Traffic Optimization for Signalized Corridors (TOSCo) Phase 2

Modeling & Benefits Estimation – SH105 Final Report

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U.S. Department of Transportation
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16. Abstract

This report summarizes the potential mobility and environmental benefits associated with implementing the Traffic Optimization for Signalized Corridor (TOSCo) System in simulation on the State Highway 105 corridor in Conroe, 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 potential mobility and environmental benefits under different market penetration levels during both the A.M. and P.M. peak periods. The researchers found that the TOSCo system reduces the stop delay and the number of stops on an intersection and corridor basis. The simulated version of the TOSCo system reduced total delay per vehicle at some intersections along the SH105 corridor without heavy turning movements. Intersections on the SH105 corridor with heavy turning movements and lots of weaving did experience some increases in total delay with increased TOSCo MPR. TOSCo also reduced fuel usage at most intersections, but increased fuel usage at intersections with queue spillback issues. Overall TOSCo reduced stops, stop delay, and relieved congestion-based queueing at several intersections on SH105. TOSCo simulation efforts later in Phase 2 of the project were on FM1960 in Houston, Texas because of the transition of the deployment corridor to FM 1960.

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Executive Summary

The purpose 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. 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 DSRC 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 window 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, they would then revert to their previous operating mode, Free Flow (CACC).

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 update 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 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.

The research team utilized a VISSIM model of SH105 that was developed in Phase 1 of the TOSCo Project to assess benefits of an updated version of TOSCo developed in Phase 2. The corridor along Texas State Highway 105 (SH105) consists of fifteen intersections between Montgomery, Texas and Conroe, Texas covering about 12 miles. The posted speed limit in most of the analysis corridor is 55 mph, with the easternmost quarter-mile posted at 45 mph. It takes about fifteen minutes to drive from one end of the corridor to the other. The research team used the same calibration and parameter settings from Phase 1 of the TOSCo Project for the simulations described in this report. The simulation covered a range of market penetration rates of TOSCo on the simulated corridor.

The following provides a summary of the mobility and environmental benefits observed by modeling TOSCo in the SH105 corridor.

- TOSCo was able to achieve reductions in stop delay and number of stops in both A.M and P.M. analysis periods. Stop delay decreased by around 50 % across the corridor as TOSCo MPR increases. Similar reductions in stops per vehicle occurred as TOSCo MPR increased in both east and westbound direction as well as A.M. and P.M. analysis periods.
- TOSCo reduced total delay at intersections without queue spillback or weaving traffic and sufficient traffic.
- TOSCo showed improved performance for both Tosco-equipped as well as non-TOSCo-equipped vehicles in total delay, stop delay, and number of stops as market penetration increased on most of the approaches.
- TOSCo increased total delay at intersections with significant queue spillback because of how simulated TOSCo vehicles were discouraged from performing lane changes.
- TOSCo did not cause substantial changes in the total delay experienced by travelers in the corridor, considering the travel time for vehicle to traverse SH105. As TOSCo vehicles were slowing down

further upstream of intersections, minor changes in total delay were expected, but these changes are not likely to be noticeable to travelers.
- Intersections with higher than average queues experienced reductions in average queue lengths as TOSCo MPR increased. These reductions in queues were consistent if there were not any queue spillback issues and varied across MPR in cases where queue spill-back is observed.
- Total travel time and travel speed were not significantly impacted because of implementing TOSCo.
- TOSCo reduced fuel consumption in the A.M. peak period gradually as TOSCo MPR increased. The eastbound direction experienced about a 7.6 percent reduction in fuel use, and the westbound direction of travel experienced about a 1.9 percent reduction in fuel.
- TOSCo temporarily increased fuel consumption in the P.M. peak period, and fuel use gradually decreased from the 20 % MPR scenario until slight reductions in fuel occurred at 90 and 100 % MPR. The research team believes that the increases in fuel are caused by the increased stops caused by the interactions between TOSCo vehicles and weaving traffic attempting to turn either left or right.

Ultimately TOSCo was not deployed on SH105 due to schedule delays resulting from the COVID19 Pandemic causing conflicts with construction plans for the corridor. TOSCo was implemented on FM1960 in Houston, Texas. As a result, the research team shifted focus to the new corridor. This work is covered in a separate report (*1*).

In addition to updating the version of TOSCo used for later simulations in Phase 2 on the FM 1960 corridor model, the research team addressed a couple of other nuances in benefits estimation simulations on SH105 on the FM 1960 corridor simulation:

- In the SH105 simulation, TOSCo vehicles did not respond well to queue spillback scenarios. Non-TOSCo vehicles would change lanes to an open lane to continue their trip, but TOSCo vehicles would wait in the travel lane until the left turning traffic is no longer blocking the lane for the vehicle, which leads to an over-estimation of the total delay for TOSCo vehicles. The TOSCo analysis on FM 1960 allows simulated TOSCo vehicles to change lanes when the vehicle is within a queue caused by a left turn bay spillback.
- Speeds in all modes of TOSCo, except for Free-flow, were limited to the posted speed limit. Thus, when comparing TOSCo operations to the baseline traffic (which is not limited to the speed limit), the mobility benefits may be underestimated. The research team examined the impact of this constraint with simulation work in the FM 1960 corridor.

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.

This report describes the simulation results for the SH105 corridor, which was originally considered as the deployment corridor for the TOSCo system. The COVID 19 pandemic caused a delay in the project schedule which pushed the deployment into conflict with a road work project on the SH105 corridor. As a result, the research team identified another corridor for TOSCo deployment. Even though TOSCo was not deployed on the SH105 corridor, the research team determined that the simulation efforts described in this report remain valuable to the analysis of TOSCo and relevant to the greater research community.

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 (*2, 3*), 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 (*4*).

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 Conroe, 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 State Highway (SH) 105. These analyses include addressing single intersections 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.

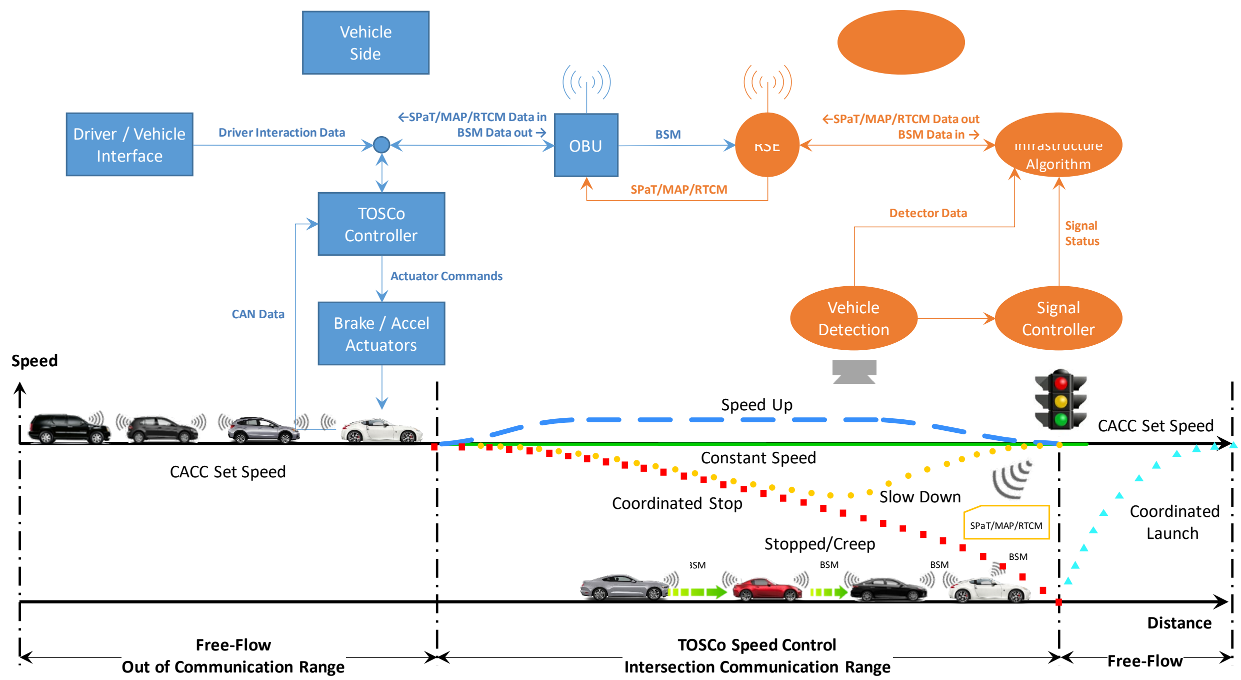
Chapter 2. TOSCo System Overview

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 (*5*).

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 Dedicated Short-range Communications (DSRC) 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(*5*). 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.

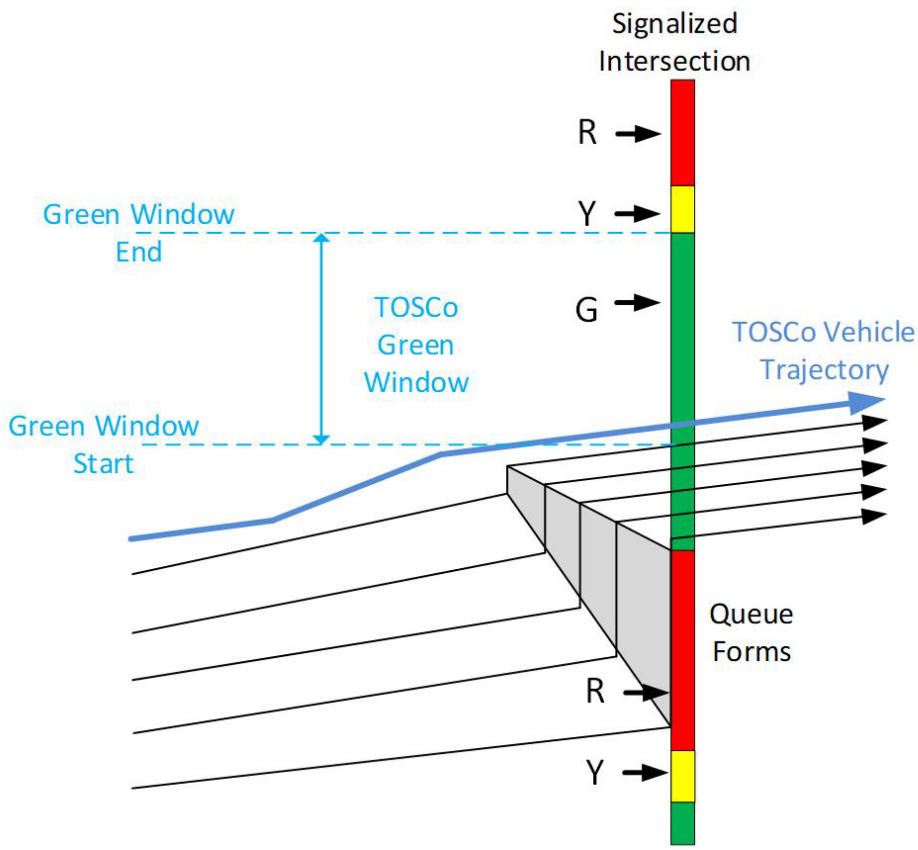
The following are critical components that the infrastructure needs to provide for the TOSCo system to operate properly.

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 (TTI), 2022

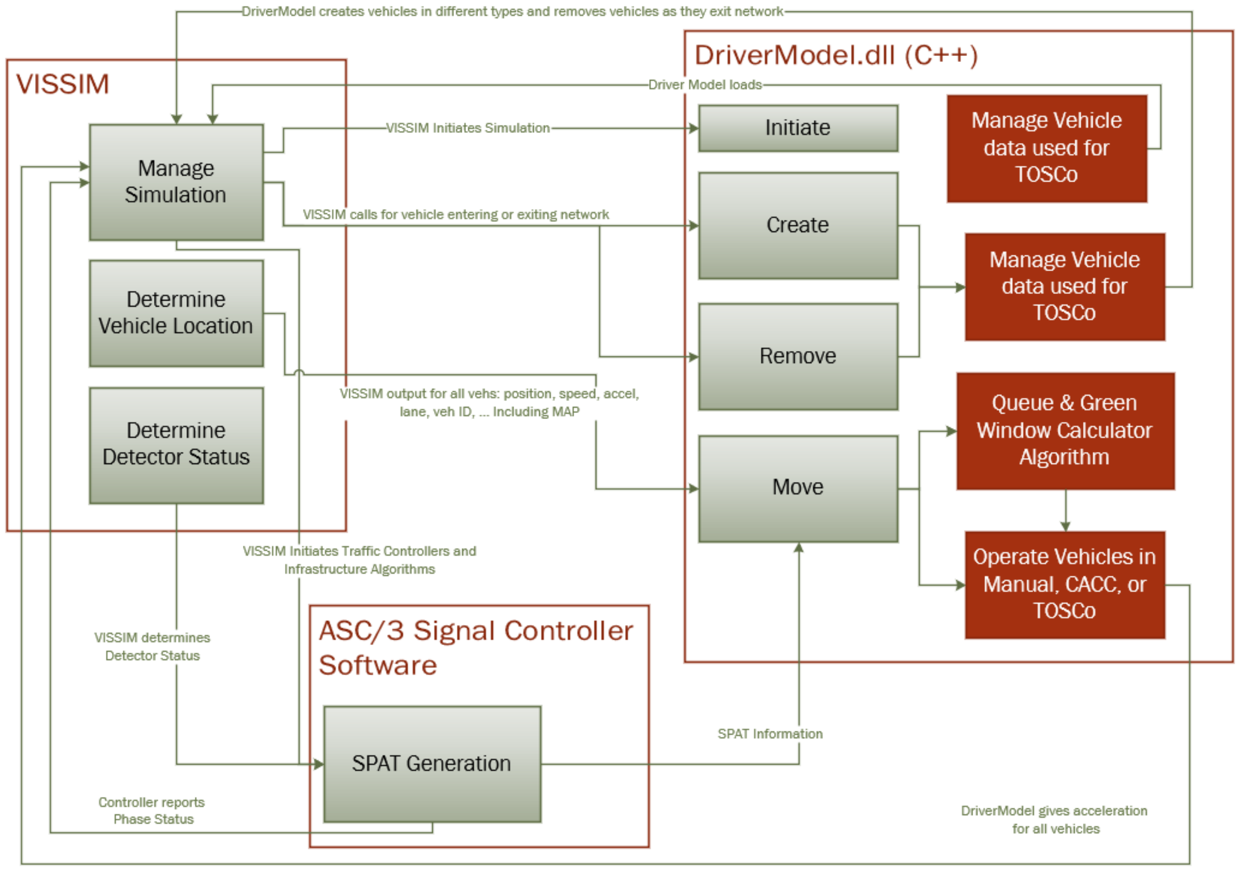
Figure 2. Definition of Green Window

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.

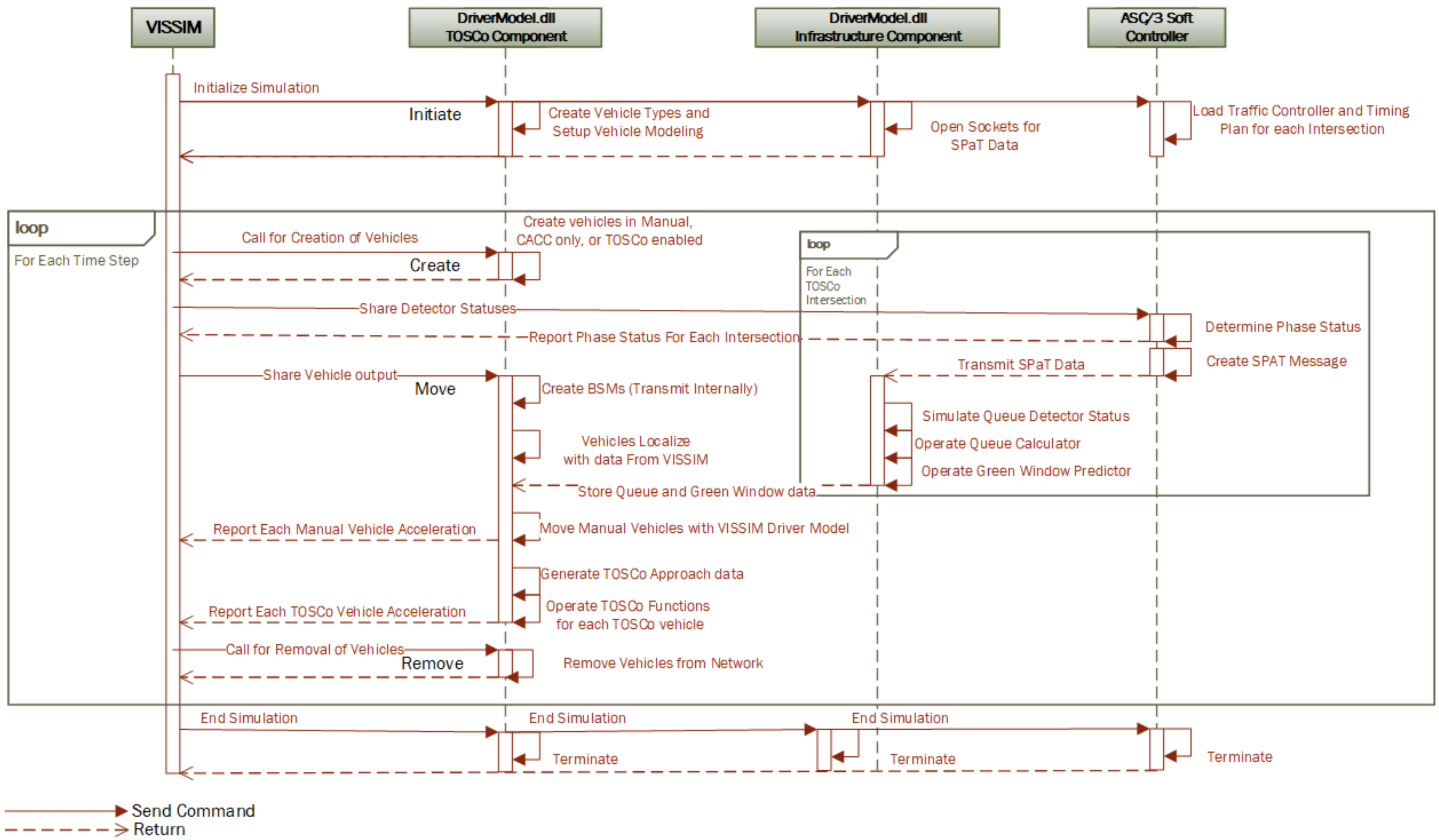
Figure 3 shows the architecture of the TOSCo Performance Assessment Environment used for Phase 2 simulations. The research team developed the TOSCo Performance Assessment Environment to evaluate the potential mobility and environmental benefits associated with TOSCo. In the figure, the maroon block on 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 (TTI), 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 (TTI), 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 DSRC 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 DSRC 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

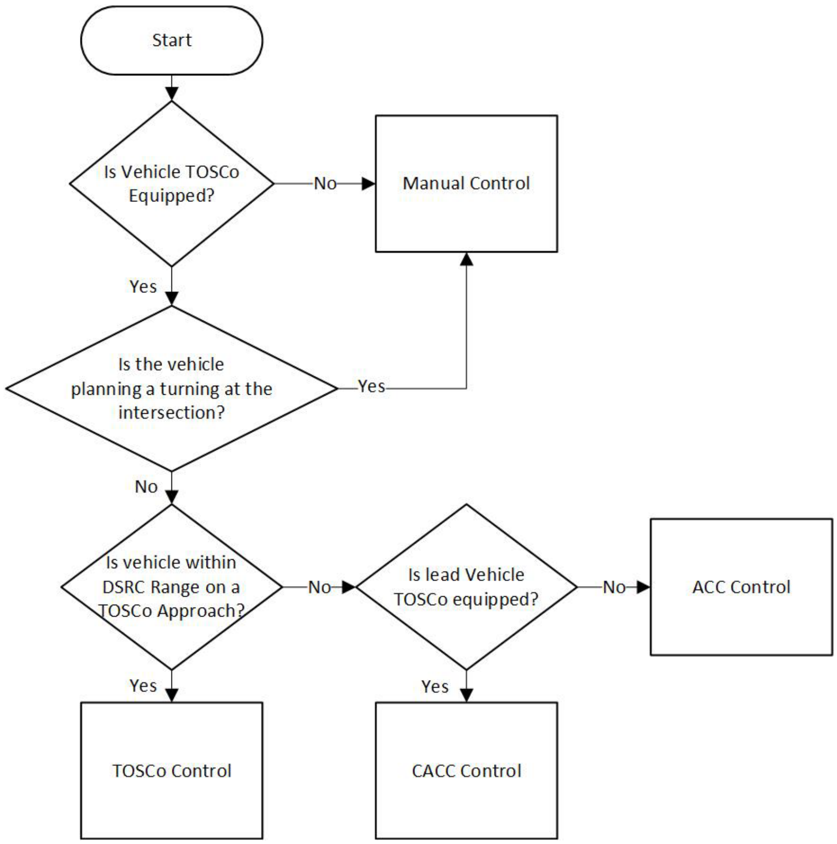
To model the behavior of vehicles under manual control, the evaluation team uses the default VISSIM driver model (the Wiedemann 74 model) developed by PTV to model vehicle under manual control (*6*).

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 *(7,8*). 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 (*10,11*). 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 *(9*). 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 (TTI), 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 (*12*).

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. The analysis of TOSCo benefits in this report assumes that TOSCo vehicles will not perform discretionary lane changes, but, for mandatory lane changes, the traffic level simulation must allow lane changes for TOSCo vehicles. However, the research team uses the Driver Model DLL to impose some control over the lane-changing behavior to help keep the strings together, which the research team believes will be an objective of TOSCo users. The restriction prohibits TOSCo vehicles from changing lanes unless the vehicle is in free-flow mode or if the vehicle must change lanes to position itself to make a turn at an intersection as dictated by its route. If a vehicle needs to turn at the next intersection, it performs a lane change. Otherwise, the simulation does not allow lane changes. The researchers allow lane changing in free-flow mode so vehicles can perform a discretionary passing maneuver to represent travel behavior more accurately on the corridor and avoid artificially raising the total delay measurements.

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 (*13, 15*). 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.

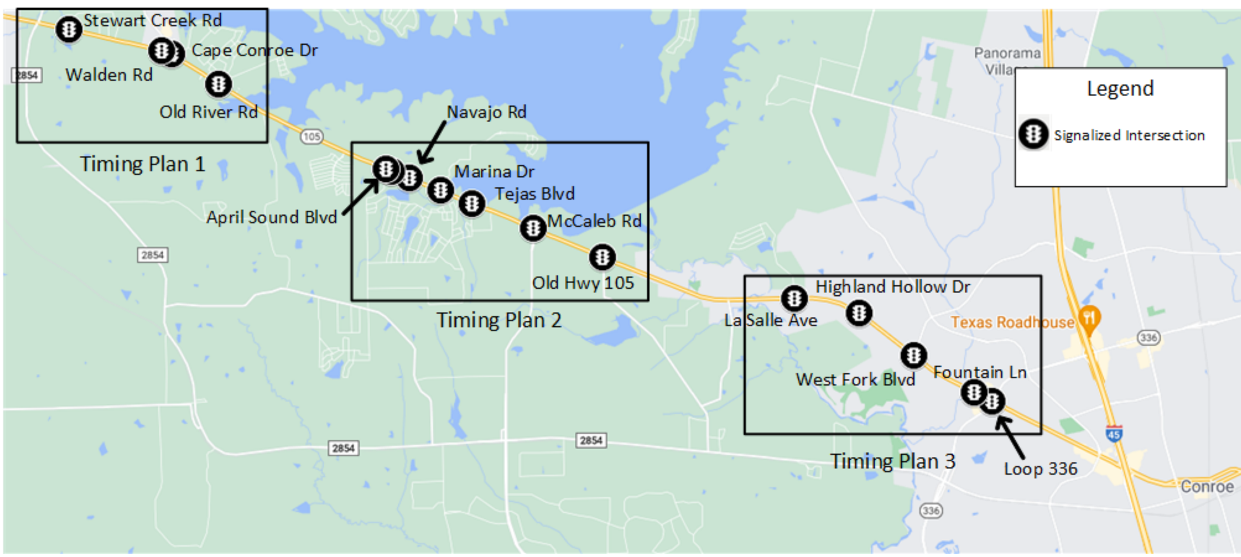
The TOSCo Infrastructure System Specification Report provides a complete description of the queue calculation and green window prediction methodologies used to generate information for the TOSCo system (*4*).

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 Bed 2.2 evaluation completed in March 2021. The research team verified the TOSCo traffic-level simulation by 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 – State Highway 105, Conroe, Texas

The corridor along Texas State Highway 105 (SH105) consists of fifteen intersections between Montgomery, Texas and Conroe, Texas covering about 12 miles. Figure 6 shows the location of the signalized intersections considered along SH105. The City of Conroe, Texas operates all the intersections on this length of SH-105. The posted speed limit in most of the analysis corridor is 55 mph, with the easternmost quarter mile posted at 45 mph. It takes about fifteen 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 SH105 corridor. Table 4 shows the volume and volume divided by capacity (v/c) ratio analysis of each intersection for both directions.



Source: Imagery ©2019 Google. Map Data ©2018 Google

Figure 6. Location of Signalized Intersections Considered on the SH-105 Corridor in Texas

The signals along SH-105 operate as three independent coordinated systems. The section between Stewart Creek Road to Old River Road are one system, Marina Drive to Old 105 Road is another system and La Salle Avenue to Loop 336 is a third system. These three systems have cycle lengths of 90, 105, and 120 seconds, respectively.

Table 1. Characteristics of Road Segments on the SH105 Corridor in Conroe, Texas

Intersection One	Intersection Two	Distance (ft)	Speed Limit (mph)	Number of Lanes (EB/WB)	Number of Driveway
Stewart Creek Rd.	Walden Rd.	5578	55	2/2	34
Walden Rd.	Cape Conroe Dr.	671	55	2/2	3
Cape Conroe Dr.	Old River Rd.	3230	55	2/3	28
Old River Rd.	April Sound Blvd. W.	11194	55	3/3	26
April Sound Blvd. W.	April Sound Blvd. E.	370	55	3/3	0
April Sound Blvd. E.	Navajo Dr.	1139	55	3/3	0
Navajo Dr.	Marina Dr.	1976	55	3/3	4
Marina Dr.	Tejas Blvd.	1901	55	3/3	10
Tejas Blvd.	McCaleb Rd.	4013	55	3/3	31
McCaleb Rd.	Old 105 Hwy.	4477	55	3/3	28
Old 105 Hwy.	La Salle Ave.	11827	55	3/3	58
La Salle Ave.	Highland Hollow Dr.	16315	55	3/3	29
Highland Hollow Dr.	West Fork Blvd.	4066	55	3/3	18
West Fork Blvd.	Fountain Ln.	4200	50	3/3	16
Fountain Ln.	Loop 336	1200	50	3/3	5

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

Table 2. Characteristics of Intersections on the SH105 Corridor

Intersection Name	Exclusive Left Turn Lane	Exclusive Right Turn Lane	Traffic Signal Control
Stewart Creek Rd.	EB and WB	WB Only	Coordinated Actuated
Walden Rd.	EB and WB	WB Only	Coordinated Actuated
Cape Conroe Dr.	EB and WB	None	Coordinated Actuated
Old River Rd.	EB and WB	None	Coordinated Actuated
April Sound Blvd W.	WB Only	None	Coordinated Actuated
April Sound Blvd E.	EB Only	WB Only	Coordinated Actuated
Navajo Dr.	WB Only	None	Coordinated Actuated
Marina Dr.	EB and WB	None	Coordinated Actuated
Tejas Blvd.	EB and WB	None	Coordinated Actuated

Intersection Name	Exclusive Left Turn Lane	Exclusive Right Turn Lane	Traffic Signal Control
McCaleb Rd.	EB and WB	None	Coordinated Actuated
Old 105 Hwy.	EB and WB	None	Coordinated Actuated
La Salle Ave.	EB and WB	None	Actuated
Highland Hollow Dr.	EB and WB	WB Only	Actuated
West Fork Blvd.	EB and WB	None	Actuated
Fountain Ln.	EB and WB	None	Coordinated Actuated
Loop 336	EB and WB	EB and WB	Coordinated Actuated

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

Table 3. SH105 Corridor Volume and v/c Ratio Analysis

Intersection	Eastbound Volume (veh/hr)	Eastbound v/c Ratio	Westbound Volume (veh/hr)	Westbound v/c Ratio
Stewart Creek Rd.	905	0.39	937	0.40
Walden Rd.	647	0.46	524	0.38
Cape Conroe Dr.	1343	0.94	822	0.50
Old River Rd.	1297	0.61	907	0.43
April Sound Blvd. W.	1551	0.61	758	0.30
April Sound Blvd. E.	1871	0.73	762	0.30
Navajo Dr.	1763	0.43	1345	0.28
Marina Dr.	1858	0.40	1280	0.34
Tejas Blvd.	1852	0.52	1296	0.38
McCaleb Rd.	1820	0.53	1267	0.37
Old 105 Hwy.	1970	0.58	1401	0.41
La Salle Ave.	1826	0.56	978	0.25
Highland Hollow Dr.	2166	0.61	1010	0.28
West Fork Blvd.	1766	0.50	1407	0.39
Fountain Ln.	1913	0.54	892	0.25
Loop 336	748	0.26	388	0.23
Average	-	0.54	-	0.34

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

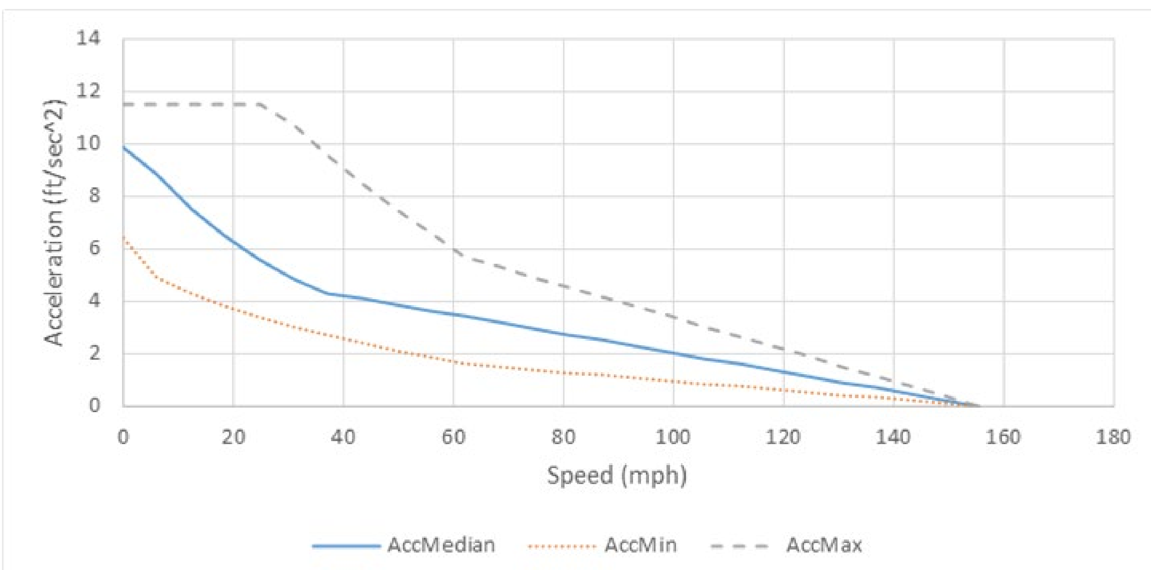
The research team adjusted the settings of the intersection controllers to cause the green window to close reliably. To do this, the research team adjusted the signal timing for the simulated controllers to have minimum recalls on each non-TOSCo phase. This adjustment ensures that the green phase for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

SH105 Acceleration Profile Development

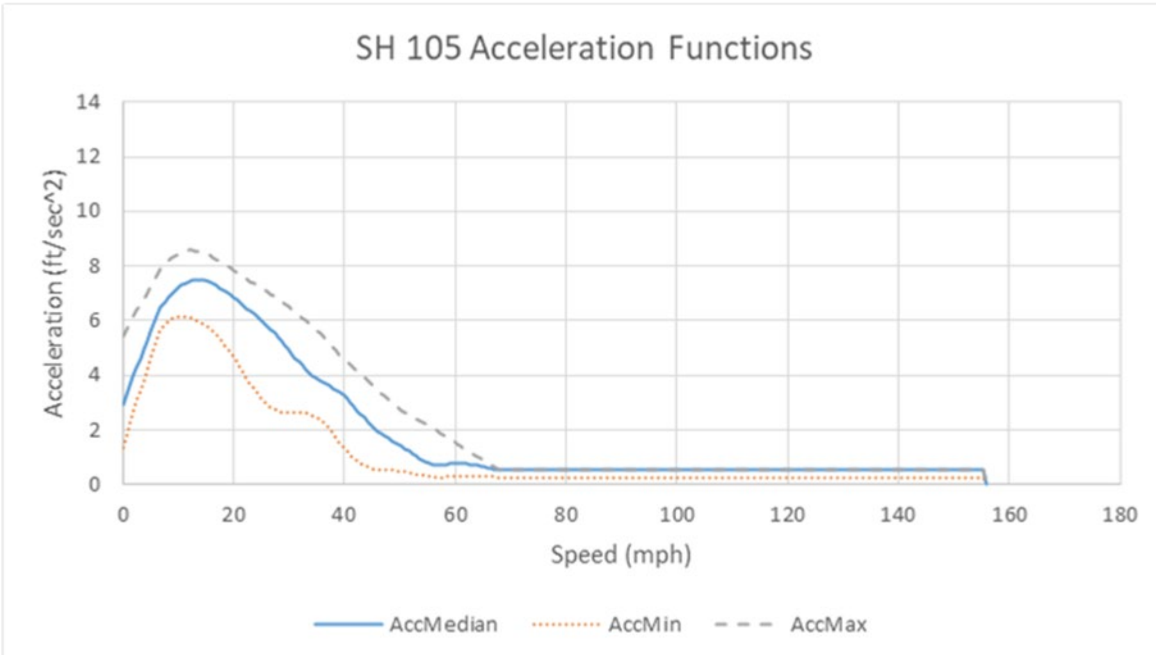
Information on the acceleration behavior from DSRC vehicles was not available for the high-speed corridor, leading the team to use the default desired acceleration distribution provided in VISSIM. Figure 7 shows the VISSIM default acceleration. The VISSIM default accelerations for the non-equipped vehicles 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 traffic on SH105 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 SH105 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 SH105 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 (twelve).



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

Figure 8. Acceleration Profile Calibrated from SH105 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 profile has a wider range of speed compared to the profile for the low speed corridor, due to the higher speeds on SH105. Moreover, the calibrated VISSIM acceleration is different from the VISSIM default acceleration profile at every speed range as demonstrated in Table 4.

Table 4: Comparisons on Averaged Acceleration for VISSIM Default and SH105 Acceleration Profiles

Speed Range	Average VISSIM Default Acceleration (ft/s^2)	Average SH105 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

Speed Range	Average VISSIM Default Acceleration (ft/s^2)	Average SH105 Acceleration (ft/s^2)	Difference (ft/s2)
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

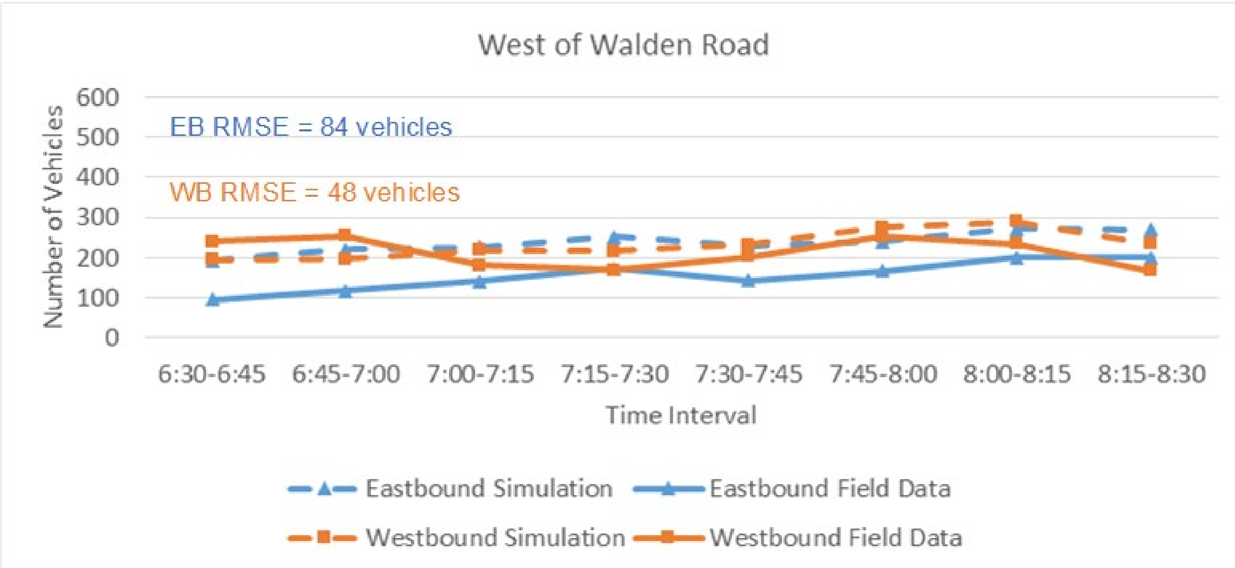
Source: Texas A&M Transportation Institute (TTI), 2022

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.

Model Calibration for Traffic Volumes

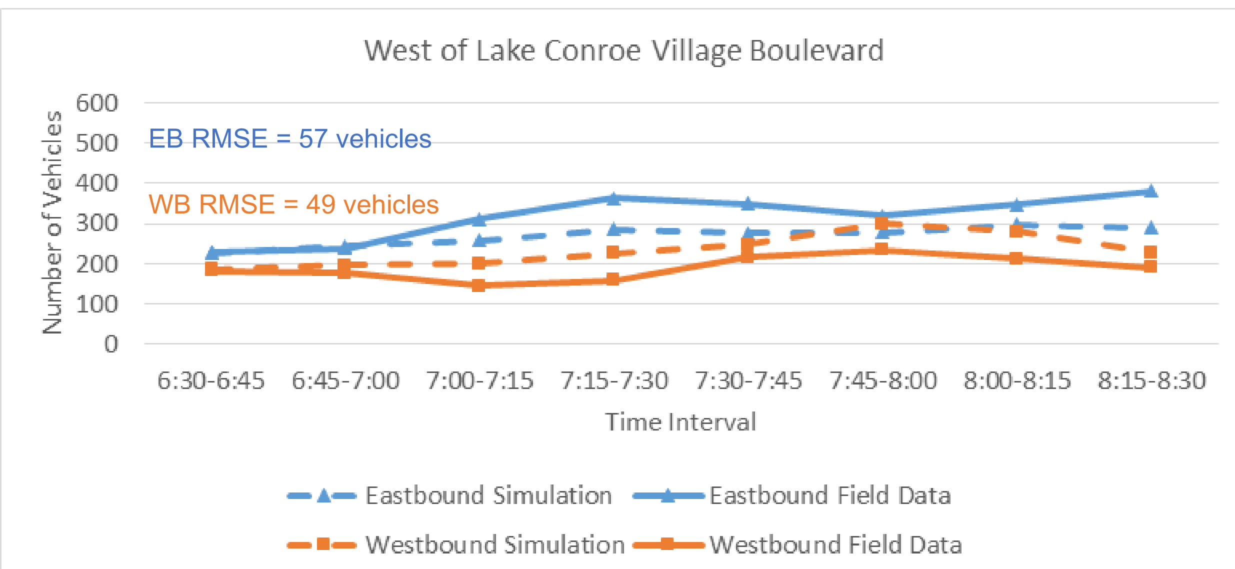
The research team collected volume and mobility data to characterize SH105 for the traffic simulation. The data collection crew placed the tube counters in five locations along the SH105 corridor for a week to collect volume data to aid the team in determining the proper analysis period and volumes for the simulation. The research team used data from the tube counts to calibrate the volume inputs into the model.

Figure 9 through Figure 14 show the simulated volumes and the field volumes in both eastbound and westbound directions of the simulation counted locations. Generally, the simulation counted more vehicles West of Walden Road than observed in the field. The overestimation of traffic for eastbound Walden Road traffic in the simulation is acceptable because the traffic from this measurement increase volumes at the other locations, which estimate less traffic in the simulation, to achieve more accurate estimates. The Lake Conroe Village Boulevard count location had less eastbound vehicles and more westbound vehicles than the field data. The research team deemed these differences acceptable. The eastbound direction of traffic near Tejas Boulevard did not achieve the same peak flow as the field data recorded but has a good fit for westbound volumes. The Blake Road location showed a very close fitting of the simulation to the field data. Like the Tejas Boulevard count location, the La Salle Drive location does not achieve the same peak flow in the eastbound direction and has a good fit for the westbound volumes. The FM-3083 count location has slightly less eastbound vehicles and a good fit for westbound vehicles.



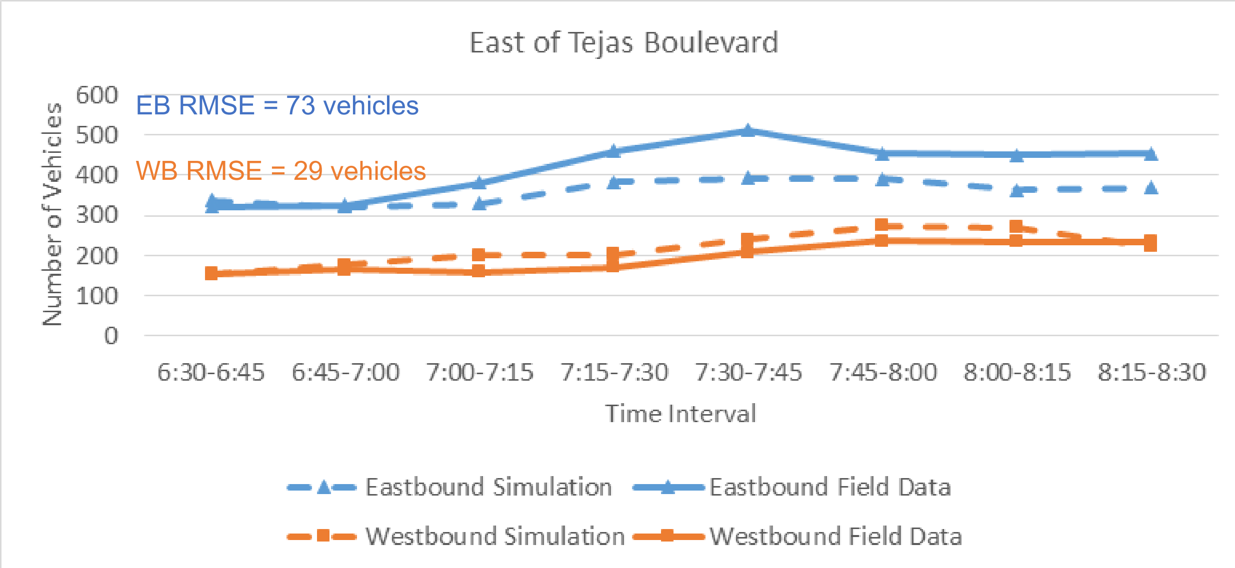
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 9. Comparison of Simulated to Field Measured Traffic Volume West of Walden Road



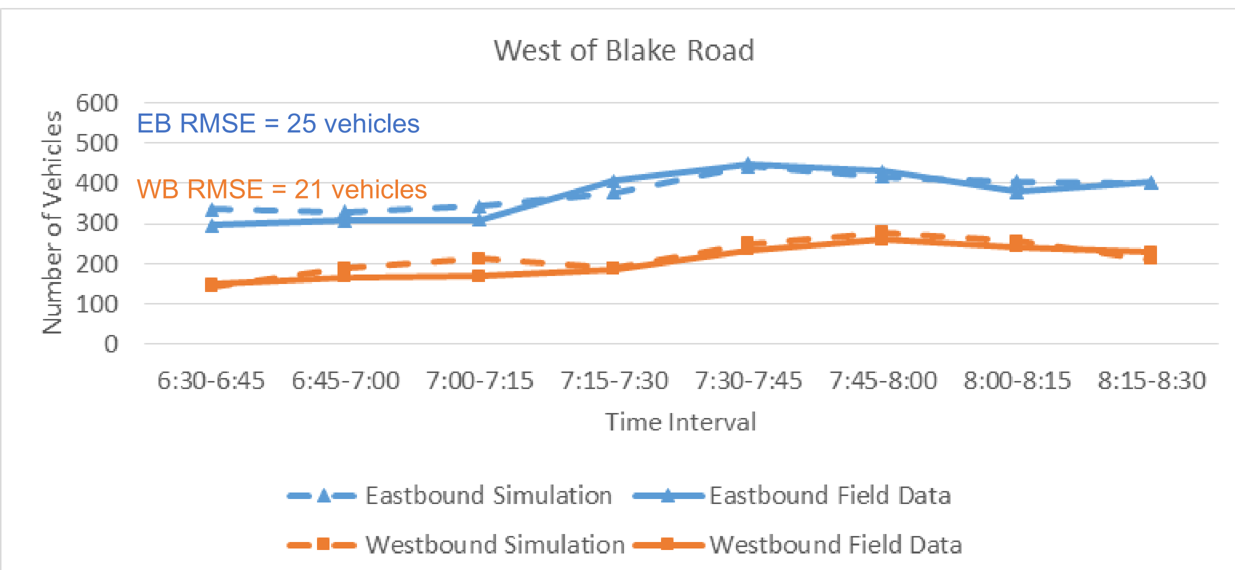
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 10. Comparison of Simulated to Field Measured Traffic Volume West of Lake Conroe Village Boulevard



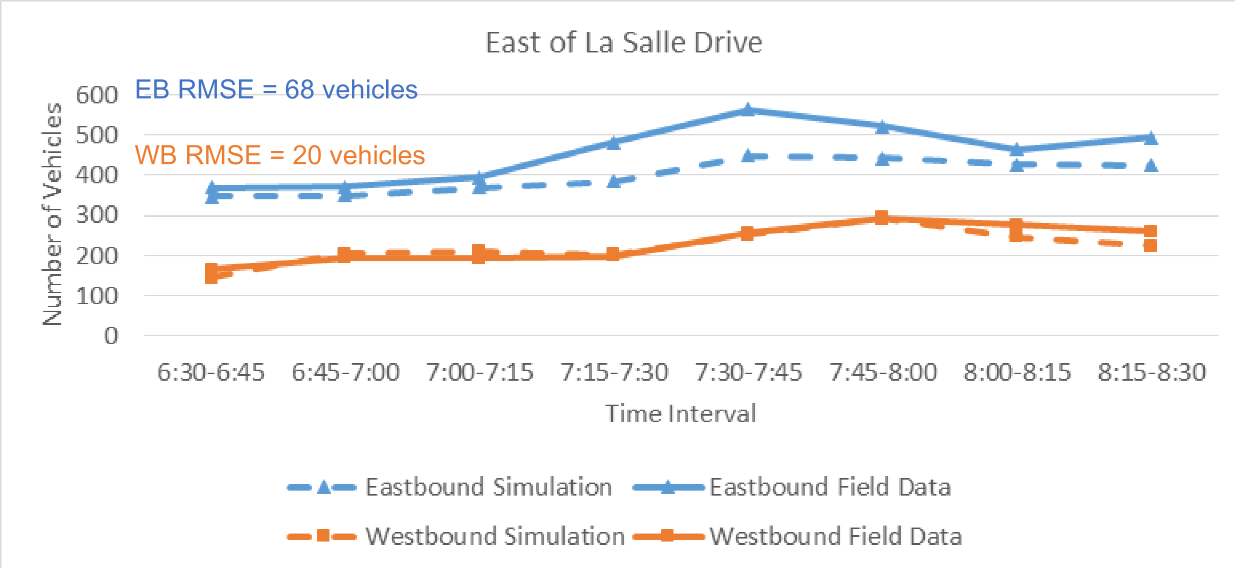
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 11. Comparison of Simulated to Field Measured Traffic Volume East of Tejas Boulevard



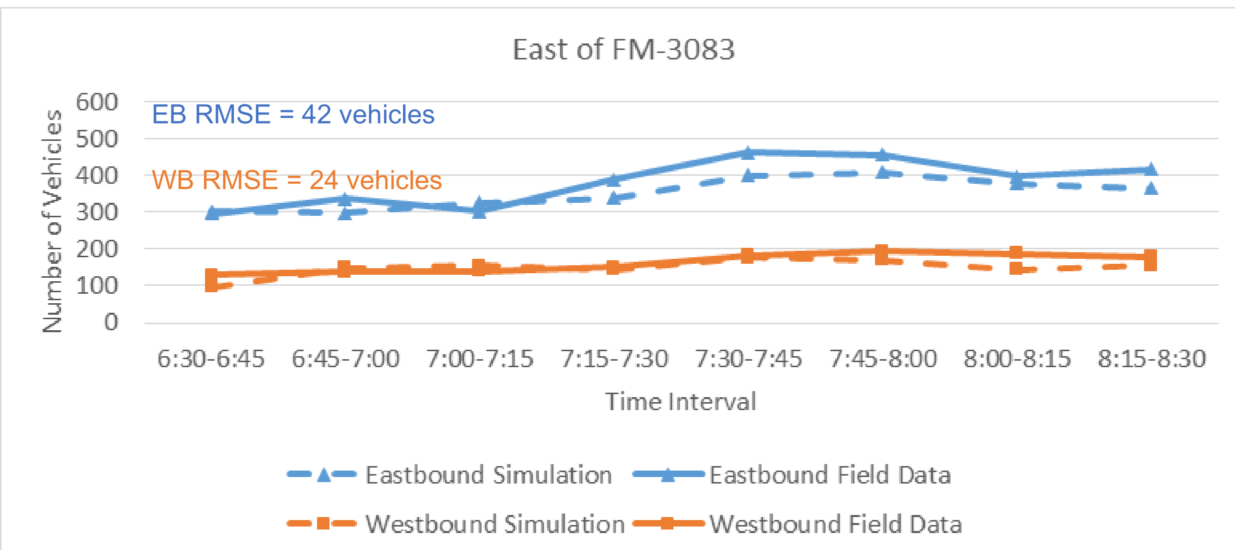
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 12. Comparison of Simulated to Field Measured Traffic Volume West of Blake Road



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

Figure 13. Comparison of Simulated to Field Measured Traffic Volume East of La Salle Drive



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

Figure 14. Comparison of Simulated to Field Measured Traffic Volume East of La Salle Drive

Model Calibration for Travel Times

The research team collected travel time in the corridor to use in calibrating the revised model. The team collected three runs of travel time data in both directions for the A.M. peak and four runs in both directions for the P.M. peak. The team compared the simulated travel times to the field-measured travel time data collected to calibrate the model. Table 5 and Table 6 show the average calibrated and the field-measures travel times for the A.M. and P.M. peaks, respectively.

Table 5. A.M. Peak Period Field Measured Travel Times After Calibration

Direction of Travel	2019 Field Measured Travel Time (sec)	Simulated Travel Times with Revised Acceleration Profile (sec)	Difference (%)
Eastbound	879.0	908.4	3.3
Westbound	893.3	904.3	1.2

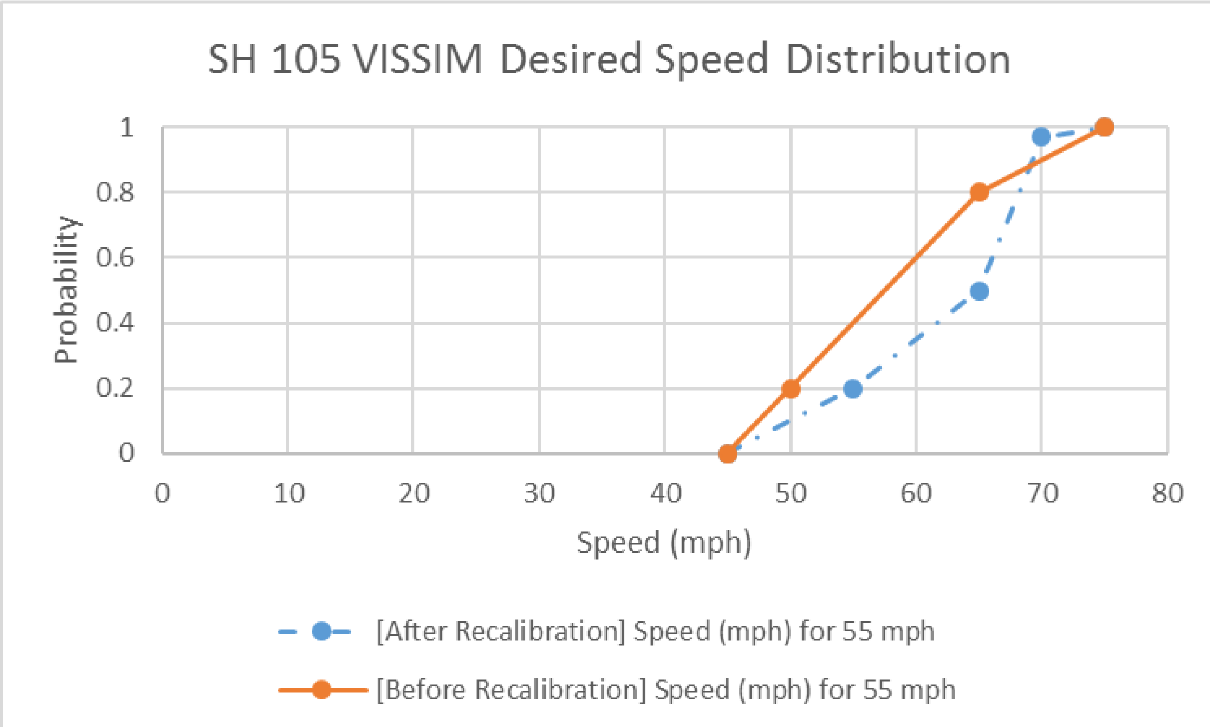
Source: Texas A&M Transportation Institute, 2022

Table 6. P.M. Peak Period Field Measured Travel Times and Travel Times After Calibration

Direction of Travel	2019 Field Measured Travel Time (sec)	Simulated Travel Times w/ Revised Acceleration Profile (sec)	Difference (%)
Eastbound	951.7	1,108.8	16.5
Westbound	972.0	995.3	2.4

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

To decrease the travel time from simulation for calibration, the research team then modified the desired speed profile in VISSIM for the baseline traffic as shown in Figure 15. The recalibration effort increased the average speeds of vehicles to match the travel times recorded in the field. Both A.M. and P.M. peak simulations used the recalibrated desired speed distribution in Figure 15.



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

Figure 15. Speed Profiles for Before and After Recalibration

With the recalibrated model, the travel times from simulations are close to the travel times collected in field study and within the 10 % difference (See Table 5).

Simulation Experimental Plan

Table 7 contains the simulation scenarios and default settings for the SH105 corridor benefits assessment.

Table 7. Base Settings for Intersection Pair Simulation Experiments

Variables	Experimental Settings
TOSCo MPR	• 0% (baseline) • 10% • 20% • 30% • 40% • 50% • 70% • 90% • 100%
Vehicle volumes	• A.M. Peak • P.M. Peak
Signal Operation	Coordinated Actuated Control – with Min Recalls
Speed limit	55 mph
Desired Speeds	Calibrated Speeds
TOSCo Settings	• Coordinated Launch ON • Maximum Acceleration: 1.5 m/s^2 • Maximum Deceleration: -3 m/s^2 • TOSCo Optimization Range: 300 meters • TOSCo Time Gap: 1 second

Source: Texas A&M Transportation Institute (TTI), 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.
- Throughput (at each intersection)
- Average and Maximum Queue Length

These performance metrics allow the research team to evaluate the impacts of TOSCo on SH105 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.

Chapter 5. State Highway 105 Model Assessment

This chapter discusses the simulation results of SH105 for select intersections and the whole corridor. The evaluation covers both peak periods and focuses on the corridor performance. These simulations cover the A.M. and P.M. peak period and cover a range of market penetration rates (MPR) from 0, also considered the baseline, to 100 % MPR of TOSCo. Below is a list of a few settings in the simulation used for this analysis:

- The high-speed corridor uses signal timing from the City of Conroe to represent the SH105 corridor with minimum recalls placed on the non-coordinated phases.
- This high-speed corridor model included truck volumes in the analysis to represent SH105. The truck percentage on SH105 in the A.M. peak is about 3 percent of the traffic.
- Each simulation scenario has five simulation seeds to help account for randomness in the model.
- Each simulation run on SH105 is 8,100 simulation seconds, with a 900 second warm-up period and a 7,200 simulation second data collection period.

