Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project

Infrastructure System Requirements and Architecture Specification Report

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16. Abstract

This document specifies the infrastructure design requirements, architecture, and data processes developed in Phase I of the TOSCo Phase 1 Project.

It provides the following:

- High-level requirements of the hardware and software components that reside on the infrastructure side of the queue
- Descriptions of data elements that communicate the data needed by TOSCo-equipped vehicles to plan their speed profiles as they are approaching as TOSCo-enabled intersection
- Descriptions of processes developed by the development team to produce those data elements

These processes and data element may be refined as the development team transitions from proof-of-concept testing to field demonstration.

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1 Introduction

The Traffic Optimization for Signalized Corridors (TOSCo) system is a series of innovative applications designed to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based connected-vehicle communications to assess the state of vehicle queues and cooperatively control the behavior of strings of equipped vehicles approaching designated series of signalized intersections to minimize the likelihood of stopping. Along with Signal Phase and Timing (SPaT) and intersection map (MAP) data, information about the state of a queue, if present, is continuously recomputed and broadcast to approaching connected vehicles. Leveraging previous Crash Avoidance Metrics Partners LLC (CAMP)/Federal Highway Administration (FHWA) work on cooperative adaptive cruise control, approaching vehicles equipped with TOSCo functionality use this real-time infrastructure information to plan and control their speeds to enhance the overall mobility and reduce emissions outcomes across the corridor. This document focuses on the development of the infrastructure-side algorithms required to realize TOSCo functionality along an equipped corridor.

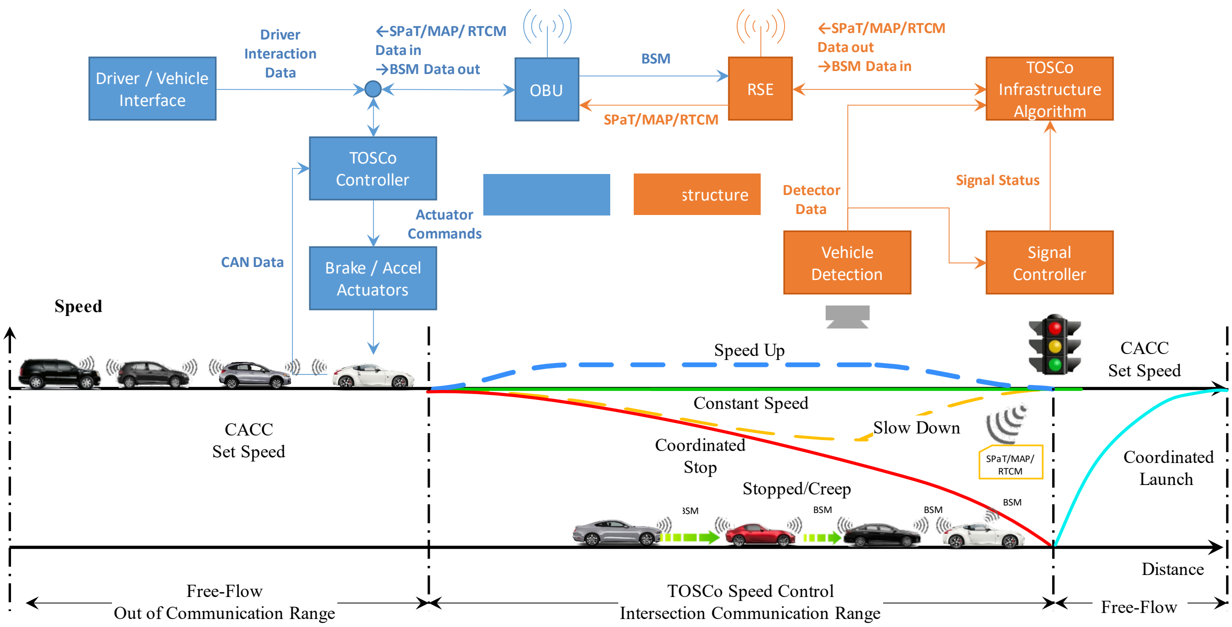
Figure 1 provides a high-level illustration of the overall TOSCo system concept of operations. The TOSCo system uses a combination of infrastructure- and vehicle-based components and algorithms along with wireless data communications to position the equipped vehicle to arrive during the "green window" at specially designated signalized intersections. The vehicle side of the system uses applications located in a vehicle to collect SPaT and MAP messages defined in SAE standard J2735 using vehicle-to-infrastructure (V2I) communications and data from nearby vehicles using vehicle-to-vehicle (V2V) communications. The applications also introduced a new SPaT regional extension, used to convey information about the "green window" to individual vehicles. The "green window," computed by the infrastructure, is based on the estimated time that a queue will clear the intersection during the green interval. Upon receiving these messages, the individual vehicles perform calculations to determine a speed trajectory that is likely to either pass through the upcoming traffic signal on a green light or decelerate to a stop in an eco-friendly manner. This onboard speed trajectory plan is then sent to the onboard longitudinal vehicle control capabilities in the host vehicle to support partial automation. This vehicle control leverages previous work to develop cooperative adaptive cruise control (CACC) algorithms.

