FINAL REPORT WY2103F

CONNECTED-AUTONOMOUS TRAFFIC SIGNAL CONTROL ALGORITHMS FOR TRUCKS AND FLEET VEHICLES

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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), Queue Warning (Q-WARN), and Speed Harmonization (SPD-HARM) 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). Communication and information sharing was modeled using Python programming language, while signal control applications was programmed directly in the signal control software. The test-case networks included six signalized intersections adjacent to I-80, in Wyoming. Model scenarios included different rates of CAV-equipped trucks. Additionally, the study tested CAV-based Transit Signal Priority using a test-network in Salt Lake City, Utah. First, the study developed a communication process which uses latitude/longitude coordinates of CAVs and intersections to define the detection zone and enabled information sharing. Once the communication was established, CAV application can be called and implemented as needed. FSP provides extra time for trucks approaching a signalized intersection, therefore, minimizing delays. The implementation of FSP has the potential to reduce truck intersection delays between 10 and 70 percent, with minimal impacts on other traffic. Q-WARN can warn drivers on a downstream queue of the conditions and allow extra time to slow down. This application can reduce CAV truck delays 2 to 6 percent, with a significant increase in spacing between vehicles. SPD-HARM optimizes the speed of vehicles as they approach an intersection so that the delay is minimized. The results show that SPD-HARM can reduce intersection delays for trucks between 4 and 82 percent. TSP implementation allows extra time to transit vehicles at signalized intersections, and the developed algorithm has the potential to reduce transit delays up to six percent. The developed control programs can be directly implemented in the field, as they use the information which exists within CAV technology and the field-based signal control software.

17. Key Words Connected and Autonomous Vehicles; Traffic Signal Control; Intelligent Traffic Signals; Freight Signal Priority; Queue Warning; Speed Harmonization; Transit Signal Priority; Wyoming	**18. Distribution Statement** This document is available through the National Transportation Library and the Wyoming State Library. Copyright © 2018. All rights reserved. State of Wyoming, Wyoming Department of Transportation, and the University of Wyoming.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ASC/3	Advanced Signal Controller series 3
AV	Autonomous Vehicles
BRT	Bus Rapid Transit
CAV	Connected-Autonomous Vehicles
CV	Connected Vehicles
DDI	Diverging Diamond Interchange
DOT	Department of Transportation
EG	Early Green
FHWA	Federal Highway Administration
FSP	Freight Signal Priority
GE	Green Extension
HCM	Highway Capacity Manual
I-80	Interstate 80
INFLO	Intelligent Network Flow Optimization
ISIG	Intelligent Traffic Signal System
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
MAP	Intersection map file
NCHRP	National Cooperative Highway Research Program
OBE	On-Board Equipment
PR	Phase Rotation
Q-WARN	Queue Warning
RSE	Road Side Equipment
RSU	Road Side Unit
SCP	Signal Control Priority
SD	Standard Deviation
SIL	Software-in-the-Loop
SPaT	Signal Phasing and Timing
SPD-HARM	Speed Harmonization
SRM	Signal Request Message
SSM	Signal Status Message
TRB	Transportation Research Board
TSP	Transit Signal Priority
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VISSIM	Traffic in Cities Simulation Model (German acronym)
VMT	Vehicles Miles Travelled
WYDOT	Wyoming Department of Transportation

EXECUTIVE SUMMARY

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. 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 to sense their surroundings and take driving functions from the driver at different levels. 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.

These technologies create 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 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. The focus of this research project was on Intelligent Traffic Signal Systems (ISIG), Freight Signal Priority (FSP), Queue Warning (Q-WARN), and Speed Harmonization (SPD-HARM) applications. The analysis was performed considering different model scenarios with different rates of CAV-equipped trucks.

As a part of the ISIG applications, this study developed an approach that used the latitude and longitude 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, as well as the status of the current signal phase in each time step (taken as 0.1 seconds in this research). Furthermore, the study used the current vehicle routing, which can be communicated through the use of turn signals, to separate individual turning movements at intersections. The study showed that this information can be utilized to implement the signal control programs.

The FSP application allows extra time for freight vehicles as they approach the signal, or wait for the signal to change, in order 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. The results of the analyses showed that the FSP application has the ability to reduce the intersection delay of CAV-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 utilized the position, speed, and heading of CAV-equipped trucks, along with 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. The results showed that the CAV-based Q-WARN applications were effective in reducing truck delays by an average of 2 to 5 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.

SPD-HARM application developed in this study applies communication between the vehicles on the same approach and heading, as well as 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 4 and 82 percent depending on location.

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.

Overall, this study shows the potential of CAV 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 CAV technologies. Although the focus of this research is on CAV-equipped heavy trucks, it can also be applied to other vehicle types, and the algorithms can easily be customized.

1. INTRODUCTION

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 (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 control signals use vehicle detection and preset signal timing parameters to adjust their operation to changing demand. They also introduce special operations for emergency, transit, and freight vehicles. These operations can provide certain levels of priorities for these vehicles, reducing the delay and improving safety. However, the traditional detection and communication technologies have been based on lower fidelity detection and less intelligent control techniques. The CAV technology offers new venues 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. 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 need to be covered through research.

1.1. CAV Traffic Signal Control Applications

The USDOT has defined several CV applications for mobility improvements. This study focuses on the following (ITS JPO, 2018c):

- Intelligent Traffic Signal System (ISIG).
- Queue Warning (Q-WARN).
- Dynamic Speed Harmonization (SPD-HARM).
- Freight Signal Priority (FSP).
- Transit Signal Priority (TSP).

The Intelligent Traffic Signal System (ISIG) is using high-fidelity data collected from vehicles through V2V and V2I communications (as well as 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, as well as 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).

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 is 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.

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 in order 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 that the platoon reaches the signal during the green phase time.

Freight transported by trucks within the US exceeds 11,000 millions of tons per year, equaling to more than $11,000 billion (Bureau of Transportation Statistics, 2018). Fast and on-time freight delivery is of outmost economic importance. 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 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 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, in addition to improving 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 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 utilize 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.

1.2. Study Goal and Methodology

The goal of this study was to develop and test CAV-based traffic signal control algorithms and programs to be used with heavy vehicles to improve their operations and safety at signalized intersections. The study focuses on five locations (with six signalized intersections) in Wyoming, namely Elk Street and Stagecoach Street in Rock Springs, Cedar Street and Airport Road in Rawlins, Front Street and 2nd Street in Evanston, Curtis Street and McCue Street in Laramie, and I-25 and College Drive, a Diverging Diamond Interchange (DDI) with two signalized ramps, in Cheyenne. The research was performed using high-fidelity traffic microsimulation in PTV VISSIM, coupled with real-world traffic control software, Econolite ASC/3 through Software-in-the-Loop (SIL) implementation. The main tested operational strategies included Freight Signal Priority (FSP), Queue Warning (Q-WARN) applications, and Speed Harmonization (SPD-HARM). Furthermore, the study was expanded to assess different Transit Signal Priority (TSP) strategies using test-case networks from Salt Lake City, UT. All the strategies developed in this research were interchangeable so they can be implemented at any location with minimal modifications to the code. These applications belong to the Intelligent Traffic Signal Systems (ISIG) cluster, as defined by the US Department of Transportation (USDOT)

Findings from this study will help WYDOT transportation engineers with designing and optimizing traffic signals in the upcoming CAV era, especially those which experience high heavy truck traffic. Furthermore, the algorithms and control programs developed in this research are universal so they can be transferred to any other location.

2. MICROSIMULATION MODELS DEVELOPMENT

The assessment and testing of the developed algorithms and control programs was performed using VISSIM microsimulation. The six signalized intersections in Rock Springs, Rawlins, Evanston, Laramie and Cheyenne, shown in Figures 1 to 5, were replicated in simulation using actual data on geometry, traffic demand, and signal operations. The intersections geometry data were 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 Wyoming Department of Transportation (WYDOT) 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 evening peak period (5:00-6:00 p.m.).

Figure 1. Illustration. Study test-bed in Rock Springs. Source: Google Earth, modified from source.

Figure 2. Illustration. Study test-bed in Rawlins. Source: Google Earth, modified from source.

Figure 3. Illustration. Study test-bed in Evanston. Source: Google Earth, modified from source.

Figure 4. Illustration. Study test-bed in Laramie. Source: Google Earth, modified from source.

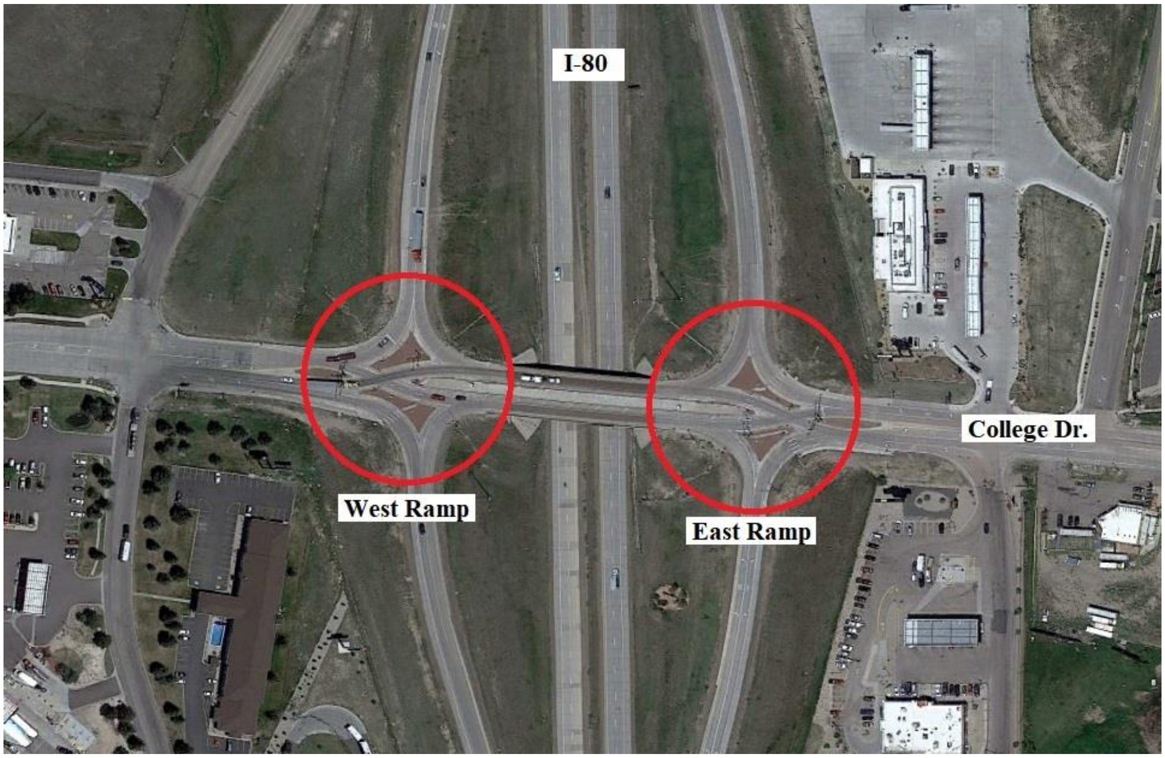
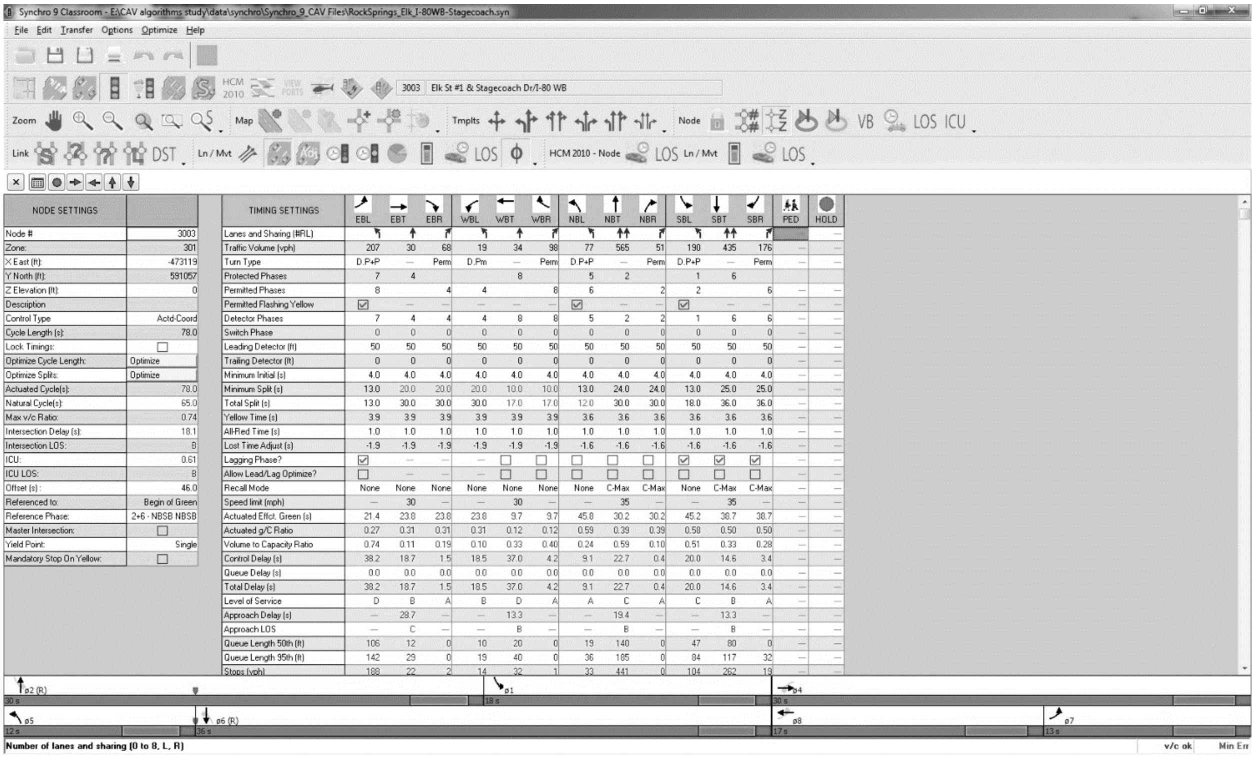


Figure 5. Illustration. Study test-bed in Cheyenne. Source: Google Earth, modified from source.

