Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project Report

Acknowledgement and Disclaimer

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Abstract

This report provides a roadmap to details contained in six TOSCo Phase 1 detailed reports that focus on specific aspects of the four key technical objectives undertaken in the TOSCo Phase 1 project. The four key technical objectives that the project team focused their efforts on in the project were:

1. Assessing TOSCo performance through simulation
2. Defining infrastructure and vehicle level algorithms, architectures and requirements
3. Conducting a functional safety assessment
4. Implementing Cooperative Adaptive Cruise Control (CACC) into test vehicles

The six detailed reports produced as a result of the work undertaken are:

1. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Traffic-Level Simulation and Performance Analysis Report
2. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Infrastructure System Requirements and Architecture Specification
3. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Functional Safety Concept and Hazard Analysis Report
4. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Vehicle System Requirements and Architecture Specification
5. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Vehicle-Level Simulation Report
6. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Cooperative Adaptive Cruise Control (CACC) Build and Testing Report

This report is structured according to the order of the technical objective listed above. High level summaries of each of the four key technical objectives are provided along with references to the appropriate sections in the six detailed reports where the reader can obtain technical details.

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Executive Summary

The Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project was undertaken by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium, consisting of Ford, General Motors, Honda, Hyundai Motor Group, Mazda, Nissan, Subaru, Volkswagen Group of America and Volvo Truck, in conjunction with the University of Michigan Transportation Research Institute (UMTRI), the Texas A&M Transportation Institute (TTI) and the University of California-Riverside (UCR). The United States Department of Transportation (USDOT), through the Federal Highway Administration (FHWA), funded the project under Cooperative Agreement No. DTFH6114H00002 Work Order 0005.

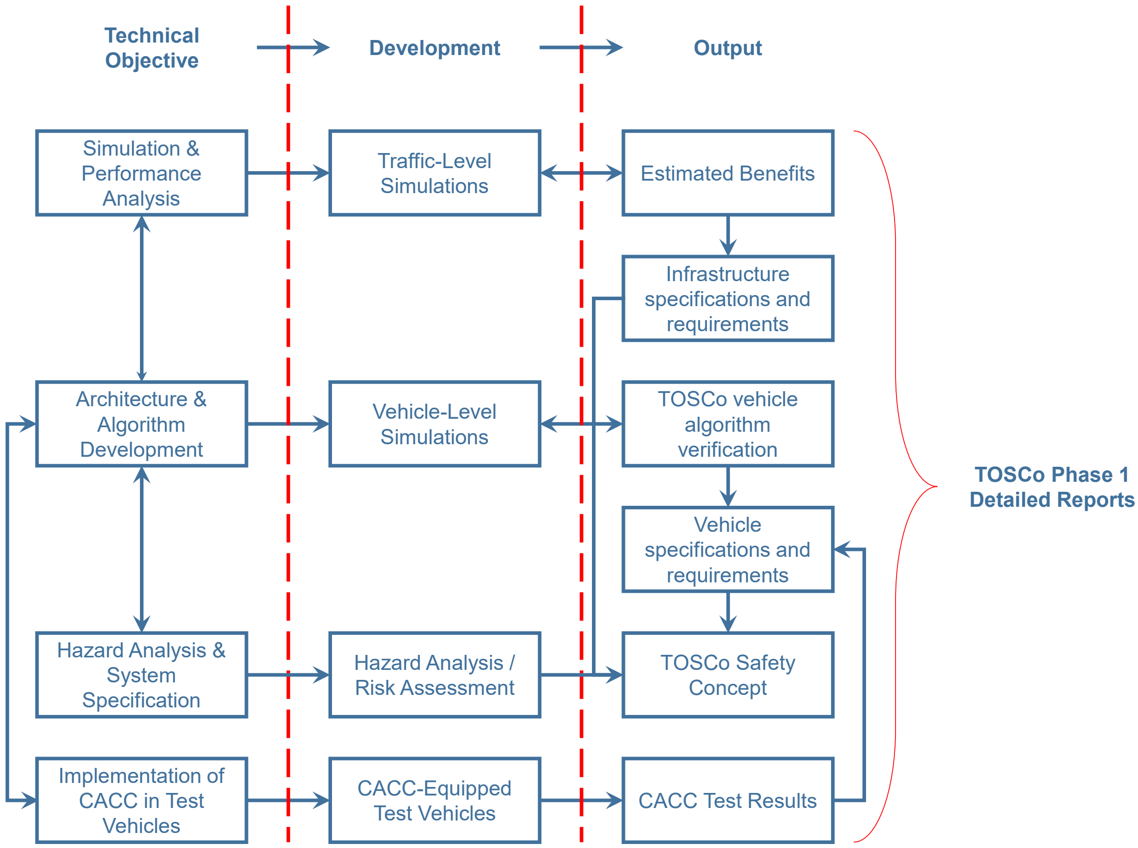
Subsequent to creating a concept of operations for the Traffic Optimization for Signalized Corridors (TOSCo) system under a previous effort, the project team initiated the TOSCo Phase 1 Project in July 2016. The project team began by selecting candidate corridors that would first be used to model traffic simulations and potentially used for actual on-road testing. The project team focused on fulfilling four key technical tasks in an effort to demonstrate the potential benefits a TOSCo system could generate in terms of improved mobility, increased fuel efficiency and decreased emissions. The four key technical objectives that the project team focused their efforts on in the TOSCo Phase 1 Project were:

1. Assessing TOSCo performance through simulation
2. Defining infrastructure and vehicle level algorithms, architectures and requirements
3. Conducting a functional safety assessment
4. Implementing Cooperative Adaptive Cruise Control (CACC) into test vehicles

The project team selected two candidate corridors, a low-speed corridor in Ann Arbor, Michigan and a high-speed corridor in Conroe, Texas, where low-speed is defined as posted arterial speeds of between 35 and 45 miles per hour and high-speed is defined as posted arterial speeds of 55 miles per hour or more. The project team worked in two parallel paths; one focused on traffic-level and the other focused on vehicle-level simulations where the traffic-level simulations provided estimated mobility benefits based on the TOSCo system concept of operations, while the vehicle-level simulations verified the TOSCo-equipped vehicle strings would operate as designed.

The project team began by evaluating single-vehicle operation, evolving to analysis of multi-vehicle string operation using Level 1 automation in the form of automated longitudinal control provided by CACC to improve traffic-level optimization.

The estimated benefits derived from the traffic-level simulations served to provide a basis for defining the infrastructure system requirements and architecture specifications while the results of the vehicle-level simulations provided a basis for defining the vehicle system requirements and architecture specifications. Both infrastructure and vehicle system requirements and specifications provided the basis for the TOSCo safety concept. Finally, the work done implementing CACC in test vehicles provided critical input into the vehicle system requirements and specifications. The overall interconnectivity of tasks and work output are shown in Figure 1 below.



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

Figure 1: TOSCo Phase 1 Project Task Interconnectivity

Overall, the traffic-level simulations demonstrated mobility improvements in average total delay (in seconds / vehicle), stop delay (in seconds / vehicle) and number of stops per vehicle, which can be achieved in both low-speed and high-speed environments. Additionally, environmental improvements defined as reductions in CO_2, hydrocarbons and NOx generation were also demonstrated on both low- and high-speed environments as well as improvements in energy efficiency as defined in terms of kJ / mile. Estimated benefits also demonstrated a consistent improvement with increased market penetration rate. Based on the results obtained from traffic-level simulations, the project team concluded that there is merit in exercising the TOSCo system in the actual environments that the simulations were modeled after to better understand if real-world benefits can be achieved through deployment.

This report provides a map to information contained in six detailed reports that focus on specific aspects of the work undertaken in the TOSCo Phase 1 Project as follows:

1. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Traffic-Level Simulation and Performance Analysis Report
2. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Infrastructure System Requirements and Architecture Specification

3. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Vehicle System Requirements and Architecture Specification
4. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Vehicle-Level Simulation Report
5. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Functional Safety Concept and Hazard Analysis Report
6. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Cooperative Adaptive Cruise Control (CACC) Build and Testing Report

The subsequent sections in this report are organized according to the four key technical objectives identified above. The estimated benefits are covered first followed by the simulation methodology used to obtain the estimations. The infrastructure and vehicle system architectures used to model the simulations are then covered along with the TOSCo system requirements that were defined to support the architecture. The functional safety assessment follows and finally the work accomplished in implementing CACC into test vehicles, a key element in the overall TOSCo architecture, is discussed.

Key takeaways from the TOSCo Phase 1 Project are listed below.

- TOSCo was able to produce substantial reductions in stop delays and the number of stops in both corridors. Stop delays decreased on the order of 40% in the low-speed corridor and 80% in the high-speed corridor after TOSCo was implemented. Similar reductions in the total number of stops were recorded in both corridors.
- TOSCo did not cause substantial changes in the total delay experienced by travelers in the corridor. As TOSCo vehicles were slowing down further upstream of intersections, minor changes in total delay were expected, but these changes are not likely to be noticeable to travelers.
- Total travel time and travel speed were not significantly impacted by implementing TOSCo in either corridor.
- TOSCo did not have a substantial impact on vehicle emissions or fuel consumption. One potential explanation for not seeing significant changes in air quality impacts is because average speed was not significantly changed by TOSCo.
- TOSCO did result in minor reductions in hydrocarbon and NOx emissions in each deployment
- Data suggests that TOSCo can improve the capacity of individual intersections since it can discharge more vehicles within the same signal interval, using the coordinated launch function. In Phase 2, the issue of whether such capacity improvements can be realized across an entire corridor will be examined further.
- TOSCo traffic-level simulation results demonstrated smoother traffic flow especially at higher penetration rates. Coordinated launch, especially, has significant positive impact in discharging queues of TOSCo-equipped vehicles.

The project team developed a number of recommendations based on their experiences with modeling the potential mobility and environmental benefits of the TOSCo system.

For traffic-level simulations:

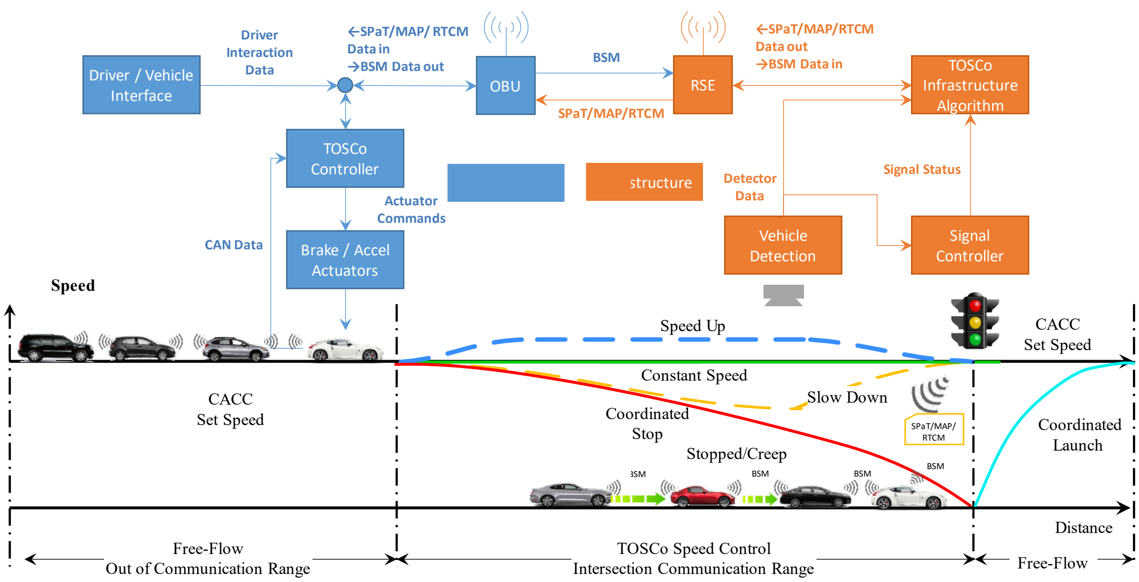
- TOSCo parameters (e.g., maximum acceleration, CACC set speed) should be selected to match the corridor characteristics and driving behaviors.
- Traffic-level simulation assumes that lateral and longitudinal position of vehicles can be detected by sensors installed at an intersection. More research is needed to understand the limitations of field equipment to better simulate the TOSCo infrastructure component.
- Additional simulations should be run to analyze which queueing information is most helpful for TOSCo, because analysis suggests that calculating the green window with predictive queue estimation performs better than current queue information, especially with increased Dedicated Short-range Communication (DSRC) range.
- Under actuated signal control in low-volume conditions, a more efficient means of predicting the duration of the green window is needed because low-traffic volume on side streets along a TOSCo-equipped corridor may generate inaccurate Signal Phase and Timing (SPaT) information when the traffic signal on the TOSCo approach is in a green rest state.

For vehicle-level simulations:

- Vehicle system modifications are needed to better match TOSCo vehicle string behavior with surrounding traffic, improve trajectory planning, and account for dynamically varying conditions.
- Expand the TOSCo-vehicle algorithms to account for: 1) road grade, 2) different power-train characteristics, and 3) imperfection of sensors (e.g., GPS) and communications

1 Introduction

Figure 2 illustrates the overall concept of the Traffic Optimization for Signalized Corridors (TOSCo) system. TOSCo is an innovative connected vehicle application that has the potential to generate substantial mobility, environmental, and fuel-savings benefits. Vehicles equipped with TOSCo functionality use signal phase and timing and queue information from the infrastructure to plan speed trajectories that allow them to reduce the likelihood of stopping at TOSCo-supported intersections. 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 queued 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 function, 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



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

Figure 2: TOSCo Concept

The project team began by evaluating single-vehicle operation evolving to analysis of multi-vehicle string operation using Level 1 automation in the form of automated longitudinal control provided by CACC to improve traffic-level optimization.

This report provides a map to information contained in six detailed reports that focus on specific aspects of the work undertaken in the TOSCo Phase 1 Project as follows:

1. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Traffic-Level Simulation and Performance Analysis Report

2. Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Infrastructure System Requirements and Architecture Specification
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The subsequent sections in this report are organized according to the four key technical objectives that the project team focused their efforts on in the TOSCo Phase I Project, which were:

1. Assessing TOSCo performance through simulation
2. Defining infrastructure and vehicle level algorithms, architectures, and requirements
3. Conducting a functional safety assessment
4. Implementing Cooperative Adaptive Cruise Control (CACC) into test vehicles

The estimated benefits are covered first followed by the simulation methodology used to obtain the estimations. The infrastructure and vehicle system architectures used to model the simulations are then covered along with the TOSCo system requirements that were defined to support the architecture. The functional safety assessment follows and finally, the work accomplished in implementing CACC into test vehicles, a key element in the overall TOSCo architecture, is discussed.

2 TOSCo Simulation and Performance Analysis

The TOSCo Traffic-Level Simulation and Performance Analysis Report documents traffic-level simulation and performance analysis that the project team conducted for the TOSCo Phase 1 Project. The research team developed an innovative simulation environment to support the development and assessment of TOSCo functionality. The environment consists of three platforms: a vehicle-simulation platform, an infrastructure-simulation platform, and a performance-assessment platform. Using a series of three simulation models, the vehicle simulation platform gives the project team the ability to test and verify algorithm code that will eventually reside in TOSCo-equipped vehicles. The infrastructure-simulation platform was developed to test and verify detection and estimation algorithms that reside on infrastructure devices. The project team used this platform to simulate the detection outputs of different queue detection devices and to access accuracy and precision impacts of queue estimates on TOSCo processes. The TOSCo performance assessment platform (i.e., traffic-level simulation) was developed to allow the team to quantify the potential intersection, corridor, and network-level benefits of deploying TOSCo in the real-world. Using simplified vehicle logic, this platform gives the team the ability to examine the environmental and mobility benefits associated with the various operating conditions and scenarios.

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

- The potential mobility and environmental benefits of using TOSCo in different operating environments, a low-speed corridor (Plymouth Rd., Michigan) and a high-speed corridor (SH 105, Texas)
- The impacts of different market penetration rates of vehicles equipped with TOSCo functionality on mobility and environmental benefits
- The use of different infrastructure algorithms for estimating the queuing profiles: a basic safety message (BSM) and loop-detector approach on the low-speed corridor and a radar-based detector approach on the high-speed corridor

Based on the simulation experiments, the research team identified the following findings related to deploying TOSCO in the two simulated corridors.

- TOSCo was able to produce substantial reductions in stop delay and number of stops in both corridors. In both corridors, stop delay decreased on the order of 40% in the low-speed corridor and 80% in the high-speed corridor after TOSCo was implemented. Similar reductions in the total number of stops were recorded in both corridors.
- For the low-speed corridor, TOSCo did not cause substantial changes in the total delay experienced by travelers in the corridor. Increase in total delay was observed for the high-speed corridor, however, the increase in delay was not significant compared to overall travel

time. Constraints placed on the TOSCo system in terms of speed limits (cannot travel faster than the speed limit) coupled with limited acceleration were seen as contributing to the increase for the higher speed environment.

- Total travel time and travel speed were not significantly impacted by implementing TOSCo in either corridor
- The TOSCo system produced similar mobility benefit trends in both low-speed and high-speed corridors.
- Emission benefits tend to be higher in the low-speed corridor. Because the changes in speeds in the low-speed corridor occur in the range where environmental impacts are the greatest, emissions benefits in the low-speed corridor are more sensitive to smaller changes in speed.
- The string of TOSCo vehicles formed more easily as the penetration rates increased. This caused more vehicles to drive in a cooperative fashion.
- With more strings, queues at intersections can clear faster due to TOSCo's coordinated launch feature.
- As the market penetration rate of TOSCo vehicles increased, the accuracy of the queue prediction also increased.