The A.M. and P.M. peak period results focus on three different types of information. First, the report reviews the data collected at select intersections along the facility. The team selected three intersections of interest across the corridor based on queueing and delay data. The three intersections, which are shown on the map in Figure 16, are Old River Road West Fork Boulevard, and Loop 336. Next is a summary of the eastbound and westbound performance for vehicles that travel the length of the corridor. Third, the respective A.M. and P.M. peak sections of this chapter summarize the network-wide performance metrics for the SH105 facility across the different market penetration rates.

Source: Imagery ©2021 Google. Map Data ©2021 Google, 2021

Figure 16. Location of Intersections of Interest along SH105

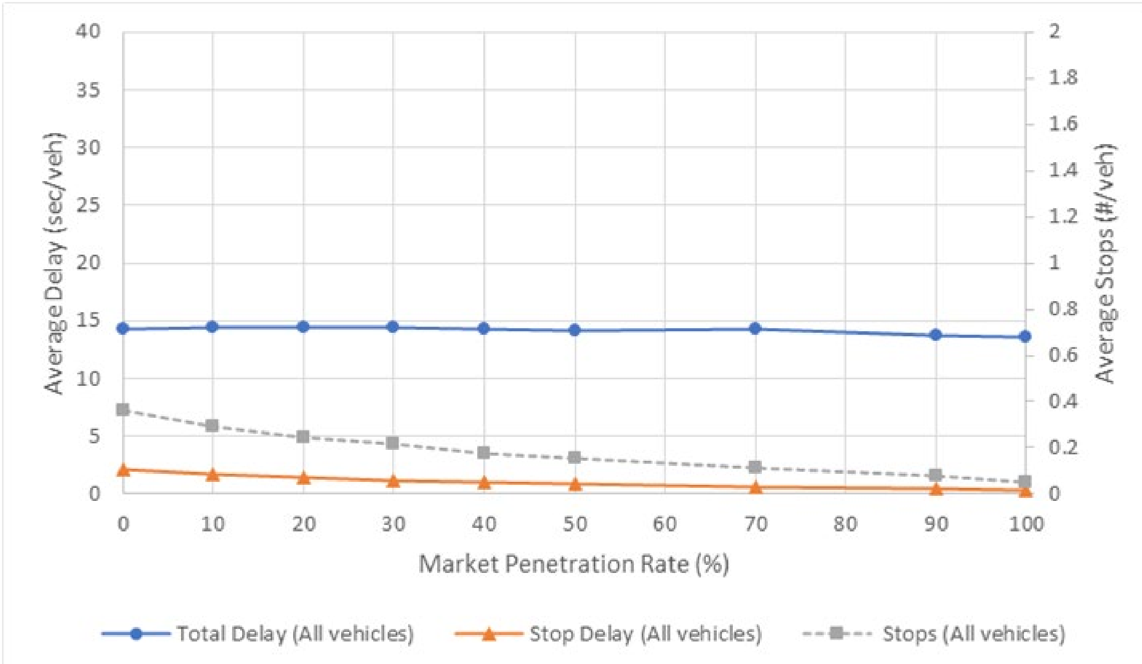
A.M. Peak Period Performance Results

The A.M. peak period for the SH105 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 A.M. peak are such that the eastbound direction of travel, towards Houston, Texas, is the peak direction of travel. There are some that have left turn movements in the A.M. peak period, especially at the eastbound West Fork Boulevard intersection. The following sections describe performance metrics for the intersections, through traffic on the corridor, and the entire corridor as a whole.

Performance at a Single Intersection

Intersection 1: Old River Road and SH105

The intersection of Old River Road and SH105 has about 3,200 feet between the upstream intersection to the east and over 2 miles to the next intersection to the west. The research team selected Old River Road as an intersection of interest because it has some of the higher queues in the P.M. peak period. The delay measurements and stops recorded for eastbound Old River Road are given in Figure 17 and Tables 8 to Table 10.



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

Figure 17. Impacts of TOSCo on A.M. Peak Mobility—Old River Road Intersection (Eastbound)

Table 8. Comparison of Total Delay at Old River Road – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	14.3	—	0.53	—
10	14.4	0.4%	0.46	0.861
20	14.4	0.5%	0.57	0.866
30	14.5	1.1%	0.61	0.706
40	14.3	-0.3%	0.56	0.888
50	14.1	-1.4%	0.55	0.532
70	14.3	-0.1%	0.38	0.941
90	13.8	-3.8%	0.24	0.076
100	13.6	-5.2%	0.35	0.091

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 9. Comparison of Stop Delay at Old River Road – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	2.1	—	0.30	—
10	1.7	-20.9%	0.24	0.038
20	1.4	-36.3%	0.16	0.004
30	1.2	-43.7%	0.19	0.002
40	1.0	-54.5%	0.15	0.001
50	0.8	-62.0%	0.10	<0.001
70	0.6	-73.8%	0.09	<0.001
90	0.4	-81.4%	0.04	<0.001
100	0.3	-86.1%	0.03	<0.001

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

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

Table 10. Comparison of Number of Stops per Vehicle at Old River Road – A.M. Peak, All Vehicle Types (Eastbound)

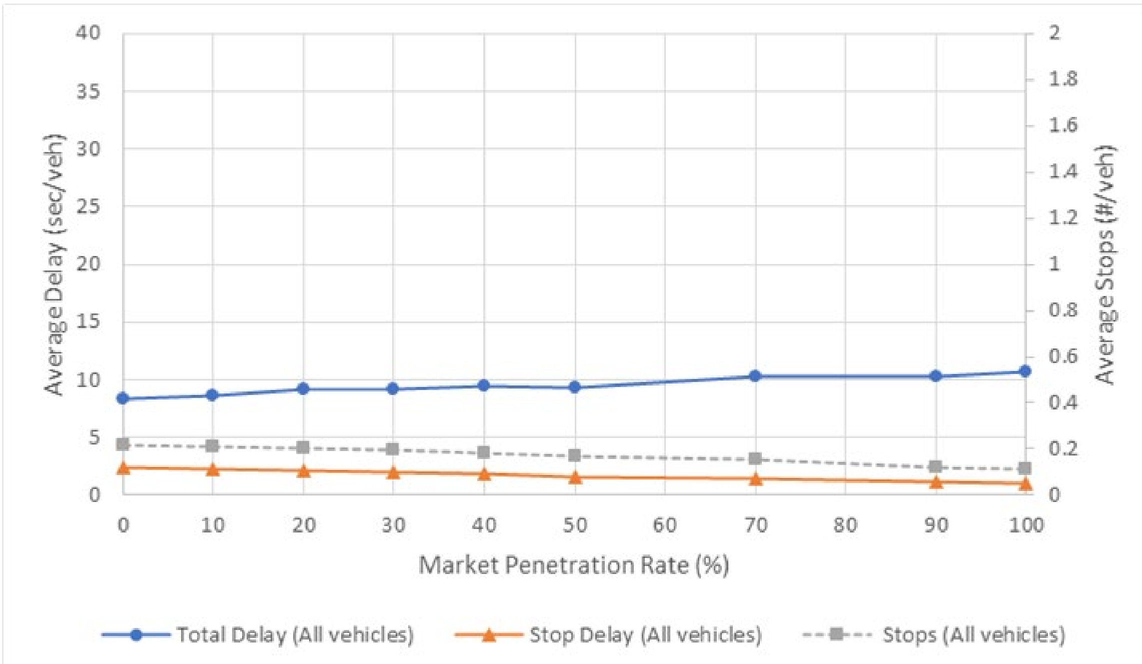
Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.36	—	0.036	—
10	0.29	-18.8%	0.019	0.017
20	0.24	-32.4%	0.021	0.001
30	0.22	-40.4%	0.026	0.002
40	0.18	-50.6%	0.013	<0.001
50	0.16	-56.5%	0.011	<0.001
70	0.11	-69.1%	0.003	<0.001
90	0.08	-77.9%	0.002	<0.001
100	0.05	-85.9%	0.003	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

As market penetration increases, there is a decrease of total delay of 1.0 seconds per vehicle and a decrease in stop delay of 1.8 seconds per vehicle. There is a steady decline in the stop delay and stops per vehicle in the eastbound direction between the baseline and 100 % market penetration rate. These benefits do not represent a very large change in the overall delay for vehicles that travel across the corridor.

Figure 18 and Table 11 to Table 13 show the westbound delays and stops at the Old River Road intersection. The westbound total delay for Old River Road increases slightly as MPR increases. Stop delay drops 1.4 seconds per vehicle, and the number of stops drops gradually.



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

Figure 18. Impacts of TOSCo on A.M. Peak Mobility—Old River Road Intersection (Westbound)

Table 11. Comparison of Total Delay at Old River Road – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	8.3	—	0.68	—
10	8.6	3.8%	0.55	0.428
20	9.2	11.0%	0.42	0.131
30	9.2	10.9%	0.75	0.073
40	9.4	13.5%	0.68	0.075
50	9.3	12.8%	0.60	0.051
70	10.2	23.4%	0.57	<0.001
90	10.3	24.5%	0.41	0.001
100	10.7	28.9%	0.44	0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 12. Comparison of Stop Delay at Old River Road – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	2.4	—	0.26	—
10	2.3	-5.1%	0.25	0.507
20	2.2	-8.9%	0.16	0.317
30	2.0	-16.6%	0.19	0.086
40	1.8	-24.2%	0.17	0.024
50	1.6	-31.1%	0.15	0.003
70	1.5	-38.2%	0.16	<0.001
90	1.2	-51.1%	0.08	<0.001
100	1.1	-55.4%	0.10	0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

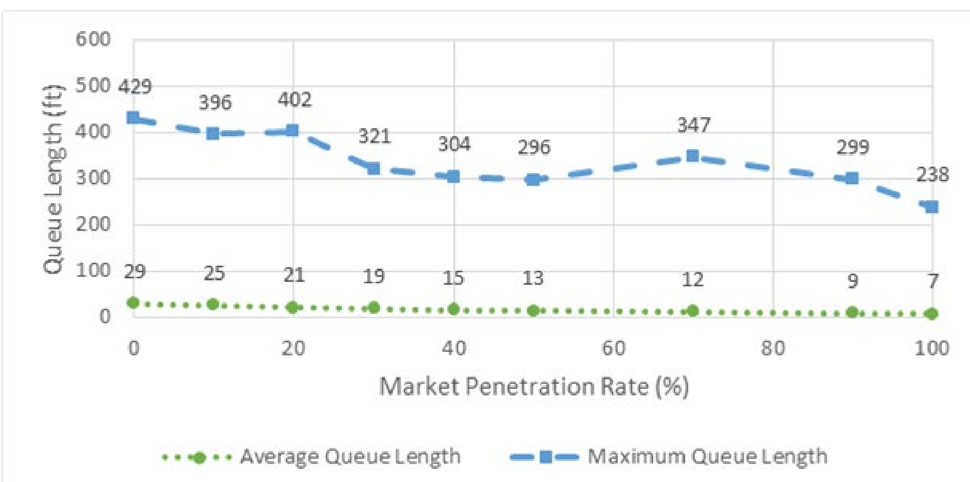
Table 13. Comparison of Number of Stops per Vehicle at Old River Rd. – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.21	—	0.017	—
10	0.21	-1.9%	0.016	0.708
20	0.20	-5.0%	0.017	0.495
30	0.19	-9.5%	0.016	0.087
40	0.18	-16.7%	0.018	0.049
50	0.17	-21.6%	0.011	0.006
70	0.15	-28.6%	0.017	<0.001
90	0.12	-43.6%	0.008	<0.001
100	0.11	-46.8%	0.006	<0.001

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

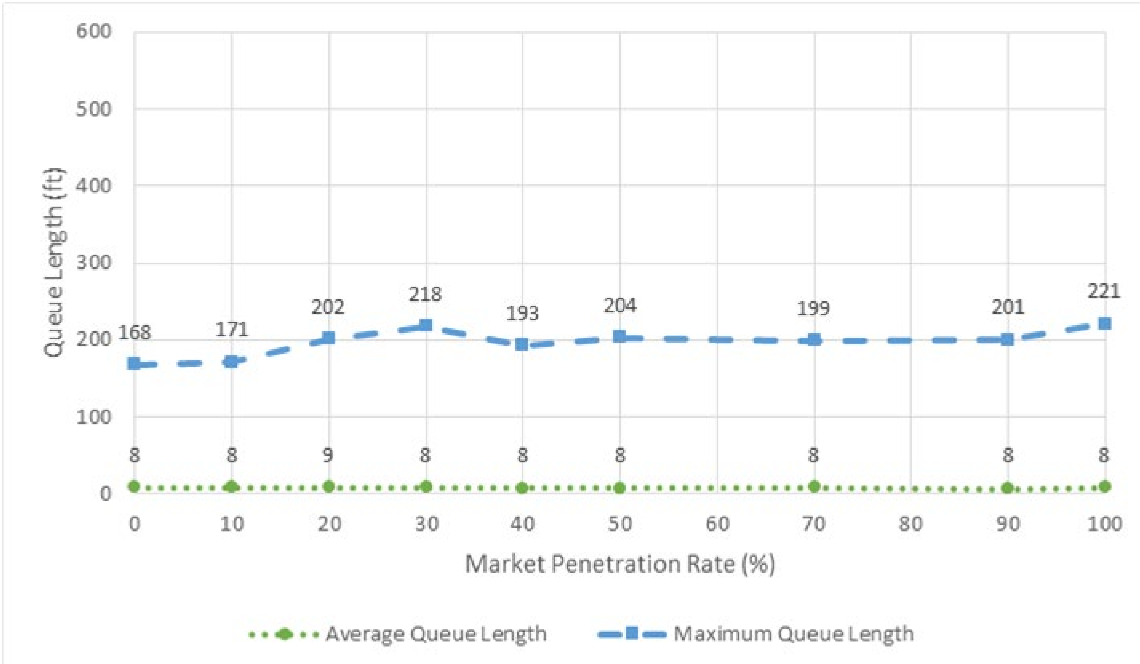
Source: Texas A&M Transportation Institute (TTI), 2022

The simulation recorded the average and maximum queue lengths for each direction at each intersection. Figure 19 and Figure 20 show the average and maximum queue length values for eastbound and westbound traffic, respectively, at Old River Road, averaged for the 5 simulation runs.



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

Figure 19. Queue Length Measurements for A.M. Peak Traffic at SH105 and Old River Road (Eastbound)



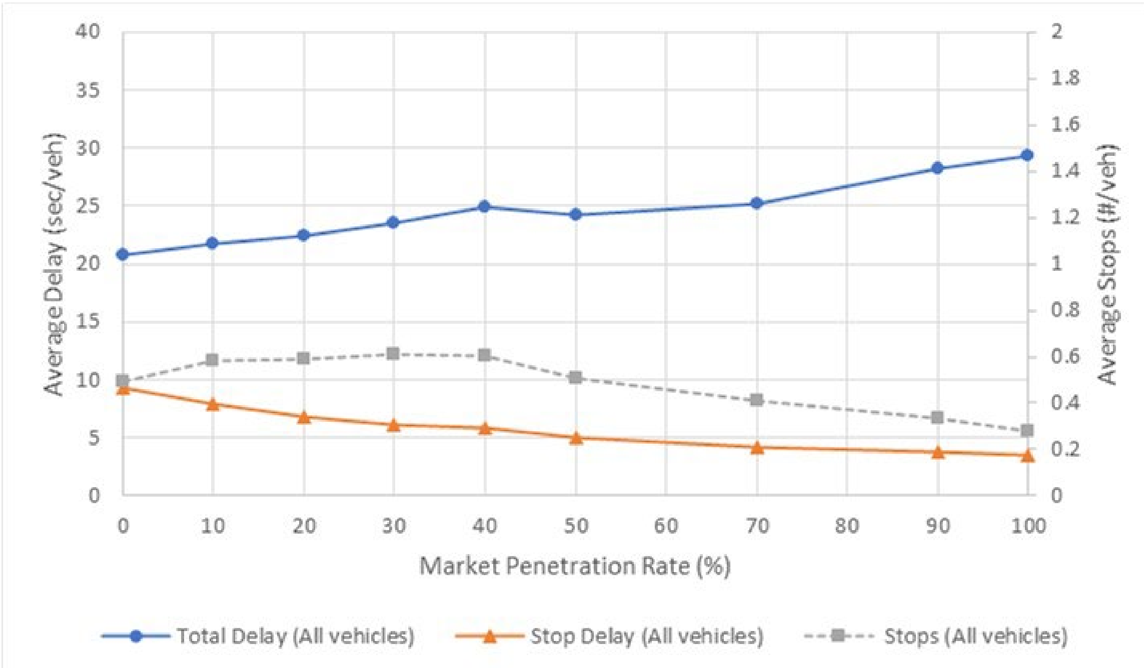
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 20. Queue Length Measurements for A.M. Peak Traffic at SH105 and Old River Road (Westbound)

Old River Road does experience some large queues in the A.M. peak period, but the average queue remains very short. The queueing in the eastbound direction does reduce as TOSCo market penetration increases. On the other hand, the westbound queueing at Old River Road experiences no change in average queue and a slight increase in the maximum queue of about 20 ft, which is about one car length.

Intersection 2: West Fork Boulevard and SH105

The next intersection of interest is SH105 and West Fork Boulevard (also known as FM 3083). This intersection has a little over 4,000 foot distance to the next intersections in each direction. West Fork Boulevard is of interest for the A.M. peak period because there is a significant eastbound left-turn movement which generates some weaving along the approach. Figure 21 and Table 14 through Table 16 show the potential mobility benefits resulting from deploying TOSCo at the West Fork Boulevard intersection.



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

Figure 21. Impacts of TOSCo on A.M. Peak Mobility - West Fork Boulevard Intersection (Eastbound)

Table 14. Comparison of Total Delay at West Fork Boulevard – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	20.8	—		—
10	21.7	4.1%		0.278
20	22.4	7.5%		0.186
30	23.6	13.4%		0.120
40	25.0	19.9%		0.003
50	24.3	16.6%		0.083
70	25.2	21.2%		0.015
90	28.2	35.5%		0.001
100	29.4	41.2%		0.010

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 15. Comparison of Stop Delay at West Fork Boulevard – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	9.3	—	0.79	—
10	7.9	-14.9%	0.77	0.012
20	6.8	-27.0%	0.46	0.002
30	6.2	-33.7%	0.79	0.004
40	5.9	-37.3%	0.24	0.001
50	5.0	-46.9%	0.39	<0.001
70	4.2	-54.8%	0.35	<0.001
90	3.8	-59.2%	0.43	<0.001
100	3.5	-62.8%	0.42	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 16. Comparison of Number of Stops per Vehicle at West Fork Boulevard – A.M. Peak, All Vehicle Types (Eastbound)

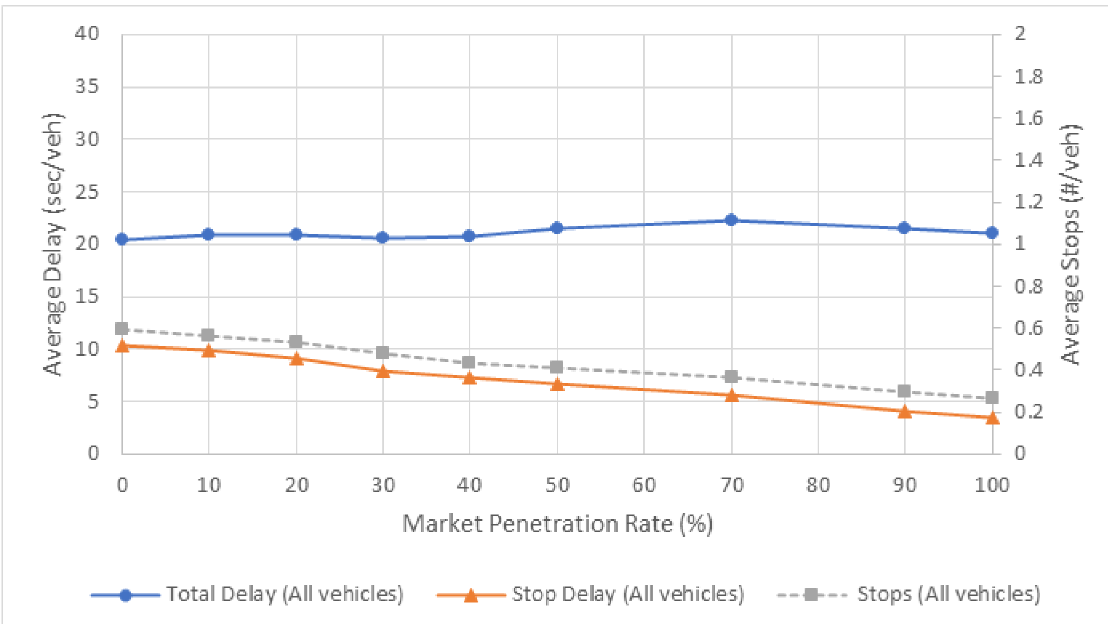
Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.49	—	0.021	—
10	0.58	17.9%	0.071	0.020
20	0.59	19.5%	0.070	0.018
30	0.61	23.6%	0.108	0.049
40	0.60	21.6%	0.046	0.003
50	0.51	3.1%	0.061	0.575
70	0.41	-17.1%	0.043	0.005
90	0.34	-31.8%	0.047	<0.001
100	0.28	-43.8%	0.028	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

The average eastbound total delay for vehicles on West Fork Boulevard increases by approximately 9 seconds per vehicle as market penetration goes from zero to 100 % in the A.M. peak period. However, the stops and stop delay both gradually decrease by more than half as market penetration increases.

Figure 22 and Table 17 to Table 19 show the westbound direction delay measurements and stops for West Fork Boulevard. The westbound direction of travel at West Fork Boulevard and SH105 does not experience much delay, amounting to less than 23 seconds of total delay across all market penetration rates. There is a slight increase of total delay as TOSCo MPR increases, but the increase amounts to less than 2 seconds as compared to the baseline scenario. Both stops and stop delay decrease gradually by more than half between the baseline and 100 % TOSCo MPR.



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

Figure 22. Impacts of TOSCo on A.M. Peak Mobility - West Fork Boulevard Intersection (Westbound)

Table 17. Comparison of Total Delay at West Fork Boulevard – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	20.5	—	0.59	—
10	20.9	1.9%	0.45	0.309
20	20.9	1.8%	0.65	0.417
30	20.5	0.3%	0.87	0.883
40	20.8	1.6%	1.40	0.661
50	21.5	4.7%	0.72	0.101
70	22.2	8.4%	0.96	0.037
90	21.6	5.3%	0.50	0.059
100	21.1	3.0%	0.55	0.055

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 18. Comparison of Stop Delay at West Fork Boulevard – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	10.4	—	0.52	—
10	9.9	-5.2%	0.33	0.133
20	9.1	-12.6%	0.49	0.024
30	7.9	-24.0%	0.56	0.003
40	7.3	-30.4%	0.83	0.003
50	6.7	-36.1%	0.50	0.001
70	5.6	-46.6%	0.38	<0.001
90	4.2	-60.0%	0.23	<0.001
100	3.5	-66.2%	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] Two-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 (TTI), 2022

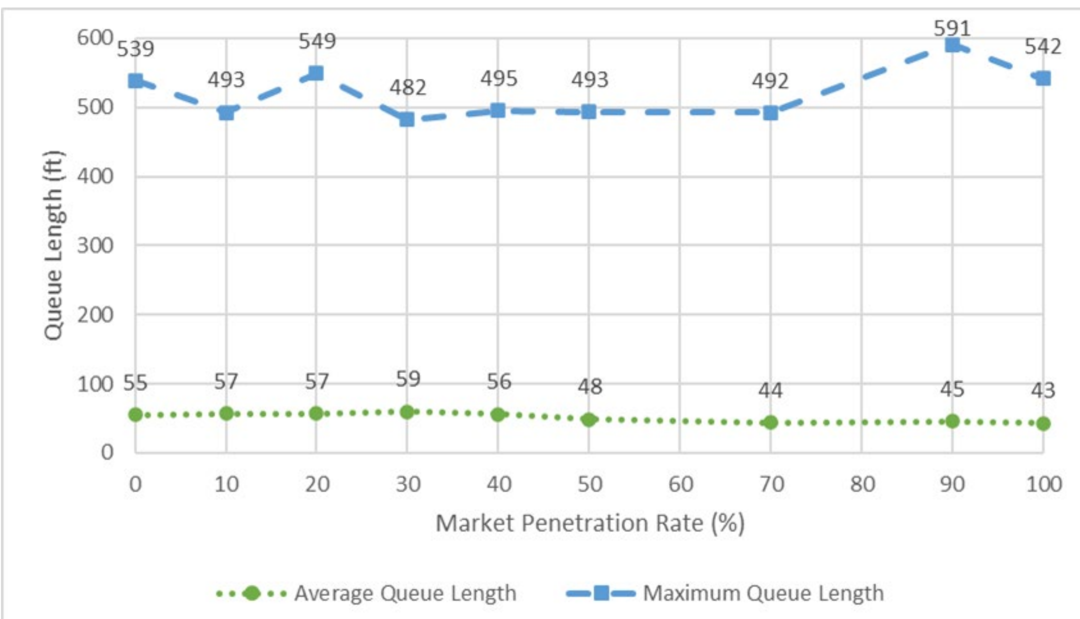
Table 19. Comparison of Number of Stops per Vehicle at West Fork Boulevard – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.59	—	0.020	—
10	0.56	-5.2%	0.014	0.056
20	0.53	-10.6%	0.032	0.022
30	0.48	-19.6%	0.026	0.002
40	0.44	-26.1%	0.024	0.001
50	0.41	-30.9%	0.014	<0.001
70	0.36	-38.7%	0.018	<0.001
90	0.30	-49.9%	0.008	<0.001
100	0.27	-55.2%	0.010	<0.001

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

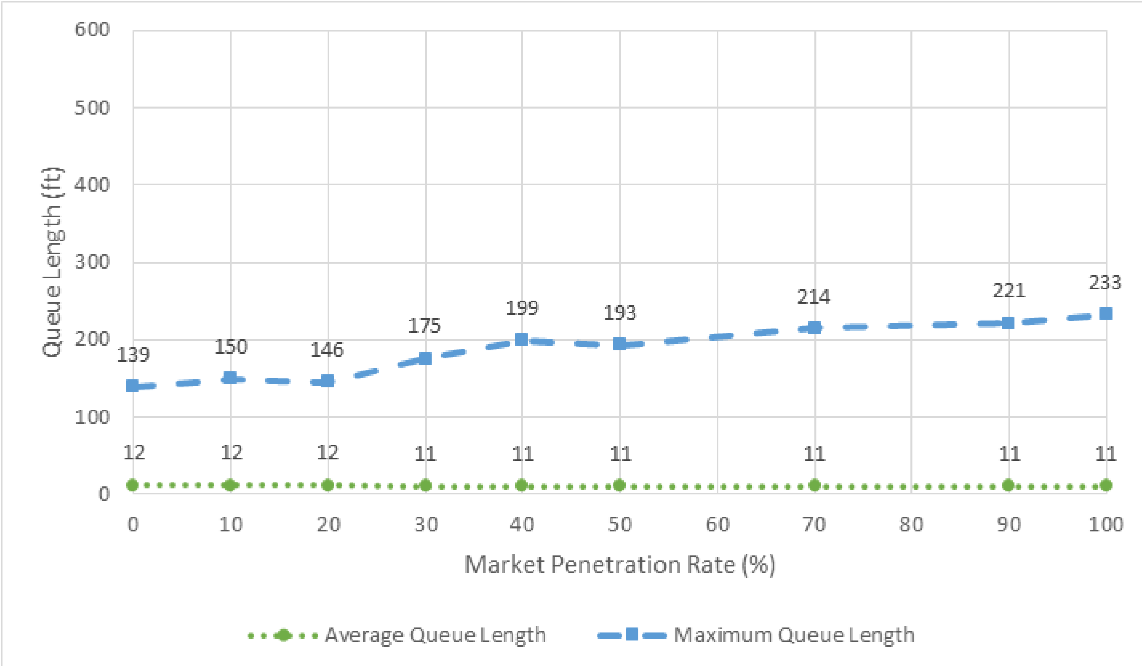
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 25 and Figure 26 contain the maximum and average queue lengths recorded for West Fork Boulevard in the eastbound and westbound direction.



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

Figure 23. Queue Length Measurements for A.M. Peak Traffic at SH105 and West Fork Boulevard (Eastbound)



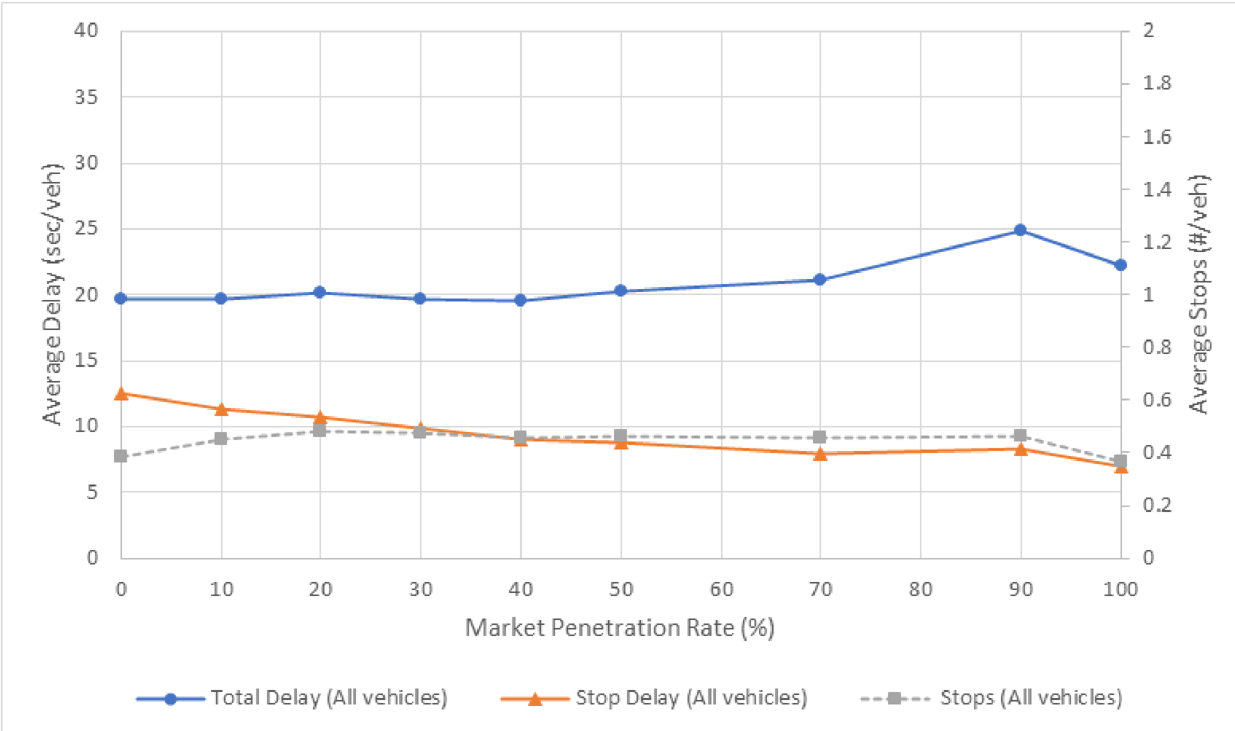
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 24. Queue Length Measurements for A.M. Peak Traffic at SH105 and West Fork Boulevard (Westbound)

Neither the eastbound nor the westbound direction of travel at West Fork Boulevard experience a change in average queue length that is greater than one car length. The eastbound average queue length at West Fork Boulevard does decrease by about 12 feet between the zero and the 100 % MPR. The maximum queue length for the eastbound direction varies across market penetration but by no more than 60 feet, which is about 3 car lengths.

Intersection 3: Loop 336 and SH105

Loop 336 is the farthest east intersection of the study section of SH105. This intersection has high volumes because all the vehicles going eastbound, towards Houston, have accumulated from the rest of the study section. Figure 25 and Table 20 through Table 22 show the delays and number of stops per vehicle for the eastbound traffic on Loop 336.



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

Figure 25. Impacts of TOSCo on A.M. Peak Mobility - Loop 336 (Eastbound)

Table 20. Comparison of Total Delay at Loop 336 (West) – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	19.7	—	1.54	—
10	19.7	0.2%	0.33	0.965
20	20.1	2.2%	0.68	0.600
30	19.7	0.1%	0.52	0.985
40	19.5	-0.8%	1.24	0.896
50	20.3	3.0%	1.56	0.522
70	21.1	7.4%	1.75	0.322
90	24.9	26.5%	5.43	0.109
100	22.2	12.8%	2.48	0.117

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 21. Comparison of Stop Delay at Loop 336 (West) – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	12.5	—	1.11	—
10	11.3	-9.2%	0.37	0.108
20	10.7	-14.5%	0.33	0.037
30	9.8	-21.4%	0.37	0.008
40	9.0	-27.7%	0.63	0.007
50	8.7	-29.9%	0.70	0.002
70	8.0	-36.0%	0.67	0.004
90	8.3	-33.2%	1.58	0.010
100	7.0	-43.8%	0.75	0.004

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 22. Comparison of Number of Stops per Vehicle at Loop 336 (West) – A.M. Peak, All Vehicle Types (Eastbound)

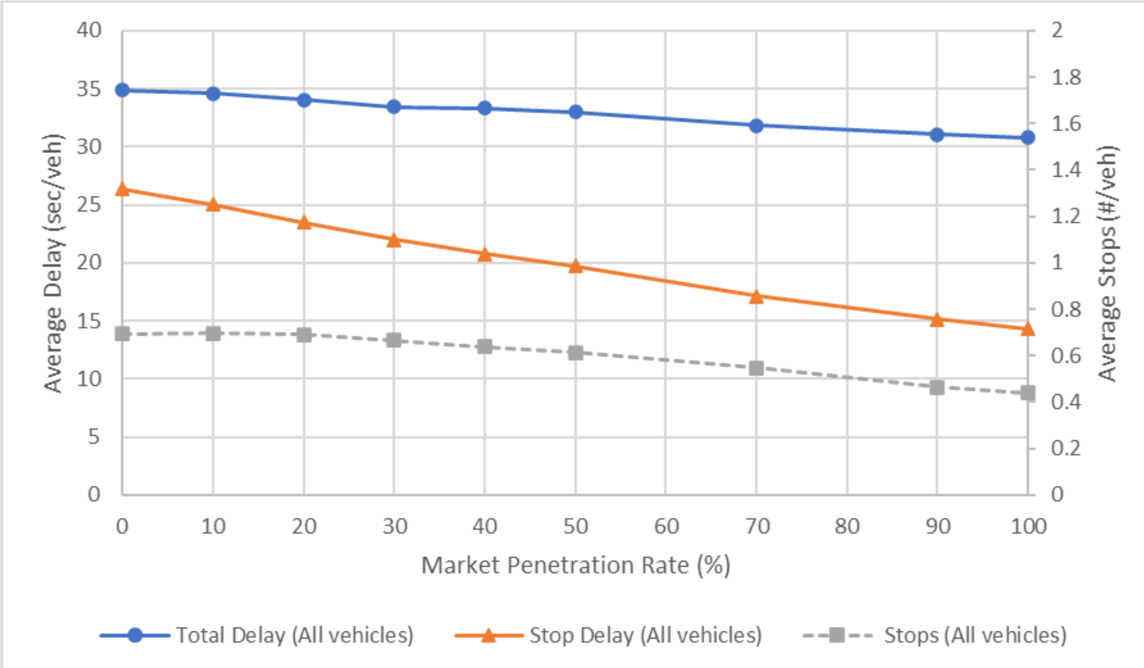
Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.38	—	0.021	—
10	0.46	19.8%	0.012	0.004
20	0.48	25.5%	0.033	0.002
30	0.47	23.5%	0.015	0.001
40	0.46	18.5%	0.047	0.068
50	0.46	20.5%	0.040	0.015
70	0.46	19.2%	0.082	0.144
90	0.47	21.3%	0.135	0.247
100	0.37	-4.5%	0.056	0.781

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

There is a 2.5 second increase in total delay per vehicle and a 5.5 second decrease in stop delay per vehicle between the baseline and 100 % market penetration rate scenarios. The worst case for total delay for the TOSCo vehicles was the 90 % MPR scenario which experienced a 5.2 second increase in total delay but a 4.2 second decrease in stop delay.

Figure 26 and Table 23 to Table 25 contain the Loop 336 westbound delays and stops per vehicle. The westbound Loop 336 total decrease by about 3 seconds per vehicle and the stop delays and stops reduce by 16.4 seconds per vehicle and 0.26 stops per vehicle, respectively.



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

Figure 26. Impacts of TOSCo on A.M. Peak Mobility— Loop 336 (Westbound)

Table 23. Comparison of Total Delay at Loop 336 (West) – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	34.9	—	1.07	—
10	34.6	-0.7%	0.87	0.646
20	34.1	-2.3%	1.12	0.329
30	33.5	-4.1%	1.09	0.122
40	33.3	-4.4%	0.86	0.069
50	33.0	-5.3%	1.00	0.049
70	31.8	-8.7%	1.28	0.015
90	31.1	-10.9%	1.38	0.011
100	30.8	-11.7%	1.36	0.009

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 24. Comparison of Stop Delay at Loop 336 (West) – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	26.4	—	0.92	—
10	25.1	-5.0%	0.73	0.037
20	23.5	-10.9%	0.83	0.006
30	22.0	-16.6%	0.78	0.001
40	20.8	-21.3%	0.61	<0.001
50	19.7	-25.2	0.59	<0.001
70	17.1	-35.0%	0.81	<0.001
90	15.2	-42.5%	0.74	<0.001
100	15.0	-43.2%	0.60	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

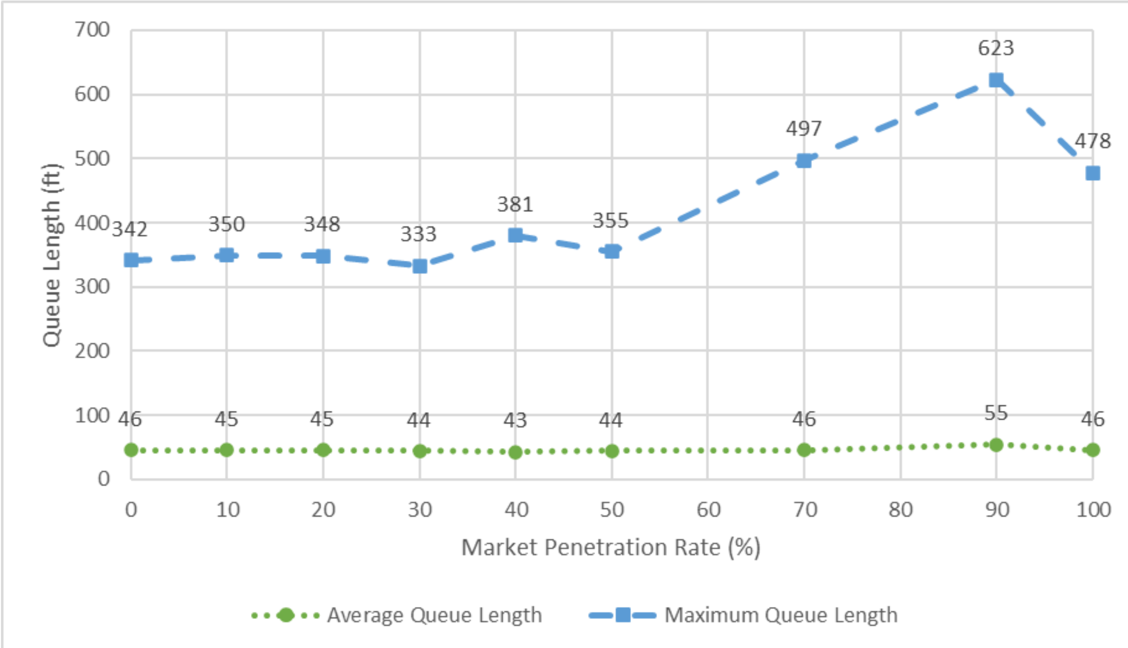
Table 25. Comparison of Number of Stops per Vehicle at Loop 366 (West) – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.70	—	0.027	—
10	0.70	0.3%	0.030	0.934
20	0.69	-0.4%	0.050	0.933
30	0.67	-4.3%	0.027	0.235
40	0.64	-8.0%	0.036	0.061
50	0.61	-11.8%	0.030	0.013
70	0.55	-21.3%	0.026	0.002
90	0.46	-33.1%	0.023	<0.001
100	0.44	-36.7%	0.020	<0.001

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

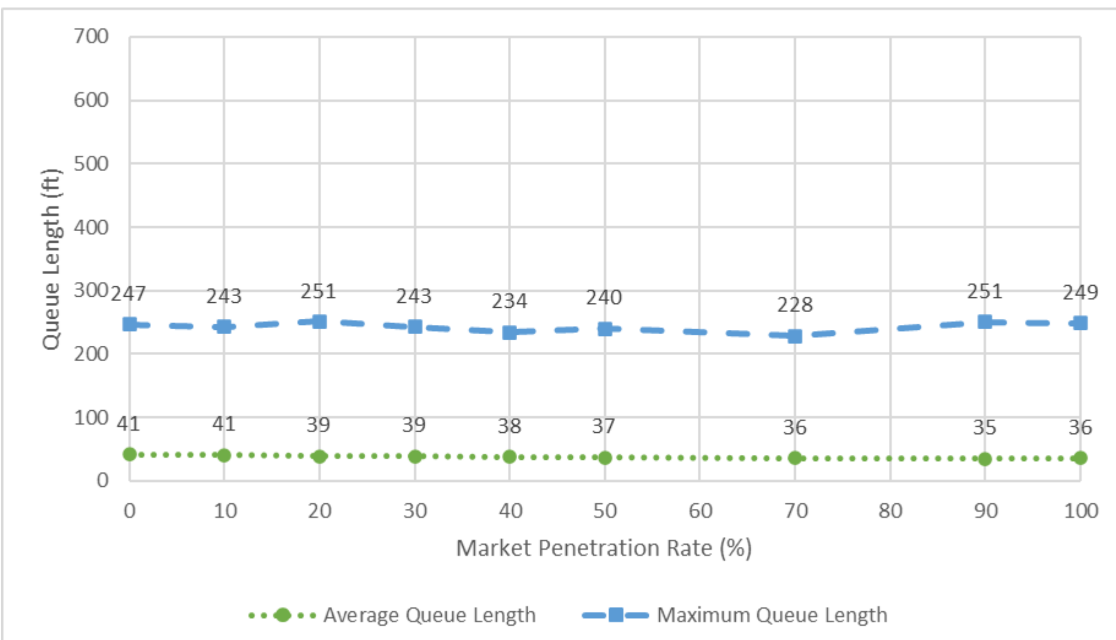
Source: Texas A&M Transportation Institute (TTI), 2022

The average and maximum queues at Loop 336 are shown in Figure 27 and Figure 28. The average queue length means remain constant in for both directions. The maximum queue length increases substantially in the eastbound direction and remains steady in the westbound direction as MPR increases.



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

Figure 27. Queue Length Measurements for A.M. Peak Traffic at SH105 and Loop 336 (Eastbound)



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

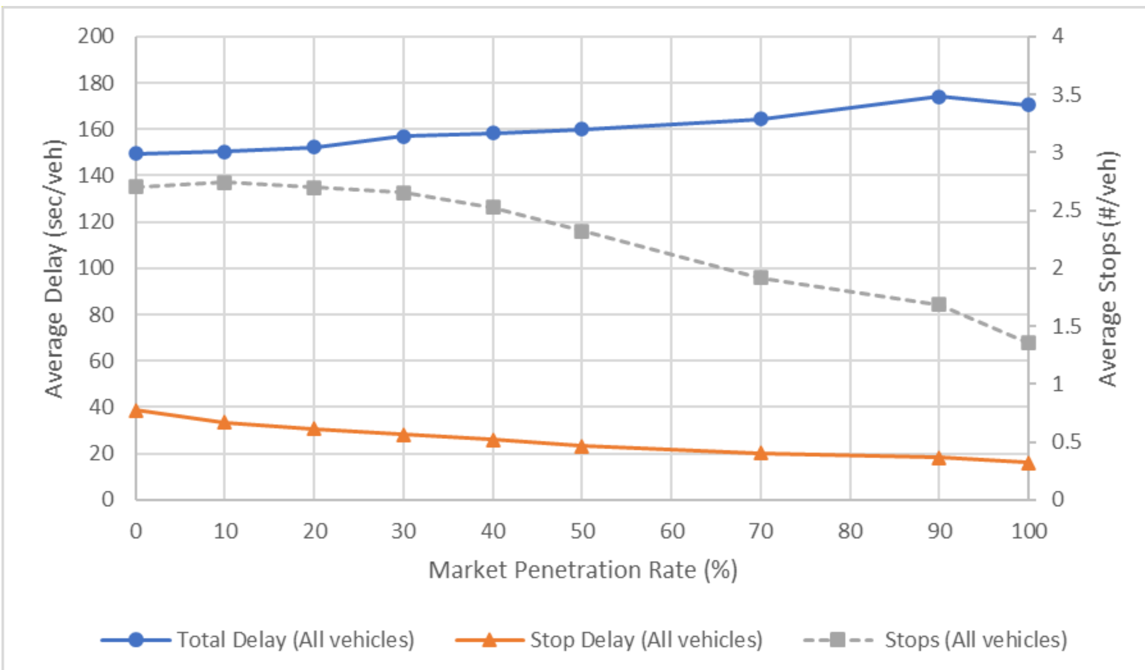
Figure 28. Queue Length Measurements for A.M. Peak Traffic at SH105 and Loop 336 (Westbound)

Corridor Performance

This section discusses the performance measures from the standpoint of a commuter traveling from one end of SH105 to the other in both directions. The performance measures shown are the measurements of the entire trip from end-to-end of the SH105 corridor in each direction.

Cumulative Delays and Stops

Figure 29 shows the total delay, stop delay, and number of stops per vehicle aggregated over all intersections in the corridor in the eastbound direction for various levels of market penetration. Figure 30 shows the changes in the same performance measures aggregated over 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 26 to Table 31 show the values and % changes for Figure 29 and Figure 30.



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

Figure 29. Corridor-level Mobility Measures for SH105 (Eastbound) - All Vehicle Types

Table 26. Comparison of Total Delay at the Corridor Level – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	149.4	—	6.96	—
10	150.5	0.7%	5.45	0.818
20	152.2	1.8%	10.49	0.684
30	156.9	5.0%	8.11	0.250
40	158.5	6.0%	6.47	0.157
50	160.0	7.1%	6.09	0.062
70	164.5	10.1%	5.27	0.036
90	174.0	16.4%	7.96	0.009
100	170.6	14.2%	4.59	0.011

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 27. Comparison of Stop Delay at the Corridor Level – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	38.8	—	2.87	—
10	33.5	-13.7%	1.67	0.017
20	30.7	-20.8%	1.73	0.010
30	28.2	-27.2%	2.20	0.006
40	26.1	-32.8%	2.22	0.003
50	23.4	-39.7%	1.82	0.001
70	20.1	-48.1%	1.45	<0.001
90	18.2	-52.9%	2.26	<0.001
100	16.0	-58.7%	0.83	<0.001

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

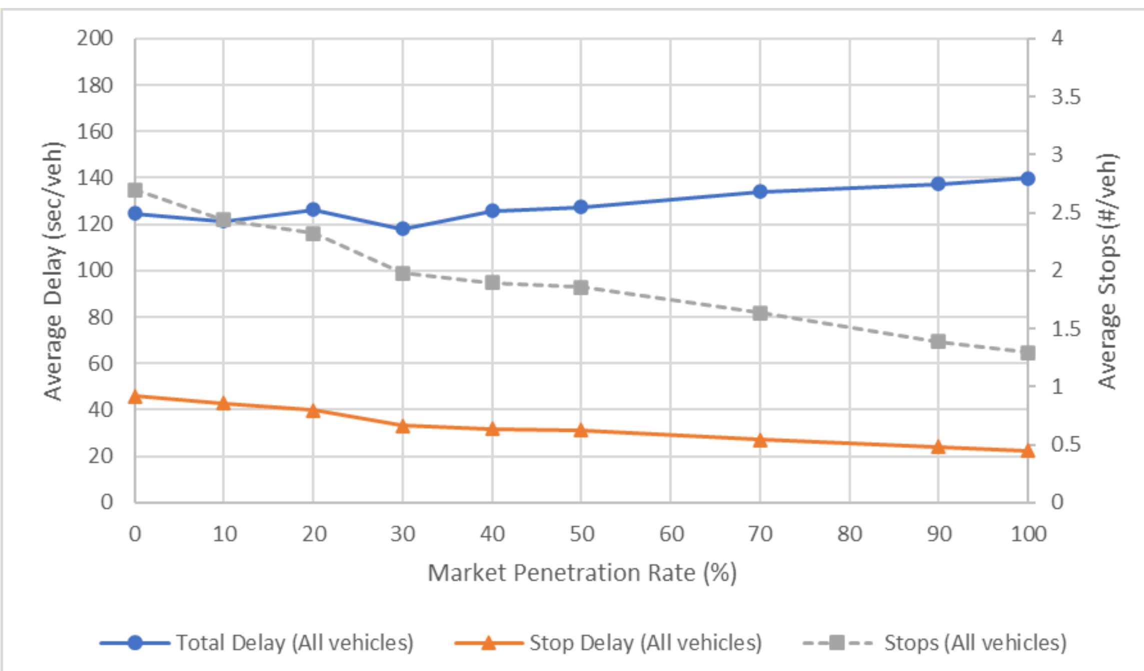
Source: Texas A&M Transportation Institute (TTI), 2022

Table 28. Comparison of Number of Stops per Vehicle at the Corridor Level – A.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	**# of Stops/ Vehicle**	**% Change[1]**	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	2.70	—	0.083	—
10	2.74	1.4%	0.093	0.395
20	2.70	-0.1%	0.265	0.981
30	2.65	-1.8%	0.198	0.677
40	2.53	-6.5%	0.159	0.082
50	2.32	-14.1%	0.154	0.011
70	1.92	-28.9%	0.134	<0.001
90	1.69	-37.6%	0.202	<0.001
100	1.36	-49.8%	0.007	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2]Two-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 (TTI), 2022



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

Figure 30. Corridor-level Mobility Measures for SH105 A.M. Peak (Westbound) - All Vehicle Types

Table 29. Comparison of Total Delay at the Corridor Level – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	124.5	—	3.05	—
10	121.4	-2.6%	3.22	0.120
20	126.5	1.5%	5.33	0.433
30	118.1	-5.2%	7.82	0.205
40	125.9	1.1%	9.04	0.795
50	127.4	2.3%	4.98	0.223
70	133.9	7.5%	4.90	0.024
90	137.5	10.4%	5.03	0.008
100	139.8	12.3%	8.16	0.012

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 30. Comparison of Stop Delay at the Corridor Level – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	46.0	—	1.46	—
10	42.8	-7.0%	3.36	0.087
20	39.9	-13.3%	2.54	0.002
30	33.3	-27.7%	5.60	0.011
40	31.7	-31.0%	4.34	0.003
50	31.3	-32.0%	3.00	<0.001
70	27.1	-41.1%	1.78	<0.001
90	24.1	-47.6%	1.73	<0.001
100	22.4	-51.3%	1.93	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2]Two-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 (TTI), 2022

Table 31. Comparison of Number of Stops per Vehicle at the Corridor Level – A.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	2.70	—	0.127	—
10	2.44	-9.5%	0.125	0.041
20	2.32	-14.0%	0.203	0.020
30	1.98	-26.6%	0.251	0.005
40	1.90	-29.7%	0.243	0.001
50	1.86	-31.1%	0.112	<0.001
70	1.64	-39.2%	0.177	0.001
90	1.39	-48.6%	0.049	<0.001
100	1.29	-52.0%	0.076	<0.001

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

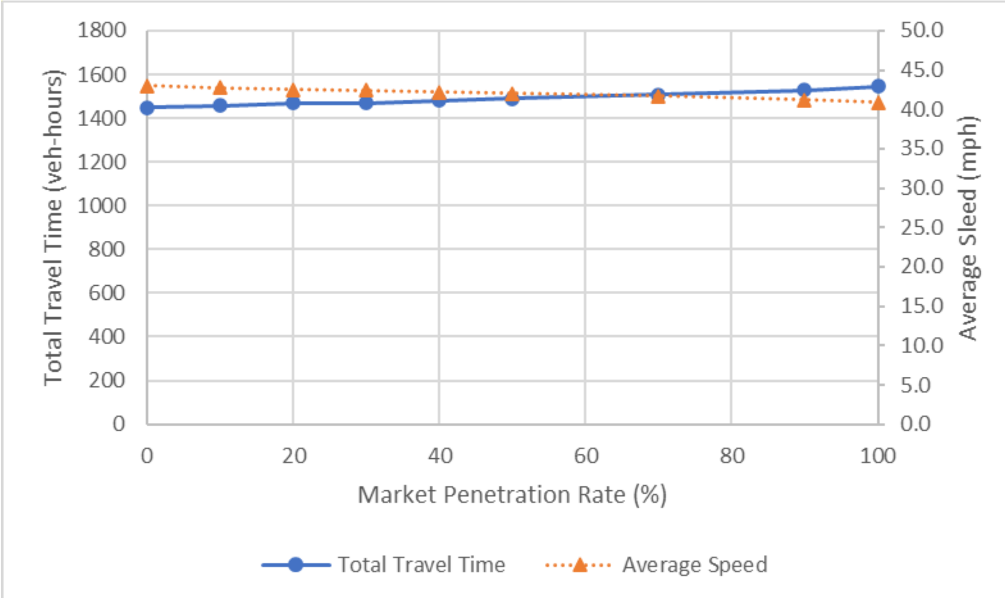
Source: Texas A&M Transportation Institute (TTI), 2022

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 149.4 seconds per vehicle to 170.6 seconds per vehicle. In the westbound direction, the total delay increased from 124.5 seconds per vehicle to 139.8 seconds per vehicle. This change is a 25.9-second increase in the eastbound direction and a 14.4-second increase in the westbound direction. The research expected the increases in total delay given the low volumes and how the 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 amount to only 21.2 and 15.3 seconds per vehicle for eastbound and westbound directions of travel spread over 15 total intersections in a 12-mile long corridor. The travel time for eastbound and westbound traffic is around 900 seconds and 870 seconds for eastbound and westbound vehicles, meaning that 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 TOSCo is in stopped delay and in the average number of stops per vehicle in the corridor. Table 27 and Table 30 show that average stop delay per vehicle in the corridor decreased by activating TOSCo. Stopped delay decreased by 22.8 and 23.6 seconds per vehicle in the eastbound and westbound directions of travel, respectively. The average number of stops per vehicle decreased from 2.70 stops per vehicle to 1.69 in the eastbound direction and from 2.70 stops per vehicle to 1.29 stops per vehicle in the westbound direction.

Total Travel Time and Average Speed

Figure 31 and Table 32 through Table 33 show the total travel time and average speeds on SH105. There are decreases in average speeds and increases in total travel time up to 6.6 % as the market penetration of TOSCo vehicle increased.