The traffic signal data were obtained from WYDOT in the form of Synchro files. For each signalized intersection used in the models, these data contained intersection layout, signal phasing, signal timing, and volume parameters. An example of the Synchro files is shown in Figure 6, for the Rock Springs, Wyoming test intersection.



NODE SETTINGS	
Node #	3003
Zone:	301
X East (ft):	-473119
Y North (ft):	591057
Z Elevation (ft):	0
Description	
Control Type	Actd-Coord
Cycle Length (s):	78.0
Lock Timings:	☐
Optimize Cycle Length:	Optimize
Optimize Splits:	Optimize
Actuated Cycle(s):	78.0
Natural Cycle(s):	65.0
Max v/c Ratio:	0.74
Intersection Delay (s):	18.1
Intersection LOS:	B
ICU:	0.61
ICU LOS:	B
Offset (s) :	46.0
Referenced to:	Begin of Green
Reference Phase:	2+6 - NBSB NBSB
Master Intersection:	☐
Yield Point:	Single
Mandatory Stop On Yellow:	☐

TIMING SETTINGS	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR	PED	HOLD
Lanes and Sharing (#RL)	↰	↑	↱	↰	↑	↱	↰	↑↑	↱	↰	↑↑	↱		—
Traffic Volume (vph)	207	30	68	19	34	98	77	565	51	190	435	176	—	—
Turn Type	D.P+P	—	Perm	D.Pm	—	Perm	D.P+P	—	Perm	D.P+P	—	Perm	—	—
Protected Phases	7	4			8		5	2		1	6			
Permitted Phases	8		4	4		8	6		2	2		6	—	—
Permitted Flashing Yellow	☑	—	—	—	—	—	☑	—	—	☑	—	—	—	—
Detector Phases	7	4	4	4	8	8	5	2	2	1	6	6	—	—
Switch Phase	0	0	0	0	0	0	0	0	0	0	0	0	—	—
Leading Detector (ft)	50	50	50	50	50	50	50	50	50	50	50	50	—	—
Trailing Detector (ft)	0	0	0	0	0	0	0	0	0	0	0	0	—	—
Minimum Initial (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	—	—
Minimum Split (s)	13.0	20.0	20.0	20.0	10.0	10.0	13.0	24.0	24.0	13.0	25.0	25.0	—	—
Total Split (s)	13.0	30.0	30.0	30.0	17.0	17.0	12.0	30.0	30.0	18.0	36.0	36.0	—	—
Yellow Time (s)	3.9	3.9	3.9	3.9	3.9	3.9	3.6	3.6	3.6	3.6	3.6	3.6	—	—
All-Red Time (s)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	—	—
Lost Time Adjust (s)	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	—	—
Lagging Phase?	☑	—	—	—	☐	☐	☐	☐	☐	☑	☑	☑	—	—
Allow Lead/Lag Optimize?	☐	—	—	—	☐	☐	☐	☐	☐	☐	☐	☐	—	—
Recall Mode	None	None	None	None	None	None	None	C-Max	C-Max	None	C-Max	C-Max	—	—
Speed limit (mph)	—	30	—	—	30	—	—	35	—	—	35	—	—	—
Actuated Effct. Green (s)	21.4	23.8	23.8	23.8	9.7	9.7	45.8	30.2	30.2	45.2	38.7	38.7	—	—
Actuated g/C Ratio	0.27	0.31	0.31	0.31	0.12	0.12	0.59	0.39	0.39	0.58	0.50	0.50	—	—
Volume to Capacity Ratio	0.74	0.11	0.19	0.10	0.33	0.40	0.24	0.59	0.10	0.51	0.33	0.28	—	—
Control Delay (s)	38.2	18.7	1.5	18.5	37.0	4.2	9.1	22.7	0.4	20.0	14.6	3.4	—	—
Queue Delay (s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	—	—
Total Delay (s)	38.2	18.7	1.5	18.5	37.0	4.2	9.1	22.7	0.4	20.0	14.6	3.4	—	—
Level of Service	D	B	A	B	D	A	A	C	A	C	B	A	—	—
Approach Delay (s)	—	28.7	—	—	13.3	—	—	19.4	—	—	13.3	—	—	—
Approach LOS	—	C	—	—	B	—	—	B	—	—	B	—	—	—
Queue Length 50th (ft)	106	12	0	10	20	0	19	140	0	47	80	0	—	—
Queue Length 95th (ft)	142	29	0	19	40	0	36	185	0	84	117	32	—	—
Stops (vph)	188	22	2	14	32	1	33	441	0	104	262	19	—	—

Number of lanes and sharing (0 to 8, L, R)

Figure 6. Screenshot. Synchro file for Rock Springs intersection.

In the simulation models, the traffic signal operation was replicated using actual traffic signal control software, Econolite ASC/3, through SIL application. The ASC/3 controller is able to support basic and complex signal timing settings through Logic Processors, which can emulate external logic that is not included in the default settings. A total of 200 logic commands is available in the controller, and these commands can control and combine all the controller features. The ASC/3 SIL version of the controller software has been specifically 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. Another benefit of the ASC/3 SIL is that it can run at 10 times normal speed during simulation, which greatly reduces the time needed to test a scenario in VISSIM.

The VISSIM and ASC/3 interfaces are coupled as a system. It allows VISSIM to pass detector and other input and output functions to the simulated ASC/3 controllers and to receive controller status information back. All these components, unified under the Windows operating environment and integrated with VISSIM, provide the ability to simulate one or more intersections with a unifying controller management interface, and the ability to model different signal timing strategies. The VISSIM-ASC/3 integration is shown in Figure 7.

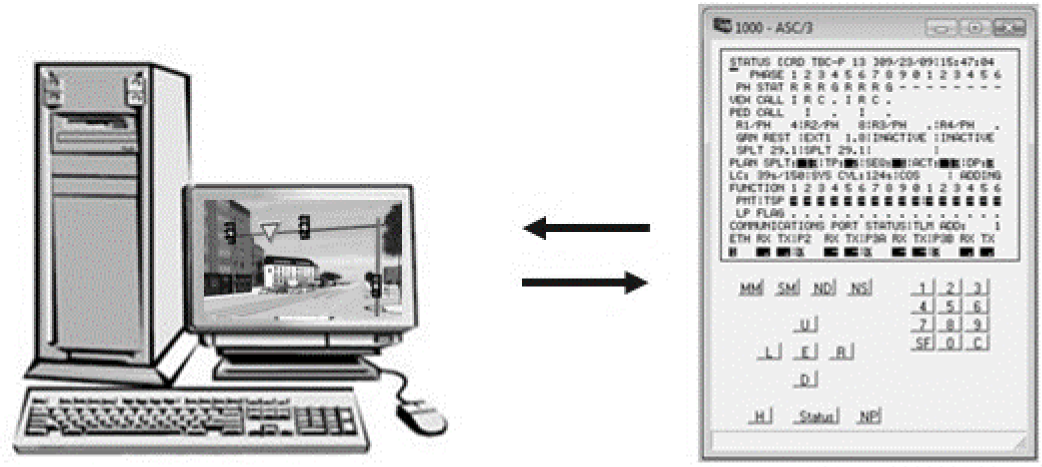
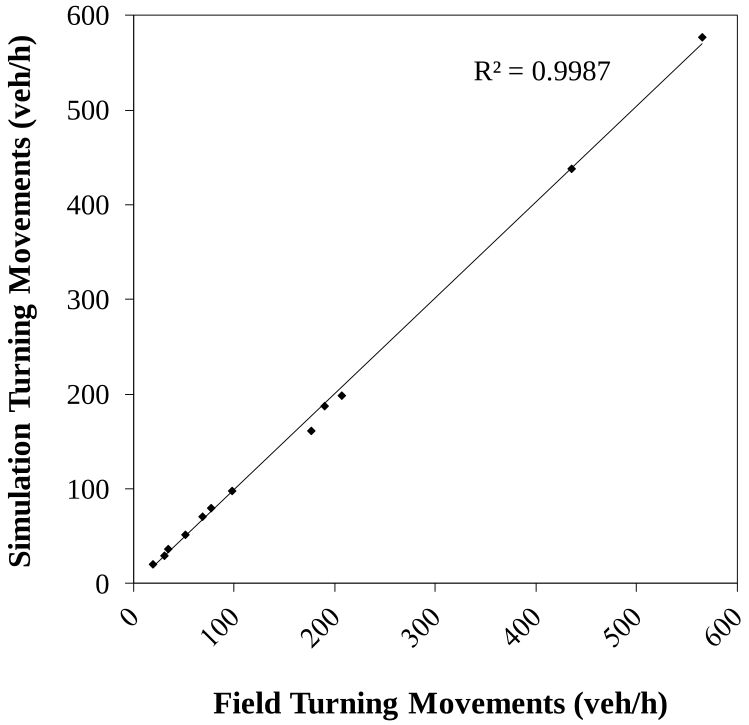


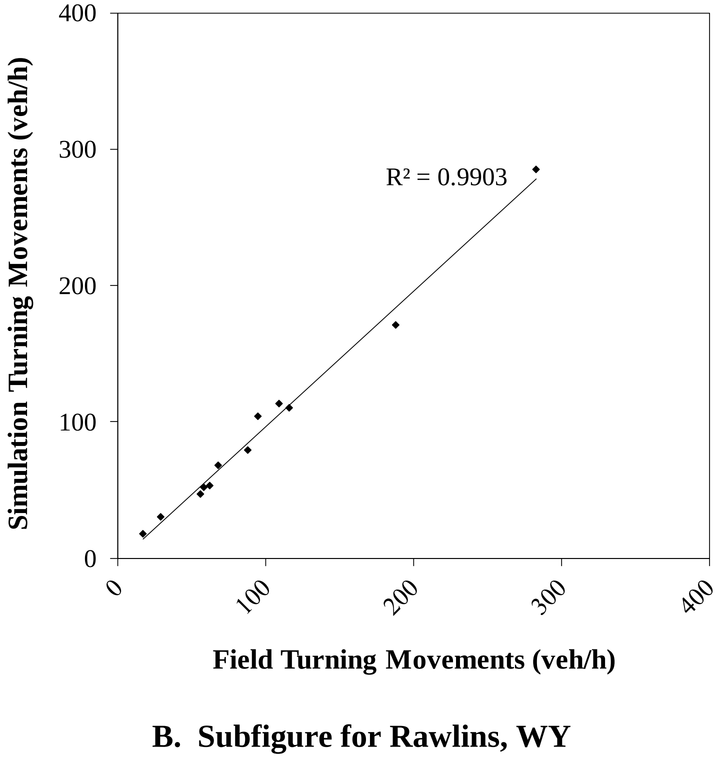
Figure 7. Illustration. VISSIM-ASC/3 integration.