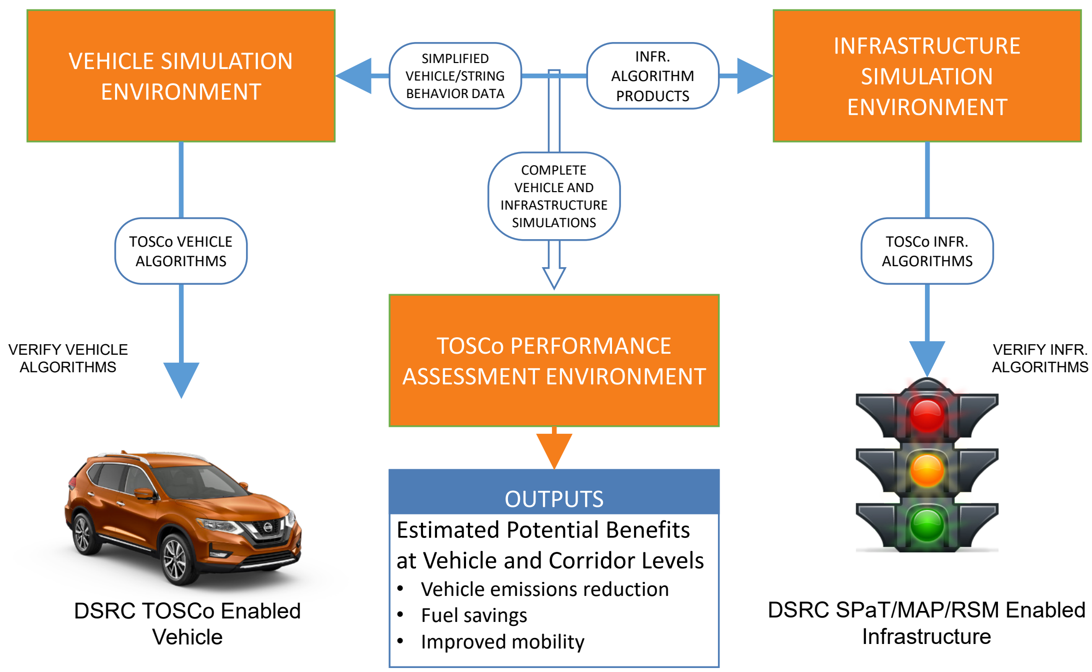
The research team developed the following recommendations based on their experiences with modeling the potential mobility and environmental benefits of the TOSCo System.

- TOSCo parameters (e.g., maximum acceleration, CACC set speed) should be selected to match the corridor characteristics and driving behaviors
- TOSCo vehicles need to utilize profiles that accelerate different than the version currently in the simulation model. Acceleration from a stop should incorporate a buildup of the increasing acceleration, constant acceleration, and a reduction of acceleration, so that a TOSCo vehicle is able to reach speed in a reasonable amount of time.
- The simulations need to be revised with the final vehicle level algorithm and evaluated to understand benefits of the revised TOSCo algorithm
- The TOSCo-vehicle algorithms should be expanded to account for 1) non-trivial initial acceleration for trajectory planning 2) road grade, 3) different power-train characteristics and 4) imperfection of sensors (e.g., GPS) and communications
- The simulation experiments assume that lateral and longitudinal position of vehicles can be detected by sensors installed at an intersection. More research and field tests are needed to understand the limitations of field equipment to better simulate the TOSCo Infrastructure component.
- Data in this report indicates predictive queue estimation performs better with increased DSRC range than current queue information used for the green window calculation. Additional simulations should be run to analyze which queueing information is most helpful for TOSCo.

- Results from both corridors show that TOSCo is less effective at low-traffic volume and low-delay intersections. When the traffic volume is low, or signal coordination provides good progression, most of the vehicles don't need to stop or slow down at the intersection, which leaves very limited space for TOSCo to adjust vehicle trajectories In addition, low traffic volumes on side streets may generate inaccurate SPaT information when the traffic signal on the TOSCo-supported approach is in what is referred to as a "green rest state." When in this state, the signal may report a static value, such as 0 seconds, to the next phase change unless a condition referred to as "minimum recall" is active. Minimum recall is defined in the Signal Timing Manual – Second Edition as a parameter for a type of phase recall that times the minimum duration of a green phase for a particular movement, regardless of the demand on the movement.

2.1 TOSCo Simulation Environments

The project team developed three simulation environments for evaluating the TOSCo system. Figure 3 shows the relationship between the three environments which are the Vehicle Simulation, Infrastructure Simulation and TOSCo Performance Assessment Environments. This figure shows how the vehicle and infrastructure simulations work with each other in development and feed into the performance evaluation.



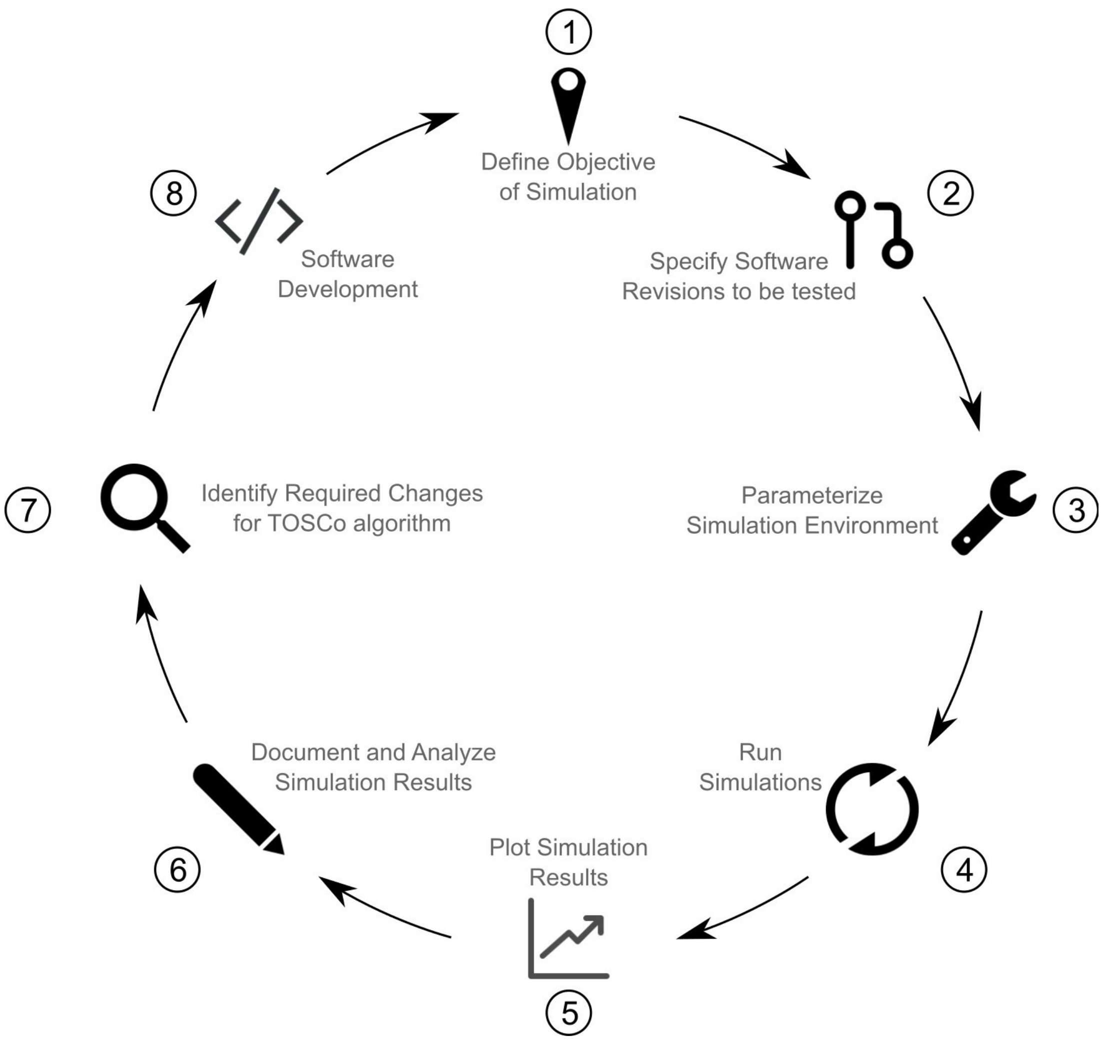
Source: Texas A&M Transportation Institute

Figure 3: TOSCo Simulation Evaluation Environment

2.1.1 TOSCo Vehicle Simulation Environment

The TOSCo vehicle simuation environment is used to test and verify the developed TOSCo algorithm. Next to the vehicle algorithm, the vehicle simulation environment employs an infrastructure component to compute and provide information required to verify system functionality and assess adjustments to the vehicle control systems. The vehicle simulation environment was developed to simulate, in high detail, many of the low-level components that could impact a TOSCo vehicle, such as speed control algorithm, radar sensor algorithms, GPS errors, and more. The vehicle simulation environment acts as a platform for testing and verifying the algorithms that will eventually be used in TOSCo-enabled vehicles and evaluation of very specific vehicle behaviors at a low-level.

The TOSCo Vehicle-Level Simulation Report provides a detailed account of the work done in verifying the vehicle algorithm function via the simulation environment. This environment provides the opportunity to rapidly test, modify and then re-test specific aspects of the TOSCo algorithm without having to deploy a specific version in a vehicle and run several tests on a closed track, thereby reducing costs. When identical initial parameters are used, this environment also provides deterministic outcomes which are more useful for evaluating impacts of various parameters compared to field testing which is inherently stochastic in nature. This property allows for incremental delta tests, in which the cause of a particular result can be identified by gradually modifying a single parameter only, while keeping all others unchanged. Figure 4 below illustrates the workflow utilized in conducting vehicle-level simulations.



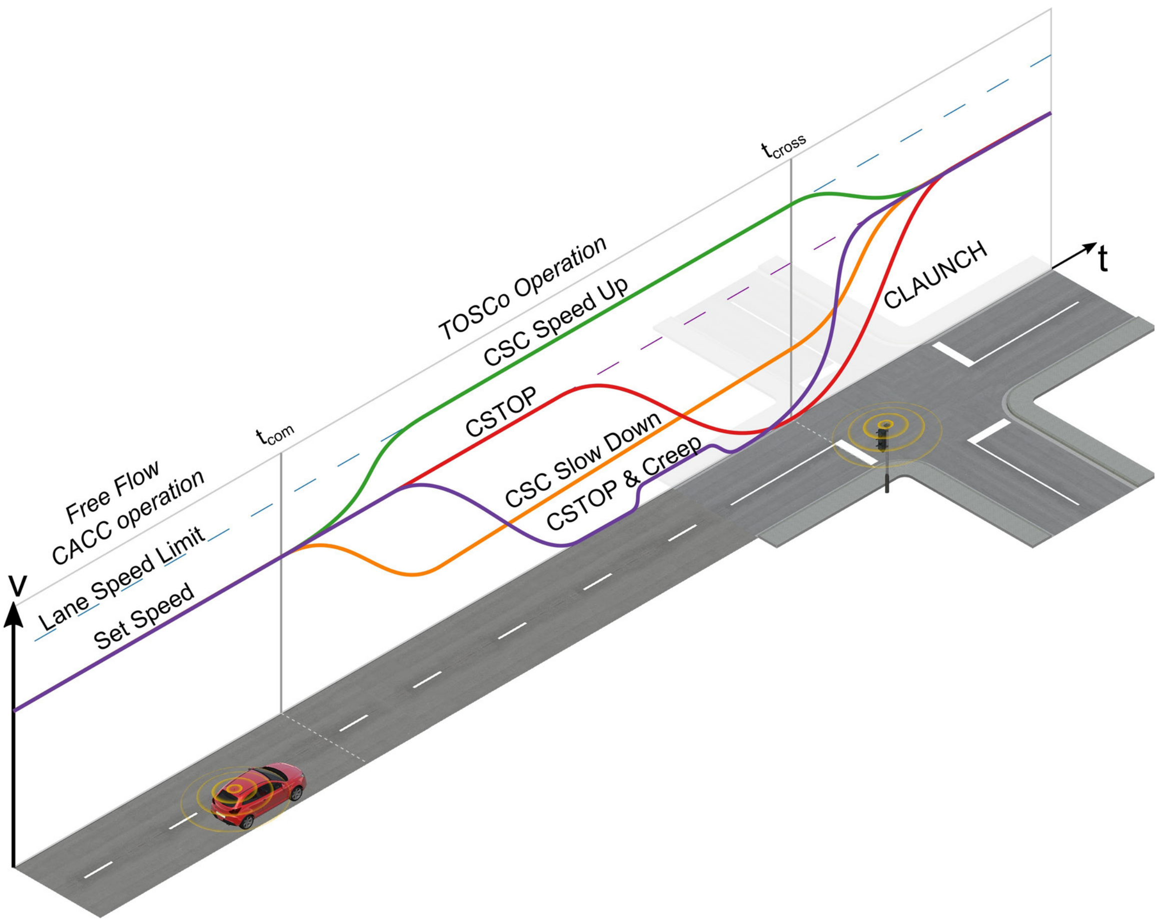
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 4: TOSCo Vehicle-level Simulation Workflow

A description of the key sections of the TOSCo Vehicle-level Simulation Report follows:

Section 2 TOSCo Vehicle-Level Simulation Report provides details of the vehicle-level simulation environment, and the development process.

Section 3.1 TOSCo Vehicle-Level Simulation Report provides details of the possible TOSCo operating modes summarized in Figure 5 below.



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

Figure 5: TOSCo Operating Modes and Corresponding Idealized Speed Profiles

Section 3.2 of TOSCo Vehicle-Level Simulation Report provides details of the generation of speed profiles.

Section 4 of the TOSCo Vehicle-Level Simulation Report provides details of the TOSCo vehicle-level simulation results for the following operating modes as show in Table 1:

Table 1: Vehicle Simulation Scenarios

Scenario Name	Section	Short Description and Purpose
Constant Speed Scenario	4.2	String of TOSCo-enabled vehicles is able to pass intersection without need for stopping or slowing down.
Speed-up Scenario	4.3	String of TOSCo-enabled vehicles has to speed up to pass intersection. String splits if not every vehicle is able to pass when speeding up.
Slow-down Scenario	4.4	String of TOSCo-enabled vehicles would arrive too early at stop location without slowing down during the approach.
Coordinated Stop and Launch Scenario	4.5	String of TOSCo-enabled vehicles has to come to a full stop. Upon green, all vehicles launch simultaneously.
Speed-up with Dissipating Queue at Intersection Scenario	4.6	String of TOSCo-enabled vehicles has to speed up to pass intersection at which a queue of non-equipped vehicles is discharging.
Slow-down with Dissipating Queue at Intersection Scenario	4.7	String of TOSCo-enabled vehicles would arrive too early at stop location without slowing down during the approach. String approaches a discharging queue at the intersection.
Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario	4.8	String of TOSCo-enabled vehicles has to come to a full stop. Upon green, all vehicles launch simultaneously. TOSCo-enabled vehicles thereby come to a stop behind a string of non-equipped vehicles.
Creep at Intersection Scenario	4.9	Vehicle is stopped and the preceding queue partially or fully dissipates, the vehicle creeps forward to close the distance gap between itself and its current target stop location in order to optimize the use of the roadway for large amounts of traffic.

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

Section 5 of the TOSCo Vehicle-Level Simulation Report summarizes the vehicle-level simulation work. The following key findings have been identified:

- The TOSCo algorithm is able to perform as specified in most of the simulation scenarios without the need of further modifications. In some specific cases, the expected behavior differs from the observation which is mainly caused by different initial velocities.
- In the Constant Speed Scenario, it is successfully demonstrated that the developed TOSCo system is able to create a constant speed profile and is able to transition to a *Coordinated Speed Control – Speed Up* TOSCo operating mode
- In the Speed-up Scenario, the developed TOSCo system is not only able to speed up vehicles in a string to pass the intersection but also to split up the vehicle string when it detects situations in which not all of the members of a vehicle string can pass the intersection in the current green window. It was also observed that in case of re-computations occurring while a vehicle is already decelerating, the current speed profile definitions are insufficient, as initial accelerations are not considered.
- In the Slow-down Scenario, as a vehicle enters the RSU communication range, the *Slow Down* operating mode is entered. The vehicles compute a time duration for which the predetermined target speed is maintained until the vehicles pass the intersection. Different

parameter variations resulted in successful deceleration of the TOSCo-string vehicles to a predetermined target speed to pass the intersection in the oncoming green window.

- In the Coordinated Stop and Launch Scenario, it is demonstrated that all vehicles within the TOSCo string are able to come to a full stop in case the pre-defined slow-down speed is insufficient to reach the oncoming green window, otherwise slowing down rather than coming to a full stop is preferred for reasons of traffic efficiency and energy consumption
- In the Speed-up with Dissipating Queue at Intersection Scenario, the developed TOSCo system successfully demonstrates the ability to operate in cases of a queue present at the intersection. It is shown that in case a queue is detected, the underlying CACC system can control the vehicle to deviate from its computed *best-case* trajectory.
- In the Slow-down with Dissipating Queue at Intersection Scenario, the introduction times of the vehicles were varied in order for the approaching TOSCo string to reach the end of a queue of non-TOSCo vehicles just at the moment the traffic light turns green and the queue dissipates
- In the Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario, it is demonstrated that all vehicles in the RSU communication range can come to a full stop when approaching the end of a queue of DSRC-only-equipped vehicles
- In the Creep at Intersection scenario, it is successfully demonstrated that the developed TOSCo system is able to stop the vehicles behind the end of a queue. In this scenario, the first non-TOSCo vehicle of the queue waiting at the intersection turns right on red, causing every other waiting vehicle to creep forward. It is shown that the transition to and from the creep mode in this scenario operates as intended.

Section 5 of the TOSCo Vehicle-Level Simulation Report also identifies several key work items that should be addressed before implementing the software in an actual vehicle environment:

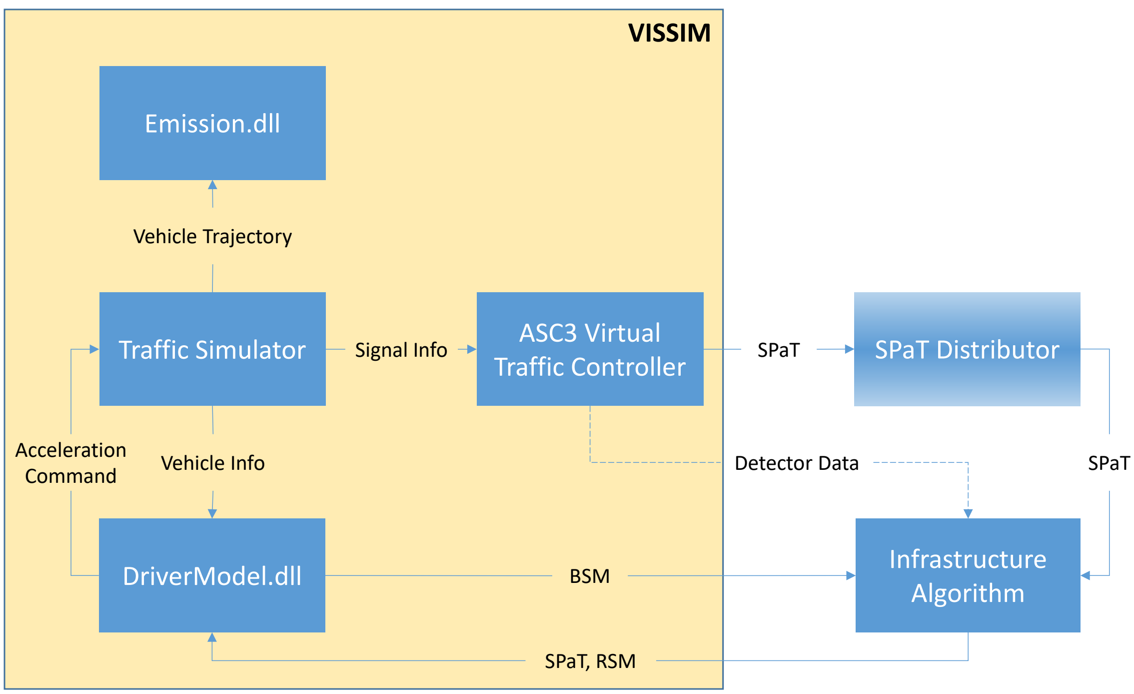
- **Speed Profile Definitions:** The specification of the speed profiles has to be revisited for cases in which the vehicle is currently decelerating when computing the optimized profile. The current definition does not take potential initial acceleration into account, resulting in undesirable behavior in case the vehicle is currently decelerating.
- **Mode Selection Refinements:** Future work should aim at revisiting the behavior of TOSCo vehicles, especially at low speeds. Due to increased difficulty of low-speed vehicle control, a real-life test will provide valuable insight into vehicle- and controller-behavior.
- **Simulation Environment Refinements:** Future work should aim at automating the simulation process. Due to the number of different interlinked simulation software and initialization steps that have to be performed manually, simulation runs tend to be time-consuming and error prone, especially when setting up the simulation environment for a particular run. Since very different simulation tools from different vendors run on the three simulation computers, an automation framework is not readily available.

