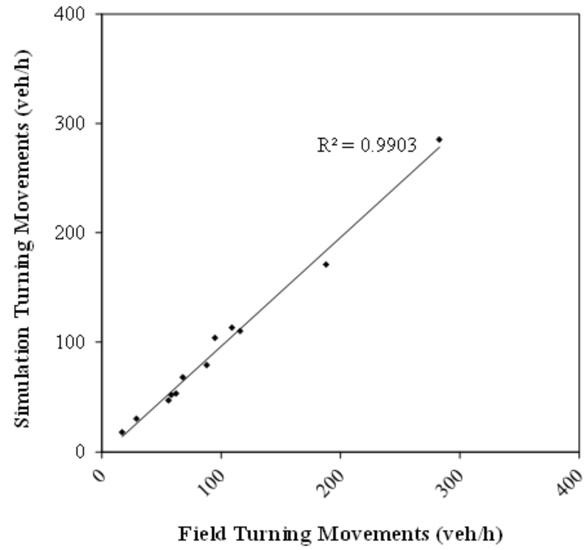
The six signalized intersections in Rock Springs (Stagecoach Dr. and Elk St.), Rawlins (Airport Rd. and Cedar St.), Evanston (2nd and Front St.), Laramie (Curtis and McCue) and Cheyenne, WY, (east and west ramps of the I-25 and College Dr. interchange) were replicated in VISSIM microsimulation using real-world data on geometry, traffic demand, and signal operations. The geometry of the intersections was collected from field observations, Google Earth, and Open Street Map background provided by VISSIM microsimulation with information on the number of lanes, road and lane widths, and speed limits. Traffic volumes, composition and turning movement counts data were collected from the WYDOTs Monthly Hourly Volume for April 2019 and through field observations. Detailed traffic signal control data for these intersections were obtained from WYDOT in the form of Synchro files, which also contained additional traffic volume information. The data used to develop, calibrate, and validate the microsimulation test-case models were collected using the afternoon peak period (5–6 p.m.).

The traffic signal operation was replicated using actual traffic signal control software — Econolite ASC/3 — through SIL application. The ASC/3 controller can support basic and complex signal timing settings through Logic Processors, which can emulate external logic not included in the default settings. The ASC/3 SIL version of the controller software has been configured to operate as a virtual controller within the VISSIM environment. This allows full ASC/3 controller functionality to be used during simulations under VISSIM.

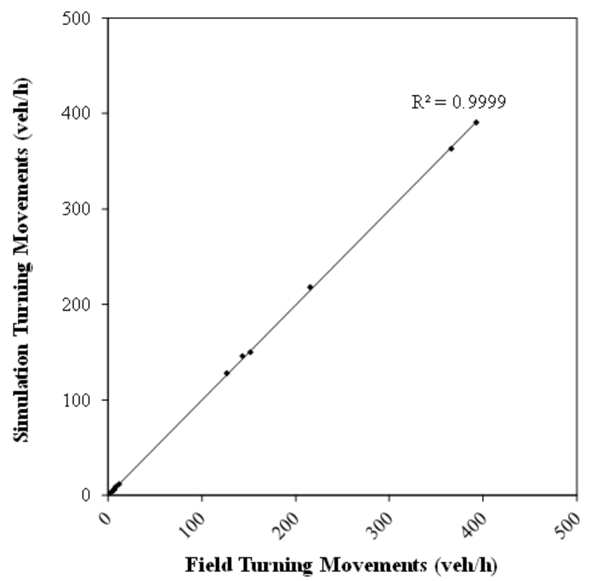
Baseline models were developed and calibrated for the 2019 existing traffic conditions for the six signalized intersections. The outputs were averaged from 10 simulation runs with different random seeds. The baseline models were calibrated for intersection turning movements, as shown in Figure 3.1. The coefficient of determination (R^2) for calibration, ranging between 0.84 and 1.0, shows a good fidelity of the baseline models.



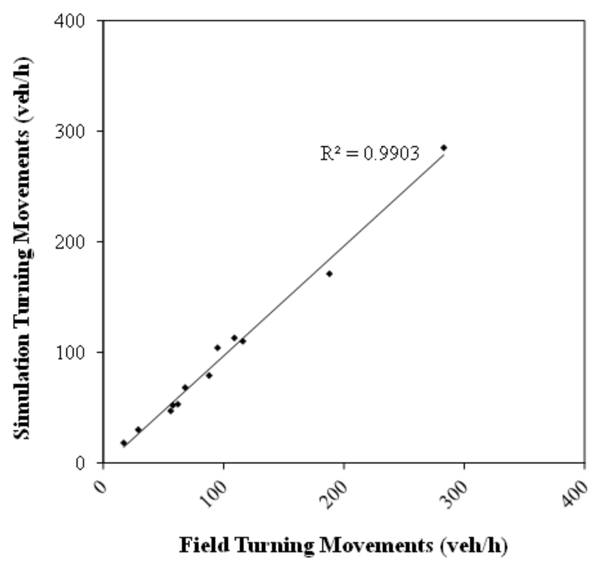
a) Rock Springs



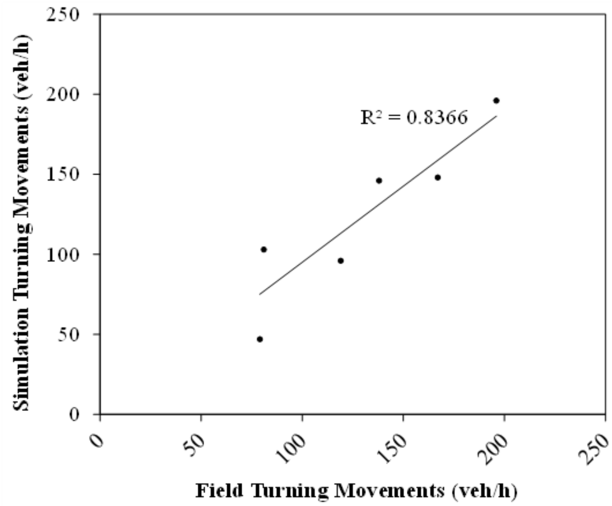
b) Rawlins



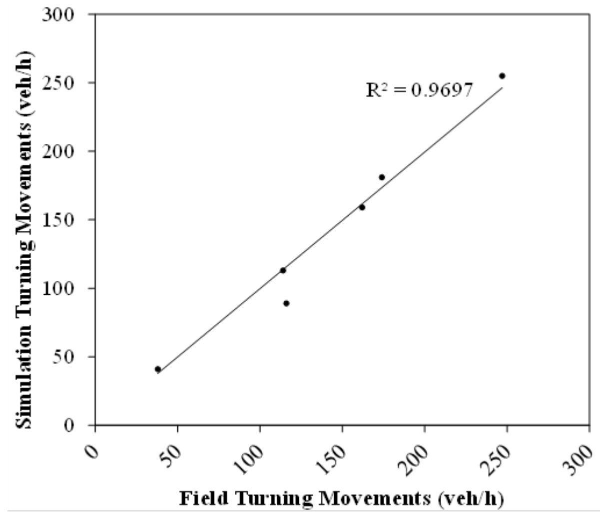
c) Evanston



d) Laramie



e) Cheyenne, West ramp



f) Cheyenne, East ramp

Figure 3.1 Calibration of Base VISSIM Models

Once the base models were developed and calibrated, they were used to develop CV scenarios and implement the FSP algorithm. Six scenarios for each of the models were defined as follows:

- A base model without FSP, with the existing traffic volumes, traffic composition, and traffic operations.
- An FSP model with 10 percent CV-equipped trucks in the traffic composition, with the existing traffic volumes and signal operations. FSP consists of 15 seconds of green extension time for prioritized movements, and five to 10 seconds of early green, depending on the preceding signal phase.
- An FSP model with 25 percent CV-equipped trucks, with the existing traffic volumes, signal operations and FSP implementation as in the previous model.
- An FSP model with 50 percent of CV trucks.
- An FSP model with 75 percent of CV trucks.
- An FSP model with 100 percent of CV trucks.

The communication was based on the vehicle's latitude/longitaude coordinates, which are being transmitted in each time step. The request for FSP was sent to the controller when the distance between the vehicle and the traffic signal was 600 to 1,000 ft. This approach ensured an accurate data exchange among the CV-equipped vehicles and roadside infrastructure. The traffic signal control programs were developed and tested in Econolite ASC/3 SIL signal control simulation implemented in VISSIM microsimulation software. The vehicles on main approaches were filtered out based on the heading/route information from the BSM. The FSP request and strategies were programmed through a combination of RSU operations, and built-in controller logic and FSP features. When the RSU detected a request, it would activate the internal controller logic and enable GE/EG FSP strategies. All models were run for the PM peak hour (5–6 p.m.), with a 15 minutes of warm-up time.

3.2 FSP Algorithm

The FSP algorithm is based on the communication between the approaching trucks and the traffic signal. The actual priority application uses built-in ASC/3 controller function with additional control features provided through custom-built logic processes. When the RSU detects a request, it activates the internal controller logic and enable GE/EG FSP strategies. GE was set to 15 seconds maximum, while the maximum green time reductions for EG were set at five seconds for left turns along the main street and 10 seconds for through movements from the side streets. FSP was defined as unconditional, meaning that all CV trucks would send a request and receive priority. The CV FSP algorithm is based on the time the vehicle needs to reach an intersection and the queue conditions on the intersection approach. The time that a vehicle needs to reach an intersection should not exceed the GE time to be considered eligible for priority. Once a truck enters the detection range, the algorithm starts checking the actual arrival time and queue conditions ahead of the truck. If the truck can reach the intersection within GE at the actual speed, the FSP will be granted. If the vehicle cannot reach the intersection within that time, even though it is at a distance that is possible, the algorithm checks the queue conditions ahead. The COM interface in VISSIM allows this function with user-defined attributes settings, such as speed, headway, and queue length. If the algorithm confirms the queue conditions, the FSP will be granted, and in that way, the queue will have enough time to dissipate and clear ahead of the truck. Therefore, the RSU receives a constant update on the truck location and speed, and when the conditions are met, the RSU sends an FSP request. The actual speed of freight vehicles and latitude/longitude coordinates are constantly updated in each simulation step, and the algorithm constantly computes and updates a truck's time to reach the intersection. The FSP request is terminated when the truck crosses the stop bar. The location from which a truck sends the priority request depends directly on traffic conditions in real time.

The main BSM information used for communication with traffic signals through RSU was the vehicles' latitude/longitude coordinates. RSU contained the latitude/longitude coordinates of the center of the intersection, which was used as a reference point. As a vehicle was approaching the intersection, it would send its lat/long coordinates, and the RSU would compute the current distance in every time step. The distance was computed using the Haversine formula as follows (GIS map, 2019):

$$\mathrm{a} = \sin^2\left(\frac{\Delta\mathrm{lat}}{2}\right) + \cos(\mathrm{lat}_{\mathrm{veh}}) \cdot \cos(\mathrm{lat}_{\mathrm{int}}) \cdot \sin^2\left(\frac{\Delta\mathrm{lon}}{2}\right) \tag{1}$$

$$\mathrm{c} = 2 \cdot \mathrm{atan2} \cdot \left(\sqrt{\mathrm{a}}, \sqrt{(1-\mathrm{a})}\right) \tag{2}$$

$$\mathrm{d} = \mathrm{R} \cdot \mathrm{c} \tag{3}$$

Where:

lat_{veh}, lat_{int} – latitude values of the vehicle and the center of the intersection, respectively
Δlat – lat_{veh} – lat_{int} (difference of latitudes)
$\Delta lon = lon_{veh} - lon_{int}$ (difference of longitudes)
R – Earth radius (20,902,231 ft ≈ 6,371,000 m)
d – distance between the vehicle and the center of the intersection (ft), updated every time step

The latitude/longitude coordinates in VISSIM were computed through user-defined attributes, which converted the current VISSIM into the world coordinates. In each time step the intersection had the information about the position of the approaching vehicles. Although this procedure was developed in simulation, it can easily be transferred to field implementation, since latitude/longitude coordinates are contained in the BSM, while the RSU has that information for the intersection. When the CV-equipped truck enters the detection range, it starts transmitting the information to the signal, as in the example shown in Figure 3.2.

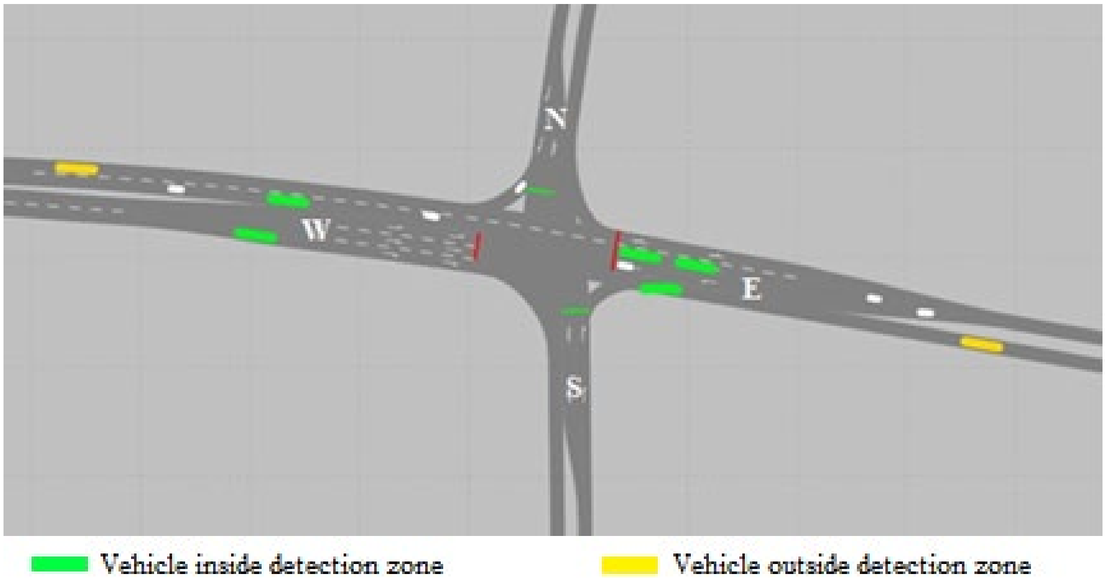


Figure 3.2 Detection Range and Information Sharing

3.3 FSP Results and Discussion

All models (locations and CV market rates) were run for 10 randomly seeded simulation runs. The final results were averaged from the 10 simulation runs to capture the variation and stochasticity in traffic patterns. The assessment was performed using individual intersection performance and network vehicular performance results.