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

Figure 31. Total Vehicle Hours Traveled and Average Speeds for SH105 in Conroe, Texas - A.M. Peak Period

Table 32. A.M. Peak Period Total Vehicle Hours Traveled on SH105 Corridor

MPR (%)	Total Travel Time (veh-hours)	% Change[1]	Standard Deviation (veh-hours)	Statistical Significance (p-value)[2]
0	1449	—	21	—
10	1457	0.5%	22	0.636
20	1470	1.4%	18	0.207
30	1470	1.4%	20	0.216
40	1481	2.2%	19	0.090
50	1489	2.7%	15	0.036
70	1507	4.0%	14	0.011
90	1528	5.4%	13	0.003
100	1545	6.6%	11	0.003

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

[2] Two-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 (TTI), 2022

Table 33. A.M. Peak Period Average Speed Values for SH105 Corridor

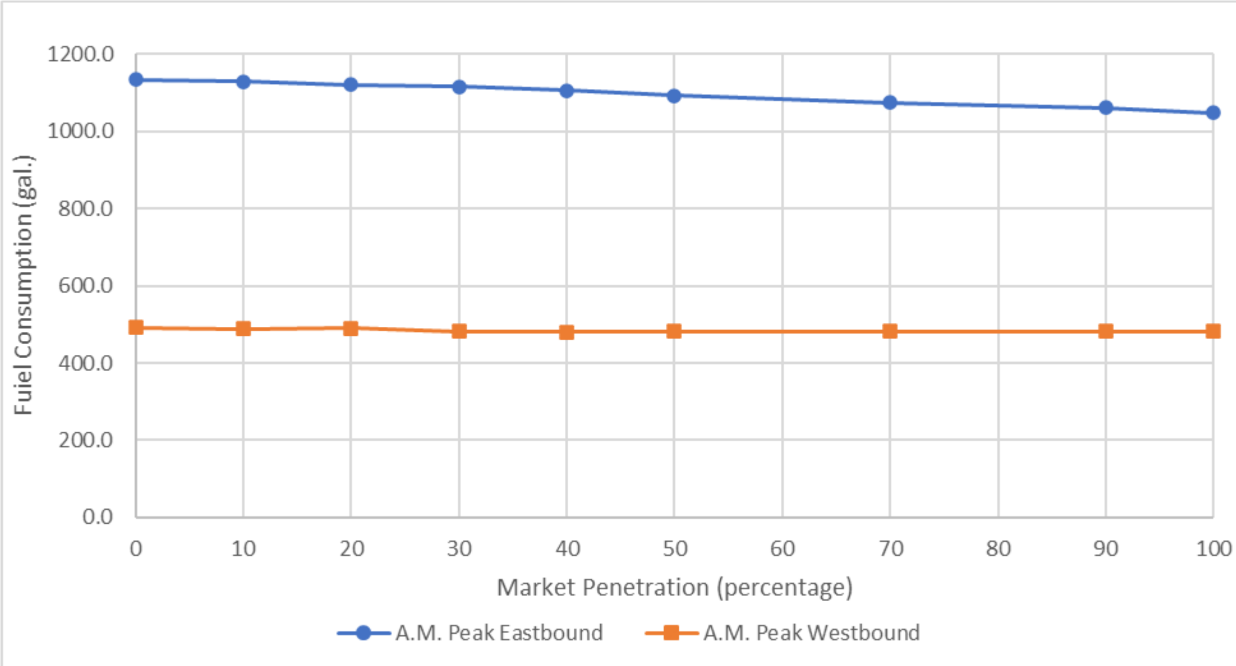
MPR (%)	Avg Speed (mph)	% Change[1]	Standard Deviation (mph)	Statistical Significance (p-value)[2]
0	43.0	—	0.6	—
10	42.8	-0.5%	0.5	0.547
20	42.5	-1.2%	0.5	0.188
30	42.4	-1.3%	0.5	0.161
40	42.2	-1.9%	0.5	0.064
50	42.0	-2.3%	0.5	0.035
70	41.7	-3.1%	0.4	0.010
90	41.2	-4.1%	0.3	0.007
100	40.9	-4.9%	0.5	0.005

[1] From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.
[2] Two-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 (TTI), 2022

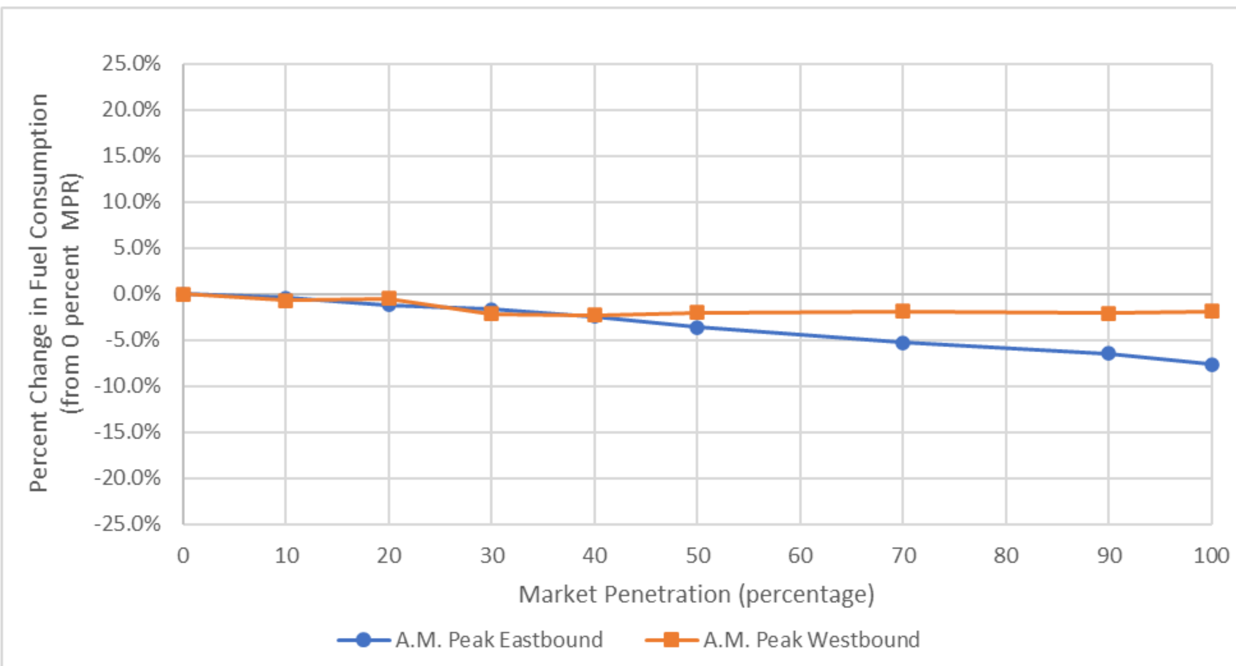
Fuel Consumption

Figure 32 and Figure 33 show the summation of the fuel usage for eastbound and westbound TOSCo approaches and the % change in fuel consumption, respectively. Each direction experiences a reduction in fuel usage as TOSCo MPR increases with the eastbound direction experiencing the larger reduction in fuel usage of up to 87 gallons of fuel saved from TOSCo which amounts to about 7.6 % of the baseline fuel consumed. The westbound reductions in fuel for the A.M. peak period amount to about 2.3 % of the fuel used in the baseline.



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

Figure 32. A.M. Peak Period Fuel Consumption – All TOSCo Approaches



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

Figure 33. A.M. Peak Period Percent Change in Fuel Consumption – All TOSCo Approaches

Discussion of Performance Results

In the A.M. peak period, the Old River Road intersection does not have many turning movements and not much delay. The total delay per vehicle remains practically constant in the A.M. peak period in both directions considering that a two-second change in delay is not enough for most travelers to notice. The reductions in stops and stop delay for Old River Road are similar, even though there are considerable decreases in stops and stop delay, however, the number of stops and reduction in stop delay are not great enough for many travelers to notice. The queues in the eastbound direction experience improvements as TOSCo MPR increase. The queues on this approach are caused by the traffic signal more than turning movements so the TOSCo system is able to plan trajectories and lower the amount of queueing observed at the intersection. The queueing improvements are likely enhanced since the intersection to the east is on the same timing plan as Old River Road. The westbound queues do not experience noticeable changes which makes sense given the large space between Old River Road and April Sound.

The eastbound traffic at West Fork has significant weaving and some left turn spillback that blocks the thru lane in the eastbound direction. As TOSCo MPR increases at this intersection, there is about a 9 second increase in total delay which can be attributed, at least in part, to how TOSCo vehicles are discouraged from changing lanes on the approach to the intersection. This behavior leads to more TOSCo vehicles becoming stuck behind left turning vehicles on the approach to the intersection than non-TOSCo vehicles.

Loop 336 has a right lane drop on the eastbound approach which causes a merging situation for the thru traffic. In addition, there is a heavy left-turn movement for the eastbound direction of travel at Loop 336. The eastbound total delay at Loop 336 increases by 2.5 and 2.5 seconds per vehicle in the A.M. peak period between the baseline and 90% MPR and 100% MPR, respectively. This is caused by the need for weaving of traffic on this approach, how TOSCo strings are discouraged from changing lanes, and how the strings will make lane changes more challenging for all vehicles. This behavior also explains the slight increase in stops for the eastbound approach. The westbound direction of travel sees significant decreases in total delay, stop delay, and number of stops as market penetration increases in the A.M. peak period. The westbound direction of travel in the A.M. peak period has less left-turning traffic than the same movement in the P.M. peak period.

Overall total delay increases for the traffic on SH105 as market penetration of TOSCo goes up. However, this is because TOSCo vehicles have more delay inherently. They accelerate gradually to conserve fuel, and they will decelerate earlier than non-TOSCo vehicles on an approach. The trends for TOSCo and non-TOSCo individual vehicle classes is no change in total delay or a slight decrease in total delay. This means that TOSCo vehicles are not affecting total delay for non-TOSCo vehicles in low market penetrations and are reducing the delay for non-TOSCo vehicles at higher market penetrations.

TOSCo 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.

TOSCo causes some reduction in fuel usage as MPR increases. The peak direction experiences the greater amount of fuel saved and the greater percentage of fuel savings. This is possible because TOSCo vehicles avoid stops and there are not compounded queue spillback scenarios in the A.M. peak period.

The research team used the same methodology as the Phase 1 TOSCo Simulation Report to quantify travel time 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 (*16*). 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. The research team used $2.01 per gallon, which is the average fuel costs in Texas in December 2018 (*17*). Table 34 contains the costs of total travel time and fuel for the SH105 Corridor.

Table 34. A.M. Peak SH105 Corridor User Cost Analysis

Penetration Rate	Value of Total Travel Time	Fuel Cost (Texas Gasoline Price, 2018)	Total User Costs
0	$ 1,716.20	$ 3,268.38	$ 4,984.58
10	$ 1,754.20	$ 3,251.41	$ 5,005.61
20	$ 1,794.57	$ 3,235.81	$ 5,030.38
30	$ 1,791.03	$ 3,208.91	$ 4,999.94
40	$ 1,778.16	$ 3,190.01	$ 4,968.16
50	$ 1,785.45	$ 3,166.25	$ 4,951.71
70	$ 1,859.90	$ 3,129.52	$ 4,989.42
90	$ 1,882.55	$ 3,100.38	$ 4,982.93
100	$ 1,895.65	$ 3,076.06	$ 4,971.71

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

The total user costs remain practically constant between the baseline and the 100 % market penetration rate. The travel time for through traffic gradually increases and the fuel costs gradually decreases, which averages out to approximately a constant user cost with the evaluated version of TOSCo.

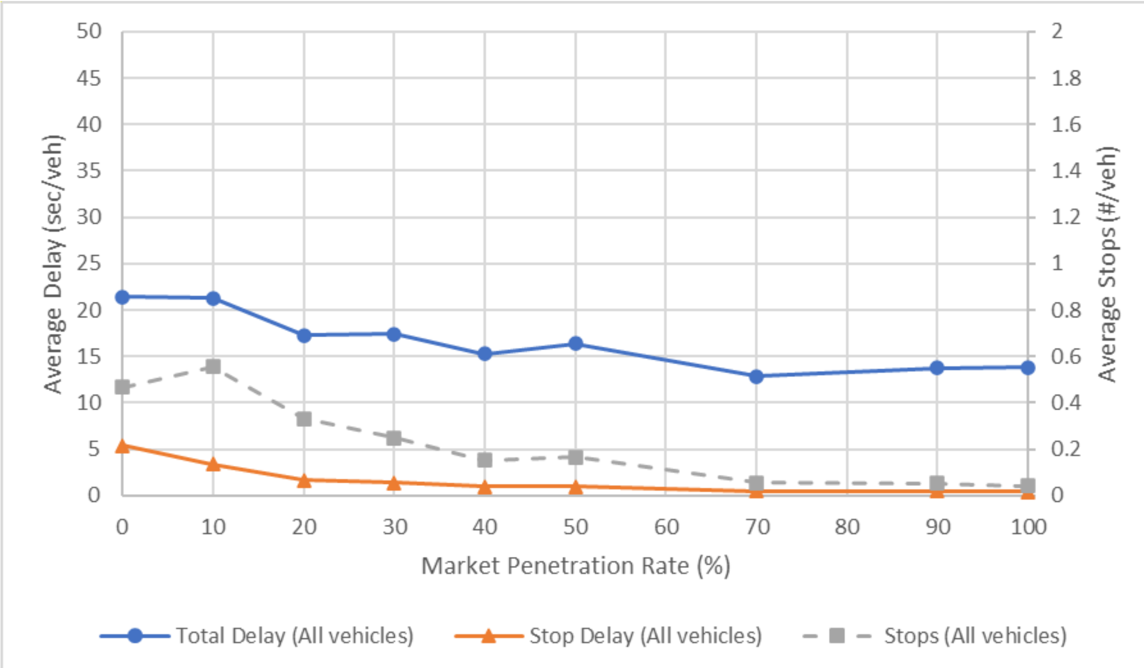
P.M. Peak Performance Results

The P.M. peak period on SH105 has some isolated cases of over-saturation on the corridor, thus indicating that the volumes in the P.M. peak period are much higher than the volumes in the A.M. peak period. The SH105 corridor is unique because the eastbound direction of travel, towards Houston, Texas, is still the peak direction of travel in the evening peak period. The following sections describe performance metrics for the intersections, thru traffic on the corridor, and the entire corridor.

Performance at a Single Intersection

Intersection 1: Old River Road and SH105

The intersection at Old River Road and SH105 is one of the intersections with a portion of the peak period where the intersection is over-saturated during the analysis period. This is also an intersection without any major turning movements, which reduces the weaving on the approach to the intersection in both directions. The delay measurements and stops recorded for eastbound Old River Road are given in Figure 34 and Table 35 to Table 37.



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

Figure 34. Impacts of TOSCo on P.M. Peak Mobility—Old River Road (Eastbound)

Table 35. Comparison of Total Delay at Old River Road – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	21.4	—	5.95	—
10	21.3	-0.5%	6.65	0.966
20	17.3	-19.2%	6.66	0.088
30	17.4	-18.7%	5.84	0.257
40	15.3	-28.8%	2.64	0.016
50	16.4	-23.7%	4.92	0.006
70	12.9	-39.8%	0.43	0.029
90	13.8	-35.6%	1.32	0.074
100	13.8	-35.5%	1.68	0.057

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 36. Comparison of Stop Delay at Old River Road – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	5.4	—	3.03	—
10	3.4	-37.3%	1.84	0.121
20	1.7	-68.5%	1.13	0.024
30	1.4	-74.6%	0.60	0.038
40	1.0	-81.7%	0.30	0.022
50	1.0	-81.6%	0.46	0.020
70	0.5	-90.2%	0.05	0.022
90	0.5	-90.7%	0.07	0.024
100	0.4	-92.2%	0.08	0.022

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 37. Comparison of Number of Stops per Vehicle at Old River Road – P.M. Peak, All Vehicle Types (Eastbound)

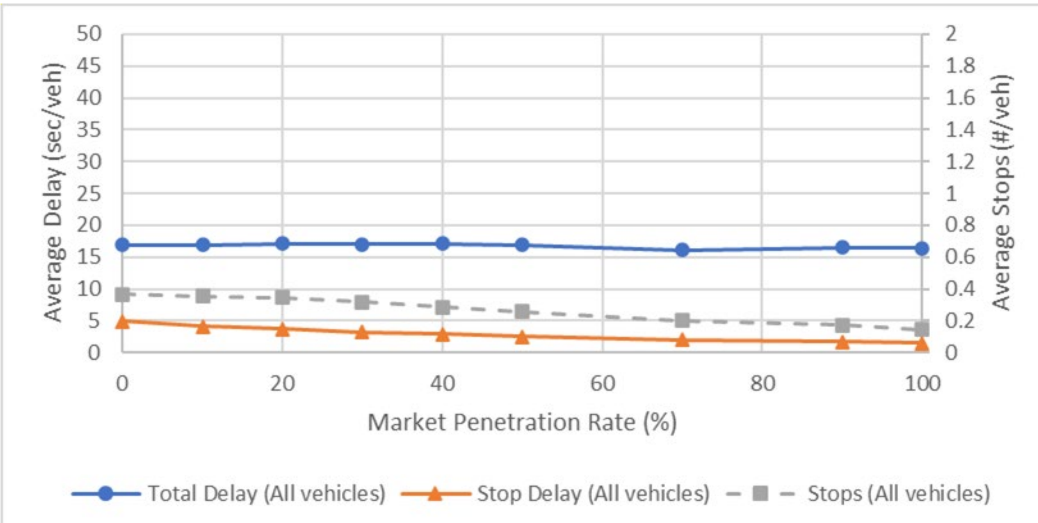
Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.47	—	0.214	—
10	0.56	19.3%	0.352	0.464
20	0.33	-29.0%	0.367	0.256
30	0.25	-46.6%	0.238	0.064
40	0.15	-67.5%	0.095	0.005
50	0.17	-64.6%	0.134	0.003
70	0.06	-87.9%	0.008	0.011
90	0.05	-88.9%	0.008	0.014
100	0.04	-90.7%	0.010	0.012

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

As market penetration increases, there is a gradual decrease of up to a total delay of 7.6 seconds per vehicle and up to 5 seconds per vehicle in stop delay for Old River Road in the P.M. peak period. The number of stops for eastbound traffic at Old River Road in the P.M. peak period is reduce to almost zero stops per vehicle.

Figure 35 and Table 38 to Table 40 show the westbound delays and stops at the Old River Road intersection. The westbound total delay for Old River Road does not change much with market penetration rate, and all differences in total delay are less than half a second per vehicle. Stop delay drops up to 3.4 seconds per vehicle, and the number of stops drops by more than half.



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

Figure 35. Impacts of TOSCo on P.M. Peak Mobility—Old River Road (Westbound)

Table 38. Comparison of Total Delay at Old River Road – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	16.9	—	0.70	—
10	16.9	0.1%	0.65	0.971
20	17.1	1.2%	1.15	0.575
30	17.0	0.9%	0.72	0.548
40	17.1	1.1%	1.10	0.576
50	16.9	0.2%	1.05	0.929
70	16.1	-4.4%	0.53	0.068
90	16.5	-2.5%	0.55	0.087
100	16.4	-2.9%	1.18	0.227

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

[2] Two-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 (TTI), 2022

Table 39. Comparison of Stop Delay at Old River Road – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	4.9	—	0.16	—
10	4.1	-16.3%	0.17	<0.001
20	3.7	-24.6%	0.43	0.001
30	3.2	-33.8%	0.32	<0.001
40	2.9	-41.4%	0.18	<0.001
50	2.5	-49.3%	0.03	<0.001
70	2.0	-59.1%	0.11	<0.001
90	1.7	-65.9%	0.15	<0.001
100	1.5	-70.0%	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] Two-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 (TTI), 2022

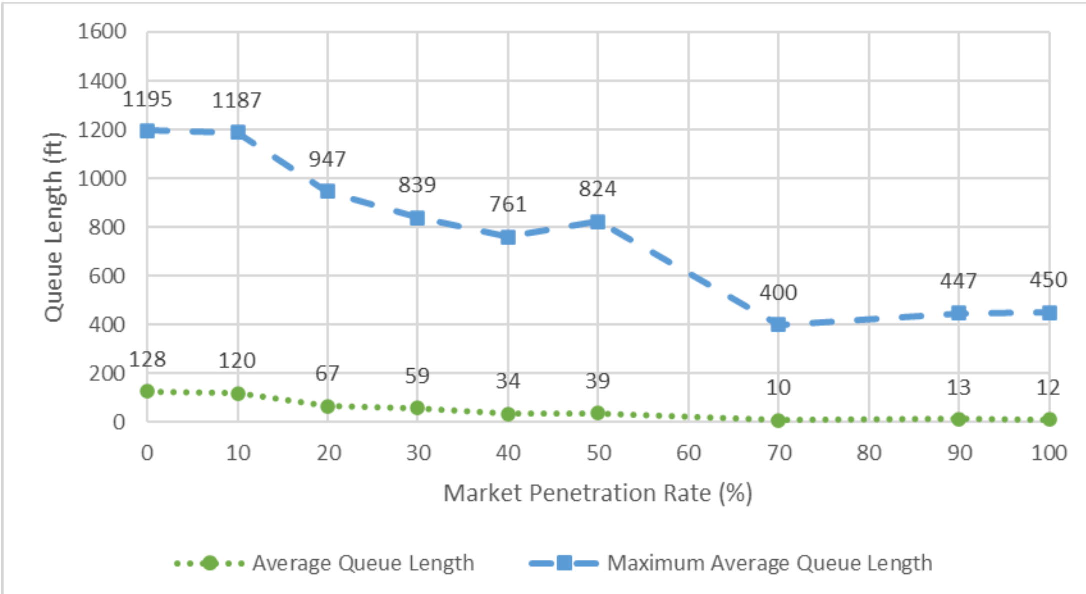
Table 40. Comparison of Number of Stops per Vehicle at Old River Road – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.37	—	0.019	—
10	0.36	-3.2%	0.020	0.344
20	0.34	-6.3%	0.039	0.146
30	0.32	-13.3%	0.032	0.005
40	0.29	-21.9%	0.024	<0.001
50	0.26	-29.7%	0.024	<0.001
70	0.20	-45.4%	0.012	<0.001
90	0.17	-53.5%	0.023	<0.001
100	0.15	-60.2%	0.016	<0.001

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

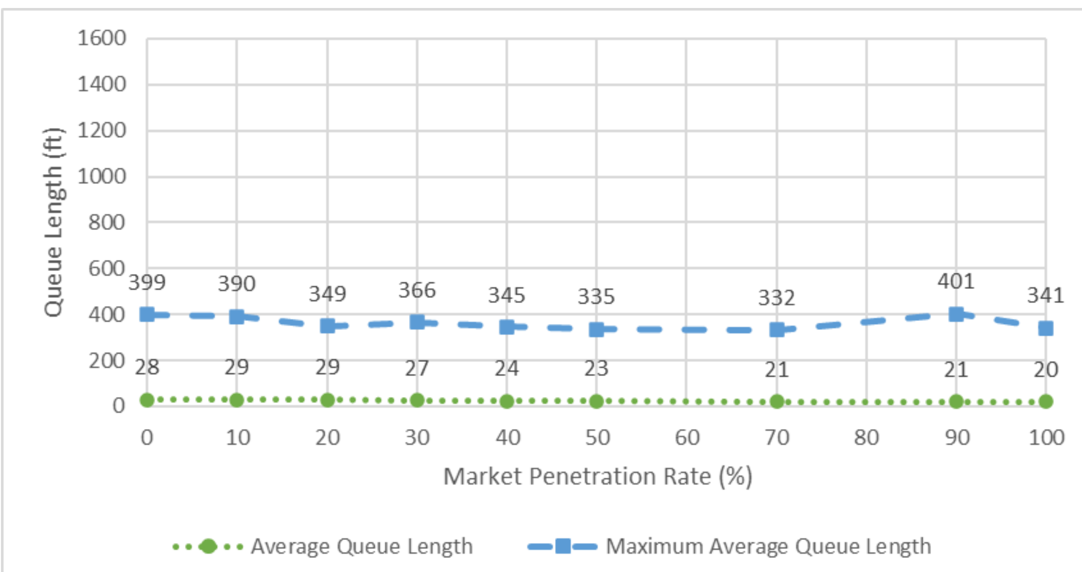
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 36 and Figure 37 show the average and maximum P.M. peak period queue length values for eastbound and westbound traffic, respectively, at Old River Road, averaged for the 5 simulation runs.



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

Figure 36. Queue Measurements for P.M. Peak Traffic at SH105 and Old River Road (Eastbound)



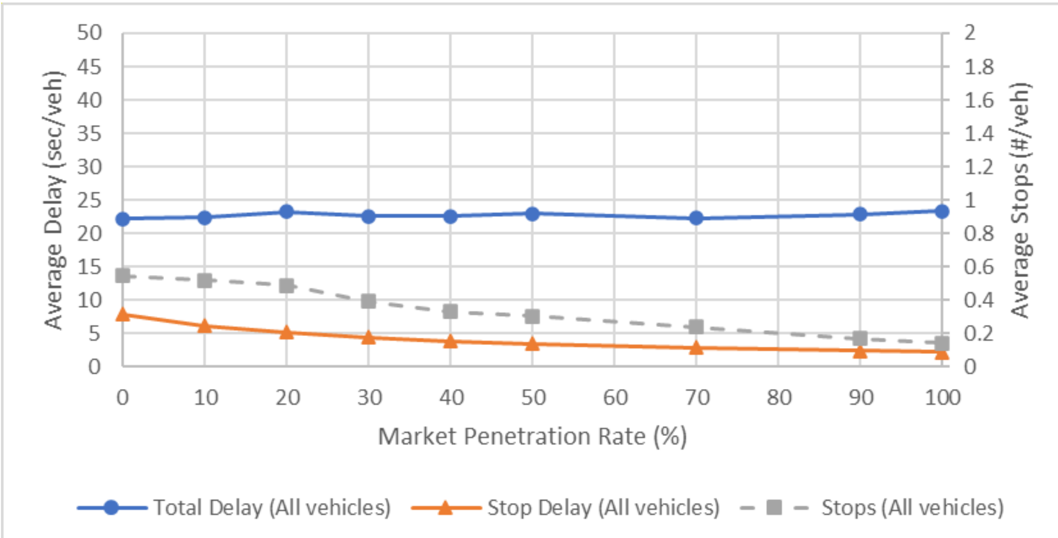
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 37. Queue Measurements for P.M. Peak Traffic at SH105 and Old River Road (Westbound)

The eastbound queues at Old River Road gradually decrease as TOSCo MPR increases, and the queues for westbound traffic at Old River Road remain approximately constant as TOSCo MPR increases.

Intersection 2: West Fork Boulevard and SH105

The West Fork Boulevard and SH105 intersection does not have very much cross street or turning traffic in the P.M. peak period. Figure 38 and Table 41 to Table 43 show the P.M. peak period results for the West Fork Boulevard intersection.



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

Figure 38. Impacts of TOSCo on P.M. Peak Mobility - West Fork Boulevard (Eastbound)

Table 41. Comparison of Total Delay at West Fork Boulevard – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	22.2	—	0.75	—
10	22.4	0.7%	0.80	0.709
20	23.3	4.8%	1.74	0.254
30	22.6	1.8%	1.51	0.585
40	22.6	1.5%	1.62	0.671
50	23.0	3.4%	2.41	0.536
70	22.3	0.4%	1.71	0.854
90	22.9	3.0%	3.02	0.654
100	23.3	5.0%	1.36	0.154

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

[2] Two-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 (TTI), 2022

Table 42. Comparison of Stop Delay at West Fork Boulevard – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	7.9	—	0.39	—
10	6.2	-21.5%	0.21	0.001
20	5.2	-33.7%	0.61	0.001
30	4.4	-43.8%	0.33	<0.001
40	3.9	-50.9%	0.56	<0.001
50	3.5	-55.9%	0.61	<0.001
70	2.9	-63.7%	0.33	<0.001
90	2.4	-69.5%	0.60	<0.001
100	2.2	-72.4%	0.25	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 43. Comparison of Number of Stops per Vehicle at West Fork Boulevard – P.M. Peak, All Vehicle Types (Eastbound)

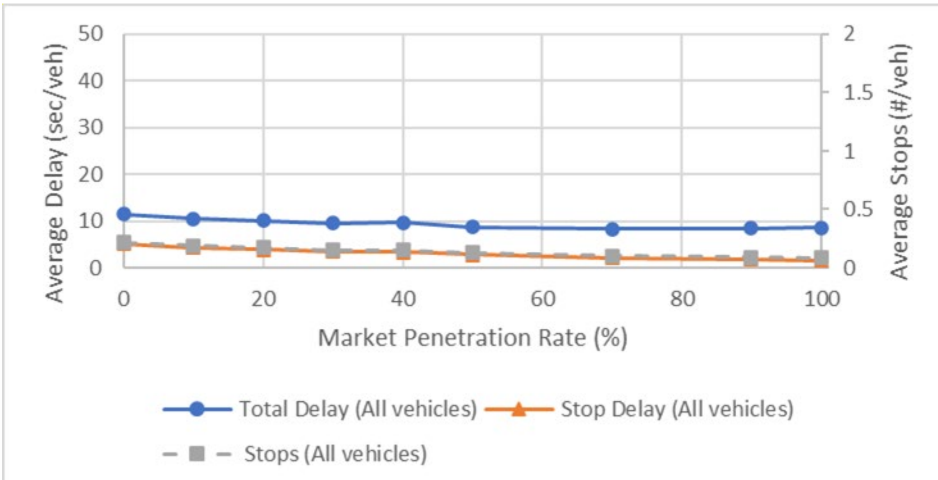
Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.55	—	0.020	—
10	0.52	-4.9%	0.028	0.091
20	0.49	-10.7%	0.059	0.127
30	0.39	-28.0%	0.044	0.001
40	0.33	-39.6%	0.039	<0.001
50	0.30	-44.3%	0.045	0.001
70	0.24	-56.1%	0.043	<0.001
90	0.17	-69.0%	0.038	<0.001
100	0.14	-74.0%	0.019	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Notice that there are no substantial changes in total delay, stop delay, or number of stops per vehicle. This approach already has good performance in each of these performance measures because of good progression with this signal timing plan.

Figure 39 and Table 44 to Table 46 show the westbound direction delay measurements and stops. Like the eastbound direction, this westbound approach does not experience much delay due to good progression from the upstream intersection. There are decreases in total delay, stop delay, and number of stops per vehicle. However, these are not substantial changes in the performance measures considering that the total delay only decreased by 2.9 seconds per vehicle and the stop delay decreased by only 3.8 seconds per vehicle on average between the baseline and 100 % TOSCo MPR scenarios.



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

Figure 39. Impacts of TOSCo on P.M. Peak Mobility—West Fork Boulevard (Westbound)

Table 44. Comparison of Total Delay at West Fork Boulevard – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	11.5	—	0.32	—
10	10.6	-7.9%	0.58	0.063
20	10.1	-11.9%	0.63	0.006
30	9.6	-16.3%	0.58	0.001
40	9.7	-15.7%	0.88	0.011
50	8.7	-23.8%	0.23	<0.001
70	8.4	-27.1%	1.21	0.004
90	8.5	-26.2%	2.06	0.027
100	8.6	-24.7%	1.35	0.017

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

[2] Two-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 (TTI), 2022

Table 45. Comparison of Stop Delay at West Fork Boulevard – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	5.1	—	0.29	—
10	4.3	-15.2%	0.38	0.025
20	3.9	-24.3%	0.41	0.001
30	3.4	-32.7%	0.28	<0.001
40	3.3	-35.5%	0.38	0.001
50	2.8	-45.7%	0.17	<0.001
70	2.2	-57.1%	0.44	<0.001
90	1.9	-63.4%	0.65	<0.001
100	1.6	-68.4%	0.39	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

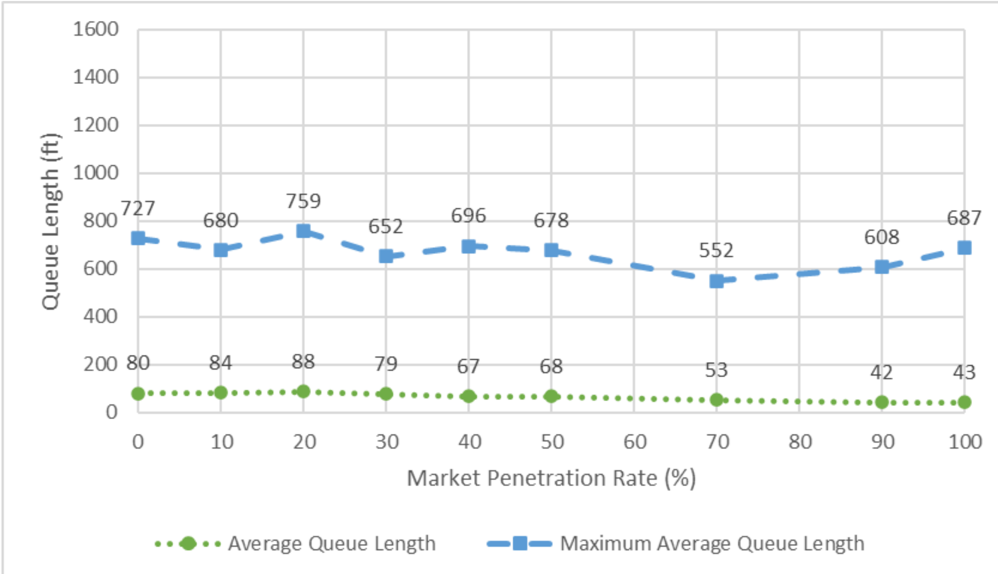
Table 46. Comparison of Number of Stops per Vehicle at West Fork Boulevard – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.22	—	0.010	—
10	0.19	-12.3%	0.011	0.025
20	0.17	-21.1%	0.009	0.001
30	0.15	-29.1%	0.012	<0.001
40	0.15	-29.6%	0.021	0.002
50	0.13	-41.0%	0.006	<0.001
70	0.10	-52.8%	0.018	<0.001
90	0.09	-58.9%	0.018	<0.001
100	0.08	-61.7%	0.018	<0.001

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

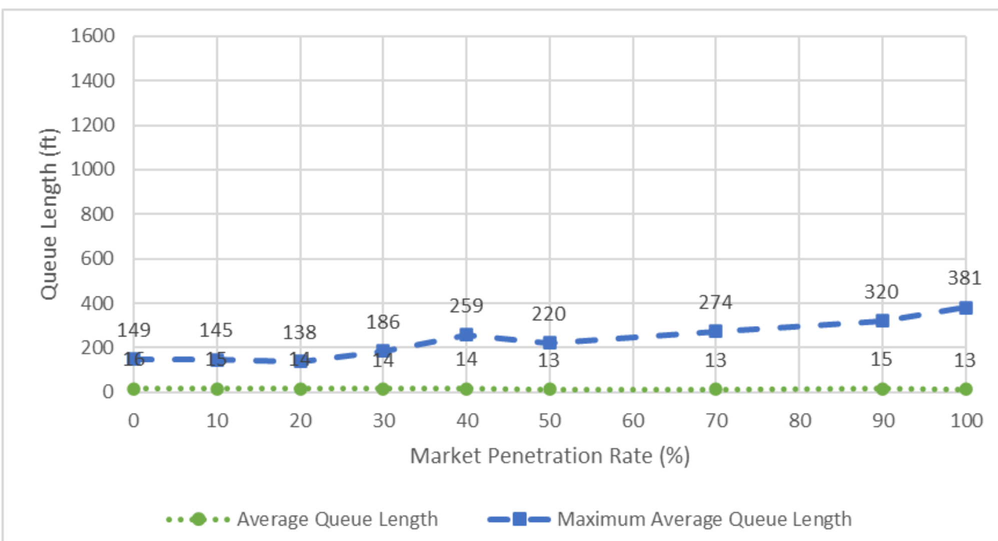
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 40 and Figure 41 show the average and maximum queue length values at West Ford Boulevard for the P.M. peak period traffic eastbound and westbound, respectively, averaged for the five simulation runs.



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

Figure 40. Queue Measurements for P.M. Peak Traffic at SH105 and West Fork Boulevard (Eastbound)



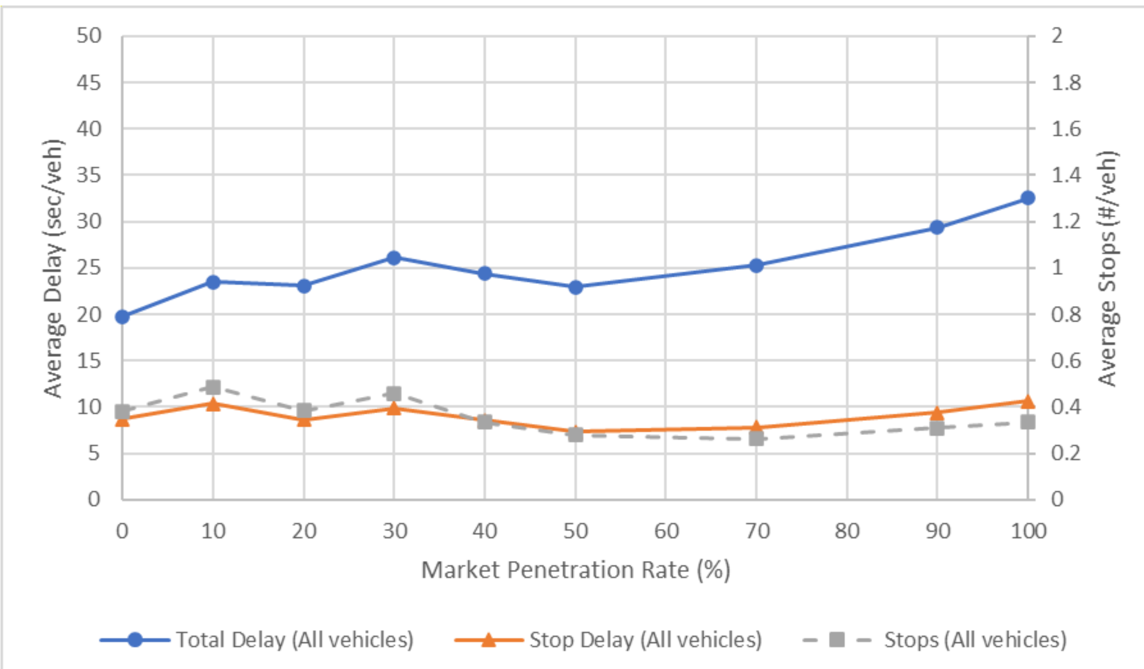
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 41. Queue Measurements for P.M. Peak Traffic at SH105 and West Fork Boulevard (Westbound)

The eastbound maximum queues at West Fork Boulevard and SH105 do not consistently change in the P.M. peak period, but the average queues for eastbound traffic at West Fork Boulevard do gradually decrease as TOSCo MPR increases. The westbound P.M. peak traffic trends are the exact opposite. The westbound P.M. peak traffic at West Fork Boulevard and SH105 does see a gradual increase in maximum queue length but no impacts in average queue length as TOSCo MPR increases.

Intersection 3: Loop 336 and SH105

Loop 336 is the farthest east intersection of the study section of SH105. This intersection has high volumes because of all the vehicles going eastbound, towards Houston, have accumulated from the rest of the study section. In the P.M. peak period, the westbound movement at Loop 336 has a heavy left-turn movement, too, which causes queueing issues on the westbound approach. Figure 42 and Table 47 to Table 49 show the delays and number of stops per vehicle for the eastbound traffic on Loop 336.



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

Figure 42. Impacts of TOSCo on P.M. Peak Mobility— Loop 336 (Eastbound)

Table 47. Comparison of Total Delay at Loop 336 (West) – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	19.7	—	3.66	—
10	23.5	19.0%	4.99	0.012
20	23.1	17.1%	3.86	0.332
30	26.1	32.3%	8.78	0.057

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
40	24.4	23.5%	5.87	0.027
50	23.0	16.3%	7.76	0.235
70	25.3	28.1%	3.61	0.049
90	29.4	48.9%	3.67	0.001
100	32.6	64.9%	7.09	0.012

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 48. Comparison of Stop Delay at Loop 336 (West) – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	8.7	—	2.39	—
10	10.4	19.2%	3.18	0.042
20	8.6	-0.6%	1.81	0.974
30	9.9	13.5%	4.70	0.369
40	8.6	-1.3%	2.88	0.837
50	7.4	-15.5%	3.38	0.221
70	7.8	-10.0%	1.47	0.469
90	9.4	8.0%	1.57	0.388
100	10.7	22.6%	2.71	0.153

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 49. Comparison of Number of Stops per Vehicle at Loop 336 (West) – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	0.38	—	0.112	—
10	0.49	27.5%	0.169	0.033
20	0.39	0.6%	0.115	0.980
30	0.46	19.9%	0.306	0.443

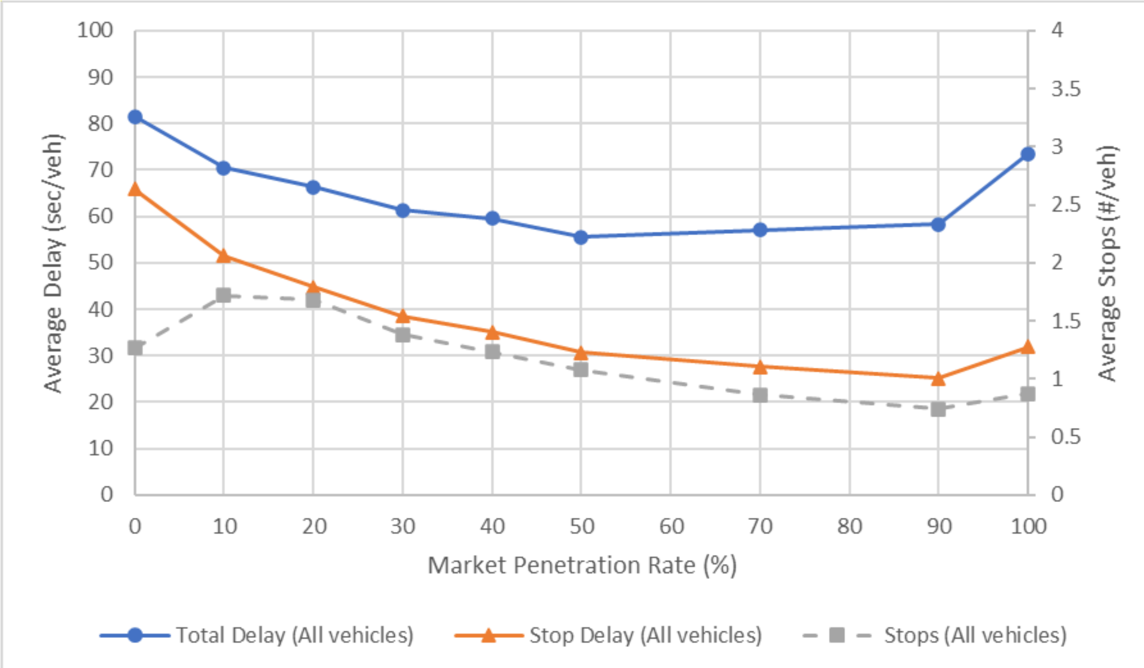
Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
40	0.34	-12.2%	0.157	0.191
50	0.28	-26.8%	0.177	0.110
70	0.33	-13.3%	0.039	0.071
90	0.31	-19.3%	0.058	0.126
100	0.33	-12.6%	0.090	0.374

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

There is a 12.9 second increase in total delay per vehicle and a 2 second increase in stop delay per vehicle between the baseline and 100 % market penetration rate scenarios for eastbound traffic at Loop 336. The number of stops and stop delay remain relatively constant across all TOSCo MPR scenarios. These increases in total delay and constant stop measurements are a result of the TOSCo response to the left turn bay spill back and the weaving from the rightmost lane drop.

Figure 43 and Table 50 through Table 51 contain the Loop 336 westbound delays and stops per vehicle. Note that the scale changed for delay and stop measurements in Figure 43 compared to Figure 44 and other previous figures in this section. The westbound Loop 336 total delay and stop delay gradually decrease from zero to 90 % TOSCo MPR and then increases from 90 % to 100 % TOSCo MPR. The average number of stops per vehicle increases from zero to 10 % TOSCo MPR and from 90 to 100 % TOSCo MPR but stops per vehicle otherwise declines. Each of these performance measures decrease when comparing the baseline to the 100 % TOSCo MPR scenario for westbound Loop 336 traffic.



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

Figure 43. Impacts of TOSCo on P.M. Peak Mobility— Loop 336 (Westbound)

Table 50. Comparison of Total Delay at Loop 336 (West) – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	81.6	—	7.03	—
10	70.4	-13.7%	8.04	0.038
20	66.4	-18.6%	5.13	0.043
30	61.4	-24.8%	4.62	0.003
40	59.5	-27.1%	4.21	<0.001
50	55.6	-31.9%	3.65	0.002
70	57.1	-30.0%	5.24	0.002
90	58.3	-28.6%	6.53	0.001
100	73.5	-9.9%	19.32	0.340

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 51. Comparison of Stop Delay at Loop 336 (West) – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	65.9	—	6.06	—
10	51.6	-21.7%	6.67	0.010
20	44.8	-32.1%	3.72	0.007
30	38.6	-41.4%	2.71	<0.001
40	35.1	-46.7%	2.68	<0.001
50	30.7	-53.5%	2.16	<0.001
70	27.7	-58.0%	2.70	<0.001
90	25.2	-61.8%	3.65	<0.001
100	31.9	-51.6%	9.45	0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

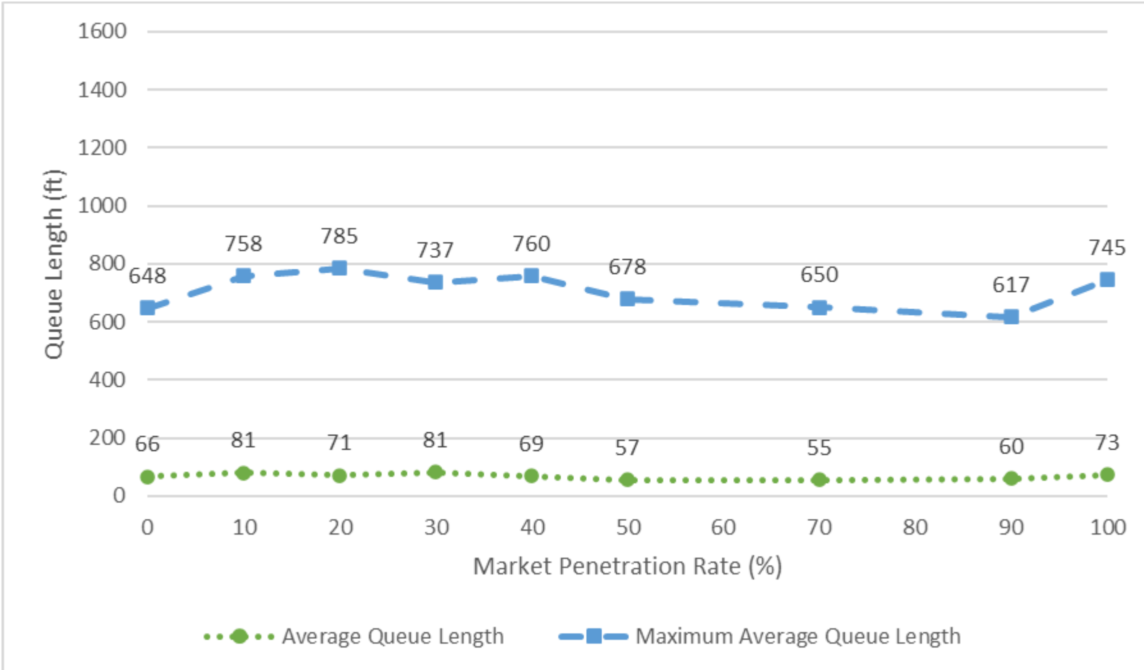
Table 52. Comparison of Number of Stops per Vehicle at Loop 336 (West) – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	1.27	—	0.099	—
10	1.72	35.9%	0.268	0.013
20	1.68	32.6%	0.213	0.039
30	1.38	8.9%	0.238	0.371
40	1.23	-2.6%	0.112	0.566
50	1.08	-15.1%	0.118	0.068
70	0.86	-31.9%	0.093	0.004
90	0.74	-41.4%	0.091	<0.001
100	0.87	-30.9%	0.269	0.019

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

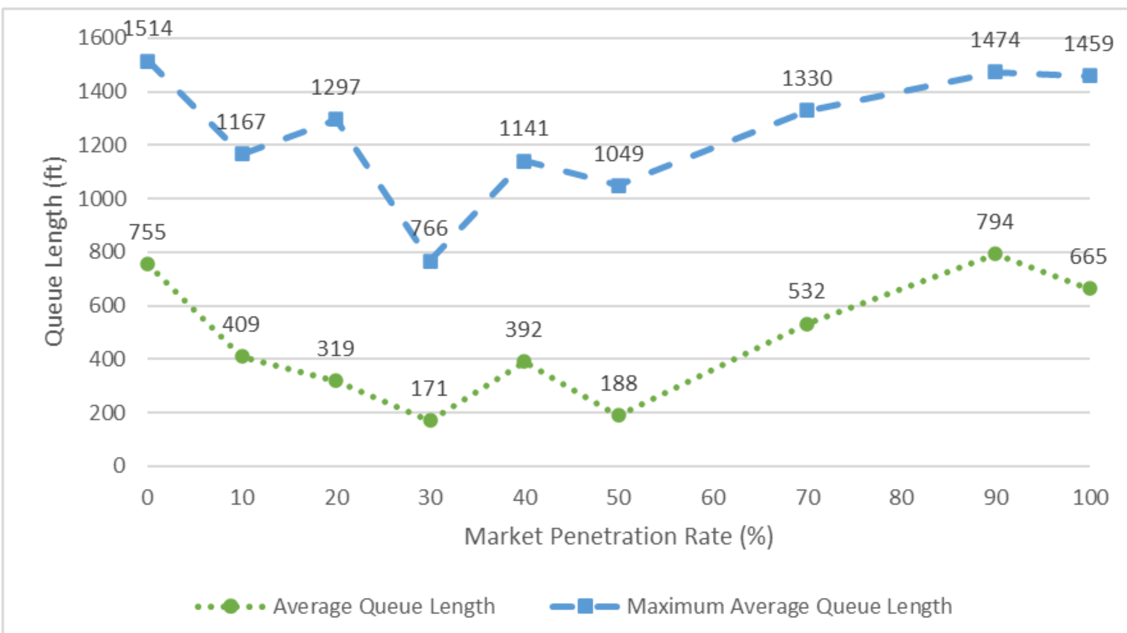
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 44 and Figure 45 show the average and maximum P.M. peak period queue length values for eastbound and westbound traffic, respectively, at Old River Road, averaged for the 5 simulation runs.



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

Figure 44. Queue Measurements for P.M. Peak Traffic at SH105 and Loop 336 (Eastbound)



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

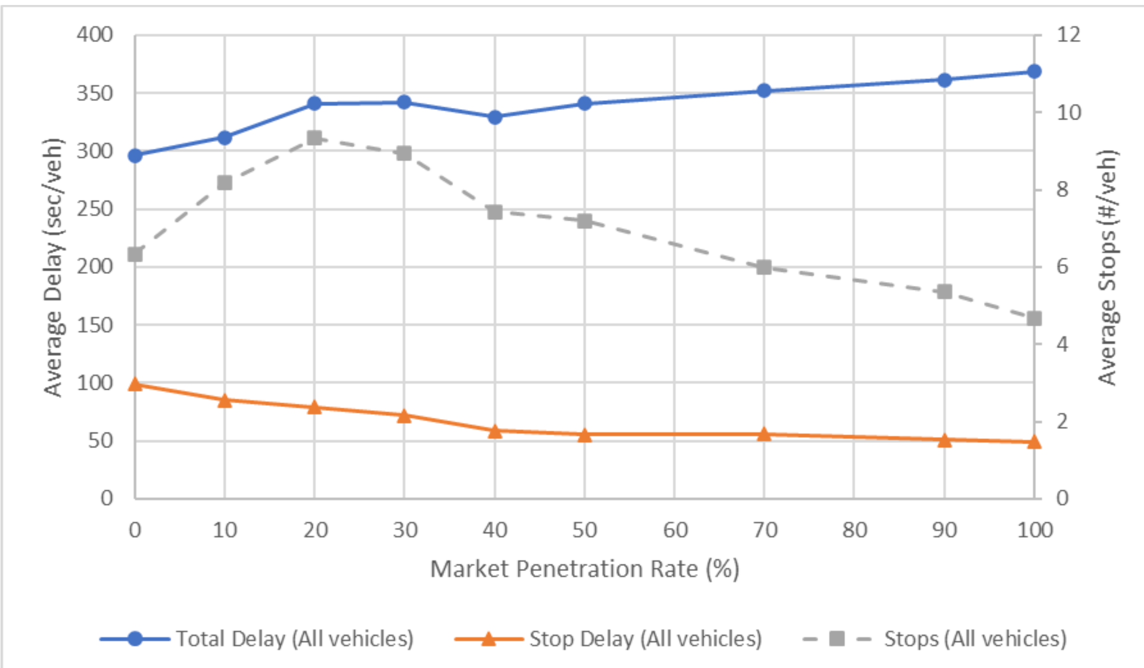
Figure 45. Queue Measurements for P.M. Peak Traffic at SH105 and Loop 336 (Westbound)

Corridor Performance

The P.M. peak conditions are over saturated in both directions at several intersections along SH105. The traffic volumes in eastbound and westbound directions are more evenly distributed, and the eastbound direction is still the direction with the peak flow. Eastbound traffic remains the peak direction because the P.M. peak period involves trips to shopping locations along SH105 in addition to commuter traffic. Note, the eastbound travel time measurement exceeds the calibration target of 10% change from the field measurement, and the westbound travel time measurement is within the calibration target.

Cumulative Delays and Stops

The delay and number of stop results for eastbound and westbound directions of travel are shown in Figure 46 and Figure 47 and the values are shown in Table 53 through Table 58.



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

Figure 46. Corridor-level Mobility Measures for SH105 P.M. Peak (Eastbound)—All Vehicle Types

Table 53. Comparison of Total Delay at the Corridor Level – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	296.3	—	23.1	—
10	311.8	5.2%	27.3	0.093
20	341.2	15.1%	43.0	0.012

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
30	342.3	15.5%	36.5	0.010
40	329.6	11.2%	16.7	0.002
50	340.9	15.0%	28.1	0.002
70	351.8	18.7%	51.1	0.043
90	361.7	22.1%	67.7	0.068
100	368.8	24.5%	27.8	0.002

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 54. Comparison of Stop Delay at the Corridor Level – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	98.9	—	11.4	—
10	85.0	-14.1%	10.6	0.007
20	79.1	-20.0%	13.1	0.006
30	71.7	-27.5%	12.2	0.002
40	58.5	-40.8%	4.0	<0.001
50	55.4	-44.0%	6.6	<0.001
70	55.8	-43.6%	17.3	0.003
90	51.0	-48.5%	19.8	0.004
100	49.4	-50.1%	7.4	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

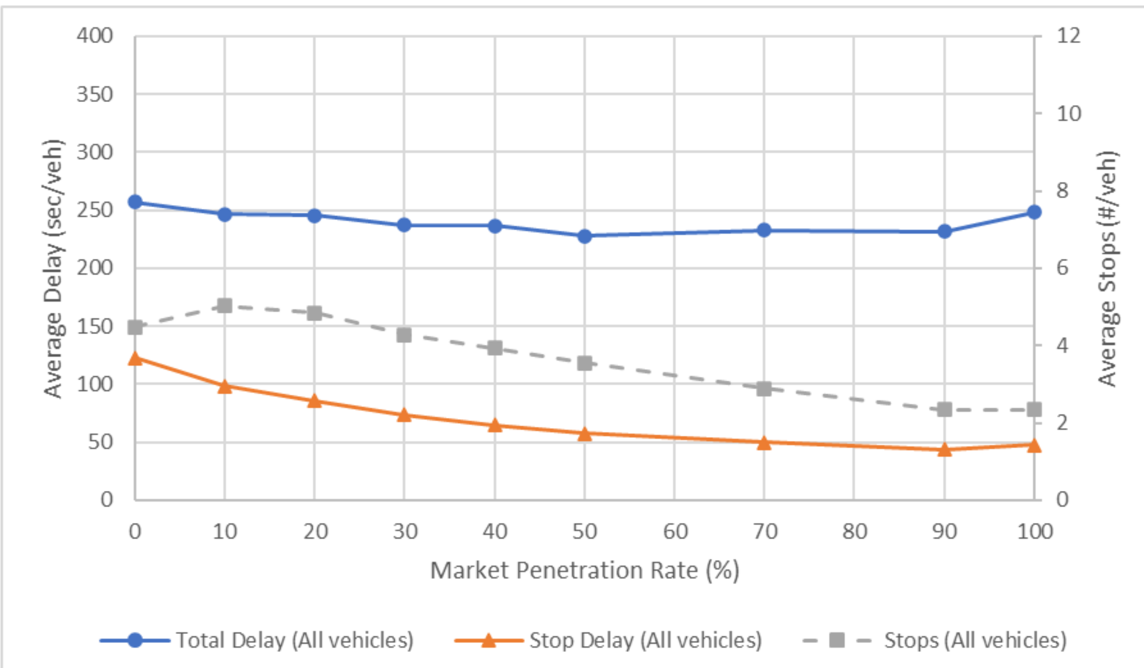
Table 55. Comparison of Number of Stops per Vehicle at the Corridor Level – P.M. Peak, All Vehicle Types (Eastbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	6.33	—	0.63	—
10	8.17	29.0%	1.28	0.015

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
20	9.34	47.5%	1.98	0.008
30	8.94	41.2%	1.82	0.013
40	7.43	17.3%	0.56	0.005
50	7.20	13.6%	0.85	0.034
70	5.98	-5.5%	1.44	0.572
90	5.35	-15.5%	2.31	0.333
100	4.67	-26.2%	0.66	0.010

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022



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

Figure 47. Corridor-level Mobility Measures for SH105 P.M. Peak (Westbound)—All Vehicle Types

Table 56. Comparison of Total Delay at the Corridor Level – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Total Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	256.9	—	15.2	—
10	246.4	-4.1%	9.0	0.257
20	245.6	-4.4%	8.3	0.233
30	237.2	-7.7%	6.5	0.037
40	236.4	-8.0%	9.0	0.053
50	227.9	-11.3%	8.6	0.020
70	232.9	-9.4%	9.5	0.021
90	231.7	-9.8%	9.0	0.012
100	248.3	-3.4%	20.6	0.524

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 57. Comparison of Stop Delay at the Corridor Level – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	Stop Delay (sec/veh)	% Change[1]	Standard Deviation (sec/veh)	Statistical Significance (p-value)[2]
0	123.0	—	9.0	—
10	98.7	-19.7%	4.4	0.008
20	85.8	-30.2%	5.8	0.003
30	73.6	-40.2%	3.2	<0.001
40	64.9	-47.2%	1.8	<0.001
50	57.5	-53.2%	3.6	<0.001
70	49.7	-59.5%	5.4	<0.001
90	44.0	-64.3%	4.0	<0.001
100	47.5	-61.3%	5.6	<0.001

[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 58. Comparison of Number of Stops per Vehicle at the Corridor Level – P.M. Peak, All Vehicle Types (Westbound)

Market Penetration (%)	# of Stops/ Vehicle	% Change[1]	Standard Deviation (#/veh)	Statistical Significance (p-value)[2]
0	4.47	—	0.17	—
10	5.03	12.6%	0.20	0.013
20	4.84	8.3%	0.41	0.146
30	4.29	-4.1%	0.40	0.434
40	3.94	-12.0%	0.19	0.010
50	3.55	-20.5%	0.20	0.002
70	2.88	-35.6%	0.18	<0.001
90	2.35	-47.5%	0.16	<0.001
100	2.35	-47.5%	0.23	<0.001

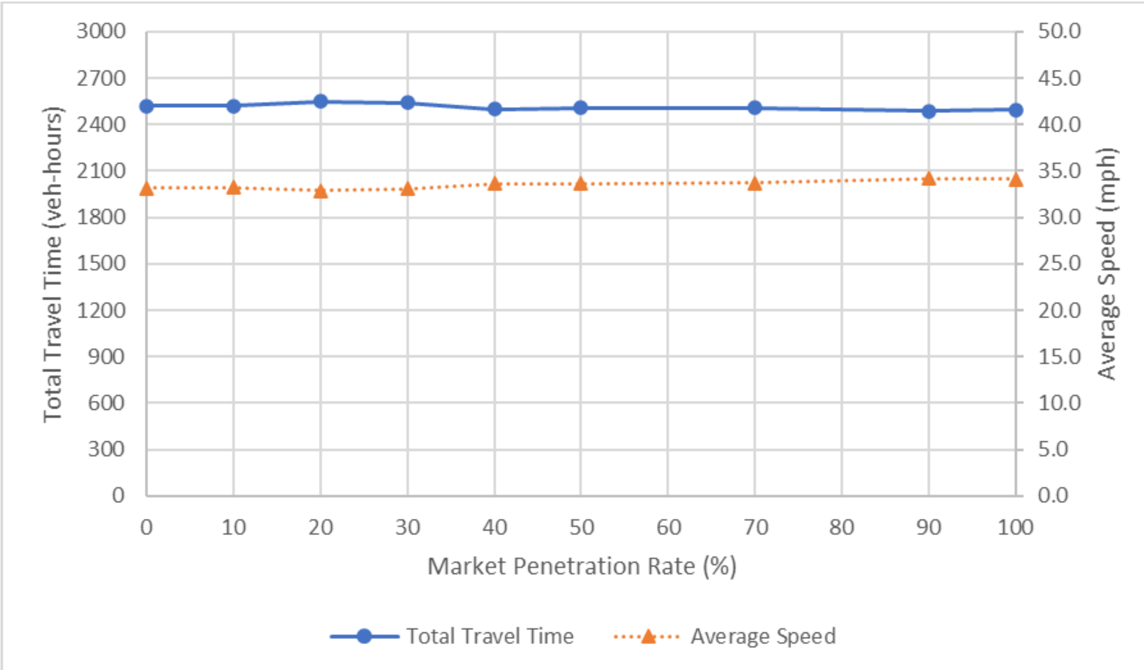
[1]From 0% MPR. A positive value indicates an increase while a negative value indicates a reduction in the performance measure.
[2] Two-tailed t-test comparing the results of the 5 simulations from the subject MPR scenario to the 5 runs form the baseline.

