Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960

Final Report

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16. Abstract

This report summarizes the potential mobility and environmental benefits associated with deploying the Traffic Optimization for Signalized Corridor (TOSCo) System on the FM 1960 corridor in Houston, Texas. In this study, researchers integrated the TOSCo infrastructure and vehicle algorithms into a microscopic simulation model to simulate TOSCo performance under normal operating conditions. The researchers estimated performance under different market penetration levels in two different simulation environments. First the research team analyzed various TOSCo settings in a single intersection model of one of the intersections along FM 1960. Next, the team took the best, or revised, settings and the default TOSCo settings to the corridor model for analysis. The researchers found that the TOSCo system reduces the stop delay and the number of stops on an intersection and corridor basis. The simulated TOSCo system reduced total delay per vehicle with the revised settings along the FM 1960 corridor. However, close intersections on the FM 1960 corridor did experience increases in total delay with high TOSCo MPR because of TOSCo entering CREEP early. TOSCo also reduced fuel usage, but increased fuel usage initially because of increased stops of non-TOSCo vehicles. Overall TOSCo reduced stops, stop delay, and total delay in some cases.

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Executive Summary

The purpose of the Traffic Optimization for Signalized Corridors (TOSCo) system is to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based connected-vehicle communications to assess the state of vehicle queues and 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 is continuously recomputed and broadcast to approaching connected vehicles. By leveraging previous Crash Avoidance Metrics Partners LLC (CAMP)/Federal Highway Administration (FHWA) work on Cooperative Adaptive Cruise Control (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 emissions outcomes across the corridor.

When activated and outside of the communication range, TOSCo-equipped vehicles operate in a Free-flow mode (CACC). TOSCo-equipped intersections are constantly broadcasting information about the intersection geometry, status of the signal phase and timing (SPaT) at the intersection (J2735 SPaT message), and the presences of any traffic waiting in queues at the intersection. As a TOSCo-equipped vehicle enters the communication range of at least 1000 feet at the intersection, it receives the intersection geometry, signal phase and timing and queue information. Using this information, the TOSCo vehicle then plans a speed profile that would allow 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 must stop at an intersection perform a coordinated launch maneuver at the start of a green window that allows them to clear the intersection in a more efficient manner than manual driving. Once the TOSCo vehicles leave the communications range of the intersection, they revert to their previous operating mode, Free Flow.

TOSCo vehicles use the speed profile computations to the intersection stop location to determine the appropriate operating mode. The TOSCo vehicle behavior can be represented as one of the following operating states:

- Free Flow
- Coordinated Speed Control
- Coordinated Stop
- Stopped
- Coordinated Launch
- Creep

A brief description of each of these operating modes is provided within the report. Free Flow mode is for when TOSCo is unable to provide a speed profile, or the vehicle is outside of communication range. The other operation modes are for cases where the vehicle determines to either speed up, maintain speed, slow down, or stop and start moving after the signal indication turns from red to green.

The infrastructure subsystem of TOSCo provides information to help the vehicles approach an intersection. The infrastructure is required to provide SPaT and intersection geometry data in MapData (MAP) messages 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 as well as information about the time until the next change in the signal indication state. The research team is using regional extensions in the SPaT message to broadcast green window and queue length information. The research team refers to a SPaT message with green window and queue information as an enhanced SPaT message. The MAP 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 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. The SPaT message is broadcast at 10 Hz while the MAP information is broadcast at 1 Hz. In simulation, the SPaT data comes from the software controller and the MAP data is not simulated since the simulation is automatically able to match the vehicles to lanes as observed in the field.

One major component to the traffic-level representation is that the TOSCo Performance Assessment Environment uses source code from both the vehicle and infrastructure alogorthms to represent TOSCo behavior. The resulting driver model was used to evaluate the performance of TOSCo by estimating potential benefits at a single intersection, corridor and network resolution. These benefits include a reduction in emissions, fuel savings, and improved mobility as described below. These performance measures were collected for different market penetration rates of TOSCo-enabled vehicles.

The research team built and utilized a VISSIM model of FM 1960 to assess benefits of an updated version of TOSCo developed in Phase 2. The corridor along Texas Farm-to-Market Road 1960 (FM 1960) consists of 13 intersections in north Houston, Texas between Westfield and Humble, Texas covering about 7 miles. The posted speed limit in most of the analysis corridor is 55 mph, with the easternmost two miles posted at 50 mph. It takes about twelve minutes to drive from one end of the corridor to the other. The research team calibrated the model based on travel time data available through the National Performance Management Research Data Set (NPMRDS) analytics website. The simulation covered a range of market penetration rates of TOSCo on the simulated corridor. The research team used a single intersection extracted from the corridor model as a testbed to analyze various settings for TOSCo and incorporate those findings into a set of revised parameters for a second analysis of TOSCo on the corridor.

The following provides a summary of the mobility and environmental benefits observed by implementing TOSCo with the deployed, or default, settings in the FM 1960 simulation analysis.

- With default TOSCo settings, the eastbound total delay increases gradually but does not represent a large increase in the travel time associated with the trips. The westbound total delay decreases initially but has no significant changes at high market penetration rates.
- Default TOSCo was able to achieve reductions in stop delay and number of stops depending on the market penetration rate. Stop delay decreased by around 50 percent across the corridor as TOSCo MPR increases. TOSCo vehicles had lower number of stops than the baseline traffic in simulation.
- TOSCo showed improved performance for each respective vehicle class, TOSCo-equipped as well as non-equipped, in total delay, stop delay, as market penetration increased on most of the approaches.
- TOSCo did not cause substantial changes in the total travel time for vehicles on the FM 1960 network.

- TOSCo temporarily increased fuel consumption. Fuel use gradually decreased from the 20 percent MPR scenario until reductions in fuel use compared to the baseline were achieved around 40 or 90 percent TOSCo MPR depending on the direction of travel. The research team believes that the increases in fuel are caused by the increased stops caused by the interactions between TOSCo vehicles.
- The default TOSCo generated little impact on user costs based on travel time and fuel use in the MPR scenarios considered for this study.

The research team used the single intersection model to analyze several configurations of TOSCo. This helped guide the corridor model toward a revised configuration of TOSCo that would be used for a secondary analysis of the corridor model. The following statement summarizes the key findings from the single intersection model.

- TOSCo settings impact the ability of the TOSCo system to reduce the delays experienced by the vehicles. By allowing the speed trajectory to accept speeds higher than the posted speed limit, increasing TOSCo range, and allowing TOSCo vehicles to enter in yellow, reduced the amount of delay experienced relative to the default TOSCo settings. These delay reductions were increased further when the three changes in settings were combined into a “revised” representation of TOSCo.
- By allowing the vehicle to compute a long CSC-Down speed profile, it either made no difference in performance or led to worse performance than the default TOSCo behavior.
- With increased volumes, TOSCo was able to reduce the number of stops on the approach from many stops to less than one stop on the approach, indicating an increase in capacity at the intersection.
- The best performing modifications from the default configuration were to allow TOSCo vehicles to plan a trajectory at the set speed if it was above the speed limit, thus, allowing vehicles to enter on a yellow light with up to 2 seconds after the onset of yellow and doubling the TOSCo range.

The research team generated a revised configuration of TOSCo to consider in the corridor model based on the combination of the best settings from the intersection model. The following statements describe the results of the revised TOSCo configuration on the corridor.

- TOSCo reduced total delay in the eastbound and westbound directions with the revised TOSCo settings. However, the westbound total delay increased at high market penetration levels because of the difficulty experienced by turning vehicles attempting to change lanes to complete their maneuvers.
- TOSCo was able to achieve greater reductions in stop delay and number of stops with the revised TOSCo settings than the default settings. Stop delay decreased by around 50 percent across the corridor as TOSCo MPR increases.
- TOSCo showed greater improvements in performance for each respective vehicle class with the revised TOSCo settings compared to the default TOSCo settings in each performance metric.
- With the revised settings, TOSCo still did not cause substantial changes in the total travel time for vehicles on the FM 1960 network. The total travel time decreased slightly with 70 percent MPR, but the percent change was small.
- TOSCo increased fuel consumption initially and then reduced fuel consumption gradually as TOSCo MPR increased. The revised version of TOSCo experienced a maximum reduction in fuel use at 90 percent market penetration when the strings began to prevent turning traffic from completing their maneuvers. These reductions constituted a 16 percent reduction in fuel use for the eastbound direction and a 22 percent reduction in fuel use for the westbound direction.

- The revised TOSCo also temporarily increased fuel consumption fuel use gradually decreased from the 20 percent MPR scenario. The research team believes that the increases in fuel are caused by the increased stops caused by the interactions between TOSCo vehicles.
- The revised TOSCo has the potential to reduce user costs based on travel time and fuel costs especially in the mid ranges of TOSCo MPR considered for this study.

The research team identified some tasks that would further enhance the evaluation of TOSCo. Those recommendations to consider for benefits estimation simulation are as follows:

- The simulated version of TOSCo in this study did not incorporate the CAMP CACC algorithm the TOSCo vehicles in the field use in conjunction with TOSCo operations. To better simulate the TOSCo behavior for evaluation, future versions of the DriverModel.dll should explore generating a better representation of the CACC behavior of the CAMP algorithm.
- In the default settings speeds in all modes of TOSCo, except for Free-flow, the speeds were limited to the posted speed limit. The revised TOSCo setting relaxes this constraint and shows how this setting leads to a limitation of the delay reduction ability of the TOSCo system. The implementation of TOSCo may consider relaxing the speed limit constraint in favor of allowing TOSCo vehicles to plan trajectories at the speed deemed appropriate by the driver of the vehicle. In such a case, the driver would be responsible for maintaining a lawful speed of travel since the vehicle would not alter the speed down to the speed limit.
- Limits to the TOSCo strings and gap settings that allow for easier lane changing for ambient traffic should be considered. Additional TOSCo simulations may consider coding the ability for TOSCo vehicle to deactivate TOSCo for the cooperative vehicle breaking a traveler might execute in the field to help ambient traffic change lanes.
- Further investigate and resolve the increased number of stops by the non-TOSCo vehicles in response to slow TOSCo vehicles. The increase in stops is not realistic and better smoothing than slow travel would likely impact the fuel use estimation.

Chapter 1. Introduction

The Traffic Optimization for Signalized Corridors (TOSCo) system is a series of innovative applications designed to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based connected-vehicle communications to assess the state of vehicle queues and 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 is continuously recomputed and broadcast to approaching connected vehicles. Leveraging previous Crash Avoidance Metrics Partners LLC (CAMP)/Federal Highway Administration (FHWA) work on cooperative adaptive cruise control (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 emissions outcomes across the corridor. This report focuses on the design and use of traffic-level simulation environments, including both infrastructure and vehicle components, to estimate the mobility and emissions advantages of TOSCo.

Project Description

This project was undertaken by CAMP's Vehicle-to-Infrastructure (V2I) Consortium, consisting of Ford, General Motors, Honda, Hyundai Motor Group, Nissan and Volkswagen Group of America, in conjunction with IAV Automotive Engineering (IAV) and Texas A&M Transportation Institute (TTI). The United States Department of Transportation (USDOT)/ FHWA funded the project under Cooperative Agreement No. DTFH6114H00002. Participants of the V2I Consortium guided and supervised the development of the processes and algorithms governing the behavior of vehicles equipped with the TOSCo system.

Building upon the FHWA's Eco Approach and Departure Concept (*1, 2*), the TOSCo system uses a combination of infrastructure- and vehicle-based components and applications along with wireless data communications to position the equipped vehicle to arrive during the "green window" at specially designated signalized intersections. The vehicle side of the system uses applications located in a vehicle to collect Signal Phase and Timing (SPaT), and MAP messages defined in SAE Standard J2735 using V2I communications and data from nearby vehicles using Vehicle-to-Vehicle (V2V) communications. The applications also introduced a new concept of a "green window" to approaching vehicles. The "green window," computed by the infrastructure, is based on the estimated time that a queue will clear the intersection during the green interval. This green window is provided as a regional element in the SPaT message to vehicles in the field. Upon receiving these messages, the individual vehicles perform calculations to determine a speed trajectory that is likely to either pass through the upcoming traffic signal on a green light or decelerate to a stop in an eco-friendly manner if a stop is unavoidable. This onboard speed trajectory plan is then sent to the onboard longitudinal vehicle control capabilities in the host vehicle to support partial automation. This vehicle control leverages previous work by CAMP, FHWA, University of Michigan Transportation Research Institute (UMTRI) and IAV to develop CACC algorithms (*3*).

Scope of this Report

This report presents the methodology and results of computer simulation activities supporting the evaluation of the TOSCo system. The research team used computer simulation to evaluate the effectiveness and potential mobility and environmental benefits that could be generated through the application of the TOSCo system in a high-speed corridor environment. The specific objectives of the performance analysis were to quantify the potential mobility and environmental benefits of the TOSCo system.

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

Organization of the Report

The remainder of this report consists of several chapters and appendices. Chapter 2 presents a high-level overview of the TOSCo functionality. Chapter 3 provides a discussion of the simulation environment developed to support this project, including the design of the simulation environments and descriptions of key simulation model features, including both the infrastructure and vehicle components of TOSCo. Chapter 4 introduces the evaluation corridor in Houston, Texas and discusses calibration of the model and verification simulation scenarios that allowed the team to gain confidence in the simulation tools.

The simulation platforms that are developed and verified in Chapters 3 and 4 are then used to analyze the mobility and energy performance of TOSCo, at differing levels of market penetration, relative to a baseline of traffic without TOSCo. Chapter 5 presents the results of the analysis of Farm-to-Market (FM) 1960. These analyses include a single intersection as well as the entire corridors.

Chapter 6 summarizes the findings and identifies areas of future work to further understand the benefits of TOSCo including investigating characteristics of corridors that may benefit the most from TOSCo. A series of appendices then follow. These appendices support specific topics that are within the main body of the report and are referenced where applicable.

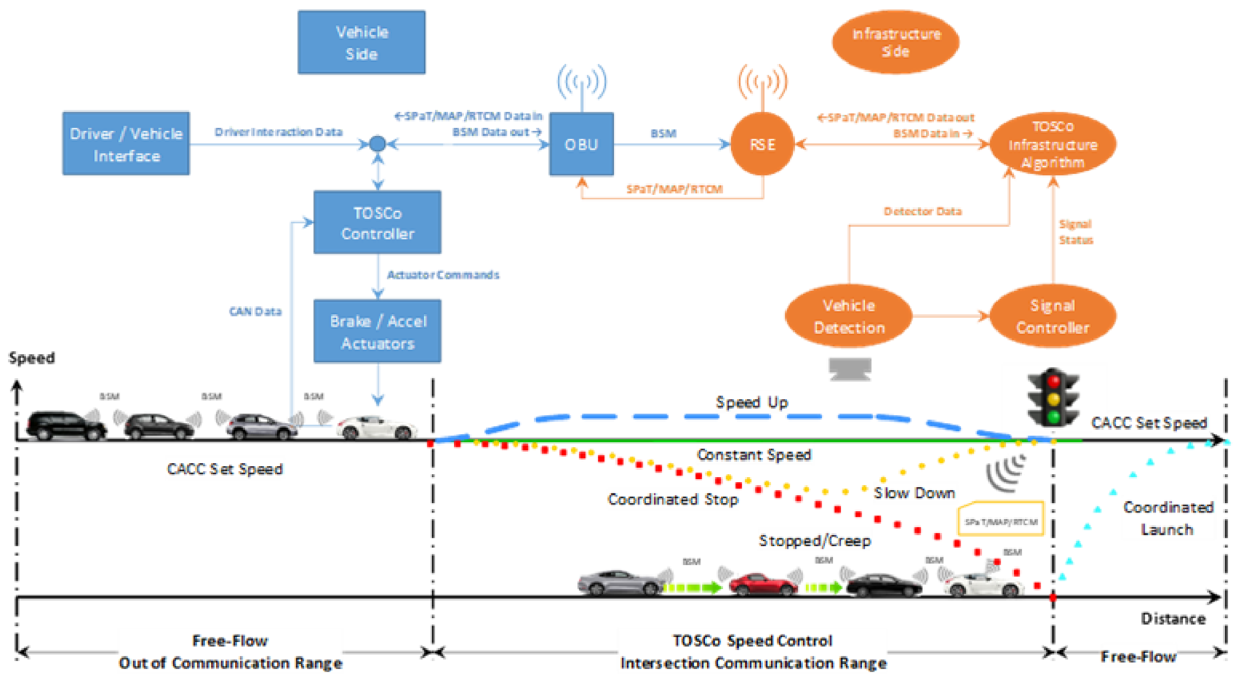
Chapter 2. TOSCo System Overview

This chapter provides a high-level overview of the TOSCo system, its Concept of Operations (ConOps) and the different operating states of the TOSCo-equipped vehicles. For more information on the specific algorithms and operations of the TOSCo system, consult the Vehicle-to-Infrastructure (V2I) Program Traffic Optimization for Signalized Corridors (TOSCo) System Requirements and Architecture Specification Report (*4*).

TOSCo Concept of Operations

Figure 1 illustrates the basic concept of 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 at the intersection (J2735 SPaT message), and the presence of any traffic waiting in queues at the intersection. As a TOSCo-equipped vehicle enters the communication range at the intersection, it would receive the intersection geometry, signal phase and timing and queue information. Using this information, the TOSCo vehicle would then plan a speed trajectory that would allow 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 must stop at an intersection would perform a coordinated launch maneuver at the start of a green notification that would allow them to clear the intersection in a more efficient manner than manual driving. Once the TOSCo vehicles leave the communications range of the intersection, the vehicles would then revert to their previous operating mode of Free Flow (CACC).

Planning the appropriate trajectory requires information from the infrastructure, specifically, information about the signal phase and timing and time estimates of when any queued traffic waiting at the stop bar would clear the intersection. To provide this information, the infrastructure would need to be equipped with technology to not only provide information of the signal status but also to detect the presence of queues and predict when these queues would clear the approach.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium, 2022

BSM = Basic Safety Message
CACC = Cooperative Adaptive Cruise Control
CAN = Controller Area Network
OBU = Onboard Units
RSE = Roadside Equipment
RTCM = Radio Technical Commission for Maritime Services
SPaT = Signal Phase and Timing

Figure 1. The TOSCo Concept

The TOSCo string concept is the same as the CAMP CACC string except, of course, a TOSCo string is composed of vehicles with TOSCo engaged. Vehicles within a TOSCo string are divided to two categories, "leader" and "follower." The "leader" refers to 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(s), which means that the control of a follower only depends on the information (such as instantaneous speed and acceleration) of the vehicles ahead. Wireless BSMs are received and CACC filters those messages to identify any string members ahead (but not behind). The CACC uses both radar and the BSMs to control the gap to the vehicle ahead, sometimes using the preview provided by BSMs ahead of the immediate predecessor to anticipate sudden decelerations and react even before the immediate predecessor slows. The CAMP CACC assumes the use of an extension to the BSM which contains data elements that represent the ID 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 simply use CACC/Adaptive Cruise Control (ACC) if it is the leader and outside of communication range. 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 messages from an equipped intersection. CACC vehicles do not have the same capabilities as TOSCo vehicles but can end up being at the front, middle, or back of a string that is partially CACC and partially TOSCo. Like the CAMP CACC approach, the TOSCo algorithms onboard the vehicle decides 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 influence its motion.

To plan a trajectory, the TOSCo system onboard each vehicle calculates speed profiles to determine the behavior on a through movement for approaching the intersection. The TOSCo algorithm first checks if the data going into the algorithm is valid, meaning that the green window, queue, and other components of the data to support TOSCo are valid. If the data is valid, the vehicle will calculate two speed profiles ("best case" or "worst case") to determine the operating bounds. The vehicle calculates a "best case" or optimal speed profile which represents the approach to the intersection that covers the most amount of distance in a short time. The vehicle also calculates a "worst case", or least-optimal speed profile which represents the minimum speed possible for the attempted operating mode. If one of the speed profiles is not valid, meaning that the calculated speed profile exceeds the bounds of TOSCo parameters set for that operating mode, the vehicle algorithm will continue searching for a TOSCo operating mode that produces a valid set of speed profile containers. Once the vehicle finds a valid set of speed profiles, the vehicle attempts to follow the "best case" speed profile. The vehicle will keep the calculated speed profile until either there is a change in external conditions, such as the green window changes the points in time, or the vehicle's speed and positions is no longer within the speed profile solution space, which can happen if the TOSCo vehicle is behind a manual vehicle that is traveling slower than TOSCo desires. The solution space represents the speeds at given positions on the approach to an intersection that are between the optimal and least optimal speed profiles.

TOSCo vehicles use the speed profile computations to the intersection stop location to determine the appropriate operating mode. The TOSCo vehicle behavior can be represented as one of the following operating states:

- Free Flow
- Coordinated Speed Control
- Coordinated Stop
- Stopped
- Coordinated Launch
- Creep

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 operations modes, the reader should consult the Vehicle-to-Infrastructure (V2I) Program Traffic Optimization for Signalized Corridors (TOSCo) System Requirements and Architecture Specification Report(*4*). For purposes of the traffic-level simulation, the TOSCo algorithm from the field is incorporated into simulation, with the majority of the simplifications from modeling the CACC algorithm that runs alongside TOSCo.

Free Flow

If a TOSCo-equipped Host Vehicle (HV) is in Free-flow Mode while the TOSCo function is active, the equipped vehicles operate in speed/gap control under CACC. The HV speed range in Free Flow is from zero to CACC Set Speed. The following conditions must be met for a HV to be allowed to leave Free Flow mode. TOSCo is enabled by the driver, HV is receiving SPaT and MAP messages from the next signalized intersection, HV is matched to an ingress lane of the upcoming intersection, and HV is within TOSCo optimization range of the upcoming stop bar.

Coordinated Speed Control

Coordinated Speed Control occurs when a TOSCo-equipped HV when TOSCo is active and is receiving SPaT and MAP messages from the next signalized intersection in the HV's path and is matched to one of the intersection's ingress lanes. The HV speed range in Coordinated Speed Control Mode is from a minimum of the Creep Mode threshold to a maximum of the posted speed limit. If the reported traffic signal phase is red and a TOSCo-equipped HV determines that it will pass through the intersection on the upcoming green phase without coming to a full stop, the HV employs SPaT message content to plan a speed profile that allows the vehicle to arrive at a virtual stop bar some offset upstream of the physical stop bar with a maximum speed of 35 mph at the transition to the green phase, as a risk mitigation technique. Typically, a slow-down speed profile will be employed. In case a TOSCo-equipped vehicle has determined that it cannot enter the Coordinated Speed Control Mode and must employ the Coordinated Stop Mode, it will transmit a CSTOP flag. A directly following vehicle that receives the CSTOP flag is prohibited to enter Coordinated Speed Control Mode since its solution space is limited by the preceding stopping vehicle ahead. This mechanism enforces CSTOP operation in the whole TOSCo vehicle string, produces matching stopping behavior between all vehicles and prevents driver confusion. If the reported traffic light phase is green and a TOSCo-equipped HV determines that it will pass through the intersection prior to the amber phase, it employs SPaT message content to plan a speed profile that allows the vehicle to pass through the intersection by adjusting the TOSCo speed to achieve optimization objectives. Depending on current circumstances, the HV will employ a speed up speed profile or at least maintain current speed.

Coordinated Stop

A TOSCo-equipped HV enters this strategy when TOSCo is active, cyclically receiving SPaT and MAP messages from the next signalized intersection in the HV's path and is matched to one ingress lane of the intersection. HV speed range in Coordinated Stop Mode is from a TOSCo speed range of the speed limit to a final speed of zero and the HV is transmitting a CSTOP flag through its Basic Safety Message (BSM). If after processing information from the SPaT and MAP messages the TOSCo-equipped HV determines that it will not pass through the intersection prior to the amber phase, it employs the content of the infrastructure messages to plan a speed profile that allows the vehicle to come to a stop at the stop bar or end of a queue while meeting optimization objectives. A TOSCo-equipped HV will enter Coordinated Stop Fallback Mode, if SPaT and MAP message reception or map matching to an ingress lane is lost and it has been operating in CSTOP previously. The Coordinated Stop Fallback Mode shall ensure a safe stop at the stop bar or the previously known stop location.

Stopped

A TOSCo-equipped HV enters a stopped strategy when the vehicle is stationary in TOSCo range and is matched to an ingress lane either at the stop bar or in a queue. Any movement from this mode requires driver action. During this time, all TOSCo-equipped vehicles are receiving SPaT messages that the TOSCo on-board system uses to determine the time remaining before the signal phase will transition to green. Vehicle speed range in Stopped Mode is zero. When the signal is about to change to green, the TOSCo on-board system prompts the driver to confirm readiness for launch. The system first checks whether the driver has applied the brakes. If so, the system prompts the driver to release the brakes. If the brakes are not applied, the system notifies the driver of an impending launch at which point the driver must respond to indicate readiness for launch otherwise the vehicle will not move. This is applicable to all vehicles in the queue.

Coordinated Launch

The TOSCo-equipped vehicle inside a TOSCo string broadcasts a Coordinated Launch message after the driver indicates readiness for launch during a stopped mode operation. The first TOSCo-equipped vehicle at a stop bar will become the Lead Vehicle (LV) of a TOSCo string if no preceding vehicles are present. Any HV behind the LV will check the BSM of its directly preceding vehicle for existence of a Coordinated Launch message and will transition to Coordinated Launch Mode after its driver indicated readiness for launch during a stopped mode operation. While the SPaT message indicates a red phase, all TOSCo-equipped vehicles will remain stationary. Once the signal transition to the green phase is indicated in the SPaT message for a specific lane, every TOSCo-equipped vehicle therein that broadcasts a Coordinated Launch message will compute a Coordinate Launch speed profile and the TOSCo string will startup simultaneously. If any member of the TOSCo string fails to indicate driver readiness, or a TOSCo-equipped vehicle has a non-TOSCo-equipped vehicle as a directly preceding vehicle, Coordinated Launch Mode will not be allowed since the behavior of the preceding vehicle cannot be anticipated. In this case, a one-by-one launch as used by ACC-equipped vehicles will be executed.

Creep

The TOSCo-equipped vehicle is allowed to creep forward in the direction towards the stop bar to fill gaps left by preceding vehicles if the gap is more than a creep threshold distance. A common example would be a vehicle in the right lane of a multi-lane corridor making a permissible right turn during a red phase. A less common example would be a vehicle making a permissible left turn during a red phase when the cross-street is a one-way street with traffic moving right to left from the point of view of the driver waiting at a red light. A TOSCo-equipped vehicle enters Creep Mode when TOSCo is active and the gap towards the stop bar or the directly preceding vehicle is more than the creep distance threshold. Under these circumstances, the driver will be requested to acknowledge movement under the Creep Mode and after the driver provides confirmation the TOSCo-equipped vehicle will move forward to close the gap towards the stop bar or the preceding vehicle. Vehicle speed range in Creep Mode is from a minimum of zero to a maximum of the creep speed threshold.

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 unequipped with connected-vehicle technology or not.

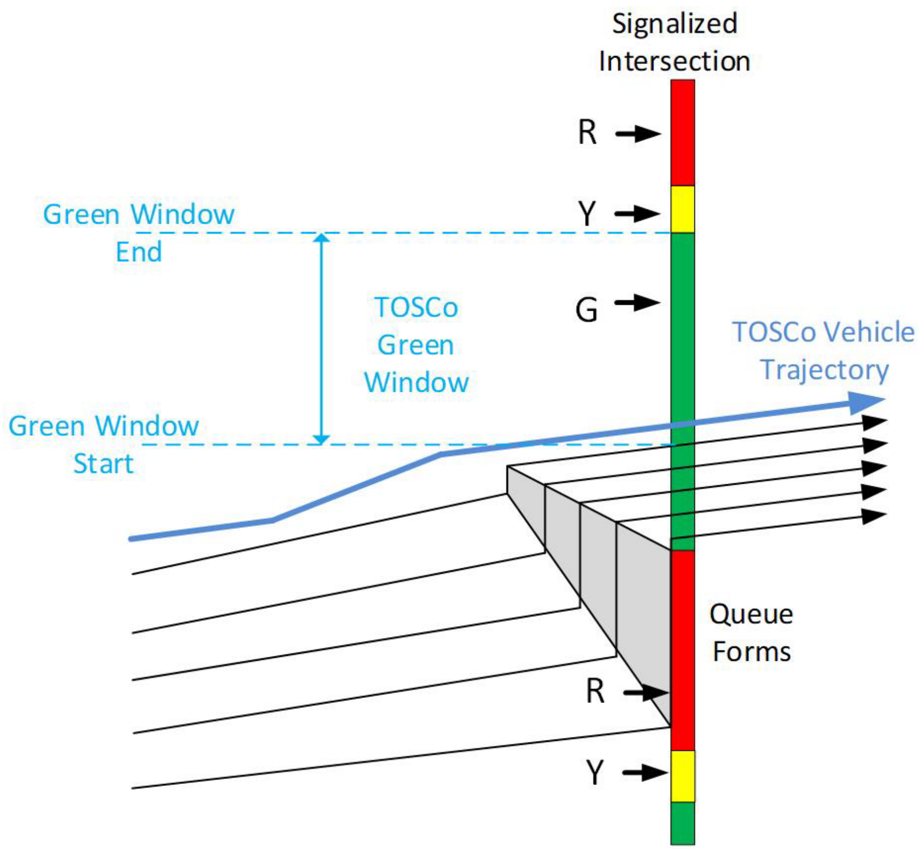
The following are critical components that the infrastructure needs to provide for the TOSCo system to operate properly.

Signal Phase and Timing (SPaT) and Geometric Intersection Description (GID) Data

The infrastructure is required to provide SPaT and intersection geometry data in a MapData (MAP) messages 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 as well as information about the time until the next change in the signal indication state. The research team is using regional extensions in the SPaT message to hold the green window information and the queue. The research team refers to a SPaT message with a green window and queue information as an enhanced SPaT message. The MAP 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 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. The SPaT message is broadcast at 10 Hz while the MAP information is broadcast at 1 Hz. In simulation, the SPaT data comes from the software controller and the MAP data is not simulated since the simulation is automatically able to match the vehicles to lanes as observed in the field.

Green Window Data

One critical function of the infrastructure in the TOSCo system is to estimate the green window. As shown in Figure 2, the “green window” represents the time during the green interval 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 duration 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.



Source: Texas A&M Transportation Institute. 2022

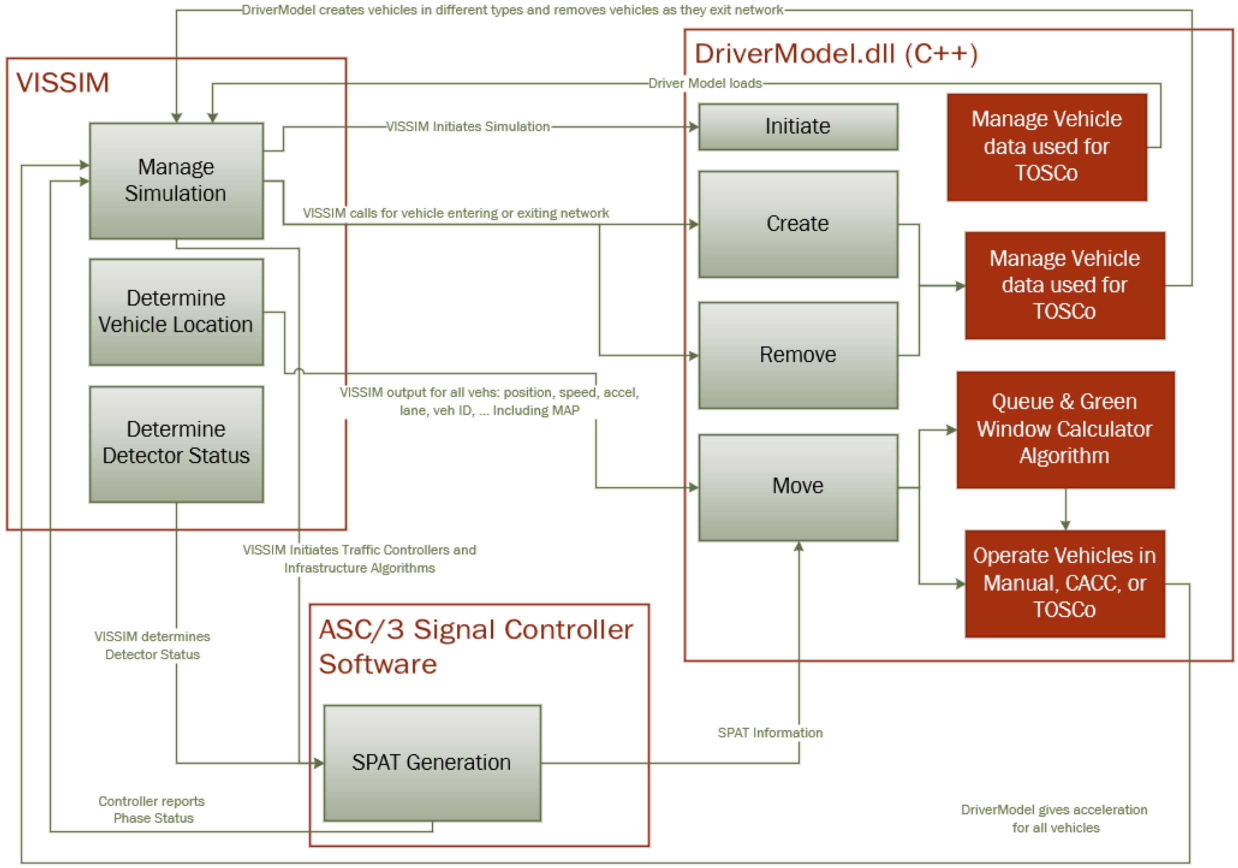
Figure 2. Definition of Green Window

Chapter 3. TOSCo Simulation Environment

TOSCo Performance Assessment Environment

The TOSCo Performance Assessment Environment uses source code from both vehicle and infrastructure alogirthms to represent TOSCo behavior. The resulting driver model was used to evaluate the performance of TOSCo by estimating potential benefits at a single intersection, corridor and network resolution. These benefits could include a reduction in emissions, fuel savings, and improved mobility. These performance measures were collected for different market penetration rates of TOSCo-enabled vehicles.

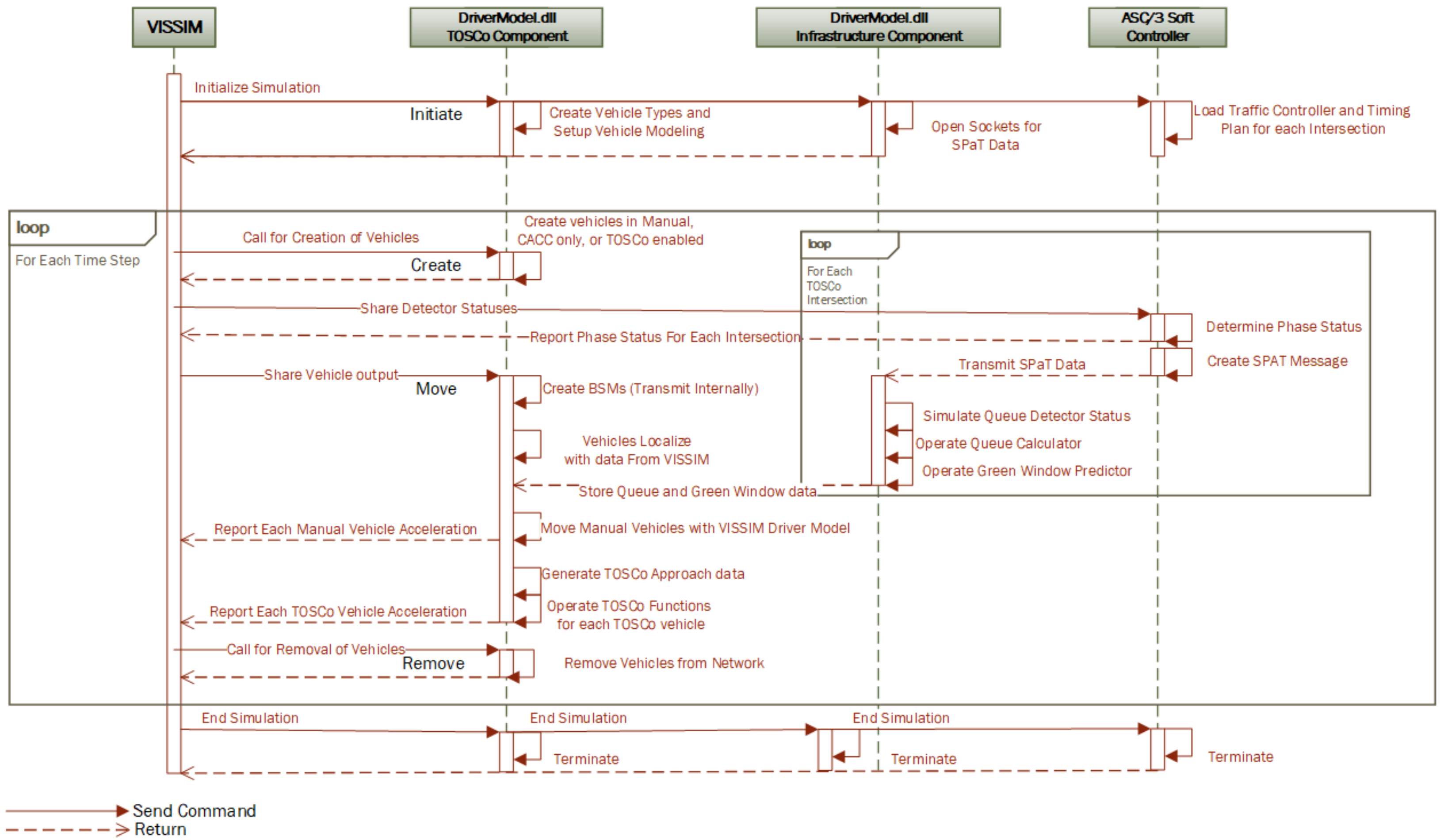
Figure 3 shows the architecture of the TOSCo Performance Assessment Environment used for Phase 2 simulations. The research team developed the TOSCo Performance Assessment Environment to evaluate the potential mobility and environmental benefits associated with TOSCo. In the figure, the maroon block on the left contains all VISSIM components. This 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 VISSIM component transmits vehicle information to the DriverModel.dll, where the vehicle information is used to simulate both the infrastructure and vehicle components, a major change from simulation in Phase 1 of the TOSCo Project. Meanwhile, a Virtual Traffic Controller transmits SPaT data to the Infrastructure Component in the DriverModel.dll. In this project, the Econolite ASC/3 controller was selected as a representative controller in part because software exists to simulate this controller within VISSIM. Utilizing BSM, SPaT and generated detector status data, the Infrastructure Algorithm Component predicts queue length and estimates the green window with functions designed to represent the infrastructure algorithms in the field. The simulation stores this information in the DriverModel.dll so simulated vehicles can easily access the data based in their map-matching provided by VISSIM. Based on signal timing and localization information provided through VISSIM and the infrastructure representation, the vehicle algorithm portion of the DriverModel.dll Component stores data for operating TOSCo in the same structures used to operate vehicles in the real world. The driver model then calls functions used for TOSCo operations that are performed onboard for each simulated TOSCo vehicle. These computations plan each TOSCo vehicle's intended speed profile on the approach to the intersection 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 MOVES model.



Source: Texas A&M Transportation Institute, 2022

Figure 3. Overall Performance Assessment Architecture

Figure 4 illustrates the operation of the data exchange for a simulation run. Generally, VISSIM sends commands to the DriverModel.dll and the ASC/3 Controller at each simulation step. The ASC/3 Controller sends signal timing data to the Infrastructure Algorithm Component within the DriverModel.dll software to perform the needed calculations to determine the queue and green window data elements and the corresponding TOSCo and manual vehicle behavior.



Source: Texas A&M Transportation Institute, 2022

Figure 4. TOSCo Simulation Data Flows

The following subsections describe the different algorithms incorporated into both simulations.

Modeling Vehicle Behavior

The TOSCo vehicle algorithm in the performance evaluation simulation is a simplified version of the more detailed onboard sensing and computations of TOSCo, as developed by CAMP. Figure 5 shows the process by which the VISSIM model through the DriverModel.dll controls vehicle 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 traveling through the approaching intersection, following a non-TOSCo vehicle or following a TOSCo vehicle and if the vehicle is within communication range of the upcoming intersection. If a TOSCo vehicle is following a non-TOSCo vehicle, the simulation uses the ACC logic to control the movement of the vehicle. If the TOSCo vehicle is following another TOSCo vehicle while outside of communication range, the simulation model uses a CACC logic to control how the vehicle behaves. If the TOSCo vehicle is traveling through the intersection within communication range, it uses algorithms to speed up, maintain, or slow down the vehicle, depending on its identified operating state. Note, part of TOSCo control is to operate either CACC or ACC in the background, depending on the type of vehicle in front of the TOSCo vehicle. TOSCo uses the minimum acceleration between the TOSCo and CACC system for the timestep to ensure safe operation. This is consistent with how TOSCo works in the field.

The following describes the logic used to control the vehicle's behavior under the different control modes.

Manual Control Model

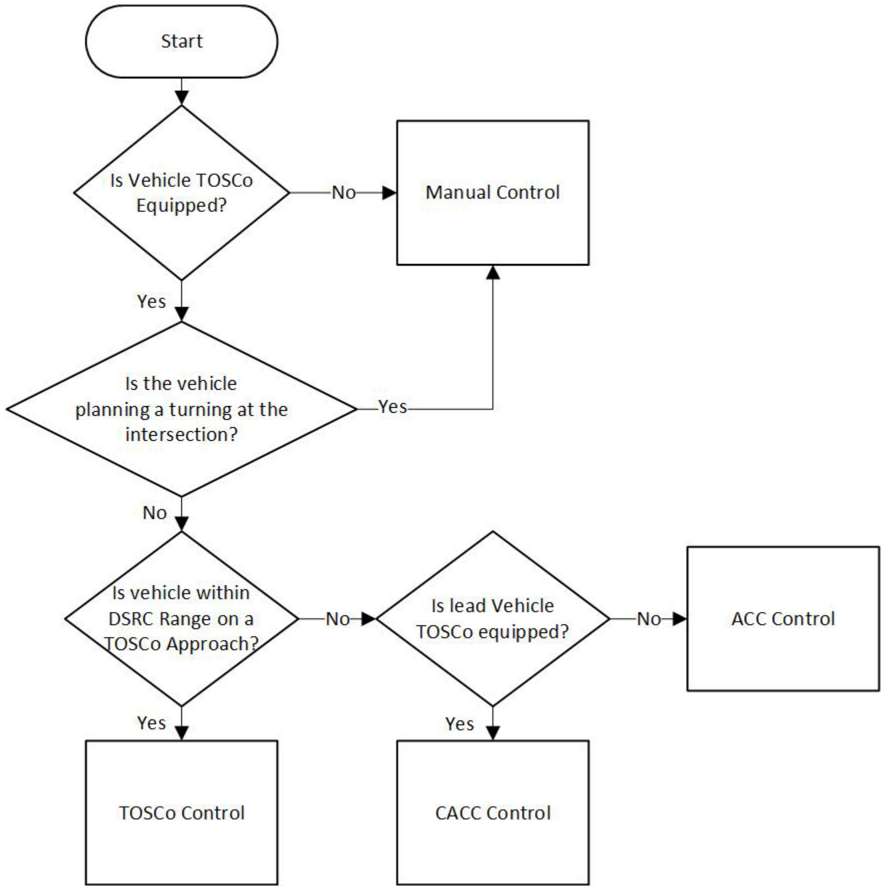
To model the behavior of vehicles under manual control, the evaluation team uses the default VISSIM driver model (the Wiedemann 74 model) developed by PTV to model vehicle under manual control (*5*).

Adaptive Cruise Control Mode

To model the behavior of vehicles under ACC control, the evaluation team uses the Intelligent Driver Model (IDM) developed by Treiber and Helbing *(6,7*). Compared to the Wiedemann 74 Model (the default car-following model in VISSIM), the IDM algorithm is widely used to model a more advanced car-following behavior because it considers physical and psychological aspects of the drivers. The research team also believes that the IDM algorithm uses more stable vehicle dynamics that best represent the cruising behavior of ACC-equipped vehicles than other models.

Cooperative Adaptive Cruise Control

Over the years, numerous CACC algorithms have been proposed (*9,10*). CACC is like ACC except, in addition to ACC's use of a remote sensor, for instance, a radar or a vision system to monitor the distance and relative speed of vehicles ahead, CACC fuses the remote sensor information with information from connected vehicle BSMs to better predict the motion of the vehicle ahead. The CAMP 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 *(8*). Figure 5 depicts a flow chart about how the control mode is selected for TOSCo vehicle in the traffic-level simulation.



Source: Texas A&M Transportation Institute, 2022

Figure 5. Process for Determining Control Mode for Vehicles in the VISSIM Model

The CAMP CACC approach to CACC operations is decentralized, in that CACC is a driver-initiated feature, and the vehicle joins a string simply by approaching another CACC-engaged vehicle or changing lanes behind a CACC-engaged vehicle. “Leaders” are those CACC-engaged vehicles without another CACC vehicle ahead (within the CACC controllers’ headway of regard), and “followers” are CACC-engaged vehicles that in fact do have another CACC-engaged vehicle in front. A “string” is defined as two or more CACC-engaged vehicles, with one leader and at least one follower. Note that in a CAMP CACC string, the vehicles make decisions and perform control without real-time consideration of vehicles behind. The concept of a string is different than some definitions of a platoon in that a vehicle may need to request to join the platoon and another platoon vehicle granting or denying the request. Some platoon systems also give the leader special emphasis, i.e., with following vehicles computing their longitudinal control using data broadcast by the leader, as well as consideration for the vehicle directly in front. Platoons therefore have a centralized aspect to them that a string does not.

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. TOSCo vehicles evaluate whether a change in operate state is needed and whether to maintain its current speed, slow down, or speed up to arrive in the green window using the queue and signal status information provided by infrastructure. Once a TOSCo vehicle selects an operating mode, it evaluates a corresponding set of parameters to produce a speed profile (from the piecewise trigonometric-linear function family) that aims to minimize the trip-level fuel consumption without compromising the mobility of TOSCo-enabled vehicle. The TOSCo Vehicle System Specification Report provides a detailed description of the functions that control the speed up and slow down behavior of TOSCo vehicles approaching and departing the intersection (*11*).

Vehicle Lane-changing Behavior

TOSCo functionality is active only for through vehicle movements traveling on the main-street approach (i.e., the coordinated phase). For these through vehicle movements, CAMP assumes that lane choice is the driver’s decision, with no support from TOSCo. One key update to this benefits assessment as compared to previous analyses of TOSCo is that the research team lifted the lane change restrictions for TOSCo vehicles so vehicles can change lanes at their discretion.

Modeling Infrastructure Components

Infrastructure algorithms estimate the current queue lengths and calculate a green window for TOSCo strings at lane level (i.e., for each lane approaching the intersection). The infrastructure populates a portion of the SPaT messages with estimated parameters such as current queue length, beginning time of the green window, and end time of the green window and transmits the data to approaching vehicles for their use in their trajectory planning. The following two sub-sections describe how the infrastructure algorithms generated data required for TOSCo.

Generation of SPaT and MAP Data

The TOSCo simulation uses the Econolite ASC/3 Software-in-the-loop Controllers to operate each intersection and produce SPaT information. The Econolite ASC/3 Controllers operate the signal heads at each intersection in the VISSIM network via an API for the Econolite ASC/3 Controller built into VISSIM. The default version of the Econolite 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. To provide consistent data for the TOSCo vehicles, the controllers use minimum recalls on the cross street phases to ensure that the green window closes at a reliable time. 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 UDP address. The research teams used the “enable SPaT” batch file, provided by Econolite, 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 timestep, the infrastructure algorithm, nested in the DriverModel.dll, listens over each intersection's socket to capture the SPaT information which the green window prediction includes in the data package for each simulated TOSCo vehicle.

Note that the simulation architecture does not include the MAP message because vehicles use the VISSIM internal mapping mechanism. In field implementation, the purpose of the MAP message is for vehicle or infrastructure algorithms to locate the vehicle in the corridor and calculate corresponding information (e.g., approaching lane, 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 to simplify the simulation architecture and increase computation speed.

Green Window Estimation

The methodology for estimating/predicting queue information uses queue detector status typically provided by a radar-based queue monitoring system available to practitioners. These systems provide an estimate of the current queue length during each sample period (*12, 13*). To simulate this methodology, the research team replicated the data collection zone in each lane, covering approximately 500 feet upstream of the stop bar in the simulation model. The team configured the data zone to provide the speed and position of all vehicles (lateral and longitudinal) in the detection zone at each simulation time step. The team prepared an algorithm that compared each vehicle speed to a user-defined threshold speed. If the vehicle speed was less than the threshold speed and in the location of a simulated detector, the algorithm declares the detector active. The location of each active detector feeds into the queue calculation algorithm to determine the current location of the back of the queue. This methodology utilizes the current queue length for determining the start of the green window.

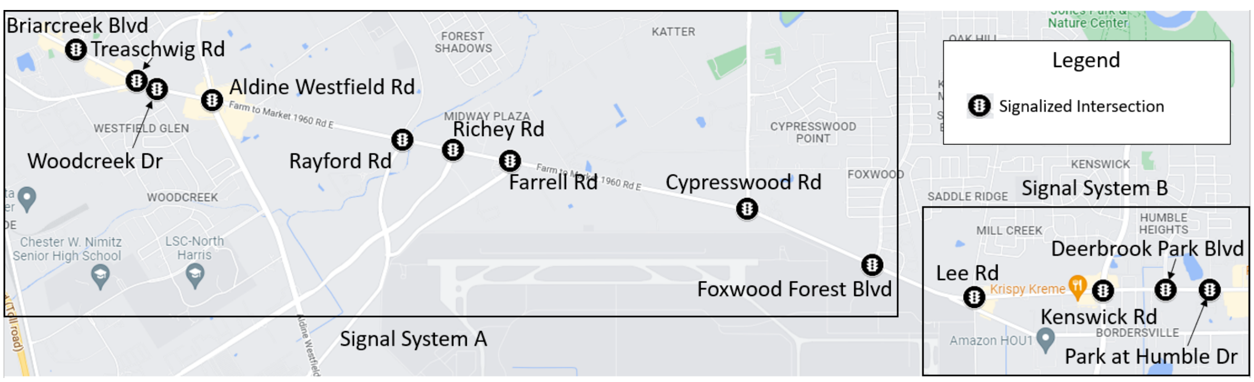
The TOSCo Infrastructure System Specification Report provides a complete description of the queue calculation and green window prediction methodologies used to generate information for the TOSCo system (*4*).

TOSCo Representation Verification

The revised traffic-level simulation for TOSCo's Phase 2 Project involved incorporating the TOSCo functions for both infrastructure and vehicle algorithms into the VISSIM simulation. The intention of this revision was to both represent TOSCo in simulation as close to the true operation as reasonable and to enable revisions to the TOSCo algorithm to be easily incorporated into simulation as the TOSCo system continues to be refined from field testing throughout Phase 2. The version of TOSCo represented in this simulation exercise is the version CAMP used in the Test 4.5 evaluation completed in February 2022. This version of TOSCo includes many minor updates compared to the March 2021 version analyzed in the TOSCo SH 105 Report (*14*). Therefore, the research team used a subset of the interim report scenarios to verify the TOSCo traffic-level simulation. The verification still involved comparing the speeds, accelerations, and modes of the TOSCo traffic-level simulated vehicle to the vehicle-level simulated vehicles. Appendix A describes the results of the verification that the traffic-level simulation is representative of TOSCo operation.

Chapter 4. Evaluation Corridor Setup – Farm-to-Market Road 1960, Houston, Texas

The corridor along Texas Farm-to-Market 1960 consists of 13 intersections between Houston, Texas and Humble, Texas covering about 7 miles. Figure 6 shows the location of the signalized intersections considered along FM 1960. The Texas Department of Transportation (TxDOT) operates all the intersections on this length of FM 1960. The posted speed limit in most of the analysis corridor is 55 mph, with the easternmost two miles posted at 50 mph. It takes about twelve minutes to drive from one end of the corridor to the other. Table 1 and Table 2 list the characteristics of each segment and each intersection in the FM 1960 corridor. Note that although there are not dedicated right turn lanes at each intersection, this roadway has large shoulders along the entire length of this segment which allows for vehicles to make right turns off the shoulder. The research team assumed that these shoulders are utilized close to the intersection for vehicles to make right turns even if there is not a dedicated right turn lane. All left turn movements at the intersections in this corridor are protected only. No permissive left turns are allowed at the intersections. Table 2 also notes the intersection numbers assigned to the intersections along the corridor by the research team. These intersection numbers were introduced to increase the ease of understanding the order of intersections and documentation for field implementation. Although the field implementation is not covered in this document, the numbering convention for intersections is maintained for brevity.



Source: Imagery ©2022 Google. Map Data ©2022 Google

Figure 6. Location of Signalized Intersections on the FM 1960 Corridor in Texas

The signals along FM 1960 in this segment operate as two independent coordinated systems. The section from intersection 101 to 109 are one system and 110 to 111 is another system. These two systems have cycle lengths of 90 and 150 seconds, respectively.

Table 1. Characteristics of Road Segments on the FM 1960 Corridor in Houston, Texas

Intersection One	Intersection Two	Distance (ft)	Speed Limit (mph)	Number of Lanes (EB/WB)	Number of Driveway
Briarcreek Blvd.	Treaschwig Rd.	1980	55	4/4	19
Treaschwig Rd.	Woodcreek Dr.	620	55	3/3	2
Woodcreek Dr.	Aldine Westfield Rd.	1650	55	3/3	7
Aldine Westfield Rd.	Rayford Rd.	5700	55	3/3	37
Rayford Rd.	Richey Rd.	1550	55	3/3	0
Richey Rd.	Farrell Rd.	1725	55	3/3	11
Farrell Rd.	Cypresswood Dr.	7130	55	3/3	12
Cypresswood Dr.	Foxwood Forest Blvd.	4030	55	3/3	11
Foxwood Forest Blvd.	Lee Rd.	3180	55	3/3	10
Lee Rd.	Kenswick Dr.	3800	50	3/3	31
Kenswick Dr.	Deerbrook Park Blvd.	1810	50	3/3	13
Deerbrook Park Blvd.	Park at Humble Dr.	1310	50	3/3	4

Source: Texas A&M Transportation Institute, 2022

Table 2. Characteristics of Intersections on the FM 1960 Corridor

Intersection Name	Assigned Intersection Number	Exclusive Left Turn Lane	Exclusive Right Turn Lane
Briarcreek Blvd.	101	EB Only	None
Treaschwig Rd.	102	EB and WB	EB Only
Woodcreek Dr.	103	EB and WB	None
Aldine Westfield Rd.	104	EB and WB	EB and WB
Rayford Rd.	105	EB and WB	None
Richey Rd.	106	WB Only	None
Farrell Rd.	107	WB Only	None
Cypresswood Dr.	108	EB Only	WB Only
Foxwood Forest Blvd.	109	EB and WB	WB Only
Lee Rd.	110	EB and WB	WB Only

Intersection Name	Assigned Intersection Number	Exclusive Left Turn Lane	Exclusive Right Turn Lane
Kenswick Dr.	111	EB and WB	WB Only
Deerbrook Park Blvd.	112	EB Only	None
Park at Humble Dr.	113	EB and WB	None

Source: Texas A&M Transportation Institute, 2022

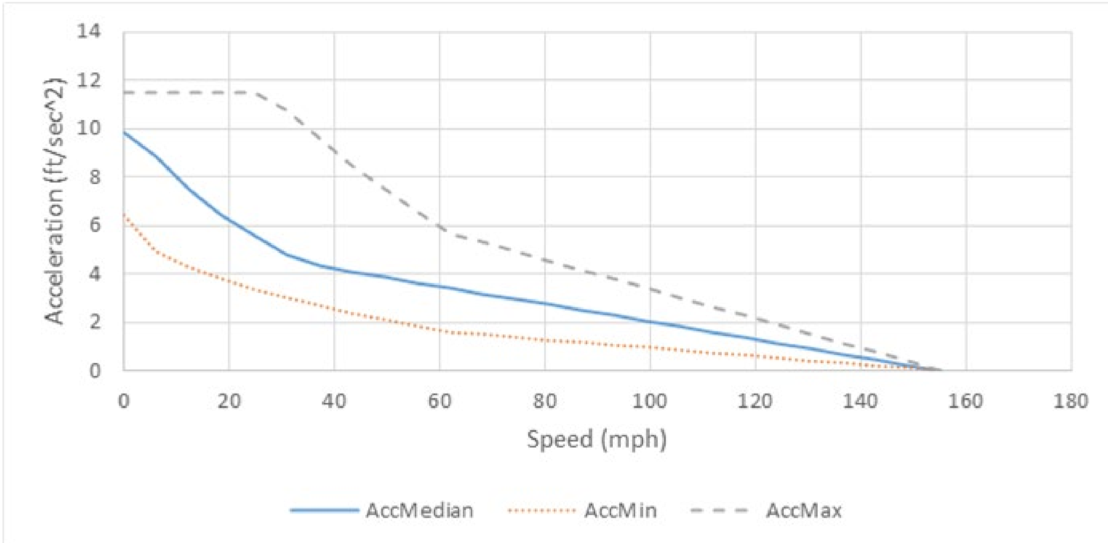
The research team adjusted the settings of the intersection controllers to cause the green window to close reliably. To do this, the research team adjusted the signal timing for the simulated controllers to have minimum recalls on each non-TOSCo phase. This adjustment ensures that the green phase for the TOSCo approaches end at the expected time.

Traffic-level Simulation Reassessments and Refinements

As part of the initial infrastructure simulations, the research team reevaluated some of the results and made some refinements associated with the default acceleration profile governing vehicle behaviors by enhancing the representation of non-TOSCo vehicles on the high-speed corridor. To accomplish this, the team designed an acceleration study to collect acceleration behaviors on the SH105 corridor in Phase 1 and provide data needed to generate a revised acceleration distribution for the non-TOSCo vehicles within VISSIM. The team used this revised acceleration distribution to evaluate the impacts of TOSCo compared to the refined representation of baseline traffic.