3.3.1 Intersection Performance

The intersection performance for the six intersections was based on the average vehicular delays. The delays were recorded for cars, CV trucks and regular trucks individually. The comparison was made for different CV truck market rates. The results are provided in Table 3.1.

As the vehicular volumes are relatively low at all intersections, the vehicular delays are generally low for all vehicle types even during the peak hours. The delay of the CV-equipped trucks is significantly lower than the delay of the conventional trucks. For certain scenarios, the CV truck delay reduction reaches as much as 70 percent. If both CV and conventional trucks are considered combined, the higher CV penetration rates result in lower overall delay for all trucks. For the tested locations, the CV truck rates of more than 50 percent bring significant benefits for truck traffic with the implemented FSP algorithm.

FSP can lead to negative impacts on vehicular traffic. However, for the analyzed locations, the increase in vehicular delays is small and statistically insignificant. In the future, the algorithm needs to be analyzed and assessed along busy truck corridors.

Table 3.1 Intersection Performance – Average Vehicular Delays

Scenario	Mode	Average Intersection Delay per Vehicle (s/veh)					
		Rock Springs	Rawlins	Evanston	Laramie	Cheyenne West	Cheyenne East
Base	Car	11	11	9	7	4	6
	CV Truck	N/A	N/A	N/A	N/A	N/A	N/A
	Truck	12	12	11	7	3	5
	CV Truck Delay Reduction	N/A	N/A	N/A	N/A	N/A	N/A
10% CV	Car	11	11	10	7	4	4
	CV Truck	7	4	7	4	3	4
	Truck	12	12	11	7	4	4
	CV Truck Delay Reduction	-42.1%	-71.0%	-39.0%	-45.4%	-24.7%	4.4%
25% CV	Car	12	11	11	7	5	5
	CV Truck	8	4	6	4	4	4
	Truck	12	12	11	7	3	6
	CV Truck Delay Reduction	-34.4%	-69.3%	-41.4%	-43.8%	6.7%	-34.5%
50% CV	Car	12	11	11	7	5	5
	CV Truck	9	4	7	4	4	5
	Truck	13	12	12	7	4	5
	CV Truck Delay Reduction	-29.8%	-65.0%	-41.0%	-43.6%	5.3%	1.9%
75% CV	Car	12	11	11	7	5	6
	CV Truck	10	4	7	4	4	5
	Truck	13	13	11	8	5	5
	CV Truck Delay Reduction	-24.8%	-65.0%	-38.3%	-49.6%	-2.6%	3.7%
100% CV	Car	12	11	11	7	6	6
	CV Truck	10	4	7	4	5	6
	Truck	N/A	N/A	N/A	N/A	N/A	N/A
	CV Truck Delay Reduction	N/A	N/A	N/A	N/A	N/A	N/A

3.3.2 Vehicular Network Performance

The assessment of the FSP algorithm on the network-wide level was performed using the average network vehicular delay and average speed. The network-wide results are shown in Table 3.2. In this case the Cheyenne network was analyzed as one, as the West and East ramps are a part of the same network.

The FSP generally increases the average network-wide delay, which is attributed to the impacts on vehicles that are not granted FSP, such as cars and non-CV trucks. It was found that this impact is statistically significant for the Rawlins and Cheyenne networks for CV truck rates of more than 50 percent, and the Rock Springs network for CV truck rates between 10 and 50 percent. For other locations and scenarios, the increase network-wide vehicular delays was not significant.

The implemented FSP algorithm did not have significant impacts on average network-wide vehicle speeds, with the exception of the Rawlins network for CV market rates in excess of 50 percent. Speed reduction was mainly observed on approaches that conflict FSP signal phases.

Table 3.2 Vehicular Network Performance – Average Vehicular Delays and Speeds

Scenario	Network Performance	Rock Springs	Rawlins	Evanston	Laramie	Cheyenne
Base	Veh. Delay (s/veh)	9.7	10.6	9.8	6.1	7.5
	Veh. Speed (mph)	35.2	46.0	33.4	45.7	45.2
10% CV	Veh. Delay (s/veh)	11.4	11.5	7.7	6.1	7.4
	Veh. Speed (mph)	32.4	44.7	37.1	45.8	45.4
25% CV	Veh. Delay (s/veh)	11.5	12.8	8.4	6.2	7.6
	Veh. Speed (mph)	32.7	42.8	36.3	45.9	45.3
50% CV	Veh. Delay (s/veh)	11.3	14.4	9.6	6.3	8.0
	Veh. Speed (mph)	33.4	40.2	35.0	46.1	45.1
75% CV	Veh. Delay (s/veh)	10.7	15.5	10.2	6.3	8.2
	Veh. Speed (mph)	34.2	38.1	34.0	46.4	45.0
100% CV	Veh. Delay (s/veh)	10.7	16.1	10.8	6.3	8.4
	Veh. Speed (mph)	34.9	36.2	33.1	46.7	44.9

3.4 Conclusions

The implemented FSP application can use the built-in signal control priority features of Econolite ASC/3 controllers, in addition to customized signal operations programmed through the controllers' logic processor. It could also be implemented in other traffic signal controllers that support signal priority and logic processing. The results show that the CV-based FSP application was effective in reducing intersection delays for the CV-equipped trucks by 10 to 70 percent, depending on location. On the network-wide level, the implemented FSP increased the delays and reduced speeds for non-FSP movements. Overall, the most benefits of the FSP implementation were recorded for CV truck rates between 50 and 75 percent.

The algorithm was tested on signalized intersections in Wyoming, which typically do not experience excessive traffic demands. Therefore, the delays for all vehicle types are generally low. In future research, this algorithm needs to be implemented and tested along truck corridors with heavy traffic demand, to assess the complete effects on the developed FSP strategies.

4. TRANSIT SIGNAL PRIORITY

The CAV-based TSP algorithm was developed and tested in VISSIM microsimulation. TSP is based on the built-in signal control priority functions of the Econolite ASC/3 traffic controller software, implemented through the SIL application in VISSIM, and additional strategies achieved through the logic processor. With minor modifications, the algorithm can be implemented in various traffic controllers which support preemption.

4.1 Test-Case Network and VISSIM Simulation Models

The test-case network for the TSP study consists of a 10-intersection corridor along State Street in Salt Lake City, UT, between 500 S street on the north and 2100 S street on the south end of the corridor, as shown in Figure 4.1. This is a multi-modal corridor that carries a significant amount of traffic, with AADT of close to 36,000 vehicles per day along the busiest sections (UDOT AADT map 2014). 500 S and 600 S are one way streets, WB and EB respectively, carrying traffic to and from I-15, which is about 1.6 km west of State Street. The busiest intersection in the test-case corridor is 2100 S, used by more than 9,500 vehicles during the PM peak period (4– 6 p.m.), which is the interval used in this study (700 S, Kensington Avenue and 1910 S are minor streets/signalized driveways with insignificant traffic; therefore, they were not included in the analysis). State Street also carries significant transit ridership. The major bus route along the corridor is Route 200, which is one of the Utah Transit Authority's (UTA's) routes with highest ridership. This bus route is planned for a BRT conversion in the future. State Street has approximately seven percent of truck traffic in the traffic flow. Bicycle traffic is high, because of the flat topography and the vicinity of the downtown area. Significant pedestrian traffic also exists in the area.\

The data collection was performed in 2015 for the purpose of a previous multimodal study for the State Street corridor and was used in this paper. The data were obtained through field data collection, the Utah Department of Transportation (UDOT) and UTA's databases, and included traffic volumes/intersection turning movements, travel times, signalized intersection control parameters and transit operation characteristics. These data are used to develop, calibrate and validate the base microsimulation model.

The first dataset consisted of intersection turning movement counts, which included vehicular traffic, pedestrians and bicyclists. These data were collected in the field for seven signalized intersections within the analysis networks (excluding 700 S, Kensington Avenue and 1910 S), for the PM peak period (4–6 p.m.). UDOT's Automated Traffic Signal Performance Measures (ATSPM) system was also used for checking the turning movement counts, approach volumes, and signal timing data.

The second dataset consisted of travel time runs, which were performed using the floating car technique. Additional travel time data were obtained through online services, such as INRIX travel times, WAZE, and Google Maps. The third dataset consisted of signal timing data, which were obtained from the UDOT Traffic Operations Center (TOC), in the form of pdf files for all 10 signalized intersections in the analyzed network. The forth dataset consisted of transit data, including ridership, GPS, transit schedules, and vehicle capacities. These data were obtained from UTA for September 2015 as the representative month for this analysis. All the collected data were used to develop the base microsimulation model.

Figure 4.1 State Street Test-Case Network (*Source*: GoogleEarth)

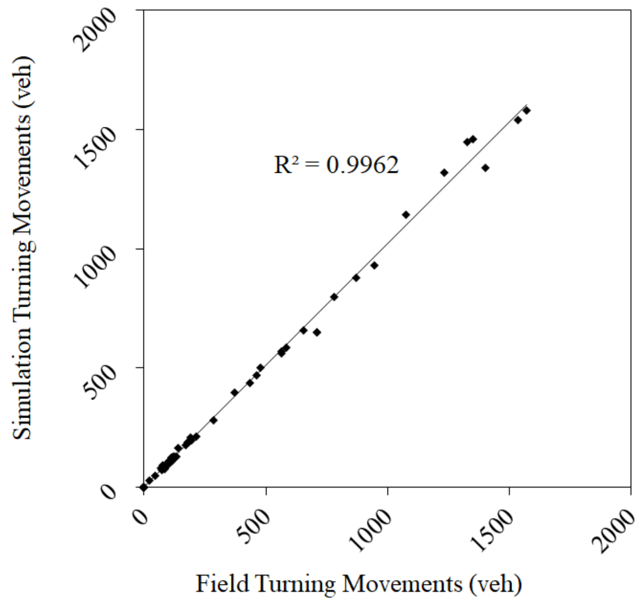
The development, testing and assessment of the TSP algorithms were performed through VISSIM microsimulation, coupled with Econolite ASC/3 SIL controller software. Communication, BSM, and RSU operations were programmed in Python and embedded in microsimulation. All signal control operations, priority and controller logic were programmed directly in ASC/3 controllers. Five model scenarios were created:

- Base model, which was created, calibrated and validated for 2015 PM traffic conditions.
- 2025 Do-Nothing model, which includes traffic projections for the year 2025, using a 2.4 percent traffic growth rate obtained through the analysis of historical trends. The geometry of the model remained unchanged from the Base model; however, traffic signals were optimized in Synchro for the projected demand levels.
- 2025 CV TSP model, which introduced CV-equipped buses. It is assumed that all buses, as fleet vehicles, will be equipped with CV technologies by 2025. This scenario, however, does not include CV-equipped passenger cars. A detailed description of the CV and TSP algorithms is provided in later subsections of the paper.
- 2025 Bus Rapid Transit (BRT) model, which introduces a center-running BRT line along State Street, with higher-capacity buses (110 spaces per bus) running every 15 minutes, fewer bus stops located at high-demand locations with improved pedestrian access and increased ridership. The new ridership demand was computed based on the 2.4 percent yearly growth rate. The signals were re-phased for protected-only left turns because of the center BRT lanes, so Synchro was used to re-optimize the signal timings. Additional design and operational improvements included longer storage space for turn lanes at intersections and a dual left-turn lane in the WB direction at the 2100 S intersection.
- 2025 CV BRT TSP model, which upgrades the previous model by introducing CV-equipped BRT vehicles and three-level custom conditional TSP. A detailed description of the TSP algorithms is provided in later subsections of the paper.

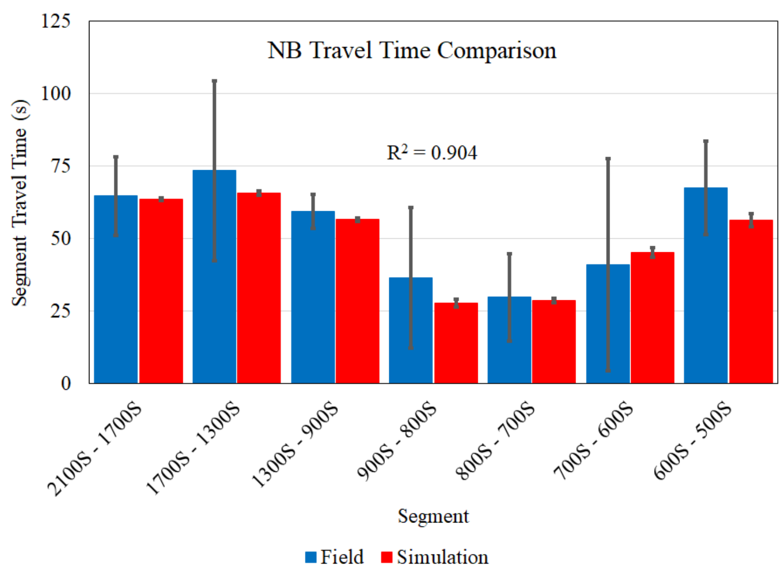
Each model was created for the two-hour PM peak period (4–6 p.m.). The simulations included a 15-minute warm-up period and two hours of output recordings. The outputs were averaged from 10 randomly-seeded simulation runs for each scenario, with the same sequence of random seeds among scenarios to allow for a reasonable comparison.