1.1 Scope

This document specifies the infrastructure design requirements, architecture, and data processes developed in Phase I of the TOSCo deployment project. It provides the following:

- High-level requirements of the hardware and software components that reside on the infrastructure side of the queue (the orange boxes shown in Figure 1)
- Descriptions of data elements that communicate the data needed by TOSCo-equipped vehicles to plan their speed profiles as they are approaching as TOSCo-enabled intersection
- Descriptions of processes developed by the development team to produce those data elements

It should be noted that these processes and data element may be refined as the development team transitions from proof-of-concept testing to field demonstration.



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

Figure 1: TOSCo System Architecture

1.2 Organization of the Report

This report is organized as follows:

- Chapter 2 provides a high-level description of the system requirements and architectures for the TOSCo infrastructure components
- Chapter 3 provides a description to the processes used to provide queue information and compute the green window
- Chapter 4 provides a description of the data elements for communicating needed infrastructure-based information to TOSCo vehicles

2 Infrastructure System Requirements and Architecture

This chapter provides a brief introduction to define the infrastructure requirements to include the following:

- Infrastructure Requirements
- Infrastructure System Architecture

2.1 TOSCo Infrastructure System Requirements

To deploy a TOSCo system, several requirements need to be met by the infrastructure. Those requirements are listed in Table 1 below.

Table 1: TOSCo Infrastructure-side Requirements

Summary	Description
Transmission of SPaT/MAP (J2735 – Appendix H : MAP and SPaT Message Use and Operation)	• Every intersection in a corridor defined as TOSCo-enabled shall transmit SPaT and MAP through DSRC • Each intersection in the corridor shall transmit the Intersection ID and the approaching LaneIDs of the next downstream intersection in each direction • The MAP message shall contain grade data for the approach to the current intersection
TOSCo Supported Locations	• Each TOSCo supported approach at an intersection shall have the ability to measure actual queue lengths in real-time
Reception and Decoding of BSM	The infrastructure shall be able to receive and decode the BSM (including the BSM extension which contains a flag indicating that a vehicle is TOSCo enabled) • The infrastructure shall be able to distinguish TOSCo-equipped vehicles from CACC-enabled vehicles or regular Connected Vehicles (CVs) • The infrastructure shall be able to identify whether the BSMs are within the geo-fence range of current intersection • The infrastructure shall be able to identify whether the received BSMs are originating from vehicles traveling on the TOSCo-equipped corridor • The infrastructure shall be able to locate each received BSM on the map and calculate additional information such as distance to stop bar, estimated time of arrival, requested SPaT, and approach states (approaching current intersection, leaving current intersection)

Summary	Description
Sensor Requirements for Queue Determination	The infrastructure shall be equipped with vehicle detectors that provide lane-level traffic data such as volume and occupancy • The infrastructure shall be able to identify the status of each detector • The vehicle detectors shall be able to provide data every 1 second
Adjusting Signal Phase	• If appropriate, the infrastructure may use information from vehicles to adjust its signal phase (sequence) and timing parameters to accommodate TOSCo-equipped vehicles approaching the intersection
Generation and Transmission of Target Window Information for each Lane	The infrastructure shall provide the TOSCo-equipped vehicle a target window of time • The beginning of the green window shall be the time when current queue is estimated to clear at the stop bar of the approaching intersection • The end of the green window shall be the end of the current green phase • The infrastructure shall update the target green window data every second (1Hz)
Generation and Transmission of Queue Information	The infrastructure shall be able to provide approaching TOSCo-equipped vehicles with information related to the location of the queues present at the intersection. A TOSCo-equipped vehicle is defined to be in a “queued” state when its distance to the preceding vehicle is less than or equal to 6.1 meters (20 ft) AND when its speed is less than or equal to 2.24 m/s (5 mph). • The infrastructure shall have the capability of providing queue information by lane for each approach to support TOSCo • The infrastructure shall provide the TOSCo-equipped vehicle with updated queue information every second • The infrastructure shall provide the TOSCo-equipped vehicle the current location of the back of the queue relative to the stop bar of the intersection, measured in meters • The infrastructure may provide the TOSCo-equipped vehicle with an estimate of the time when the predicted maximum length of queue (in meters) will clear the intersection • If the infrastructure is unable to estimate the queue, the infrastructure shall not broadcast SPaT and MAP messages • The infrastructure shall be capable of fusing information from vehicle BSM data with information obtained from the infrastructure-based detection systems to determine the location of the back of queue
Advanced Traffic Signal Controller	• The traffic signal controller shall provide the TOSCo system with status of each phase at a frequency of 10 Hz • The infrastructure shall have the capability of providing the time to change in phase state for each phase at a frequency of 10 Hz
Road-side Unit (RSU)	• The RSU shall be able to receive the signal data and broadcast in SAE J2735 SPaT format • RSU shall be able to read a local map description file and broadcast in SAE J2735 MAP format • RSU shall be able to receive, and decode, BSMs from connected vehicles (including TOSCo vehicles)

