Developing Analysis, Modeling, and Simulation Tools for Connected Automated Vehicle Applications: Traffic Optimization for Signalized Corridors—Case Studies in Ann Arbor, MI, and Conroe, TX

PUBLICATION NO. FHWA-HRT-21-085

SEPTEMBER 2021

U.S. Department of Transportation

Federal Highway Administration

Research, Development, and Technology
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FOREWORD

Connected and automated vehicles are expected to produce significant mobility, safety, and environmental benefits to the traveling public. Real-world case studies are needed to articulate reasonable benefits attributable to the technology. This report details a case study of the impact of integrating real-time traffic signal data with vehicle connectivity and automated longitudinal control (i.e., Society of Automotive Engineers [SAE] J3016 driving automation level 1) on signalized corridors in Ann Arbor, MI, and Conroe, TX. The benefits of the specific application, Traffic Optimization for Signalized Corridors, are explored. This final report will be of interest to State and local departments of transportation who are interested in better understanding possible real-world impacts of connected and automated vehicle technology.

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Research and Development

Recommended citation: Federal Highway Administration, *Developing Analysis, Modeling, and Simulation Tools for Connected Automated Vehicle Applications: Traffic Optimization for Signalized Corridors—Case Studies in Ann Arbor, MI, and Conroe, TX* (Washington, DC: 2021) https://doi.org/10.21949/1521672

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-21-085	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Developing Analysis, Modeling, and Simulation Tools for Connected Automated Vehicle Applications: Traffic Optimization for Signalized Corridors—Case Studies in Ann Arbor, MI, and Conroe, TX		5. Report Date September 2021 6. Performing Organization Code
7. Author(s) Zhitong Huang (ORCID: 0000-0003- 2871-6302); Jiaqi Ma (ORCID: 0000-0002-8184-5157); Yi Guo (ORCID: 0000-0002-4778-1823); Nagham Matout; Yiheng Feng (ORCID: 0000-0001-5656-3222); David Florence (ORCID: 0000-0001-9923-4242); Kevin Balke (ORCID: 0000-0002-4961-5431); David Leblanc; Guoyuan Wu; Rawa Adla; Hendrik-Joern Guenther; Shah Hussain; Ehsan Moradi-Pari; Tyler Naes; Neal Probert; Vivek Vijaya Kumar; Richard Williams; Hiroyuki Yoshida; Tuncer Yumak; Richard Deering; Roy Goudy		8. Performing Organization Report No.
9. Performing Organization Name and Address Leidos Inc. 11251 Roger Bacon Drive Reston, VA 20190		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH6116D00030-0022
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered 14. Sponsoring Agency Code HRDO-30
15. Supplementary Notes The Government Task Managers were John Halkias (HOTM-1), who managed application development, and Gene McHale (HRDO-30; ORCID: 0000-0003-1031-6538), who managed the case study.		

16. Abstract

Traffic Optimization for Signalized Corridors (TOSCo) is an innovative connected and automated vehicle application that has the potential to generate substantial mobility and air quality benefits for public agencies and potential fuel savings benefits for the traveling public. Under the TOSCo system, vehicles equipped with TOSCo functionality use signal phase and timing and queue information from the infrastructure to plan speed trajectories that allow them to reduce the likelihood of stopping at TOSCo-supported intersections. The TOSCo system also includes a coordinated launch feature that allows a string of TOSCo-equipped vehicles to leave an intersection simultaneously, in a coordinated fashion, to reduce the startup loss time, which, in turn, increases the capacity of the intersection. This report presented the methodology and results of traffic simulation activities supporting the development of the TOSCo system, especially the infrastructure-based algorithms. This report used a developed traffic simulation to evaluate the effectiveness and potential mobility and environmental benefits that could be generated through the application of the TOSCo system in both low- and high-speed corridor environments.

17. Key Words Traffic Optimization for Signalized Corridors; signal timing and phasing; connected and automated vehicles		18. Distribution Statement No restrictions	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 92	22. Price n/a

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

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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

ACC	adaptive cruise control
ASC	advanced system controller
AM	morning
API	application programming interface
BSM	basic safety message
CACC	cooperative adaptive cruise control
CV	connected vehicle
DSRC	dedicated short-range communication
EB	eastbound
EPA	U.S. Environmental Protection Agency
FHWA	Federal Highway Administration
FM	farm-to-market
ft/s	ft per second
GEH	Geoffrey E. Havers
HC	hydrocarbon
MOVES	Motor Vehicle Emission Simulator
mph	miles per hour
MPRs	market penetration rates
NB	northbound
NOx	nitrogen oxide
PM	afternoon
RSM	road safety messages
RSU	roadside unit
SH	State Highway
SPaT	signal phase and timing
TOA	time of arrival
TOSCo	Traffic Optimization for Signalized Corridors
UDP	user diagram protocol
v/c	volume divided by capacity
V2I	vehicle-to-infrastructure
vph	vehicles per hour
WB	westbound

EXECUTIVE SUMMARY

PURPOSE OF REPORT

This report leveraged a previous Federal Highway Administration (FHWA) project (Cooperative Agreement No. DTFH6114H00002) to document two case studies on the traffic-level simulation and performance analysis for the Traffic Optimization for Signalized Corridors (TOSCo) in a high-speed corridor in Conroe, TX, and a low-speed corridor in Ann Arbor, MI. This report shares the latest research results about the mobility and environmental benefits of TOSCo for public agencies, academia, and private sectors interested in evaluating and deploying TOSCo to achieve early benefits of connected and automated vehicles (CAV). All results of this report are from the traffic-level simulation and performance analysis report of the previous FHWA project (Feng et al. 2019).

METHODOLOGY

The prior project research team developed an innovative simulation environment to support the development and assessment of TOSCo functionality. The environment consists of three platforms: a vehicle simulation platform, an infrastructure simulation platform, and a performance assessment platform. Using a series of three simulation models, the vehicle simulation platform gives the TOSCo team the ability to test and verify algorithm code that will eventually reside in TOSCo-enabled vehicles. The infrastructure simulation platform was developed to test and verify detection and processing algorithms that reside on infrastructure devices. The team used this platform to simulate the detection outputs of different queue detection devices and to assess the impact of accuracy and precision of queue estimates on TOSCo processes. The TOSCo performance assessment platform was developed to quantify the potential intersection, corridor, and network-level benefits of deploying TOSCo in the real world. Using simplified vehicle and infrastructure logic, this platform enabled the prior research team to examine the environmental and mobility benefits associated with varying operating conditions and scenarios.

Using the performance assessment simulation environment, the prior research team conducted simulation experiments to assess the potential mobility and environmental benefits of deploying the TOSCo system in two suburban corridors: a low-speed corridor in Michigan and a high-speed corridor in Texas. The team developed simulation experiments to examine the following:

- The potential mobility and environmental benefits of using TOSCo in different operating environments: a low-speed corridor (Plymouth Road, Michigan) and a high-speed corridor (State Highway [SH] 105, Texas).
- The mobility and environmental benefits of different market penetration rates of TOSCo-equipped vehicles.

- The use of different infrastructure algorithms for estimate queuing—a basic safety message (BSM) and/or loop-detector approach on the low-speed corridor and a radar-based detector approach on the high-speed corridor.

KEY RESULTS

Based on the simulation experiments, the following findings related to deploying TOSCo in the two simulated corridors were identified:

- TOSCo produced substantial reductions in stop delay and the number of stops in both corridors. Stop delay decreased in the order of 40 percent in the low-speed corridor and 80 percent in the high-speed corridor after TOSCo was implemented. Similar reduction in the total number of stops was recorded in both corridors.

- TOSCo did not cause substantial changes in the total delay experienced by travelers in the corridor.

- TOSCo did not significantly affect the total travel time and travel speed in either corridor.

- TOSCo did not have a substantial impact on vehicle emissions or fuel consumption. The TOSCo system produced similar mobility benefit trends in both low- and high-speed corridors.

- Emission benefits tended to be greater in the low-speed corridor. Because changes in speeds in the low-speed corridor are in the range where environmental impacts are the greatest, emissions benefits in the low-speed corridor are more sensitive to smaller changes in speed.

- The string of TOSCo vehicles formed more easily as more penetration rates increased. This increased ability for string formation allowed more vehicles to drive in a cooperative fashion.

- With more strings, TOSCo's coordinated launch feature enabled queues at intersections to clear faster.

- As the market penetration rate of TOSCo vehicles increased, the accuracy of the queue prediction also improved.

- Results from both corridors show that TOSCo is less effective at low-traffic volume and low-delay intersections. When the traffic volume is low, or signal coordination provides good progression, most of the vehicles do not need to stop or slow down at the intersection, which leaves very limited space for TOSCo to adjust vehicle trajectories. In addition, low-traffic volume on side streets may generate inaccurate signal timing and phasing information when the traffic signal of TOSCo approach is under the green rest state unless minimum recall is in place.

Based on the experiences modeling the potential mobility and environmental benefits of the TOSCo system, the following recommendations were developed:

- TOSCo parameters (e.g., maximum acceleration and cooperative adaptive cruise control [CACC] set speed) should be selected to match the corridor characteristics and driving behaviors.
- TOSCo vehicles need to utilize profiles that accelerate differently than the analyzed version. Acceleration from a stop should incorporate a buildup of the acceleration, constant acceleration, and a reduction of acceleration, so that a TOSCo vehicle can reach the desired speed in a reasonable amount of time and level of jerk.
- TOSCo vehicles need to be coded to account for unexpected queues or vehicles changing lanes in front of them.
- The simulations need to be revised with the final vehicle-level algorithm and evaluated to understand the benefits of the revised TOSCo algorithm.
- The TOSCo vehicle algorithms need to be expanded to account for the following:
    - Non-trivial initial acceleration for trajectory planning.
    - Inclusion of road grade change.
    - Customization of different power-train characteristics.
    - Imperfection of sensors (e.g., global positioning system [GPS]) and communications.
- The simulation experiments assume that lateral and longitudinal positions of vehicles can be detected by sensors installed at an intersection. More research is needed to understand the limitations of field equipment to better simulate the TOSCo infrastructure component.
- Data in this report indicate that predictive queue estimation performs better with increased dedicated short-range communication (DSRC) range than current queue information used for the green window calculation. Additional simulations should be run to analyze which queueing information is most helpful for TOSCo.

CHAPTER 1. INTRODUCTION

BACKGROUND

The best way to understand the impact of connected automated vehicles (CAV) on traffic mobility and energy consumption and emissions is through microscopic simulation with proper modeling of the dynamic interactions between CAVs and manually driven vehicles. The Federal Highway Administration (FHWA) sponsored three case studies (I–66, SR–99, and Traffic Optimization for Signalized Corridors [TOSCo]) under this project to investigate the traffic and energy impact of CAV and the bundled applications of CAV and traffic management strategies at various freeway and arterial corridors.

This report uses Feng's (2019) report to document two case studies on the traffic-level simulation and performance analysis for the TOSCo application in a high-speed corridor in Conroe, TX, and a lower-speed corridor in Ann Arbor, MI. All results of this report are from Feng's report. The case studies were selected to conduct simulation testing since both cities are interested in using emerging transportation technologies (e.g., CAV) to solve existing and future transportation problems. The engineers from both cities were also willing to be interviewed by the project team to indicate their opinions for TOSCo application and emerging transportation technologies (e.g., CAV).

The TOSCo system is a series of innovative applications designed to optimize traffic flow and minimize stopping on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based connected vehicle (CV) communications to assess the state of vehicle queues and the point in time when the queue will clear within the green indication. The remaining time in the green phase, between when the queue clears and the end of the green phase, represents the start and end of the "green window." This information enables the vehicles to cooperatively control the behavior of strings of equipped vehicles approaching designated signalized intersections to minimize the likelihood of stopping. Information about the state of the queue and the green window are computed and broadcast to approaching CVs once every s. Leveraging previous work on cooperative adaptive cruise control (CACC), approaching TOSCo-equipped vehicles use real-time infrastructure information about queues and traffic signal operations to plan and control their speeds to enhance overall mobility and reduce emissions across the corridor.

Low-Speed Corridor

Ann Arbor is interested in emerging transportation technologies, such as CAV. The city actively provides support to the development and testing of CAV technology by working closely with the nearby university, and other institutions and agencies, to allow for testing and demonstration of CAVs in the city. The Safety Pilot Model Deployment project (Bezzina and Sayer 2014) is one example of such collaborations.

The city of Ann Arbor's current vision, policies, and strategic plan do not reflect or address the deployment and operation of CAVs or TOSCo. However, the city's vision and policies include traffic signal optimization and are related to safety and congestion. The city will be adopting the

"Vision Zero" initiative for the new update of the strategic plan; the goal is to attain zero fatalities by 2025. The updated strategic plan might address new forms of mobility, such as CAVs, and new emerging technologies that can be used to advance the community's values.

The city of Ann Arbor is a regional employment center where 80,000 people commute into and out of the city daily, making congestion one of the major challenges and concerns in the city. As an infrastructure owner and operator, the city of Ann Arbor is also concerned with the safety of all road users. To improve mobility of the local transportation system, traffic signal optimization and enhancement of "virtual capacity building" (i.e., improve roadway capacity without having to build more lanes) are two major approaches used by the city.

The city of Ann Arbor believes that TOSCo could potentially fit into current practices or existing policies related to traffic signal operations. In addition, the results of the TOSCo application demonstrate it could reduce delays and improve the throughputs of the study site without constructing more lanes. The city thinks that TOSCo has great potential to solve safety and capacity issues and to serve not only Ann Arbor, MI but also other communities.

The Plymouth, MI corridor (i.e., one of the study sites of TOSCo applications) is also a good location to test new technology such as TOSCo. The speed limit in the corridor varies from 35 miles per hour (mph) on the west end to 50 mph on the east end. The corridor has a variety of intersection types. Part of the corridor's traffic signal control is running on Split Cycle Offset Optimization Technique (SCOOT™), while the portion of the county side may still be running on a fixed time or time-of-the-day phasing and timing plans.[1]

High-Speed Corridor

- Conroe, TX, is responsible for maintaining all traffic signals in the city and along the SH 105 corridor. The city is interested in comparing the impact on mobility before and after the deployment of the TOSCo system along this corridor. The city of Conroe expects the TOSCo application to reduce traffic congestion and speed, resulting in improved mobility along the corridor. The city is also hoping that the TOSCo application will help vehicles come to smoother stops at intersections along the corridor. Some factors explaining the disruptive stopping behavior of drivers along the corridor are topography (i.e., presence of grades and slopes) and traffic composition (i.e., high presence of heavy vehicles, recreational vehicles, and vehicles towing boats).

- The city of Conroe is excited to be involved in the initial testing and deployment of the TOSCo system. Depending on the results of the initial TOSCo implementation testing, the city would support continued TOSCo testing on the corridor. The city is very interested in this technology to help improve mobility and safety and will consider the results of the TOSCo testing in making future investment decisions.

[1]Interview conducted with Luke Liu and Raymond Hess. March 2019. Ann Arbor, MI.

- The SH 105 study corridor is between Interstate 45 (I–45) on the east to Montgomery, TX, on the west. The study corridor has 15 intersections along its 12-mi length. The speed limits of this corridor ranges from 45 mph on the east to 55 mph to the west. Most of the study corridor has a 55-mph posted speed limit. Along the corridor, there are three different traffic signal coordination plans. The study corridor serves heavily as a commuting and recreational route, which explains the presence of congestion in this area. Speeding has been observed on this corridor, which can be attributed to various factors, including, but not limited to, the road environment (i.e., three lanes in each direction) and impatient driving behavior, potentially as a result of abrupt stops along the corridor and existing congestion.

- Currently, the city of Conroe, along with Texas Department of Transportation and the Houston Galveston Area Council, conducts traditional studies to investigate and solve congestion issues within local areas in the road network. However, since the TOSCo application could smooth traffic and reduce the number of stops, the city of Conroe is hopeful that the TOSCo application would improve mobility, reduce speeding, and enhance safety (e.g., improve spacing between vehicles).[2]

REPORT OVERVIEW

This report presents the methodology and results of computer simulation activities supporting the development of the TOSCo system, especially the infrastructure-based algorithms. The research team also uses traffic simulation to evaluate the effectiveness and potential mobility and environmental benefits of the TOSCo system in both low- and high-speed corridors. The objectives of the performance analysis are to quantify the potential mobility and environmental benefits of the TOSCo system in the following variety of settings and strategies:

- Different operating environments—a low-speed corridor (Plymouth Road, Michigan) and a high-speed corridor (SH 105, Texas).

- Different penetration rates of vehicles equipped with TOSCo functionality.

- Different CV market penetration rates—this report assumes the use of dedicated short-range communication (DSRC), but other low-latency technologies can be used.

- Different infrastructure algorithms to estimate queue—a basic safety message (BSM) on the low-speed corridor, loop-detector approach on the low-speed corridor, and a radar-based detector approach on the high-speed corridor.

- Different traffic control strategies—fixed-time control and coordinated actuated signal control.

[2]Phone interview conducted with Christopher Bogert and Norman McGuire. September 2019. Conroe, TX.

The simulation experiments consist of verification scenarios and evaluation scenarios. Seven verification scenarios are specifically designed to test the TOSCo operating modes with or without traffic that does not have TOSCo functionality. The evaluation scenarios generate vehicles based on local traffic patterns, which are calibrated from the field data. Simplified TOSCo algorithms, described in chapter 2, are implemented. The simulation experiments are conducted according to a defined test plan. Both mobility and fuel consumption and emission benefits are analyzed.

The remainder of this report consists of several chapters and appendices. Chapter 2 presents an overview of TOSCo functionality. Chapter 3 discusses two real-world corridors: a high-speed corridor in Conroe, TX, and a low-speed corridor in Ann Arbor, MI. These corridors are used in the simulation analyses. Chapter 4 describes simulation modeling assumptions and performance measures, including mobility and fuel/emissions measures.

Chapter 5 and chapter 6 present results of these analyses for the low- and high-speed corridors. These analyses address single intersections and entire corridors and represent hundreds of extended simulations with populated corridors to explore—among other factors—the influence of market penetration and effects of different working ranges on the wireless communication between intersections and approaching traffic.

Chapter 7 summarizes the findings and identifies areas of future work to understand further benefits of TOSCo, including investigating characteristics of corridors that may benefit the most from TOSCo.

CHAPTER 2. TOSCO APPLICATION

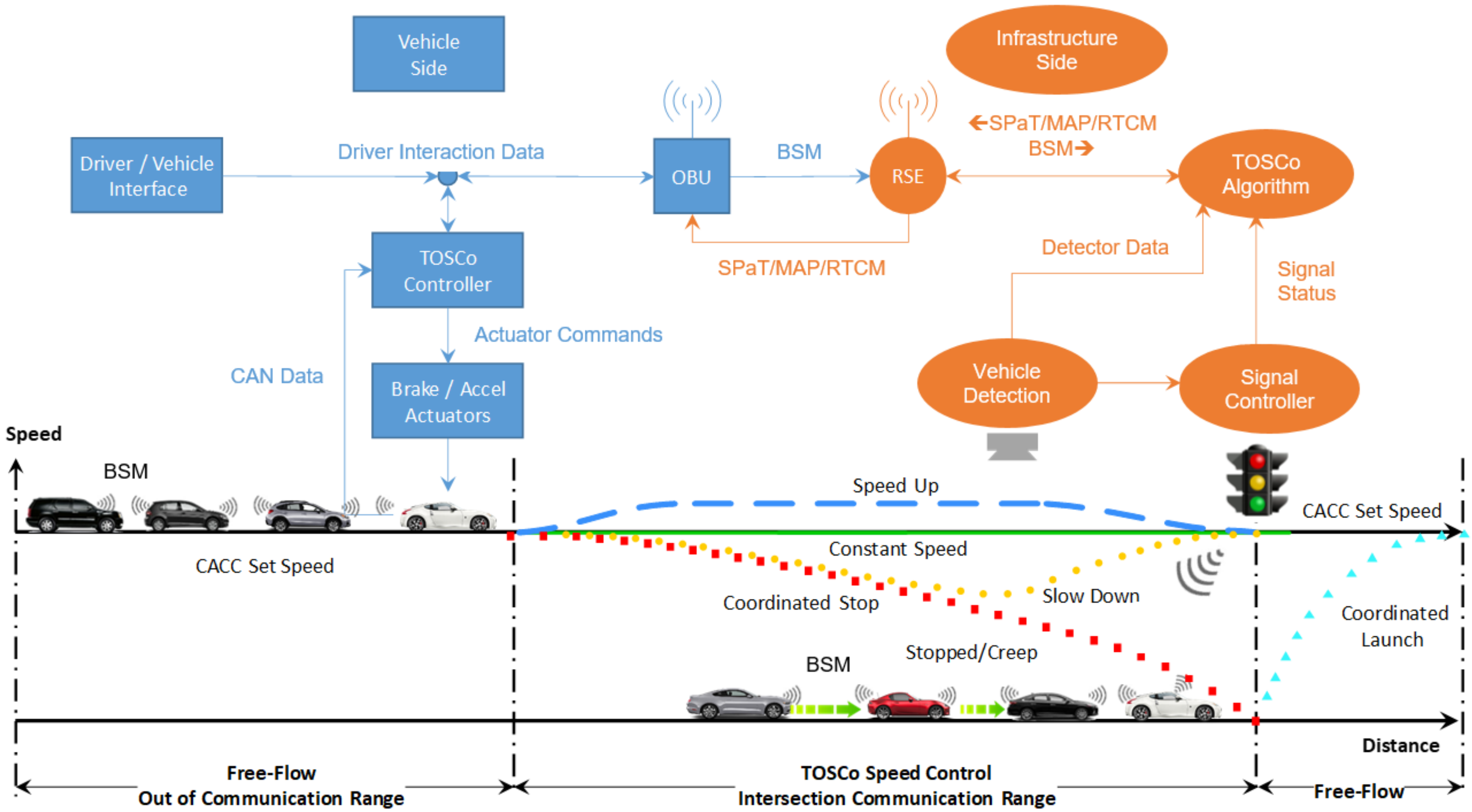
This chapter provides an overview of the TOSCo system, its concept of operations, and the different operating states of the TOSCo-equipped vehicles.

CONCEPT OF OPERATIONS

The TOSCo system is a series of innovative applications designed to optimize traffic flow and minimize vehicle stops on signalized arterial roadways. The TOSCo system applies infrastructure- and vehicle-based CV communications to assess vehicle queues and cooperatively control the behavior of strings of TOSCo-equipped vehicles approaching equipped signalized intersections to minimize the likelihood of stopping. Leveraging previous work on CACC, approaching vehicles equipped with TOSCo functionality use this real-time infrastructure information about queues to plan and control their speeds to enhance the overall mobility and reduce emission outcomes across the corridor.

Figure 1 illustrates the basic concept of the TOSCo system. When activated and outside of the communication range, TOSCo-equipped vehicles would operate in a free-flow mode. TOSCo-equipped intersections are constantly broadcasting information about the intersection geometry, status of the signal phase and timing (SPaT) at the intersection, and presence of any traffic queues at the intersection. As a TOSCo-equipped vehicle enters the DSRC range of the intersection, it receives the intersection geometry, SPaT, and queue information. Using this information, the TOSCo vehicle then plans a speed trajectory that allows it to either pass through the intersection without stopping (either by speeding up slightly, maintaining a constant speed, or slowing down slightly to allow the queued vehicles ahead of it to clear the intersection before it arrives), or stopping in a smooth, coordinated fashion to lessen the amount of time stopped at the intersection. TOSCo vehicles that are stopped at an intersection would perform a coordinated launch maneuver at the start of green that would allow them to clear the intersection in a more efficient manner. Once the TOSCo vehicles leave the communications range of the intersection, they revert to their previous operating mode (i.e., CACC).