4.1.1 Base Model

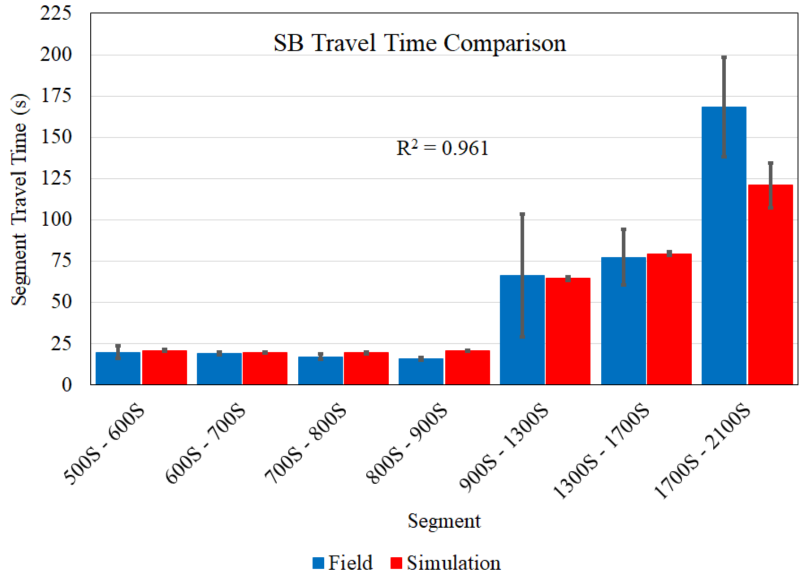
The Base model was developed, calibrated and validated for 2015 existing traffic conditions along the State Street corridor. VISSIM version 11, coupled with Econolite ASC/3 SIL traffic controller software, was used for modeling. The data used in modeling included actual roadway and intersection geometries, traffic counts for vehicles, pedestrians and bicyclists, corridor travel times, transit route and other ridership data, and signal timing data. The outputs were averaged from 10 simulation runs with different random seeds. The Base model was calibrated for intersection turning movements, and validated for corridor travel times. The calibration was performed for five major signalized intersections: 500 S, 600 S, 800 S, 1300 S and 2100 S. For this purpose, the two-hour PM peak (4–6 p.m.) intersection turning movement counts were used. The comparison was performed for each approach and each movement separately. Figure 4.2. a) shows compiled calibration results for the five intersections and each movement, where the field counts were compared to the results obtained from the simulation. The coefficient of determination (R^2) for calibration was close to 1.0 for the entire network, showing satisfactory calibration results. For validation purposes, the corridor was split into seven segments in each direction, where one segment was between a pair of major signalized intersections. Travel times collected in the field were used to validate the model. The field travel times were averaged from five travel time runs in each direction during the PM peak period, using the floating car technique. Model validation is shown in Figure 4.2. b) and 2. c). It represents a comparison between the average field travel times and the travel times obtained from the simulation, including the standard deviation. The R2 value for validation was 0.904 in the northbound (NB) and 0.961 in the southbound (SB) direction. The calibration and validation results show a good fidelity of the Base model.



a) Base Model Calibration



b) Base Model Validation, NB



c) Base Model Validation, SB

Figure 4.2 Base Model Calibration and Validation

4.1.2 2025 CV TSP Model

The 2025 Do-Nothing model was developed assuming 2.4 percent traffic growth in the area and did not include any geometrical modifications. Traffic signal timings were optimized through Synchro for the new demand levels. The 2025 CV TSP model was based on the 2025 Do-Nothing model, and introduced CVs and SCP for transit buses. No other vehicles were equipped with CV technologies in this study. The algorithm for 2025 CV TSP assumes that all (100 percent) of buses will be CV-equipped. When the transit vehicle enters the defined detection range, it starts sharing its location with the RSU. The distance between the bus and the intersection, and the estimation of the bus arrival time, are updated in each time step. According to the current signal phase and vehicle location, the RSU triggers TSP actuation. Each transit vehicle in the detection range is eligible for priority, regardless of the schedule adherence or bus capacity utilization, i.e. the priority is unconditional. When the vehicle leaves the intersection, the TSP is canceled. Following the constant updates of the distance between the bus and the intersection, the RSU can cancel TSP if it estimates that the bus cannot reach the intersection during the pre-defined time period. A new TSP initiation is possible in the next cycle.

The CV protocols, communication, BSM information and RSU operations were programmed through VISSIM's COM using Python programming language. TSP operations were programmed through built-in signal control priority functions in ASC/3 controllers. The main information contained in the BSM that was used for communication with traffic signals through RSU was the vehicles' latitude/longitude coordinates. RSU contained the latitude/longitude coordinates of the center of the intersection, which was used as a reference point. As a vehicle was approaching the intersection, it would send its latitude/longitude coordinates, and the RSU would compute the current distance in every time step. The distance was computed using the Haversine formula as given in Eq. 1 through in Chapter 3.

The communication range between the vehicles and the intersections was set to 600 ft., mainly for two reasons. First, the intersections on the north side of the network are spaced at around 700 ft., so a longer communication range would contain two intersections at certain times. This was not optimal for the TSP requests in this case. Second, the green extension times were set to 15 seconds maximum, so the distance traveled by the vehicles at the speed limit (30 mph) was close to 650 ft. during that time, which would ensure an effective GE strategy.

Once a CV-equipped vehicle entered the 600-ft. detection zone, it would be allowed to send a TSP request to the signal. In this study, SCP was provided only to the buses along the main corridor (NB and SB through on State Street), although the controller was able to identify those vehicles on all approaches. The vehicles on NB/SB through phases were filtered out based on the heading/route information from the BSM. The TSP request and strategies were programmed through a combination of RSU operations, and built-in controller logic and SCP features. When the RSU noticed a request, it would activate the internal controller logic and enable GE/EG TSP strategies. GE was set to 15 seconds maximum, while the maximum green time reductions for EG were set as five seconds for left turns along the main corridor, and 10 seconds for through movements from side streets. In this case, the TSP was unconditional, meaning that all CVs (all buses) would send a request and receive priority. The re-service cycle was set to one. The TSP check-out zone was set to 35 ft., meaning when the vehicle is within 35 ft. from the center of the intersection the call would be canceled. This was optimized for the current intersection geometries in this network.

4.1.3 2025 CV BRT TSP Model

Because of the significant multimodal features of the State Street corridor, the local transportation agencies recognized the need for BRT implementation (The Planning Center 2011; UDOT 2015; Wasatch Front Regional Council 2015). This study considered a BRT implementation with center-running exclusive lanes, upgraded buses with 110 spaces capacity, upgraded stations and passenger routing. The BRT ridership demand was computed based on the existing data and travel demand projections. Signal operations were changed because of the center-running buses, therefore permitted left turns were not allowed along State Street. Synchro was used to optimize signal timings in this case. The 2025 BRT model included BRT operations, but did not incorporate TSP for comparison purposes. Due to the negative effects on the side-streets, BRT with unconditional TSP has not been considered for this study (Al-Deek et al. 2017). Furthermore, it is assumed that for the future BRT operations UDOT and UTA will implement conditional CV-based TSP, according to the current field tests (Leonard et al., 2019). The 2025 CV BRT TSP model included BRT operations, CV-equipped buses and three-level custom conditional TSP strategies. The CV communication, RSU operations, check-in and check-out actuation were the same as in the previously described CV model. The three levels of conditional TSP were defined as follows:

- No TSP: buses are running on time, and the BRT bus capacity utilization is less than 20 percent.
- Low TSP: buses are running on time, and the BRT capacity utilization is more than 20 percent, OR buses are running 0 – 2 minutes behind schedule, and bus capacity utilization is less than 20 percent. GE/EG strategies are implemented in this case. GE was 15 seconds maximum, while the maximum green time reductions for EG were 5 seconds for left turns along the main corridor, and 10 seconds for through movements from side streets.
- High TSP: buses are running 0 – 2 minutes behind schedule and the capacity utilization is more than 20 percent, OR buses are running more than two minutes behind schedule, regardless of bus capacity utilization. This TSP includes GE/EG as previously described, with addition of phase rotation (PR). The signals along the main corridor operate with leading left phases in the regular mode. PR changes this sequence, allowing the stopped bus to leave the intersection earlier with leading through phases. PR works in combination with EG, while GE is provided to a vehicle that approaches the intersection during the green phase, if the TSP request is still active.

The BRT time-check points for each intersection were defined based on the free-flow speeds and station dwell times in both directions. These check points were used to assess the schedule adherence for each intersection. The 20 percent capacity utilization equals 22 passengers on board for the 110-space buses. These two parameters were used to determine the TSP level for each bus, direction, and intersection. GE/EG strategies were programmed through built-in SCP in ASC/3 controllers. PR was achieved through the controllers' logic processor by activating an alternate action plan with a sequence that was programmed with leading through phases. The multi-level TSP algorithm is shown in Figure 4.3.

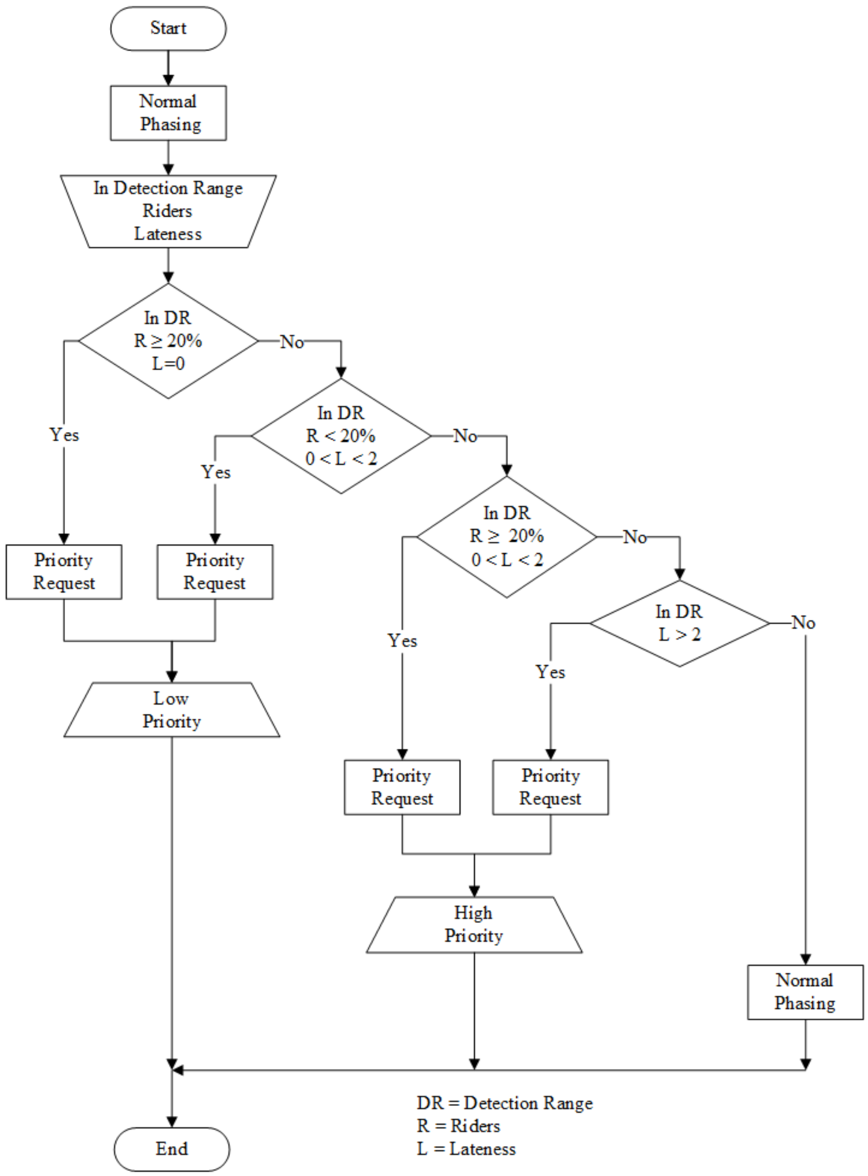


Figure 4.3 Three-Level Conditional TSP

4.2 Results and Discussion

The results collected from the simulations and used in the analysis include intersection performance measures and vehicle speeds. The results were collected and averaged from 10 simulation runs for each model. Where applicable, two-tailed paired t-test with a 95 percent confidence level was used to check if the differences in results were statistically significant.

4.2.1 Intersection Performance

Intersection performance for the seven major intersections on the corridor (500 S, 600 S, 800 S, 900 S, 1300 S, 1700 S and 2100 S) was assessed through the average vehicle delays per vehicle type for each scenario. The vehicle delays, weighted for the entire intersection, are provided in Table 4.1.

Table 4.1 Intersection Performance – Average Vehicular Delays

Intersection	Mode	Average Delay per Vehicle (s/veh)				
		Base	2025 Do-Nothing	2025 CV TSP	2025 BRT	2025 CV BRT TSP
500 S	Car	31.7	81.2	91.2	88.8	95
	Bus	52.6	95.3	102.9	19.2	26.3
	Bus vs. Base 2025	*N/A*	*N/A*	*8.0%*	*-79.9%*	*-72.4%*
600 S	Car	35.7	60	112.4	28.2	32.6
	Bus	15.6	53.7	117.3	54.1	46.9
	Bus vs. Base 2025	*N/A*	*N/A*	*118.4%*	*0.7%*	*-12.7%*
800 S	Car	33.7	42.7	47.9	38.1	38.9
	Bus	34.3	56.9	48	14.9	12.2
	Bus vs. Base 2025	*N/A*	*N/A*	*-15.6%*	*-73.8%*	*-78.6%*
900 S	Car	13.9	21.4	21	20.1	22.6
	Bus	14.6	14.2	21.3	21.2	22.1
	Bus vs. Base 2025	*N/A*	*N/A*	*50.0%*	*49.3%*	*55.6%*
1300 S	Car	41.3	55.4	68.8	41.9	43.4
	Bus	19.6	47.1	56	30.9	30.2
	Bus vs. Base 2025	*N/A*	*N/A*	*18.9%*	*-34.4%*	*-35.9%*
1700 S	Car	14.9	62.6	84	38.9	27.8
	Bus	12.6	58.4	83.3	34.1	28.1
	Bus vs. Base 2025	*N/A*	*N/A*	*42.6%*	*-41.6%*	*-51.9%*
2100 S	Car	41.2	94.9	126.2	73.8	74.9
	Bus	37.8	81	127.9	35.8	31.6
	Bus vs. Base 2025	*N/A*	*N/A*	*57.9%*	*-55.8%*	*-61.0%*
Average	**Car**	**30.4**	**59.7**	**78.8**	**47.1**	**47.9**
	Bus	**26.7**	**58.1**	**79.5**	**30**	**28.2**
	Bus vs. Base 2025	***N/A***	***N/A***	***36.8%***	***-48.4%***	***-51.5%***

The average vehicle delays would increase 50 percent or more for all vehicle types in 2025 if no improvements are made along the corridor. The 1700 S and 2100 S intersections would experience the most increase in vehicle delays — almost up to four times. All the increases are statistically significant. The unconditional TSP significantly increase delay for cars and buses, in excess of 35 percent, while for the trucks, delay reduces 10 to 40 percent in this scenario. Bus priority is not effective in this case. Therefore, the unconditional TSP is not recommended for implementation for high percentage of target vehicles. BRT implementation without TSP benefits all modes, with the decrease in delays most evident for buses (close to 50 percent compared to 2025 Do-Nothing). Cars and trucks experience a 21 percent delay reduction. The implementation of the three-level conditional TSP has different effects on an intersection-by-intersection basis. In general, it reduces BRT delays by six percent while it increases car and truck delays by up to two percent. None of these changes is statistically significant. The increase in car and truck delays is mostly attributed to the left turns along State Street and through movements on side streets.