Acceleration Profile Development

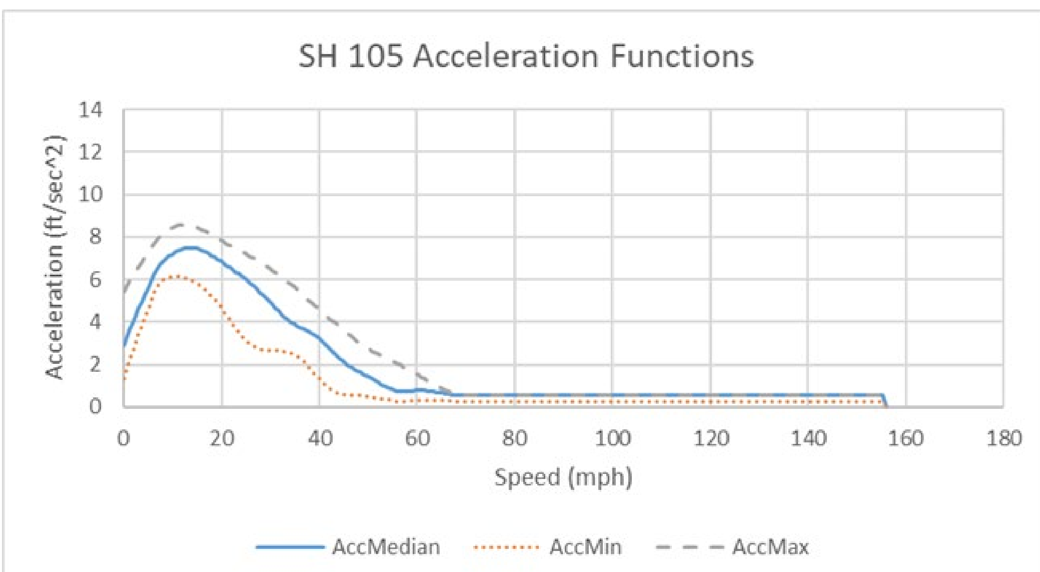
Information on the acceleration behavior from V2X communication-equipped vehicles was not available for the corridor, leading the team to initially use the default desired acceleration distribution provided in VISSIM. Figure 7 shows the VISSIM default acceleration. The VISSIM default accelerations for the non-equipped vehicles are more aggressive than expected by the research team. The VISSIM profile averages at 10 ft/s^2 acceleration from a stop. The research team determined that more work is needed to be done to better represent the acceleration behavior of the ambient traffic to compare to the simulated TOSCo behavior, so the research team designed a study to collect the acceleration data needed to create a profile to represent SH 105 acceleration behavior.



Source: PTV VISSIM, 2022

Figure 7. Default Acceleration Distribution to Model Accelerations of Non-TOSCo Vehicles

The research team conducted the acceleration study in Phase 1 of the TOSCo Project. The resulting calibrated VISSIM acceleration distribution is shown in Figure 8. For more information on the development of the acceleration profile see the TOSCo Phase 1 Traffic-Level Simulation and Performance Analysis Report (15).



Source: Texas A&M Transportation Institute, 2022

Figure 8. Acceleration Profile Calibrated from SH 105 Field Study

The team did not allow the minimum desired acceleration to reach zero so vehicles that follow the minimum acceleration behavior are always able to accelerate, if desired. Additionally, the team extended the minimum, median, and maximum curves up to 150 mph to allow vehicles to accelerate to desired speeds beyond the acceleration profile. These two edits ensured that all VISSIM controlled vehicles could accelerate to their desired speed.

The calibrated VISSIM acceleration is different from the VISSIM default acceleration profile at every speed range as demonstrated in Table 3.

Table 3: Comparisons on Averaged Acceleration for VISSIM Default and SH 105 Acceleration Profiles

Speed Range	Average VISSIM Default Acceleration (ft/s^2)	Average SH 105 Acceleration (ft/s^2)	Difference (ft/s2)
0-30 mph	8.9	6.2	2.6
30-50 mph	5.6	5.9	-0.3
50-70 mph	4.3	3.6	0.7
70-100 mph	3.6	1.3	2.3
100+ mph	1.6	0.7	1.0

Source: Texas A&M Transportation Institute, 2022

The revised VISSIM acceleration profile has an average of 2.9 ft/s^2 acceleration from stop, which builds up to 7.5 ft/s^2 as the vehicle gains speed and follows the research teams expectations. The revised profile reflects behavior observed from the field study where vehicles accelerated gradually from a stop and maintained acceleration until reaching their desired speeds.

This SH 105 acceleration profile from TOSCo Phase 1 was used for the FM 1960 simulation under the assumption that an acceleration profile for a vehicle collected in Conroe, Texas (30 miles away from the FM 1960 corridor) is more representative of acceleration behavior of FM 1960 traffic than the default VISSIM acceleration profile.

FM 1960 Model Traffic Volumes

The research team estimated the traffic volumes for the FM 1960 model based on an understanding of the queue lengths from field observations. The volumes were part of calibrating the travel time where increased volumes were an option for increasing travel times across the network.

Model Calibration for Travel Times

The research team utilized the National Performance Management Research Data Set (NPMRDS) analytics website to extract the historic travel times across FM 1960 in both directions between January 24, 2022 and January 31, 2022 excluding Friday July 28, Saturday July 29, and Sunday July 30 (16). The analyst pulled data for the time period between 9 am and 1 pm for travel times on each segment in the NPMRDS tool and added the segment for each direction together. The team took the average of the 5 hours each day to use as the calibration target for both eastbound and westbound off-peak simulation models. The team compared the simulated travel times to the NPMRDS travel time data collected to calibrate the model. Table 4 shows the average calibrated and the field-measures travel times for the FM 1960 model.

Table 4. Off Peak Period Calibration to Field Measured Travel Times

Direction of Travel	2022 NPMRDS Field Measured Travel Time (sec)	Simulated Travel Times with Revised Acceleration Profile (sec)	Difference (%)
Eastbound	737.9	686.5	-7.0
Westbound	729.7	710.6	-2.6

Source: Texas A&M Transportation Institute, 2022

The calibration showed that the simulated travel times are within ten percent difference from the NPMRDS measured travel times and within one minute difference in average travel time duration. This meets the suggested calibration criteria of travel times within 15 percent or less than one minute difference for the model from the Traffic Analysis Toolbox (17).

Simulation Experimental Plan

This evaluation of TOSCo used two different key models to estimate the benefits of the TOSCo system, that is a single intersection model and a corridor model. The single intersection model is an extraction of the corridor model that only enables TOSCo at intersection 109. This model includes intersections 108 and 110 in the model to properly simulate the arrivals at intersection 109, but intersections 108 and 110 are not modeled as TOSCo equipped. The single intersection model is designed as a virtual testbed where TOSCo can be simulated with various settings across a subset of the market penetration rates so the research team can explore the impacts of different configurations of TOSCo. The key advantage of the single intersection model is the faster simulation speed which is about ten times as fast as the corridor model. The corridor model represents the TOSCo performance across all 13 equipped intersections in the field. The model includes Townsen Blvd., which is the intersection to the east of intersection 113as this intersection is close enough to influence the arrival rates at intersection 113. Townsen Boulevard is modeled as an unequipped intersection.

The simulation experiment was executed in multiple stages. The single intersection model was simulated with various settings for TOSCo including the TOSCo settings as deployed on the FM 1960 corridor. Table 5 contains the simulation scenarios and default settings for the single intersection model for FM 1960 benefits assessment. These scenarios explore different settings of TOSCo to identify the impacts of changing parameters and includes one scenario that combines metrics to identify the combined effects of adjusting TOSCo parameters. The research team analyzed a total of six different TOSCo Modes:

- **Default TOSCo**: TOSCo with the configuration identical to the parameters of TOSCo deployed on the FM 1960 corridor
- **Set-Speed TOSCo**: a setting of TOSCo where the trajectory planning is based on the maximum of either the speed limit or the desired speed (or set speed) of the simulated vehicle

- **Long CSC-Down TOSCo**: a setting of TOSCo where the vehicle is allowed to execute a Coordinated Speed Control-Down (CSC-Down) profile upon entering communication range and is not limited based on the distance to the intersection
- **Double Range TOSCo**: the TOSCo optimization range is doubled from 360 meters to 720 meters.
- **Enter Yellow TOSCo**: TOSCo vehicles are allowed to enter the intersection up to two seconds after the onset of yellow, which is consistent with the conservative estimate of when 90 percent of traffic will stop if two seconds away from the intersection in the Traffic Control Systems Handbook (18).
- **Revised TOSCo**: the combination of all beneficial settings from the preliminary data analysis. The combination included the Set-Speed, Double Range, and the Enter Yellow TOSCo settings.

Table 5. Settings for Single Intersection Model Simulation Experiments

Variables	**Experimental Settings**
TOSCo MPR	• 0% (baseline) • 10% • 30% • 50% • 70% • 90% • 100%
Vehicle volumes	• Mid-day Off-peak Period • 20% Increases Volumes based on Off-peak volumes
Signal Operation	Coordinated Actuated Control – with Min Recalls
Speed limit	55 mph
Desired Speeds	Calibrated Speeds
TOSCo Settings	• Default TOSCo • Set-Speed TOSCo • Long CSC-Down TOSCo • Double Range TOSCo • Enter Yellow TOSCo • Revised TOSCo

Source: Texas A&M Transportation Institute, 2022

The corridor model was simulated with the TOSCo settings as deployed on the FM 1960 corridor and the TOSCo setting from the single intersection that yielded the overall best performance. Table 6 contains the simulation scenarios and default settings for the corridor model for FM 1960 benefits assessment.

Table 6. Settings for Corridor Model Simulation Experiment

Variables	Experimental Settings
TOSCo MPR	• 0% (baseline) • 10% • 20% • 30% • 40% • 50% • 70% • 90% • 100%
Vehicle Volumes	• Mid-day Off-peak Period
Signal Operation	Coordinated Actuated Control – with Min Recalls
Speed Limit	55 mph
Desired Speeds	Calibrated Speeds
TOSCo Settings	• Default TOSCo • Revised TOSCo

Source: Texas A&M Transportation Institute, 2022

Performance Metric Selection

The research team selected several performance metrics used across several planned experiments to answer the simulation questions. The team collected the following performance metrics at each intersection:

- Total Delay per vehicle
- Stop Delay per vehicle
- Number of Stops per vehicle
- Total Travel Time
- Fuel usage

These performance metrics allow the research team to evaluate the impacts of TOSCo on FM 1960 operations and the performance of TOSCo overall. The research team used the internal emissions model within VISSIM to calculate the fuel usage at each intersection to measure the impacts of TOSCo on emissions and fuel costs.

Field Benefits Assessment Plan

The analysis team utilized the physical deployment for an experiment to analyze the TOSCo vehicle performance on the FM 1960 corridor. The analysis involved driving each TOSCo vehicle individually in either direction with two going opposite directions at the same time. These trips started from the west of intersection 101 and continued past intersection 113 where the vehicle turned around in a parking lot. Trips in the opposite direction started from the lot past intersection 113 and continued past intersection 101. A random number generator was used to assign the vehicles driving behavior where the driver would either activate TOSCo or not activate TOSCo. The random number generator was meant to help ensure that the driving mode for each run was randomly assigned to avoid biasing the results from the TOSCo mode always arriving at the same time in the cycle. If the run does not involve activating TOSCo, the driver traveled in the middle lane and attempted to pace with traffic.

This experiment was executed two times. First, on March 25, 2022, the experiment was executed where the data collection involved all the TOSCo measurements so the research team could analyze travel time, stops, and estimate emissions. During the second time the experiment was executed, the research team continued to collect the TOSCo measurements and collected emissions readings from a portable tailpipe emissions measurement device on a separate research effort not related to the research efforts described in this report. This report discusses the travel time and stop study and a future addendum will cover the emissions measurement from the second execution of the travel time study.

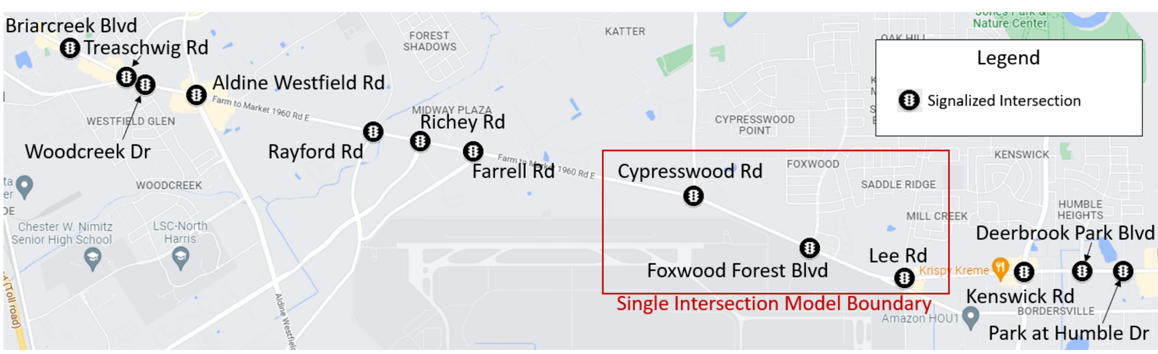
Travel time for the field benefits assessment is defined as the amount of time to travel from map matching of the first intersection to crossing the stop bar of the last intersection. For example, eastbound travel time boundaries are from when the TOSCo vehicle first map matches to intersection 101 to when the vehicle crosses the stop bar at intersection 113. The stops are counted between those two times based on the number of times when a vehicle's speed drops below 5 miles per hour.

Chapter 5. Farm-to-Market 1960 Model Assessment

This chapter discusses the simulation results of FM 1960 for the single intersection model and the corridor model. The evaluation includes multiple potential representations of TOSCo and focuses on the corridor performance. These simulations cover the off-peak period and cover a range of market penetration rates (MPR) from 0, also considered the baseline, to 100 % MPR of TOSCo. The off-peak period was used for the analysis because this is the time where the deployed version of TOSCo operated. Below is a list of a few settings in the simulation used for this analysis:

- The corridor uses signal timing from the Texas Department of Transportation Houston district to represent the FM 1960 corridor with minimum recalls placed on the non-coordinated phases.
- This model excluded truck volumes in the analysis. The truck percentage on FM 1960 was considered zero to help isolate the comparison of TOSCo versus Non-TOSCo control to only the relevant vehicle classes – passenger cars.
- Each simulation scenario has five simulation seeds to help account for randomness in the model.
- Each simulation run of the FM 1960 model is 3,600 simulation seconds of data collection with either a 300 or a 900 second warm-up period at the beginning of the simulation depending on the model. The single intersection model has a total simulation time of 3900 seconds and the corridor model has a total simulation time of 4500 seconds.

The benefits estimate analyses two simulation models with various scenarios. First, the report reviews the data collected at the single intersection model. The boundaries of the single intersection model are shown on the map in Figure 9. The single intersection model is centered around Intersection 109, or Foxwood Forest Blvd., and it includes Cypresswood Rd. and Lee Rd. in the model to create the expected arrival rates at Intersection 109. The next section is a summary of the performance for the entire corridor including eastbound and westbound performance for vehicles that travel the length of the corridor. The corridor model sections of this chapter also summarize the network-wide performance metrics for the FM 1960 facility across the different market penetration rates.



Source: Imagery ©2022 Google. Map Data ©2022 Google, 2022

Figure 9. Location of the Intersection Model for FM 1960

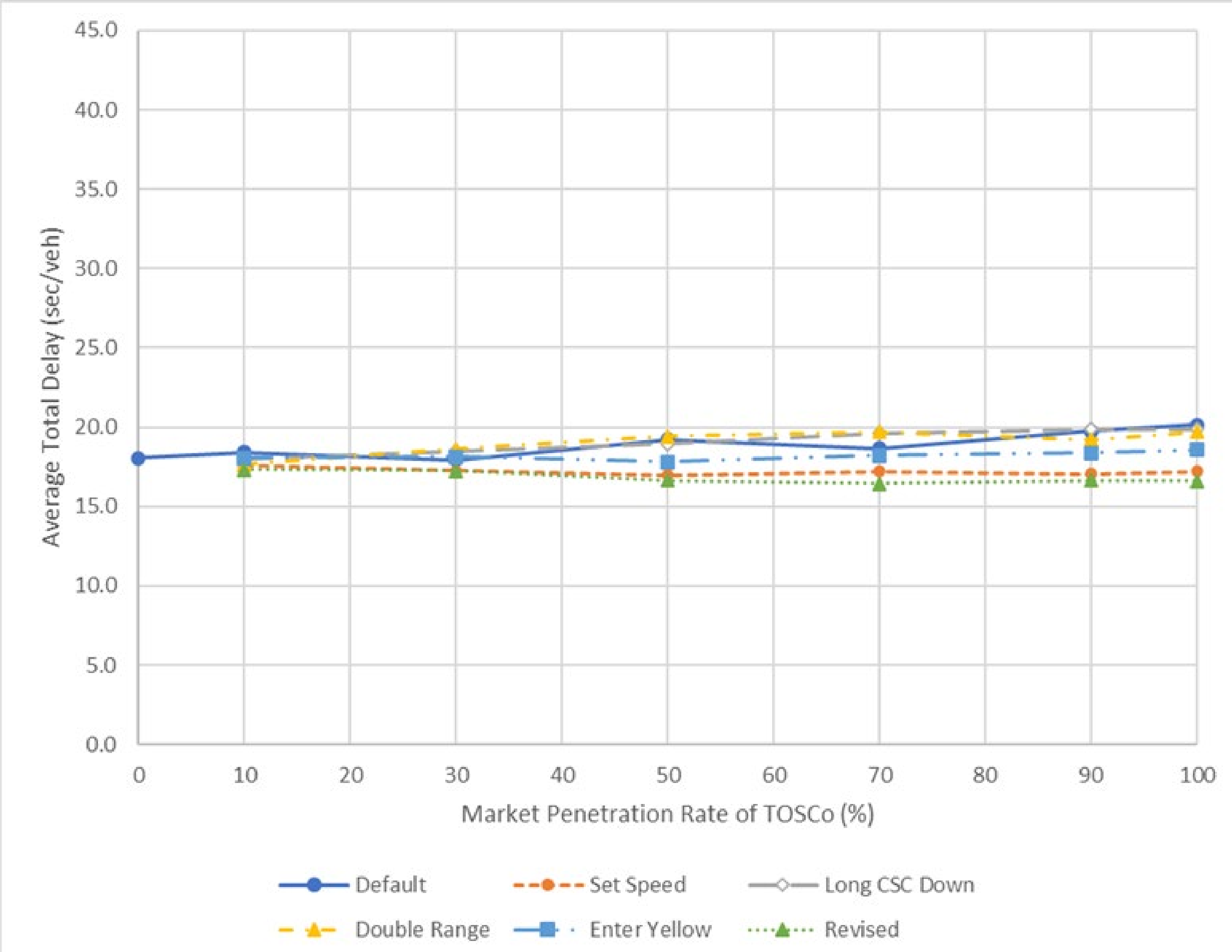
The off-peak period for the FM 1960 corridor does not have any cases of over-saturation, meaning that all the queues at each intersection were able to cross the stop bar within one green indication. The traffic patterns in the off-peak are such that the westbound direction of travel is the peak direction of travel especially on the west end of the corridor. Intersection 109 occasionally has cycle failures where the queue does not clear within the allotted green time, but the queue does clear in the next cycle. The following sections describe performance metrics for the intersections, through traffic on the corridor, and the entire corridor.

Performance at a Single Intersection

The single intersection model simulates the performance at intersection 109 with a variety of TOSCo settings and two different volumes. The evaluation of the single intersection model includes two different volume levels: the off-peak volumes and an increased volume scenario where the off-peak volumes are increased by 20 percent. The various TOSCo settings across each market penetration were analyzed for each volume setting. Intersection 109 is 4,000 feet away from intersection 108 and 3,200 feet away from intersection 110. The eastbound traffic coming from intersection 108 is in the same timing plan as intersection 109 while westbound traffic from intersection 110 is on a different timing plan with a longer cycle length. Most of the traffic on FM 1960 at intersection 109 goes through the intersection and the intersection has long approaches in both directions which causes low amounts of weaving on both approaches. The measurements for this intersection are separated by direction and summarized for the intersection. The analysis involved running TOSCo with five different settings and then creating a sixth set of parameters for TOSCo that combined each favorable adjustment to TOSCo behavior.

Off-peak Volumes

The normal off-peak volumes of the single intersection model was analyzed with the five TOSCo configurations. The preliminary results showed that the set-speed, double range, and enter yellow settings for TOSCo each yielded reductions in the average delay for the intersection. Therefore the revised TOSCo setting combined the Set-Speed, Double Range, and the Enter Yellow TOSCo settings. The delay measurements for eastbound traffic at 109 across all settings are given in Figure 10 and Table 7.



Source: Texas A&M Transportation Institute, 2022

Figure 10. Intersection 109 Average Eastbound Through Movement Total Delay

Table 7. Comparison of Total Delay at Intersection 109, All Vehicle Types (Eastbound)

TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	18.1	—	0.46	—
Default	10	18.4	2%	0.96	0.232
Default	30	17.9	-1%	0.81	0.385
Default	50	19.2	6%	1.37	0.059
Default	70	18.7	3%	0.96	0.119
Default	90	19.7	9%	1.22	0.012
Default	100	20.1	11%	0.80	<0.001
Set Speed	10	17.6	-3%	0.61	0.100

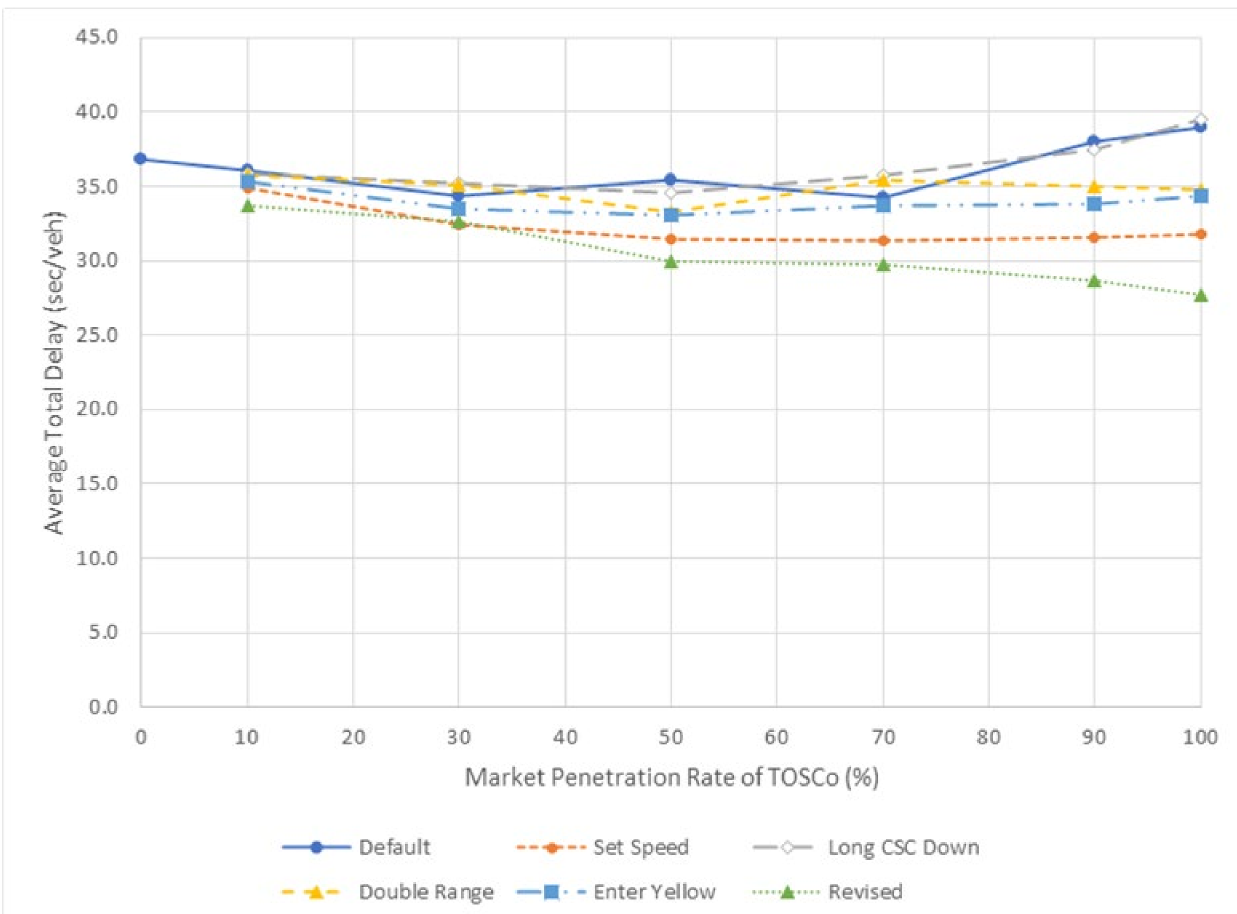
TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Set Speed	30	17.2	-5%	0.73	0.035
Set Speed	50	17.0	-6%	0.85	0.020
Set Speed	70	17.2	-5%	0.85	0.041
Set Speed	90	17.1	-6%	0.96	0.037
Set Speed	100	17.2	-5%	0.74	0.030
Long CSC Down	10	18.0	0%	0.83	0.464
Long CSC Down	30	18.5	2%	1.10	0.214
Long CSC Down	50	19.0	5%	0.79	0.033
Long CSC Down	70	19.6	9%	1.38	0.023
Long CSC Down	90	19.9	10%	0.79	0.002
Long CSC Down	100	19.9	10%	1.01	0.004
Double Range	10	17.6	-2%	0.75	0.156
Double Range	30	18.6	3%	0.98	0.149
Double Range	50	19.4	8%	2.89	0.167
Double Range	70	19.7	9%	1.30	0.016
Double Range	90	19.2	6%	0.67	0.008
Double Range	100	19.7	9%	1.00	0.006
Enter Yellow	10	18.0	0%	0.79	0.475
Enter Yellow	30	18.1	0%	0.92	0.455
Enter Yellow	50	17.8	-1%	1.04	0.311
Enter Yellow	70	18.2	1%	1.03	0.385
Enter Yellow	90	18.4	2%	1.03	0.270
Enter Yellow	100	18.6	3%	1.06	0.174
Revised	10	17.3	-4%	0.72	0.051
Revised	30	17.2	-5%	0.90	0.056
Revised	50	16.6	-8%	1.07	0.014
Revised	70	16.4	-9%	0.70	0.002
Revised	90	16.7	-8%	0.60	0.002
Revised	100	16.6	-8%	0.55	0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

As market penetration increases, the default TOSCo operation causes an increase of total delay of 2.0 seconds per vehicle. The double range, long CSC down, and enter yellow modifications each also increase the average total delay experienced by eastbound traffic. The set speed trajectory planning modification resulted in a decrease of total delay per vehicle by almost one second each vehicle and the revised TOSCo setting reduced the total delay by about 1.5 seconds per vehicle on average. These benefits do not represent a very large change in the overall delay for vehicles that travel across the corridor.

Figure 11 and Table 8 show the westbound total delays in the intersection 109 model. The westbound total delay increases slightly as MPR increases with both the default and long CSC down TOSCo settings. The double range and enter in yellow settings for TOSCo experience a slight reduction in delay at the 10 and 30 percent MPR but level out to a decrease in total delay of 2.1 and 2.5 seconds per vehicle at 100 percent MPR, respectively. The set speed and revised TOSCo settings both led to a reduction of over 5 seconds per vehicle on average between the baseline and the 100 MPR scenario. The revised TOSCo setting led to gradual decreases of average total delay 9.1 seconds per vehicle. The westbound direction of travel has higher delays than the eastbound direction primarily because traffic on this approach is not coordinated with the analysis intersection. Westbound traffic arrives at different times in the cycle for intersection 109 thus resulting in worse performance for westbound traffic than the eastbound direction.



Source: Texas A&M Transportation Institute, 2022

Figure 11. Intersection 109 Average Westbound Through Movement Total Delay

Table 8. Comparison of Total Delay at Intersection 109, All Vehicle Types (Westbound)

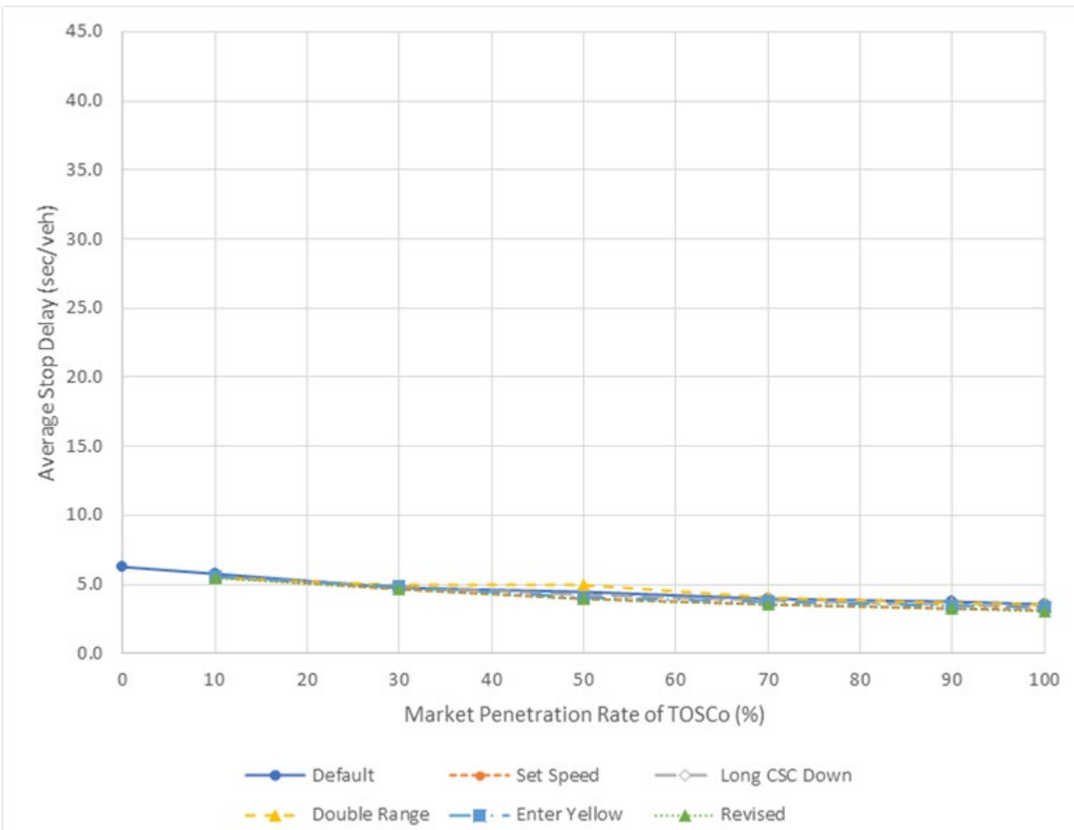
TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	36.8	—	2.58	—
Default	10	36.1	-2%	2.72	0.338
Default	30	34.4	-7%	1.77	0.063
Default	50	35.4	-4%	1.37	0.160
Default	70	34.3	-7%	1.86	0.060
Default	90	38.0	3%	1.53	0.207
Default	100	38.9	6%	2.73	0.121
Set Speed	10	34.9	-5%	2.43	0.136
Set Speed	30	32.4	-12%	1.43	0.006
Set Speed	50	31.4	-15%	1.82	0.003
Set Speed	70	31.3	-15%	1.87	0.003
Set Speed	90	31.5	-14%	1.42	0.003
Set Speed	100	31.7	-14%	2.08	0.006
Long CSC Down	10	35.8	-3%	2.07	0.264
Long CSC Down	30	35.2	-4%	2.08	0.159
Long CSC Down	50	34.6	-6%	2.15	0.094
Long CSC Down	70	35.7	-3%	1.30	0.214
Long CSC Down	90	37.4	2%	1.70	0.326
Long CSC Down	100	39.5	7%	3.19	0.090
Double Range	10	35.8	-3%	2.72	0.279
Double Range	30	35.1	-5%	3.12	0.184
Double Range	50	33.2	-10%	1.58	0.017
Double Range	70	35.4	-4%	1.11	0.158
Double Range	90	35.0	-5%	2.84	0.161
Double Range	100	34.7	-6%	1.77	0.093
Enter Yellow	10	35.3	-4%	2.63	0.195
Enter Yellow	30	33.5	-9%	1.70	0.024
Enter Yellow	50	33.1	-10%	1.48	0.014
Enter Yellow	70	33.8	-8%	1.62	0.030
Enter Yellow	90	33.8	-8%	1.82	0.035
Enter Yellow	100	34.3	-7%	1.72	0.059
Revised	10	34.6	-6%	2.15	0.097
Revised	30	32.2	-13%	1.97	0.008
Revised	50	30.0	-18%	1.14	<0.001
Revised	70	29.8	-19%	1.55	<0.001
Revised	90	28.8	-22%	1.57	<0.001

TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Revised	100	27.7	-25%	1.17	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs form the baseline.

Source: Texas A&M Transportation Institute, 2022

Figure 12 and Table 9 show the changes in stop delay for the eastbound traffic at the single intersections model. Every set of TOSCo settings analyzed led to gradual reductions in stop delay as market penetration increased. The revised settings of TOSCo causes greatest reduction in stop delay of 3.3 seconds which accounts for over 50 percent of the stop delay, at 100 percent MPR. All reductions in stop delay are statistically significant at a 95 percent probability except for the 50 percent MPR for the double range setting, which is only significant at a 90 percent probability. Many differences in stop delay are statistically significant at over a 99 percent probability.



Source: Texas A&M Transportation Institute, 2022

Figure 12. Intersection 109 Average Eastbound Through Movement Stop Delay

Table 9. Comparison of Stop Delay at Intersection 109, All Vehicle Types (Eastbound)

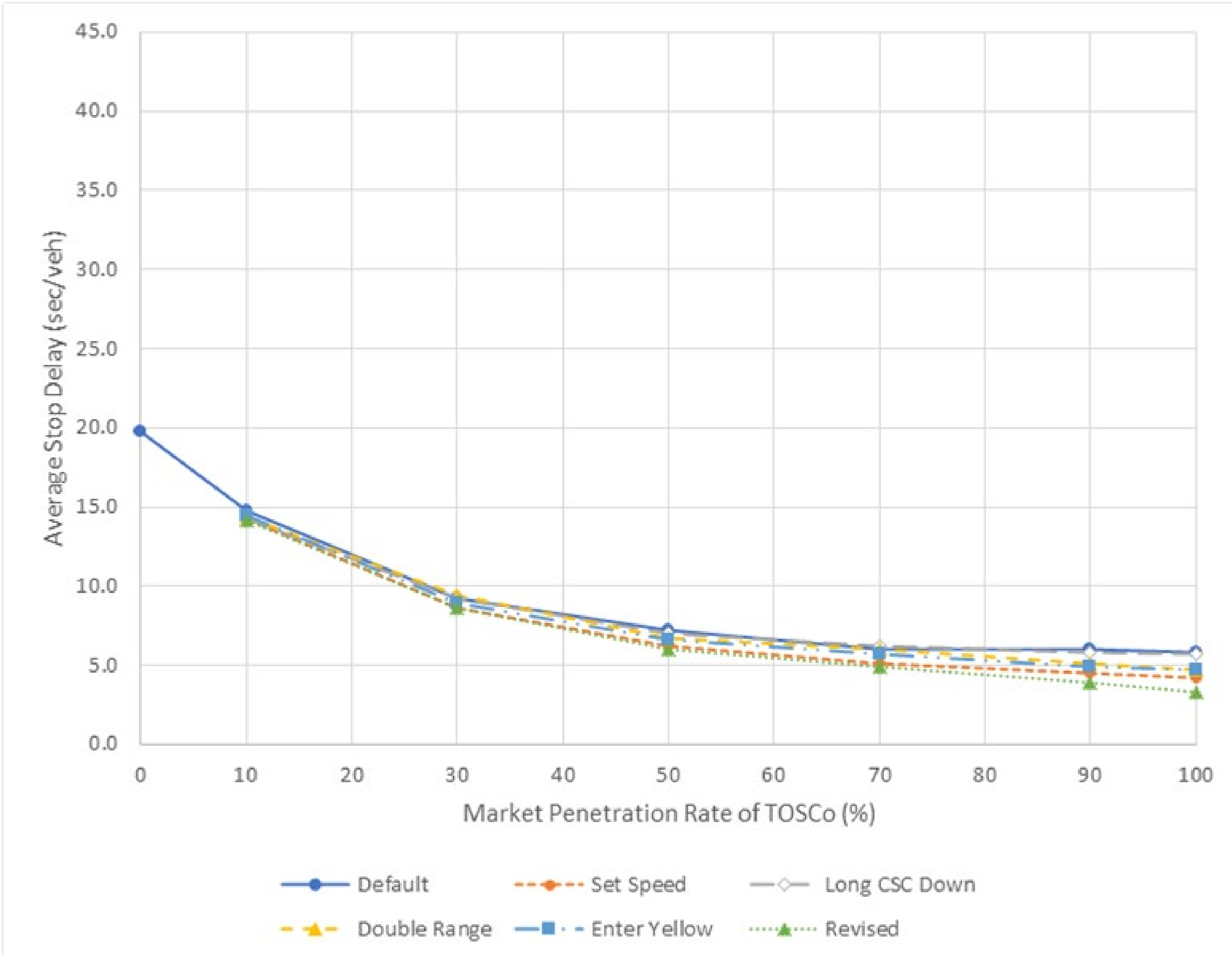
TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	6.3	—	0.15	—
Default	10	5.8	-8%	0.43	0.024
Default	30	4.8	-24%	0.24	<0.001
Default	50	4.5	-28%	0.35	<0.001
Default	70	4.0	-36%	0.14	<0.001
Default	90	3.7	-40%	0.20	<0.001
Default	100	3.6	-43%	0.14	<0.001
Set Speed	10	5.6	-11%	0.20	<0.001
Set Speed	30	4.6	-26%	0.27	<0.001
Set Speed	50	4.0	-37%	0.23	<0.001
Set Speed	70	3.6	-43%	0.11	<0.001
Set Speed	90	3.2	-48%	0.12	<0.001
Set Speed	100	3.1	-50%	0.12	<0.001
Long CSC Down	10	5.6	-11%	0.37	0.003
Long CSC Down	30	4.8	-23%	0.40	<0.001
Long CSC Down	50	4.3	-32%	0.25	<0.001
Long CSC Down	70	3.9	-38%	0.19	<0.001
Long CSC Down	90	3.6	-43%	0.13	<0.001
Long CSC Down	100	3.4	-46%	0.13	<0.001
Double Range	10	5.5	-12%	0.29	<0.001
Double Range	30	5.0	-20%	0.38	<0.001
Double Range	50	5.0	-20%	1.53	0.058
Double Range	70	4.1	-35%	0.22	<0.001
Double Range	90	3.7	-41%	0.10	<0.001
Double Range	100	3.5	-43%	0.24	<0.001
Enter Yellow	10	5.6	-11%	0.38	0.004
Enter Yellow	30	4.8	-23%	0.32	<0.001
Enter Yellow	50	4.1	-34%	0.27	<0.001
Enter Yellow	70	3.8	-39%	0.13	<0.001
Enter Yellow	90	3.5	-45%	0.15	<0.001
Enter Yellow	100	3.3	-47%	0.19	<0.001
Revised	10	5.5	-12%	0.28	<0.001
Revised	30	4.6	-26%	0.33	<0.001
Revised	50	4.0	-36%	0.26	<0.001
Revised	70	3.5	-44%	0.13	<0.001
Revised	90	3.2	-48%	0.12	<0.001

TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Revised	100	3.0	-52%	0.12	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Figure 13 Table 10 shows the westbound stop delays in the intersection 109 model. The westbound stop delay decreases with every TOSCo setting. The revised settings of TOSCo generated the greatest reductions in stop delay for the average westbound vehicle. The default and revised settings of TOSCo represented the greatest and least amount of stop delay at 100 percent MPR. Each of these scenarios generated at least 14 second reduction of stop delay per vehicle. The revised TOSCo led to the greatest reduction of average stop delay, amounting to 16.5 seconds. Every reduction in stop delay is significant at greater than a 99.9 percent probability.



Source: Texas A&M Transportation Institute, 2022

Figure 13. Intersection 109 Average Westbound Through Movement Stop Delay

Table 10. Comparison of Stop Delay at Intersection 109, All Vehicle Types (Westbound)

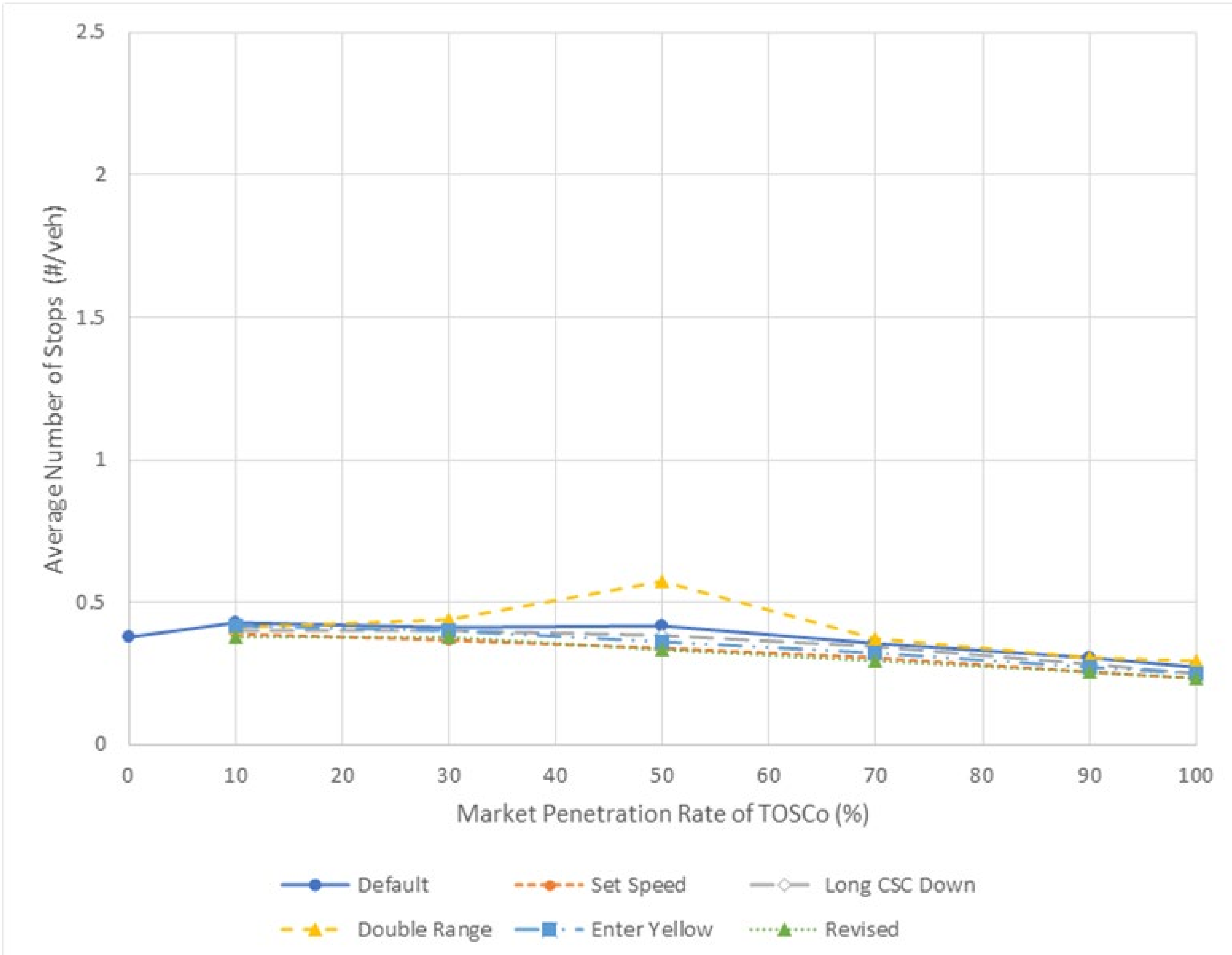
TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	19.8	—	1.60	—
Default	10	14.7	-26%	1.21	<0.001
Default	30	9.2	-54%	0.35	<0.001
Default	50	7.2	-63%	0.58	<0.001
Default	70	6.0	-70%	0.38	<0.001
Default	90	6.0	-70%	0.41	<0.001
Default	100	5.8	-71%	0.46	<0.001
Set Speed	10	14.2	-28%	1.22	<0.001

TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Set Speed	30	8.6	-57%	0.31	<0.001
Set Speed	50	6.2	-69%	0.45	<0.001
Set Speed	70	5.1	-74%	0.46	<0.001
Set Speed	90	4.5	-77%	0.33	<0.001
Set Speed	100	4.2	-79%	0.44	<0.001
Long CSC Down	10	14.3	-28%	0.93	<0.001
Long CSC Down	30	9.3	-53%	0.56	<0.001
Long CSC Down	50	7.0	-65%	0.68	<0.001
Long CSC Down	70	6.2	-69%	0.22	<0.001
Long CSC Down	90	5.8	-71%	0.46	<0.001
Long CSC Down	100	5.7	-71%	0.64	<0.001
Double Range	10	14.4	-27%	1.16	<0.001
Double Range	30	9.4	-52%	1.02	<0.001
Double Range	50	6.7	-66%	0.47	<0.001
Double Range	70	6.0	-70%	0.45	<0.001
Double Range	90	5.1	-74%	0.62	<0.001
Double Range	100	4.7	-76%	0.45	<0.001
Enter Yellow	10	14.4	-27%	1.26	<0.001
Enter Yellow	30	8.9	-55%	0.30	<0.001
Enter Yellow	50	6.6	-67%	0.49	<0.001
Enter Yellow	70	5.7	-71%	0.35	<0.001
Enter Yellow	90	4.9	-75%	0.38	<0.001
Enter Yellow	100	4.7	-76%	0.38	<0.001
Revised	10	14.2	-28%	0.98	<0.001
Revised	30	8.6	-56%	0.50	<0.001
Revised	50	6.0	-70%	0.28	<0.001
Revised	70	4.9	-75%	0.46	<0.001
Revised	90	3.9	-80%	0.24	<0.001
Revised	100	3.3	-83%	0.22	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Figure 14 and Table 11 show the average number of stops for eastbound traffic with every setting of TOSCo parameters considered in this analysis.



Source: Texas A&M Transportation Institute, 2022

Figure 14. Intersection 109 Average Eastbound Number of Stops

Table 11. Comparison of Number of Stops at Intersection 109, All Vehicle Types (Eastbound)

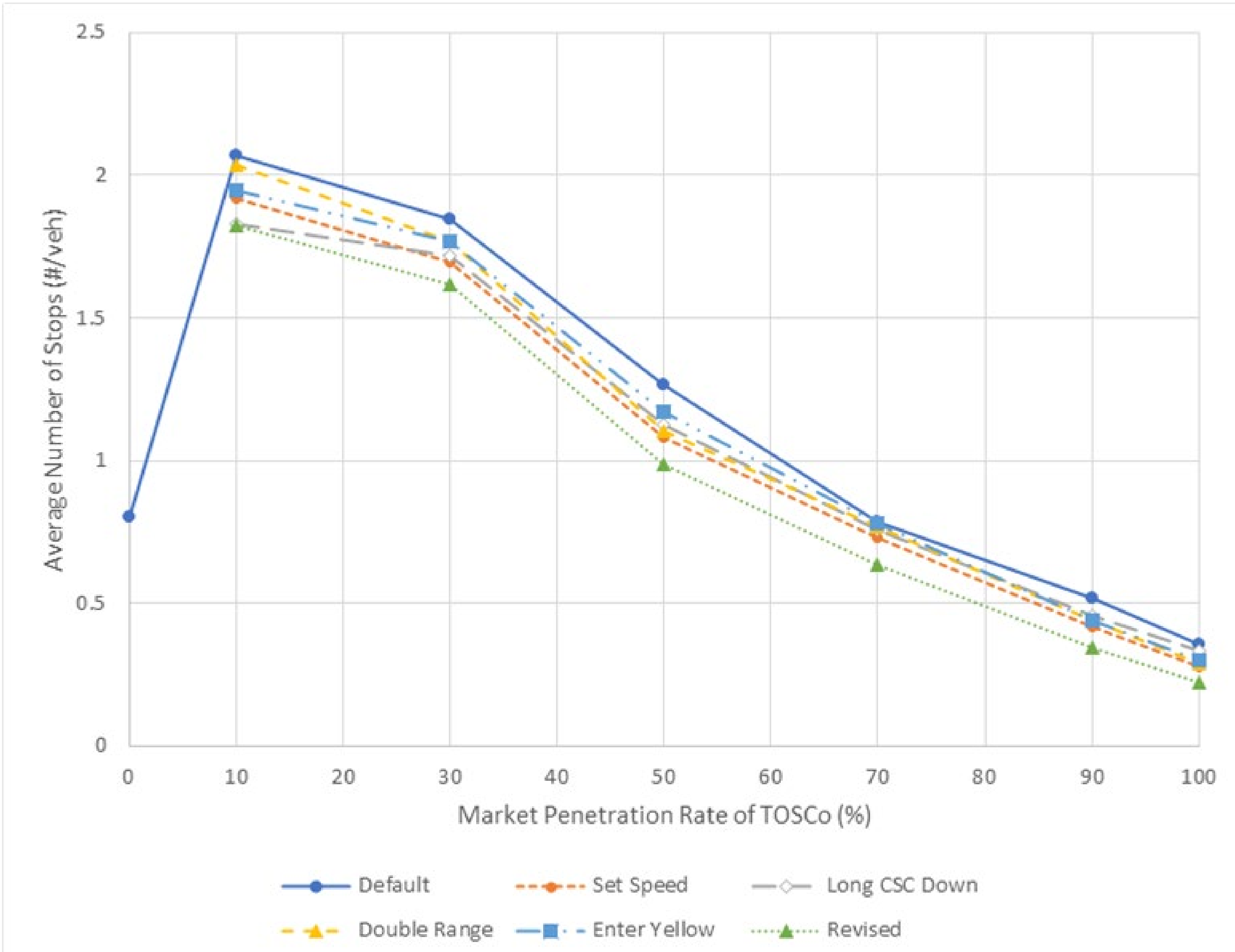
TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	0.38	—	0.02	—
Default	10	0.43	14%	0.02	0.001
Default	30	0.41	9%	0.04	0.046
Default	50	0.42	11%	0.06	0.088
Default	70	0.36	-5%	0.02	0.085
Default	90	0.31	-19%	0.02	<0.001
Default	100	0.27	-28%	0.01	<0.001

TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Set Speed	10	0.39	3%	0.03	0.235
Set Speed	30	0.37	-2%	0.02	0.320
Set Speed	50	0.34	-10%	0.03	0.017
Set Speed	70	0.30	-19%	0.02	<0.001
Set Speed	90	0.26	-32%	0.01	<0.001
Set Speed	100	0.23	-38%	0.01	<0.001
Long CSC Down	10	0.40	7%	0.03	0.077
Long CSC Down	30	0.40	6%	0.05	0.181
Long CSC Down	50	0.38	2%	0.04	0.376
Long CSC Down	70	0.34	-9%	0.04	0.052
Long CSC Down	90	0.29	-24%	0.01	<0.001
Long CSC Down	100	0.25	-34%	0.01	<0.001
Double Range	10	0.41	9%	0.03	0.035
Double Range	30	0.44	17%	0.04	0.008
Double Range	50	0.57	52%	0.40	0.157
Double Range	70	0.37	-1%	0.04	0.435
Double Range	90	0.31	-18%	0.01	<0.001
Double Range	100	0.29	-22%	0.04	0.003
Enter Yellow	10	0.42	11%	0.01	0.002
Enter Yellow	30	0.40	7%	0.04	0.113
Enter Yellow	50	0.36	-4%	0.04	0.189
Enter Yellow	70	0.32	-14%	0.03	0.005
Enter Yellow	90	0.27	-28%	0.01	<0.001
Enter Yellow	100	0.25	-34%	0.01	<0.001
Revised	10	0.38	1%	0.02	0.414
Revised	30	0.38	1%	0.03	0.455
Revised	50	0.34	-11%	0.03	0.026
Revised	70	0.29	-22%	0.02	<0.001
Revised	90	0.26	-32%	0.01	<0.001
Revised	100	0.23	-38%	0.01	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

The research team found an increase in number of stops between the baseline scenario and the 10 percent MPR in many cases. This is caused by the definition of stops for VISSIM and the nuances of the driver behavior for the non-TOSCo vehicles in the simulation. VISSIM reports the number of stops performance metric based on the number of times a vehicle comes to a complete stop (5). The relevance of this is that the non-TOSCo vehicles come to a brief complete stop multiple times behind a creeping TOSCo vehicle. The research team finds these frequent and short duration stops unrealistic and an artifact to the simulation. For this reason, the average number of eastbound stops increases in the low market penetration rates for each set of TOSCo parameters and the number of stops eventually decreases compared to the baseline. Note, the average number of eastbound stops per vehicle is low. The double range TOSCo parameters experienced a spike in the number of stops at 50 percent MPR, but the numeric increase in stops is not large. Figure 15 and Table 12 show the westbound average number of stops in the intersection 109 model. The westbound stops increase greatly between the baseline and 10 percent MPR for every TOSCo setting. After 10 percent MPR the average number of stops decreases gradually for every representation of TOSCo. At 70 percent MPR, VISSIM estimates that the number of stops will decrease below the number of stops estimated for the baseline westbound traffic. The revised TOSCo generated the greatest reductions in stops overall for the average westbound vehicle. The stop delay performance metrics shown in Figure 13 support the observation since every TOSCo setting showed a decrease in average stop delay of several seconds for 10 percent MPR.



Source: Texas A&M Transportation Institute, 2022

Figure 15. Intersection 109 Average Westbound Number of Stops

Table 12. Comparison of Number of Stops at Intersection 109, All Vehicle Types (Westbound)

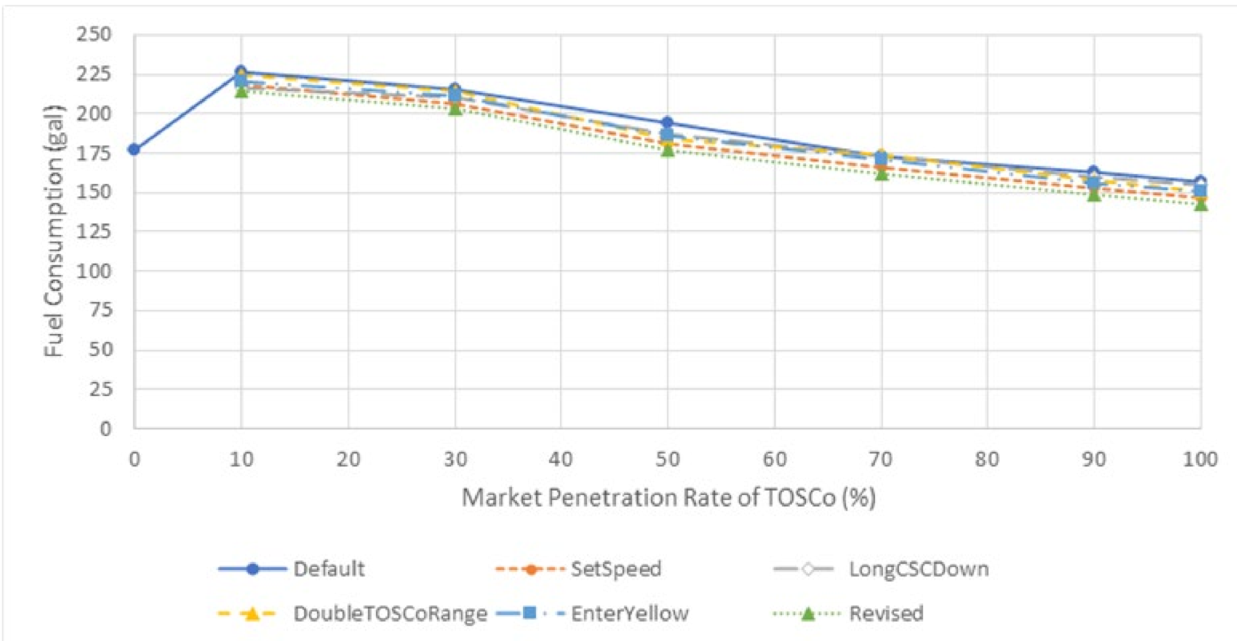
TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	0.80	—	0.06	—
Default	10	2.07	157%	0.28	<0.001
Default	30	1.85	130%	0.11	<0.001
Default	50	1.27	58%	0.06	<0.001
Default	70	0.79	-2%	0.06	0.355
Default	90	0.52	-36%	0.03	<0.001
Default	100	0.36	-56%	0.03	<0.001

TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Set Speed	10	1.92	139%	0.17	<0.001
Set Speed	30	1.69	111%	0.07	<0.001
Set Speed	50	1.08	35%	0.05	<0.001
Set Speed	70	0.73	-9%	0.07	0.058
Set Speed	90	0.42	-48%	0.02	<0.001
Set Speed	100	0.27	-66%	0.02	<0.001
Long CSC Down	10	1.83	128%	0.24	<0.001
Long CSC Down	30	1.72	114%	0.17	<0.001
Long CSC Down	50	1.13	40%	0.07	<0.001
Long CSC Down	70	0.76	-5%	0.06	0.141
Long CSC Down	90	0.46	-43%	0.03	<0.001
Long CSC Down	100	0.34	-58%	0.03	<0.001
Double Range	10	2.03	153%	0.23	<0.001
Double Range	30	1.77	120%	0.15	<0.001
Double Range	50	1.10	37%	0.03	<0.001
Double Range	70	0.77	-4%	0.03	0.177
Double Range	90	0.44	-45%	0.05	<0.001
Double Range	100	0.29	-64%	0.02	<0.001
Enter Yellow	10	1.95	142%	0.20	<0.001
Enter Yellow	30	1.77	120%	0.11	<0.001
Enter Yellow	50	1.17	46%	0.01	<0.001
Enter Yellow	70	0.78	-3%	0.06	0.291
Enter Yellow	90	0.44	-45%	0.02	<0.001
Enter Yellow	100	0.30	-62%	0.01	<0.001
Revised	10	1.82	127%	0.18	<0.001
Revised	30	1.62	102%	0.08	<0.001
Revised	50	0.99	23%	0.04	<0.001
Revised	70	0.64	-21%	0.07	0.002
Revised	90	0.34	-57%	0.02	<0.001
Revised	100	0.22	-72%	0.01	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

The research team also extracted the fuel use for all vehicles traveling around intersection 109 as estimated by VISSIM. The fuel use estimates are presented in Figure 16 and Table 13, below. Like the average number of stops, the fuel usage does increase initially with every TOSCo settings option. The increase in fuel use is associated with the increase stops observed primarily by non-TOSCo vehicles. This appears to be related to the unrealistic number of stops artifact of the simulation. By 70 percent MPR, the fuel usage is less than or equal to the baseline fuel use which is consistent when the westbound number of stops is less than or equal to the baseline average number of stops for each TOSCo setting.