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

In the P.M. peak period, both directions experience gradual reductions in stop delay and number of stops 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. Total delay per vehicle increases in the heavier eastbound direction and decreases for the westbound direction of travel. Overall, TOSCo reduces stop delay and stops per vehicle.

Total Travel Time and Average Speed

Figure 48, Table 59, and Table 60 show the total travel time and average speed results from the P.M. peak. 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 100 % TOSCo MPR. None of the total travel time reductions are statistically significant. However, 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 (TTI), 2022

Figure 48: Total Vehicle Hours Traveled and Average Speeds for SH105 in Conroe, Texas – P.M. Peak

Table 59: P.M. Peak Period Total Vehicle Hours Traveled on SH105 Corridor

MPR (%)	Total Travel Time (veh-hours)	% Change[1]	Standard Deviation (veh-hours)	Statistical Significance (p-value)[2]
0	2520	—	64	—
10	2522	0.1%	61	0.848
20	2549	1.2%	90	0.136
30	2540	0.8%	91	0.243
40	2499	-0.8%	68	0.268
50	2510	-0.4%	76	0.463
70	2508	-0.5%	166	0.834
90	2486	-1.3%	161	0.549
100	2496	-0.9%	78	0.429

[1] From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.
[2] Two-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 (TTI), 2022

Table 60: P.M. Peak Period Average Speed Values for SH105 Corridor

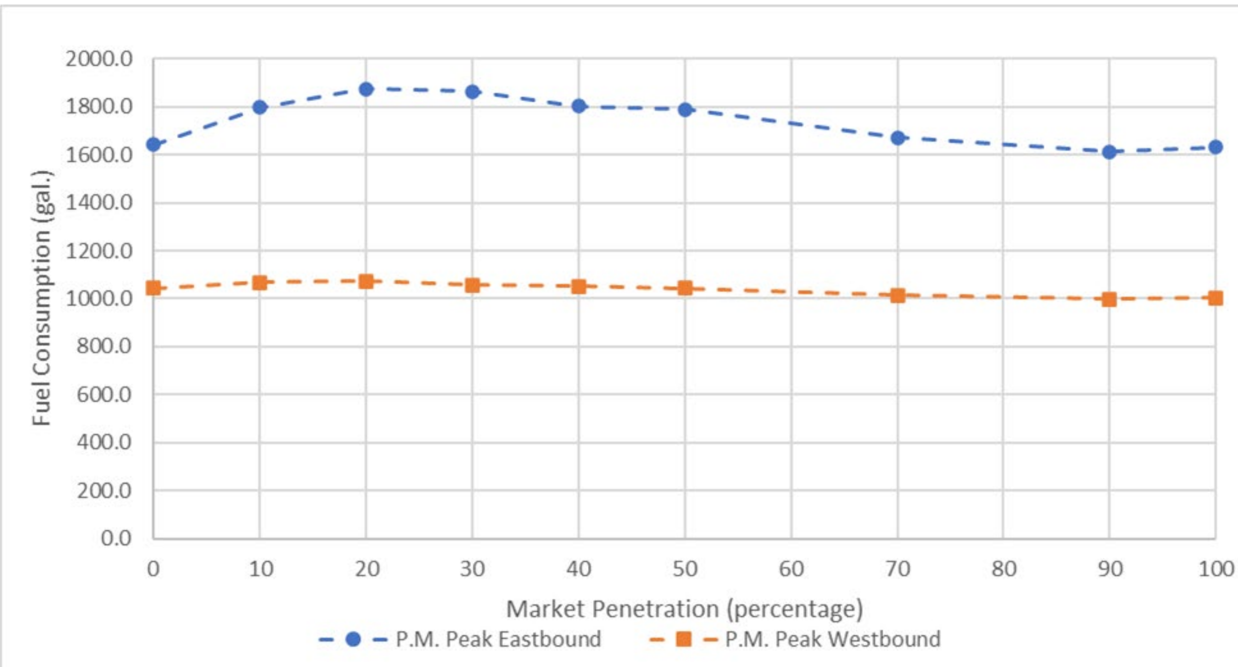
MPR (%)	Avg Speed (mph)	% Change[1]	Standard Deviation (mph)	Statistical Significance (p-value)[2]
0	33.2	—	1.0	—
10	33.2	0.2%	1.0	0.739
20	32.9	-0.8%	1.5	0.348
30	33.1	-0.2%	1.5	0.793
40	33.7	1.6%	1.2	0.071
50	33.7	1.5%	1.1	0.031
70	33.7	1.7%	2.6	0.517
90	34.2	3.3%	2.5	0.219
100	34.1	3.0%	1.2	0.087

[1] From 0% MPR. A positive value implies an increase while a negative value implies a reduction in the performance measure.
[2] Two-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 (TTI), 2022

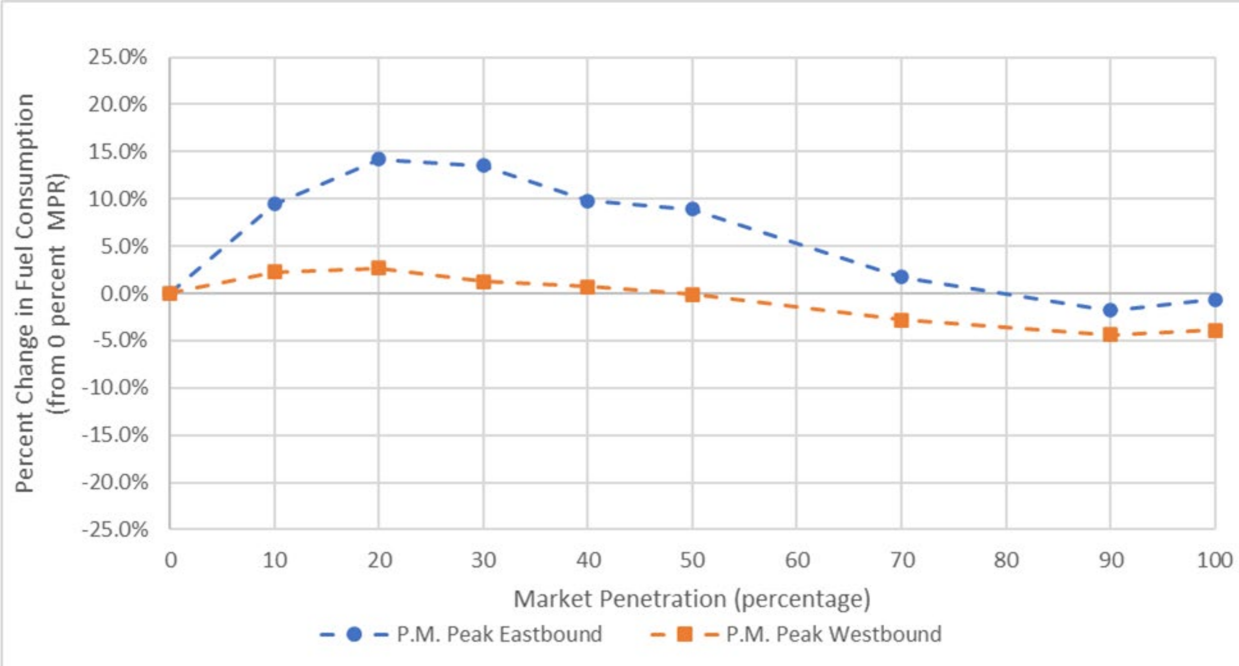
Fuel Consumption

Figure 49 and Figure 50 show the summation of the fuel usage for eastbound and westbound TOSCo approaches and the % change in fuel consumption, respectively. Each direction experiences an initial increase in fuel usage and then gradually reduces fuel consumption to approximately the same fuel usage as the baseline. The increase in fuel usage is in large part caused by weaving segments along the corridor and the large volumes. The TOSCo vehicles are discouraged from 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. Another contributing factor is that TOSCo vehicles that stop behind a vehicle waiting to turn do not change lanes to get around the stopped vehicle while non-TOSCo vehicles will change lanes. This behavior has an adverse impact on fuel consumption on some intersections like Loop 336, McCaleb, and April Sound. The research team identified that that these increases in fuel consumption coincide with increases in the number of stops, which are also caused by the weaving segments in the intersection.



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

Figure 49. P.M. Peak Period Fuel Consumption – All TOSCo Approaches



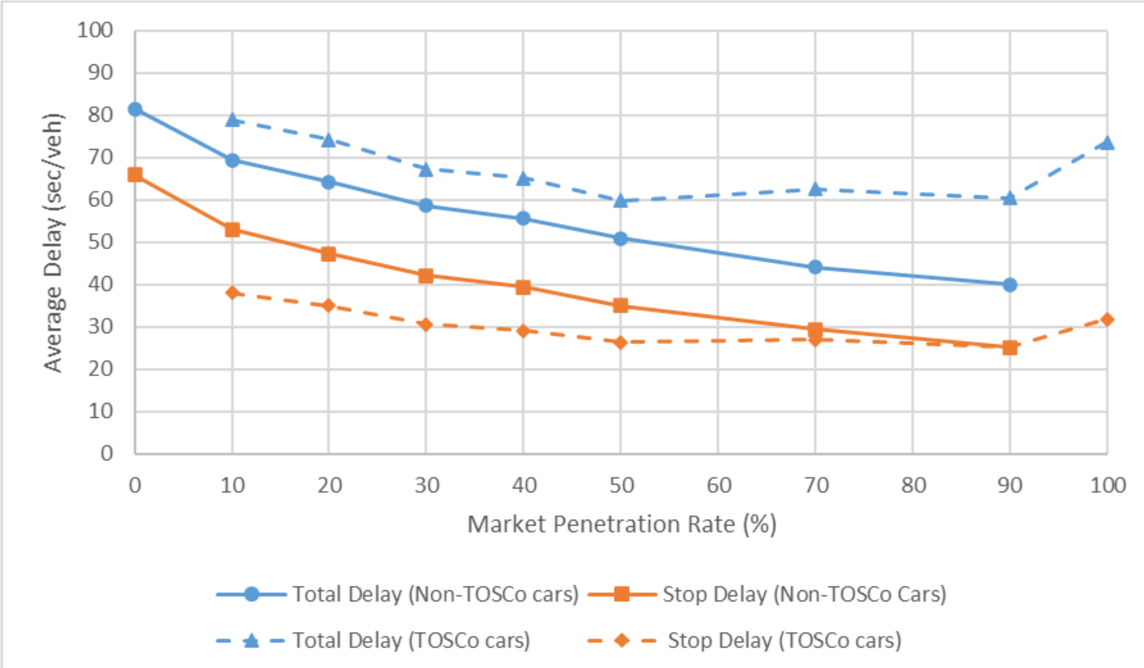
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 50. P.M. Peak Period Percent Change in Fuel Consumption – All TOSCo Approaches

If the most problematic intersection from a fuel use standpoint, April Sound, were removed from the analysis, the fuel usage for TOSCo would show slight reductions by 40 % MPR and about 15 % reductions in fuel use for the eastbound direction between the baseline and 100 % TOSCo MPR.

Discussion of Performance Results

Between the two directions of travel at the three intersections discussed in this report, most of the approaches experienced either constant or a decrease in total delay. The approaches that had queue spillback from a turning or a merging scenario, such as eastbound Loop 336, experienced increases in total delay as TOSCo MPR increased. This increase in total delay was true for other intersections with queue spillback, such as eastbound April Sound Boulevard, which also experienced increases in total delay in the P.M. peak period. Intersections where there were queueing problems or delays caused by volumes of thru traffic, such as eastbound Old River or eastbound West Fork, can benefit from TOSCo from a total delay standpoint. These approaches experienced statistically significant reductions in average queue lengths as a result of increased TOSCo MPR. Eastbound Old River experienced a consistent decrease in average and maximum queues as TOSCo MPR increased, thus indicating that TOSCo was able to increase throughput at this approach. The queueing at westbound Loop 336 has a similar improvement from zero to 30 % MPR but the queueing does increase again on this approach. The research team generated Figure 51 to help understand the trends at westbound 336.



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

Figure 51. Total and Stop Delay for P.M. Peak Divided by Vehicle Class on Westbound Loop 336

The dashed lines in Figure 51 represent the average performance for TOSCo vehicles and the solid 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 and less stop delay than non-TOSCo vehicles. You can also see that the total delay and stop delay decrease for both vehicle classes as TOSCo MPR increases. This reduction of delay per vehicle for both vehicle classes but higher delay for TOSCo vehicles is the reason for the U-shaped graphs, which were observed for performance measures at some intersections, such as westbound traffic at Loop 336 in Figure 45. 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 increased delays caused by queue spillback are amplified by the representation of TOSCo lane change behavior. In simulation, the TOSCo vehicles are discouraged from changing lanes on the approach unless necessary to complete their route which then results in TOSCo vehicles unrealistically getting stuck in a queue caused by a queue spillback.

Table 61 shows the monetization of the TOSCo approaches considering travel time and fuel costs for the P.M. peak results.

Table 61: P.M. Peak SH105 Corridor User Cost Analysis

Penetration Rate	Value of Total Travel Time	Fuel Cost (Texas Gasoline Price, 2018)	Total User Costs
0	$ 3,488.32	$ 5,402.15	$ 8,890.46
10	$ 3,551.06	$ 5,761.40	$ 9,312.46
20	$ 3,651.43	$ 5,927.09	$ 9,578.52
30	$ 3,630.11	$ 5,874.70	$ 9,504.81
40	$ 3,633.10	$ 5,740.81	$ 9,373.91
50	$ 3,641.29	$ 5,693.26	$ 9,334.55
70	$ 3,642.52	$ 5,399.54	$ 9,042.06
90	$ 3,695.58	$ 5,251.70	$ 8,947.28
100	$ 3,735.57	$ 5,299.45	$ 9,035.02

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

The total user costs initially increase between the baseline and the 20 % market penetration rate up to about a $700 user increase in costs. This is caused by the increased travel time at the intersections with the queue spillback behavior. The user costs decrease from the 20 % MPR scenario to 100 % TOSCo MPR scenarios to about even costs as the baseline. TOSCo does result in some fuel cost savings between the baseline and 100 % MPR for the P.M. peak period. Nonetheless, the changes in user costs is only ever a small percentage of the total user costs indicating that there is no meaningful change in user costs as a result of this version of TOSCo.

Discussion of Differences between A.M. and P.M. Peak Results for SH105

The A.M. and P.M. peak periods have different trends in mobility measurements. This is primarily due to all intersections during the different volumes and turning percentages between the two time periods. The P.M. peak period has large volumes which generates additional opportunity for the coordinated launch feature to increase the throughput of the intersection. However, there are intersections in the P.M. peak that have significantly more turning behavior which leads to some adverse impacts.

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 computer 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 SH105 corridor. The main revision from the Phase 1 model for TOSCo was the incorporation of the actual speed profile generation and mode selection logic for TOSCo into the traffic-level simulation environment, which improved the representation of TOSCo. The research team used this simulation evaluation environment to accomplish the following:

- Assess the potential mobility and environmental benefits of using TOSCo on SH105 on Conroe, 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. The research team continued to use the simulation environment platforms to develop, refine, and evaluate the infrastructure and vehicle algorithms throughout the life of the project, including applying the TOSCo analysis tools to FM 1960, the new deployment corridor for TOSCo.

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 SH105 corridor:

- TOSCo was able to achieve reductions in stop delay and number of stops in both A.M. and P.M. analysis periods. Stop delay decreased by around 50 % across the corridor as TOSCo MPR increases. Similar reductions in stops per vehicle occurred as TOSCo MPR increased in both direction and analysis periods.
- TOSCo reduced total delay at intersections without queue spillback or weaving traffic and sufficient traffic.
- TOSCo showed improved performance for each respective vehicle class, TOSCo-equipped as well as non-equipped, in total delay, stop delay, and number of stops as market penetration increased on most of the approaches.
- TOSCo increased total delay at intersections with significant queue spillback because of how simulated TOSCo vehicles were discouraged from performing lane changes.
- TOSCo did not cause substantial changes in the total delay experienced by travelers in the corridor, considering the travel time for vehicle to traverse SH105. As TOSCo vehicles were slowing down further upstream of intersections, minor changes in total delay were expected, but these changes are not likely to be noticeable to travelers.
- Intersections with high average queues experienced reductions in average queue lengths as TOSCo MPR increased. These reductions in queues were consistent if there were not any queue spillback issues and varied across MPR in cases where queue spill-back is observed.
- Total travel time and travel speed were not adversely impacted because of implementing TOSCo in the corridor.
- TOSCo reduced fuel consumption in the A.M. peak period gradually as TOSCo MPR increased. The eastbound direction experienced about a 7.6 % reduction in fuel use and the westbound direction of travel experienced about a 1.9 % reduction in fuel consumption.
- TOSCo temporarily increased fuel consumption in the P.M. peak period and fuel use gradually decreased from the 20 % MPR scenario until slight reductions in fuel occurred at 90 and 100 % MPR. The research team believes that the increases in fuel are caused by the increased stops caused by the interactions between TOSCo vehicles and weaving traffic attempting to turn either left or right.

Recommendations for Future Simulations in Phase 2

The research team continued to run simulations to estimate the benefits of the TOSCo system with the updated version of the TOSCo system source code and changes to the traffic-level representation constraints. With the transition to the FM1960 corridor due to the COVID 19 pandemic delays, the research team also employed some changes to the modeling of TOSCo. The following are enhancements developed by the research team based on their experiences with modeling the potential mobility and environmental benefits of the TOSCo system on SH105.

TOSCo Vehicle Simulation Enhancements

- In the SH105 simulation, TOSCo vehicles did not respond well to queue spillback scenarios. Non-TOSCo vehicles would change lanes to an open lane to continue their trip, but TOSCo vehicles would wait in the travel lane until the left turning traffic is no longer blocking the lane for the vehicle, which leads to an over-estimation of the total delay for TOSCo vehicles. The TOSCo analysis on FM 1960 allows simulated TOSCo vehicles to change lanes when the vehicle is within a queue caused by a left turn bay spillback.
- Speeds in all modes of TOSCo, except for Free-flow, were limited to the posted speed limit. Thus, when comparing TOSCo operations to the baseline traffic (which is not limited to the speed limit), the mobility benefits may be underestimated. The research team examined the impact of this constraint with simulation work in the FM 1960 corridor.

Implementation of TOSCo

Results from the two analysis periods show that TOSCo is less effective at low traffic volume and low delay intersections. When the traffic volume is low, or signal coordination provides good progression, most of the vehicles do not need to stop or slow down at the intersection, which leaves very limited space for adjusting vehicle trajectories. In some cases, TOSCo was able to improve performance for intersections with heavy through movements. Some of the TOSCo settings such as the lane change restrictions and the speed restrictions cause TOSCo vehicles to have inherently more delays than non-TOSCo vehicles at all MPR scenarios but did not adversely impact the average total delay for non-TOSCo vehicles. TOSCo vehicle market penetration could improve the total delay for the non-TOSCo vehicles and cause reduction of delays at mid-range MPR for some intersections with high through movements. In all cases, TOSCo vehicles were able to reduce the amount of stop delays observed at each intersection.

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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 62. 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 (TTI), 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 52 to Figure 54 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 54, 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.

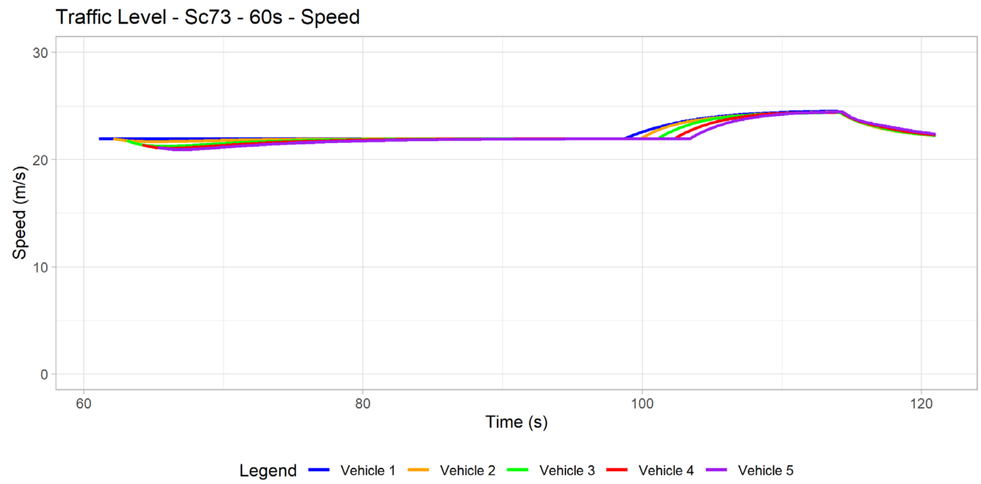
Figure 55 to Figure 57 show the results for the 66 second introduction time. As expected, the traffic-level scenario resulted in three vehicles crossing the intersection and two stopping, just like the vehicle-level simulation. The acceleration graphs show that the accelerations and decelerations are at the same simulation times and occur at the same amount of time. Vehicles cross the stop bar at the same times.

Figure 58 through Figure 60 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.

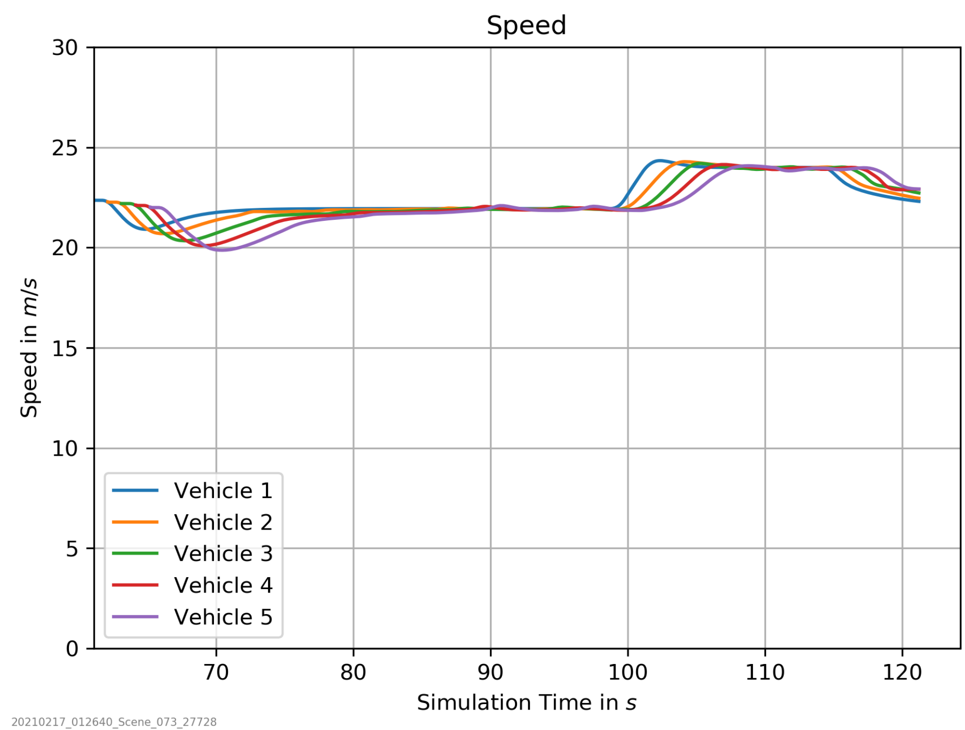
Figure 61 through Figure 63 show the results for the 105 second introduction time. The vehicle-level and the traffic-level representations both choose to CSC-DOWN and switch to CSC-UP at the same times. The lead vehicle chooses a similar set speed in both simulations and the vehicles cross the stop bar (i.e., go to free-flow) at approximately the same time.

Figure 64 through Figure 66 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.



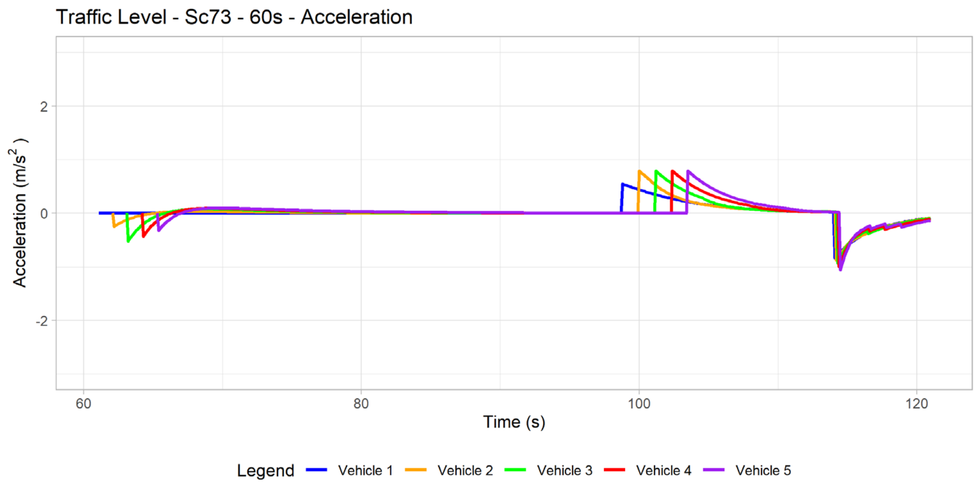
(a) Traffic-level Profile



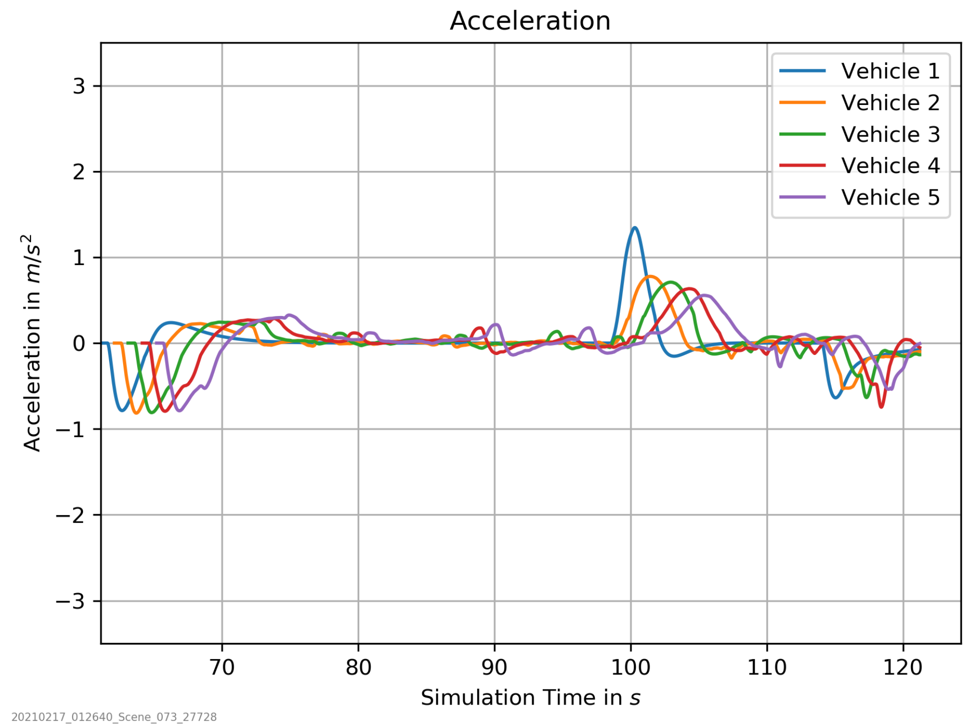
(b) Vehicle-level Profile

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

Figure 52. Verification Scenario 1 – 60 Second Introduction Time – Speed Profiles



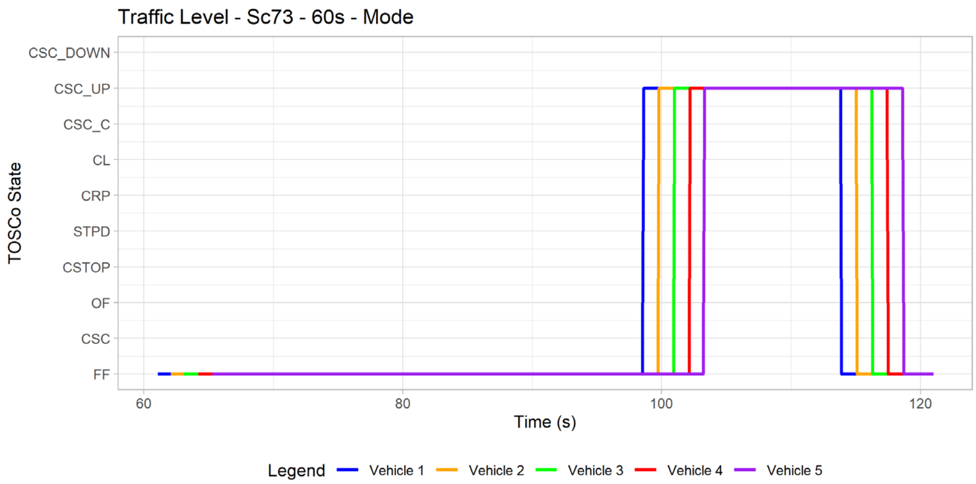
(a) Traffic-level Profile



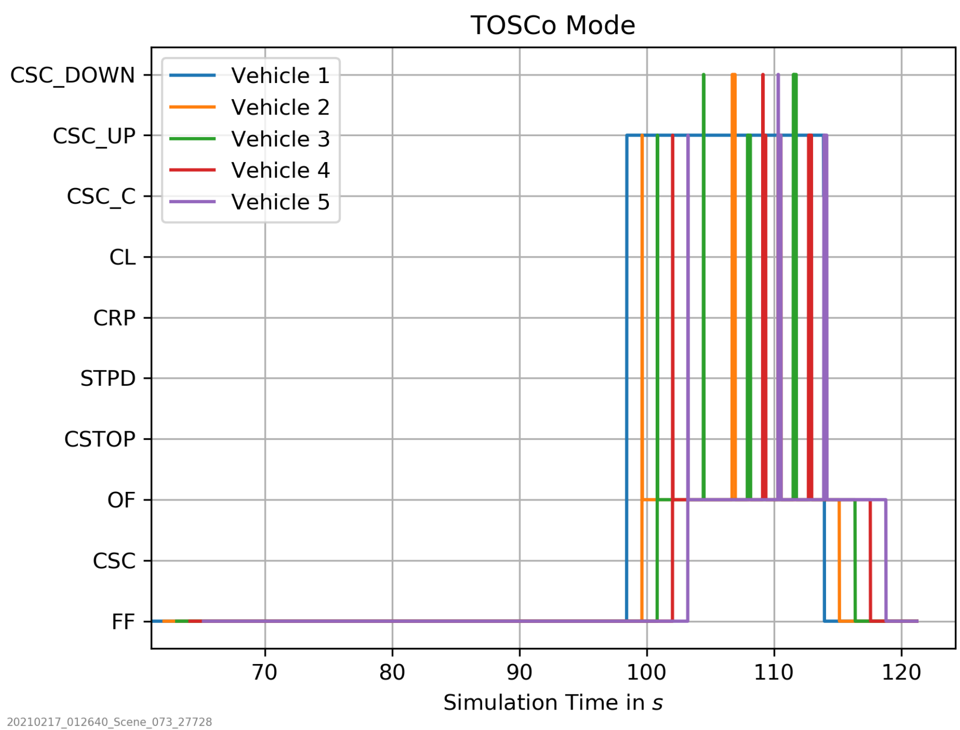
(b) Vehicle-level Profile

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

Figure 53. Verification Scenario 1 – 60 Second Introduction Time – Acceleration Profiles



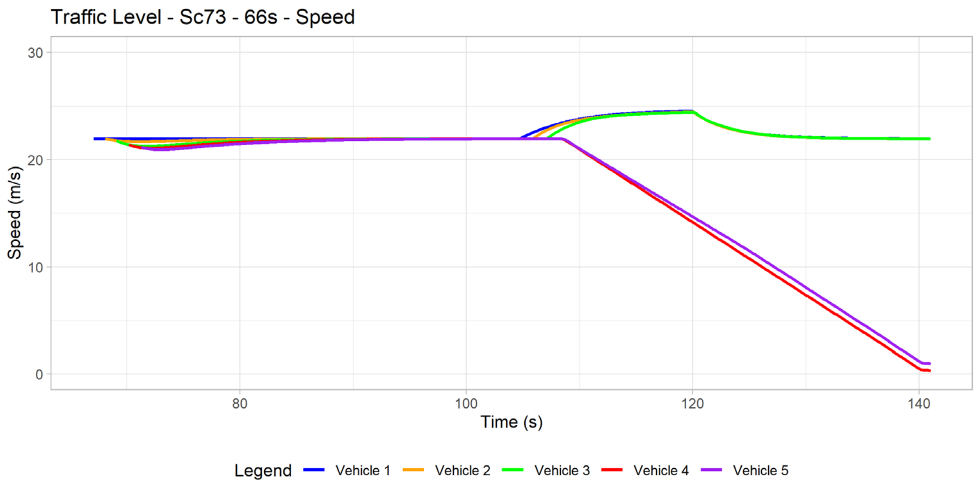
(a) Traffic-level Profile



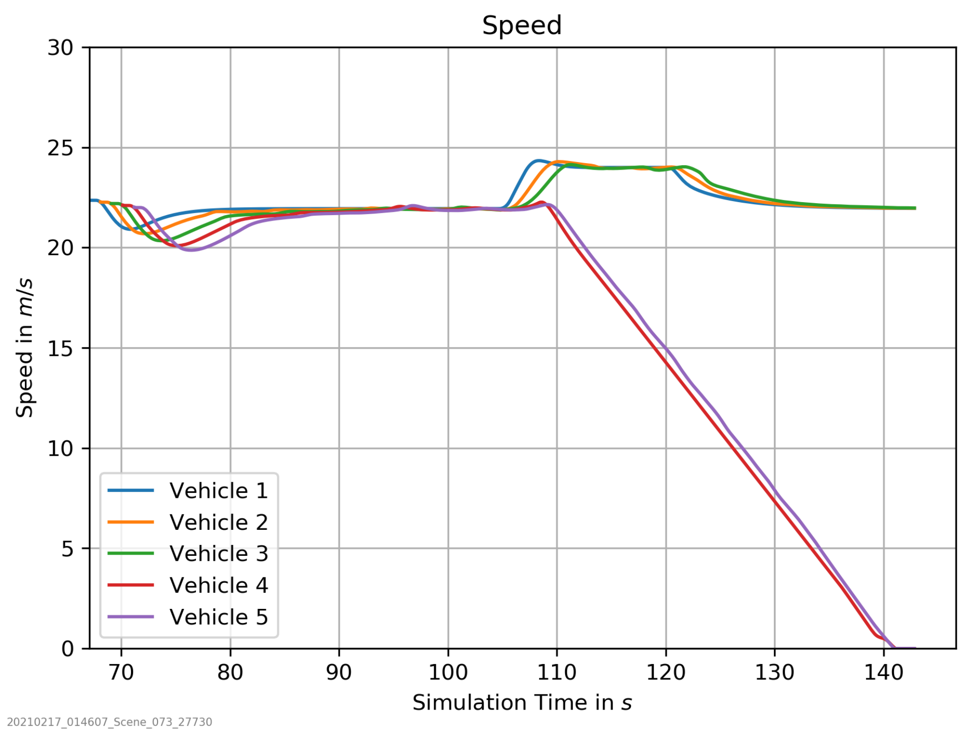
(b) Vehicle-level Profile

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

Figure 54. Verification Scenario 1 – 60 Second Introduction Time – Mode Profiles



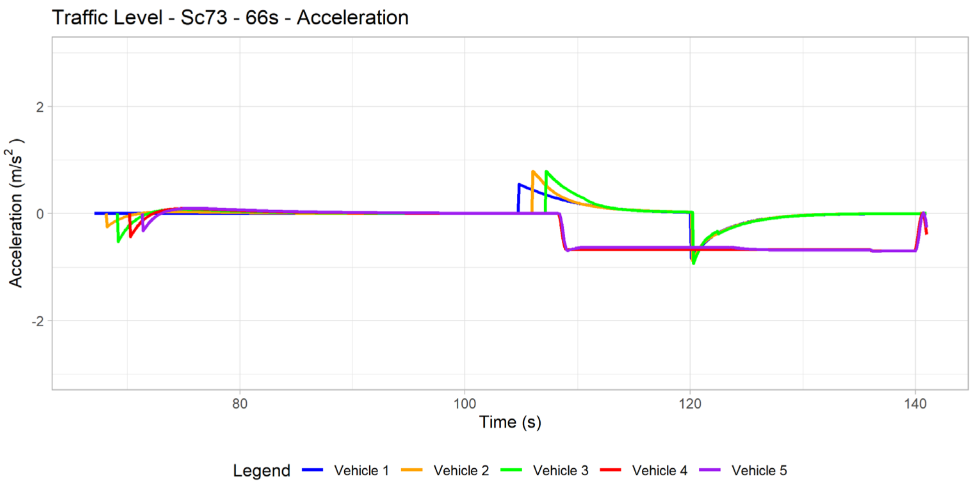
(a) Traffic-level Profile



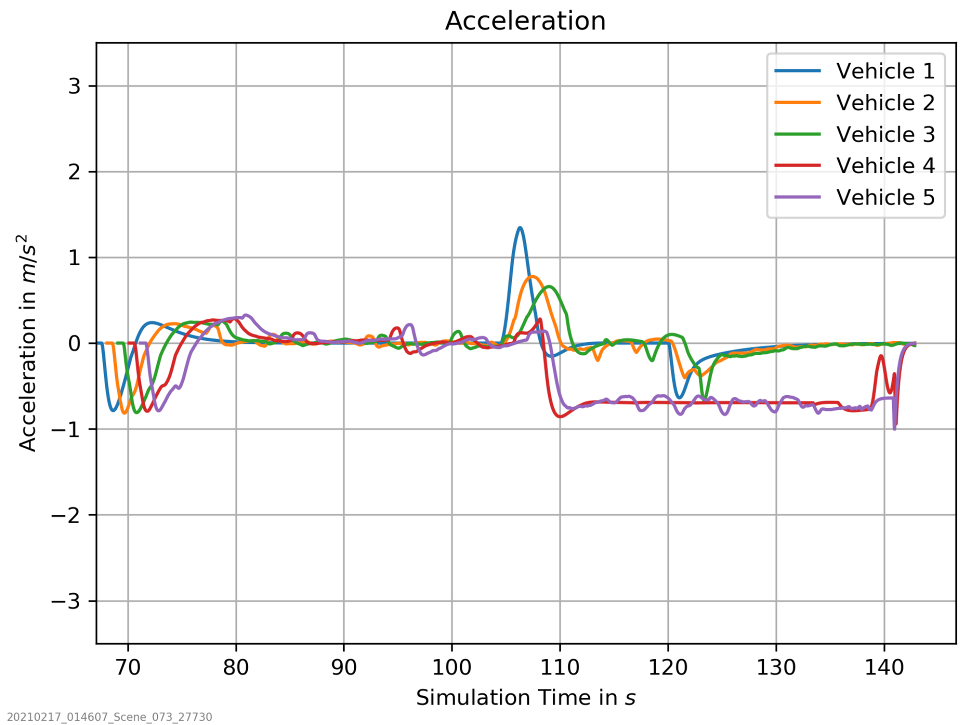
(b) Vehicle-level Profile

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

Figure 55. Verification Scenario 1 – 66 Second Introduction Time – Speed Profiles



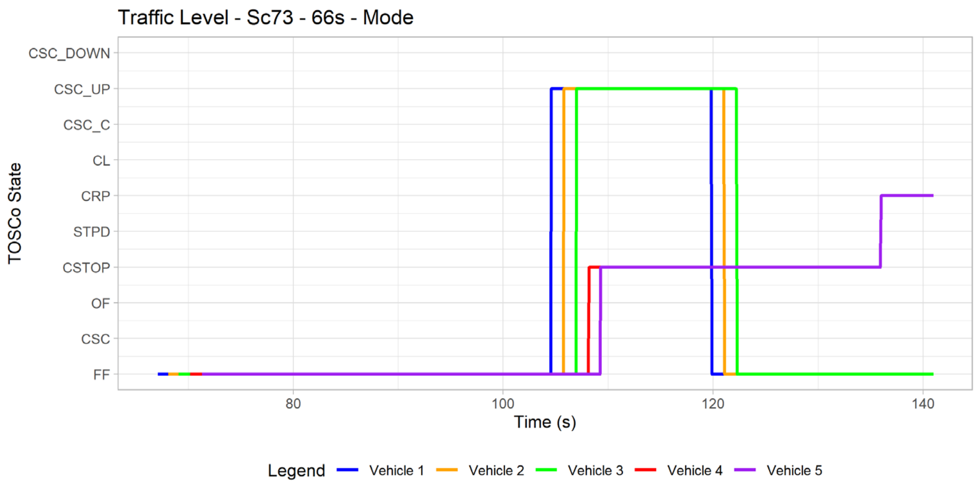
(a) Traffic-level Profile



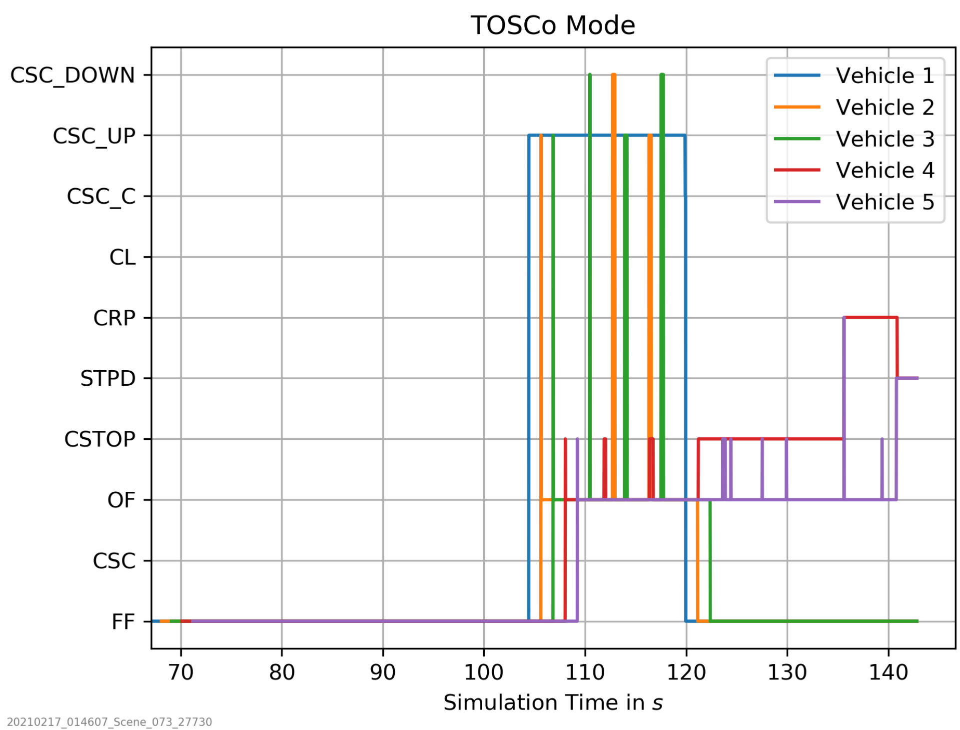
(b) Vehicle-level Profile

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

Figure 56. Verification Scenario 1 – 66 Second Introduction Time – Acceleration Profiles



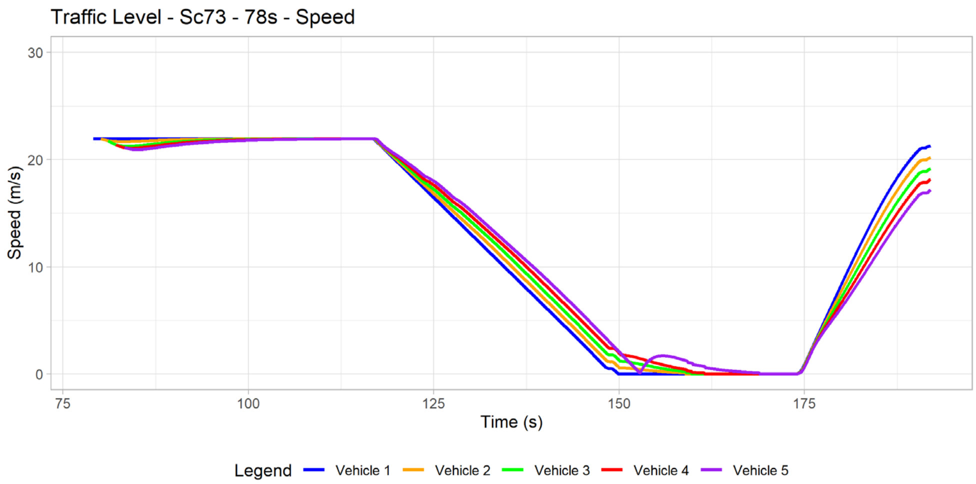
(a) Traffic-level Profile



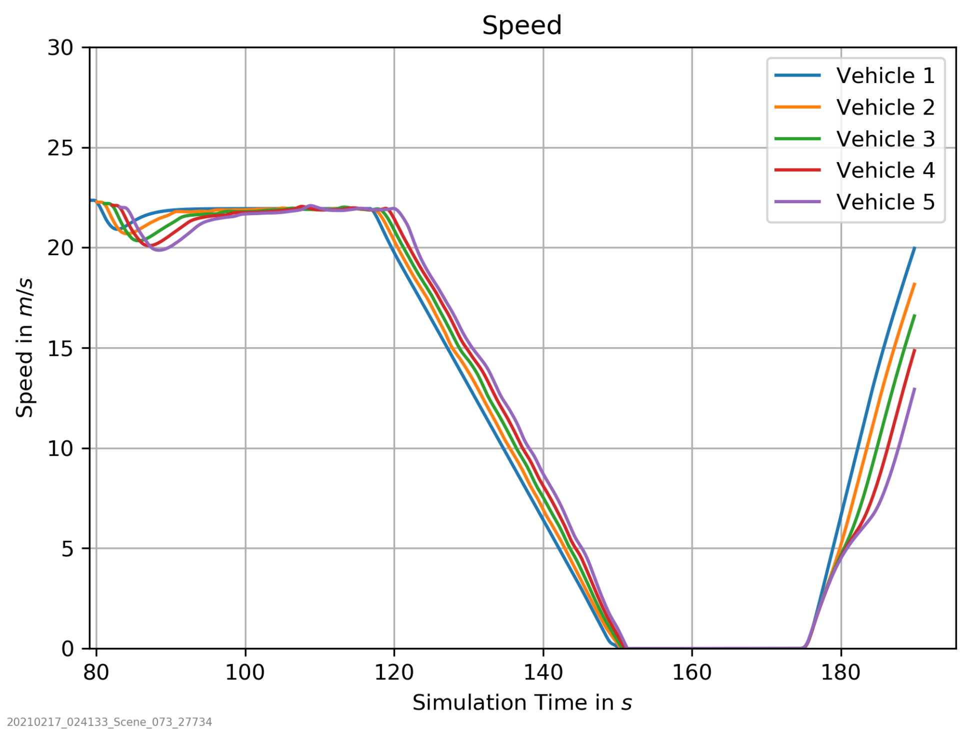
(b) Vehicle-level Profile

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

Figure 57. Verification Scenario 1 – 66 Second Introduction Time – Mode Profiles



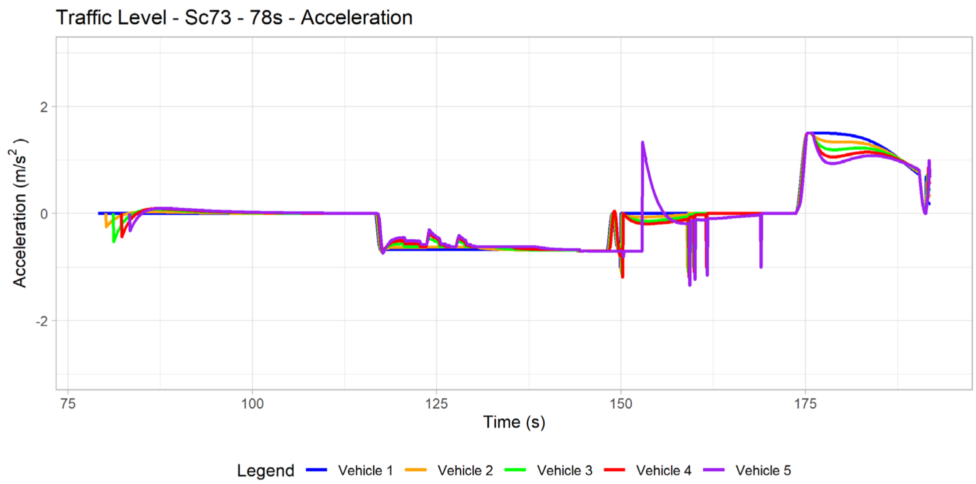
(a) Traffic-level Profile



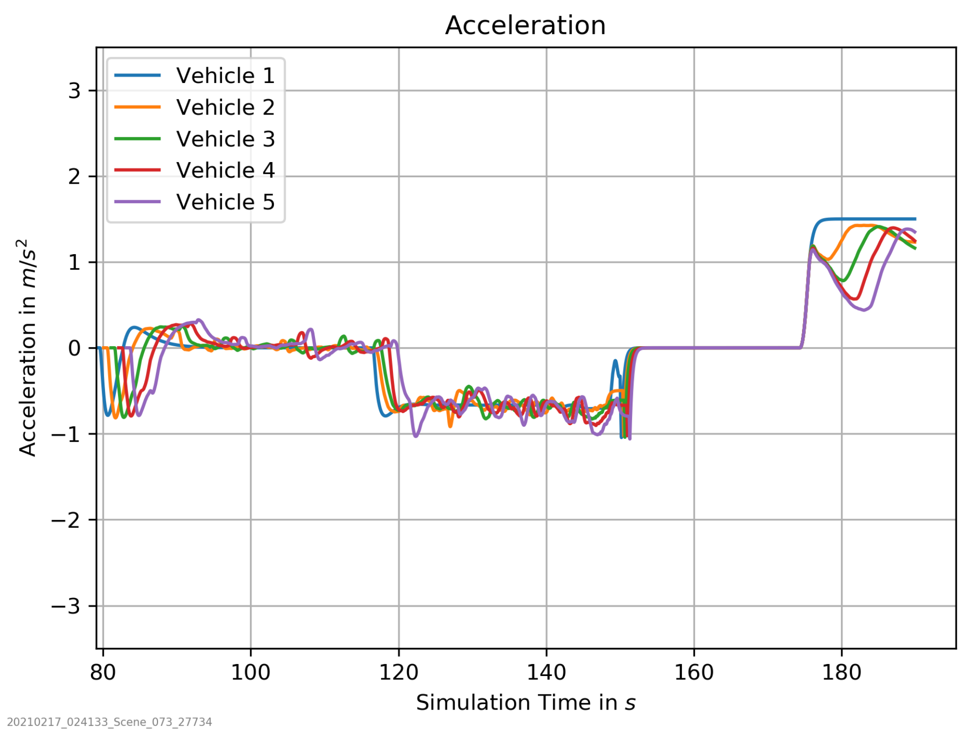
(b) Vehicle-level Profile

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

Figure 58. Verification Scenario 1 – 78 Second Introduction Time – Speed Profiles