2.1.2 TOSCo Infrastructure Simulation Environment

The project team also developed an infrastructure simulation environment to develop and verify the infrastructure components to be deployed as part of a TOSCo test deployment. Alongside the vehicle level simulation, the TOSCo infrastructure simulation environment was developed to model and evaluate infrastructure algorithm components needed for TOSCo deployments. The infrastructure simulation environment was also developed to assess how accuracy and latency associated with the infrastructure-based algorithms might impact performance of TOSCo-equipped vehicles. The project team is able to test varying levels of accuracy for measuring the current queue, predicted maximum queue, and the green window so implementors can more easily determine their capability to support TOSCo on a given corridor.

2.1.3 TOSCo Performance Assessment Environment

The project team developed the TOSCo Performance Assessment Environment to evaluate the potential mobility and environmental benefits associated with TOSCo. The TOSCo Performance Assessment Environment models TOSCo vehicles at a higher level, replicating the typical vehicle/string behavior and providing a simplified version of TOSCo vehicle-level simulation, in order to simulate hundreds of TOSCo vehicles. It is 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 and DSRC-enabled vehicles. Figure 6 below shows the architecture of the TOSCo performance assessment environment. Section 2.5 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details regarding the TOSCo performance assessment environment.



Source: University of Michigan Transportation Research Institute (UMTRI)

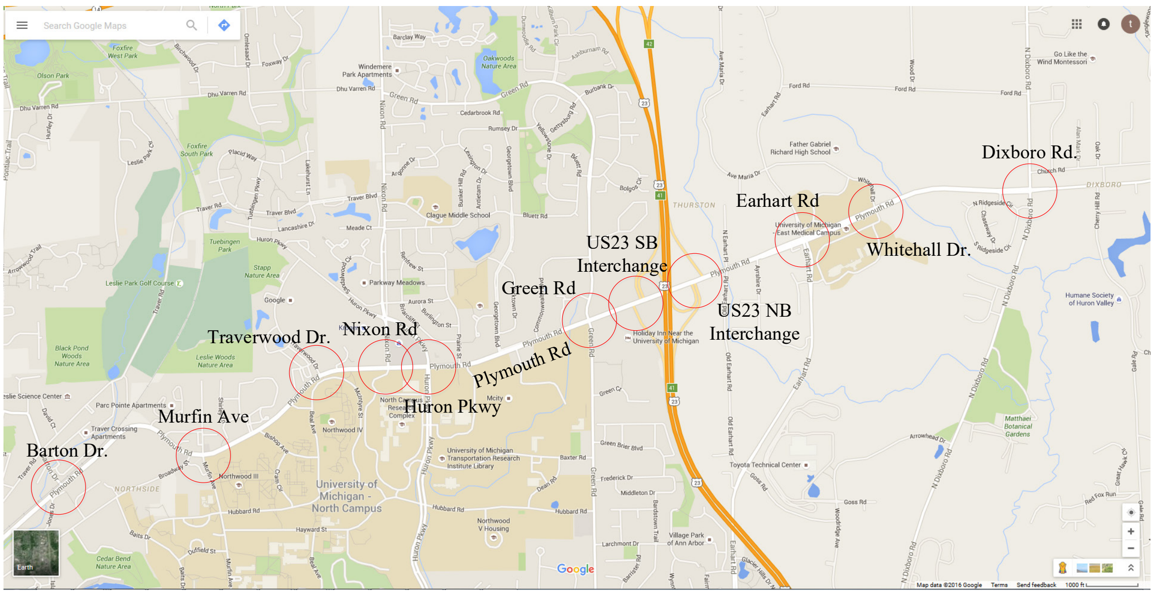
Figure 6: Performance Assessment Environment Architecture

2.2 Evaluation Corridors for TOSCo Development

The project team selected two corridors to evaluate the potential benefits to be derived from the TOSCo system, one low-speed corridor located in Ann Arbor, Michigan and one high-speed corridor located in Conroe, Texas. UMTRI was responsible for modeling the performance of the TOSCo system in the low-speed corridor while TTI was responsible for modeling the performance of the TOSCo system in the high-speed corridor.

2.2.1 Low-speed Corridor

The low-speed corridor (i.e., Plymouth Corridor) is located in Ann Arbor, Michigan and is shown in Figure 7 below. The corridor consists of 11 intersections from Barton Dr. on the west to Dixboro Rd. on the east. It includes nine arterial intersections and two free interchanges. The posted speed limits range from 35 mph on the west end to 50 mph to the east. Figure 7 shows the signalized intersections in the corridor. Section 3.1 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details regarding the low-speed corridor.

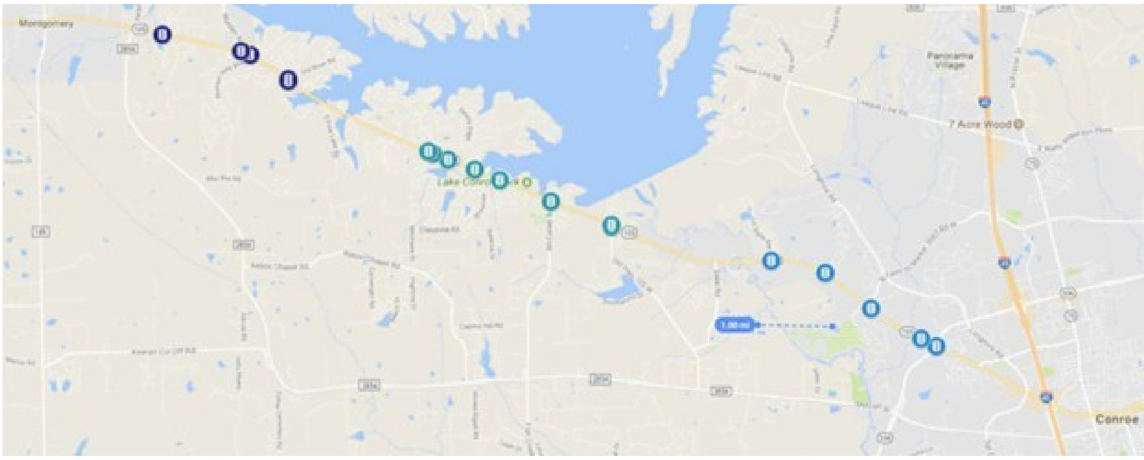


Source: Map data @2016 Google

Figure 7: Low-speed Corridor

2.2.2 High-speed Corridor

The corridor along SH-105 consists of 15 intersections between Montgomery, Texas and Conroe, Texas covering about 12 miles and is shown in Figure 8 below. The City of Conroe operates all the intersections on this length of SH-105. The posted speed limits range from 45 mph on the east end to 55 mph to the west. Most of the corridor has a posted speed of 55 mph. The easternmost quarter-mile has a posted speed limit of 45 mph. It takes about fifteen minutes to drive from one end of the corridor to the other. Section 3.2 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details regarding the high-speed corridor.



Source: Map data ©2018 Google

Figure 8: High-speed Corridor

2.3 Modeling Assumptions and Performance Metrics

The project team compared TOSCo vehicle behaviors at different TOSCo market penetration rates to a baseline to assess the potential benefits and impacts on mobility and fuel/emission performance. A common set of model assumptions and performance metrics were employed to perform the assessment on two separate corridors. Section 4 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details regarding the modeling assunptions and performance metrics used.

2.3.1 Common Modeling Assumptions and Parameters

Section 4.1 of the TOSCo Traffic-Level Simulation and Performance Analysis Report summarizes the parameters and coding assumptions the project team used. The modeling parameters and coding assumptions are divided into four categories listed below:

- Vehicle Model Parameters and Coding Assumptions – 16 items
- TOSCo String Model Parameters and Coding Assumptions – eight items
- Traffic Model Parameters and Coding Assumptions – five items
- Infrastructure Model Parameters and Coding Assumptions – five items

The assumptions and parameters differ at times from the intended vehicle algorithms to simplify the simulations. The project team only made simplifications that were not expected to significantly impact the traffic-level performance outcomes. TOSCo only operates on the through movement of major arterial. When TOSCo vehicles are planning trajectories, they only use information for the immediate downstream intersection. The minimum cruise speed threshold parameter regulates the minimum speed that a TOSCo vehicle can slow down to without stop. If the TOSCo vehicle cannot maintain the minimum cruise speed, it needs to plan a complete stop trajectory. A very low-cruise speed may be disruptive to other traffic and cause frequent lane changing and cut-in behaviors. In TOSCo speed control assumption, “exact follow” means when a TOSCo vehicle is under optimized follow operating mode, it can perfectly follow its leading vehicle without any delay in time or space. There is also no limit for maximum string size in simulation to simplify the problem.

One of the major assumptions for the originally proposed trajectory planning algorithm is that the vehicle can complete the entire transition stage from current speed to the target speed before it reaches the stop-bar. However, this condition does not always hold when a vehicle's current speed is low and close to the intersection. In such a case, the constraint on acceleration and deceleration limits lead to illogical accelerations so the project team coded a module for traffic simulation to check if the optimization problem is feasible prior to attempting to perform the speed profile. The vehicle uses the Verkehr In Städten – SIMulationsmodell (VISSIM) default car-following logic if the trajectory is not solvable.

For simulation purposes, the project team generated data on a per-vehicle basis that is consistent with data expected from field equipment capable of estimating queue length. Modules to calculate the queue length were created separately and treated as if they were to be deployed in the field. Details in Appendix B discusses the methodology the project team used to simulate how an infrastructure-based sensor system might measure queues is provided in Appendix B of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details of the high-speed corridor performance assessment.

The low-speed corridor utilized, information on the acceleration behavior recorded from DSRC vehicles in the field to produce a calibrated acceleration distribution for baseline traffic on Plymouth Rd. Acceleration data was not available for the high-speed corridor, so the project team used the default desired acceleration distribution provided in VISSIM for non-TOSCo vehicles which was later updated to an acceleration model that more accurately reflected actual traffic on the high=speed corridor.

Section 7.1 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details regarding the parameters used for the high-speed corridor.

2.3.2 Performance Measures

Section 4.2 of the TOSCo Traffic-Level Simulation and Performance Analysis Report describes the performance measures the project team defined to estimate the potential benefits of implementing TOSCo in arterial corridors. The performance measures are divided into mobility and fuel consumption/emissions categories.

For mobility performance measures, the project team defined total delay, stop delay, number of stops, average vehicle speed and total travel time.

For fuel consumption/emissions performance measures, the project team employed a simplified application of the U.S. Environmental Protection Agency's MOtor Vehicle Emission Simulator (MOVES) emissions modeling system [2]. In order to employ the MOVES model, two major procedures were needed; the first was acquiring the emission rate tables from MOVES and the second was developing the code to calculate the operating mode for each vehicle at each time step in the simulation. These procedures are detailed in section 4.2.2 of the TOSCo Traffic-Level Simulation and Performance Analysis Report.

2.4 Verification Scenarios Analysis

The project team (TTI and UMTRI) programed the TOSCo vehicle control logic into the DriverModel.DLL API used by VISSIM for the low-speed and high-speed corridors. To ensure that each team modeled the behavior of the TOSCo-equipped vehicles accurately, the research team identified the following eight vehicle scenarios which represented different situations that the TOSCo-equipped vehicles might encounter.

- Scenario 1: TOSCo string cruise without queue
- Scenario 1a: TOSCo string speed up to arrive at the green window as early as possible
- Scenario 2: TOSCo string speed up and split without queue
- Scenario 3: TOSCo string slow down without queue
- Scenario 4: TOSCo string stop without queue
- Scenario 5: TOSCo string speed up and split with queue
- Scenario 6: TOSCo string slow down with queue
- Scenario 7: TOSCo string stop with queue

Section 5 of the TOSCo Traffic-Level Simulation and Performance Analysis Report describes the detail results of the eight verification scenarios in terms of vehicle trajectory, speed profile, acceleration profile, and TOSCo operating state transitions.

2.5 Low-speed Corridor Performance Assessment

To reflect real-world driving behaviors and the operational environment in the low-speed corridor, UMTRI calibrated the vehicle acceleration profiles and DSRC communication range for the low-speed corridor using naturalistic driving data (NDD) from the Safety Pilot Model Deployment Project (SPMD) [1]. UMTRI selected 2,593 acceleration events on Plymouth Rd. from the NDD database to construct the acceleration distribution. Only the accelerations of the lead vehicle in a queue were selected because the preceding vehicle may affect the acceleration of the following vehicle.

UMTRI also calibrated the DSRC communication range from the same NDD database. To determine the communication range, UMTRI queried the database to determine when the RSUs at each intersection received BSMs from SPMD vehicles. Section 6.1 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides the communication ranges for each intersection along the low-speed corridor.

2.5.1 Low-speed Corridor Model Calibration

Section 6.2 of the TOSCo Traffic-Level Simulation and Performance Analysis Report describes the VISSIM model calibration process of the low-speed corridor. UMTRI calibrated the VISSIM model for the low-speed corridor using video data collected in the corridor and data from the SPMD Project

2.5.2 Low-speed Corridor Evaluation Scenarios Analysis

Section 6.3 of the TOSCo Traffic-Level Simulation and Performance Analysis Report describes the experimental setup for the evaluation scenarios of the low-speed corridor.

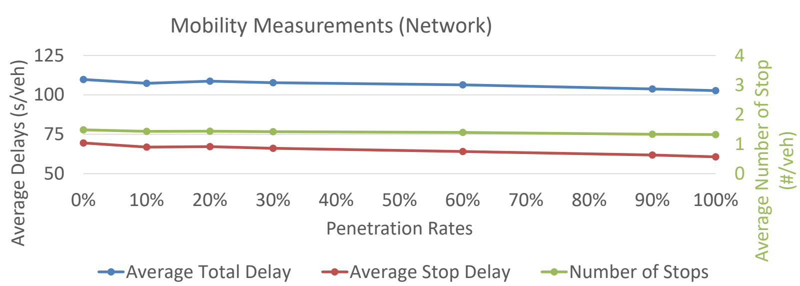
UMTRI assessed the performance of the TOSCo algorithm under two different implementation scenarios. The first scenario assumed two types of vehicles, TOSCo-equipped and non-TOSCo-equipped vehicles. Only TOSCo-equipped vehicles at each market penetration rate were equipped with DSRC radios and contributed information to the queue predication algorithm.

For the second scenario, the project team assumed three types of vehicles, DSRC-only equipped vehicles, TOSCo-equipped vehicles, and non-equipped vehicles. In this implementation scenario, only half of the vehicles at each market penetration level were TOSCo-equipped vehicles and the other half were DSRC-equipped vehicles. This meant that the DSRC-equipped vehicles could provide information to the queue prediction algorithm but were not capable of performing TOSCo functions.

Section 6.3 of the TOSCo Traffic-Level Simulation and Performance Analysis Report also presents very detailed simulation results and estimated benefits for the low-speed corridor.

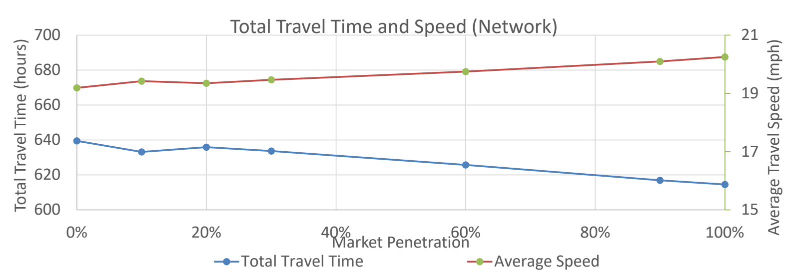
Results show that TOSCo brings both mobility (total delay, stop delay, number of stop and average speed) and environmental benefits (total energy, CO_2 emission, HC emission, and NOx emission), and the benefits increase as the TOSCo penetration rate increases. Section 6.5 presents a very detailed discussion of the results for the low-speed corridor.

Mobility measurements of the entire low-speed network are shown in Figure 9 and Figure 10 below. Figure 9 shows average total delay in seconds per vehicle, average stop delay in seconds per vehicle and number of stops per vehicle while Figure 10 shows total travel time in hours and average speed in miles per hour. Figure 9 illustrates a declining trend in all three mobility measures as TOSCo penetration increases. Figure 10 also illustrates a declining trend in total travel time and an increasing trend in average speed as TOSCo penetration increases.



