Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project

Final Report

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Final Report – June 30, 2022

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U.S. Department of Transportation
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16. Abstract

This report provides a roadmap to details contained in four TOSCo Phase 2 detailed reports that focus on specific aspects of the four key technical objectives undertaken in the TOSCo Phase 2 Project. The four key technical objectives that the project team focused their efforts on in the project were:

1. Implement TOSCo vehicle algorithm in vehicles
2. Implement TOSCo infrastructure algorithm in infrastructure components
3. Verify and refine TOSCo system in a closed course setting then exporting it onto an actual corridor
4. Assess TOSCo functional safety and performance using real-world observations and actual on-road data

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

1. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Modeling & Benefits Estimation – FM1960 Final Report
2. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Infrastructure System Requirements and Architecture Specification
3. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Functional Safety Concept and Hazard Analysis Report
4. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Vehicle System Requirements and Architecture Specification
5. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project - Modeling & Benefits Estimation – SH105 Final Report

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

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Executive Summary

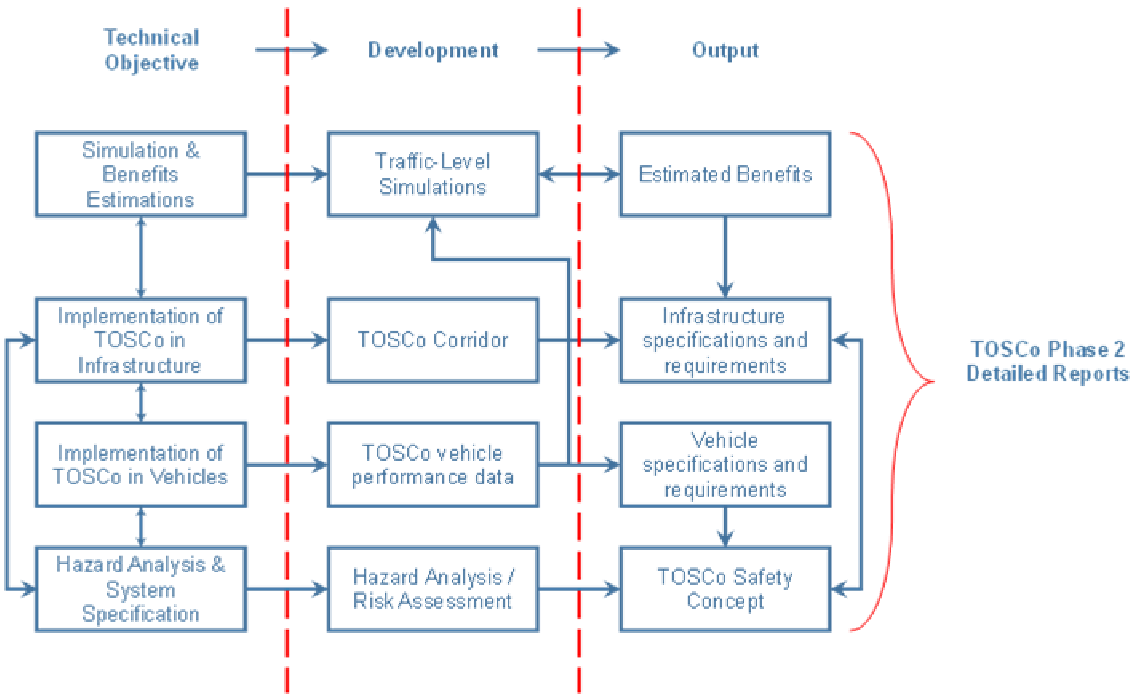
The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project was undertaken by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium, consisting of Ford, General Motors, Honda, Hyundai Motor Group, Nissan and Volkswagen Group of America, in collaboration with the Texas A&M Transportation Institute (TTI). 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 TOSCo system and exercising the concept in simulation under previous efforts, the Project Team initiated the TOSCo Phase 2 Project in July 2019. 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 2 Project were:

1. Implement TOSCo vehicle algorithm in vehicles. The details of this effort are provided in the Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Vehicle System Requirements and Architecture Specification
2. Implement TOSCo infrastructure algorithm in infrastructure components. The details of this effort are provided in the Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Infrastructure System Requirements and Architecture Specification
3. Verify and refine TOSCo system in a closed course setting then exporting it onto an actual corridor. Various aspects of this effort are reported in the Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Vehicle System Requirements and Architecture Specification and the Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Infrastructure System Requirements and Architecture Specification.
4. Assess TOSCo functional safety and performance using real-world observations and actual on-road data. The details of this effort are provided in the Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Functional Safety Concept and Hazard Analysis Final Report and Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Modeling & Benefits Estimation – FM 1960 Final Report, respectively.

The Project Team initially selected State Highway 105 in Conroe, Texas for implementing TOSCo. However, the COVID-19 Pandemic of 2020 through 2021 resulted in a delay of several months for the implementation of TOSCo. When the Project Team was able to continue implementation efforts and begin installing equipment along State Highway 105, a planned construction project on State Highway 105 conflicted with the TOSCo project schedule which required the Project Team to seek an alternate location. With the assistance of engineers from the Houston District of the Texas Department of Transportation (TxDOT), the Project Team selected Farm to Market Road (FM) 1960 just north of the Bush Intercontinental Airport as the site of the TOSCo corridor. Since State Highway 105 was the planned deployment corridor, the Project Team conducted a TOSCo performance analysis in simulation using updates and refinements developed during the TOSCo Phase 2 Project. The report is available, however, this report will focus on the results of the performance analysis conducted for FM 1960 because this analysis incorporates actual vehicle data, which is not available for State Highway 105.

The Project Team initiated implementation of TOSCo in infrastructure by using portable on-board equipment in regular vehicles to verify the validity of the messages broadcast from a Road-side Unit (RSU) installed at the smart intersection on the test course at the TTI's RELLIS (Respect Excellence Loyalty Leadership Integrity Service) campus. In parallel, the Project Team initiated implementation of TOSCo on board a fleet of four vehicles comprised of a 2015 Cadillac Escalade, 2015 Hyundai Sonata, 2019 Volkswagen Jetta and a 2018 Volkswagen Tiguan. 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. 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, 2022

Figure 1: TOSCo Phase 2 Project Task Interconnectivity

This report provides a map to information contained in four detailed reports that focus on specific aspects of the work undertaken in the TOSCo Phase 2 Project as follows:

1. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Modeling & Benefits Estimation – FM 1960 Final Report
2. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Infrastructure System Requirements and Architecture Specification
3. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Vehicle System Requirements and Architecture Specification

4. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Functional Safety Concept and Hazard Analysis Final 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 performance requirements used to define the TOSCo architectures that were deployed along FM 1960 are covered next followed by the functional safety assessment.

From test results, on-road observations and simulation result, the Project Team concluded that overall:

- In heavy traffic (over-saturated conditions), TOSCo showed the ability to reduce the number of stops from an average of five stops per vehicle in half by 30 percent MPR and by 80 percent by 70 percent market penetration.
- TOSCo simulations demonstrate that TOSCo can reduce fuel use by up to 180 gallons across the corridor with default settings and by about 260 gallons with the revised settings across the 13 intersections in the off-peak analysis period of 9:00 AM and 1:00 PM.
- The revised settings of TOSCo cause a reduction in delays and stops for all users on FM 1960. The revised representation included extending communication range from 360 to 720 meters thus allowing the TOSCo-equipped vehicle to travel up to the ACC set-speed rather than the posted speed limit and allowing the TOSCo-equipped vehicle to pass through the intersection within two seconds of a signal phase transition to yellow instead of having to stop on yellow.

TOSCo Performance Using Real-world Observations and Actual On-road Data

The Project Team built and utilized a Verkehr In Städten – SIMulationsmodell (A Traffic Flow Simulation) (VISSIM) model of Farm-to-Market (FM) 1960 to assess benefits of an updated version of TOSCo developed in Phase 2. The Project Team calibrated the model based on travel time data available through the National Performance Management Research Data Set (NPMRDS) analytics website. The simulation covered a range of market penetration rates of TOSCo on the simulated corridor. The Project Team used a single intersection extracted from the corridor model as a testbed to analyze different configurations and conditions for TOSCo that were not possible on the slower computing corridor model.

Key takeaways of the mobility and environmental benefits observed by implementing TOSCo in the FM 1960 simulation analysis are listed below:

- TOSCo settings impact the ability of the TOSCo system to reduce the delays experienced by the vehicles. Allowing the speed trajectory to accept speeds higher than the speed limit, increasing TOSCo range, and allowing TOSCo vehicles to enter in yellow each reduced the amount of delay experienced relative to the default TOSCo settings. These delay reductions were increased further when the three changes in settings were combined into a “revised” representation of TOSCo.
- Allowing the vehicle to compute a long CSC-Down speed profile either made no difference in performance or led to worse performance than the default TOSCo behavior.
- With increased volumes, TOSCo was able to reduce the stops on the approach from many stops to less than one stop on the approach, indicating an increase in throughput at the intersection.

- TOSCo was able to achieve reductions in stop delay and number of stops with both TOSCo settings. Stop delay decreased by approximately 50 percent across the corridor as TOSCo market penetration rates (MPR) increases. The average stops per vehicle increased initially with the introduction of TOSCo because the non-TOSCo vehicles stopped more times as the TOSCo finished their speed profiles. TOSCo vehicles had lower number of stops than the baseline traffic in simulation.

- TOSCo reduced total delay in the westbound direction with both TOSCo settings and the eastbound direction with the revised TOSCo settings. These reductions were greater with the revised TOSCo settings. The high TOSCo MPR scenarios experienced increases in total delay relative to the baseline and the 90 percent MPR scenarios because of the difficulty experienced by turning vehicles attempting to change lanes to complete their maneuvers.

- TOSCo showed improved performance for each respective vehicle class. TOSCo-equipped as well as non-equipped vehicles experienced either constant performance or reductions in total delay and reductions in stop delay as market penetration increased on most of the approaches. These improvements were most noticeable with the revised TOSCo settings where total delay reduced for both TOSCo and non-TOSCo vehicles.

- TOSCo did not cause substantial changes in the total travel time for vehicles on the FM 1960 network.

- TOSCo increased fuel consumption initially and then reduced fuel consumption gradually as TOSCo MPR increased. When the TOSCo system operation is configured to a maximum speed of the posted speed limit, communication range of 360 meters and not being allowed to enter the intersection on a yellow signal (default TOSCo version), the eastbound direction experienced about a 7 percent reduction in fuel use, and the westbound direction of travel experienced about a 19 percent reduction in fuel consumption at 100 percent TOSCo. When the TOSCo system operation is configured to a maximum speed of the set-speed selected by the driver, communication range of 720 meters and allowing the vehicle to enter the intersection within two seconds of the onset of a yellow signal (revised TOSCo version), TOSCo experienced a maximum reduction in fuel use at 90 percent market penetration when the strings began to prevent turning traffic from completing their maneuvers. These reductions constituted a 16 percent reduction in fuel use for the eastbound direction and a 22 percent reduction in fuel use for the westbound direction.

- TOSCo initially increased fuel consumption but fuel use gradually decreased from the 20 percent MPR scenario until reductions in fuel use compared to the baseline were achieved around 40 or 90 percent TOSCo MPR depending on the direction of travel and the TOSCo settings. The research team believes that the increases in fuel are caused by the increased stops caused by unrealistic (i.e., where non-TOSCo vehicles are starting and stopping multiple times) interactions between TOSCo vehicles and non-TOSCo vehicles.

- TOSCo has the potential to reduce user costs especially in the mid ranges of TOSCo MPR considered for this study.

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

- The simulated version of TOSCo in this study did not incorporate the CAMP Cooperative Adaptive Cruise Control (CACC) algorithm the TOSCo vehicles in the field use in conjunction with TOSCo operations. To better simulate the TOSCo behavior for evaluation, future versions of the DriverModel.dll should explore generating a better representation of the CACC behavior of the CAMP algorithm.

- In the default settings, speeds in all modes of TOSCo, except for Free-flow, were limited to the posted speed limit. The revised TOSCo setting relaxes this constraint and shows how this setting leads to a limitation of the delay reduction ability of the TOSCo system. The implementation of TOSCo may consider relaxing the speed limit constraint in favor of allowing TOSCo vehicles to plan trajectories at the speed deemed appropriate by the driver of the vehicle. In such a case, the driver would be responsible for maintaining a lawful speed of travel since the vehicle would not alter the speed down to the speed limit.
  - Limits to the TOSCo strings and gap settings to allow for easier lane changing for ambient traffic should be considered. Additional TOSCo simulations may consider coding the ability for TOSCo vehicle to deactivate TOSCo for the cooperative breaking a traveler might execute in the field to help ambient traffic change lanes.

Finally, the Project Team made a number of observations and recommendations for improved performance specific to the TOSCo-equipped vehicles, infrastructure and functional safety, which are listed below.

Vehicle:

Implementing TOSCo vehicle algorithm in vehicles:

- In order to focus on the functionality of the TOSCo system, security was not implemented on the vehicle side of Vehicle-to-Everything (V2X) communications.

Multiple Intersections:

- Profile planning based on multiple intersections may improve TOSCo functionality. Consider the next intersection if it can be reached within one cycle length.
- Avoid accelerating on first intersection only to brake again at the next one to fulfill TOSCo objectives.

TOSCo Range:

- Increasing TOSCo range will afford the on-board system more time to calculate a proper speed profile to the intersection. However, increasing TOSCo range will also require increasing the length of ingress lanes in the MAP message.
- Allowing speed profile generation at longer distances will allow vehicles to react earlier, thus improving TOSCo functionality.

Approaching Queues under Coordinated Speed Control (CSC) Control:

- Take desired time gap into account when planning Coordinated Speed Control (CSC) towards a queue in order to improve braking performance within the string.
- There is a need to better detect static objects such as stopped vehicles waiting in queue in order to improve system performance.

Infrastructure:

Implementing TOSCo infrastructure algorithm in infrastructure:

- In order to focus on the functionality of the TOSCo system, security was not implemented on the infrastructure side of Vehicle-to-Everything (V2X) communications.

Queue Detection:

- The TOSCo system requires a high accuracy, high precision detection system that provides lane-by-lane measurements of queued vehicles. This deployment utilized only one type of detection system (combination of radar and video detection). This technology is highly dependent on clear lines of sight. Because of deployment limitations, occlusion by high profile vehicles or from traffic in adjacent lanes may cause over reporting of queue lengths at some intersections. Positioning the detector unit in line with the travel lanes may help reduce these types of false detection but may not solve occlusion issues.
- Considerations such as mounting height, detection angle, and placement at intersections with master arms vs. span wires dramatically impacts the effectiveness of the sensors to detect queues. Care should be taken to ensure sensors have as direct line of sight on the roadway as possible for detecting queues. The installer should ensure that overhead wires do not block the line of sight of the detectors at the intersection.
- Calibration radar-based zones, both latitudinal and longitudinal, in each lane is critical. Care should be taken to ensure that sensors are adequately tracking vehicles as they progress towards the stop bar.
- The way the video-based detectors are used in TOSCo is different than those traditionally used for stop bar detection. With traditional stop bar detection, multiple loops are often configured to call the same detector input into the controller. TOSCo requires lane-by-lane detection, therefore, each lane must be treated separately. Each detection zone should be configured to cover a specific distance upstream of the stop bar.
- Persistency (the propensity of the detector to remain in the "ON" state as long as a vehicle occupies the detection zone) of detection impacted the overall performance of the TOSCo system. Some intersections had issues with unstable detection where certain detection zones would drop calls, even though the detector was occupied. Unstable detection was problematic at intersections that experienced long queues of greater than 90 meters. To overcome this situation, the Project Team implemented logic in the queue detection system to hold queue lengths until the projected queue clearance time on the signal indication turned green on an approach.
- The queue detection technology experienced accuracy issues when detecting queue lengths over 122 meters from the stop bar. To address detection accuracy issues, the Project Team found it necessary to adjust the speed threshold defining stopped vehicle to 10 mph. This impacted the stability of the estimated queue lengths.

Green Window Prediction:

- The Project Team decided to deploy the green window estimation based on the minimum time remaining until the TOSCo phase turns green (e.g., minimum time remaining reference) and found that the revision worked with the TOSCo vehicles and required little corrections for intersections with low volumes on the cross streets.
- The Project Team also concluded that intersections with higher volumes on the cross streets would benefit from using the maximum time remaining until the TOSCo phase turns green (e.g., maximum

time remaining reference) since that initial estimate would be more accurate. However, the minimum time remaining reference was functional and remained as the reference for the entire corridor.

- Future deployments of TOSCo would benefit from a configuration parameter that indicates which time remaining reference from the SPaT data should be used for each intersection in a TOSCo-enabled corridor.

MAP Generation:

- Care must be taken to ensure that the tools to generate the MAP message use the map datum (WGS84) as the vehicle.
- Generated MAP messages must be verified in the field. Verification can be done by graphing vehicle trajectories over an appropriate map image. Verification is needed to ensure the proper representation of locations of critical lane elements (e.g., stop bars, center of lanes) Up-to-date satellite imaging tools provided valuable in assessing the accuracy of the broadcast maps.

SPaT and Green Window Determination:

- The implementation relied on Signal Phase and Timing (SPaT) data to be pushed from the controller every 100 milliseconds. Traffic signal controllers can generate SpaT data in different formats using different protocols. Future deployments need to be aware that different controllers may utilize different protocol to produce SPaT data.
- Deployment agencies need to verify the accuracy of SPaT information coming from the controller. Some controllers treat all-red intervals differently.
- The green window parameters for queue dissipation should be calibrated. The perception reaction time and acceleration rate parameters may vary from intersection to intersection and can be calibrated through the configuration file.
- The green window may be based on minEndTime or maxEndTime as an initial estimate based on the likely amount of traffic at a given intersection’s cross streets. The minEndTime is the preferred reference for the green window especially if non-coordinated phases gap out regularly at the given intersection. This may depend upon how agencies implement gap outs of non-coordinated phases.
- Future deployments need to take care to ensure that the downstream link for a TOSCo approach has sufficient space to store vehicles that are approaching.

RSU Operations:

- Deployment agencies need to verify the timeliness of the messages broadcast by the Roadside Unit (RSU). In an TOSCo deployment, this was done by comparing the frequency of packets going into the RSU as well as packets received by the vehicles.
- Logging data on the RSU had a significant impact on RSU broadcast performance. High load on the RSU can be caused by the RSU hearing messages from multiple adjacent intersections.
- Hardware that generates messages to support TOSCo needs to be configured to ensure that it maintains continuous operations. Information Technology update policies need to be considered in the design of the system. The hardware needs to be designed to run utilizing a real-time operating system such as Linux.