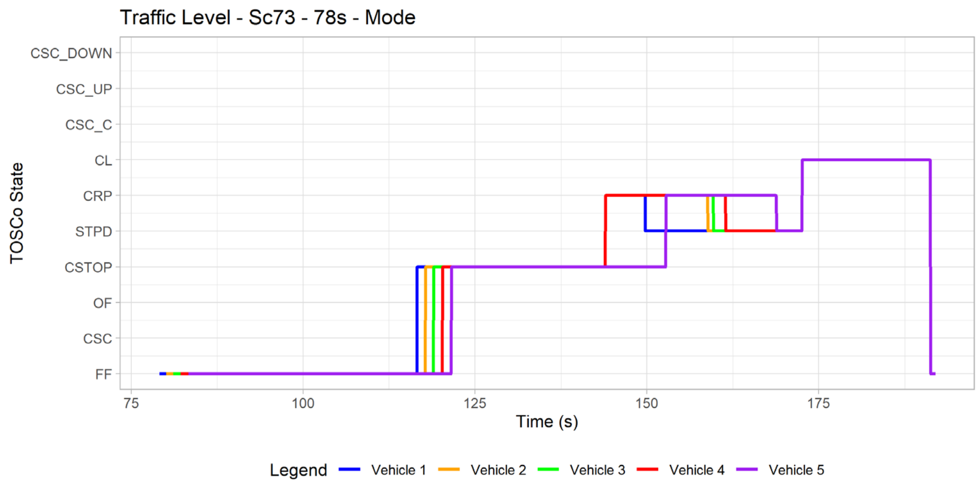
(a) Traffic-level Profile



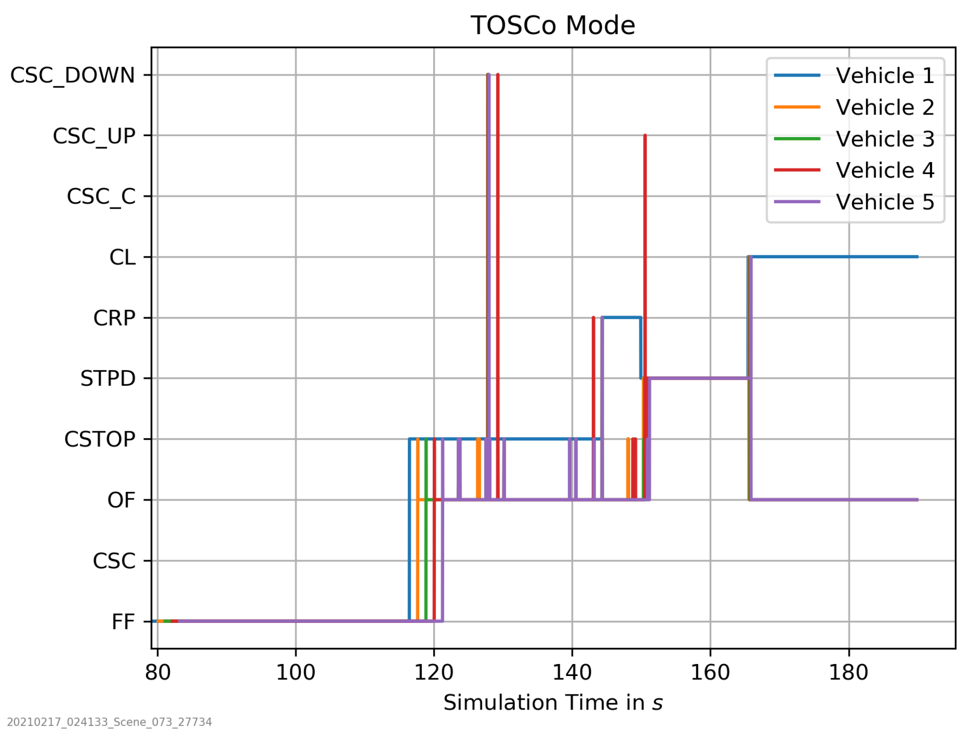
(b) Vehicle-level Profile

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

Figure 59. Verification Scenario 1 – 78 Second Introduction Time – Acceleration Profiles



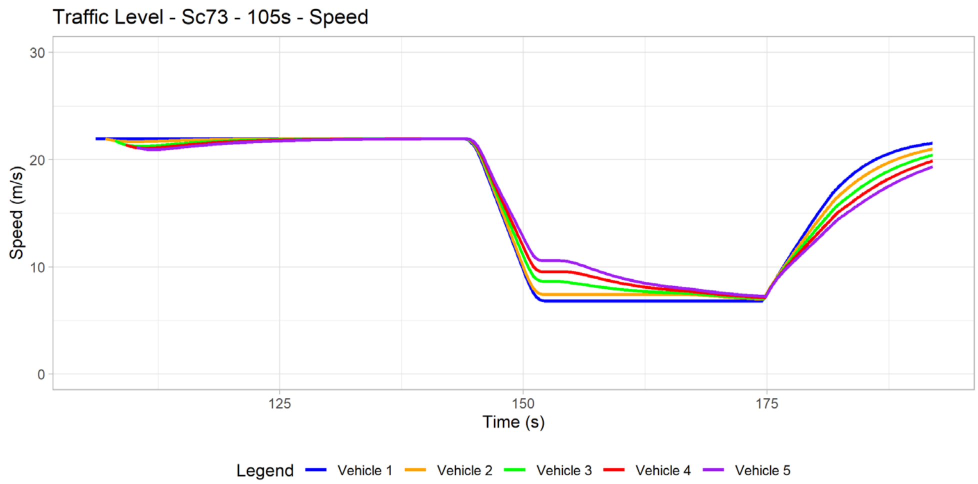
(a) Traffic-level Profile



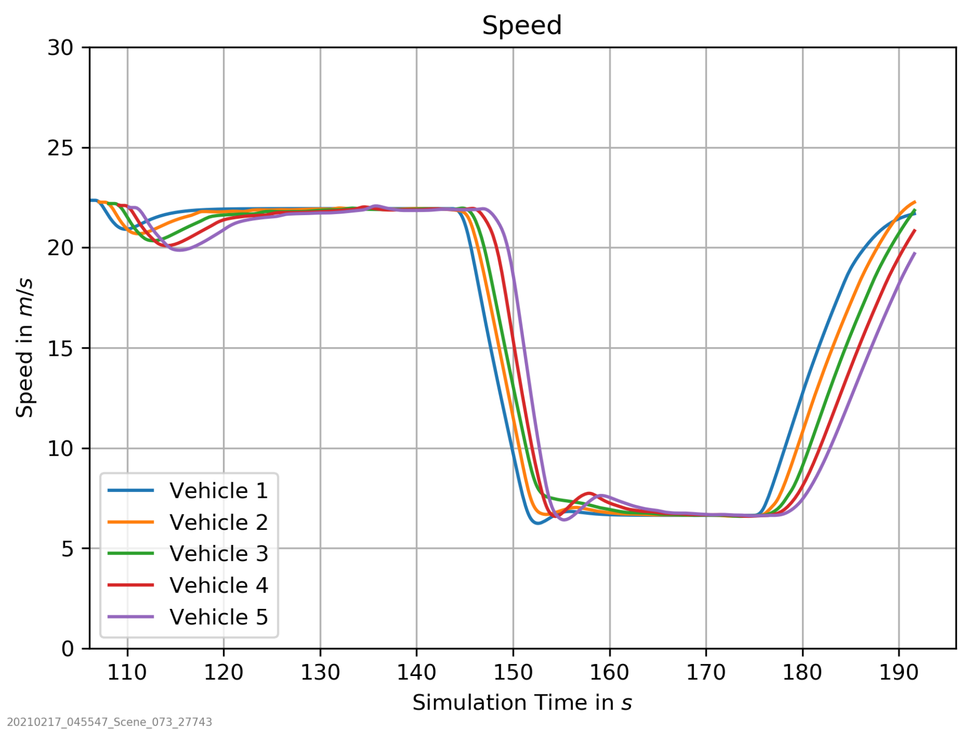
(b) Vehicle-level Profile

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

Figure 60. Verification Scenario 1 – 78 Second Introduction Time – Mode Profiles



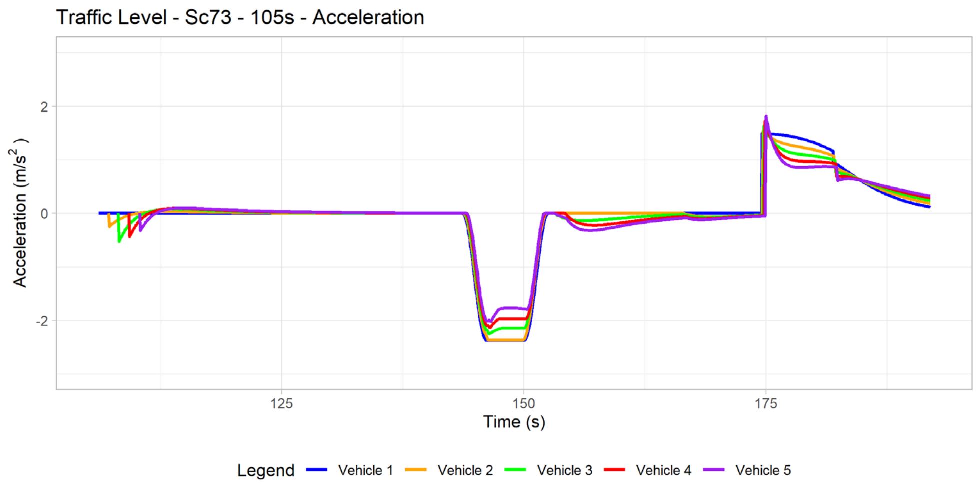
(a) Traffic-level Profile



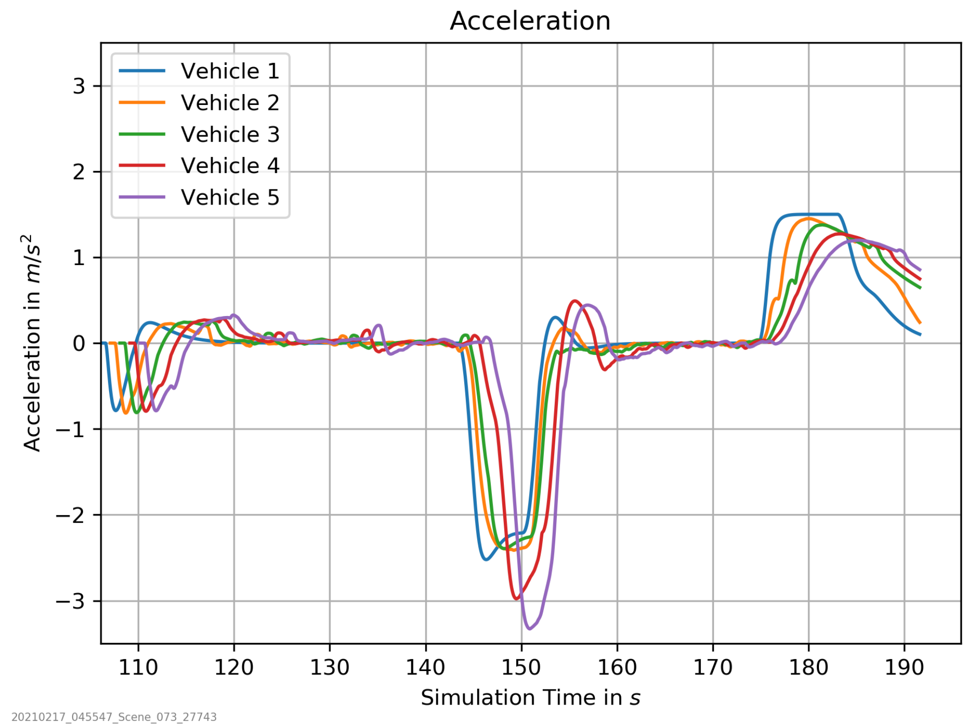
(b) Vehicle-level Profile

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

Figure 61. Verification Scenario 1 – 105 Second Introduction Time – Speed Profiles



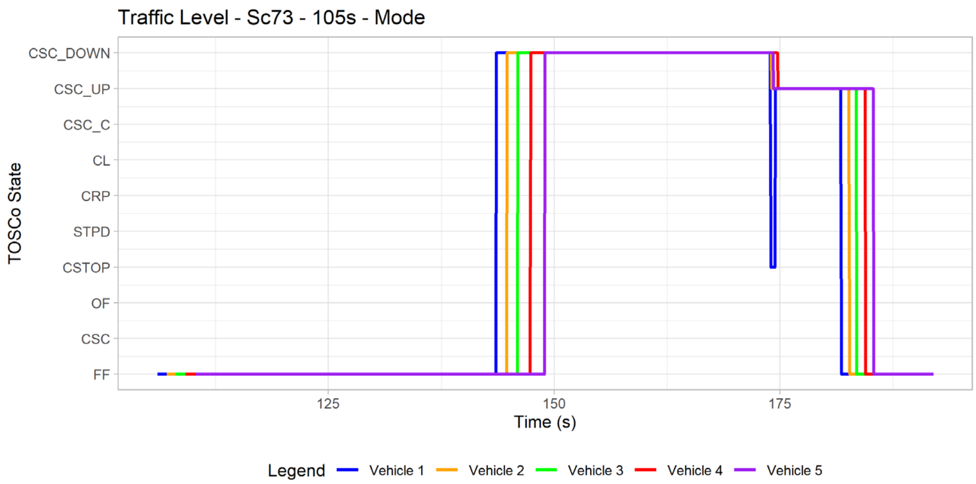
(a) Traffic-level Profile



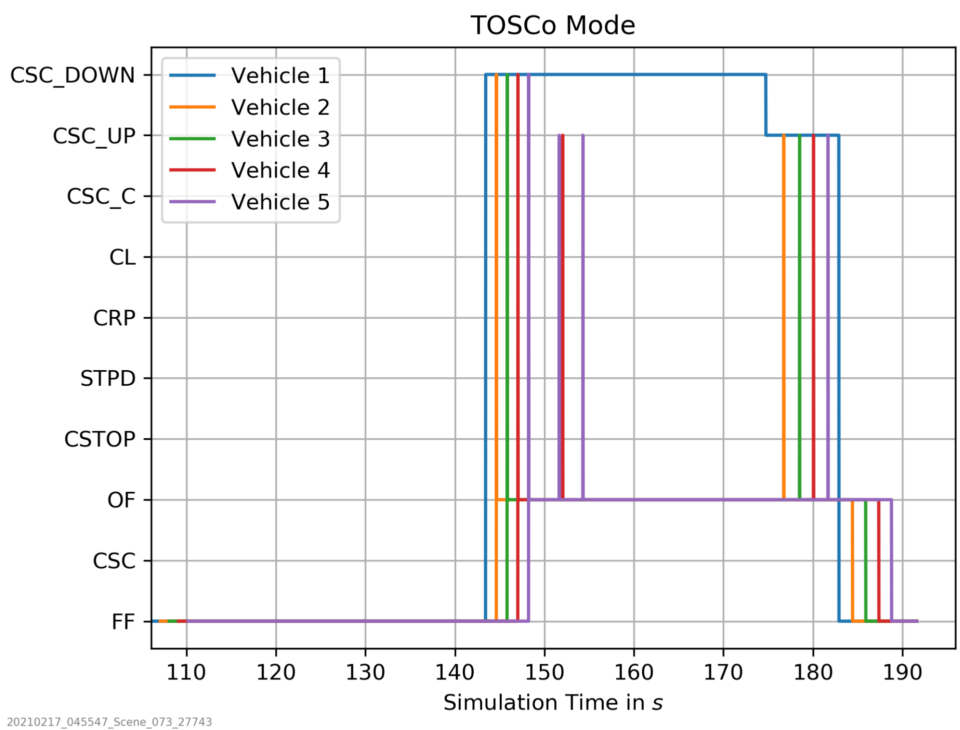
(b) Vehicle-level Profile

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

Figure 62. Verification Scenario 1 – 105 Second Introduction Time – Acceleration Profiles



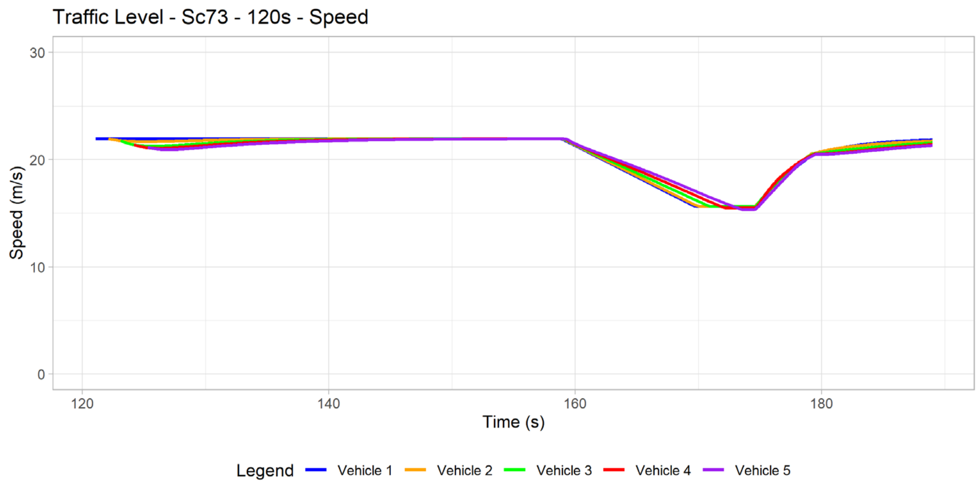
(a) Traffic-level Profile



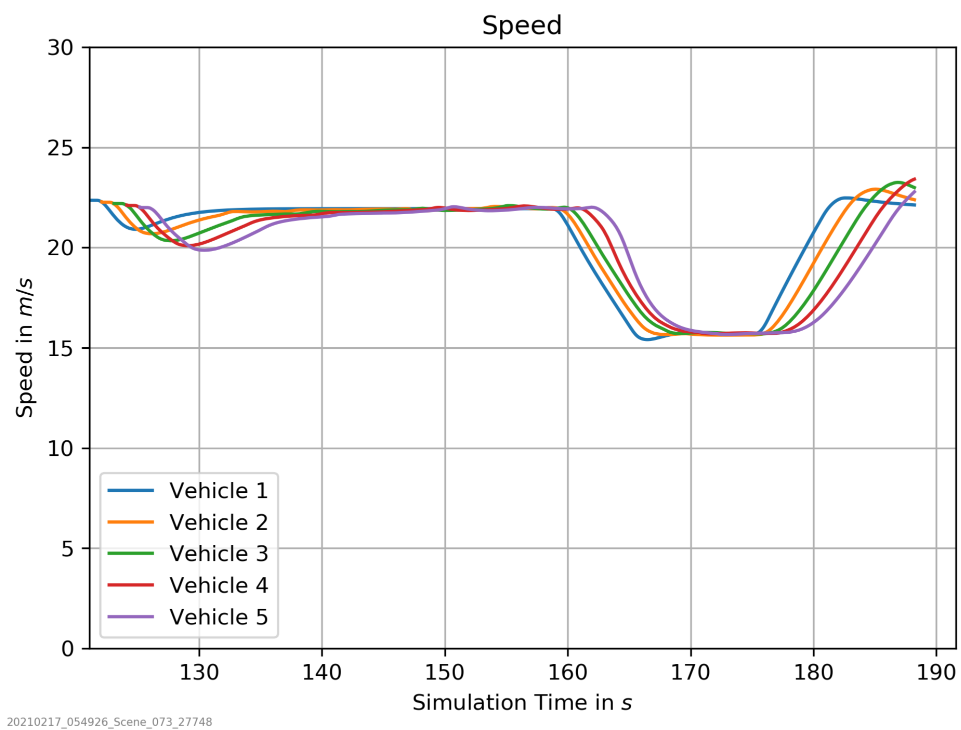
(b) Vehicle-level Profile

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

Figure 63. Verification Scenario 1 – 105 Second Introduction Time – Mode Profiles



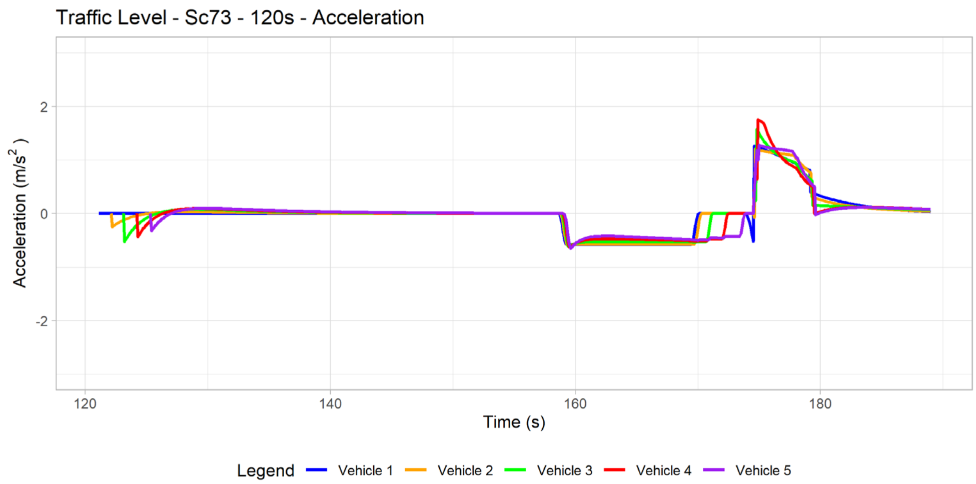
(a) Traffic-level Profile



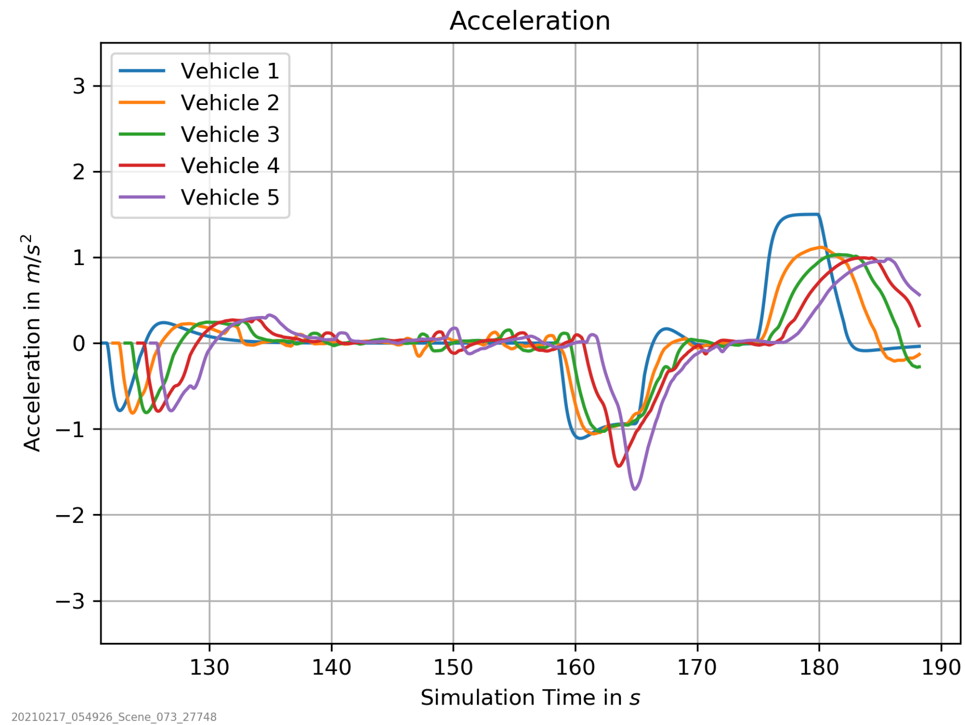
(b) Vehicle-level Profile

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

Figure 64. Verification Scenario 1 – 120 Second Introduction Time – Speed Profiles



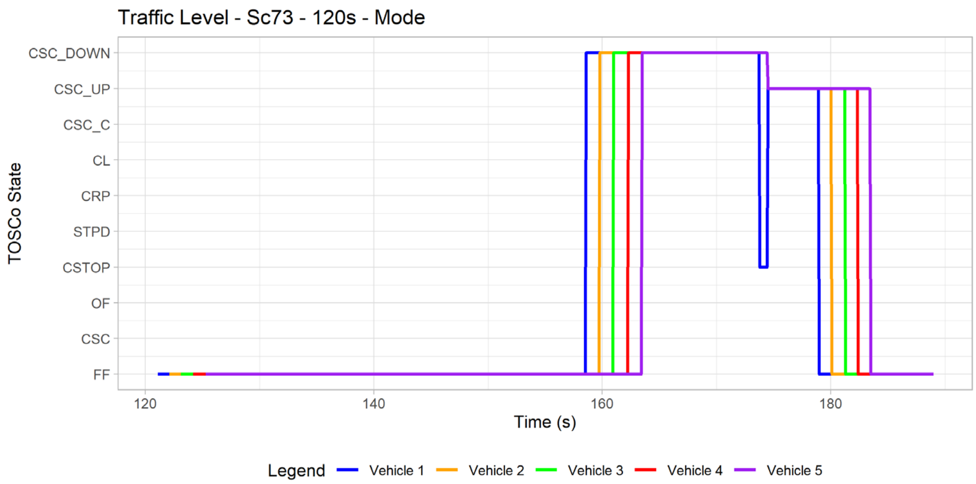
(a) Traffic-level Profile



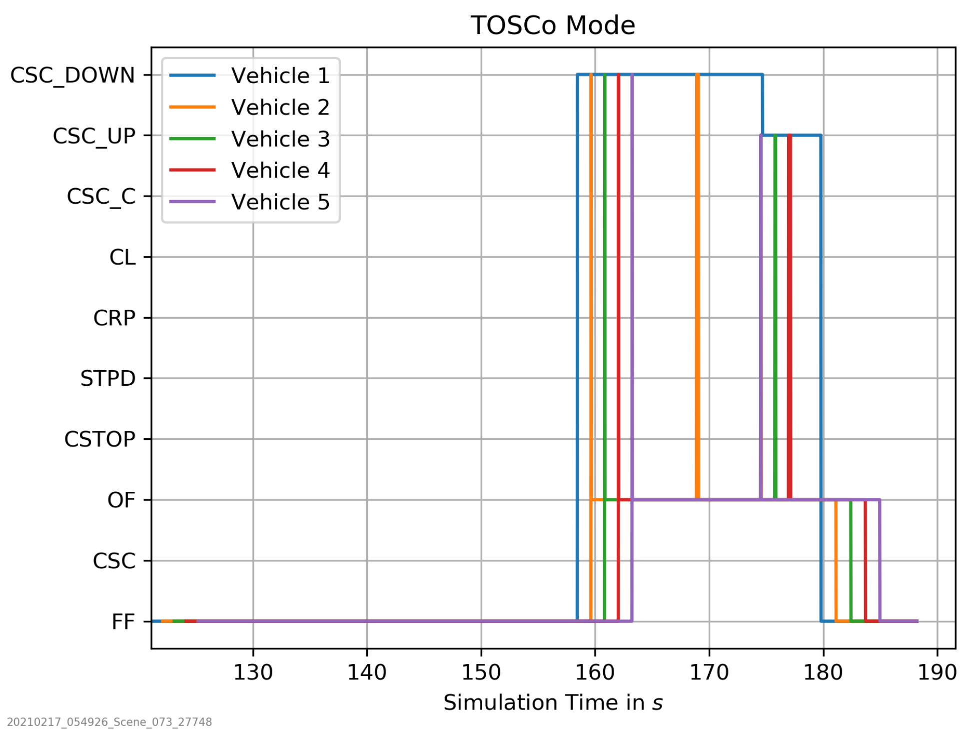
(b) Vehicle-level Profile

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

Figure 65. Verification Scenario 1 – 120 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 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 67 through Figure 69 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.

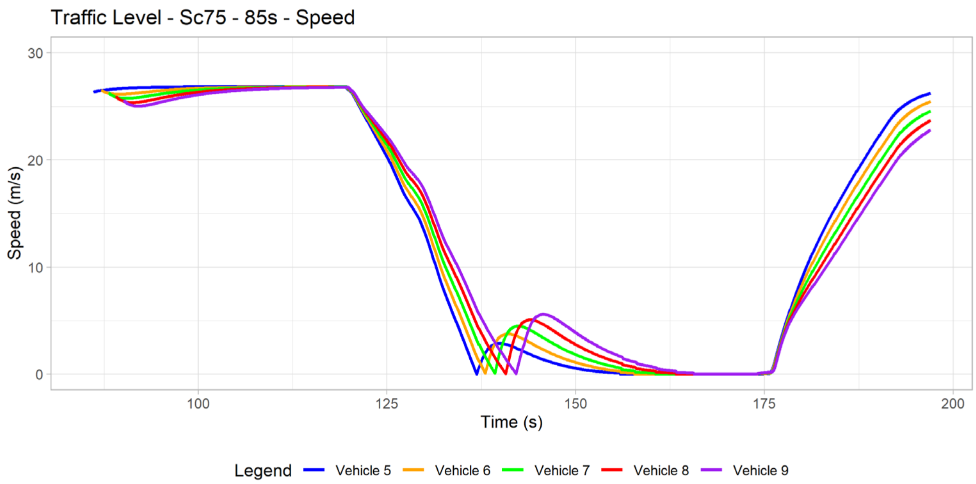
Figure 70 through Figure 72 show the results for the 97 second introduction time. The string chooses to perform a coordinated stop. The traffic level has different CREEP behavior than the vehicle-level simulation and the strings stop at a similar time. In both scenarios, all vehicles come to a stop and then begin to move after the vehicles in front of the TOSCo string depart the intersection.

Figure 73 through Figure 75 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.

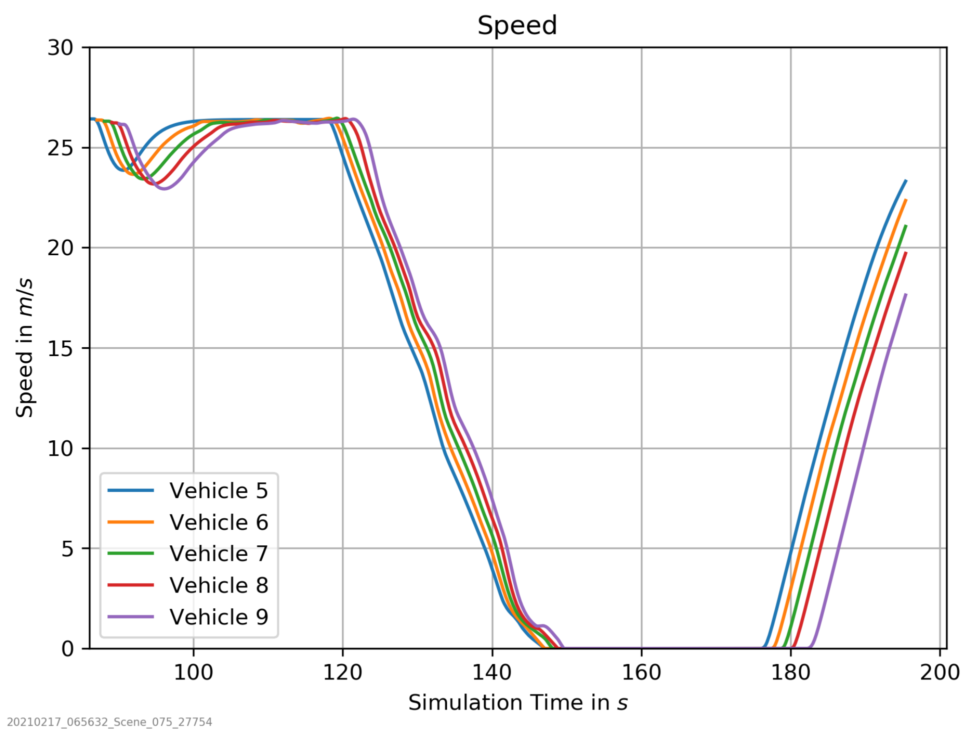
Figure 76 through Figure 78 show the results for the 130 second introduction time. In this scenario, both strings respond initially at the same time, but the traffic-level response does not slow down as much in the beginning. Both simulated strings ultimately slow down to about the same speed, but the 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 65 Figure 67 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.



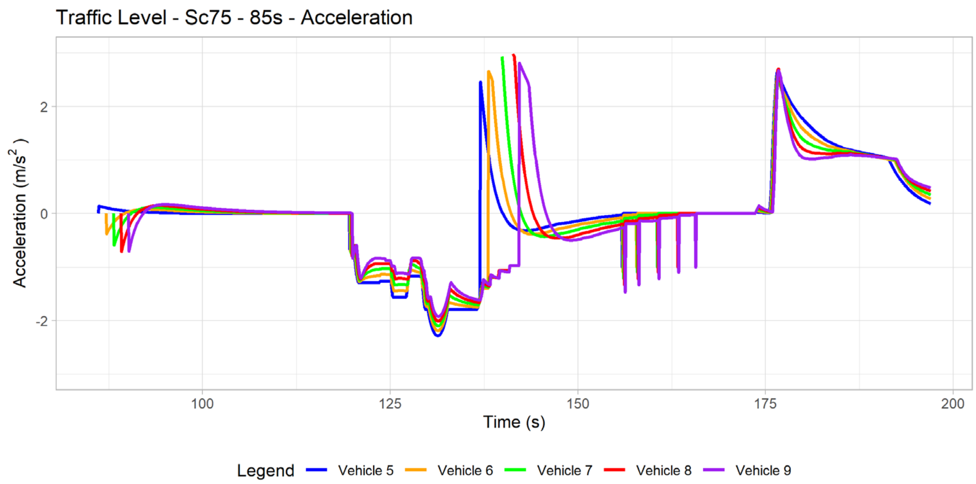
(a) Traffic-level Profile



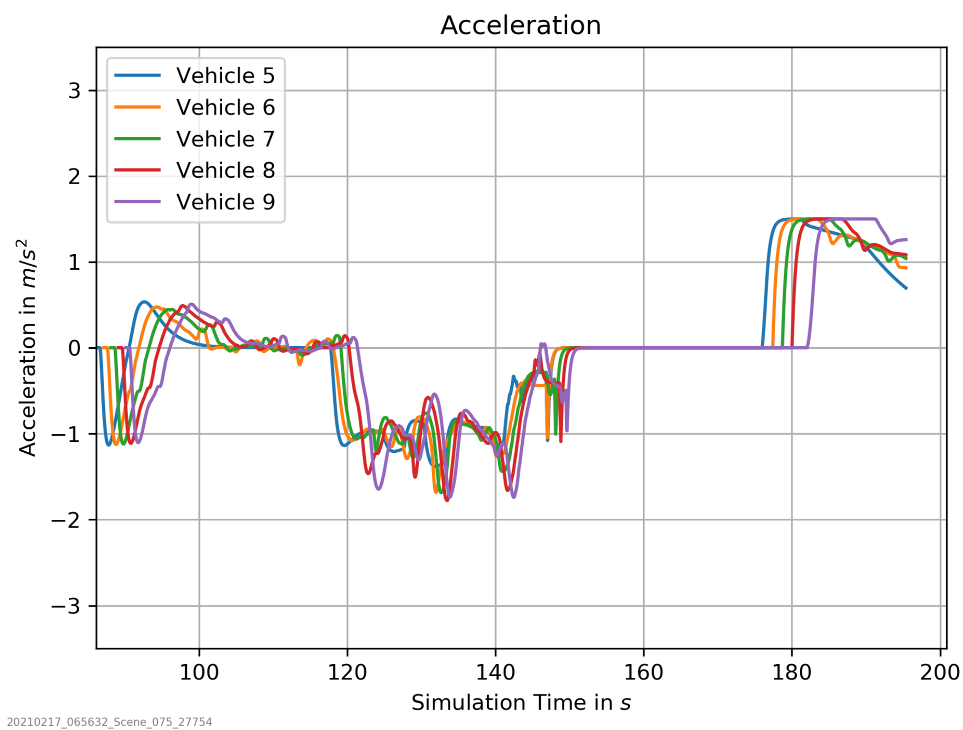
(b) Vehicle-level Profile

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

Figure 67. Verification Scenario 2 – 85 Second Introduction Time – Speed Profiles



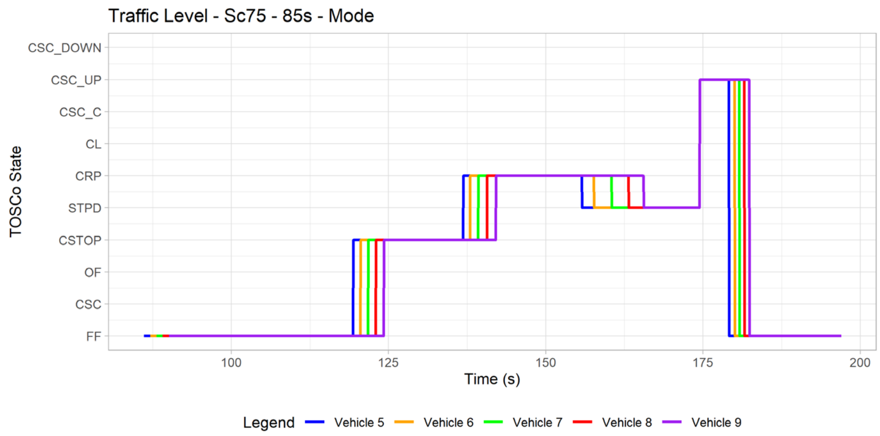
(a) Traffic-level Profile



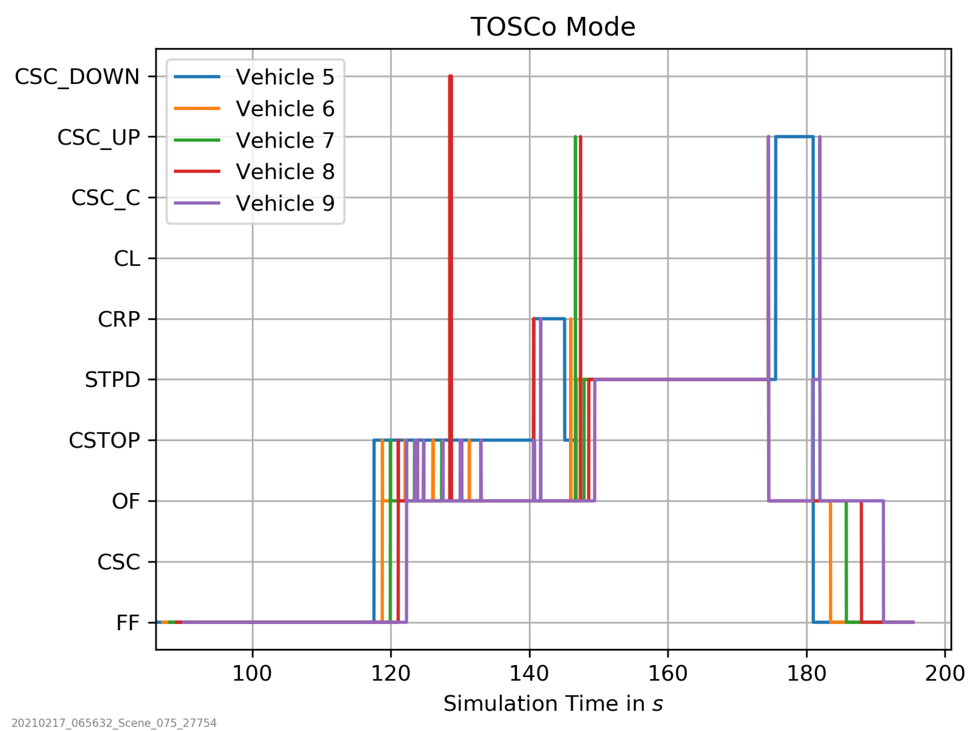
(b) Vehicle-level Profile

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

Figure 68. Verification Scenario 2 – 85 Second Introduction Time – Acceleration Profiles



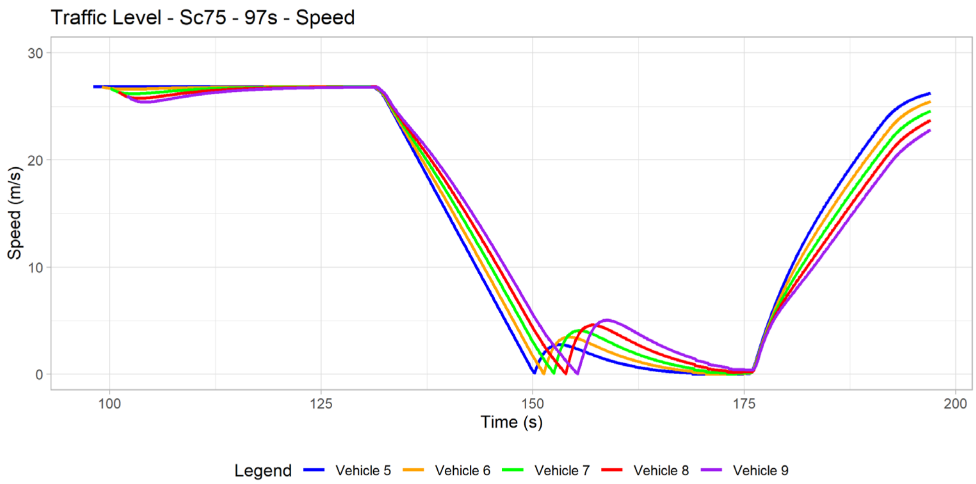
(a) Traffic-level Profile



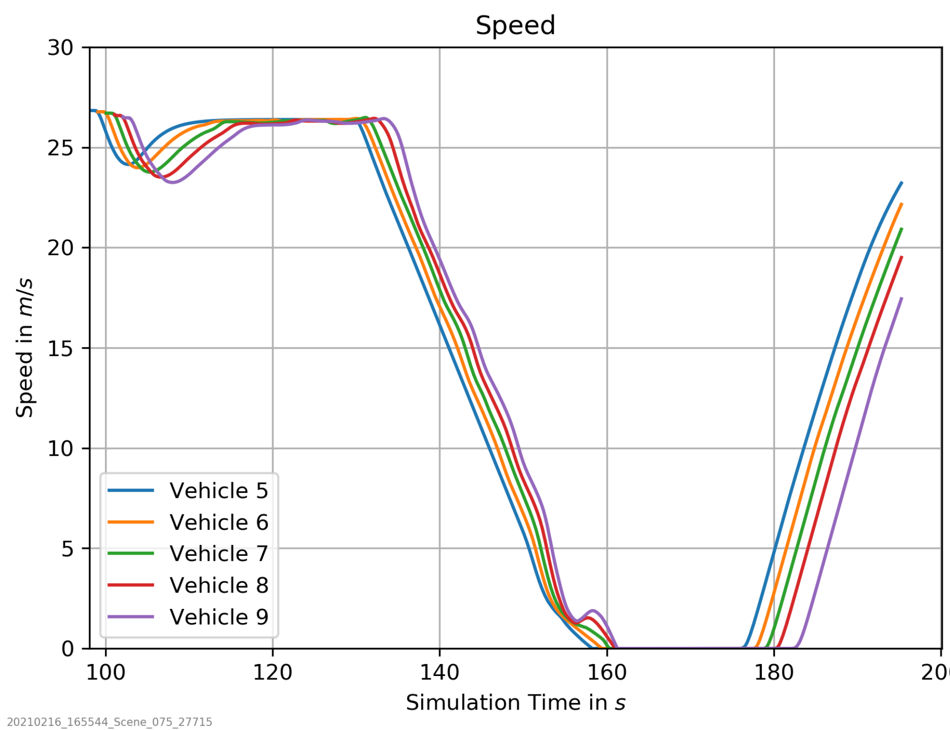
(b) Vehicle-level Profile

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

Figure 69. Verification Scenario 2 – 85 Second Introduction Time – Mode Profiles



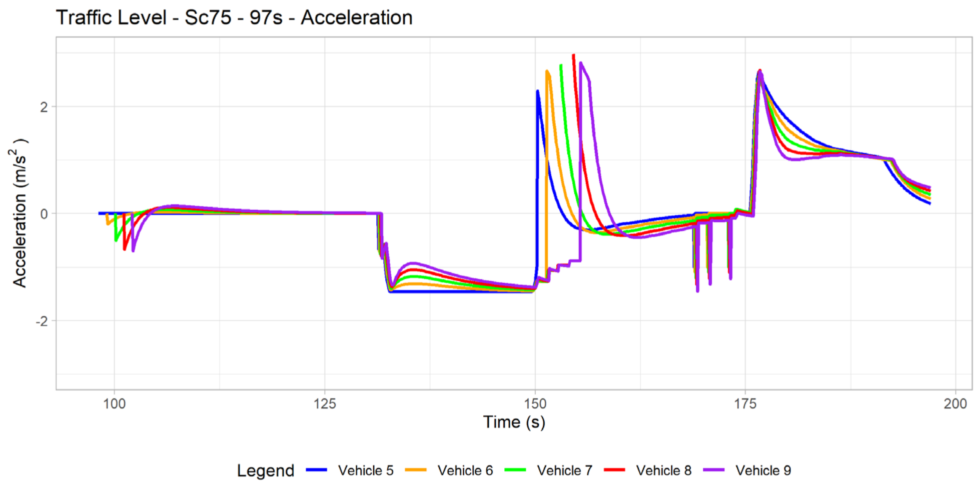
(a) Traffic-level Profile



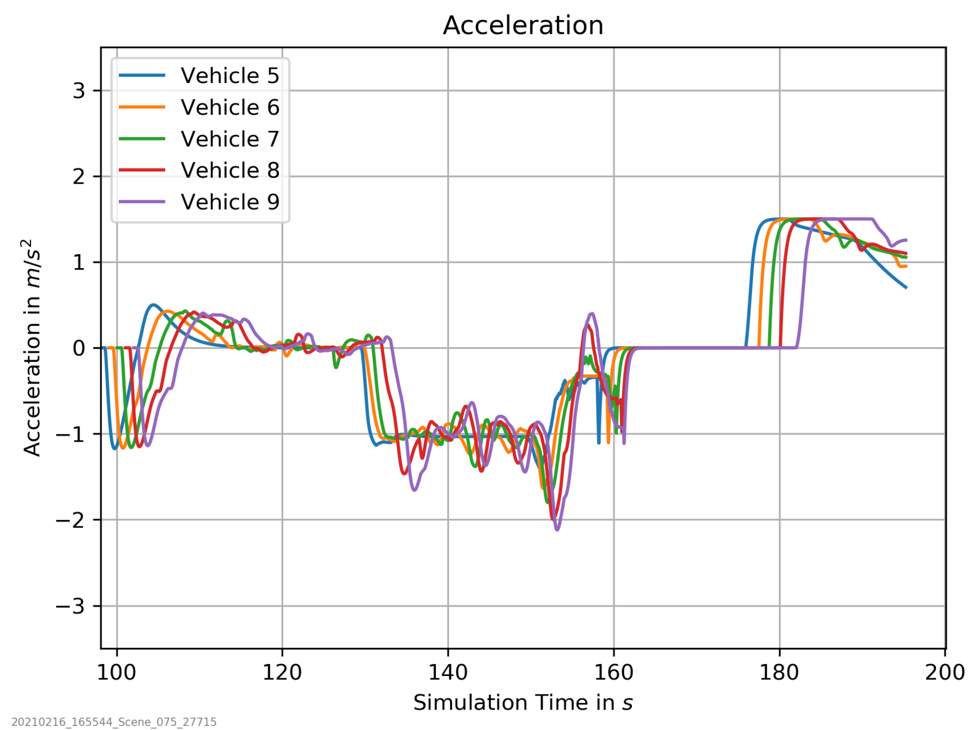
(b) Vehicle-level Profile

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

Figure 70. Verification Scenario 2 – 97 Second Introduction Time – Speed Profiles



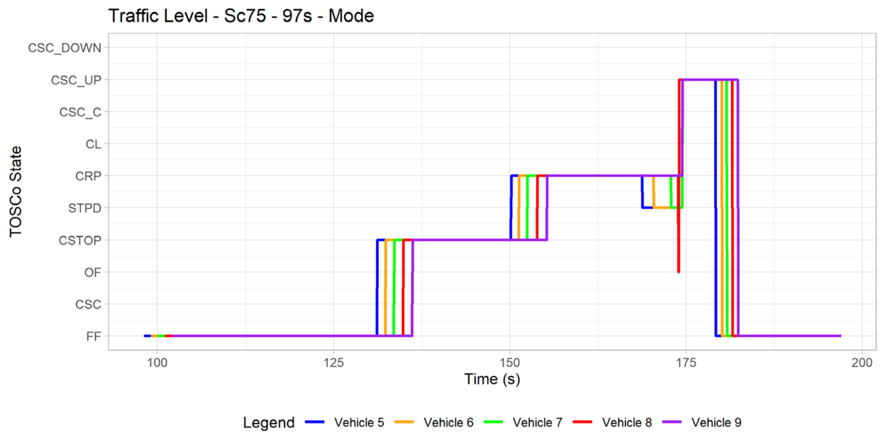
(a) Traffic-level Profile



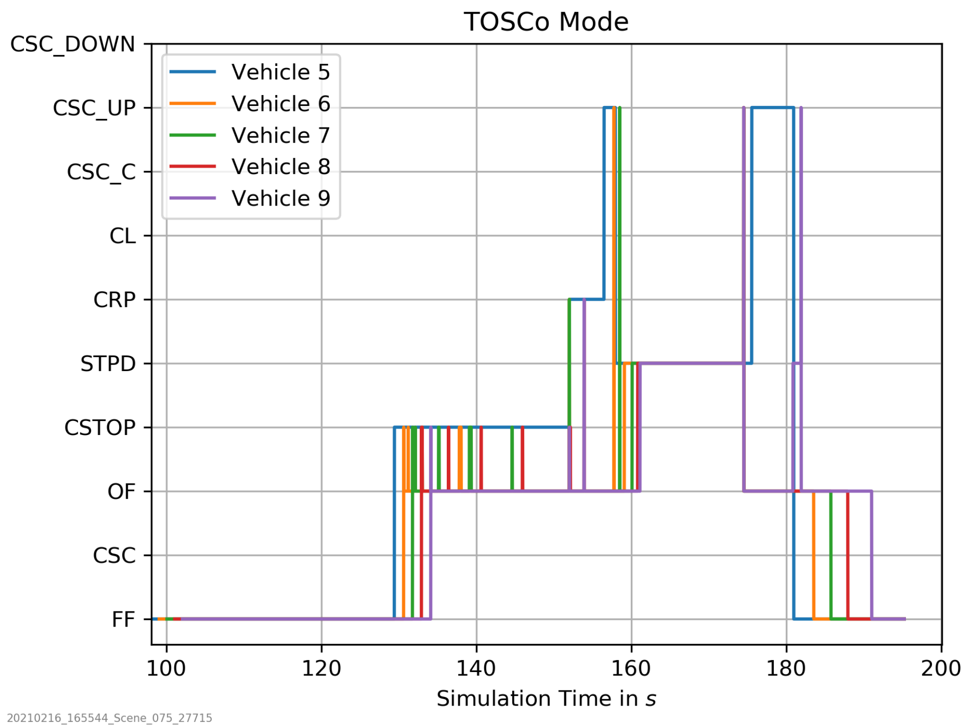
(b) Vehicle-level Profile

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

Figure 71. Verification Scenario 2 – 97 Second Introduction Time – Acceleration Profiles



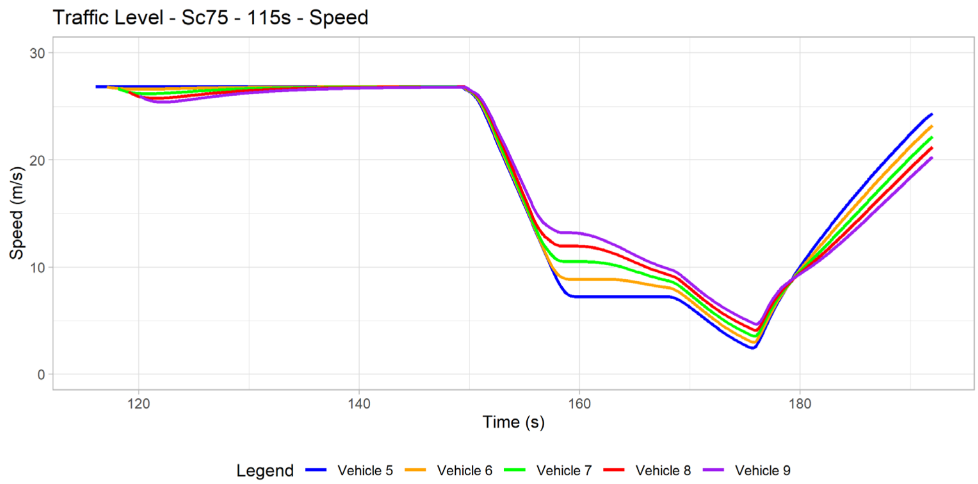
(a) Traffic-level Profile



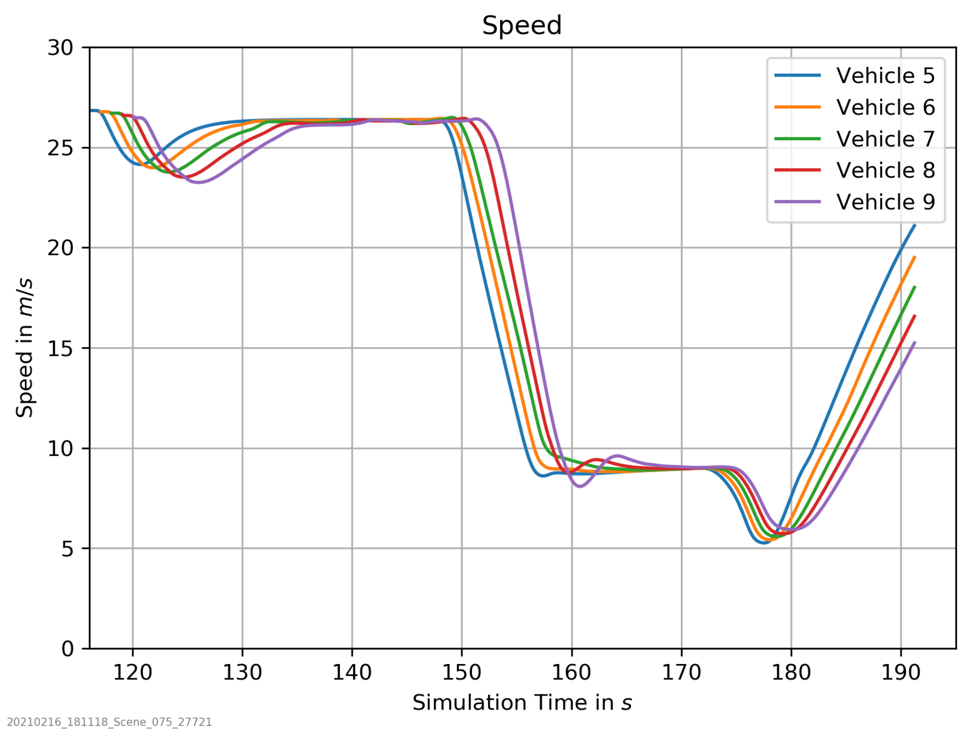
(b) Vehicle-level Profile

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

Figure 72. Verification Scenario 2 – 97 Second Introduction Time – Mode Profiles



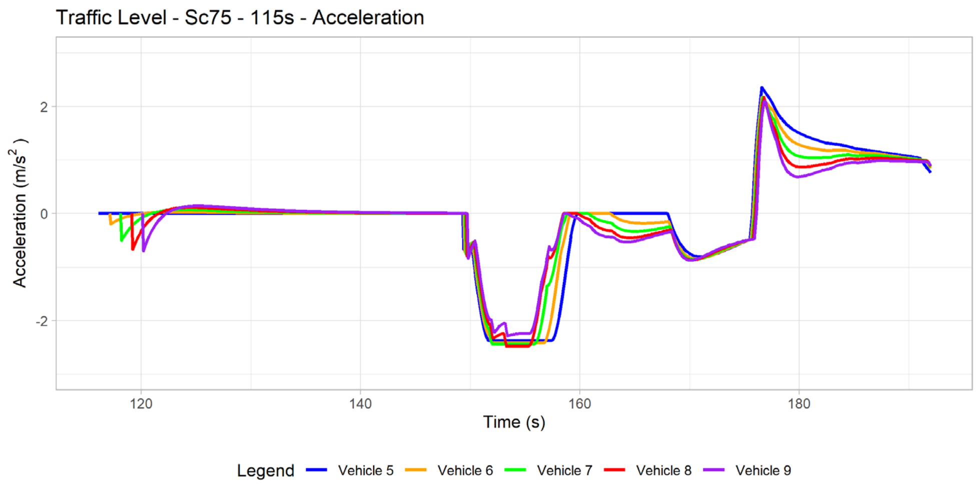
(a) Traffic-level Profile



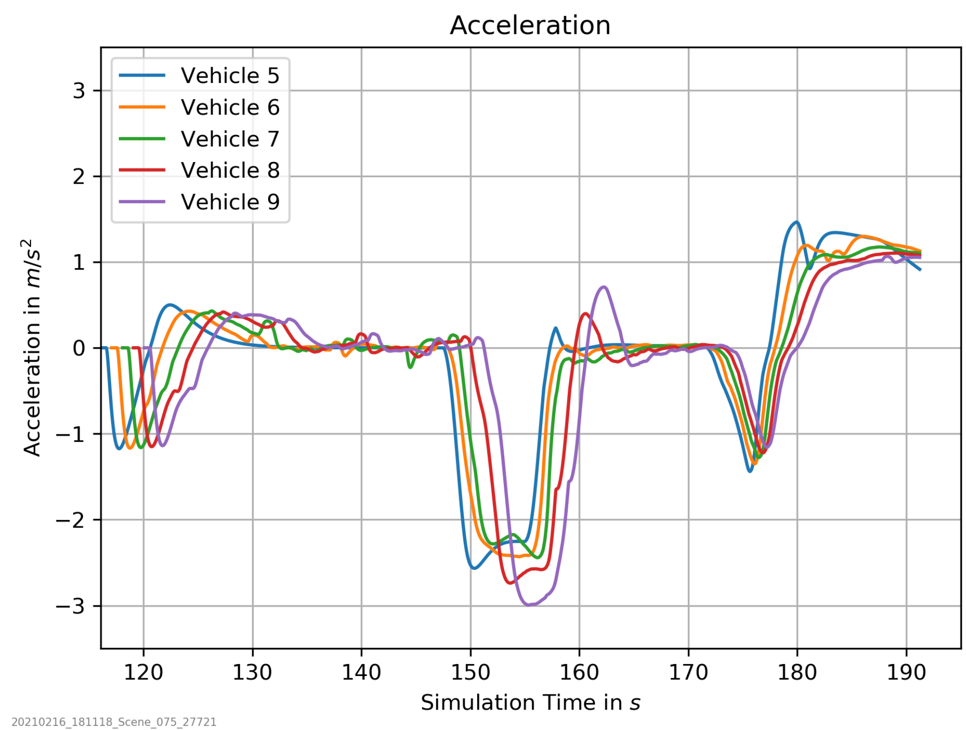
(b) Vehicle-level Profile

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

Figure 73. Verification Scenario 2 – 115 Second Introduction Time – Speed Profiles