Source: Texas A&M Transportation Institute, 2022

Figure 16. Intersection 109 Average Fuel Usage Around Intersection

Table 13. Comparison of Fuel Usage at Intersection 109, All Vehicle Types

TOSCo Parameters	Market Penetration (%)	Fuel Usage (gal)	% Change[1]	Standard Deviation (gal)	Statistical Significance (p-value)[2]
None	0	177	—	6.3	—
Default	10	227	28%	14.5	<0.001
Default	30	215	22%	7.8	<0.001
Default	50	194	10%	5.2	<0.001
Default	70	173	-2%	4.5	0.141
Default	90	163	-8%	3.1	0.002
Default	100	157	-12%	3.7	<0.001
Set Speed	10	218	23%	10.1	<0.001
Set Speed	30	206	17%	5.2	<0.001

TOSCo Parameters	Market Penetration (%)	Fuel Usage (gal)	% Change[1]	Standard Deviation (gal)	Statistical Significance (p-value)[2]
Set Speed	50	181	2%	5.0	0.138
Set Speed	70	166	-6%	5.1	0.011
Set Speed	90	153	-14%	3.1	<0.001
Set Speed	100	147	-17%	3.7	<0.001
Long CSC Down	10	216	22%	11.3	<0.001
Long CSC Down	30	211	19%	11.1	<0.001
Long CSC Down	50	188	6%	6.1	0.015
Long CSC Down	70	172	-3%	3.0	0.096
Long CSC Down	90	159	-10%	3.4	<0.001
Long CSC Down	100	154	-13%	4.8	<0.001
Double Range	10	224	27%	12.1	<0.001
Double Range	30	214	21%	10.5	<0.001
Double Range	50	184	4%	5.9	0.060
Double Range	70	174	-2%	3.3	0.197
Double Range	90	158	-11%	4.0	<0.001
Double Range	100	151	-15%	3.2	<0.001
Enter Yellow	10	221	25%	11.4	<0.001
Enter Yellow	30	211	19%	7.8	<0.001
Enter Yellow	50	187	5%	4.4	0.014
Enter Yellow	70	171	-3%	4.7	0.061
Enter Yellow	90	156	-12%	3.7	<0.001
Enter Yellow	100	150	-15%	3.1	<0.001
Revised	10	214	21%	10.3	<0.001
Revised	30	204	15%	6.6	<0.001
Revised	50	177	0%	2.3	0.456
Revised	70	162	-9%	3.0	<0.001
Revised	90	148	-16%	2.7	<0.001
Revised	100	142	-20%	2.5	<0.001

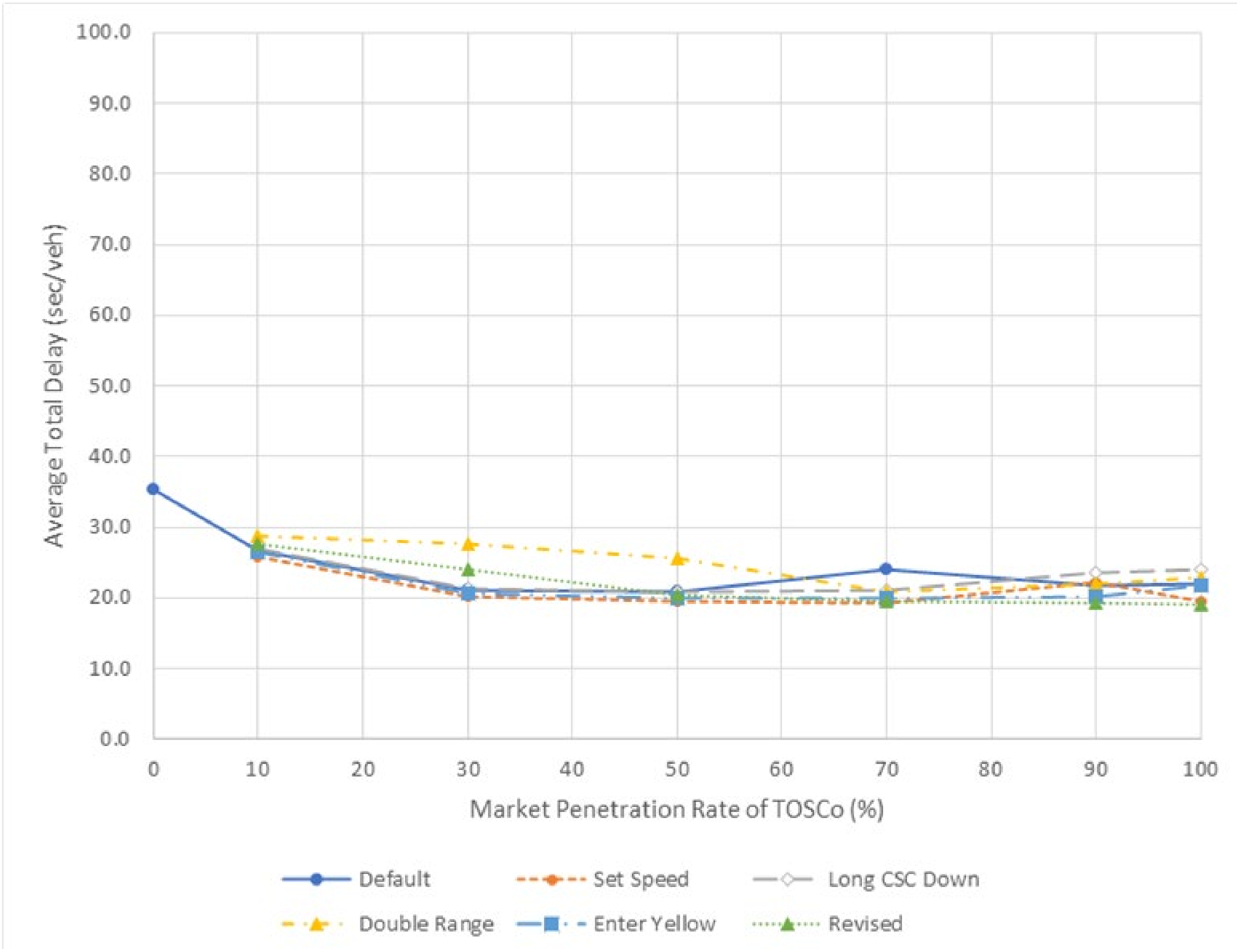
[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.

[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Increased Volumes

The next set of simulation runs involved increasing the traffic in the intersection model by 20 percent to observe how TOSCo impacts performance with oversaturated conditions in the westbound direction. The increase in traffic volumes were applied universally throughout the model, meaning that all inputs into the single intersection network had 20% more traffic. The turning percentages remained constant. Figure 17 and Table 14 present the average total delay per vehicle for the eastbound movement across each of the TOSCo settings considered.



Source: Texas A&M Transportation Institute, 2022

Figure 17. Intersection 109 Average Eastbound Through Movement Total Delay with 20 Percent More Traffic

Table 14. Comparison of Total Delay at Intersection 109 with 20 Percent More Traffic, All Vehicle Types (Eastbound)

TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	35.4	—	3.90	—
Default	10	26.8	-24%	4.13	0.006
Default	30	21.1	-40%	1.02	<0.001
Default	50	20.9	-41%	0.81	<0.001

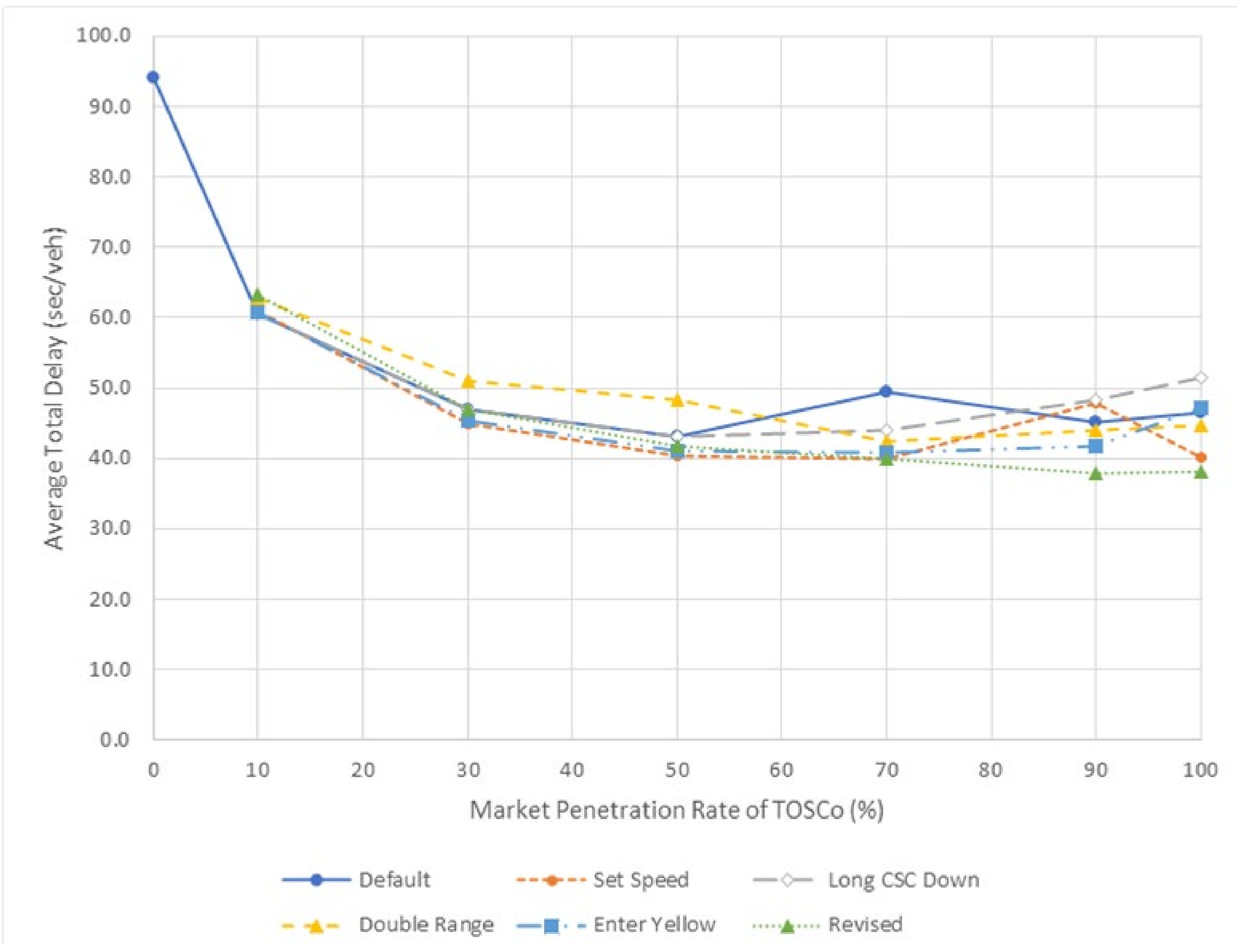
TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Default	70	24.1	-32%	2.00	<0.001
Default	90	21.8	-38%	0.83	<0.001
Default	100	21.9	-38%	1.20	<0.001
Set Speed	10	25.9	-27%	5.24	0.007
Set Speed	30	20.1	-43%	1.09	<0.001
Set Speed	50	19.4	-45%	0.46	<0.001
Set Speed	70	19.2	-46%	0.58	<0.001
Set Speed	90	22.2	-37%	1.73	<0.001
Set Speed	100	19.5	-45%	0.96	<0.001
Long CSC Down	10	26.9	-24%	4.16	0.006
Long CSC Down	30	21.4	-40%	1.53	<0.001
Long CSC Down	50	20.9	-41%	0.59	<0.001
Long CSC Down	70	21.1	-40%	0.69	<0.001
Long CSC Down	90	23.6	-33%	2.19	<0.001
Long CSC Down	100	24.0	-32%	0.39	<0.001
Double Range	10	28.8	-19%	4.10	0.018
Double Range	30	27.6	-22%	3.78	0.008
Double Range	50	25.6	-28%	2.51	0.001
Double Range	70	20.8	-41%	0.87	<0.001
Double Range	90	22.0	-38%	1.25	<0.001
Double Range	100	23.0	-35%	0.83	<0.001
Enter Yellow	10	26.6	-25%	4.77	0.008
Enter Yellow	30	20.6	-42%	0.76	<0.001
Enter Yellow	50	19.9	-44%	0.41	<0.001
Enter Yellow	70	19.8	-44%	0.41	<0.001
Enter Yellow	90	20.1	-43%	0.74	<0.001
Enter Yellow	100	21.8	-38%	0.66	<0.001
Revised	10	27.5	-22%	4.22	0.009
Revised	30	24.1	-32%	2.05	<0.001
Revised	50	20.4	-42%	1.45	<0.001
Revised	70	19.5	-45%	0.98	<0.001
Revised	90	19.2	-46%	2.08	<0.001
Revised	100	19.1	-46%	0.95	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

As market penetration increases, all TOSCo operation cause a decrease of total delay of up to 16.3 seconds per vehicle. The double range and revised modifications each experience higher total delays at low market penetration rates, but they still cause a reduction in total delay compared to the baseline. At low market penetration rates, the standard deviation of total delay increases slightly for each 10 percent MPR but then drops in each TOSCo setting as TOSCo MPR increases.

Figure 18 and Table 15 show the westbound total delays in the intersection 109 model with increased traffic. The westbound total delay decreases as the MPR increases until about 50 percent MPR for each TOSCo setting and then either increases slightly as MPR exceeds 50 percent or remains relatively constant. The default and long CSC down setting of TOSCo experience a similar reduction in delay until 50 percent MPR but increase between 50 and 100 percent MPR. The default and long CSC down both reduce the total delay per westbound vehicle by about 50 percent at 100 percent MPR. The revise TOSCo setting led to the greatest gradual decreases in average total delay of 55.8 seconds per vehicle. This indicates that the benefits of TOSCo are realized by the 50 percent MPR in the westbound direction. The light increases and fluctuations are believed to be random perturbations of the simulation tool.



Source: Texas A&M Transportation Institute, 2022

Figure 18. Intersection 109 Average Westbound Through Movement Total Delay with 20 Percent More Traffic

Table 15. Comparison of Total Delay at Intersection 109 with 20 Percent More Traffic, All Vehicle Types (Westbound)

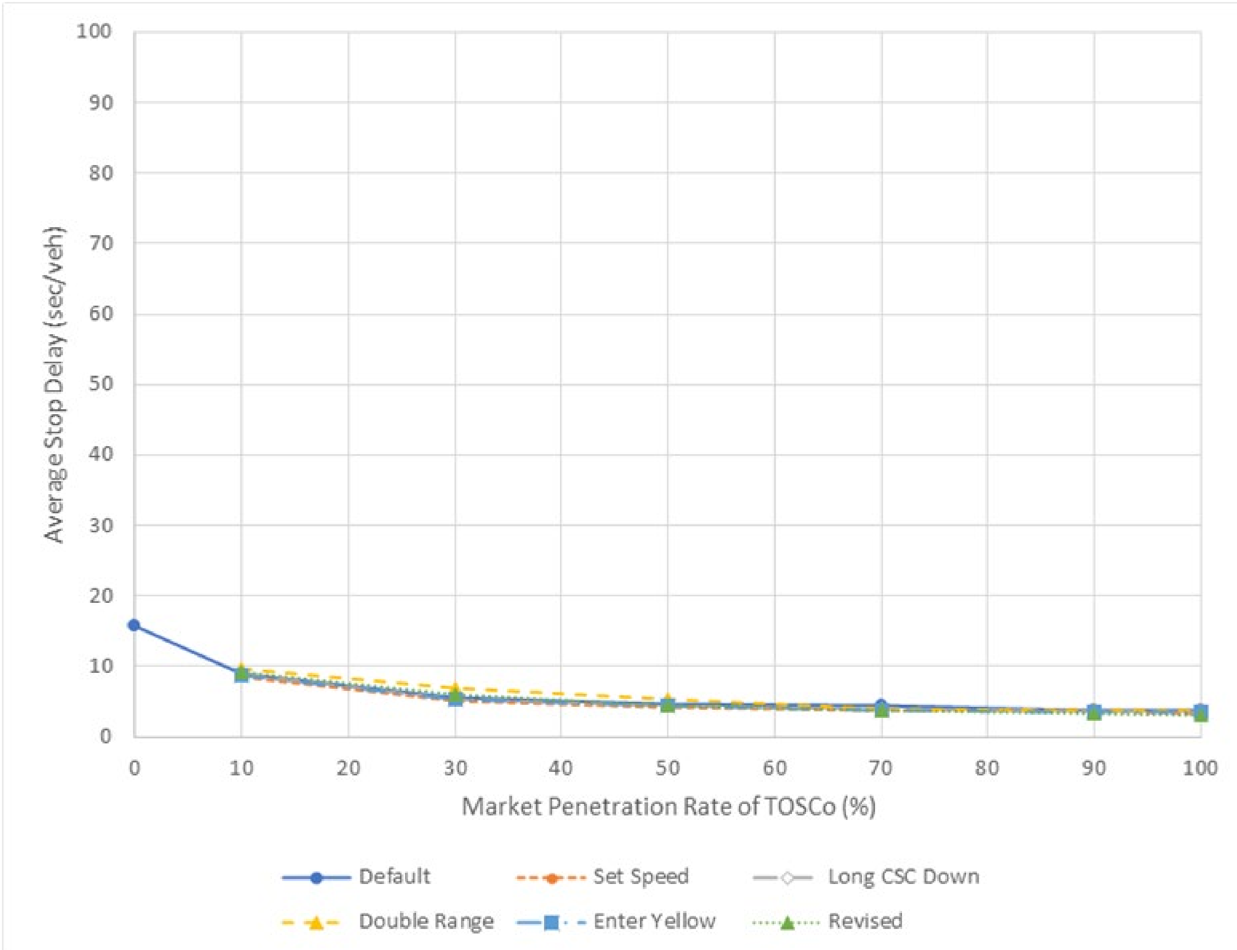
TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	94.0	—	37.20	—
Default	10	60.6	-35%	6.53	0.044
Default	30	46.9	-50%	3.03	0.013
Default	50	43.2	-54%	2.17	0.009
Default	70	49.5	-47%	4.09	0.016
Default	90	45.2	-52%	2.59	0.011
Default	100	46.4	-51%	2.47	0.012
Set Speed	10	61.1	-35%	6.65	0.046
Set Speed	30	44.9	-52%	3.23	0.011
Set Speed	50	40.4	-57%	2.33	0.007
Set Speed	70	40.0	-57%	2.06	0.007
Set Speed	90	48.0	-49%	6.06	0.015
Set Speed	100	40.1	-57%	2.22	0.007
Long CSC Down	10	60.7	-35%	7.97	0.045
Long CSC Down	30	46.9	-50%	3.53	0.013
Long CSC Down	50	43.2	-54%	2.02	0.009
Long CSC Down	70	44.1	-53%	2.34	0.010
Long CSC Down	90	48.3	-49%	3.24	0.014
Long CSC Down	100	51.5	-45%	4.95	0.020
Double Range	10	62.7	-33%	7.55	0.054
Double Range	30	51.0	-46%	3.16	0.018
Double Range	50	48.2	-49%	2.98	0.014
Double Range	70	42.5	-55%	1.64	0.009
Double Range	90	43.9	-53%	1.56	0.010
Double Range	100	44.8	-52%	1.84	0.011
Enter Yellow	10	60.8	-35%	6.98	0.045
Enter Yellow	30	45.3	-52%	3.41	0.011
Enter Yellow	50	41.1	-56%	2.43	0.008
Enter Yellow	70	40.9	-57%	1.87	0.008
Enter Yellow	90	41.9	-55%	2.39	0.008
Enter Yellow	100	47.2	-50%	7.88	0.014
Revised	10	61.5	-35%	8.46	0.049
Revised	30	46.4	-51%	3.87	0.012
Revised	50	41.9	-55%	4.42	0.009
Revised	70	40.1	-57%	2.89	0.007

TOSCo Parameters	Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Revised	90	38.0	-60%	2.58	0.006
Revised	100	38.2	-59%	2.16	0.006

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Figure 19 and Table 16 show the changes in stop delay for the eastbound traffic at the single intersections model. Like the standard volume results, every TOSCo setting analyzed led to gradual reductions in stop delay as market penetration increased. The revised TOSCo causes greatest reduction in stop delay of 12.7 seconds, accounting for over 80 percent of the stop delay, at 100 percent MPR.



Source: Texas A&M Transportation Institute, 2022

Figure 19. Intersection 109 Average Eastbound Through Movement Stop Delay with 20 Percent More Traffic

Table 16. Comparison of Stop Delay at Intersection 109 with 20 Percent More Traffic, All Vehicle Types (Eastbound)

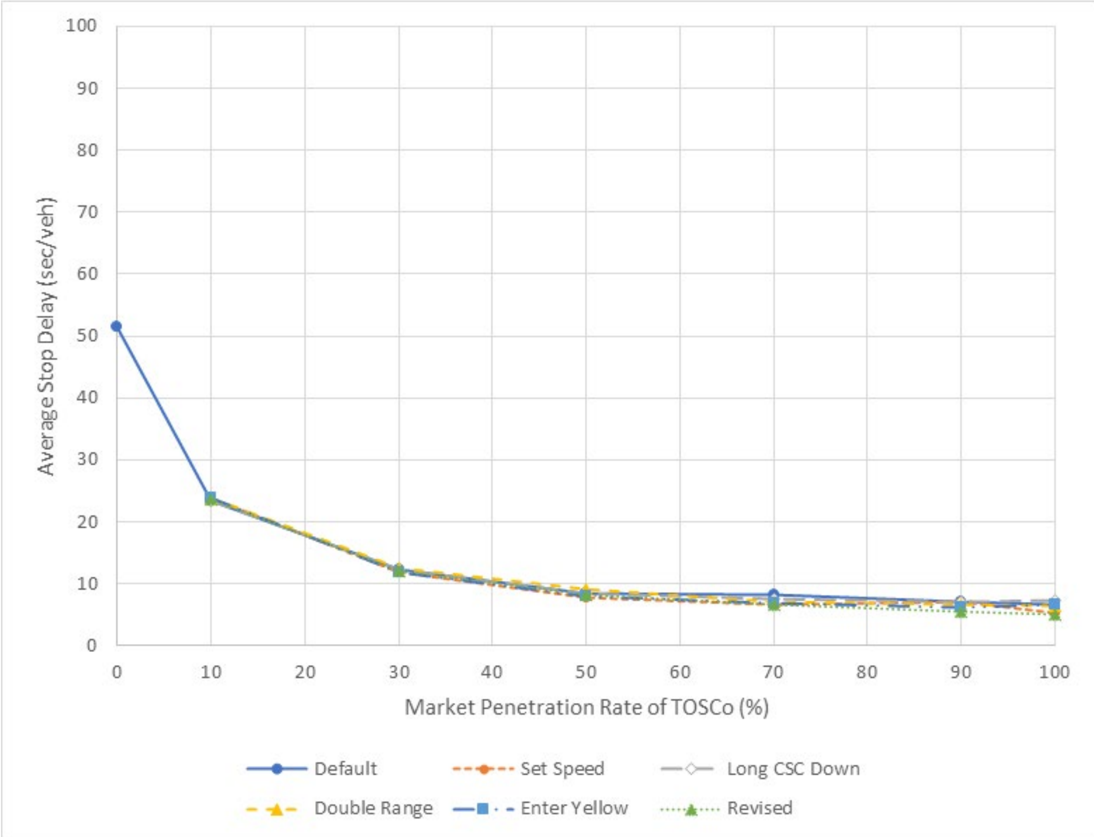
TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	15.8	—	2.24	—
Default	10	8.9	-44%	1.60	<0.001
Default	30	5.5	-65%	0.23	<0.001
Default	50	4.6	-71%	0.16	<0.001
Default	70	4.5	-71%	0.20	<0.001
Default	90	3.9	-76%	0.11	<0.001
Default	100	3.7	-77%	0.16	<0.001

TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Set Speed	10	8.5	-46%	2.06	<0.001
Set Speed	30	5.2	-67%	0.31	<0.001
Set Speed	50	4.2	-73%	0.12	<0.001
Set Speed	70	3.7	-76%	0.13	<0.001
Set Speed	90	3.6	-77%	0.25	<0.001
Set Speed	100	3.2	-80%	0.11	<0.001
Long CSC Down	10	8.8	-44%	1.76	<0.001
Long CSC Down	30	5.4	-66%	0.44	<0.001
Long CSC Down	50	4.4	-72%	0.11	<0.001
Long CSC Down	70	4.0	-75%	0.25	<0.001
Long CSC Down	90	3.8	-76%	0.29	<0.001
Long CSC Down	100	3.6	-77%	0.12	<0.001
Double Range	10	9.6	-39%	1.51	<0.001
Double Range	30	6.9	-57%	0.86	<0.001
Double Range	50	5.3	-67%	0.36	<0.001
Double Range	70	4.1	-74%	0.16	<0.001
Double Range	90	3.7	-76%	0.17	<0.001
Double Range	100	3.7	-77%	0.14	<0.001
Enter Yellow	10	8.8	-45%	1.75	<0.001
Enter Yellow	30	5.3	-66%	0.17	<0.001
Enter Yellow	50	4.4	-72%	0.17	<0.001
Enter Yellow	70	3.8	-76%	0.13	<0.001
Enter Yellow	90	3.5	-78%	0.11	<0.001
Enter Yellow	100	3.5	-78%	0.16	<0.001
Revised	10	9.1	-43%	1.77	<0.001
Revised	30	6.1	-62%	0.47	<0.001
Revised	50	4.4	-72%	0.34	<0.001
Revised	70	3.8	-76%	0.11	<0.001
Revised	90	3.3	-79%	0.24	<0.001
Revised	100	3.1	-81%	0.16	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Figure 20 and Table 17 show the westbound stop delays in the intersection 109 model. The westbound stop delay decreases with every TOSCo setting. Every TOSCo setting results in over a 50 percent reduction in total delay on average for westbound through vehicles by as little as 10 percent MPR. In addition, each TOSCo setting resulted in large reductions in the standard deviation of total delay, meaning that the traffic stream was more stable with TOSCo. Each of these scenarios generated at least 44 second reduction of stop delay per vehicle. The revised TOSCo led to the greatest reduction of average stop delay out of all of the TOSCo settings, amounting to 46.3 seconds less delay.



Source: Texas A&M Transportation Institute, 2022

Figure 20. Intersection 109 Average Westbound Through Movement Stop Delay with 20 Percent More Traffic

Table 17. Comparison of Stop Delay at Intersection 109 with 20 Percent More Traffic, All Vehicle Types (Westbound)

TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	51.4	—	17.82	—
Default	10	23.5	-54%	2.24	0.005
Default	30	12.3	-76%	0.76	<0.001
Default	50	8.6	-83%	0.45	<0.001
Default	70	8.3	-84%	0.69	<0.001

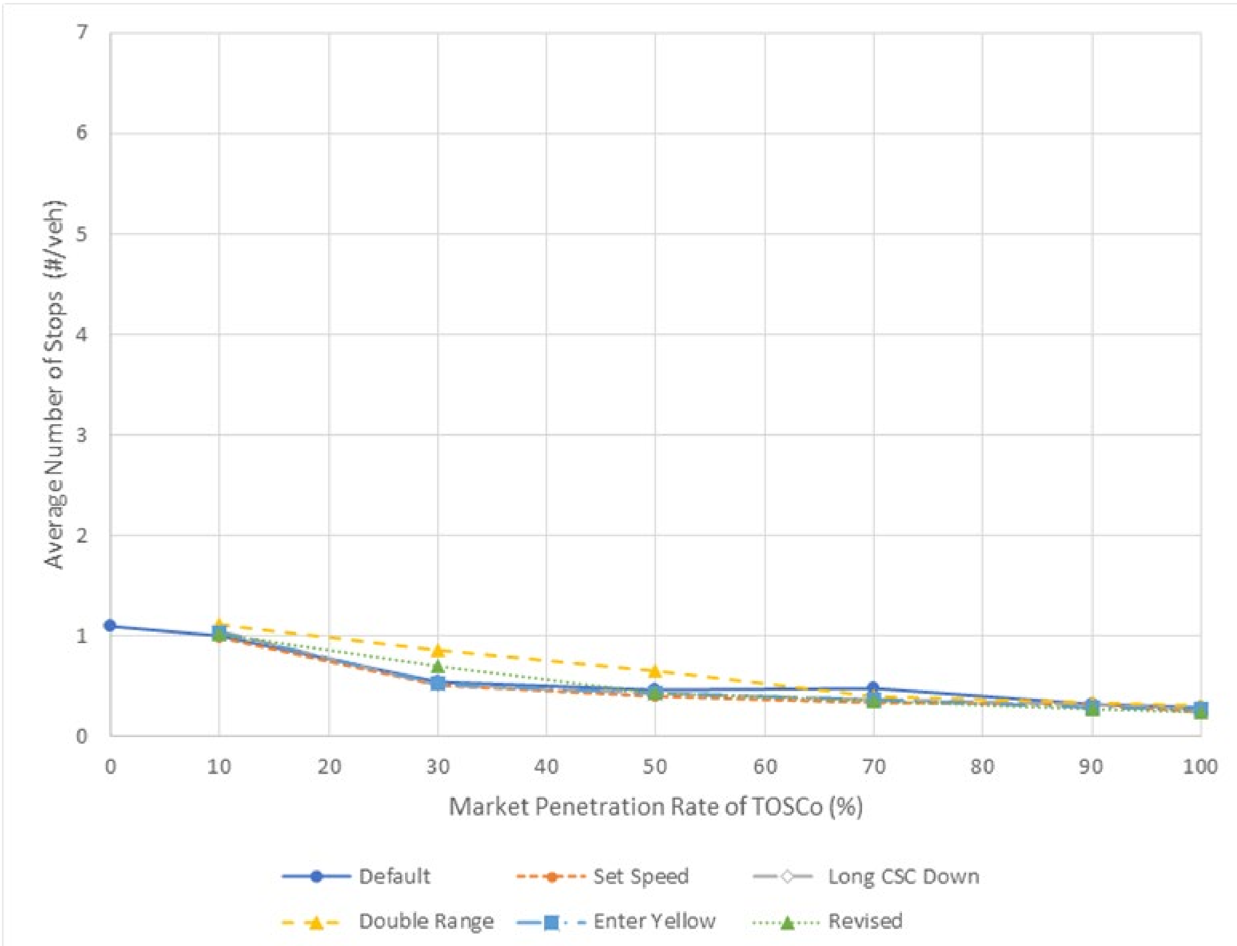
TOSCo Parameters	Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Default	90	7.0	-86%	0.59	<0.001
Default	100	6.7	-87%	0.51	<0.001
Set Speed	10	23.8	-54%	2.12	0.005
Set Speed	30	11.9	-77%	0.88	<0.001
Set Speed	50	7.9	-85%	0.56	<0.001
Set Speed	70	6.8	-87%	0.59	<0.001
Set Speed	90	7.0	-86%	1.16	<0.001
Set Speed	100	5.4	-89%	0.48	<0.001
Long CSC Down	10	23.3	-55%	2.46	0.005
Long CSC Down	30	12.2	-76%	0.79	<0.001
Long CSC Down	50	8.4	-84%	0.53	<0.001
Long CSC Down	70	7.5	-85%	0.48	<0.001
Long CSC Down	90	7.2	-86%	0.61	<0.001
Long CSC Down	100	7.3	-86%	1.01	<0.001
Double Range	10	23.8	-54%	1.80	0.005
Double Range	30	12.6	-76%	1.03	<0.001
Double Range	50	9.2	-82%	0.63	<0.001
Double Range	70	7.1	-86%	0.37	<0.001
Double Range	90	6.6	-87%	0.43	<0.001
Double Range	100	6.4	-88%	0.45	<0.001
Enter Yellow	10	23.8	-54%	2.30	0.005
Enter Yellow	30	11.9	-77%	0.88	<0.001
Enter Yellow	50	8.0	-84%	0.57	<0.001
Enter Yellow	70	6.8	-87%	0.50	<0.001
Enter Yellow	90	6.1	-88%	0.56	<0.001
Enter Yellow	100	6.6	-87%	1.91	<0.001
Revised	10	23.6	-54%	2.53	0.005
Revised	30	12.1	-76%	0.96	<0.001
Revised	50	8.3	-84%	1.01	<0.001
Revised	70	6.7	-87%	0.59	<0.001
Revised	90	5.4	-89%	0.66	<0.001
Revised	100	5.1	-90%	0.52	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.

[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Figure 21 and Table 18 show the average number of stops for eastbound traffic with every variation of TOSCo parameters considered in this analysis.



Source: Texas A&M Transportation Institute, 2022

Figure 21. Intersection 109 Average Eastbound Number of Stops with 20 Percent More Traffic

Table 18. Comparison of Number of Stops at Intersection 109 with 20 Percent More Traffic, All Vehicle Types (Eastbound)

TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	1.11	—	0.37	—
Default	10	1.00	-10%	0.42	0.342
Default	30	0.54	-51%	0.05	0.006
Default	50	0.47	-58%	0.04	0.003
Default	70	0.47	-57%	0.03	0.003

TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Default	90	0.33	-70%	0.01	0.001
Default	100	0.29	-74%	0.02	<0.001
Set Speed	10	0.99	-11%	0.55	0.351
Set Speed	30	0.51	-54%	0.08	0.005
Set Speed	50	0.41	-63%	0.03	0.002
Set Speed	70	0.33	-70%	0.03	0.001
Set Speed	90	0.32	-71%	0.04	0.001
Set Speed	100	0.25	-78%	0.01	<0.001
Long CSC Down	10	1.05	-5%	0.49	0.428
Long CSC Down	30	0.51	-54%	0.10	0.005
Long CSC Down	50	0.44	-61%	0.03	0.002
Long CSC Down	70	0.38	-66%	0.03	0.002
Long CSC Down	90	0.33	-71%	0.04	0.001
Long CSC Down	100	0.28	-75%	0.01	<0.001
Double Range	10	1.12	2%	0.48	0.475
Double Range	30	0.87	-21%	0.19	0.122
Double Range	50	0.65	-41%	0.11	0.017
Double Range	70	0.40	-64%	0.04	0.002
Double Range	90	0.33	-70%	0.02	0.001
Double Range	100	0.30	-73%	0.02	<0.001
Enter Yellow	10	1.04	-6%	0.56	0.411
Enter Yellow	30	0.52	-53%	0.03	0.005
Enter Yellow	50	0.43	-61%	0.03	0.002
Enter Yellow	70	0.36	-67%	0.03	0.001
Enter Yellow	90	0.30	-73%	0.01	<0.001
Enter Yellow	100	0.27	-75%	0.01	<0.001
Revised	10	1.03	-7%	0.40	0.380
Revised	30	0.70	-36%	0.12	0.027
Revised	50	0.44	-60%	0.05	0.003
Revised	70	0.35	-68%	0.01	0.001
Revised	90	0.28	-75%	0.04	<0.001
Revised	100	0.24	-78%	0.02	<0.001

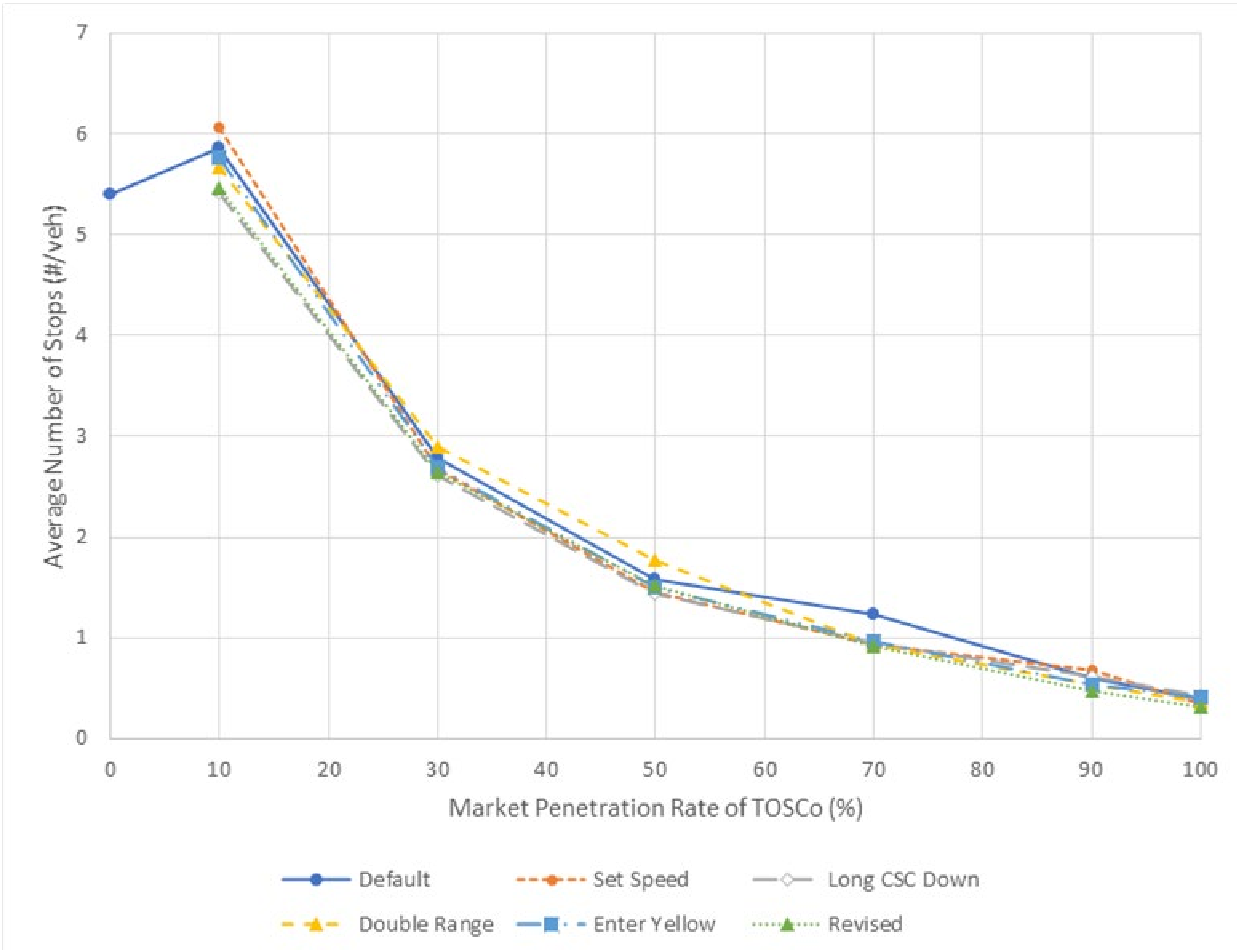
[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

The average number of eastbound stops decreases gradually for all TOSCo settings analyzed. The double-range settings experiences a negligible increase in the lowest market penetration compared to the baseline and decreases the average number of stops as a lower rate than the other TOSCo settings.

There is greater benefit observed for the westbound direction but the delays and stops per vehicle remain higher in the westbound direction than the eastbound direction. The project team observed the number of stops in the westbound direction decreasing from five stops at zero MPR by about half to 2.6 stops at 30 percent MPR. At 70 percent MPR, the number of stops are reduced by 80 percent to about one stop per vehicle for most TOSCo settings. This indicates the westbound direction is oversaturated at 0 percent TOSCo MPR and undersaturated by 70 percent TOSCo MPR. The westbound direction produces better benefits than the eastbound direction despite poorer performance in terms of signal timing and volumes. The eastbound direction performs better than the westbound direction because the eastbound movement is coordinated and undersaturated at intersection 109 (Foxwood Forrest Blvd) at 0 percent TOSCo MPR. The eastbound movement does not have as much room for improvement as the westbound movement at intersection 109.

Figure 22 and Table 19 show the westbound average number of stops in the intersection 109 model with increased traffic. The westbound stops increase between the baseline and 10 percent MPR for every TOSCo setting and drops dramatically by 30 percent MPR. The revised TOSCo setting generated the greatest reductions in stops overall for the average westbound vehicle. The increase in stops at the 10 percent MPR is caused by the non-TOSCo vehicles coming to a brief complete stop multiple times behind a creeping TOSCo vehicle, however, it has less impact on the higher volume analysis since the TOSCo vehicles increase the throughput. Moreover, the increase in average stops at the 10 percent MPR is not statistically significant for any of the TOSCo settings. Over saturated conditions are evident by how the baseline traffic in the increased volume scenarios stop more than five times on average on this westbound movement which indicates over-saturated conditions because vehicles are stopping several times in a queue without the influence of TOSCo. TOSCo vehicles could reduce the average number of stops to less than one stop per vehicle on average by 90 percent MPR which indicates that vehicles are not stopping multiple times in a queue traveling westbound at intersection 109 with TOSCo.



Source: Texas A&M Transportation Institute, 2022

Figure 22. Intersection 109 Average Westbound Number of Stops with 20 Percent More Traffic

Table 19. Comparison of Number of Stops at Intersection 109 with 20 Percent More Traffic, All Vehicle Types (Westbound)

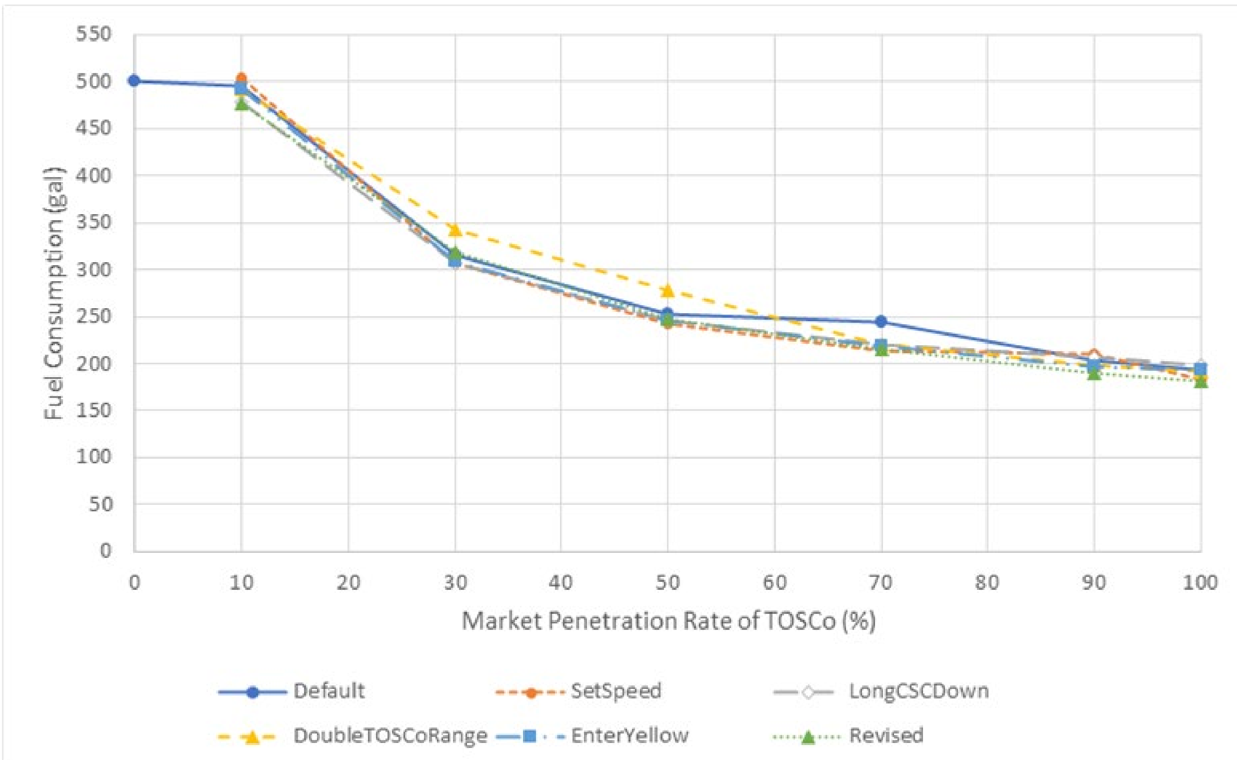
TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
None	0	5.41	—	4.93	—
Default	10	5.86	8%	1.28	0.424
Default	30	2.79	-48%	0.37	0.137
Default	50	1.58	-71%	0.07	0.063
Default	70	1.23	-77%	0.08	0.050
Default	90	0.59	-89%	0.05	0.033

TOSCo Parameters	Market Penetration (%)	Number of Stops (#/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
Default	100	0.40	-93%	0.03	0.029
Set Speed	10	6.06	12%	1.33	0.392
Set Speed	30	2.67	-51%	0.36	0.128
Set Speed	50	1.45	-73%	0.08	0.058
Set Speed	70	0.94	-83%	0.07	0.041
Set Speed	90	0.68	-87%	0.11	0.035
Set Speed	100	0.34	-94%	0.02	0.028
Long CSC Down	10	5.41	0%	1.54	0.499
Long CSC Down	30	2.61	-52%	0.32	0.123
Long CSC Down	50	1.45	-73%	0.07	0.058
Long CSC Down	70	0.96	-82%	0.05	0.042
Long CSC Down	90	0.61	-89%	0.06	0.033
Long CSC Down	100	0.43	-92%	0.06	0.029
Double Range	10	5.66	5%	1.39	0.457
Double Range	30	2.90	-46%	0.31	0.147
Double Range	50	1.77	-67%	0.10	0.071
Double Range	70	0.93	-83%	0.04	0.041
Double Range	90	0.53	-90%	0.04	0.031
Double Range	100	0.37	-93%	0.02	0.028
Enter Yellow	10	5.76	6%	1.24	0.441
Enter Yellow	30	2.70	-50%	0.39	0.130
Enter Yellow	50	1.50	-72%	0.08	0.060
Enter Yellow	70	0.96	-82%	0.04	0.042
Enter Yellow	90	0.54	-90%	0.05	0.032
Enter Yellow	100	0.41	-92%	0.10	0.029
Revised	10	5.47	1%	1.58	0.489
Revised	30	2.64	-51%	0.35	0.126
Revised	50	1.51	-72%	0.20	0.061
Revised	70	0.92	-83%	0.08	0.041
Revised	90	0.47	-91%	0.04	0.030
Revised	100	0.31	-94%	0.03	0.027

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

The research team extracted the fuel use for all vehicles traveling around intersection 109 with increased traffic as estimated by VISSIM. The fuel use estimates are presented in Figure 23 and Table 20, below. The fuel usage remains effectively steady with every TOSCo setting between the baseline and 10 percent MPR and then decreases between 10 and 100 percent MPR by about 75 percent.



Source: Texas A&M Transportation Institute, 2022

Figure 23. Intersection 109 Average Fuel Usage Around Intersection with 20 Percent More Traffic

Table 20. Comparison of Fuel Usage at Intersection 109 with 20 Percent More Traffic, All Vehicle Types

TOSCo Parameters	Market Penetration (%)	Fuel Usage (gal)	% Change[1]	Standard Deviation (gal)	Statistical Significance (p-value)[2]
None	0	500	—	230.9	—
Default	10	496	-1%	77.6	0.486
Default	30	315	-37%	17.1	0.059
Default	50	253	-49%	6.3	0.024
Default	70	244	-51%	7.6	0.021
Default	90	203	-59%	4.8	0.012
Default	100	193	-61%	4.3	0.010

TOSCo Parameters	Market Penetration (%)	Fuel Usage (gal)	% Change[1]	Standard Deviation (gal)	Statistical Significance (p-value)[2]
Set Speed	10	503	1%	79.5	0.489
Set Speed	30	307	-39%	18.4	0.052
Set Speed	50	242	-52%	5.9	0.021
Set Speed	70	214	-57%	4.6	0.014
Set Speed	90	210	-58%	8.9	0.013
Set Speed	100	183	-63%	3.7	0.009
Long CSC Down	10	478	-4%	90.2	0.424
Long CSC Down	30	307	-39%	16.7	0.052
Long CSC Down	50	246	-51%	3.6	0.022
Long CSC Down	70	221	-56%	4.6	0.015
Long CSC Down	90	206	-59%	5.8	0.012
Long CSC Down	100	198	-60%	6.7	0.011
Double Range	10	492	-2%	82.4	0.471
Double Range	30	343	-31%	15.2	0.086
Double Range	50	277	-45%	12.6	0.034
Double Range	70	219	-56%	4.3	0.015
Double Range	90	199	-60%	3.8	0.011
Double Range	100	191	-62%	3.2	0.010
Enter Yellow	10	492	-2%	74.7	0.472
Enter Yellow	30	309	-38%	16.8	0.053
Enter Yellow	50	246	-51%	5.4	0.022
Enter Yellow	70	218	-56%	3.3	0.015
Enter Yellow	90	196	-61%	4.5	0.011
Enter Yellow	100	194	-61%	10.6	0.011
Revised	10	477	-5%	86.7	0.421
Revised	30	319	-36%	22.7	0.062
Revised	50	248	-50%	15.5	0.023
Revised	70	215	-57%	7.4	0.014
Revised	90	190	-62%	5.5	0.010
Revised	100	181	-64%	2.8	0.009

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.

[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Discussion of Single Intersection Results

The single intersection model results illustrate how impactful TOSCo parameters are in the effectiveness of TOSCo performance on overall delay. Each TOSCo setting tested led to large decreases in stop delay in both volume levels considered. The default settings of TOSCo involved limiting the trajectory planning to the speed limit, the TOSCo range at about 1000 feet, CSC-down must be close to the intersection, and the vehicle must enter the intersection on green. Each of the variations challenged one of those four settings. Set speed, double range, and enter yellow parameters each led to decreases in delay compared to the default TOSCo settings. Therefore, these parameters were combined to generate the revised settings for TOSCo. The revised settings for TOSCo consistently led to the greatest reductions in delays, stops, and fuel use at both volume levels. This makes sense because the greater allowed speed does not force some vehicles to slow on the approach, greater range allows more space to alter behavior, and the ability to enter on yellow creates more time for the vehicles to plan to enter the intersection compared to the default settings. There were some cases where both the revised and double range TOSCo settings had higher stops at lower market penetration rates, but the revised TOSCo settings were most beneficial to most performance metrics. The long CSC-down setting had similar results to the default TOSCo settings option in most cases and did not show meaningful improvement over the default setting.

The two different volume levels considered for the single intersection level illustrated the performance of TOSCo in under and over saturated conditions for the westbound direction of travel. When the intersection is under saturated, the TOSCo system settings are more likely to influence trajectory planning because there is a non-zero green window. In over saturated conditions, the green window is zero and the primary trajectory planning is coordinated stop. TOSCo's tool to improve the performance in over-saturated conditions is the coordinated launch feature which reduces the perception reaction time for vehicles to start moving in response to their leader. For a TOSCo string at the stop bar, the coordinated launch feature allows all vehicles to begin moving once the signal indication turns green. Thereby effectively removing the startup loss time cause by perception reaction time of a manually driven vehicle. This results in a large reduction in all types of delays, stops, and fuel usage. When the signal was no longer in saturated conditions because of sufficient TOSCo market penetration of any kind, the best performing settings were similar between both volume conditions with the revised TOSCo setting performing best overall.

Corridor Performance

This section discusses the performance measures from the standpoint of a commuter traveling from one end of FM 1960 to the other in both directions. The performance measures shown are the measurements of the entire trip from end-to-end of the FM 1960 corridor in each direction. This analysis considers two different settings of TOSCo which are default and revised. The default TOSCo settings are consistent with the TOSCo parameters on the physical TOSCo vehicles used for field testing. The revised TOSCo settings are those found as most beneficial with the single intersection model. Specifically, the key differences of the revised TOSCo settings are that the trajectory speed limit was the maximum of either the speed limit or the set speed, the TOSCo range was twice as long, and the TOSCo vehicles were allowed to enter the intersection up to two seconds into the yellow interval.

Default TOSCo Results

This section describes the results for the simulation of TOSCo as TOSCo was built. This TOSCo operation limits the speed trajectory to the speed limit, does not allow entering on yellow, and has a TOSCo range of about 1000 feet.

Cumulative Delays and Stops

Figure 24 shows the total delay, stop delay, and number of stops per vehicle across all intersections in the corridor in the eastbound direction for various levels of market penetration. Figure 25 shows the changes in the same performance measures across all intersections in the westbound direction for various levels of market penetration. Note that these figures are for all vehicle types, including both TOSCo and non-TOSCo vehicles combined. Table 21 to Table 26 show the values, percent changes, and statistics for the performance metrics in Figure 24 and Figure 25.

Source: Texas A&M Transportation Institute, 2022

Figure 24. Corridor-level Mobility Measures for FM 1960 (Eastbound) – Default TOSCo, All Vehicle Types

Table 21. Comparison of Total Delay at the Corridor Level – Default TOSCo, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	234.2	—	8.27	—
10	233.6	-0.2%	5.98	0.454
20	241.7	3.2%	10.19	0.121
30	241.6	3.2%	6.23	0.076
40	243.0	3.8%	4.36	0.036
50	245.6	4.9%	6.74	0.024
70	264.4	12.9%	2.6	<0.001
90	254.5	8.7%	13.13	0.011
100	275.5	17.6%	7.41	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 22. Comparison of Stop Delay at the Corridor Level – Default TOSCo, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	117.4	—	6.45	—
10	101.8	-13.2%	3.00	<0.001
20	94.1	-19.9%	6.00	<0.001
30	86.1	-26.6%	3.93	<0.001
40	81.7	-30.4%	2.19	<0.001
50	78.2	-33.4%	4.20	<0.001
70	75.6	-35.6%	2.14	<0.001
90	67.6	-42.4%	3.56	<0.001
100	68.1	-42.0%	1.62	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2]One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

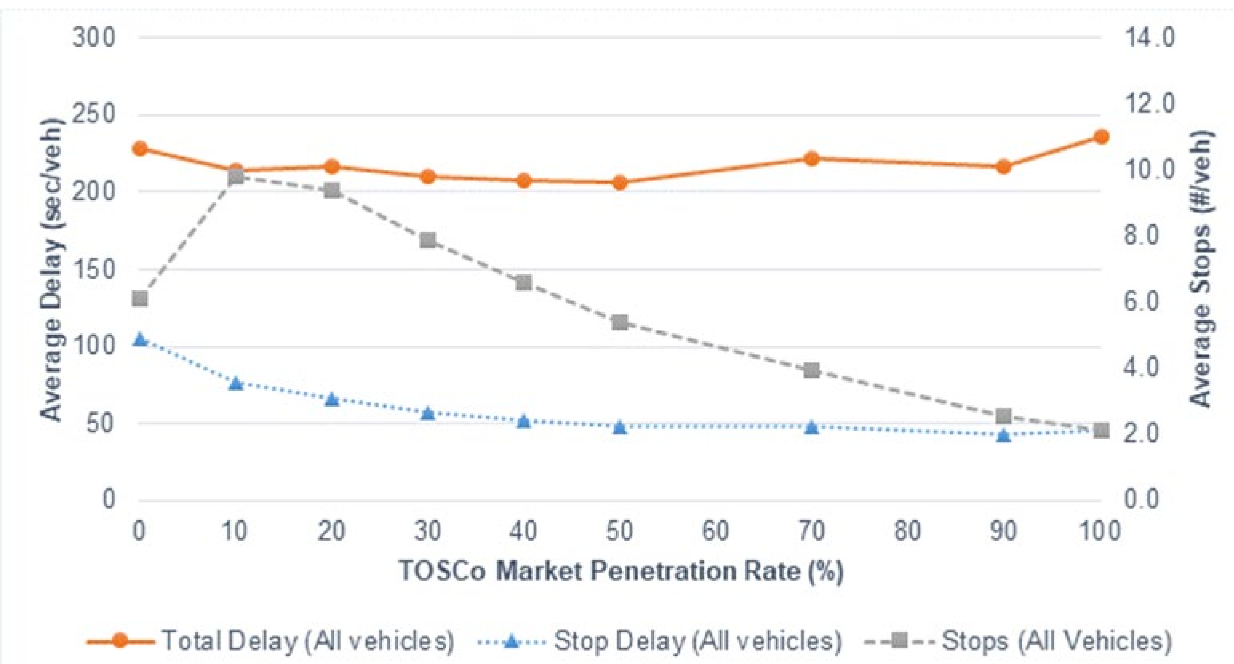
Source: Texas A&M Transportation Institute, 2022

Table 23. Comparison of Number of Stops per Vehicle at the Corridor Level – Default TOSCo, All Vehicle Types (Eastbound)

Market Penetration (%)	**# of Stops/ Vehicle**	**% Change[1]**	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	5.89	—	0.12	—
10	8.53	44.8%	0.58	<0.001
20	9.51	61.5%	0.76	<0.001
30	9.13	55.0%	0.4	<0.001
40	8.56	45.3%	0.56	<0.001
50	7.81	32.6%	0.33	<0.001
70	7.05	19.7%	0.19	<0.001
90	5.06	-14.1%	0.09	<0.001
100	4.50	-23.6%	0.14	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2]One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022



Source: Texas A&M Transportation Institute, 2022

Figure 25. Corridor-level Mobility Measures for FM 1960 (Westbound) - Default TOSCo, All Vehicle Types

Table 24. Comparison of Total Delay at the Corridor Level – Default TOSCo, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	228.5	—	21.08	—
10	213.6	-6.5%	11.56	0.104
20	216.1	-5.4%	7.72	0.128
30	210.8	-7.7%	9.53	0.066
40	207.6	-9.2%	8.91	0.040
50	206.3	-9.7%	10.04	0.035
70	222.0	-2.8%	9.39	0.275
90	216.9	-5.1%	7.62	0.143
100	235.7	3.1%	10.26	0.259

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 25. Comparison of Stop Delay at the Corridor Level – Default TOSCo, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	105.1	—	11.80	—
10	77.3	-26.4%	5.60	0.001
20	67.0	-36.2%	4.24	<0.001
30	57.4	-45.4%	3.08	<0.001
40	51.6	-51.0%	3.47	<0.001
50	48.4	-54.0%	3.67	<0.001
70	47.8	-54.5%	2.93	<0.001
90	43.3	-58.8%	2.99	<0.001
100	45.2	-57.0%	3.63	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2]One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 26. Comparison of Number of Stops per Vehicle at the Corridor Level – Default TOSCo, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	6.10	—	1.41	—
10	9.79	60.5%	1.22	0.002
20	9.36	53.4%	0.82	0.001
30	7.87	29.0%	0.65	0.019
40	6.58	7.9%	0.27	0.240
50	5.38	-11.8%	0.22	0.148
70	3.96	-35.1%	0.31	0.006
90	2.56	-58.0%	0.06	<0.001
100	2.14	-64.9%	0.16	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

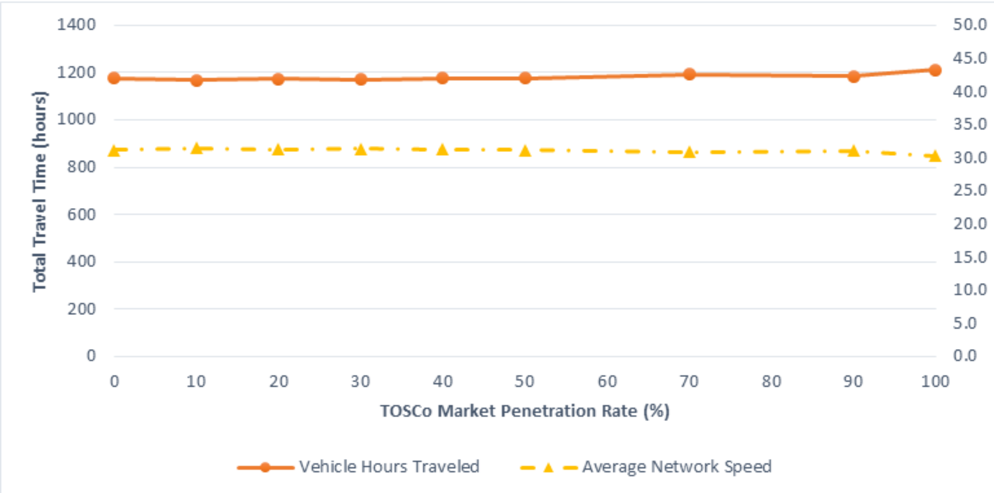
Source: Texas A&M Transportation Institute, 2022

These figures and tables show that the general trend that exists in the corridor is that average total delay per vehicles increases slightly in both directions of travel as market penetration increases. In the eastbound direction, total delay increased from 234.2 seconds per vehicle to 275.5 seconds per vehicle. In the westbound direction, the total delay increased from 228.5 seconds per vehicle to 235.7 seconds per vehicle. This change is a 41.3-second increase in the eastbound direction and a 14.4-second increase in the westbound direction. The research team expected the increases in total delay given the low volumes and how the default TOSCo algorithm is designed to slow vehicle approaching in intersections further upstream to minimize their likelihood of stopping at the intersection. It should also be noted that these increases in delay are spread over 13 total intersections in a 7-mile long corridor. The travel time for eastbound and westbound traffic is around 700 seconds each, which means hat the increase in travel time does not amount to very much time in the context of the travel time to traverse the network.