Summary	Description
	• The RSU shall be able to make any received BSMs available to the TOSCo System • RSU shall be able to broadcast customized DSRC messages (e.g., SPaT regional extension)
Road-side Processor (RSP)	RSP holds the infrastructure algorithms • RSP shall be able to estimate queue length and calculate green window based on received BSMs

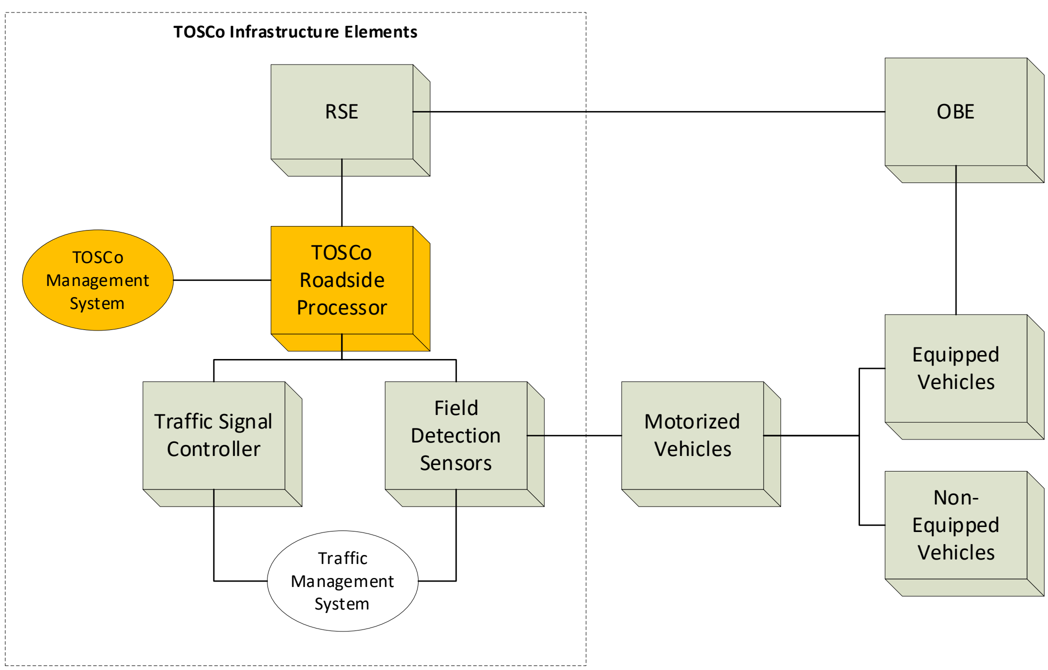
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

2.2 TOSCo Infrastructure System Architecture

The TOSCo system includes both vehicle and infrastructure elements. This section provides a description of both the physical and software components of the TOSCo Infrastructure elements. A high-level description of the TOSCo vehicle elements is contained in the Traffic Optimization for Signalized Corridors (TOSCo) Vehicle System Requirements and Architecture Specification [2]

2.2.1 Physical Components

Figure 2 shows the physical components of the TOSCo System. Each box represents a physical entity in the TOSCo system while the ovals represent systems (or processes) that manage and configure the physical components of the system. The following describes the purpose and functions of each of these physical elements.



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

Figure 2: TOSCo Physical Components

The Roadside Equipment (RSE) is a device that allows the TOSCo Roadside Processor to communicate to TOSCo-equipped vehicles. This device manages all the communications between the infrastructure and TOSCo-equipped vehicles, including SPaT and MAP messages containing TOSCo information elements. While not shown in the figure, the RSE can also support other functions which may be needed to improve the performance of the TOSCo processes, such as real-time GPS correction information, Radio Technical Commission for Maritime Services (RTCM), roadside service announcements, and other connected vehicle applications that may reside at the intersection. The RSE also contains the MAP artifact, which is the digital description of the intersection geometry and associated traffic control definitions.