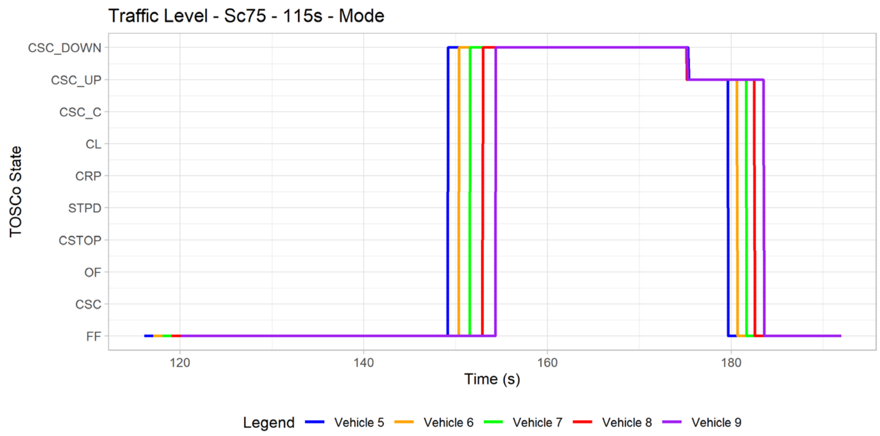
(a) Traffic-level Profile



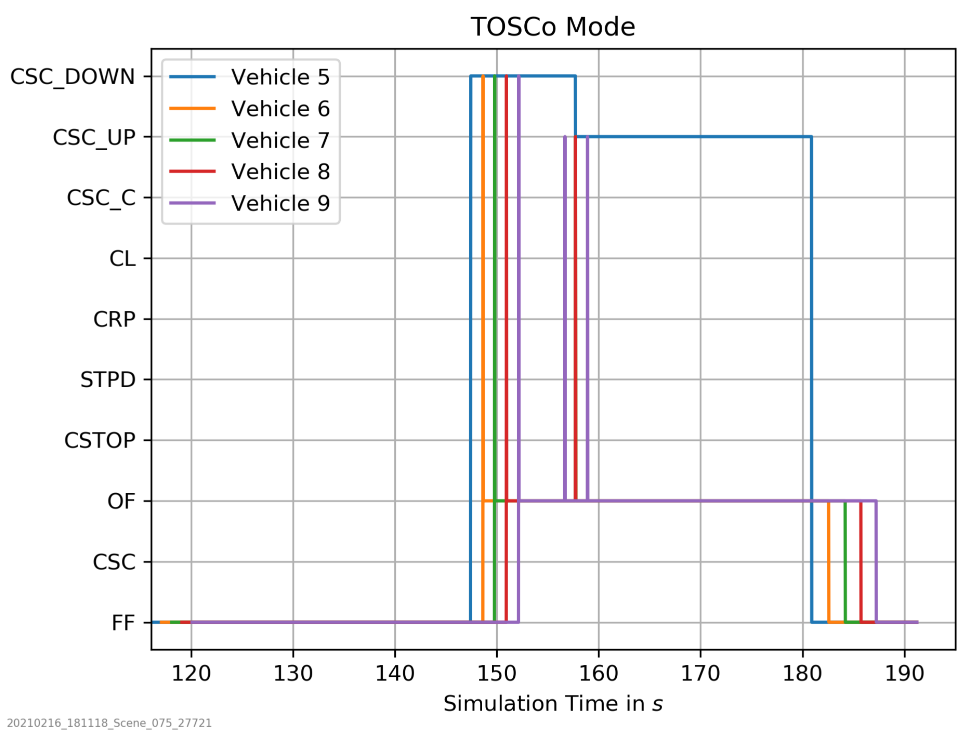
(b) Vehicle-level Profile

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

Figure 74. Verification Scenario 2 – 115 Second Introduction Time – Acceleration Profiles



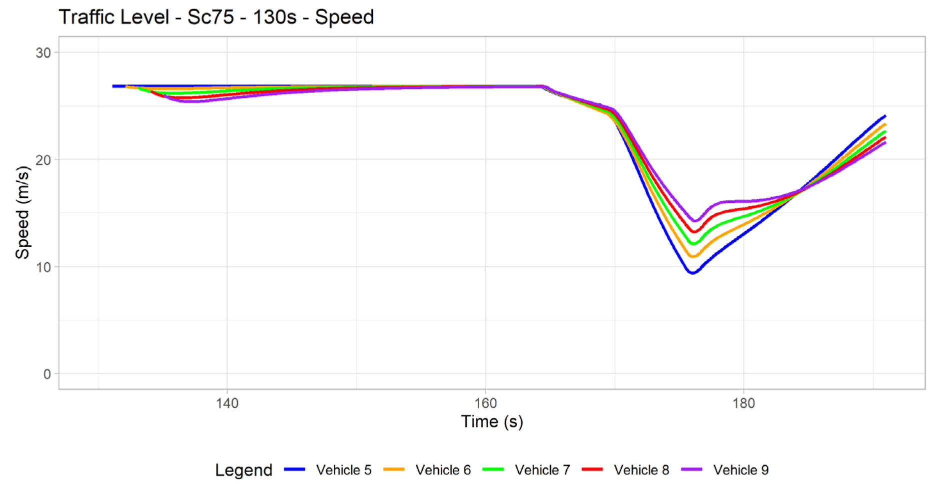
(a) Traffic-level Profile



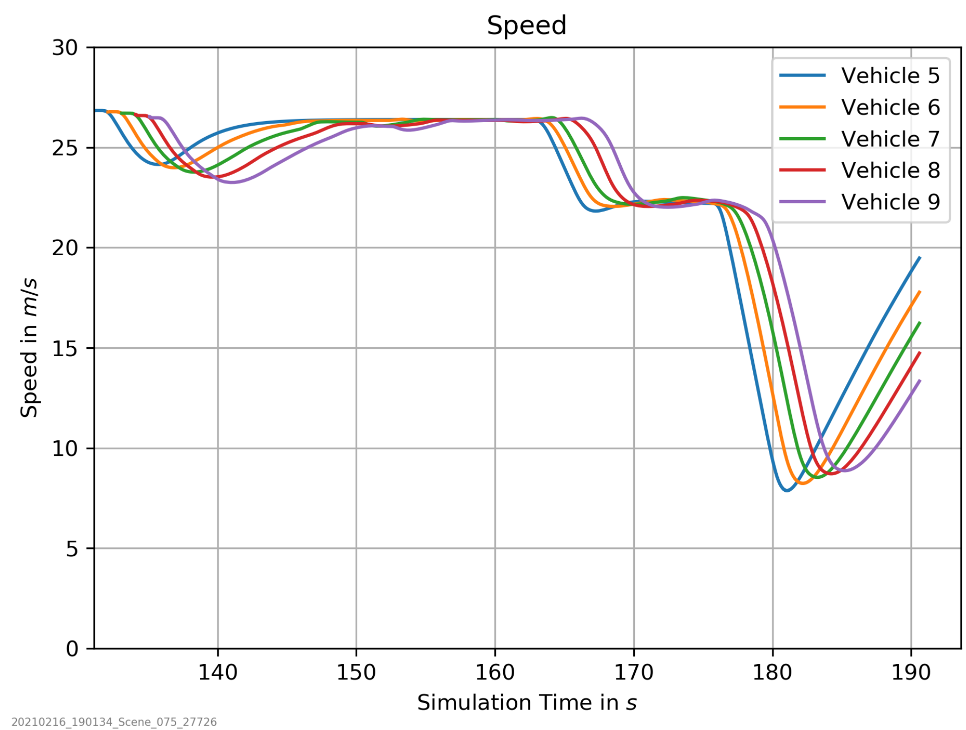
(b) Vehicle-level Profile

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

Figure 75. Verification Scenario 2 – 115 Second Introduction Time – Mode Profiles



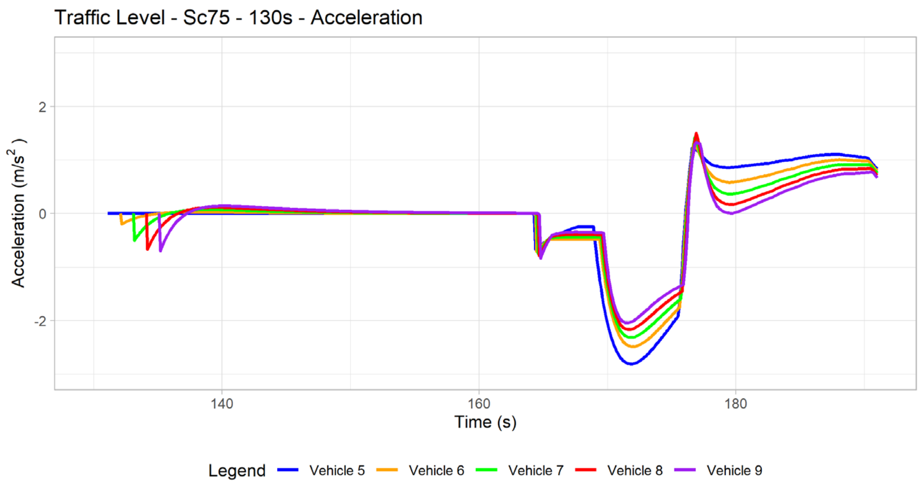
(a) Traffic-level Profile



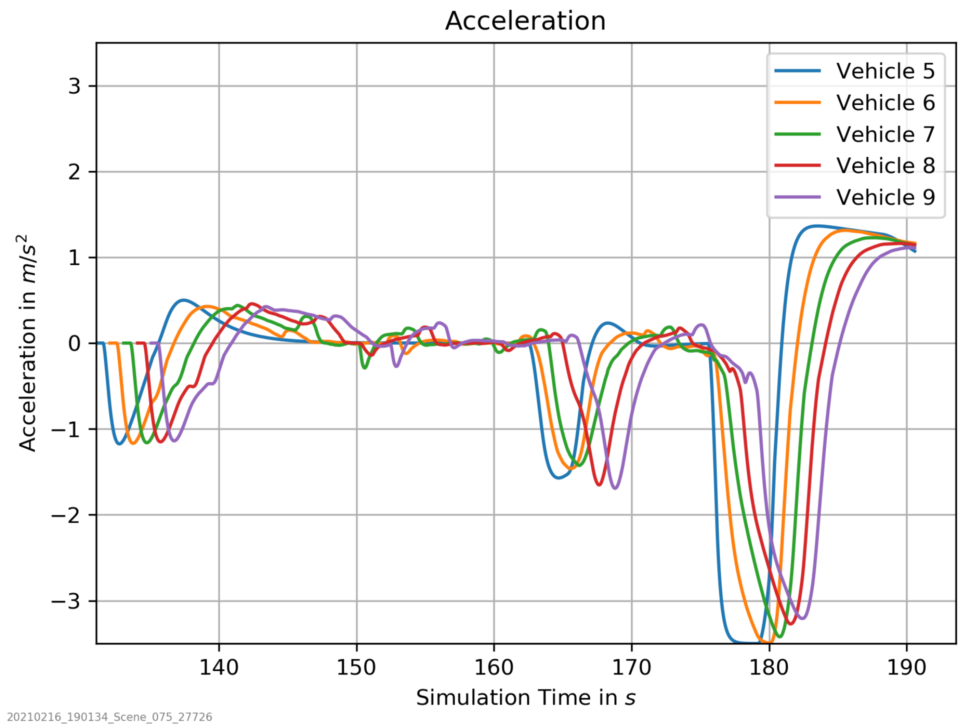
(b) Vehicle-level Profile

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

Figure 76. Verification Scenario 2 – 130 Second Introduction Time – Speed Profiles



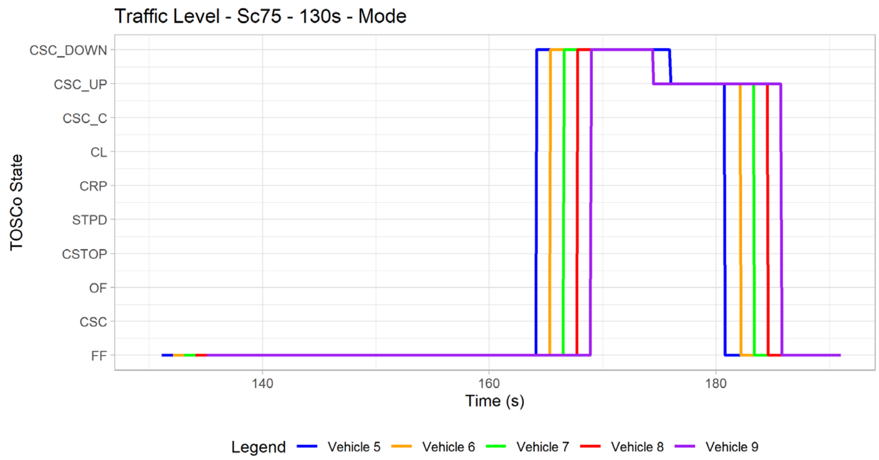
(a) Traffic-level Profile



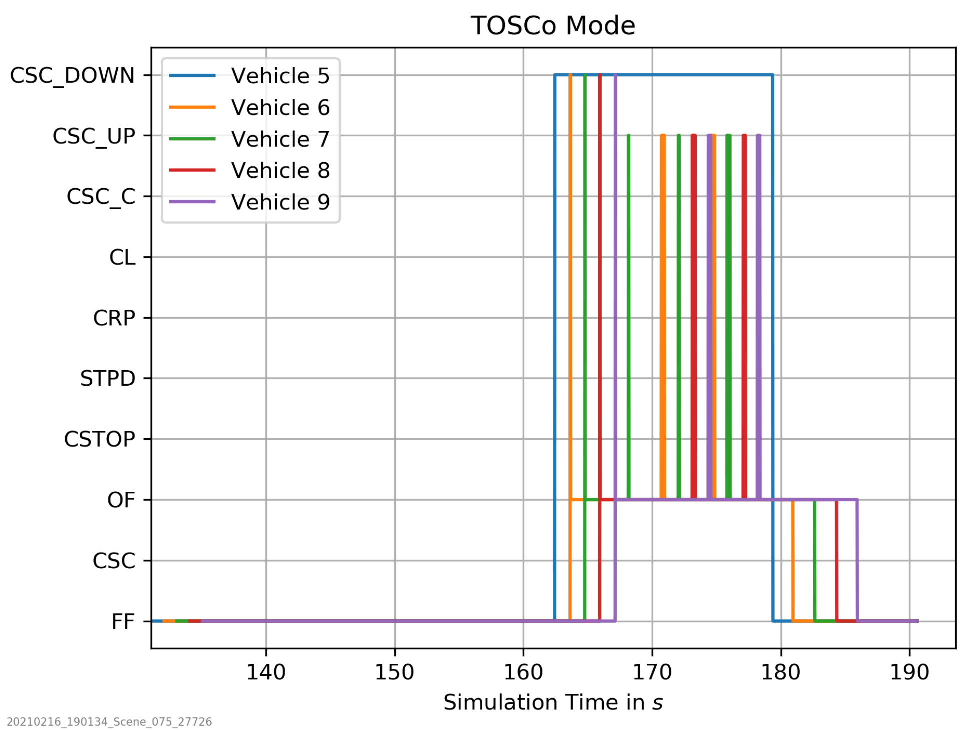
(b) Vehicle-level Profile

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

Figure 77. Verification Scenario 2 – 130 Second Introduction Time – Acceleration Profiles



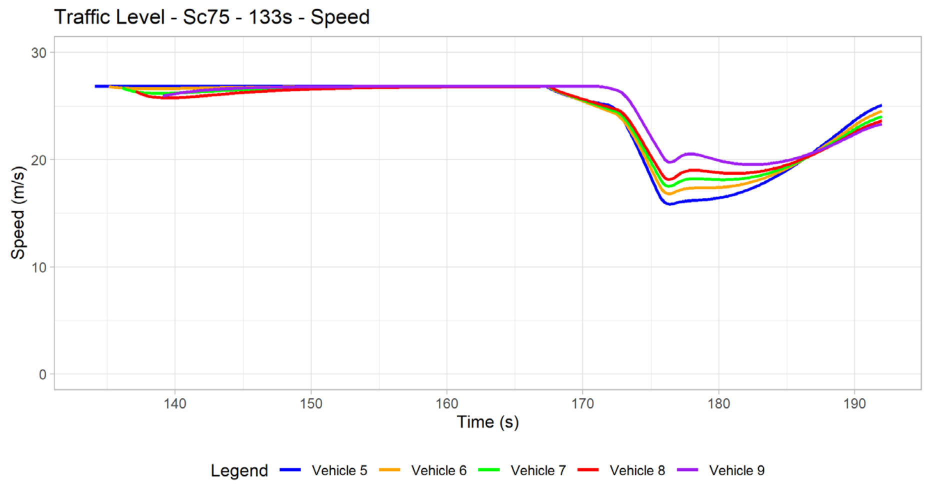
(a) Traffic-level Profile



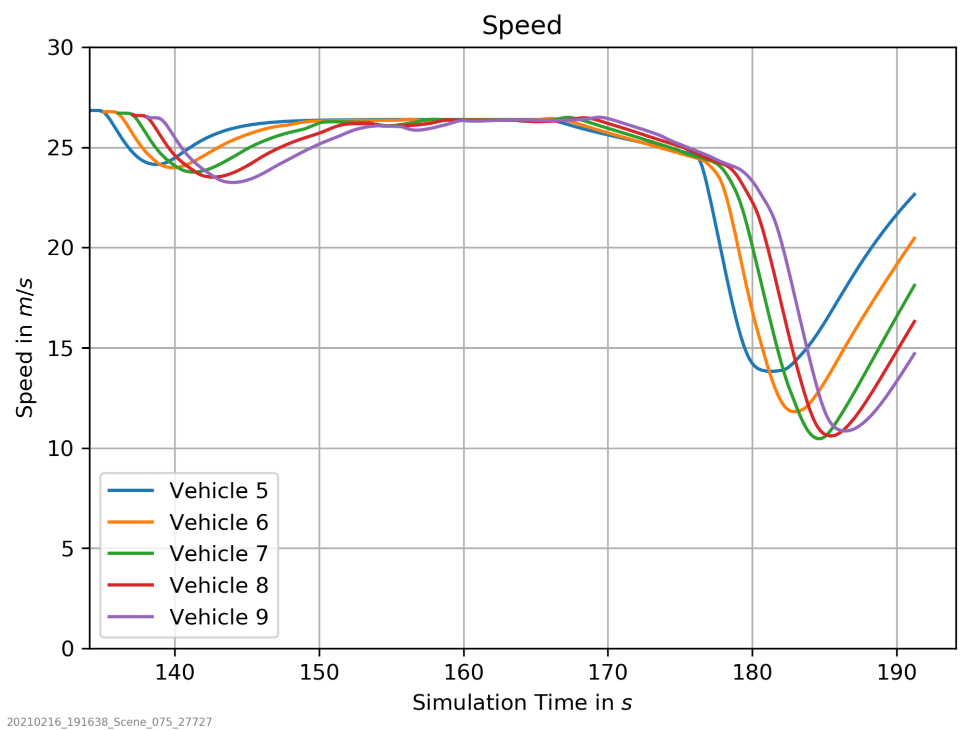
(b) Vehicle-level Profile

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

Figure 78. Verification Scenario 2 – 130 Second Introduction Time – Mode Profiles



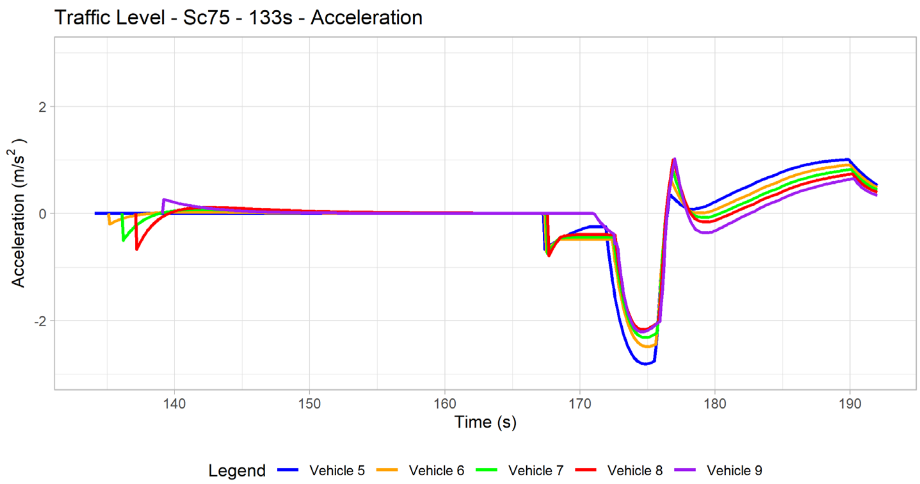
(a) Traffic-level Profile



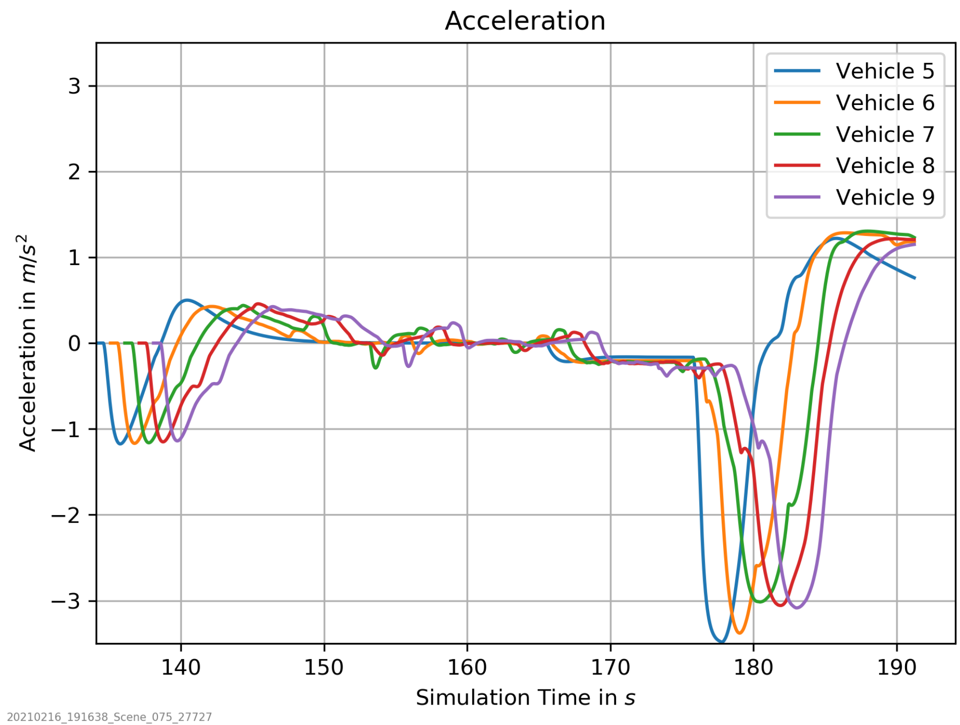
(b) Vehicle-level Profile

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

Figure 79. Verification Scenario 2 – 133 Second Introduction Time – Speed Profiles



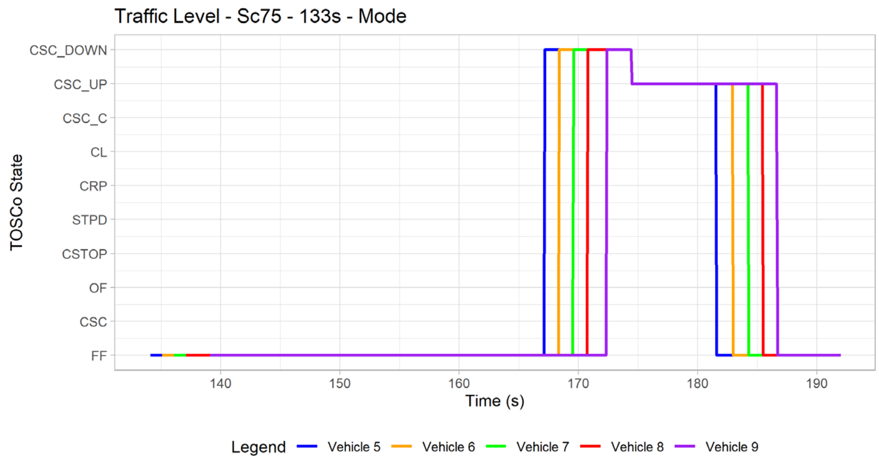
(a) Traffic-level Profile



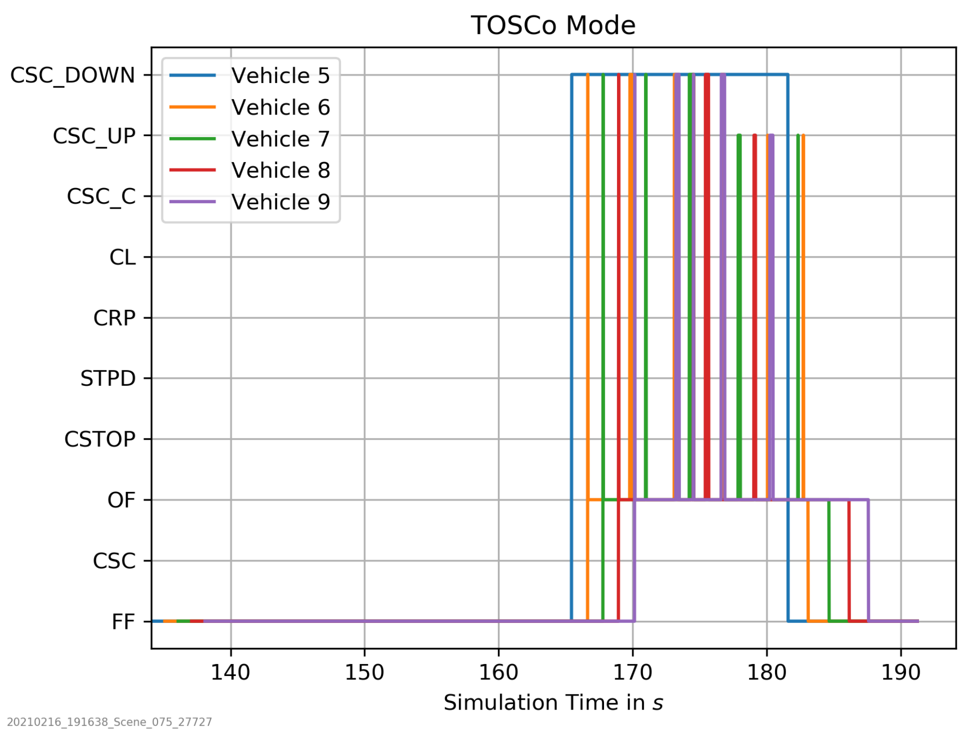
(b) Vehicle-level Profile

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

Figure 80. 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 81. 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 82 through Figure 84 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.

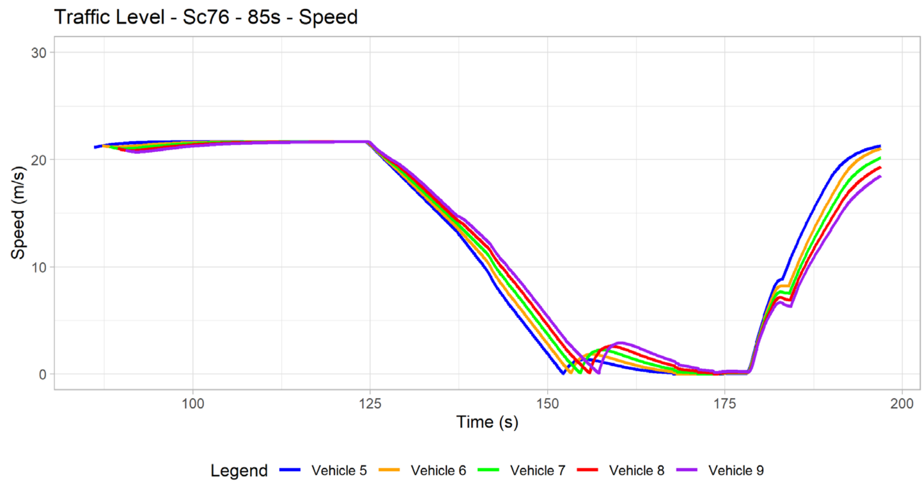
Figure 85 through Figure 87 show the scenario 3 results for the 97 second introduction time. Both simulations choose CSC-DOWN and decelerate to a similar speed. The strings slow in response to the queue some time before crossing the intersection. The first vehicle in the traffic-level representation crosses the intersection at about the same time as the vehicle-level simulation.

Figure 88 through Figure 90 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.

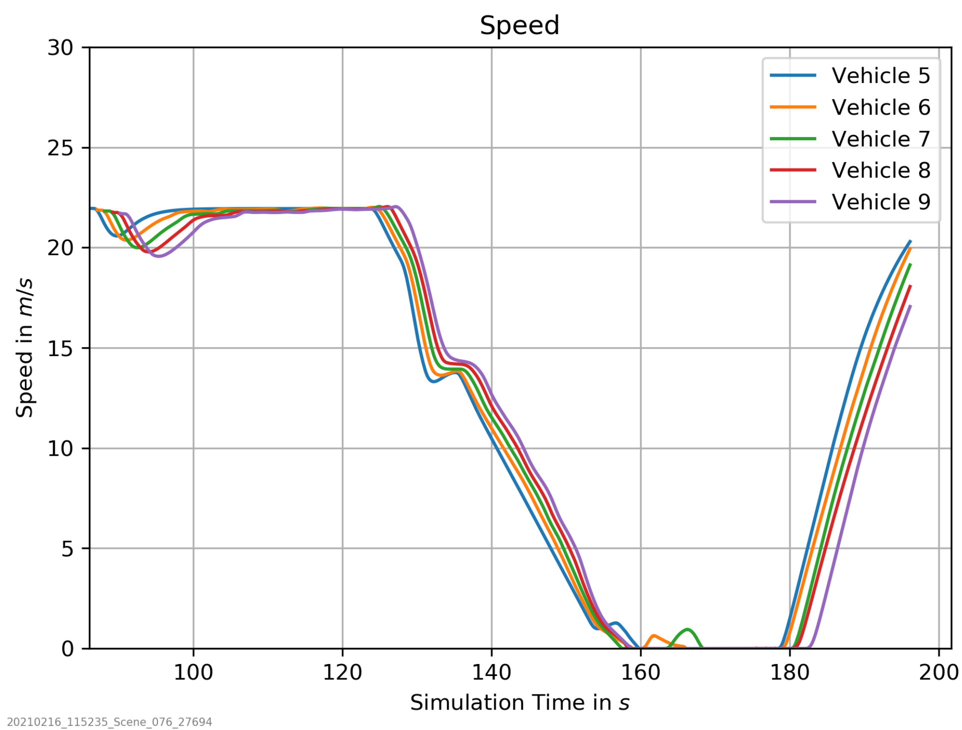
Figure 91 through Figure 93 show the results for the 130 second introduction time. Both environments show the string accelerate initially and then slow in response to the queue at the intersection. The traffic level string crosses the intersection one second earlier than the vehicle-level simulation.

Figure 80 through Figure 82 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.



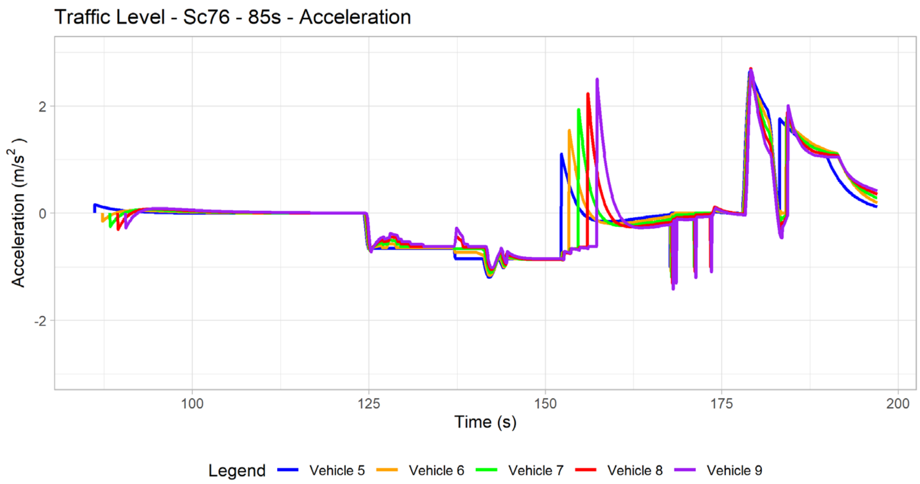
(a) Traffic-level Profile



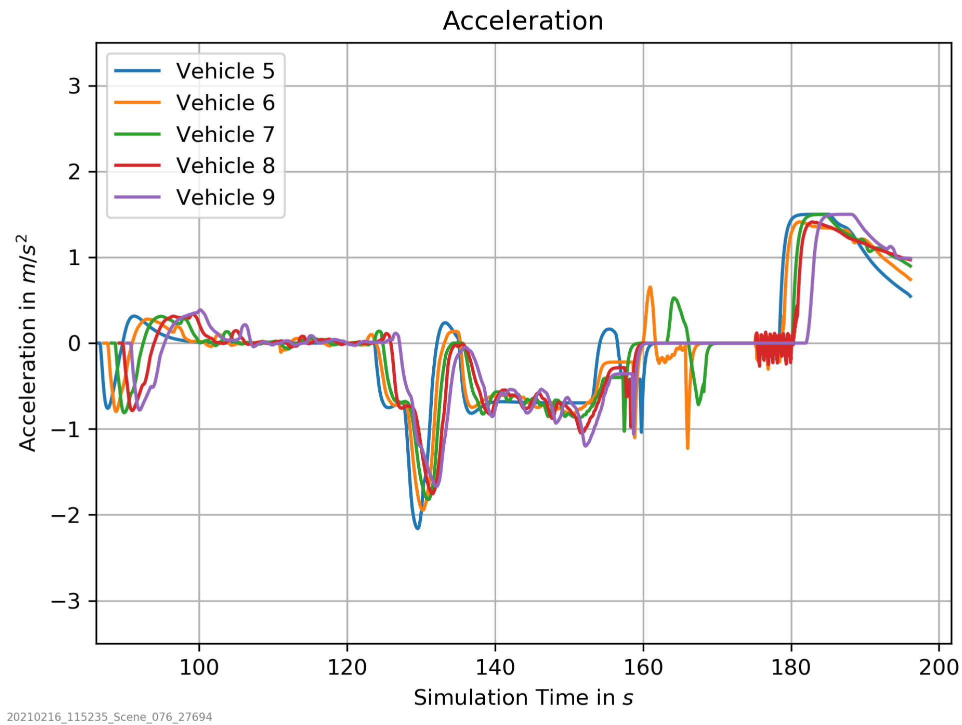
(b) Vehicle-level Profile

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

Figure 82. Verification Scenario 3 – 85 Second Introduction Time – Speed Profiles



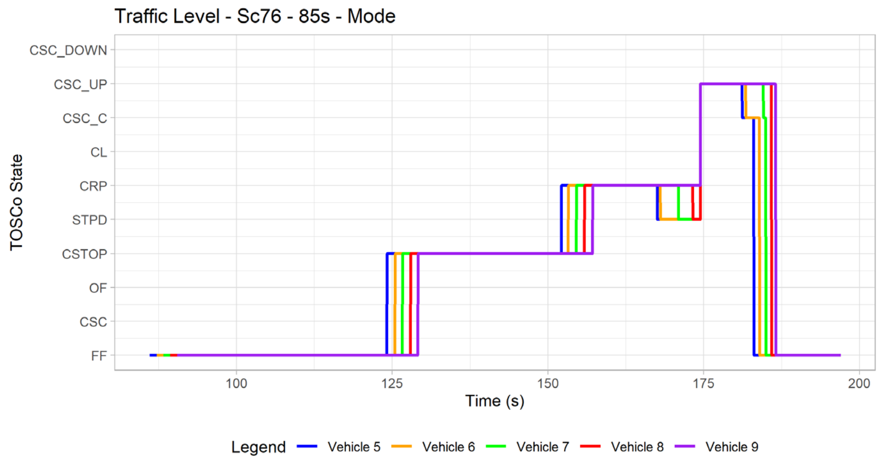
(a) Traffic-level Profile



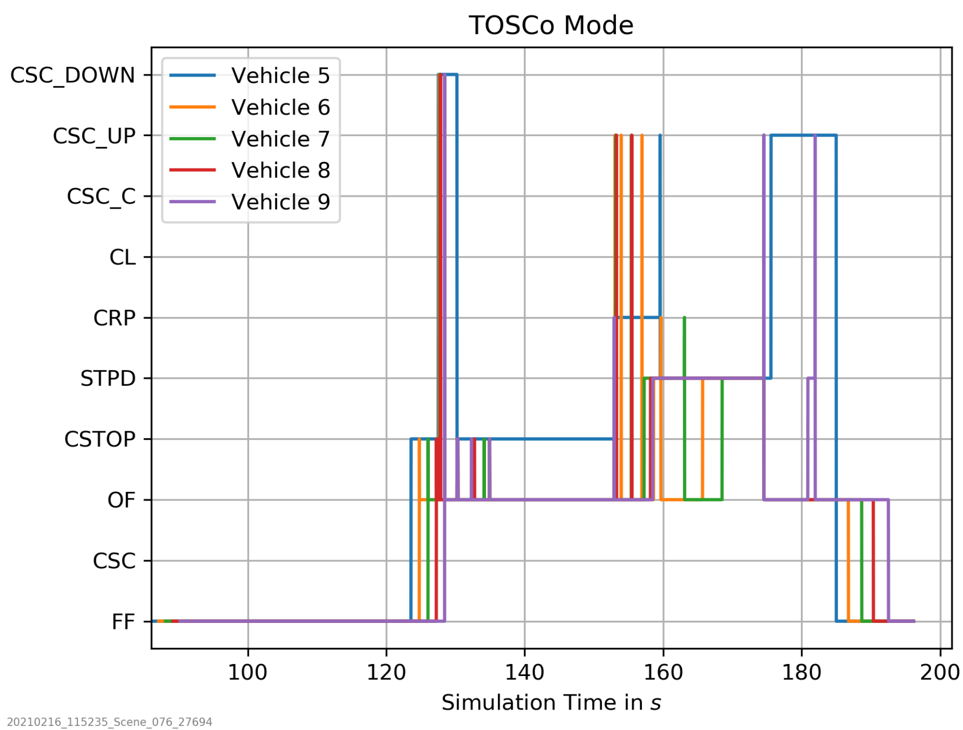
(b) Vehicle-level Profile

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

Figure 83. Verification Scenario 3 – 85 Second Introduction Time – Acceleration Profiles



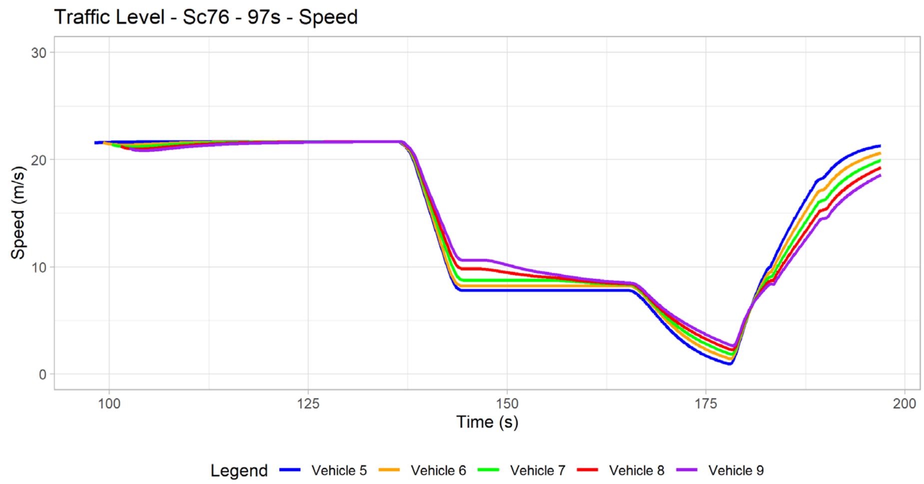
(a) Traffic-level Profile



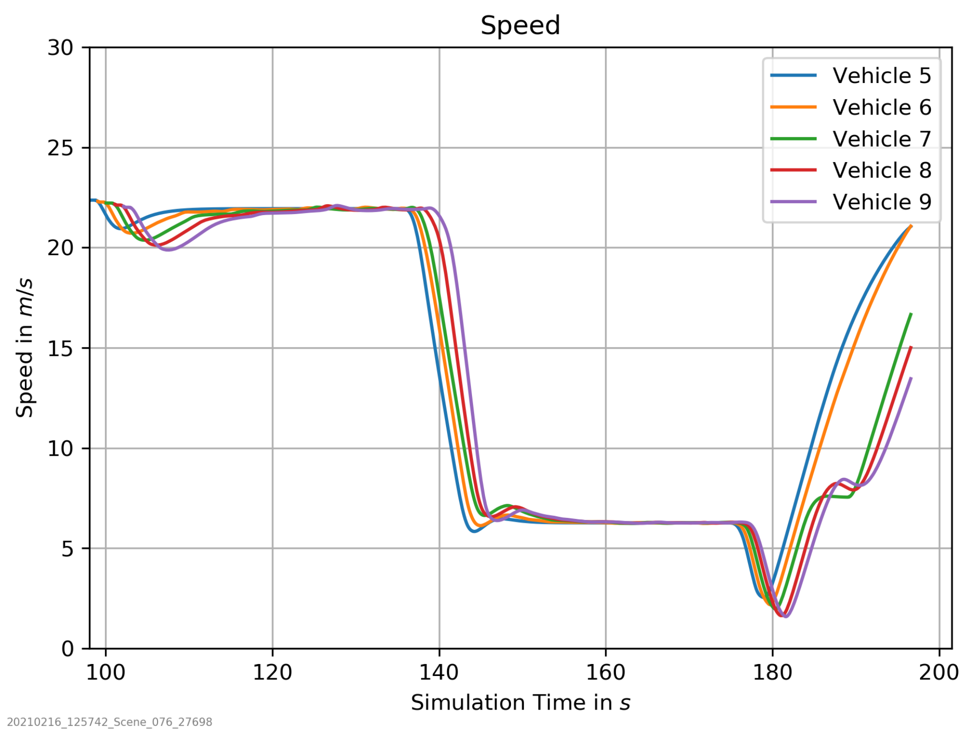
(b) Vehicle-level Profile

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

Figure 84. Verification Scenario 3 – 85 Second Introduction Time – Mode Profiles



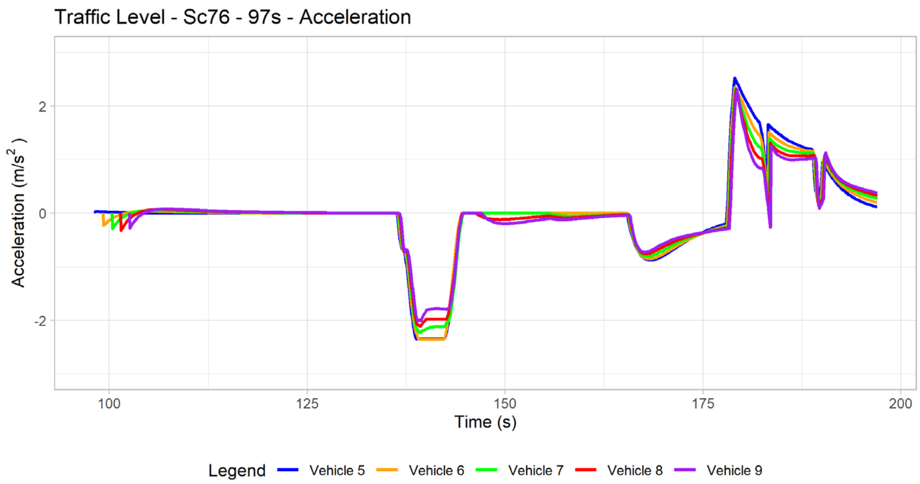
(a) Traffic-level Profile



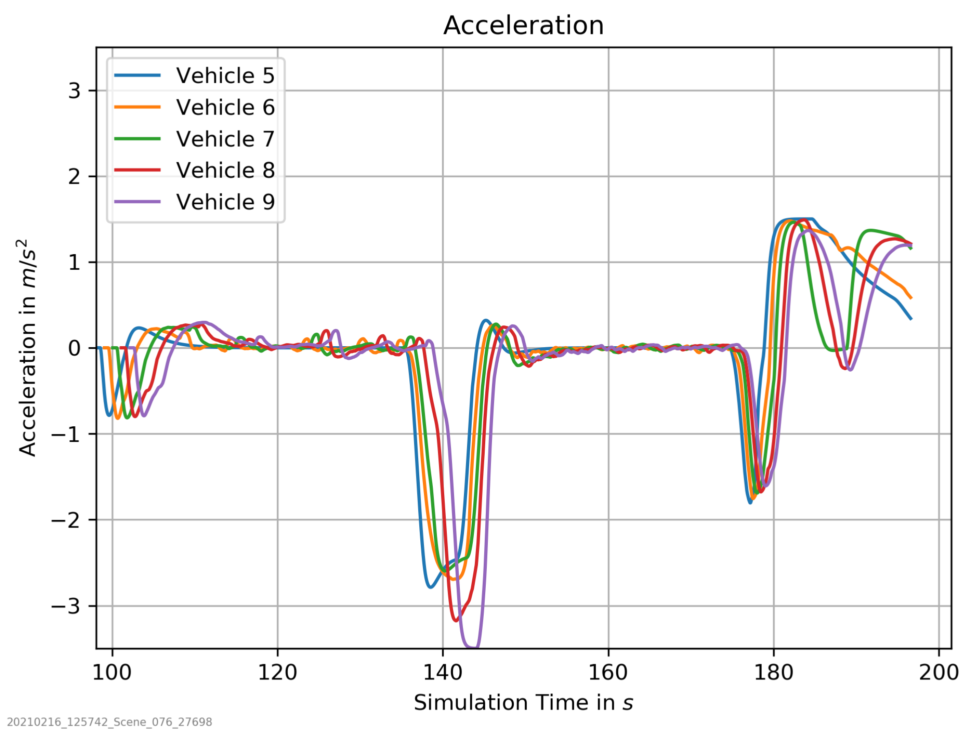
(b) Vehicle-level Profile

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

Figure 85. Verification Scenario 3 – 97 Second Introduction Time – Speed Profiles



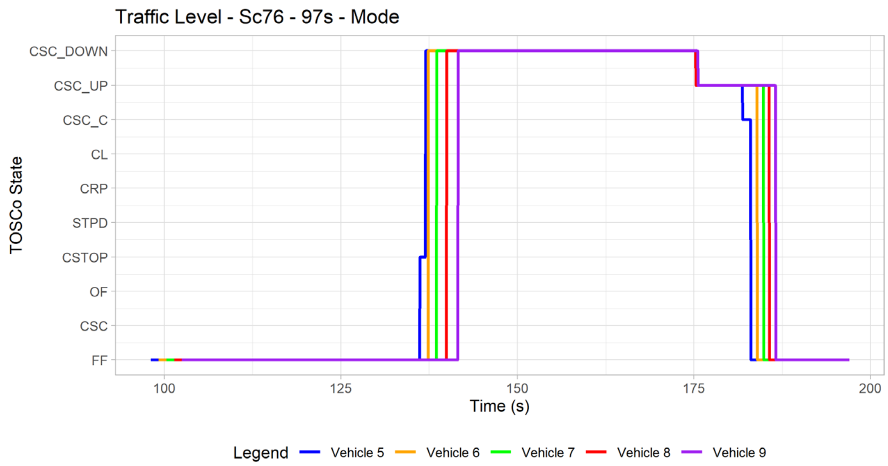
(a) Traffic-level Profile



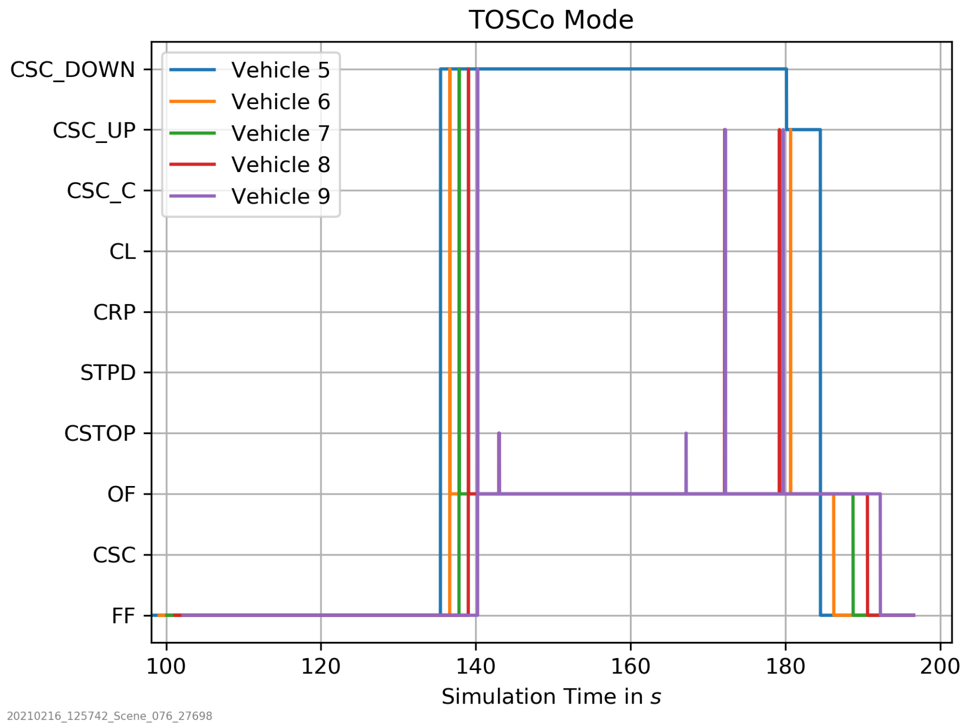
(b) Vehicle-level Profile

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

Figure 86. Verification Scenario 3 – 97 Second Introduction Time – Acceleration Profiles



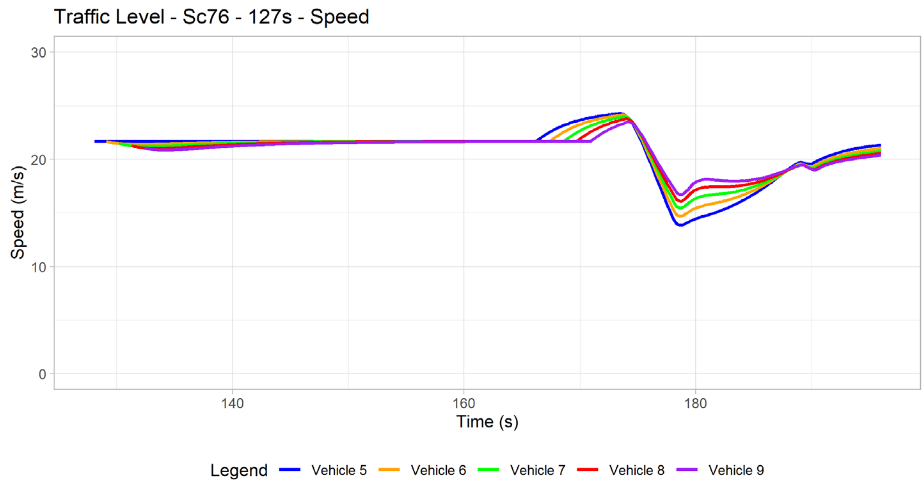
(a) Traffic-level Profile



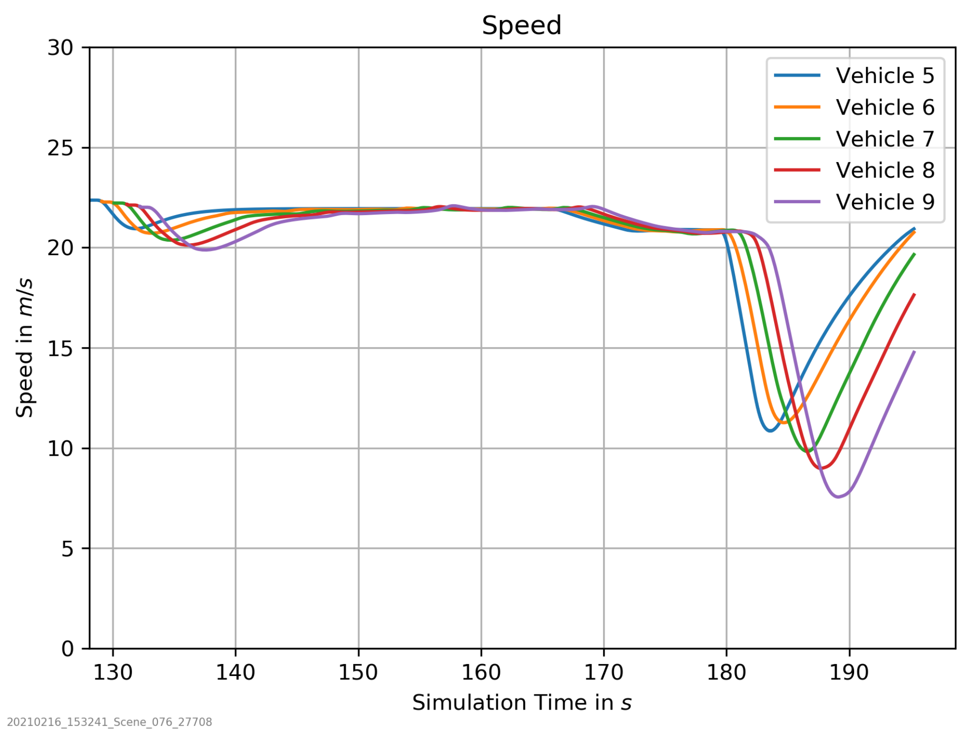
(b) Vehicle-level Profile

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

Figure 87. Verification Scenario 3 – 97 Second Introduction Time – Mode Profiles



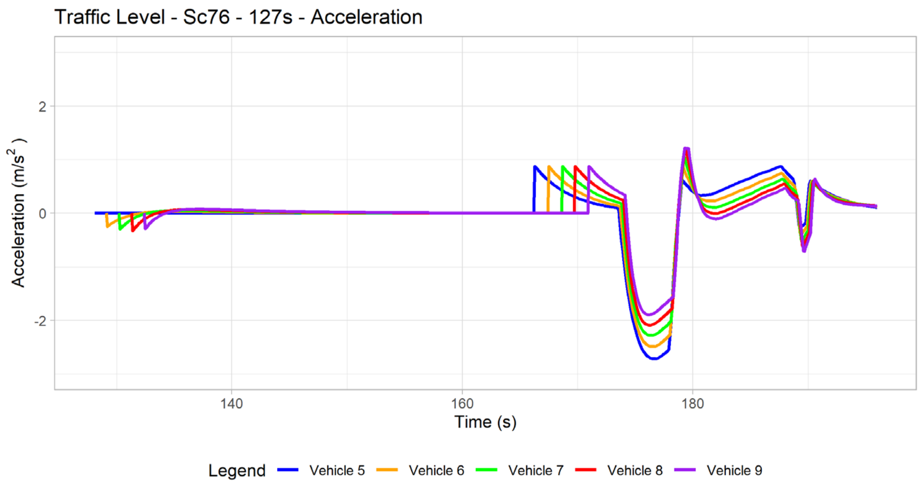
(a) Traffic-level Profile



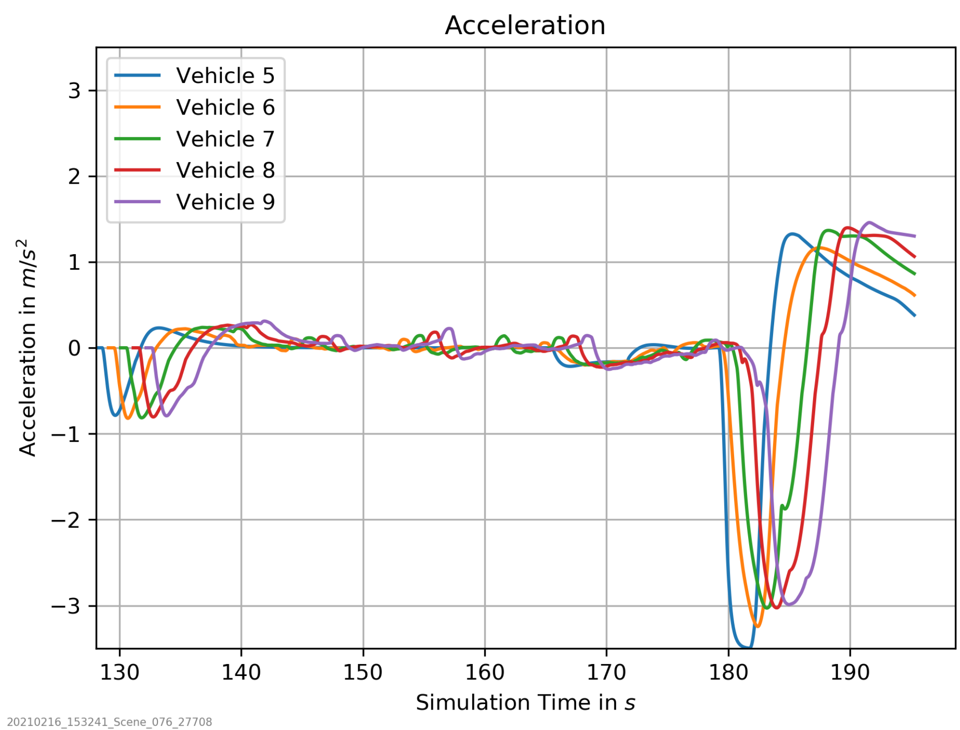
(b) Vehicle-level Profile

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

Figure 88. Verification Scenario 3 – 127 Second Introduction Time – Speed Profiles