The greatest benefits to deploying the default TOSCo is in stopped delay and in the average number of stops per vehicle in the corridor. Table 22 and Table 25 show that average stop delay per vehicle in the corridor significantly decreased by activating TOSCo. Stopped delay decreased by 49.3 and 59.9 seconds per vehicle in the eastbound and westbound directions of travel, respectively. The average number of stops per vehicle decreased from 5.89 stops per vehicle to 4.5 in the eastbound direction and from 6.10 stops per vehicle to 2.14 stops per vehicle in the westbound direction. Each direction experiences an initial increase in stops from non-TOSCo vehicles where the non-TOSCo vehicles are stopping multiple times behind creeping TOSCo vehicles.

Total Travel Time and Average Speed

Figure 26, Table 27, and Table 28 show the total travel time and average speeds on FM1960. There are decreases in average speeds and increases in total travel time up to 3.0 percent as the market penetration of TOSCo vehicles increased. The 100 percent TOSCo MPR averages are the only statistically significant differences, but the numeric difference of about a 3 percent change are not meaningful increases.



Source: Texas A&M Transportation Institute, 2022

Figure 26. Total Vehicle Hours Traveled and Average Speeds for FM 1960 in Houston, Texas - Default TOSCo

Table 27. Default TOSCo Off-Peak Period Total Vehicle Hours Traveled on FM 1960 Corridor

MPR (%)	Total Travel Time (veh-hours)	% Change[1]	Standard Deviation (veh-hours)	Statistical Significance (p-value)[2]
0	1177	—	31	—
10	1169	-0.7%	23	0.327
20	1175	-0.2%	24	0.446
30	1172	-0.4%	24	0.391
40	1175	-0.2%	25	0.460
50	1177	0.0%	22	0.498
70	1192	1.2%	20	0.205
90	1184	0.6%	21	0.337
100	1212	3.0%	31	0.059

[1] From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.

[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 28. Default TOSCo Off-Peak Period Average Speed Values for FM 1960 Corridor

MPR (%)	Avg Speed (mph)	% Change[1]	Standard Deviation (mph)	Statistical Significance (p-value)[2]
0	31.2	—	0.4	—
10	31.4	0.7%	0.3	0.200
20	31.3	0.3%	0.3	0.367
30	31.4	0.5%	0.3	0.279
40	31.3	0.2%	0.4	0.411
50	31.2	-0.1%	0.4	0.470
70	30.9	-1.2%	0.2	0.074
90	31.0	-0.6%	0.2	0.224
100	30.3	-2.9%	0.4	0.007

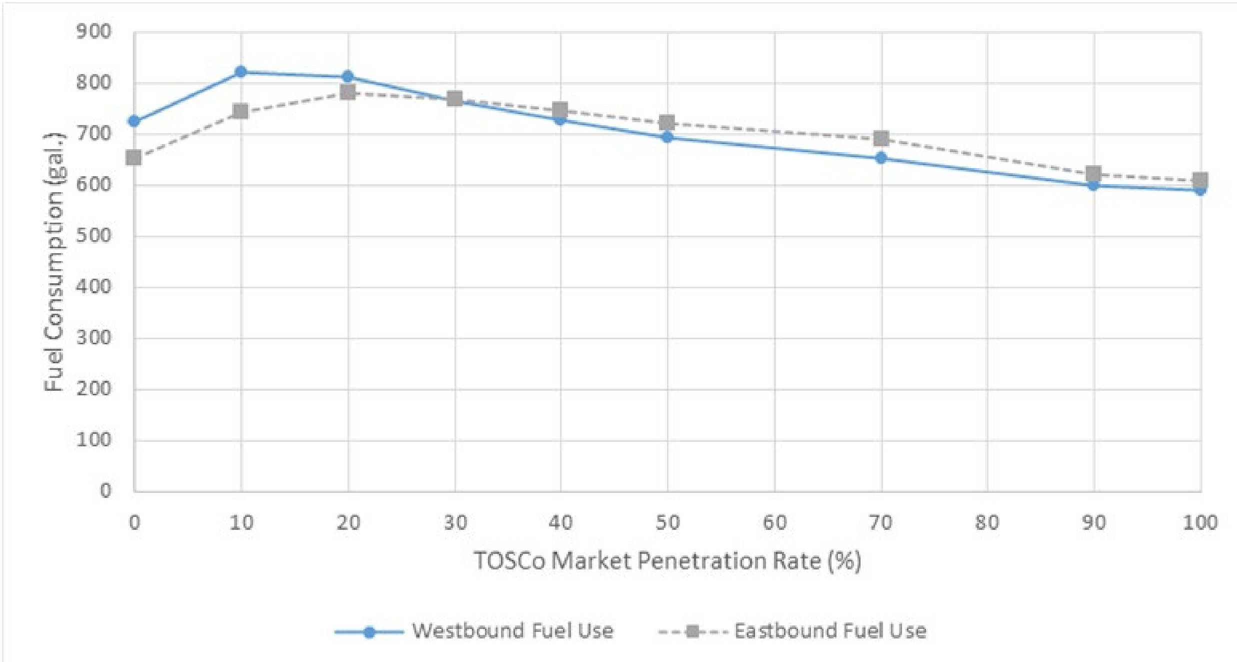
[1] From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.

[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

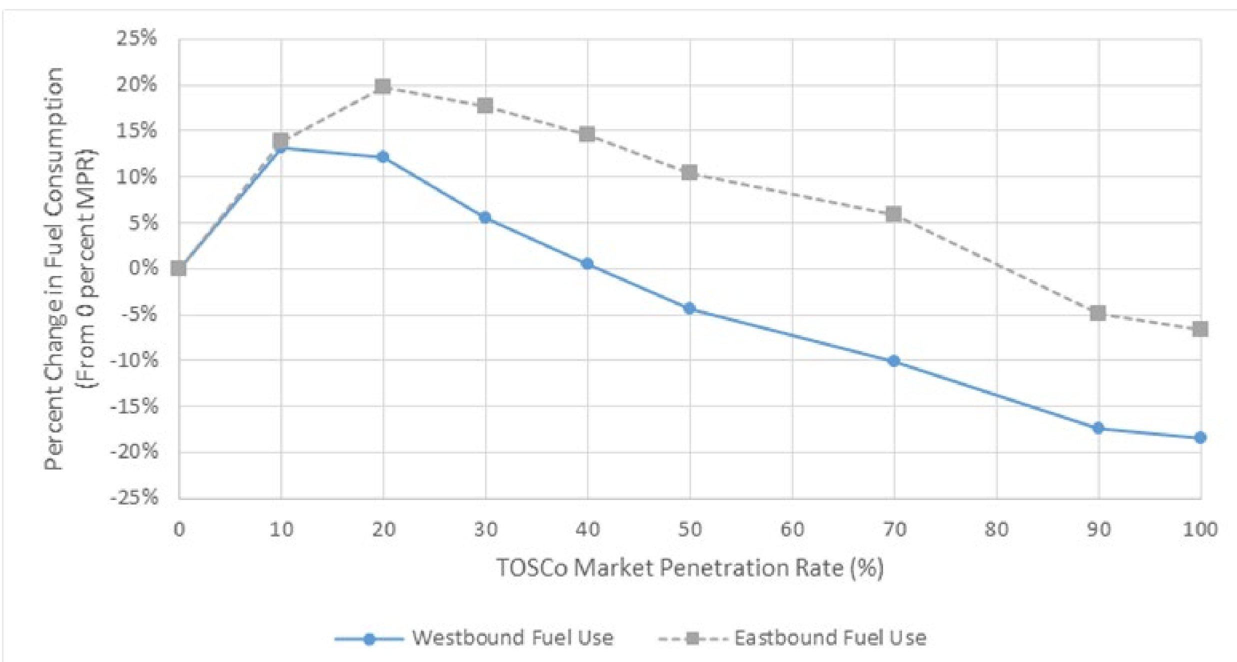
Fuel Consumption

Figure 27 and Figure 28 show the summation of the fuel usage for eastbound and westbound TOSCo approaches and the percent change in fuel consumption, respectively. Each direction experiences an initial increase in fuel use and then a gradual reduction in fuel usage as TOSCo MPR increases with the westbound direction experiencing the larger reduction in fuel usage of up to 135 gallons of fuel saved from TOSCo which amounts to about 19 percent reduction in fuel consumed. The reduction of fuel use for both directions combined is about 180 gallons of gasoline across the seven-mile corridor. This describes the fuel used around each intersection, about 1200 ft in each direction, during the off-peak hour analysis. This amounts to about 3 fewer gallons of fuel consumed at across the corridor every minute. The eastbound reductions in fuel for the off-peak period amount to about 6.6 percent of the fuel used in the baseline. The increase in fuel usage for both directions at low market penetration follows the same trends as the number of stops which indicates that the increased fuel usage is caused by the non-TOSCo vehicles making more stops in response to slow moving TOSCo vehicles stopping at a red light.



Source: Texas A&M Transportation Institute, 2022

Figure 27. Default TOSCo Directional Fuel Consumption – All TOSCo Approaches

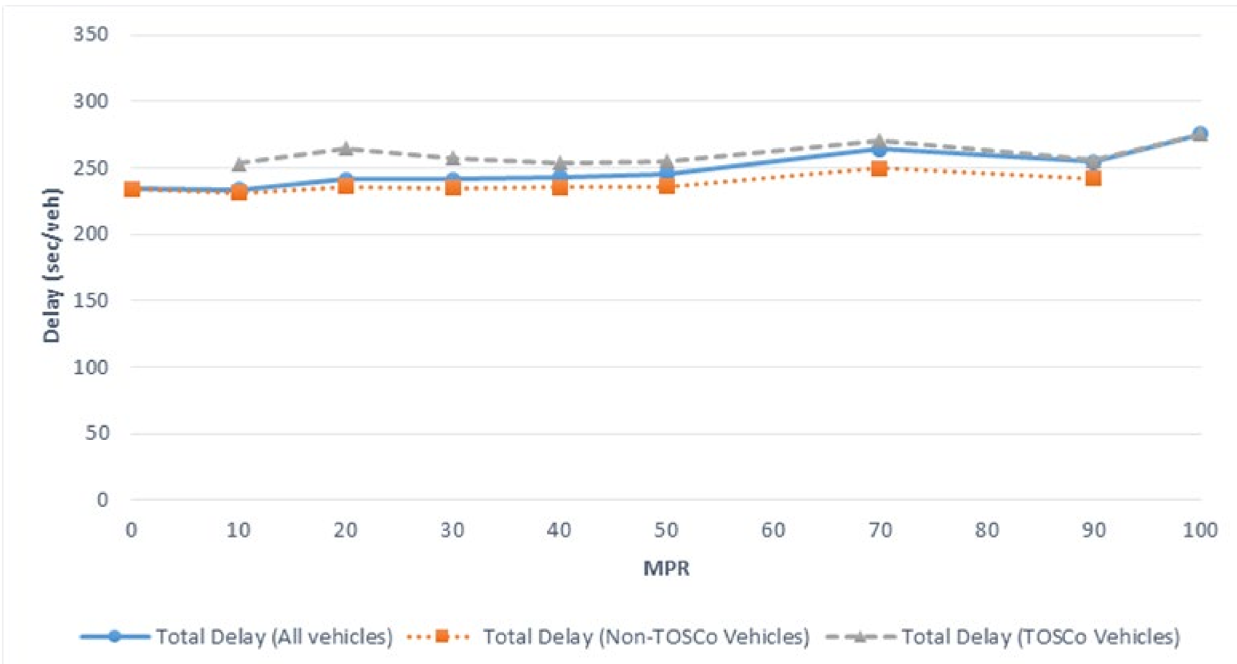


Source: Texas A&M Transportation Institute, 2022

Figure 28. Default TOSCo Percent Change in Fuel Consumption – All TOSCo Approaches

Discussion of Performance Results

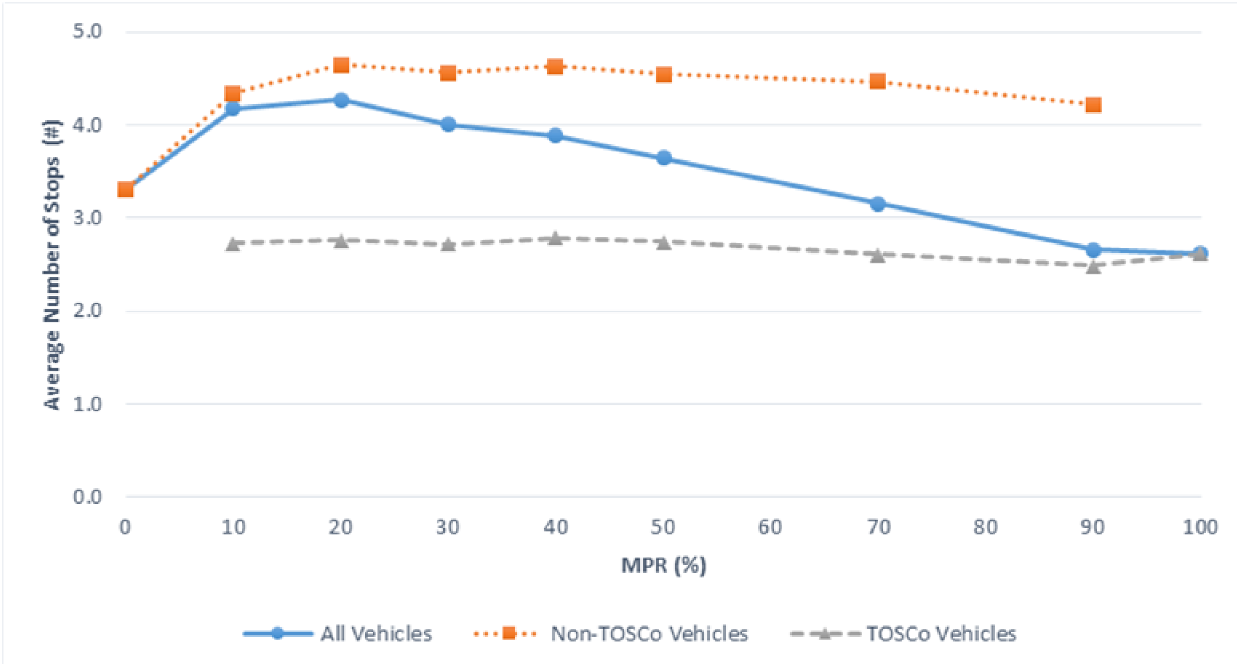
Eastbound total delay increases for the traffic on FM 1960 as market penetration of TOSCo goes up and westbound total delay decreases slightly, but it is not statistically significant at a 95 percent likelihood in any market penetration rate except 40 and 50 percent MPR. At MPR below 40 percent, the eastbound increase in total delay is not statistically significant. The increase in delay is because default TOSCo vehicles have more delay than non-TOSCo vehicles in modes other than coordinated launch. They accelerate gradually to conserve fuel, and they will decelerate earlier than non-TOSCo vehicles on an approach. TOSCo vehicles also generally stop less than non-TOSCo vehicles. The trends for TOSCo and non-TOSCo individual vehicle classes is no change in total delay or a slight decrease in total delay, shown in Figure 29. This means that TOSCo vehicles are not affecting total delay for non-TOSCo vehicles in general.



Source: Texas A&M Transportation Institute, 2022

Figure 29. Eastbound Total Delay by Vehicle Class – Default TOSCo

TOSCo significantly reduces stop delay for all vehicle types at market penetration increases. Reducing stopped delay is one of the primary functions of the TOSCo system, therefore, the research team expected the reductions in stop delay. VISSIM estimates that TOSCo initially increases the number of stops, but the reduction in stop delay shows that the increased stops are brief. Figure 30 illustrates how non-TOSCo vehicles experience increased stops with the introduction of TOSCo vehicles into the traffic stream, but TOSCo vehicles stop less on average than non-TOSCo vehicles and keep a constant number of stops on average across all market penetration rates.



Source: Texas A&M Transportation Institute, 2022

Figure 30. Average Stops by Vehicle Class – Default TOSCo

TOSCo causes some reduction in fuel usage as MPR increases after an initial increase. The initial increase in fuel use is caused because the increased number of brief stops from the non-TOSCo vehicles.

The research team used the same methodology as the Phase 1 TOSCo Simulation Report to quantify travel time and fuel cost so the costs remain comparable to Phase 1 of the TOSCo Project. The research team used parameters from the USDOT Value of Travel Time Guidance (*19*). The value of travel time is calculated by the trip type, trip purpose, trip distribution and value of the trip. The research team used thirteen dollars ($13) per hour value to represent all purposes of local travel. This value describes the total travel time costs for all vehicles in the network for the off-peak hour. The research team used $2.01 per gallon which is the average fuel costs in Texas in December 2018 to be consistent with other TOSCo simulation analyses (*20*). Table 29 contains the network costs of total travel time and fuel for the FM 1960 Corridor.

Table 29. FM 1960 Corridor User Cost Analysis – Default TOSCo

Penetration Rate	Network Travel Time Costs	Fuel Cost (Texas Gasoline Price, 2018)	Total User Costs
0	$3,387.21	$2,768.95	$6,156.16
10	$3,255.71	$3,140.49	$6,396.21
20	$3,326.55	$3,203.91	$6,530.46
30	$3,271.88	$3,082.41	$6,354.30
40	$3,258.40	$2,965.14	$6,223.54
50	$3,258.84	$2,841.18	$6,100.01
70	$3,499.74	$2,698.19	$6,197.93
90	$3,382.14	$2,450.15	$5,832.29
100	$3,679.09	$2,411.72	$6,090.81

Source: Texas A&M Transportation Institute, 2022

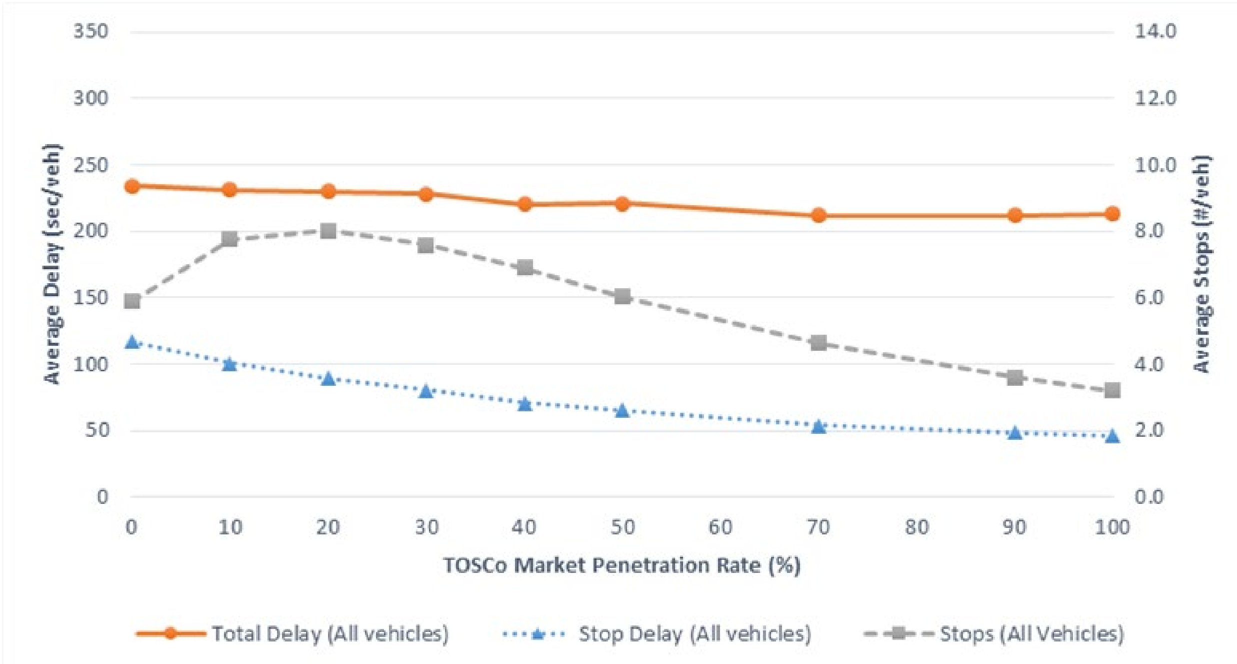
The total user costs remain practically constant between the baseline and the 100 percent market penetration rate. The travel time for through traffic gradually increases and the fuel costs gradually decreases. This is, in part, due to an increase in stops observed by non-TOSCo vehicles in response to TOSCo behavior at low speeds. The research team considers this an artifact of the simulation and not realistic. There is an initial increase in total costs at low market penetration rates and gradual decrease in costs as market penetration increases.

Revised TOSCo Results

The revised TOSCo simulation utilizes the same off-peak model and analyzed TOSCo with the settings found most beneficial in the single intersection model. The following sections describe performance metrics for thru traffic on the corridor and the entire network.

Cumulative Delays and Stops

The delay and number of stop results for eastbound and westbound directions of travel are shown in Figure 31 and Figure 32 and the values are shown in Table 30 through Table 35.



Source: Texas A&M Transportation Institute, 2022

Figure 31. Corridor-level Mobility Measures for FM 1960 (Eastbound) – Revised TOSCo, All Vehicle Types

Table 30. Comparison of Total Delay at the Corridor Level – Revised TOSCo, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	234.2	—	8.27	—
10	231.5	-1.1%	8.25	0.316
20	230.1	-1.7%	6.23	0.205
30	228.3	-2.5%	8.36	0.153
40	220.3	-5.9%	4.38	0.007
50	221.4	-5.5%	5.13	0.011
70	212.3	-9.3%	5.88	<0.001
90	212.1	-9.4%	6.82	0.001
100	213.3	-8.9%	6.08	0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 31. Comparison of Stop Delay at the Corridor Level – Revised TOSCo, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	117.4	—	6.45	—
10	101.1	-13.8%	4.84	0.001
20	89.3	-23.9%	2.76	<0.001
30	80.9	-31.1%	4.33	<0.001
40	71.2	-39.4%	2.59	<0.001
50	65.6	-44.1%	2.84	<0.001
70	54.4	-53.7%	1.64	<0.001
90	48.5	-58.7%	2.22	<0.001
100	46.7	-60.2%	1.53	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

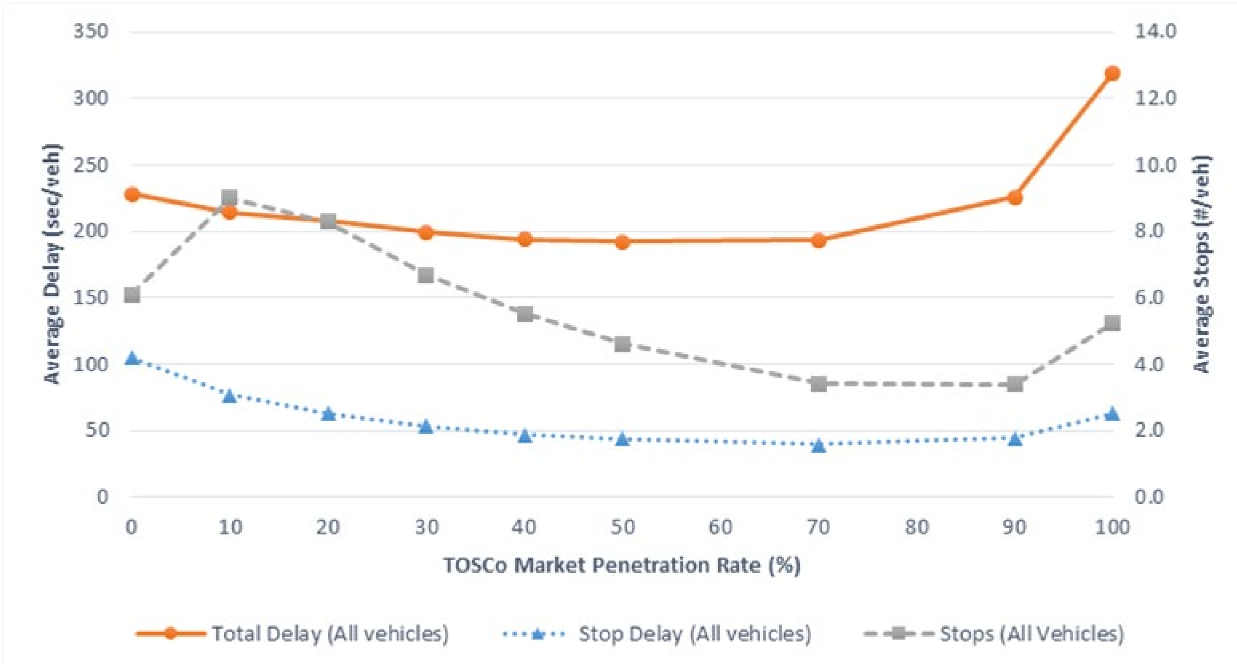
Source: Texas A&M Transportation Institute, 2022

Table 32. Comparison of Number of Stops per Vehicle at the Corridor Level – Revised TOSCo, All Vehicle Types (Eastbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	5.89	—	0.12	—
10	7.75	31.6%	0.54	<0.001
20	8.02	36.2%	0.47	<0.001
30	7.60	29.0%	0.66	<0.001
40	6.90	17.1%	0.20	<0.001
50	6.03	2.4%	0.19	0.103
70	4.63	-21.4%	0.19	<0.001
90	3.62	-38.5%	0.09	<0.001
100	3.20	-45.7%	0.07	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022



Source: Texas A&M Transportation Institute, 2021Institute, 2022

Figure 32. Corridor-level Mobility Measures for FM 1960 (Westbound) - Revised TOSCo, All Vehicle Types

Table 33. Comparison of Total Delay at the Corridor Level – Revised TOSCo, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	228.5	—	21.08	—
10	214.3	-6.2%	8.45	0.102
20	207.6	-9.1%	6.07	0.035
30	199.4	-12.8%	5.13	0.010
40	193.9	-15.1%	4.77	0.004
50	192.4	-15.8%	6.76	0.004
70	193.4	-15.4%	7.24	0.005
90	225.9	-1.2%	20.91	0.423
100	319.6	39.9%	58.74	0.007

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 34. Comparison of Stop Delay at the Corridor Level – Revised TOSCo, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	105.1	—	11.80	—
10	77.2	-26.5%	3.22	<0.001
20	63.4	-39.6%	2.79	<0.001
30	53.9	-48.7%	2.17	<0.001
40	47.1	-55.2%	2.17	<0.001
50	43.9	-58.2%	2.85	<0.001
70	39.5	-62.4%	2.47	<0.001
90	44.7	-57.4%	5.85	<0.001
100	63.3	-39.8%	14.03	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 35. Comparison of Number of Stops per Vehicle at the Corridor Level – Revised TOSCo, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	6.10	—	1.41	—
10	9.00	47.5%	1.18	0.005
20	8.30	36.1%	0.76	0.009
30	6.68	9.5%	0.31	0.199
40	5.53	-9.3%	0.28	0.202
50	4.62	-24.3%	0.15	0.026
70	3.42	-43.9%	0.21	0.002
90	3.39	-44.4%	0.43	0.002
100	5.25	-13.9%	1.55	0.197

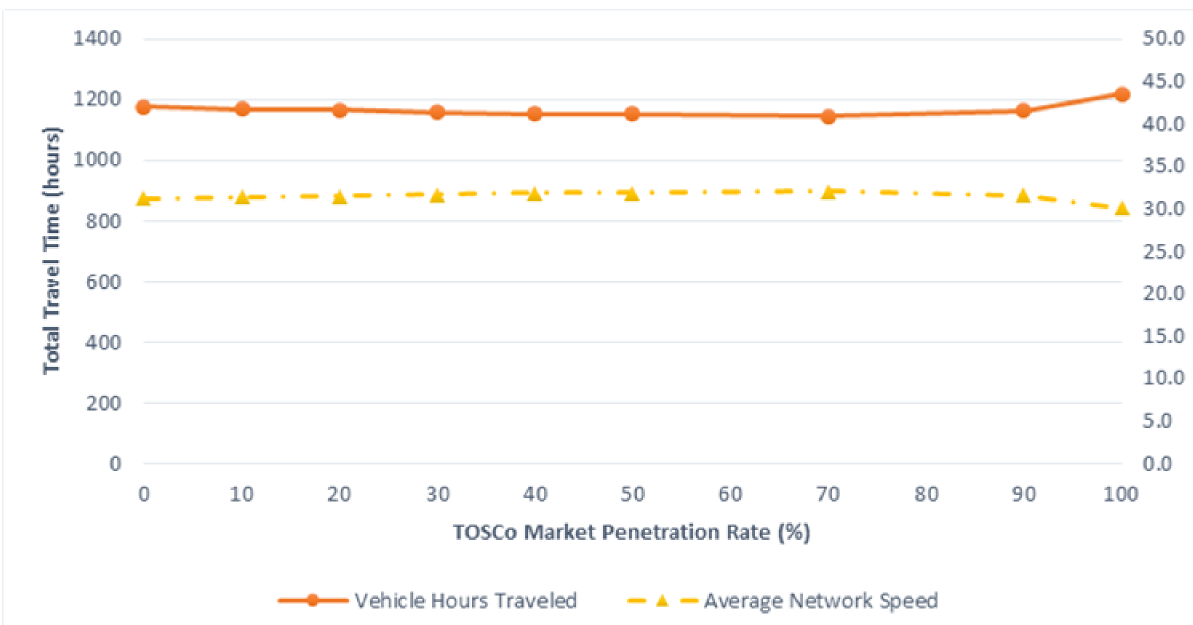
[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

With the revised TOSCo, both directions experience gradual reductions in total delay until about 90 percent MPR where the westbound total delay begins to increase and exceeds the baseline westbound total delay significantly. This is a result from significant increases in total delay at intersection 102 and 103 where the westbound direction has some TOSCo vehicles entering creep too early. These TOSCo vehicles cross the stop bar at intersection 102 and immediately enter CREEP mode and travel at low speed on the approach to intersection 101 instead of speeding up on the departure in FREE FLOW mode like the vehicles did with the default TOSCo operations. This change in behavior is caused by the increased TOSCo ranges. The high TOSCo MPR scenarios experience greater negative effects because the TOSCo vehicles do not have an unequipped vehicle in front of them and enter coordinated speed control modes instead of CREEP. This TOSCo state transition was only observed in simulation with the revised TOSCo configuration because no other TOSCo analysis considered increased ranges between intersections. The stop delay and number of stops each decrease as market penetration of TOSCo increases. Both directions experience a slight increase in number of stops between the baseline and 20 % MPR and then gradually decreases as TOSCo MPR increases. These additional stops are brief as indicated from the lack of increase in stop delay.

Total Travel Time and Average Speed

Figure 33, Table 36, and Table 37 show the total travel time and average speed results for the revised TOSCo simulation. These measurements remain practically constant across increased TOSCo MPR. This measurement includes vehicles on cross streets and turning movements which indicates that TOSCo was able to generate a slight increase in speed between the baseline and 70 percent TOSCo MPR, but the average speed drops at the highest market penetration rates. The total travel time reductions at 40, 50 and 70 percent MPR are statistically significant at 90 percent confidence. The travel time increase at 100 percent MPR is also statistically significant at 90 percent. The increases in speed in market penetration rates 40, 50, and 100 are statistically significant at a 90 % confidence.



Source: Texas A&M Transportation Institute, 2021Institute, 2022

Figure 33: Total Vehicle Hours Traveled and Average Speeds for FM 1960 in Houston, Texas – Revised TOSCo

Table 36: P.M. Peak Period Total Vehicle Hours Traveled on SH 105 Corridor

MPR (%)	Total Travel Time (veh-hours)	% Change[1]	Standard Deviation (veh-hours)	Statistical Significance (p-value)[2]
0	1177	—	31	—
10	1170	-0.6%	25	0.350
20	1166	-1.0%	22	0.263
30	1160	-1.5%	22	0.170
40	1153	-2.1%	21	0.096
50	1153	-2.1%	19	0.089
70	1145	-2.7%	22	0.052
90	1165	-1.1%	26	0.254
100	1218	3.5%	49	0.080

[1] From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

Table 37: P.M. Peak Period Average Speed Values for SH 105 Corridor

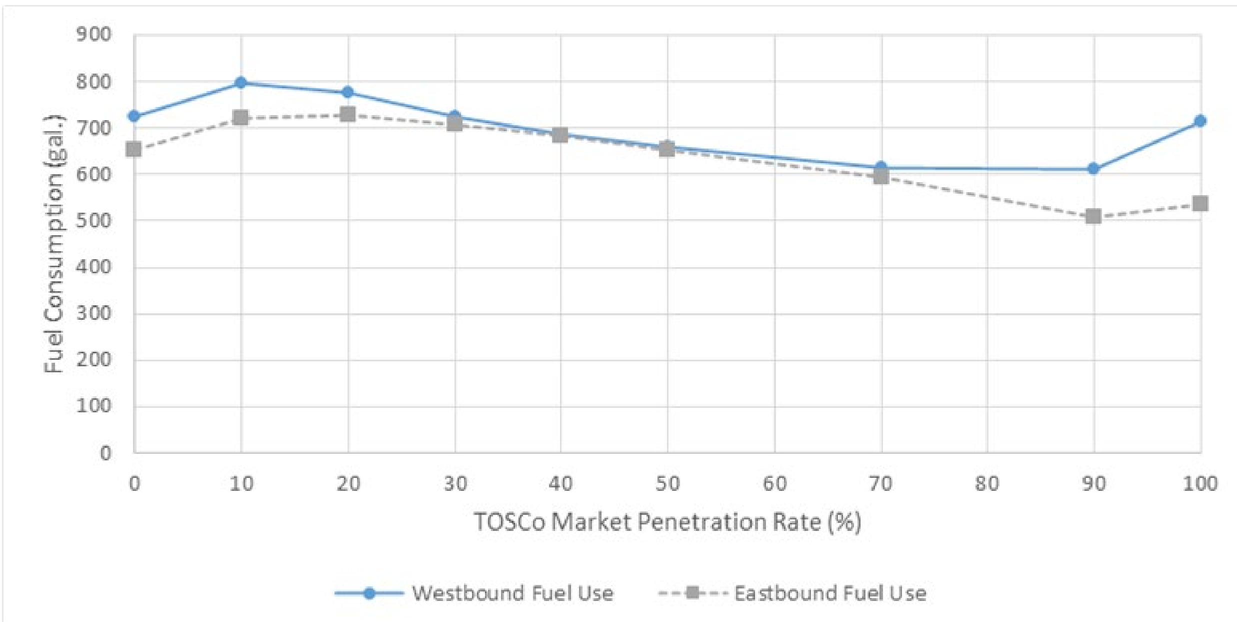
MPR (%)	Avg Speed (mph)	% Change[1]	Standard Deviation (mph)	Statistical Significance (p-value)[2]
0	31.2	—	0.4	—
10	31.4	0.7%	0.3	0.211
20	31.5	1.0%	0.3	0.108
30	31.7	1.5%	0.3	0.046
40	31.9	2.1%	0.3	0.011
50	31.9	2.1%	0.3	0.012
70	32.1	2.8%	0.3	0.004
90	31.6	1.2%	0.3	0.089
100	30.1	-3.4%	0.9	0.021

[1] From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.
[2] One-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs from the baseline.

Source: Texas A&M Transportation Institute, 2022

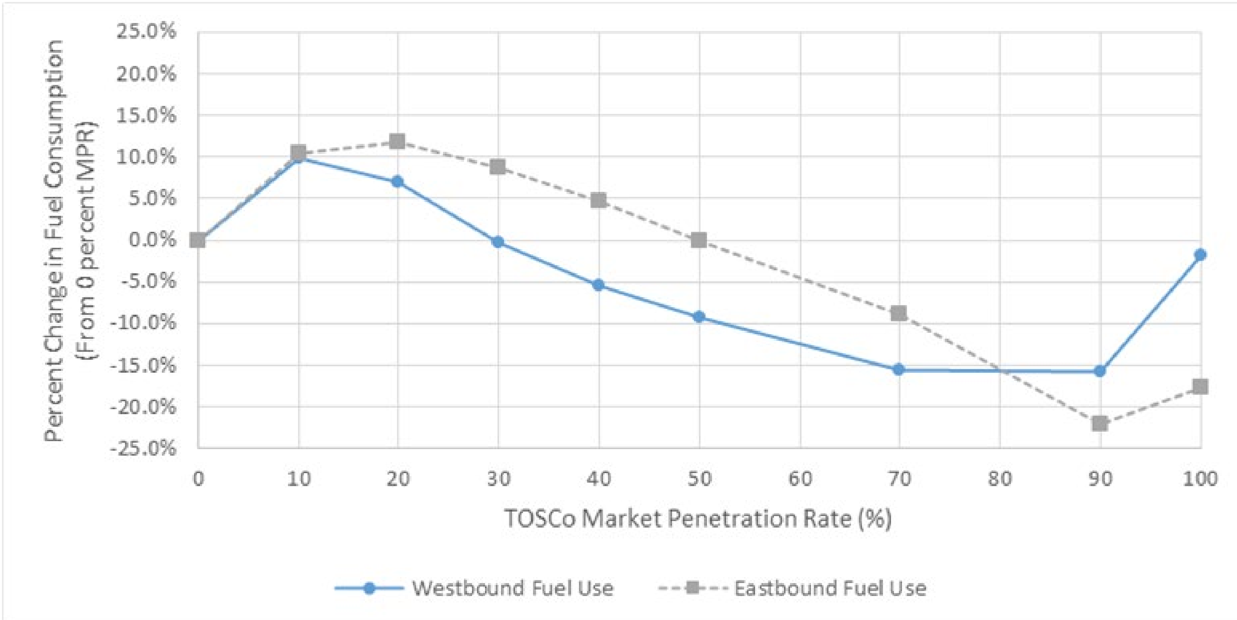
Fuel Consumption

Figure 34 and Figure 35 show the summation of the fuel usage for eastbound and westbound TOSCo approaches and the percent change in fuel consumption, respectively. Each direction experiences an initial increase in off-peak hour fuel usage with increased MPR and then gradually reduces fuel consumption up to 144 and 114 gallons in the eastbound and westbound directions, respectively. Each direction experiences an increase in fuel usage between the 90 and 100 percent MPR which is in large part caused by the increased propensity of TOSCo vehicles entering CREEP instead of speeding up between intersections, especially in the westbound direction of travel. The TOSCo vehicles produce long strings that make few gaps for changing lanes and they accelerate to optimize the through movement. If a vehicle needs to change lanes for a turning movement, there is more difficulty with TOSCo vehicles in the network. See Appendix B for the fuel usage in each direction for all TOSCo modes.



Source: Texas A&M Transportation Institute, 2022

Figure 34. Revised TOSCo Directional Fuel Consumption – All TOSCo Approaches

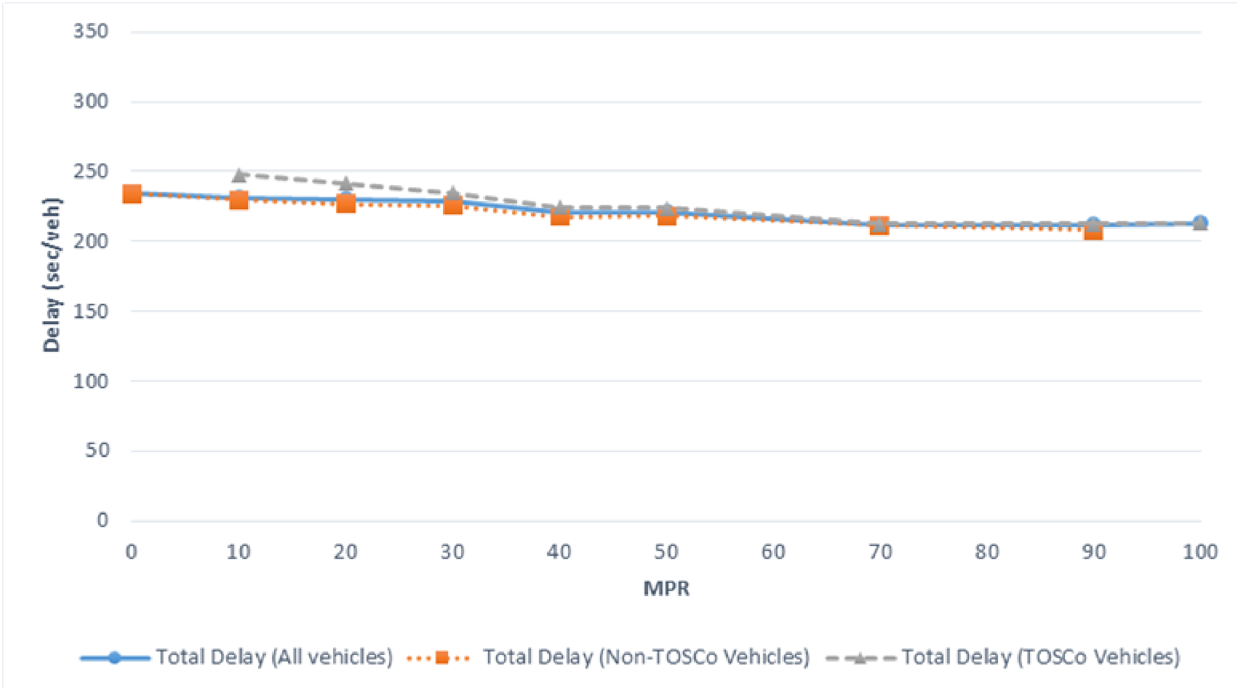


Source: Texas A&M Transportation Institute, 2022

Figure 35. P.M. Peak Period Percent Change in Fuel Consumption – All TOSCo Approaches

Discussion of Performance Results

The revised TOSCo settings produced a decrease in total delay in both directions until high market penetration rates of 70 or 90 percent. Some intersections experienced increases in total delay at high market penetration rates especially the closely spaced intersections like 101, 102, and 103 where TOSCo vehicles would enter CREEP states while still far from the intersection because the vehicle had no lead vehicle, was traveling slow, and was approaching a red signal at the time. Intersections with spacing larger than the configured TOSCo range and with different signal timing did not experience the same CREEP behavior. Intersections where there were queueing problems or delays caused by volumes of thru traffic, such as intersection 109, can benefit from TOSCo from a total delay standpoint. The research team generated Figure 36 to show the eastbound total delay separated by vehicle class. The revised TOSCo experiences a reduction in total delay for TOSCo vehicles as MPR increases. This leads to a corresponding reduction in total delay for the non-TOSCo vehicles in the network.



Source: Texas A&M Transportation Institute, 2022

Figure 36. Eastbound Total Delay by Vehicle Class – Revised TOSCo

The dashed lines in Figure 36 represent the average performance for TOSCo vehicles and the dotted lines represent the performance for Non-TOSCo cars in each scenario. The lines do not cover the exact same MPR scenarios because the Non-TOSCo vehicles do not have data for the 100 MPR scenario, and the TOSCo vehicles do not have data for the baseline scenario. This figure shows that TOSCo vehicles start with more total delay than non-TOSCo vehicles. It also be seen that the total delay decreases for both vehicle classes as TOSCo MPR increases. The research team found that this trend of reduced or constant delays for both vehicle classes true for each approach that did not have queue spillback issues on the corridor. The revised TOSCo results show that the TOSCo vehicles in the network impact the average stop delay at low market penetration and as market penetration grows the average total delay decreases too until there is a high enough market penetration for the strings to make it difficult for vehicles to change lanes to reach their destination.

The total travel time reduces slightly but remains effectively constant for across the TOSCo market penetration rates. This shows that TOSCo is not adversely impacting the overall network while decreasing the total delay for the through movements at each intersection. TOSCo does increase the average speed slightly with 90 percent confidence by 30 percent MPR and experiences a decrease in speed at 100 percent MPR because of the CREEP state tendency with increased range described above.

Table 38 shows the monetization of the TOSCo approaches considering travel time and fuel costs for the revised TOSCo results.

Table 38: FM 1960 Corridor User Cost Analysis – Revised TOSCo

Penetration Rate	Network Travel Time Costs	Fuel Cost (Texas Gasoline Price, 2018)	Total User Costs
0	$3,387.21	$2,768.95	$6,156.16
10	$3,249.74	$3,049.85	$6,299.59
20	$3,179.88	$3,026.60	$6,206.48
30	$3,102.02	$2,880.17	$5,982.19
40	$3,016.35	$2,750.58	$5,766.93
50	$3,009.78	$2,634.13	$5,643.92
70	$2,931.63	$2,426.77	$5,358.40
90	$3,011.84	$2,251.39	$5,263.23
100	$3,908.59	$2,511.61	$6,420.20

Source: Texas A&M Transportation Institute, 2022

The total user costs in the off-peak hour initially increase between the baseline and the 20 percent market penetration rate up to about a $140 user increase in costs. This is caused by the increased fuel use from the non-TOSCo vehicles stopping multiple times in response to TOSCo behavior. This increase in stops is not realistic and is an artifact of the simulation. The user costs decrease from the 20 percent MPR scenario to 90 percent TOSCo MPR scenarios to about $900 less than the baseline which constitutes about a 15 percent reduction in off-peak hour user costs. The user costs jump up at 100 percent MPR to about $260 greater than the baseline due to additional travel time and fuel usage from the CREEP state tendencies at the closely spaced intersections.

Discussion of Differences between Default and Revised TOSCo Results

The default and revised peak periods have different trends in mobility measurements. The default TOSCo leads to higher delays while the revised setting of TOSCo leads to reductions in delays until very high market penetration rates, especially for the eastbound direction of travel. The three changes in settings for revised TOSCo (the increase range, the ability to enter in yellow, and the higher allowed trajectory speed) led to reduce delay. The settings in the revised TOSCo mode led to a set of TOSCo parameters that did not negatively impact operations at low market penetrations and a reduction in total delay in the mid-range TOSCo MPR. Both TOSCo settings experienced an upward trend in delay between 70 percent and 100 percent MPR. These are each due to the increase difficulty to complete a lane change maneuver for turning vehicles due to the large TOSCo strings.

There are also numerous similarities between the two sets of TOSCo parameters considered. Both TOSCo settings lead to significant reductions in stop delay and the same trend of average number of stops. That is, each TOSCo settings leads to a slight initial increase in stops, and then a large reduction in stops as TOSCo MPR increases.

Field Benefits Estimate Results

The benefits analysis for TOSCo included a study in the field with the four real TOSCo vehicles with the default TOSCo settings. This analysis reviewed the travel times and stops between manual (non-TOSCo) driving and TOSCo control with each TOSCo vehicle individually. The trips span the entire corridor and the TOSCo or non-TOSCo vehicle control was randomly assigned and varied throughout the day. The travel time results of the study are shown in Table 39.

Table 39. Field Measured Travel Time Comparison Between TOSCo and Non-TOSCo Trips

Direction of Travel	Driving Mode	Number of Trips	Average Travel Time (sec/veh)	Standard Deviation (sec/veh)	Statistical Significance (p-value)[1]
Eastbound	Non-TOSCo	20	679	42	—
Eastbound	TOSCo	21	704	58	0.060
Westbound	Non-TOSCo	19	741	44	—
Westbound	TOSCo	19	774	42	0.012

[1] One-tailed t-test comparing the results of the non-TOSCo trips to the TOSCo trips.

Source: Texas A&M Transportation Institute, 2022

These results show that non-TOSCo vehicles traverse the corridor with less travel time than TOSCo vehicles. The difference in travel times for the eastbound direction are consistent with the differences in delays between TOSCo and non-TOSCo vehicles as reported in Figure 29, about 20 seconds.

The number of stops, defined as number of times speed dropped below 5 mph, is shown in Table 40. The analysis showed that the number of stops between TOSCo and non-TOSCo behavior was not statistically different. This differs from the simulation of TOSCo vehicles for a few potential reasons. First, the definition of stops is different between the simulation and the field analysis. Another reason these values are different is that the simulation analysis considers the stops by all vehicles across the entire period and the field analysis only has data from about twenty trips each direction that was depended on available gaps in the traffic flow at the starting point of each trip. This means that the samples and trips collected in the field may not be comparable between the benefits analysis and the simulation. The final reason is that the simulation uses simplified representations of TOSCo behavior that does not perfectly represent TOSCo behavior, especially at low speeds. The CACC algorithm supporting TOSCo in simulation is not the same algorithm as the deployed TOSCo vehicles.

The TOSCo vehicles in the field were designed to drive conservatively. These vehicles will not enter an intersection with a yellow indication or exceed the speed limit on the facility. The simulation efforts show that these design decisions limit the performance of the TOSCo vehicles in the field. With sufficient MPR the TOSCo vehicles could create smoother flow with less red-light running violations as deployed. If the TOSCo settings were adjusted according to some of the beneficial settings found in the single intersection analysis, the TOSCo vehicles could experience shorter travel times and less stops.

Table 40. Field Measured Number of Stops Comparison between TOSCo and Non-TOSCo Trips

Direction of Travel	Driving Mode	Number of Trips	# of Stops/ Vehicle	Standard Deviation (#/veh)	Statistical Significance (p-value)[1]
Eastbound	Non-TOSCo	20	4.0	1.30	—
Eastbound	TOSCo	21	4.1	1.74	0.384
Westbound	Non-TOSCo	19	5.7	1.56	—
Westbound	TOSCo	19	5.9	1.22	0.323

[1] One-tailed t-test comparing the results of the Non-TOSCo trips to the TOSCo trips.

Source: Texas A&M Transportation Institute, 2022

Chapter 6. Findings and Recommendations

TOSCo is an innovative connected vehicle application that aims to generate improved 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, green window and queue information from the infrastructure to plan speed trajectories that allow them to reduce the likelihood of stopping at TOSCo-supported intersections. TOSCo vehicles use this information to automatically speed up or slow down to reach the stop bar at the intersection during the "green window," the time in the signal cycle when all the queue traffic in the travel lane ahead of the TOSCo vehicle has cleared the intersection. If a TOSCo vehicle must stop at the intersection, the control algorithm in the vehicle gradually slows the vehicle to reduce the amount of idle time at the intersection. The TOSCo system also includes a coordinated launch feature which allows a string of TOSCo-equipped vehicles to leave an intersection simultaneously, in a coordinated fashion, to reduce the start lost time which, in turn, increases the capacity through the intersection.

This report presented the methodology and results of computer simulation activities supporting the development of the TOSCo system. The research team revised a traffic simulation environment to evaluate the effectiveness and potential mobility and environmental benefits that could be generated through the application of the TOSCo system on the FM 1960 corridor. This included incorporation of the minor edits to the TOSCo system made between the interim Phase 2a analysis and the TOSCo logic utilized for demonstration of the TOSCo behavior on FM 1960. The research team used this simulation evaluation environment to accomplish the following:

- Assess the potential mobility and environmental benefits of using TOSCo on FM 1960 in Houston, Texas
- Quantify the impacts of different market penetration rates of vehicles equipped with TOSCo functionality on mobility and environmental benefits.

One significant outcome of this project has been the refinement of the TOSCo Simulation Environment. This innovative environment has proved to be an invaluable tool in supporting the development and assessment of TOSCo functionality. This revision consisted of combining the vehicle subsystem and the infrastructure subsystem of TOSCo into a performance assessment platform. The revision also increases flexibility of the TOSCo simulation which enables users to apply the TOSCo algorithm to different properly configured VISSIM models easily by adjusting a configuration text file read by the DriverModel.dll that hosts the complete TOSCo algorithm. Such ability was demonstrated in the project with the application of the DriverModel.dll code to the FM 1960 corridor after building the code and utilizing the software on the SH 105 corridor model.

Summary of Findings

The following provides a summary of the benefits produced by the simulation experiments.

Mobility and Environmental Benefits

The following provides a summary of the mobility and environmental benefits observed by implementing TOSCo on the FM 1960 corridor:

- TOSCo settings impact the ability of the TOSCo system to reduce the delays experienced by the vehicles. Allowing the speed trajectory to accept speeds higher than the speed limit, increasing TOSCo range, and allowing TOSCo vehicles to enter in yellow each reduced the amount of delay experienced relative to the default TOSCo settings. These delay reductions were increased further when the three changes in settings were combined into a “revised” representation of TOSCo. Allowing the vehicle to computer a long CSC-Down speed profile either made no difference in performance or led to worse performance than the default TOSCo behavior.
- The high-volume single intersection experiment was set up such that the intersection was over capacity in the westbound direction in the baseline scenario. As TOSCo MPR increases the congestion clears to under-saturated (i.e., less than one stop per vehicle on average) in the westbound direction. With no change in green time, the increased throughput suggests increased saturation flow rate and increased capacity as a result of TOSCo.
- TOSCo was able to achieve reductions in stop delay and number of stops with both TOSCo settings. Stop delay decreased by around 50 percent across the corridor as TOSCo MPR increases. The average stops per vehicle increased initially with the introduction of TOSCo because the non-TOSCo vehicles stopped more times as the TOSCo finished their speed profiles. TOSCo vehicles had lower number of stops than the baseline traffic in simulation.
- With default TOSCo settings, the eastbound total delay increases gradually but does not represent a large increase in the travel time associated with the trips. The westbound total delay decreases initially but increases at high market penetration rates back to the delays observed at the baseline because with the default settings TOSCo vehicles have more delay than non-TOSCo vehicles.
- TOSCo reduced total delay in the westbound direction with both TOSCo settings and the eastbound direction with the revised TOSCo settings. Both eastbound and westbound directions were undersaturated and took approximately the same amount of time to traverse the corridor. The westbound direction is slightly more congested than the eastbound direction of travel, especially at intersection 109. These reductions were greater with the revised TOSCo settings.
- The westbound high TOSCo MPR scenarios experienced increases in total delay with the revised configuration relative to the baseline and the 90 percent MPR scenarios because TOSCo vehicles were entering a CREEP state once crossing the stop bar of the upstream intersection and maintaining a slow speed while far from the intersection. This behavior limited the number of vehicles that could cross the stop bar and increased the total delay. The TOSCo vehicle entered CREEP early in the revised setting because of the proximity between intersections 102 and 103 and the offsets in the signal timing force the vehicle to stop. The offsets at these intersections in the eastbound direction do not force vehicles to stop at both intersections.
- TOSCo showed improved performance for each respective vehicle class, TOSCo-equipped as well as non-equipped, in total delay and stop delay as market penetration increased on most of the approaches. These improvements were most noticeable with the revised TOSCo settings.
- TOSCo did not cause substantial changes in the total travel time for vehicles on the FM 1960 network.
- TOSCo increased fuel consumption initially and then reduced fuel consumption gradually as TOSCo MPR increased. With default settings the eastbound direction experienced about a 7 percent reduction in fuel use and the westbound direction of travel experienced about a 19 percent reduction in fuel consumption at 100 percent TOSCo in the midday off-peak hour across the seven-mile

corridor. The revised TOSCo experienced a maximum reduction in fuel use at 90 percent market penetration when the strings began to prevent turning traffic from completing their maneuvers. These reductions constituted a 16 percent reduction in fuel use for the eastbound direction and a 22 percent reduction in fuel use for the westbound direction.
- TOSCo temporarily increased fuel consumption and fuel use gradually decreased from the 20 percent MPR scenario until reductions in fuel use compared to the baseline were achieved around 40 or 90 percent TOSCo MPR depending on the direction of travel and the TOSCo settings. The research team believes that the increases in fuel are caused by the increased stops caused by the interactions between TOSCo vehicles.
- TOSCo has the potential to reduce user costs especially in the mid ranges of TOSCo MPR considered for this study.
- ***In heavy traffic (over-saturated conditions), TOSCo showed the ability to reduce the number of stops from an average of five stops per vehicle in half by 30 percent MPR and by 80 percent by 70 percent market penetration.***
- ***TOSCo simulations demonstrate that TOSCo can reduce fuel use by up to 180 gallons across the corridor with default settings and by about 260 gallons with the revised settings across the 13 intersections in the off-peak analysis period.***
- ***The revised settings of TOSCo cause a reduction in delays and stops for all users on FM 1960.***

Recommendations for Future Simulations

The following are recommendations developed by the research team based on their experiences with modeling the potential mobility and environmental benefits of the TOSCo system.

TOSCo Vehicle Recommendations

- The simulated version of TOSCo in this study did not incorporate the CAMP CACC algorithm the TOSCo vehicles in the field used in conjunction with TOSCo operations. To better simulate the TOSCo behavior for evaluation, future versions of the DriverModel.dll should explore generating a better representation of the CACC behavior of the CAMP algorithm.
- In the default settings speeds in all modes of TOSCo, except for Free-flow, were limited to the posted speed limit. The revised TOSCo setting relaxes this constraint and shows how this setting leads to a limitation of the delay reduction ability of the TOSCo system. The implementation of TOSCo may consider relaxing the speed limit constraint in favor of allowing TOSCo vehicles to plan trajectories at the speed deemed appropriate by the driver of the vehicle. In such a case, the driver would be responsible for maintaining a lawful speed of travel since the vehicle would not alter the speed down to the speed limit.
- Limits to the TOSCo strings and gap settings to allow for easier lane changing for ambient traffic should be considered. Additional TOSCo simulations may consider coding the ability for TOSCo vehicle to deactivate TOSCo for the cooperative breaking a traveler might execute in the field to help ambient traffic change lanes.
- Further investigate and resolve the increased number of stops by the non-TOSCo vehicles in response to slow TOSCo vehicles. The increase in stops is not realistic and better smoothing of that slow travel would likely impact the fuel use estimation.

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Appendix A. Verification of Traffic-level TOSCo Representation

The research team ran several simulations to verify that the traffic-level operation of TOSCo represents the system performance in the field. The team used a select set of scenarios from the vehicle level simulation on the version used for Test 2.2 as the scenarios to verify the traffic level representation.

Verification Scenarios

The vehicle-level simulation has a series of scenarios from 71 to 78 to analyze TOSCo performance in various operational scenarios. This report renumbers the scenarios used for verification of the traffic level to make the report easier to follow. The verification was completed with three scenarios which are described in Table 62. Note the speed limit in all scenarios is 55 mph.

Table 41. Traffic-level Verification Scenario Descriptions

Traffic-level Verification Name	Vehicle-level Simulation Scenario	TOSCo Vehicle Set Speed	Queue Length at Intersection
Operating Scenario 1	Scenario 73	50 mph	No queues
Operating Scenario 2	Scenario 75	60 mph	2 vehicles
Operating Scenario 3	Scenario 76	50 mph	4 vehicles

Source: Texas A&M Transportation Institute, 2022

The research team used select introduction times of the TOSCo vehicles for each operating scenario to result in each of the TOSCo modes. Each of the three simulation scenarios for verification used five different introduction times, totaling to 15 different comparisons between the traffic-level and vehicle-level simulations for verification.

The following sections describe the performance of the traffic-level simulation compared to the TOSCo operation in the vehicle-level simulation. The research team searched for operations that resulted in similar performance metrics. Differences in behavior are noted, but the research team is looking for similar results between the two simulations, meaning that the vehicles cross the stop bar at a similar time, resulting in similar travel times and delays.