4.2.2 Vehicle Speeds

The vehicle speed results for cars and buses along corridors are given in Tables 4.2 and 4.3, respectively. The speeds were measures in each direction on segments between the seven major intersections (14 segments in total). The 2025 Do-Nothing scenario reduces speeds for all vehicle types between 11 and 31 percent, and all these reductions are statistically significant. The introduction of BRT operations improves speeds for all vehicle types, most evidently for transit, when compared to 2025 Do-Nothing. Car speeds increase about 15 percent, while transit speeds increase more than 70 percent. The transit speed increase is statistically significant. The unconditional bus SCP generally reduces speeds for all vehicles when compared to 2025 Do-nothing. The 17 percent reduction in car speeds is statistically significant, while the bus speed reductions are not. Due to the exclusive bus lanes and upgraded operations, transit speeds in the 2025 BRT scenario are higher than those in the Base scenario. The introduction of TSP does not have statistically significant impacts on any of the speeds. It does improve transit speeds on majority of segments, but this increase is not significant. Car speeds remain mainly unchanged.

Table 4.2 Vehicle Speeds - Cars

		Car Speeds (mph)				
Segments		**Base**	**2025 DN**	**2025 CV TSP**	**2025 BRT**	**2025 CV BRT TSP**
SB	500 S - 600 S	26.1	12.1	11.9	13.3	11.5
	600 S - 700 S	28.0	26.7	28.1	18.1	16.3
	700 S - 800 S	28.2	10.8	10.2	11.0	10.8
	800 S - 900 S	26.2	20.0	20.5	23.7	21.1
	900 S - 1300 S	31.8	15.7	13.9	32.7	31.3
	1300 S - 1700 S	25.4	5.5	5.0	13.1	20.0
	1700 S - 2100 S	16.5	4.5	4.6	6.2	7.8
NB	2100 S - 1700 S	31.8	21.5	20.8	22.1	22.4
	1700 S - 1300 S	30.7	22.2	21.3	24.1	23.1
	1300 S - 900 S	36.1	33.5	33.7	34.4	33.6
	900 S - 800 S	19.4	20.9	17.1	22.8	21.4
	800 S - 700 S	19.0	23.3	11.7	24.2	23.7
	700 S - 600 S	12.0	9.7	4.4	13.8	10.2
	600 S - 500 S	9.7	9.3	6.0	10.6	9.8
Average		**24.3**	**16.8**	**14.9**	**19.3**	**18.8**

Table 4.3 Vehicle Speeds - Buses

	Bus Speeds (mph)					
Segments		Base	2025 DN	2025 CV TSP	2025 BRT	2025 CV BRT TSP
SB	500 S - 600 S	14.3	6.4	7.6	10.1	10.8
	600 S - 700 S	19.1	19.2	19.0	7.6	8.8
	700 S - 800 S	9.5	6.8	6.9	25.9	23.6
	800 S - 900 S	11.7	10.3	10.1	30.1	24.6
	900 S - 1300 S	15.8	10.6	9.3	14.1	13.2
	1300 S - 1700 S	18.6	4.8	4.5	13.4	14.4
	1700 S - 2100 S	11.7	4.1	4.2	14.6	15.3
NB	2100 S - 1700 S	15.3	14.7	15.2	14.5	15.6
	1700 S - 1300 S	18.7	14.9	15.3	16.1	17.2
	1300 S - 900 S	18.2	18.4	18.6	12.3	12.3
	900 S - 800 S	14.2	8.2	8.3	30.9	31.4
	800 S - 700 S	10.3	11.1	7.3	34.5	34.4
	700 S - 600 S	9.8	6.2	4.0	6.3	6.3
	600 S - 500 S	6.3	5.3	5.3	12.8	12.1
Average		**13.8**	**10.1**	**9.7**	**17.4**	**17.1**

4.3 Conclusions

The goal of this section of the study was to develop, test, and assess the effectiveness of conditional TSP in various CV applications in a congested urban corridor. The control programs were developed and tested in Econolite ASC/3 SIL signal control simulation implemented in VISSIM microsimulation. CV protocols, communication, BSM information and RSU operations were implemented through Python programming language. TSP operations were programmed through built-in SCP functions in ASC/3 controllers. The algorithms used latitude/longitude coordinates of intersections and approaching vehicles to determine the detection zone. The study developed a three-level customized conditional TSP that uses bus schedule adherence and real-time ridership to determine the level of TSP for each approaching vehicle (no TSP, low TSP or high TSP).The tests were performed on a 10-intersection corridor along State Street in Salt Lake City, UT.

The analysis of the test-case corridor shows a major deterioration of future traffic conditions if no improvements are made. Vehicle delays would increase and speeds would reduce significantly, about 50 percent and 30 percent respectively, with a significant deterioration in transit operations. The implementation of unconditional TSP for buses provided significant delay savings for trucks, up to 40 percent, but it also caused significant delay increase for other vehicles, in excess of 35 percent. Speeds for all vehicles would reduce if unconditional TSP is provided to all target vehicles. A BRT implementation would benefit all transportation modes, reducing delays by more than 20 percent and improving speeds by 15 percent for general-purpose traffic. Transit delays would reduce more than 50 percent and their speeds increase more than 70 percent.

The information sent from CV-equipped transit vehicles can be used to create different forms of conditional priority. This study used schedule adherence and real-time ridership to determine the level of granted TSP for BRT. Green extension, early green, and phase rotation were the strategies implemented for different combinations of vehicle lateness and ridership. The introduced TSP strategies generally reduced transit delays by about six percent, without significant impacts on other traffic and transit operations.

This study is the first step toward creating field-ready traffic control programs for special signal operations. For this study, only the vehicles' position, heading, schedule adherence, and ridership were used to develop signal control priority algorithms. However, CV-equipped vehicles can provide more information, which can be used to further fine tune traffic control. Furthermore, it only assumed that transit vehicles will be fully equipped. In reality, it can be expected that a percentage of other vehicles will also have CV equipment. Future studies will be focused on expanding the conditional priority algorithms with additional constraints, and developing adaptive SCP programs that use the information from all CV-equipped vehicles and real-time data from other traffic sensors and systems, such as the ATSPM.

5. SPEED HARMONIZATION AND PLATOONING

The CAV-based SPD-HARM and vehicle platoonin algorithms were developed and tested in VISSIM microsimulation. The algorithms use the communication among the vehicles, and the vehicles and the infrastructure, to determine the optimal speed at intersection approaches or along the corridor. The algorithms were tested in two settings, mainly rural (the six locations described in Chapter 3), and a congested urban corridor (the State Street corridor described in Chapter 4).

5.1 Speed Harmonization Algorithm

The SPD-HARM algorithm is developed and applied to connected trucks, using the six Wyoming locations described in Chapter 3. It uses the current CV truck position, speed, and current signal timing state on vehicle approach. Once the vehicle enters the detection zone, it starts communicating with the signal. The signal sends the current phase status, and the algorithm determines the optimal speed of the vehicle, so it can cross the intersection during green. If the current phase is green, the algorithm checks if the vehicle can cross the stop line during green at its current speed. If yes, the algorithm does not recommend speed adjustment. If no, then the algorithm recommends a higher speed, so the vehicle arrives during green. To keep the vehicle speeds reasonable, the algorithm limits the maximum speed to 10 percent over the speed limit. If the vehicle approaches on red, the algorithm recommends speed reduction, so the vehicle arrives closer to the beginning of green. Similarly, the minimum vehicle speed is limited to no less than 85 percent of the speed limit.

5.2 SPD-HARM Results and Discussion

The development and calibration of the models used to assess the SPD-HARM algorithm is described in Chapter 3. The assessment is performed on the intersection level, using average vehicle delays as the main parameters. In this case, three model scenarios were used: Base, 50 percent CV trucks, and 100 percent CV trucks. The reason for this classification is due to the low vehicle demand at the analyzed intersections. When the CV rates are low (less than 50 percent), the speed harmonization algorithm was ineffective in forming platoons. For this reason, the SPD-HARM, in combination with platooning, was performed on a congested urban corridor, described later in this chapter. The base SPD-HARM algorithm was implemented and tested on the six signalized intersections for the main through movements. The only exception is the Cheyenne network, where the speed harmonization was implemented for off-ramp right turns as well, since this is a diverging diamond interchange. Table 14 shows the average vehicle delay results and comparisons.

The implementation of SPD-HARM has the potential to reduce CV truck delays, in some cases, significantly. This reduction varies between 4 and 82 percent, depending on the location and CV truck percentage. The highest reduction was observed in the Cheyenne network and 100 percent CV trucks. Car traffic was not impacted by the SPD-HARM implementation. In fact, in some cases, cars benefit from it, as they join the platoon of trucks through the intersection.

Table 5.1 SPD-HARM Intersection Performance – Vehicle Delays

Scenario	Mode	Average Intersection Vehicle Delays (s)					
		Rock Springs	Rawlins	Evanston	Laramie	Cheyenne West	Cheyenne East
Base	**Car**	10.7	10.9	9.4	6.9	3.9	5.9
	Truck	11.6	12.0	11.1	7.0	3.4	5.4
50% CV	**Car**	11.3	10.7	9.7	6.1	4.2	6.2
	CV Truck	11.2	9.6	10.3	7.5	0.8	2.3
	Truck	10.6	11.7	9.5	7.0	3.5	5.1
	CV Truck vs. Base	*-3.4%*	*-20.4%*	*-6.7%*	*6.7%*	*-76.5%*	*-57.0%*
100% CV	**Car**	10.9	11.0	9.2	6.0	3.7	5.8
	CV Truck	10.2	10.5	9.8	7.0	0.6	1.7
	CV Truck vs. Base	*-12.0%*	*-12.3%*	*-11.6%*	*-0.4%*	*-82.4%*	*-68.2%*

5.3 Platooning and Platoon Priority Algorithm

The congested urban corridor along State Street in Salt Lake City, UT, was used to asses the effectiveness of a combined SPD-HARM and platooning algorithm, and the implementation of transit and platoon signal priority. The development, calibration, and validation of the base VISSIM model for this corridor is described in Chapter 4.

Based on the distance between intersections along the corridor and the maximum distance that vehicles can travel during the green extension, the range that vehicles can broadcast information is set to 300 ft. for transit and 600 ft. for vehicle platoons. Transit vehicles are enabled to share trajectory data while the occupancy rate is used as a criterion to grant conditional priority. The occupancy rate is part of the SRM message that transit vehicles exchange with RSU. The TSP strategies used for transit vehicles include a 15-second GE for the transit-related signal phases along the corridor.

Passenger cars in a platoon are also eligible for signal control priority if a platoon has three to six vehicles. The threshold of maximum six vehicles in a platoon is the maximum number of vehicles that can pass through the intersection during the preset 10 seconds of GE, considering the speed of vehicles and the gap time of 0.85 seconds. Only vehicles in one lane are eligible to participate in a platoon. All vehicles in a platoon are assigned the same driving behavior, which differs from the driving behavior for conventional vehicles. The proposed algorithm recognizes the platoon condition according to speeds and vehicle positions. The passenger car platoon can be created only of CV-equipped vehicles. The algorithm is presented in Figure 5.1.

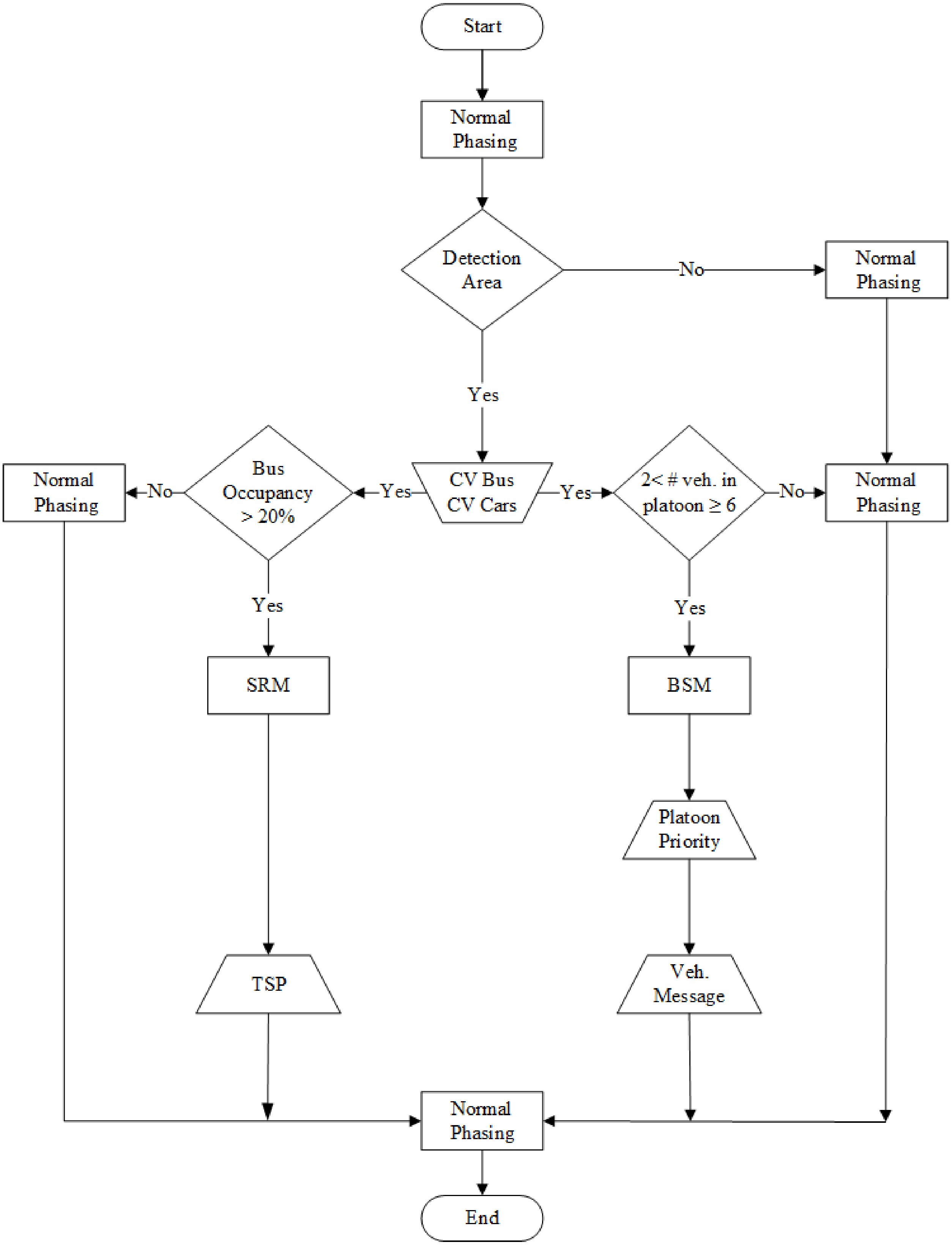


Figure 5.1 Platooning and Signal Control Priority Algorithm

5.4 Platooning Model Scenarios

Using the 2019 model as the base, the study developed five additional models for the year 2029 for different percentages of CVs in the traffic flow. Each model was implemented for the two-hour PM peak period (4:00 – 6:00), with additional 15 minutes for model warm-up. The 2029 models are summarized as follows:

1. Base2029 model, built on the bas 2019 model, following the same geometry characteristic. The model includes traffic projections for the year 2029 using an annual growth rate of 2.4 percent. Signal timing is optimized in Synchro according to estimated demands.