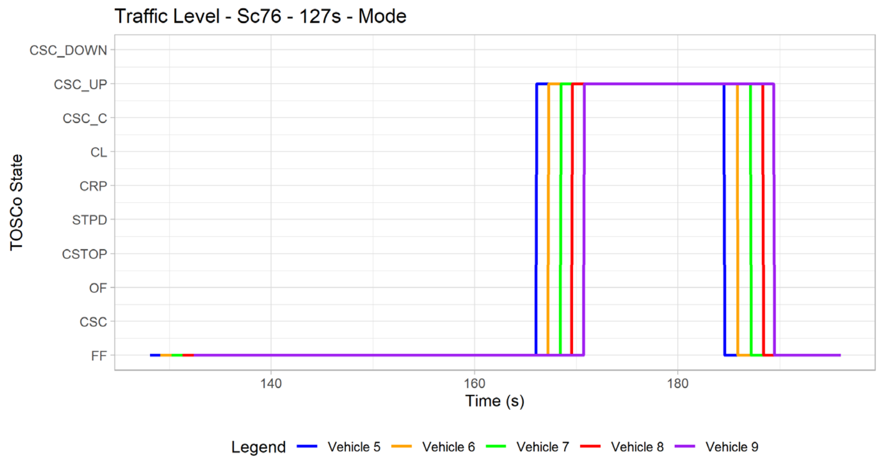
(a) Traffic-level Profile



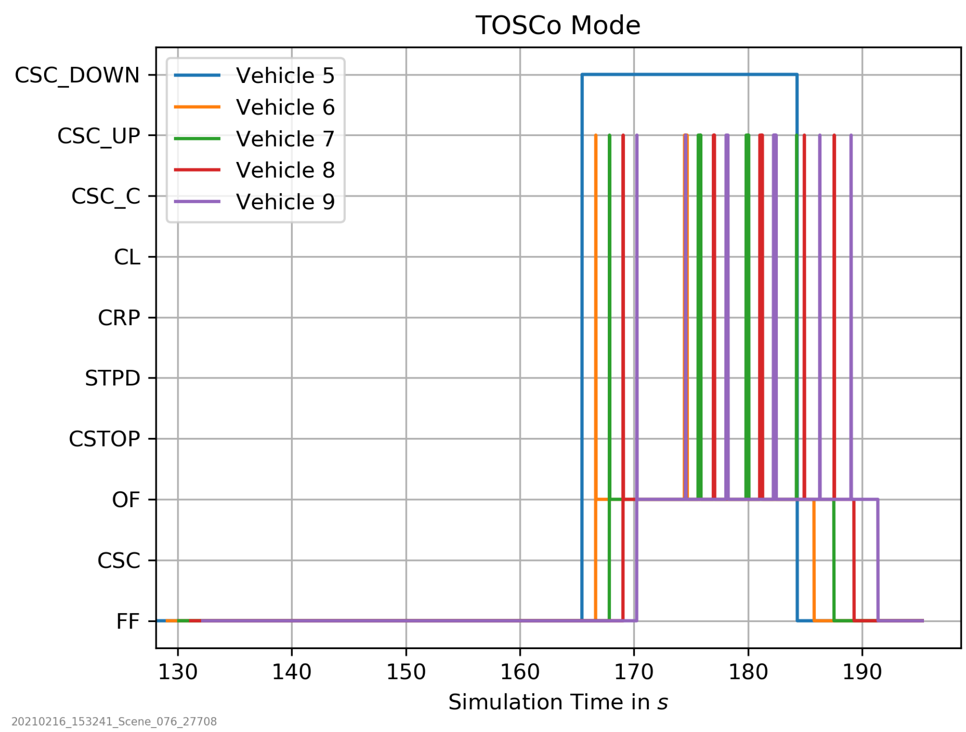
(b) Vehicle-level Profile

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

Figure 89. Verification Scenario 3 – 127 Second Introduction Time – Acceleration Profiles



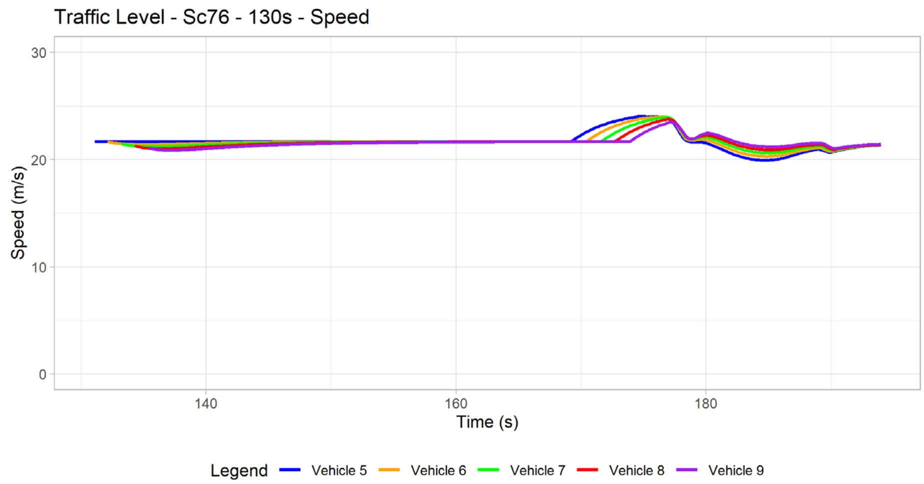
(a) Traffic-level Profile



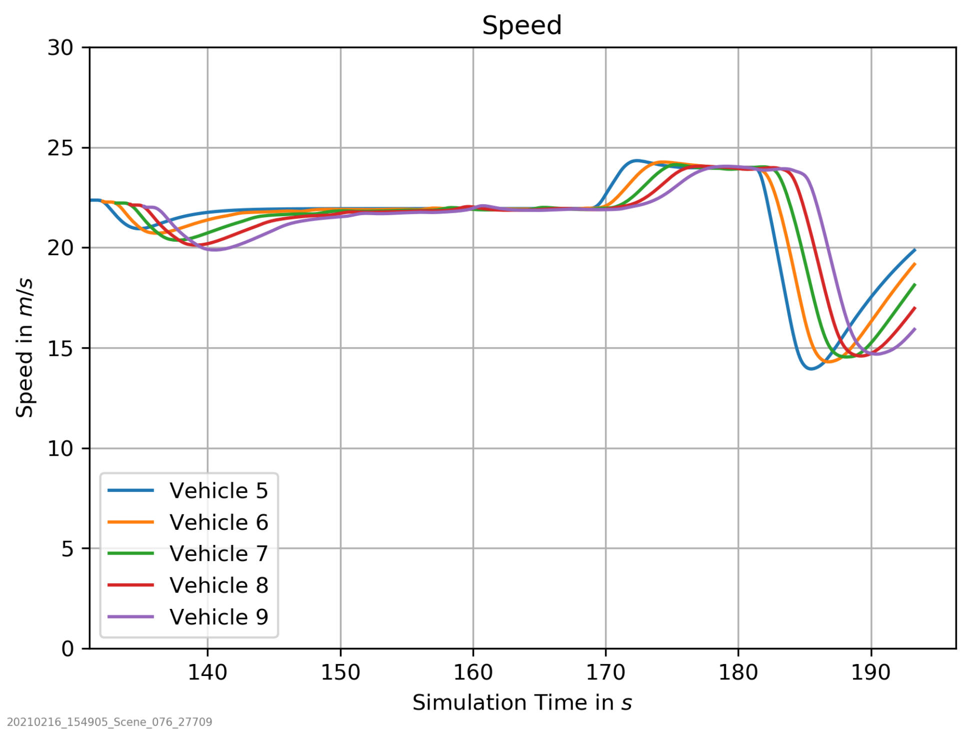
(b) Vehicle-level Profile

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

Figure 90. Verification Scenario 3 – 127 Second Introduction Time – Mode Profiles



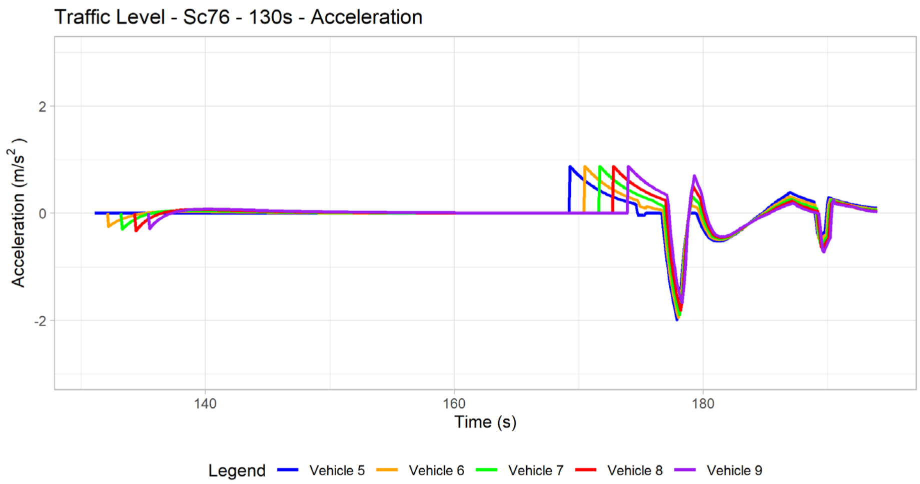
(a) Traffic-level Profile



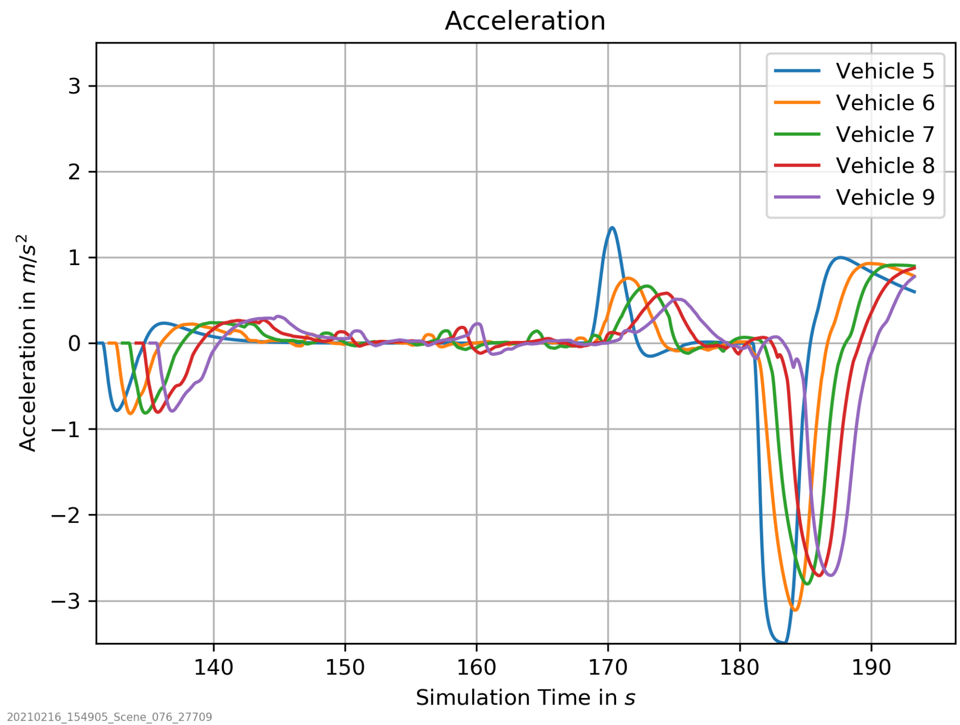
(b) Vehicle-level Profile

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

Figure 91. Verification Scenario 3 – 130 Second Introduction Time – Speed Profiles



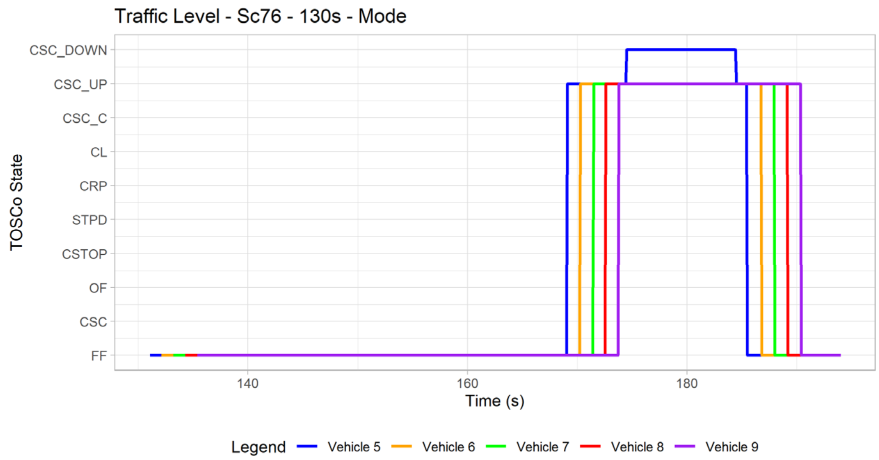
(a) Traffic-level Profile



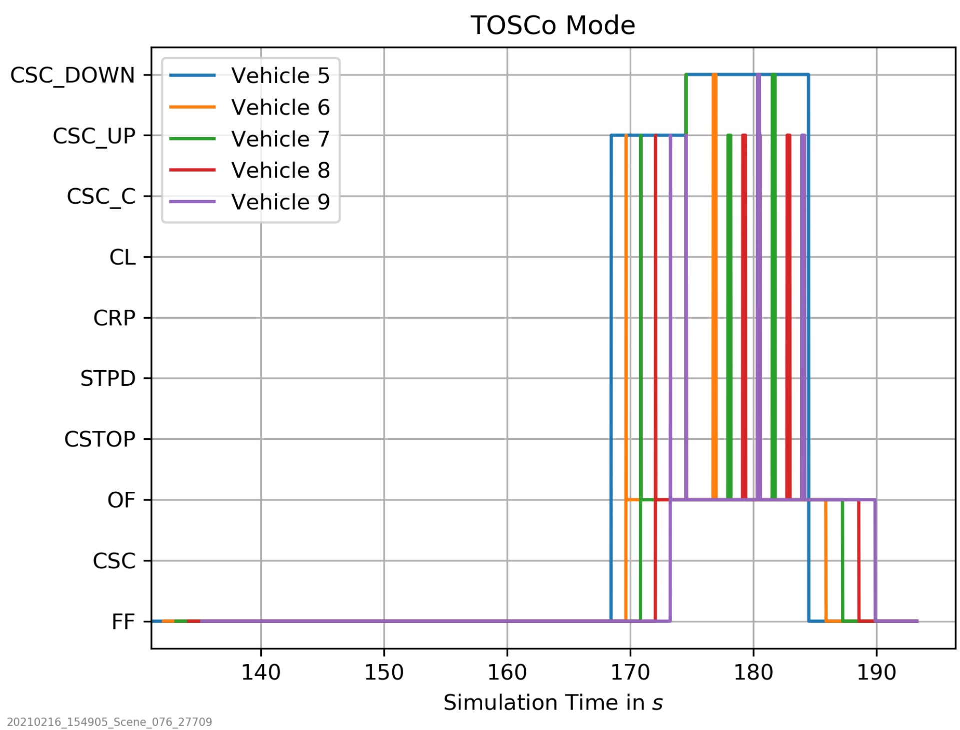
(b) Vehicle-level Profile

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

Figure 92. Verification Scenario 3 – 130 Second Introduction Time – Acceleration Profiles



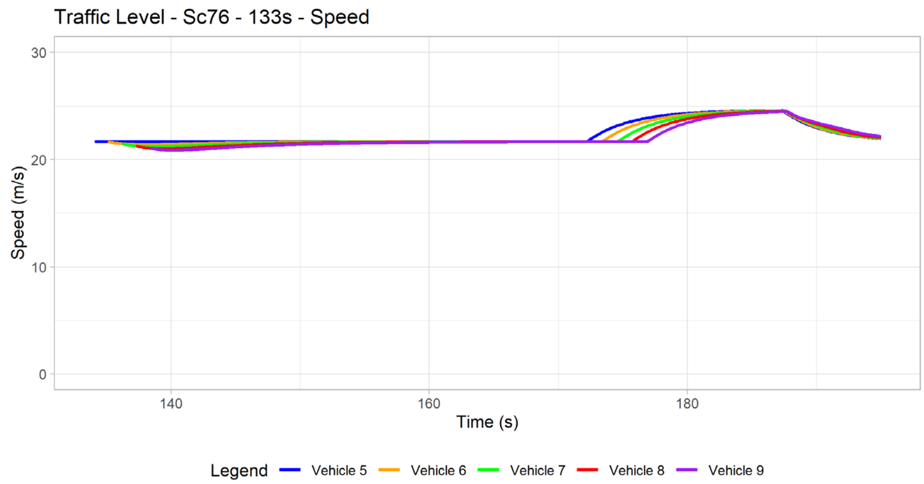
(a) Traffic-level Profile



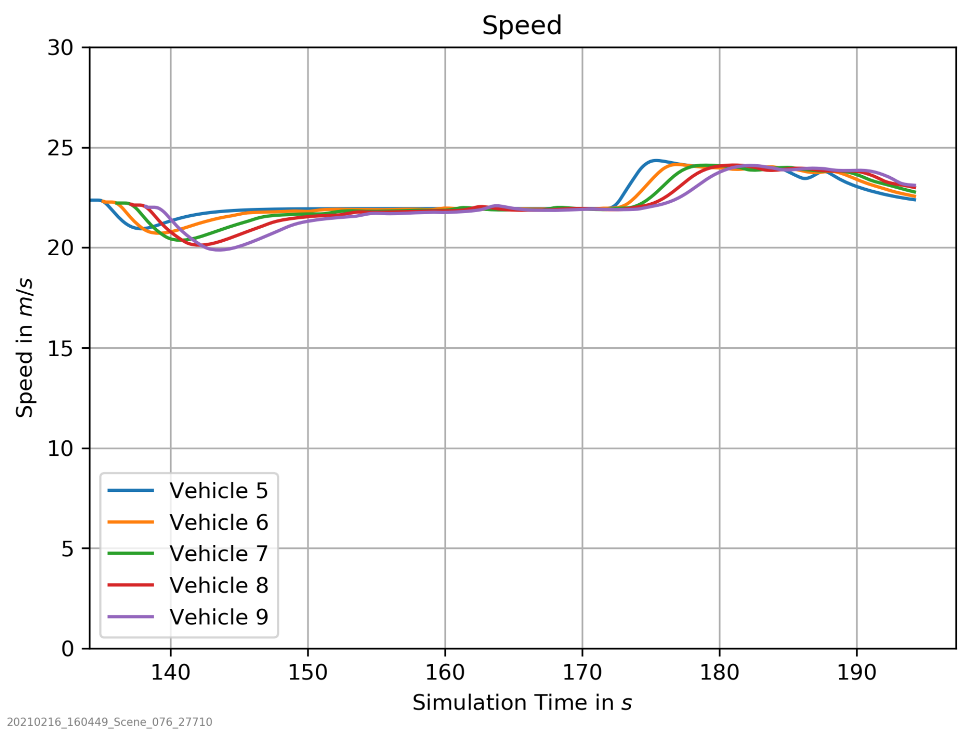
(b) Vehicle Level Profile

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

Figure 93. Verification Scenario 3 – 130 Second Introduction Time – Mode Profiles



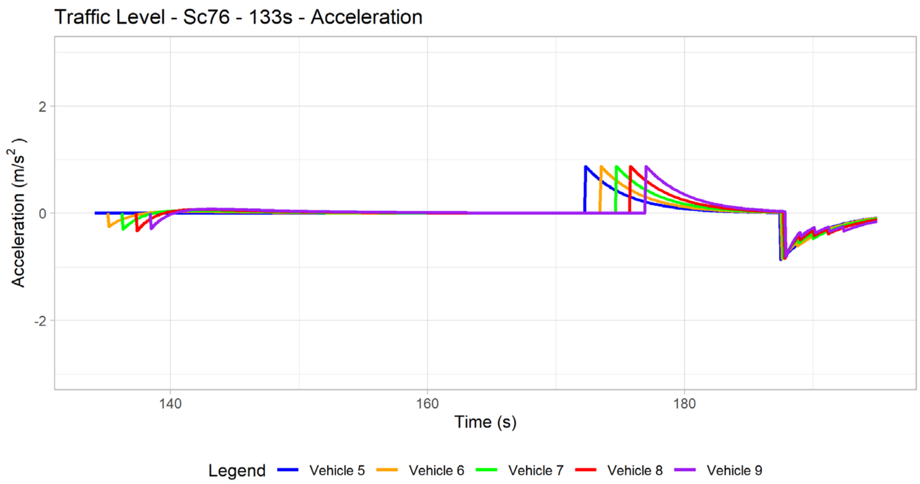
(a) Traffic-level Profile



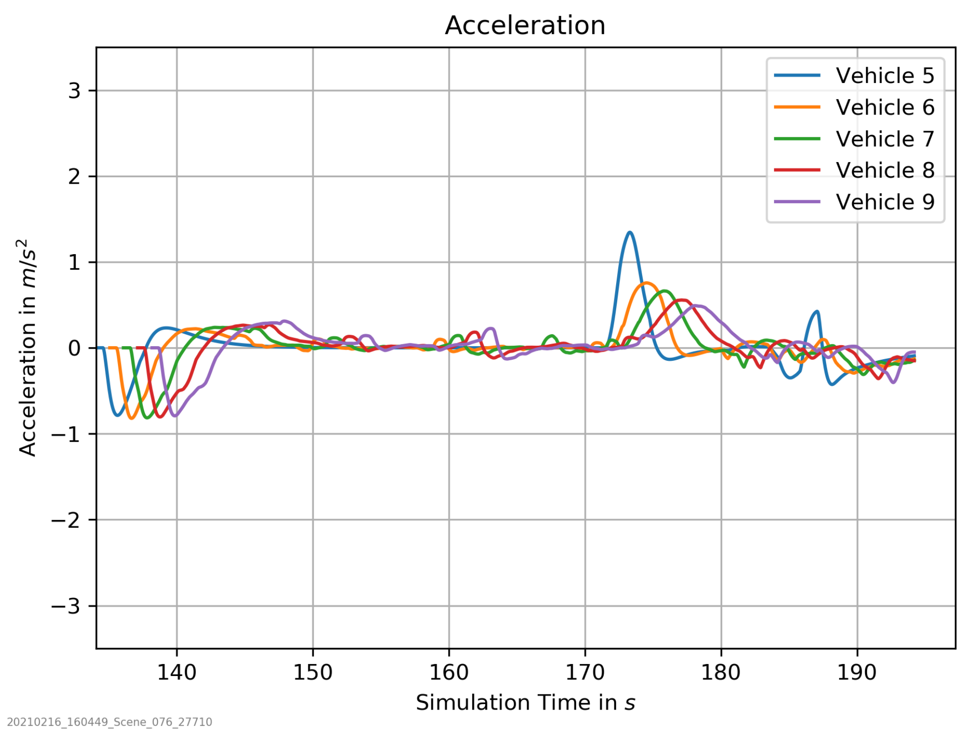
(b) Vehicle-level Profile

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

Figure 94. Verification Scenario 3 – 133 Second Introduction Time – Speed Profiles



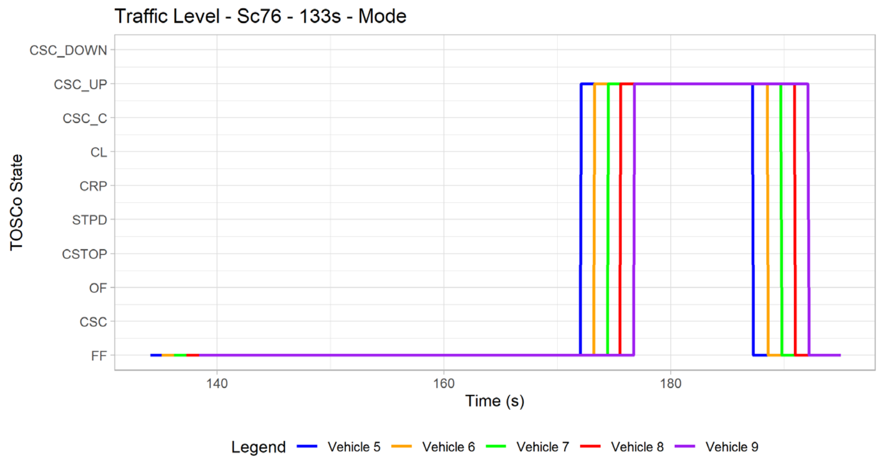
(a) Traffic-level Profile



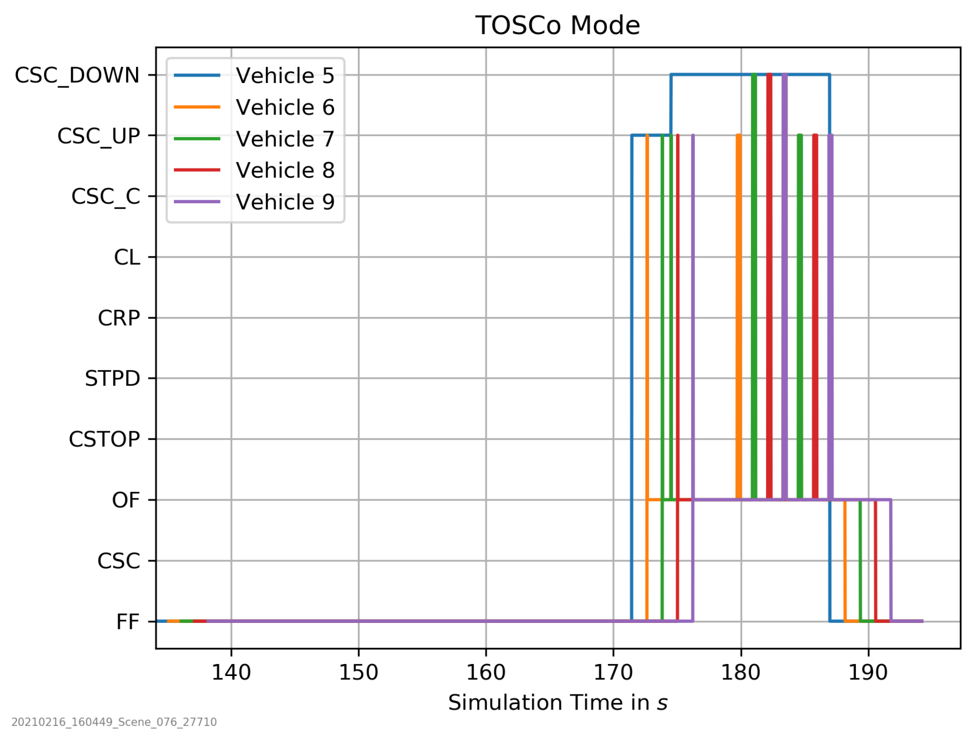
(b) Vehicle-level Profile

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

Figure 95. 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 96. Verification Scenario 3 – 133 Second Introduction Time – Mode Profiles

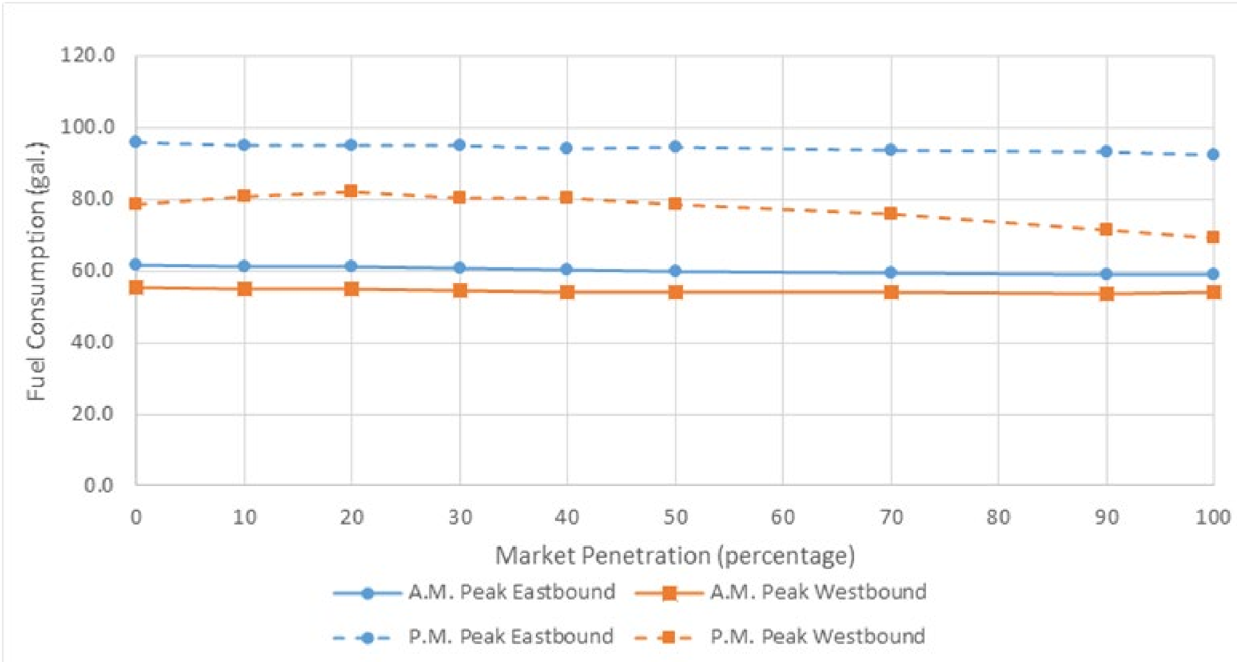
Appendix B. Fuel Use Benefits By Intersection

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 the A.M. and P.M. peak period. This appendix also shows the corridor wide changes, which is calculated by the summation of the fuel use from all the intersections.

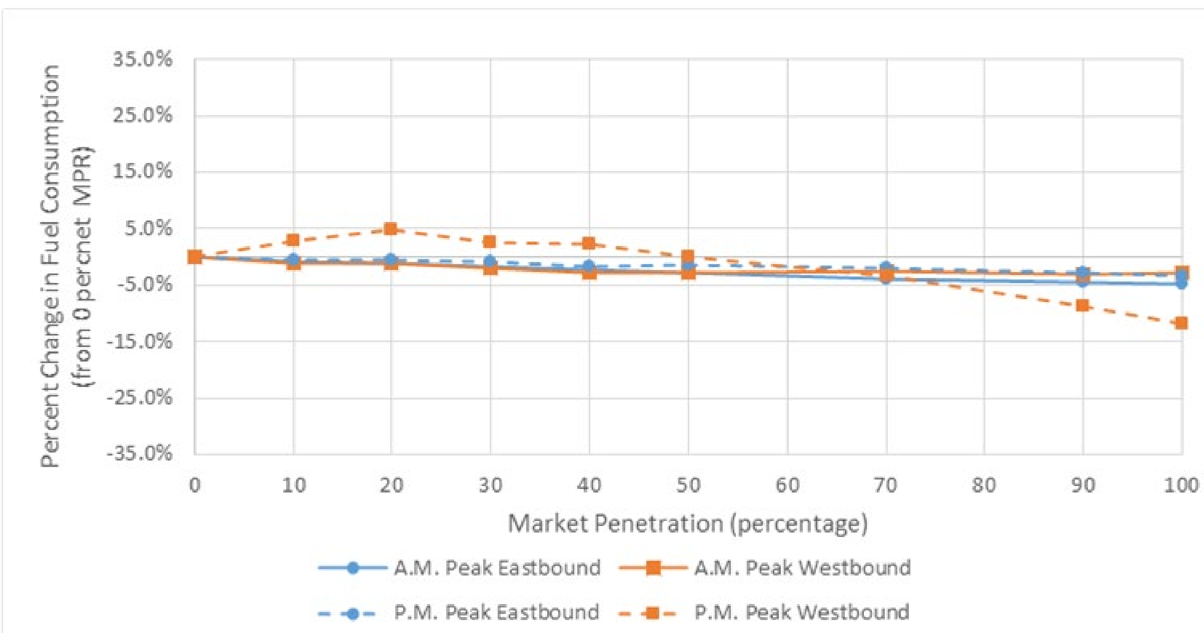
Fuel Use Figures

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



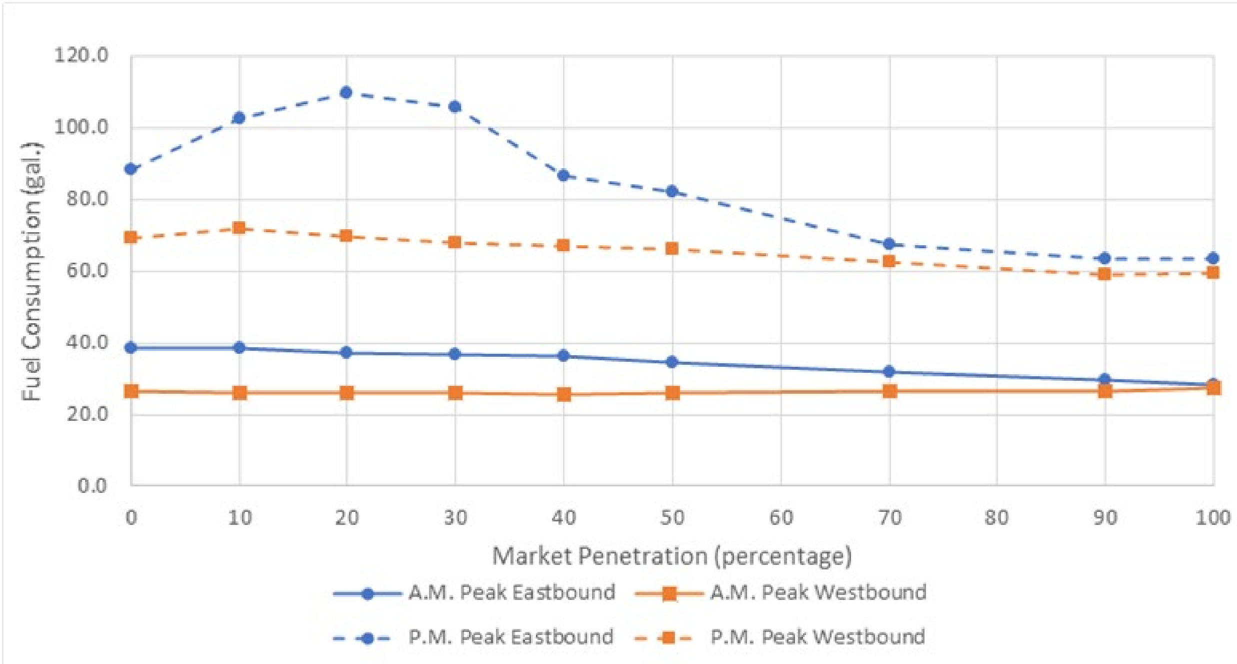
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 97. Fuel Consumption at Stewart Creek Road



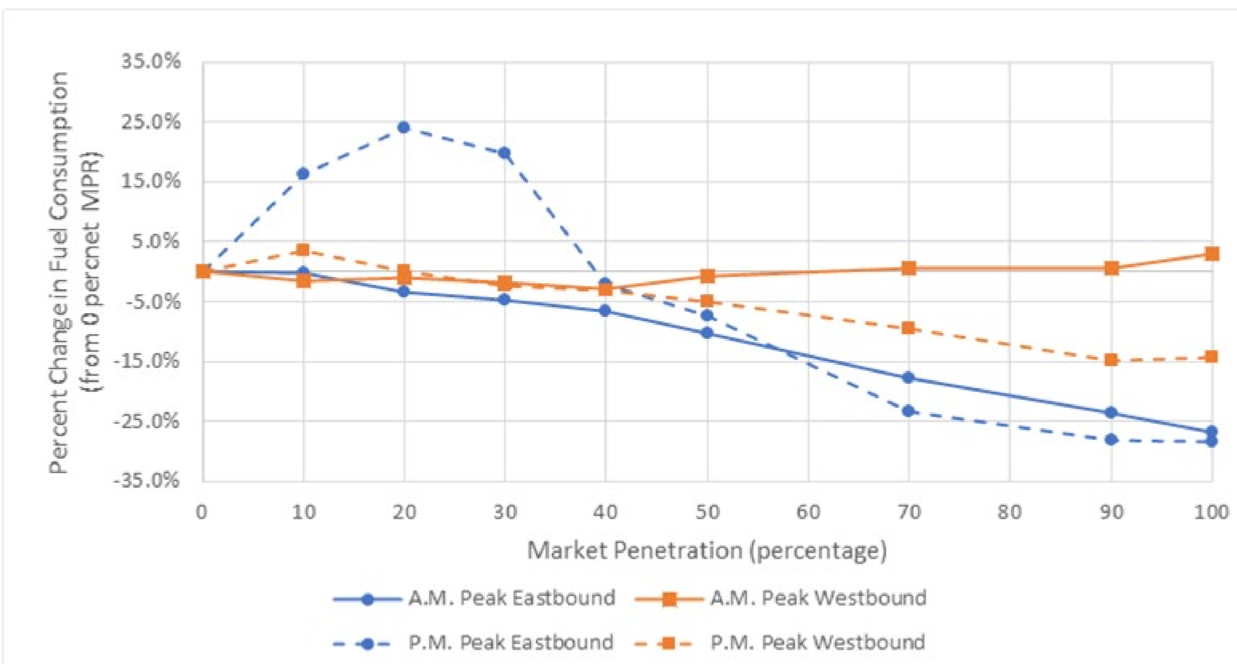
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 98. Percent Change in Fuel Consumption for Stewart Creek Road



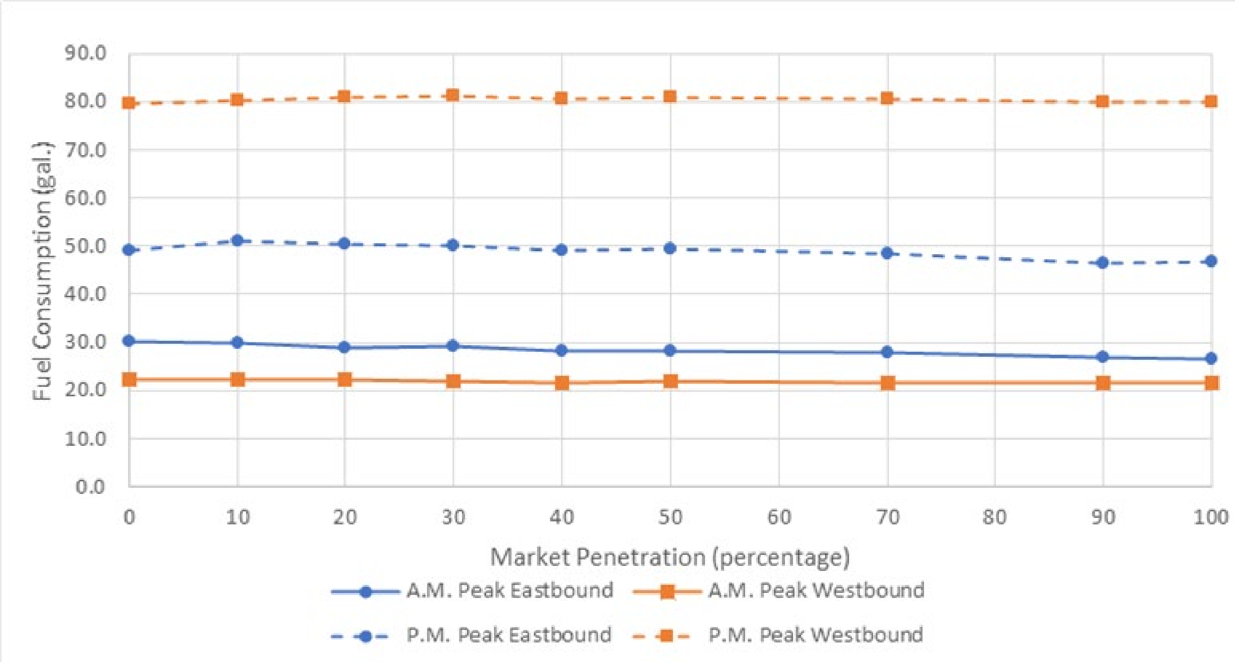
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 99. Fuel Consumption at Walden Road



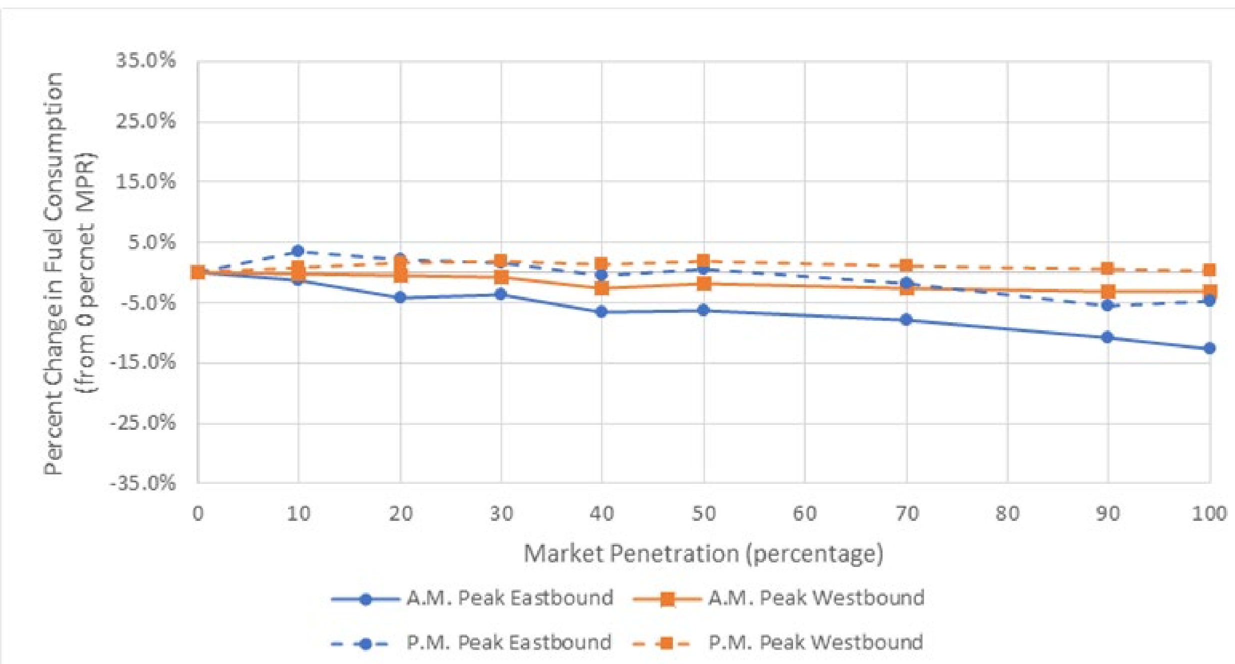
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 100. Percent Change in Fuel Consumption for Walden Road



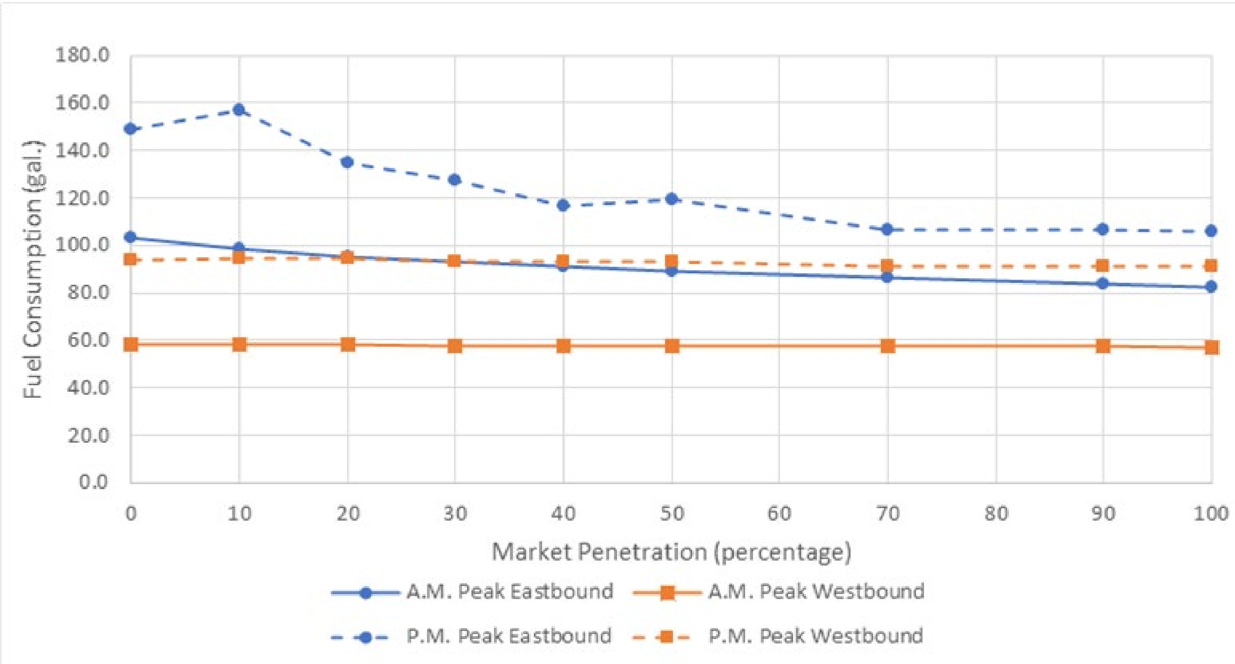
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 101. Fuel Consumption at Cape Conroe Drive



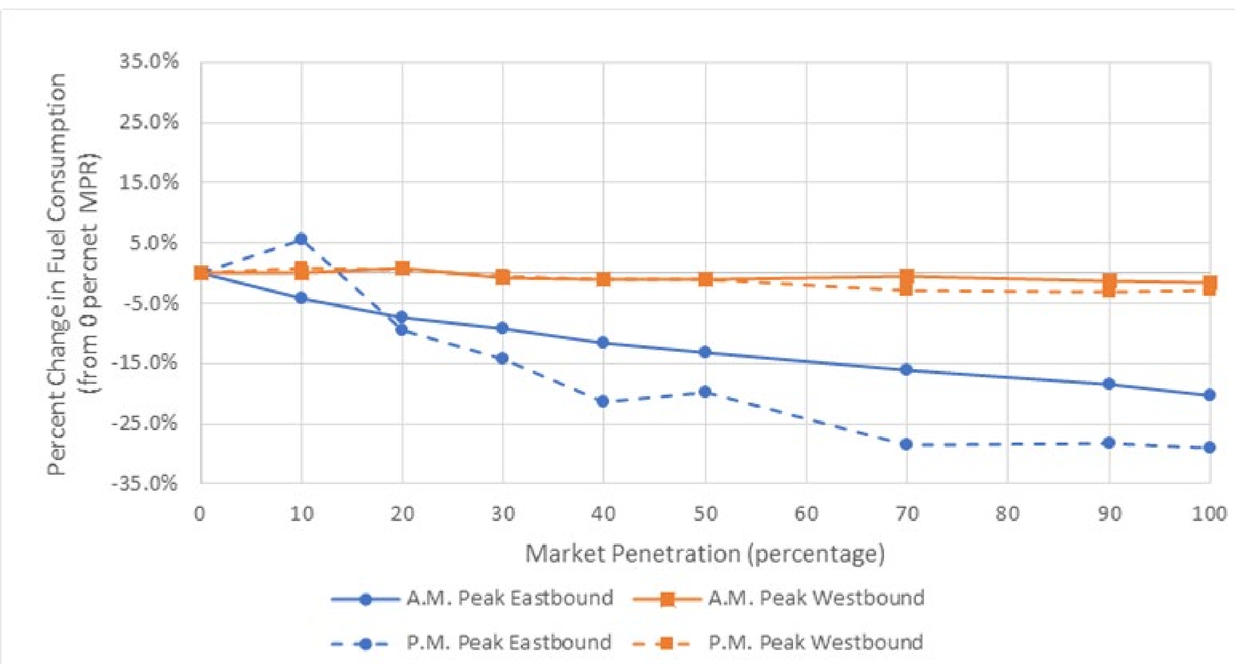
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 102. Percent Change in Fuel Consumption for Cape Conroe Drive



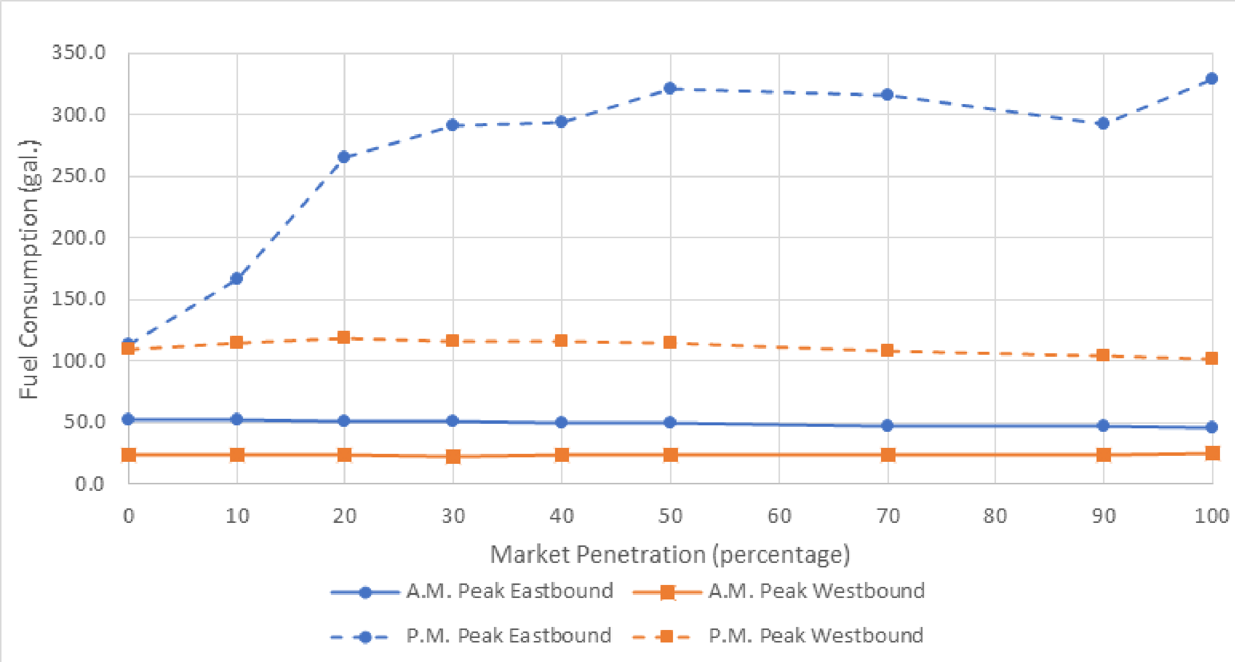
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 103. Fuel Consumption at Old River Road



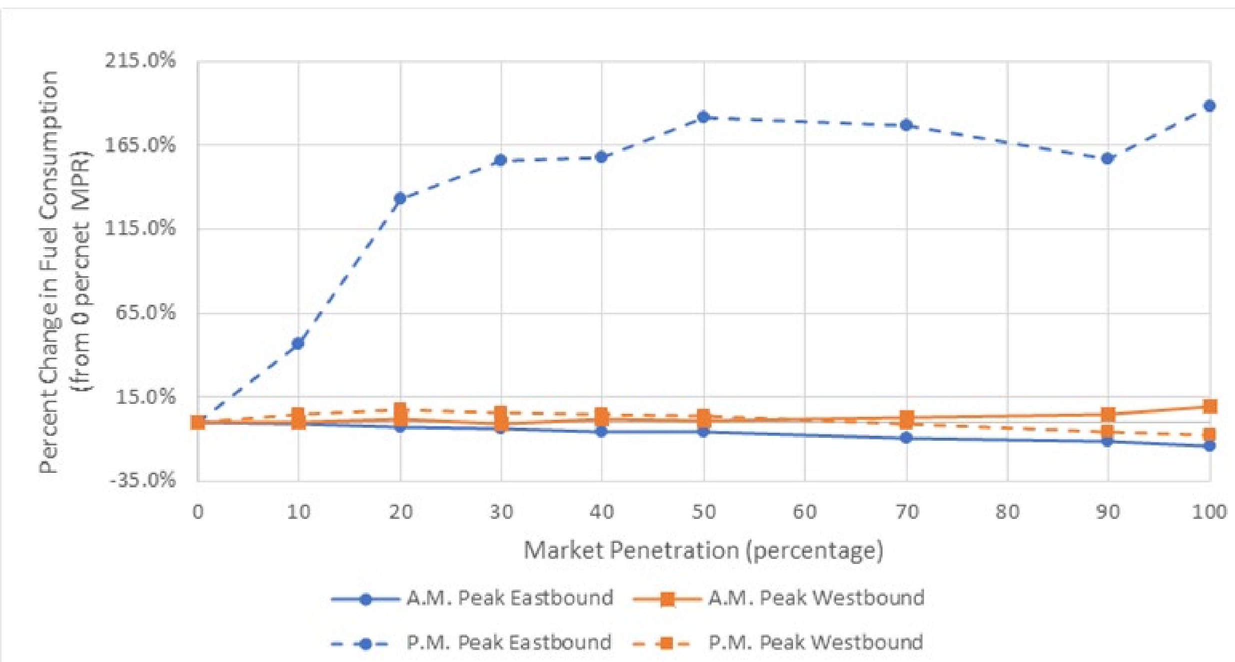
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 104. Percent Change in Fuel Consumption for Old River Road



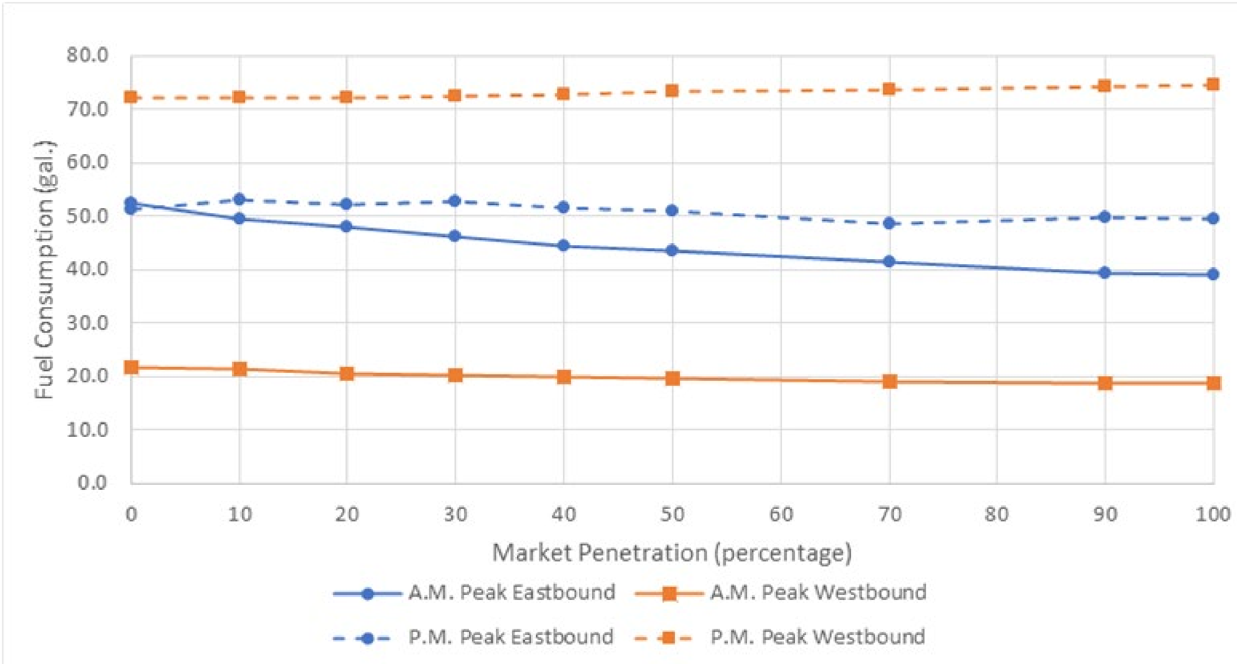
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 105. Fuel Consumption at April Sound Boulevard