Source: University of Michigan Transportation Research Institute (UMTRI)

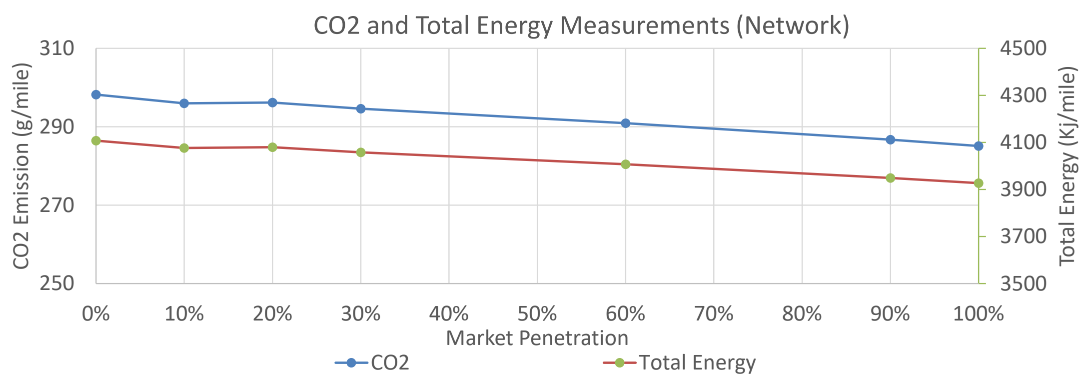
Figure 9: Low-speed Corridor Network Level Mobility Measurements



Source: University of Michigan Transportation Research Institute (UMTRI)

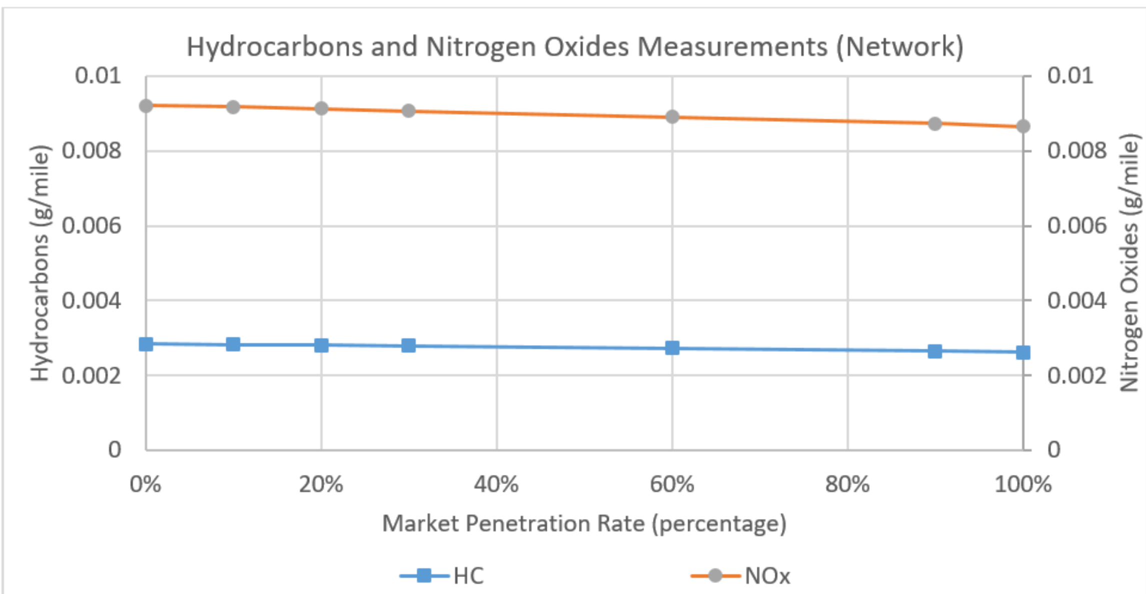
Figure 10: Low-speed Corridor Network Level Total Travel Time & Average Speed

Environmental measurements of the entire network are shown in Figure 11 and Figure 12 below. Figure 11 shows production CO_2 in grams per mile and total energy consumption in kilojoules per mile while Figure 12 shows hydrocarbon and NOx production in grams per mile. Figure 11 illustrates a declining trend in CO_2 production and total energy consumption as TOSCo penetration increases while Figure 12 illustrates a declining trend in hydrocarbon and NOx production as TOSCo penetration increases.



Source: University of Michigan Transportation Research Institute (UMTRI)

Figure 11: Low-speed Corridor Total Energy Consumption and CO_2 Production



Source: University of Michigan Transportation Research Institute (UMTRI)

Figure 12: Low-speed Corridor Hydrocarbon and NOx production

2.5.3 Low-speed Corridor Range Sensitivity Analysis

To analyze the impact of DSRC communication range, the project team assumed the maximum range of the DSRC communications for all intersections to be 300 meters, which is much shorter than the range from the NDD. To be consistent with previous assumptions, if the spacing between two intersections is less than 300 meters, the project team used the actual intersection spacing as the range. The results of the range sensitivity analysis suggest that benefits of TOSCo increases with DSRC communication range.

Section 6.4 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides a DSRC range sensitivity assessment of the low-speed corridor.

2.5.4 Network Cost Analysis for Low-speed Corridor

At the network level, not all vehicles travel through the entire corridor. The total average delay represents the average delay of all vehicles coming from different origins and going to different destinations. As a result, total travel time is used as the indicator for travel time cost calculation. Similarly, total miles traveled is used to calculate the fuel consumption cost. Table 2 shows the travel time cost, fuel consumption cost and total cost of the network. Both travel time cost and fuel consumption cost decrease as TOSCo penetration rate increases. The total combined cost is reduced from $9,735 at 0% penetration to $9,367 at 100% penetration, for a decrease of 3.8%.

Section 6.6 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides a network cost analysis of the low-speed corridor.

Table 2: Low-speed Corridor Network Level Cost Analysis

Market Penetration Rate (Percent)	Total Energy (KJ/mi)	Total Miles Travel (veh-mi)	Total Fuel Cost ($)	Total Travel Time (veh-hr)	Total Travel Time Cost ($)	Total Cost ($)	Percent Change[1] (Percent)
0	4107.69	12285	1422.14	639.48	8313.28	9735.43	—
10	4081.35	12312	1416.16	633.20	8231.62	9647.78	-0.90
20	4079.88	12316	1416.11	635.92	8266.90	9683.01	-0.54
30	4058.13	12348	1412.25	633.68	8237.84	9650.09	-0.88
60	4007.23	12368	1396.80	625.74	8134.60	9531.41	-2.10
90	3949.45	12413	1381.70	616.93	8020.05	9401.75	-3.43
100	3927.35	12456	1378.71	614.51	7988.66	9367.37	-3.78

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

Source: University of Michigan Transportation Research Institute (UMTRI)

2.6 High-speed Corridor Performance Assessment

The project team also developed a simulation model to evaluate the potential impacts and benefits of the TOSCo system in a high-speed corridor. The high-speed corridor used many of the same simulation parameters as the low-speed corridor. The project team initially focused specifically on the AM peak period for the assessment to ensure that all intersections operated in an under-saturated condition, however, in a subsequent reassessment and refinement effort detailed in Section 6.2.7 of the Traffic-Level Simulation and Performance Analysis Report, the team considered both AM and PM peak periods.

The project team performed a corridor analysis using data from 15 intersections along the Texas State Highway (SH) 105 corridor. The corridor analysis used the same market penetration rates as the low-speed corridor. However, the infrastructure algorithm for the high-speed corridor does not distinguish between vehicles that are transmitting BSMs and those that are not. Therefore, the only relevant market penetration rate for the high-speed corridor is the TOSCo market penetration rate.

Section 6.2 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details of the high-speed corridor performance assessment.

2.6.1 High-speed Corridor Model Calibration

The project team calibrated the SH 105 model based on traffic volumes at several locations along the corridor and travel times in both directions on the corridor. The project team collected volume and mobility data to characterize SH 105 for the traffic simulation. The calibration involved placing data collection tools in the simulation to count the vehicles crossing the same locations as the tube counts and travel time measurements to record the travel times of vehicles traveling the same route as the travel time study. This calibration effort involved running the simulation and checking the difference between the performance measures and the field data.

Calibration started with the volumes known from the turning movement counts at each intersection serving as the input volumes for the model and a speed distribution around 55 mph. The research team adjusted volumes and speeds until the simulation results were within acceptable limits from the field data.

Section 6.2.2 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details regarding the calibration of the high-speed corridor.

2.6.2 High-speed Corridor Evaluation Scenarios Analysis

Section 6.2.3 of the Traffic-Level Simulation and Performance Analysis Report provides details regarding the simulation results from evaluation of a single intersection along the corridor while Section 6.2.5 presents a very detailed discussion of the results for the high-speed corridor. The revised corridor results will be added. The experimental setup is very similar to the setup for the low-speed corridor, using the same penetration rates and local traffic patterns and volumes. The differences in the experimental setup for the high-speed corridor are described below.

- The high-speed corridor uses signal timing from the City of Conroe to represent the SH 105 corridor
- The non-TOSCo vehicles initially used the VISSIM default acceleration profile The high-speed corridor analysis was accomplished using 18 random number seeds to obtain statistical significance between some of the scenario performance measures. The random seed determines the initial time in which vehicles are inserted into the simulation run. The high-speed corridor included truck volumes in the analysis to represent SH 105. The truck percentage on SH 105 in the AM peak is about 3% of the traffic.
- The Infrastructure algorithm used for the high-speed corridor analysis does not distinguish between DSRC-equipped and non-DSRC equipped vehicles. Therefore, the high-speed corridor analysis does not have differences between TOSCo and DSRC penetration rates.
- Each simulation run on SH 105 is 8100 simulation seconds, with a 900 second warm-up period and a 7200 simulation second data collection period

Initial results showed significant decreases in number of stops and stop delay per vehicle as TOSCo market penetration increases. Increased market penetration of TOSCo led to a limited increase in total delay and travel time, decrease in travel speeds, and virtually no impact on emissions. The limited change in emissions followed the changes and was consistent with the changes in speeds because MOVES uses the speed as one of the variables to estimate emissions.

2.6.3 High-speed Corridor Range Sensitivity Analysis

The project team assessed the DSRC range impacts by comparing the results from the analysis to another data set where the team limited the DSRC range to 300 meters for all intersections. The team also used one seed per DSRC range scenario.

The DSRC sensitivity analysis for the high-speed corridor shows that increased DSRC range does not consistently improve TOSCo function. Increased DSRC range tends to have worse performance than the 300-meter range at high market penetration. The research time attributes this to how the Infrastructure algorithm does not use a predicted queue length to determine a green window but the current queue length. This means that with increased DSRC range, TOSCo vehicles receive information that may not be relevant to the vehicle because the queue lengths might grow, or the signal actuation may gap out the side street while the TOSCo vehicle is approaching. Gap-out refers to the termination of a green phase due to an excessive time interval between the actuations of vehicles arriving on the green, so green may be served to a competing phase.

Section 6.2.4 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides a DSRC range sensitivity assessment of the low-speed corridor.

2.6.4 Network Cost Analysis for High-speed Corridor

The high-speed corridor utilized the same methodology for assessing the user costs at different market penetration rates as the low-speed corridor. However, the project team used $2.01 per gallon, which is the average fuel costs in Texas in December 2018 (*26*).

The user costs steadily increase between the baseline and the 100% market penetration rate up to about a $550 total user increase in costs. The increases are caused by increased travel time and the minimal changes in fuel costs with the evaluated version of TOSCo.

Section 6.2.6 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides a network cost analysis of the high-speed corridor.

Table 3: High-speed Corridor Network Level Cost Analysis

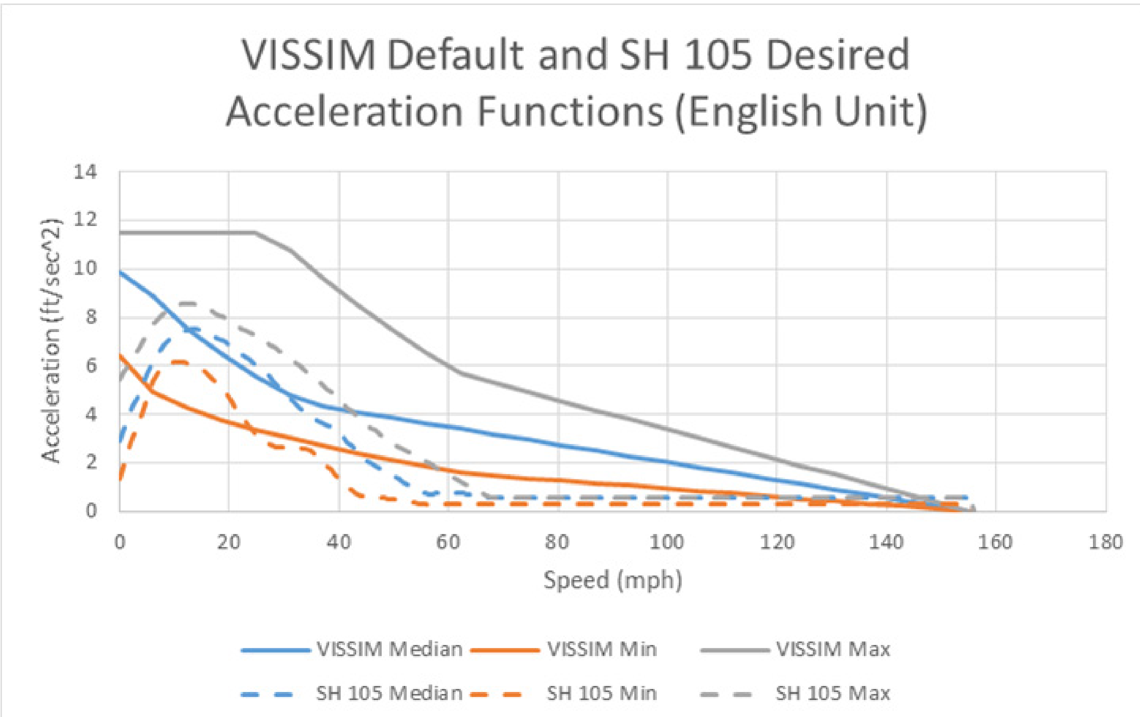
Penetration Rate	Value of Total Travel Time	Fuel Cost (Texas Gasoline Price, 2018)	Total User Costs
0	$ 12,858.15	$6,650.95	$ 19,509.10
10	$ 12,925.13	$6,601.89	$ 19,527.02
20	$ 12,987.86	$6,658.21	$ 19,646.07
30	$ 13,066.87	$6,740.56	$ 19,807.43
60	$ 13,192.81	$6,726.21	$ 19,919.02
90	$ 13,375.54	$6,663.22	$ 20,038.76
100	$ 13,447.03	$6,617.34	$ 20,064.37

Source: Texas A&M Transportation Institute (TTI)

2.6.5 Traffic-level Simulation Reassessments and Refinements

As part of the initial infrastructure simulations, the project team reevaluated some of the results and made refinements associated with the default acceleration profile governing vehicle behaviors by enhancing the representation of non-TOSCo vehicles on the high-speed corridor. Section 6.2.7 of the Traffic-Level Simulation and Performance Analysis Report provides details regarding the reassessments and refinements made and the accompanying results. To accomplish reassessment, the team designed an acceleration study to collect acceleration behaviors on the State Highway (SH) 105 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.

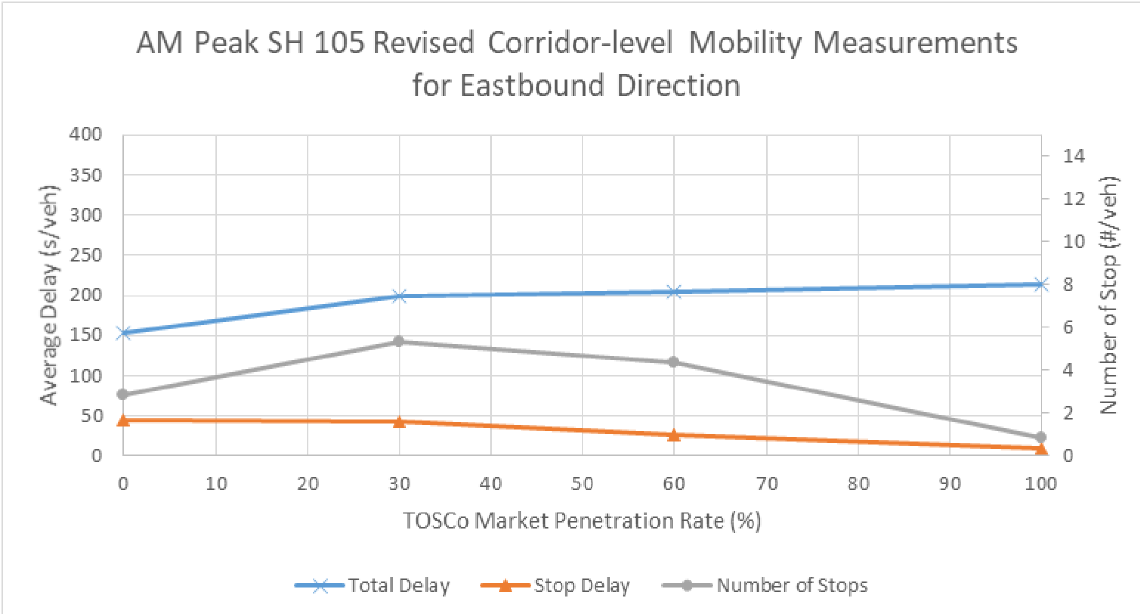
The acceleration study is detailed in Section 6.2.7.1 of the Traffic-Level Simulation and Performance Analysis Report, the results of which are shown in Figure 13.



Source: Texas A&M Transportation Institute (TTI)

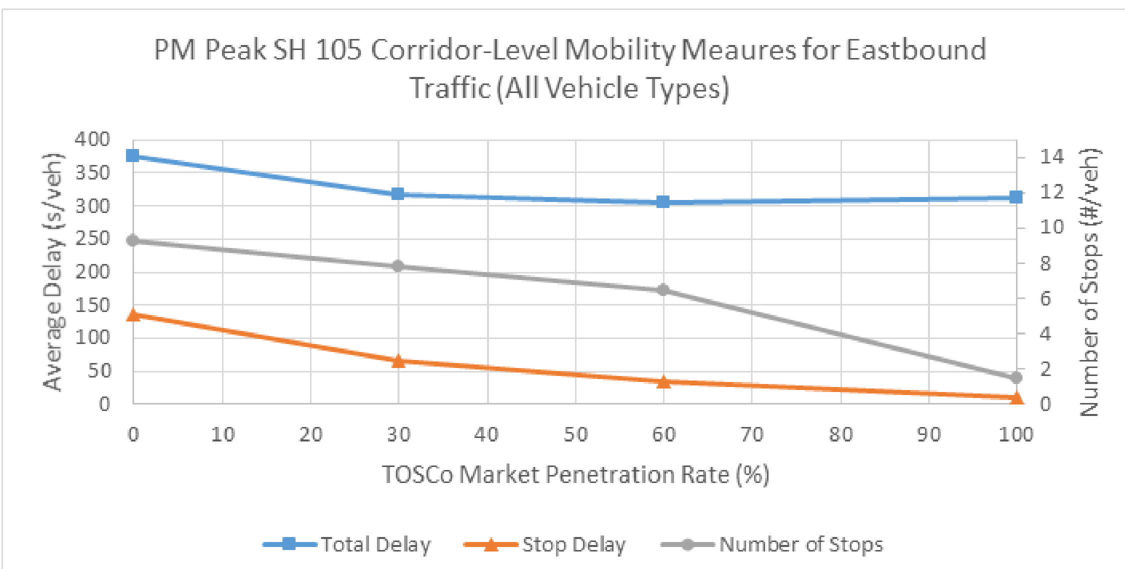
Figure 13: Acceleration Profile Calibrated from SH 105 Field Study

Based on the revised calibration of acceleration, the project team selected a reduced number of Market Penetration Rates (MPR) and simulation seeds to run to expedite the process. The team decided to use the baseline, 30, 60, and 100% TOSCo MPRs because previous simulation delay results were typically flat between these MPRs. Each scenario used the same parameters as before, with a 900 second warm-up period and a 7200 second evaluation period for each of the five simulation seeds in these refined results. The eastbound and westbound AM and PM peak revised results are shown in the figures below.