- Updates specific to Phase 2 of the TOSCo Project along with changes and modifications that were made for the functional safety work products are listed below.
    - Traffic Infrastructure Sub-system is now within scope of the TOSCo Item Boundary (including external influences on the system and communication channel with TOSCo Vehicle).
    - Updated Hazard Analysis identified highest Automotive Safety Integrity Level (ASIL) criteria as ASIL D for “Excessive Acceleration” and “Insufficient Deceleration” hazard for a specific scenario where the TOSCo Vehicle is “too close to the intersection.”
    - Assumptions on infrastructure functionality (such as queue object detection, Green Window determination and their limitations) has been documented in the Hazard Analysis and Functional Safety Concept.

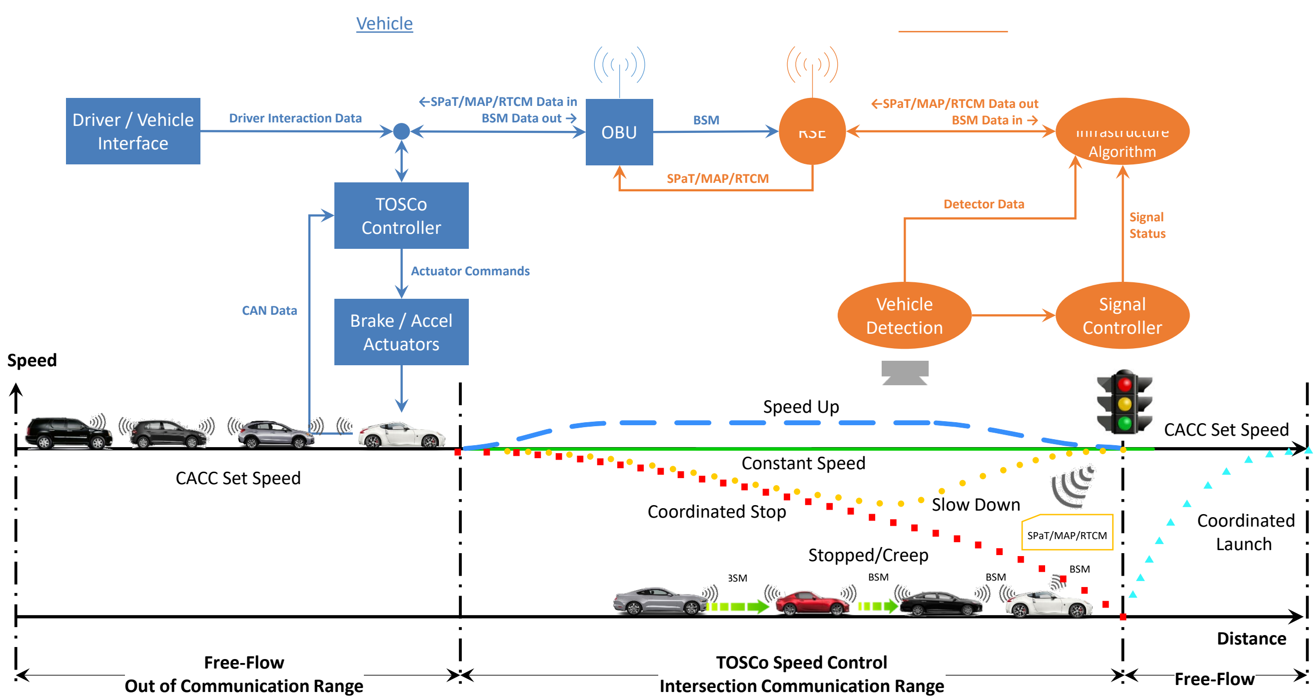
Safety Relevant Functionality for the Infrastructure Sub-system:

- Queue detection and determination of queue by the infrastructure processor are identified to be non - safety critical and only provide enhancements and optimization to the TOSCo trajectory calculations.
- Common Time Source for Clock Synchronization shall be used by all infrastructure elements to ensure data accuracy.
- Several safety parameters have been considered to mitigate potential failure modes in SPaT generation by the infrastructure by verifying the:
    - Data elements are populated
    - Accuracy of the content of the data elements
    - Periodicity of valid SPaT within logical bounds
- Green Window determination that does not match the expected periodic rates within tolerances result in loss of enhanced SPaT to the TOSCo vehicle(s).
- No enhanced SPaT values are sent out to the TOSCo vehicle to indicate that TOSCo functionality needs to be disabled in case of identification of relevant safety critical faults (MAP, Green Window Prediction, Time Synchronization) in the infrastructure. The TOSCo vehicle shall transition to safe state based on this “undefined” value from the infrastructure.

Chapter 1. Introduction

Figure 2 illustrates the overall concept of the Traffic Optimization for Signalized Corridors (TOSCo) system, which is comprised of both in-vehicle and infrastructure-based elements. The on-board equipment employs data transmitted via wireless communications from Roadside Units (RSU) to optimize vehicle fuel economy, emissions reduction and traffic mobility along a signalized corridor equipped to provide information required for TOSCo to operate.

The on-board application collects Signal Phase and Timing (SPaT), intersection geometry (SAE J2735 MAP Data Message, or MAP) Radio Technical Commission for Maritime Services (RTCM) corrections as well as data from nearby vehicles using Vehicle-to-Vehicle (V2V) communications to calculate the vehicle's optimal speed to pass through one or more traffic signals on a green light or to decelerate to a stop and subsequently launch in the most performance-optimized manner. Information is then sent to longitudinal vehicle control capabilities in the TOSCo-equipped vehicle to support partial automation.



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

Figure 2: TOSCo Concept

The Project Team began by evaluating single-vehicle operation evolving the analysis of multi-vehicle string operation using Level 1 automation in the form of automated longitudinal control provided by Cooperative Adaptive Cruise Control (CACC) to improve traffic-level optimization.

In order to implement the TOSCo function, the Project Team developed data elements broadcast in the SPaT message to provide information regarding the length of queues that may have formed at an upcoming intersection as well as information on the beginning and end of a green window. The green window concept is unique to TOSCo and provides TOSCo-equipped vehicles with the means to calculate a speed profile that allows TOSCo-vehicles to clear an intersection with a queue present after the queue clears, without having to stop.

The Project Team also developed data elements for the Basic Safety Message (BSM) to support Coordinate Stop and Coordinated Launch operating modes.

This report provides a map to information contained in four detailed reports that focus on specific aspects of the work undertaken in the TOSCo Phase 2 Project as follows:

1. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Vehicle System Requirements and Architecture Specification
2. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Infrastructure System Requirements and Architecture Specification
3. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project – Functional Safety Concept and Hazard Analysis Report
4. Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Project - Modeling & Benefits Estimation – FM 1960 Final Report

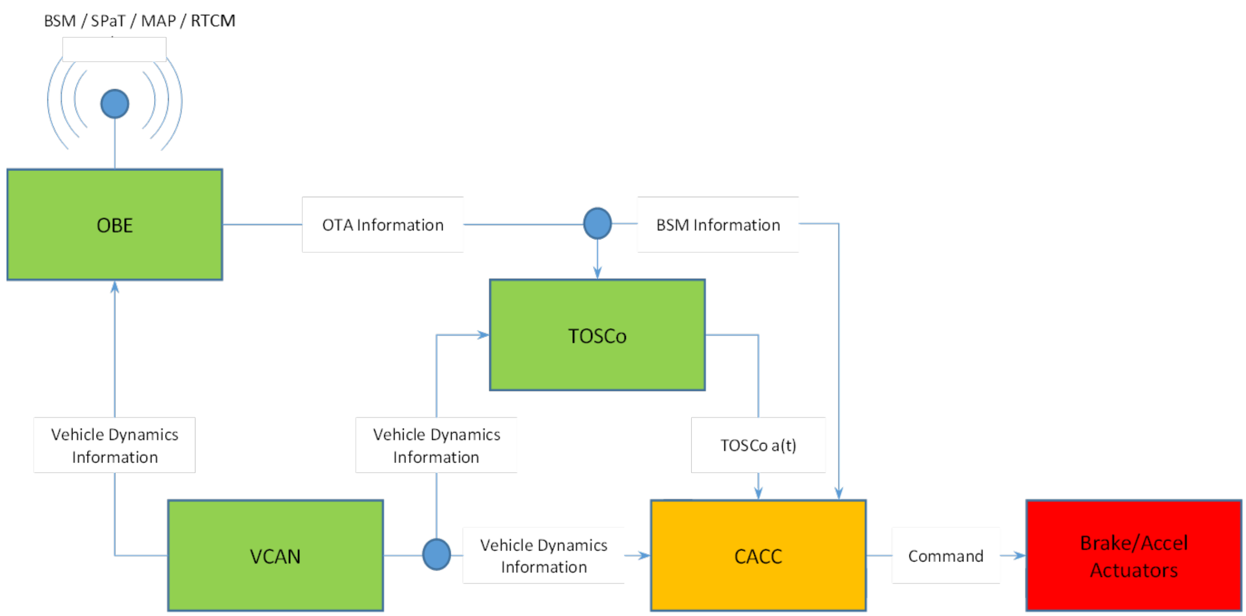
The subsequent sections in this report are organized according to the four key technical objectives identified above. The vehicle and infrastructure system architectures and requirements are covered first followed by the functional safety assessment and concluding with the estimated benefits and simulation methodology used to obtain the estimations.

Chapter 2. Implement TOSCo Vehicle Algorithm in Vehicles

The TOSCo system is a series of innovative applications designed to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based connected-vehicle communications to assess the state of vehicle queues and cooperatively control the behavior of strings of equipped vehicles approaching designated signalized intersections to minimize the likelihood of stopping. Information about the state of the queue is continuously recomputed and broadcast to approaching connected vehicles. Leveraging previous Crash Avoidance Metrics Partners LLC (CAMP)/Federal Highway Administration (FHWA) work on CACC, approaching vehicles equipped with TOSCo functionality use this real-time infrastructure information about queues to plan and control their speeds to enhance the overall mobility and reduce emissions outcomes across the corridor.

TOSCo System Architecture Overview

Figure 3 below provides a simplified block diagram of the TOSCo vehicle system.



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

Figure 3. TOSCo In-vehicle System Block Diagram

TOSCo Speed Profile

The Traffic Optimization for Signalized Corridors (TOSCo) Vehicle System Requirements and Architecture Specification Final Report provides a detailed description of the speed profile generation process. When computing an optimized speed profile for a given approach scenario, the required target speed to pass the intersection in an optimized fashion is usually not known a priori. Instead, there exists an infinite number of possible combinations of a_{max} and v_{final} enabling an approaching vehicle to pass the stop bar without coming to a full stop. Both the maximum and minimum acceleration levels are bound by the vehicle system's capabilities so that:

$$a_{min,system} \leq a_{max} \leq a_{max,system} \quad (1)$$

Figure 4. Equation

Furthermore, the vehicle's allowed target speed levels are bound by the posted speed limit:

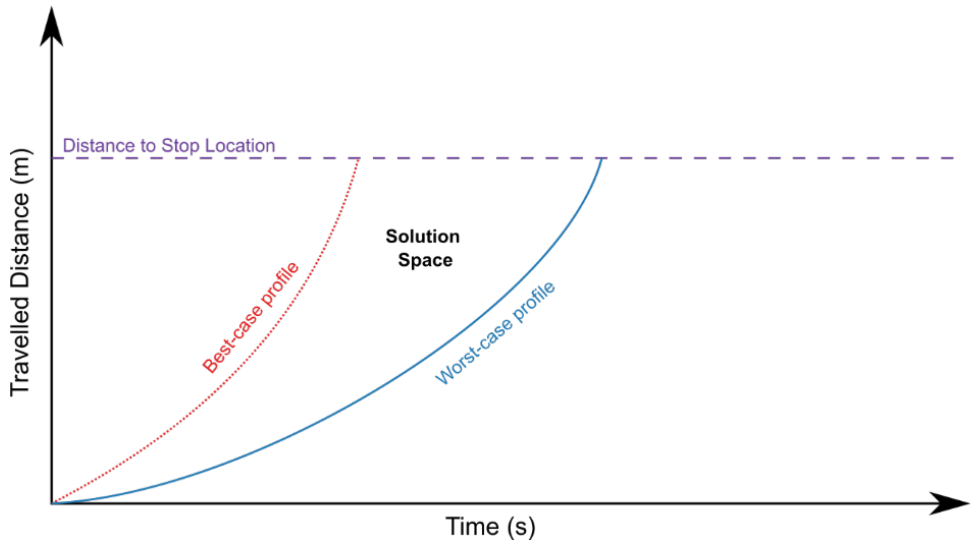
$$0 \leq v_{final} \leq v_{lim} \quad (2)$$

Figure 5. Equation

For each TOSCo operating mode, the vehicle creates a solution space of a best-case and a worst-case profile.

The *best-case* profile resembles a valid profile that 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 basic idea 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 resembles a valid profile that enables a vehicle to just pass the intersection at a green light, i.e., as late as possible. Figure 6 depicts this concept and the corresponding basic logic in more detail for any speed profile. The total distance traveled must be in the range of best-case and worst-case distance at the point in time the vehicle is along the speed profile.

Even though the system is designed in a way that a vehicle will always aim at following the *best-case* profile, there will be traffic situations in which a vehicle might have to deviate from this profile, e.g., in case of a preceding traffic participant slowing down unexpectedly or because of another traffic participant changing onto the same lane as the host vehicle. However, these situations might not always require a re-computation of the existing speed profiles as long as other conditions do not warrant such action.

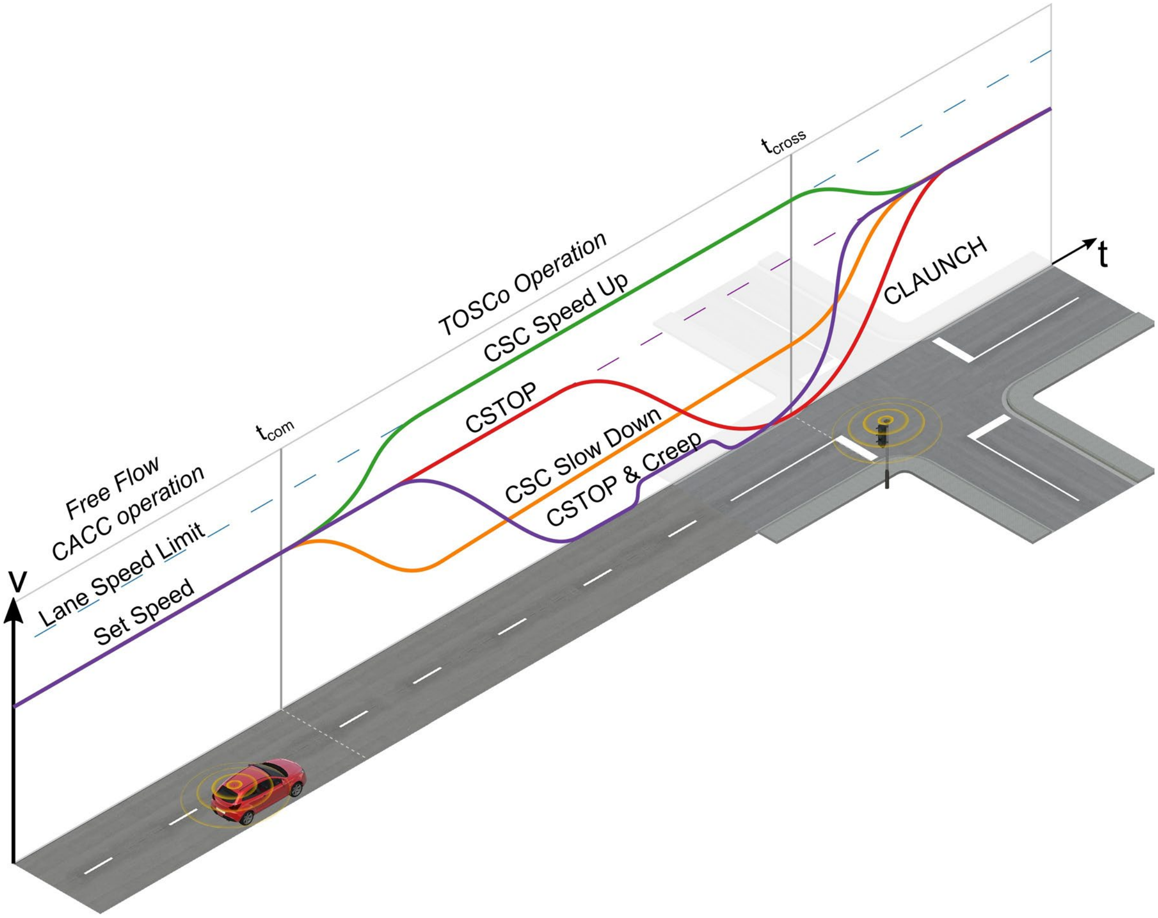


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium, 2022

Figure 6. Speed Profile Solution Space (Generalization, Depicts CSC Speed Up Case)

TOSCo Operating Modes

Six operating modes are defined under TOSCo. TOSCo is dependent upon CACC for vehicle control as shown in Figure 7.



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

Figure 7. TOSCo Operating Modes and Corresponding Idealized Speed Profiles

Free Flow (FF)

When the TOSCo function on a TOSCo-equipped Vehicle is active, the vehicle operates in Free Flow (FF) mode if the vehicle is not receiving SPaT/MAP messages from an approaching intersection. While in FF, the vehicle operates in speed/gap control under CACC. The vehicle's speed range in FF is from zero to CACC set speed.

In order for the vehicle to transition from FF to another operating mode, the following conditions must be met:

- The TOSCo function is enabled.
- The vehicle is receiving SPaT and MAP messages from the approaching intersection.
- The vehicle is matched to an approach lane of the approaching intersection.
- The vehicle is within a distance $d_{toscoRange}$ from the stop bar of the approaching intersection.

Coordinated Speed Control (CSC)

A TOSCo-equipped vehicle enters this operating mode when TOSCo is active, the vehicle is receiving SPaT and MAP messages from the approaching intersection, and it is matched to an approach lane. The vehicle speed range in Coordinated Speed Control (CSC) mode is from a minimum of v_{creep} to a maximum of the posted speed limit, v_{lim}.

If the traffic signal is red and a TOSCo-equipped vehicle determines that it will pass through the intersection on the upcoming green phase without coming to a full stop, the vehicle employs enhanced SPaT message content to plan a speed profile that allows the vehicle to arrive at a distance defined as the virtual stop bar $d_{virtStopBar}$ which is located upstream of the intersection at a speed of 35 mph at the time the signal transitions to the green phase. Typically, a slow-down speed profile will be employed.

If the traffic signal is green and a TOSCo-equipped vehicle determines that it will pass through the intersection prior to the amber phase, the vehicle employs enhanced SPaT message content to plan a speed profile that allows the vehicle to pass through the intersection by adjusting the vehicle speed to achieve optimization objectives. Depending on current circumstances, the vehicle will employ a speed up speed profile or at least maintain current speed.