2. 25-CV29TSP model, which introduces CVs in the previous base model from 2029. The percentage of CVs in this model is up to 25 percent. This model introduces conditional TSP for buses and signal priority for car platoons. The proposed algorithm is explained in detail in the following subsections.

3. 50-CV29TSP model, which is the same as the previous model 25-CV29TSP, but with an increase of the MPR to 50 percent.

4. 75-CV29TSP model, which follows the previous model with an increase in the MPR to 75 percent.

5. 100-CV29TSP model assumes that all passenger cars are equipped with CV technologies, while all other characteristics from the previous model remained the same.

5.4.1 CV-based TSP models

CV-based models are built on the Base2029 model, following the same traffic, geometry, and signal timing. These models introduce a CV-based TSP algorithm for transit and platooned passenger cars. MPR of CVs in the scenarios is 25, 50, 75, and 100 percent. The truck traffic is represented with only seven percent of the total traffic; therefore, they are not considered for any signal control treatment. The distance from which the CV vehicles are allowed to broadcast messages is equal to the distance they can pass during the GE period traveling at the maximum permitted speed, which is approximately 600 ft. For transit vehicles the communcation distance was reduced to 300 ft. because of bus stops in the vicinity of the intersections. Once the transit vehicle enters the detection range, it can transmit information to the RSU. The priority is conditional and will be granted to transit vehicles with an occupancy rate over 20 percent, while in all other cases, the TSP will not be activated. The second part of the CV-based priority is reserved for platoon priority. Any platoon that contains three to six vehicles is eligible for control priority at intersections, to facilitate their movement through the corridor and prevent platoon breaking up. The algorithm checks for platoons on the main approach only during the green interval on through phases (Φ2 and Φ6 in this case), since only GE is the applied signal control strategy. Once they enter the CV communication range, platooned vehicles change the driving behavior parameters, resulting in reduced headways and oscillation in speeds, while vehicles exchange messages.

5.5 Platooning and Platoon Priority Results and Discussion

The results were collected and averaged from five randomly-seeded simulation runs for each scenario. The analyzed outputs include intersection performance measures and corridor vehicle speeds. Where applicable, a two-tailed paired t-test with a 95 percent confidence level was used to check if the differences in results among the models were statistically significant.

5.5.1 Intersection Performance

The intersection performance was assessed through average delays per vehicle type on all approaches for all six models. The vehicle delays for the seven major intersections on the corridor are presented in Table 5.2.

Table 5.2 Platooning Intersection Performance – Vehicle Delays

Intersection	Mode	Average Delay per Vehicle (s/veh)					
		Base19	Base29	25-CV29TSP	50-CV29TSP	75-CV29TSP	100-CV29TSP
500 S	Car	35.2	84.5	86.5	86.7	106.4	N/A
	CV Car	N/A	N/A	82.9	83.7	97.4	86.5
	Bus	55.4	111.2	101.6	109.2	108.2	114.4
600 S	Car	38.3	54.5	60.4	59.4	63.4	N/A
	CV Car	N/A	N/A	61.3	60.5	20.9	60.1
	Bus	19.6	51.6	50.2	51.5	51.8	47.8
800 S	Car	35.9	48.3	68.9	68	67.6	N/A
	CV Car	N/A	N/A	79.3	79.3	30	81.1
	Bus	36.5	48	51.2	53.2	52.7	52.7
900 S	Car	14.7	19.7	22.9	23.3	23.8	N/A
	CV Car	N/A	N/A	20.9	21.9	7.1	23.3
	Bus	16.4	13	16	13.4	14.3	15.6
1300 S	Car	39	41.7	103.1	102.5	77.8	N/A
	CV Car	N/A	N/A	97	97.1	46.5	109.4
	Bus	19.8	27.8	40.8	42.1	26.1	64.2
1700 S	Car	15.6	28.8	70.3	57.2	51.8	N/A
	CV Car	N/A	N/A	68.1	55.9	54.7	55
	Bus	15.1	24.1	65	54.1	52.5	41.3
2100 S	Car	48.5	69	119.6	109.2	91	N/A
	CV Car	N/A	N/A	120.5	107.9	71.7	103.6
	Bus	43.1	35	110.1	92.1	71.1	75.2
Average	**Car**	**32.5**	**49.5**	**76**	**72.3**	**68.8**	**N/A**
	CV Car	**N/A**	**N/A**	**75.7**	**72.3**	**46.9**	**74.1**
	Bus	**29.4**	**44.4**	**62.1**	**59.4**	**53.8**	**58.7**

The increased traffic demand for the year 2029 would increase delays for all vehicles and intersections, and this increase is statistically significant. The introduction of 25 percent CV-equipped cars eligible for platoon priority and CV-based conditional TSP will increase the average delay along the corridor. The delay results differ from intersection to intersection for each vehicle type. The highest delay increase in this scenario is for conventional vehicles, and this increase is statistically significant. Further increase in the MPR to 50 percent would reduce the delays up to 19 percent, especially at the busiest intersections (1300 S, 1700 S, and 2100 S). These reductions are statistically significant. The delays continue to decline in the scenario with CV MPR of 75 percent. This reduction is also statistically significant and benefits the busiest intersections. However, the 100 percent MPR for CV cars could lead to an increase in delays for almost all intersections. This is due to the continuous interruptions in signal operations, caused by the calls for platoon priority. Therefore, for 100 percent MPR, the algorithm would need to be adjusted. The current proposed platooning and priority algorithm perform the best for the 75 percent MPR.

5.5.2 Vehicle Speeds

The vehicle speeds for all scenarios are shown in Figures 5.2 and 5.3 for CV cars and buses, respectively. The speeds were measured in both directions, for each vehicle type and each segment; there are 14 segments in total.

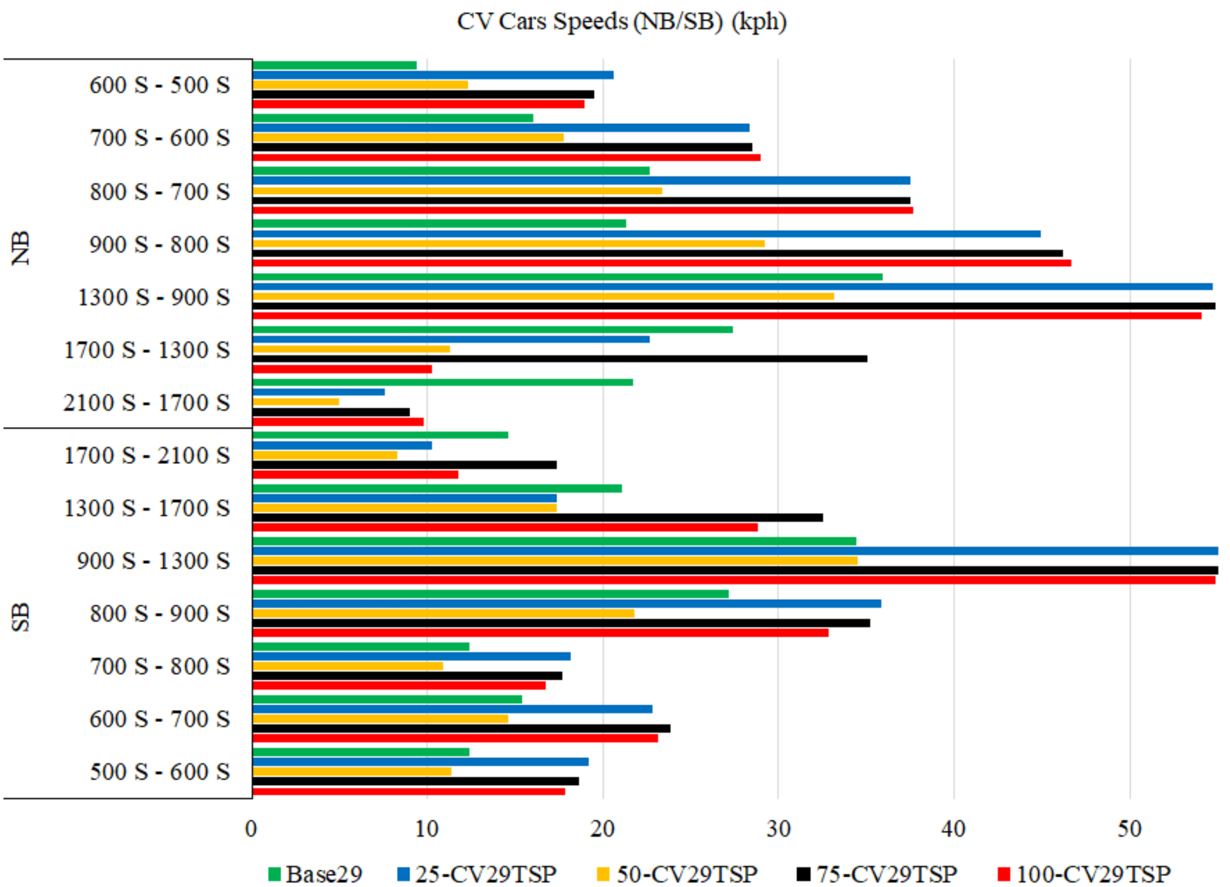


Figure 5.2 Platooning Algorithm CV Cars Speed Comparison

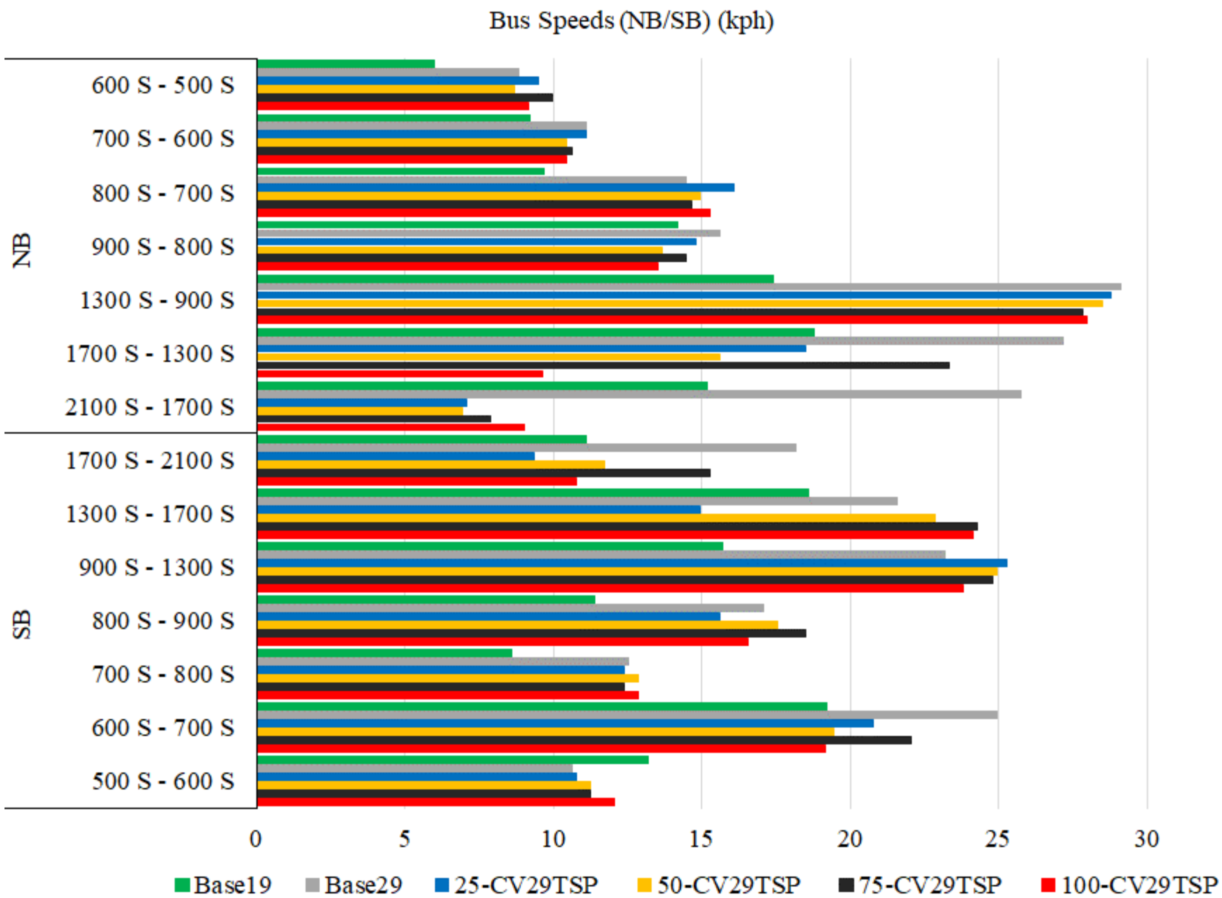


Figure 5.3 Platooning Algorithm Bus Speed Comparison

The increased traffic demand for 2029 would decrease speeds for all vehicles and all segments, as can be expected. The introduction of platoon priority with a 25 percent MPR, and conditional TSP for buses, would decrease speeds for all vehicles on the segments between intersections with the highest traffic demand (1300 S, 1700 S, and 2100 S) in both directions, while for other segments, the speed will increase slightly. The increase in MPR to 50 percent would increase average speed by two percent, while speeds between the busiest intersections are still lower than in the Base29 model. The platoon priority and occupancy-based conditional TSP will increase average speeds by eight percent in the model with 75 percent CV MPR. The speed increase for buses and conventional cars is significant. The segments between the intersections with the highest traffic demand will still be recording a lower speed than the base model, while all other segments will experience a speed increase. The model that considers all cars to be CV-equipped and eligible for platoon priority will decrease the average speed on the corridor by 10 percent compared to the base model, but with oscillation by a segment. CV cars will also decrease their speed, and this difference is significant. The conditional priority for buses performs best in the model with 75 percent of CV-equipped cars. Overall, an MPR of 75 percent has the best performance for all vehicle types at the study corridor.