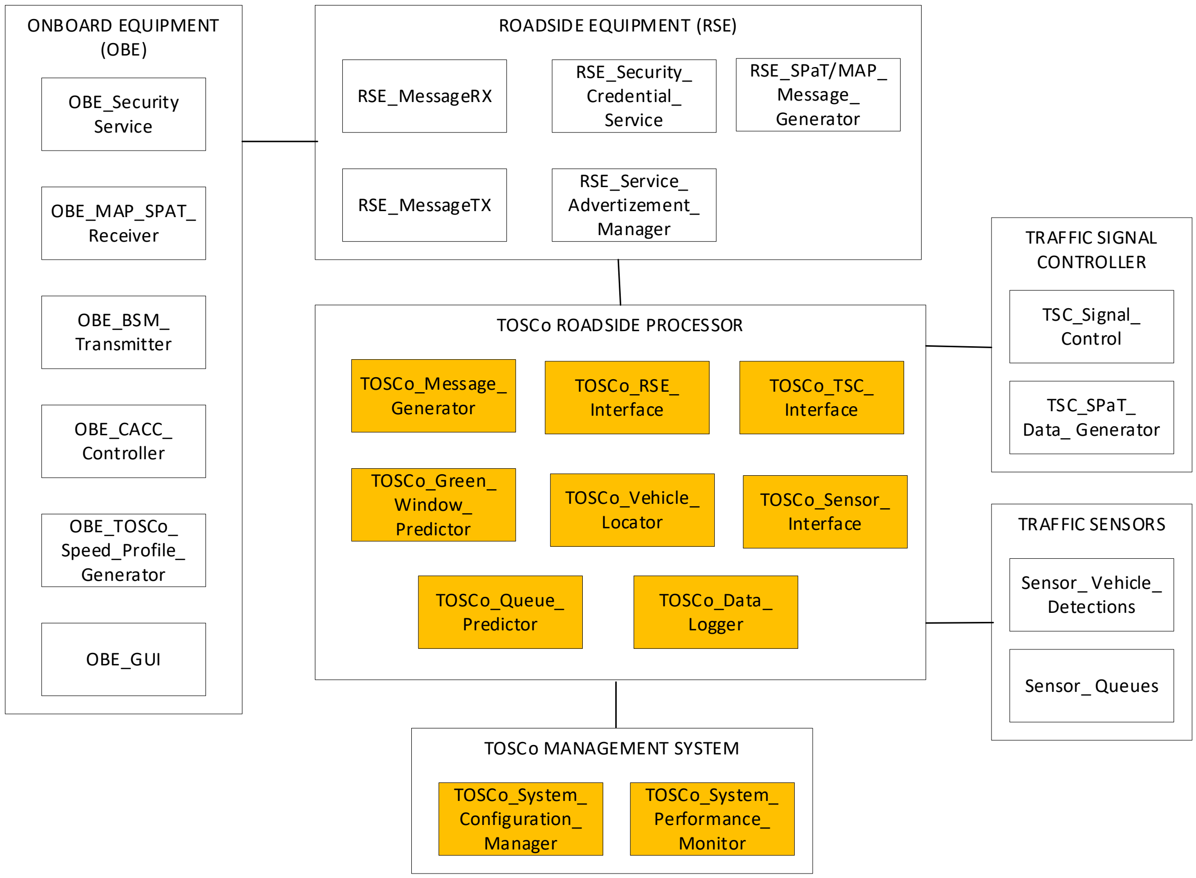
The TOSCo Roadside Processor is a device which contains all the processes that the TOSCo vehicles need from the infrastructure. This processor could potentially reside on a card that can be inserted into a traffic signal controller or embedded on a stand-alone device, such as a V2I Hub. The TOSCo Roadside Processor is expected to communicate with the traffic signal controller, the intersection detection sensor systems and the RSE using an Ethernet communications. The processes that will reside on the TOSCo Roadside Processor are described in the next section.

To support TOSCo functionality, the TOSCo Roadside Processor is connected to both the traffic signal controller (TSC) and the vehicle detection sensors (Sensors) installed at the intersection. TOSCo was designed to interface with a NEMA TS-2 TSC that supports NTCIP communications over Ethernet communications. The TSC is also required to support the generation of SPaT information directly.

The TOSCo Roadside Processor also communicates with the Vehicle Detection Sensor System. This represents a collection of detection technologies that have been installed to monitor traffic demands and provide information about queues at the intersection, including inductive loops, radar, video detection, microwave and other common detection technologies. The detection system must support both the normal control functions of the traffic signal controller as well as detect and monitor queue formation and dissipation.

2.2.2 Software Components

Figure 3 shows the software components of the TOSCo System. The boxes highlighted in yellow represent processes developed specifically for TOSCo. This section provides a high-level description of the purposes and functions of these software elements.



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

Figure 3: TOSCo Infrastructure Software Components

2.2.2.1 TOSCo Roadside Processor

The TOSCo Roadside Processor is responsible for producing the infrastructure data elements needed by TOSCo-equipped vehicles to plan their speed profiles. Currently, the TOSCo Roadside Processor contains the following processes:

2.2.2.1.1 TOSCo TSC Interface

This TOSCo TSC Interface is responsible for managing the communications between the TOSCo Roadside Processor and the traffic signal controller. The TOSCo TSC interface receives traffic SPaT information that is pushed from the controller and processes this message to unpack and store the SPaT information used by other TOSCo infrastructure processes. Currently, the interface is envisioned to be a one-way interface (receiving only). However, this interface may need to support sending messages (e.g., control commands) to the traffic signal controller in future development efforts.