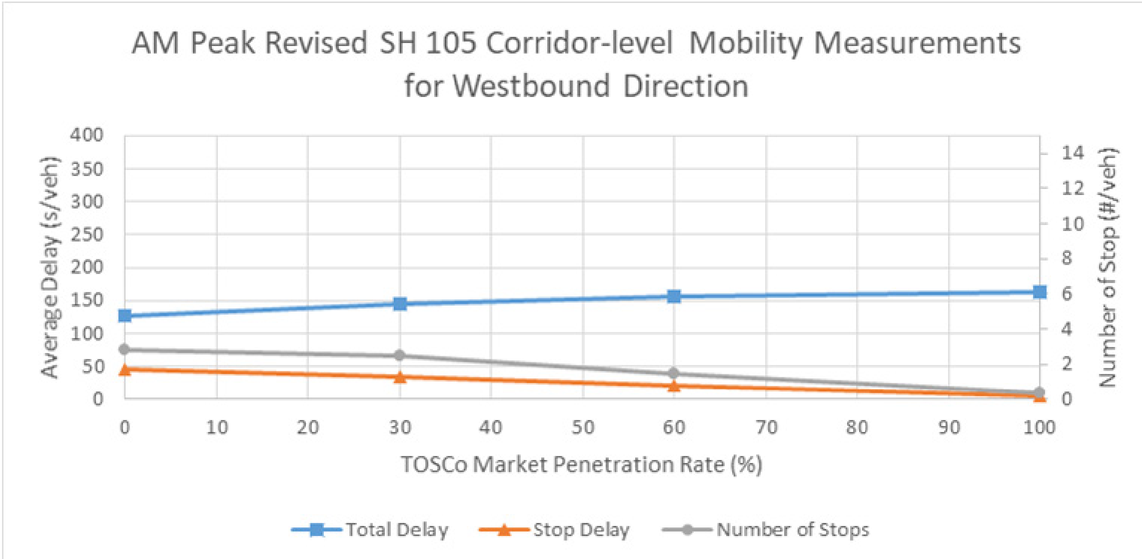
Source: Texas A&M Transportation Institute (TTI)

Figure 14: AM Peak Revised Corridor-Level Mobility Measures for SH 105 (Eastbound)—All Vehicle Types



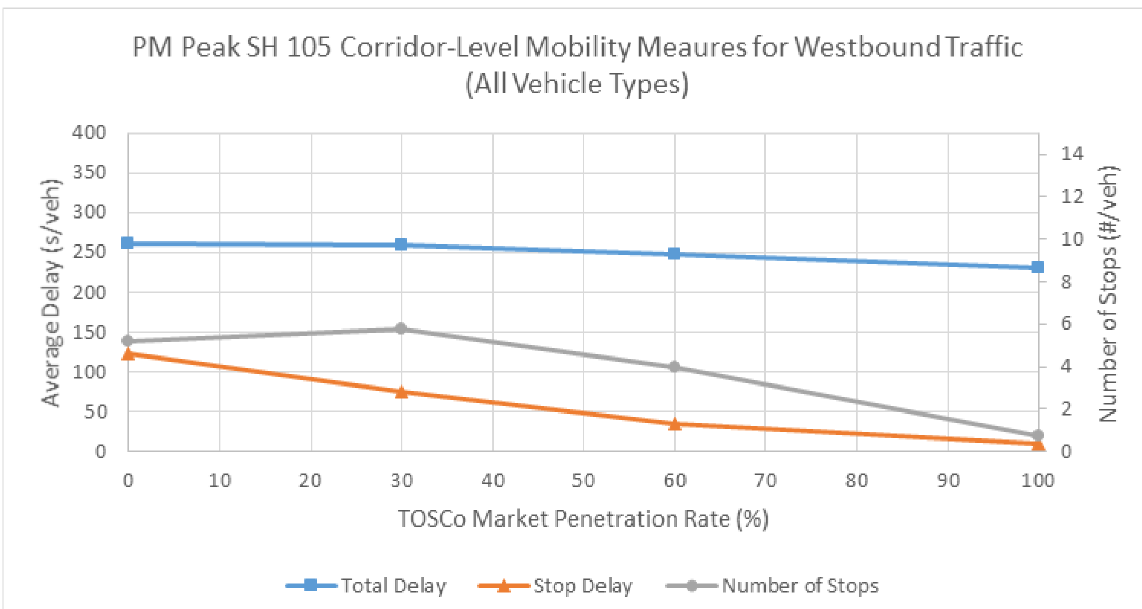
Source: Texas A&M Transportation Institute (TTI)

Figure 15: PM Peak Revised Corridor-Level Mobility Measures for SH 105 (Eastbound)—All Vehicle Types



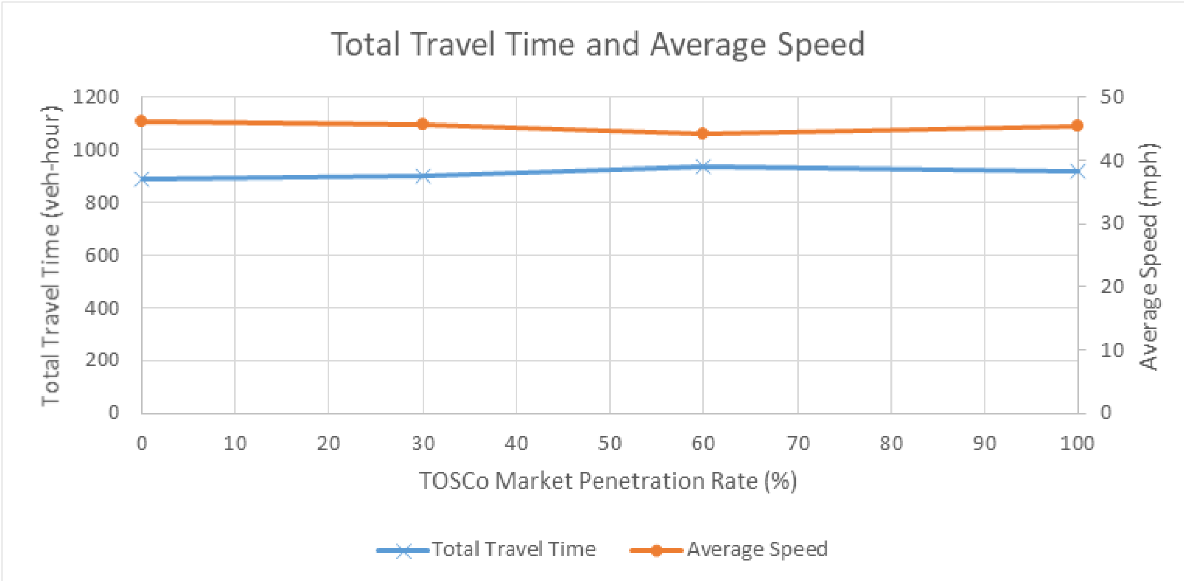
Source: Texas A&M Transportation Institute (TTI)

Figure 16: AM Peak Revised Corridor-Level Mobility Measures for SH 105 (Westbound)—All Vehicle Types



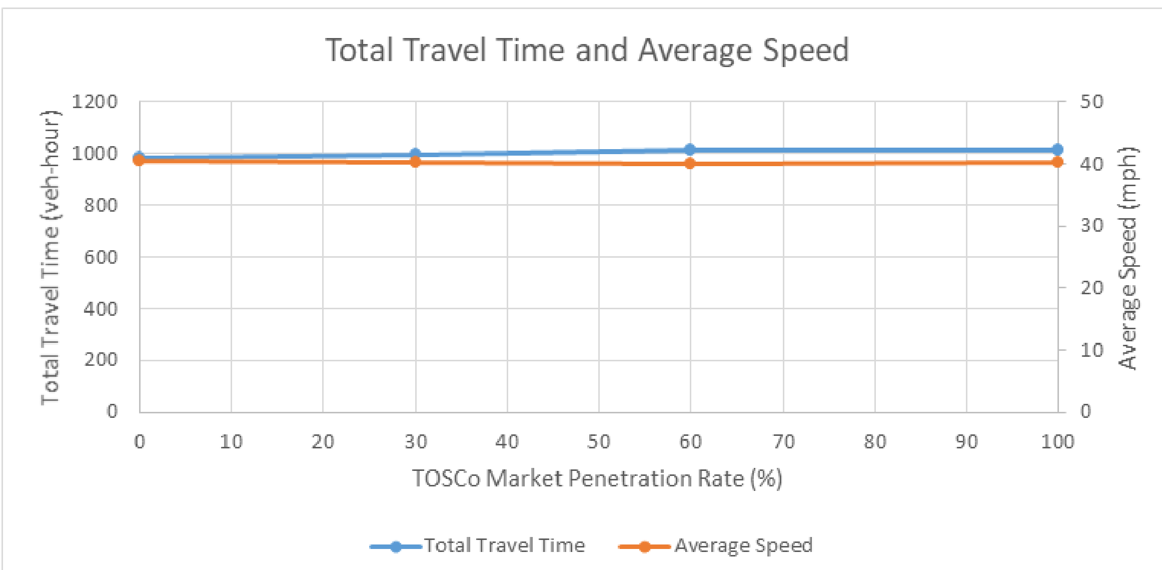
Source: Texas A&M Transportation Institute (TTI)

Figure 17: PM Peak Revised Corridor-Level Mobility Measures for SH 105 (Westbound)—All Vehicle Types



Source: Texas A&M Transportation Institute (TTI)

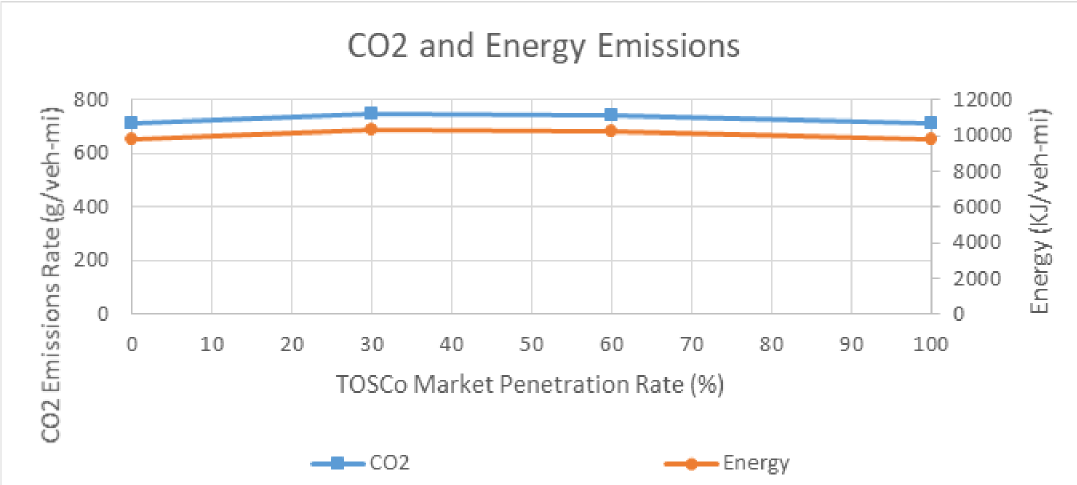
Figure 18: Total Vehicle Hours Traveled and Average Speeds for High-speed Corridor AM Peak Revision



Source: Texas A&M Transportation Institute (TTI)

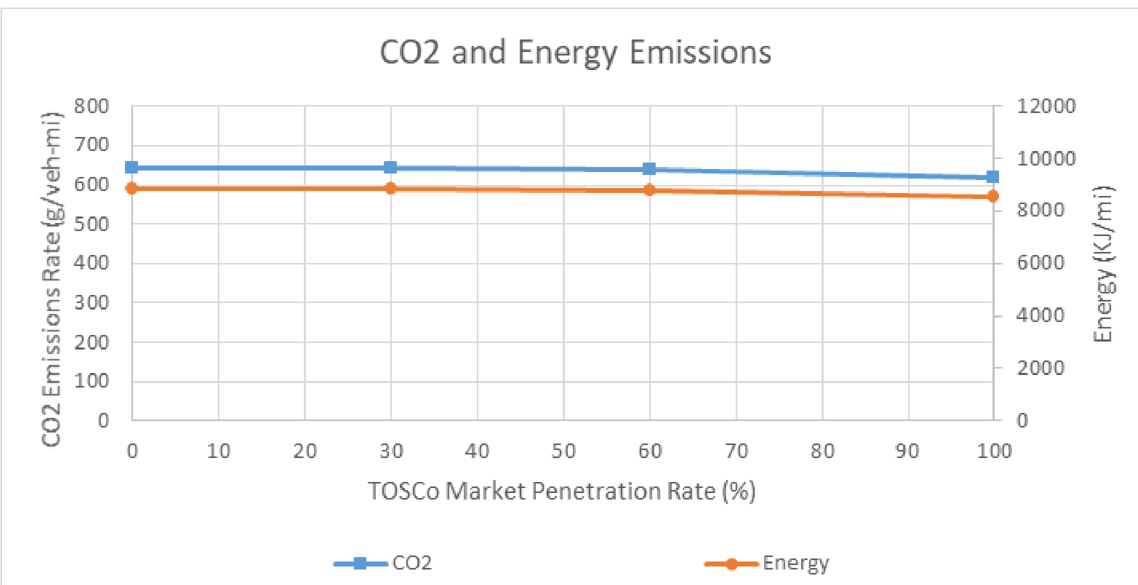
Figure 19: Total Vehicle Hours Traveled and Average Speeds for High-speed Corridor PM Peak Revision

Emissions results for the revised AM and PM peaks are shown in Figure 20 and Figure 21 below. Emissions and energy rates increase slightly in the 30% and 60% MPRs and return to values similar to the baseline at the 100% MPR scenario. These changes are likely caused by the increases in stops and the slight changes in average speed, since the MOVES model is very sensitive to changes in speeds. The team needs to investigate environmental impacts in the high-speed corridor further in future work.



Source: Texas A&M Transportation Institute (TTI)

Figure 20: CO_2 Emissions and Energy Usage Rates for High-speed Corridor AM Peak Revision



Source: Texas A&M Transportation Institute (TTI)

Figure 21: CO_2 Emissions and Energy Usage Rates for High-speed Corridor PM Peak Revision

2.7 Traffic-level Simulation Reassessments and Refinements Key Takeaways

The following are the key takeaways from the reassessment of the High-speed Corridor TOSCo simulation work:

- The research team developed a calibrated VISSIM acceleration profile for baseline traffic on SH 105 and recalibrated the model. Revised representation of baseline vehicles results in a better comparison between TOSCo vehicles and non-TOSCo vehicles.
- In the AM peak simulation with completely undersaturated conditions:
    - TOSCo reduces stop delays and the number of stops with slight increases in total delay. TOSCo vehicles experience more total delay because they take more time to reach their desired speed and will slow to the speed limit, if necessary, while in communication range of an intersection.
    - Total travel times and average speeds across the network had slight increases and decreases, respectively, as TOSCo penetration increased.
- In the PM peak, with some saturated conditions:
    - TOSCo vehicles have a greater degree of progression. (fewer stops and less time stopped) which reduces occurrence of saturation at intersection.
    - TOSCo reduces total delay, stop delay and number of stops. The increases in capacity from reduced headways in TOSCo strings are great enough to overcome the average increase in total delay by TOSCo operating behavior. Nearly all increases in capacity from TOSCo in the eastbound direction were attained by the 30% TOSCo MPR.
    - Total travel times and average speeds across the network had remained constant as TOSCo penetration increased. The speeds are referred to as constant since the changes are at most 3 mph on average, which is not considered a substantial change. A 3 mph change would amount to less than a 10 second change in travel time for the length of the corridor.
- The AM peak (unsaturated conditions) and PM peak (saturated conditions) experience slight increases and decreases in emission rates, respectively. These changes correspond to number of complete stops recorded by the simulation for the two periods. The team needs to investigate emission impacts further in future work.

Section 6.2.7 of the TOSCo Traffic-Level Simulation and Performance Analysis Report provides details of reassessment and refinement of the high-speed corridor simulations.

3 TOSCo Architecture and Algorithm Development

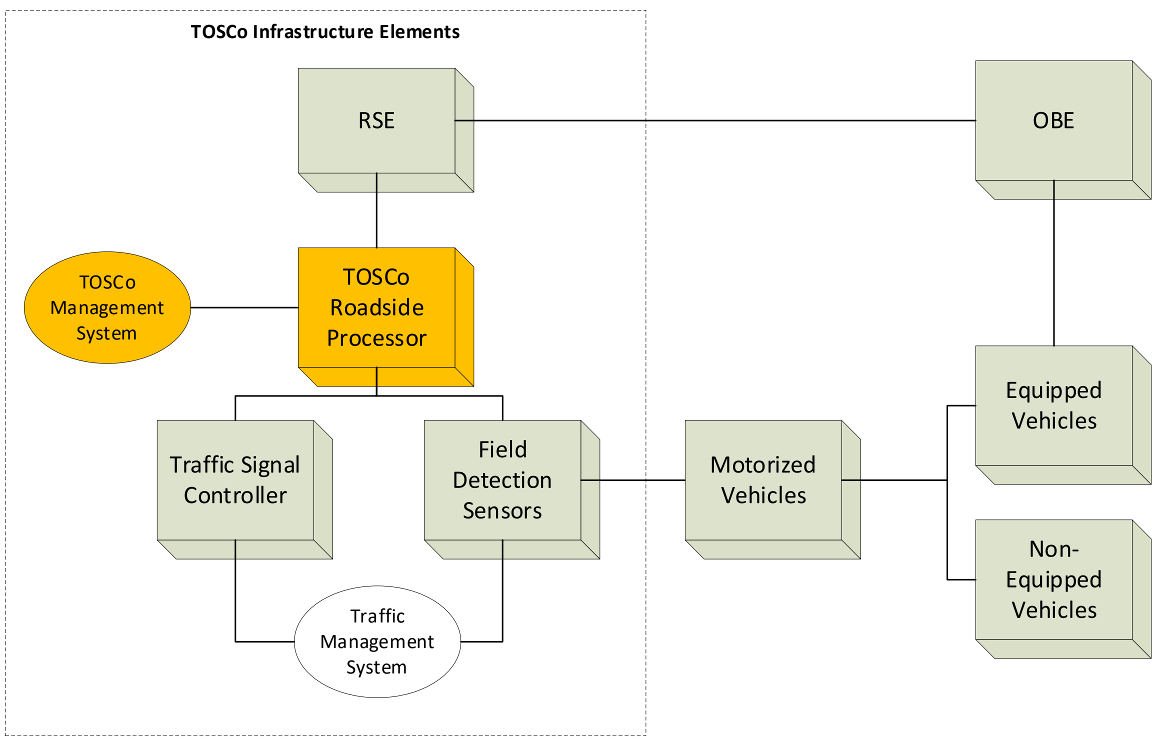
The Project Team developed detailed requirements and specifications for both the infrastructure-level and vehicle-level parts of the overall TOSCo system, which are described below.