5.6 Conclusions

This part of the study developed and tested SPD-HARM and platooning application. SPD-HARM application optimizes the speeds of CAV-equipped vehicles as they approach an intersection. By communicating position and current signal state, the algorithm recommends the optimal speed, so the vehicles can reach the intersection during (or close to) the green interval. The application is tested at the six intersections for three model scenarios: Base, 50 percent CV trucks, and 100 percent CV trucks.

The results show that the CV-based SPD-HARM algorithm can bring significant benefits to truck traffic, with reduction in delays between four and 82 percent, without impacts on other traffic. This application can also be combined with Q-WARN and FSP, which would bring even more operational and safety benefits.

The platooning algorithm uses two types of signal control priority. One type is reserved for transit vehicles, and it is conditional TSP based on the transit vehicle capacity utilization. Any transit vehicle that exceeds the occupancy rate of 20 percent is eligible for TSP activation. The other control priority type is allocated to platooned cars equipped with CV technologies. The algorithm checks the platoon conditions at the intersection approaches and grants priority treatment based on the size of the platoon. The maximum platoon size was set to six vehicles, which is the number of vehicles that can traverse the intersection during the GE of 10 seconds, considering the speed of vehicles and the gap time of 0.85 seconds, adopted as the driving behavior of human operators in a CV environment. These two priority treatments are part of one algorithm capable to check the entire traffic flow on the intersection approach. The percentage of CV cars in the traffic flow can vary according to the deployment phases of CV technologies. Therefore, the study provides scenarios that could accommodate these variations with thresholds of 25, 50, 75, and 100 percent of CV cars.

Obtained results showed that the difference in MPR leads to differences in the performance of the proposed algorithm. The 25 percent of CV cars in the traffic flow using the proposed algorithm could not bring notable benefits to any type of vehicle, and at most intersections, it caused increase in delays and reduction in speeds. Since the phase durations did not change significantly in this model, the number of priority requests granted to cars is very low. An increase in the MPR to 50 percent alleviates these conditions, but they are still not statistically significant. The third model with a traffic composition of 75 percent CV cars changed the results significantly, with the reductions in delays up to 68 percent, eight percent increase in speeds, and significant changes in phase durations. This percentage of CV vehicles is enough to ensure platoon formation upstream of the intersections, while requests for priority do not exceed the capacity of traffic signals to grant them. The last model that considers all cars as CV-equipped cannot outperform the previous scenario, and showed increases in the delays and reduced speeds. Although this model has the potential for more platoons than any of the previous scenarios, constant requests for priority caused deterioration in intersection performances. In future research, the proposed algorithm will be upgraded with additional priority strategies and granting conditions to overcome its disadvantages recorded in this study.

6. QUEUE WARNING

The CV-based Q-WARN algorithm was developed and tested in VISSIM microsimulation. The algorithm uses the communication among the vehicles, and the vehicles and the traffic signals, to broadcast the information on potential queues of vehicles due to red lights. The algorithm was tested using locations in Wyoming, described in Chapter 3.

6.1 Q-WARN Algorithm

The communication, BSM information and RSU operations were programmed through VISSIM COM interface using Python programming language. The main information contained in the BSM that was used for communication with traffic signals through RSU was the vehicles' lat/long coordinates.

Once a CV-equipped freight vehicle enters the 600-ft. detection zone, it would start communicating with the traffic signal. When the RSU detects more than two freight vehicles on the approach while the traffic signal for the particular movement (through or left) is red, it activates the Q-WARN system and sends a message stating "Queue Ahead!" to the approaching upstream vehicles. When these vehicles receive the message, they start reducing their speed by about 20 percent until they reach the end of the queue. When the signal turns green and the vehicles start moving, the Q-WARN system is deactivated. For the left turning vehicles, the system works the same way regardless of the left turn treatment. In VISSIM simulation, the vehicle movement information is obtained through a combination of the current vehicle position, route decision and vehicle link. In the actual application, this can be achieved using the turn signal indication, combined with the vehicle location and speed.

6.2 Q-WARN Models and Scenarios

The development, testing, and assessment of the signal priority and Q-WARN algorithms were performed through VISSIM microsimulation. The communication protocols, BSM, and RSU operations were programmed in Python and embedded in microsimulation. All signal control operations were programmed directly in ASC/3 SIL traffic signal controllers. Six model scenarios were created at each of the intersections as follows:

1. Baseline model without the CV Q-WARN system implemented. This model was created and calibrated with the existing traffic volumes and operations, as described in Chapter 3.
2. A Q-WARN model with 10% of CV trucks and fleet vehicles.
3. A Q-WARN model with 25% of CV trucks and fleet vehicles.
4. A Q-WARN model with 50% of CV trucks and fleet vehicles.
5. A Q-WARN model with 75% of CV trucks and fleet vehicles.
6. A Q-WARN model with 100% of CV trucks and fleet vehicles.

Each model was created for the PM peak hour (5–6 p.m.) in which the data were collected. The simulations included a 10-minute warm up period and an hour of output recordings. The outputs were averaged from ten randomly seeded simulation runs for each scenario with the same sequence of random seeds among scenarios to allow for a rational comparison.

The main information contained in the BSM used for communication with traffic signals through RSU was the vehicles' latitude/longitude coordinates. RSU contained the latitude/longitude coordinates of the center of the intersection, which was used as a reference point. As a vehicle was approaching the intersection, it would send its latitude/longitude coordinates, and the RSU would compute the current distance in every time step. The distance was computed using the Haversine formula, as described earlier.

The communication range between the vehicles and the intersections was set to 600 ft., mainly because all the tested intersections are located 750 – 1,000 ft. from the on and off ramps to the interstate. Once a CV-equipped freight vehicle enters the 600 ft. detection zone, it would start communicating with the traffic signal. When the RSU detects more than two freight vehicles on the approach while the traffic signal for the particular movement (through or left) is red, it activates the Q-WARN system and sends a message stating "Queue Ahead!" (Figure 6.1, green vehicles) to the approaching upstream vehicles. When these vehicles receive the message, they start reducing their speed by about 20% until they reach the end of the queue. When the signal turns green and the vehicles start moving, the Q-WARN system is deactivated (Figure 6.1, yellow vehicles).

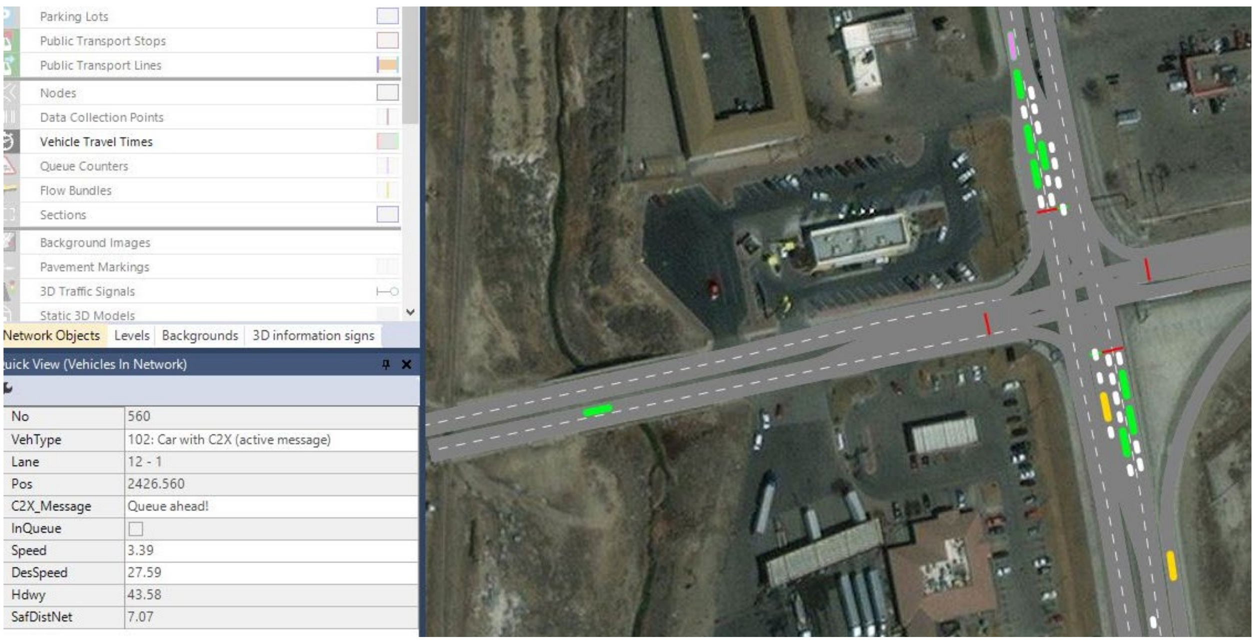


Figure 6.1 Example of Vehicles Queuing and Sending Q-WARN Message

6.3 Q-WARN Operational Results and Discussion

The final outputs from the 10 simulation runs were averaged for each model and intersection. The operational assessment is based on intersection performance measures. Where applicable, two-tailed paired t-test with a 95 percent confidence level was used to check if the differences in results were statistically significant.

The intersection performance was assessed through the average intersection delays (for passenger cars and trucks separately), and the average queue lengths. These results are shown in Tables 6.1–6.3.

Table 6.1 Intersection Performance – Car Delays

Scenario	Average passenger car intersection delays (s/veh)					
	Rock Springs	**Rawlins**	**Evanston**	**Laramie**	**Cheyenne West ramp**	**Cheyenne East ramp**
Base	10.7	11.0	9.4	6.2	4.2	5.8
10% CV	11.0	10.9	9.7	6.8	4.2	6.0
vs. Base	*2.7%*	*-0.4%*	*3.7%*	*9.2%*	*1.0%*	*3.8%*
25% CV	11.0	10.9	9.7	6.7	4.2	6.1
vs. Base	*2.4%*	*-0.5%*	*3.3%*	*7.4%*	*1.2%*	*5.4%*
50% CV	10.8	11.1	9.6	6.8	4.1	6.1
vs. Base	*1.0%*	*0.9%*	*2.1%*	*8.9%*	*-0.5%*	*5.9%*
75% CV	10.8	11.0	9.5	6.7	4.2	6.1
vs. Base	*0.7%*	*0.5%*	*1.0%*	*8.4%*	*0.0%*	*4.5%*
100% CV	10.6	11.0	9.3	6.7	4.1	6.0
vs. Base	*-0.7%*	*0.1%*	*-0.4%*	*8.4%*	*-0.7%*	*4.1%*

Table 6.2 Intersection Performance – Truck Delays

Scenario	Average truck intersection delays (s/veh)					
	Rock Springs	**Rawlins**	**Evanston**	**Laramie**	**Cheyenne West ramp**	**Cheyenne East ramp**
Base	11.6	12.3	11.1	7.7	3.4	5.2
10% CV	8.6	12.0	11.3	6.9	3.4	5.4
vs. Base	*-25.6%*	*-2.2%*	*1.7%*	*-10.7%*	*-0.9%*	*3.8%*
25% CV	11.9	12.0	11.0	7.5	3.4	5.3
vs. Base	*2.8%*	*-2.1%*	*-1.2%*	*-2.3%*	*-1.5%*	*0.6%*
50% CV	10.9	12.0	10.8	7.2	3.3	5.4
vs. Base	*-5.4%*	*-2.0%*	*-2.9%*	*-6.6%*	*-3.8%*	*3.3%*
75% CV	10.4	12.4	10.5	7.3	3.3	5.3
vs. Base	*-9.9%*	*1.1%*	*-5.2%*	*-5.3%*	*-4.4%*	*1.5%*
100% CV	10.9	11.9	10.6	7.5	3.3	5.5
vs. Base	*-5.5%*	*-2.7%*	*-4.9%*	*-2.0%*	*-4.1%*	*4.6%*

Table 6.3 Intersection Performance – Queue Lengths

Scenario	Average intersection approach queue length (ft)					
	Rock Springs	**Rawlins**	**Evanston**	**Laramie**	**Cheyenne West ramp**	**Cheyenne East ramp**
Base	9.7	8.0	8.1	2.0	1.5	3.4
10% CV	9.9	8.1	8.6	2.4	1.6	3.7
vs. Base	*1.3%*	*1.9%*	*6.7%*	*18.0%*	*5.9%*	*8.8%*
25% CV	9.9	8.1	8.5	2.3	1.6	3.7
vs. Base	*1.4%*	*1.3%*	*5.1%*	*16.0%*	*3.3%*	*7.3%*
50% CV	9.7	8.0	8.4	2.2	1.5	3.6
vs. Base	*0.1%*	*0.3%*	*4.1%*	*10.0%*	*-2.6%*	*5.9%*
75% CV	9.7	8.0	8.2	2.0	1.5	3.5
vs. Base	*-0.2%*	*0.3%*	*1.9%*	*2.7%*	*-3.3%*	*2.1%*
100% CV	9.6	7.9	8.0	2.0	1.5	3.6
vs. Base	*-0.9%*	*-0.5%*	*-0.6%*	*-0.3%*	*-2.0%*	*4.1%*

The results showed that the average car delays slightly increase with the increase in CV truck penetration rates, until about 75 percent. For the 100 percent CV rate the average car delays reduce. However, none of these changes is statistically significant. These findings are consistent for all locations. The results show that the passenger cars are not impacted by the truck Q-WARN applications. The average truck delays generally reduce with the increase in truck CV rates. The lowest truck delay is recorded for CV rates between 50 and 75 percent. Only the Cheyenne East ramp shows an increase in truck delays as the CV percentage increases. These changes however are not statistically significant. The results indicate that the Q-WARN application has the ability to reduce truck delays. The average queue length increases until the CV rate reaches 50 percent, after which it starts to reduce. In general, the queue length is not significantly impacted by the Q-WARN application.