Coordinated Speed Control with Risk Mitigation Strategy

During a red phase, and in case no queue is reported, the CSC speed profile is modified according to the Risk Mitigation Strategy. This approach mitigates failures in situations where a system error could mean running a red light, since a CSC speed profile is planned to cross the stop bar. If no target is ahead and the infrastructure stops updating relevant information, the vehicle might cross the stop bar during red.

To alleviate the risk of running a red signal indication, any CSC speed profile during red is planned to stop at the stop bar by adding a CSTOP speed profile to the CSC segments. The CSC approach during red will target to arrive at a virtual stop bar positioned $d_{virtStopBar}$ in front of the real stop bar at the change to green. The higher the CSC cruise speed at the virtual stop bar, the greater $d_{virtStopBar}$ since the TOSCo vehicle will need a higher distance to come to a full stop when following the CSTOP speed profile section.

During a regular approach, a TOSCo vehicle will follow the CSC speed profile and arrive at the virtual stop bar when the signal changes to green. This external condition change triggers a recomputation of the speed profile and allows the vehicle to enter a CSC speed up solution to cover the remaining distance to the real stop bar and cross the intersection.

In case the infrastructure does not update its signal phase, the CSC speed profile will not be recomputed and the vehicle will enter the CSTOP segments beginning a deceleration to come to a stop at the real stop bar.

The Functional Safety Report discusses additional measures that were introduced for On-Road testing during the course of this project.

Coordinated Stop (CSTOP)

A TOSCo-equipped vehicle enters this strategy when TOSCo is active, the vehicle is cyclically receiving SPaT and MAP messages from the next signalized intersection in the HV's path, and it is matched to one ingress lane of the intersection. The Host Vehicle (HV) speed range in Coordinated Stop mode is from a TOSCo speed range of v_{lim}, to a final speed of zero and the HV is transmitting a CSTOP flag through its BSM.

If after processing information from the SPaT and MAP messages the TOSCo-equipped vehicle determines that it will not pass through the intersection prior to the amber phase, it employs the content of the messages to plan a speed profile that allows the vehicle to come to a stop at the stop bar or end of a queue while meeting optimization objectives.

A TOSCo-equipped vehicle will enter the Coordinated Stop fallback mode if SPaT and MAP message reception or map matching to an ingress lane is lost and has been operating in CSTOP before. The Coordinated Stop fallback mode shall ensure a safe stop at the stop bar or the previously known stop location.

In case a TOSCo-equipped vehicle has determined that it cannot enter Coordinated Speed Control mode and has to employ Coordinated Stop mode, it will transmit a CSTOP flag. A directly following vehicle that receives the CSTOP flag is prohibited to enter Coordinated Speed Control mode since its solution space is limited by the preceding stopping vehicle ahead. This mechanism enforces CSTOP operation in the whole TOSCo vehicle string, produces matching stopping behavior between all vehicles, and prevents driver confusion.

Stopped

A TOSCo-equipped vehicle enters this strategy when the vehicle is stationary in TOSCo range and matched to an ingress lane either at the stop bar or in a queue. Any movement from this mode requires driver action.

During this time, all TOSCo-equipped vehicles are receiving enhanced SPaT messages that the TOSCo on-board system uses to determine the time remaining before the signal phase will transition to green. Vehicle speed range in Stopped mode is zero.

When the signal is about to change to green, the TOSCo on-board system prompts the driver's readiness for launch. If the brakes are not applied, the system notifies the driver of an imminent launch at which point the driver must respond to indicate readiness for launch otherwise the vehicle will not move. This is applicable to all vehicles in the queue. (Pressing the brake pedal in a prototype vehicle will disengage CACC and TOSCo at any point in time due to the limitation of building on top of Original Equipment Manufacturer (OEM) production Adaptive Cruise Control (ACC) systems.)

Creep

TOSCo-equipped vehicles are allowed to creep forward towards the stop bar to fill gaps left by preceding vehicles if the gap is more than d_{creep}.

A common example would be a preceding vehicle turning right during a red phase. The gap produced can then be filled by the TOSCo-equipped vehicle after the driver has confirmed their desire to move forward. A less common example would be a preceding vehicle making a permissible left turn during a red phase when the cross-street is a one-way street with traffic moving right to left from the point of view of the driver waiting at the red light.

A TOSCo-equipped vehicle enters Creep mode when TOSCo is active and the gap towards the stop bar or the directly preceding vehicle is more than d_{creep}. Under these circumstances, the driver will be requested to acknowledge movement under the Creep mode and after the driver provides confirmation, the TOSCo-equipped vehicle will move forward to close the gap towards the stop bar or the preceding vehicle. Vehicle speed range in Creep mode is from a minimum of zero to a maximum of v_{creep}.

Coordinated Launch (CLAUNCH)

The TOSCo-equipped vehicle inside a TOSCo string broadcasts a Coordinated Launch message after the driver indicated readiness for launch during a STOPPED mode operation.

The first TOSCo-equipped vehicle at a stop bar will become the Lead Vehicle (LV) of a TOSCo string if no preceding vehicles are present. Any HV behind the LV will check the BSM of its directly preceding vehicle for existence of a Coordinated Launch message and will transition to COORDINATED_LAUNCH after its driver indicated readiness for launch during a STOPPED mode operation.

While the enhanced SPaT message indicates a red phase, all TOSCo-equipped vehicles will remain stationary. Once the signal transition to the green phase is indicated in the enhanced SPaT message for a specific lane, every TOSCo-equipped vehicle therein that broadcasts a Coordinated Launch message will compute a Coordinate Launch speed profile and the TOSCo string will startup simultaneously.

If any member of the TOSCo string fails to indicate driver readiness or a TOSCo-equipped vehicle has a non-TOSCo-equipped vehicle as a directly preceding vehicle, COORDINATED_LAUNCH mode will not be allowed since the behavior of the preceding vehicle cannot be anticipated. In this case, a 1-by-1 launch as used by ACC-equipped vehicles will be executed.

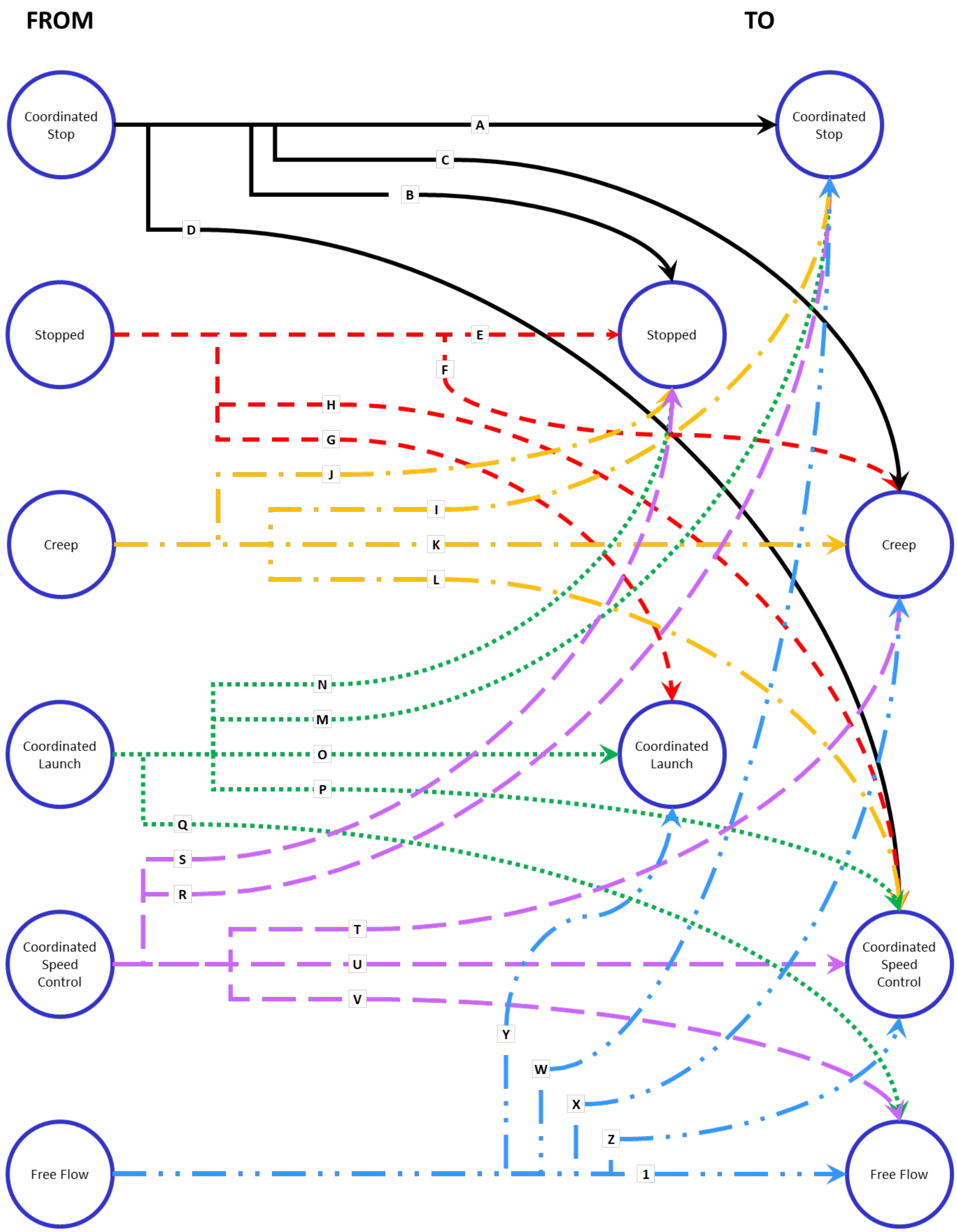
TOSCo Transitions

The numbers and capital letters in Table 1 below indicate transitions that are allowable while the lower case Greek letters indicate transitions that are not allowed. Figure 8 below illustrates all allowable TOSCo transitions.

Table 1. TOSCo Operating Modes Matrix

	Operating Mode	To					
		CStop	Stopped	Creep	CLaunch	CSC	Free Flow
From:	CStop	A	B	C	α	D	β
	Stopped	γ	E	F	G	H (sequential launch)	δ
	Creep	I	J	K	ε	L	ζ
	CLaunch	M	N	η	O	P	Q
	CSC	R	S	T	θ	U	V
	Free Flow	W	ι	X	Y (from standstill)	Z	1

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



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

Figure 8. Allowable TOSCo Transitions

The following paragraphs describe transitions between the TOSCo operating modes that are allowed and the TOSCo operating modes that are not allowed.

Allowed TOSCo Transitions

The following table (Table 2) identifies allowable transitions between TOSCo operating modes.

Table 2. Allowable TOSCo Transitions

Transition	Operating Mode Before Transition	Operating Mode After Transition
A	Coordinated Stop	Coordinated Stop
B	Coordinated Stop	Stopped
C	Coordinated Stop	Creep
D	Coordinated Stop	Coordinated Speed Control
E	Stopped	Stopped
F	Stopped	Creep
G	Stopped	Coordinated Launch
H	Stopped	Coordinated Speed Control (1-by-1 launch)
I	Creep	Coordinated Stop
J	Creep	Stopped
K	Creep	Creep
L	Creep	Coordinated Speed Control
M	Coordinated Launch	Coordinated Stop
N	Coordinated Launch	Stopped
O	Coordinated Launch	Coordinated Launch
P	Coordinated Launch	Coordinated Speed Control
Q	Coordinated Launch	Free Flow
R	Coordinated Speed Control	Coordinated Stop
S	Coordinated Speed Control	Stopped
T	Coordinated Speed Control	Creep
U	Coordinated Speed Control	Coordinated Speed Control
V	Coordinated Speed Control	Free Flow
W	Free Flow	Coordinated Stop
X	Free Flow	Creep
Y	Free Flow	Coordinated Launch (from standstill)
Z	Free Flow	Coordinated Speed Control
1	Free Flow	Free Flow

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

TOSCo Transitions Not Allowed

Table 3 below lists the transitions that are not allowed.

Table 3. TOSCo Transitions Not Allowed

Transition	Operating Mode Before Transition	Operating Mode After Transition
α	Coordinated Stop	Coordinated Launch

Transition	Operating Mode Before Transition	Operating Mode After Transition
β	Coordinated Stop	Free Flow
γ	Stopped	Coordinated Stop
δ	Stopped	Free Flow
ε	Creep	Coordinated Launch
ζ	Creep	Free Flow
η	Coordinated Launch	Creep
θ	Coordinated Speed Control	Coordinated Launch
ι	Free Flow	Stopped

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

Traffic Scenarios Encountered by TOSCo

TOSCo-equipped vehicles can encounter a variety of traffic scenarios as they travel along a signalized corridor. The scenarios encountered during system testing and performance assessment are listed below.

- Constant Speed Intersection Crossing
- Speed Up Intersection Crossing
- Slow Down Intersection Crossing
- Stop at Stop Bar
- Speed Up Intersection Crossing with Queue
- Slow Down Intersection Crossing with Queue
- Stop at Stop Location with Queue
- Creep Scenario to the Stop Bar

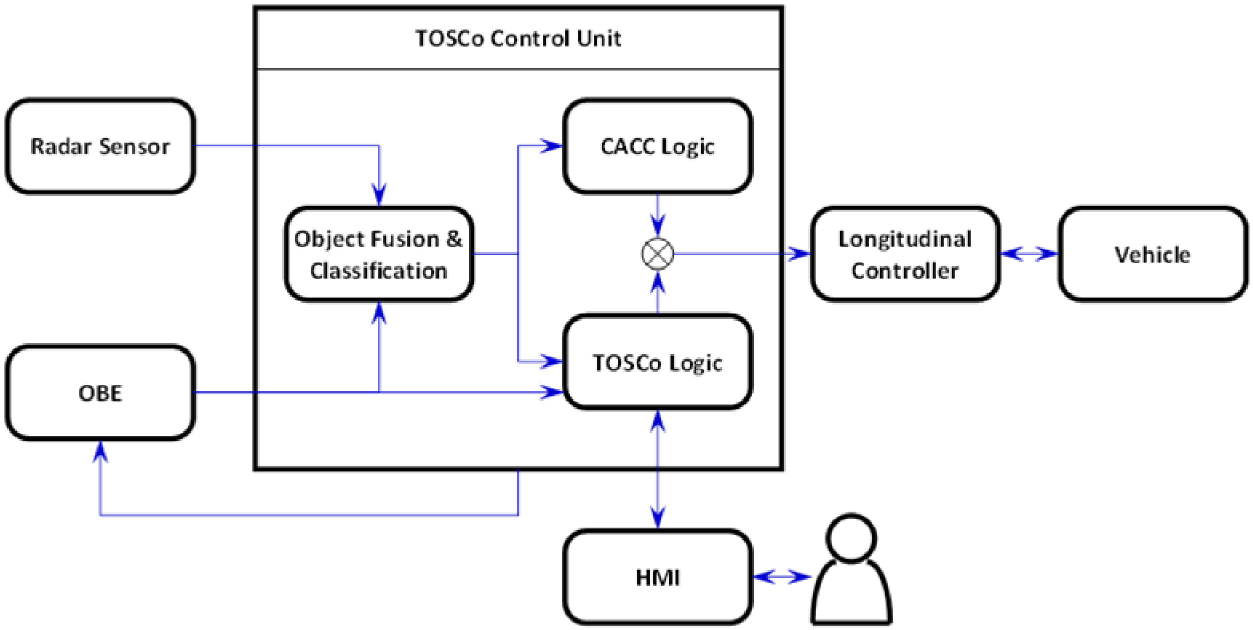
Detailed descriptions of each scenario can be found in Traffic Optimization for Signalized Corridors (TOSCo) Vehicle System Requirements and Architecture Specification Final Report.

TOSCo Vehicle Algorithm Architecture

The Traffic Optimization for Signalized Corridors (TOSCo) Vehicle System Requirements and Architecture Specification Final Report details the principles and architecture of the TOSCo vehicle algorithm.

Basic Vehicle Architecture

The basic architecture and components found in the vehicle are depicted in Figure 9 below and provides an abstract representation of the core components constituting a TOSCo system implemented in a vehicle. Detailed descriptions for each component shown are provided in the TOSCo Vehicle System Requirements and Architecture Specification Final Report.



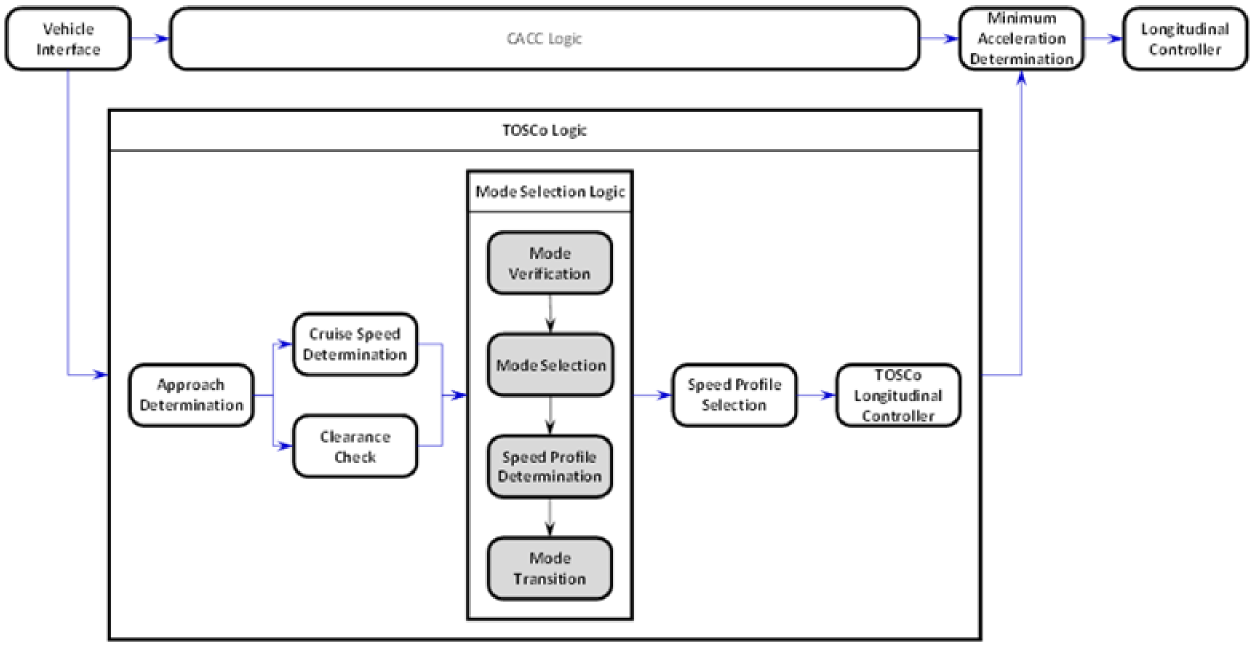
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium, 2022

Figure 9. Basic System Components

TOSCo Software Architecture

The software components of the *TOSCo Control Unit* identified in Figure 9 are implemented using the Automotive Data and Time-Triggered Framework (ADTF)[1] and runs on a Windows 10 embedded operating system. All software components identified in Figure 10 below are implemented in C++11, using MSVC10 compiler environments. Interaction with other software modules is realized by means of the ADTF message bus, Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) interfaces. The implemented software modules of the *TOSCo Control Unit* 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. Detailed descriptions for each software component shown are provided in the TOSCo Vehicle System Requirements and Architecture Specification Final Report.