3.1 Infrastructure System Architecture Specification

The infrastructure requirements are described in the TOSCo Infrastructure System Requirements and Architecture Specification.

3.1.1 Infrastructure Physical Components

Figure 17 below provides a block diagram of the physical components of the TOSCo System. The boxes represent a physical entity in the TOSCo system while the ovals represent systems or processes that manage and configure the physical components of the system.



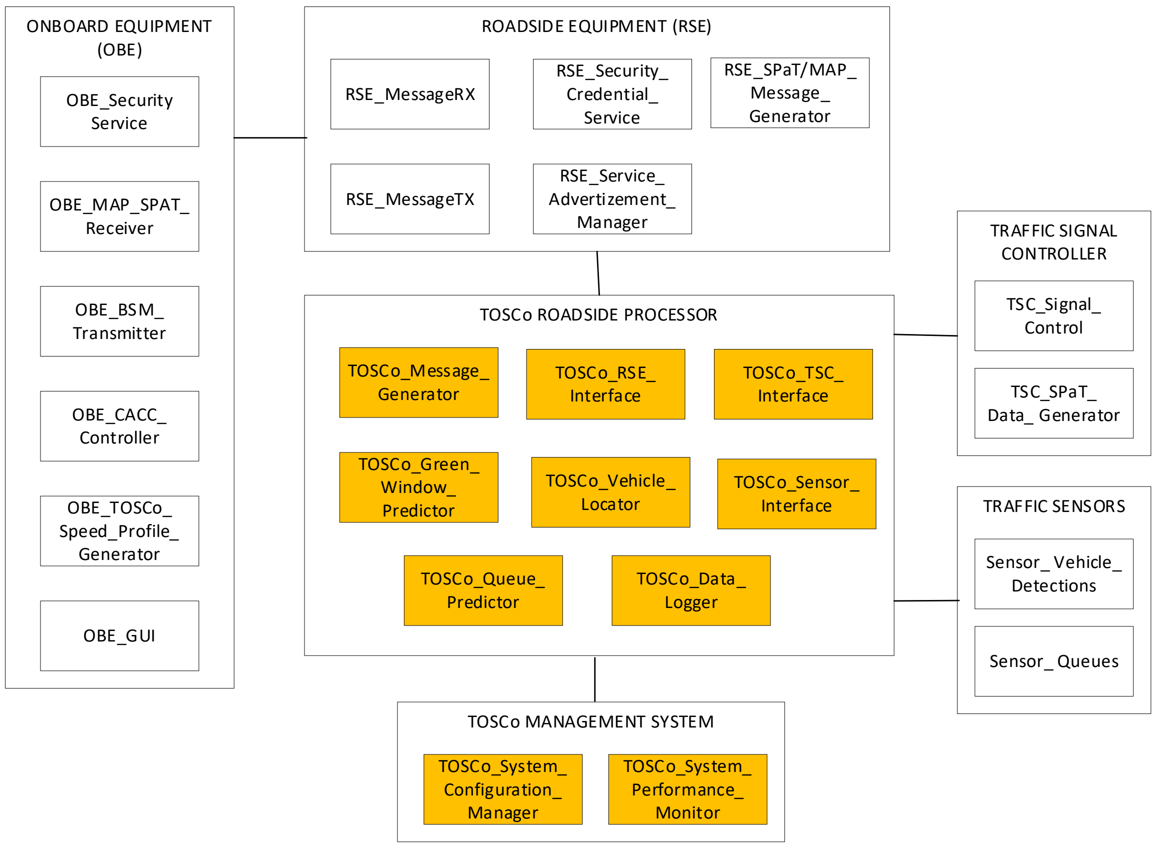
Source: Texas A&M Transportation Institute

Figure 22: TOSCo Physical Components

The purpose and functions of the physical components are described in detail in Section 2.2.1 of the TOSCo Infrastructure System Requirements and Architecture Specification.

3.1.2 Infrastructure Software Components

Figure 18 provides a block diagram of the software components of the TOSCo System. The blocks highlighted in yellow represent processes developed specifically for TOSCo.



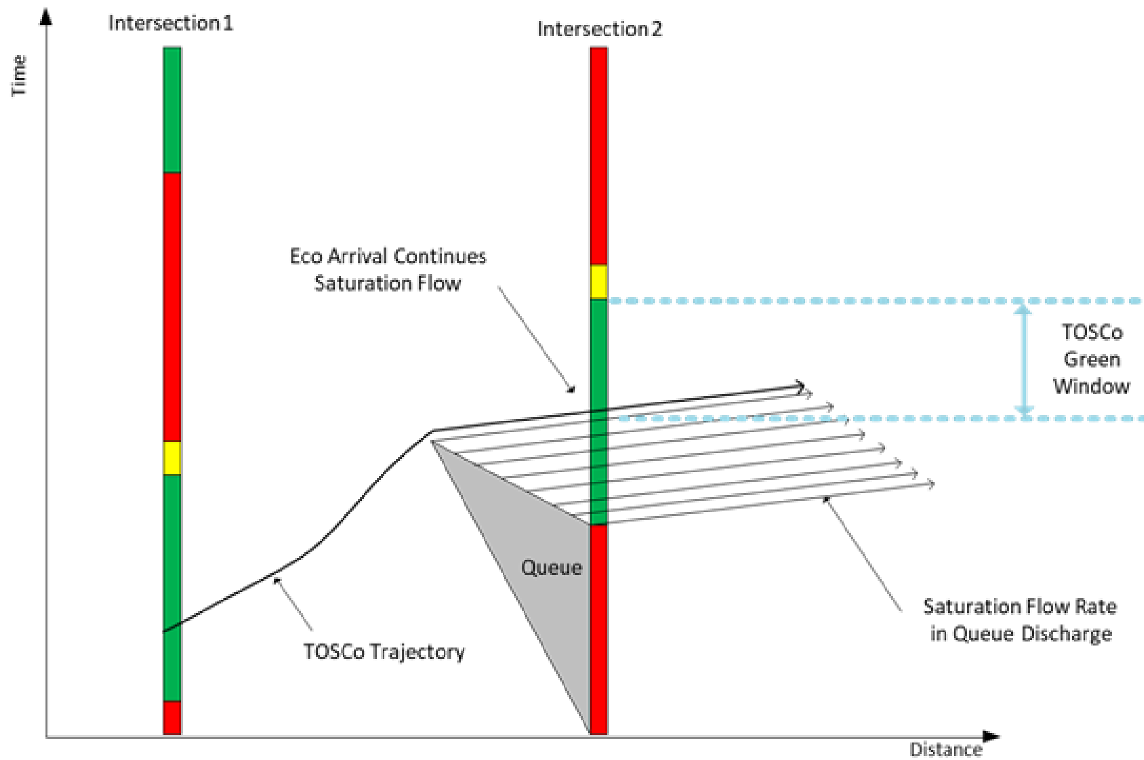
Source: Texas A&M Transportation Institute

Figure 23: TOSCo Infrastructure Software Components

The purpose and functions of each of the ten highlighted software components is described in detail in Section 2.2.2 of TOSCo Infrastructure System Requirements and Architecture Specification.

3.1.3 Infrastructure Processes

Section 3 of the TOSCo Infrastructure System Requirements and Architecture Specification provides descriptions of the main processes performed by the TOSCo infrastructure. These processes include the vehicle location process, the queue detection and predictions process, and the green window determination process. The concept of a green window is a cornerstone of the TOSCo system and defines the period of time in which a TOSCo-equipped vehicle can pass through a TOSCo-equipped intersection during the green phase. A visual representation of the green window is show in Figure 19 below.



Source: Texas A&M Transportation Institute

Figure 24: Green Window Definition

The queue detection and predictions process is divided into three separate approaches; infrastructure-only, shockwave profile model and combined infrastructure and input-output approach. Each approach is described in Section 3.2 of the TOSCo Infrastructure System Requirements and Architecture Specification.

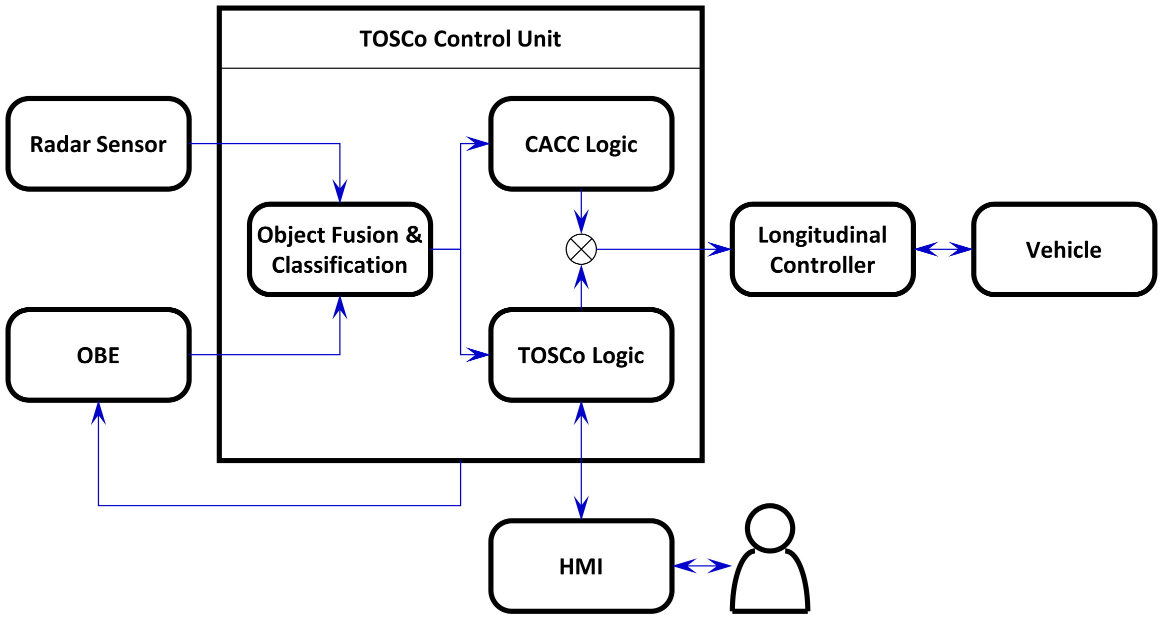
The process for determining the green window is described in the Section 3.3 of TOSCo Infrastructure System Requirements and Architecture Specification.

3.2 TOSCo Vehicle System Architecture Specification

The TOSCo vehicle system architecture is described in the TOSCo Vehicle System Requirements and Architecture Specification.

3.2.1 TOSCo Vehicle Architecture

A high-level representation of the in-vehicle architecture of the TOSCo system is depicted in Figure 20 below. Short descriptions of each component are provided below, but the reader is directed to Section 4.1 of the TOSCo Vehicle System Requirements and Architecture Specification for detailed descriptions.



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

Figure 25: TOSCo Vehicle System Block Diagram

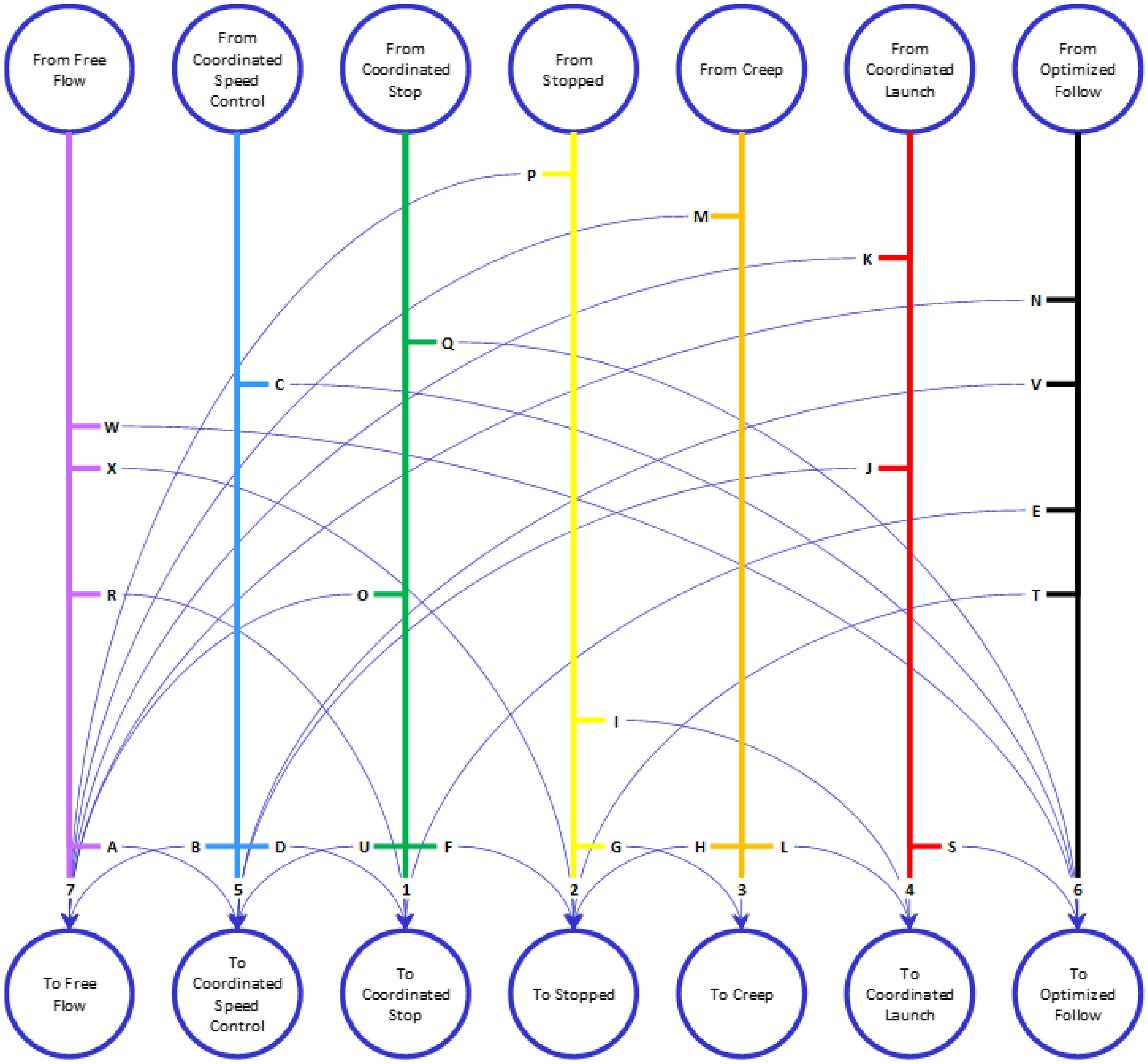
- Radar Sensor
    - The TOSCo vehicle system employs the radar sensor to detect preceding vehicles. The TOSCo system utilizes the object list provided by the radar sensor to acquire a target object to be followed.
- OBE
    - The TOSCo-equipped vehicles employ the OBE to broadcast and receive BSMs to detect similarly equipped surrounding vehicles outside of the range of the radar sensor. TOSCo-equipped vehicles also employ the OBE to receive SPaT and MAP messages broadcast by TOSCo-equipped intersections.
- TOSCo Control Unit
    - The TOSCo Control Unit is the central computation unit that is comprised of the object fusion and classification, CACC logic and TOSCo logic modules that create the proper acceleration command to the longitudinal controller
- Longitudinal Controller
    - The longitudinal controller controls vehicle speed based on acceleration command input from the TOSCo control unit
- Human Machine Interface (HMI)
    - The HMI provides the interface necessary for the vehicle driver to interact with the TOSCo system, especially during Coordinated Launch and Creep operating modes

3.2.2 TOSCo Operating Modes

Seven operating modes are defined under TOSCo. Brief descriptions are provided below. More detailed descriptions can be found in Section 2 of the TOSCo Vehicle System Requirements and Architecture Specification.

- Free Flow
  - TOSCo-equipped vehicles operate in Free Flow (FF) mode when CACC and TOSCo are active, but they are not receiving SPaT and MAP messages. Under these circumstances, TOSCo-equipped vehicles operate in speed/gap control under CACC.
- Coordinated Speed Control
  - TOSCo-equipped Lead Vehicles (LV) enter this strategy when TOSCo is active, the LV is receiving SPaT and MAP messages from the nearest signalized intersection in the LV's path and there are no preceding vehicles in the path of the LV. LV speed range in Coordinated Speed Control mode is from a defined minimum in order to avoid inconveniencing unequipped surrounding traffic, to a maximum of the posted speed limit. During the course of operating under coordinated speed control, the TOSCo-equipped LV may 1) speed up (to the speed limit), 2) slow (to a defined minimum) or 3) maintain current speed.
- Coordinated Stop
  - TOSCo-equipped LVs enter this operating mode when after processing information from the SPaT and MAP messages the TOSCo-equipped LV determines that it will not pass through the intersection prior to the amber phase and come to a stop at the stop bar or end of a queue while meeting optimization objectives
- Stopped
  - TOSCo-equipped vehicles are stationary at the stop bar or in a queue. 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.
- Creep
  - TOSCo-equipped vehicles are allowed to creep forward toward the stop bar to fill gaps left by vehicles that turned during the red phase
- Coordinated Launch
  - TOSCo-equipped vehicles broadcast a coordinated launch message as it launches upon the signal transition to the green phase
- Optimized Follow
  - TOSCo-equipped vehicles operate predominately as a member of a string under CACC speed and gap control, but it also continually receives SPaT and MAP messages to calculate its optimized speed profile which could cause it to leave the string and become the TOSCo-equipped LV in a new string if the vehicle determines that remaining in the string will cause it to operate outside its range of optimized control

In addition to each TOSCo operating mode, Section 2 also provides details on the transitions from one operating mode to another that are allowed and not allowed in TOSCo. Figure 21 illustrates transitions that are allowed. Transitions that not allowed are described in Section 2.8.2 of the TOSCo Vehicle System Requirements and Architecture Specification. In all, there are 31 allowed transitions and 18 transitions that are not allowed.