Planning the appropriate trajectory requires information from the infrastructure—specifically, information about the SPaT and time estimates of when queued traffic at the stop bar will clear the intersection. The infrastructure would need to be equipped with technology that not only provides signal status information, but also detects the presence of queues and predicts when they will clear the approach. The movement groups for which this information is provided are called TOSCo approaches. TOSCo approaches would typically include through movements on the main street, under coordination, and are not intended to include turning movements, since such a maneuver is outside of the scope for TOSCo operations. A TOSCo approach could include through movements on a cross-street facility. For this simulation study, the TOSCo approaches are always the through movements on the main street facility.



CAN = controller area network; OBU = onboard units; RSE = roadside equipment; RTCM = radio technical commission for maritime services.

Figure 1. Diagram. Concept of the TOSCo system (Feng et al. 2019).

The concept of a string in TOSCo is the same as the prior project's CACC string, except that a TOSCo string is composed of vehicles with TOSCo engaged. Vehicles within a TOSCo string are divided into two categories: leader and follower. The leader is the first vehicle in the string, and all other vehicles are followers. One key feature of the adopted CACC algorithm is its distributed communication and control architecture (i.e., follower-predecessor), which means that the control of a follower only depends on the information (e.g., instantaneous speed and acceleration) from the vehicles ahead of it. Wireless BSMs are received, and CACC filters those messages to identify any string members ahead (but not behind). CACC uses both radar and BSMs to control the gap to the vehicle ahead of it, sometimes using the preview provided by BSMs ahead of the immediate predecessor to anticipate sudden decelerations and react before the immediate predecessor slows. The prior project's CACC algorithm assumes the use of an extension to the BSM that contains data elements that represent the identity of each vehicle's immediate predecessor (allowing other vehicles to construct a linked list of the string's participants), the host vehicle's CACC commanded acceleration and a time constant to help other vehicles anticipate how that command will lead to speed changes.

A TOSCo vehicle will use CACC/adaptive cruise control (ACC) if it is the leader. It will automatically transition into ACC if it begins to follow a vehicle that is not engaged in CACC or TOSCo. It will transition into CACC if it begins to follow a CACC-engaged vehicle. It will transition into TOSCo following mode if it begins to receive the required messages while approaching an intersection. CACC vehicles do not have the same capabilities as TOSCo vehicles, but they can be at the front, middle, or back of a string that is partially CACC and partially TOSCo. Like the prior project's CACC approach, the onboard TOSCo algorithms decide the host vehicle's actions. There is no central coordination within the string, and there are no explicit control recommendations from outside the vehicle that influences its motion.

The onboard TOSCo vehicle estimates its time of arrival (TOA) at the stop bar to plan its trajectory. The TOA module is developed to estimate the TOA at the upcoming stop bar for TOSCo-equipped vehicles within a string. For the lead vehicle in the string, the TOA is estimated based on the maximum of either: the travel time to the stop bar with its predefined speed profile, or the time elapsed to the start of the imminent green window (with consideration of queue-length estimation). For a vehicle following another TOSCO vehicle, the following vehicle estimates its TOA by first assuming it can follow its predecessor closely enough (with a user-defined time gap). Then it is scrutinized if its estimated leaving time from the stop-bar falls in a green phase or not. If yes, then there is no update on the TOA. Otherwise, the TOA is set as the start of next green window. With the same logic, it can be determined if a vehicle in a TOSCo-string can pass the intersection or not. For a follower, if it cannot pass the stop bar within the same green widow as its predecessor, then its role will transition to a leader, and the original TOSCo string will be split accordingly.

TOSCo vehicles use TOA estimates to the intersection stop bar to determine the appropriate operating mode. Figure 2 illustrates the behavior of a TOSCo-engaged vehicle traveling from left to right and encountering two TOSCo intersections. The circles represent the distance at which vehicles can receive road safety messages (RSM), SPaT, and MAP messages from the intersections. The TOSCo vehicle behavior can be represented as one of the following operating states:

- Free-flow.
- Coordinated speed control.
- Coordinated stop.
- Stopped.
- Coordinated launch.
- Optimized follow.
- Creep.

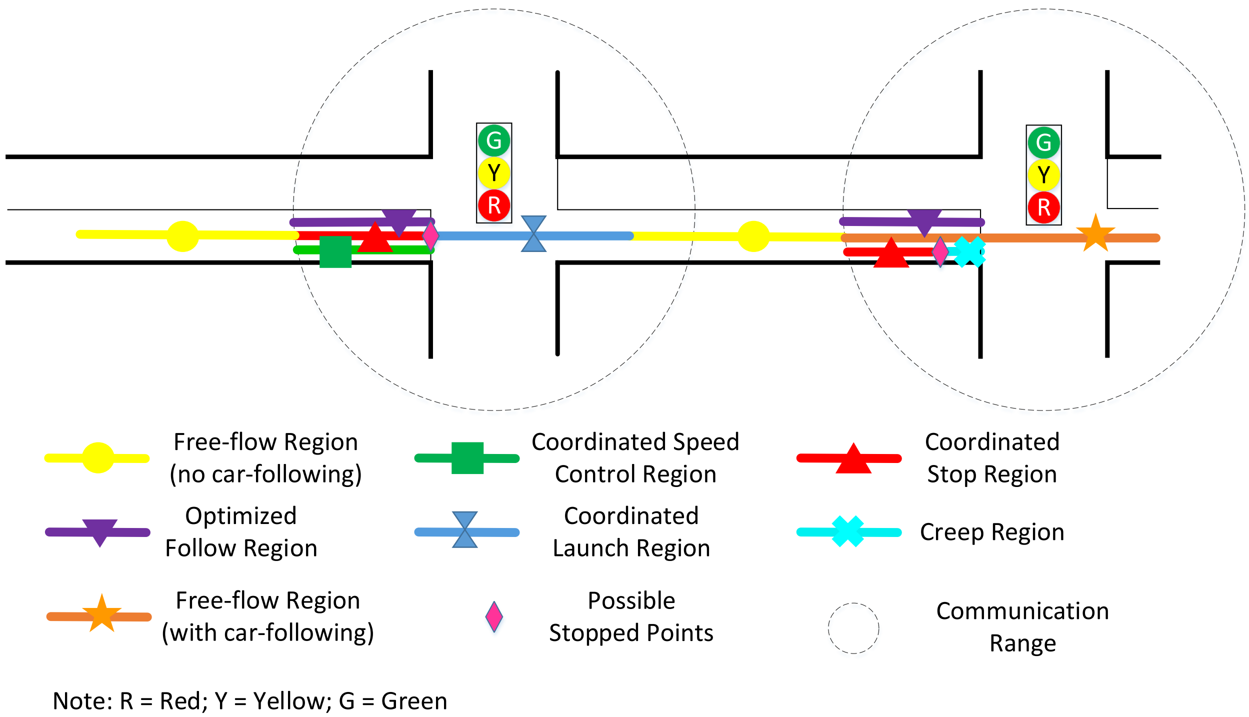


Figure 2. Diagram. Operating states of Traffic Optimization for Signalized Corridors vehicles (Feng et al. 2019).

Figure 2 shows examples of the different operating states for a TOSCo vehicle near an intersection. A brief description of each of these operating modes is provided below. For more details about how the vehicle is expected to behave in these operating modes, the reader should consult the Vehicle-to-Infrastructure Program TOSCo System Requirements and Architecture Specification (Balke et al. 2019). For purposes of the traffic-level simulation, the behavior for TOSCo is modeled to reflect the aspects of TOSCo that are most important to the simulation, so that an exact version of the onboard TOSCo code is not necessarily required.

Free-Flow

The free-flow operating mode (Free-flow Region in figure 2) occurs when a TOSCo vehicle is outside the communication range (indicated by the circle) where no SPaT, MAP, or RSM messages are available to the vehicle. If the TOSCo vehicle is the leader, its behavior is simulated using an ACC model. If the TOSCo vehicle is a follower within a TOSCo string, then its behavior is simulated using a CACC model.

Coordinated Speed Control

The coordinated speed control operating mode (Coordinated Speed Control Region in figure 2) only occurs within the DSRC range where SPaT, MAP, and RSM messages are available. This operating mode only applies to the leader of the TOSCo string when it determines that it will pass through the intersection before the start of the amber phase. In this operating mode, the TOSCo vehicle will apply TOSCo trajectory planning to generate a CACC set speed profile that allows the vehicle to pass through the intersection as early as possible after the start of the green window by adjusting the CACC set speed to achieve optimization objectives. One of the three possible speed profiles may be employed, depending on the available green window: slow down, speed up, or maintain a constant speed. Vehicles under TOSCo-coordinated speed control are limited to a maximum speed of the posted speed limit.

Coordinated Stop

The coordinated stop operating mode (Coordinated Stop Region in figure 2) only occurs within the DSRC range where SPaT, MAP, and RSM messages are available. This operating mode only applies to the leader of the TOSCo string when it determines that it cannot pass through the intersection prior to the amber phase. In this operating mode, the TOSCo vehicle will apply TOSCo trajectory planning to generate a speed profile that allows the vehicle to come to a stop at the stop bar or the end of the queue while meeting optimization objectives.

Stopped

The stopped operating mode only occurs within the DSRC range where SPaT, MAP, and RSM messages are available. This operating mode can apply to both a leader and a follower within the TOSCo string when the vehicle's speed is slower than a small threshold of 0.033 ft per s (ft/s). When a TOSCo vehicle stops outside the DSRC range, TOSCo remains in a free-flow state.

Coordinated Launch

The coordinated launch operating mode (Coordinated Launch Region in figure 2) only occurs within the DSRC range where SPaT, MAP, and RSM messages are available. This operating mode only applies to the leader of the TOSCo string. This operating mode is usually triggered when the traffic signal turns to green and the vehicle queue starts to discharge.

Optimized Follow

The optimized follow operating mode (Optimized Follow Region in figure 2) only occurs within the DSRC range where SPaT, MAP, and RSM messages are available. This operating mode only applies to the follower of the TOSCo string. Under this operating mode, the TOSCo vehicle operates predominantly as a member of a string under CACC speed and gap control. The vehicle also employs information from SPaT, MAP, and RSM messages to determine if it will be able to clear an approaching intersection before the next phase change. If the vehicle determines that it will not clear the intersection, it will become the leader of a new string and transition to other operating modes (e.g., coordinated stop).

Creep

The creep operating mode (Creep Region in figure 2) represents the behavior of the vehicle after it is in a queue. In creep mode, the vehicle is moving slowly toward the stop line or the end of the queue at speeds generally less than 5 mph. The vehicle would enter this mode to move up in the queue as vehicles vacate the queue up ahead of the TOSCo vehicle. This type of behavior might occur as vehicles in the queue turn right on red, causing the need for vehicles to move up in the queue.

The creep TOSCo operating mode is not directly coded into the traffic-level simulation because the simplified models for CACC and ACC behavior sufficiently represent the behavior expected out of the creep operating mode.

INFRASTRUCTURE REQUIREMENTS

TOSCo is envisioned to function both at the individual intersection level and at the corridor level where multiple intersections would be equipped to accommodate TOSCo vehicles. TOSCo corridors would be expected to support all types of vehicles, whether equipped with CV technology or not. TOSCo-equipped vehicles are required to have CACC capability and beyond that to be TOSCo equipped. TOSCo operation does require an enhanced version of the CACC to perform coordinated launch and creep functions. There are additional controller requirements for these modes. The driver must engage TOSCo for their vehicle to be able to perform the TOSCo functions. The following are critical components the infrastructure needs to provide for the TOSCo system to operate properly.

SPaT and Geometric Intersection Description Data

The infrastructure is needed to provide SPaT and intersection geometry (MAP message) to the TOSCo vehicle. SPaT can be obtained from the traffic signal controller and provides information about the current operating status of the traffic signal and the time until the next change in the signal indication state.

The MAP message provides the vehicle with an understanding of the intersection geometry and allows the vehicle to compute its position relative to the stop bar of the approach. The MAP message also allows the vehicle to determine the lane in which it is located and what queue and signal timing information pertains to it.

Both SPaT and MAP messages are standard SAE J2735-2016 (SAE International 2016). The SPaT message is broadcast at 10 Hz, and while the geometric intersection description information is broadcast at 1 Hz.

Green Window Data

One critical function of the infrastructure in the TOSCo system is to estimate the green window. The green window is currently only defined for coordinated actuated operations. How the green window could be defined for actuated and, perhaps, adaptive signals is being investigated. The challenge for actuated or adaptive signals is that the cycle length is not defined. Without an expected cycle length and a guaranteed amount of green time, it is not possible to provide a satisfactory prediction of the green window.

The end of the green window is more predictable for both the coordinated actuated signal and adaptive signal, since the end of the green time is (mostly) determined by either a coordination mechanism or signal optimization. However, the start of the green window not only depends on the start of green (time point when the queue begins to be discharged), but also the queue length and queue discharge time. Under any type of signal strategy, due to variations of the traffic demand, the start of the green window needs to be estimated cycle by cycle. As shown in figure 3, the green window is the time during the green interval (i.e., the G section in figure 3) when the last vehicle in the queue clears the stop bar of the intersection and the end of the green interval. The green window is the time in the green interval in which a TOSCo vehicle can traverse through the intersection without stopping. The TOSCo algorithms use the green window to target the vehicle's arrival to minimize the likelihood of having to stop.

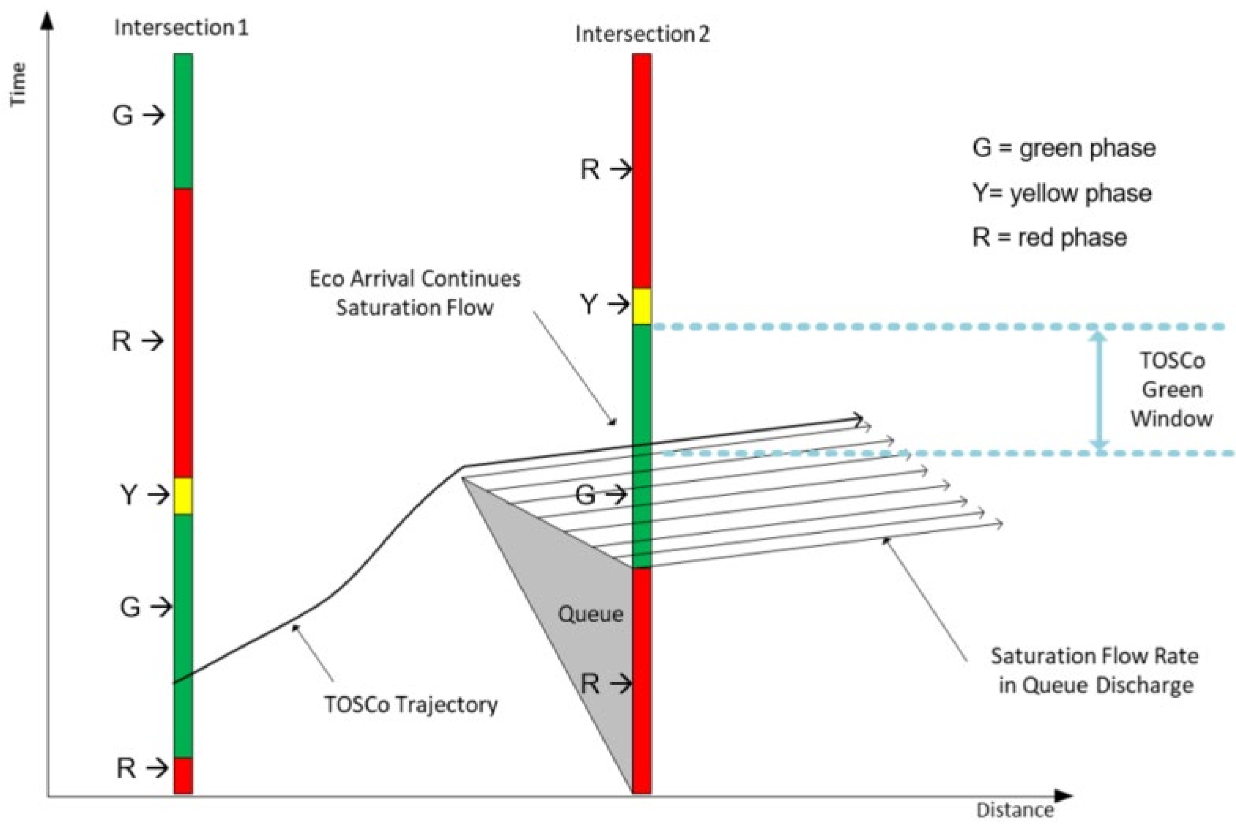


Figure 3. Diagram. Definition of the green window (Feng et al. 2019).

Road Safety Messages

Information about queues and the green window is envisioned to be broadcast to the vehicle through RSM (Sharma et al. 2007). The RSM follows a container-based logic. The message structure allows different “containers” of data to be developed for different applications. The TOSCo container would contain the following data elements:

- The current location of the back of the queue (in meters) for each lane relative to the stop bar of the intersection.
- An estimate of the predicted maximum location of the back of the queue for each lane.
- An estimate of the time when the predicted maximum back of queue would clear the stop bar of the intersection.
- The beginning and end time of the green window defining when the queue is expected to clear the stop bar of the intersection.

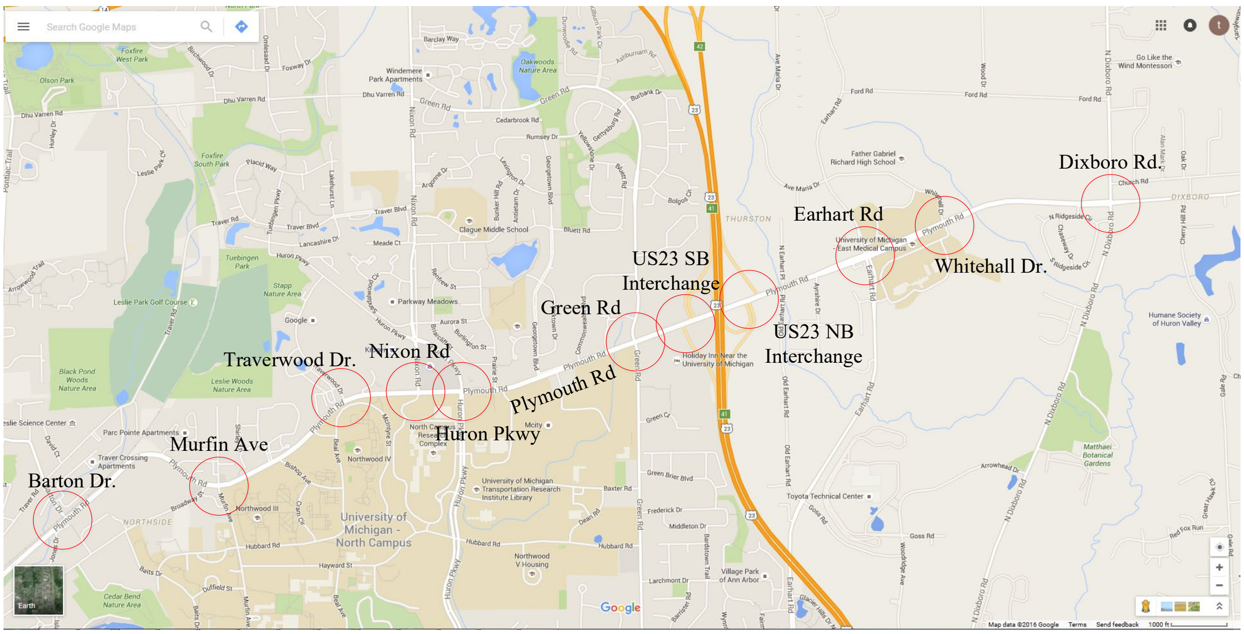
This information is used by the TOSCo vehicle to plan the vehicle speed trajectories. The infrastructure is required to broadcast this information via the roadside unit (RSU) every s. Information about the queue can be derived from infrastructure-based detection sensors. The infrastructure could also fuse information from detected TOSCo and other BSM-broadcasting vehicles to refine the queue and green window estimates.

CHAPTER 3. CASE STUDY LOCATION DESCRIPTION

Two corridors were selected to evaluate the potential benefits of the TOSCo system: a low-speed corridor located in Ann Arbor, and a high-speed corridor located in Conroe.

ANN ARBOR

The low-speed corridor (i.e., Plymouth corridor) is located in the city of Ann Arbor. The corridor consists of 11 intersections, from Barton Drive on the west to Dixboro Road on the east. It is a suburban corridor and includes nine arterial intersections and two freeway interchanges. Figure 4 shows the signalized intersections in the corridor.



Original map: © 2016 Google®. Annotated by FHWA (see Acknowledgments section).

Figure 4. Map. Signalized intersections in the Plymouth corridor (Feng et al. 2019).

The total length of the corridor is approximately 3.9 mi. The speed limit in the corridor varies from 35 mph on the west end to 50 mph on the east end. The corridor has two lanes in each direction, and most of the intersections have a dedicated left-turn lane and a shared through-right-turn lane.

Table 1 and table 2 list the characteristics of each segment and each intersection, respectively. All intersections are modeled under either fixed-time signals or actuated signals. There are four midblock pedestrian crossing warning devices installed between Murfin Avenue and Green Road.

Table 1. Characteristics of road segments on the Plymouth corridor.

Intersection One	Intersection Two	Distance (ft)	Speed Limit (mph)	No. Lanes in Each Direction*	No. of Driveways
Barton Drive	Murfin Avenue	3,320	35	2	7
Murfin Avenue	Traverwood Drive	2,792	35	2	6
Traverwood Drive	Nixon Road	1,327	35	2	3
Nixon Road	Huron Parkway	777	35	2	3
Huron Parkway	Green Road	3,257	45	2	8
Green Road	US–23 SB Interchange	1,220	45	2	3
US–23 SB Interchange	US–23 NB Interchange	1,026	45	2	0
US–23 NB Interchange	Earhart Road	2,317	45	2	5
Earhart Road	Whitehall Drive	1,492	50	2	0
Whitehall Drive	Dixboro Road	3,072	50	2	1

*The total number of lanes in each direction.
NB = northbound; SB = southbound.

Table 2. Characteristics of intersections on the Plymouth corridor.

Intersection Name	Intersection Configuration	Exclusive Left-Turn Lane	Exclusive Right-Turn Lane	Traffic Signal
Barton Drive	Three-leg intersection	EB[1] only	WB[2] only	Adaptive
Murfin Avenue	Four-leg intersection	EB and WB	None	Adaptive
Traverwood Drive	Three-leg intersection	EB only	None	Adaptive
Nixon Road	Four-leg intersection	EB and WB	None	Adaptive
Huron Parkway	Four-leg intersection	EB and WB	None	Adaptive
Green Road	Four-leg intersection	EB and WB	WB only	Adaptive
US–23 SB Interchange	Four-leg intersection	WB only	EB and WB	Actuated
US–23 NB Interchange	Four-leg intersection	None	EB and WB	Actuated
Earhart Road	Four-leg intersection	EB and WB	None	Actuated
Whitehall Drive	Four-leg intersection	EB and WB	EB and WB	Actuated
Dixboro Road	Four-leg intersection	EB and WB	EB only	Actuated

[1]EB direction of travel.
[2]WB direction of travel.
EB = eastbound; WB = westbound.