[1] Digitalwerk GmbH, "Automotive Data and Time-triggered Framework. Accessed 12/19/2018. (https://www.digitalwerk.net/adtf/)."



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

Figure 10. Software Components of the TOSCo Control Unit

Requirements Needed to Enact TOSCo

In order to deploy a TOSCo system, a number of requirements need to be met by the vehicle. Those requirements are listed below.

Table 4. Vehicle Requirements Needed to Enact TOSCo

Summary	Description
Adherence to CACC (Ref : CACC Final Report)	• Vehicle shall comply with performance requirements defined in the Cooperative Adaptive Cruise Control (CACC) Project. The vehicle shall use the more conservative acceleration command.
Reception of SPaT/MAP (Ref : J2735 – Appendix H : MAP and enhanced SPaT Message Use and Operation)	• Vehicle shall be capable of receiving and decoding SPaT. • Vehicle shall be capable of receiving and decoding MAP.
Reception of Radio Technical Commission for Maritime Services (RTCM) (Ref : J2735 – I.5 RSU Broadcast Operations)	• Vehicle shall be capable of receiving and decoding RTCM.
Information Tracking	• Vehicle shall be capable of tracking the information decoded from SPaT/MAP. • Vehicle shall be capable of matching the information decoded from SPaT/MAP.

Summary	Description
Differentiating Intersections (Ref : J2735 – Appendix H : MAP and enhanced SPaT Message Use and Operation)	• Vehicle shall be capable of using message ID to differentiate intersections. • Vehicle shall be capable of using intersection ID to differentiate intersections. • Vehicle shall be capable of using MAP message to differentiate intersections.
MAP Matching (Ref : V2I-SA Final Report Chapter 6.2)	• Vehicle shall comply with MAP matching requirements.
Speed Profile Determination	• Vehicle shall be capable of generating its own set of available speed profiles and determine which speed profile to follow (See Chapter 4).
Traffic Situation Determination	• Vehicle shall be capable of generating traffic conditions data such as queue formation and discharge rates. (Not implemented)
Control Brake/Accelerator	• Vehicle shall be capable of controlling brake when waiting at a red signal for up to 120 seconds. • Vehicle shall be capable of controlling accelerator when it is necessary.
Coordinated Stop	• Vehicle shall be capable of adjusting speed profile to come to a stop. • Vehicle shall be capable of stopping without deactivating its ACC/CACC/TOSCo system.
Optimized Trajectory Planning	• Vehicle shall be capable of estimating its emission and fuel economy performance for its trajectory planning. (Not implemented) • Vehicle shall be capable of following generated speed profile within the calculated solution space.
CACC w/ TOSCo Optimization	• Vehicle shall be capable of determining vehicle performance profile with the objective of promoting a time- and energy-efficient driving style that lowers vehicle emissions and fuel consumption.
Position with the String Determination	• The vehicle shall be capable of determining if it is the head of the string or within the string.
Transmission of TOSCo State	• The TOSCo/CACC state data element inside the BSM shall be set to the current state that the longitudinal control system is operating in (enumeration shall cover both CACC and TOSCo states).
Coordinated Launch / Stop Flag	• The vehicle will be able to send a coordinated launch / stop flag inside the BSM to other vehicles in the string if it is in either CSTOP or CLAUNCH.
Imminent Launch/Creep Forward	• Vehicle shall be capable of determining that the signal is about to transition to green. • Vehicle shall be capable of notifying the driver of an imminent launch. • Vehicle shall be capable of notifying the driver that the vehicle will move forward while in a queue. • Vehicle shall be capable of providing means for driver to indicate readiness for launch. • Vehicle shall be capable of interpreting that the driver is ready for launch.
Vehicle in Motion	• Vehicle shall be capable of determining if vehicle speed is above a defined stationary speed threshold (0.1 m/s).
Transmission of BSM with TOSCo Extension	• Vehicle shall be capable of decoding BSM with TOSCo extension.

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

Content of TOSCo BSM Extension Container

It is envisioned that the BSM will be employed to support TOSCo. A number of Data Elements and Data Frames are currently being studied with the intention of proposing them to the appropriate SAE Technical Committee for addition in SAE J2735. The Data Frames and Data Elements are described below.

Data Frame: DF_TOSCo

This data frame is the top level data frame for the TOSCo extension and contains three data elements. This data frame is used on the LongitudinalControlExtension level of a BSM and shall only be transmitted if TOSCo is active.

Data Element: DE_TOSCoBehavior

This data element is a TOSCoBehavior enumeration value to represent whether or not a vehicle is operating under TOSCo control. If TOSCo is active, the value *coordination-active* shall be transmitted. If a TOSCo vehicle is operating under CSTOP mode, the value *coordination-active-stopping* shall be transmitted. If a TOSCo vehicle is operating under CLAUNCH mode, the value *coordination-active-launching* shall be transmitted.

Data Element: DE_ IntersectionReferenceID

This data element is a IntersectionReferenceID value that refers to the ID of the intersection a TOSCo vehicle is approaching next and optimizing its approach to. This data element can be sent optionally by a TOSCo vehicle and can be used by other traffic participants or the infrastructure for optimizing their operations.

Data Element: DE_ LaneID

This data element is a LaneID value that refers to the ID of the ingress lane of a specific intersection a TOSCo vehicle is currently map-matched and optimizing its approach to. This data element can be sent optionally by a TOSCo vehicle and can be used by other traffic participants or the infrastructure for optimizing their operations.

Chapter 3. Implement TOSCo Infrastructure Algorithm in Infrastructure Components

The Project Team developed detailed requirements and specifications for the infrastructure-level components of the overall TOSCo system, which are described below. The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides details regarding the deployed TOSCo infrastructure.

Infrastructure System Requirements and Architecture

The functional requirements of the infrastructure system needed to support TOSCo operations at an intersection are listed below.

- The infrastructure shall provide TOSCo vehicles with information about the current state of operations of the traffic signal system at each intersection in the deployment corridor.
    - The infrastructure shall provide TOSCo vehicles with information about the current state of the signal indications for each movement at the intersection.
    - The infrastructure shall provide TOSCo vehicles with information about the minimum end time (the shortest time point) that the signal indication for each movement (left, and through) at the intersection will remain in its current state.
        - The time point shall express this a time mark from the beginning of the hour.
        - This time point shall represent the guaranteed amount of time that the traffic signal will remain in its current state.
    - The infrastructure shall provide TOSCo vehicles with information about the maximum end time (the longest time point) that the signal indication for each movement at the intersection will remain in its current state.
        - The time point shall express this as a time mark from the beginning of the hour.
        - This time point shall represent the maximum possible amount of time that the traffic signal will remain in its current state.
- The infrastructure shall provide TOSCo vehicles with information about the current state of queues in each TOSCo-supported lane of TOSCo-supported approaches.
    - The infrastructure shall provide TOSCo vehicles with information about the length of queues, from the stop bar to the rear of the last queued vehicle, for each TOSCo-supported lane.
    - The infrastructure shall provide TOSCo vehicles with an estimated time in the current signal cycle when the last queued vehicle in each lane expects to clear the stop bar on the green indication as a time mark with the green window start data element.

  - The infrastructure shall provide TOSCo vehicles with an estimated time in the current signal cycle when the last TOSCo vehicle may cross the stop bar on a green signal indication as a time mark with the green window end data element.
- The infrastructure shall provide TOSCo vehicles with information to determine their position accurately in each lane of the intersection supporting TOSCo operations.
  - The infrastructure shall provide TOSCo vehicles with information about the geometry of the intersection.
  - The infrastructure shall provide TOSCo vehicles with the maximum permissible travel speed (speed limit) for each lane supporting TOSCo operations.
- The infrastructure shall provide TOSCo vehicles information to perform differential corrections to its positioning calculations.
  - The infrastructure shall provide TOSCo vehicles with lane connection information for each allowed maneuver from ingress to egress lane at the intersection.
- The infrastructure shall communicate with the vehicle using standard messages defined in the Society of Automotive Engineers (SAE) J2735 – 2016.

TOSCo Infrastructure Operating Assumptions and Requirements

Seven key operating assumptions in which TOSCo must operate are listed below:

- Each TOSCo intersection algorithm will function independently of the other intersections in the corridor.
  - Each intersection is equipped with its own TOSCo system and interact only with those TOSCo vehicles within communication range of the intersection which is defined as 300 meters.
- The TOSCo system shall operate with standard traffic signal controllers in a typical traffic signal cabinet.
  - The TOSCo system must be able to work with standard traffic signal control equipment.
  - The traffic signal controller must produce J2735 SPaT information and disseminate this information to the TOSCo system in real-time.
  - The traffic signal controller must be a modern traffic signal controller (either a TS-2 or Advanced Traffic Control (ATC) standard controller) and must communicate with external devices using National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) 1202: Actuated Traffic Signals v3.
  - The controller must also be able to communicate to the TOSCo system through an Ethernet port.
- The TOSCo system must operate within the bounds of actuated-coordinated control.
  - Previous TOSCo-like applications have assumed fixed timing operations for the traffic signal controller. However, most agencies use coordinated actuated control in their corridors to progress through vehicle movement traffic on main-street approaches.
- The TOSCo vehicles shall not alter the base signal timing plan implemented by the agency.
  - Agencies have planned their signal operations to achieve mobility and safety objectives, therefore, the TOSCo vehicles should not alter these base timings to receive priority operations at the intersection.

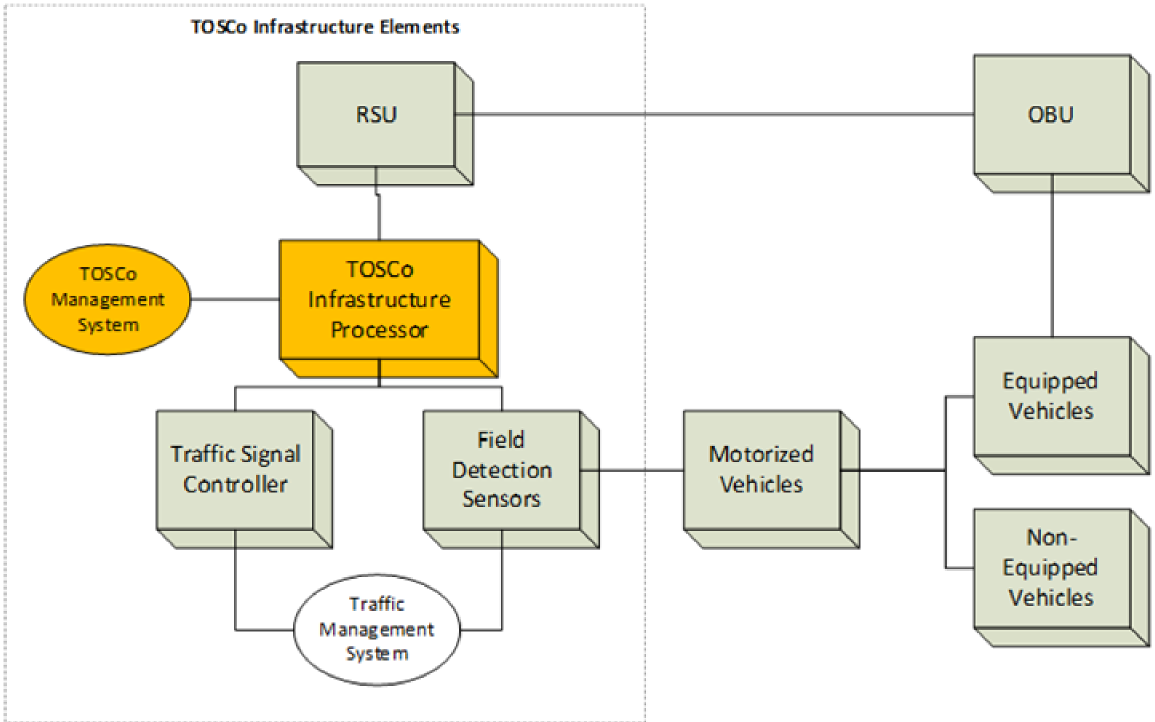
- TOSCo vehicles must operate cooperatively in a mixed-traffic environment (Connected Vehicle (CV) - equipped and non-equipped).
    - The current vehicle mix at any given intersection is likely to be composed of both equipped and unequipped vehicles, therefore, the TOSCo system must detect and gather information from all vehicles in the traffic stream, not just equipped vehicles.
    - Data from equipped vehicles can supplement data obtained from existing infrastructure detection, but it cannot be the sole source for information about operating conditions on TOSCo approaches.
- The TOSCo infrastructure systems must be able to detect and gather information using commercial off the shelf detection technologies.
    - TOSCo requires that queue information be provided at the lane-level.
    - Many agencies have made significant investments in detection technologies at their intersections, particularly related to queue detection. Therefore, the Project Team developed the TOSCo system around existing approaches and technologies for detecting intersection queues.
- TOSCo will be deployed on passenger vehicles only.
    - The Project Team assumed that only passenger vehicles have TOSCo functionality.
    - This assumption allows the developers to apply industry-accepted values for the operating characteristics of unequipped vehicles such as vehicle lengths, acceleration and deceleration characteristics and perception/reaction times of drivers.
    - The Project Team has coded these as parameters that operators can adjust to reflect typical corridor operating characteristics.

TOSCo Infrastructure System Architecture

The TOSCo system includes both vehicle and infrastructure elements. The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report describes both the physical and software components and data flows of the TOSCo Infrastructure elements.

Physical Components

Figure 11 below shows the physical components of the TOSCo System.



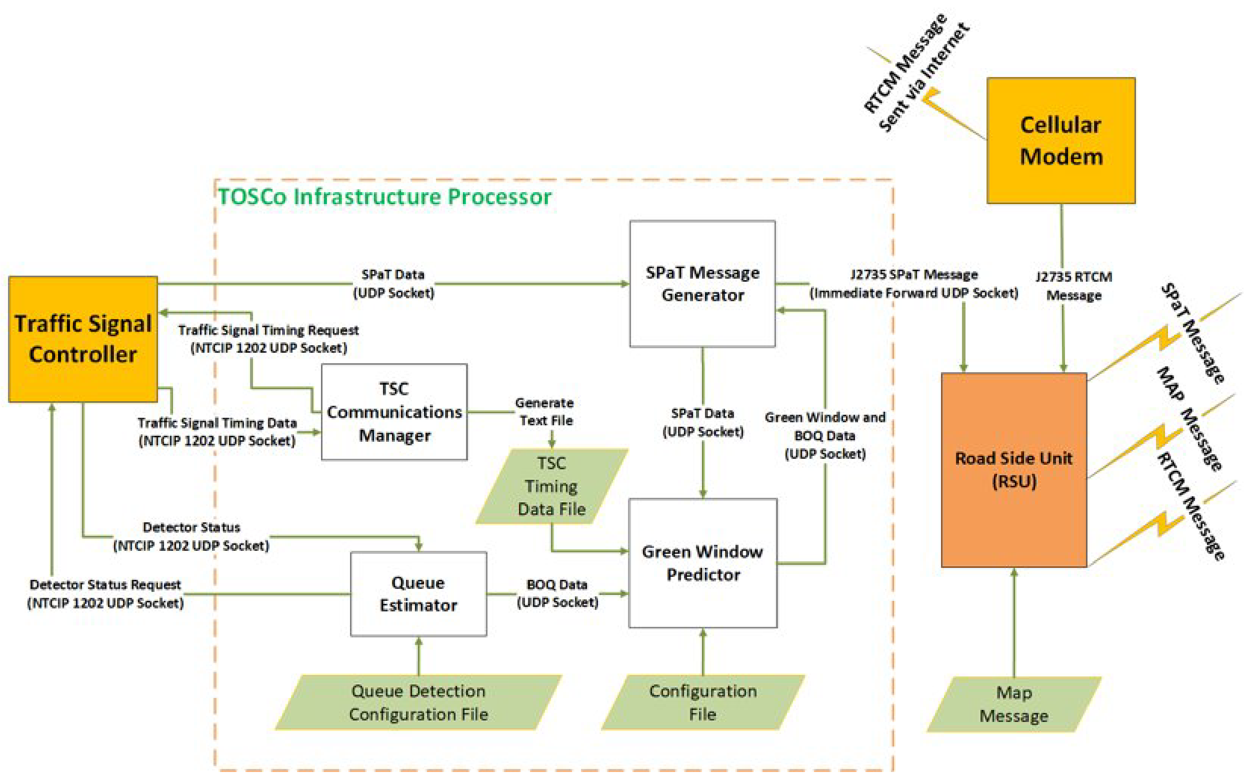
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium, 2022

Figure 11. TOSCo Physical Components

Each box represents a physical entity in the TOSCo system, while the ovals represent systems (or processes) that manage and configure the system's physical components. The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides greater detail for each component.

Software Components

Figure 12 below shows the software components of the TOSCo Infrastructure System.



Source: Texas A&M Transportation Institute, 2022

Figure 12.TOSCo Infrastructure Software Components

The boxes inside the dashed box represent processes explicitly developed for TOSCo. The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides greater detail for each component.