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

Figure 26: Allowable TOSCo Transitions

3.2.3 Traffic Scenarios Encountered by TOSCo

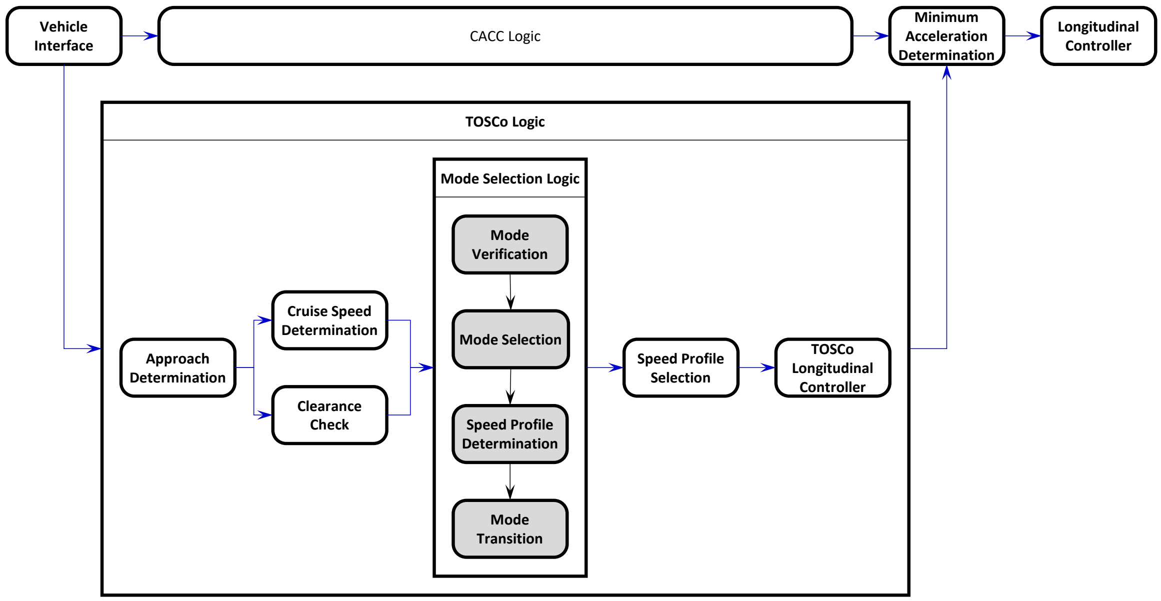
TOSCo-equipped vehicles can encounter a number of traffic scenarios that are detailed in Section 3 of the TOSCo Vehicle System Requirements and Architecture Specification where detailed graphical representations are available. The eight scenarios described in the section are:

- Constant Speed Intersection Crossing
    - TOSCo-equipped vehicles travel through an intersection at constant speed. The lead vehicle maintains constant speed through the intersection while vehicles in the TOSCo string maintain speed and time gap.

- Speed Up Intersection Crossing
    - TOSCo-equipped vehicles speed up in order to clear the intersection before the end of the current green window
- Slow Down Intersection Crossing
    - TOSCo-equipped vehicles slow down in order to pass the intersection's stop bar at the beginning of the green window
- Stop Scenario at Stop Bar
    - TOSCo-equipped vehicles come to a stop at the intersection. The lead vehicle stops at the stop bar. In the case of a string of TOSCo-equipped vehicles, the following vehicles come to a stop behind the preceding vehicle.
- Speed Up Intersection Crossing with Queue
    - TOSCo-equipped vehicles speed up in order to clear the intersection before the end of the current green window. However, the presence of a queue of vehicles that are currently stopped at the intersection may require the TOSCo-equipped vehicles to make additional speed profile adjustments.
- Slow Down Intersection Crossing with Queue
    - TOSCo-equipped vehicles slow down in order to pass the intersection's stop bar at the beginning of the green window. However, the presence of a queue of vehicles that are currently stopped at the intersection may require the TOSCo-equipped vehicles to make additional speed profile adjustments.
- Stop Scenario at Stop Location with Queue
    - TOSCo-equipped vehicles come to a stop at the intersection. The lead vehicle stops behind the last vehicle in a queue that is present. In the case of a string of TOSCo-equipped vehicles the following vehicles come to a stop behind the preceding vehicle.
- Creep Scenario to the Stop Bar
    - TOSCo-equipped vehicles come to stop behind a queue of vehicles present at the intersection. As the queue of vehicles progressively turn right, space in front of the TOSCo-equipped vehicle opens up, allowing the TOSCo-equipped vehicles to creep up to fill the gap created.

3.2.4 TOSCo Vehicle Algorithm Architecture

A high-level representation of the vehicle algorithm architecture of the TOSCo in-vehicle system is depicted in below in Figure 27. Short descriptions of each component are provided below but the reader is directed to Section 4.2 of the TOSCo Vehicle System Requirements and Architecture Specification for detailed descriptions.



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

Figure 27: TOSCo Vehicle Algorithm Architecture Block Diagram

The software components of the TOSCo control unit shown in Figure 22 are implemented using the Automotive Data and Time-Triggered Framework (ADTF) and runs on a Windows 7 embedded operating system. All software components are implemented in C++11, using MSVC10 compiler environments. Interaction with other software modules is realized by means of the ADTF message bus, TCP and UDP interfaces. The implemented software modules are split up into smaller stand-alone modules called “filters” within ADTF. Each filter defines its required input and provides manipulated or generated output data based on the implemented filter-criteria.

- Vehicle Interface
  - The vehicle interface filter is responsible for gathering all required input data for the TOSCo system by interacting with the vehicle’s Controller Area Network (CAN) bus, radar sensor and OBE
- CACC Logic
  - The CACC Logic was developed under a previous CAMP project. A detailed description and specification of this component can be found in Cooperative Adaptive Cruise Control Small-Scale Test (CACC-SST) Project Final Report[1] .The CACC Logic forms the basis of the TOSCo vehicle system and must be enabled in order for TOSCo to function.

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[1] Meier, J., Abuchaar, O, Abubakr, M., Adla, R., Ali, M., Bitar, G., Ibrahim, U., Kailas, A., Kelkar, P., Kumar, V., Moradi-Pari, E., Parikh, J., Rajab, S., Sakakida, M., Yamamoto, M. and Deering, R., Cooperative Adaptive Cruise Control Small-Scale Test (CACC-SST) Project Final Report, publication in process (2017).

- TOSCo Logic
    - The TOSCo logic is a parallel computation track alongside the CACC logic. TOSCo logic is active only when valid SPaT and MAP messages are available otherwise the TOSCo-equipped vehicle falls under CACC control.
- Approach Determination
    - This module compares input data timestamps to the current time to ensure input data contain valid timestamps. This module also provides a TOSCo Approach Clearance Flag that is used by subsequent modules for TOSCo system activation.
- Cruise Speed Determination
    - When TOSCo is active, the driver's cruise control set-speed is maintained as long as the TOSCo-equipped vehicle is under CACC-only control and a slower preceding vehicle is not present to cause the TOSCo-equipped vehicle to make adjustments to speed and/or gap. As soon as a vehicle receives valid TOSCo data from the infrastructure, the TOSCo-equipped vehicle will adjust speed to the posted speed limit. The Cruise Speed Determination module ensures that the cruise speed fed to the longitudinal controller can be adapted to the posted speed limit, when appropriate and when a TOSCo-enabled vehicle is following a TOSCo-generated speed profile.
- Clearance Check
    - This module checks if the driver provided confirmation to start moving when the vehicle is stopped, and it sets the Takeoff Clearance. Clearance is maintained for an adjustable duration before reverting clearance. In conjunction with the Approach Determination module, the Clearance Check module ensures that the TOSCo system may be activated.
- Mode Selection Logic
    - The TOSCo vehicle algorithm initiates specific actions depending on the TOSCo operating mode. The TOSCo Mode Selection Logic is responsible for selecting the appropriate operating mode with respect to the provided input data. A detailed description of the TOSCo Mode Selection is provided in Section 4.3 of the Vehicle System Requirements and Architecture Specification.
        - Mode Verification
            - Within the Mode Verification module, pre-checks before re-evaluating new TOSCo modes are performed. The output of this module is a flag to determine if the currently active mode and corresponding speed profiles are valid.
        - Mode Selection
            - If valid speed profiles were computed by the Mode Verification component, further computation within this module is skipped. Otherwise, the Mode Selection module determines if the STOP, CLAUNCH or CREEP mode needs to be entered. If any of these modes is selected, a corresponding speed profile is determined and passed on to the Speed Profile Determination module, otherwise, existing profiles will be marked as invalid.

        - Speed Profile Determination
            - This module is responsible for computing profiles for coordinated speed control and coordinated stopping modes and calculates new speed profiles in the event the current profile becomes invalid. If the previous module has already determined a valid speed profile, further computation is skipped.
        - Mode Transition
            - This optional module prevents the system from prematurely selecting a new operating mode. The previous steps of the system need to result in selecting the same operating mode for a configurable number of times before selecting the operating mode
    - Speed Profile Selection
        - A best- and worst-case speed profile is computed for every TOSCo operating mode requiring the generation of a speed profile. The best-case profile enables a vehicle to cross the stop location as early as possible (i.e., as close as possible to the start of the green window). This is in line with the fundamental concept of TOSCo to improve traffic efficiency by increasing the throughput at an intersection by means of clearing as many vehicles as possible. The worst-case profile enables a vehicle to just pass through the intersection as late as possible before the traffic signal transitions to yellow. The Speed Profile Selection module selects the default profile that is provided as an input to the TOSCo Longitudinal Controller, which is currently set to the best-case profile.
    - TOSCo Longitudinal Controller
        - This controller receives the reference speed and acceleration as well as distance error from the current speed profile and computes a corresponding desired acceleration to follow a selected speed profile. The controller consists of three separate control modules for distance, velocity and acceleration control.
        - Minimum Acceleration Determination
            - This module determines the most conservative acceleration value from all provided input values. When TOSCo is active, both CACC and TOSCo control logics compute acceleration values independently. The two values are compared, and the more conservative value is passed on to the Longitudinal Controller.
    - Longitudinal Controller
        - The Longitudinal Controller directly controls vehicle speed, taking input from the Minimum Acceleration Determination module and translating it to throttle control.

3.2.5 TOSCo Core: Mode Selection

The Mode Selection Logic component within the TOSCo software architecture represents the core of the TOSCo vehicle algorithm. It is responsible for selecting the appropriate operating mode with respect to the provided input data. Section 4.3 of the TOSCo Vehicle System Requirements and Architecture Specification Report details this component.

3.3 Requirements Needed to Enact TOSCo

TOSCo requirements are located in the following two documents:

- TOSCo Infrastructure System Requirements and Architecture Specification
- TOSCo Vehicle System Requirements and Architecture Specification

Specific locations of the requirements are identified in the following subsections.

3.3.1 Infrastructure Requirements

TOSCo Infrastructure requirements are described in Section 2.1 of the TOSCo Infrastructure System Requirements and Architecture Specification and in Section 5.2 of the TOSCo Vehicle System Requirements and Architecture Specification where descriptions of the following requirements are provided.

Transmission of SPaT/MAP

- Every intersection in a corridor defined as TOSCo-enabled shall transmit SPaT and MAP through DSRC
- Each intersection in the corridor shall transmit the Intersection ID and the approaching LaneIDs of the next downstream intersection in each direction
- The MAP message shall contain grade data for the approach to the current intersection

TOSCo Supported Locations

- TOSCo supported intersections shall be capable of broadcasting a flag indicating that the intersection supports TOSCo
- Each TOSCo supported approach at an intersection shall have the ability to measure actual queue lengths in real-time

Reception and Decoding of BSM

- The infrastructure shall be able to receive and decode the BSM (including the BSM extension which contains a flag indicating that a vehicle is TOSCo enabled)

Sensor Requirements for Queue Determination

- The infrastructure shall be equipped with vehicle detectors that provide lane-level traffic data such as volume and occupancy

Adjusting Signal Phase

- If appropriate, the infrastructure may use information from vehicles to adjust its signal phase (sequence) and timing parameters to accommodate TOSCo-equipped vehicles approaching the intersection

Generation and Transmission of Target Window Information for each Lane

- The infrastructure shall provide the TOSCo-equipped vehicle a target window of time

Generation and Transmission of Queue Information

- The infrastructure shall be able to provide approaching TOSCo-equipped vehicles with information related to the location of the queues present at the intersection.
- The infrastructure shall have the capability of providing queue information by lane for each approach to support TOSCo
- The infrastructure shall provide the TOSCo-equipped vehicle the current location of the back of the queue relative to the stop bar of the intersection
- The infrastructure shall be capable of fusing information from vehicle BSM data with information obtained from the infrastructure-based detection systems to determine the location of the back of queue

Advanced Traffic Signal Controller

- The traffic signal controller shall provide the TOSCo system with status of each phase at a frequency of 10 Hz
- The infrastructure shall have the capability of providing the time to change in phase state for each phase at a frequency of 10 Hz

Road-side Unit (RSU)

- Shall be able to:
    - Receive the signal data and broadcast in SAE J2735 SPaT format
    - Read a local map description file and broadcast in SAE J2735 MAP format
    - Receive, and decode, BSMs from connected vehicles (including TOSCo vehicles)
    - Make any received BSMs available to the TOSCo System
    - Broadcast customized DSRC messages (e.g., SPaT regional extension)

Road-side Processor (RSP)

- RSP shall be able to estimate queue length and calculate green window based on received BSM

3.3.2 Vehicle Requirements

TOSCo vehicle requirements are described in Section 5.1 of the TOSCo Vehicle System Requirements and Architecture Specification. TOSCo-equipped vehicles shall comply with performance requirements defined in the CACC Project. The vehicle shall use the more conservative acceleration command. The TOSCo/CACC state data element shall be set to the current state that the longitudinal control system is operating in (enumeration shall cover both CACC and TOSCo states).

The TOSCo-equipped vehicle shall be capable of:

- Receiving and decoding SPaT
- Receiving and decoding MAP

- Decoding BSM with TOSCo extension
- Tracking the information decoded from SPaT / MAP
- Matching the information decoded from SPaT / MAP
- Using message ID to differentiate intersections
- Using intersection ID to differentiate intersections
- Using MAP message to differentiate intersections
- Complying with MAP matching requirements
- Generating its own set of available speed profiles and determine which speed profile to follow (See Chapter 4)
- Generating traffic conditions data, such as queue formation, discharge rates
- Controlling brake when waiting at a red signal
- Controlling accelerator when it is necessary
- Adjusting speed profile to come to a stop
- Stopping without deactivating its ACC/CACC/TOSCo system
- Estimating its emission and fuel economy performance for its trajectory planning
- Following generated speed profile with a deviation of less than x.x% from acceleration/velocity/distance
- Determining vehicle performance (speed, acceleration, power-train currently out of scope) profile with the objective of promoting a time- and energy-efficient driving style that lowers vehicle emissions and fuel consumption
- Determining if it is the head of the string or within the string
- Sending a coordinated launch / stop flag to other vehicles in the string if it determines itself to be the head of the string and it is in either CSTOP or CLAUNCH
- Determining that the signal is about to transition to green
- Notifying the driver of an impending launch
- Notifying the driver that the vehicle will move forward while in a queue
- Providing means for driver to indicate readiness for launch
- Interpreting that the driver is ready for launch
- Notifying the driver to release brake during impeding launch
- Determining if vehicle speed is above a defined stationary speed threshold

3.3.3 TOSCo Messages

TOSCo message requirements include the BSM, SPaT and MAP messages described in SAE J2735.

4 TOSCo Hazard Analysis and System Specification

For the TOSCo Phase 1 Project, the project team brought ISO 26262 to bear in conducting a hazard analysis of the TOSCo system. A step-by-step framework was developed in accordance with the process defined in ISO 26262. The TOSCo Functional Safety Concept and Hazard Analysis Report provides a detailed summary and findings of the functional safety analysis. The report begins with a review of the TOSCo system and is followed by an introduction of the ISO 26262 functional safety process. The report then provides details on the work products listed below, focusing on the concept phase for automotive applications.

- Item definition (identify the TOSCo boundary and its intended features and functions)
- Hazard Analysis and Risk Assessment (HARA) (determination of safety goals and Automotive Safety Integrity Levels (ASILs)
- Functional safety concept (provide requirements for functional safety management, design and implementation)

The analysis did not cover product design and integration. The functional requirements focused on technical implementation into specific TOSCo components at a system level which can be utilized for subsequent integration and implementation.

4.1 Item Definition Process

The purpose of the item definition is to define and describe the TOSCo system, its dependencies on, and interaction with, the environment and other items. Also, the item definition is developed to provide an adequate understanding of the TOSCo system so that the activities in subsequent safety lifecycle phases can be performed. Within ISO 26262, "item" is a key term that is used to refer to a specific system or group of systems that implements a function at the vehicle level to which the ISO 26262 Safety Life Cycle is applied. The "item" is the highest identified object in the process, making it the starting point for product-specific safety development as described in the standard. The purpose of the item definition is to define and describe the TOSCo system, its dependencies on, and interaction with, the environment and other items.

The TOSCo hazard analysis and risk assessment is carried out on the basis of the item definition, and the Functional Safety Concept is derived from the definition. Section 4 of the TOSCo Functional Safety Concept and Hazard Analysis Report provides a detailed summary of the item definition process. Three key elements that make up the item definition process for the TOSCo system are highlighted in the following sections.

4.1.1 Definition of the TOSCo Boundary and Its Interaction with Other Components

Four TOSCo elements, where failure would result in a hazardous condition, were identified, RSE, OBE, TOSCo Algorithm, and Longitudinal Controller, and are detailed in Section 4.1 of the TOSCo Functional Safety Concept and Hazard Analysis Report.

4.1.2 Definition of TOSCo Functions

Nine primary functions were identified for the TOSCo system and are described in detail in Section 4.2 of the TOSCo Functional Safety Concept and Hazard Analysis Report.

4.1.3 Assumptions Regarding TOSCo Behavior

Eight key assumptions of TOSCo behavior were made and are listed in Section 4.3 of the TOSCo Functional Safety Concept and Hazard Analysis Report.

4.2 Hazard Analysis Development Process

Section 5 of the TOSCo Functional Safety Concept and Hazard Analysis Report provides detailed coverage of the hazard analysis development process. The hazard analysis identifies and categorizes the potential vehicle-level hazards due to a malfunctioning behavior of TOSCo and is also used to formulate the safety goals related to the prevention or mitigation of the hazardous events in order to avoid unreasonable risk.