Table 3 shows the volume and volume divided by capacity (v/c) ratio analysis of each intersection, for both directions, collected from field observations. The v/c ratios are calculated based on a saturation flow rate of 1,800 vehicles per hour per lane. A value of 2 s per vehicle (s/vehicle) was employed as the saturation flow headway because it is a commonly adopted value in research and practice. On average, the eastbound (EB) direction has higher v/c ratios than the westbound (WB) direction.

Table 3. Plymouth corridor volume and volume divided by capacity ratio analysis.

Intersection	EB Volume (vph)	EB v/c Ratio	WB Volume (vph)	WB v/c Ratio
Barton Drive	726	0.26	818	0.30
Murfin Avenue	830	0.44	1,145	0.57
Traverwood Drive	934	0.33	1,123	0.40
Nixon Road	734	0.36	906	0.60
Huron Parkway	789	0.59	751	0.43
Green Road	1,200	0.86	966	0.67
US–23 West	1,739	0.64	985	0.36
US–23 East	824	0.29	973	0.34
Earhart Road	956	0.77	429	0.47
Whitehall Drive	1,198	0.43	366	0.13
Dixboro Road	603	0.81	287	0.51
Overall	—	0.53	—	0.44

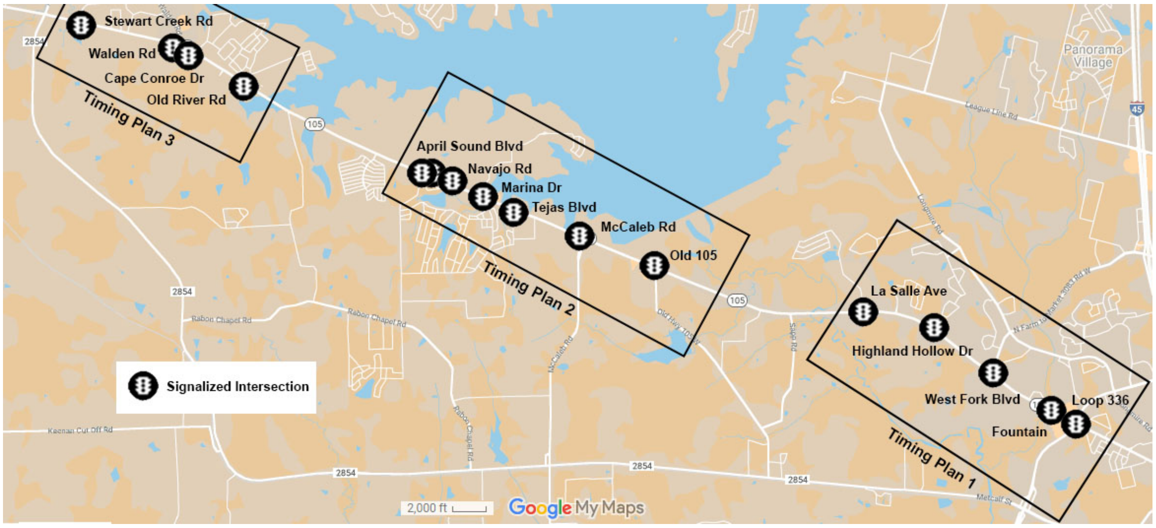
—No data (base case).
vph = vehicles per hour.

Close observation of the current situation of traffic conditions along the Plymouth corridor reveals multiple key transportation problems that local agencies could potentially mitigate or solve through TOSCo. Although the v/c ratios of the EB and WB intersections do not indicate high congestion or oversaturation (except a few EB intersections), travelers may still experience a certain delay (i.e., stop delay) due to varying traffic and geometric patterns along the corridor and different signal control types at various intersections. TOSCo could potentially decrease the number of stops and therefore reduce delay and fuel consumption.

CONROE

The high-speed corridor along SH 105 is located in Conroe and consists of 15 intersections between Montgomery and the city of Conroe. The corridor covers about 12 mi. Figure 5 shows the location of the signalized intersections considered along SH 105. The posted speed limits range from 45 mph on the east end to 55 mph on the west end. Most of the corridor has a posted speed of 55 mph. It takes about 15 min to drive from one end of the corridor to the other.

Table 4 shows the volume and v/c ratio analysis of each intersection for both directions.



Original map © 2016 Google®. Annotated by TTL (see Acknowledgments section).

Figure 5. Map. Signalized intersections in the SH 105 corridor (Feng et al. 2019).

Table 4. SH 105 corridor volume and v/c ratio analysis.

Intersection	EB Volume (vph)	EB v/c Ratio	WB Volume (vph)	WB v/c Ratio
Stewart Creek Road	905	0.39	937	0.40
Walden Road	647	0.46	524	0.38
Cape Conroe Drive	1,343	0.94	822	0.50
Old River Road	1,297	0.61	907	0.43
April Sound Boulevard West	1,551	0.61	758	0.30
April Sound Boulevard East	1,871	0.73	762	0.30
Navajo Drive	1,763	0.43	1,345	0.28
Marina Drive	1,858	0.40	1,280	0.34
Tejas Boulevard	1,852	0.52	1,296	0.38
McCaleb Road	1,820	0.53	1,267	0.37
Old 105 Highway	1,970	0.58	1,401	0.41
La Salle Avenue	1,826	0.56	978	0.25
Highland Hollow Drive	2,166	0.61	1,010	0.28
West Fork Boulevard	1,766	0.50	1,407	0.39
Fountain Lane	1,913	0.54	892	0.25
Loop 336	748	0.26	388	0.23
Average	—	0.54	—	0.34

—Not applicable.
v/c = volume divided by capacity.

The signals along SH 105 operate on three different coordination timing plans: from Stewart Creek Road to Old River Road, from Marina Drive to Old 105 Highway, and from La Salle Avenue to Loop 336. These three-timing plans have cycle lengths of 90, 105, and 120 s, respectively. None of the intersections on SH 105 are DSRC equipped. Table 5 and table 6 list the characteristics of each segment and each intersection in the SH 105 corridor, respectively.

Table 5. Characteristics of road segments on the SH 105 corridor.

Intersection One	Intersection Two	Distance (ft)	Speed Limit (mph)	No. of Lanes (EB/WB)	No. of Driveways
Stewart Creek Road	Walden Road	5,578	55	2/2	34
Walden Road	Cape Conroe Drive	671	55	2/2	3
Cape Conroe Drive	Old River Road	3,230	55	2/3	28
Old River Road	April Sound Boulevard West	11,194	55	3/3	26
April Sound Boulevard West	April Sound Boulevard East	370	55	3/3	0
April Sound Boulevard East	Navajo Drive	1,139	55	3/3	0
Navajo Drive	Marina Drive	1,976	55	3/3	4
Marina Drive	Tejas Boulevard	1,901	55	3/3	10
Tejas Boulevard	McCaleb Road	4,013	55	3/3	31
McCaleb Road	Old 105 Highway	4,477	55	3/3	28
Old 105 Highway	La Salle Avenue	11,827	55	3/3	58
La Salle Avenue	Highland Hollow Drive	16,315	55	3/3	29
Highland Hollow Drive	West Fork Boulevard	4,066	55	3/3	18
West Fork Boulevard	Fountain Lane	4,200	50	3/3	16
Fountain Lane	Loop 336	1,200	50	3/3	5

Table 6. Characteristics of intersections on the SH 105 corridor.

Intersection Name	Exclusive Left-Turn Lane	Exclusive Right-Turn Lane	Traffic Signal Control
Stewart Creek Road	EB and WB	WB only	Coordinated actuated
Walden Road	EB and WB	WB only	Coordinated actuated
Cape Conroe Drive	EB and WB	None	Coordinated actuated
Old River Road	EB and WB	None	Coordinated actuated
April Sound Boulevard West	WB only	None	Coordinated actuated
April Sound Boulevard East	EB only	WB only	Coordinated actuated
Navajo Drive	WB only	None	Coordinated actuated
Marina Drive	EB and WB	None	Coordinated actuated
Tejas Boulevard	EB and WB	None	Coordinated actuated
McCaleb Road	EB and WB	None	Coordinated actuated
Old 105 Highway	EB and WB	None	Coordinated actuated
La Salle Avenue	EB and WB	None	Actuated
Highland Hollow Drive	EB and WB	WB only	Actuated
West Fork Boulevard	EB and WB	None	Actuated
Fountain Lane	EB and WB	None	Coordinated actuated
Loop 336	EB and WB	EB and WB	Coordinated actuated

Close observation of the current situation of traffic conditions along the SH 105 corridor reveals multiple key transportation problems the local agencies could potentially mitigate or solve using TOSCo. Compared with the low-speed Ann Arbor corridor, the v/c ratios of the EB Conroe intersections indicate a higher level of congestion, with the v/c ratios of a few intersections near saturation. Travelers experience a delay when traversing the Conroe corridor, particularly stop delay, due to high traffic volume, varying traffic and geometric patterns along the corridor, and different signal control types at various intersections. TOSCo could potentially decrease the number of stops and therefore reduce delay and fuel consumption.

CHAPTER 4. MODELING METHODOLOGY

This chapter introduces the modeling and simulation methodology to evaluate TOSCo under different scenarios. Both case studies adopt the modeling framework with a limited number of differences in handling certain modeling details, such as queue estimation.

MODELING FRAMEWORK FOR TOSCO MODEL DEVELOPMENT AND CALIBRATION

Three simulation environments (i.e., vehicle simulation, infrastructure simulation, and TOSCo performance assessment) exist for evaluating the TOSCo system. Figure 6 shows the relationship among the three environments. This figure shows how the vehicle and infrastructure simulations work with each other in development and feed into the performance evaluation.

The research team selected PTV Vissim® software as the microscopic simulation tool for each environment because of the flexibility it provides to define vehicle behaviors—in this case, to introduce TOSCo behaviors to some or all simulated vehicles (PTV Group 2018). Vissim's application programming interface (API) for defining vehicle behavior allows utilization of C++ to control vehicles, encoded as a dynamic link library, which can communicate with other software on the machine, such as software running the infrastructure simulation. This API is called the DriverModel.dll, and it is what the research team used to represent TOSCo vehicle behavior.

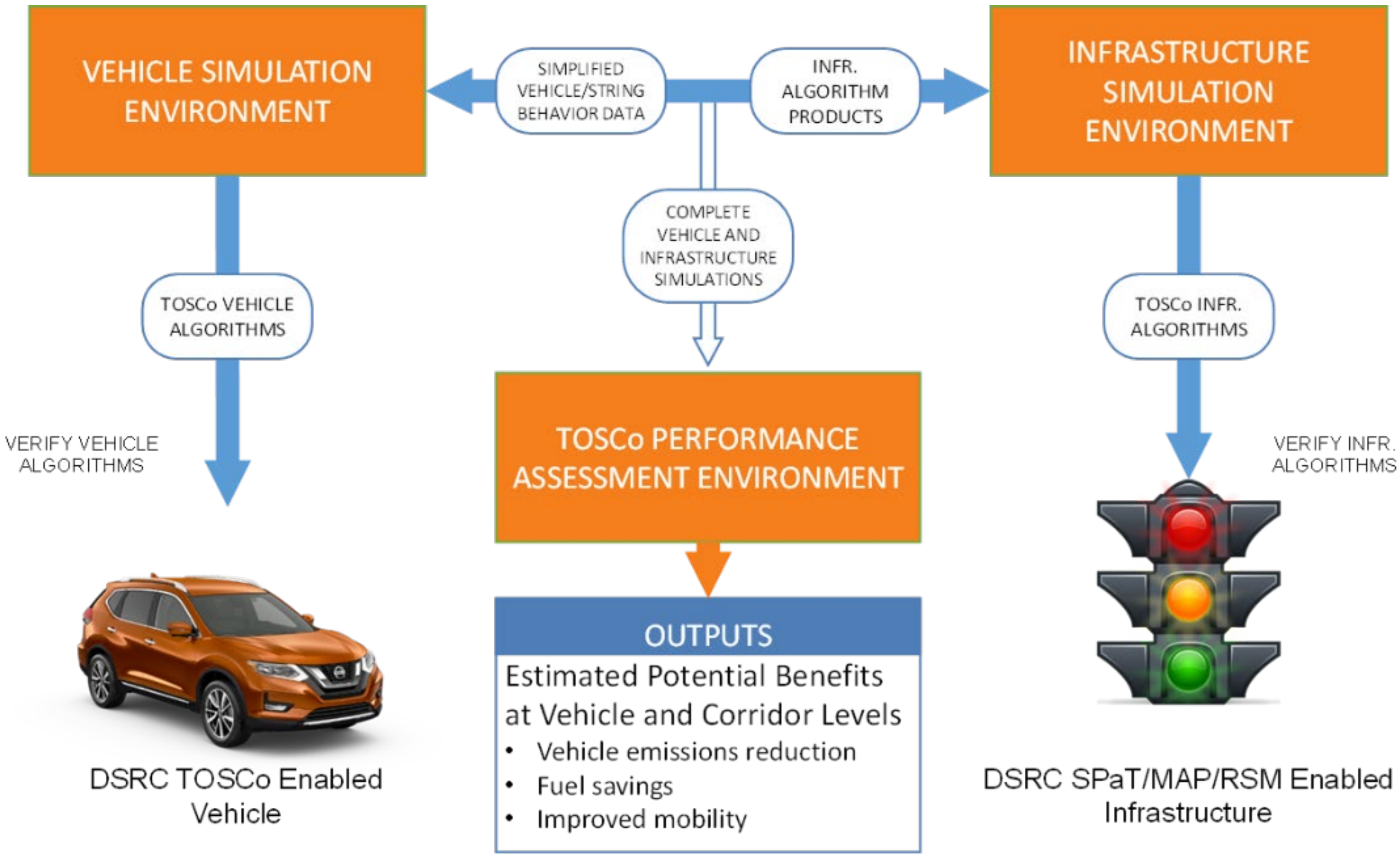
TOSCo Vehicle Simulation Environment

The purpose of the TOSCo vehicle simulation platform is to test and verify the software system embedded in the vehicles. The vehicle simulation environment works with the infrastructure to verify system functionality and assess adjustments to the vehicle control systems. The vehicle simulation environment is developed to simulate, in detail, many of the low-level components that could impact a TOSCo vehicle (e.g., speed control algorithm, radar sensors algorithms, GPS error, and so on. The vehicle simulation environment acts as a platform for testing and verifying the algorithms that will eventually be used in TOSCo-enabled vehicles and for evaluating specific vehicle behaviors at a low level. More information on the vehicle simulation environment can be found in Meier et al. (2017).

TOSCo Infrastructure Simulation Environment

The purpose of the TOSCo infrastructure simulation environment is to develop and verify the infrastructure components as part of a TOSCo test deployment. Alongside the vehicle-level simulation, the TOSCo infrastructure simulation environment is developed to model and evaluate infrastructure algorithm components needed for TOSCo deployments, particularly those associated with RSM data elements. The infrastructure simulation environment is also developed to assess how accuracy and latency associated with the infrastructure-based algorithms might impact the performance of TOSCo-equipped vehicles. In this environment, varying levels of accuracy for measuring the current queue, predicted maximum queue, and the green window can be tested, which allows implementors to more easily determine the capability of each to support TOSCo on a given corridor.

The infrastructure simulation environment models TOSCo vehicles at a higher level, replicating the typical vehicle/string behavior and providing a simplified version of TOSCo to simulate hundreds of TOSCo vehicles.



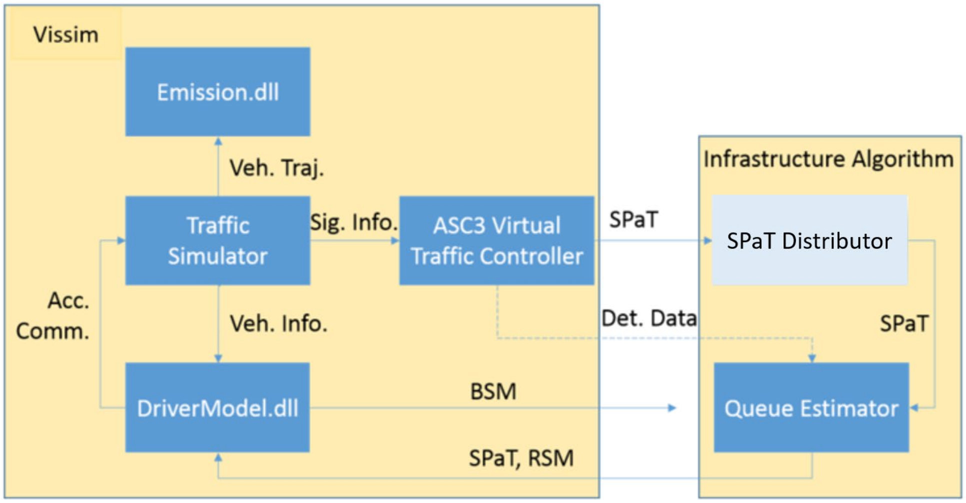
DSRC = dedicated short-range communication; INFR = infrastructure.

Figure 6. Diagram. Simulation evaluation environment of the TOSCo system (Feng et al. 2019).

TOSCo Performance Assessment Environment

The TOSCo performance assessment environment uses both simplified vehicle and infrastructure simulations to evaluate the performance of TOSCo by estimating potential benefits at a single intersection, corridor, and network resolution. These benefits include reduced emissions, saved fuel, and improved mobility. These performance measures are collected for different market penetration rates of TOSCo- and DSRC-enabled vehicles.

Figure 7 shows the architecture of the TOSCo Performance Assessment Environment. The prior project's research team developed the TOSCo Performance Assessment Environment to evaluate the potential mobility and environmental benefits associated with TOSCo. The large block on the left contains all Vissim components. The Traffic Simulator Component is responsible for moving vehicles on the road network, updating traffic signal status, and collecting performance measurements at the individual vehicle level, intersection level, corridor level, as well as the network level. The Traffic Simulator Component transmits vehicle information to the DriverModel.dll, where the vehicle information is packed to BSMs and sent to the Infrastructure Algorithm Component, shown in the smaller block on the right in figure 7. Meanwhile, a virtual traffic controller in Vissim transmits SPaT and detector data to the Infrastructure Algorithm Component. In this project, the advanced system controller (ASC)/3 (Econolite 2014) was selected as a representative controller in part because software exists to simulate this controller within Vissim. Utilizing BSM, SPaT, and detector data, the Infrastructure Algorithm Component predicts queue length and estimates the green window. This information is packed into the RSM. In actual practice, the RSM would be broadcast to nearby vehicles. The simulation sends the RSM packet to the DriverModel.dll component along with the SPaT message. Based on signal timing and RSM, the DriverModel.dll component includes separate instances for individual vehicles approaching the intersection. These instances represent computations that are performed onboard for each vehicle. These computations plan each TOSCo vehicle's intended speed trajectory and represent the calculation of onboard vehicle acceleration commands. All vehicle trajectories during the simulation run are sent to the Emission.dll component for emission and fuel consumption estimation using the motor vehicle emission simulator (MOVES) (2014) model.



Veh = vehicle; Traj = trajectory; Sig = signal; Acc. = access; Comm = communication; Info = information; Det = detector; ASC = advanced system controller; dll = dynamic linked library.

Figure 7. Diagram. Overall performance assessment architecture (Feng et al. 2019).

BASELINE NETWORK SIMULATION CALIBRATION AND VERIFICATION (WITHOUT TOSCO)

This section details the efforts of model calibration to ensure the simulation network reflects real-world field conditions in traffic demand, driving behavior, and communication performance.

Ann Arbor

A Vissim simulation model was built for the 11-intersection corridor at Plymouth Road in Ann Arbor. Plymouth Road consists of two lanes in each direction, and it is one of the busiest commuting routes serving US–23 to the north campus of the University of Michigan and downtown Ann Arbor. Some crossing roadways are major arterials that carry a large volume of traffic (e.g., Green Road and Huron Parkway), and others are side streets with less traffic demand (e.g., Whitehall Drive). The road geometries are calibrated with satellite maps from Google® Earth™ (Google Earth 2018).

The following road geometry and traffic attributes are modeled explicitly in Vissim:

- Vehicle inputs.
- Lane assignments and connections.
- Traffic signals and loop detectors.
- Stop signs and reduced-speed areas for turning.
- Conflict areas.
- Route choice decision.
- Zones to collect travel time/delay measurements.
- Data collection points.

The research team calibrated the Vissim model for the low-speed corridor using data from two sources: video data collected in the corridor and in the SPMD project (Bezzina and Sayer 2014). The video data were collected from each intersection simultaneously at afternoon (PM) peak hours (4–5 p.m.) on May 16, 2017. The video data were used to obtain vehicle counts for each movement, turning ratios at each approach, and SPaT information. The SPMD data were used to calibrate the acceleration profiles.

The vehicle volumes and turning ratios collected at each intersection were used as inputs to the Vissim model. To quantitatively evaluate the accuracy of the calibration, a value developed by Geoffrey E. Havers (GEH) for comparing the differences between modeled and observed volumes was used to calculate each movement (Smith et al. 2014).

A general rule to determine if a simulation network is well calibrated is if GEH values for more than 85 percent of the traffic volume at selected movements are less than five (Chu et al. 2003). A total of 112 movements along the corridor are identified. Out of 112 movements, 108 (96.4 percent) have a GEH value of less than five, which indicates a well-calibrated network.

To better reflect real-world driving behaviors and operational environment in the low-speed corridor, the vehicle acceleration profiles and DSRC range were calibrated using naturalistic driving data (The University of Michigan Transportation Research Institute 2012). The NDD were analyzed from the SPMD project (Bezzina and Sayer 2014) to calibrate the parameters. The SPMD database (National Operations Center of Excellence 2021) is one of the largest databases in the world that records naturalistic driving behaviors across 34.9 million mi from 2,842 equipped vehicles in Ann Arbor.

To construct the acceleration distribution, 2,593 acceleration events on Plymouth Road were selected from the database. Only accelerations of the front vehicle of the queue were selected because accelerations of the following vehicles might have been limited by their leading vehicle, such that the desired acceleration could not be reflected. Results showed a general pattern that the acceleration rate decreases with the increase in vehicle speed. The calibrated acceleration distribution was applied to non-TOSCo vehicles in the simulation.

The DSRC communication range was also calibrated from the same database. To determine the communication range, the NDD database was queried to determine when the RSUs at each intersection received BSMs from SPMD vehicles (National Operations Center of Excellence 2021). However, the SPMD project (Bezzina and Sayer 2014) only equipped six intersections, from Baron Drive to Green Road. The other five intersections on the east side of the corridor were not equipped. Based on similar road geometry profiles, the average DSRC communication range of the six equipped intersections was used to represent the range of the five unequipped intersections (i.e., 1640.42 ft). Furthermore, some intersections on Plymouth Road are close-spacing intersections where the link length between the intersections is shorter than the DSRC range. In this case, the communication range in the simulation was limited to be the shorter one between the link length and the range from NDD. Table 7 shows the calibrated DSRC range of each intersection on Plymouth Road. About 65 percent of the roadway is covered by the DSRC range in which TOSCo functions are active.

Table 7. Calibrated DSRC ranges of Plymouth corridor.

Intersection	DSRC Range EB (Ft)	DSRC Range WB (Ft)
Barton	2,123.00	1,824.44
Murfin	1,038.25	1,638.45
Traverwood	1,136.00	1,110.30
Nixon	1,110.30	656.17
Huron	656.17	1,256.27
Green	1,894.85	791.01
US–23 West	791.01	682.42
US–23 East	682.42	1,640.42
Earhart	1,049.87	1,194.23
Whitehall	1,194.23	1,640.42
Dixboro	1,640.42	1,640.42

Conroe

Tube counters were placed in five locations along the SH 105 corridor for 1 wk to collect volume data to aid in determining the proper analysis period and volumes for the simulation. Data from the tube counts were used to calibrate the volume inputs into the model. The star icons in figure 8 represent the locations of the tube counts.