TOSCo Queue Estimator

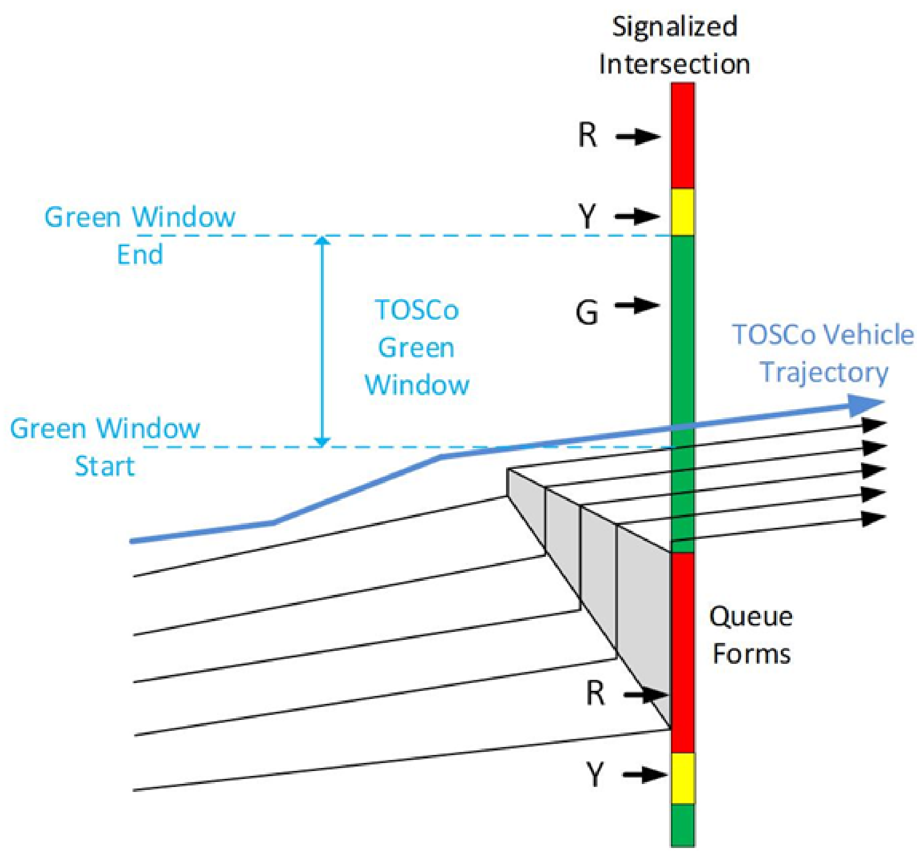
TOSCo requires an estimation of the queue length for TOSCo-equipped vehicles to use in identifying a stop location and to adjust the start of the Green Window.

The queue estimation algorithm was designed to use radar-based sensors at the intersection to detect slow-moving vehicles in each through lane on the TOSCo approaches. The Queue Estimator estimates queue lengths in each lane based on current observations of detector states. The Queue Estimator does not attempt to forecast future queue lengths based on incoming demand. Sensors at the intersection detect all vehicles, regardless of whether they are connected vehicles or not. As the vehicle traverses a detection zone, the radar sensor uses the vehicle speed to determine if the vehicle is in a queued state. When a vehicle speed is below a specific user-defined threshold, five mph for this project, the sensor places a call on a particular channel in the traffic signal controller representing the presence of a stopped vehicle on that detection zone. The sensor continues to activate the detection channel as long as vehicle speeds are below the threshold. The sensor has its defined detection range from 30 m to 183 m away from the stop bar. The Project Team configured 16 queue zones numbered from 17 to 32 on the TOSCo approach of each intersection on the corridor. The TOSCo

Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides greater detail for the queue length estimation concept.

TOSCo Green Window Predictor

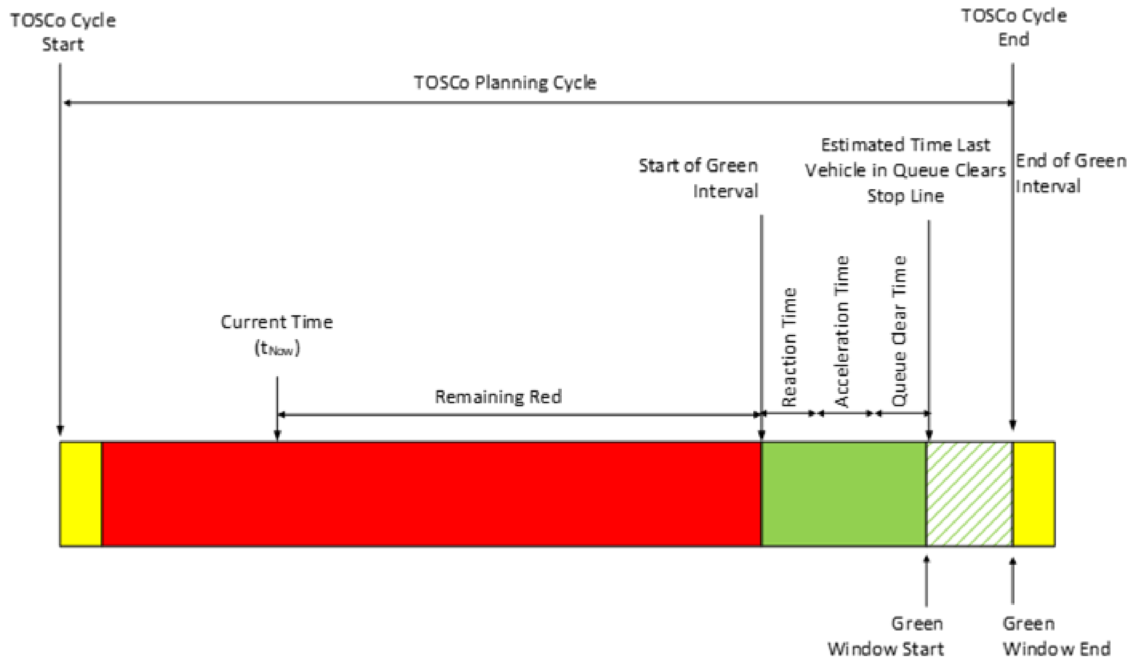
One critical function of the TOSCo Infrastructure System is to predict the Green Window. As shown in Figure 13 below, the “Green Window” represents the time during the green interval when the last vehicle in the queue clears the stop bar of the intersection and the end of the green interval. The “Green Window” represents the planning horizon in the green interval in which a TOSCo-equipped vehicle can traverse through the intersection without stopping. The TOSCo algorithms use the Green Window to target the vehicle’s arrival to minimize the likelihood of stopping.



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

Figure 13. Definition of Green Window

For the purpose of vehicle trajectory planning, TOSCo defines the signal cycle as the start of the yellow interval on the approach to start the yellow interval of the next the coordinated phase. Various elements are used determining the Green Window. These elements are shown in Figure 14 below.



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

Figure 14. Definition of TOSCo Planning Cycle

The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides greater detail for each component.

Several inputs into the Green Window Predictor algorithm come from configuration data stored in a file. These configuration parameters, listed below, do not change during normal TOSCo operation. The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides greater detail for each parameter.

- *IntersectionID*: The identification number of the intersection corresponding to the configuration file. Used for logging and error checking.
- *VehLength*: Represents the total distance (in feet) occupied by a vehicle in a queue.
- *SpeedLimit*: Speed limit of the roadway converted into meters-per-second.
- *DistanceLastVideoDetectorFeet*: Corresponds to the location where the queue length converts from video to radar-based detection.
- a: The assumed acceleration for a vehicle as it accelerates from a stop to its desired speed.
- Time*PR_FirstVehicle*: The amount of time for the first vehicle in a queue to perceive that the signal is green and react by beginning to accelerate (i.e., start-up lost time). The default value for this parameter is 2 seconds.
- *TimePR_perVehicle*: The amount of time for manually driven vehicles to perceive that the lead vehicle in a queue has started to accelerate and react by accelerating.

- *NumTOSCoLanes*: The number of TOSCo lanes at the intersection and is used as a reference for the storage of lane-specific parameters and the number of green windows to calculate.
- *TOSCoLaneID*: The lane identification numbers used to describe which lane a given green window means. This parameter must be consistent between each TOSCo infrastructure module.
- *LanePhaseMap*: Contains the phases corresponding to each TOSCo approach, *i*.
- *PatternNumber*: The coordination plan stored in the traffic signal controller that the Green Window Predictor references to identify the active timing plan so the Green Window Predictor can select the appropriate cycle length and phase split times.
- *CycleLength*: The cycle lengths for each coordination pattern stored in the controller.
- *YellowTime*: An array with the yellow times for each phase in the configuration file based on the controller database.
- *RedTime*: An array with the all-red times for each phase in the configuration file generated based on the controller database.
- *PhaseSplitTime*: An array with the split durations for each pattern saved on the controller. This data comes from the configuration file generated based on the controller database.

The Green Window Predictor uses the variables listed below as dynamic inputs to predict the start and end times of the Green Window. These values are obtained dynamically from other processes in the TOSCo computer. The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides greater detail for each parameter.

- *TOSCoPhaseStatus*: This array contains the phase status of the TOSCo-enabled phases at the intersection.
- *TOSCoPhase.MaxTime*: This variable returns the maximum time remaining for the current phase status of the TOSCo phase, k.
- *TOSCoPhase.MinTime*: This variable returns the minimum time remaining for the current phase status of the TOSCo phase, k.
- *NumQueuedVeh*: This array provides the number of queued vehicles estimated for each TOSCo lane, i, in the queue calculation.
- *LaneBOQ:* This array contains the distance, in meters, from the stop bar to the back of the queue.
- *TNow*: This value is the current UTC time. The Green Window Predictors uses UTC to convert data into the green window start and end times.
- *LaneFOQ*: This array contains the distance, in meters, from the stop bar to the front of the queue, measured from the stop bar to the front vehicle's front bumper.

The process used to calculate the start and end of the Green Window for the TOSCo regional elements is detailed in The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report. The Green Window Predictor uses signal timing and kinematics to estimate the start and end of the Green Window. These elements dynamically represent the times the back of the queue will clear the stop bar (denoted as the *GreenWindowStart)* and the time when the TOSCo phase will end for the lane (shown as the *GreenWindowEnd*).

The steps to calculate the start and end of the Green Window are discussed in detail in the TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report.

After each iteration, the Green Window Predictor forwards its output to the SPaT Message Generator for packaging the relevant elements into the TOSCo SPaT message. The Green Window Predictor sends the following five outputs to the SPaT Message Generator:

- *LaneBOQ*: This array describes the location of the back of the queue of each lane based on *TOSCoLaneID* as calculated by the Queue Estimator unless the Green Window Predictor invalidates the data.
- *GWStart*: This array describes the time mark of the estimated beginning of the Green Window for TOSCo for each *TOSCoLaneID*.
- *GWEnd*: This array describes the time mark for the end of the Green Window for TOSCo for each *TOSCoLaneID.* Note this always corresponds with the expected end of the green indication.
- *GWMsgNo*: This parameter contains a unique ID for the Green Window calculation for debugging purposes.
- *GWDFlag*: This parameter is a Boolean for tracking if the Green Window changes.

TOSCo Signal Phase and Timing (SPaT) Message

The SPaT Message Generator provides SPaT and intersection geometry (MAP) data to TOSCo vehicles. For the TOSCo Project, SPaT is obtained from the Traffic Signal Controller (TSC) and provides information about the current operating status of the traffic signal and time change values to the equipped vehicles. In addition to the information defined in SAE J2735, the SPaT Message Generator also provides queue length and Green Window information to TOSCo vehicles. The SPaT Message Generator uses regional extensions to convey Green Window information to TOSCo vehicles.

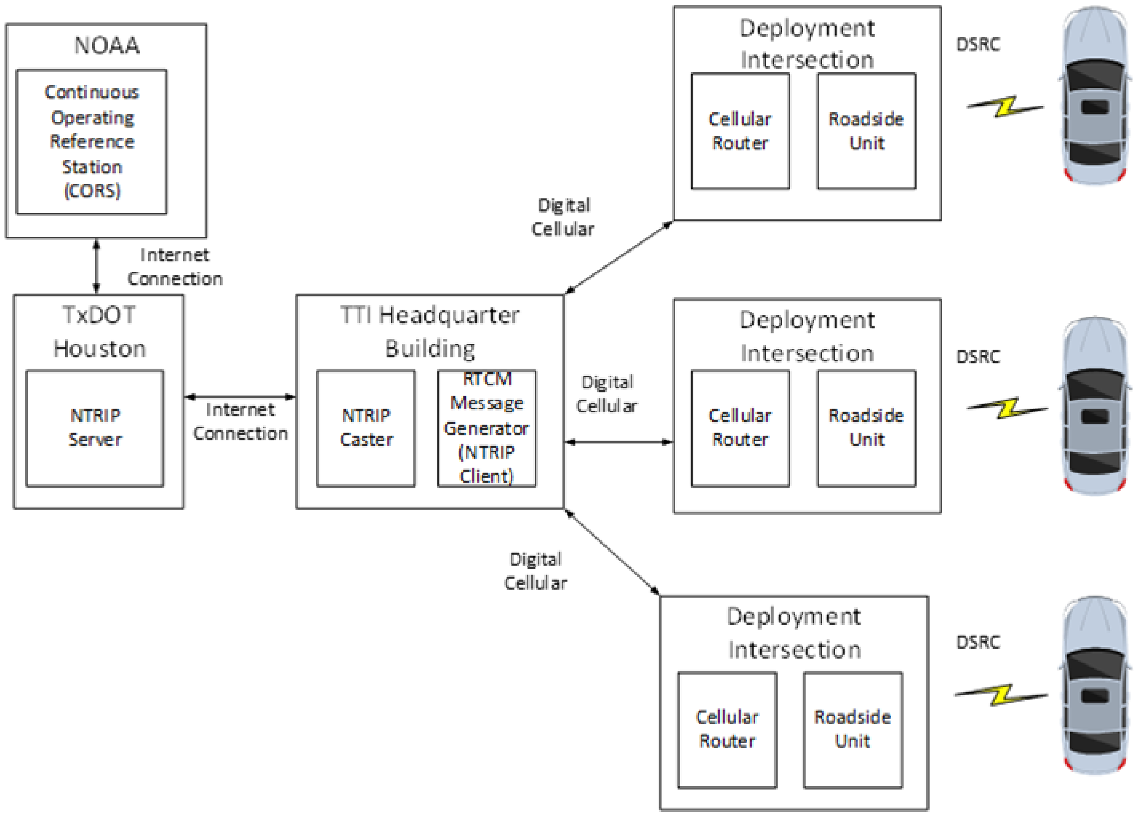
The TSC pushes signal phase and timing data every 100 milliseconds. The signal phase and timing data include the status of 16 phases, overlaps, and pedestrian signals in the TSC. It also contains the estimated minimum and maximum time remaining until a change in state in each phase, overlap, and pedestrian indication. Other information pushed by the TSC in the SPaT data includes the plan action number that indicates the current timing plan running in the controller and the intersection status.

The TOSCo SPaT Message Generator receives the SPaT data pushed by the controller and Green Window information from the Green Window Predictor module. The TOSCo SPaT module uses the above information together with configuration information read from a configuration file at the start of the application to produce an enhanced SAE J2735 SPaT 2016 message every 100 milliseconds and broadcasts the message to vehicles at the intersection via the RSU.

The SPaT Message Generator requires additional configuration information to determine the status of each lane movement and the time remaining until a status change. These configuration parameters define the different phases, overlaps control movements at the intersection, and pedestrian signals control traffic movements at the intersection. This Phase-to-Lane-Movement (PTLM) configuration file is usually created by the agency that manages the intersection. An example of a PTLM Configuration file for the RELLIS Smart Intersection is provided in the Appendix of the TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report.

TOSCo Differential Position Corrections

The TOSCo Infrastructure is also responsible for providing correction messages to the vehicles as defined by the RTCM Special Committee Number 14. The J2735 RTCM Messages encapsulates the differential corrections information for the Global Positioning System (GPS) that the vehicle system can use to improve its positioning and map-matching capabilities. J2735 RTCM messages “wrap” standard position correction information (as defined by the RTCM standards) for transport via the Dedicated Short-range Communications (DSRC) media. The TOSCo vehicle is responsible for reconstructing the content of the message into the final expected format defined by the RTCM standards. Figure 15 below shows the architecture for generating the RTCM correction data for the TOSCo Project.



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

Figure 15. Architecture for Providing RTCM Correction Information from TOSCo Infrastructure

The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides details on how the Project Team created and broadcast the RTCM message.

MAP Message Generation

The MAP information provides the vehicle with an understanding of the intersection geometry and allows the vehicle to compute its position relative to the stop bar of the approach. The MAP information also enables the TOSCo vehicle to locate itself in a lane approaching the intersection and identify which queue and signal timing information to use.

The Project Team used the ISD Message Creator tool available at the USDOT Connected Vehicle Tool Library to generate the initial MAP message. USDOT developed this tool to assist users in producing the basic SAE J2735 MAP message for an intersection. TOSCo requires MAP elements that are beyond the basic MAP message. The creation of a MAP message using the tool follows a three-step process:

- Establish Reference Point at Intersection

- Create Initial MAP Configurations
- Add lane-level speed limit

The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides details on how the Project Team developed the MAP messages for the FM 1960 corridor.

TOSCo Infrastructure Data Logs

The Project Team developed several logs that provide information about the performance of the TOSCo infrastructure elements. The team developed these logs primarily for debugging and calibration purposes. The primary TOSCo infrastructure data logs include the following:

- Detector Status Log
- Queue Data Log
- Green Window Data Log
- SPaT Message Log
- SPaTTSC Data logs

The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides details for each of these data logs.

Field Deployment on FM 1960

The Project Team selected the FM 1960 corridor located in Houston, Texas to deploy TOSCo and to evaluate the potential benefits to be derived from the TOSCo system. The corridor along FM 1960 consists of 13 intersections between the Park at Humble to the east and Briarcreek Boulevard to the west covering about 6.6 miles and is shown in Figure 16. The corridor consists of two different signal timing plans, the split taking place between the Foxwood Forrest intersection (#109) and Lee intersection (#110). The posted speed limits range from 50 mph on the east end to 55 mph to the west. Most of the corridor has a posted speed of 55 mph. It takes about twelve minutes to drive from one end of the corridor to the other.

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

Figure 16. FM 1960 Corridor

The Project Team successfully deployed a prototype TOSCo system on FM 1960 in Houston, Texas and conducted a series of tests along FM 1960. Highlights of each test series are listed below.

Test 4.1 (58 Test Runs)

Test Highlights

- First nighttime testing on FM 1960
- Used latest stable vehicle software from Test 3
- Verified queue detection systems and message generation (single intersection runs)

Test 4.2 (109 Test Runs)

- Major vehicle software update (Risk Mitigation)

- Verified software release on RELLIS Campus before doing nighttime testing on FM 1960
- Set up different “queue scenarios” with manual vehicles on single intersections

Test 4.3 (61 Test Runs)

- Nighttime testing on full corridor
- Tested min/max recall performance and queue/GW algorithm

Test 4.4 (70 Test Runs)

- First day time testing on FM 1960
- Overall robustness tests

Test 4.5 (81 Test Runs)

- Benefits Assessment Data Collection + Final Demo
- Verified vehicle software functionality using “minEndTime” for GW_start estimation

The Project Team generated data for 379 test runs for each vehicle for a total of 1,516 test runs. Of these test runs, select data from the final performance verification testing for closed course, corridor and benefits estimation is posted and is available on the Virginia Tech Transportation Institute (VTTI) Dataverse.