Operating Scenario 1: Low Set Speed Without Queue

Scenario 1 represents a case where the TOSCo string is approaching a signal with a set speed of 50 mph and no queues at the intersection. The speed limit is 55 mph. Vehicles in each scenario are released into the network one second after another on the same lane. The model for verification generates vehicles in the rightmost lane of the Texas vehicle-level network developed in Task 9.6. This model does not allow any lane changing for generated vehicles. The introduction times in this operating scenario target five different TOSCo modes:

- 60 Second introduction time, coordinated speed control – speed up
- 66 Second introduction time, string split
- 78 Second introduction time, coordinated stop and coordinated launch
- 105 Second introduction time, coordinated speed control – slow down
- 120 Second introduction time, coordinated speed control – slow down

Figure 37 to Figure 39 show the simulation results for the 60 second introduction time for scenario 1. Both simulations result as the first vehicle begin to accelerate at about the 99 second mark and crosses the stop bar at about the 104 second mark, seen on the mode diagram in Figure 39, when vehicle 1 switches back to free-flow (FF) mode. Note the acceleration behavior between the two simulation environments is different. This is caused by the different CACC algorithms used to represent TOSCo behavior. The vehicle-level environment uses the CAMP CACC algorithm which builds acceleration more gradually and reaches greater acceleration levels than the CACC representation used in the traffic-level algorithm which is modeled from literature. The research team knows of the differences between the CACC algorithms and concluded that the traffic-level representation is a reasonable representation of TOSCo in this scenario.

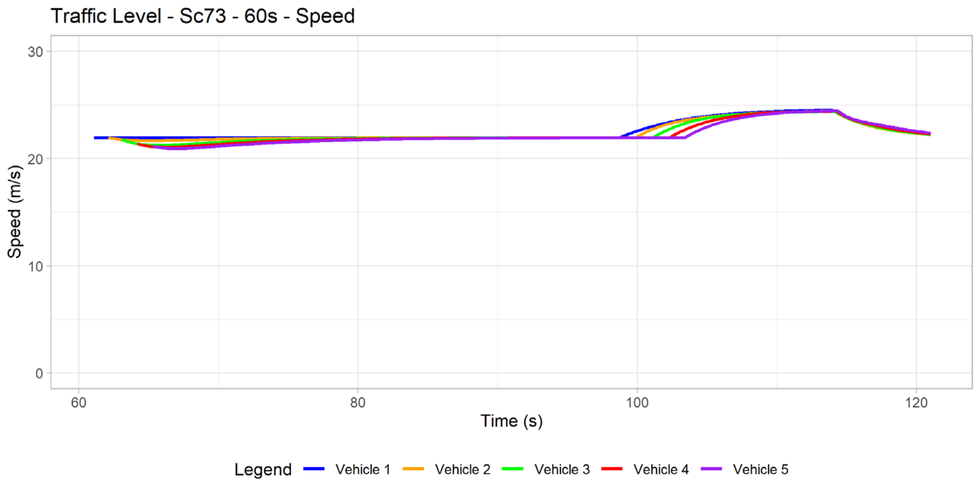
Figure 40 to Figure 42 show the results for the 66 second introduction time. As expected, the traffic-level scenario resulted in three vehicles crossing the intersection and two stopping, just like the vehicle-level simulation. The acceleration graphs show that the accelerations and decelerations are at the same simulation times and occur at the same amount of time. Vehicles cross the stop bar at the same times.

Figure 43 through Figure 45 show the results for the 78 second introduction time. Vehicles begin to slow down and the first vehicle stops at the same time. Vehicles begin to accelerate from a stop at the same time. The mode selection shows a similar pattern between the two simulations.

Figure 46 through Figure 48 show the results for the 105 second introduction time. The vehicle-level and the traffic-level representations both choose to CSC-DOWN and switch to CSC-UP at the same times. The lead vehicle chooses a similar set speed in both simulations and the vehicles cross the stop bar (i.e., go to free-flow) at approximately the same time.

Figure 49 through Figure 51 show the results for the 120 second introduction time. In both simulation environments, the vehicles choose CSC-DOWN to CSC-UP at similar times. The vehicles choose similar set speeds in CSC-DOWN, but the traffic-level simulation takes a longer time decelerating at the lower speed. However, the traffic-level simulation also results in the vehicles crossing the stop bar one second earlier.

The differences in these five scenarios are largely caused by simplifications in the CACC algorithm running alongside TOSCo. The research team found that the two simulation environments are very similar, and the differences are acceptable for representing TOSCo behavior for evaluation in the traffic-level simulation.



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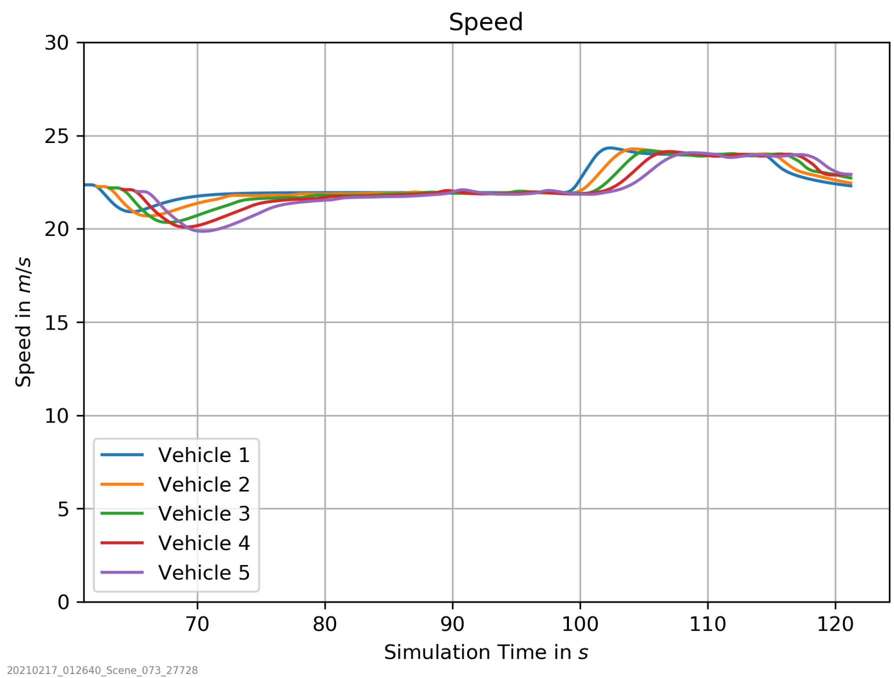
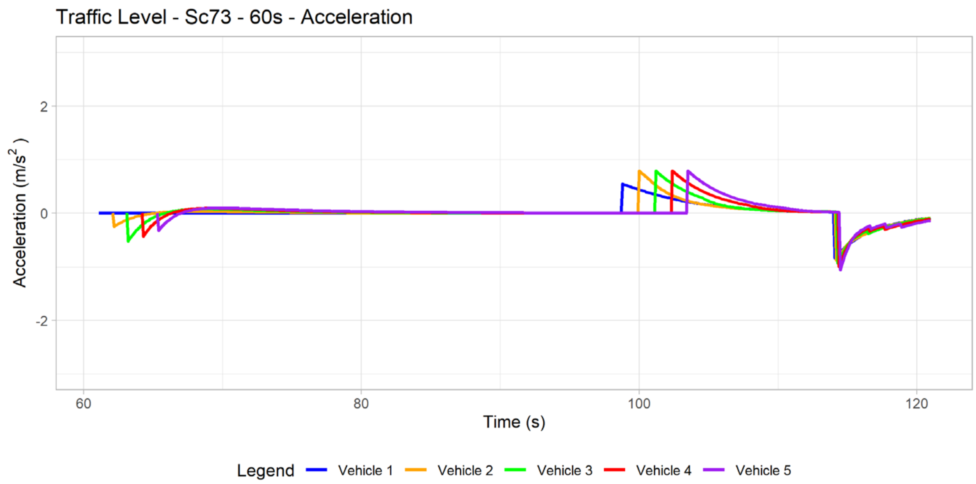


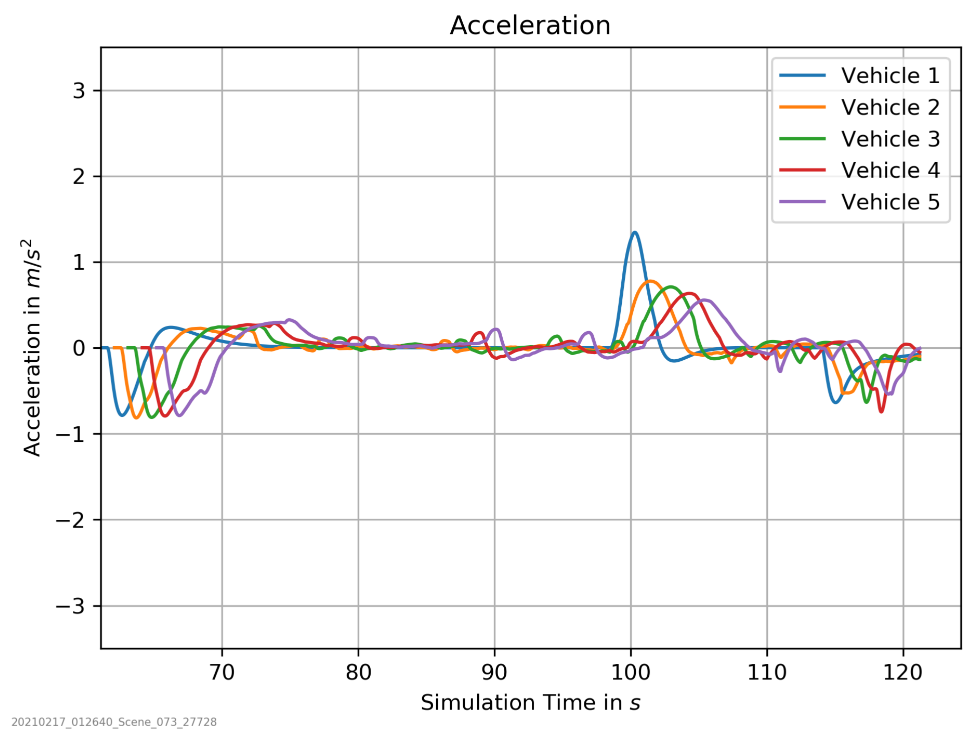
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 37. Verification Scenario 1 – 60 Second Introduction Time – Speed Profiles



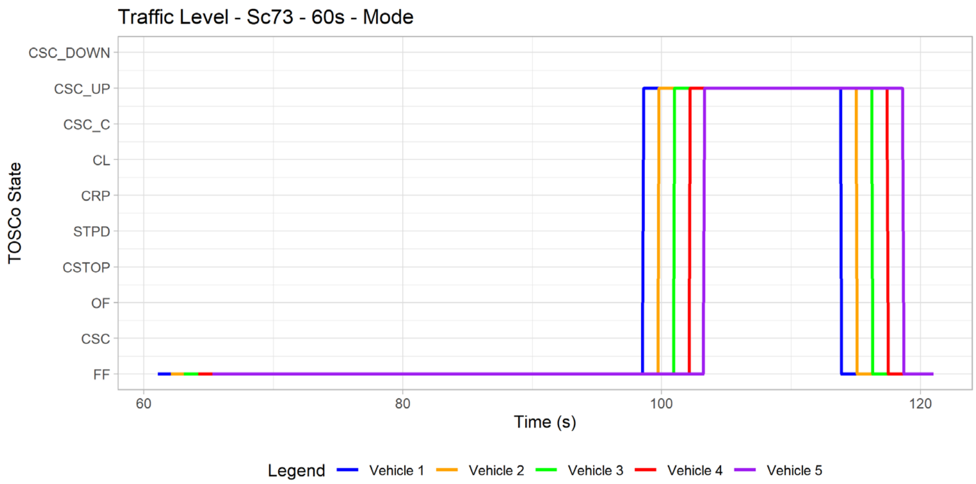
(a) Traffic-level Profile



(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 38.Verification Scenario 1 – 60 Second Introduction Time – Acceleration Profiles



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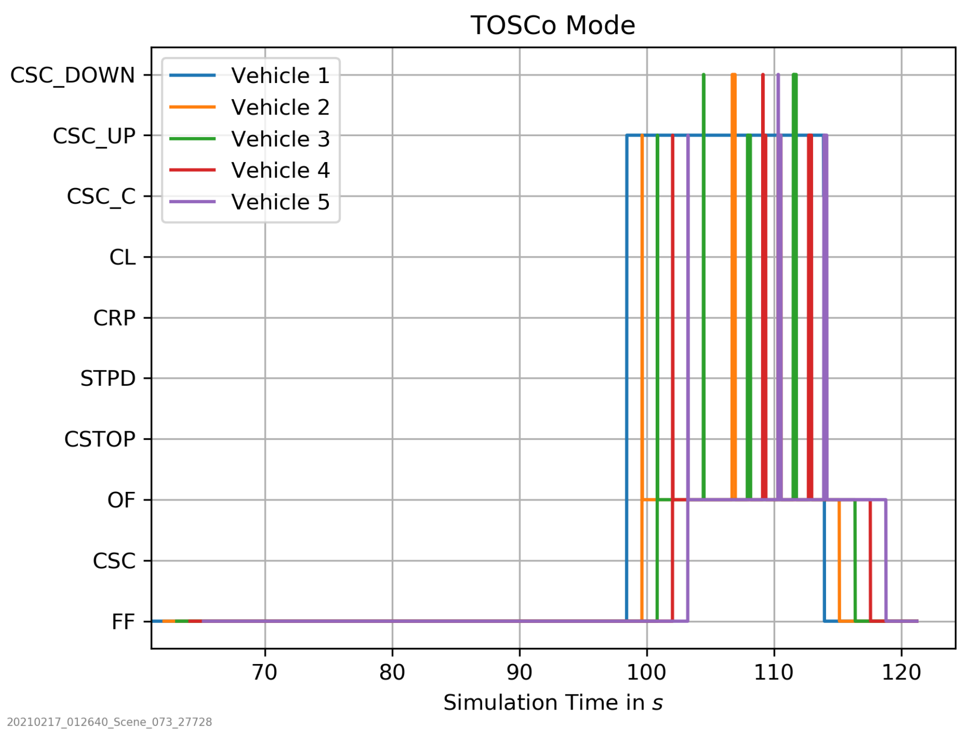
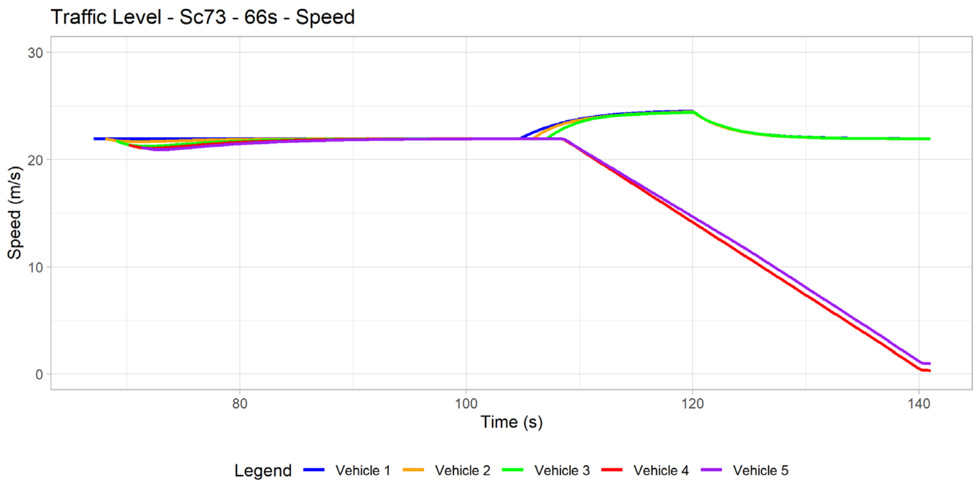


(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 39. Verification Scenario 1 – 60 Second Introduction Time – Mode Profiles



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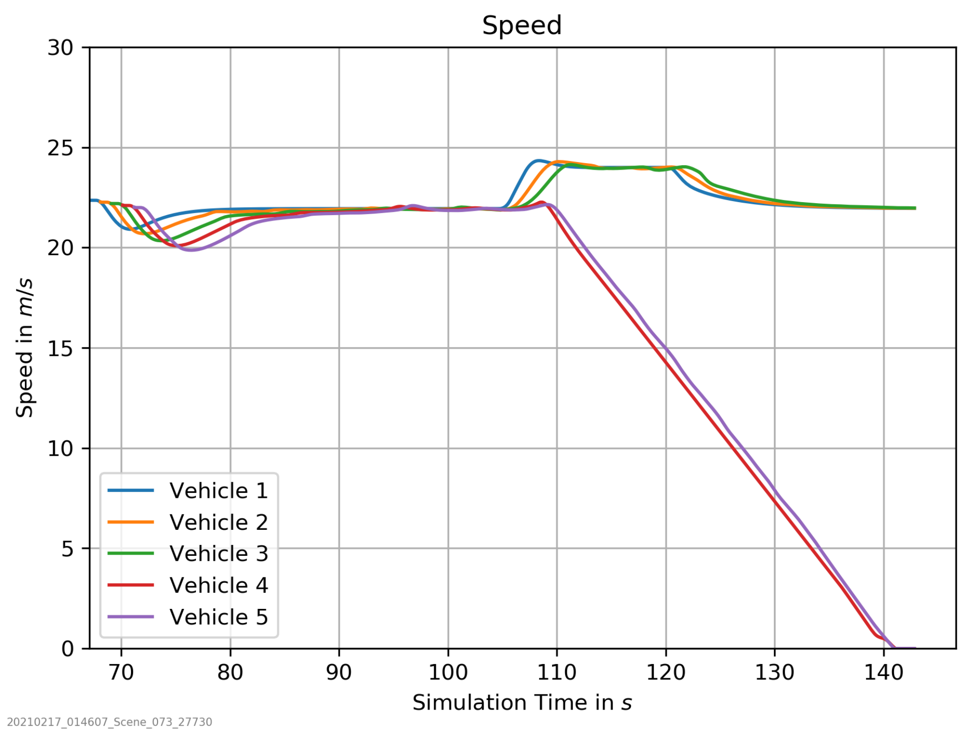
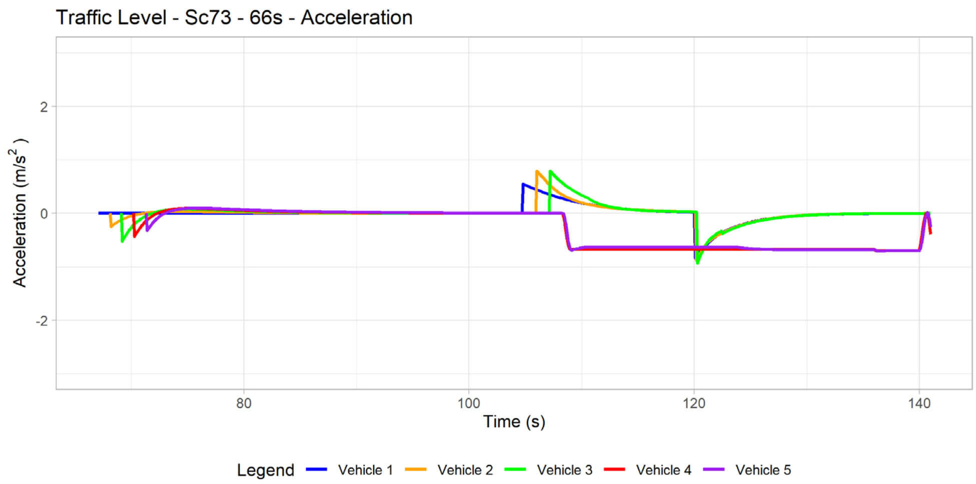


(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 40. Verification Scenario 1 – 66 Second Introduction Time – Speed Profiles



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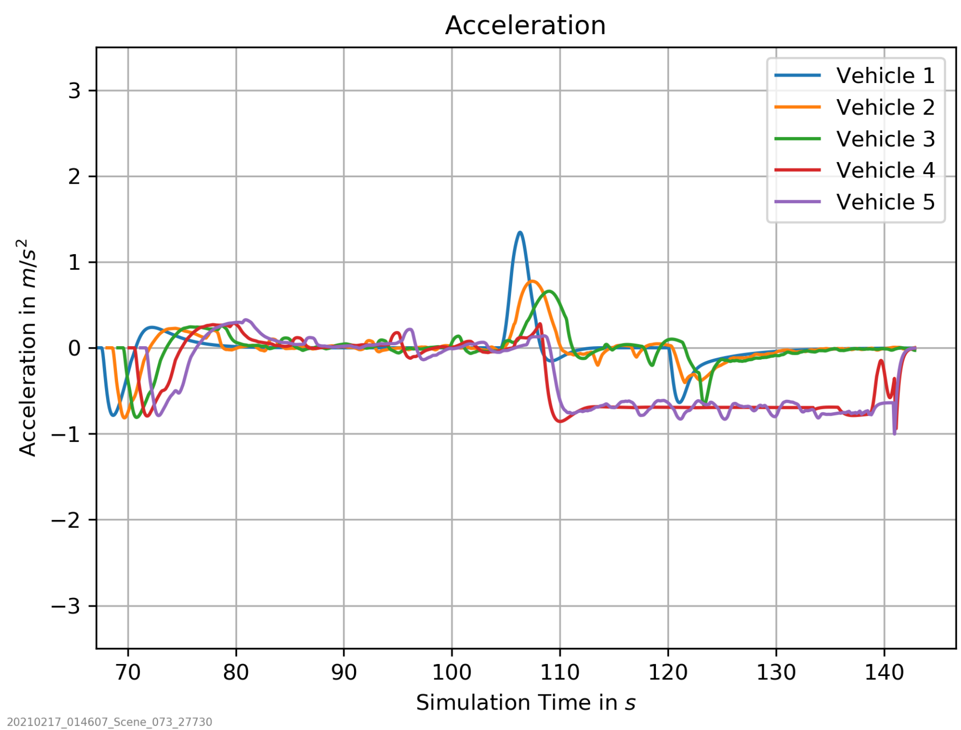
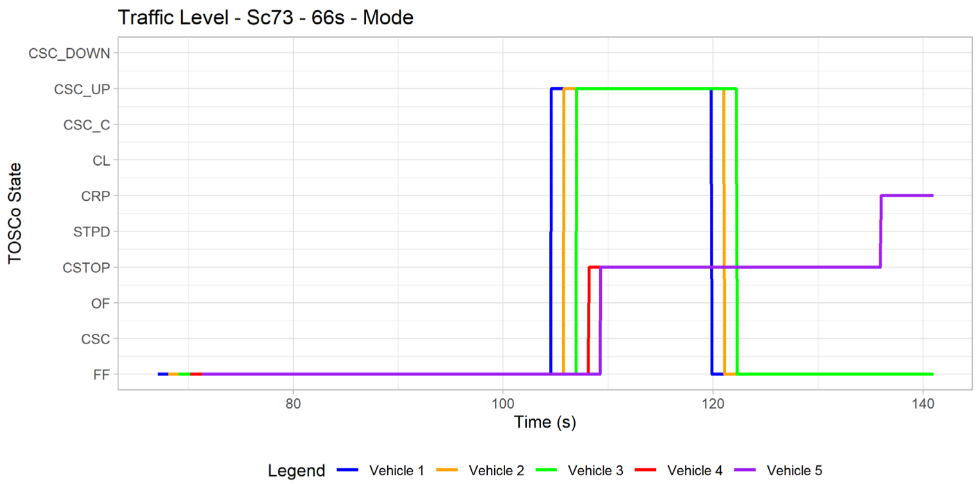


(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 41. Verification Scenario 1 – 66 Second Introduction Time – Acceleration Profiles



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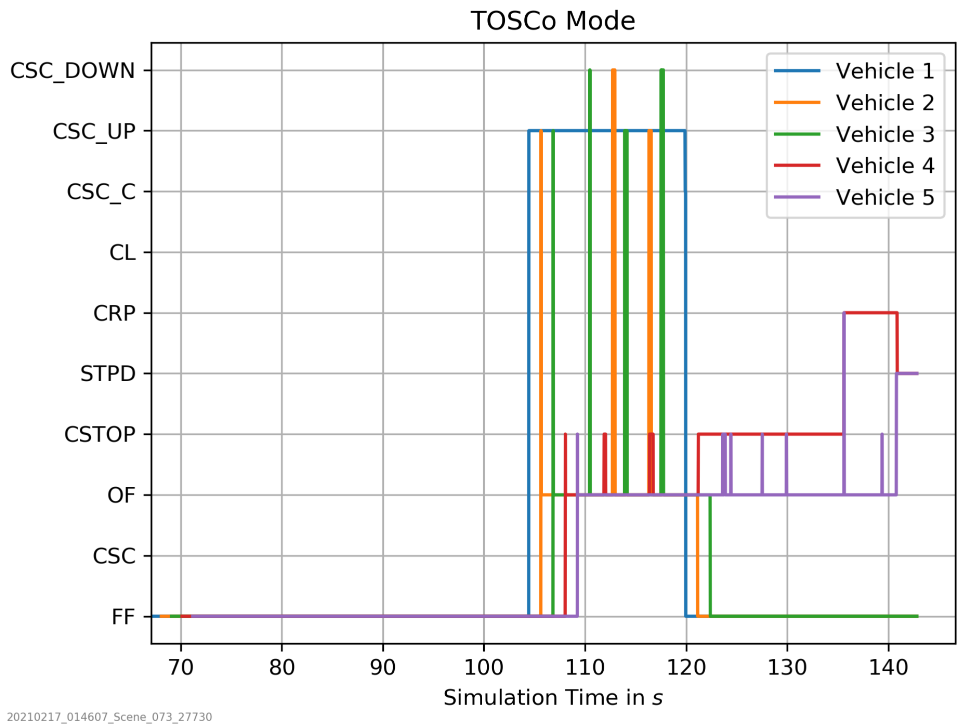
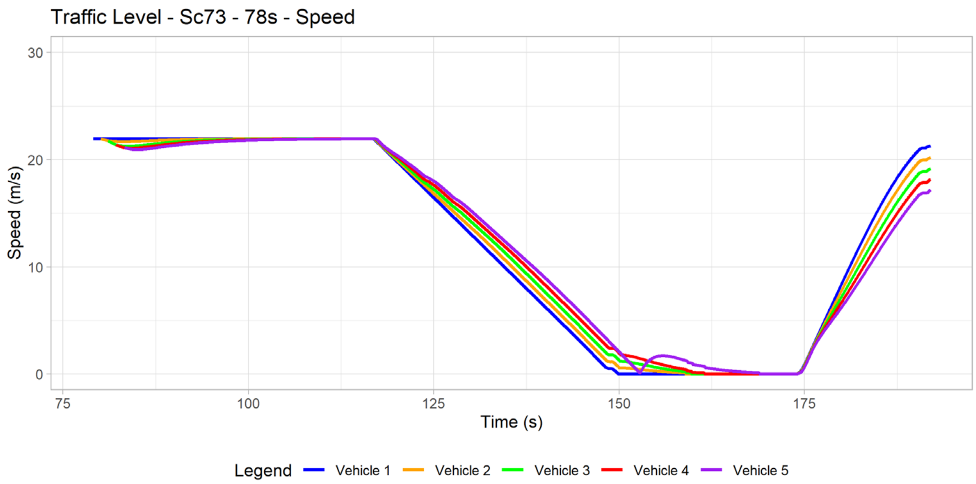


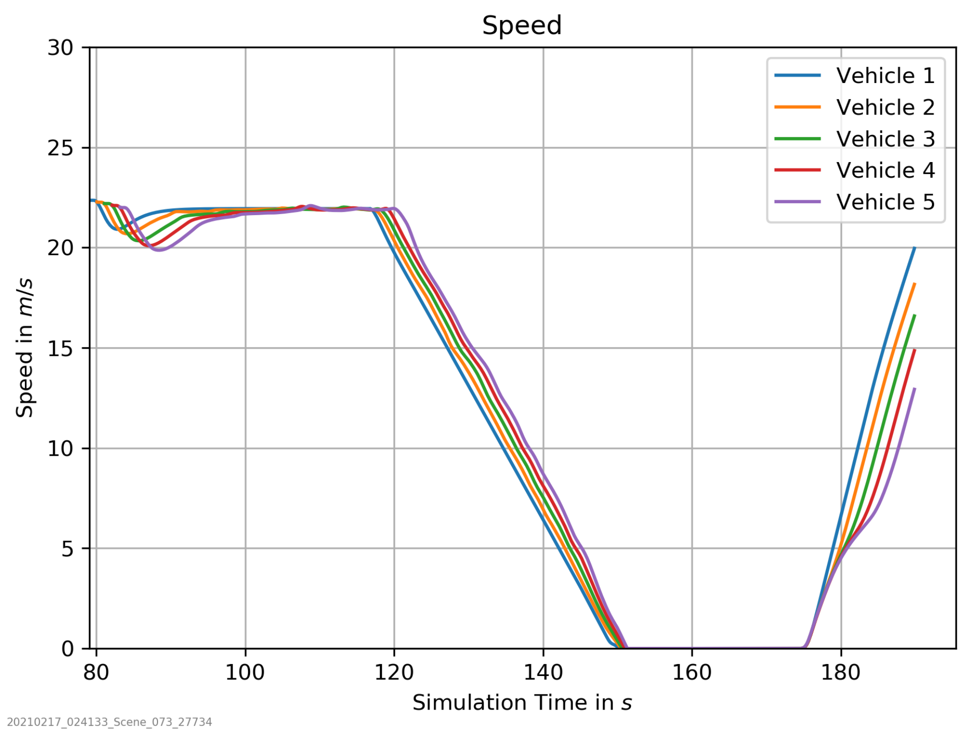
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 42. Verification Scenario 1 – 66 Second Introduction Time – Mode Profiles



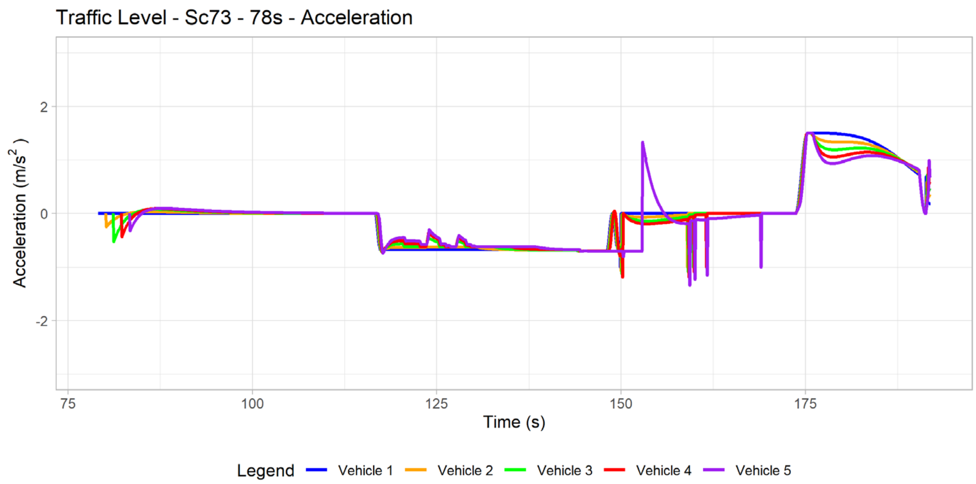
(a) Traffic-level Profile



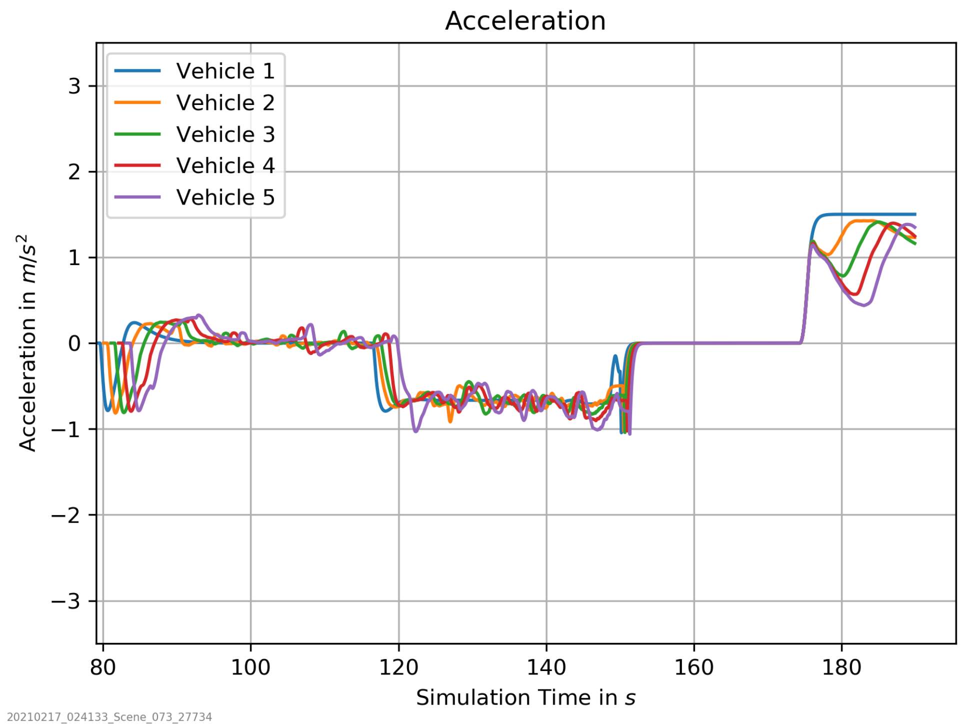
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 43. Verification Scenario 1 – 78 Second Introduction Time – Speed Profiles



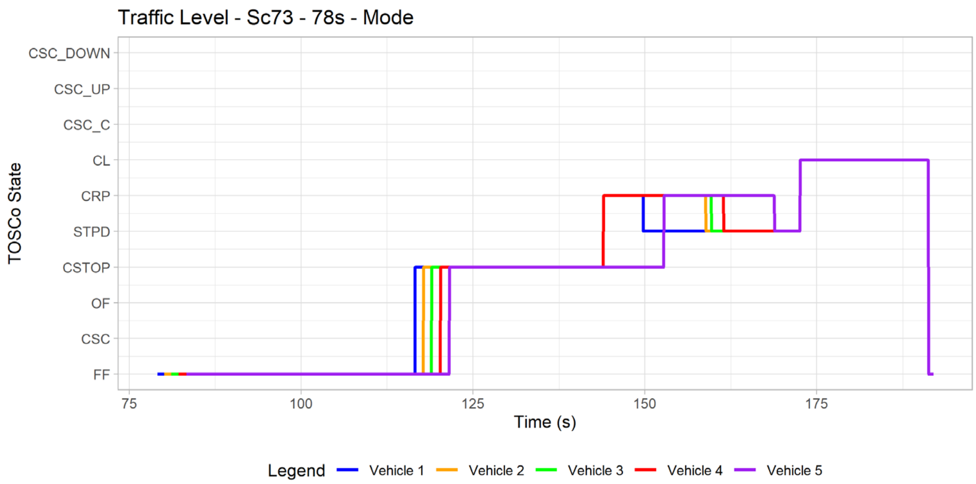
(a) Traffic-level Profile



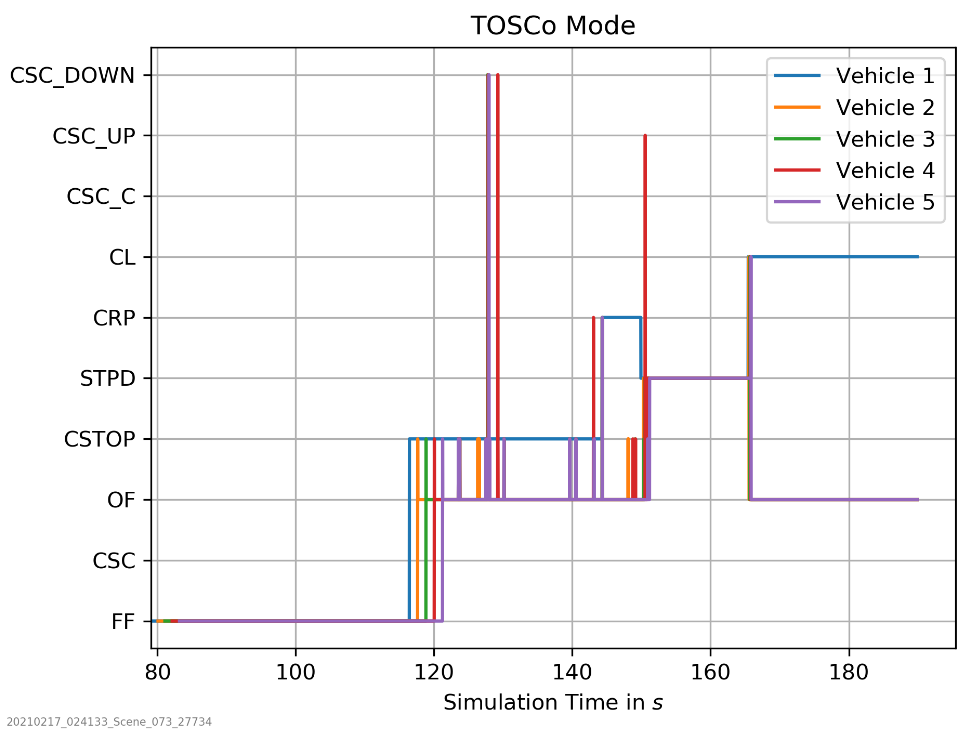
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 44. Verification Scenario 1 – 78 Second Introduction Time – Acceleration Profiles



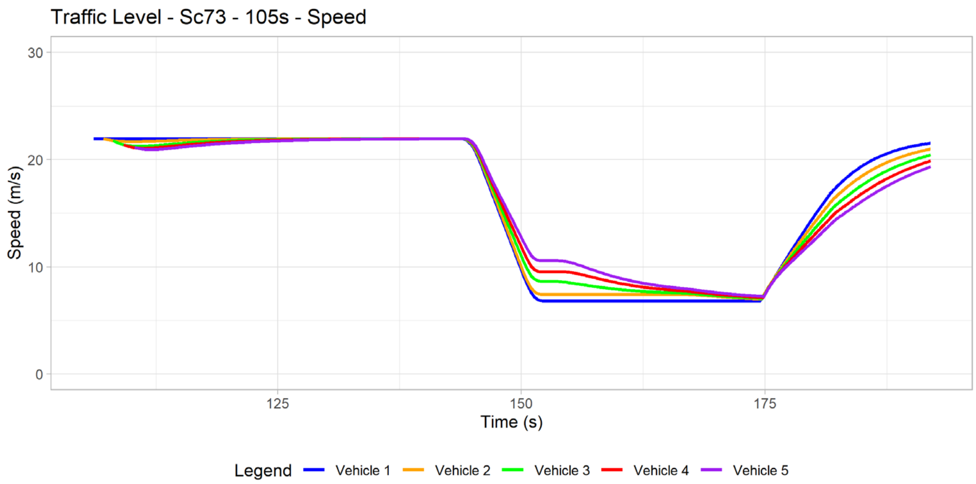
(a) Traffic-level Profile



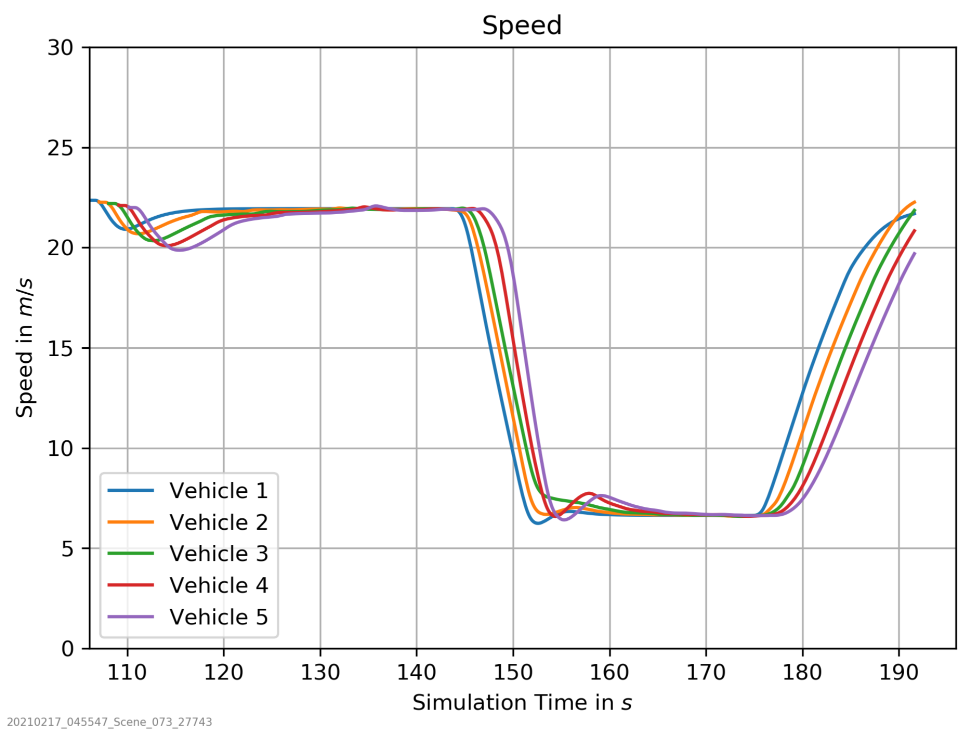
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 45. Verification Scenario 1 – 78 Second Introduction Time – Mode Profiles



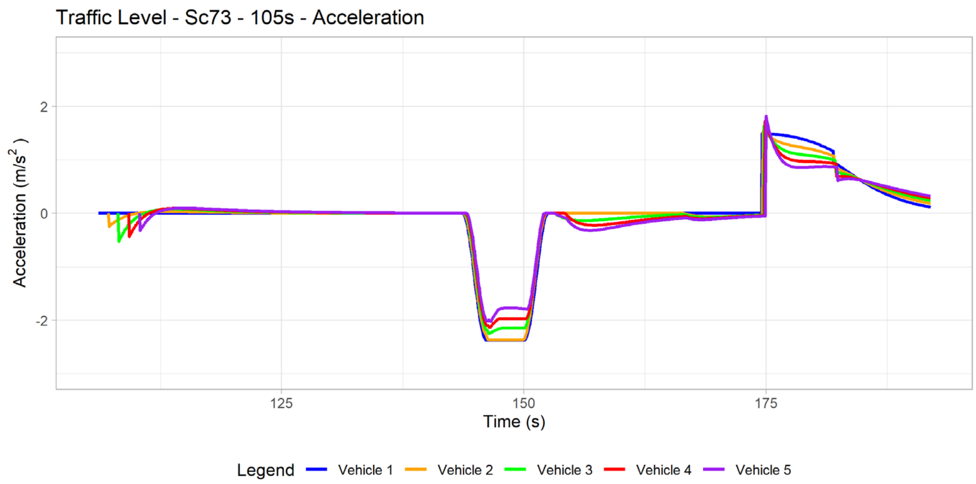
(a) Traffic-level Profile



(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 46. Verification Scenario 1 – 105 Second Introduction Time – Speed Profiles



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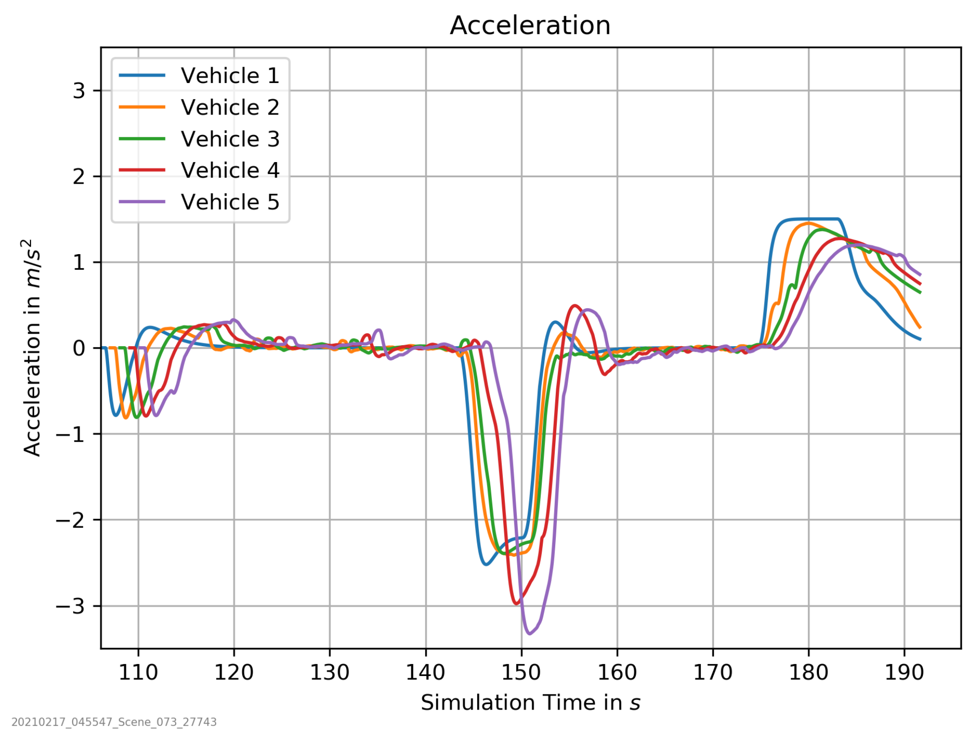
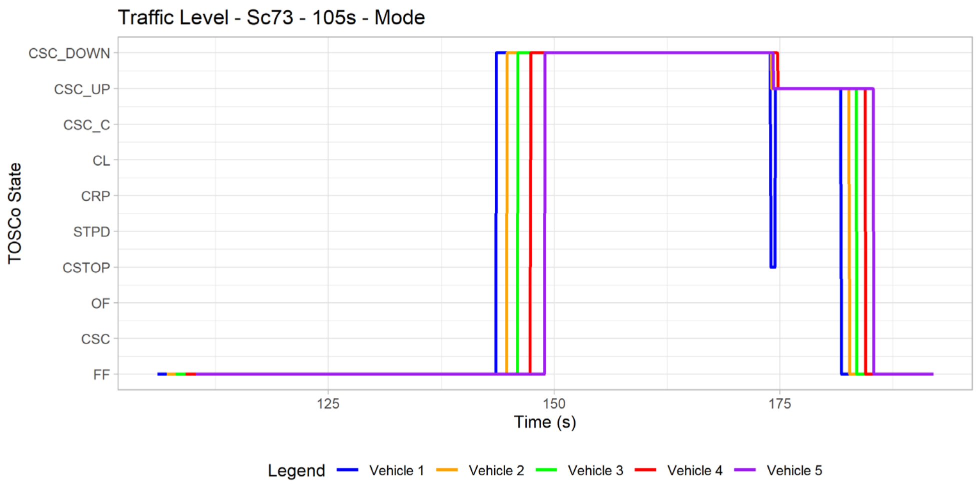


(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 47. Verification Scenario 1 – 105 Second Introduction Time – Acceleration Profiles



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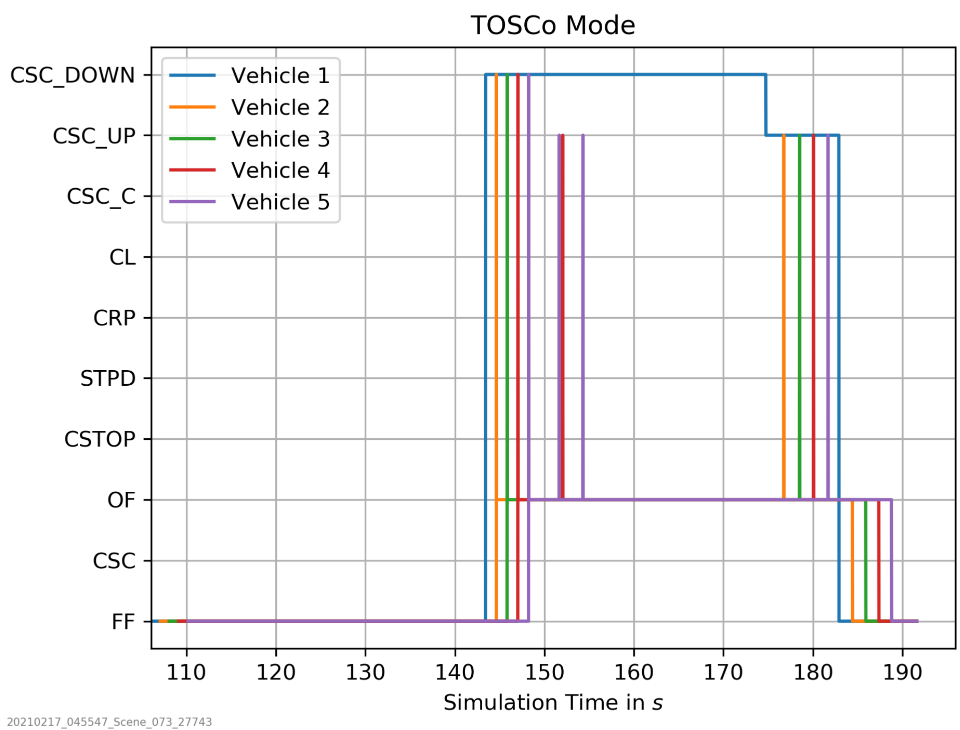
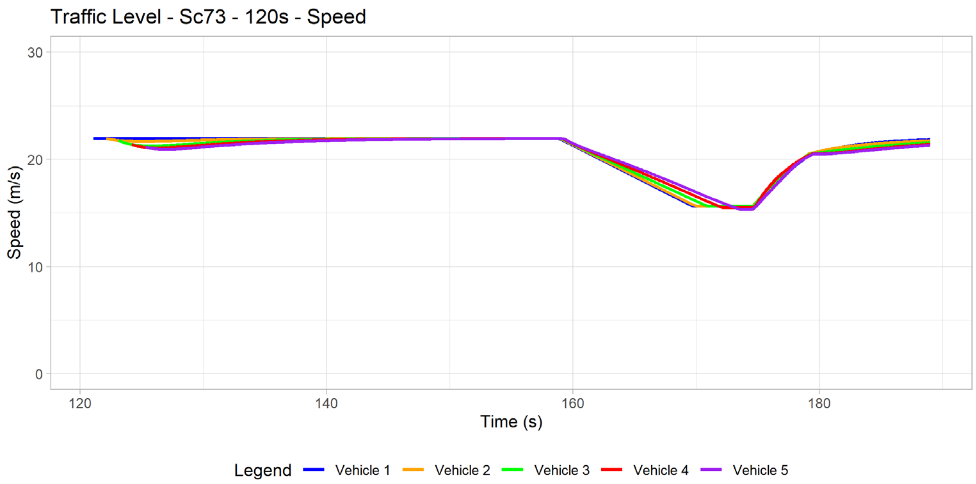


(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 48. Verification Scenario 1 – 105 Second Introduction Time – Mode Profiles



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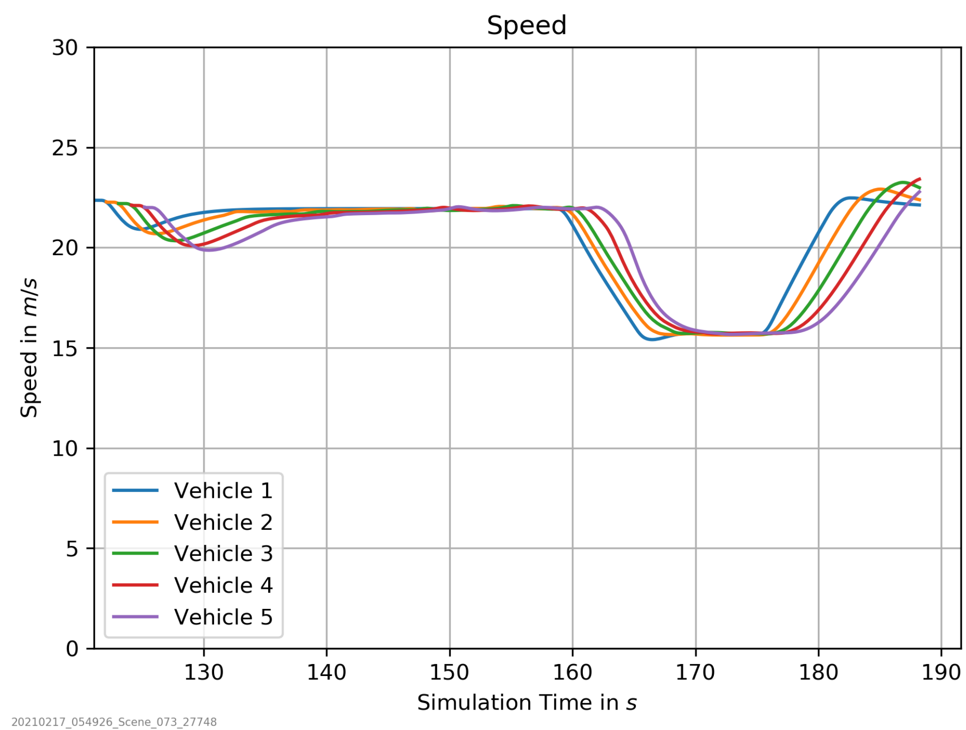
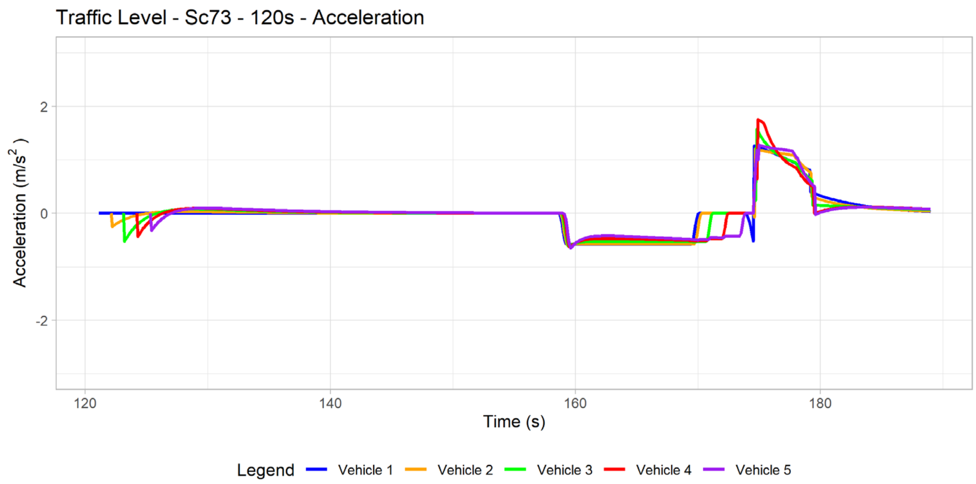


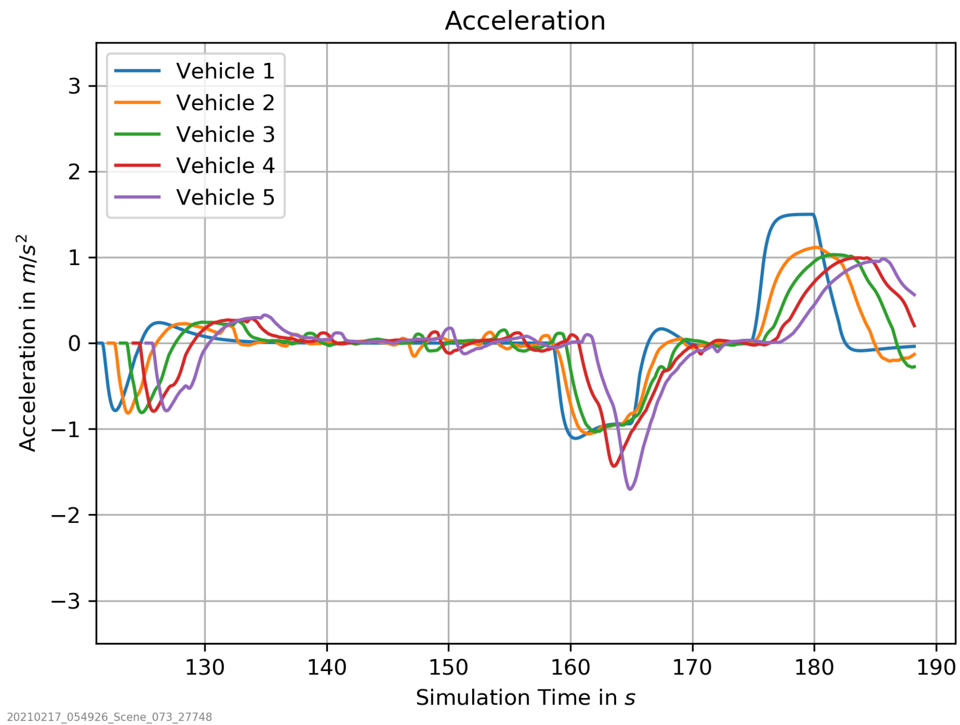
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 49. Verification Scenario 1 – 120 Second Introduction Time – Speed Profiles



(a) Traffic-level Profile



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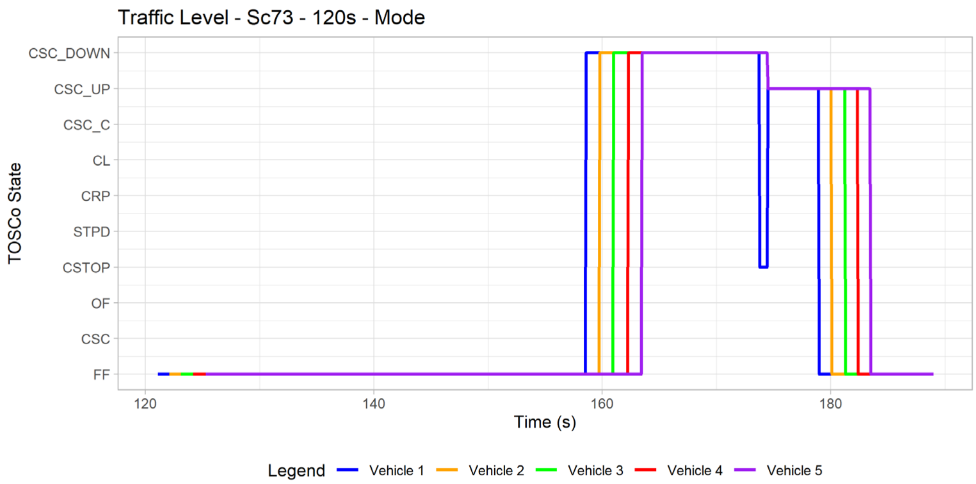
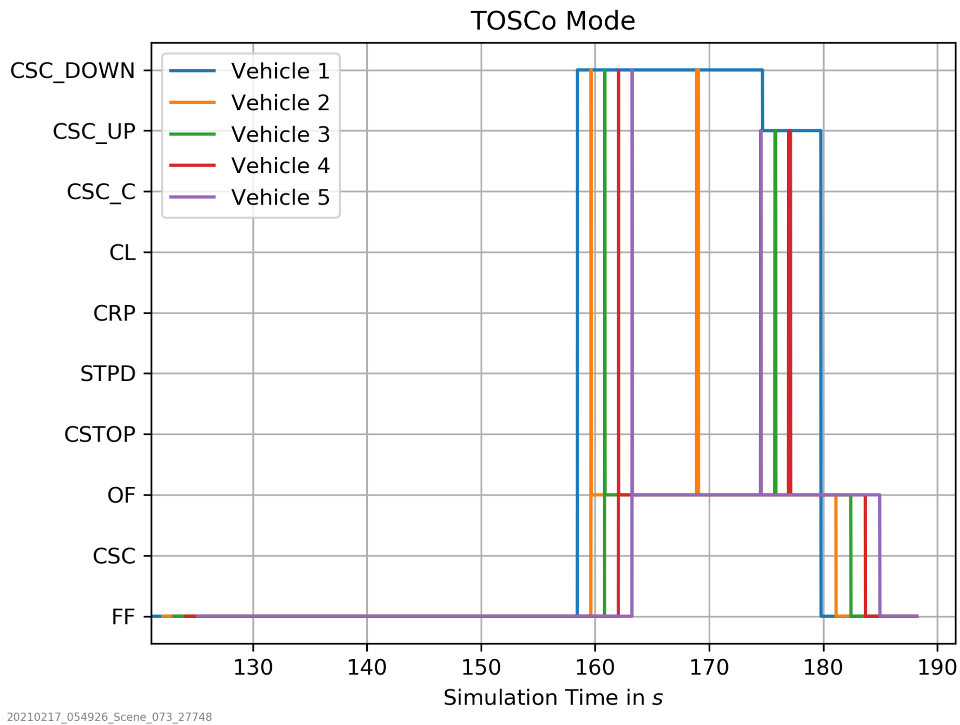
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 50. Verification Scenario 1 – 120 Second Introduction Time – Acceleration Profiles



(a) Traffic-level Profile



(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 51. Verification Scenario 1 – 120 Second Introduction Time – Mode Profiles

Operating Scenario 2: High Set Speed With Two Vehicle Queue

Scenario 2 represents a case where the TOSCo string is approaching a signal with a set speed of 60 mph and a two-vehicle queue at the intersection. The speed limit is 55 mph. The queued vehicles in this scenario are not TOSCo equipped and are generated at the 82 and 83 simulation second mark. Vehicles in each scenario are released into the network one second after another on the same lane. The model for verification generates vehicles in the rightmost lane of the Texas Vehicle-level network developed in Task 9.6. This model does not allow any lane changing for generated vehicles. The TOSCo vehicle introduction times in this operating scenario target two different TOSCo modes across 5 introduction times:

- 85 Second introduction time, coordinated stop
- 97 Second introduction time, coordinated stop
- 115 Second introduction time, coordinated speed control – slow down
- 130 Second introduction time, coordinated speed control – slow down
- 133 Second introduction time, coordinated speed control – slow down

Figure 52 through Figure 54 show the results of the 85 second introduction time. In this scenario. both simulated strings respond at the 120 second mark and come to a stop. The traffic-level simulation appears to stop and then gain speed and stop again. This is caused by the traffic-level representation of the CREEP state, which is different from the vehicle-level representation to avoid cases where the TOSCo string fails to accelerate.