In conclusion, the intersection performance is not impacted by the implementation of the developed Q-WARN application. In fact, the results show that the truck delays will benefit from this application and experience reduction.

6.3 Q-WARN Safety Results and Discussion

The Q-WARN application outputs extracted from VISSIM microsimulation for Rock Springs, Evanston, Rawlins and Laramie, WY, were analyzed for potential conflicts by traffic interactions from the microsimulation models. This analyses were conducted based on Surrogate Measure of Safety (SMoS) and evaluated using Surrogate Safety Assessment Model (SSAM) software. SSAM is used as a post-processor to analyze the ten randomly seeded VISSIM trajectory (TRJ) files to analyze V2V interactions to classify potential conflicts found throughout the simulation runs. Two SMoS were used in this analysis, the Minimum Time to Collision (TTC), and the Minimum Post-Encroachment Time (PET). TTC is defined the time required for two vehicles to collide if they continue at their present speeds on the same path. It is a measure that reflects crash risks, and the collision risk index varies from 0 to 1.5, with 0 being the riskiest situation. PET calculates the time lapse from the moment the first vehicle departs a conflict to the moment a second vehicle approaches the conflict point. PET threshold was set at the standard maximum of five seconds; a lower PET indicates higher probability of collision.

6.3.1 Rock Springs Model

The Rock Springs model outputs from SSAM were examined at six different market penetration rates for TTC, PET, and the difference in the number of conflicts between each scenario and the following scenario. Figure 6.2 shows how the mean TTC increases as the CV-Q-WARN market penetration rate increases. Mean TTC has peaked at the 100 percent with a mean TTC of 1.31 increasing from mean TTC of 0.25 at the base model. PET has also showed an increase in mean groups as the MPR increased. There were statistically significant differences between mean groups.

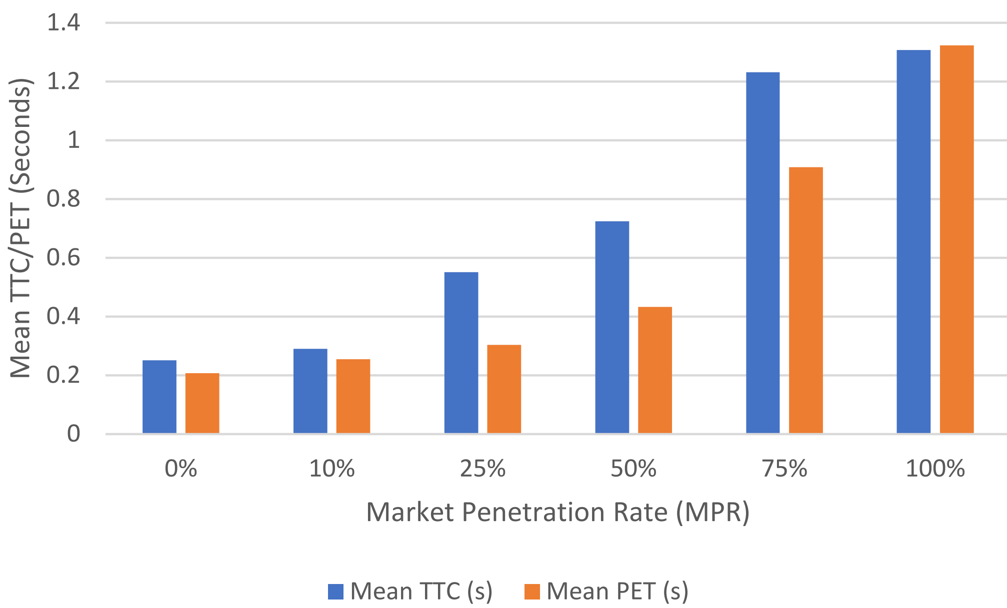


Figure 6.2 Relationship Between MPR and Mean TTC/PET - Rock Springs

6.3.2 Evanston Model

The same type of analysis was applied to the Evanston model as for the Rock Springs model. Figure 6.3 shows how the mean TTC increases as the CV-Q-WARN market penetration rate increases. Mean TTC has peaked at the 100% with a mean TTC of 1.27 increasing from mean TTC of 0.334 at the base model. PET has also showed an increase in mean groups as the MPR increased. Statistically significant differences were found between mean groups.

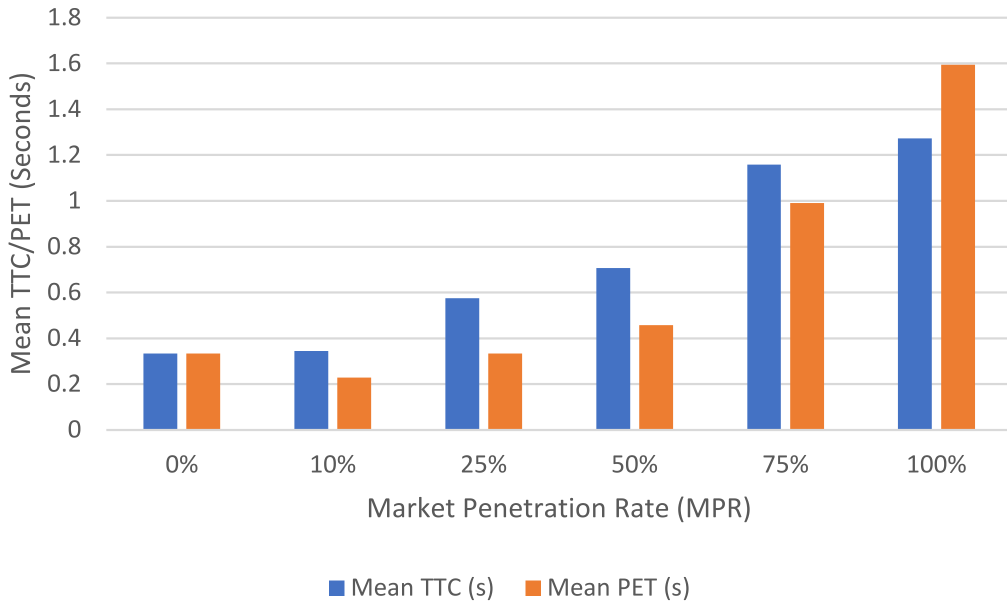


Figure 6.3 Relationship Between MPR and Mean TTC/PET - Evanston

6.3.3 Rawlins Model

The SSAM analysis was applied to the Rawlins model. Figure 6.4 shows how the mean TTC increases as the CV-Q-WARN market penetration rate increases. Mean TTC has peaked at the 100% with a mean TTC of 1.228 increasing from mean TTC of 0.053 at the base model. PET has also showed an increase in mean groups as the MPR increased. There were again statistically significant differences between mean groups.

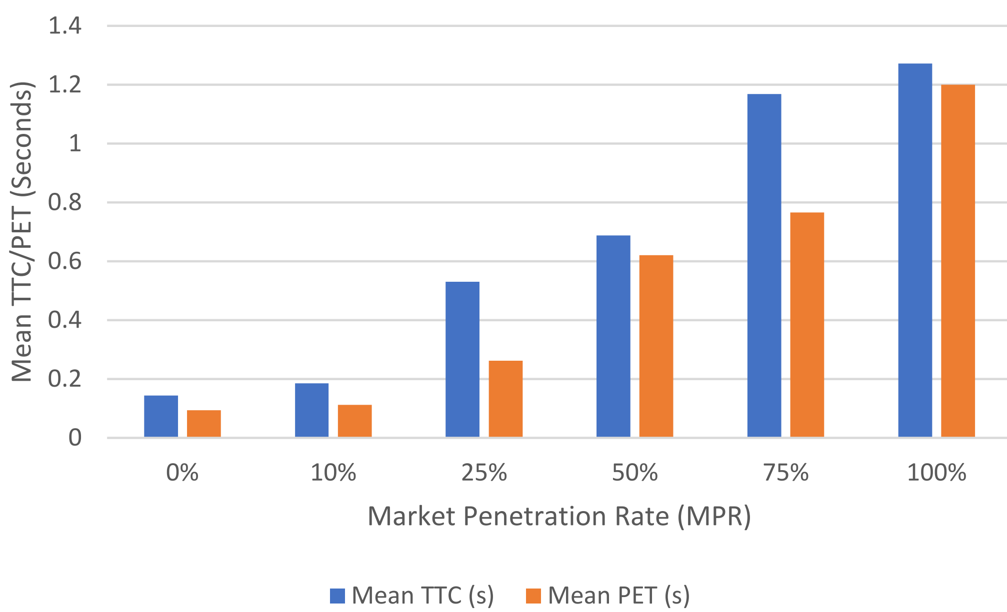


Figure 6.4 Relationship Between MPR and Mean TTC/PET - Rawlins

6.3.4 Laramie Model

Figure 6.5 shows the mean TTC and PET results obtained from SSAM for the Laramie model. The mean TTC increases as the CV-Q-WARN market penetration rate increases. Mean TTC has peaked at the 100% with a mean TTC of 0.962 increasing from mean TTC of 0.040 at the base model. PET has also showed an increase in mean groups as the MPR increased. There were significant differences between mean groups in this model as well.

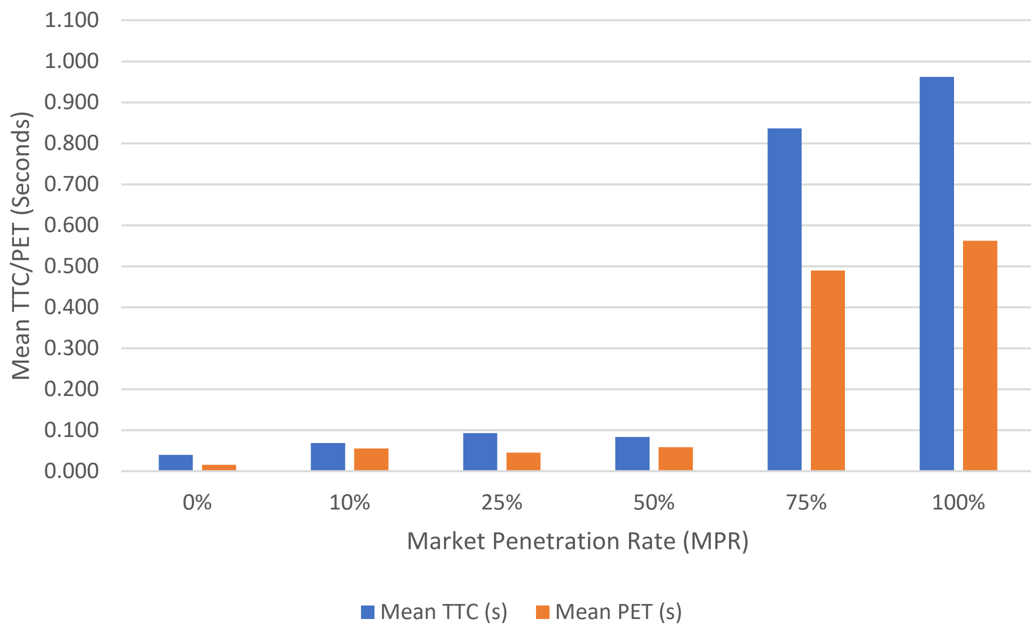


Figure 6.5 Relationship Between MPR and Mean TTC/PET - Laramie

6.4 Conclusions

This section describes the development and testing of a Q-WARN algorithm on traffic operations and safety. The Q-WARN algorithm was created and analyzed through VISSIM microsimulation. The analysis of each model was performed for the evening peak hour, 5–6 p.m.

The operational results showed that the CV-based queue warning systems were effective in reducing truck delays by an average of two to five percent. No significant changes were found in queue lengths at intersection approaches. The safety analysis showed that the means of SMoS were increasing, consequently leading to to safety enchancement of the developed Q-WARN application.

The limitations of this research are mainly related to the test-bed networks used. The analyzed intersections typically do not carry a lot of vehicular traffic, therefore the results might be skewed. In future research, this application should be implemented and assessed in congested corridors.

7. EMERGENCY VEHICLE PREEMPTION

The CV-based emergency vehicle PREEMPT algorithm was developed and tested in VISSIM microsimulation. The algorithm uses the communication between the emergency vehicles and the traffic signals, to broadcast the information on location and speed of the approaching vehicle. The algorithm was tested using the State Street test-bed, described in Chapter 4.

7.1 PREEMPT Algorithm

The communication, BSM information and traffic signal operations were programmed through VISSIM COM interface using Python programming language. The main information contained in the BSM used for communication with traffic signals through RSU was the emergency vehicles' position (lat/long) coordinates, their speeds, and the request for preemption. When the EV appears within 600 ft. of the intersection, it starts transmitting the information to the traffic signal controller. The controller receives the information on the EV's location, speed and route. It then enters a special preemption phase, maintaining in the green stage if it was green when the request was received, or ending green for conflicting approaches and switching to green for the EV signal phase. This ensures the approach is clear of vehicles, so the EV can cross the intersection without delays. The preemption was programmed directly in the ASC/3 signal controller software, using the built-in function for preemption. As this is EV preemption, the highest level of preemption is activated. The activation was achieved through a series of logical commands, programmed directly in the controller through its logic processor.

7.2 Microsimulation Models

The PREEMPT algorithm was tested using the State Street test-bed, whose development, calibration and validation are described in Chapter 4. The only difference in the PREEMPT models is the presence of EVs in the traffic stream. In the models, EVs would appear randomly and travel through the network. The majority of them would be using State Street, although some traverse the cross streets. Four simulation scenarios were developed and used for this purpose:

1. Base 2019 model. This is the base model developed, calibrated, and validated for 2019 traffic data, as described in Chapter 4. The model also introduces random EVs traveling through the network, but no preemption is enabled.