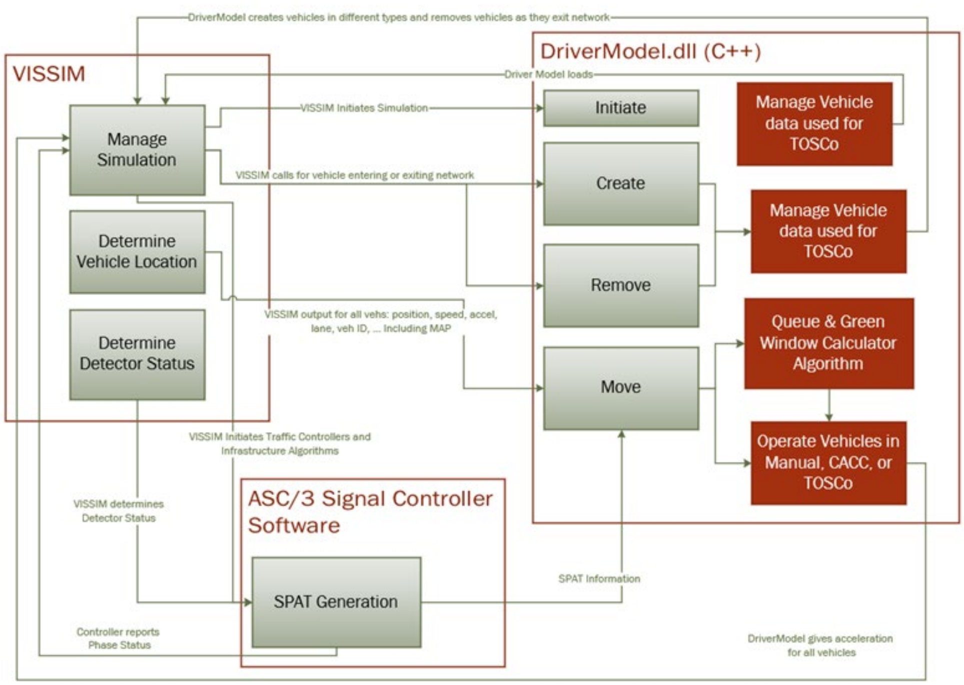
The TOSCo Phase 2 Infrastructure System Requirements and Architecture Specification Final Report provides details regarding traffic signal operations, MAP recalibrations, queue detection, detector zone configurations and calibrations and finally, the installation of the Green Window calibration parameters on the FM 1960 corridor.

Chapter 4. Assessing TOSCo Performance

The TOSCo Performance Assessment Environment uses source code from both vehicle and infrastructure alogirthms to represent TOSCo behavior. The resulting driver model was used to evaluate the performance of TOSCo by estimating potential benefits at a single intersection, corridor and network resolution. These benefits could include a reduction in emissions, fuel savings, and improved mobility. These performance measures were collected for different market penetration rates of TOSCo-enabled vehicles. The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM1960 Final Report provide details on the TOSCo simulation environment that the Project Team developed.

TOSCo Performance Assessment Environment

Figure 17 illustrates the architecture of the TOSCo Performance Assessment Environment used for Phase 2 simulations. The Project Team developed the TOSCo Performance Assessment Environment to evaluate the potential mobility and environmental benefits associated with TOSCo. The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM1960 Final Report provides a detailed walkthrough of the TOSCo performance assessment environment.



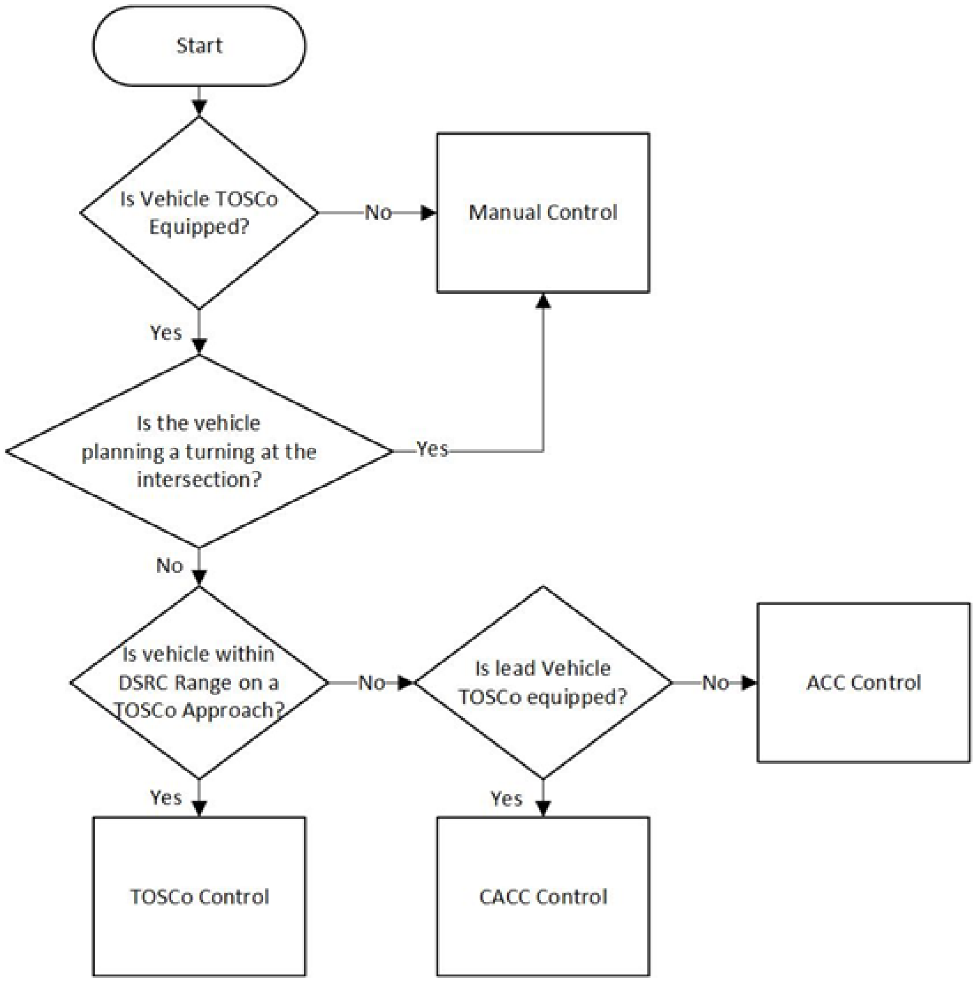
Source: Texas A&M Transportation Institute, 2022

Figure 17. Overall Performance Assessment Architecture

Modeling TOSCo Vehicle Behavior

The TOSCo vehicle algorithm in the performance evaluation simulation is a simplified version of the more detailed onboard sensing and computations of TOSCo as developed by CAMP. The process by which the VISSIM model controls vehicles entering the network through the DriverModel.dll is illustrated in Figure 18 below. The DriverModel.dll first checks to see if a vehicle generated by VISSIM is a TOSCo-equipped vehicle. Non-TOSCo vehicles operate under manual control. This mode utilizes the VISSIM default driver model for the vehicles driving behavior. The behavior of TOSCo vehicles in the simulation model depends on whether the vehicle is traveling through the approaching intersection, following a non-TOSCo vehicle or a TOSCo vehicle, and if the vehicle is within communication range of the upcoming intersection. The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides details of how vehicle behavior is modeled.

As part of the initial infrastructure simulations, the Project Team reevaluated some of the results and made some refinements associated with the default acceleration profile governing vehicle behaviors by enhancing the representation of non-TOSCo vehicles on the high-speed corridor. To accomplish this, the team designed an acceleration study to collect acceleration behaviors on the State Highway 105 corridor from the TOSCo Phase 1 Project and provided data needed to generate a revised acceleration distribution for the non-TOSCo vehicles within VISSIM. The Project Team used this revised acceleration distribution to evaluate the impacts of TOSCo compared to the refined representation of baseline traffic. The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides details of the traffic model calibration.



Source: Texas A&M Transportation Institute, 2022

Figure 18. Process for Determining Control Mode for Vehicles in the VISSIM Model

Modeling TOSCo Infrastructure Components

Infrastructure algorithms estimate the current queue lengths and calculate a green window for TOSCo strings at lane level (i.e., for each lane approaching the intersection). The infrastructure populates a portion of the SPaT messages with estimated parameters such as current queue length, beginning time of the Green Window, and end time of the green window, and transmits the data to approaching vehicles for their use in their trajectory planning. The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides a description of how the infrastructure algorithms generated SPaT, MAP and Green Window estimation data required for TOSCo.

Assessment Corridor

The Project Team developed a VISSIM microscopic model of a section of Texas Farm-to-Market (FM) 1960 in north Houston, Texas to investigate the potential mobility and environmental benefits associated with deploying TOSCo. The corridor consists of 13 intersections between Houston, Texas and Humble, Texas covering about 6.6 miles. The Texas Department of Transportation (TxDOT) operates all the intersections on this length of

FM 1960. The posted speed limit in most of the analysis corridor is 55 mph, with the easternmost two miles posted at 50 mph. It takes about twelve minutes to drive from one end of the corridor to the other. The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides a detailed list of the characteristics of each segment and each intersection in the FM 1960 corridor. All left turn movements at the intersections in this corridor are protected only. No permissive left turns are allowed at the intersections.

The Project Team used the mid-day traffic conditions (9 AM to 2 PM) to assess the potential mobility and environmental benefits of TOSCo. The Project Team used this period to be consistent with the evaluation period from which the field performance data were also collected. The Project Team also examined TOSCo performance over a range of market penetration rates (MPR) from 0 percent, also considered the baseline, to 100 percent. Below is a list of settings in the simulation used for this analysis:

- The corridor uses signal timing from the TxDOT Houston district to represent the FM 1960 corridor with minimum recalls placed on the non-coordinated phases.
- This model excluded truck volumes in the analysis. The truck percentage on FM 1960 was considered as a negligible percent of the traffic.
- Each simulation scenario has five simulation seeds to help account for randomness in the modelled background traffic.
- Each simulation run on FM 1960 is 3,600 simulation seconds of data collection with a 900 second warm-up period at the beginning of the simulation depending on the model. The corridor model has a total simulation time of 4500 seconds.

The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides a detailed examination of performance at a single Intersection, as well as for the entire corridor. The intersection at Foxwood Forest Boulevard (Intersection #109) was used for the single-intersection modelling.

Traffic-level Simulation Reassessments and Refinements

As part of the initial infrastructure simulations, the Project Team reevaluated some of the results and made some refinements associated with the default acceleration profile governing vehicle behaviors by enhancing the representation of non-TOSCo vehicles on the high-speed corridor. To accomplish this, the team designed an acceleration study to collect acceleration behaviors on the State Highway 105 corridor from the TOSCo Phase 1 Project and provided data needed to generate a revised acceleration distribution for the non-TOSCo vehicles within VISSIM. The Project Team used this revised acceleration distribution to evaluate the impacts of TOSCo compared to the refined representation of baseline traffic. The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides details of the traffic model calibration.

Performance Metric Selection

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

- Total Delay per vehicle
- Stop Delay per vehicle

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

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

Farm-to-Market 1960 Model Assessment

The simulations cover the off-peak period and cover a range of market penetration rates (MPR) from 0, also considered the baseline, to 100 % MPR of TOSCo. The off-peak period was used for the analysis because this is the time where the deployed version of TOSCo operated. Below is a list of settings in the simulation used for this analysis:

- The corridor uses signal timing from the TxDOT Houston district to represent the FM 1960 corridor with minimum recalls placed on the non-coordinated phases.
- This model excluded truck volumes in the analysis. The truck percentage on FM 1960 was considered as a negligible percent of the traffic.
- Each simulation scenario has five simulation seeds to help account for randomness in the model.
- Each simulation run on SH 105 is 3,600 simulation seconds of data collection with either a 300 or a 900 second warm-up period at the beginning of the simulation depending on the model. The single intersection model has a total simulation time of 3900 seconds and the corridor model has a total simulation time of 4500 seconds.

The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides a detailed examination of performance at a single Intersection, as well as for the entire corridor. The intersection at Foxwood Forest Boulevard (Intersection #109) was used for the single-intersection modelling.

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

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

- With default TOSCo settings, the eastbound total delay increases gradually but does not represent a large increase in the travel time associated with the trips. The westbound total delay decreases initially but has no significant changes at high-market penetration rates.
- Default TOSCo was able to achieve reductions in stop delay and number of stops depending on the market penetration rate. Stop delay decreased by around 50 percent across the corridor as TOSCo MPR increases. TOSCo vehicles had lower number of stops than the baseline traffic in simulation.
- TOSCo showed improved performance for each respective vehicle class with TOSCo-equipped as well as non-equipped, in total delay, and stop delay as market penetration increased on most of the approaches.
- TOSCo did not cause substantial changes in the total travel time for vehicles on the FM 1960 network.
- TOSCo temporarily increased fuel consumption. Fuel use gradually decreased from the 20 percent MPR scenario until reductions in fuel use compared to the baseline were achieved around 40 or 90 percent TOSCo MPR depending on the direction of travel. The research team believes that the increases in fuel are caused by the increased stops caused by the interactions between TOSCo vehicles.
- The default TOSCo generated little impact on user costs based on travel time and fuel use in the MPR scenarios considered for this study.

Altering TOSCo Operating Parameters

The Project Team performed a comparison study between what the team referred to as “Default TOSCo” and “Revised TOSCo. The differences between the two are illustrated below.

Table 5. Comparison of “Default” and “Revised” TOSCo Parameters

Parameter	Default TOSCo	Revised TOSCo
Communication Range	360 Meters	720 Meters
Speed Limit	Posted Speed Limit	ACC Set Speed
Enter Intersection on Yellow	Not Allowed	Allowed within 2 seconds

With the revised TOSCo, both directions experience gradual reductions in total delay until about 90 percent MPR where the westbound total delay begins to increase and exceeds the baseline westbound total delay significantly. This is a result from significant increases in total delay at intersection 102 and 103 where the westbound direction has some weaving related to vehicles attempting to turn at the grocery store to the north of FM 1960. The stop delay and number of stops each decrease as market penetration of TOSCo increases. Both directions experience a slight increase in number of stops between the baseline and 20 percent MPR and then gradually decreases as TOSCo MPR increases. These additional stops are brief as indicated from the lack of increase in stop delay.

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

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

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

- TOSCo reduced total delay in the eastbound and westbound directions with the revised TOSCo settings. However, the westbound total delay increased at high market penetration levels because of the difficulty experienced by turning vehicles attempting to change lanes to complete their maneuvers.
- TOSCo was able to achieve greater reductions in stop delay and number of stops with the revised TOSCo settings than the default settings. Stop delay decreased by around 50 percent across the corridor as TOSCo MPR increases.
- TOSCo showed greater improvements in performance for each respective vehicle class with the revised TOSCo settings compared to the default TOSCo settings in each performance metric.
- With the revised settings, TOSCo still did not cause substantial changes in the total travel time for vehicles on the FM 1960 network. The total travel time decreased slightly until 70 percent MPR, but the percent change was small.
- TOSCo increased fuel consumption initially and then reduced fuel consumption gradually as TOSCo MPR increased. The revised version of TOSCo experienced a maximum reduction in fuel use at 90 percent market penetration when the strings began to prevent turning traffic from completing their maneuvers. These reductions constituted a 16 percent reduction in fuel use for the eastbound direction and a 22 percent reduction in fuel use for the westbound direction.
- The revised TOSCo also temporarily increased fuel consumption, and fuel use gradually decreased from the 20 percent MPR scenario. The research team believes that the increases in fuel are caused by the increased stops caused by the interactions between TOSCo vehicles.
- The revised TOSCo has the potential to reduce user costs based on travel time and fuel costs especially in the mid ranges of TOSCo MPR considered for this study.

Field Benefits Estimate Results

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

The travel time results indicate that non-TOSCo vehicles traverse the corridor with less travel time than TOSCo vehicles. The difference in travel times for the eastbound direction are consistent with the differences in delays between TOSCo and non-TOSCo vehicles according to the The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report.

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

The Traffic Optimization for Signalized Corridors (TOSCo) Phase 2 Modeling & Benefits Estimation – FM 1960 Final Report provides a detailed analysis of these results.

Chapter 5. Functional Safety Concept

The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides an introduction to the technical scope of the TOSCo feature along with a background of the ISO 26262 processes for functional safety. The applicable safety relevant work products for ISO 26262 specific to the TOSCo Project included only the conceptual phase requirements. That included creating an item boundary surrounding the features and functions of TOSCo.

The Project Team created an Item Definition which considered assumptions of behavior of the system and listed out vehicle-level functions to be performed by the system. The safety development followed closely to the V-model of product development and was linked to the TOSCo System Specification and the System Architecture.

The Project Team completed a hazard analysis that included identification of malfunctions from the TOSCo feature and then identification of vehicle-level hazards. The Project Team identified the following four hazards.

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

The Hazard classification methods of ISO 26262 was 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 then developed a functional safety concept that utilized the parameters and guidelines of ISO 26262 to develop safety requirements and allocate them to the respective safety critical modules of the TOSCo feature. ASILs were assigned to each functional requirement along with identification of safe states, in case of a potential failure. These requirements focused on only one TOSCo boundary and its operating environment. The vehicle parameters that could be integrated to TOSCo were left generic in nature and could be applicable for any potential interface.

The functional safety requirements can be refined for more technical detail when the preliminary system design physical architecture is available. Safety mechanisms for the system components, requirements for the actual elements and interfaces, and the fault handling capabilities would be defined in the technical safety requirements during system design and implementation.

Finally, the Project Team performed a System Safety Analysis through a Fault Tree Analysis (FTA) for the overall physical system along with its external interfaces to verify the completeness and correctness of the functional safety requirements and verify the effectiveness of the safety mechanisms based on identified causes of faults and the effects of failures. The FTA also provided a complete traceability to the malfunctions of the hazard analysis and primary functions from the Item Definition.

Summary of Updates for Phase 2

Updates specific to Phase 2 of the TOSCo Project and changes and modifications that were made for the functional safety work products are listed below.

- Traffic Infrastructure Sub-system is now within scope of the TOSCo Item Boundary (including external influences on the system and communication channel with TOSCo vehicle).
- Updated Hazard Analysis identified highest ASIL criteria as ASIL D for “Excessive Acceleration” and “Insufficient Deceleration” hazard for a specific scenario where the TOSCo vehicle is “too close to the intersection.”
- Assumptions on infrastructure functionality (such as queue object detection, Green Window determination and their limitations) have been documented in the Hazard Analysis and Functional Safety Concept.

Summary of Safety Relevant Functionality for the Infrastructure Sub-system

- Queue detection and determination of queue by the infrastructure processor are identified to be non - safety critical and only provide enhancements and optimization to the TOSCo trajectory calculations.
- Common Time Source for Clock Synchronization shall be used by all infrastructure elements to ensure data accuracy.
- In the case of SPaT determination by the infrastructure, certain safety parameters have been considered to mitigate failure modes as follows:
    - Verification of Periodicity of valid SPaT within logical bounds
    - Accuracy of the content of the data elements
    - Verify if data elements are populated
- Green Window determination that does not match the expected periodic rates within tolerances result in loss of enhanced SPaT to the TOSCo vehicle(s).
- The MAP configuration is broadcasted periodically to the TOSCo vehicle.