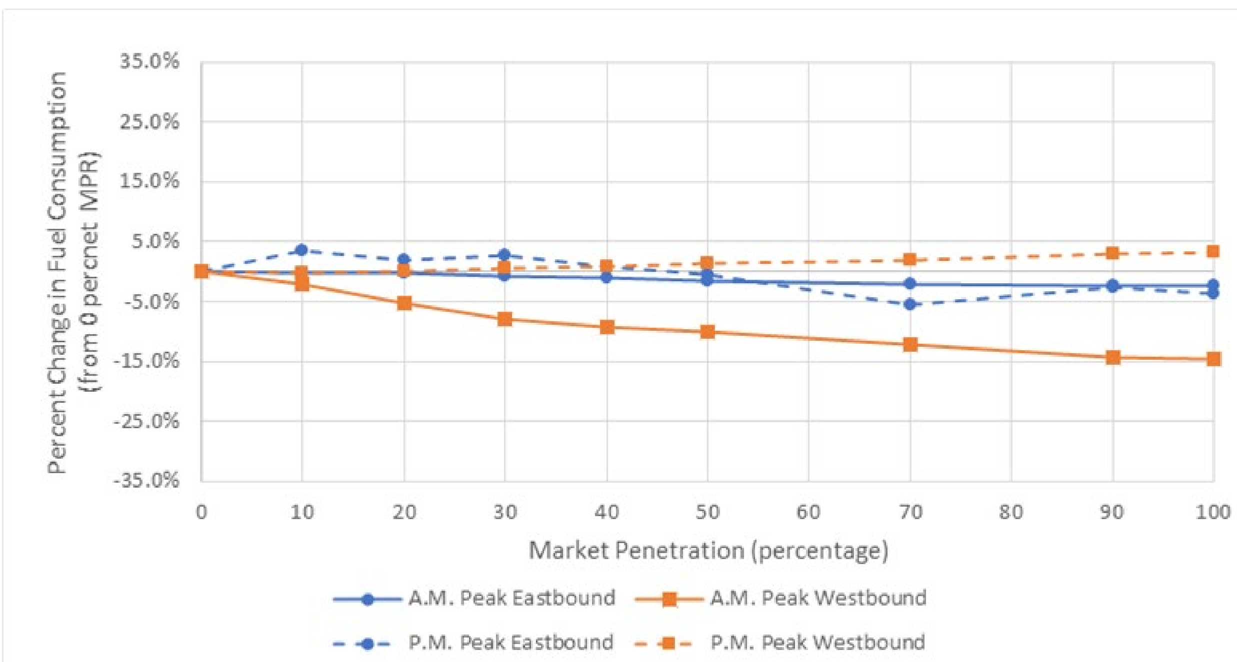
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 106. Percent Change in Fuel Consumption for April Sound Boulevard



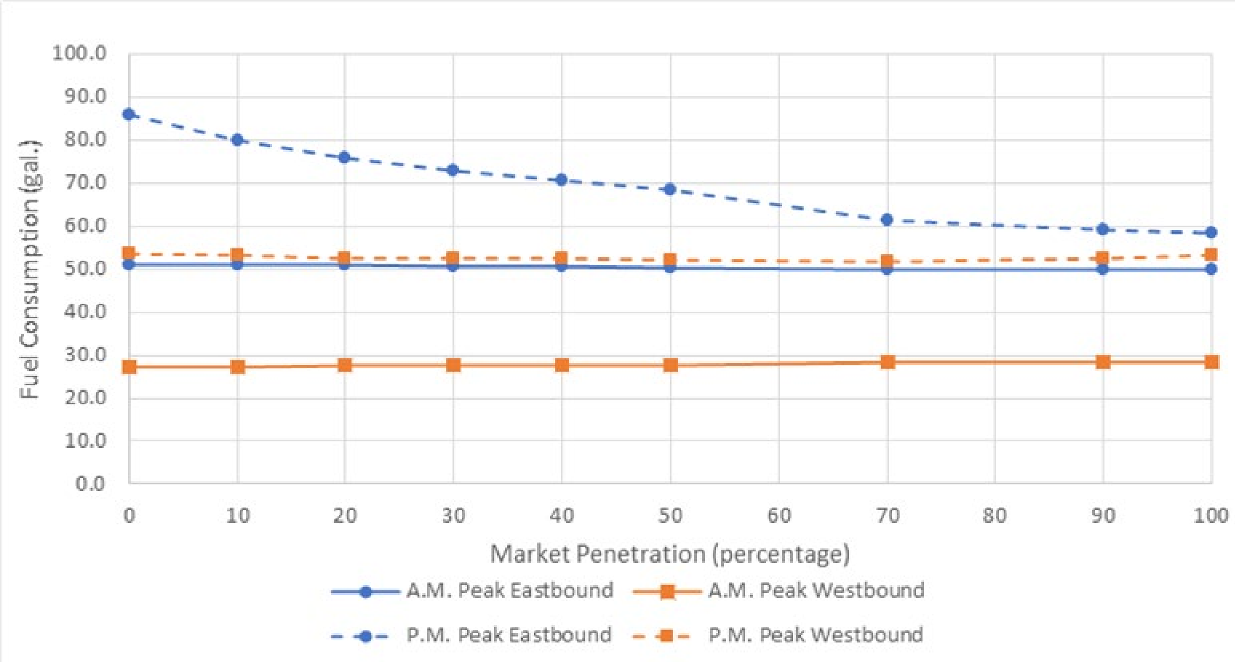
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 107. Fuel Consumption at Navajo Road



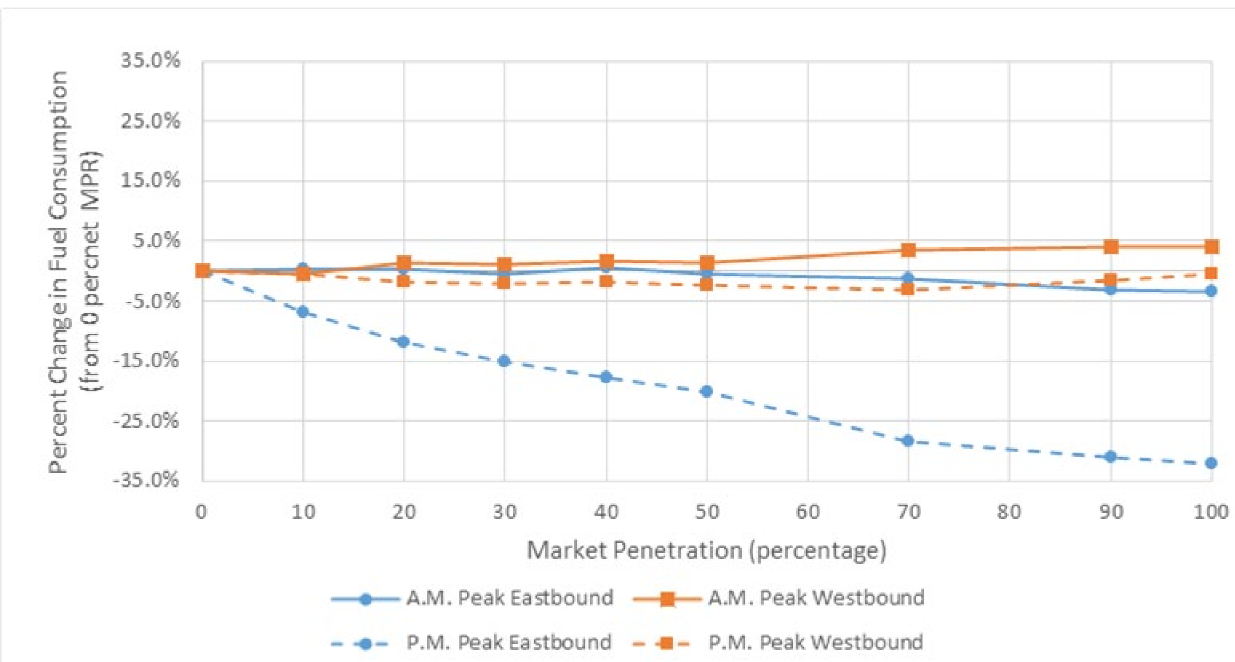
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 108. Percent Change in Fuel Consumption for Navajo Road



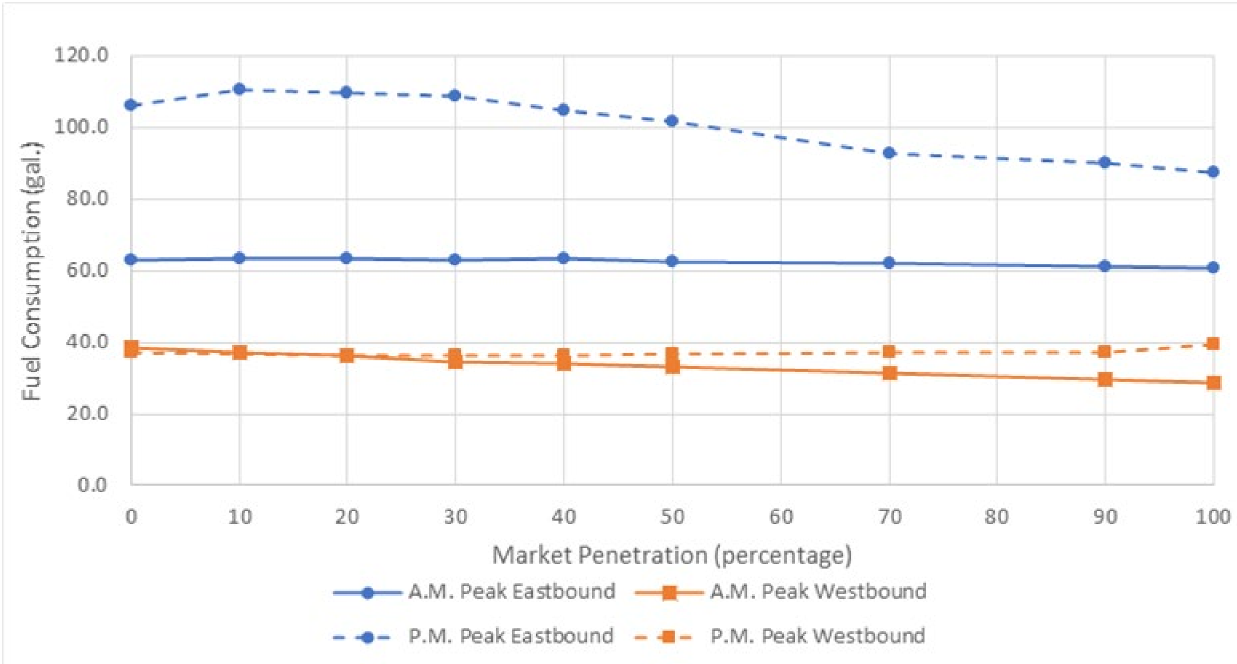
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 109. Fuel Consumption at Marina Drive



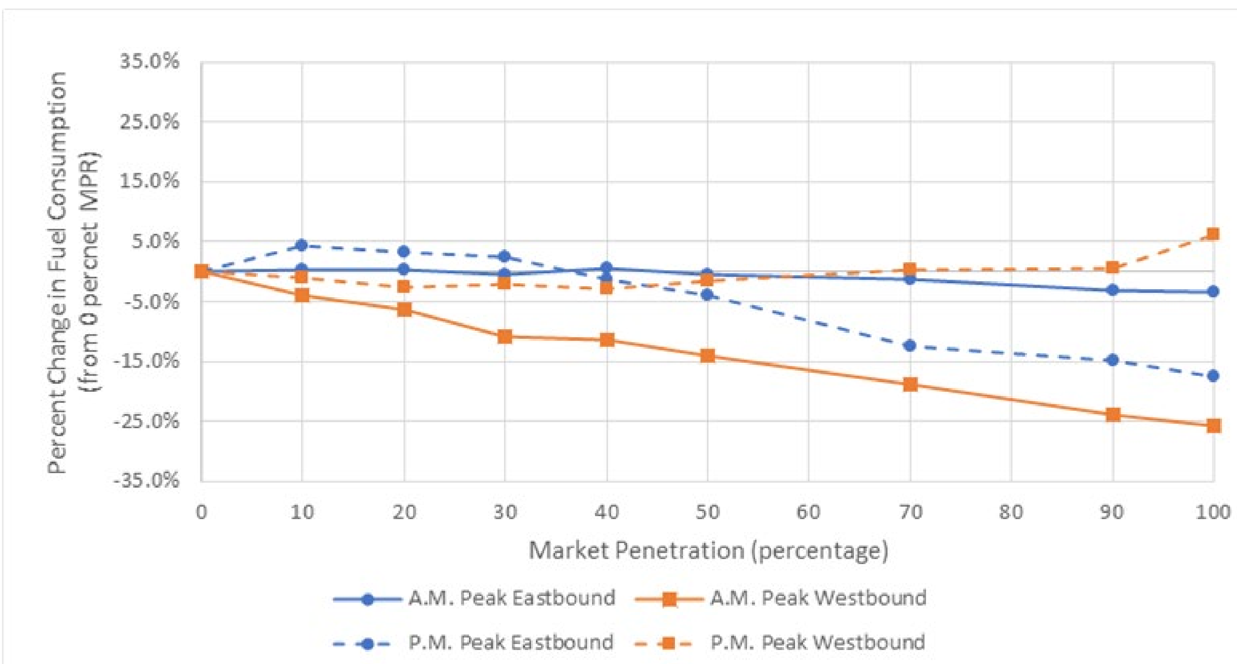
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 110. Percent Change in Fuel Consumption for Marina Drive



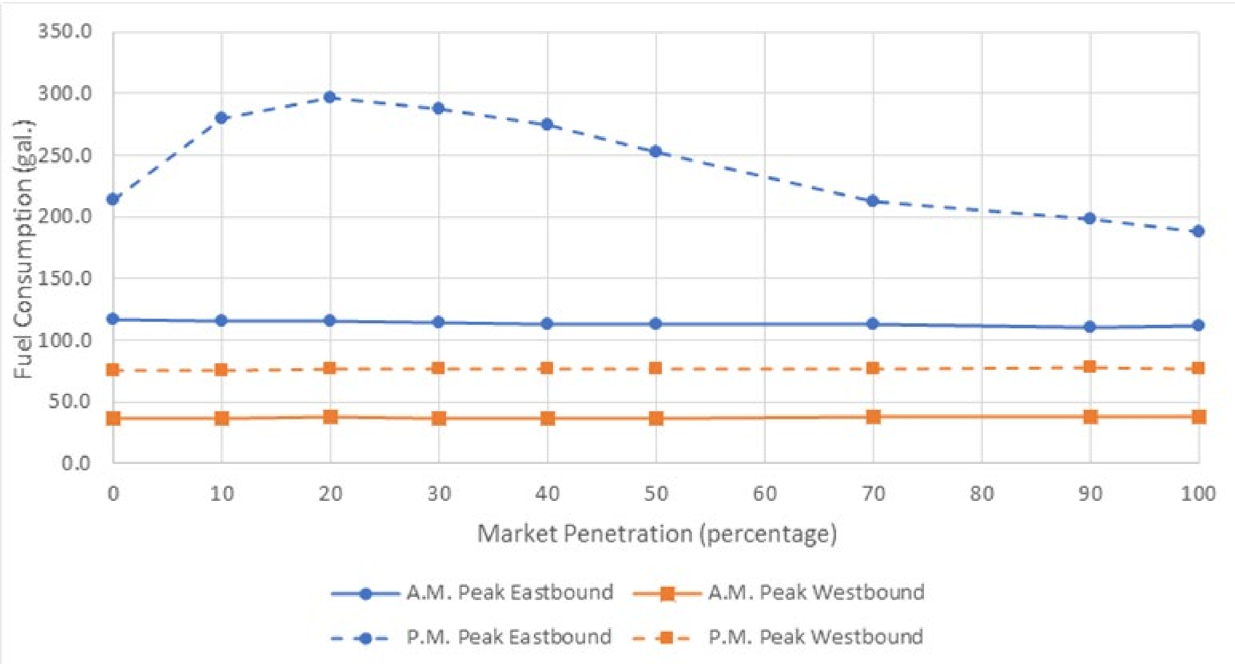
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 111. Fuel Consumption at Tejas Boulevard



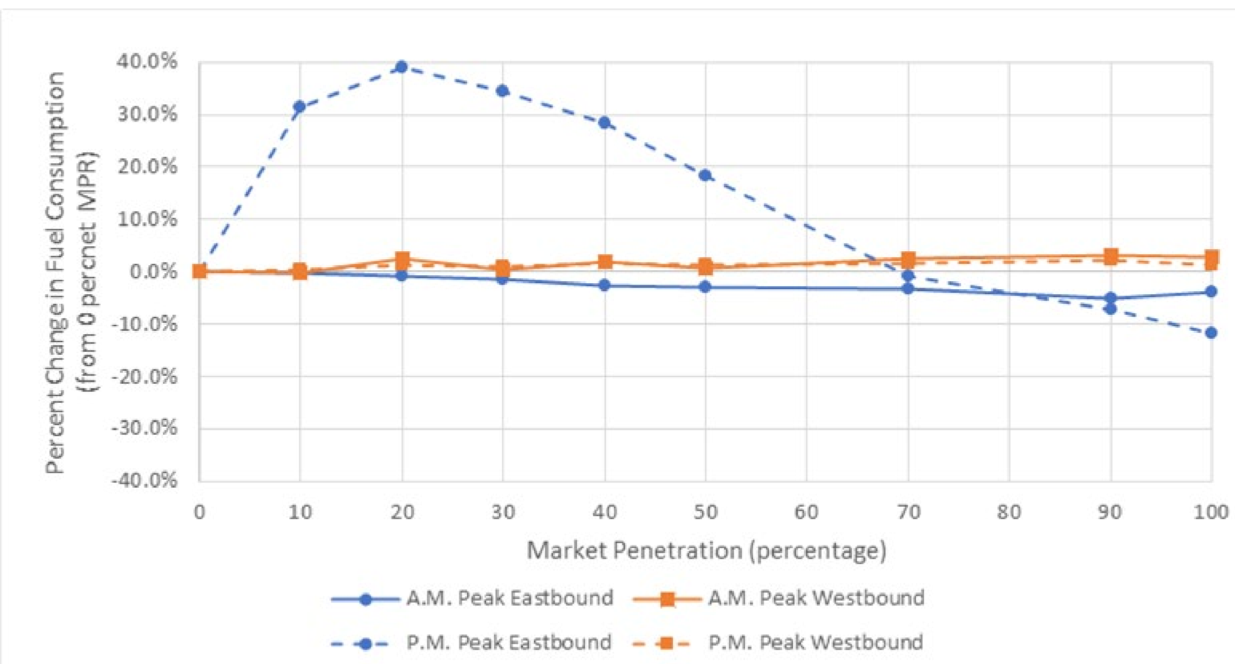
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 112. Percent Change in Fuel Consumption for Tejas Boulevard



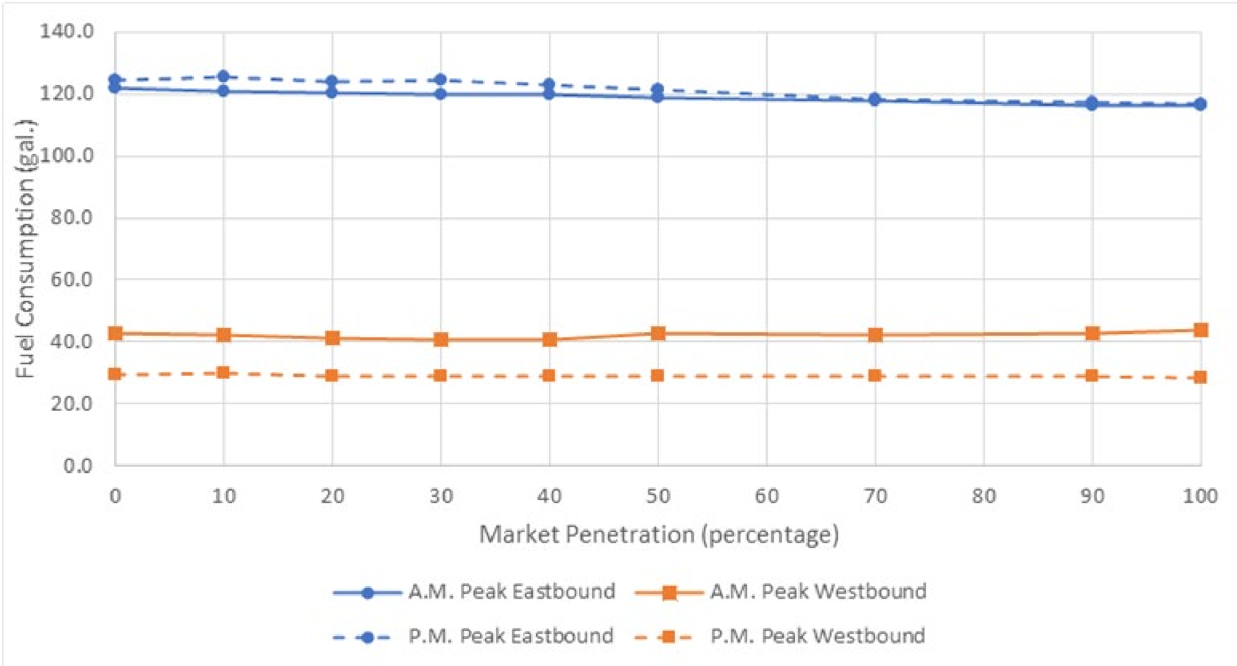
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 113. Fuel Consumption at McCaleb Road



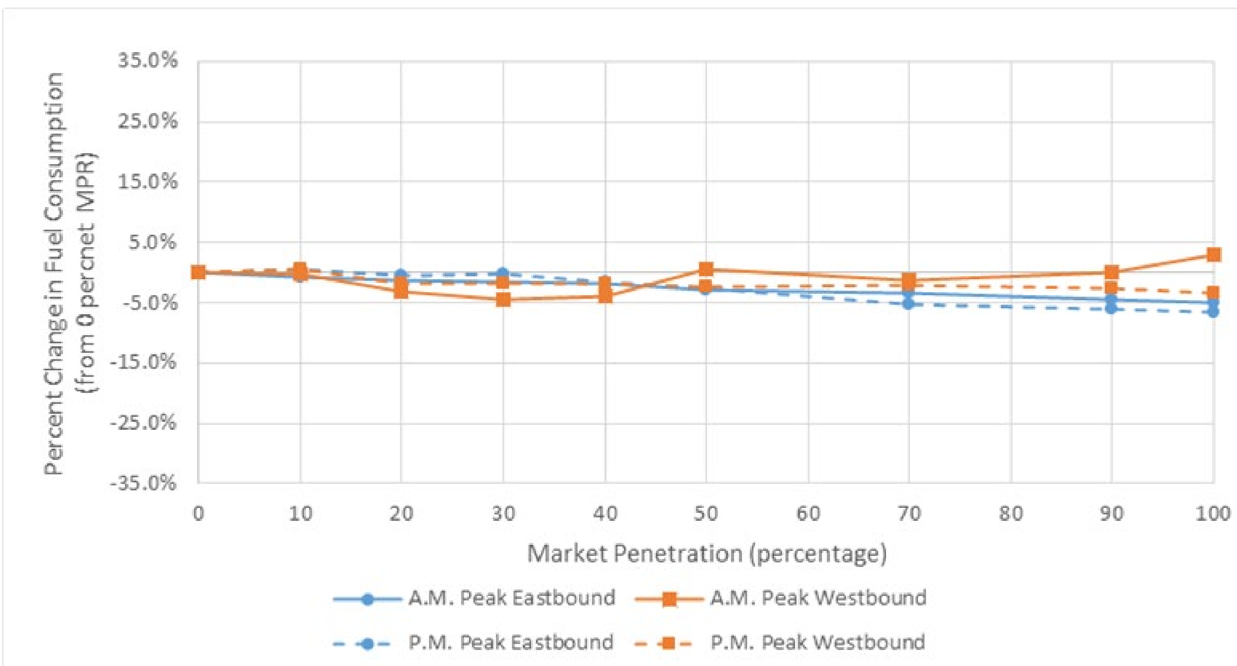
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 114. Percent Change in Fuel Consumption for McCaleb Road



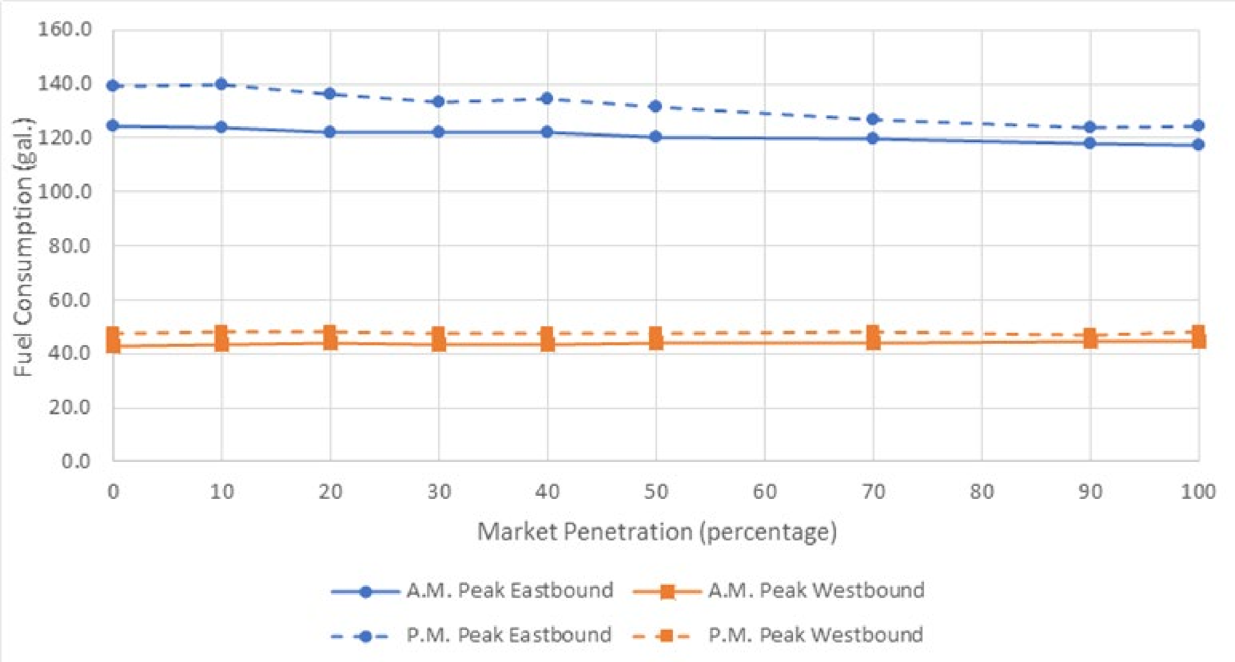
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 115. Fuel Consumption at Old 105



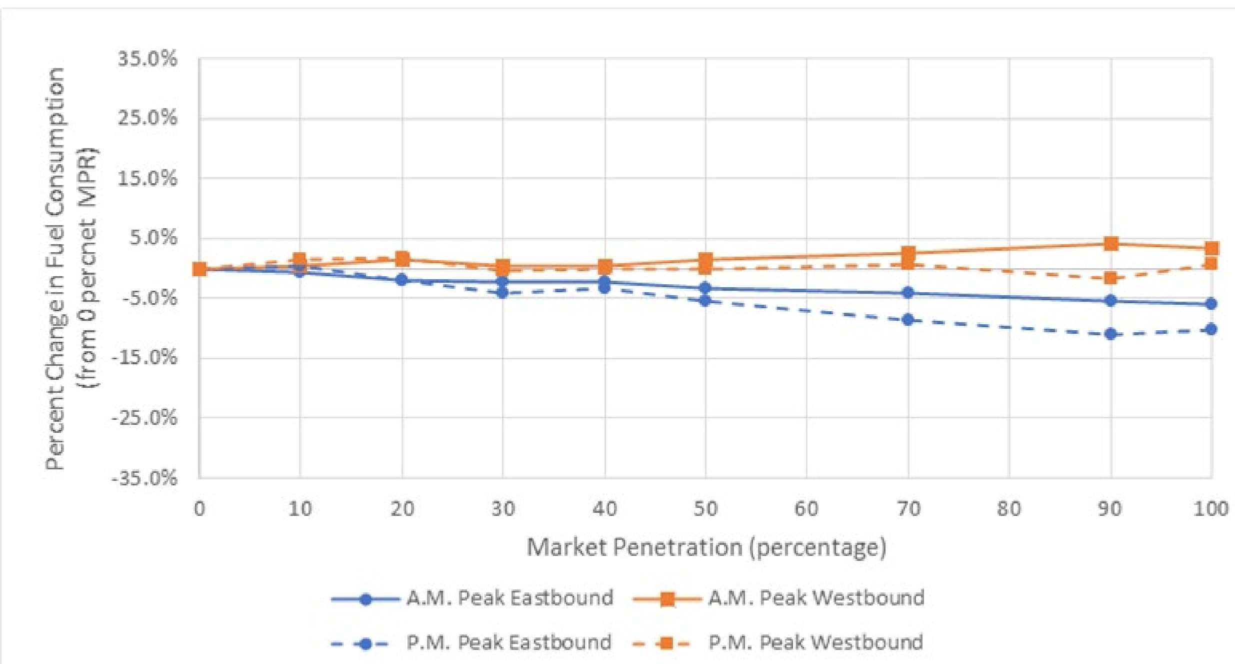
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 116. Percent Change in Fuel Consumption for Old 105



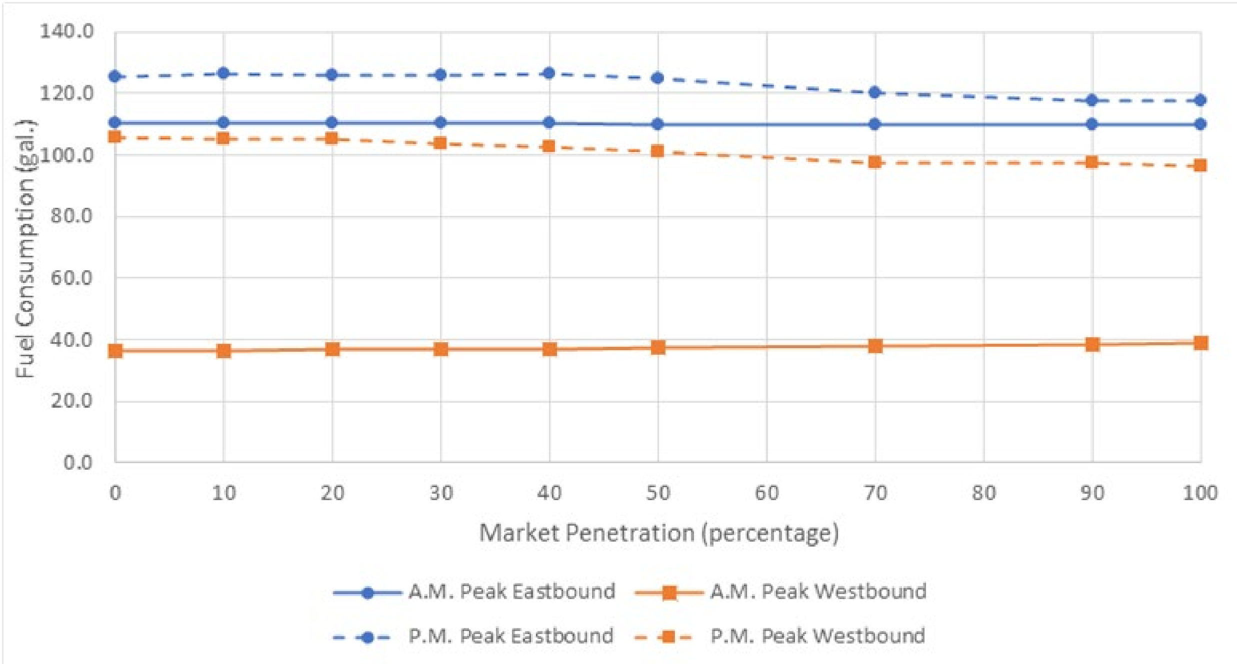
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 117. Fuel Consumption at La Salle Avenue



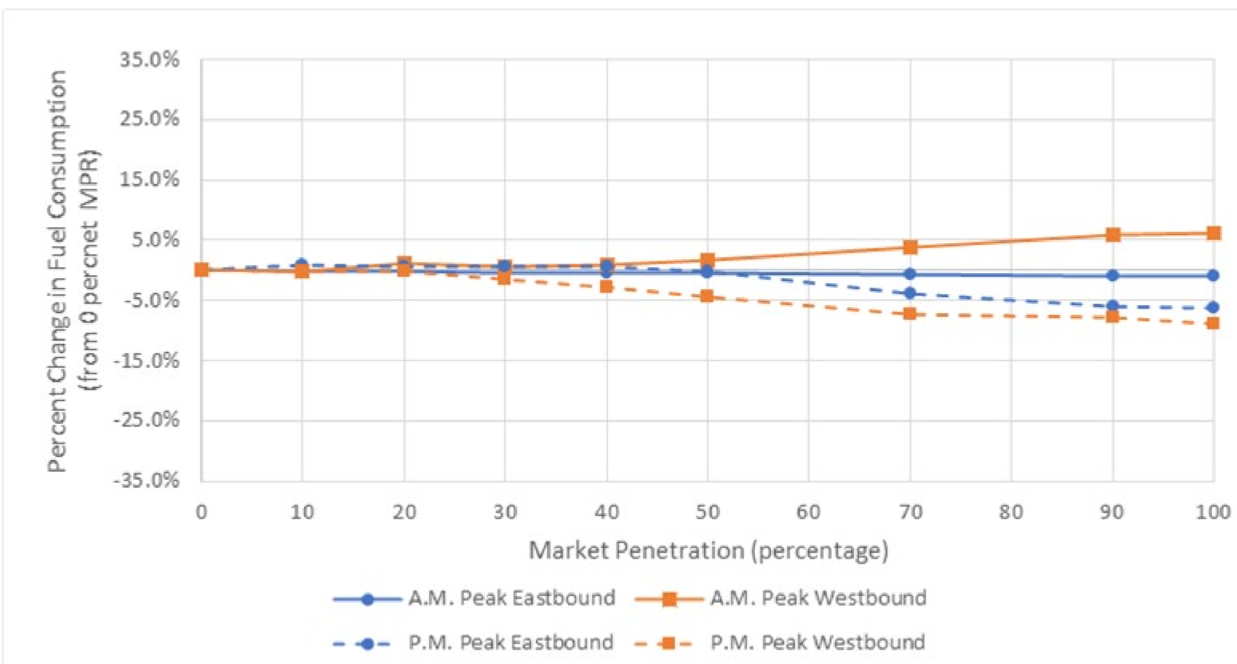
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 118. Percent Change in La Salle Avenue



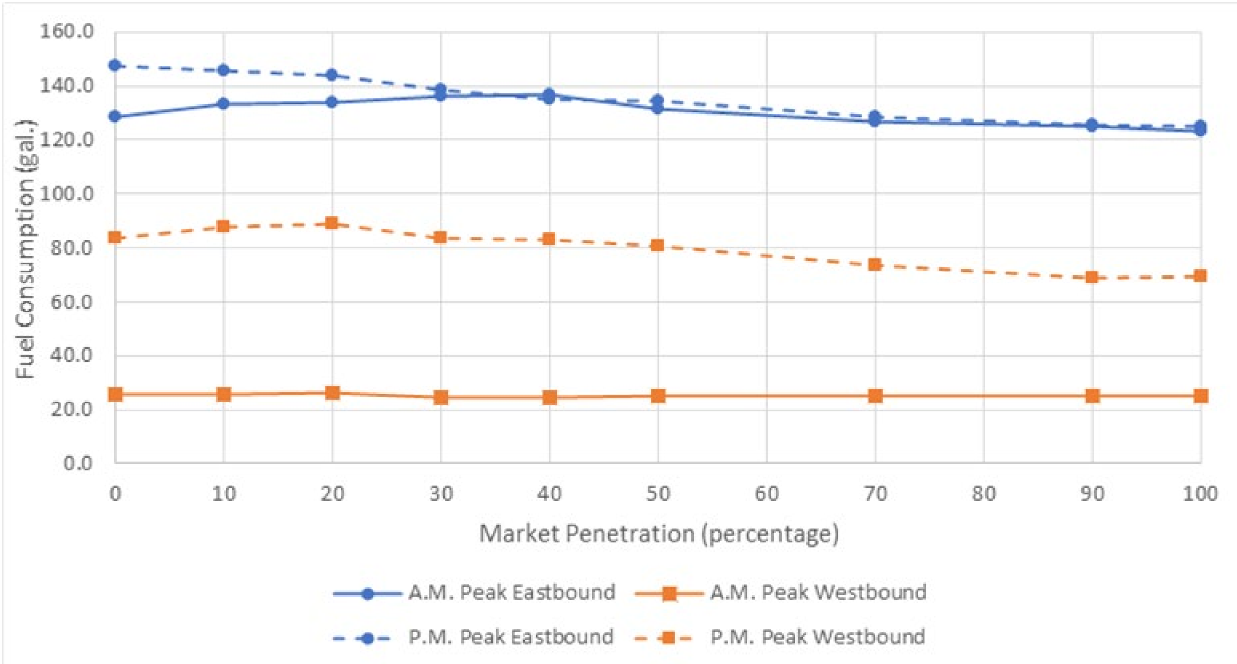
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 119. Fuel Consumption at Highland Hollow Drive



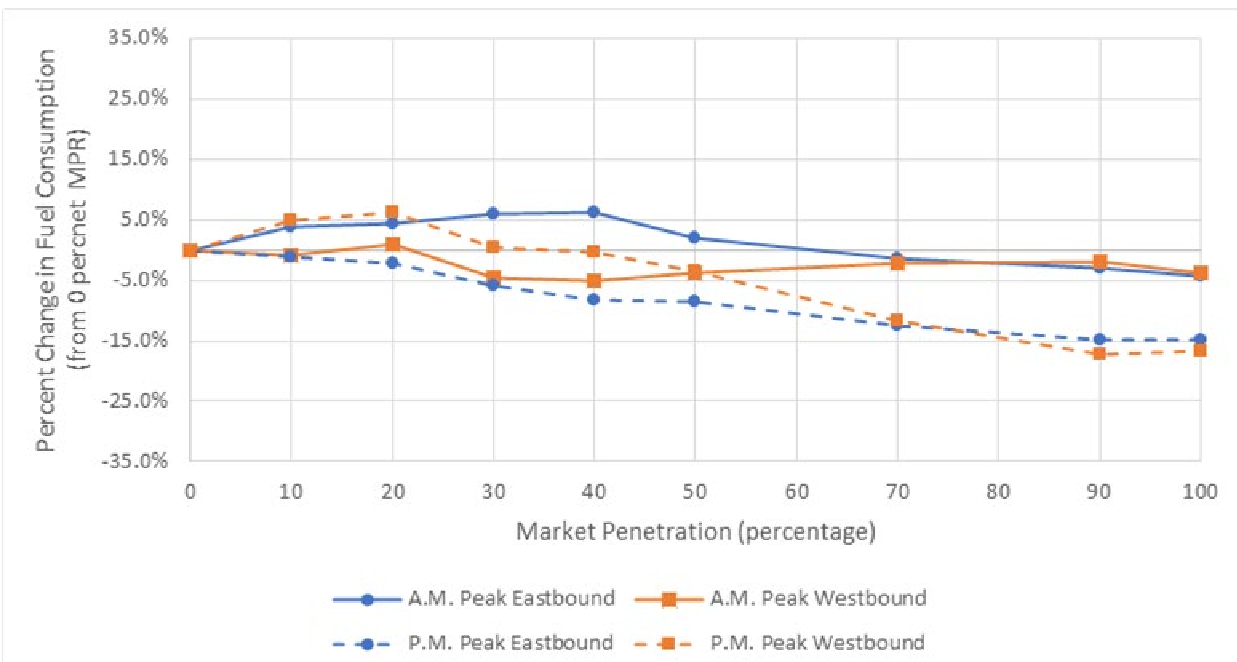
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 120. Percent Change in Fuel Consumption for Highland Hollow Drive



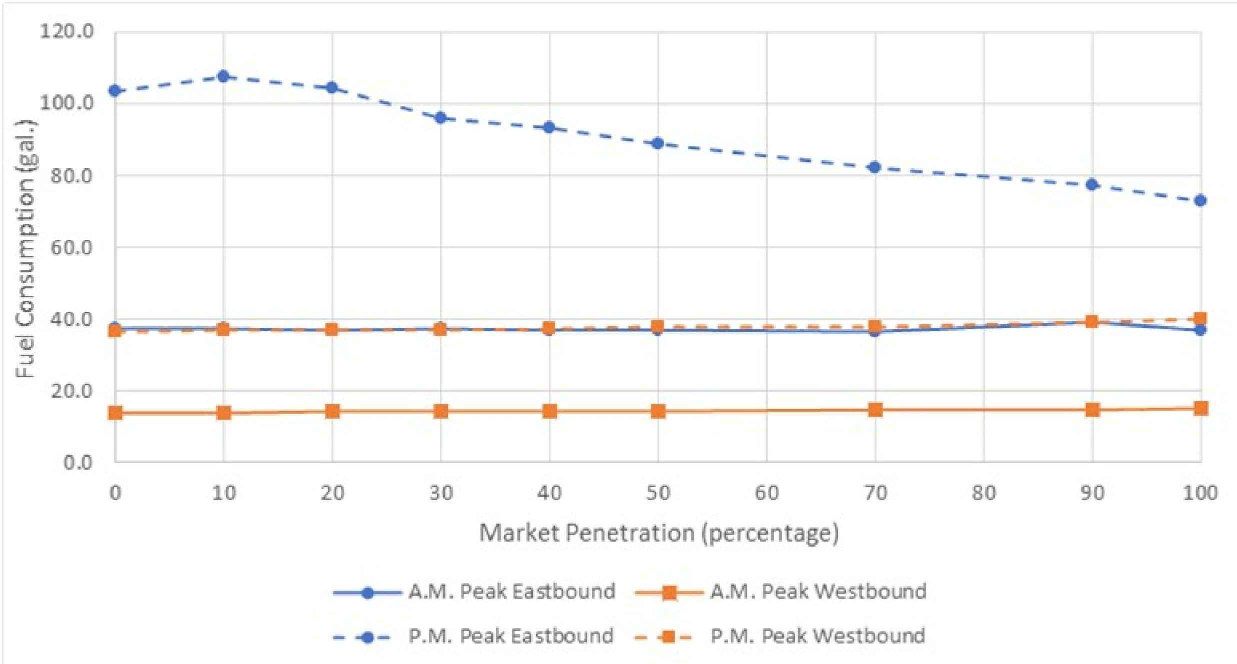
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 121. Fuel Consumption at West Fork Boulevard



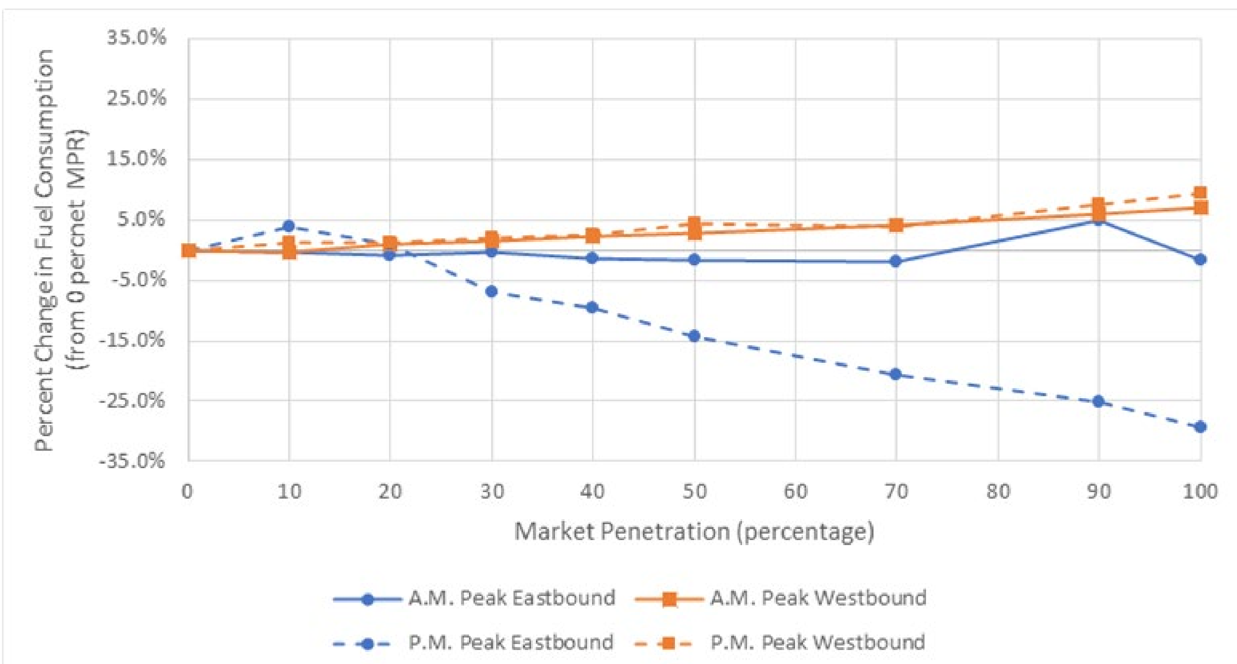
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 122. Percent Change in West Fork Boulevard



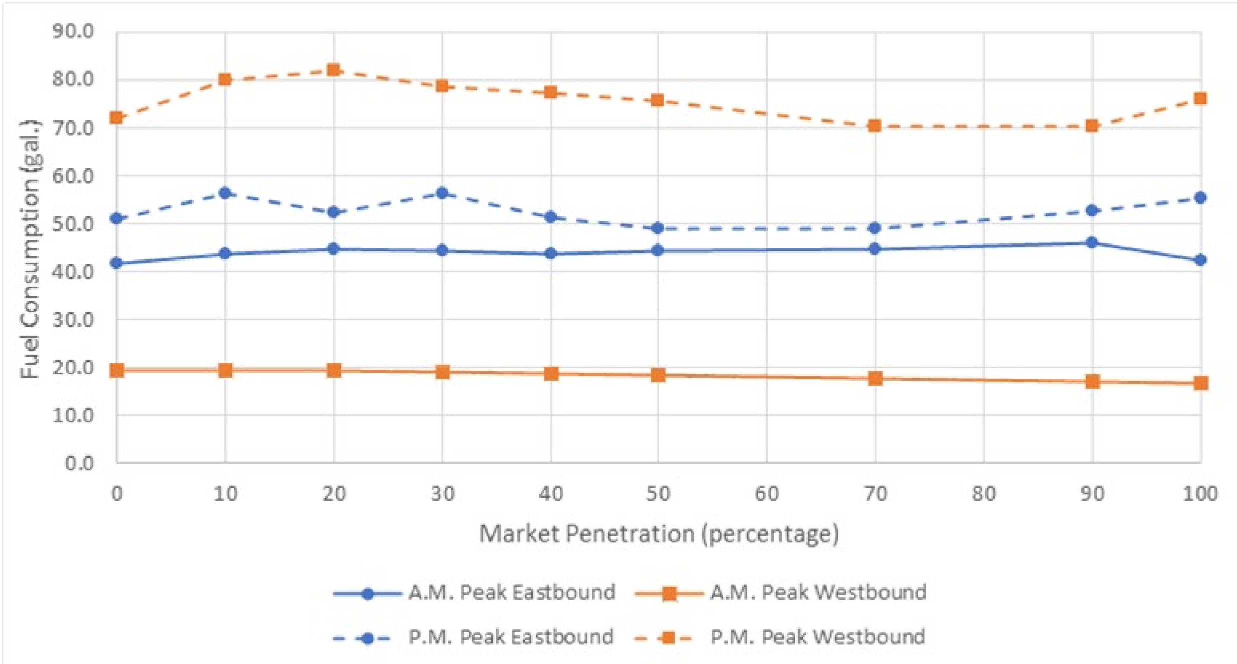
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 123. Fuel Consumption at Fountain



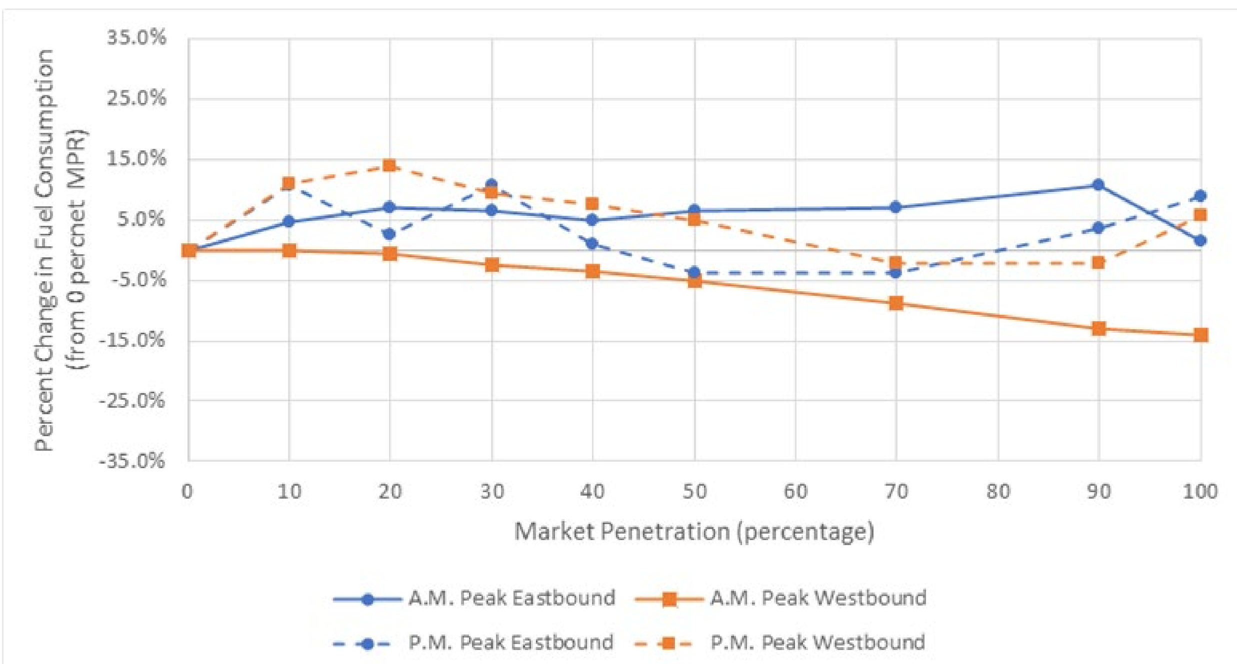
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 124. Percent Change in Fuel Consumption for Fountain



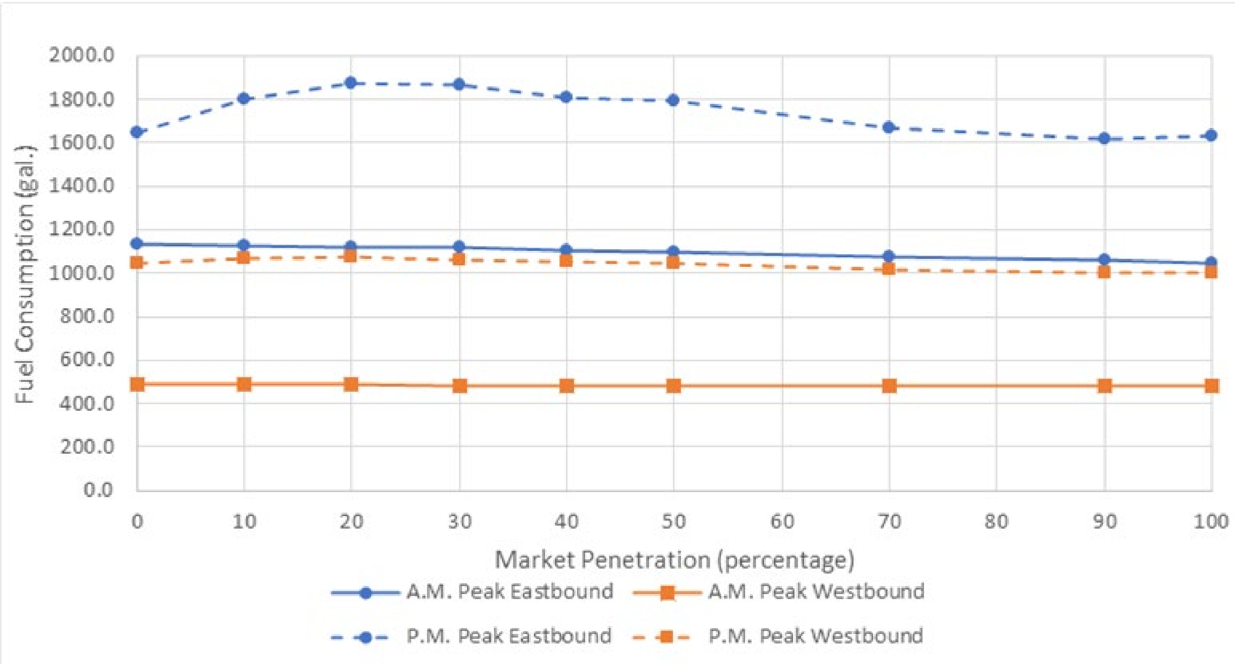
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 125. Fuel Consumption at Loop 336



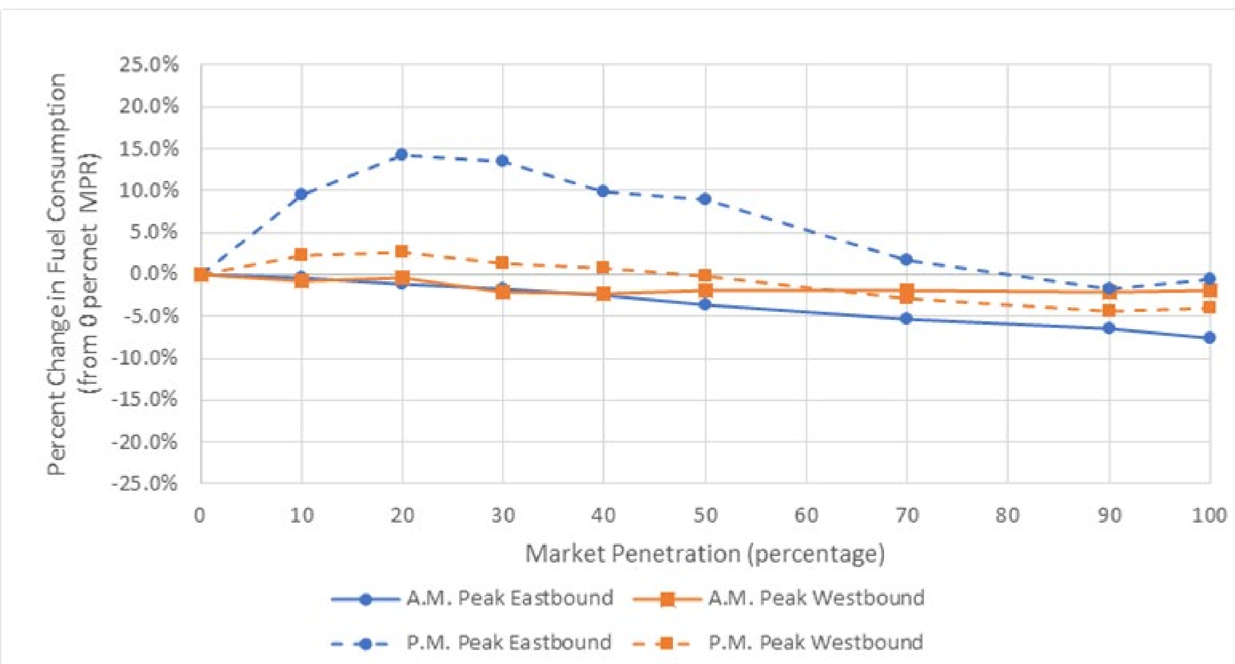
Source: Texas A&M Transportation Institute (TTI), 2022

Figure 126. Percent Change in Fuel Consumption for Loop 336



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

Figure 127. Fuel Consumption across SH105 Corridor



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

Figure 128**. Percent Change in Fuel Consumption for SH105 Corridor**

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