FM = farm-to-market.

Figure 8. Map. Tube count locations on SH 105 (Feng et al. 2019).

The simulated volumes and the field volumes were compared in both the EB and WB directions of the simulation-counted locations shown in figure 8. Generally, the simulation counted more vehicles west of Walden Road than observed in the field. The east end of the corridor needed higher volumes than were generated with the initial volume inputs entered into the network. The overall EB volumes were increased to adjust the volumes recorded in the simulation, which led to some overestimation of EB traffic at the SH 105 and Walden Road intersection. The Lake Conroe Village Boulevard count location had less EB vehicles and more WB vehicles than the field data showed. These differences were deemed acceptable. The EB direction of traffic near Tejas Boulevard did not achieve the same peak flow as the field data recorded but had a good fit for WB volumes. The Blake Road location showed a very close fitting of the simulation to the field data. Like the Tejas Boulevard count location, the La Salle Avenue location did not achieve the same peak flow in the EB direction but had a good fit for the WB volumes. The farm-to-market (FM)–083 count location had slightly less EB vehicles and a good fit for WB vehicles.

A travel time study was conducted to characterize mobility during peak periods. This travel time study used one vehicle and a floating car method, where the study vehicle attempts to pass as many vehicles as the passing vehicle. Six runs were completed in both the EB and WB directions in the morning (AM) and PM peak periods. The travel time study produced data for trip durations and number of stops in each direction. The speed profile of the baseline traffic was the key parameter changed to match the simulation and field data. Table 8 and table 9 show the mobility calibration results.

Table 8. Comparison of simulated versus observed travel times for calibration of SH 105 corridor.

Direction of Travel	Simulation (s/Vehicle)	Field Data (s/Vehicle)	Difference (s/Vehicle)
EB	883.7	803	80.7
WB	875.3	842.9	32.4

s/vehicle = s per vehicle.

Table 9. Comparison of simulated versus observed number of stops for calibration of SH 105 corridor.

Direction of Travel	Simulation (No. of Stops)	Field Data (No. of Stops)	Difference (No. of Stops)
EB	2.5	1.8	0.68
WB	2.6	2.5	0.06

Table 8 shows travel times in the simulation are higher than those in the field data in both directions, but within an approximate 10-percent difference. Table 9 shows that the stops in each direction were each within the target difference of one stop from the field data.

MODELING TOSCO FUNCTIONALITY

Modeling Infrastructure Components

Infrastructure algorithms estimate the queuing profile and calculate a green window for TOSCo strings at lane level (i.e., for each lane approaching the intersection). The estimated parameters (e.g., current queue length, predicted maximum position of the back of the queue, beginning time of the green window, and end time of the green window) are populated in RSMs and transmitted to approaching vehicles for their use in trajectory planning. The following two sections describe how the infrastructure algorithms generate data required for TOSCo.

The infrastructure algorithms implemented in the low-speed corridor simulation tool and the high-speed corridor simulation tool were designed differently according to different queue and approaching vehicle data sources. The following two subsections describe the algorithms.

Generating SPaT and MAP Messages

ASC/3 (Econolite 2014) software-in-the-loop traffic signal controllers were used to operate each intersection and produce SPaT information in both low-speed and high-speed corridors. The ASC/3 controllers operate the signal heads at each intersection in the Vissim network via an API for the ASC/3 controller built into Vissim. The default version of the ASC/3 controller that comes with the Vissim software is not capable of producing SPaT packets, so the software must be replaced with an ASC/3 executable that can produce SPaT packets for the TOSCo simulation to function. The ASC/3 controllers operate in coordinated-actuated mode using detector statuses sent to the software from Vissim. The team configured controllers to send SPaT packets to the infrastructure algorithm, which uses the information in the green window calculation for the TOSCo vehicles.

The controller databases send SPaT information to the local IP address at a unique user diagram protocol (UDP) address. The research teams used the "enable SPaT" batch file, provided by the ASC/3 controller vendor, to activate the transmission of SPaT data to the UDP address. The infrastructure algorithm opens and binds sockets to the UDP addresses corresponding to each of the controllers. At each time step, the infrastructure algorithm listens over each intersection's socket to capture the SPaT information, which feeds into the RSM data element calculation. Data elements for the RSM are sent to the DriverModel.dll.

The simulation architecture does not include the MAP message because vehicles use the Vissim internal mapping mechanism. In the field implementation, the purpose of the MAP message is to allow the vehicle algorithms to locate the vehicle in the corridor and calculate corresponding information (e.g., approaching lane and signal phase). However, each vehicle in Vissim obtains this information directly through data elements in the DriverModel.dll component. Therefore, the simulation does not include the MAP message in order to simplify the simulation architecture and increase computation speed.

Green Window Detection

Three approaches were used to perform queue-length detection. The first two approaches, used in the Ann Arbor simulation, are based on BSMs and/or loop detector data. The first approach is to estimate the queuing dynamics using a shockwave profile model (Wu et al. 2011). This methodology assumes all vehicles can provide BSM-type data. The first methodology populates the start of the green window using the time that the estimated maximum back of queue will clear the stop bar. The second approach is an input-and-output model (Sharma et al. 2007), which considers both CVs and non-CVs. For this approach, detection zones are used in the simulation to count the number of vehicles entering and exiting each approach to the intersection. The input-output, BSM, and signal timing information are all used to determine the green window estimate utilizing the maximum estimated queue length.

The third approach, used in the Conroe simulation, represents queue-length information similar to the data expected from a radar-based queue monitoring system available to practitioners (Wang et al. 2017; Milanés et al. 2014). To simulate this methodology, the data collection zone in each lane was replicated, covering approximately 500 ft upstream of the stop bar in the simulation model. The data zone was configured to provide the speed and position of all vehicles (lateral and longitudinal) in the detection zone in each simulation time step. This methodology utilizes the current queue length for determining the start of the green window.

Modeling Vehicle Behavior

Figure 9 shows the process by which the Vissim model, through the DriverModel.dll, controls vehicles entering the network. The DriverModel.dll first checks to see if a vehicle generated by Vissim is a TOSCo-equipped vehicle. Non-TOSCo vehicles operate under manual control. This mode utilizes the Vissim default driver model for the vehicles driving behavior. The behavior of the TOSCo vehicles in the simulation model depends on whether the vehicle is leading a string, following a non-TOSCo vehicle, or following a TOSCo vehicle and if the vehicle is within DSRC range of the upcoming intersection. If the vehicle is following a non-TOSCo vehicle, the simulation will use the ACC logic to control the movement of the vehicle. If the TOSCo vehicle is following another TOSCo vehicle, the CACC logic is used to control how the vehicle behaves in the simulation model. If the TOSCo-equipped vehicle is the lead vehicle but outside of DSRC range of an upcoming intersection, it operates in ACC control because it cannot plan a speed profile. If the TOSCo vehicle is at the head of a string of vehicles and within DSRC range, it uses algorithms to speed up or slow down the vehicle, depending on its identified operating state.

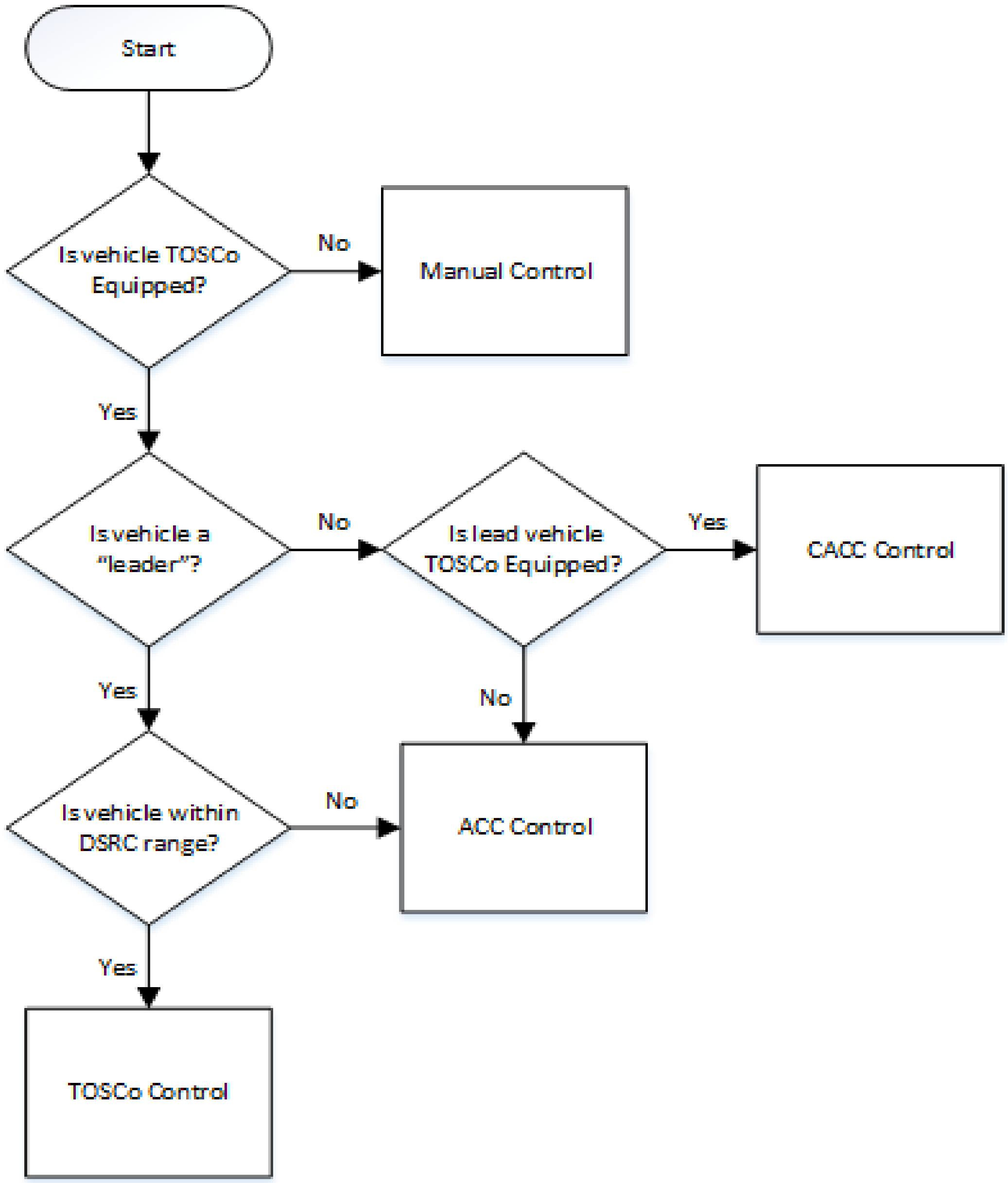


Figure 9. Diagram. Process for determining control mode for vehicles in the Vissim model (Feng et al. 2019).

The following logic was used to control the vehicle's behavior under different control modes:

- Manual control model: To model the behavior of vehicles under manual control, the evaluation team used the default Vissim driver model (PTV Group 2018).
- ACC model: To model the behavior of vehicles under ACC control, Intelligent Driver Model was used (Treiber and Helbing 2002; Treiber et al. 2004).

- CACC model: CACC is like ACC, except it uses an additional remote sensor, such as a radar or a vision system, to monitor the distance and relative speed of vehicles ahead of it. CACC fuses the remote sensor information with information from CV BSMs to better predict the motion of the vehicle ahead of it. The CACC approach employs an extension to the BSM that includes lead-vehicle acceleration commands and estimates of the time constants associated with the lead-vehicle response to those commands (Van Arem et al. 2006).

- TOSCo vehicle speed control: At each simulation time step, the TOSCo vehicles, after receiving the queue and signal status message from the infrastructure, determine what operating state is best for the vehicle, given the current conditions in the network. The TOSCo vehicles evaluate whether a change in operating state is needed. If a change is necessary, the algorithm uses the queue and signal status information provided by the infrastructure to determine if the vehicle should maintain its current speed, slow down, or speed up to arrive in the green window.

- Vehicle lane-changing behavior: To date, TOSCo development has assumed that lane choice is the driver's decision, with no support from TOSCo. The analysis of TOSCo benefits in this report assumes that TOSCo vehicles will not perform discretionary lane changes, but, for mandatory lane changes, the traffic level simulation must allow lane changes for TOSCo vehicles. However, the research team used the DriverModel.dll to impose some control over the lane-changing behavior to help keep the strings together, which the research team believes will be an objective of TOSCo users. The restriction prohibits TOSCo vehicles from changing lanes unless the vehicle is in free-flow mode or the vehicle must change lanes to position itself to make a turn at an intersection as dictated by its route. If a vehicle needs to turn at the next intersection, it will perform a lane change; otherwise, lane changes are not allowed. The research allowed lane changing in free-flow mode, so vehicles can perform a discretionary passing maneuver to more accurately represent travel behavior on the corridor and avoid artificially raising the total delay measurements.

MODELING ASSUMPTIONS

To assess the potential benefits and impacts of TOSCo vehicle behaviors on mobility and fuel/emission performance, the research team compared TOSCo vehicle behaviors at different TOSCo market penetration rates to a baseline. In the baseline case, Vissim's internal driving model controlled the behavior of unequipped (or non-TOSCo) vehicles. The research team assessed the performance of the TOSCo simulation on their respective corridors. Although the research team performed the assessment on two separate corridors, a common set of modeling assumptions and performance metrics existed between both evaluations. This section describes the common modeling assumptions used in this report.

Table 10 summarizes the parameters, assumptions, and specifications to model vehicle behaviors in the simulations. The assumptions/specifications and parameters differ at times from the intended vehicle algorithms to simplify the computational load of the traffic simulations.

Simplifications were only made that were not expected to significantly impact traffic-level performance outcomes. TOSCo vehicles only operate on the through movement of major arterials. When TOSCo vehicles are planning trajectories, they only use the information for the immediate downstream intersection. The minimum cruise speed threshold parameter regulates the minimum speed that a TOSCo vehicle can slow down to without stop. If the TOSCo vehicle cannot maintain the minimum cruise speed, it needs to plan a complete stop trajectory. A very low-cruise speed may be disruptive to other traffic and cause frequent lane-changing and cut-in behaviors. In the TOSCo speed control assumption, the term exact follow means that when a TOSCo vehicle is operating in the optimized-follow mode, it follows its leading vehicle perfectly, without any delay in time or space.

Table 10. TOSCo vehicle model parameters and simulation specifications.

Item	Simulation Specifications
TOSCo approach	Through movement
TOSCo strategy	Intersection by intersection
Control logic type	Manual and TOSCo
Minimum cruise speed threshold	70 percent of roadway speed limit
Maximum cruise speed threshold	Vary with network (equal to the posted speed limit)
Onboard radar model	No
Vehicle dynamics model	As is in Vissim (no powertrain modeling)
TOSCo speed control	Exact follow
TOSCo speed profile planning cases	4 (speed up, slow down, cruise, and stop)
TOSCo operating mode	7 (free-flow, stopped, coordinated speed control, coordinated stop, coordinated launch, optimized follow, creep)
ACC headway	1.3 (s)
Maximum acceleration	4.9 ft/s^2
Maximum deceleration	-11.5 ft/s^2
Maximum jerk	6.6 ft/s^3
Stopped speed threshold	0.33 ft/s
Start-up speed threshold	0.33 ft/s

ft/s^2 = ft per s squared; ft/s^3 = ft per s cubed.

Table 11 summarizes the model parameters and simulation assumptions/specifications used to govern the behavior of TOSCo vehicle strings. There is no limit for maximum string size in the simulation to simplify the problem. The string model parameters are consistent with the simulation specifications in table 10. CACC-engaged distance means that when a TOSCo vehicle is approaching another leading TOSCo vehicle from far away, the following TOSCo vehicle will switch to the optimized follow model when the distance is less than 164 ft. Clearance at stop indicates the distance between two stopped vehicles. The CACC functionality assumes that each TOSCo vehicle plans its own trajectory independently when it is operating in CACC mode. In addition, the lead vehicle shares its estimated TOA with its following vehicle. The following vehicle uses this information to decide whether it should remain in the following mode or transition to the leader of a new string (leader-follower role transition).

Table 11. TOSCo string model parameters and simulation specifications.

Item	Simulation Specifications
Maximum string size	No limit
CACC headway	0.9 s
CACC disengaged distance (to intersection)	164 ft
Clearance at stop	6.6 ft
CACC engaged distance	164 ft
V2V communication model	Not applicable
CACC functionality	Distributed control (in predecessor-follower mode)
Leader-follower role transition	Time-of-arrival shared by predecessor

V2V = vehicle-to-vehicle.

Table 12 summarizes traffic-level model parameters and simulation assumptions/specifications. The evaluation team considered undersaturated traffic conditions only, reflecting the measured traffic volumes of the actual corridors. The queuing patterns at each intersection depend on vehicle arrivals, which are random. According to *Highway Capacity Manual* (Transportation Research Board 2016), a vehicle is in the queued state when its speed is less than 5 mph. Currently, pedestrian interactions are not modeled on system performance. The vehicle composition is based on the real vehicle compositions that exist in each corridor. For the low-speed corridor, only passenger cars were simulated because the percentage of trucks is negligible in the modeled corridor, while trucks were included in the simulation of the high-speed corridor. Passenger vehicles were all modeled as having the same controllers and responses to control. Trucks were never TOSCo-enabled and therefore were not part of any TOSCo strings.

Table 12. Traffic model parameters and simulation specifications.

Item	Simulation Specifications
Congestion level	v/c ratio between 0.2 and 0.9*
Queuing pattern	Random
Queued vehicle	Speed less than 5 mph
Pedestrian interaction	No
Vehicle mixture	Representative of the corridor conditions (passenger cars)

*The v/c ratios of the intersections in the two corridors vary from ~0.2 to ~0.9, which is a very wide range. However, none of the v/c ratios are above 1.0.

Table 13 summarizes infrastructure level TOSCo model parameters and simulation assumptions/specifications. Both fixed time (verification scenario evaluation) and coordinated-actuated traffic signal control (corridor evaluation) strategies are considered. No communication and road grade are modeled in the simulation.

Table 13: Infrastructure model parameters and coding assumptions

Item	Specification
Traffic signal operation	Fixed time and coordinated-actuated
V2I/I2V communication Model	Simplified without communication delay
Intersection spacing	Vary with network
Roadway speed limit	Vary with network
Model road grade	No

PERFORMANCE MEASURES

To estimate the potential benefits of implementing TOSCo in an urban corridor, both mobility and environmental performance metrics were examined. This section describes the performance measures used in the performance assessments.

Mobility

Each simulation recorded vehicle performance for several different performance measures aggregated by vehicle type to identify how TOSCo vehicles compare to, and affect, non-TOSCo vehicles. The following performance measures were used:

- Total delay: delay associated with vehicles slowing in advance of an intersection, time spent stopped on an intersection approach, time spent as vehicles move up in the queue, and time needed for vehicles to accelerate to their desired speed (Transportation Research Board 2016).

- Stop delay: the amount of time a vehicle's speed equals zero recorded by Vissim.

- Number of stops: the number of complete stops (speed equals zero) recorded by Vissim.

- Average speed: average speed of all vehicles in the network during the entire simulation period in mph, including vehicles that travel only part of the corridor and on side streets.

- Total travel time: total travel time of all vehicles in the network during the entire simulation period in hours, including vehicles that travel only part of the corridor and on side streets.

The total delay, stop delay, and the number of stops metrics are normalized on a per-vehicle basis.

Emission/Fuel Consumption

Over the past years, the U.S. Environmental Protection Agency (EPA) has been developing MOVES, a state-of-the-science emissions modeling system that estimates emissions for mobile sources at the National, county, and project level for criteria such as air pollutants, greenhouse gases (GHG), and air toxics (Xia et al. 2013). However, the model is not suitable for online interaction with microscopic traffic simulation (due to heavy computational loads). Therefore, the research team has developed an alternative approach in this project to simplify the application of MOVES for simulation while keeping reasonable fidelity of the original MOVES model. Similar efforts were performed in the EPA (2012).

CHAPTER 5. SIMULATION EXPERIMENT AND RESULTS AT ANN ARBOR, MI CORRIDOR

To assess the performance of TOSCo in the low-speed corridor, the TOSCo vehicle behaviors and associated mobility and fuel/emission performance were compared to a baseline, where Vissim's internal driving model controlled all vehicles. This chapter presents the findings from the low-speed corridor performance assessment.

SUMMARY OF SIMULATION SCENARIO

The performance of the TOSCo algorithm was assessed, and two types of vehicles in the implementation scenario were assumed: TOSCo and non-TOSCo. All TOSCo vehicles at each market penetration level were equipped with DSRC radio, contributed information to the queue prediction algorithm, and performed all TOSCo functions. The non-TOSCo vehicles were not equipped with DSRC. The cases are listed in table 14, and the baseline is case 1. The infrastructure algorithm version 1 is applied to this scenario.

Table 14. Vehicle composition modeled in implementation.

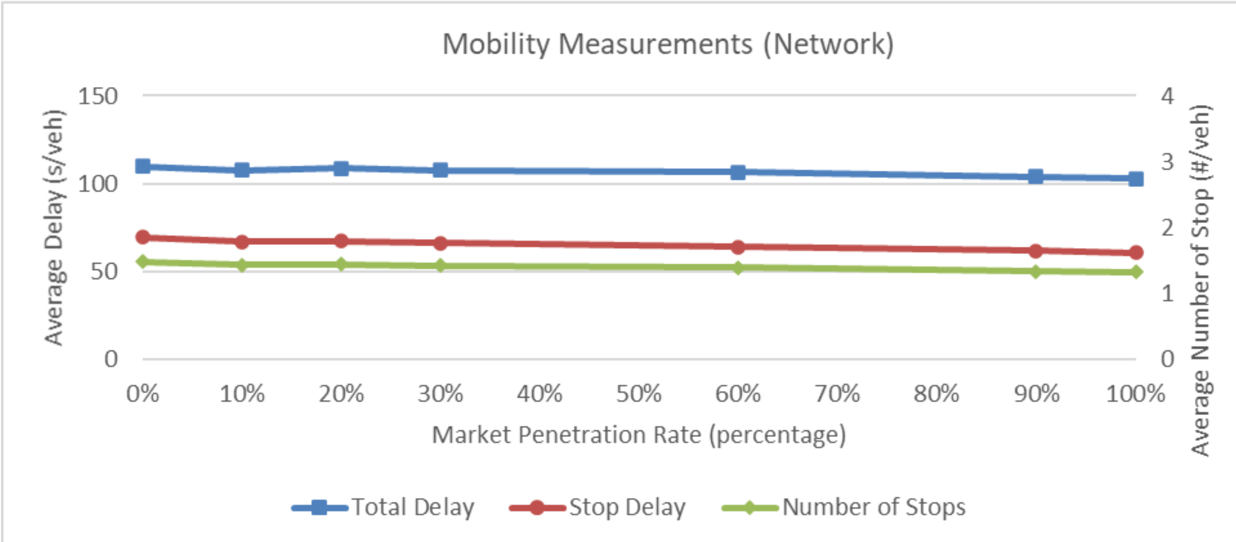
Case Number	TOSCo (Percent)	Non-TOSCo (Percent)
1 (Baseline)	0	100
2	10	90
3	20	80
4	30	70
5	60	40
6	90	10
7	100	0

SIMULATION RESULTS

The following sections describe the results of the simulations.