No enhanced SPaT values are sent out to the TOSCo vehicle to indicate that TOSCo functionality needs to be disabled in case of identification of relevant safety critical faults (MAP, Green Window Prediction, Time Synchronization) in the infrastructure. The TOSCo vehicle shall transition to safe state based on this “undefined” value from the infrastructure

ISO 26262 Process Development

The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides a detailed explanation of the overall structure of the ISO 26262 standard and the portions relevant to the scope of the TOSCo Project Safety Lifecycle Process

The Project Team created three work products as required by the ISO 26262 standard to develop a concept phase version of the TOSCo feature that includes all the necessary functional safety attributes. These work products are:

A) Item Definition to define Safety Critical Functions of the TOSCo System

B) Hazard Analysis and Risk Assessment (HARA) to identify Vehicle-level Hazardous behavior caused by malfunctions

C) Functional Safety Concept to specify safety requirements and achieve fault tolerance or mitigation of relevant faults

As a verification that the three items above were concise, complete, and sufficient, a Safety Analysis of the TOSCo feature was conducted. The safety analysis used in the Phase 2 TOSCo development was a qualitative Fault Tree Analysis.

The role and contribution of each of these work products are described in detail in the TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report. The Concept Phase (Part 3) of the ISO 26262 Standard follows the engineering V-model, hence each work product must be performed in sequential order as the next work product builds off the previous work product.

Item Definition Development Process

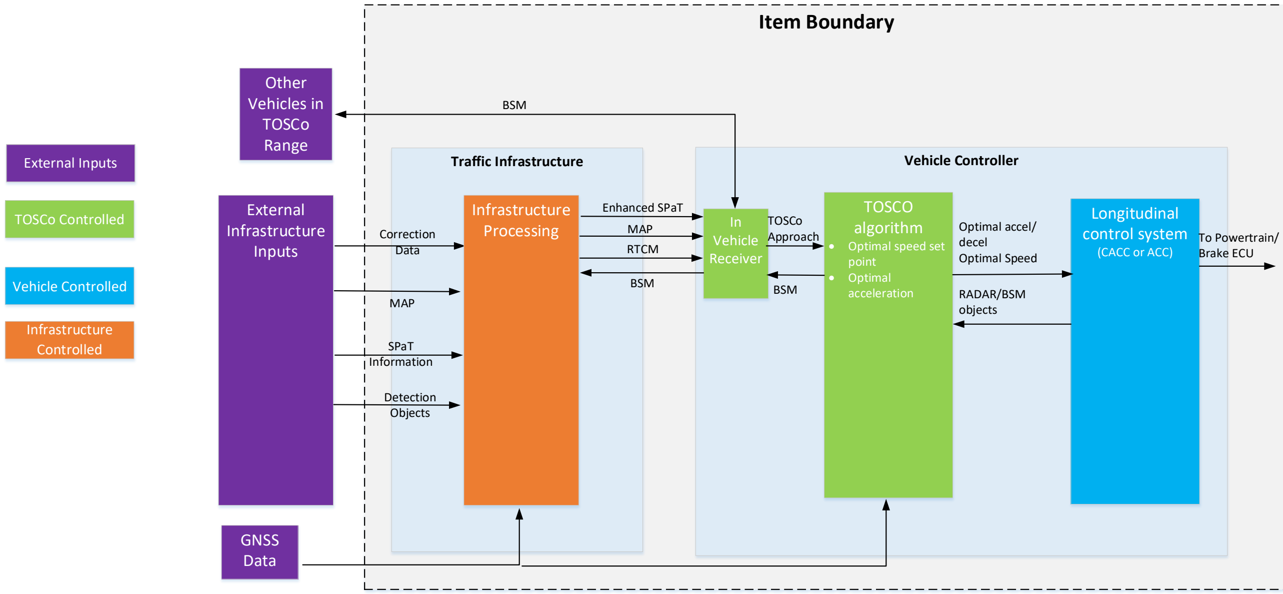
The purpose of the Item Definition is to define and describe the item including its functionality and any dependencies on or interactions with the driver, environment, and other items at a vehicle-level. Also, the Item Definition is developed to provide an adequate understanding of the item so that the activities in subsequent safety lifecycle phases can be performed.

The Hazard Analysis and Risk Assessment is the follow-on step that utilizes the Item Definition to determine hazards, risks, and necessary Safety Goals prior to kicking off the Functional Safety Concept also derived from the Item Definition.

The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides a detailed review of the item definition development process undertaken for the TOSCo Project.

Item Boundary

Figure 19 below specifies the boundary of the TOSCo item and its interaction with other components of the vehicle and infrastructure. The known system or item architecture, components, and interactions are shown at a high level. These provide a list of all elements, systems, and interfaces within the boundary of the item.



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

Figure 19. Preliminary Block Diagram of TOSCo Covered Under Functional Safety

Functions of the Item

The TOSCo Feature is comprised of functions from the perspectives of the infrastructure and the vehicle. Both are utilized together to implement a safe and controlled driving behavior as part of both individual vehicle and a vehicle string through a connected and TOSCo-equipped signalized corridor.

The Project Team identified nine vehicle functions and six infrastructure functions of the TOSCo Feature. These functions were utilized for identifying malfunctions and hazards at the vehicle level and are listed below.

Vehicle Functions

The following list the vehicle functions examined as part of the TOSCo Functional Safety analysis:

- Acquire target remote vehicle(s)
- Provide vehicle acceleration command
- Provide vehicle deceleration command
- Send/Receive communication between vehicle(s)
- Receive communication from Infrastructure
- Provide driver take-over request/ warning
- Allow driver take-over
- Provide the trajectory based on queue, Green Window and stop bar
- Receive GNSS Data for TOSCo vehicle(s)

Infrastructure Functions

The following lists the infrastructure functions examined as part of the TOSCo Functional Safety analysis:

- Collect BSM information from connected vehicles(s) when available (Not safety critical functionality)
- Provide information to TOSCo vehicle(s) (enhanced SPaT, MAP, RTCM, Security Credentials)
- Determine queue at the intersection (queue detections are not safety critical)
- Determine Green Window prediction based on queue information
- Establish communication with external infrastructure elements
- Receive GPS data for TOSCo infrastructure

Assumptions of Behavior of the Item

The following assumptions of behavior were generated by considering these conditions:

- TOSCo performance and behavior under different operational modes and operational states
- TOSCo behavior under different vehicle scenarios, environmental and roadway conditions, and external influences
- Expectation of TOSCo's behavior during maintenance, decommissioning, and repair
- TOSCo's behavior while entering or recovering from a safe state
- Interactions of TOSCo with other elements and items on-board the vehicle
- Interactions of other elements and components within the TOSCo item boundary

The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides a detailed review of the assumptions of behavior of the TOSCo Feature under various conditions and situations.

Hazard Analysis and Risk Assessment (HARA) Development Process

The purpose of the Hazard Analysis and Risk Assessment (HARA) is to identify and to categorize the potential vehicle-level hazards due to a malfunctioning behavior of the item and to formulate the safety goals related to the prevention or mitigation of the hazardous events in order to avoid unreasonable risk.

For this project, TOSCo was evaluated with regard to its potential hazardous events. Safety goals and their assigned ASIL are determined 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 tasks comprising a HARA are:

a. Situation analysis and hazard identification

b. Classification of hazardous events (determination of severity, probability of exposure and controllability ratings)

c. Determination of ASIL and related safety goals

The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides a detailed review of the HARA development process for TOSCo.

Hazard Analysis Operability (HAZOP) Study and Identification of Hazards

The primary functions from the item definition for the TOSCo Feature and the initial estimate of the malfunctions and hazards from item definition are utilized to initiate a Hazard Analysis Operability (HAZOP)

Study. The HAZOP is an explorative type of analysis where applicable guidewords are applied to each of the functions of an item to postulate malfunctioning behaviors.

The Project Team identified the following fifty eight malfunctions during the HAZOP study. The Project Team covered both vehicle and infrastructure-level functions. The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides a detailed matrix between the primary functions of the TOSCo feature that were identified from the item definition and a probable list of guidewords, which were utilized to develop the matrix of potential malfunctions.

[MF_1] Loss of Target Acquisition

[MF_2] False Positive Target Acquisition

[MF_3] Target Acquisition Stuck

[MF_4] Loss of Acceleration Command

[MF_5] Unintended Acceleration Command

[MF_6] Excessive Acceleration Command

[MF_7] Insufficient Acceleration Command

[MF_8] Loss of Deceleration Command

[MF_9] Unintended Deceleration Command

[MF_10] Excessive Deceleration Command

[MF_11] Insufficient Deceleration Command

[MF_12] Loss of Communication between Remote Vehicle(s)

[MF_13] Incorrect Communication between Remote Vehicle(s)

[MF_14] Loss of Communication from Infrastructure

[MF_15] Incorrect Communication from Infrastructure

[MF_16] Loss of Driver Take-over Request/Warning

[MF_17] False Driver Take-over Request/Warning

[MF_18] Loss of Driver Take-over

[MF_19] False Driver Take-over

[MF_20] Partial Drive Take-over

[MF_21] Inability to Follow Trajectory Leading to Loss of Determining Approach/Departure

[MF_22] Unintended Activation Leading to Significant Speed Differential between Vehicles in Queue

[MF_23] Wrong Approach/Departure Determination

[MF_24] Intermittent TOSCo Approach Based on Trajectory Calculation

[MF_25] Inability to Determine Vehicle Location and Time Values

[MF_26] Incorrect GPS Data Leading to Incorrect Determination of Vehicle Location and Time Values

[MF_27] Unstable GPS Data Leading to Incorrect determination of Vehicle Location and Time Values

[MF_28] Inability to Perform Trajectory Planning as the TOSCo Vehicle(s) Cannot Receive a Green Window

[MF_29] Inadvertent Activation of the TOSCo during the Wrong Scenario(s) Due to Unintended TOSCo Information from the Infrastructure

[MF_30] Vehicle Unable to Determine Speed Trajectory Due to Excessive SPaT Information from Infrastructure

[MF_31] Incorrect Enhanced SPaT Information Leading to Wrong Trajectory Planning

[MF_32] Intermittent Enhanced SPaT Information

[MF_33] Inability to Provide MAP Data to TOSCo Vehicle(s)

[MF_34] Incorrect MAP Data to TOSCo Vehicle(s) Leading to Inaccurate TOSCo Approach Determination

[MF_35] Delayed MAP Data to TOSCo Vehicle(s) Leading to Inability to Calculate Trajectory Planning

[MF_36] Wrong RTCM Message Leading to Inability to Calculate Vehicle Position

[MF_37] Delayed or Expired RTCM Message Leading to Inability to Determine Vehicle Position

[MF_38] Inability to Determine Queue Attributes (Length, Dispersal, etc.) at the Intersection

[MF_39] False Positive -- Queue Detected when None Exists

[MF_40] False Negative -- No Queue Detected when One Exists

[MF_41] Incorrect Queue Determination

[MF_42] Inability to Determine Green Window Leading to Inability to Plan Vehicle Trajectory

[MF_43] False Positive -- Provide Green Window when Not Intended

[MF_44] Determine Green Window More Often than Necessary, Leading to Inhibiting Enhanced SPaT Transmission

[MF_45] Determine Green Window Less Frequently, Leading to Inaccurate Determination of the Trajectory Planning

[MF_46] Incorrect Green Window Prediction A) Behind the Intersection or the Opposite Direction of the Intersection) Receive Green Window from the Wrong Lane

[MF_47] Determine Green Window Too Early, Leading to Inaccurate Determination of the Trajectory Planning

[MF_48] Determine Green Window Too Late, Leading to Inaccurate Determination of the Trajectory Planning

[MF_49.1] Determine Green Window Intermittently, Leading to Inaccurate Determination of the Trajectory Planning

[MF_49.2] Sudden Change in Green Window Prediction Leading to a Sudden Change in TOSCo Trajectory Causing a Vehicle Hazard (Not Safety Critical)

[MF_50] Loss of Correction Data Leading to Loss of RTCM at a Vehicle Level

[MF_51] Receive Corrupted Data (or Data Not Updated/Updated Data Not Utilized) Leading to Incorrect Determination of Vehicle Location

[MF_53] Loss of Queue Objects Leading to Inability to Predict Green Window

[MF_54] Incorrect Queue Objects Received Leading to Incorrect Queue Determination

[MF_55] Intermittent Queue Objects Received

[MF_56] Loss of MAP Data Leading to Loss of TOSCo Functionality *(Reliability Concern)*

[MF_57] Incorrect MAP Data Leading to Wrong Calculation of TOSCo Functionality

[MF_58] Inability to Determine Clock Data Leading to Inaccurate Time Values to TOSCo Vehicle(s)

[MF_59] Incorrect Clock Data Leading to Inaccurate Time Values to TOSCo Vehicle(s)

The Project Team then mapped to these malfunctions to the nine vehicle functions and the six infrastructure functions that the Project Team identified to distinguish vehicle-level hazards for the TOSCo Feature. From the HAZOP study, the Project Team identified the following hazards:

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

For the TOSCo Phase 2 Project, hazardous behavior of input processing of the Infrastructure, control logic and communication from the Infrastructure to TOSCo vehicles were evaluated. From the HAZOP study, the Project Team recorded the following observations:

- Infrastructure failure(s) usually lead to all hazards except for certain cases in queue length determination.

- Failure due to Enhanced SPaT (Green Window determination) and MAP have severe safety critical impacts from the infrastructure.

From these observations, a HARA can be performed for each of these four unique hazards. The HARA is an analysis procedure that identifies potential hazards, develops a set of specific hazardous events, and assesses the risk of each hazardous event to determine the ASIL and the safety goal. This is a four-step process that begins with determining the level of exposure to the hazard followed by a determination of the severity of the hazard. The controllability of the hazard is next determined followed by the determination of the Automotive Safety Integrity Level (ASIL) for the hazard.The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides a detailed walkthrough of this procedure.

Updated HARA Study for Phase 2. Identification of ASIL D Risk

During the TOSCo Phase 1 Project, the Project Team identified an ASIL C criterion for the TOSCo feature for excessive acceleration. During Phase 2 analysis, the Project Team identified certain corner case scenarios.

Scenario A: Vehicle is in TOSCo Mode, queue is absent, and no vehicle is in front. This is a Coordinated Stop. Vehicle Stopping on a RED light and further out of the intersection.

Analysis: The driver may not be able to distinguish between an unintended acceleration and intended acceleration as, from the driver's perspective, an unintended acceleration may be identical to the Speed Up case in CSC Mode. It will be too late for the driver to react towards the end of the intersection. General driver expectations of change in acceleration during a RED light including reaction times need to be evaluated.

Scenario B: Vehicle is in TOSCo Mode, queue is absent, and no vehicle is in front. This is in a Coordinated Speed Control. Vehicle Slow Down on a RED light.

Analysis: If the vehicle is in SLOW DOWN and vehicle accelerates, driver will not be sure if it intended SPEED UP or unintended acceleration until the vehicle is too close to the intersection, which will be difficult to avoid.

From observations made during on-road testing, normal operation of TOSCo has a tendency to ‘train’ the driver to trust the system that the traffic signal will be green when the vehicle arrives at the intersection regardless of the traffic signal state while approaching the intersection. Requirements specifically assigned as ASIL D are due to a scenario where the applicable failure (such as faulty Enhanced SPaT, MAP, or propulsion command) occurs and the hazardous situation of the vehicle being “too close to the intersection” with no queue present and the traffic signal is red. The hazard is determined at a location that does not allow the driver sufficient time to control the vehicle before running the red traffic signal and hence ASIL D is allocated to such faults and their corresponding safety mechanisms.

For Phase 2 of the TOSCo Project, the Project Team determined that the TOSCo controller and related safety critical components at the Vehicle and Infrastructure levels to be considered at ASIL D integrity.

To mitigate the risk of the driver not having time to react to a red signal during on-road operation, the Project Team developed a “virtual traffic cone” to provide the driver with an audible prompt when the vehicle was 90 meters from the intersection stop bar. This device stored GPS coordinates for points located 90 meters from the stop bars of each intersection on the corridor for both eastbound and westbound directions. When the TOSCo vehicle was within 90 meters of the stop bar, the virtual traffic cone wound generate an audible tone. Upon hearing the tone, the driver of the TOSCo vehicle could determine if the vehicle could safely pass through the intersection or if the driver needed to take action to stop the vehicle due to the broadcast of an incorrect phase (i.e., signal reporting green phase in SPaT message when the signal was actually red). It should be noted that although the Project Team took this precaution, no driver ever had to take control to stop the vehicle due to the vehicle not responding properly to an incorrect SPaT message.

Functional Safety Concept

The purpose of the Functional Safety Concept (FSC) is to derive the functional safety requirements from the safety goals and allocate them to the preliminary architectural elements of the item, or to external measures. To comply with the safety goals, the FSC contains safety measures, including the safety mechanisms, to be implemented in the item's architectural elements and specified in the functional safety requirements. The functional safety concept addresses the following:

- Occurrence of fault and degradation of functionality when fault has occurred
- At vehicle level, how the timing requirements are met i.e., how the fault tolerant time interval shall be met by defining a fault handling time interval
- In case of occurrence of fault, the driver warnings needed to increase the controllability by the driver
- In case of occurrence of fault, the warnings that the driver should get for reduction of the risk exposure time to acceptable duration
- Fault detection and failure mitigation
- Transitioning to a safe state, if applicable from a safe state
- Fault avoidance and fault tolerance mechanisms, where a fault does not lead directly to the violation of the safety goal(s) and which maintains the item in a safe state (with or without degradation)
- Arbitration logic to select the most appropriate control requires from multiple requests generated simultaneously by different functions

Functional Safety Strategy

The TOSCo Feature Functional Safety Strategy considers the traffic Infrastructure portion, the communication path to the TOSCo vehicle(s) and the TOSCo Algorithm within the TOSCo vehicle(s). The Safety Strategy also includes external inputs to the Infrastructure and the TOSCo vehicle(s) that are responsible to ensure a safe TOSCo trajectory when the TOSCo vehicle is within range of the TOSCo intersection. Inputs from the Item Definition and the Hazard Analysis are considered to refine the preliminary safety architecture and develop functional safety requirements for both the Infrastructure and the Vehicle portion, including the safety communication path between the two control systems. The Functional Safety Requirements were derived based on a Fault Tree Safety Analysis performed at a feature level for the TOSCo Feature. A traceability structure has been established between the Fault Tree Analysis and the Functional Safety Requirements where the Fault Tree events have been associated to the requirements. This provides the ability to derive safety requirements from the identified malfunctions and failure modes from the Hazard Analysis as well as from the safety measures identified from the Fault Tree Analysis.