2.1. Baseline Models

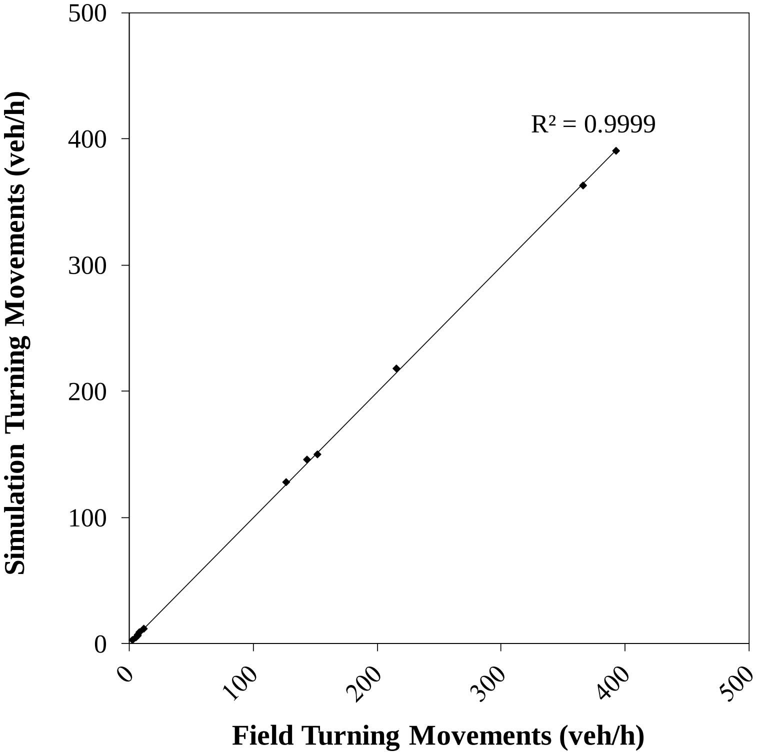
The baseline models were developed and calibrated for the 2019 existing traffic conditions for the six signalized intersections. The data used in modeling included actual roadway and intersection geometries, traffic counts, traffic composition, and signal timing data. The outputs were averaged from ten simulation runs with different random seeds. The baseline models were calibrated for intersection turning movements, where the calibration was performed for each signalized intersection separately. Model calibration results are shown in Figure 8. The coefficient of determination (R^2) for calibration shows a good fidelity of the baseline models.



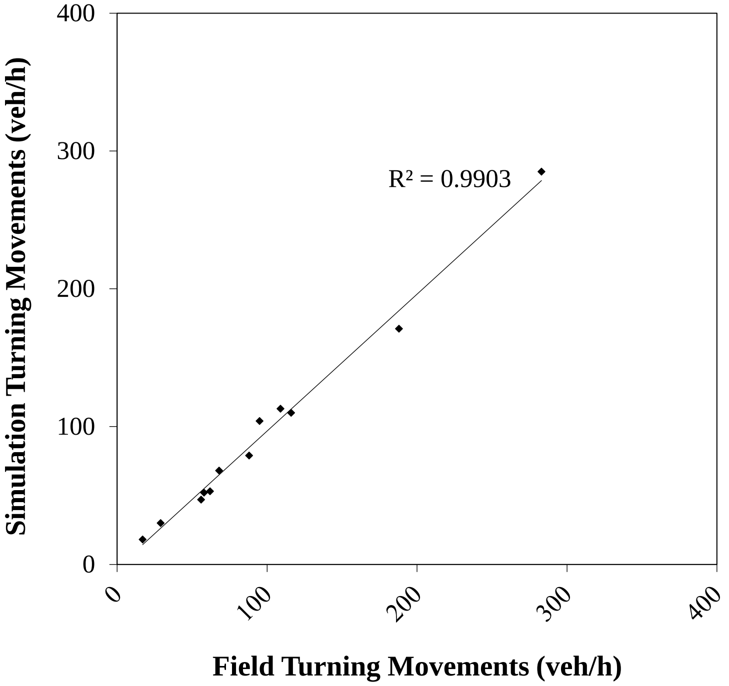
A. Subfigure for Rock Springs, WY



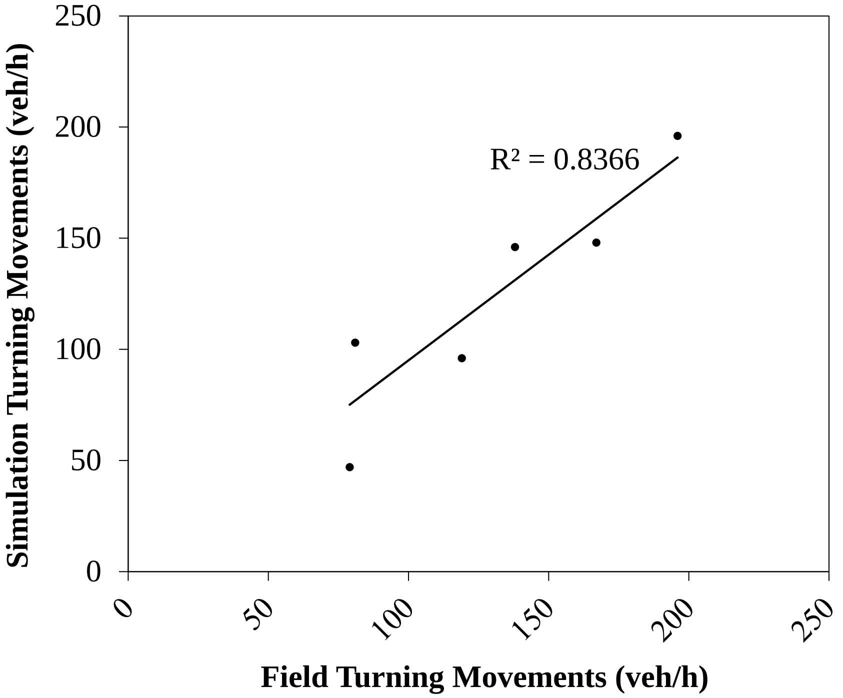
B. Subfigure for Rawlins, WY



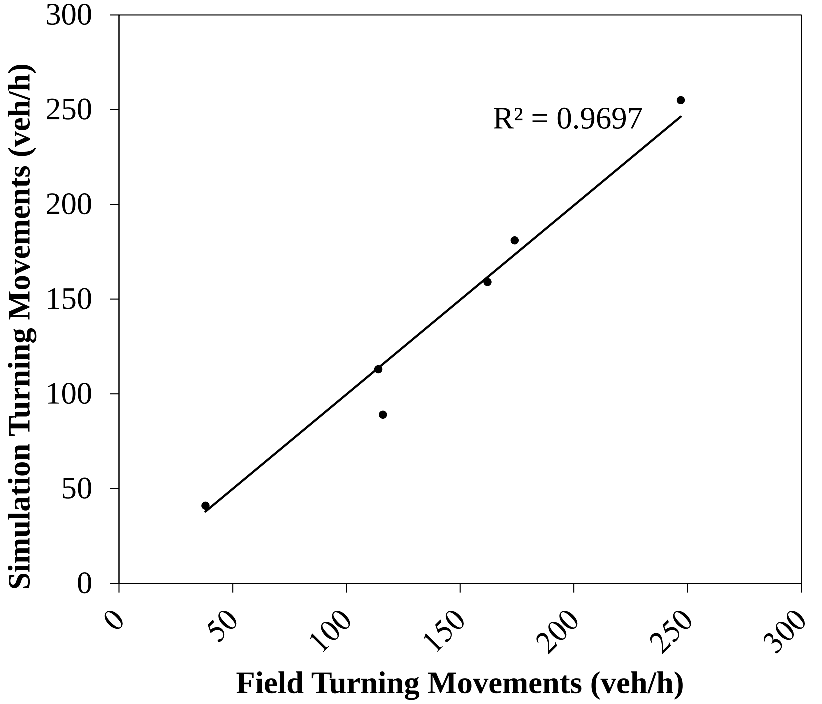
C. Subfigure for Evanston, WY



D. Subfigure for Laramie, WY



E. Subfigure for Cheyenne, WY, West Ramp



F. Subfigure for Cheyenne, WY, East Ramp

Figure 8. Graph. Calibration of baseline VISSIM models for the six areas set out in the Subfigures.

2.2. CAV Models

CAV protocols, communication, BSM information and RSU operations were programmed through VISSIM's Component Object Model (COM) using Python programming language. The main information contained in the BSM that was used for communication with traffic signals through RSU was the vehicles' types, latitude and longitude (lat/long) coordinates, and speeds. RSU contained the lat/long coordinates of the center of the intersections, 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 given in Figure 9:

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

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

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

Figure 9. Equation. Haversine formula and distance calculation.

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)

$\Delta long = long_{veh} – long_{int}$ (difference of longitudes)

R – Earth radius (20,902,231 ft, approximately 3,960 mi)

d – distance between the vehicle and the center of the intersection (ft), updated every time step

The lat/long coordinates in VISSIM were computed through user-defined attributes that converted the current VISSIM into the world coordinates. The models were created on top of the world map provided as a background in VISSIM, which ensured correct lat/long coordinates of the network. In each time step the intersection had the information about the position of the approaching vehicles. Although this procedure is developed in simulation, it can easily be transferred to field implementation, since lat/long coordinates are contained in the BSM, while the RSU can have that information for the intersection. The communication range between the vehicles and the intersections was set to about 600 ft., mainly because all the tested intersections are located 750 – 1,000 ft. from the on and off ramps to the interstate. Depending on the application, as described in next sections, this base algorithm was updated and included additional vehicle (such as speed), or traffic signal state information, as needed. The communication and information was further used to develop traffic signal control logic. The detailed description of algorithms and signal control programs is provided for each application.

3. FREIGHT SIGNAL PRIORITY

Freight signal 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, and higher capacity due to the reduced start-up lost time and similar benefits (Urbanik et al., 2015). The FSP is one of the ITS components that prioritizes freight and transit vehicles, reduces delay and travel time, and improves the performance of their movements. This priority allows extra time for trucks to clear the intersection without stopping (GE) or an earlier return to green phase (EG), if the truck is stopped, improving their travel time reliability and enhancing safety. 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, that can change the order of phase sequences, as needed. These additional strategies can have significant safety benefits, in addition to improving operations.

This section of the research develops CAV-based FSP, implements them in the simulation models, and tests their effectiveness. FSP is based on the built-in signal control priority functions of the traffic controller software, as well as additional strategies achieved through the logic processor. The developed FSP programs can easily be implemented in the field using the information shared through CAV technologies, and any signal control software that supports signal control priority and logic processing.

3.1. Literature Review

One of the main parts of the economy of any country is the trucking industry. In 2018, 11,320 million tons of freight in the United States were transported by trucks, and it is expected that this amount will exceed 14,000 million tons in the next 20 years (Bureau of Transportation Statistics, 2018). Due to significantly different physical characteristics compared to passenger cars, trucks require more space and time for maneuvering. In order to avoid stopping at an intersection, especially on the routes with a high percentage of trucks, strategies such as FSP are implemented to improve truck traffic operations. This priority allows extra time for trucks to clear the intersection without stopping, or an earlier return to the green phase, if the truck is stopped. This improves their travel time reliability and enhances 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 the trucks have limited visibility of the traffic control devices. In order for FSP strategies to accomplish their goals, roadside infrastructure (traffic signals) have to 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. 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). FSP can improve mobility in the range between 15 and 25 percent, and reduce energy consumption 5 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 9 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 3 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 5 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 a VISSIM microsimulation testbed. The results showed that the FSP, besides improvements in operations, can 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 2 percent and 20 percent, respectively. The FSP algorithms were tested on a 2-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 2 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 project aims to develop CV-based FSP algorithms that rely on CV in order to alleviate shortages of conventional detection systems and to 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.

3.2. FSP Methodology

This part of the research developed and tested a CV communication protocol for FSP applications, and assessed the effectiveness of FSP strategies in a case of heavy truck percentages. The communication was based on vehicle’s lat/long 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. This algorithm was tested in simulation, but was convenient for field implementation, since lat/long coordinates of the vehicles are contained in the CV’s BSM.

FSP is based on the green time extension (GE) for the main approach, or on the early green (EG) – a truncation of the red time for conflicting approaches. The communication range between the vehicles and controllers was set to 600 to 1,000 ft, depending on the intersection, while the green extension times were set to 15 seconds maximum. With the free-flow speed of close to 45 mph for most location, for 15 seconds, the vehicle can travel distance of close to 1,000 ft, which would ensure an effective GE strategy. Each CV-equipped vehicle sends a request for priority to the traffic controller when it enters the detection zone. In this study, FSP was provided only to trucks and fleet vehicles for the main movements, although the controller was able to identify those vehicles on all approaches, as shown in Figure10.