2.2.2.1.2 TOSCo RSE Interface

The TOSCo RSE Interface is responsible for managing the communications between the TOSCo Roadside Processor and the RSE. It is responsible for receiving and unpacking BSMs from equipped vehicles to extract the vehicle speed, heading, and location information used by the TOSCo Vehicle Locator process. This process is expected to receive BSM data at 10 Hz from the RSE. The TOSCo RSE module will also forward the SPaT data received from the TSC to the RSE.

2.2.2.1.3 TOSCo Sensor Interface

This process is responsible for obtaining and processing the queue information as well as vehicle count information from the vehicle detection system(s) for each lane on TOSCo-supported approaches. This information is used by the TOSCo Queue Predictor process which estimates the queue parameters such as the back of queue and time when the queue is expected to dissipate. This interface is expected to support one-way communications from the vehicle detection sensor systems. This process is expected to receive queue information at 1 Hz.

2.2.2.1.4 TOSCo Message Generator

The TOSCo Message Generator is the process responsible for generating the content for the SPaT regional extension that is broadcast to equipped vehicles via the RSE. It is responsible for processing the outputs of the TOSCo Queue Predictor and TOSCo Green Window Predictor processes and packaging it in the proper format for broadcast to TOSCo-equipped vehicles via the RSE. This process shall provide the TOSCo RSE Interface with the TOSCo container information at 1 Hz.

2.2.2.1.5 TOSCo Vehicle Locator

The function of TOSCo Vehicle Locator is to process the BSM data from the equipped vehicles that are in communication range of the RSE. Using speed, heading, and position information, this process determines the lane-level position and estimated arrival time of each equipped vehicle relative to the stop bar on each approach to the intersection. This process also determines if the equipped vehicles are in a queued state. This information is then shared with the TOSCo Queue Predictor for use in determining and forecasting the location of the back of queue along each lane. This process is expected to occur at a frequency of 1 Hz.

2.2.2.1.6 TOSCo Queue Predictor

The TOSCo Queue Predictor is responsible for determining the current location of the back of queue, the predicted maximum location of the back of queue, and the time the maximum queue is expected to reach the stop bar during each signal cycle. These estimates are on a lane-by-lane basis and should be based on the data availability from the vehicle detection sensor system. The TOSCo Queue Predictor can also use data from equipped vehicles to update and improve vehicle detection sensor system queue information. This process is expected to occur at a frequency of 1 Hz.

2.2.2.1.7 TOSCo Green Window Predictor

This process is responsible for determining the start and end of the “green window” using data from the TOSCo Queue Predictor and SPaT data received from the TSC. The start of the green window is the time in the cycle when the last vehicle in the queue is expected to reach the stop bar. The end of the green window is the last time in the cycle that a TOSCo vehicle can arrive at the stop bar without stopping, which is typically the onset of the yellow phase. The TOSCo Green Window Predictor shall update the green window information at a frequency of 1 Hz.

2.2.2.1.8 TOSCo Data Logger

This process is responsible for collecting, managing, and storing data needed to assess the performance of TOSCo Infrastructure processes. This data should be timestamped to UTC time and contain input and output data from all the embedded TOSCo processes. This data will be used by system developers to refine and optimize the performance of the TOSCo algorithms. The data collected by the process can also be used by infrastructure owner/operators to assess the potential benefits of deploying TOSCo during different time periods and operating conditions. The process is expected to collect data from the other TOSCo processes at 1 Hz.

2.2.2.2 TOSCo Management System

The TOSCo Management System includes a suite of processes needed to support the configuration and management of the TOSCo Infrastructure components. This suite of processes contains at least two processes: the TOSCo System Configuration Manager and the TOSCo System Performance Monitor. Other processes may be required as the TOSCo system moves into the prototyping stage. The following describes the function and purpose of each of these processes.

2.2.2.2.1 TOSCo System Configuration Manager

The TOSCo System Configuration Manager allows infrastructure owner/operators to configure the TOSCo Roadside Processor to function at the intersection. This process would allow owner/operators to create, change, or delete parameters that are needed to support TOSCo operations. This functionality can be accomplished using configuration files. A simple user interface to view and edit configuration parameters will be developed to support the deployment of the demonstration system.