Under this process, the project team evaluated the TOSCo system with regard to its potential hazardous events and developed safety goals and their assigned Automotive Safety Integrity Level (ASIL) by a systematic evaluation of hazardous events. The ASIL is determined by considering the estimate of the impact factors, i.e., severity, probability of exposure and controllability. The project team undertook the following three key tasks that comprise a hazard analysis and risk assessment.

4.2.1 Hazard Analysis Operability (HAZOP) Study and Identification of Hazards

The project team used the primary functions from the item definition for the TOSCo system and the initial estimate of the malfunctions and hazards from the item definition to initiate a HAZOP study. Twenty-five malfunctions associated with the nine primary functions were identified. Section 5.1 of the TOSCo Functional Safety Concept and Hazard Analysis Report provides a detailed matrix of malfunctions that the project team identified. Section 5.1 of the TOSCo Functional Safety Concept and Hazard Analysis Report provides details on the HAZOP study. From these malfunctions, the project team identified the following four top-level hazards:

- Excessive Acceleration
- Insufficient Deceleration
- Insufficient Acceleration
- Excessive Deceleration

4.2.2 Risk Assessment of Hazardous Events

The project team next undertook a Hazard Analysis and Risk Assessment (HARA) of the four identified hazards to develop a set of specific hazardous events and assess the risk of each hazardous event to determine the ASIL and safety goal. Fifty-four different safety critical scenarios and events were identified and documented. Section 5.2 of the TOSCo Functional Safety Concept and Hazard Analysis Report provides details on the HARA.

4.2.3 Safety Goals and Safe States

After completion of the HARA, the project team produced a set of safety goals and safe states to ensure safe operation of the TOSCo system. Section 5.3 of the TOSCo Functional Safety Concept and Hazard Analysis Report identifies the following safety goals and safe states for each of the four top-level hazards.

Table 4: TOSCo Hazards, Safety Goals and Associated ASILs

SAFETY GOAL ID	ASSOCIATED HAZARD	SAFETY GOAL TITLE	SAFE STATE	HIGHSEST ASIL
SG01	Excessive Acceleration	Prevent Excessive Acceleration due to malfunctions in TOSCo	Disable TOSCo operation	C
SG02	Insufficient Deceleration	Prevent Insufficient Deceleration due to malfunctions in TOSCo	Disable TOSCo operation	C
SG03	Excessive Deceleration	Prevent Excessive Deceleration due to malfunctions in TOSCo	Disable TOSCo operation	B
SG04	Insufficient Acceleration	Prevent Insufficient Acceleration due to malfunctions in TOSCo	NA	QM

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

It should be noted that this HARA (and its results) is only meant for research purposes. It is not intended to drive development of a TOSCo system (or similar) in any series production vehicles in the present or in the future.

4.3 Functional Safety Concept

The project team next used the functional safety goals to derive the functional safety requirements under a functional safety concept and allocated the requirements to the preliminary architectural elements of the TOSCo system, or to external measures. The functional safety concept addressed the following elements.

- Fault detection and failure mitigation
- Transitioning to a safe state
- Fault tolerance mechanisms, which ensure that a fault does not lead directly to the violation of the safety goal(s) and which maintain the item in a safe state (with or without degradation)
- Fault detection and driver warning in order to reduce the risk exposure time to an acceptable interval (e.g., engine malfunction indicator lamp, ABS fault warning lamp)
- Arbitration logic to select the most appropriate control request from multiple requests generated simultaneously by different functions

Section 6 of the TOSCo Functional Safety Concept and Hazard Analysis Report provides details on the functional safety concept for TOSCo.

4.3.1 Safety Strategy

Section 6.1.1 of the TOSCo Functional Safety Concept and Hazard Analysis Report identifies the inputs that can cause the TOSCo system to cause incorrect longitudinal acceleration. The inputs identified are SPaT, MAP, RADAR or fused objects, BSM objects, GPS signal, vehicle speed, TOSCo activation button, driver confirmation and vehicle drivetrain status.

4.3.2 Functional Safety Requirements

Section 6.1.2 of the TOSCo Functional Safety Concept and Hazard Analysis Report identifies the functional safety requirements that were identified and allocated to each of the five safety critical elements of the TOSCo system. Of the 46 safety requirements identified, four were assigned to the RSE, eight were assigned to the vehicle, 16 were assigned to the TOSCo controller, four were assigned to the OBE and 14 were assigned to the operating mode transitions within the TOSCo controller.

4.4 Fault Tree Analysis

The project team conducted a Fault Tree Analysis (FTA) to systematically evaluate potential failures in a design or process, identify effects of failure modes, including safety-related effects, classify failures based on their effects and/or risks and calculate/estimate probabilities of safety-related events.

Section 6.2 of the TOSCo Functional Safety Concept and Hazard Analysis Report details the FTA conducted for the top-level TOSCo hazard of excessive acceleration. The complete FTA for TOSCo would also include analyses for insufficient deceleration, excessive deceleration and insufficient acceleration.

4.5 Conclusions and Summary

The project team identified four top-level TOSCo hazards which underwent a thorough hazard analysis processes by looking at multiple vehicle operational situations. The Hazard classification methods of ISO 26262 were utilized to determine the ASIL level for each hazard, which resulted in creating safety goals or top-level safety requirements for the TOSCo system.

The project team also conducted an FTA of the overall TOSCo system for the case of excessive acceleration along with its external interfaces to verify the effectiveness of the safety mechanisms based on identified causes of faults and the effects of failures.

.

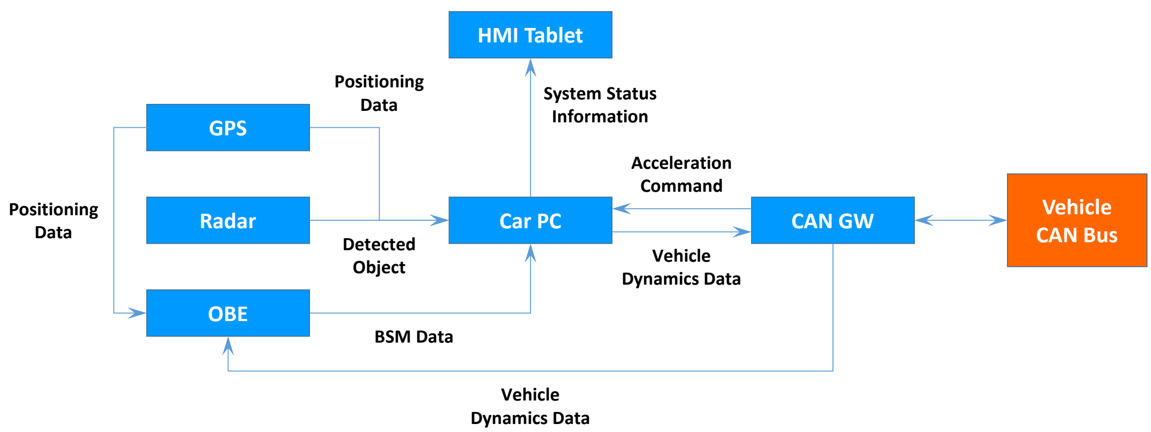
5 Implementation of CACC in Test Vehicles

The TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report documents the work completed in integrating a CACC system into four test vehicles as well as the corresponding testing to verify the performance of CACC relative to Adaptive Cruise Control (ACC).

Previous research was conducted in the Cooperative Adaptive Cruise Control – Small Scale Test (CACC-SST) Phase 1 Project. In the CACC-SST Project, the algorithm used in the CACC implementation was created along with respective simulations investigating the benefits of the CACC algorithm.

5.1 Introduction and Background

Four prototype CACC vehicles built under another project were re-purposed for this project. Section 1 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report provides details of the vehicles employed, along with the common vehicle architecture used to equip the vehicles. A high-level illustration of the hardware architecture is shown in Figure 28 below.



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

Figure 28: High-level Hardware Architecture for CACC

These vehicles were chosen to span the typical range of light vehicle size and mass and dynamic response characteristics. Different makes and models were chosen to span differences in longitudinal control system design. All vehicles contained production ACC systems capable of stop-and-go operation, which provided the base longitudinal control actuators needed to implement the experimental CACC or ACC (C/ACC) system.

To implement CACC, the OBE was modified to transmit and receive BSMs that included a CACC extension containing data elements that enhance the performance of CACC. Details are provided in Section 1.3 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

The project team developed a common Human/Machine Interface (HMI) for research purposes and was installed in each of the test vehicles. Details for the HMI are provided in Section 1.4 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

5.2 Test Description

The project team chose a set of simulation scenarios to better understand string stability and response time differences between the ACC and the CACC systems. Details are provided in Section 2 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

5.3 Data Collection and Post-Processing

Throughout each verification scenario, data was logged in a proprietary format using the CarPC installed on each test vehicle. The data collected was then post processed into a standardized format. The project team used proprietary software to generate and analyze plots Section 2.2 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report provides details of the data collection and processing that was conducted. The raw data was also exported as .csv file, at the request of FHWA.

5.3.1 Observations during Testing

Throughout vehicle build, testing, and demonstrations, the project team observed that one of the CACC-enabled vehicles had OEM-specific commanded acceleration limitations which resulted in the vehicle being unable to catch up with the other vehicles in the string. Therefore it was always positioned at the back of the string. This observation is reflected in the resultant data analysis. Other observations regarding object fusion and time synchronization are recorded in in Section 2.4 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

5.4 Verifying CACC Implementation

The project team focused on specific scenarios to verify the in-vehicle performance of the CACC system versus the experimental ACC system. The four scenarios are:

- Lane Change Detection – Cut Out, where the lead vehicle in a string of five vehicles with C/ACC activated has a lower set speed than the following vehicles. The lead vehicle then changes lanes, and the behavior of the remaining string of four vehicles is observed.
- Lane Change Detection – Cut In, where a string of four vehicles with C/ACC activated travels in a lane adjacent to a slower moving vehicle. Just before the string passes the slower moving vehicle, the vehicle cuts in front of the string, and the behavior of the four vehicle string is observed.
- Cut-In Maneuver, where a string of four vehicles with C/ACC activated travels in a lane adjacent to another vehicle. Compared to the other vehicles in the string, the second vehicle (the first CACC-equipped vehicle) has a larger time gap set between it and the preceding vehicle. These two vehicles are referred to as vehicles 0 and 2. A vehicle traveling in the

adjacent lane, referred to as vehicle 1, cuts in between vehicles 0 and 2 of the string. The behavior of the last three vehicles in the string is observed.

- Overtaking, where a string of four vehicles with C/ACC activated travel towards a vehicle in the same lane with a lower speed. The lead vehicle in the string makes a lane change to avoid the obstacle. The behavior of the remaining string of three vehicles is observed.

These scenarios focus on verifying the implementation of the CACC system with specific edge cases throughout the development of the system. To compare the performance of the CACC system versus the experimental ACC system, the stabilization time was examined. This is defined by the time elapsed between the time of the beginning of the maneuver and the time at which the velocity value of each vehicle reaches its respective target final speed value without significant fluctuation (+/- 5% of the range between the initial and final target velocities) was observed. Details for each of these scenarios are provided in Section 3 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

5.5 Comparative Data Analysis

The project team and the Volpe National Transportation Systems Center agreed upon the following string stability driving scenarios in which to perform a series of comparative tests between ACC and CACC. Details for each scenario are provided in Sections 4.2 through 4.4 and 7.6 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

- String Stability Scenario: 55 mph to 30 mph with Harsh Deceleration
- String Stability Scenario, 55 mph to Rolling Stop
- String Stability Scenario, 45 mph to 60 mph

String stability was chosen as the test metrics because it demonstrates the benefits of the use of DSRC to complement ACC. The project team then defined the following four Key Performance Indicators (KPIs) on which to base their analysis for each scenario. These KPIs require the string of vehicles to have been previously travelling in a steady C/ACC.

- Deceleration Response Delay
- Minimum Speed Value
- Time Gap Stability
- Relative Longitudinal Offset

Detailed descriptions of each KPI are provided in Section 4.1 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

A summary of the KPI results is tabulated in Section 7.1, and an extensive set of time series plots for these KPIs are contained in Section 7.2 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

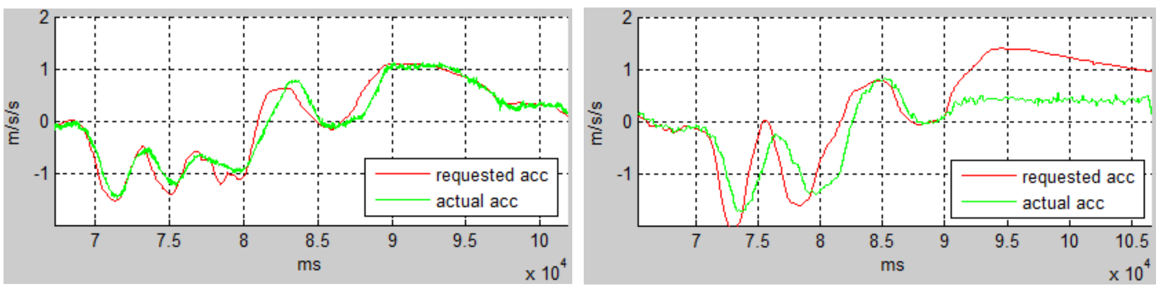
Aggregated plots of the String Stability Scenario, 55 mph to 30 mph (Moderate Deceleration), are contained in Section 7.3 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

Aggregated plots of the String Stability Scenario, 60 mph to 25 mph, are contained in Section 7.4 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

Aggregated plots of the String Stability Scenario, 55 mph to 30 mph (CACC with 0.6 Second Time Gap), are contained in Section 7.5 of the TOSCo Cooperative Adaptive Cruise Control (CACC) Build and Testing Report.

5.6 Conclusions

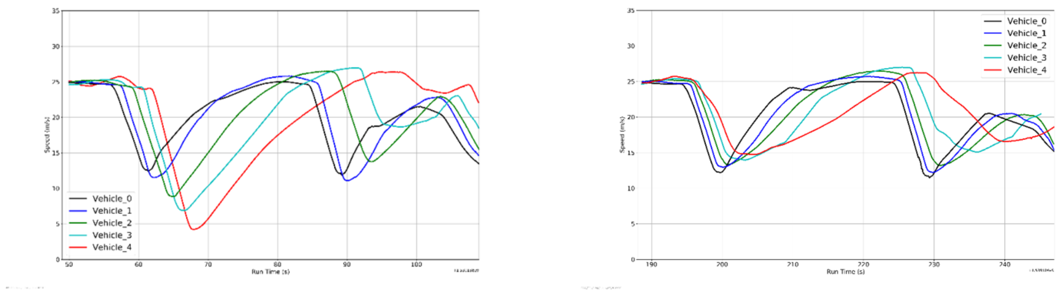
The project team observed significant differences in vehicle response during vehicle testing. On multiple occasions, it was observed that the string of vehicles would break up because some vehicles did not accelerate as fast as others. This occurred in typical driving scenarios that one would experience frequently while driving on a freeway. Data analysis indicated the cause of the observation was due to limitations in the production ACC calibration that was being used in some of the vehicles to control those vehicles. This is illustrated in Figure 29 below by comparing the requested acceleration generated by the prototype ACC system with the actual acceleration for two of the prototype ACC vehicles. The left plot shows an example where the requested acceleration closely follows the actual acceleration with a reasonable time lag. In the right plot, the requested acceleration is not followed after 91 seconds.



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

Figure 29: Vehicle Response to Acceleration Command

Figure 30 below illustrates the improvement in string stability with CACC when compared to ACC. In both cases, the vehicles decelerated from 55 mph to 30 mph. The graph on the left shows how the equipped vehicles under ACC control (vehicles 1, 2 and 3) respond to the harsh deceleration of vehicle 0 while the graph on the right shows how the equipped vehicles under CACC control (vehicles 1, 2 and 3) respond to the harsh deceleration of vehicle 0. The graph on the right (CACC control) demonstrates superior string stability when compared to the graph on the left (ACC control). Vehicle 4 in both graphs exhibited limitations in its ability to respond, whether under ACC or CACC control. This was an intentional limitation based on the design philosophy of the vehicle manufacturer in implementing a production ACC system and does not represent a limitation of the CACC controller. Based on the response of all four CACC vehicles in this project, it was observed that those vehicles with a minimum acceleration/deceleration capability of +1.0 m/s^2 to -3.5 m/s^2 were able to maintain the string.



ACC String Stability | CACC String Stability

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

Figure 30: Comparison of String Stability for ACC vs. CACC during Braking from 55 mph to 30 mph with Harsh Deceleration

Even with the observed limitations, CACC is expected to improve overall performance of the string through faster communication of the lead vehicle deceleration status or by predicting future actions thereby limiting necessary accelerations and decelerations. However, if closer vehicle following and minimizing string splits are desired for CACC, a more harmonized vehicle performance will be necessary. For CACC, it may be necessary to further specify minimum acceleration capabilities to ensure a more harmonized behavior. The project team did not explicitly focus on deriving minimum performance requirements for acceleration, but based on the response of all four CACC vehicles, it was observed that vehicles with a minimum acceleration/deceleration capability of $+1.0 m/s^2$ to $-3.5 m/s^2$ were able to maintain the string.

Given the value CACC has in maintaining string stability, it will be incorporated into the TOSCo Phase II Project.

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APPENDIX A. List of Acronyms

ACC	Adaptive Cruise Control
ADTF	Automotive Data and Time-triggered Framework
ASILs	Automotive Safety Integrity Levels
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAMP	Crash Avoidance Metrics Partners LLC
CAN	Controller Area Network
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
FF	Free Flow Mode
FHWA	Federal Highway Administration
FTA	Fault Tree Analysis
GPS	Global Positioning System
HARA	Hazard Analysis and Risk Assessment
HAZOP	Hazard Analysis Operability
HMI	Human Machine Interface
I2V	Infrastructure-to-Vehicle
ITS	Intelligent Transportation Systems
LV	Lead Vehicle
MAP	SAE J2735 Map Message
MOVES	MOtor Vehicle Emission Simulator
NDD	Naturalistic Driving Data
OEM	Original Equipment Manufacturer
RSE	Roadside Equipment

RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
SAE	SAE International
SPaT	Signal Phase and Timing
SPMD	Safety Pilot Model Deployment
SST	Small-Scale Test
TOSCo	Traffic Optimization for Signalized Corridors
TTI	Texas A&M Transportation Institute
UMTRI	University of Michigan Transportation Research Institute
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
VISSIM	Verkehr In Städten – SIMulationsmodell (A Traffic Flow Simulation)