Cumulative Delays and Stops

Figure 10 and table 15 show the mobility benefits of the entire network. The entire network includes all vehicles on both TOSCo and non-TOSCo approaches, which reflect the local traffic patterns. At the network level, mobility benefits increase with the increase of TOSCo penetration rate.



#/veh = number of vehicles; s/veh = s per vehicle.

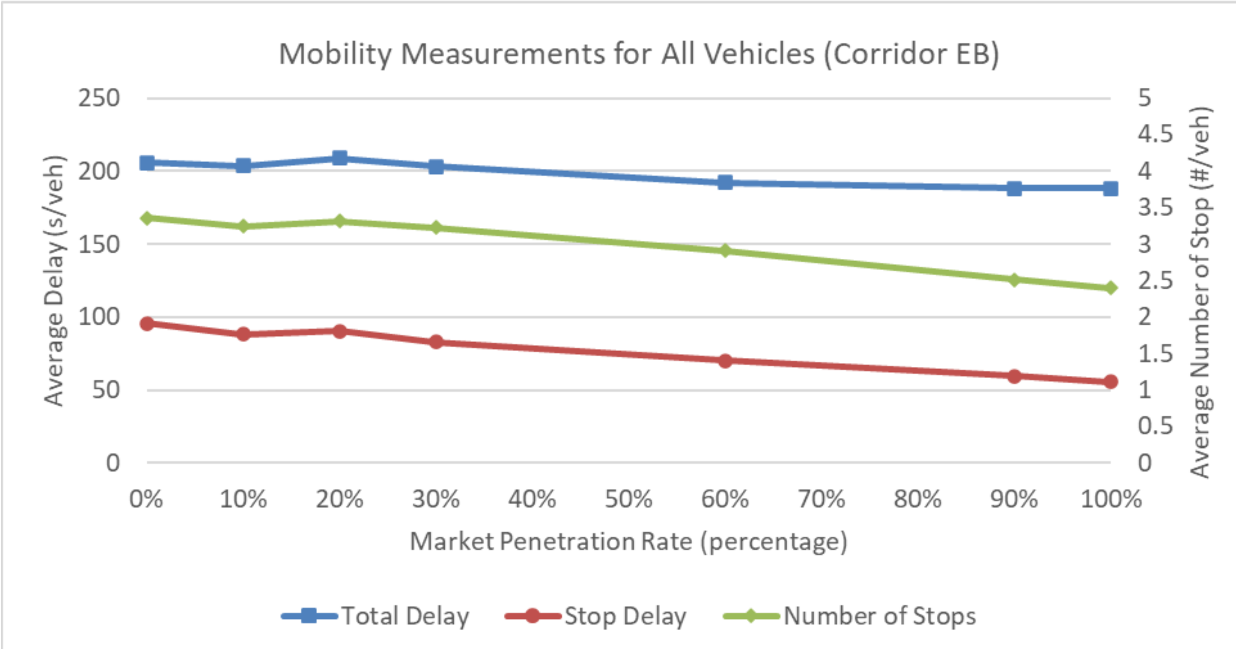
Figure 10. Chart. Mobility measurements of the entire network (Feng et al. 2019).

Table 15. Mobility comparison of the entire network.

Market Penetration Rate (Percent)	Total Delay (s/Vehicle)	Percent Change[1]	Stop Delay (s/Vehicle)	Percent Change[1]	Number of Stops per Vehicle	Percent Change[1]
0	109.78	—	69.45	—	1.48	—
10	107.83	-1.78	67.12	-3.36	1.43	-3.24
20	108.75	-0.94	67.14	-3.33	1.44	-2.84
30	107.73	-1.87	66.05	-4.90	1.42	-3.92
60	106.39	-3.09	64.01	-7.84	1.39	-5.81
90	103.83	-5.43	61.76	-11.07	1.33	-9.86
100	102.72	-6.43	60.61	-12.73	1.32	-10.68

—No data (based case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Figure 11 and table 16 show the mobility measurements of the corridor EB direction. The corridor mobility measurements represent the summation of all intersections of TOSCo approaches. All simulated intersections along the facility were equipped to enable TOSCo. At the corridor level, the mobility benefits increase as the TOSCo penetration rate increases. At 100 percent TOSCo penetration rate, the total delay, stop delay, and the number of stops decrease by 8.69 percent, 41.80 percent, and 28.69 percent, respectively, in the EB direction.



#/veh = number of vehicles; s/veh = s per vehicle.

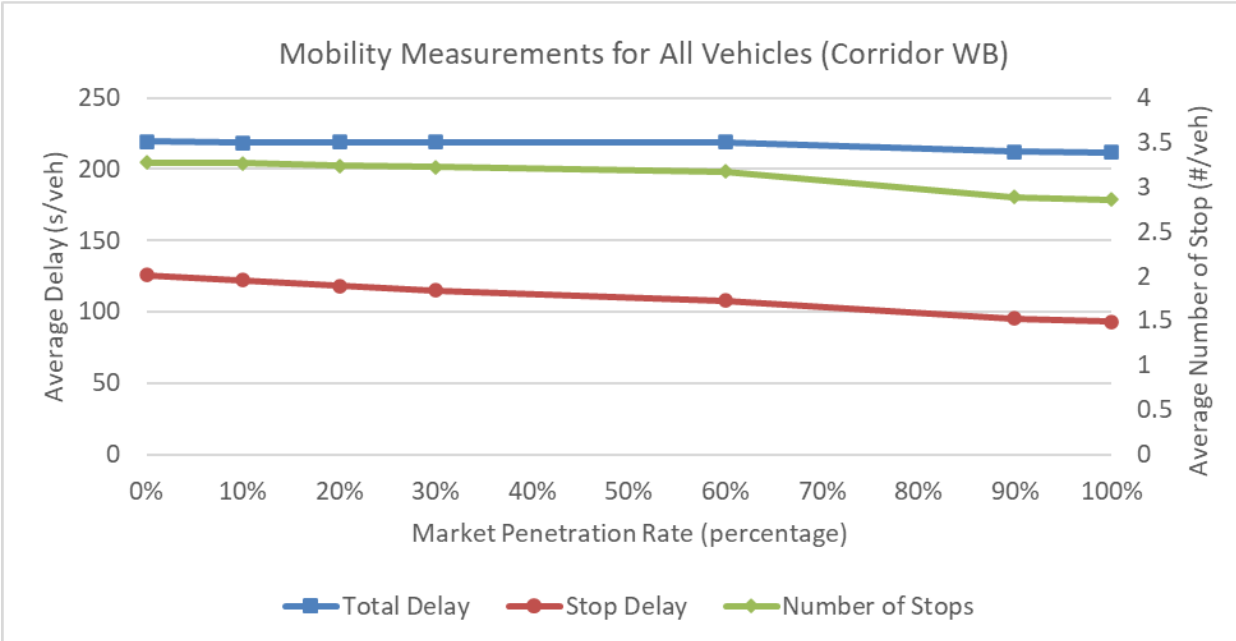
Figure 11. Chart. Mobility measurements of corridor EB (Feng et al. 2019).

Table 16. Mobility comparison of corridor EB.

Market Penetration Rate (Percent)	Total Delay (s/vehicle)	Percent Change[1]	Stop Delay (s/Vehicle)	Percent Change[1]	Number of Stops per Vehicle	Percent Change[1]
0	205.96	—	95.46	—	3.36	—
10	206.47	0.25	90.56	-5.13	3.27	-2.62
20	209.03	1.49	90.27	-5.44	3.32	-1.25
30	203.05	-1.41	82.99	-13.06	3.23	-3.99
60	192.18	-6.69	70.01	-26.66	2.91	-13.33
90	188.26	-8.59	59.48	-37.69	2.52	-25.12
100	188.05	-8.69	55.56	-41.80	2.40	-28.69

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Figure 12 and table 17 show the mobility measurements of the corridor WB direction. The general pattern in the WB direction is the same as the EB direction, but with fewer benefits. At 100 percent TOSCo penetration rate, the total delay, stop delay, and the number of stops decrease by 3.35 percent, 27.22 percent, and 13.05 percent, respectively. One potential reason is that EB traffic has a higher volume than WB traffic, and TOSCo has more benefits when the v/c ratio is higher (and below saturation).



#/veh = number of vehicles; s/veh = s per vehicle.

Figure 12. Chart. Mobility measurements of corridor WB (Feng et al. 2019).

Table 17. Mobility comparison of corridor WB.

Market Penetration Rate (Percent)	Total Delay (s/Vehicle)	Percent Change[1]	Stop Delay (s/Vehicle)	Percent Change[1]	Number of Stops per Vehicle	Percent Change[1]
0	222.06	—	129.91	—	3.39	—
10	219.76	-1.03	124.16	-4.42	3.31	-2.36
20	222.87	0.37	123.26	-5.12	3.33	-1.65
30	220.21	-0.83	118.10	-9.09	3.28	-3.13
60	220.84	-0.55	110.62	-14.85	3.22	-5.02
90	213.61	-3.80	97.06	-25.29	2.94	-13.22
100	214.62	-3.35	94.55	-27.22	2.95	-13.05

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

While the previous results show the mobility benefits of TOSCo approaches, figure 13 and table 18 show the mobility benefits from non-TOSCo approaches, meaning left turns, right turns on the main street, and all approaches on side streets. Results show that as the TOSCo penetration rate increases, the benefits of non-TOSCo approaches also increase. This increase suggests that enabling TOSCo on the through movements of the main street improves the overall traffic condition, which helps improve the performance of other approaches.

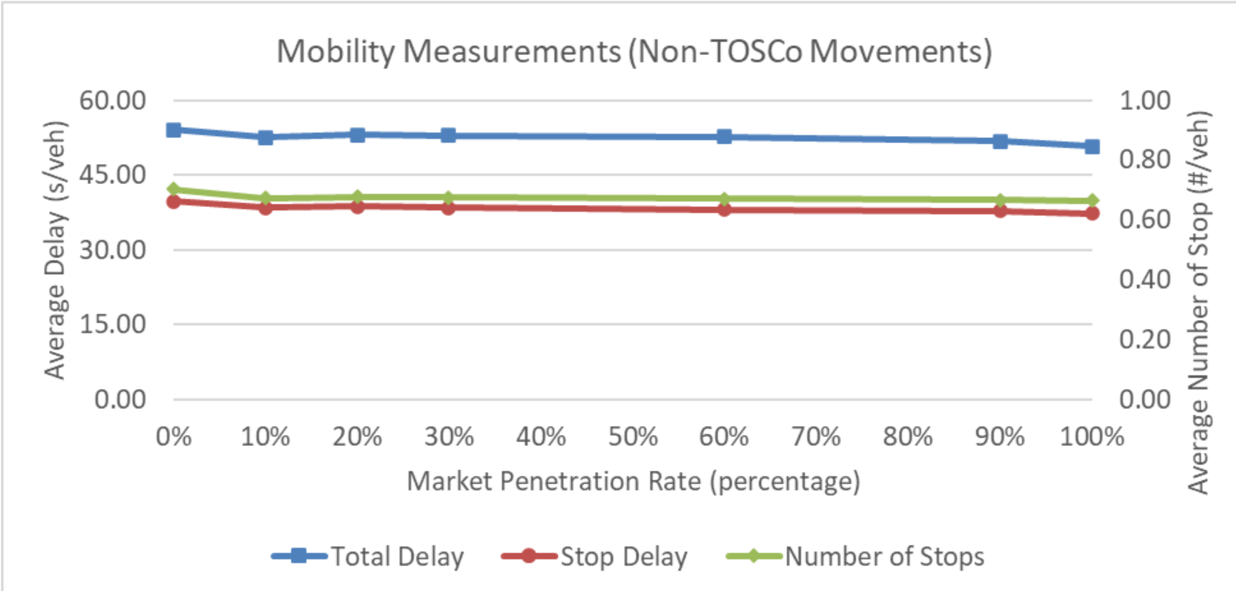


Figure 13. Chart. Mobility measurements of non-Traffic Optimization for Signalized Corridors approaches (Feng et al. 2019).

Table 18. Mobility comparison of non-TOSCo approaches.

Market Penetration Rate (Percent)	Total Delay (s/vehicle)	Percent Change[1]	Stop Delay (s/vehicle)	Percent Change[1]	Number of Stops per Vehicle	Percent Change[1]
0	54.04	—	39.76	—	0.70	—
10	52.52	-2.81	38.42	-3.37	0.67	-4.29
20	53.13	-1.68	38.71	-2.64	0.68	-2.86
30	52.98	-1.96	38.53	-3.09	0.68	-2.86
60	52.72	-2.44	38.12	-4.12	0.67	-4.29
90	51.75	-4.24	37.85	-4.80	0.67	-4.29
100	50.79	-6.01	37.37	-6.01	0.66	-5.71

—No data (base case).

[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Travel Time and Average Speed

Figure 14 and table 19 show the mobility benefits of total travel time and average vehicle speed. Total travel time is defined as the summation of travel times of all vehicles through the entire simulation period in hours. This index implies the overall traffic condition in the traffic network. From 0 percent TOSCo to 100 percent TOSCo, the total travel time decreases by about 3.9 percent, while the average speed increases by about 5.55 percent, which is consistent with delay measures. These results indicate TOSCo has a network mobility benefit.

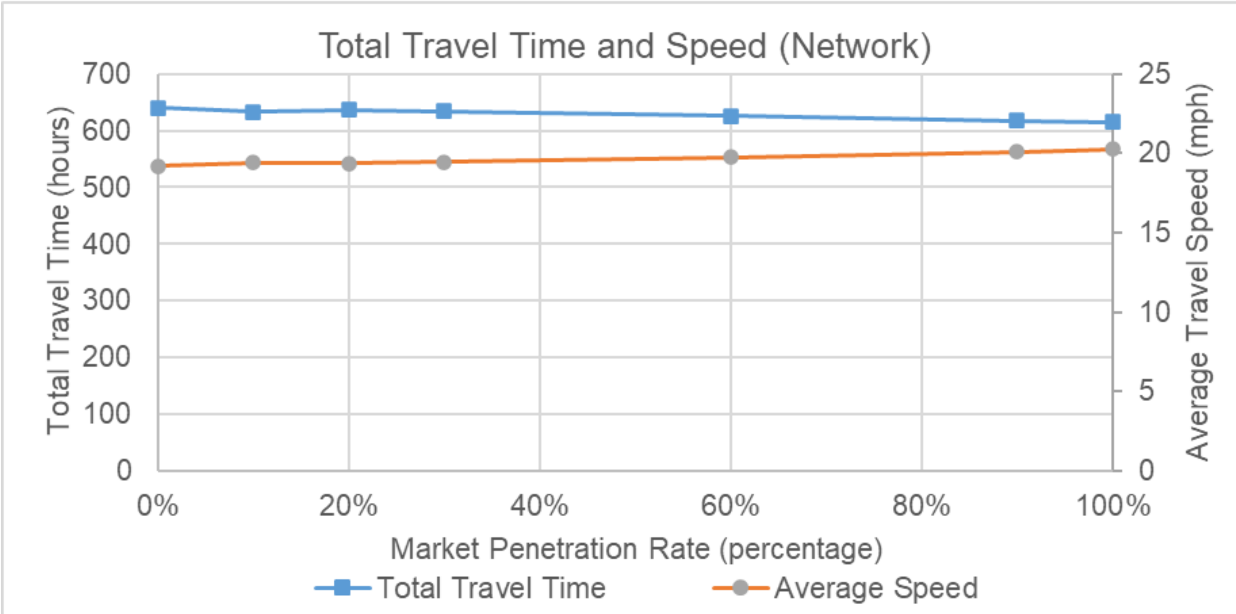


Figure 14. Chart. Average speed and total travel time measurements of the entire network (Feng et al. 2019).

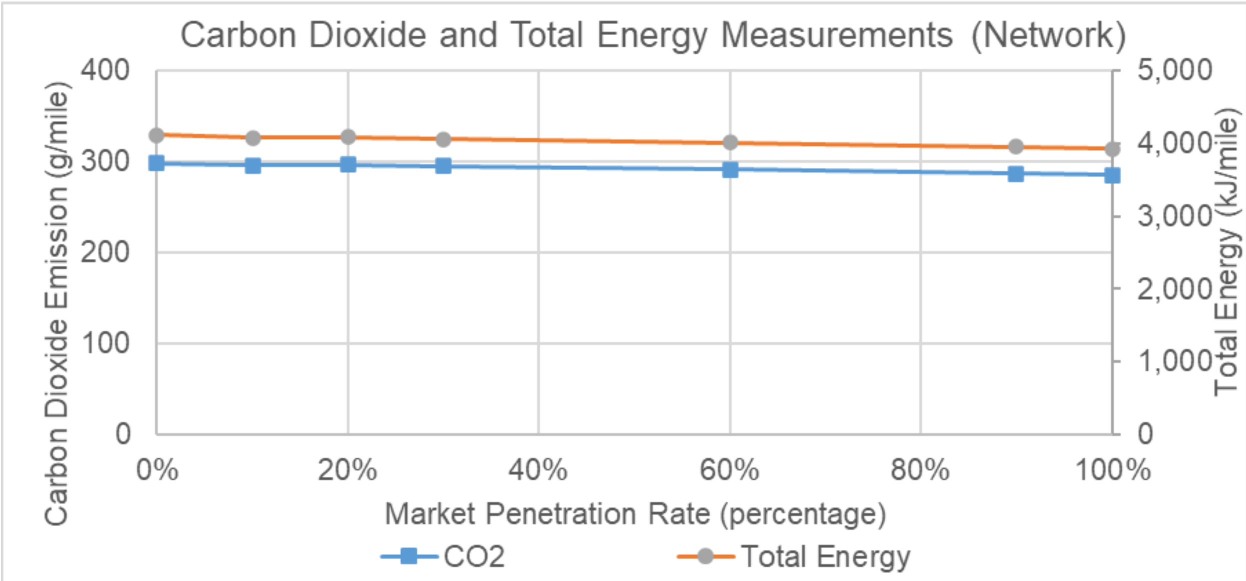
Table 19. Average speed and total travel time comparison of the entire network.

Market Penetration Rate (Percent)	Average Speed (mph)	Percent Change[1] (Percent)	Total Travel Time (Vehicle-hour)	Percent Change[1] (Percent)
0	19.19	—	639.48	—
10	19.39	1.02	634.47	-0.78
20	19.35	0.84	635.92	-0.56
30	19.47	1.45	633.68	-0.91
60	19.75	2.91	625.74	-2.15
90	20.10	4.75	616.93	-3.53
100	20.25	5.55	614.51	-3.90

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Emissions and Energy Consumption

Fuel consumption and emissions measurements are other important indexes to evaluate the performance of TOSCo functions. Figure 15, table 20, figure 16, and table 21 are measurements and comparisons of energy-related performance indexes, including carbon dioxide emission, total energy, hydrocarbon (HC) emission, and nitrogen oxide (NOx) emission. Results show that TOSCo can also achieve environmental benefits by reducing both energy consumption and different types of emissions. The patterns are the same as mobility measurements, increasing benefits with increasing TOSCo penetration rates.



CO_2 = carbon dioxide; g/mi = g per mi; kJ/mi = kilojoules per mi.

Figure 15. Chart. Carbon dioxide and total energy measurements of the entire network (Feng et al. 2019).

Table 20. Carbon dioxide and total energy comparison of the entire network.

Market Penetration Rate (Percent)	Carbon Dioxide Emission (g/mi)	Percent Change[1]	Total Energy (kJ/mi)	Percent Change[1]
0	298.22	—	4107.69	—
10	296.31	-0.64	4081.35	-0.64
20	296.20	-0.68	4079.88	-0.68
30	294.62	-1.21	4058.13	-1.21
60	290.93	-2.45	4007.23	-2.45
90	286.73	-3.85	3949.45	-3.85
100	285.13	-4.39	3927.35	-4.39

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

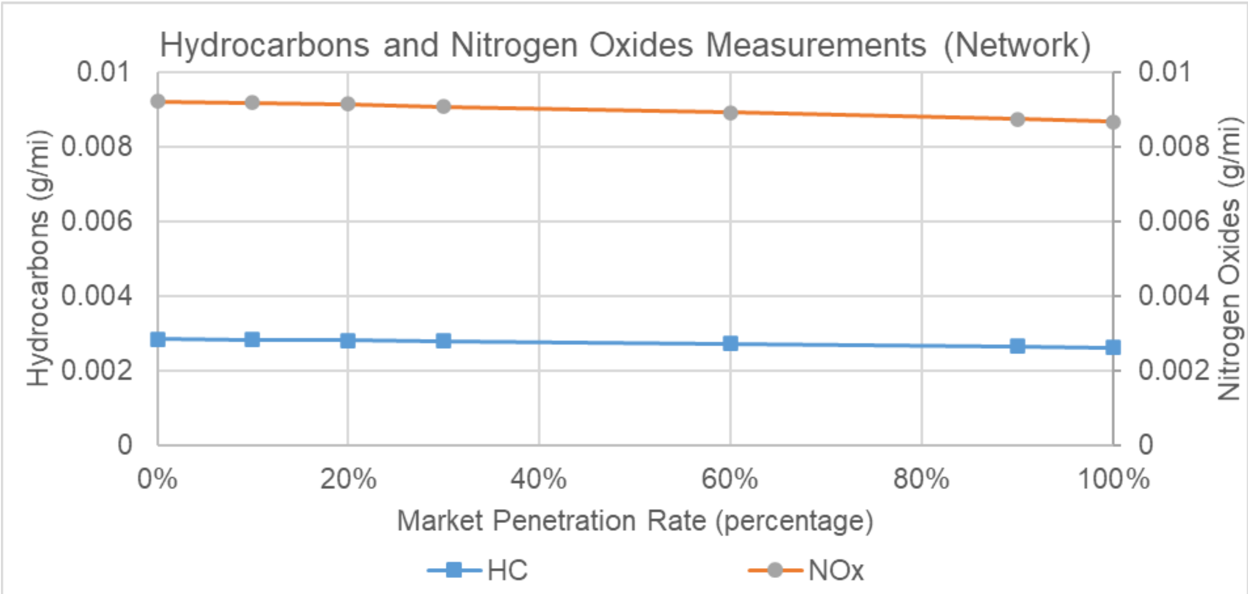


Figure 16. Chart. HC and nitrogen oxide measurements of the entire network (Feng et al. 2019).

Table 21. HC and nitrogen oxide measurements of the entire network.

Market Penetration Rate (Percent)	HC Emissions (g/mi)	Percent Change[1]	NOx Emissions (g/mi)	Percent Change[1]
0	0.00284	—	0.00921	—
10	0.00282	-0.72	0.00918	-0.36
20	0.00281	-1.11	0.00914	-0.80
30	0.00279	-1.95	0.00907	-1.55
60	0.00272	-4.09	0.00891	-3.32
90	0.00265	-6.81	0.00873	-5.27
100	0.00262	-7.81	0.00866	-5.99

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

DEDICATED SHORT-RANGE COMMUNICATION RANGE SENSITIVITY ASSESSMENT

All results presented above assume the calibrated DSRC communication range from NDD shown in table 7. To further analyze the impact of the DSRC range, the maximum range of the DSRC communications to all intersections was assumed to be 985 ft, which is much shorter than the range from NDD. To be consistent with the previous assumption, if the spacing between two intersections is less than 985 ft, then the actual intersection spacing was used as the range. Table 22 shows the modified DSRC communication range of each intersection.

Table 22. Modified DSRC range.