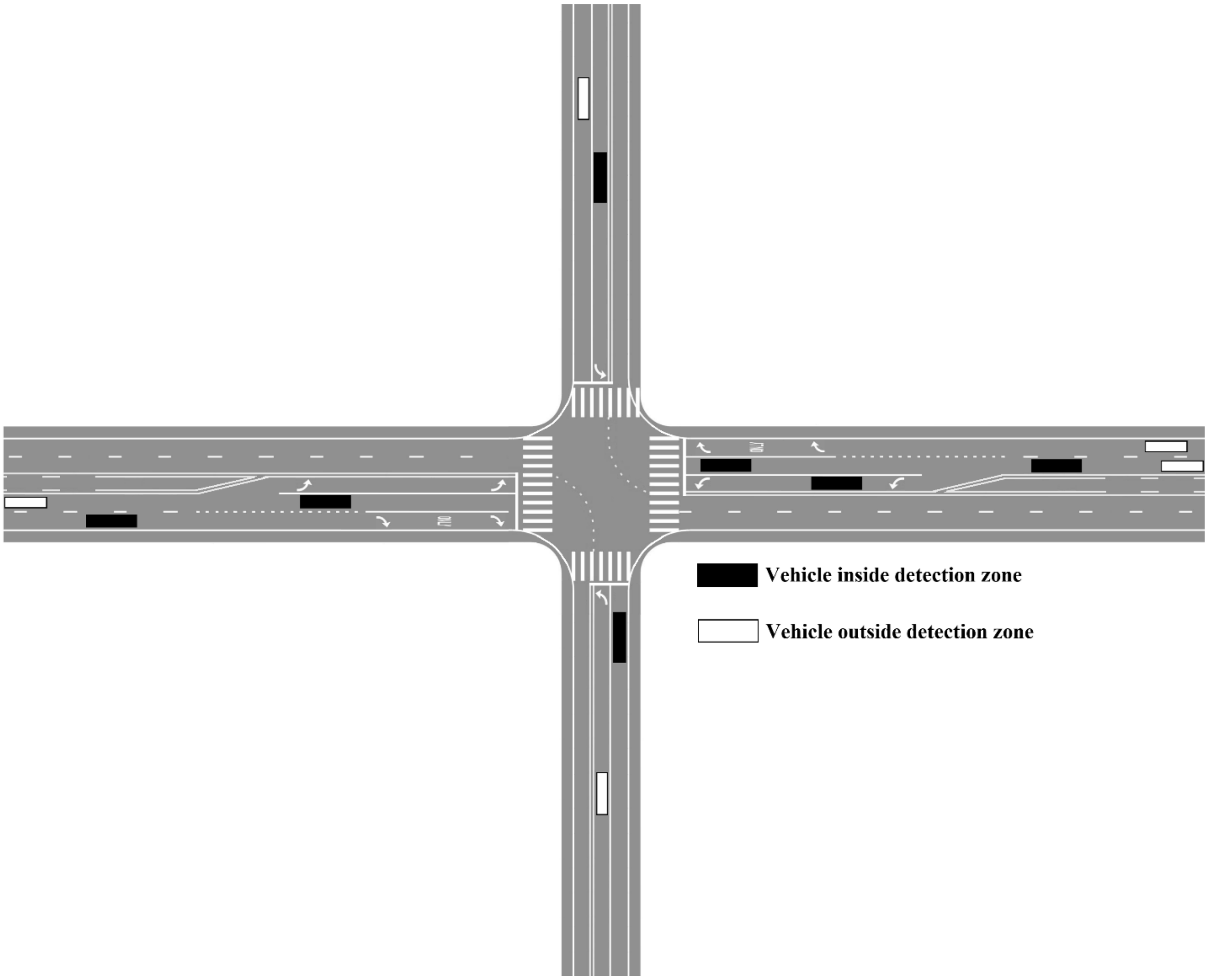


Figure 10. Illustration. Vehicles inside and outside of detection zone.

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. GE was set to 15 seconds maximum, while the maximum green time reductions for EG were set at 5 seconds for left turns along the main street, and 10 seconds for through movements from the side street. In this case, the FSP was unconditional, meaning that all CVs would send a request and receive priority. The CV FSP algorithm is based on the time which the vehicle needs to reach an intersection and on queue conditions on an approach. The time that a vehicle needs to reach an intersection should not exceed the GE time in order to be considered by the algorithm. Once a truck enters the range that can reach the intersection within the GE time based on the speed limit, the algorithm starts checking the actual arrival time and queue conditions ahead of the freight vehicle. 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 the way for the truck. These two inputs are the main pieces of information contained in the BSM, so this algorithm can easily be implemented in the field. 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 lat/long coordinates are constantly updated through the script in each simulation step. With the fixed coordinates of the stop-bars, the algorithm constantly computes and updates a truck's time to reach an intersection. The distance between the truck and the intersection and the estimated arrival time is computed in each time step. This information is updated ten times per second and sent to the RSU. 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 algorithm developed and used in this study is shown in Figure 11.

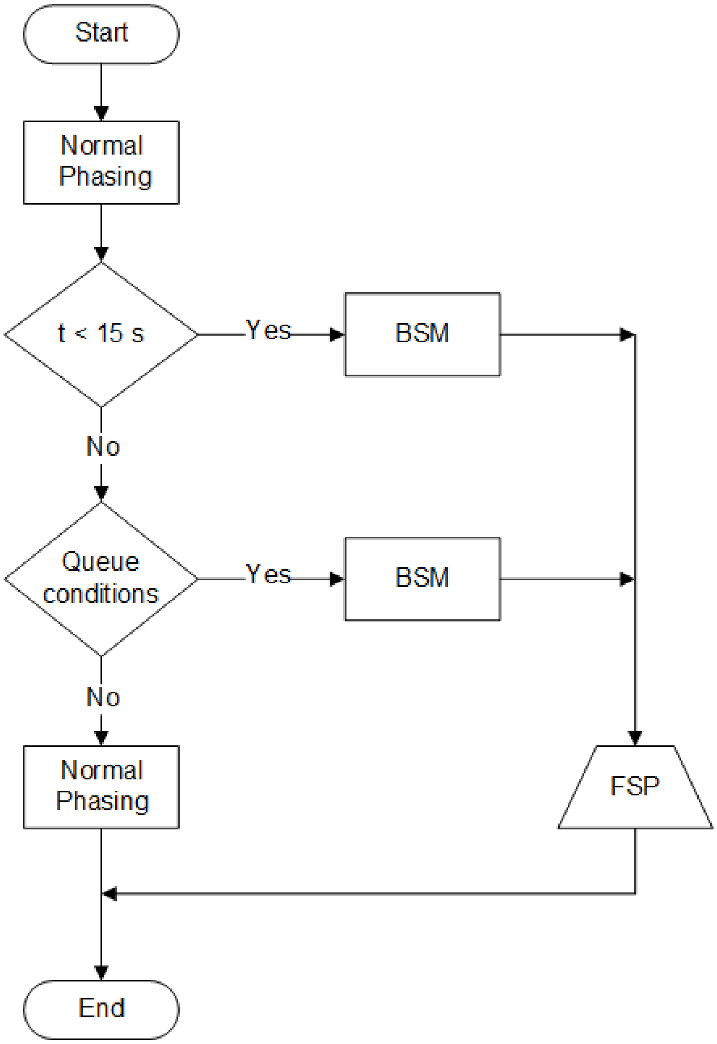


Figure 11. Flowchart. FSP algorithm.

3.3. Results and Discussion

Six model scenarios were developed, tested, and analyzed for each of the six intersections: Base (without CV trucks), 10 percent CV trucks, 25 percent CV trucks, 50 percent CV trucks, 75 percent CV trucks, and 100 percent CV trucks. The outputs for each scenario and intersection were averaged from ten simulation runs. The results were collected and analyzed on intersection and network-wide levels.

3.3.1. Intersection Performance

Due to the relatively low traffic volumes at each of these intersections, the basic performance measure used in the analysis and comparison is the average vehicle delay per vehicle type (cars, trucks and CV trucks). The average delay results are shown in Table 1.

Table 1. Intersection Performance Measures: Average Vehicle Delays (s).

Scenario	Mode	Average Intersection Delay per Vehicle (s)					
		Rock Springs	**Rawlins**	**Evanston**	**Laramie**	**Cheyenne West**	**Cheyenne East**
Base	**Car**	10.7	10.9	9.4	6.9	3.9	5.9
	CV Truck	N/A	N/A	N/A	N/A	N/A	N/A
	Truck	11.6	12.0	11.1	7.0	3.4	5.4
10% CV	**Car**	11.2	11.0	10.2	7.0	4.3	4.2
	CV Truck	6.8	3.6	6.7	3.9	2.9	4.0
	Truck	11.7	12.3	11.0	7.2	3.9	3.9
25% CV	**Car**	11.5	11.1	10.6	7.1	4.5	4.7
	CV Truck	8.0	3.7	6.4	4.0	3.7	4.0
	Truck	12.1	12.2	10.9	7.1	3.4	6.1
50% CV	**Car**	11.7	11.3	11.0	7.3	5.1	5.3
	CV Truck	8.8	4.4	7.0	4.2	4.2	4.8
	Truck	12.6	12.5	11.8	7.5	4.0	4.7
75% CV	**Car**	11.6	11.1	10.8	7.4	5.4	5.6
	CV Truck	9.5	4.4	6.9	4.1	4.5	5.1
	Truck	12.6	12.7	11.2	8.2	4.6	4.9
100% CV	**Car**	12.0	11.2	11.1	7.5	5.5	5.8
	CV Truck	9.8	4.4	6.8	4.3	4.9	5.6
	Truck	N/A	N/A	N/A	N/A	N/A	N/A

As the CV-equipped trucks request and receive priority, their delay is significantly lower than the delay of the conventional trucks in all scenarios and locations, as much as 70 percent for certain scenarios. Interestingly, the delay for CV trucks only is lower for lower CV rate percentages. This results from a lower number of FSP calls made, as the system has sufficient time to re-synchronize until the next call. However, 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.

Prioritizing trucks can also lead to negative effects on other vehicles. As can be seen from the results, the average delays for cars increase with an increase in CV truck rates. The more FSP calls are being made, the more it can affect vehicular traffic, mainly at the approaches that conflict the FSP signal phases. However, for the tested locations and scenarios, the increase in vehicular delays is not statistically significant in most cases.

3.3.2. Network Performance

The effects of FSP were also assessed on the network-wide level through network delay, average speed, and the number of stops. The results for the six model scenarios are presented in Tables 2 to 4. In this case the Cheyenne, WY, network was analyzed as one, as the West and East ramps are a part of the same network.

Table 2. Network Performance Measures: Average Vehicle Delays (s).

Scenario	**Average Network-Wide Vehicle Delay (s)**				
	Rock Springs	**Rawlins**	**Evanston**	**Laramie**	**Cheyenne**
Base	9.69	10.62	9.84	6.09	7.52
10% CV	11.38	11.48	7.72	6.11	7.42
25% CV	11.47	12.76	8.39	6.15	7.63
50% CV	11.30	14.39	9.60	6.26	7.99
75% CV	10.72	15.46	10.19	6.28	8.19
100% CV	10.70	16.07	10.80	6.28	8.44

Table 3. Network Performance Measures: Average Vehicle Speeds (mph).

Scenario	**Average Network-Wide Vehicle Speeds (mph)**				
	Rock Springs	**Rawlins**	**Evanston**	**Laramie**	**Cheyenne**
Base	35.21	46.03	33.41	45.70	45.19
10% CV	32.39	44.67	37.05	45.82	45.41
25% CV	32.71	42.83	36.29	45.94	45.31
50% CV	33.38	40.20	34.97	46.14	45.14
75% CV	34.19	38.09	34.02	46.39	45.03
100% CV	34.86	36.17	33.07	46.66	44.90

Table 4. Network Performance Measures: Total One-Hour Number of Stops per Vehicle.

Scenario	Total One-Hour Number of Stops per Vehicle				
	Rock Springs	Rawlins	Evanston	Laramie	Cheyenne
Base	813	496	605	402	361
10% CV	846	498	654	396	293
25% CV	854	501	664	402	299
50% CV	845	504	680	398	333
75% CV	835	502	662	399	342
100% CV	847	504	664	392	372

The implemented 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, WY, and Cheyenne, WY, networks for CV truck rates of more than 50 percent, and the Rock Springs. WY, network for CV truck rates between 10 and 50 percent. For other locations and scenarios, this increase was not significant.

Except for the Rawlins, WY, network for CV truck rates of more than 50 percent, the implemented FSP did not have significant impacts on average network-wide vehicle speeds. Speed reduction is mostly observed on approaches that conflict FSP signal phases.

When it comes to the total number of stops per vehicle, a significant increase is observed in Rock Springs, WY, and Evanston, WY, networks, for any CV truck rate. From this standpoint, the lowest number of stops was recorded for the 75 percent CV rate, in some instances lower than the base model.

3.4. Conclusions

This part of the research developed and tested the impacts of CV-based FSP application through VISSIM microsimulation. The implemented FSP application uses built-in signal control priority features of Econolite ASC/3 controllers, as well as customized signal operations programmed through the controllers' logic processor. Six model scenarios were created for each intersection, a base model of the current conditions, and hypothetical models with the CV-based TSP applications implemented for the freight vehicles with different percentages of CV rates. The analysis of each model was performed for the evening peak hour, 5:00-6:00 p.m.

The results showed 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 implanted FSP increases the delays and number of stops and reduces delays for non-FSP movements. Overall, the most benefits of the FSP implementation were recorded for CV truck rates between 50 and 75 percent.