Functional Safety Requirements

Based on the functional safety strategy and the requirements of the ISO standard, the Project Team derived functional safety requirements for each of the safety critical modules of the TOSCo Feature. The requirements derived are listed below. The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides greater detail for each functional safety requirement.

Requirements for Driver Confirmation to TOSCo Vehicle

TOSCO_Veh_01.1 The TOSCo Algorithm shall utilize redundant input processing to identify driver input for activation and deactivation transitions.

TOSCO_Veh_01.2 The TOSCo Algorithm shall utilize redundant input processing to identify driver confirmation input for transition to the Coordinated Launch and Creep operating modes.

TOSCO_Veh_01.3 The longitudinal control system (TOSCo and CACC) shall cede control to the driver on driver intervention (such as accelerator pedal or brake pedal input).

TOSCO_Veh_01.4 If the TOSCo algorithm identifies a faulty driver confirmation to activate TOSCo, then TOSCo function shall be disabled.

TOSCO_Veh_01.5 In case the TOSCo feature is unable to transition to Free Flow when a lead vehicle is present and TOSCo disables due to the detection of a Driver Confirmation fault, TOSCo shall still be able to warn the driver to take over

TOSCO_Veh_01.6 In case the TOSCo feature is unable to transition to Manual mode when no lead vehicle is present and TOSCo disables due to the detection of a Driver Confirmation fault, TOSCo shall still be able to warn the driver to take over.

Requirements for Communication with External Vehicle Inputs

TOSCO_Veh_02.1 TOSCo feature shall communicate with the external vehicle controllers (such as ABS, TCU) for safety critical inputs over an end-to-end protected channel.

TOSCO_Veh_02.2 If the TOSCo feature determines that an external, safety critical, vehicle input to TOSCo is invalid due to communication channel errors (data errors, out of order messages, time out, masquerading, etc.), then the TOSCo Algorithm shall disable the TOSCo function and transition to ACC when a lead vehicle is present or Manual mode if no lead vehicle is present depending on the failure mode.

TOSCO_Veh_02.3 TOSCo feature shall disable TOSCo function if it detects a TOSCo activation input that is STUCK ON.

Safety Requirements for Communication with Remote Vehicles

TOSCO_Veh_03.1 The TOSCo Vehicle Algorithm shall identify faulty elements in the BSM information corresponding to plausibility issues with remote target vehicles that could compromise string stability by comparing received BSM inputs and sensor data.

TOSCO_Veh_03.2 The OBE of the TOSCo vehicle shall incorporate end-to-end protection to ensure valid BSM messages are communicated between remote target vehicle(s).

TOSCO_Veh_03.3 If the TOSCo Algorithm determined invalid BSM information corresponding to remote target vehicles, the TOSCo Algorithm shall revert to ACC when a lead vehicle is present or Manual mode if no lead vehicle is present depending on the failure mode.

Safety Requirements for Receiving Communication from Infrastructure (Enhanced SPaT and MAP)

TOSCO_Veh_04.1 The TOSCo vehicle OBE shall receive Enhanced SPaT messages to the vehicle over an end-to-end protection channel.

TOSCO_Veh_04.2 The OBE on the TOSCo vehicle shall be capable to receive updated MAP data from the Infrastructure over an end-to-end protected channel.

Safety Requirements for GPS Reception for TOSCo Vehicles

TOSCO_Veh_05.1 If the TOSCo Algorithm determines that the HDOP (Horizontal Dilution of Precision) measurement for GPS position exceeds a specified threshold where vehicle location cannot be determined accurately, the TOSCo feature shall be turned OFF and driver shall be notified.

TOSCO_Veh_05.2 If the TOSCo vehicle receives unstable GPS or cannot determine vehicle location and time values, then the TOSCo vehicle shall transition to ACC when a lead vehicle is present or Manual mode if no lead vehicle is present depending on the failure mode and provide a driver warning.

Safety Requirements for Driver Take Over from TOSCo

TOSCO_Veh_06.1 If the TOSCo vehicle is unable to allow driver to take complete control of vehicle from TOSCo mode when needed, the driver shall be provided with an independent means to disable TOSCo function that is outside the primary control path of TOSCo.

TOSCO_Veh_06.2 If the vehicle hands over control to the driver without a warning or request from driver, the vehicle shall continue normal operation.

Safety Requirements for Valid Trajectory Calculation for TOSCo Vehicles

TOSCO_Veh_07.1 The TOSCo controller shall be incorporated with a Safety Monitor that shall be able to detect all internal single point faults due to random hardware faults or systematic software faults that could lead to invalid vehicle trajectory calculation.

TOSCO_Veh_07.2 If the Safety Monitor of the TOSCo Feature detects hardware or software faults that could result in an invalid trajectory calculation, then the TOSCo feature shall be deactivated.

TOSCo_Veh_07.3 If the TOSCo Vehicle requests the "Creep" function and either of the following occur while in CREEP:
A) An acceleration of more than CREEP_MAX_ACC m/s2 is requested
B) A creep speed greater than maximum creep speed (CREEP_MAX_SPD m/s) is requested then the TOSCo vehicle transition to or remain in STOPPED, until the next valid CREEP function request is received.

TOSCO_Veh_07.4 TOSCo shall not allow vehicle movement beyond the stop bar when in Coordinated Stop or CREEP modes.

TOSCO_Veh_07.5 TOSCo feature shall limit the maximum acceleration and deceleration requests to CACC to TOSCo_MAX_ACCEL or TOSCo_MAX_DECEL (e.g., +/-0.3*g).

TOSCO_Veh_07.6 TOSCo feature shall be disabled in case the vehicle speed goes above TOSCO_SPEED_LIMIT mph (e.g., 55 mph) inside the TOSCo range.

TOSCO_Veh_07.7 If a forbidden state transition is attempted, then TOSCo shall warn the driver and transition to ACC when a lead vehicle is present or Manual mode if no lead vehicle is present, depending on the current operating mode and driving scenario.

TOSCO_Veh_07.8 Before entering CLAUNCH on a valid GREEN window, if a driver authorization is not received when in CREEP mode, the TOSCo controller shall transition to STOPPED within:
a) Minimum stop distance if a preceding vehicle is present
b) Minimum stop distance of stop bar if no preceding vehicle is present

Safety Requirements for Propulsion Commands from TOSCo Vehicle(s)

TOSCO_Veh_08.1 A central arbitration control system shall process valid acceleration or deceleration values to be sent out from both the TOSCo and the CACC Controller by determining the most conservative propulsion command from each of the two longitudinal controllers.

TOSCO_Veh_08.2 In the case the central arbitration controller determines an invalid propulsion command from either of the two longitudinal controllers, TOSCo Feature shall be disabled, and if required, disable CACC operation depending on the operating scenario.

Safety Requirements for Providing Driver Take-over Requests or Warning

TOSCO_Veh_09.1 The TOSCo controller shall provide independent means to warn the driver to take over in the event that the TOSCo controller is unable to provide driver take over request during safety critical operating scenarios.

TOSCO_Veh_09.2 TOSCo feature shall ensure the driver is warned whenever there is a transition to Safe State due to a detected fault.

Safety Requirements for GPS Time Synchronization for Infrastructure

TOSCo_Inf_10.1 A common time source shall be utilized for all TOSCo infrastructure components within a safe threshold or margin to ensure time synchronization.

TOSCo_Inf_10.2 The TOSCo infrastructure system shall detect when the clock is not synchronized among the infrastructure components which can lead to inaccurate time values.

TOSCo_Inf_10.3 Upon detection of clock synchronization failure, the TOSCo Infrastructure System shall define the TOSCo Enhanced SPAT data elements as “undefined.”

Safety Requirements for RTCM data and Security for Infrastructure

TOSCo_Inf_12.1 The Infrastructure System shall determine the position correction information (RTCM) transmission validity by applying it to the infrastructure receiver before sending it to the vehicle.

TOSCo_Inf_12.2 Upon detection of invalid correction information from the RTCM generator, the Infrastructure System shall not broadcast the correction data to the TOSCo vehicle.

TOSCo_Veh_12.3 When the TOSCo vehicle does not receive RTCM data, the vehicle positioning system shall revert to WAAS corrections and evaluate positioning quality.

Safety Requirements for Receiving SPaT Information to Infrastructure

TOSCo_Inf_13.1 The TIP of the Connected Infrastructure shall monitor loss of SPaT information provided by the TSC to detect communication issues.

TOSCo_Inf_13.2 The TIP of the Connected Infrastructure shall verify the content of the SPaT data elements provided by the TSC to ensure the data is within reasonable and safe limits.

TOSCo_Inf_13.3 If the Spat information is lost or not within reasonable and safe limits form the TSC of the Connected Infrastructure, then the SPaT information shall be sent as not available to the TOSCo vehicles.

TOSCo_Inf_13.4 If the TIP from Infrastructure system detects faults in the queue message data (wrong queue objects), then the Connected Infrastructure shall indicate that the queue and green window portions of the Enhanced SPaT message is invalid to the TOSCo vehicles.

Safety Requirements for MAP Configuration for Infrastructure and MAP Messages Sent Between TOSCo Infrastructure and TOSCo Vehicle(s)

TOSCo_Inf_14.1 The TSC shall indicate to the RSU which MAP to broadcast to the vehicle for use.

TOSCo_Inf_14.2 The infrastructure operator shall verify the proper MAP creation and configuration using systematic processes.

TOSCo_Inf_14.3 The infrastructure operator shall verify the proper implementation of the created map on infrastructure using systematic processes.

TOSCo_Inf_14.4 The infrastructure operator shall routinely verify the Configured MAP data to ensure consistency with the desired operation of the traffic signal and the traffic signal timing plans.

TOSCo_Inf_14.5 If the TSC doesn’t indicate to the RSU which map to use at the appropriate periodic rate, then the RSU should not send any MAP data to the vehicle(s).

TOSCo_Inf_Veh_14.6 If the TOSCo Vehicle OBE stopped receiving MAP message (or never received a MAP message) from the RSU when vehicle is in TOSCo range, then the TOSCo feature shall be disabled and the vehicle transitions to ACC or Manual mode depending on the failure mode and operating scenario.

Safety Requirements for Enhanced SPaT Message Generation

TOSCo_Inf_15.1 The TIP of the Connected Infrastructure shall verify the data elements in the processing of the Enhanced SPaT generation that could lead to the inability to determine Green Window.

TOSCo_Inf_Veh_15.2 The OBE of TOSCo vehicle(s) shall verify if Enhanced SPaT message from the infrastructure is updated at defined regular intervals to ensure if the information about queue objects and Green Window is up to date.

Safety Requirements for Green Window Determination at TOSCo Infrastructure and Safety Requirements for Communicating Enhanced SPaT Message to TOSCo Vehicle(s)

TOSCo_Inf_16.1 The TIP of the connected Infrastructure System shall detect incorrect or intermittently generated Green Window information by performing periodic post-processing checks of the predicted and actual Green Window outputs.

TOSCo_Inf_16.2 If the TIP of the Infrastructure system identifies an incorrect or intermittent Green Window value between the actual and predicted outputs for Green Window calculation, the resultant Green Window shall be designated as invalid by TIP.

TOSCo_Inf_16.3 The TIP of Infrastructure system shall detect aged or slow Green Window generation outside of expected periodic transmission rate design parameters.

TOSCo_Inf_16.4 If the Green Window is determined less frequently (aged or slow), i.e., the time interval between successive Green Window updates is beyond an acceptable threshold, then the TIP system shall send Green Window as invalid in the Enhanced SPaT messages to the TOSCo vehicle.

TOSCo_Inf_16.5 The TIP of the connected Infrastructure System shall utilize a Safety Monitor to detect and verify Green Window being provided more often than necessary.

TOSCo_Inf_16.6 The TIP of the connected Infrastructure System shall utilize a Safety Monitor to detect and verify for invalid Enhanced SPaT Messages.

TOSCo_Inf_16.7 If the TIP has detected Green Window being calculated too frequently or Enhanced SPaT is invalid, then the TIP shall indicate the GW info as invalid in Enhanced SPaT Message to the RSU.

TOSCo_Inf_16.8 If the Green Window is determined too late or is missing from the TIP of Infrastructure System, then the TIP shall indicate the GW info as invalid in Enhanced SPaT Message to the RSU.

TOSCo_Inf_Veh_16.9 If the TOSCo vehicle receives an Enhanced SPaT message without Green Window information (does not receive Enhanced SPaT message), then the vehicle shall transition to ACC or Manual depending on the failure mode by deactivating TOSCo.

Functional Safety Analysis

Scope of Fault Tree Analysis for TOSCo

The Project Team developed separate fault trees for each of the safety goals. A Fault Tree Analysis was conducted for SG 01 *"Prevent Incorrect Excessive Acceleration Due to Malfunctions in TOSCo"* and then two more FTAs were performed for SG02 *"Prevent Incorrect Insufficient Deceleration Due to Malfunctions in TOSCo"* and SG03 *"Prevent Incorrect Excessive Deceleration Due to Malfunctions in TOSCo"* based on the results from SG01. The malfunctions from the Hazard Analysis were used as the primary inputs to identify failure events for the Fault Tree for both the Vehicle System and the Infrastructure System. Safety Measures for mitigating each of the failure events were also documented throughout the fault tree development process.

The fault tree analysis was performed using the Medini Analyze software. The TOSCo Phase 2 Functional Safety Concept and Hazard Analysis Final Report provides excerpts from the Fault Tree Analysis and relevant event pages from Medini Analyze for SG01 along with the chain of failure events from the top events (vehicle hazard) to the basic events (individual failure mode).

Development of FTA

For the Project Team to construct an FTA for the TOSCo system, the followings steps were performed:

1. Define top-level events for FTA.
2. For each top-level event (one for each safety goal), the sources of failure modes from the TOSCo Infrastructure System and TOSCo vehicle(s) were identified.
3. For TOSCo Vehicle and TOSCo Infrastructure Systems, failure events with respect to input processing, control logic and output behavior were considered for the intermediate level events of the fault tree.
4. The intermediate events were further broken down to the malfunctions and repeated the process until the events cannot be broken down further.
5. A safety mechanism was proposed for each failure event and merged into existing fault trees.
6. A concise Fault Tree Analysis was performed for SG02 and SG03 based on the results of the Fault Tree Analysis for SG01.

Findings from the FTA

The following are the findings from the Fault Tree Analysis:

- The safety measures identified to mitigate specific safety critical failure modes for both the vehicle and the infrastructure do not specify a physical architecture or solution on a component to achieve diagnostics, rather a methodology is proposed to identify the safety parameters for each failure modes and a design independent strategy is documented as a mitigation measure. The vehicle integrators would use these recommendations to determine their own architectures and safety solutions as per the relevant ASIL criteria.
- In case of driver confirmation, it was identified that separate sub fault trees need to be developed for:

  - Events towards faulty activation of CLAUNCH or CREEP
  - Events towards unintended activation of the TOSCo System

- The Safe State allocated for various failure modes needs to be evaluated with respect to the underlying TOSCo vehicle scenario as well to understand whether the vehicle needs to transition to Free Flow (CACC), Manual Mode (Transition to Driver) or ACC (expect other collision avoidance systems to mitigate hazards).

- In certain cases, if the TOSCo vehicle is unable to transition to Safe State, it is expected that the driver is still informed or warned to ensure the system is taken to some relevant emergency operation that is within driver control.

- The Fault Tree Analysis identified certain safety critical vehicle functions that are documented in the revised Item Definition. These include the following:

  - Driver inputs to TOSCo Vehicle
  - Communicate with external inputs (vehicle speed, PRNDL) to TOSCo vehicle
  - Receive Clock Data from External GPS

- External Safety critical inputs to the TOSCo vehicle were identified as follows:

  - Vehicle Speed
  - Vehicle Transmission (PRNDL) State
  - Vehicle Gear State
  - Accelerator Pedal or Brake Pedal Input
  - TOSCo Activation by the driver

- The current design does not have provision for detecting and controlling incorrect GPS faults. Hence, a safety requirement has been allocated to the HDOP measurement for GPS position to ensure the system does not exceed its tolerable thresholds of accuracy.

- It is assumed that if the BSM is not available from a particular vehicle, the other vehicles in the string would re-adjust trajectory depending on their current position in the queue.

- For safety relevant communication from the Infrastructure (MAP), the vehicle does not have the capability to determine MAP accuracy. It is dependent on the Infrastructure to send out an “undefined” or “no” data for the vehicle to transition to Safe State.

- Evaluation of Correction Data for safety criticality shall be considered during Vehicle Build and Test. It should be noted that the RTCM generator cannot know if the correction data is valid or not. A safety mechanism is not currently identified.

- The Connected Infrastructure shall verify the data elements in the processing of the Enhanced SPaT generation by monitoring the frequency and accuracy of the Green Window that is sent out to the TOSCo vehicle(s).

Future Actions

The Project Team prepared a list of future actions related to the TOSCo functional safety analysis.

- Safety “performance” parameters with appropriate safety threshold(s)/margin(s) need to be completely identified for all functional safety requirements for test, design, and validation purposes.
- Hazardous Behavior of TOSCo due to System Performance Limitations based on Safety of the Intended Functionality (SOTIF) may be considered in the next iteration of safety analysis..

Chapter 6. References

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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
CSC	Coordinated Speed Control
CV	Connected Vehicle
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
FF	Free Flow Mode
FHWA	Federal Highway Administration
FSC	Functional Safety Concept
FTA	Fault Tree Analysis
GPS	Global Positioning System
HARA	Hazard Analysis and Risk Assessment
HAZOP	Hazard Analysis Operability
HDOP	Horizontal Dilution of Precision
HMI	Human Machine Interface
HV	Host Vehicle
I2V	Infrastructure-to-Vehicle
ITS	Intelligent Transportation Systems
LV	Lead Vehicle

MAP	SAE J2735 Map Message
MOVES	MOtor Vehicle Emission Simulator
MPR	Market Penetration Rates
NDD	Naturalistic Driving Data
NPMRDS	National Performance Management Research Data Set
NTCIP	National Transportation Communications for Intelligent Transportation System Protocol
OEM	Original Equipment Manufacturer
PTLM	Phase-to-Lane Movement
RELLIS	Respect Excellence Loyalty Leadership Integrity Service
RSE	Roadside Equipment
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
SAE	SAE International
SOTIF	Safety of the Intended Functionality
SPaT	Signal Phase and Timing
SPMD	Safety Pilot Model Deployment
SST	Small-Scale Test
TCP	Transmission Control Protocol
TOSCo	Traffic Optimization for Signalized Corridors
TSC	Traffic Signal Controller
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
UDP	User Datagram Protocol
UMTRI	University of Michigan Transportation Research Institute
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

VISSIM	Verkehr In Städten – SIMulationsmodell (A Traffic Flow Simulation)
VTTI	Virginia Tech Transportation Institute
V2X	Vehicle-to-Everything

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