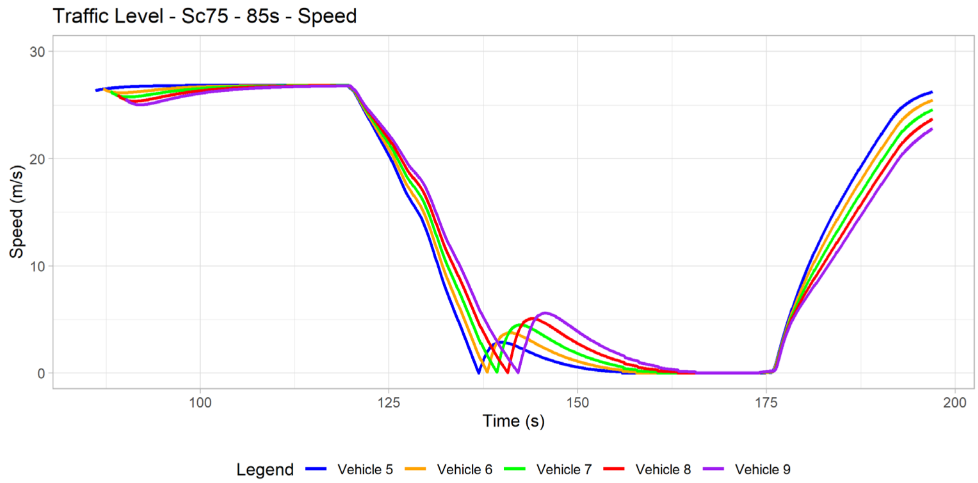
Figure 55 through Figure 57 show the results for the 97 second introduction time. The string chooses to perform a coordinated stop. The traffic level has different CREEP behavior than the vehicle-level simulation and the strings stop at a similar time. In both scenarios, all vehicles come to a stop and then begin to move after the vehicles in front of the TOSCo string depart the intersection.

Figure 58 through Figure 60 show the results for the 115 second introduction time. Both simulations choose CSC-DOWN to decelerate to a similar speed and then slow in response to the queue some time before crossing the intersection. The first vehicle in the traffic-level representation crosses the intersection about one second before the vehicle-level simulation.

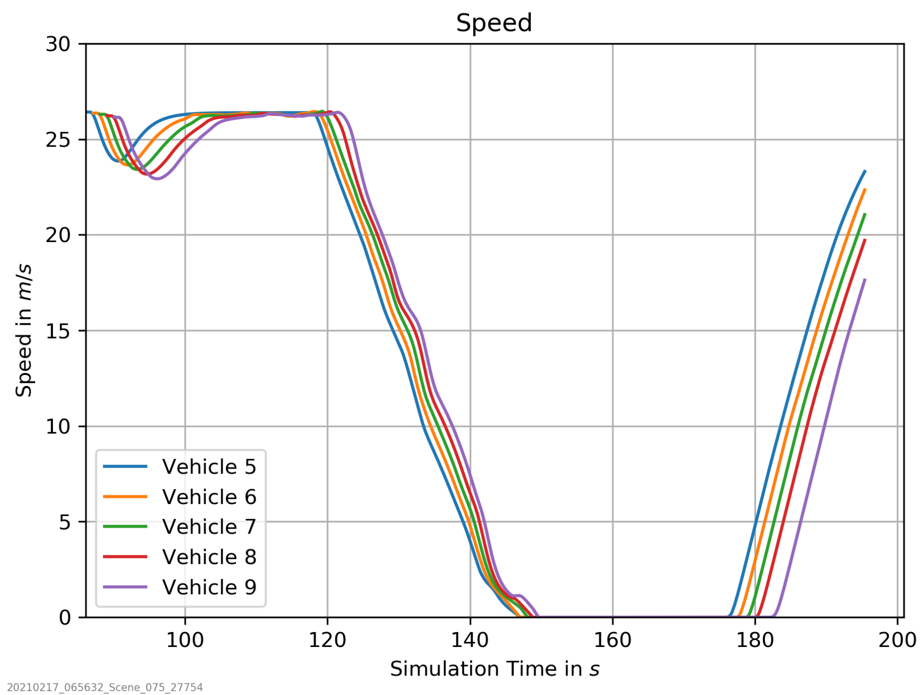
Figure 61 through Figure 63 show the results for the 130 second introduction time. In this scenario, both strings respond initially at the same time, but the traffic-level response does not slow down as much in the beginning. Both simulated strings ultimately slow down to about the same speed, but the two environments decelerate at different rates and magnitudes. In this case, the traffic-level string crosses the stop bar about one second later than the vehicle-level representation.

Figure 64 through Figure 66 show the results for the 133 second introduction time. Like the previous scenario, both strings respond initially at the same time, but the traffic-level response does not slow down as much in the beginning. The traffic-level string has a higher minimum speed than the vehicle-level string. However, the traffic-level string crosses the stop bar at about the same time as the vehicle-level representation.

The differences in these five scenarios are largely caused by simplifications in the CACC algorithm running alongside TOSCo. The research team found that the two simulation environments are very similar, and the differences are acceptable for representing TOSCo behavior for evaluation in the traffic-level simulation.



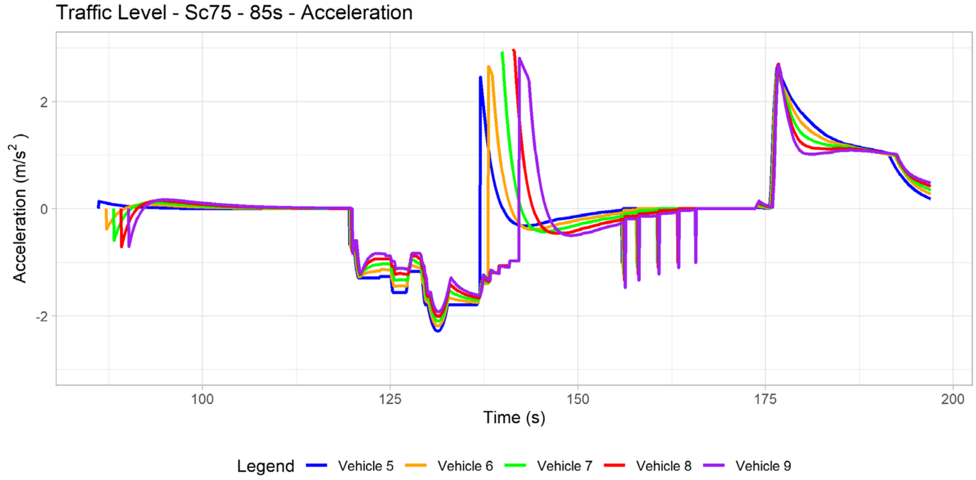
(a) Traffic-level Profile



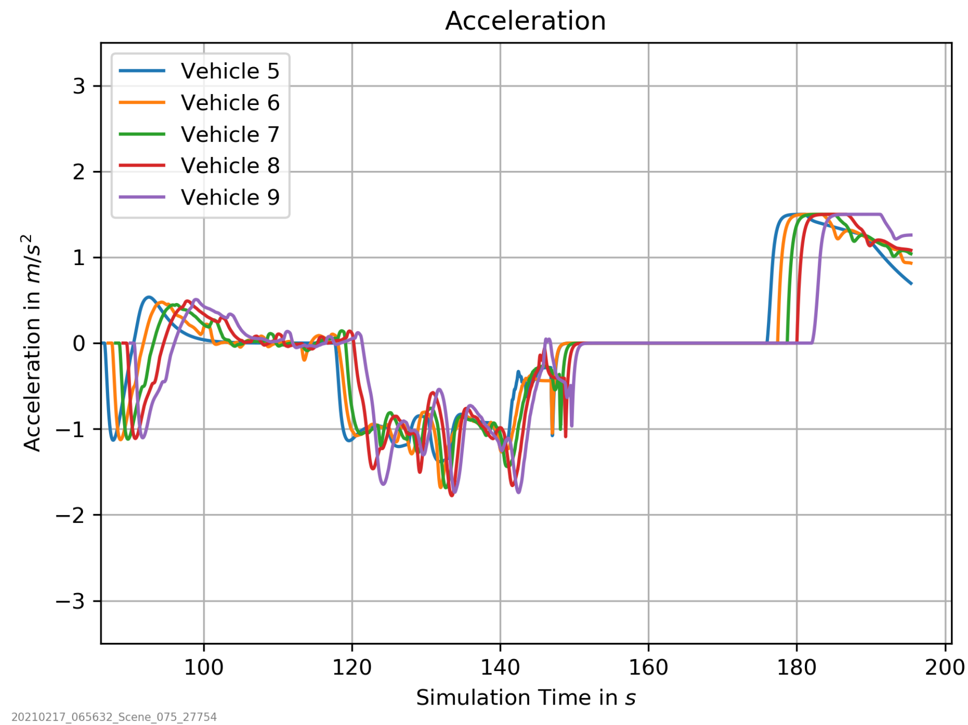
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 52. Verification Scenario 2 – 85 Second Introduction Time – Speed Profiles



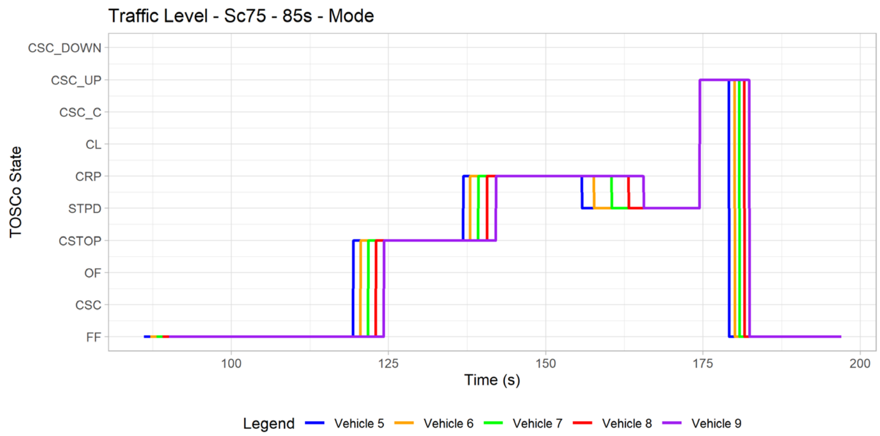
(a) Traffic-level Profile



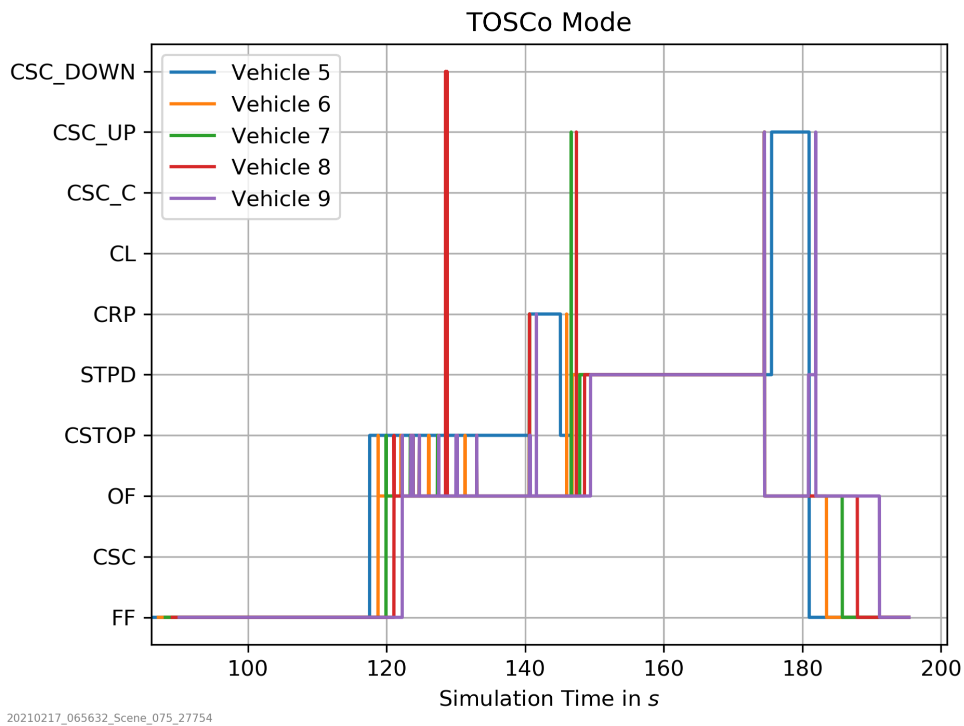
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 53. Verification Scenario 2 – 85 Second Introduction Time – Acceleration Profiles



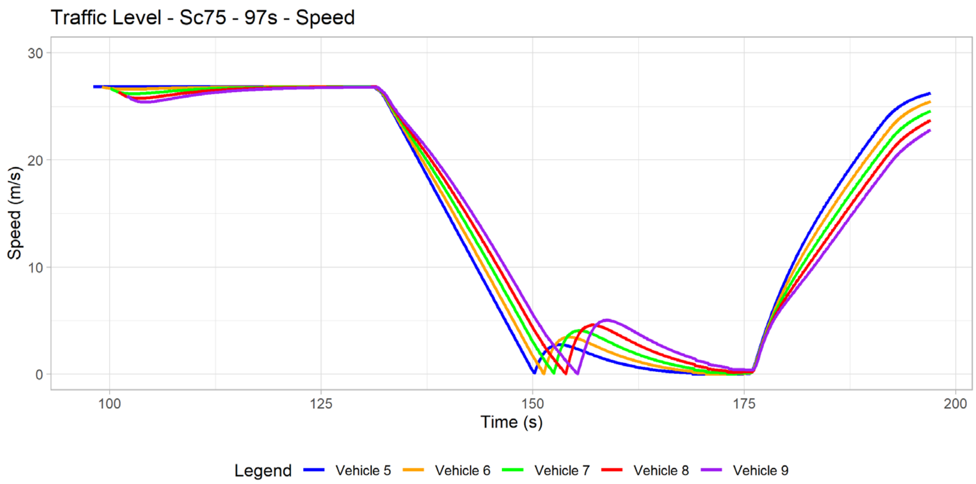
(a) Traffic-level Profile



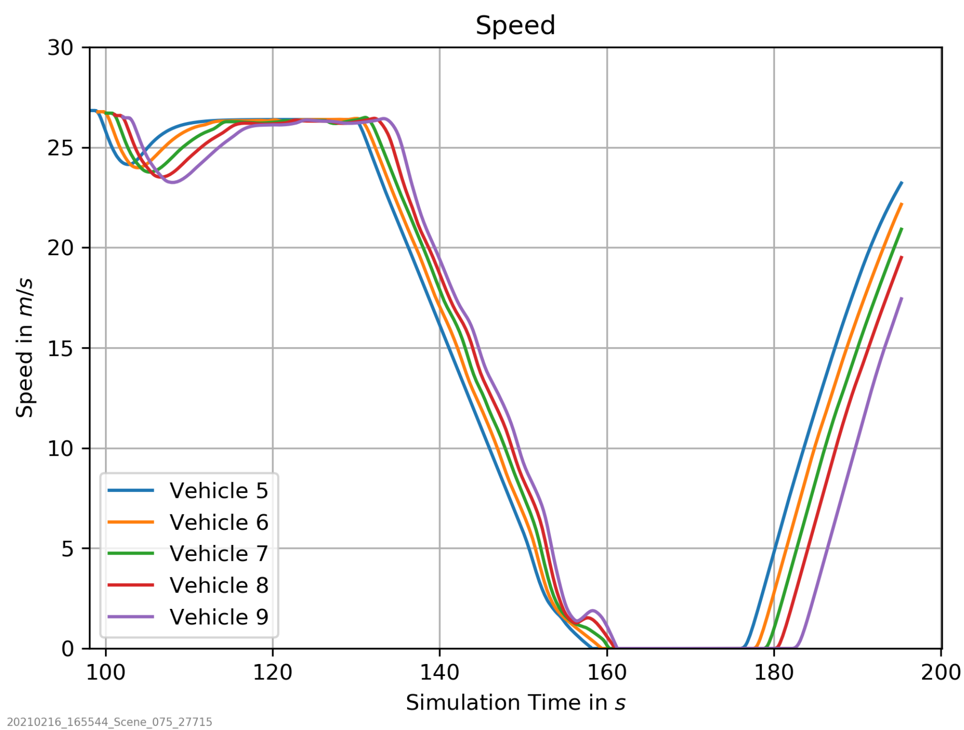
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 54. Verification Scenario 2 – 85 Second Introduction Time – Mode Profiles



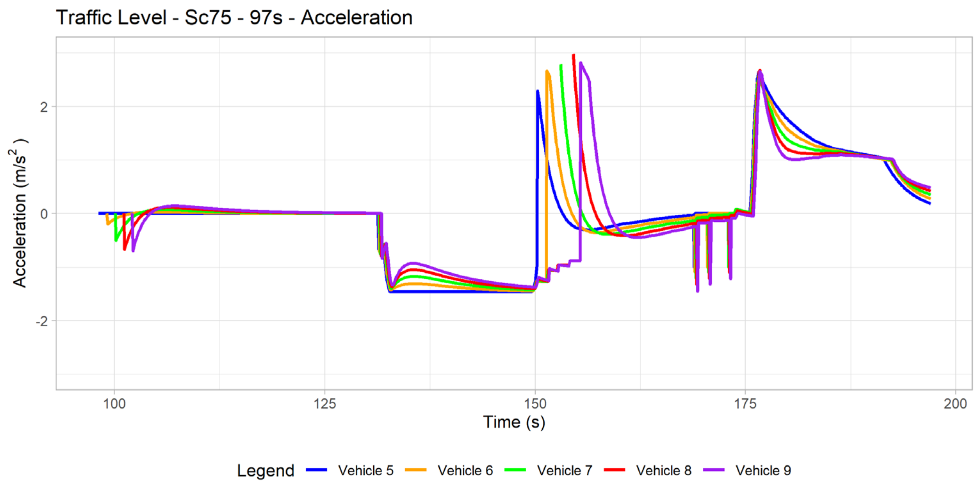
(a) Traffic-level Profile



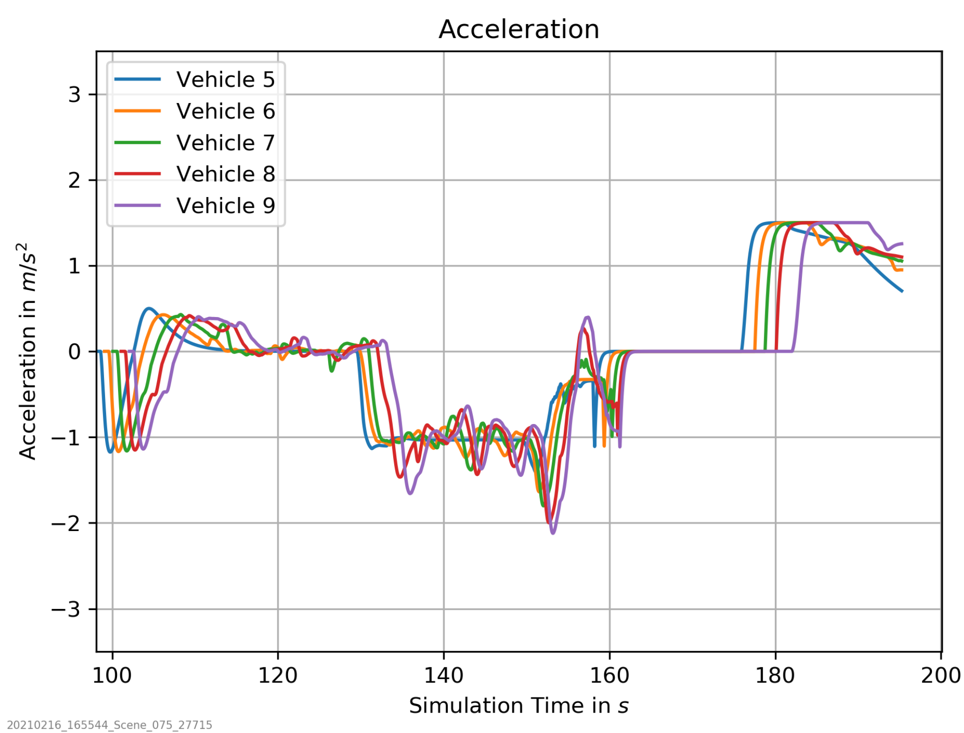
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 55. Verification Scenario 2 – 97 Second Introduction Time – Speed Profiles



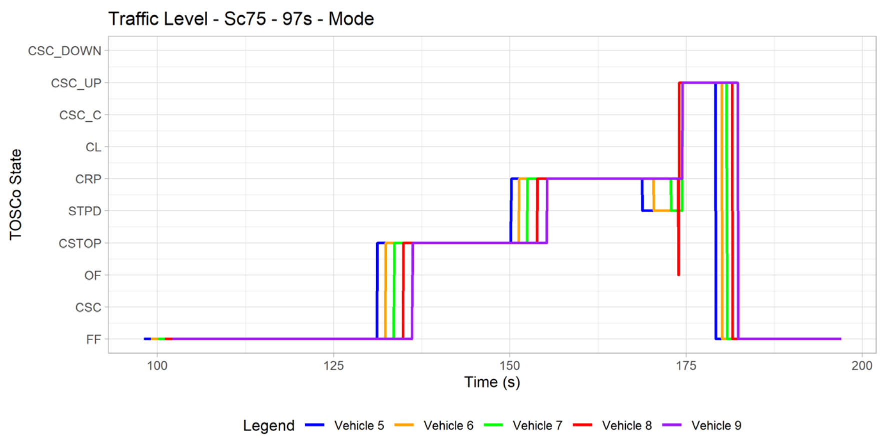
(a) Traffic-level Profile



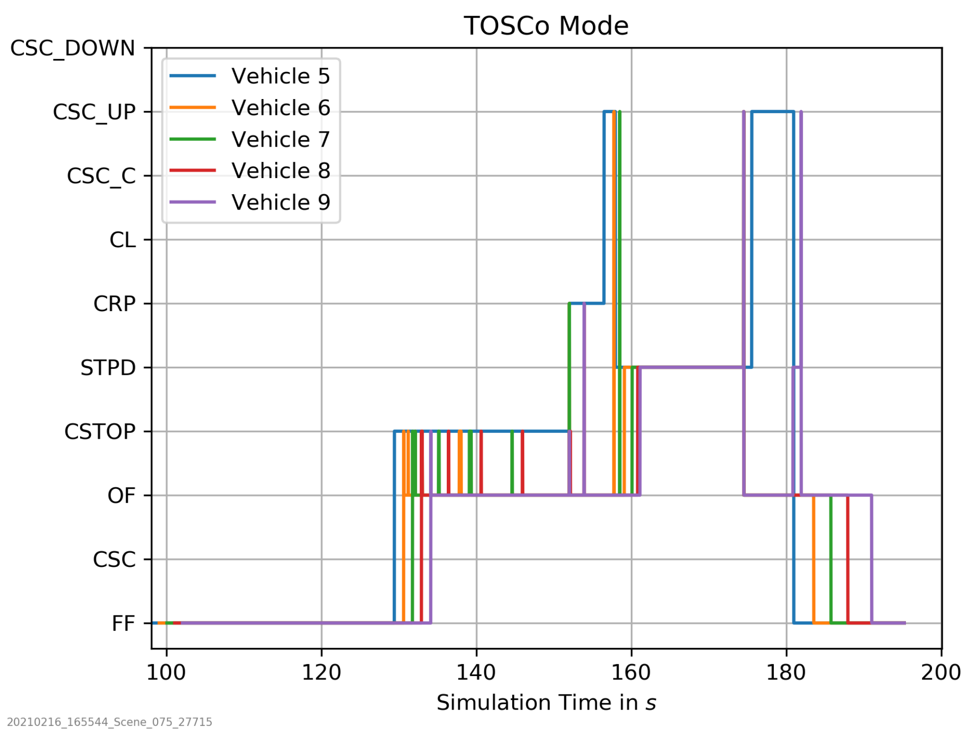
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 56. Verification Scenario 2 – 97 Second Introduction Time – Acceleration Profiles



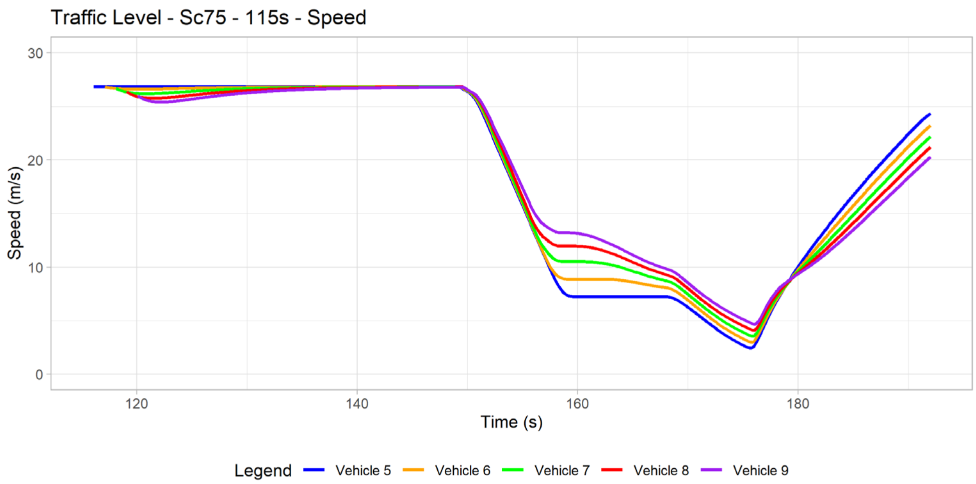
(a) Traffic-level Profile



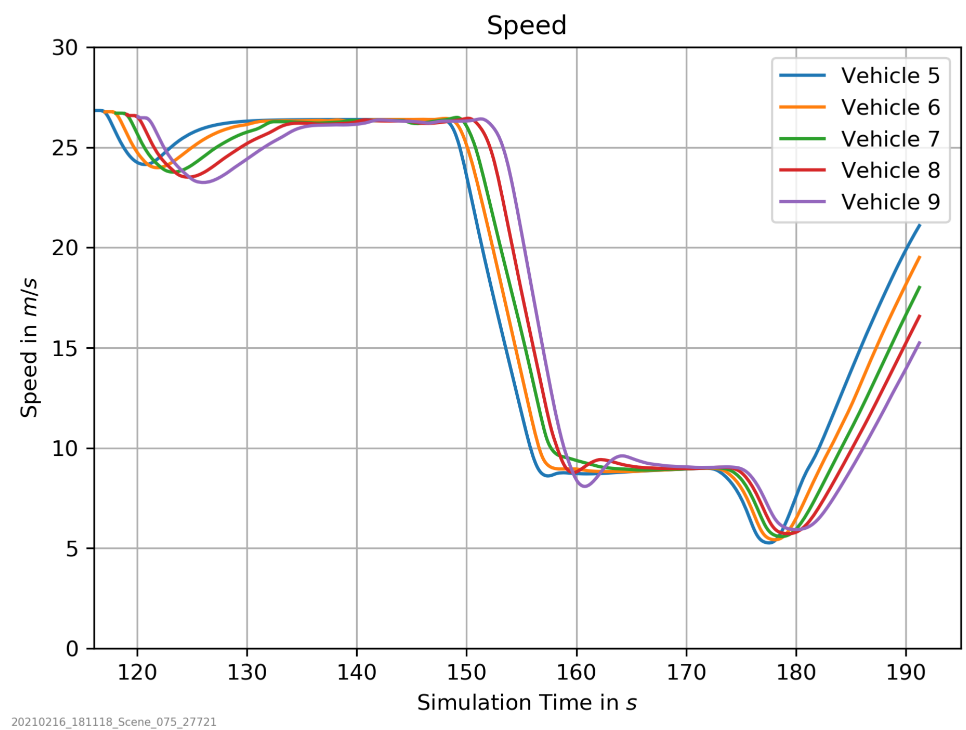
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 57. Verification Scenario 2 – 97 Second Introduction Time – Mode Profiles



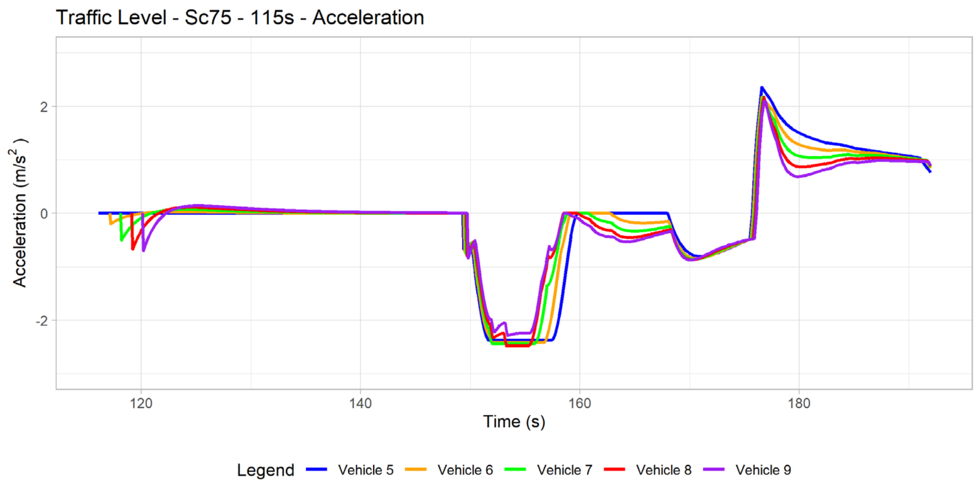
(a) Traffic-level Profile



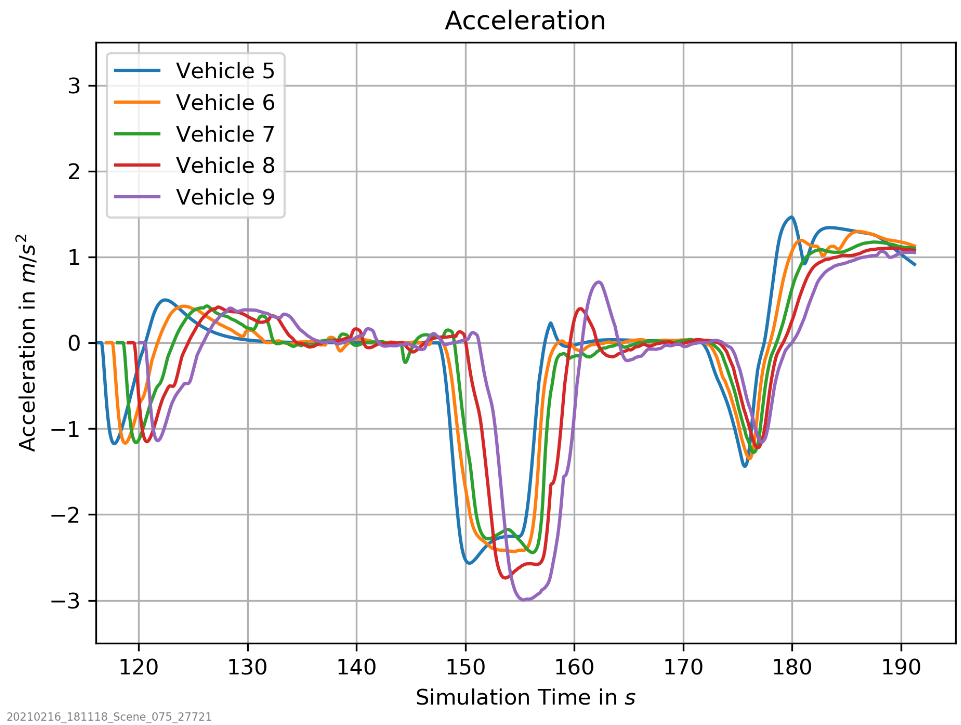
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 58. Verification Scenario 2 – 115 Second Introduction Time – Speed Profiles



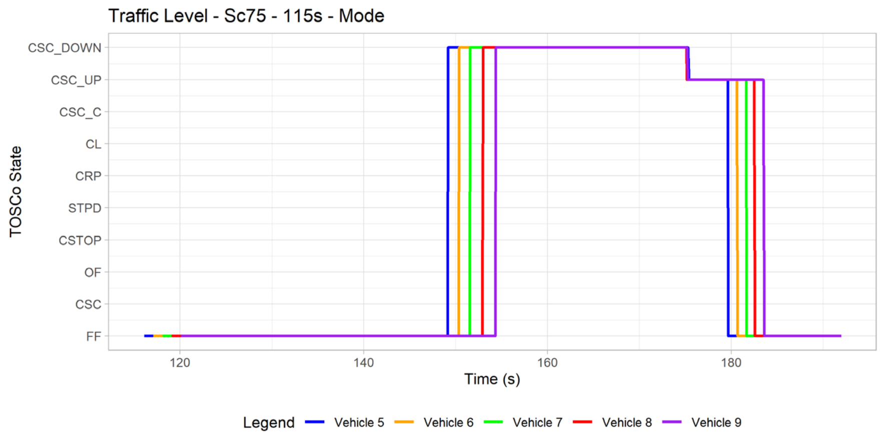
(a) Traffic-level Profile



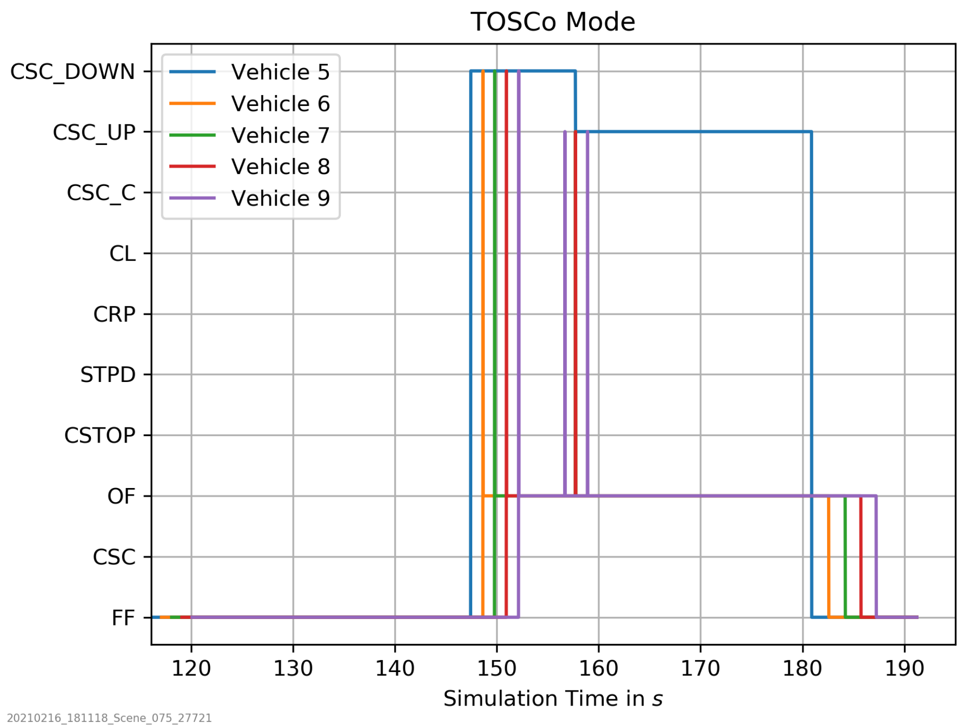
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 59. Verification Scenario 2 – 115 Second Introduction Time – Acceleration Profiles



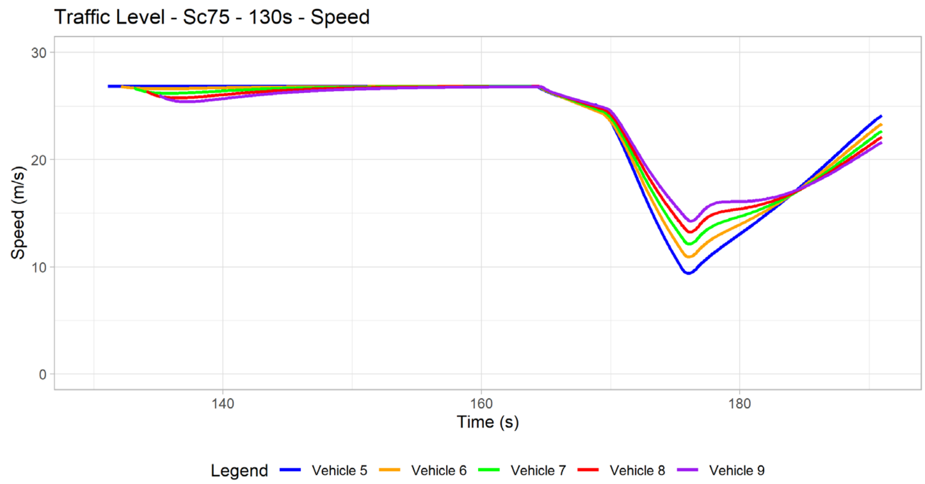
(a) Traffic-level Profile



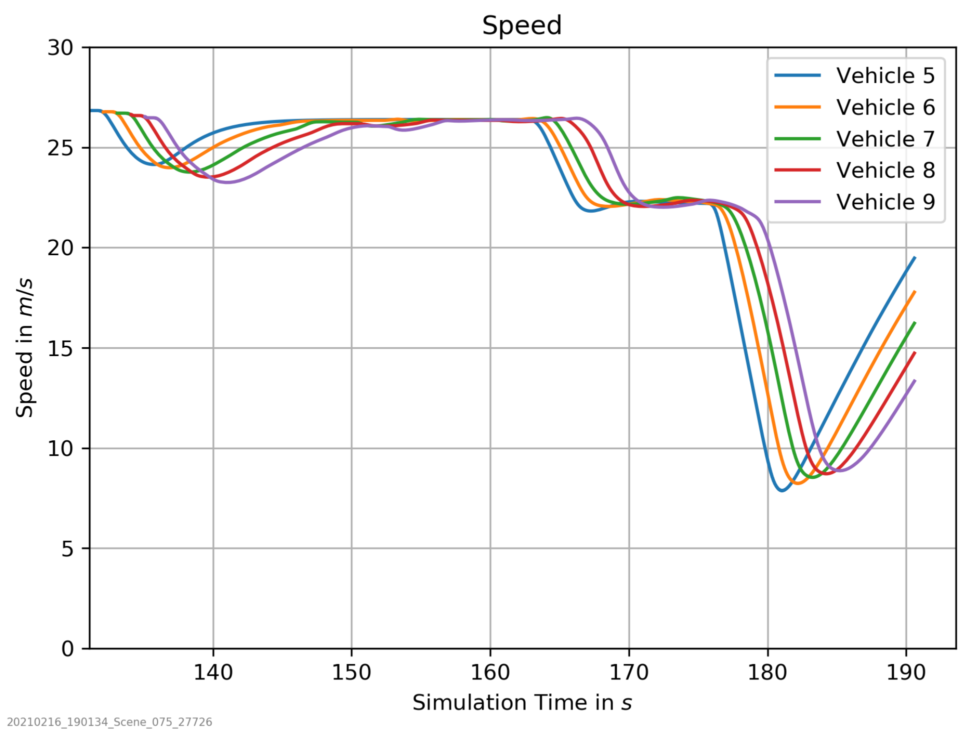
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 60. Verification Scenario 2 – 115 Second Introduction Time – Mode Profiles



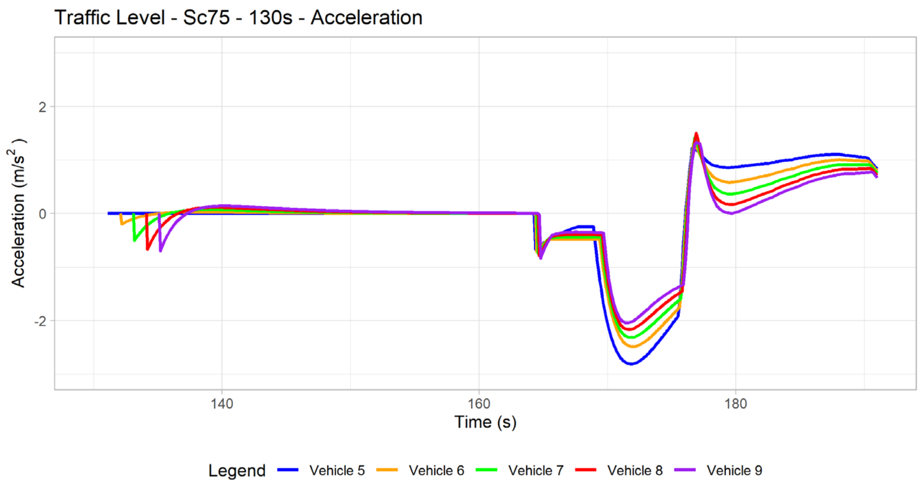
(a) Traffic-level Profile



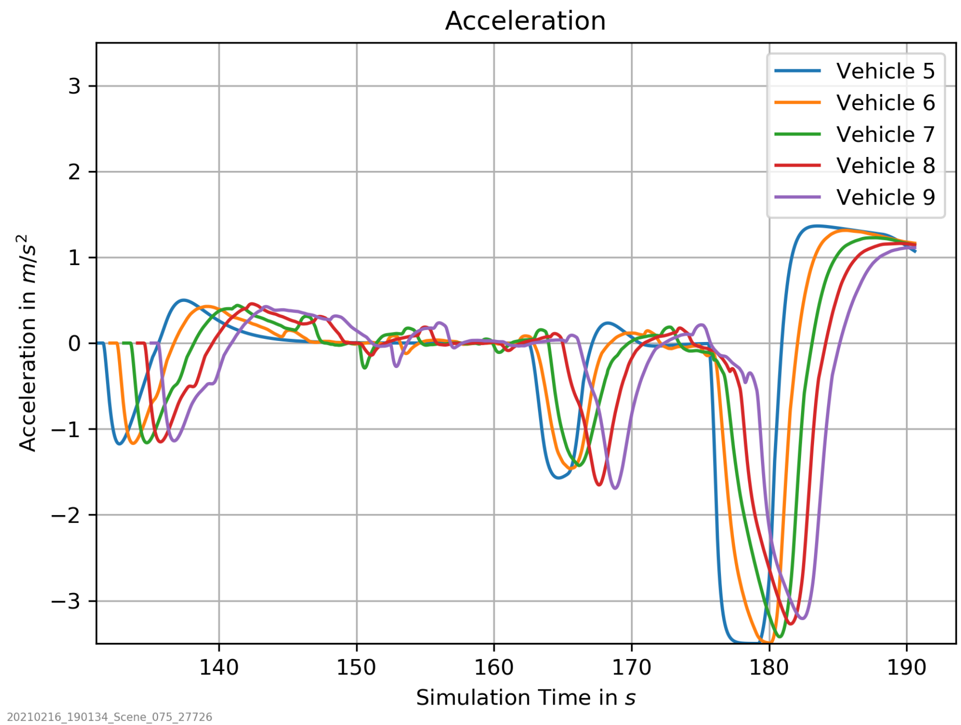
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 61. Verification Scenario 2 – 130 Second Introduction Time – Speed Profiles



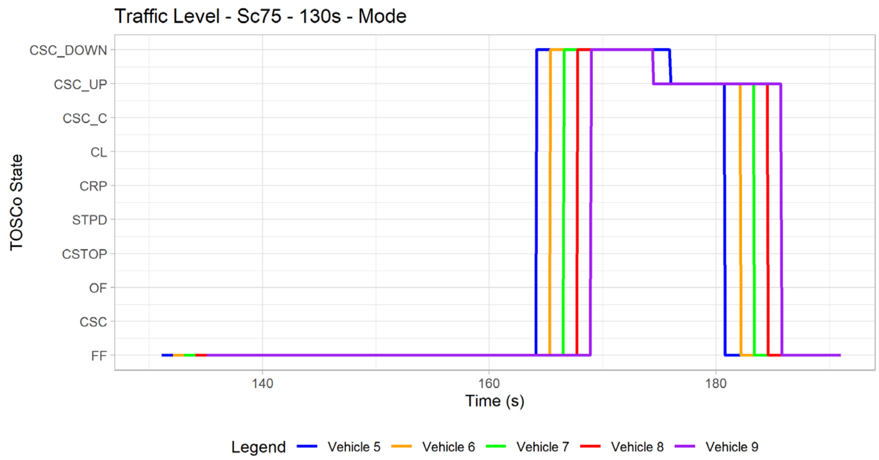
(a) Traffic-level Profile



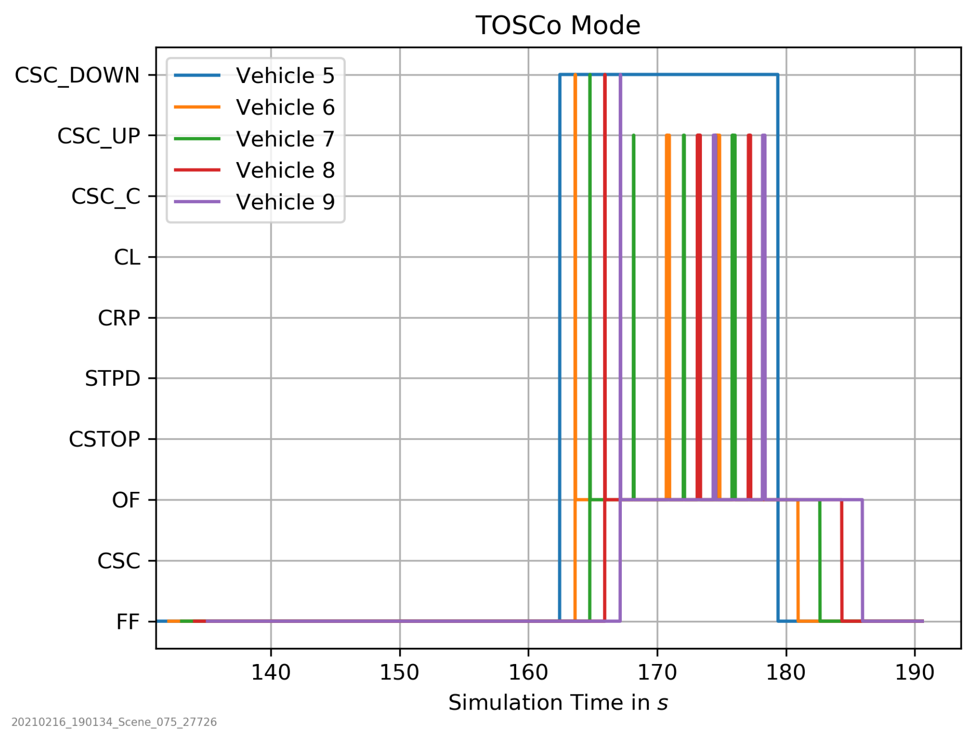
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 62. Verification Scenario 2 – 130 Second Introduction Time – Acceleration Profiles



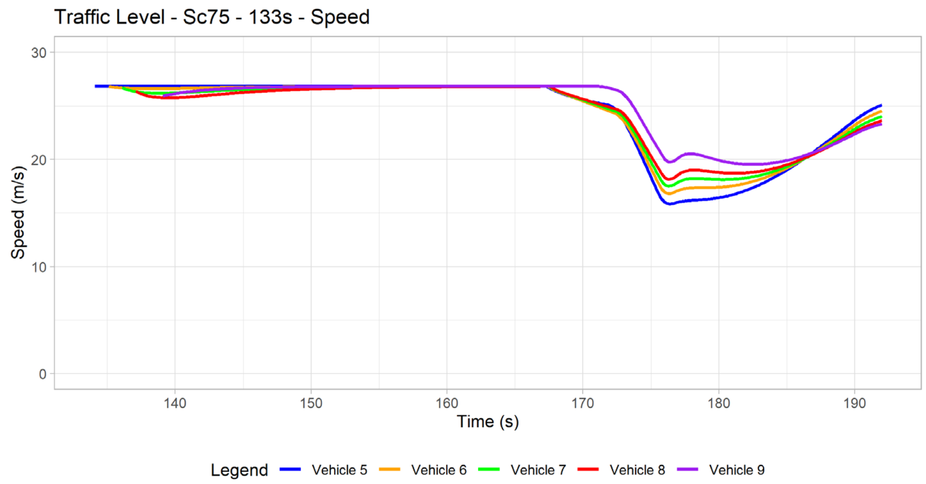
(a) Traffic-level Profile



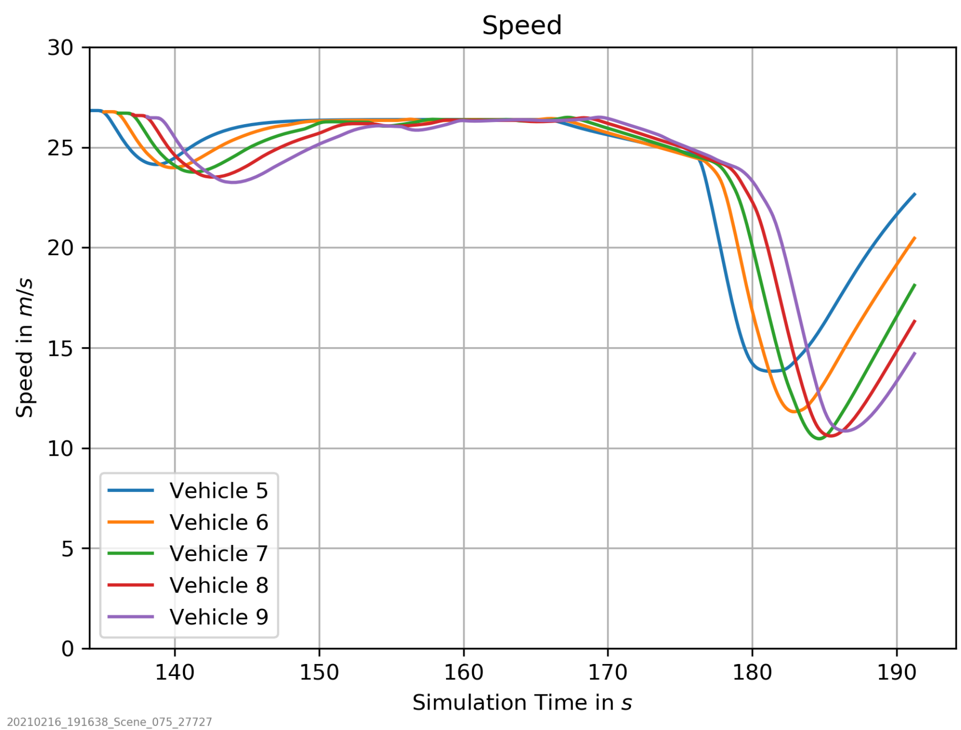
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 63. Verification Scenario 2 – 130 Second Introduction Time – Mode Profiles



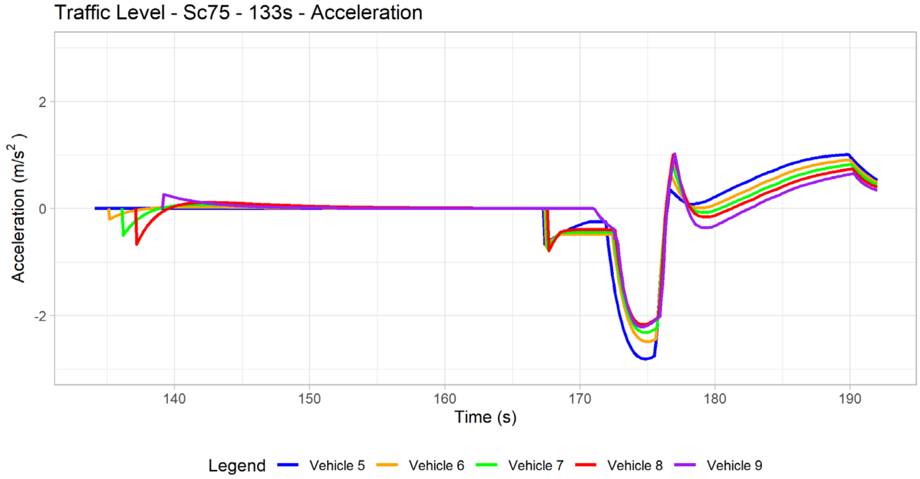
(a) Traffic-level Profile



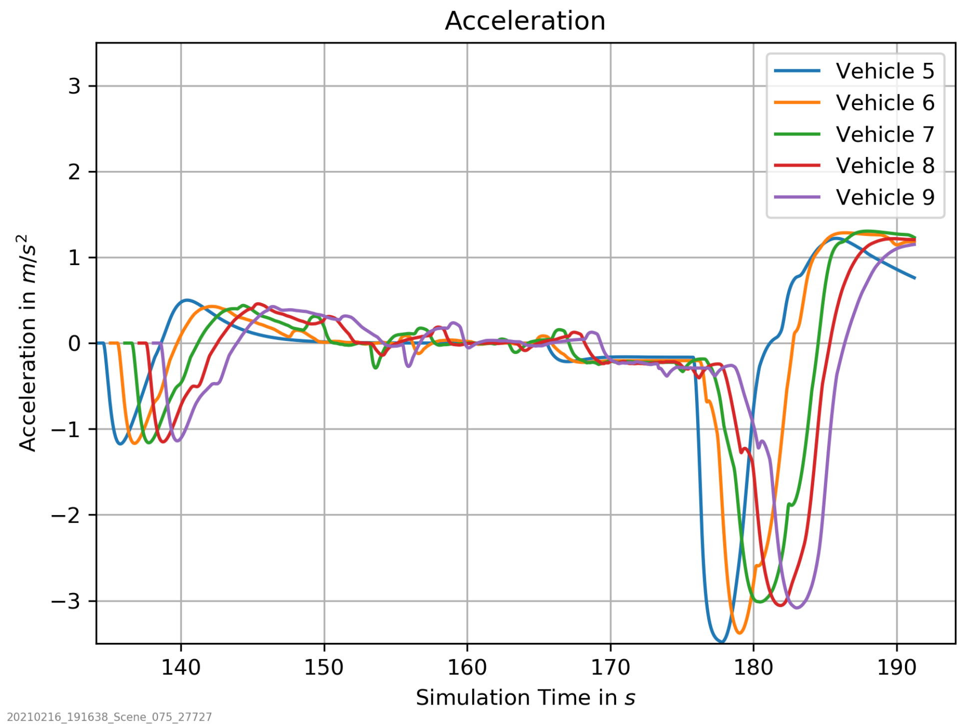
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 64. Verification Scenario 2 – 133 Second Introduction Time – Speed Profiles



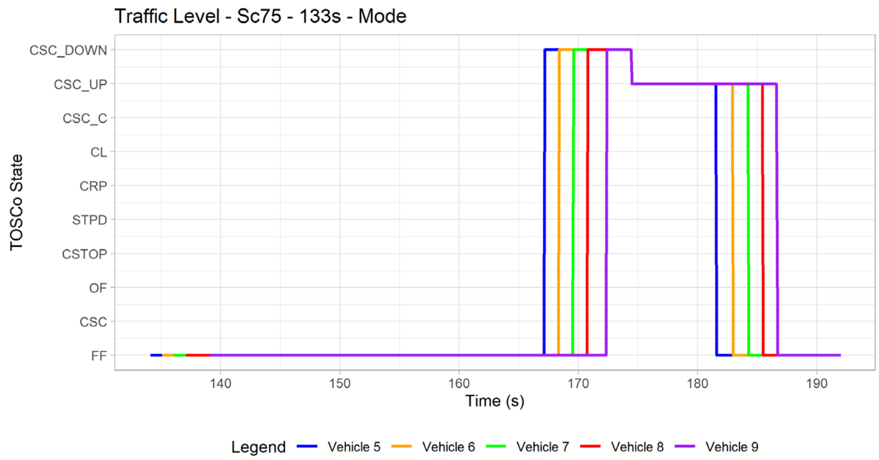
(a) Traffic-level Profile



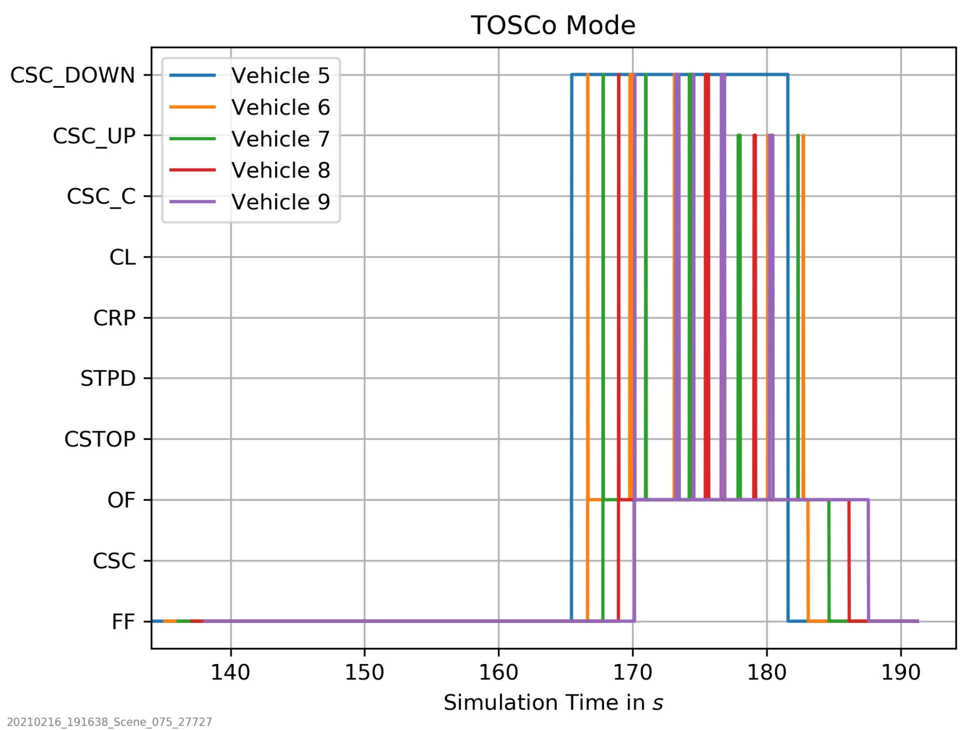
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 65. Verification Scenario 2 – 133 Second Introduction Time – Acceleration Profiles



(a) Traffic-level Profile



(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 66. Verification Scenario 2 – 133 Second Introduction Time – Mode Profiles

Operating Scenario 3: Low Set Speed With Four Vehicle Queue

Scenario 3 represents a case where the TOSCo string is approaching a signal with a set speed of 50 mph and a four-vehicle queue at the intersection. The speed limit is 55 mph. The queued vehicles in this scenario are not TOSCo equipped and are generated at the 80, 81, 82 and 83 simulation second mark. Vehicles in each scenario are released into the network one second after another on the same lane. The model for verification generates vehicles in the rightmost lane of the Texas Vehicle-level network developed in Task 9.6. This model does not allow any lane changing for generated vehicles. The TOSCo vehicle introduction times in this operating scenario target two different TOSCo modes across 5 introduction times:

- 85 Second introduction time, coordinated stop
- 97 Second introduction time, coordinated speed control – slow down
- 127 Second introduction time, coordinated speed control – slow down
- 130 Second introduction time, coordinated speed control – speed up
- 133 Second introduction time, coordinated speed control – speed up

Figure 67 through Figure 69 show the scenario 3 results for the 85 second introduction time. In each case vehicles perform a coordinated stop. The modes for the traffic-level simulation appear to be more stable than the vehicle-level simulation. The CREEP behavior in the traffic-level simulation is different than the vehicle-level simulation. The launch behavior, in CSC-UP, in the traffic-level simulation is different from the vehicle--level simulation in this scenario. Both differences are caused by the different CACC representation.