4. QUEUE WARNING APPLICATIONS

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 is 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. The application uses information from the roadways (freeway or arterial), traffic detection subsystems, weather information, available sign messages (e.g. VMS), OBE systems, driver interface, and CV broadcasting information. A lot of roadway, environment, weather, and vehicle information needs to be exchanged in order for the application to work properly (Mulligan et al., 2012).

A queue backup can be caused by many reasons, such as (ITS JPO, 2018c):

- Daily recurring congestion.
- Work zones.
- Incidents.
- Weather conditions, including icing, low visibility, sun angles, and high wind.
- Exit ramp spillovers onto freeways due to surface street traffic conditions.

In all cases, queuing is a result of significant downstream speed reductions or stopped traffic, and can occur with freeways, arterials, and rural roads. Queuing conditions present significant safety concerns, especially an increased potential for rear-end collisions. They also present disruptions to traffic throughput by introducing shockwaves into the upstream traffic flow.

This section of the research develops and optimizes algorithms and signal control programs for Q-WARN applications and tests them on the six Wyoming intersections. The control programs are applied in the Econolite ASC/3 software using the built-in controller functions and logic processor, therefore, they can be customized to be used with other traffic controller software.

4.1. Literature Review

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, California. The authors have 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 Interstate-5, in downtown Seattle, Washington, in 2015, using a prototype of intelligent network flow optimization (INFLO) (Stephens et al., 2015). The CV data were transmitted and assembled utilizing a cellular phone and dedicated short-range communications. The process of delivering the queue warning messages to drivers took less than ten seconds. The queue warning algorithm was found to detect the back-end of the queue three minutes sooner, and could locate it 0.5 to 1.5 miles within upstream than what 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 (3, 6, 9, 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.

4.2. Q-WARN Algorithm

The communication range between the vehicles and the intersections was set to 600 to 1,000 ft., mainly because all the tested intersections are located 750 to 1,000 ft. from the on and off ramps to the interstate. The models were created following a methodology described in the previous sections.

Figure 12 shows the overall algorithm of implementing CAV-based Q-WARN protocol. 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 detection zone, it starts communicating with the traffic signal, updating its position, speed, and current route in each time step. At the same time, the traffic controller is sending the current signal phasing and timing information. If the signal for a particular movement is red, the RSU activates the Q-WARN system and sends a message stating “Queue Ahead!” to the approaching upstream vehicles for that movement. As currently only heavy trucks are equipped with CV, once the signal turns red the algorithm assumes that there is at least one vehicle stopped at the signal, and activates the message. When the CV trucks receive the message, they start reducing their speed by about 20 percent until they reach the end of the queue and stop. When the vehicle stops or the signal turns green, 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.

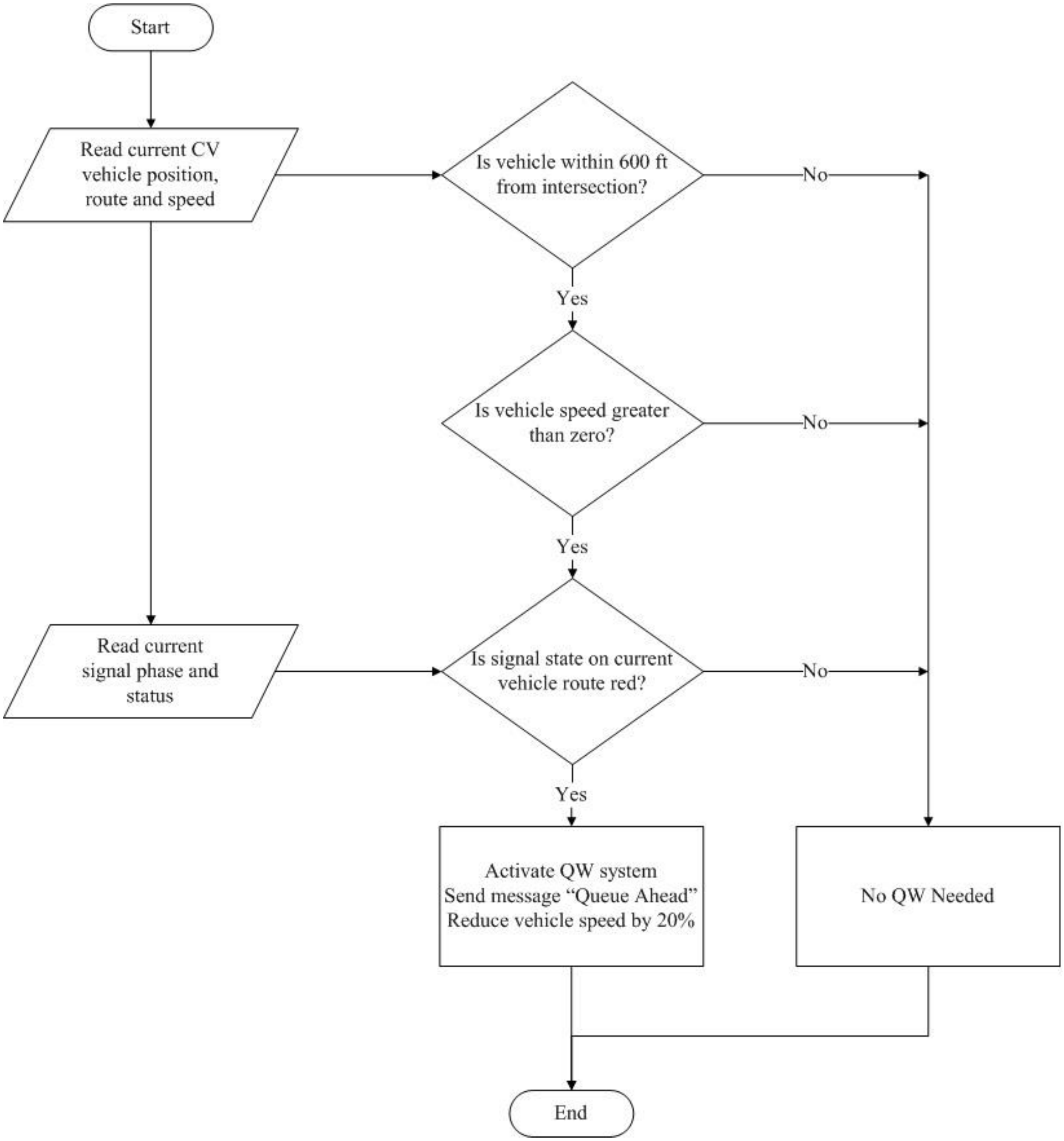


Figure 12. Flowchart. Q-WARN algorithm.

4.3. 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 for each of the intersections as follows:

- 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 Section 2
- A Q-WARN model with 10 percent of CV trucks and fleet vehicles.
- A Q-WARN model with 25 percent of CV trucks and fleet vehicles.
- A Q-WARN model with 50 percent of CV trucks and fleet vehicles.
- A Q-WARN model with 75 percent of CV trucks and fleet vehicles.
- A Q-WARN model with 100 percent of CV trucks and fleet vehicles.

The models with different CV penetration rates were created by varying the truck traffic composition input data in the model. Each model was created for the evening peak hour (5:00-6:00 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.

4.4. Results and Discussion

The final outputs from the microsimulation runs were averaged for each scenario and intersection. Those outputs included intersection performance measures, vehicle speeds, delays, and headways between vehicles. The results were collected and averaged from ten simulation runs for each model. Where applicable, a two-tailed paired t-test with a 95 percent confidence level was used to check if the differences in results were statistically significant.

4.4.1. Intersection Performance

The intersection performance was assessed through the average intersection delays (for passenger cars and trucks separately), average number of stops (for passenger cars and trucks separately), and the average queue lengths. These results are shown in Tables 5 to 9.

Table 5. Intersection Performance Measures: Average Car Delays (s).

Scenario	Average passenger car intersection delays (s)					
	Rock Springs	Rawlins	Evanston	Laramie	Cheyenne West ramp	Cheyenne East ramp
Base	10.69	10.95	9.38	6.20	4.16	5.79
10% CV	10.98	10.91	9.73	6.77	4.20	6.01
25% CV	10.95	10.89	9.69	6.66	4.21	6.10
50% CV	10.80	11.05	9.58	6.75	4.14	6.13
75% CV	10.77	11.00	9.47	6.72	4.16	6.05
100% CV	10.61	10.96	9.34	6.72	4.13	6.03

Table 6. Intersection Performance Measures: Average Truck Delays (s).

Scenario	Average truck intersection delays (s)					
	Rock Springs	Rawlins	Evanston	Laramie	Cheyenne West ramp	Cheyenne East ramp
Base	11.57	12.25	11.11	7.68	3.44	5.22
10% CV	8.61	11.98	11.30	6.86	3.41	5.42
25% CV	11.89	11.99	10.98	7.50	3.39	5.25
50% CV	10.94	12.00	10.79	7.17	3.31	5.39
75% CV	10.43	12.38	10.53	7.27	3.29	5.30
100% CV	10.93	11.92	10.57	7.53	3.30	5.46

Table 7. Intersection Performance Measures: Average Number of Stops for Cars (s).

Scenario	Average passenger car intersection number of stops					
	Rock Springs	Rawlins	Evanston	Laramie	Cheyenne West ramp	Cheyenne East ramp
Base	0.43	0.45	0.45	0.30	0.17	0.28
10% CV	0.43	0.45	0.46	0.32	0.18	0.28
25% CV	0.44	0.44	0.46	0.33	0.17	0.28
50% CV	0.43	0.45	0.46	0.32	0.17	0.28
75% CV	0.44	0.45	0.45	0.33	0.17	0.28
100% CV	0.43	0.45	0.45	0.33	0.17	0.28

Table 8. Intersection Performance Measures: Average Number of Stops for Trucks (s).

Scenario	Average truck intersection number of stops					
	Rock Springs	Rawlins	Evanston	Laramie	Cheyenne West ramp	Cheyenne East ramp
Base	0.37	0.38	0.38	0.30	0.13	0.25
10% CV	0.40	0.40	0.42	0.31	0.13	0.25
25% CV	0.47	0.39	0.41	0.32	0.13	0.26
50% CV	0.40	0.39	0.41	0.31	0.13	0.25
75% CV	0.35	0.40	0.40	0.32	0.13	0.24
100% CV	0.36	0.39	0.37	0.30	0.13	0.26

Table 9. Intersection Performance Measures: Average Queue Length (ft).

Scenario	Average intersection approach queue length (ft)					
	Rock Springs	Rawlins	Evanston	Laramie	Cheyenne West ramp	Cheyenne East ramp
Base	9.72	7.98	8.07	2.00	1.52	3.41
10% CV	9.85	8.13	8.61	2.35	1.61	3.71
25% CV	9.86	8.08	8.48	2.31	1.57	3.66
50% CV	9.73	8.00	8.40	2.19	1.48	3.61
75% CV	9.70	8.00	8.22	2.05	1.47	3.48
100% CV	9.63	7.94	8.02	1.99	1.49	3.55

The results show 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, WY, 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.

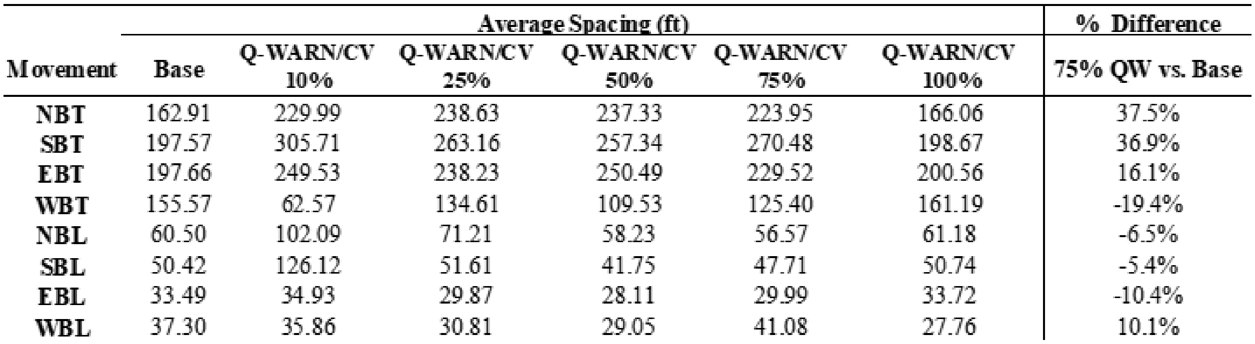
The average number of stops for passenger cars does not show any changes in most scenarios and locations. Therefore, the number of stops for cars are not impacted by the Q-WARN applications. The number of stops for trucks slightly increases until the CV rate reaches 75 percent, after which it is generally lower. These changes are not statistically significant. 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.