2.2.2.2.2 TOSCo System Performance Monitor

The TOSCo System Performance Monitor allows infrastructure owner/operators to monitor the performance of the TOSCo Infrastructure components. The TOSCo System Performance Monitor interfaces with the TOSCo Roadside Processor to acquire logs and other information generated by the TOSCo Roadside Processor. The TOSCo System Performance Monitor would be responsible for combining information from the TOSCo data logs with other information to generate and display metrics that the infrastructure owner/operator could use to assess the performance of the TOSCo system at the intersection.

3 Infrastructure Processes

This chapter provides a description of the main processes performed by the TOSCo Infrastructure. These processes include the vehicle location process, the queue detection and predictions process, and the green window determination process.

3.1 Vehicle Localization Process

The vehicle localization process combines the vehicle information from BSMs, including GPS coordinates, speed and heading, with the road geometry information from MAP messages, to locate the vehicle on the intersection map. This process first determines whether the vehicle is within a geo-fencing area, which is a virtual perimeter around the road segment. Then it determines the approaching intersection, approaching lane and corresponding signal phase. With the processed information, the queue length estimation algorithm can aggregate vehicles into different lanes and conduct lane-level estimation. The detailed localization process can be found in *Multi-Modal Intelligent Traffic Signal System – Phase II: System Development, Deployment and Field Test Final Report* (*2*) and in Reference (4).

3.2 Queue Detection/Prediction

A primary requirement of the TOSCo Infrastructure is to provide queue information to the SPaT. TOSCo vehicles use queue information in planning a speed profile when approaching a TOSCo-enabled intersection. The TOSCo Infrastructure uses lane-level queue formation and dissipation information to estimate the beginning time of the green window for each approach.

The following types of queue detection/prediction algorithms have been identified:

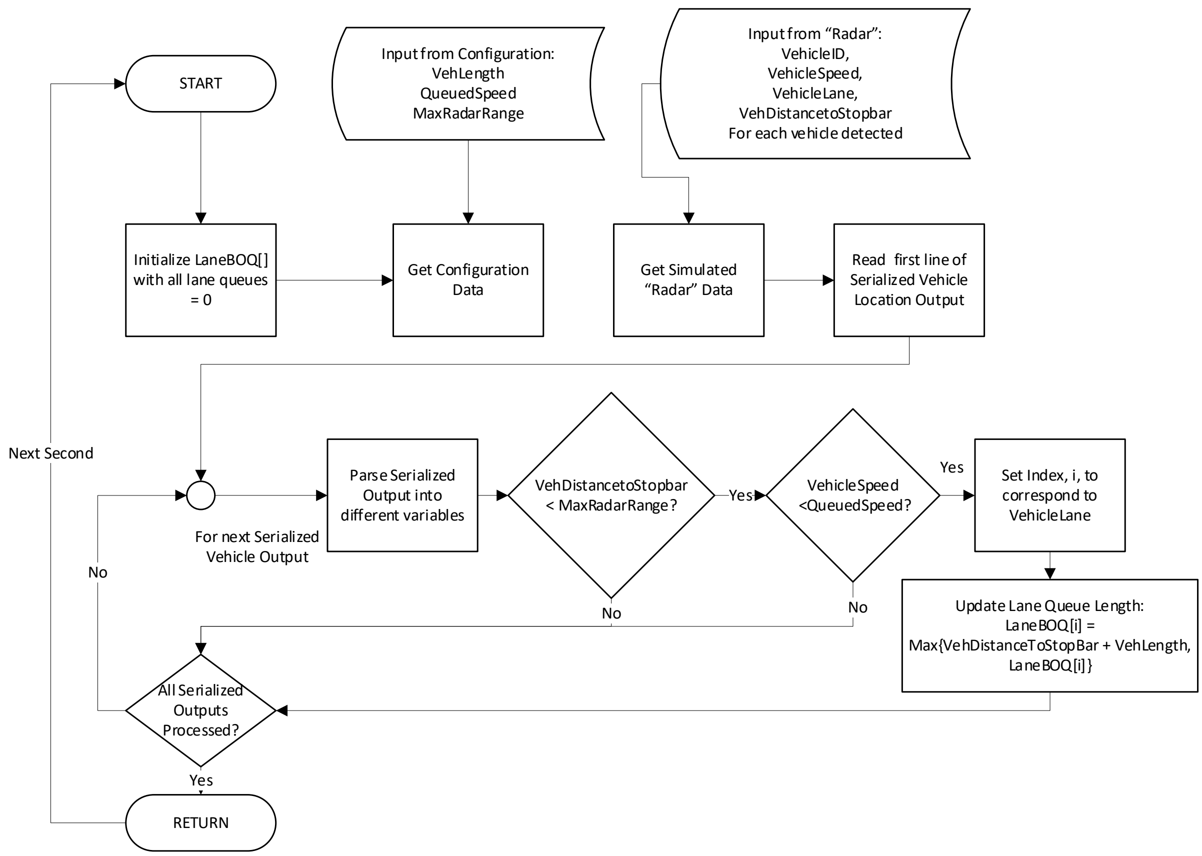
- An infrastructure-only approach
- A connected vehicle only approach
- A combined infrastructure and connected vehicle approach

Queue detection and prediction algorithms shall be refined during Phase 2 of the project.