Intersection	DSRC Range EB (Ft/meters)	DSRC Range WB (Ft/meters)
Barton Drive	985/300	985/300
Murfin Avenue	985/300	985/300
Traverwood Drive	985/300	985/300
Nixon Road	985/300	656/200
Huron Parkway	656/200	985/300
Green Road	985/300	791/241
US–23 West	791/241	682/208
US–23 East	682/208	985/300
Earhart Road	985/300	985/300
Whitehall Drive	985/300	985/300
Dixboro Road	985/300	985/300

With the modified communication range, the simulation is executed again with one random seed. Results are compared to those with the original communication range using the same random seed, as shown in table 23 through table 28 below. Table 23 and table 24 show the impact of different DSRC ranges on total and stopped delay, respectively, while table 25 and table 26 show the impact of different DSRC ranges on the number of stops and average speeds, respectively. Table 27 and table 28 show the impact of different DSRC ranges on total travel time and carbon dioxide emissions. In these tables, if the performance with the calibrated DSRC range was better than the 985-ft DSRC range, then the net effect of the change to the DSRC range was positive. Similarly, if the performance with the calibrated DSRC range was worse than the 985-ft DSRC range, then the net effect of changing the DSRC range was negative. Among all performance indexes and penetration rates, only carbon dioxide emission below 20 percent penetration rate and average speed below 20 percent penetration were negative. The results suggest that the benefits of TOSCo increase with the DSRC communication range.

Table 23. Effects of DSRC range on total delay (s/vehicle)—low-speed corridor.

Market Penetration Rate (percent)	Total Delay Modified DSRC Range	Percent Change[1]	Total Delay Calibrated DSRC Range	Percent Change[1]	Net Effect on Total Delay
0	108.24	—	108.24	—	—
10	105.79	-2.26	104.48	-3.47	Delay decreased
20	104.66	-3.31	104.59	-3.37	Delay decreased
30	105.72	-2.33	103.18	-4.67	Delay decreased
60	104.56	-3.40	102.43	-5.37	Delay decreased
90	98.17	-9.30	97.67	-9.77	Delay decreased
100	100.31	-7.33	98.78	-8.74	Delay decreased

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Table 24. Effects of DSRC range on stop delay (s/vehicle)—low-speed corridor.

Market Penetration Rate (Percent)	Stop Delay Modified DSRC Range	Percent Change[1]	Stop Delay Calibrated DSRC Range	Percent Change[1]	Net Effect on Stop Delay
0	68.66	—	68.66	—	—
10	65.36	-4.81	64.54	-6.00	Delay decreased
20	64.5	-6.06	64.47	-6.10	Delay decreased
30	64.94	-5.42	63.64	-7.31	Delay decreased
60	63.5	-7.52	61.32	-10.69	Delay decreased
90	58.03	-15.48	57.73	-15.92	Delay decreased
100	60.27	-12.22	59.1	-13.92	Delay decreased

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Table 25. Effects of DSRC range on number of stops (stops/vehicle)—low-speed corridor.

Market Penetration Rate (Percent)	Number of Stops Modified DSRC Range	Percent Change[1]	Number of Stops Calibrated DSRC Range	Percent Change[1]	Net Effect on Number of Stops
0	1.47	—	1.47	—	—
10	1.42	-3.40	1.4	-4.76	Stops decreased
20	1.42	-3.40	1.4	-4.76	Stops decreased
30	1.4	-4.76	1.37	-6.80	Stops decreased
60	1.38	-6.12	1.35	-8.16	Stops decreased
90	1.29	-12.24	1.28	-12.93	Stops decreased
100	1.29	-12.24	1.26	-14.29	Stops decreased

—No data (base case).

[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Table 26. Effects of DSRC range on average speed (mph)—low-speed corridor.

Market Penetration Rate (Percent)	Average Speed Modified DSRC Range	Percent Change[1]	Average Speed Calibrated DSRC Range	Percent Change[1]	Net Effect on Average Speed
0	19.25	—	19.25	—	—
10	19.49	1.26	19.61	1.87	Speed increased
20	19.65	2.07	19.65	2.07	None
30	19.56	1.61	19.78	2.78	Speed increased
60	19.82	2.97	20.07	4.29	Speed increased
90	20.58	6.94	20.65	7.27	Speed increased
100	20.40	5.97	20.57	6.88	Speed increased

—No data (base case).

[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Table 27. Effects of DSRC range on total travel time (vehicle-hours)—low-speed corridor.

Market Penetration Rate (Percent)	Total Travel Time Modified DSRC Range	Percent Change[1]	Total Travel Time Calibrated DSRC Range	Percent Change[1]	Net Effect on Total Travel Time
0	629.72	—	629.72	—	—
10	626.33	-0.54	621.83	-1.25	Travel time decreased
20	617.16	-1.99	616.65	-2.08	Travel time decreased
30	620.79	-1.42	613.04	-2.65	Travel time decreased
60	615.31	-2.29	608.23	-3.41	Travel time decreased
90	598.96	-4.88	597.53	-5.11	Travel time decreased
100	605.85	-3.79	602.36	-4.34	Travel time decreased

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Table 28. Effects of DSRC range on carbon dioxide emissions (g/mi)—low-speed corridor.

Market Penetration Rate (Percent)	Modified DSRC Range	Percent Change[1]	Calibrated DSRC Range	Percent Change[1]	Net Effect on Carbon Dioxide Emissions
0	297.64	—	297.64	—	—
10	295.60	-0.69	294.57	-1.03	Emissions decreased
20	293.69	-1.33	293.83	-1.28	Emissions increased
30	293.87	-1.27	292.04	-1.88	Emissions decreased
60	289.86	-2.61	288.16	-3.18	Emissions decreased
90	283.23	-4.84	282.64	-5.04	Emissions decreased
100	283.86	-4.63	282.13	-5.21	Emissions decreased

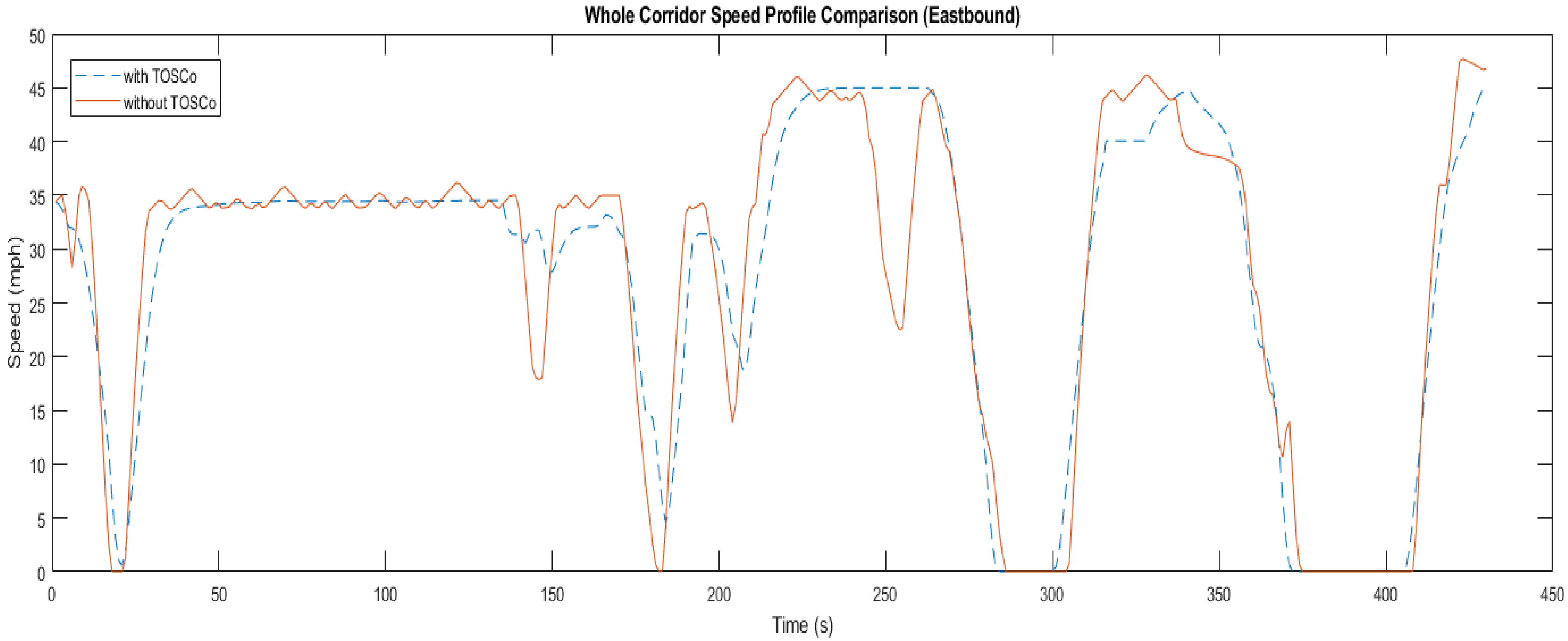
—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

DISCUSSION OF PERFORMANCE RESULTS

Results from the previous section show that TOSCo brings both mobility (total delay, stop delay, number of stops, and average speed) and environmental benefits (total energy, carbon dioxide emission, HC emission, and NOx emission). Simulated results suggest the benefits increase as the TOSCo penetration rate increases.

TOSCo brings environmental benefits because it can smooth vehicle trajectories and reduce fluctuations by incorporating traffic signal and vehicle queue information into trajectory planning. Figure 17 shows the comparison of vehicle trajectories through the EB direction of the entire corridor with and without TOSCo activation. TOSCo greatly reduces speed fluctuations (e.g., the 50th–100th s and reduces unnecessary or abrupt decelerations (e.g., around the 180th s and 250th s) by planning a smoother trajectory ahead. With smoother trajectories, the corresponding emissions are reduced.

TOSCo brings mobility benefits because the coordinated launch function increases the saturation flow rate because of shorter headways and elimination of start-up lost time. The benefits are more obvious at high-volume and high-delay approaches. To verify this statement, simulation results from the EB approach of the Green Road and Plymouth Road intersection are selected because this approach is the highest v/c ratio in the network. Capacity analysis is performed. Because the v/c ratio is still under 1.0, which is undersaturated, the first 20 s of green time are chosen to estimate the number of vehicles that pass the stop bar. Because of the long queue at the intersection, the first 20 s are fully utilized to discharge vehicles, and no capacity drop needs to be considered. Because the cycle length is 150 s and the data collection time is 1 h, there are 24 cycles in one simulation run.



CO_2 = carbon dioxide; g = gram; s = second.

Figure 17. Chart. Whole corridor speed profile comparison (EB) (Feng et al. 2019).

Figure 18 and figure 19 show the box plot and the average number of vehicles (mean) that pass the intersection with different penetration rates of TOSCo vehicles. Results show that with the increase of TOSCo penetration rate, the number of vehicles that pass within the first 20 s of green time increases more than 60 percent, which can be considered as the extra capacity brought by coordinated launch. When the TOSCo penetration rate is lower (e.g., lesser than or equal to 30 percent), the benefit is minimal, and when the TOSCo penetration rate is higher (e.g., greater than or equal to 60 percent), the benefit is significantly increased. The reason is that only a TOSCo string (i.e., greater than or equal to 2 TOSCo vehicles together) can perform a coordinated launch. When the penetration rate is low, it has lower probabilities to form a TOSCo string. In many cases, TOSCo vehicles are scattered in a larger group of vehicles in which TOSCo strings are unable to form. Under these circumstances, all vehicles in that group will launch with non-TOSCo headways.

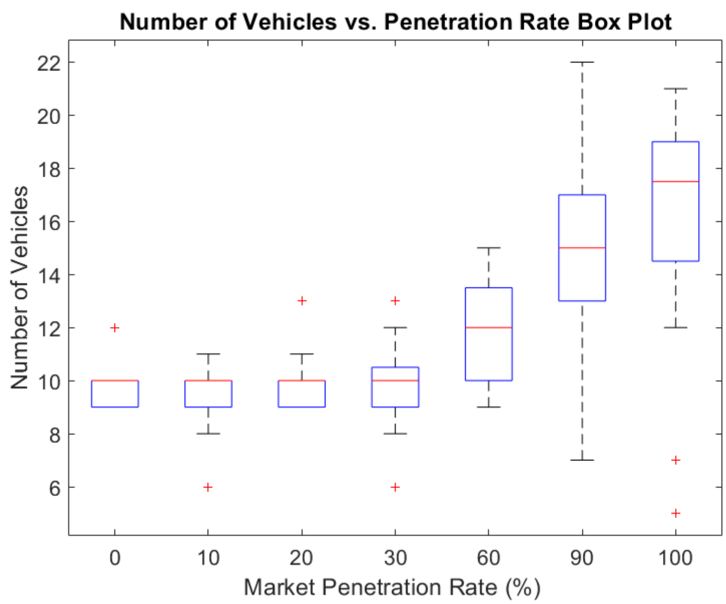


Figure 18. Chart. Number of vehicles in the first 20 s of green passing intersection under different TOSCo penetration rates (penetration rate box plot) (Feng et al. 2019).

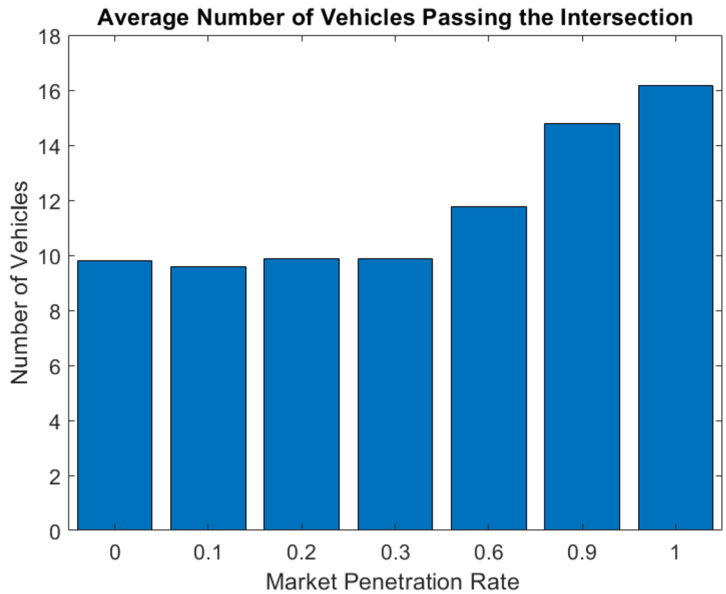


Figure 19. Chart. Average of numbers of vehicles in the first 20 s of green passing the intersection (Feng et al 2019).

CHAPTER 6. SIMULATION EXPERIMENT AND RESULTS AT CONROE, TX CORRIDOR

This chapter presents the findings from the high-speed corridor performance assessment. The high-speed corridor used many of the same simulation parameters as the low-speed corridor. The research team performed the corridor analysis using data from 15 intersections along the SH 105 corridor. The corridor analysis used the same market penetration rates as the low-speed corridor; however, the infrastructure algorithm for the high-speed corridor does not distinguish between vehicles that are transmitting BSMs and those that are not. Therefore, the only relevant market penetration rate for the high-speed corridor is the TOSCo market penetration rate.

SUMMARY OF SIMULATION SCENARIO

The experimental setup for the high-speed corridor case is similar to the low-speed corridor experimental setup, using the same penetration rates and local traffic patterns and volumes. There are some differences in the experimental setup described below:

- The high-speed corridor uses signal timing from the city of Conroe to represent the SH 105 corridor.
- The high-speed corridor analysis is done with 18 seeds to obtain statistical significance between some of the scenario performance measures.
- The high-speed corridor includes truck volumes in the analysis to represent SH 105. The truck percentage on SH 105 in the AM peak is about 3 percent of the traffic.
- The infrastructure algorithm used for the high-speed corridor analysis does not distinguish between DSRC-equipped and non-DSRC equipped vehicles. Therefore, the high-speed corridor analysis does not have differences between TOSCo and DSRC penetration rates.
- Each simulation run on SH 105 spans 8,100 simulation s, with a 900-s warm-up period and a 7,200 simulation s data-collection period.
- The desired acceleration distribution provided in Vissim for non-TOSCo vehicles is calibrated based on field data.

The research team selected the DSRC reception range for each intersection based on intersection spacing, assuming the RSU could have the transmission power adjusted to vary the distance of the transmission. Table 29 provides the DSRC ranges that the research team assumed for each intersection. Because the research team did not expect the roadway geometry to affect the omnidirectional transmission from the DSRC radio, the research team assumed the DSRC ranges to be equal in the EB and WB directions.

Table 29. Assumed range of DSRC radio reception at each intersection in the SH 105 corridor.

Intersection	DSRC Range EB (Ft/meters)	DSRC Range WB (Ft/meters)
Loop 336	985/300	985/300
Fountain Lane	985/300	985/300
FM 3083	3,280/1,000	3,280/1,000
Highland Hollow Drive	3,280/1,000	3,280/1,000
La Salle Avenue	3,280/1,000	3,280/1,000
Old 105 Highway	3,280/1,000	3,280/1,000
McCaleb Road	3,280/1,000	3,280/1,000
Tejas Boulevard	1,640/500	1,640/500
Marina Drive	1,640/500	1,640/500
Navajo Drive	985/300	985/300
April Sound Boulevard	985/300	985/300
Old River Road	2,625/800	2,625/800
Cape Conroe Drive	985/300	985/300
Walden Road	985/300	985/300
Stewart Creek Road	3,280/1,000	3,280/1,000

SIMULATION RESULTS

This section discusses performance measures from the standpoint of a commuter vehicle traveling from one end of SH 105 to the other in both directions. The performance measures shown are the summation of the performance measures at each intersection to narrow the data collection locations to areas where TOSCo vehicles would function in operating modes for approaching or departing an intersection. This methodology reduces measurement of areas where TOSCo cannot significantly impact behavior.

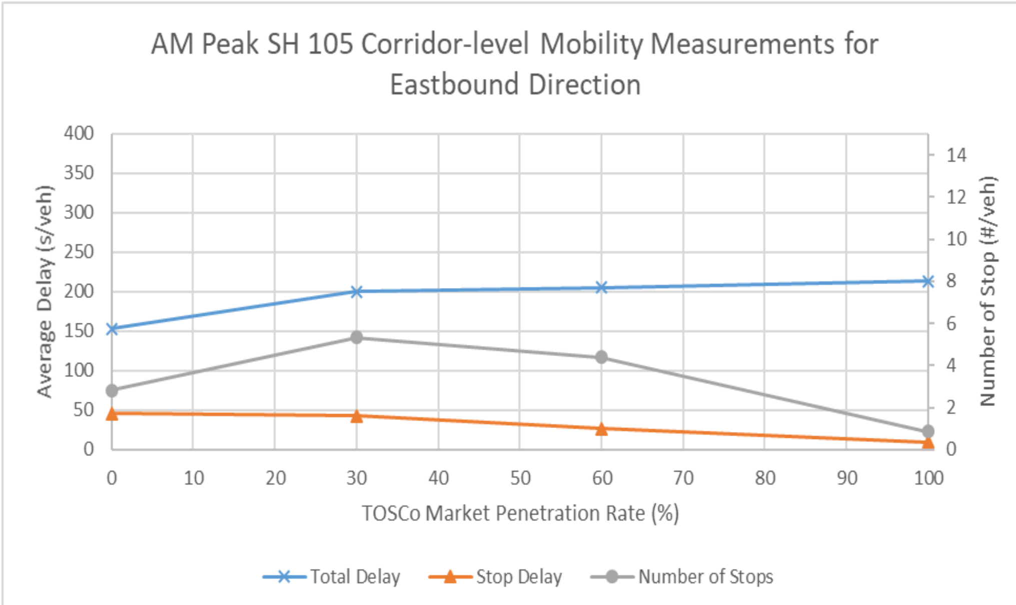
Simulation analyses were conducted to evaluate the performance of the TOSCo application for both AM and PM peak periods in this high-speed corridor.

AM Peak Performance Results

TOSCo's performance on the SH 105 corridor for the AM peak was investigated. During this peak period, all intersections were undersaturated. The detailed simulation results of the AM peak period are presented below.

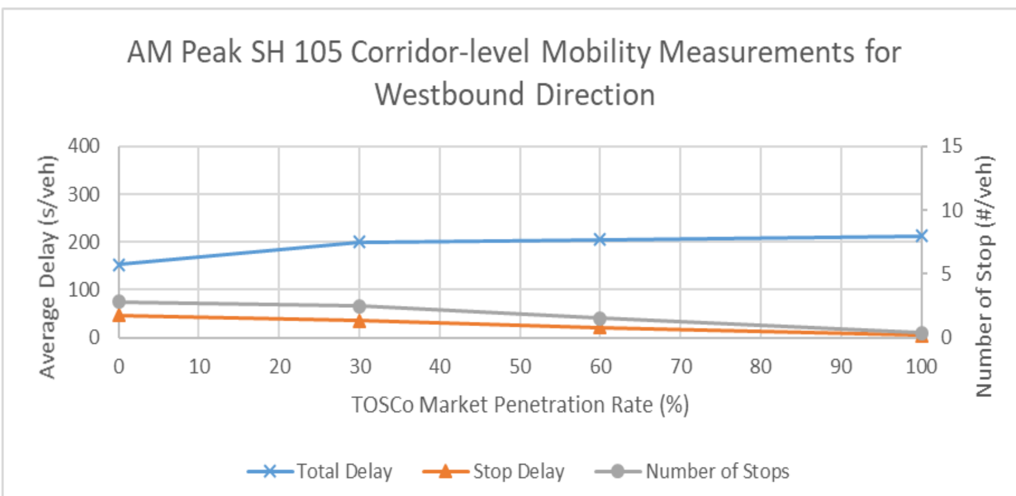
Cumulative Delays and Stops

Figure 20 and figure 21 show the total delay, stop delay, and the number of stops per vehicle aggregated over all intersections in the corridor in both directions for various levels of market penetration in the AM peak period. Note that this figure is for all vehicle types, including both TOSCo and non-TOSCo vehicles combined. Table 30 and table 31 show the values and percent changes for figure 20 and figure 21.



SH 105 = State Highway 105.

Figure 20. Chart. AM peak corridor-level mobility measures for SH 105 EB (Feng et al. 2019).



#/veh = number per vehicle; s/veh = s per vehicle.

Figure 21. Chart. AM peak corridor-level mobility measures for SH 105 WB (Feng et al. 2019).

Table 30. Mobility comparison at the corridor level in the AM peak—all vehicle types (EB).

Market Penetration Rate (Percent)	Total Delay (s/Vehicle)	Percent Change[1]	Stop Delay (s/Vehicle)	Percent Change[1] (Percent)	Number of Stops per Vehicle	Percent Change[1] (Percent)
0	153.2	—	45.6	—	2.82	—
30	199.9	30.5	42.6	-6.6	5.33	89.0
60	205.6	34.2	26.7	-41.5	4.39	55.5
100	213.1	39.1	9.9	-78.4	0.87	-69.3

—No data (base case).

[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Table 31. Mobility comparison at the corridor level in the AM peak—all vehicle types (WB).

Market Penetration Rate (Percent)	Total Delay (s/Vehicle)	Percent Change[1]	Stop Delay (s/Vehicle)	Percent Change[1]	Number of Stops per Vehicle	Percent Change[1]
0	126.9	—	46.4	—	2.82	—
30	145.8	15	35.1	-24	2.48	-11.9
60	157.2	24	20.9	-55	1.49	-47.0
100	162.2	28	4.4	-90	0.34	-87.9

—No data (base case).