4.4.2. Vehicle Spacing

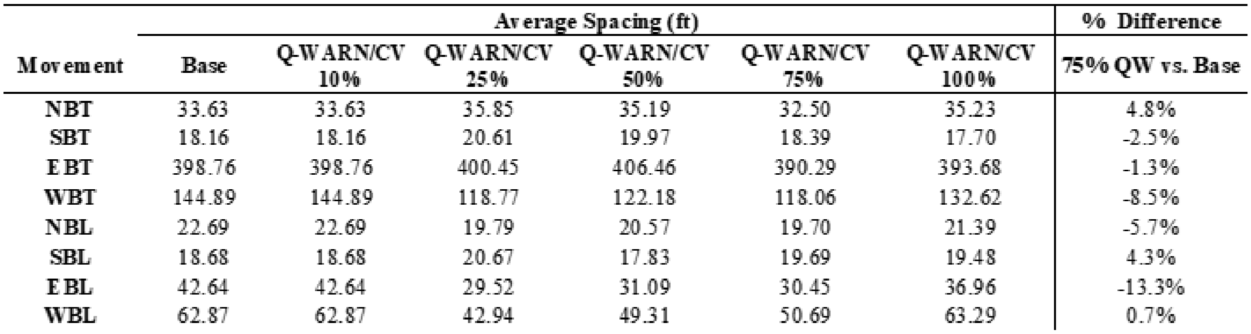
The analysis of spacing between vehicles was performed for the detection zone areas for Rock Springs, Rawlins, Evanston and Laramie scenarios, in Wyoming. Tables 10 through 13 show a comparison between vehicle spacing for the four models and various CV scenarios. The p-values from a two-sample t-test of the average spacing were calculated to be greater than 0.05, which suggests no statistically significant differences. However, the slight increase observed in spacing between vehicles as the CV rate increased helps reduce the chance of rear-end collision significantly, since it gives the drivers more time for perception, reaction, and navigation. It was noted that the spacing between vehicles stopped increasing at 75 percent CV/Q-WARN MPR following a similar pattern with lower rates, therefore, the percent difference between the base models and 75 percent CV truck rates was calculated in all four models. The Rock Springs, WY, model (Table 10) shows the 75 percent CV model spacing to be up to 38 percent higher than in the Base model in most approaches. The Rawlins, WY, model also shows the 100 percent CV rate model spacing to be about 5 percent higher (Table 11). Similarly, the Evanston, WY, model spacing analysis revealed 75 percent CV rate model spacing to be higher up to 30 percent (Table 12), and the Laramie, WY, model spacing analysis shows 75 percent CV rate model to be up to 134 percent (Table 4.9). The spacing in the 100 percent CV models is higher due to the lower vehicle speeds as they approach the back of the queue.

Table 10. Average vehicle spacing (ft) – Rock Springs, WY.



Movement	Base	Q-WARN/CV 10%	Q-WARN/CV 25%	Q-WARN/CV 50%	Q-WARN/CV 75%	Q-WARN/CV 100%	% Difference 75% QW vs. Base
	Average Spacing (ft)						
NBT	162.91	229.99	238.63	237.33	223.95	166.06	37.5%
SBT	197.57	305.71	263.16	257.34	270.48	198.67	36.9%
EBT	197.66	249.53	238.23	250.49	229.52	200.56	16.1%
WBT	155.57	62.57	134.61	109.53	125.40	161.19	-19.4%
NBL	60.50	102.09	71.21	58.23	56.57	61.18	-6.5%
SBL	50.42	126.12	51.61	41.75	47.71	50.74	-5.4%
EBL	33.49	34.93	29.87	28.11	29.99	33.72	-10.4%
WBL	37.30	35.86	30.81	29.05	41.08	27.76	10.1%

Table 11. Average vehicle spacing (ft) – Rawlins, WY.



Movement	Base	Q-WARN/CV 10%	Q-WARN/CV 25%	Q-WARN/CV 50%	Q-WARN/CV 75%	Q-WARN/CV 100%	% Difference 75% QW vs. Base
	Average Spacing (ft)						
NBT	33.63	33.63	35.85	35.19	32.50	35.23	4.8%
SBT	18.16	18.16	20.61	19.97	18.39	17.70	-2.5%
EBT	398.76	398.76	400.45	406.46	390.29	393.68	-1.3%
WBT	144.89	144.89	118.77	122.18	118.06	132.62	-8.5%
NBL	22.69	22.69	19.79	20.57	19.70	21.39	-5.7%
SBL	18.68	18.68	20.67	17.83	19.69	19.48	4.3%
EBL	42.64	42.64	29.52	31.09	30.45	36.96	-13.3%
WBL	62.87	62.87	42.94	49.31	50.69	63.29	0.7%

Table 12. Average vehicle spacing (ft) – Evanston, WY.

Movement	Base	Q-WARN/CV 10%	Q-WARN/CV 25%	Q-WARN/CV 50%	Q-WARN/CV 75%	Q-WARN/CV 100%	% Difference 75% QW vs. Base
	Average Spacing (ft)						
NBT	12.28	11.22	13.00	15.45	12.28	15.45	0.0%
SBT	29.15	26.05	26.71	29.02	31.05	28.87	6.5%
EBT	292.58	263.64	268.25	266.15	271.12	299.26	-7.3%
WBT	280.67	254.57	260.08	260.76	258.21	280.40	-8.0%
SBL	28.73	26.90	27.24	27.30	28.66	28.73	-0.2%
EBL	38.39	23.42	24.61	25.85	28.01	36.80	-27.0%
WBL	21.86	31.50	44.79	40.91	28.33	23.03	29.6%

Table 13. Average vehicle spacing (ft) – Laramie, WY.

	Average Spacing (ft)						% Difference
Movement	**Base**	**Q-WARN/CV 10%**	**Q-WARN/CV 25%**	**Q-WARN/CV 50%**	**Q-WARN/CV 75%**	**Q-WARN/CV 100%**	**75% QW vs. Base**
NBT	268.86	106.26	228.58	42.89	281.15	310.76	4.6%
SBT	109.02	158.90	157.00	128.80	88.04	93.89	-19.2%
EBT	235.36	277.82	288.63	296.49	273.34	304.50	16.1%
WBT	109.02	158.90	157.00	128.80	88.04	93.89	-19.2%
SBL	96.81	194.67	192.18	216.90	226.17	196.99	133.6%
EBL	235.36	277.82	288.63	296.49	273.34	304.50	16.1%
WBL	109.02	158.90	157.00	128.80	88.04	93.89	-19.2%

4.5. Conclusions

This part of the research developed and tested the impact of Q-WARN application in a traffic operation and mobility perspective. The Q-WARN application was created and analyzed through VISSIM microsimulation and Python programming language. The study used the current position and direction of the vehicles, combined with the current signal phasing at the signal, to detect queues and send warning to the upstream vehicles. Once the upstream vehicles received the information, they would start reducing their speeds until reaching the end of the queue. Six model scenarios were created for each intersection, a base model of the current conditions, and hypothetical models with the CV Q-WARN system implemented for the freight vehicles with different percentages of CV rates. The analysis of each model was performed for the evening peak hour, 5:00-6:00 p.m.

The results showed that the CV-based queue warning systems were effective in reducing truck delays by an average of 2 to 5 percent. The recorded vehicle spacing in the vicinity of the intersections were higher (up to 134 percent) in 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.

5. SPEED HARMONIZATION

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 in order to maximize traffic throughput and reduce crashes. A dynamic SPD-HARM system will be successful at managing upstream traffic flow by being able to: reliably detect the location, type, and intensity of downstream congestion (or other relevant) conditions; formulate an appropriate response plan (i.e., vehicle speed and/or lane recommendations) for approaching vehicles; and disseminate 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 information being shared between the vehicles and the infrastructure is the same as for the Q-WARN system. The fundamental idea of SPD-HARM is to mitigate the loss of highway performance by preventing traffic break-downs and bottlenecks. This is represented in the fundamentals of traffic flow theory: a traffic break-down 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).

This section of the research developed algorithms and signal control programs for SPD-HARM applications, and tested them on the six Wyoming intersections. The control programs were applied in the Econolite ASC/3 software using the built-in controller functions and logic processor, therefore, they can be customized to be used with other traffic controller software.

5.1. Literature Review

A study by Talebpour et al. (2013) analyzed the impacts of early shock wave detection on breakdown formation and driving hazards, and the possible improvements through speed harmonization. An algorithm based on the detection of shock wave 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 shock wave 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, as well as an 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 the 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 and they showed that the quality of communications were high and that the Q-WARN and SPD-HARM algorithms were able to 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 0 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, mostly 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 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 that 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 6 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. The results indicated that the speed harmonization can reduce travel times and increase travel speeds close to 6 percent, significantly reduce speed variance (between 20 and 30 percent), and reduce the number of stops between 8 and 19 percent.

5.2. Speed Harmonization Methodology and Algorithm

The SPD-HARM algorithm developed in this study utilizes the current CV truck position, speed, and current signal timing state on vehicle approach. Once the vehicle enters the detection zone, it start 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 that 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 that 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. The implemented algorithm is given in Figure 13.

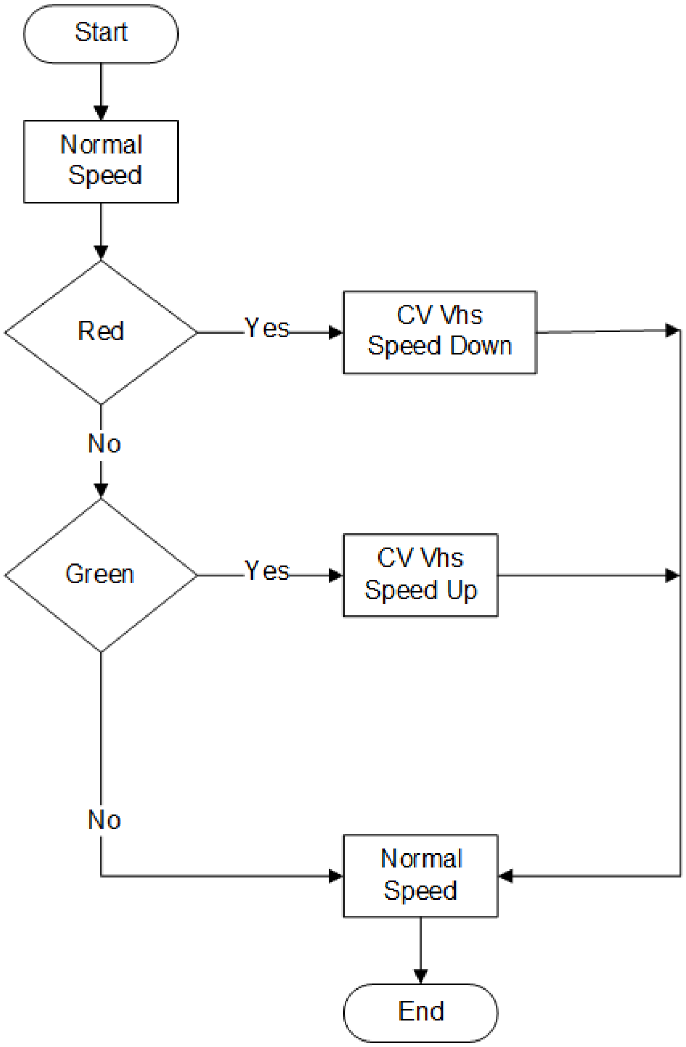


Figure 13. Flowchart. SPD-HARM algorithm.

5.3. Results and Discussion

The assessment of the SPD-HARM algorithm 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 is ineffective in forming platoons. As part of future research, this algorithm will be tested on a different network with higher volumes, so a sensitivity analysis can be performed. The algorithm is implemented and tested on the six signalized intersections for the main through movements. The only exception is the Cheyenne network, where the speed harmonization is 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.

Table 14. 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
	CV Truck	N/A	N/A	N/A	N/A	N/A	N/A
	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
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
	Truck	N/A	N/A	N/A	N/A	N/A	N/A

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 is observed in the Cheyenne, WY, network and 100 percent CV trucks. Car traffic is not impacted by the SPD-HARM implementation. In fact, in some cases, cars benefit from it as well, as they join the platoon of trucks through the intersection.

5.4. Conclusions

This part of the study developed and tested the impact of SPD-HARM application. This 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 4 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.

6. FREIGHT AND TRANSIT SIGNAL CV-BASED PRIORITY: STATE STREET, UTAH, TEST CASE

As an extension of this study, the research team developed and tested combined FSP and TSP CV-based algorithms and control programs. Initially, it was planned to use Jackson Hole, WY, as the test-case. However, due to the COVID-19 pandemic, the resaerch team was unable to collect all the required data for this corridor. Therefore, a different test-case along State Street, in Salt Lake City, UT, was selected for this purpose, as the research team had access to historic and current data for this corridor.