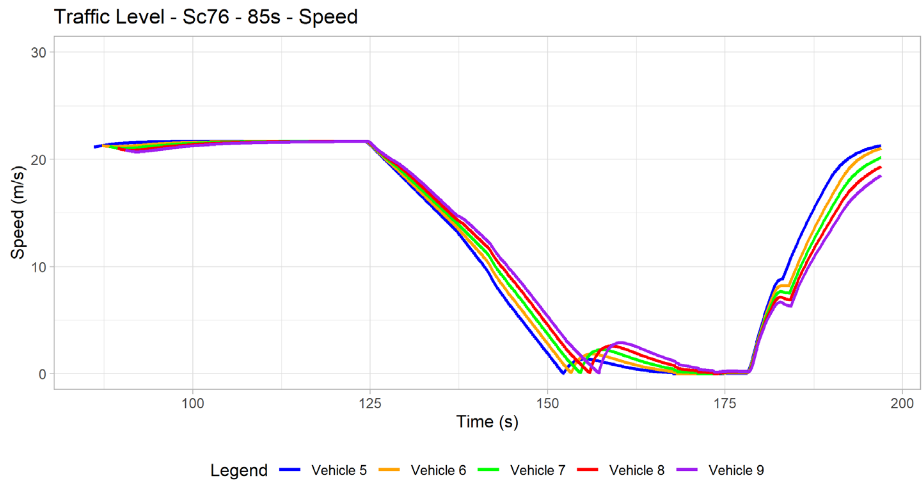
Figure 70 through Figure 72 show the scenario 3 results for the 97 second introduction time. Both simulations choose CSC-DOWN and decelerate to a similar speed. The strings slow in response to the queue some time before crossing the intersection. The first vehicle in the traffic-level representation crosses the intersection at about the same time as the vehicle-level simulation.

Figure 73 through Figure 75 show the results for the 127 second introduction time. This is the only scenario where the mode selection between the two simulation environments is different. The traffic-level environment chose CSC-UP and the vehicle-level environment chose CSC-down. The speed profile for both environments show the string change speeds to a set speed and slowdown in response to the queued vehicles. The mode selection diagram indicates that the traffic-level string crosses the stop bar before the vehicle level string.

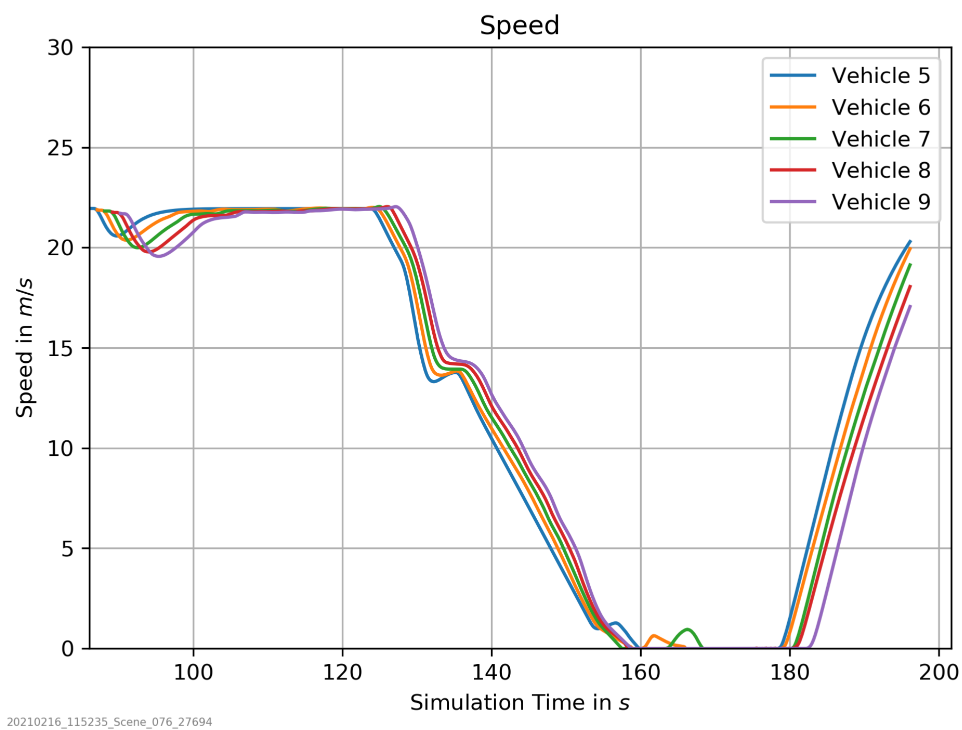
Figure 76 through Figure 78 show the results for the 130 second introduction time. Both environments show the string accelerate initially and then slow in response to the queue at the intersection. The traffic level string crosses the intersection one second earlier than the vehicle-level simulation.

Figure 79 through Figure 81 show the results for the 133 second introduction time. The traffic-level and the vehicle-level simulations both chose CSC-UP. The vehicle-level simulation switches to CSC-DOWN partway through the approach to the intersection, but the speed profiles remain similar. Both strings cross the intersection at about the same time.

The differences in these five scenarios are largely caused by simplifications in the CACC algorithm running alongside TOSCo. The research team found that the two simulation environments are very similar, and the differences are acceptable for representing TOSCo behavior for evaluation in the traffic-level simulation.



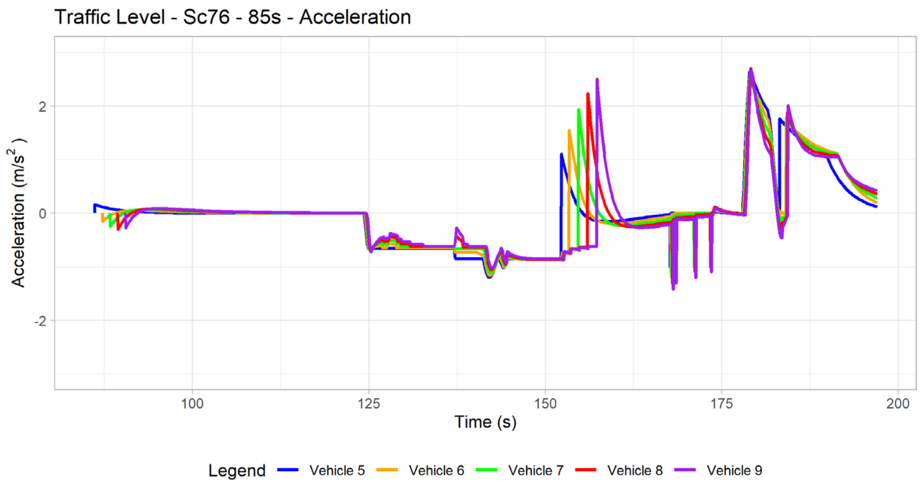
(a) Traffic-level Profile



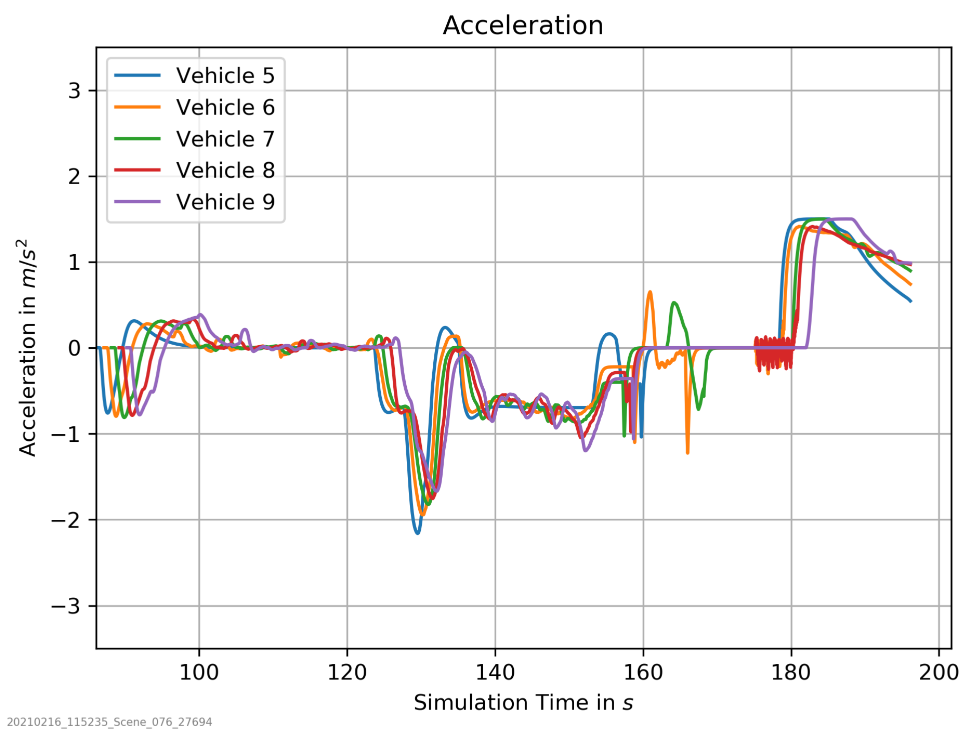
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 67. Verification Scenario 3 – 85 Second Introduction Time – Speed Profiles



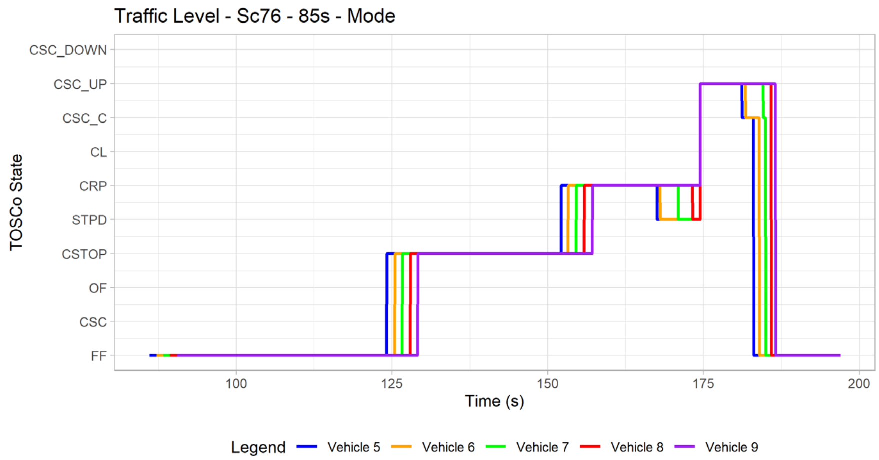
(a) Traffic-level Profile



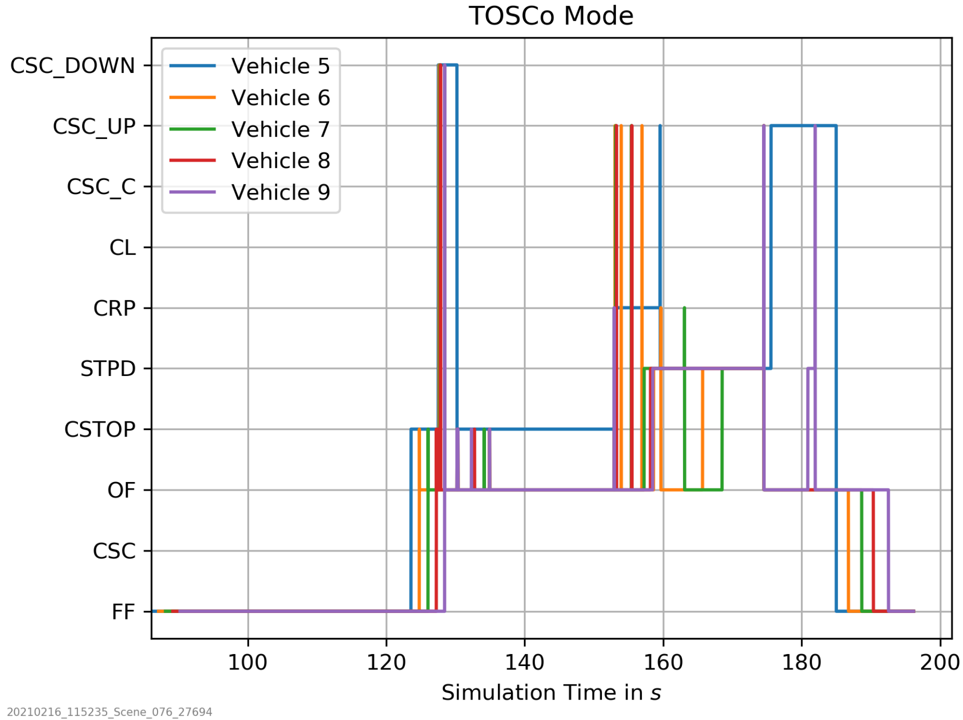
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 68. Verification Scenario 3 – 85 Second Introduction Time – Acceleration Profiles



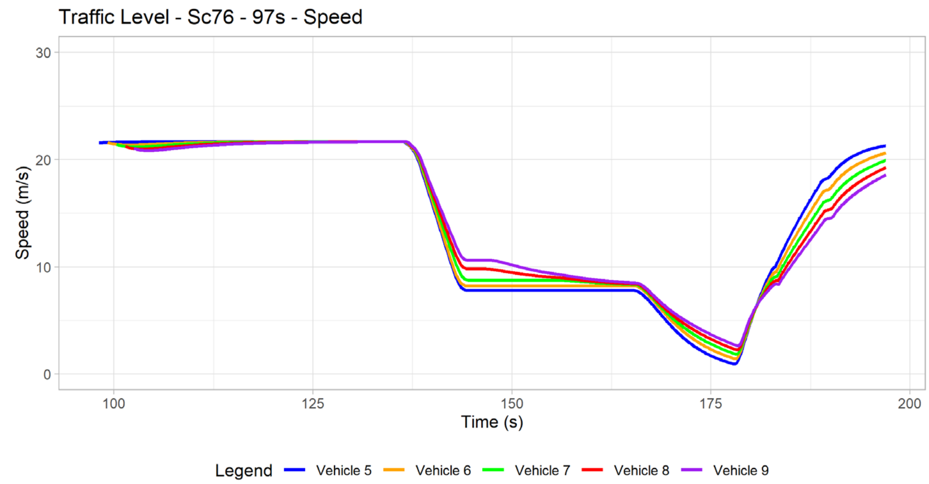
(a) Traffic-level Profile



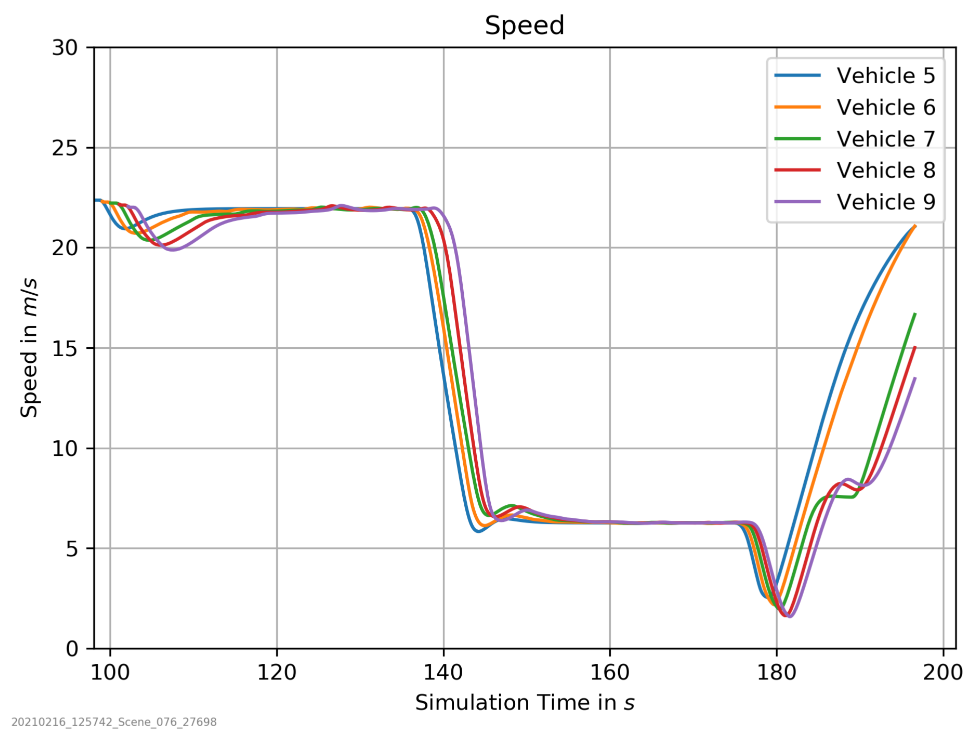
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 69. Verification Scenario 3 – 85 Second Introduction Time – Mode Profiles



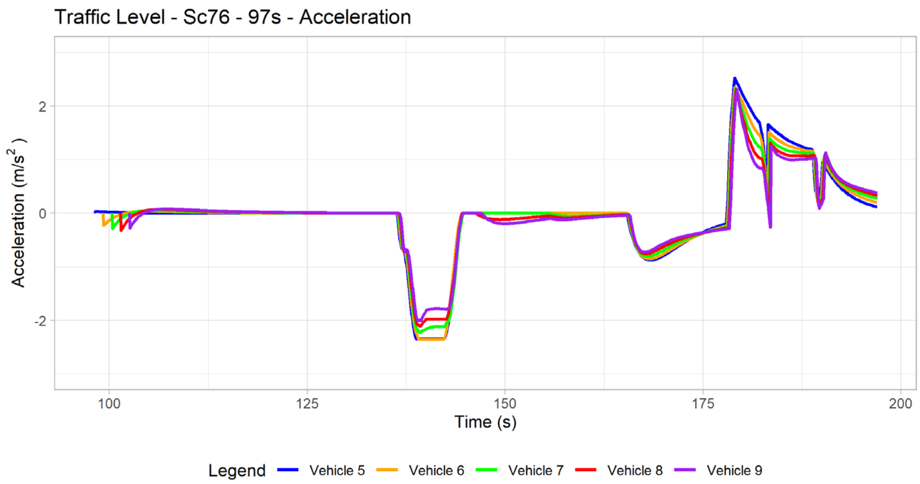
(a) Traffic-level Profile



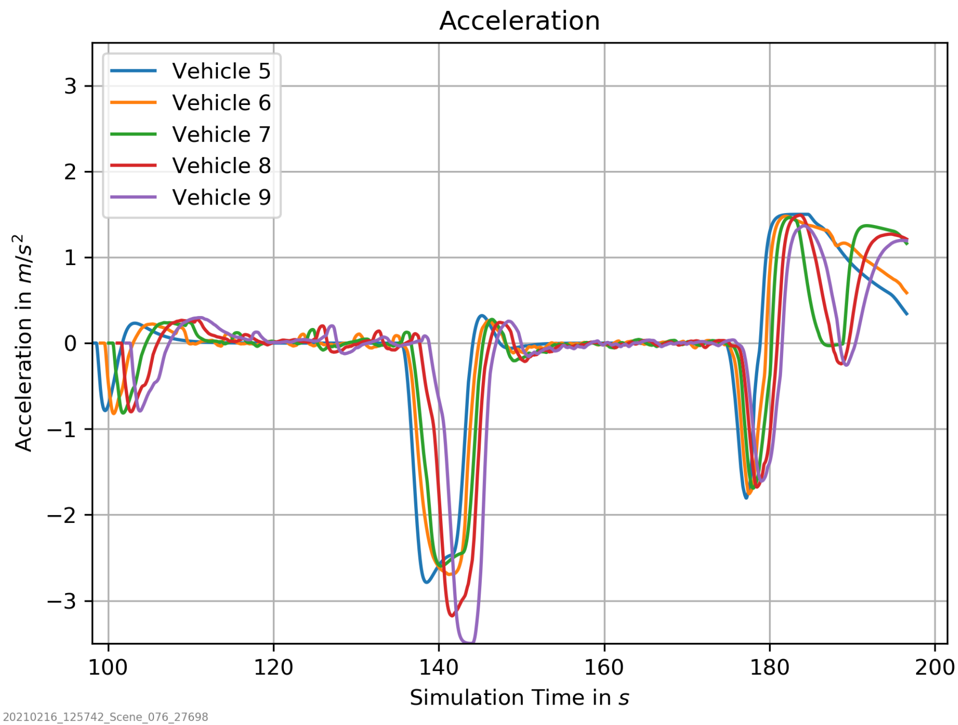
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 70. Verification Scenario 3 – 97 Second Introduction Time – Speed Profiles



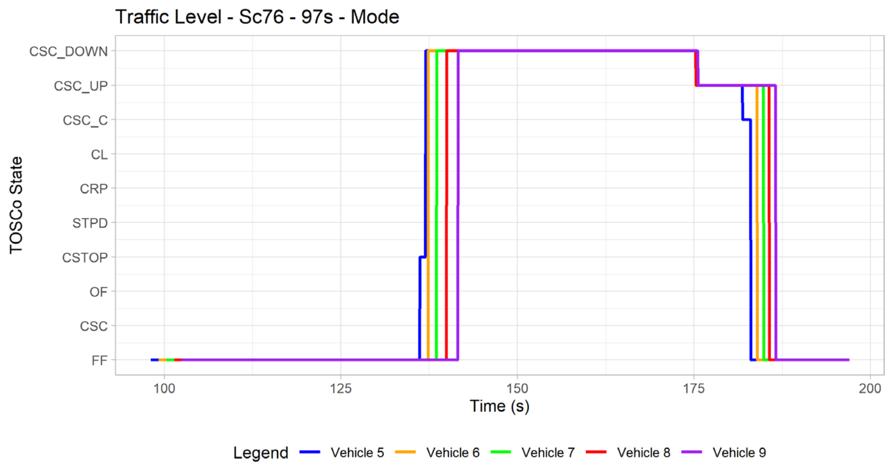
(a) Traffic-level Profile



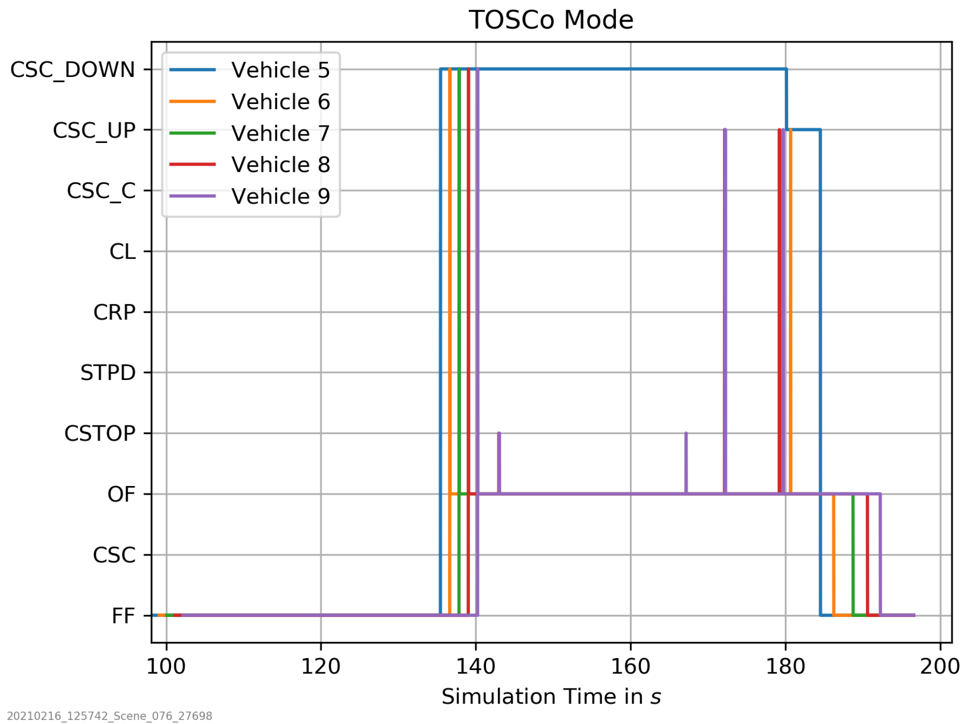
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 71. Verification Scenario 3 – 97 Second Introduction Time – Acceleration Profiles



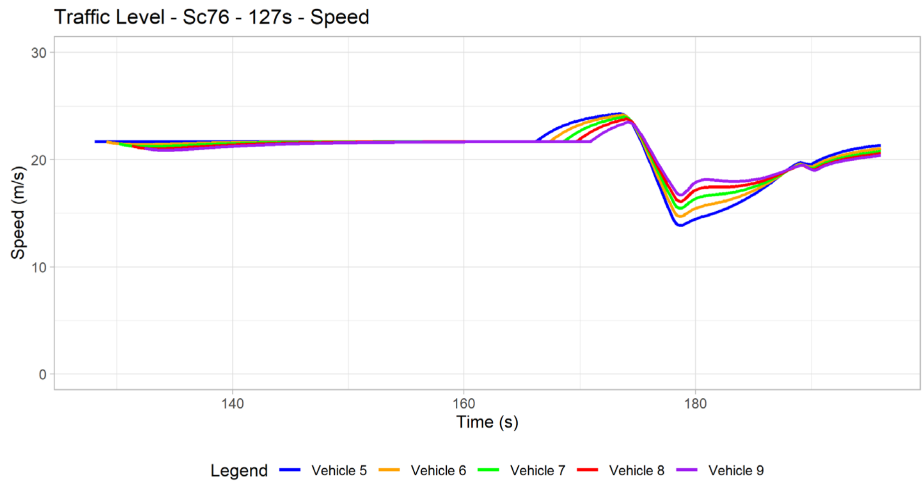
(a) Traffic-level Profile



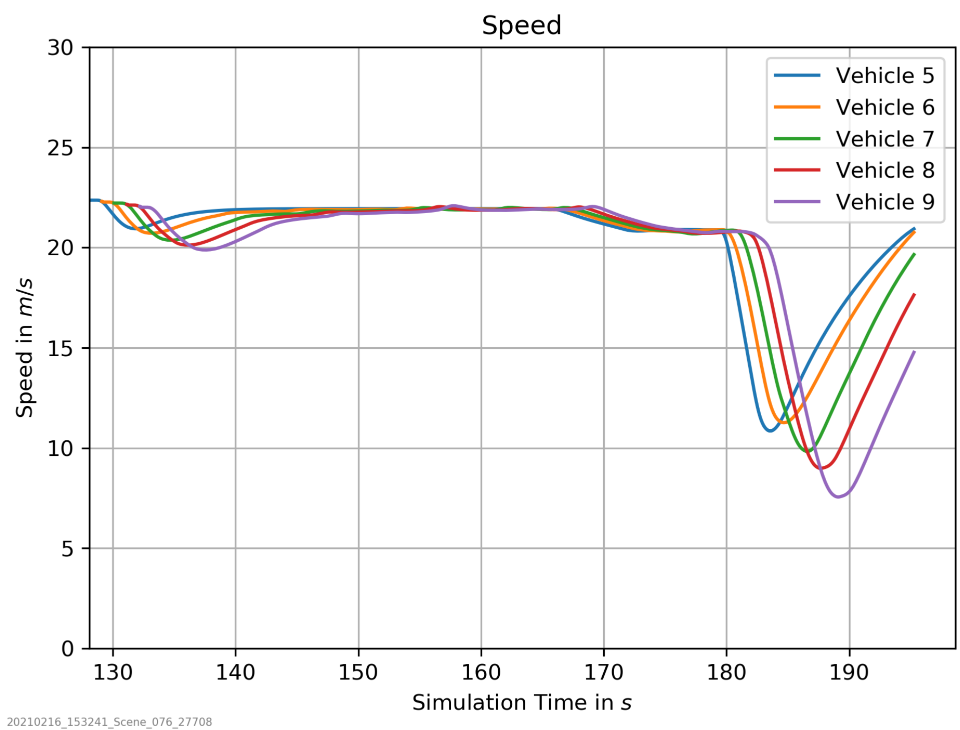
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 72. Verification Scenario 3 – 97 Second Introduction Time – Mode Profiles



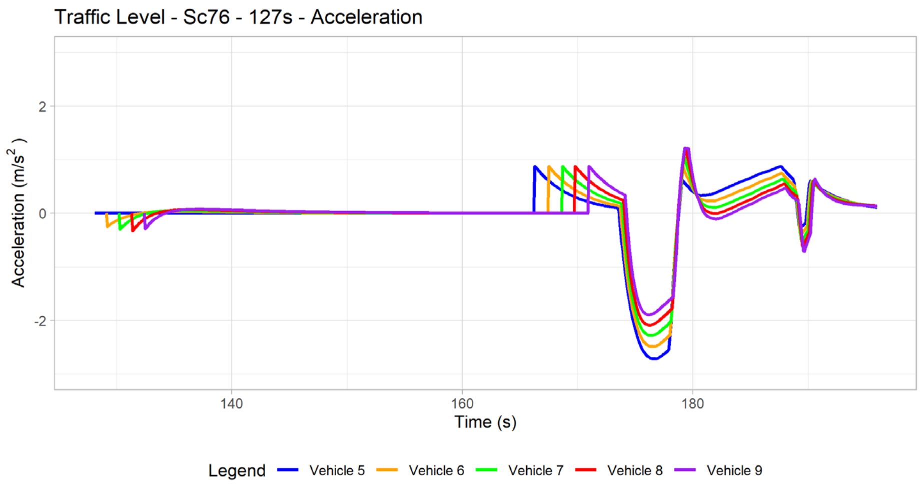
(a) Traffic-level Profile



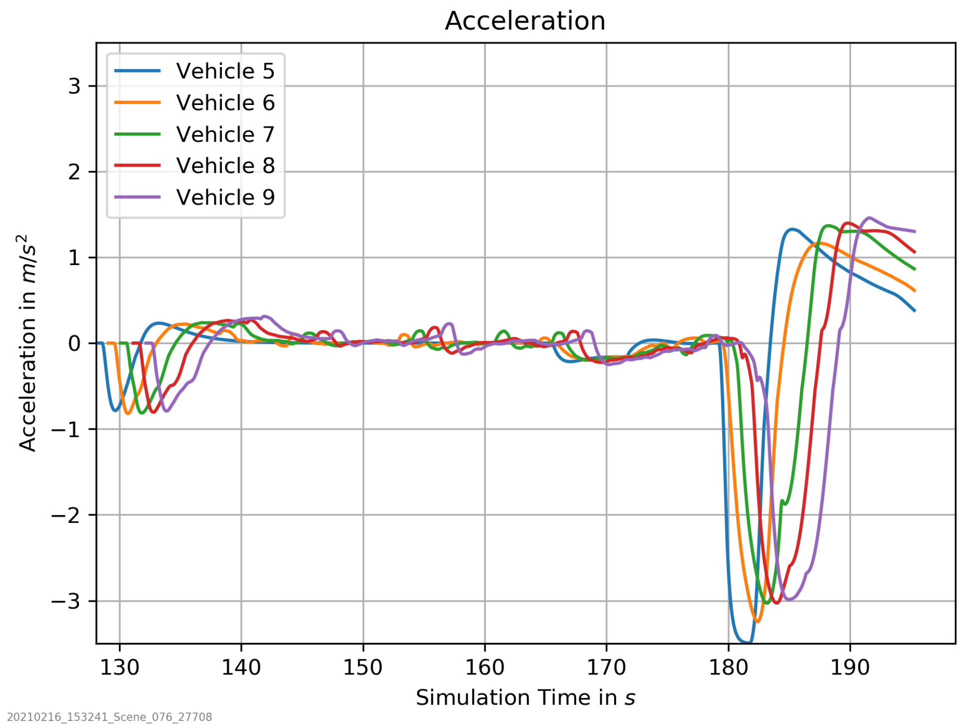
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 73. Verification Scenario 3 – 127 Second Introduction Time – Speed Profiles



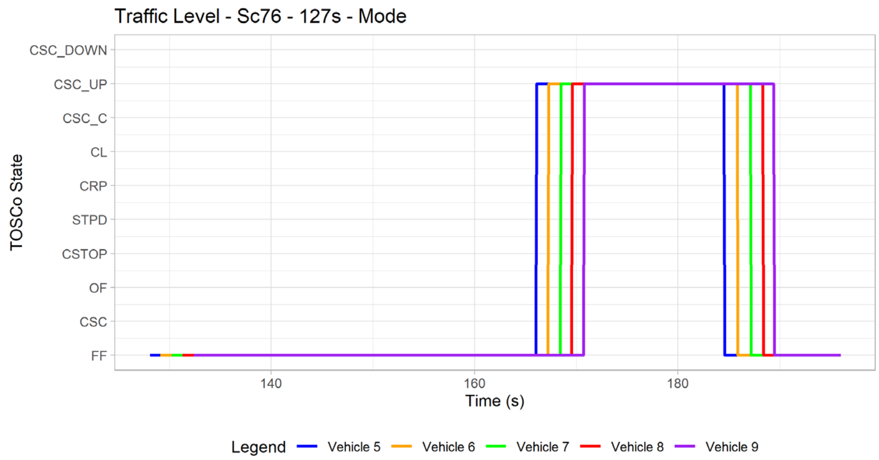
(a) Traffic-level Profile



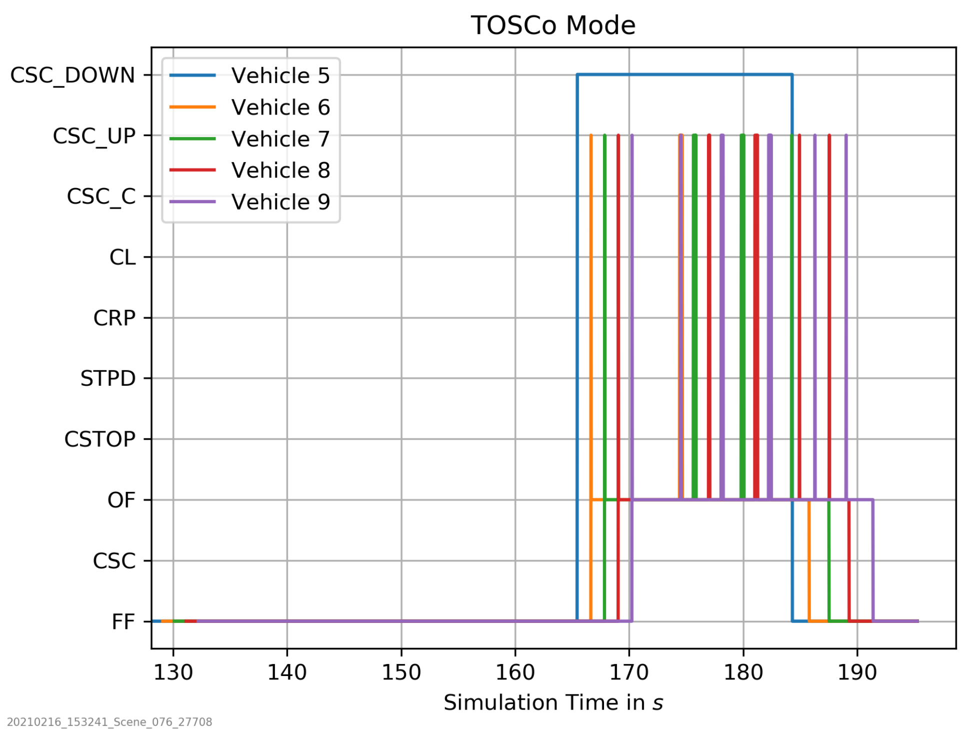
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 74. Verification Scenario 3 – 127 Second Introduction Time – Acceleration Profiles



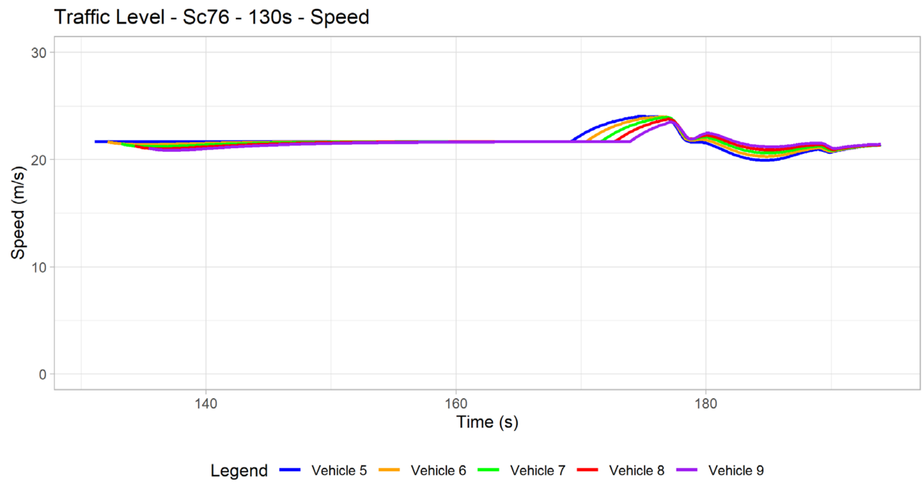
(a) Traffic-level Profile



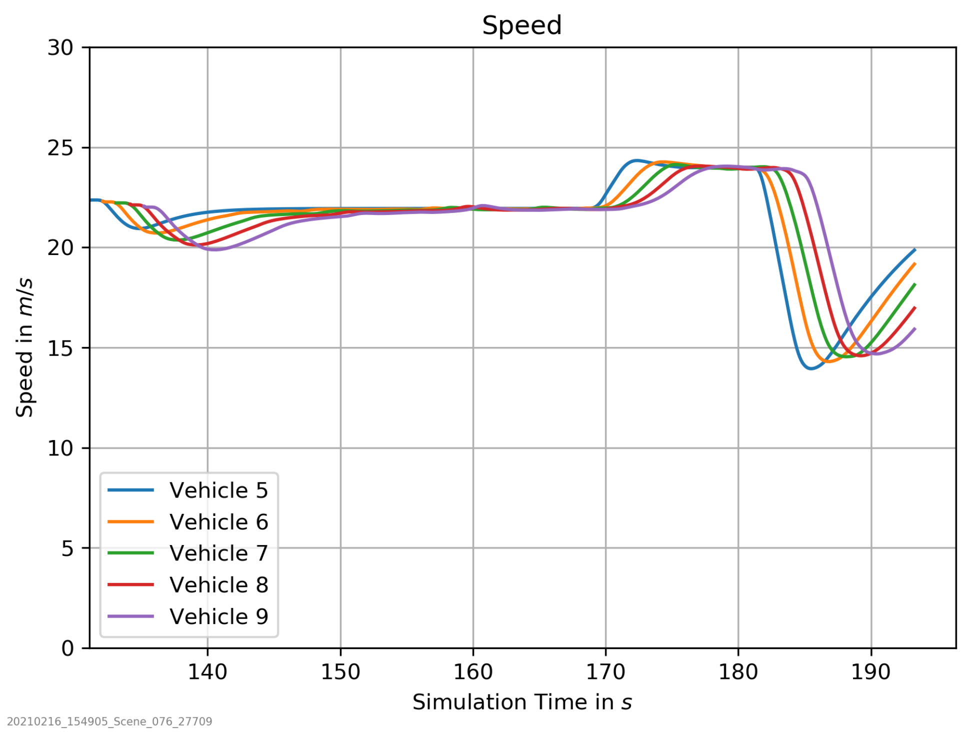
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 75. Verification Scenario 3 – 127 Second Introduction Time – Mode Profiles



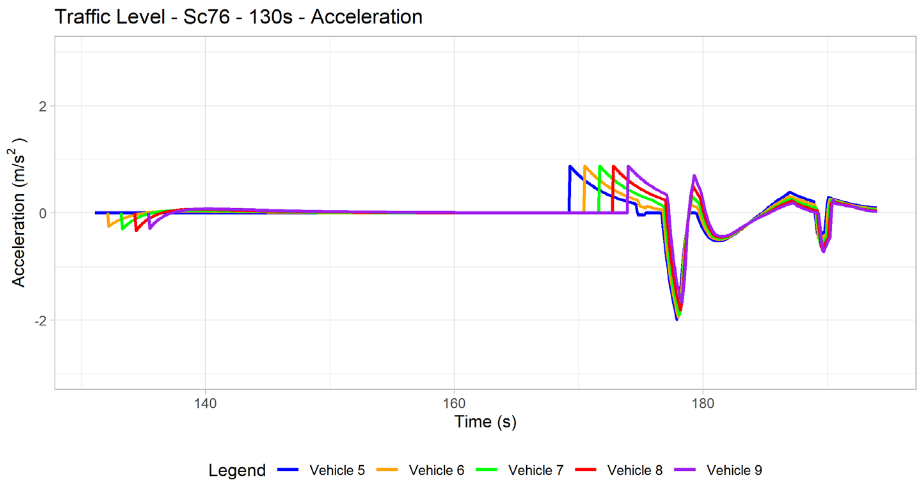
(a) Traffic-level Profile



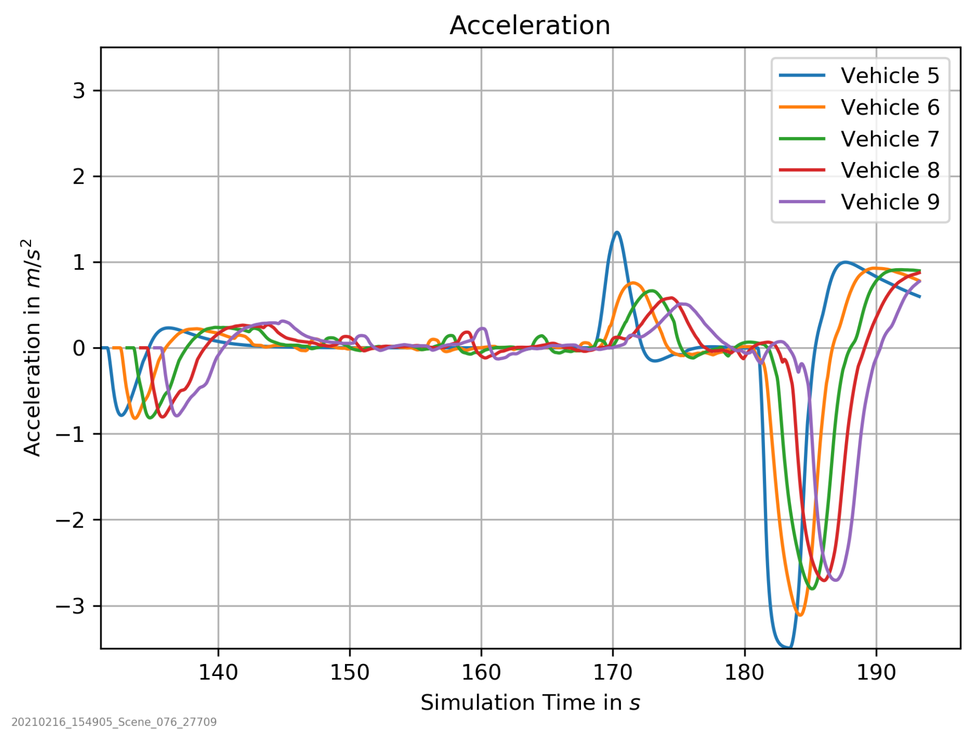
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 76. Verification Scenario 3 – 130 Second Introduction Time – Speed Profiles



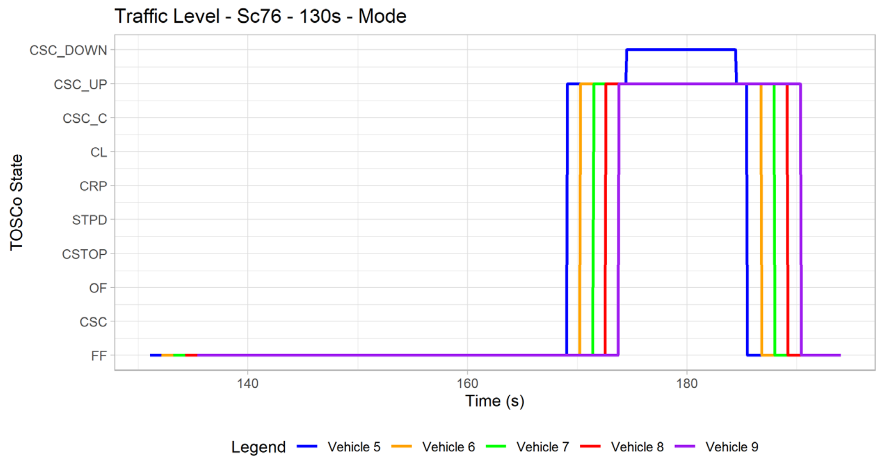
(a) Traffic-level Profile



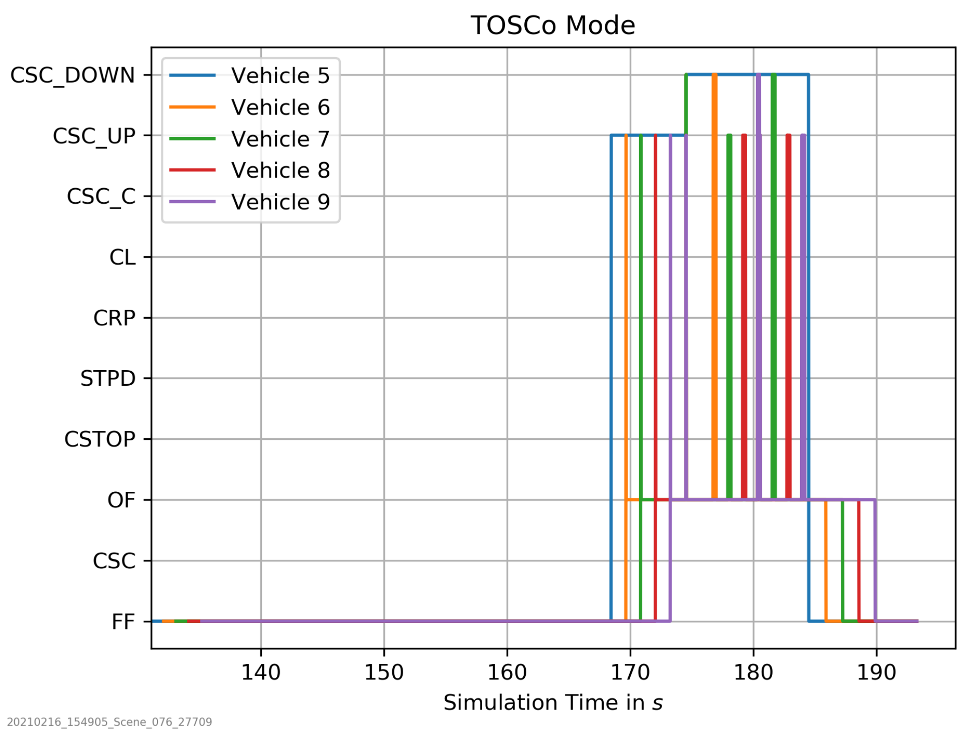
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 77. Verification Scenario 3 – 130 Second Introduction Time – Acceleration Profiles



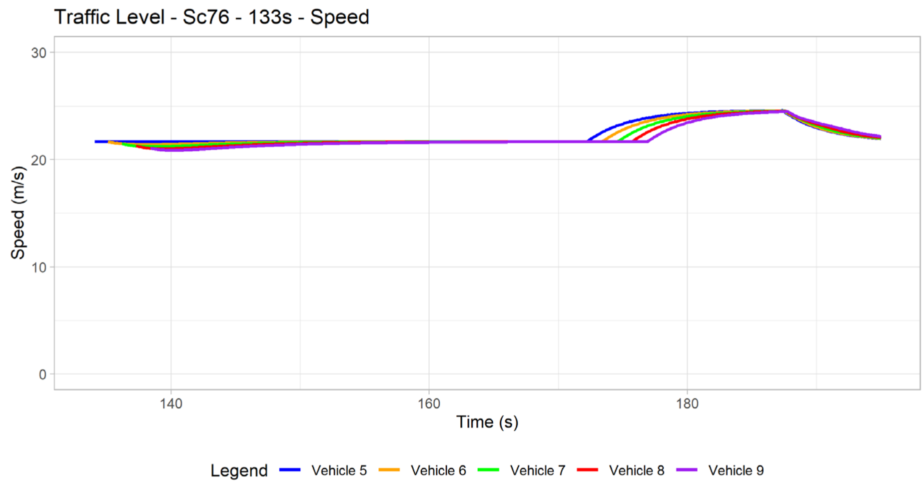
(a) Traffic-level Profile



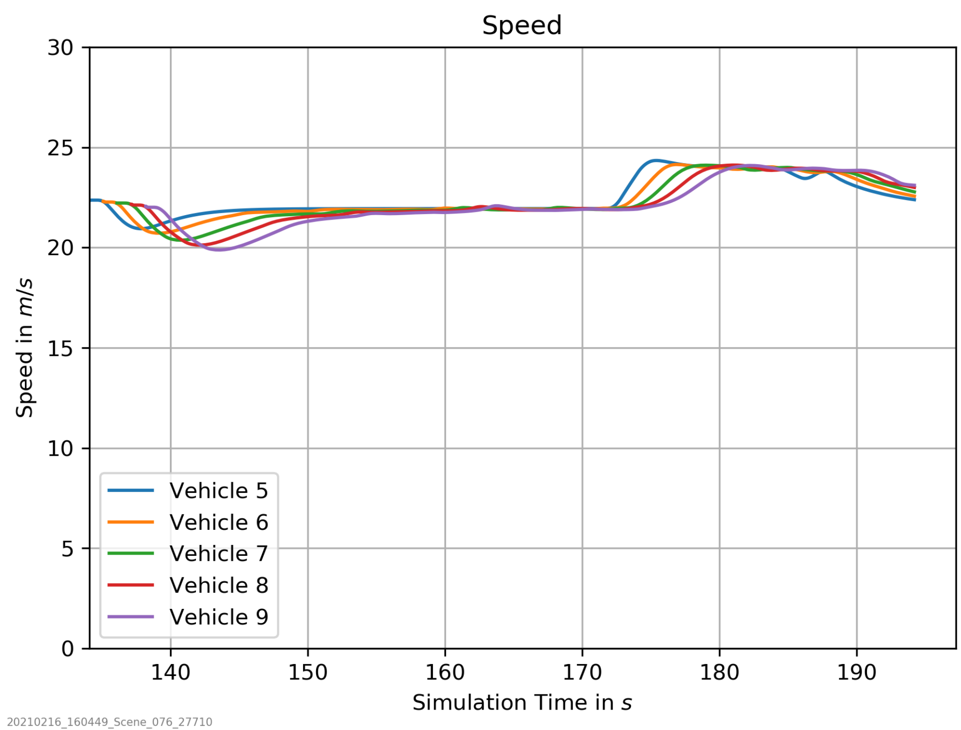
(b) Vehicle Level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 78. Verification Scenario 3 – 130 Second Introduction Time – Mode Profiles



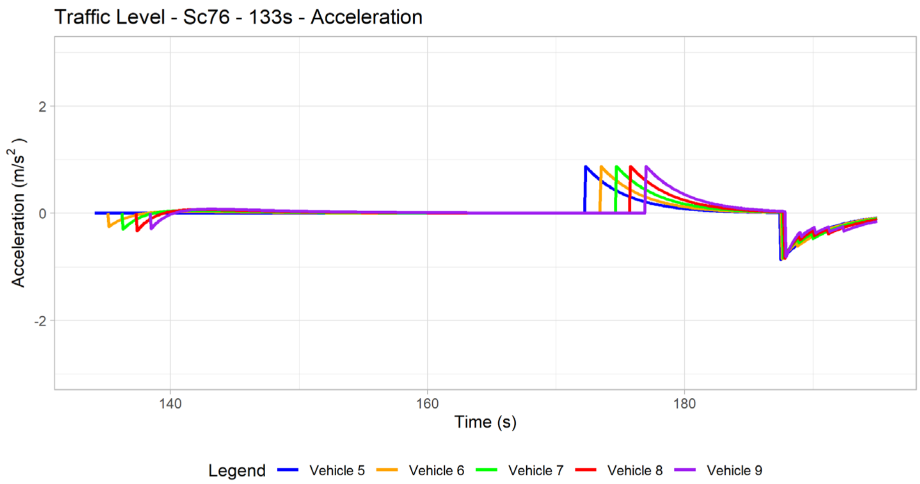
(a) Traffic-level Profile



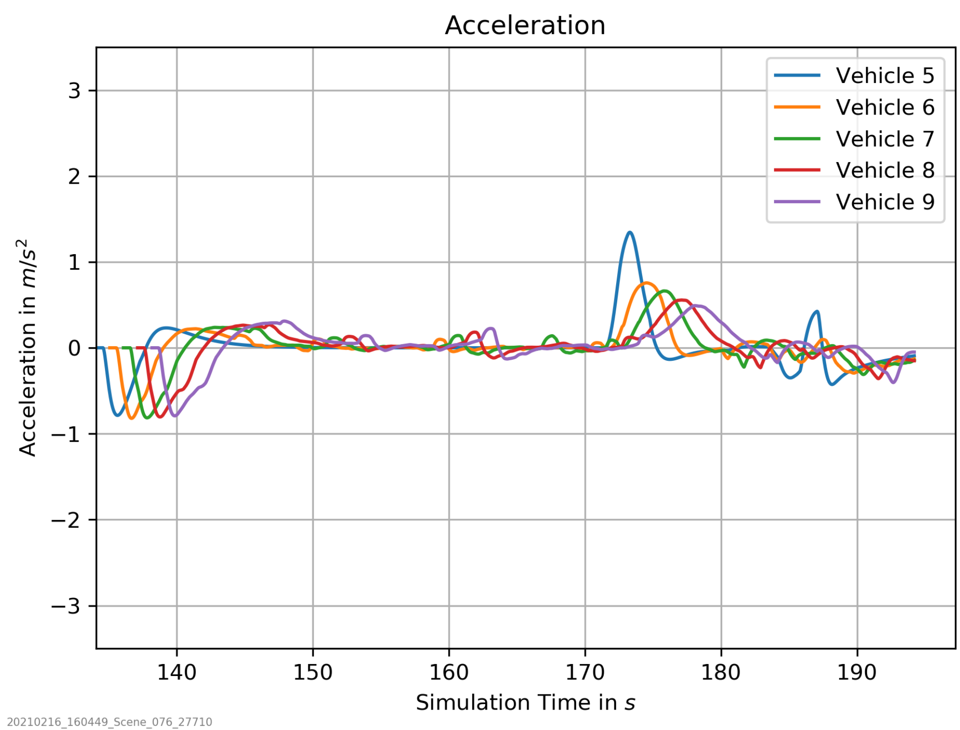
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 79. Verification Scenario 3 – 133 Second Introduction Time – Speed Profiles



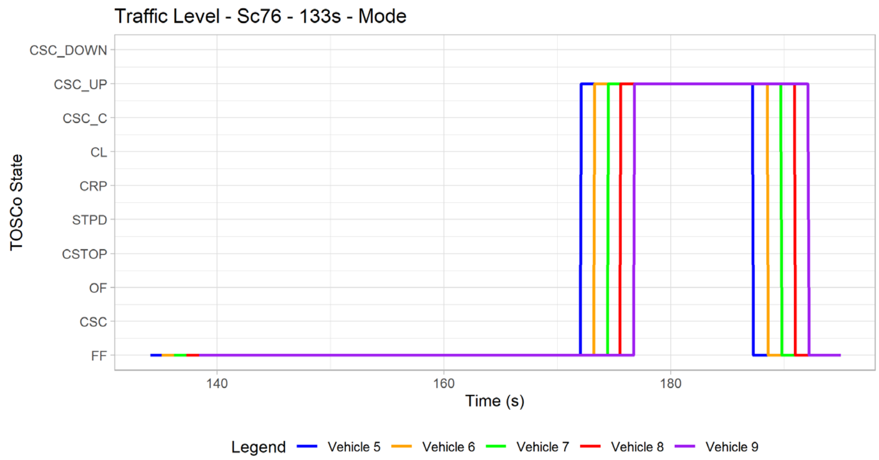
(a) Traffic-level Profile



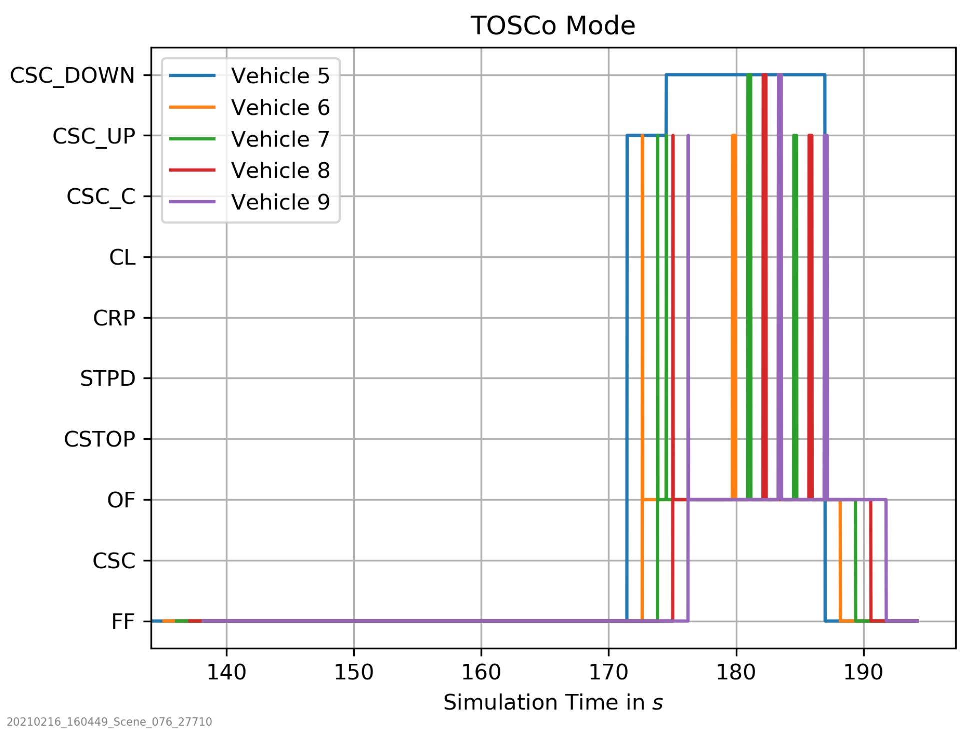
(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 80. Verification Scenario 3 – 133 Second Introduction Time – Acceleration Profiles



(a) Traffic-level Profile



(b) Vehicle-level Profile

Source: Texas A&M Transportation Institute (TTI), 2022

Figure 81. Verification Scenario 3 – 133 Second Introduction Time – Mode Profiles

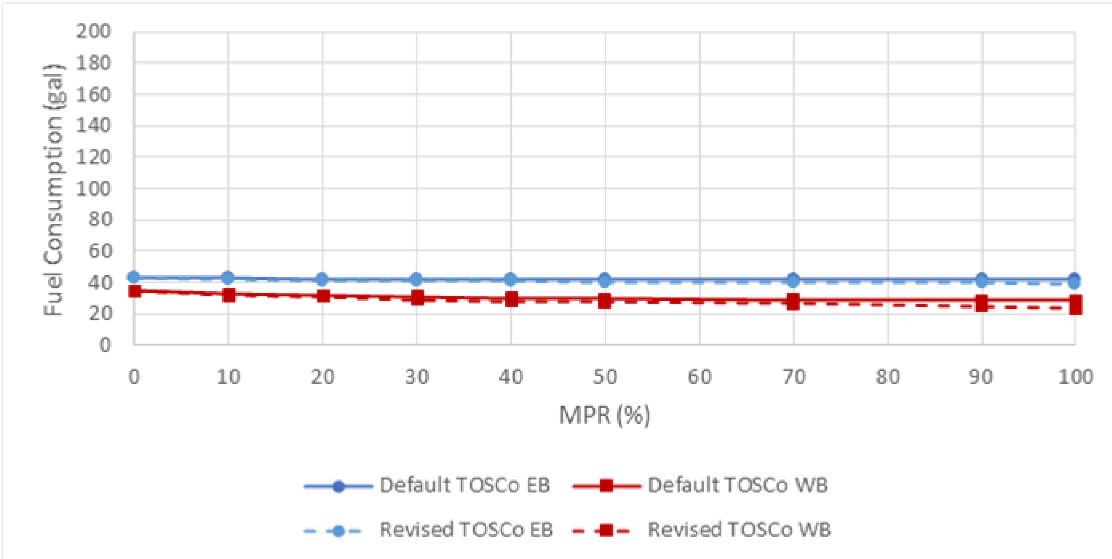
Appendix B. Fuel Use Benefits By Intersection

Fuel Use Description

VISSIM collected fuel usage data for the areas around each intersection. This appendix contains graphs for the fuel usage and the percent change in fuel consumption for each intersection. Each figure shows the fuel use for eastbound and westbound directions of travel in both default and revised TOSCo settings. This appendix also shows the corridor wide changes, which is calculated by the summation of the fuel use from all the intersections.