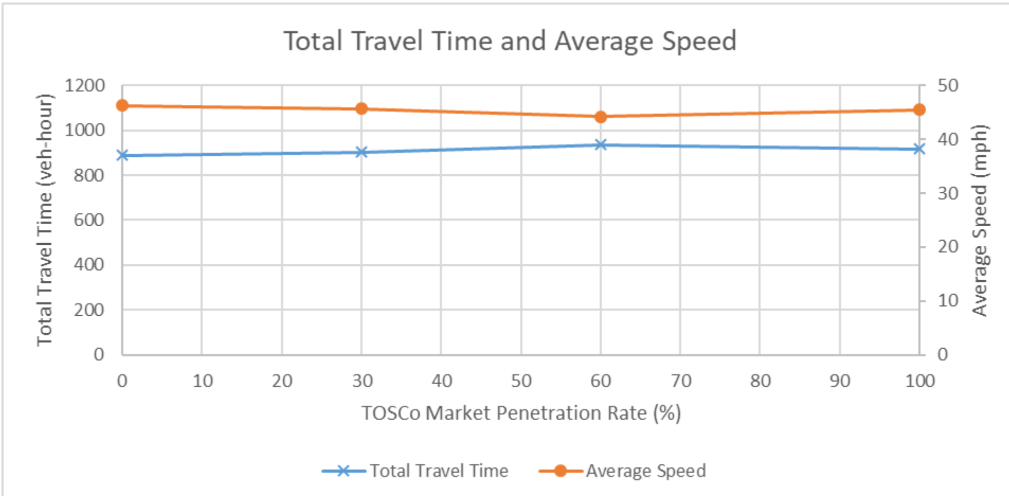
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

These figures and tables show that the general trend in the undersaturated corridor is that the average total delay per vehicle increases slightly in both directions of travel as market penetration increases. The total delay increases from 153.2 s to 213.1 s in the EB direction and from 126.9 s to 162.2 s in the WB direction. This is a 59.9-s increase in the EB direction and a 35.3-s increase in the WB direction. These increases in total delay are expected, because the TOSCo algorithm is designed to slow vehicles approaching in intersections further upstream to minimize their likelihood of stopping at the intersection. It should be noted that these increases are spread over 15 total intersections in a 12-mi-long corridor.

The greatest benefits of deploying TOSCo are in stopped delay and in the average number of stops per vehicle in the corridor. Table 30 and table 31 show that average stop delays and the number of stops per vehicle in the corridor decreased substantially by activating TOSCo. Stopped delays decrease by 35.7 s and 42.0 s in the EB and WB directions of travel, respectively. The average number of stops per vehicle decreases from 2.82 to 0.87 stops per vehicle in the EB direction and from 2.82 to 0.34 stops per vehicle in the WB direction.

Travel Time and Average Speed

Figure 22 and table 32 show the total travel time and average speeds on SH 105. There are slight decreases in average speeds and increases in total travel time up to 5.2 percent as the market penetration of TOSCo vehicles increases. These changes are not large and are caused by TOSCo's design to lower speeds to avoid a stop or to adhere to the speed limit.



veh-hour = vehicle-hour.

Figure 22. Chart. Total vehicle-hours traveled and average speeds for AM peak (Feng et al. 2019).

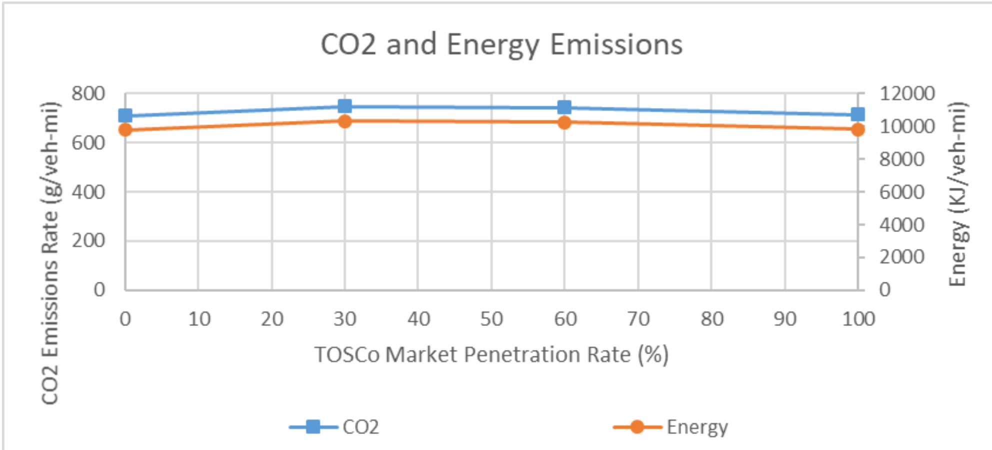
Table 32. Total vehicle-hours traveled and average speed values for AM peak.

Market Penetration Rate (Percent)	Total Travel Time (Vehicle-hours)	Percent Change[1]	Average Speed (mph)	Percent Change[1]
0	889	—	46.2	—
30	902	1.5	45.6	-1.3
60	936	5.2	44.2	-4.4
100	918	3.3	45.5	-1.7

—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase while a negative value implies a reduction in the performance measure.

Emissions and Energy Consumption

Figure 23 and table 33 show the carbon dioxide and total energy results in g per vehicle mi. Emissions and energy rates increase slightly in the 30 percent and 60 percent market penetration rates (MPRs) and return to values similar to the baseline at the 100-percent MPR scenario. These changes are likely caused by the increases in stops and the slight changes in average speed, since the MOVES model is very sensitive to changes in speeds. The team needs to investigate environmental impacts in the high-speed corridor further in future work.



CO_2 = carbon dioxide; g/veh-mi = g per vehicle-mi; kJ/veh-mi = kilojoules per vehicle-mi.

Figure 23. Chart. Carbon dioxide emissions and energy usage rates for AM peak (Feng et al. 2019).

Table 33. Emissions and energy use across Traffic Optimization for Signalized Corridors market penetration rates for AM peak.

Market Penetration Rate (Percent)	Carbon Dioxide Emissions (g/vehicle-mi)	Percent Change[1]	Total Energy (kJ/vehicle-mi)	Percent Change[1]
0	710	—	9,786	—
30	748	5.3	10,305	5.3
60	743	4.6	10,235	4.6
100	714	0.4	9,830	0.4

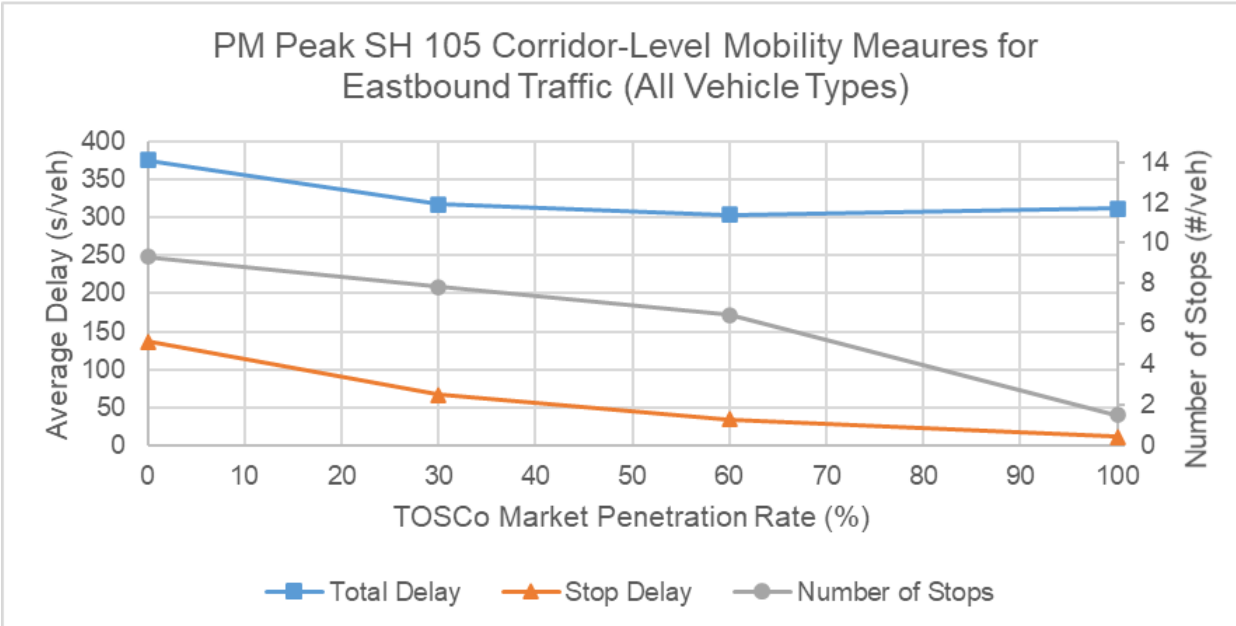
—No data (base case).
[1]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

PM Peak Performance Results

TOSCo's performance on the SH 105 corridor for the PM peak was also investigated. The PM peak conditions are oversaturated in both directions at several intersections along SH 105. The traffic volumes in both EB and WB directions are more evenly distributed. The EB direction is still the direction with the peak flow. EB traffic remains the peak direction because the PM peak period involves trips to shopping locations along SH 105 in addition to commuter traffic. The PM peak simulation also used the baseline, and 30, 60, and 100 MPRs and has one simulation seed for each scenario.

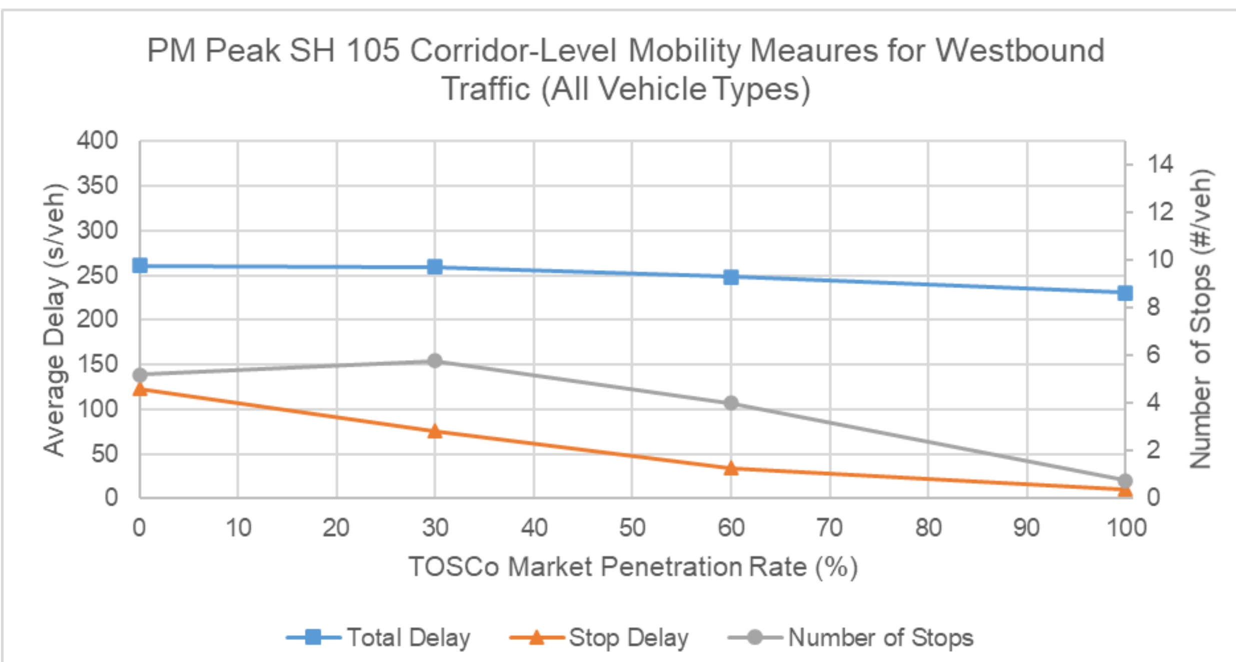
Cumulative Delays and Stops

The delay and number of stops results for EB and WB directions of travel are shown in figure 24 and figure 25, and the values and percent changes are shown in table 34 and table 35.



#/veh = number per vehicle; s/veh = s per vehicle.

Figure 24. Chart. PM peak corridor-level mobility measures for SH 105 (EB)—all vehicle types (Feng et al. 2019).



#/veh = number per vehicle; s/veh = s per vehicle.

Figure 25. Chart. PM peak corridor-level mobility measures for SH 105 (WB)—all vehicle types (Feng et al. 2019).

Table 34. PM peak mobility comparison at the corridor level—all vehicle types (EB).

Market Penetration Rate (percent)	Total Delay (s/Vehicle)	Percent Change[1]	Stop Delay (s/Vehicle)	Percent Change[1]	Number of Stops per Vehicle	Percent Change[1]
0	376.0	—	137.1	—	9.3	—
30	317.4	-15.6	67.0	-51.1	7.8	-15.9
60	304.3	-19.1	34.4	-74.9	6.5	-30.6
100	312.2	-17.0	11.2	-91.8	1.5	-84.0

—No data (base case).
[1]From 0 percent MPR. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Table 35. PM peak mobility comparison at the corridor level – all vehicle types (WB).

Market Penetration Rate (percent)	Total Delay (s/Vehicle)	Percent Change[1]	Stop Delay (s/Vehicle)	Percent Change[1]	Number of Stops per Vehicle	Percent Change[1]
0	260.7	—	123.0	—	5.2	—
30	259.5	-0.4	75.9	-38.3	5.8	11.0
60	247.9	-4.9	34.2	-72.2	4.0	-23.1
100	230.6	-11.5	10.4	-91.6	0.8	-85.6

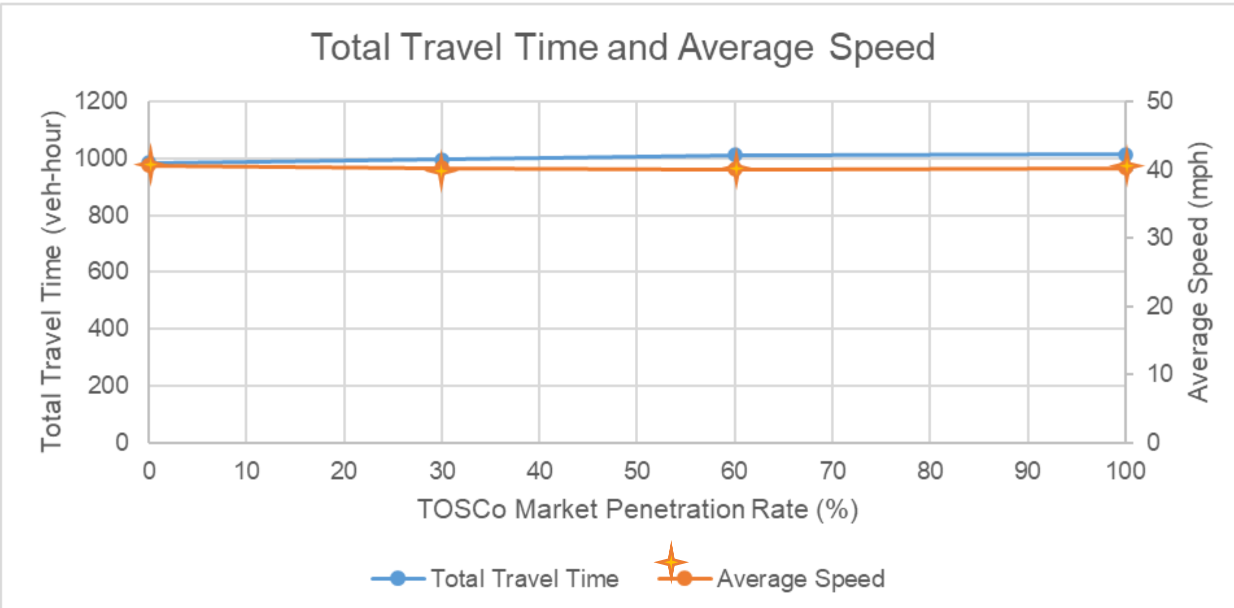
—No data (base case).
[1]From 0% MPR. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

The similar volumes and conditions in both directions lead to similar results in the two directions in the PM peak scenario. Both directions experience gradual reductions in stop delay and number of stops as market penetration of TOSCo increases. The WB direction experiences a slight increase in number of stops between the baseline and 30-percent MPR and then consistently decreases in the other scenarios. Total delay per vehicle decreases significantly between the baseline and the 30-percent MPR scenario in the heavier EB direction and remains constant for the remaining scenarios.

The WB direction experiences a slight increase in number of stops between the baseline and 30-percent MPR and then consistently decreases in the other scenarios. The WB stop delay gradually decreases as MPR goes up. Total delay remains approximately constant between the baseline and the 30-percent MPR scenario and then gradually decreases in the 60-percent and 100-percent MPRs.

Travel Time and Average Speed

Figure 26 and table 36 show the total travel time, average speed, and percent change results from the PM peak. These measurements remain constant across increased TOSCo MPR, despite reductions in total delay for vehicles traveling from end to end of the corridor. This measurement includes vehicles on cross streets and turning movements, which indicates that, although there are marginal increases in travel speed for vehicles going end to end on SH 105, the overall average speeds for all users on SH 105 remains constant with increasing TOSCo MPR.



veh-hour = vehicle-hour.

Figure 26. Chart. PM peak total vehicle hours traveled and average speeds for high-speed corridor (Feng et al. 2019).

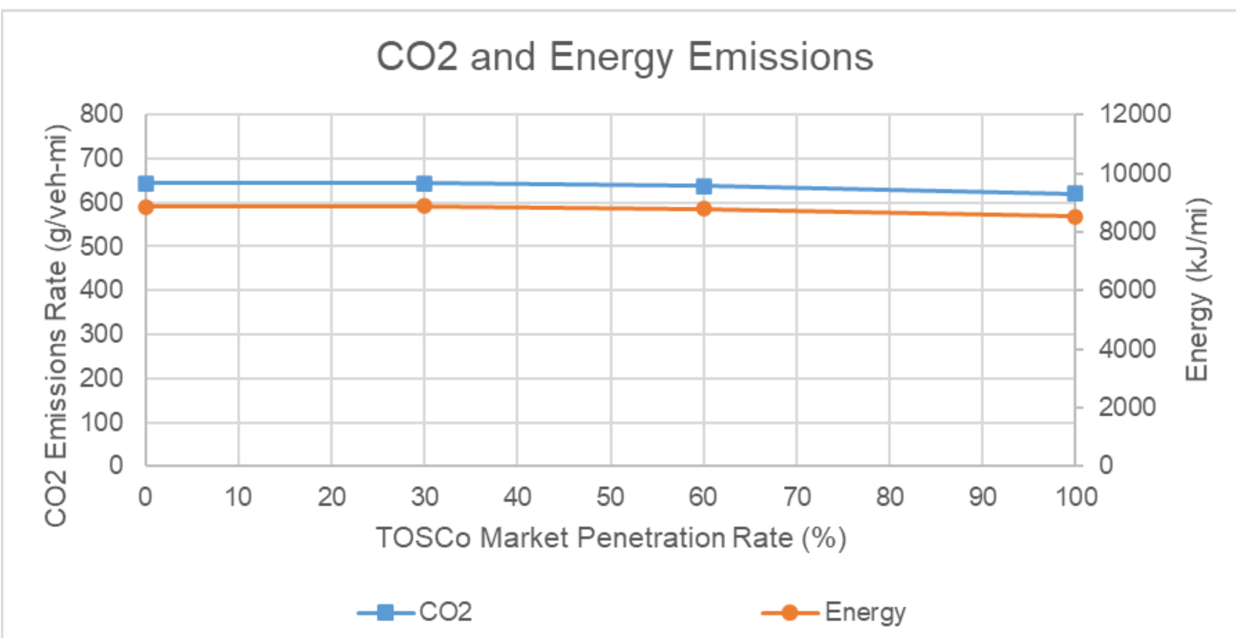
Table 36. PM peak total vehicle hours traveled and average speeds for high-speed corridor.

Market Penetration Rate (Percent)	Total Travel Time (Vehicle-hours)	Percent Change[1]	Average Speed (mph)	Percent Change[1]
0	984	—	40.6	—
30	997	1.3	40.2	-0.9
60	1011	2.7	40.1	-1.3
100	1016	3.2	40.3	-0.7

—No data (base case).
[1]From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.

Emissions and Energy Consumption

The emission and percent change results for the PM peak period are shown in figure 27 and table 37. There is a slight reduction in emission rates and energy consumption at higher TOSCo MPR in the PM peak period. Like the AM peak emissions, these changes are small compared to the magnitude of the emission rates. The reduction in emissions for the PM peak simulation is consistent with the reductions in stops.



CO_2 = carbon dioxide; g/veh-mi = g per vehicle-mi; kJ/veh-mi = kilojoules per vehicle-mi.

Figure 27. Chart. PM peak CO_2 emissions and energy usage rates for high-speed corridor (Feng et al. 2019).

Table 37. PM peak emission and energy use for high-speed corridor.

Market Penetration Rate (Percent)	Carbon Dioxide Emissions (g/vehicle-mi)	Percent Change[1]	Total Energy (kJ/vehicle-mi)	Percent Change[1]
0	643	—	8860	—
30	645	0.2	8879	0.2
60	638	-0.8	8786	-0.8
100	620	-3.6	8538	-3.6

—No data (base case).
[1]From 0% MPR. A positive value implies an increase, while a negative value implies a reduction in the performance measure.

Dedicated Short-Range Communication Range Sensitivity Assessment

The DSRC range impact was assessed by comparing the results from the analysis to another data set, where the DSRC range was limited to 985 ft for all intersections. One seed per DSRC range scenario was used. Table 38 through table 43 show how the DSRC range affected the performance of the TOSCo system in the SH 105 corridor. These tables show only the results for the AM peak direction of travel (EB) on SH 105. In these tables, if the performance with the 3,280-ft DSRC range was better than the 985-ft DSRC range, then the net effect of change in the DSRC range was positive. Similarly, if the performance with the 3,280-ft DSRC range was worse than the 985-ft DSRC range, then the net effect of changing the DSRC ranges was negative.

Table 38. Effect of DSRC range on total delay (s/vehicle).[1]

Market Penetration Rate (percent)	DSRC Range (985 ft)	Percent Change[2]	DSRC Range (3,280 ft)	Percent Change[2]	Net Effect on Total Delay
0	146.4	—	146.4	—	—
30	165.8	13.25	161.8	10.47	Delay decreased
60	167.1	14.15	166.1	13.46	Delay decreased
100	157.7	7.70	172.2	17.60	Delay increased

—No data (base case).
[1]EB direction only.
[2]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a decrease in the performance measure.

The increased DSRC range does not have a clear impact on TOSCo performance. The total delay increases less than the shorter range in the intermediate penetration rates and finally produces much more delay at higher market penetration rates.

Table 39 presents the stop delay results for the two DSRC ranges for the EB direction. The stop delays between the two DSRC ranges are similar. The 30-percent penetration rate scenario technically has less stop delay in the 3,280-ft DSRC range, but the larger difference between the two DSRC ranges in the 100-percent scenario indicates there is less stop delay with less DSRC range in this simulation.

Table 39. Effect of DSRC range on stop delay (s/vehicle).[1]

Market Penetration Rate (percent)	DSRC Range (985 ft)[1]	Percent Change[2]	DSRC Range (3,280 ft)[1]	Percent Change[2]	Net Effect on Stop Delay
0	45.5	—	45.5	—	—
30	37.4	-17.79	35.9	-20.99	Delay decreased
60	20.2	-55.54	22.4	-50.76	Delay increased
100	3.2	-93.06	7.5	-83.41	Delay increased

—No data (base case).
[1]EB direction only.
[2]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a decrease in the performance measure.