Special traffic signal operations, such as Transit Signal Priority or Freight Signal Priority, rely heavily on the communication between transit/freight vehicles and the traffic signal controllers. Traditionally, this communication was achieved through traffic detectors (loops, video, radar), or wireless technologies, such as infrared, Global Positioning System (GPS) or radar. These technologies could mainly transmit the position of the vehicle and trigger a call for priority. CV technologies are a step up from this communication, since they can share a lot more information both ways between the approaching vehicles and the signal controllers, allowing for advanced and adaptive special signal operations. Both TSP and FSP facilitate the movement of transit and heavy vehicles, respectively, through signalized intersections by allowing for additional green time, early green, or other strategies. 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). TSP is an essential element of surface rapid transit modes, such as Bus Rapid Transit (BRT). The majority of freight origins and destinations are in urban areas, therefore freight vehicles are commonly present along urban roadway facilities. 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 compared to 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 to improve their travel time reliability and enhance 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).

This section of the research developed, tested and assessed the effectiveness of TSP and FSP 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 software. The tests were performed on a 10-intersection corridor along State Street in Salt Lake City, UT, using 2015 traffic data and 2025 traffic projections. In addition to the built-in TSP features, this study also developed a 3-level customized conditional TSP combined with a future BRT system along this corridor.

6.1. Literature Review

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 mostly 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, Oregon recorded transit travel time improvements by up to 8 percent and a reduction in travel time variability by 19 percent. In Chicago, the recorded reduction in bus running times was between 7 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 the passenger 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, 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 9 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 (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 8 to 10 percent (San Mateo) and 11 to 15 percent (Maricopa), as well as 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.

FSP uses the same control strategies as TSP to provide priority for trucks. Prior studies demonstrated the benefits of FSP when properly implemented. It is proven that FSP can improve mobility in the range between 15 percent and 25 percent, and reduce energy consumption 5 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 (Mahmud, 2014). VISSIM was used to assess the FSP impacts considering 11 seconds of green time extension for truck priority. Results showed that the given FSP can ensure freight service reliability, reduce red-light running, and improve safety and smoother operations. Overall truck travel and stop delay reduced 13 percent and 20 percent, respectively, with minimum to no impact to other vehicles. The number of truck stops reduced 9 to 16 percent at the major truck moving direction. A study by 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 percent 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 3 percent. The savings were more significant for the 20 percent truck traffic. Kari et al. (2014) developed and tested and 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 5 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.

6.2. Test-Case Corridor and Data

The test-case network for this 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 14. 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). At 500 S and 600 S are one way streets, westbound and eastbound respectively, carrying traffic to and from I-15, which is about one mile west of State Street. The busiest intersection in the test-case corridor is 2100 S, used by more than 9,500 vehicles during the evening peak period (4:00 – 6:00 p.m.), which is the interval used in this study. At 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 (UTA's) routes with highest ridership. 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 Utah Transportation Authority's (UTA) 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 evening peak period (4:00 PM – 6:00 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 ten 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.

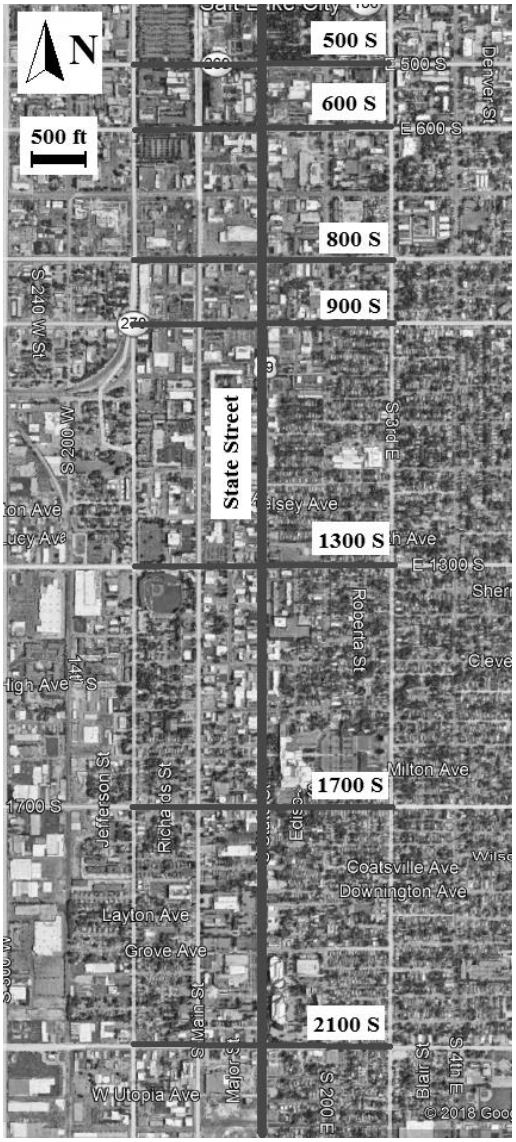


Figure 14: Illustration. Test-case network, State Street, UT. Source: Google Map, modified from source.

6.3. Microsimulation Models and Scenarios

The development, testing and assessment of the signal priority algorithms were performed through VISSIM microsimulation, coupled with Econolite ASC/3 SIL controller software. Communication, BSM and Road Side Unit (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 as follows:

- 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 Signal Control Priority (SCP) model that introduced CV-equipped trucks and buses. It is assumed that all trucks and 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 SCP algorithms is provided in later subsections of the paper.
- 2025 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 3-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 evening peak period (4:00 – 6:00 p.m.). The simulations included a 15-minute warm-up period and two hours 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 reasonable comparison.

6.3.1. Base Model

The Base model was developed, calibrated and validated for 2015 existing traffic conditions along the State Street corridor. PTV VISSIM, coupled with Econolite ASC/3 SIL traffic controller software, was used for modeling. The data used in modeling include 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 ten 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. Detailed intersection count data for the two hour evening peak period were available for these intersections. For validation purposes, the corridor was split into seven segments in each direction, where one segment was between a pair of major intersections. Travel times collected in the field were used to validate the model. Model calibration is shown in Figure 15, while the validation for the northbound (NB) and southbound (SB) directions is given in Figures 16 and 17, respectively. The coefficient of determination (R^2) for calibration was close to 1.0, while R^2 for validation was 0.904 in the southbound and 0.961 in the northbound direction. These results show a good fidelity of the Base model.

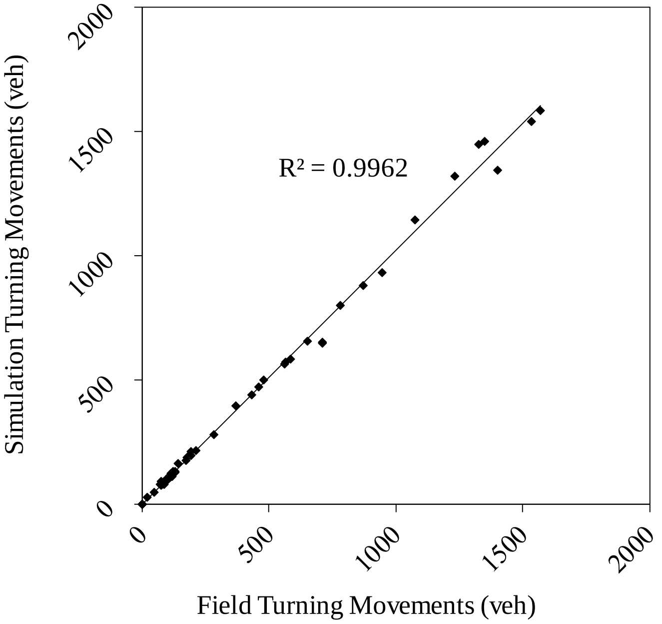


Figure 15: Graph. Base model calibration.

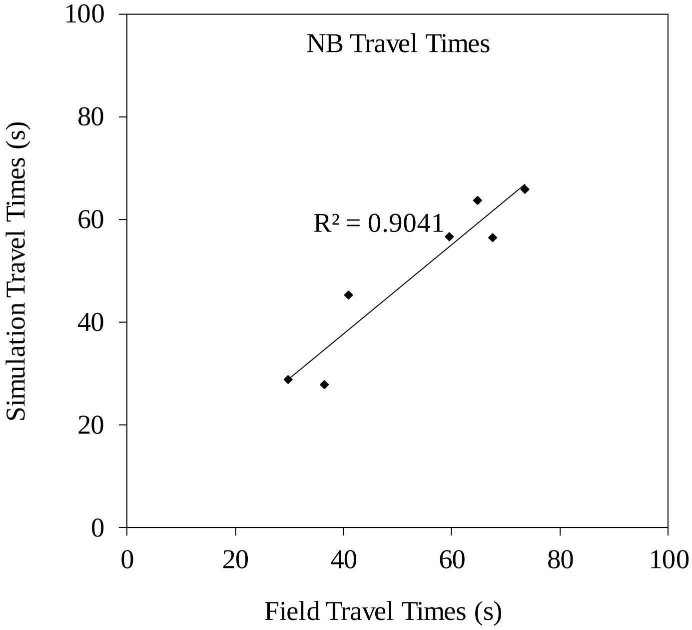


Figure 16: Graph. Base model validation SB.

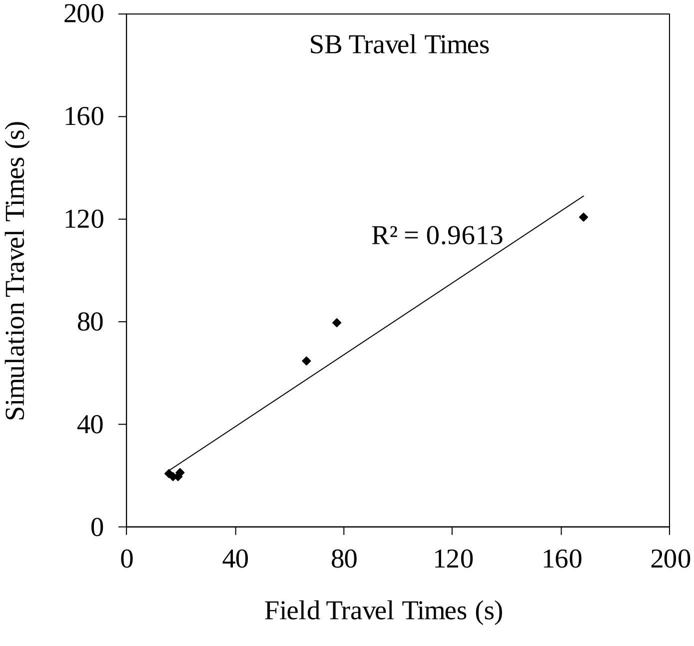


Figure 17: Graph. Base model validation NB.

6.3.2. 2025 CV Signal Control Priority 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 SCP model was based on the 2025 Do-Nothing model, and introduced CVs and SCP for trucks and transit buses. No other vehicles were equipped with CV technologies in this study. It was assumed that all (100 percent) of trucks and buses, as fleet vehicles, will be CV-equipped in 2025.

CV protocols, communication, BSM information and RSU operations were programmed through VISSIM's COM interface using Python programming language. SCP operations were programmed through built-in SCP 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' lat/long coordinates. RSU contained the lat/long 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, as described in Chapter 2 and presented in Figure 9.

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 SCP 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 send an SCP request to the signal. In this study, SCP was provided only to the trucks and 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 SCP request and strategies were programmed through a combination of RSU operations, and built-in controller logic and SCP features. When the RSU detected a request, it would activate the internal controller logic and enable GE/EG SCP strategies. GE was set to 15 seconds maximum, while the maximum green time reductions for EG were set as 5 seconds for left turns along the main corridor, and 10 seconds for through movements from side streets. In this case, the SCP was unconditional, meaning that all CVs would send a request and receive priority. The re-service cycle was set to one. The SCP 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.

6.3.3. 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. This study considered a BRT implementation with center-running exclusive lanes, upgraded buses with 110-space 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. The 2025 CV BRT TSP model included BRT operations, CV-equipped buses and 3-level custom conditional TSP strategies. The CV communication, RSU operations, check-in and check-out detection 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 2 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.

6.4. Results and Discussion

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

6.4.1. Intersection Performance

Intersection performance for the six 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 15.

Table 15. Intersection Performance: Vehicle Delays.