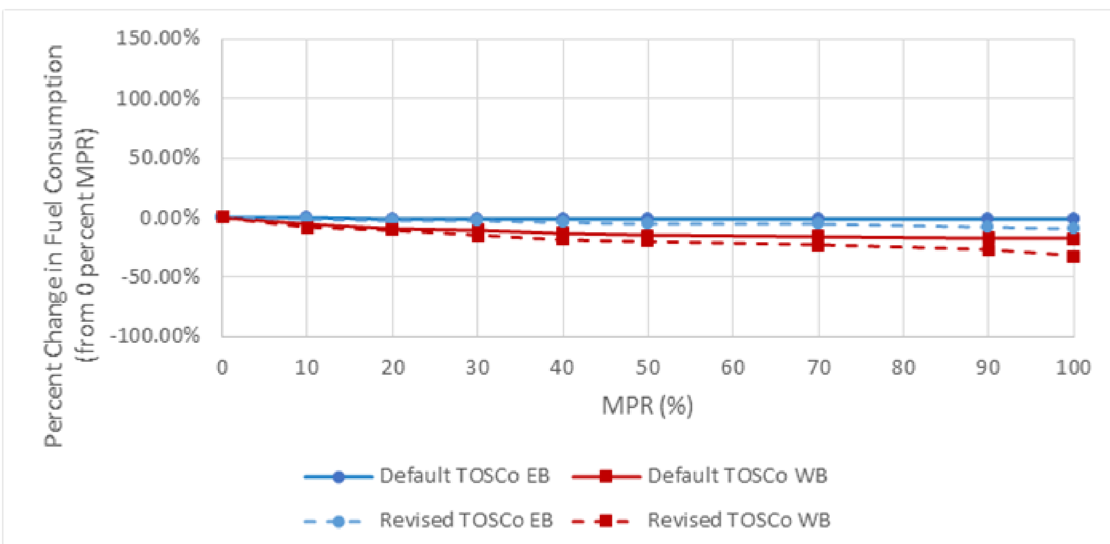
Fuel Use Figures

The following pages contain the figures for each intersection and the summation of each intersection to represent the corridor through movements.



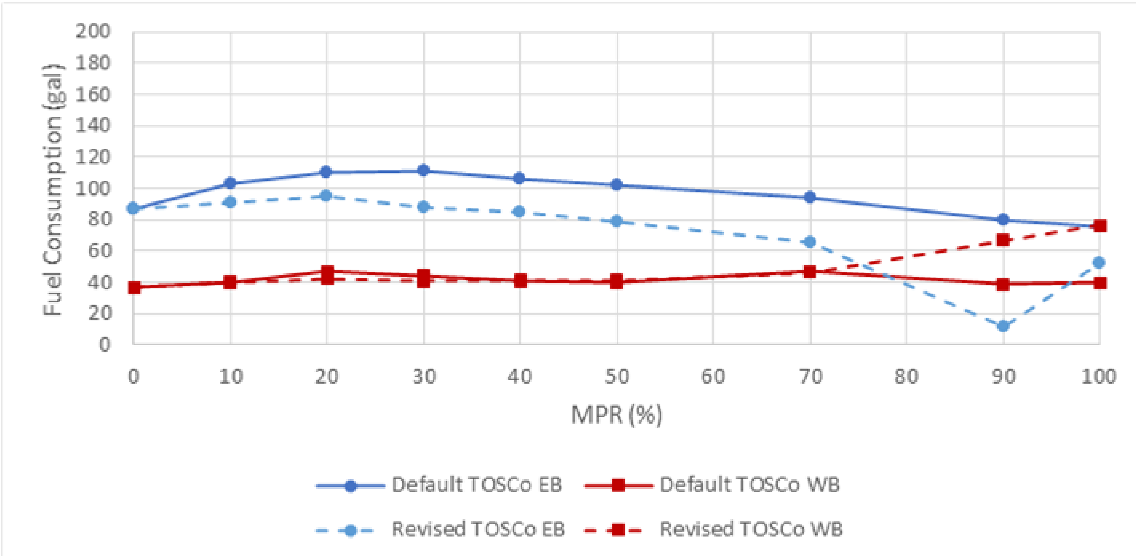
Source:
Texas A&M Transportation Institute, 2022

Figure 82. Fuel Consumption at Intersection 101



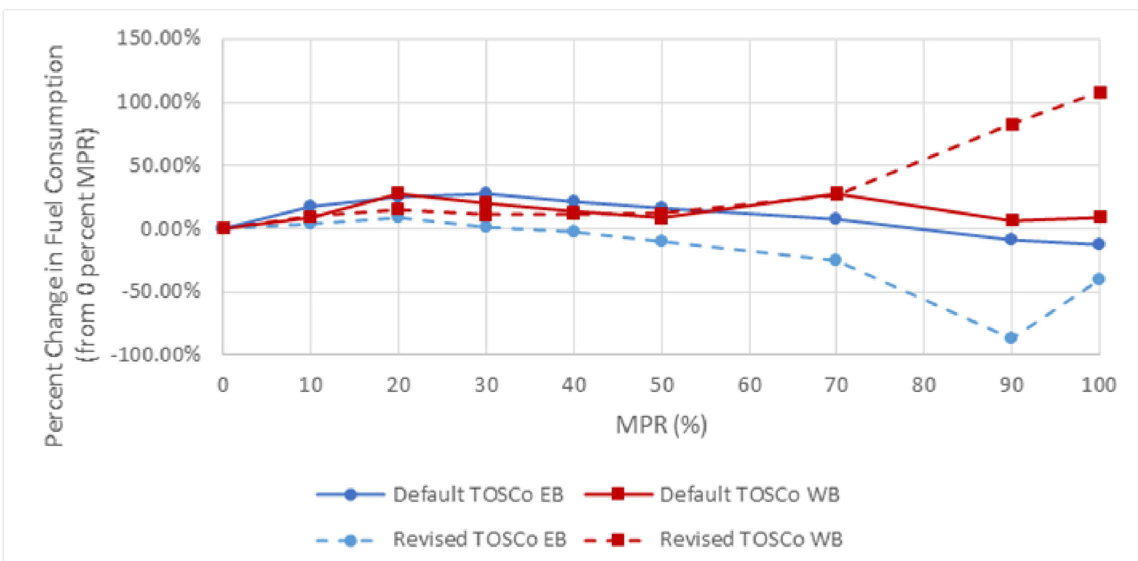
Source: Texas A&M Transportation Institute, 2022

Figure 83. Percent Change in Fuel Consumption for Intersection 101



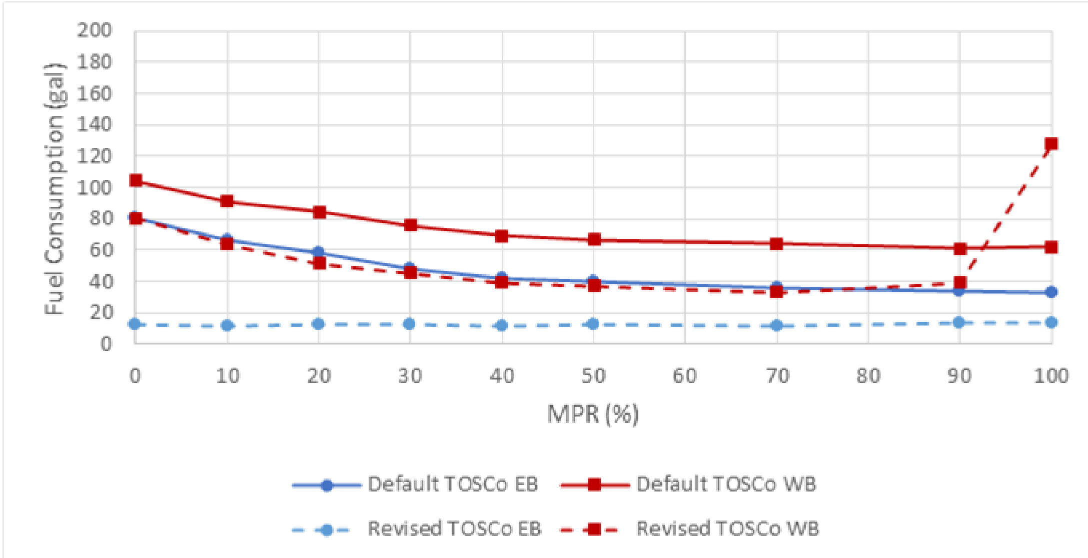
Source:
Texas A&M Transportation Institute, 2022

Figure 84. Fuel Consumption at Intersection 102



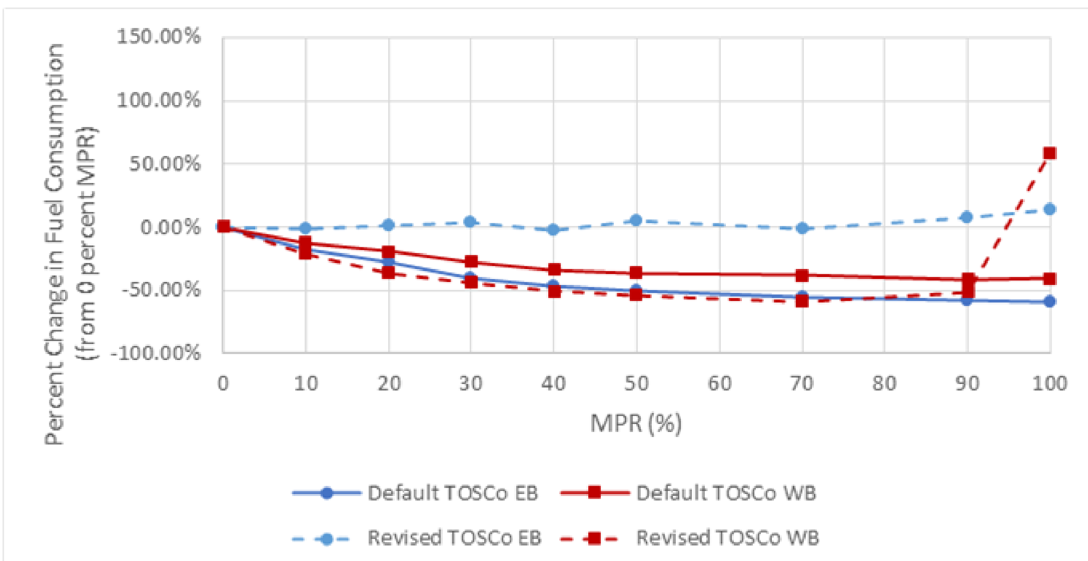
Source: Texas A&M Transportation Institute, 2022

Figure 85. Percent Change in Fuel Consumption for Intersection 102



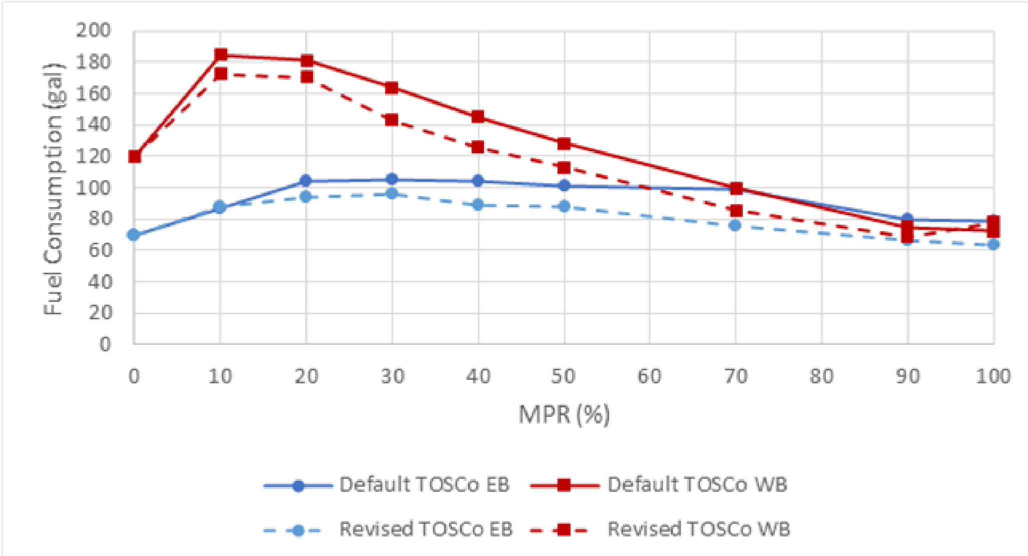
Source: Texas A&M Transportation Institute, 2022

Figure 86. Fuel Consumption at Intersection 103



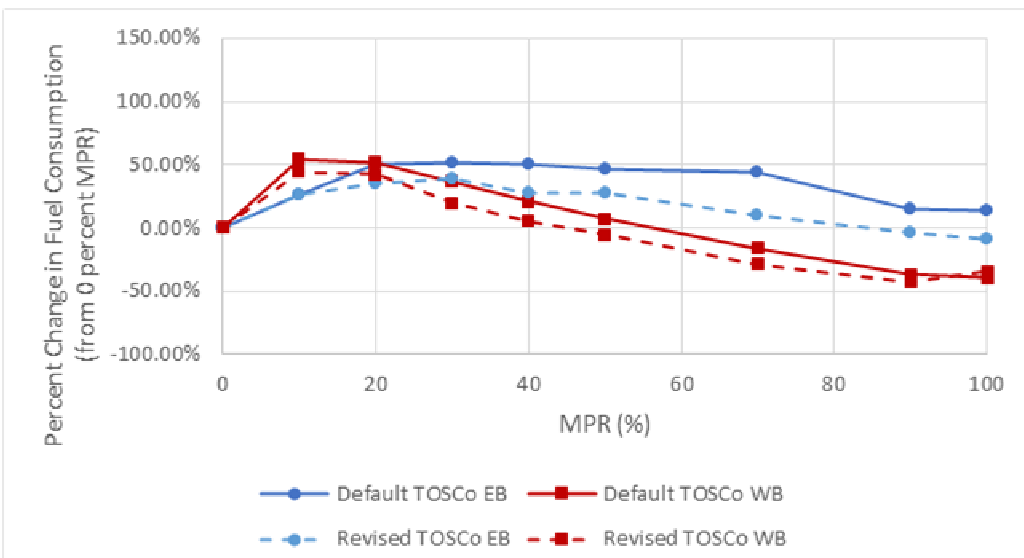
Source: Texas A&M Transportation Institute, 2022

Figure 87. Percent Change in Fuel Consumption for Intersection 103



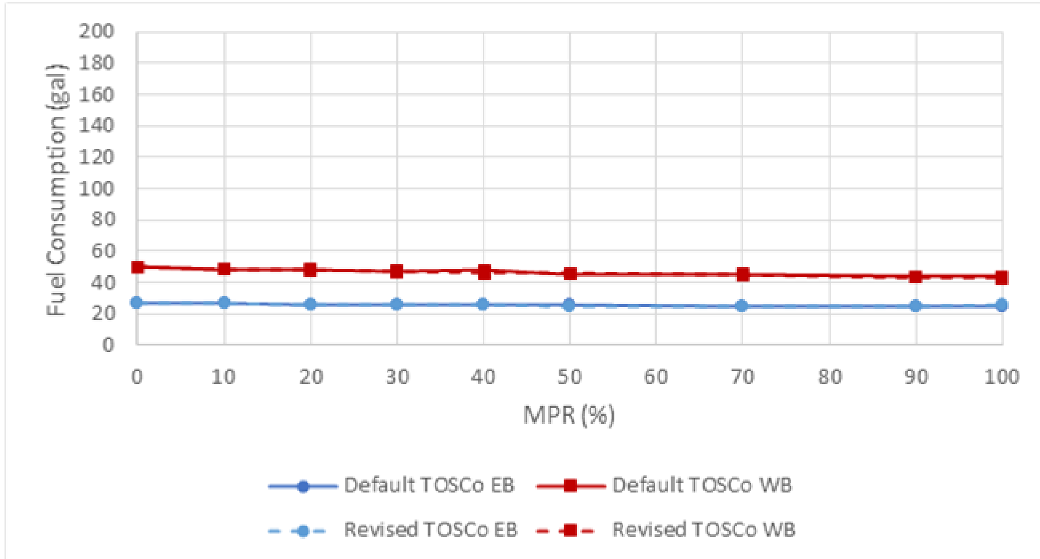
Source: Texas A&M Transportation Institute, 2022

Figure 88. Fuel Consumption at Intersection 104



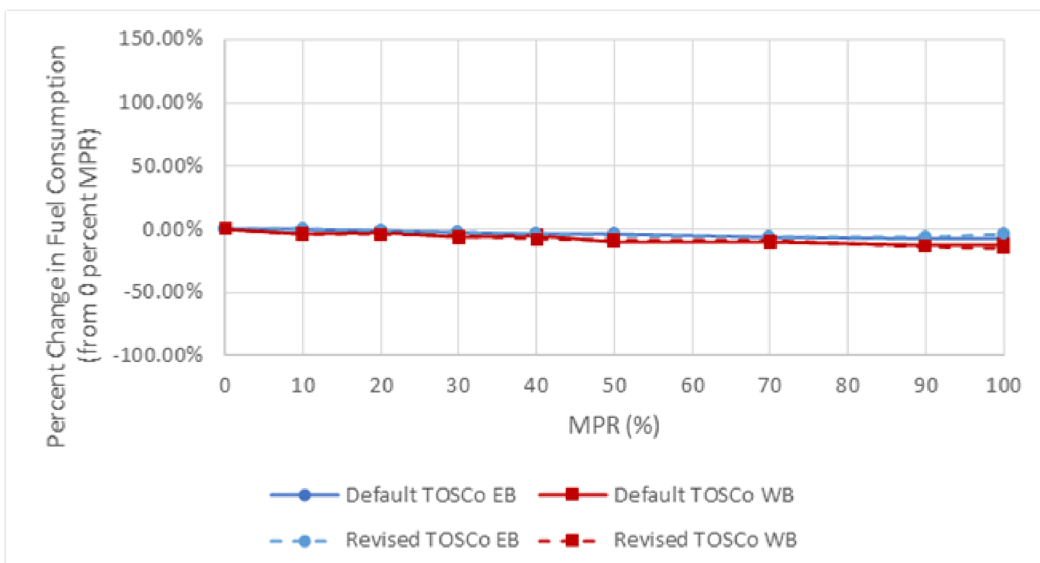
Source: Texas A&M Transportation Institute, 2022

Figure 89. Percent Change in Fuel Consumption for Intersection 104



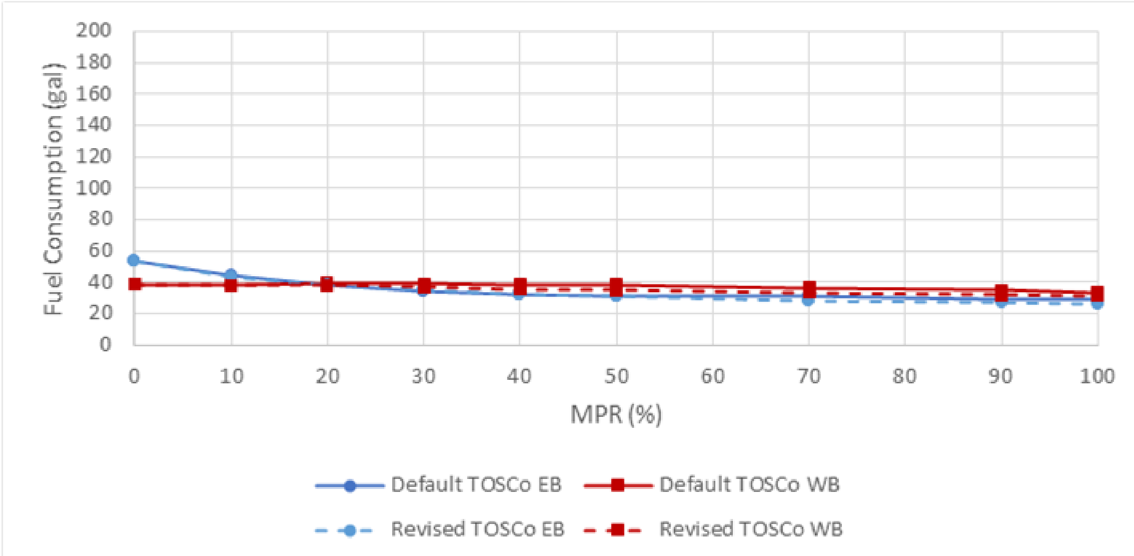
Source: Texas A&M Transportation Institute, 2022

Figure 90. Fuel Consumption at Intersection 105



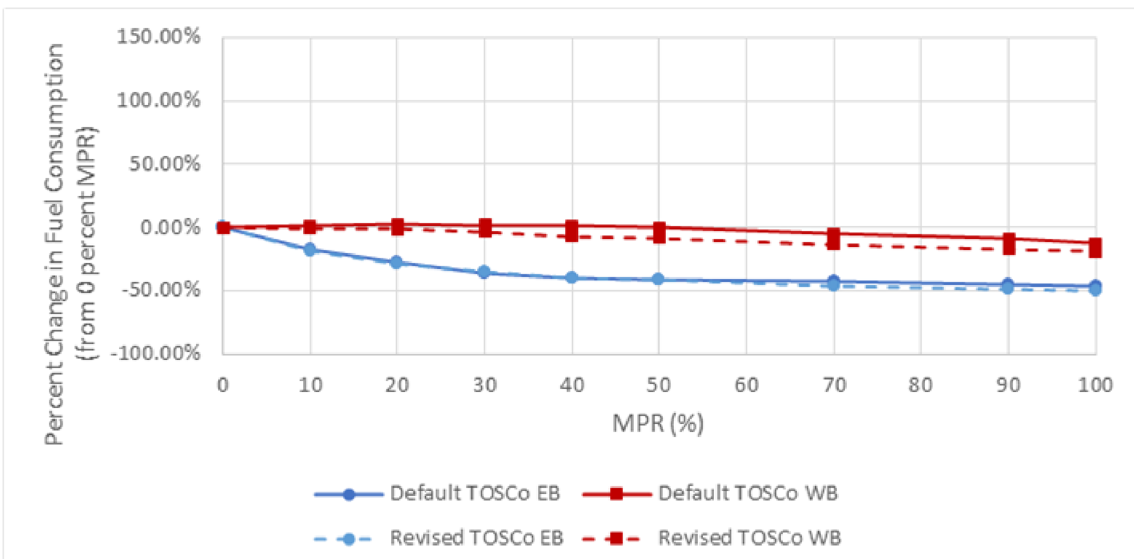
Source: Texas A&M Transportation Institute, 2022

Figure 91. Percent Change in Fuel Consumption for Intersection 105



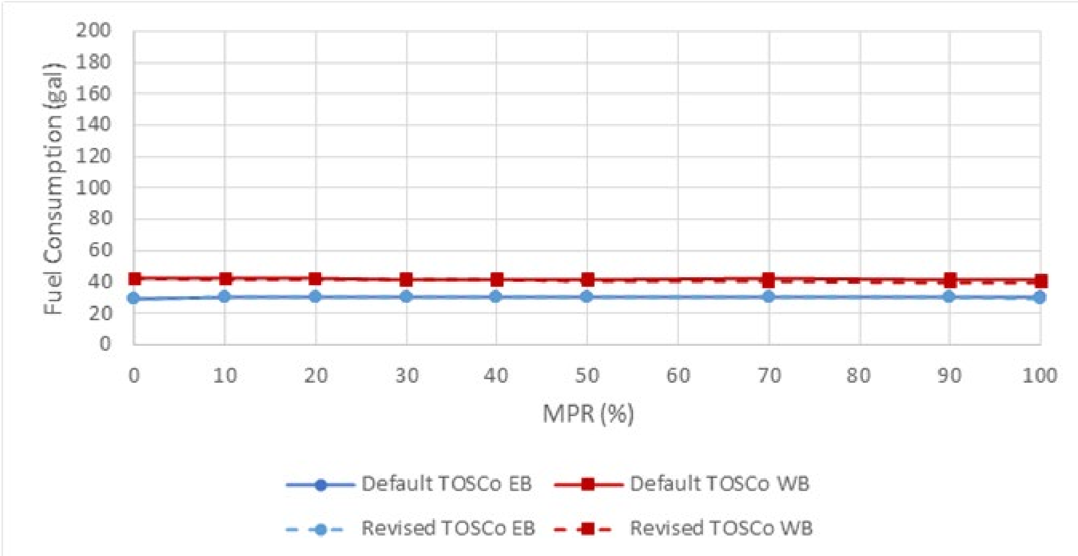
Source: Texas A&M Transportation Institute, 2022

Figure 92. Fuel Consumption at Intersection 106



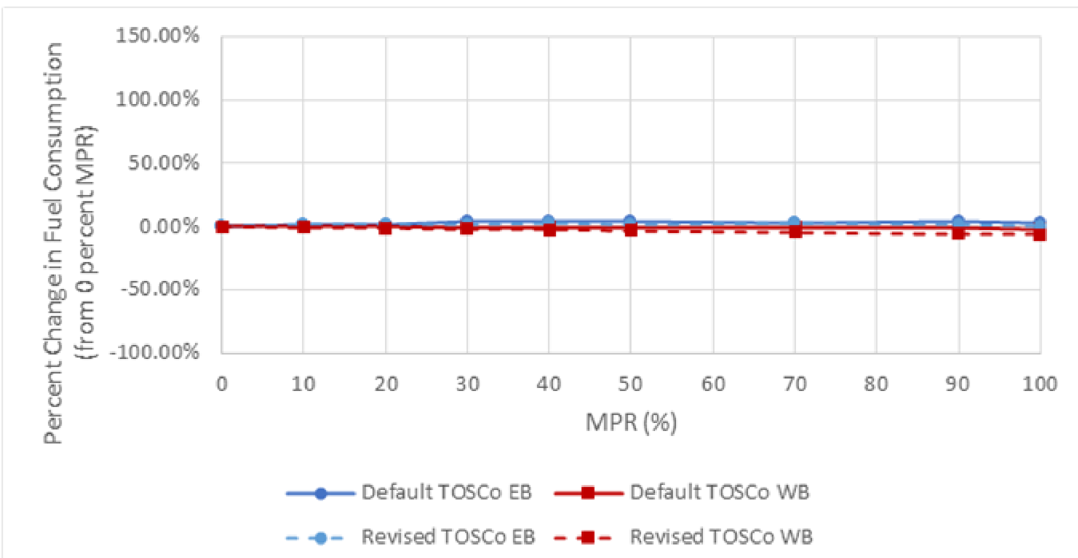
Source: Texas A&M Transportation Institute, 2022

Figure 93. Percent Change in Fuel Consumption for Intersection 106



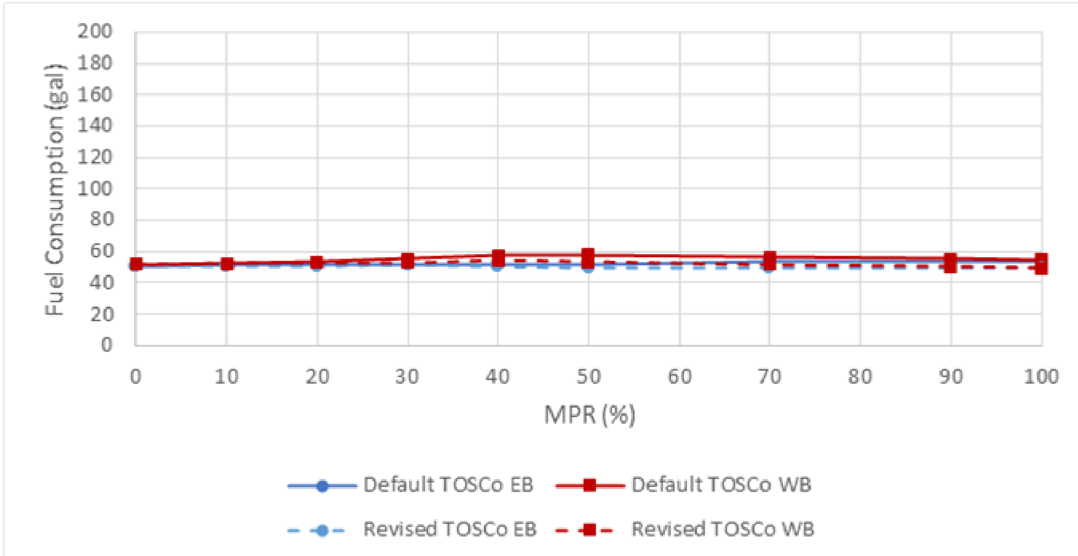
Source: Texas A&M Transportation Institute, 2022

Figure 94. Fuel Consumption at Intersection 107



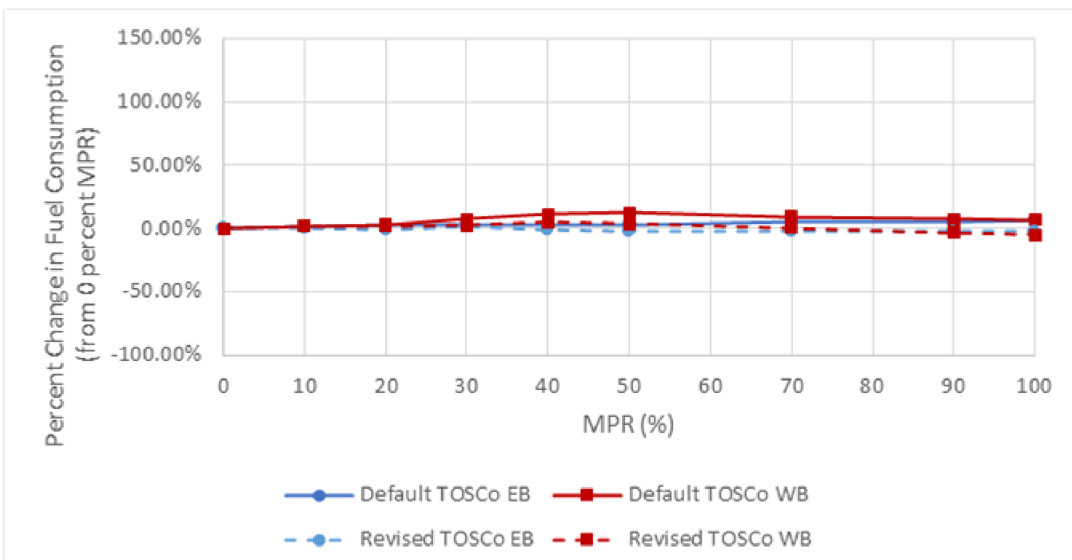
Source: Texas A&M Transportation Institute, 2022

Figure 95. Percent Change in Fuel Consumption for Intersection 107



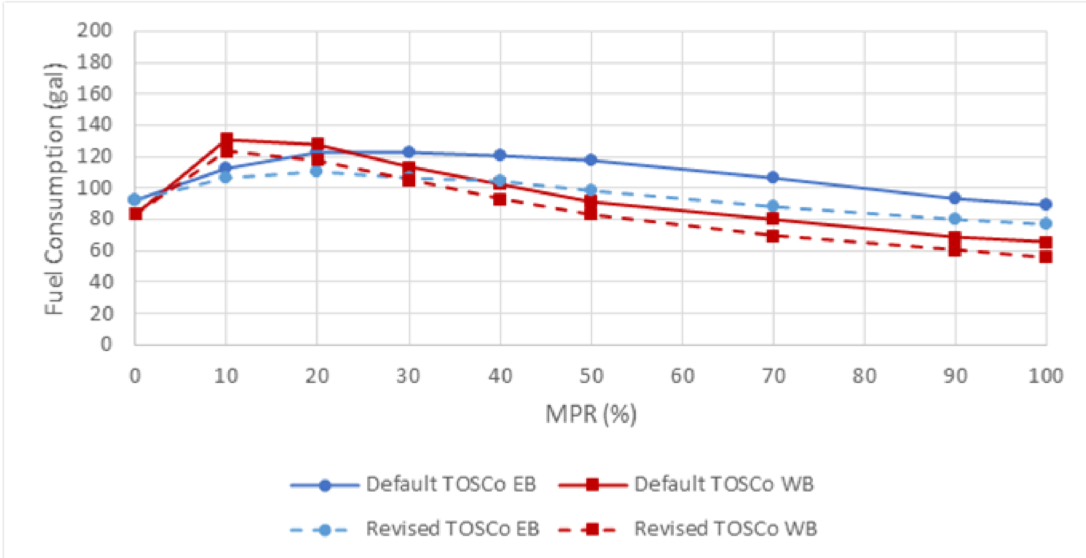
Source: Texas A&M Transportation Institute, 2022

Figure 96. Fuel Consumption at Intersection 108



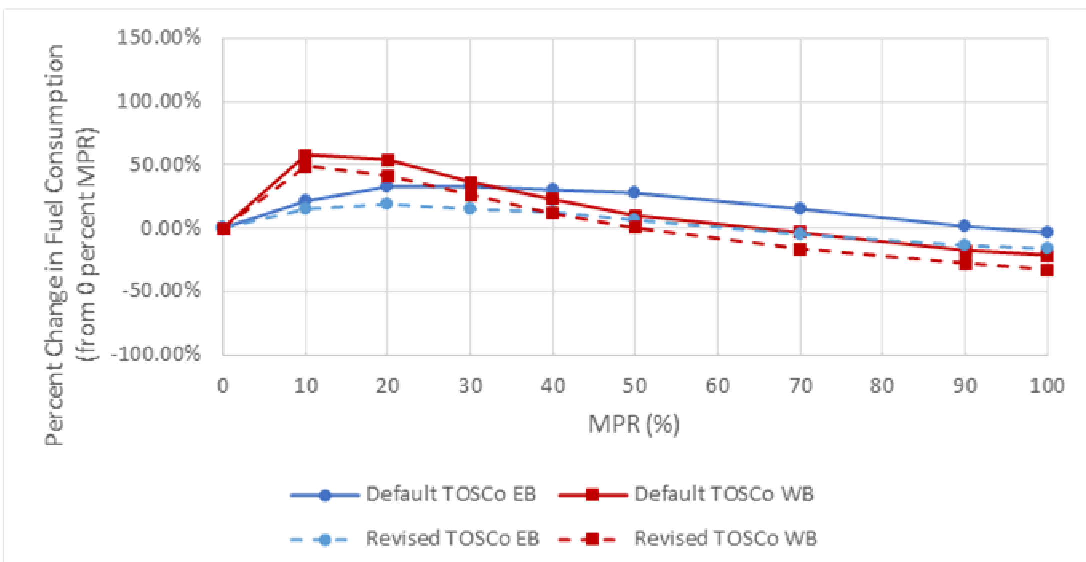
Source: Texas A&M Transportation Institute, 2022

Figure 97. Percent Change in Fuel Consumption for Intersection 108



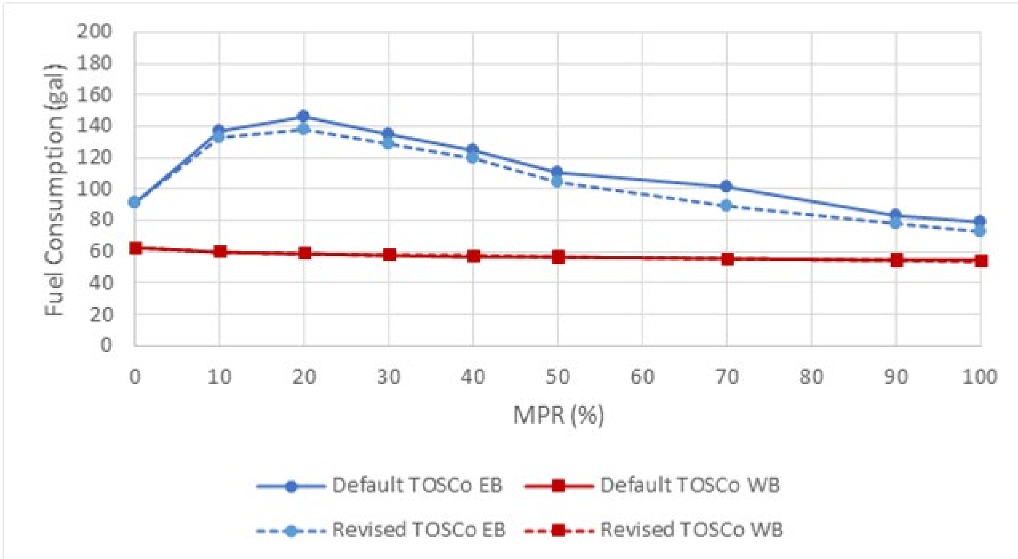
Source: Texas A&M Transportation Institute, 2022

Figure 98. Fuel Consumption at Intersection 109



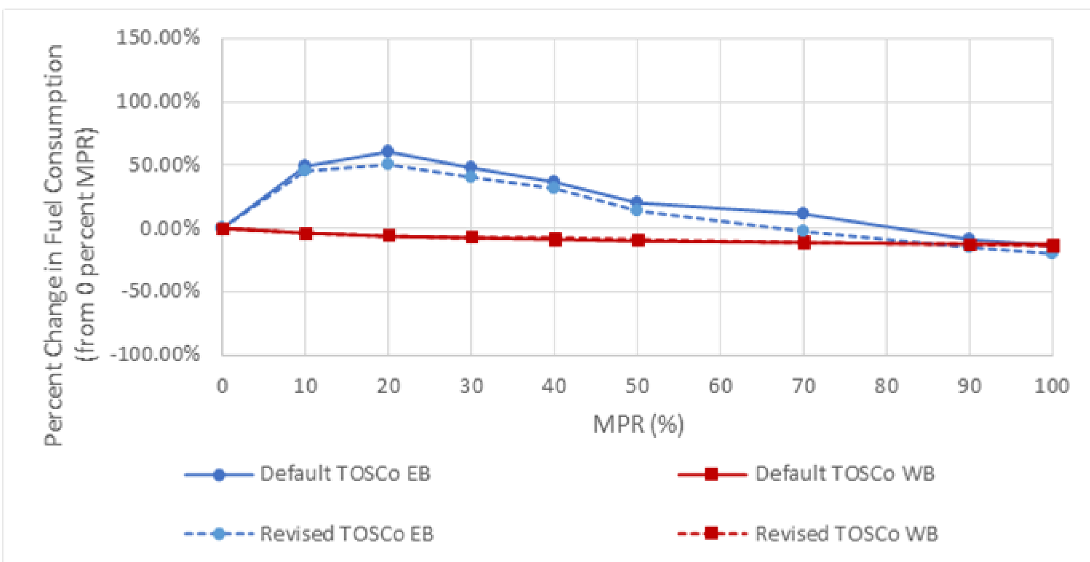
Source: Texas A&M Transportation Institute, 2022

Figure 99. Percent Change in Fuel Consumption for Intersection 109



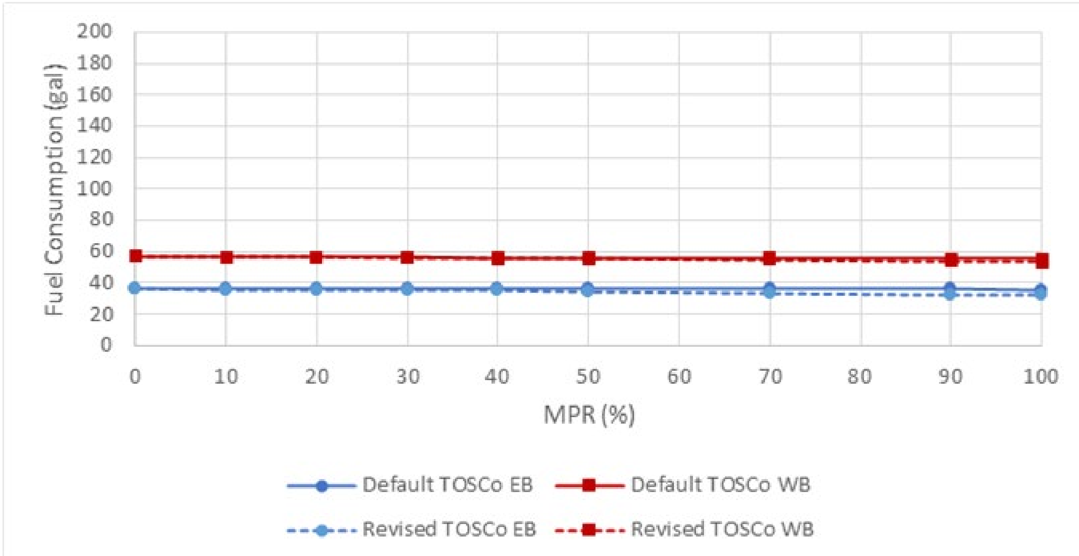
Source: Texas A&M Transportation Institute, 2022

Figure 100. Fuel Consumption at Intersection 110



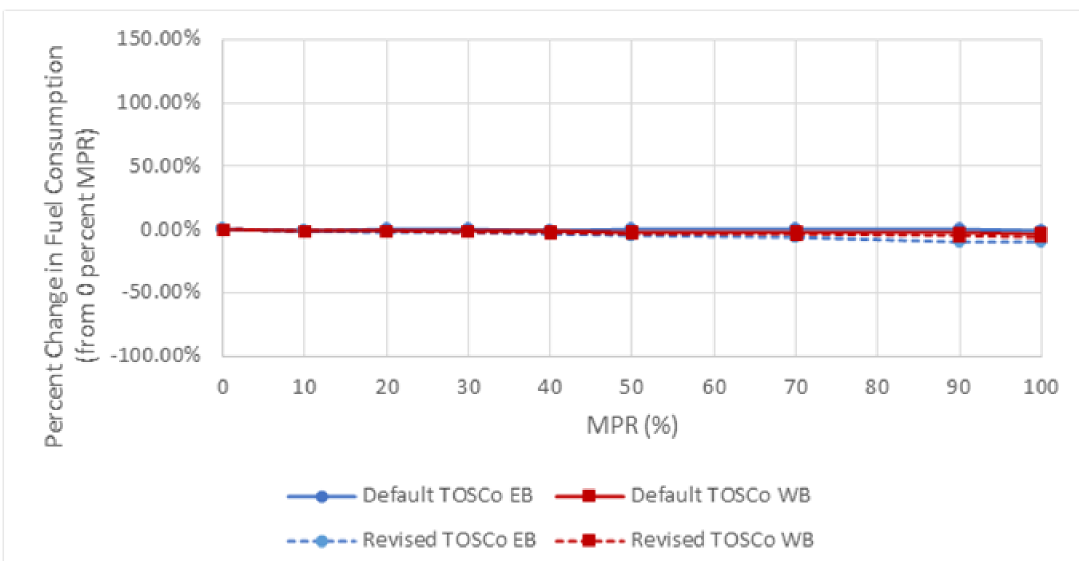
Source: Texas A&M Transportation Institute, 2022

Figure 101. Percent Change in Fuel Consumption for Intersection 110



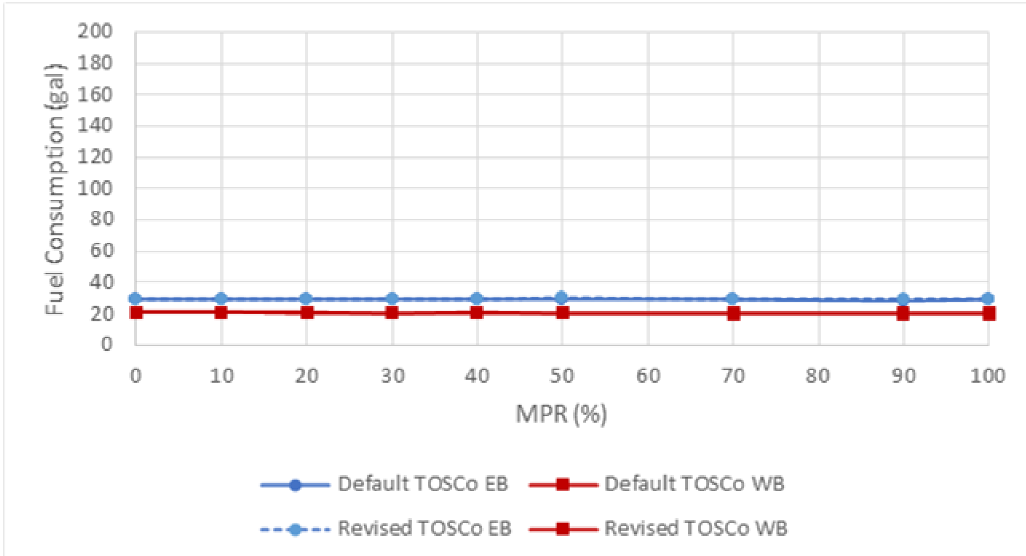
Source: Texas A&M Transportation Institute, 2022

Figure 102. Fuel Consumption at Intersection 111



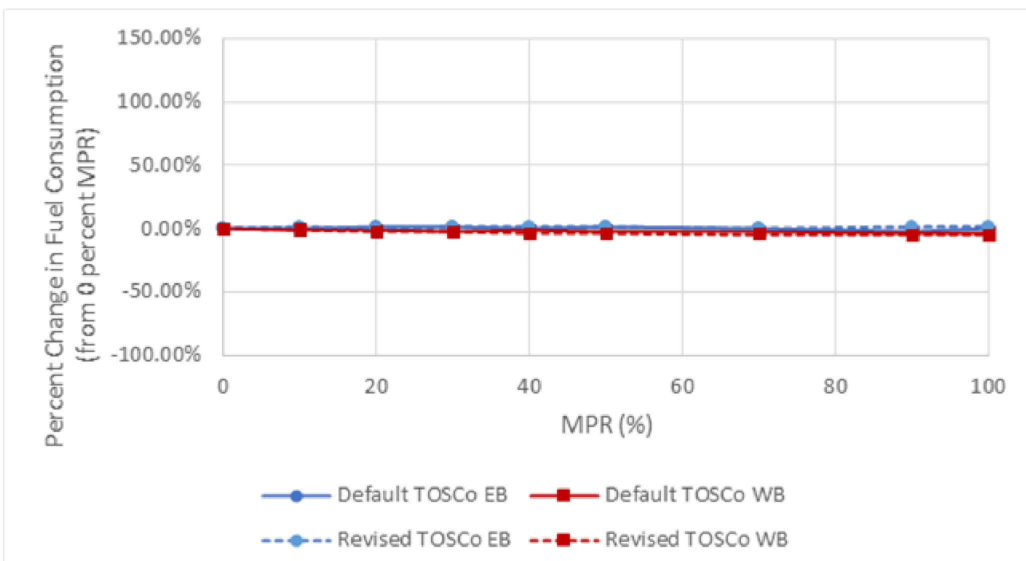
Source: Texas A&M Transportation Institute, 2022

Figure 103. Percent Change in Fuel Consumption for Intersection 111



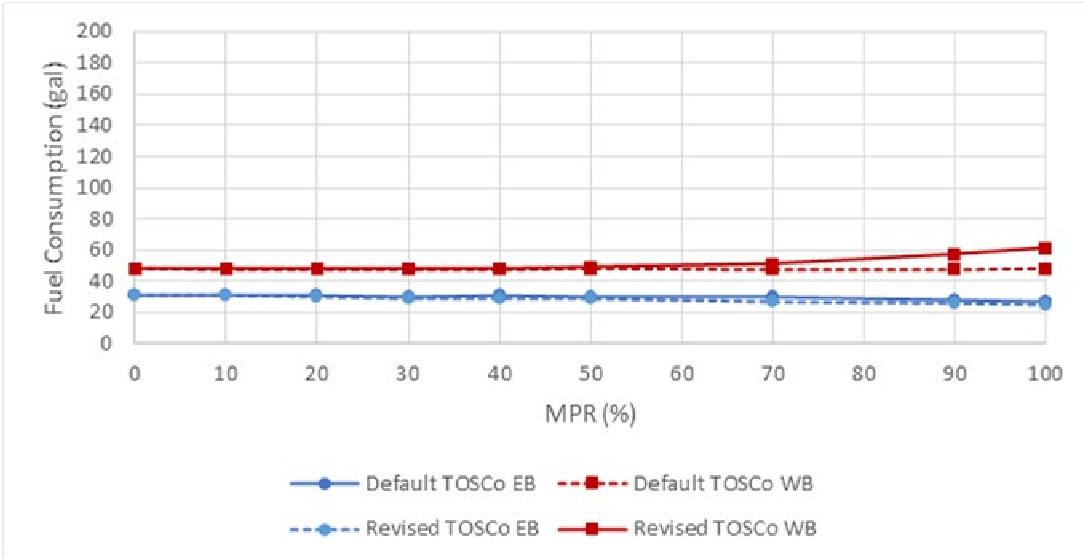
Source: Texas A&M Transportation Institute, 2022

Figure 104. Fuel Consumption at Intersection 112



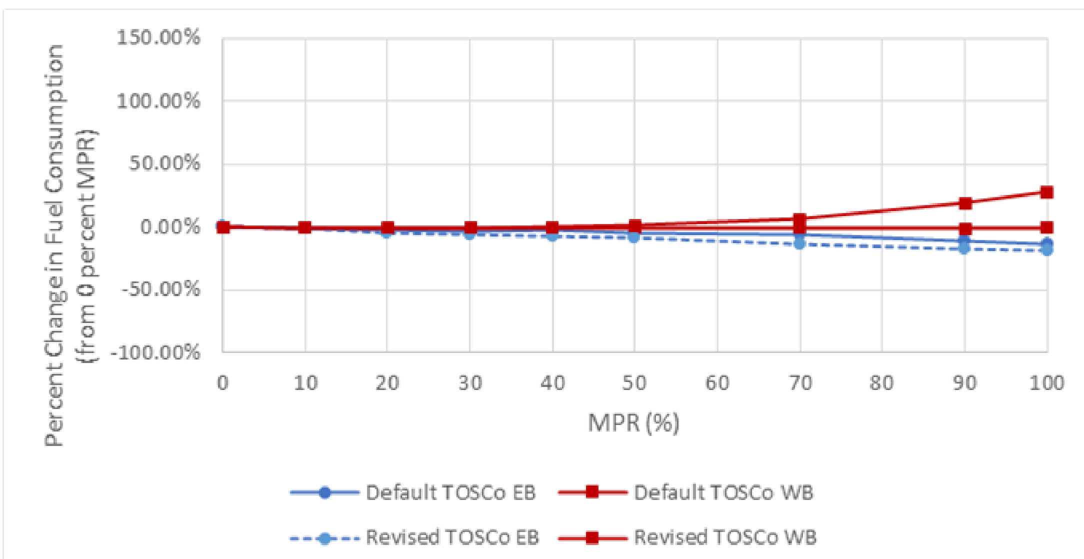
Source: Texas A&M Transportation Institute, 2022

Figure 105. Percent Change in Fuel Consumption for Intersection 112



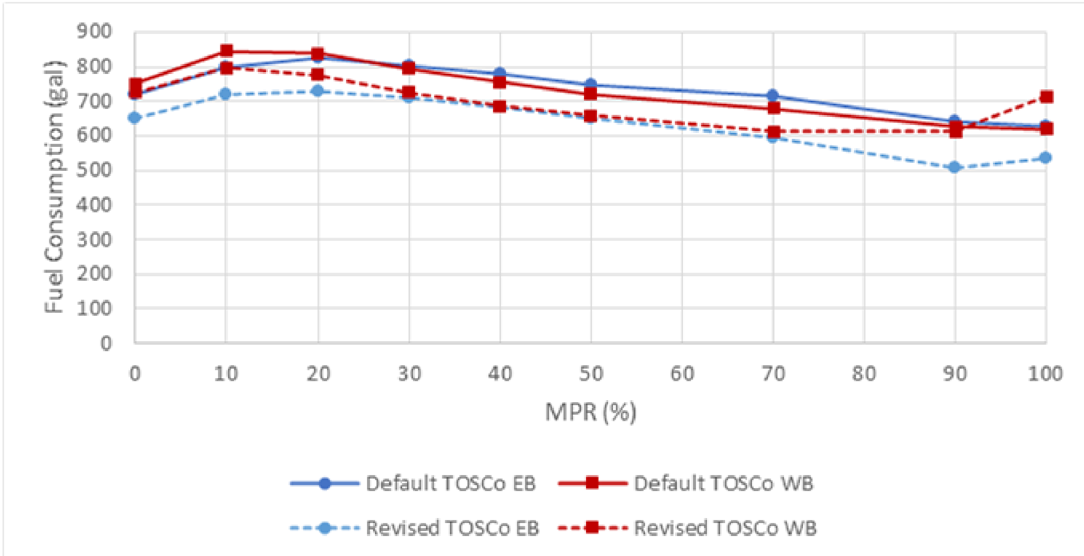
Source: Texas A&M Transportation Institute, 2022

Figure 106. Fuel Consumption at Intersection 113



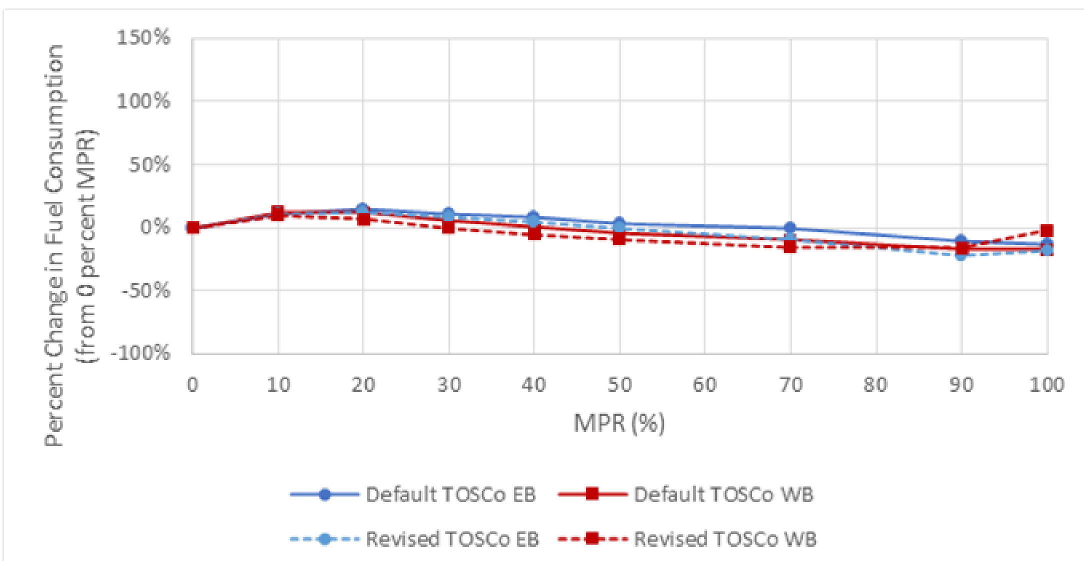
Source: Texas A&M Transportation Institute, 2022

Figure 107. Percent Change in Fuel Consumption for Intersection 113



Source: Texas A&M Transportation Institute, 2022

Figure 108. Fuel Consumption across All Intersections



Source: Texas A&M Transportation Institute, 2022

Figure 109. Percent Change in Fuel Consumption Combined for All Intersections

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