The number of stops per vehicle results across market penetration rates for the two DSRC ranges are shown in table 40. The number of stops results for the two DSRC ranges do not show any clear trend for the increased DSRC range performing better than the limited range. Rather, some of the penetration rate scenarios perform better with increased range, and other scenarios perform worse. Note that the largest difference in the number of stops per vehicle between the DSRC ranges is the 60-percent scenario with a difference of 0.35 stops per vehicle, which is a small value.

Table 40. Effect of DSRC range sensitivity on number of stops.[1]

Market Penetration Rate (Percent)	DSRC Range (985 ft)	Percent Change[2]	DSRC Range (3,280 ft)	Percent Change[2]	Net Effect on Number of Stops
0	2.85	—	2.85	—	—
30	3.62	26.80	3.58	25.73	Stops decreased
60	3.80	33.36	3.45	20.87	Stops decreased
100	0.59	-79.24	0.65	-77.24	Stops increased

—No data (base case).
[1]EB direction only.
[2]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a decrease in the performance measure.

Table 41 presents the differences in average speeds between the two DSRC ranges. The average speeds for the increased DSRC range are consistently lower than the lower DSRC range. The lower speeds make sense because, with increased DSRC range, TOSCo vehicles have additional space to travel at a speed equal to or less than the speed limit to arrive at the intersection during the green window. Furthermore, with increased DSRC range, vehicles with a set speed above the speed limit must reduce speeds so their travel speeds are within the speed limit, contributing to lower average speeds on SH 105. Note the differences in average speeds due to increased DSRC range are small and never exceed 1 mph in magnitude.

Table 41. Effect of DSRC range sensitivity on average speed (mph).[1]

Market Penetration Rate (Percent)	DSRC Range (985 ft)	Percent Change[2]	DSRC Range (3,280 ft)	Percent Change[2]	Net Effect on Average Speed
0	41.9	—	41.9	—	—
30	41.1	-1.87	41.1	-1.89	None
60	40.9	-2.54	40.7	-2.99	Speed decreased
100	41.1	-2.05	40.5	-3.50	Speed decreased

—No data (base case).
[1]EB direction only.
[2]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a decrease in the performance measure.

To see the impact of DSRC range on total travel times, refer to table 42. Increased DSRC range shows less of an increase in total travel time at lower market penetrations than the lower-range DSRC. However, at higher market penetrations, the total travel time experiences a larger increase with a larger DSRC range.

Table 42. Effect of DSRC range sensitivity on total travel time (vehicle-hour).[1]

Market Penetration Rate (Percent)	DSRC Range (985 ft)	Percent Change[2]	DSRC Range (3,280 ft)	Percent Change[2]	Net Effect on Total Travel Time
0	1,486	—	1,486	—	—
30	1,540	3.59	1,516	1.97	Travel time decreased
60	1,552	4.38	1,542	3.76	Travel time decreased
100	1,550	4.30	1,566	5.37	Travel time increased

—No data (base case).
[1]EB direction only.
[2]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a decrease in the performance measure.

Table 43 presents the impact of carbon dioxide emissions. The DSRC sensitivity analysis for the high-speed corridor shows that increased DSRC range does not consistently improve TOSCo function. Increased DSRC range tends to have worse performance than the 985-ft range at high market penetration. This result is attributed to the fact that the infrastructure algorithm uses the current queue length rather than a predicted queue length to determine a green window. The use of the current queue length means that with increased DSRC range, TOSCo vehicles receive information that may not be relevant to the vehicle because the queue lengths might grow, or the signal actuation may gap out the side street while the TOSCo vehicle is approaching.

Table 43. Effect of DSRC range sensitivity on carbon dioxide emissions (g /mi).[1]

Market Penetration Rate (percent)	DSRC Range (985 ft)	Percent Change[2]	DSRC Range (3,280 ft)	Percent Change[2]	Net Effect on Carbon Dioxide Emissions
0	313.6	—	313.6	—	—
30	317.2	1.14	319.1	1.74	Emission increased
60	316.9	1.05	317.1	1.11	Emission increased
100	309.2	-1.40	313.8	0.07	Emission increased

—No data (base case).
[1]EB direction only.
[2]From a 0 percent market penetration rate. A positive value implies an increase, while a negative value implies a decrease in the performance measure.

DISCUSSION OF PERFORMANCE RESULTS

According to both AM and PM peak results, TOSCo significantly reduces stop delay for all vehicle types as market penetration increases. This is one of the primary functions of the TOSCo system, and therefore reductions in stop delay are expected.

The emission rates at high speed remained constant as TOSCo market penetration increased. A University of California Riverside study shows that at average speeds of about 40 mph, the emission rates tend to be constant as the average speeds change (Barth and Boriboonsomsin 2008). Therefore, the speeds on SH 105 reside in an ideal spot for emission rates.

The AM and PM peak periods also have different trends in mobility measurements. These difference trends are primarily due to all intersections being undersaturated during the AM peak and some intersections being saturated during the PM peak. None of the intersections during the AM peak have average queue-length behavior that indicates saturated conditions, meaning the queue length grows longer over time until demand eventually decreases enough that the queue length begins to reduce. The PM peak does have saturated conditions at intersections, meaning that some vehicles in an EB or WB queue on SH 105 are not able to clear the intersection in the allotted green time for that phase. Figure 28 shows the queueing behavior for each market penetration rate for a saturated movement in the PM peak period at Old River Road in the EB direction. There is a large reduction in delay, and reduction in delays for vehicles across all the intersections were observed. The total travel time metric shows the travel time for all vehicles on the facility, including cross streets and turning movements. The cross-street and turning traffic are among the factors, including potential increases in delay at unsaturated intersections, that explain the change in saturated conditions and the total travel time results.

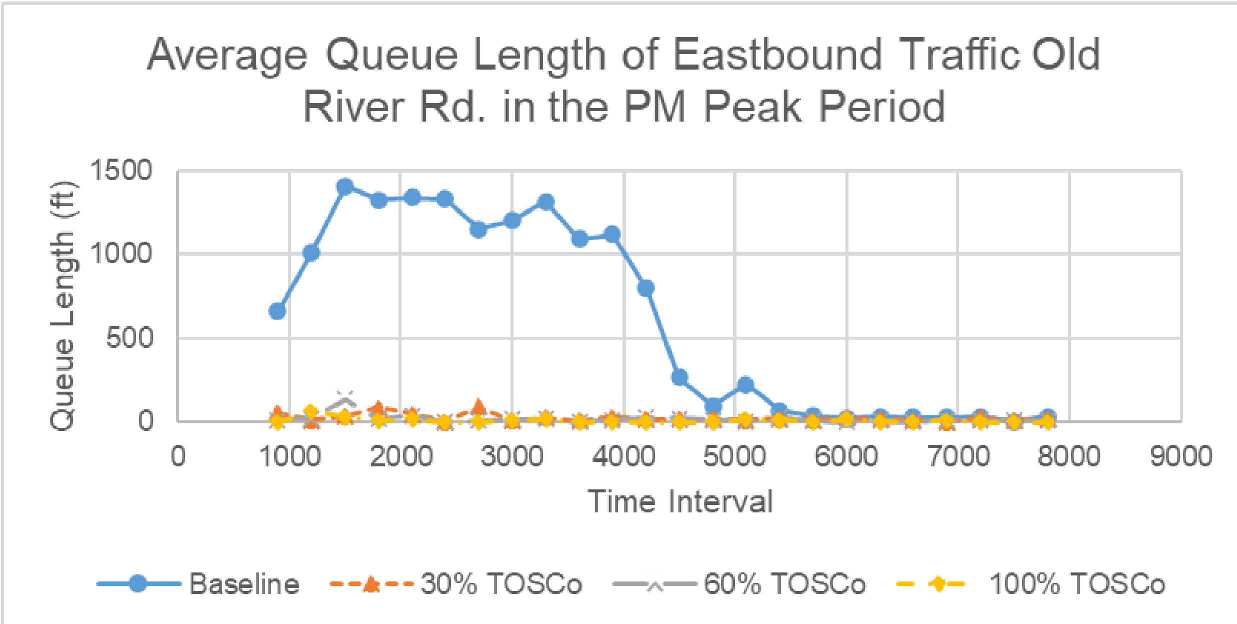


Figure 28. Chart. Average EB queue lengths across PM peak period at Old River Road (Feng et al. 2019).

TOSCo was able to provide enough increased capacity, via reduced headways between vehicles, in the 30-percent market penetration rate scenario to address the saturated conditions in the EB direction at Old River Road in the PM peak period. There is a possibility the saturated conditions at Old River Road can be addressed at lower market penetration rates, since this analysis did not consider incremental market penetration rates between the baseline and 30 percent. There is a marginal difference in the queueing behavior between the 30-, 60-, and 100-percent market penetration rates, since each case is now undersaturated. Figure 29 shows the average EB queue across the simulation at Old River Road in the AM peak baseline. The horizontal line near zero of average queue length for the baseline indicates the AM peak does not have any saturated conditions and therefore does not benefit from the reduced headways of TOSCo. Since none of the intersections in the AM peak period are saturated, there are no locations in the AM peak period where increased capacity from TOSCo is observable. The research team observed TOSCo increasing capacity in both directions in the PM peak period.

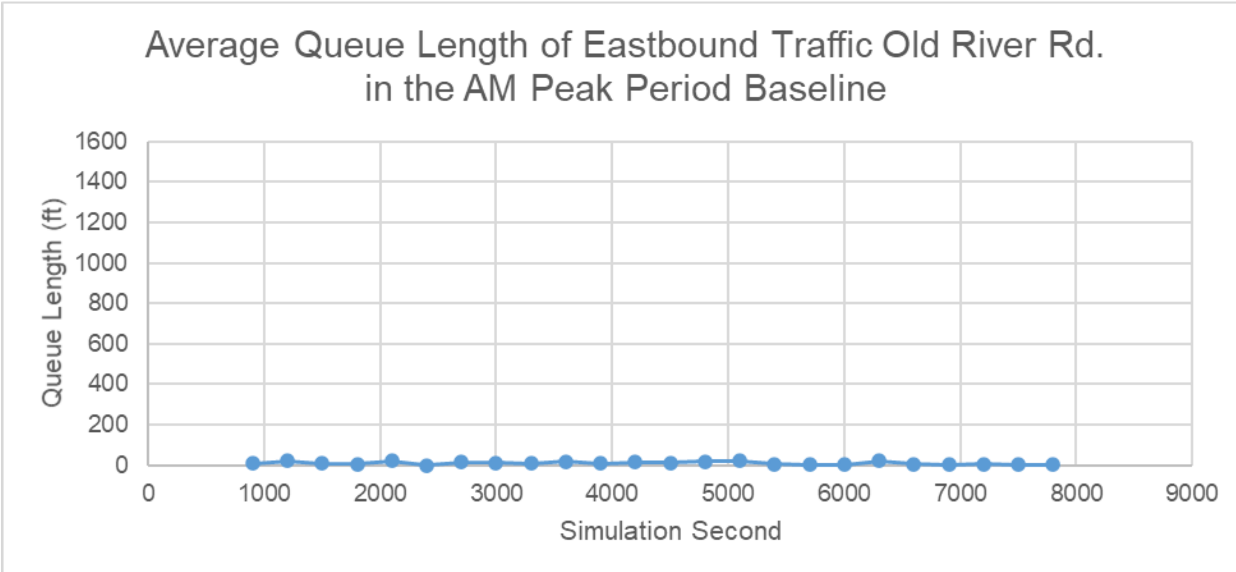


Figure 29. Chart. Average EB queue lengths across AM peak period baseline at Old River Road (Feng et al. 2019).

The differences in the average travel speeds per direction for both peak periods were explored. Figure 30 presents the average speeds for each direction in the AM and PM peak periods. TOSCo brought the travel speeds in both directions and peak periods toward the same average value.

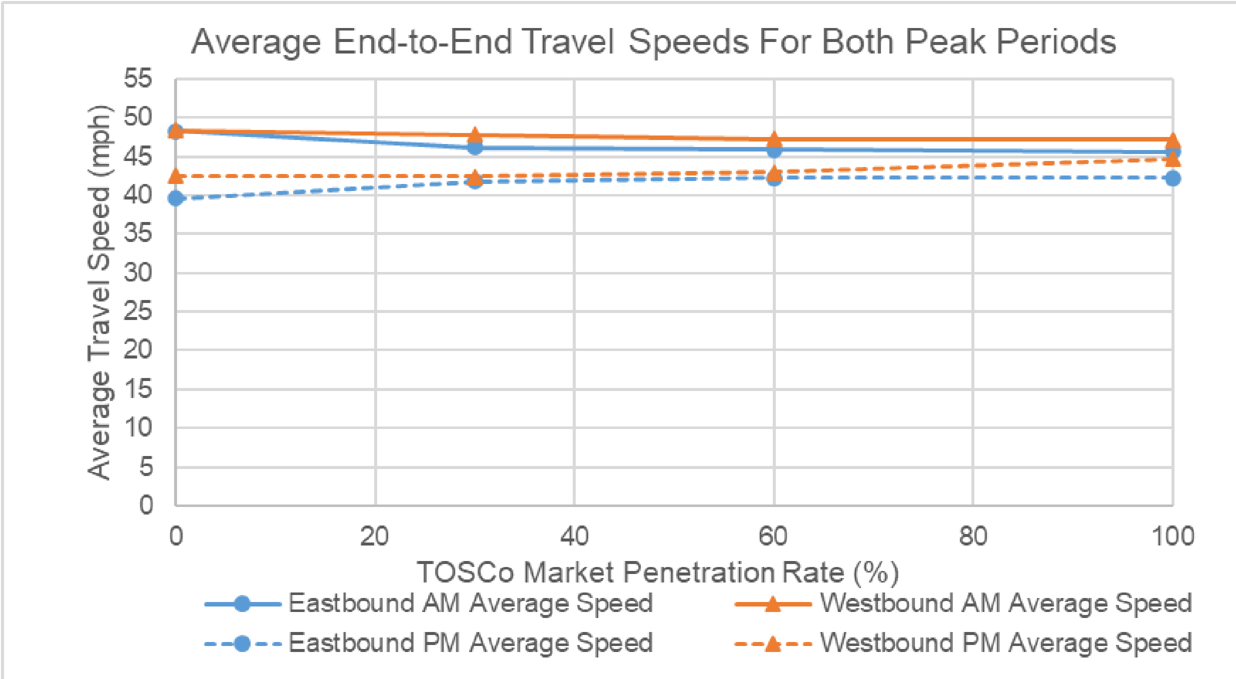


Figure 30. Chart. Average end-to-end travel speed results on SH 105 for AM and PM peak periods (Feng et al. 2019).

CHAPTER 7. CONCLUSION

This report leveraged an FHWA project (Feng et al. 2019) to document two case studies on the traffic-level simulation and performance analysis for the TOSCo in a high-speed corridor in Conroe, TX, and a low-speed corridor in Ann Arbor, MI. This report shared the latest research results about the mobility and environmental benefits of TOSCo for public agencies, academia, and private sectors interested in evaluating and deploying TOSCo to achieve early deployment benefits of CAVs. All results of this report are from the traffic-level simulation and performance analysis report of an FHWA project (Feng et al. 2019).

A computer simulation environment was developed to evaluate the effectiveness and potential mobility and environmental benefits of the TOSCo system in both low- and high-speed corridor environments. Using the evaluation environment, simulation experiments were conducted to quantify the potential mobility and environmental benefits associated with deploying the TOSCo system in a variety of settings and with different infrastructure-based methodologies for providing queue information. The simulation evaluation environment was used to:

- Assess the potential mobility and environmental benefits of using TOSCo in different operating environments: a low-speed corridor (Plymouth Road, Michigan), and a high-speed corridor (SH 105, Texas).

- Quantify the impact of different market penetration rates of TOSCo-equipped vehicles on mobility and environmental benefits.

- Assess different infrastructure algorithms for estimate queuing: a BSM and loop-detector approach on the low-speed corridor and a radar-based detector approach on the high-speed corridor.

The development of the TOSCo simulation environment has been a significant outcome. This innovative environment has proved to be an invaluable tool for supporting the development and assessment of TOSCo functionality. The environment consists of three platforms: vehicle simulation, infrastructure simulation, and performance assessment. The vehicle simulation platform was built specifically to test and verify vehicle decision and control processes. Using a series of three simulation models, the vehicle simulation platform allows the ability to test and verify algorithm code that will eventually reside in TOSCo-enabled vehicles. The infrastructure simulation platform was developed to test and verify detection and processing algorithms that reside on infrastructure devices. This platform is used to simulate the detection outputs of different queue detection methodologies and to access accuracy and precisions impacts of queue estimates on TOSCo processes. The TOSCo performance assessment platform was developed to quantify the potential intersection, corridor, and network-level benefits of deploying TOSCo in the real world. Using simplified vehicle and infrastructure logic, this platform provides the ability to examine the environmental and mobility benefits associated with operating conditions and scenarios. All three platforms have greatly enhanced the ability to explore innovations, identify issues, and accelerate the development of systems and processes toward actual implementation. The simulation environment platforms will continue to be used to develop, refine, and evaluate the infrastructure and vehicle algorithms throughout the life of the TOSCo project.

SUMMARY OF METHOD AND RESULTS

The following discussions summarize the benefits produced by the simulation experiments.

Mobility and Environmental Benefits

The following mobility and environmental benefits were observed by implementing TOSCo in the two corridors:

- TOSCo produced substantial reductions in stop delays and the number of stops in both corridors. Stop delays decreased 40 percent in the low-speed corridor and 80 percent in the high-speed corridor after TOSCo was implemented. Similar reductions in the total number of stops were recorded in both corridors.

- TOSCo did not cause substantial changes in the total delay experienced by travelers in the two corridors. As TOSCo vehicles were slowing down further upstream of intersections, minor changes in total delay were expected, but these changes are not likely to be noticeable to travelers.

- Total travel time and travel speed were not significantly affected by implementing TOSCo in either corridor.

- TOSCo did not have a substantial impact on vehicle emissions or fuel consumption. However, TOSCO did result in minor reductions in HC and NOx in each corridor. One potential reason for not seeing significant changes in air quality benefits is that average speed was not significantly affected by TOSCo.

High-Speed versus Low-Speed Corridors

Different corridors had the following impact on TOSCo performance:

- The TOSCo system produced similar mobility benefit trends in both low-speed and high-speed corridors.

- Low-speed corridors, from an emission standpoint, tended to have more sensitive changes in travel speed. Changes in emissions were greater for smaller changes in speed.

Impact of Market Penetration

Market penetration had the following impact on the expected TOSCo performance:

- The string of TOSCo vehicles formed more easily as penetration rates increased. This result caused more vehicles to drive in a cooperative fashion. With more strings, queues at intersections can clear faster due to TOSCo's coordinated launch feature.

- The market penetration rate of TOSCo vehicles increased along with the accuracy of the queue prediction for BSM-based queue estimation algorithm, implemented in the low-speed Ann Arbor corridor.

According to the results of the TOSCo simulation experiment, TOSCo generates significant mobility and environmental benefits for both low-speed and high-speed corridors. Although both the city of Ann Arbor, MI, and the city of Conroe, TX, do not have any specific CAV strategic plans, these two cities are interested in CAV technologies and involved in CAV-related projects by collaborating with local research institutions. These two cities also expect to use emerging technologies (e.g., CAV) to solve existing transportation issues (e.g., congestion and safety). Therefore, TOSCo is a promising CAV application that could be implemented to improve mobility, safety, and environmental impact of existing transportation systems.

LIMITATIONS AND FUTURE RESEARCH

The following recommendations were developed based on modeling the potential mobility and environmental benefits of the TOSCo system.

TOSCo Parameters Selection

Due to different roadway characteristics and driving behaviors, the traffic environments at the two corridors differ significantly. For example, non-TOSCo vehicles at the low-speed corridor have moderate acceleration profiles, while non-TOSCo vehicles at the high-speed corridor have more aggressive acceleration profiles. The differences in surrounding traffic have a great impact on TOSCo vehicle behavior, especially in a mixed-traffic condition. TOSCo vehicles under coordinated launch could not catch up with leading non-TOSCo vehicles because of the limitation of maximum acceleration settings. Non-TOSCo vehicles that have higher desired speeds are also blocked by TOSCo vehicles in the same lane. As a result, TOSCo parameters (e.g., maximum acceleration and CACC set speed) should be selected to match the corridor characteristics and driving behaviors.

TOSCo Vehicle Recommendations

The following recommendations for TOSCo vehicles are based on the simulation analysis conducted for both testbeds:

- TOSCo vehicles need to utilize profiles that accelerate differently than the analyzed version. Acceleration from a stop should incorporate a buildup of the acceleration, constant acceleration, and a reduction of acceleration so that a TOSCo vehicle is able to reach desired speed in a reasonable amount of time. Such an algorithm needs to provide desired behavior in both low- and high-speed scenarios.

- TOSCo vehicles need to be coded to account for unexpected queues or vehicles changing lanes in front of them. In these simulation experiments, a manually driven vehicle could change lanes in front of a TOSCo vehicle, thereby forcing a reaction.

- The simulations must be revised with the final vehicle-level algorithm and evaluated to understand the benefits of the revised TOSCo algorithm.

- Speeds in all modes of TOSCo, except for the free-flow region mode, were limited to the posted speed limit. Thus, when TOSCo operations are compared to the baseline traffic (which is not limited to the speed limit), the mobility benefits may be underestimated. Future work is recommended to examine the impact of this constraint.

- TOSCo-vehicle algorithms that are expanded are to account for the following:

  - Nontrivial initial acceleration for trajectory planning.
  - Inclusion of road grade change.
  - Customization of different power-train characteristics.
  - The imperfection of sensors (e.g., GPS) and communications.

TOSCo Infrastructure Recommendations

The following recommendations for TOSCo infrastructure are based on the simulation analysis conducted for both testbeds:

- The simulation experiments assume that the lateral and longitudinal positions of vehicles can be detected by sensors installed at an intersection. More research is needed to understand the limitations of field equipment to better simulate the TOSCo infrastructure component.

- Data in this report indicate that predictive queue estimation performs better with the increased DSRC range than current queue information used for the green window calculation. More simulation should be run to analyze which queueing information is most helpful for TOSCo.

TOSCo Implementation

Results from both corridors show that TOSCo is less effective at low traffic volume and low delay intersections. When the traffic volume is low, or signal coordination provides good progression, most of the vehicles do not need to stop or slow down at the intersection, which leaves very limited space for adjusting vehicle trajectories. In addition, low traffic volume on the side streets may generate inaccurate SPaT information when the traffic signal of TOSCo approach is under the green rest state, unless minimum recall is in place. For those intersections with minimal benefits, it may not be necessary to activate the TOSCo function.

ACKNOWLEDGMENTS

Figure 4—The original map is the copyright property of Google® Map™ and can be accessed from https://www.google.com/map. The map overlays showing the locations of 11 intersections and key roadway names were added in 2019 by the CAMP V2I Consortium.

Figure 5—The original map is the copyright property of Google® Map™ and can be accessed from https://www.google.com/map. The map overlays showing signals along the route were added in 2019 by the Texas A&M Transportation Institute. The overlays include black circles showing the placement of the signalized intersections contained in black boxes showing the timing plan associated with the group of signals. This figure was altered by FHWA in 2020 to increase the font size.

Figure 8—The original map is the copyright property of Google® Map™ and can be accessed from https://www.google.com/map. The map overlays showing locations of intersections and tube count locations on SH 105 were added in 2019 by the Texas A&M Transportation Institute.

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