2. 2019 CV-EVP model. This is a continuation of the previous model, where the traffic demand and operations are the same as in the Base model, but preemption is activated for CV-equipped Evs. When the Evs enter the communication range, they transmit BSM to the signal controller and send a preemption request. The controller assesses current signal phases and assings preemption accordingly. It is assumed that all Evs are equipped with connected vehicle technologies.

3. 2029 Base model. This model uses the same geometry as the base 2019 model, but the traffic demand is increased using 2.4 percent annual traffic growth rate, and the signal timings are updated accordingly through Synchro. No geometry updates are introduced. Evs appear randomly in the network but are not granted preemption.

4. 2029 CV-EVP model. This model combines preemption introduced in the 2019 CV-EVP model, and traffic demand and signal timings from the 2029 Base model. All Evs are assumed to be equipped and request preemption.

All models are run for 10 randomly seeded simulation runs, and the outputs are averaged, to incorporate any variations and stochasticities. The PM peak period (4–6 p.m.) was used for the analysis, with a 15-minute warm up period.

7.3 PREEMPT Results and Discussion

The main operational results included in the analysis contain of the intersection performance measures, vehiclular travel speeds, and network-wide performance measures. The results are analyzed for cars, transit buses, and EVs separately. Where applicable, the paired two-tailed t-test with a 95 percent confidence level was used to assess the statistically significant difference in obtained results.

7.3.1 Intersection Performance Measures

The intersection performance was assessed through the total vehicular delays (in veh-min) for each of the seven major intersections along the corridor. The comparison among the four models is provided in Table 7.1.

The implementation of the CV-based PREEMPT algorithm can reduce EV delays for all intersections along the corridor in both analyzed years. For the year 2019, the EV delay reduction ranges between 8 and 59 percent, with the average reduction of 36 percent. This difference is statistically significant. Only the intersection of State Street and 800 S resulted in higher delays for EVs with the preemption. For the year 2029, the EV delay reduction ranges between 2 and 34 percent, with the average reduction of 16 percent. Again, the reduction in EV delays is statistically significant.

The changes in total intersection delays for cars and buses along the corridor is not statistically significant. Depending on the intersection, it either slightly increases or reduces for both years, but overall the changes are relatively small. The delay increase for cars and buses mainly comes from the movements that conflict the EV signal phase.

Table 7.1 PREEMP Intersection Performance Results – Total Vehicle Delays (veh-min)

		Total Vehicle Intersection Delays (veh-min)					
Intersection	**Mode**	**2019 Base**	**2019 CV-EVP**	***vs. 2019 Base***	**2029 Base**	**2029 CV-EVP**	***vs. 2029 Base***
500 S	Car	5800.8	5740.4	*-1.0%*	15833.1	15866.2	*0.2%*
	Bus	13.5	13.2	*-1.6%*	27.6	28.4	*2.9%*
	EV	12.7	5.3	*-58.7%*	21.4	20.8	*-2.8%*
600 S	Car	5743.8	5568.3	*-3.1%*	9976.2	10074.7	*1.0%*
	Bus	5.5	6.5	*19.7%*	13.2	13.2	*0.0%*
	EV	9.3	6.5	*-30.2%*	10.3	8.6	*-15.8%*
800 S	Car	5178.0	5335.5	*3.0%*	8660.1	8692.4	*0.4%*
	Bus	11.3	11.5	*0.9%*	13.3	13.0	*-2.4%*
	EV	2.7	2.9	*6.2%*	5.8	5.0	*-14.0%*
900 S	Car	1675.4	1840.2	*9.8%*	2757.8	2757.0	*0.0%*
	Bus	4.8	4.5	*-6.1%*	3.8	3.7	*-4.5%*
	EV	2.1	1.5	*-31.0%*	1.2	1.1	*-8.5%*
1300 S	Car	4799.9	4762.4	*-0.8%*	6380.2	6452.6	*1.1%*
	Bus	6.5	6.4	*-2.6%*	7.6	7.6	*-0.7%*
	EV	6.4	5.5	*-13.9%*	8.9	5.9	*-34.0%*
1700 S	Car	1879.0	2015.1	*7.2%*	4250.7	4193.8	*-1.3%*
	Bus	3.7	3.4	*-8.0%*	5.8	5.6	*-2.7%*
	EV	2.3	2.1	*-8.0%*	6.4	6.6	*2.5%*
2100 S	Car	6848.4	7105.0	*3.7%*	14206.4	13757.6	*-3.2%*
	Bus	9.5	8.6	*-10.0%*	8.5	9.4	*11.1%*
	EV	16.9	9.9	*-41.5%*	25.7	19.4	*-24.6%*
Average	**Car**	**31925.2**	**32366.9**	***1.4%***	**62064.7**	**61794.3**	***-0.4%***
	Bus	**54.8**	**54.1**	***-1.4%***	**79.9**	**80.9**	***1.3%***
	EV	**52.5**	**33.6**	***-35.9%***	**79.6**	**67.3**	***-15.5%***

7.3.2 Travel Speed Results

The travel speed results were compiled for the entire corridor (between 500 S and 2100 S) for cars and buses, while for EVs they were recorded for the State Street corridor, as well as along 2100 S, 1300 S and 600 S where EVs also appear. The speed results are provided in Table 7.2.

Table 7.2 PREEMP Travel Speed Results (mph)

	Average Car Travel Speeds (mph)					
Direction	**2019 Base**	**2019 CV-EVP**	***vs. 2019 Base***	**2029 Base**	**2029 CV-EVP**	***vs. 2029 Base***
SB	26.2	24.8	*-5.3%*	19.4	19.3	*-0.5%*
NB	21.9	21.9	*0.0%*	21.8	21.8	*0.0%*

	Average Bus Travel Speeds (mph)					
Direction	**2019 Base**	**2019 CV-EVP**	***vs. 2019 Base***	**2029 Base**	**2029 CV-EVP**	***vs. 2029 Base***
SB	13.8	13.7	*-0.7%*	11.5	11.4	*-0.9%*
NB	12.5	12.4	*-0.8%*	11.9	11.9	*0.0%*

	Average EV Travel Speeds (mph)					
Direction	**2019 Base**	**2019 CV-EVP**	***vs. 2019 Base***	**2029 Base**	**2029 CV-EVP**	***vs. 2029 Base***
State SB	24.2	25.6	*5.8%*	15.0	14.6	*-2.7%*
State NB	23.8	29.1	*22.3%*	22.5	22.2	*-1.3%*
2100 S EB	13.0	17.2	*32.3%*	6.9	10.0	*44.9%*
2100 S WB	11.9	18.6	*56.3%*	7.9	9.1	*15.2%*
1300 S EB	14.0	19.9	*42.1%*	12.4	12.4	*0.0%*
1300 S WB	16.8	23.6	*40.5%*	17.0	17.2	*1.2%*
600 S EB	16.9	21.3	*26.0%*	13.4	12.7	*-5.2%*

The implementation of the PREEMPT algorithm does not results in statistically significant speed changes for cars and buses. Along the main corridor, cars and buses actually benefit from the preemption. As far as the EVs, in the 2019 models the speed increase is statistically significant for all corridors and it ranges between six and 56 percent. Overall for 2019, the EV speed is increased by 32 percent on average when the CV-based PREEMPT is active. For the 2029 analysis years, the EV speed results are somewhat mixed, with some sections/directions experiencing slight reduction in travel speeds, although they are not statistically significant. Overall, the EV speeds in 2029 increase eight percent on average with the CV PREEMPT algorithm. This means that the algorithm is less effective in congested networks, which is to be expected.

7.3.3 Network Performance Results

On the network-wide level, the analysis was performed for the average vehicle delays (s/veh), the average number of stops per vehicle, and the average network travel speed (mph) for cars, buses and EVs. The comparison of the network level results is given in Table 7.3.

Table 7.3 PREEMP Network-Level Results

	Mode	2019 Base	2019 CV-EVP	*vs. 2019 Base*	2029 Base	2029 CV-EVP	*vs. 2029 Base*
Average Vehicle Delay (s/veh)	**Car**	68.6	69.6	*1.5%*	117.6	116.6	*-0.9%*
	Bus	256.1	254.9	*-0.5%*	361.1	366.2	*1.4%*
	EV	151.8	77.6	*-48.9%*	216.5	135.5	*-37.4%*
Average Number of Stops per Vehicle	**Car**	2.1	2.1	*1.6%*	3.3	3.3	*-0.4%*
	Bus	3.4	3.4	*0.8%*	5.3	5.4	*1.3%*
	EV	1.9	0.6	*-69.5%*	3.8	2.1	*-43.9%*
Average Vehicle Speed (mph)	**Car**	13.6	13.6	*0.4%*	11.5	11.4	*-0.7%*
	Bus	13.6	13.6	*0.4%*	11.5	11.4	*-0.7%*
	EV	21.4	27.1	*26.7%*	13.3	18.4	*38.4%*

The effectiveness of the implemented CV-based PREEMPT algorithm can be best seen on the network-wide level. For the year 2019, the average EV delay and number of stops reduce significantly (49 and 70 percent, respectively), while the EV speed significantly increases (27 percent). Cars and buses do not experience any significant impacts of the PREEMPT strategies on the network-wide level. For the year 2029 the EV network performance is not as impressive as for the 2019, but the results are still statistically significant. The average EV delays and number of stops reduce 37 and 44 percent respectively, while their speeds increase 38 percent. No statistically significant impacts are observed for cars and buses on the network level. These results show that the CV-based PREEMPT is very effective in improving operations of EVs, including their response times, which is of the utmost importance in the real world.

8. CONCLUSIONS

The development of new technologies, mainly connected and autonomous vehicles, creates opportunities to develop traffic signal control strategies that have the potential to improve the operations and safety of signalized intersections. This study developed and tested CV-based traffic signal control algorithms and programs aimed at improving operations at signalized intersections, under the assumption that most fleet vehicles will be equipped with the new technologies in the near future. The test cases were intersections in Wyoming adjacent to I-80 in Rock Springs, Rawlins, Evanston, Laramie and Cheyenne, WY, and a busy urban corridor along State Street in Salt Lake City, UT. The focus of the research was on ISIG, FSP, TSP, SPD-HARM, Q-WARN and PREEMPT applications. The analysis was performed considering different model scenarios with different rates of CAV-equipped trucks, transit buses, and cars.

As a part of the ISIG applications, the study developed an approach that used the latitude and longitude (lat/long) coordinates of the CAV-equipped vehicles and signalized intersections to establish communication, define the detection zone, and update the position and speed of the vehicles, and the status of the current signal phase in each time step, taken as 0.1 seconds. At the time when this research was conducted, this study was the first of its kind to use actual lat/long coordinates in traffic simulation of CVs. The study used the current vehicle routing, which can be communicated through the use of turn signals, to separate individual turning movements at intersections. All the information shared among the vehicles and the infrastructure can be utilized to implement advanced traffic signal control programs.

The FSP application allows extra time for freight vehicles as they approach the signal, or wait for the signal to change, to minimize their delay. This also has safety benefits — it reduces conflicts between heavy trucks and other vehicles, and non-motorized transportation. The algorithm developed in this study assessed the current vehicle position, speed, and signal timing state to optimize the FSP call and service. The results of the analyses showed that the FSP application has the ability to reduce the intersection delay of CV-equipped trucks between 10 and 70 percent, which, in most case,s is a statistically significant reduction. FSP also has some negative effects on other vehicles and non-FSP signal phases, which is shown on the network-wide level. However, in most cases the negative impacts are not significant.

In addition to the control programs for heavy vehicles, this study developed, implemented, and tested priority control programs for both freight and transit vehicles. The test-case is a section of State Street, in Salt Lake City, UT, which is a busy, transit-heavy multi-modal corridor. The implementation of unconditional signal control priority provided significant delay savings for trucks, up to 40 percent, but it also caused a significant increase in delays for other vehicles, in excess of 35 percent. Speeds for all vehicles would reduce, if unconditional Signal Control Priority (SCP) was provided to all target vehicles. The information sent from CV-equipped transit vehicles can be used to create different forms of conditional priority. This study used schedule adherence and real-time ridership to determine the level of granted Transit Signal Priority (TSP) for Bus Rapid Transit (BRT). Green extension, early green, and phase rotation were the strategies implemented for different combinations of vehicle lateness and ridership. The introduced TSP strategies in general reduced transit delays by about six percent, without significant impacts on other traffic and transit operations.

The Q-WARN application alerts drivers of approaching vehicles that a queue exists downstream of their position. This is a common situation at approaches to signalized intersections. This application has the potential to improve safety by early alerting drivers, particularly in low-visibility conditions or where the geometry of the approach does not provide sufficient visibility. The Q-WARN application developed in this study utilized the position, speed, and heading of CV-equipped trucks, and the current state of the signal phase on the vehicle approach, to warn the truck drivers if there is potentially a queue at the intersection approach in their desired direction of travel, which gives them extra time to adjust their speeds as they approach the intersection. Results showed that the CV-based Q-WARN applications were effective in reducing truck delays by an average of two to five percent. The recorded vehicle spacing in the vicinity of the intersections were higher (up to 134 percent) in the CV Q-WARN models due to the earlier start of deceleration and lower lane speeds, which could be considered a safety benefit to prevent rear-end conflicts. The safety assessment of the Q-WARN algorithm showed significant safety benefits in preventing intersection-related crashes.

The SPD-HARM application developed in this study applies communication between the vehicles on the same approach and heading, and between the vehicles and the traffic signal, to optimize the speed of the approaching vehicles, so they arrive at the intersection during the green interval. The application of this algorithm has the potential to significantly reduce truck delays, between four and 82 percent, depending on location.

The State Street corridor was also used to test and assess the performance of PREEMPT strategies for emergency vehicles (EV). The algorithm used EV's location and speed to activate preemption strategies on intersection approaches and activate green light for the approaching EVs. The results showed that the implementation of CV-based PREEMPT strategies has a potential to reduce EV-signalized intersection delays up to 34 percent and increase their speeds in excess of 50 percent along busy urban corridors without impacts on other traffic.

Overall, this study shows the potential of CV technologies for the implementation of comprehensive and complex signal control programs, which can bring both operational and safety benefits. The developed algorithms and control programs are universal, meaning they can be applied to other locations and under different traffic conditions with minimum to no adjustments. The algorithms and control programs are using the existing information shared between the vehicles and the infrastructure through CV technologies. This research laid out the approach that can be used in the future to further improve and optimize CV-based signal control programs.

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