		Average Delay per Vehicle (s)				
Intersection	**Mode**	**Base**	**2025 Do-Nothing**	**2025 CV SCP**	**2025 BRT**	**2025 CV BRT TSP**
500 S	Car	31.7	81.2	90.9	88.8	95.0
	Bus	52.6	95.3	105.3	19.2	26.3
	Truck	34.1	87.7	79.7	91.9	98.3
600 S	Car	35.7	60.0	121.5	28.2	32.6
	Bus	15.6	53.7	131.8	54.1	46.9
	Truck	37.9	62.5	94.1	30.5	35.1
800 S	Car	33.7	42.7	62.4	38.1	38.9
	Bus	34.3	56.9	57.5	14.9	12.2
	Truck	35.7	44.9	60.7	42.5	42.7
900 S	Car	13.9	21.4	24.1	20.1	22.6
	Bus	14.6	14.2	25.3	21.2	22.1
	Truck	16.5	21.9	13.4	22.1	25.5
1300 S	Car	41.3	55.4	70.9	41.9	43.4
	Bus	19.6	47.1	59.9	30.9	30.2
	Truck	40.6	59.6	51.1	43.2	45.5
1700 S	Car	14.9	62.6	84.0	38.9	27.8
	Bus	12.6	58.4	86.3	34.1	28.1
	Truck	16.4	64.6	58.8	40.7	30.0
2100 S	Car	41.2	94.9	122.4	73.8	74.9
	Bus	37.8	81.0	124.3	35.8	31.6
	Truck	44.8	95.6	79.7	76.5	78.1
Average	**Car**	**30.4**	**59.7**	**82.3**	**47.1**	**47.9**
	Bus	**26.7**	**58.1**	**84.3**	**30.0**	**28.2**
	Truck	**32.3**	**62.4**	**62.5**	**49.6**	**50.7**

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 greatest increase in vehicle delays, almost up to four times. All the increases are statistically significant. The unconditional SCP implementation provided significant delay savings for trucks at most intersections, except for 600 S and 800 S where the truck delay reduces 10 percent to 40 percent in this scenario. However, it also significantly increases delays for other vehicles, in excess of 35 percent. Bus priority is not effective in this case. Therefore, the unconditional SCP 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 3-level conditional TSP has different effects on an intersection-by-intersection basis. In general, it reduces BRT delays by 6 percent while it increases car and truck delays by up to 2 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.

6.4.2. Vehicle Speeds

The vehicle speed results are given in Tables 16, 17 and 18 for cars, buses and trucks, respectively. The speeds were measured in each direction for each vehicle type, on segments between the seven major intersections (14 segments in total).

Table 16. Vehicle Speeds: Cars.

		Average Speed (s): Cars				
	Segment	**Base**	**2025 DN**	**2025 CV SCP**	**2025 BRT**	**2025 CV BRT TSP**
SB car	500 S - 600 S	25.9	12.0	11.7	13.2	11.4
	600 S - 700 S	27.8	26.5	27.0	18.0	16.2
	700 S - 800 S	28.0	10.7	11.8	10.9	10.7
	800 S - 900 S	26.0	19.9	15.6	23.6	21.0
	900 S - 1300 S	31.6	15.6	12.0	32.5	31.1
	1300 S - 1700 S	25.2	5.5	4.9	13.0	19.9
	1700 S - 2100 S	16.4	4.5	4.6	6.2	7.8
NB car	2100 S - 1700 S	31.6	21.4	20.7	22.0	22.3
	1700 S - 1300 S	30.5	22.1	21.1	24.0	23.0
	1300 S - 900 S	35.9	33.3	32.8	34.2	33.4
	900 S - 800 S	19.3	20.8	15.2	22.7	21.3
	800 S - 700 S	18.9	23.2	8.1	24.1	23.6
	700 S - 600 S	11.9	9.6	3.7	13.7	10.1
	600 S - 500 S	9.6	9.2	5.6	10.5	9.7
	Average	**24.2**	**16.7**	**13.9**	**19.2**	**18.7**

Table 17. Vehicle Speeds: Buses.

		Average Speed (s): Buses				
	Segment	**Base**	**2025 DN**	**2025 CV SCP**	**2025 BRT**	**2025 CV BRT TSP**
SB car	500 S - 600 S	14.2	6.4	7.3	10.0	10.7
	600 S - 700 S	19.0	19.1	19.4	7.6	8.7
	700 S - 800 S	9.4	6.8	7.1	25.7	23.5
	800 S - 900 S	11.6	10.2	10.0	29.9	24.5
	900 S - 1300 S	15.7	10.5	8.6	14.0	13.1
	1300 S - 1700 S	18.5	4.8	4.3	13.3	14.3
	1700 S - 2100 S	11.6	4.1	4.4	14.5	15.2
NB car	2100 S - 1700 S	15.2	14.6	14.9	14.4	15.5
	1700 S - 1300 S	18.6	14.8	15.8	16.0	17.1
	1300 S - 900 S	18.1	18.3	17.7	12.2	12.2
	900 S - 800 S	14.1	8.1	7.5	30.7	31.2
	800 S - 700 S	10.2	11.0	5.4	34.3	34.2
	700 S - 600 S	9.7	6.2	3.5	6.3	6.3
	600 S - 500 S	6.3	5.3	5.2	12.7	12.0
	Average	**13.7**	**10.0**	**9.4**	**17.3**	**17.0**

Table 18. Vehicle Speeds: Trucks.

		Average Speed (s): Trucks				
	Segment	**Base**	**2025 DN**	**2025 CV SCP**	**2025 BRT**	**2025 CV BRT TSP**
SB car	500 S - 600 S	25.4	11.6	12.3	13.0	10.8
	600 S - 700 S	28.0	26.7	28.2	18.1	17.4
	700 S - 800 S	28.4	10.7	11.4	10.5	10.5
	800 S - 900 S	24.7	19.3	14.9	22.3	18.8
	900 S - 1300 S	29.3	14.2	10.9	26.6	27.6
	1300 S - 1700 S	25.7	5.4	4.8	13.0	18.1
	1700 S - 2100 S	16.0	4.5	4.6	6.3	7.6
NB car	2100 S - 1700 S	31.5	21.0	20.2	22.0	21.9
	1700 S - 1300 S	27.3	19.8	20.1	22.1	19.7
	1300 S - 900 S	30.2	31.1	29.1	32.2	31.6
	900 S - 800 S	16.2	15.9	13.9	18.1	19.8
	800 S - 700 S	21.0	23.4	8.2	24.3	23.8
	700 S - 600 S	11.0	10.0	3.7	11.6	9.9
	600 S - 500 S	9.7	8.6	5.6	11.5	9.7
	Average	**23.2**	**15.9**	**13.4**	**18.0**	**17.7**

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 and truck speeds increase about 15 percent, while transit speeds increase more than

70 percent. The transit speed increase is statistically significant. The unconditional truck and 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 and truck 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 the majority of segments, but this increase is not significant. Car and truck speeds remain mainly unchanged.

6.4.3. Phase Split Durations

Phase split durations are provided in Table 19 for each of the seven major intersections. Only splits for through phases are shown, since the left turn phases can be skipped, depending on the left turn demand.

Most split durations in the 2025 Do-Nothing scenario are statistically significantly different than the corresponding splits in the Base scenario. This is to be expected, since the signals were optimized for 2025 demand. For the same reason the split durations in both BRT scenarios are statistically significantly different than the corresponding splits in the 2025 Do-Nothing scenario. Split durations for the majority of intersections in the 2025 CV SCP scenario are significantly different than the corresponding ones in the 2025 Do-Nothing scenario. This is due to the redistribution of green times caused by GE/EG for phases 2 and 6. Differences can also be seen between 2025 BRT and 2025 CV BRT TSP scenarios, however, they are not statistically significant in most cases. An interesting observation can be made for phases 2 and 6 in those two scenarios. These phase splits are in most cases shorter in the BRT TSP scenario, regardless of the GE/EG strategies. This can be attributed to the coordination, since the duration of these phases would be changed to maintain coordination between intersections. Furthermore, major adjustments caused by the coordination had to be made when PR was active. However, no significant differences were observed.

Table 19. Phase Split Duration.

		Phase Splits (s)				
Intersection	**Phase**	**Base**	**2025 DN**	**2025 CV SCP**	**2025 BRT**	**2025 CV BRT TSP**
500 S	2	62.5	61.5	72.0	70.6	63.3
	4	0.0	0.0	0.0	0.0	0.0
	6	50.8	46.1	47.7	49.7	42.1
	8	52.0	53.0	50.5	43.9	44.6
600 S	2	71.8	54.7	49.4	45.7	37.3
	4	42.4	55.2	57.7	50.6	54.9
	6	72.0	59.4	56.8	63.9	53.6
	8	0.0	0.0	0.0	0.0	0.0
800 S	2	72.8	63.3	67.8	57.3	57.3
	4	33.0	37.3	29.7	31.2	31.4
	6	71.7	65.1	69.8	57.0	56.6
	8	38.1	41.4	34.0	35.5	35.8
900 S	2	84.8	70.7	67.4	61.1	60.4
	4	27.6	42.7	43.7	43.6	45.2
	6	85.9	70.8	69.5	66.6	65.9
	8	27.6	42.7	43.7	43.6	45.2
1300 S	2	74.3	68.8	68.3	56.6	54.2
	4	34.1	36.9	34.3	32.9	36.3
	6	74.8	64.0	63.8	55.7	53.3
	8	38.1	42.6	39.6	36.4	39.5
1700 S	2	83.0	73.8	70.0	75.2	75.7
	4	24.8	34.0	30.1	25.8	25.8
	6	82.6	69.1	65.2	67.1	67.6
	8	31.9	40.9	41.7	33.5	33.3
2100 S	2	60.3	55.8	53.8	53.0	50.4
	4	35.5	35.2	32.6	33.7	33.3
	6	46.0	44.0	45.3	46.6	45.9
	8	46.4	43.6	38.8	37.8	37.2

6.5. Findings and Conclusions

The goal of part of the study was to develop, test, and assess the effectiveness of TSP and FSP 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. SCP operations were programmed through built-in SCP functions in ASC/3 controllers. The algorithms used lat/long coordinates of intersections and approaching vehicles to determine the detection zone. The study developed a 3-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 study first showed that vehicles' lat/long coordinates can be successfully used to communicate their position in each time step, and select a traffic control program based on this information. Although the tests were performed in simulation, this concept can easily be implemented in the field, since the same information exists in the BSM of CV-equipped vehicles. This algorithm can be used for other traffic operation purposes, which will be explored in future studies.

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 be significantly reduced, about 50 percent and 30 percent, respectively, with a significant deterioration in transit operations. The implementation of unconditional SCP provided significant delay savings for trucks, up to 40 percent, but it also caused significant delay increases for other vehicles, in excess of 35 percent. Speeds for all vehicles would reduce if unconditional SCP 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 would increase more than 70 percent.

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 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 SCP algorithms. However, CV-equipped vehicles can provide a lot more information that can be used to further fine tune traffic control. Furthermore, it only assumed that fleet 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, as well as developing adaptive SCP programs that use the information from all CV-equipped vehicles, as well as real-time data from other traffic sensors and systems, such as the ATSPM.

7. CONCLUSIONS

The State of Wyoming is experiencing a high percentage of truck traffic along all highways, especially I-80 and its vicinity, because of an expansion in oil and gas production. This creates additional strain on the signalized intersections adjacent to I-80, which experience operational and safety impacts attributed to the high truck percentages.

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 develops and tests 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 cases are intersections in Wyoming adjacent to I-80 in Rock Springs, Rawlins, Evanston, Laramie and Cheyenne. The focus of the research is on ISIG, FSP, Q-WARN and SPD-HARM applications. The analysis was performed considering different model scenarios with different rates of CAV-equipped trucks.

As a part of the ISIG applications, the study developed an approach that uses the latitude and longitude 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, as well as the current signal phase and state, in each time step (taken as 0.1 seconds in this research). Furthermore, the study uses the current vehicle routing that can be communicated through the use of turn signals to separate individual turning movements at intersections. The study showed that this information can be utilized to implement the signal control programs.

The FSP application allows extra time for freight vehicles as they approach the signal, or wait for the signal to change, in order 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 assesses the current vehicle position, speed, and signal timing state to optimize the FSP call and service. The results of the analyses show that the FSP application has the ability to reduce the intersection delay of CAV-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 utilizes the position, speed, and heading of CAV-equipped trucks, along with 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. This gives them extra time to adjust their speeds as they approach the intersection. The results showed that the CAV-based Q-WARN applications were effective in reducing truck delays by an average of 2 to 5 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.

SPD-HARM application developed in this study applies communication between the vehicles on the same approach and heading, as well as 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 results show significant benefits for truck traffic, with a reduction in delays up to 82 percent. Furthermore, this application can be combined with others (FSP and queue warning) to further improve operations and safety at signalized intersections.

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 delay increase for other vehicles, in excess of 35 percent. Speeds for all vehicles would reduce if unconditional SCP is 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 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 6 percent, without significant impacts on other traffic and transit operations.

Overall, this study shows the potential of CAV 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 CAV technologies. Although the focus of this research is on CAV-equipped heavy trucks, it can also be applied to other vehicle types, and the algorithms can easily be customized. Furthermore, the study is using actual traffic signal control software (Econolite ASC/3 in this case), so the programs can easily be transferred to the field. The future research in this area will further fine-tune the signal control strategies, explore additional ones, and expand the technologies to other vehicle types.

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