3.2.1 Infrastructure-only Approach

The TOSCo Infrastructure component can operate without BSM information from the vehicles through using infrastructure-based sensors installed at the intersection. The radar detector can be located either upstream or downstream of the queue. The infrastructure algorithm can accept a queue measurement from the sensor or a serialized output of the detection data, depending on the capabilities of the radar unit. This section describes the algorithm on the infrastructure side if the radar detector unit is providing a serialized output of detected vehicles.

Figure 4 shows a process that the TOSCo Infrastructure only algorithm could use in the case of receiving serialized vehicle data. The queue measurement system uses data from radar sensors mounted at the intersection to measure the presence and speed of vehicles approaching the intersection.



Source: Texas A&M Transportation Institute (TTI)

Figure 4: Flow Chart to Describe Queue Calculation from Serialized Vehicle Data from Radar Sensor

The first input is the serialized vehicle output generated by a radar-based vehicle detector. The function of this radar detector is to record the speed and distance of each vehicle approaching the queue in each lane. The radar detector shall create a serialized detector output with the speed and distance each vehicle is from the stop bar and places this data, along with the vehicle ID, and lane ID into a packet sent to the Infrastructure algorithm.

The algorithm works by first setting the back-of-queue to zero for each lane. Reinitializing the back-of-queue enables the queue detection algorithm to capture when the queue decreases in length.

The next input is the configuration file used for defining the queue, which contains three variables. The *MaxRadarRange* variable can be used to bound the data considered to be the maximum range of an approach in case vehicles queued at the adjacent intersection are included in the detector output. The *QueuedSpeed* is the speed at which the algorithm considers a vehicle in a queued state. The *VehLength* is the assumed length of a vehicle, applied to all vehicles regardless of their types. The algorithm needs the vehicle length because the detector radar output measures the distance from the stop bar to the rear of the vehicle.

Next, the algorithm begins to read each line of vehicle data from the detector radar packet. The infrastructure algorithm needs to convert each line of text to usable variables used to determine if the vehicle is queued.

The algorithm first checks the distance of the vehicle to the stop bar. If this value is greater than the *MaxRadarRange*, the input from that vehicle is not included in the queue length determination. For those vehicles within the detection zone, the algorithm then uses the speed of the vehicle to determine whether the vehicle is in a queued state. If the vehicle's speed is less than or equal to the *QueuedSpeed* threshold, the algorithm considers the vehicle to be in a queued state. The algorithm determines the index corresponding to the vehicle's lane and saves it. The back-of-queue value for the vehicle's lane is updated to the maximum of two values, the distance to the stop bar of the subject vehicle plus the *VehLength* or the existing back-of-queue measurement for that lane. The algorithm repeats this process until all the vehicle data from the detector radar are evaluated. In the end, the returned value is a queue length for each lane represented by the detector radar output file.

Note, if the sensor can calculate the queue lengths, the queue length data can be fed directly into the array used for the green window determination.

3.2.2 Shockwave Profile Model

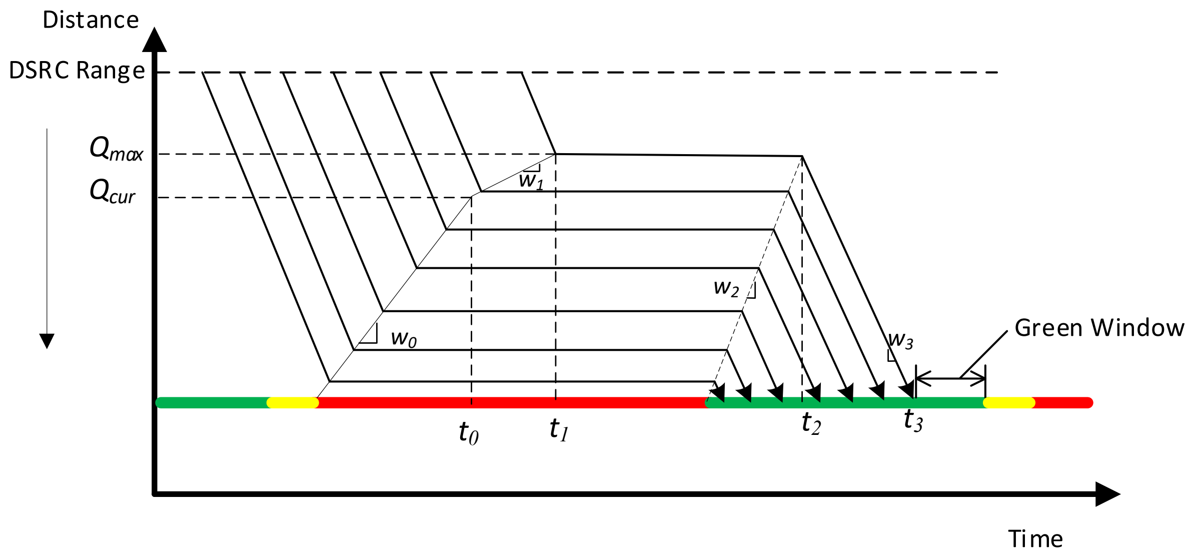
This approach utilizes data from BSM for queue length prediction. The objective is to make a real-time prediction of the vehicle queue dynamics at the intersection and calculate a green window for trajectory planning of TOSCo-equipped vehicles. Currently, the following assumptions are made to simplify the problem:

- All vehicles are connected and broadcast BSMs
- Traffic signals operate under fixed timing plan
- Traffic demand is not oversaturated

The shockwave profile model (SPM) (*5*) is implemented to predict the queuing profile with the consideration of vehicle acceleration and deceleration. The SPM tracks and estimates different types of shockwaves and their speeds at a signalized intersection and, therefore, the queuing dynamics can be constructed. The SPM is modified to consider vehicle acceleration and deceleration and make predictions of queuing dynamics instead of estimating after the queue has been discharged. The entire queuing process within a signal cycle is shown in Figure 5. Four critical time points are defined:

- t_0: Current time when the prediction is made
- t_1: Predicted point in time that the maximum queue length Q_{max} is reached (stop time of the preceding vehicle)
- t_2: Predicted point in time that the end of the queue starts to move (launch time of the preceding vehicle)
- t_3: Predicted point in time that the end of the queue reaches the intersection (departure time of the preceding vehicle). This is also the start time of the green window.

Note that the preceding vehicle is defined as the immediate downstream vehicle of the TOSCo-equipped vehicle in the same lane. The end of the green window is the end of the green signal.



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

Figure 5: Shockwave Profile Model Based Queuing Profile Prediction

The primary purpose of the queuing profile prediction algorithm is to determine the start of the green window (t_3). Four different types of shockwaves are identified in Figure 5 to calculate t_3 step by step. w_0 is the queuing shockwave speed until current time; w_1 is the predicted queuing shockwave speed until the maximum queue is reached; w_2 is the discharge shockwave speed; and w_3 is the departure shockwave speed. t_3 is also the point in time that the departure shockwave w_3 arrives at the intersection.

With the assumption of 100 percent penetration rate of connected vehicles, the current queue length Q_{cur} is known by checking each vehicle's speed and location from the BSMs. If the vehicle's speed is lower than 5 mph, it is considered in queuing state based on Highway Capacity Manual definition *(6)*. To predict the point in time that the maximum queue length is reached, we consider the vehicle deceleration rate and the stopping distance of the preceding vehicle as shown in Figure 6.

$$t_1 = \begin{cases} t_0 + \frac{v_l}{a_n} + \frac{d_{stop}^f - \frac{v_l^2}{2a_n}}{v_l} \; if \; d_{stop}^f > \frac{v_l^2}{2a_n} \\ t_0 + \frac{2d_{stop}^f}{v_l} \; otherwise \end{cases} \quad (1)$$

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

Figure 6: Time of Arrival at the End of the Queue

Where, v_l is the current speed of the preceding vehicle; a_n is the average vehicle deceleration rate, a constant parameter; d_{stop}^f is the predicted stopping distance of the preceding vehicle, from its current position to its stop location, which can be calculated by the number of downstream vehicles multiplied by an average vehicle length, l_{avg} = 5 m.

When the signal turns to green, the discharge shockwave speed w_2 is determined by the saturation flow rate, which is usually assumed to be a constant. As a result, critical time point t_2 can be predicted as shown in Figure 7.

$$t_2 = t_g + Q_{max}/w_2 \qquad (2)$$

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

Figure 7: Launch Time of the Preceding Vehicle

Where, t_g is the start time of the green signal.

The departure time t_3 is estimated based on t_2 assuming the last vehicle in the queue accelerates to free flow speed and then maintains constant speed until it clears the intersection. Based on the stopping location of the vehicle, t_3 can be calculated as shown in Figure 8.

$$t_3 = \begin{cases} t_2 + \frac{v_f - v_l}{a_p} + \frac{d_i - \frac{v_f^2 - v_l^2}{2a_p}}{v_f} & if\ d_l > \frac{v_f^2 - v_l^2}{2a_p} \\ t_2 + \frac{-v_l + \sqrt{v_l^2 + 2a_p d_l}}{a_p} & otherwise \end{cases} \qquad (3)$$

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

Figure 8: Departure Time

Where, a_p is the average vehicle acceleration.

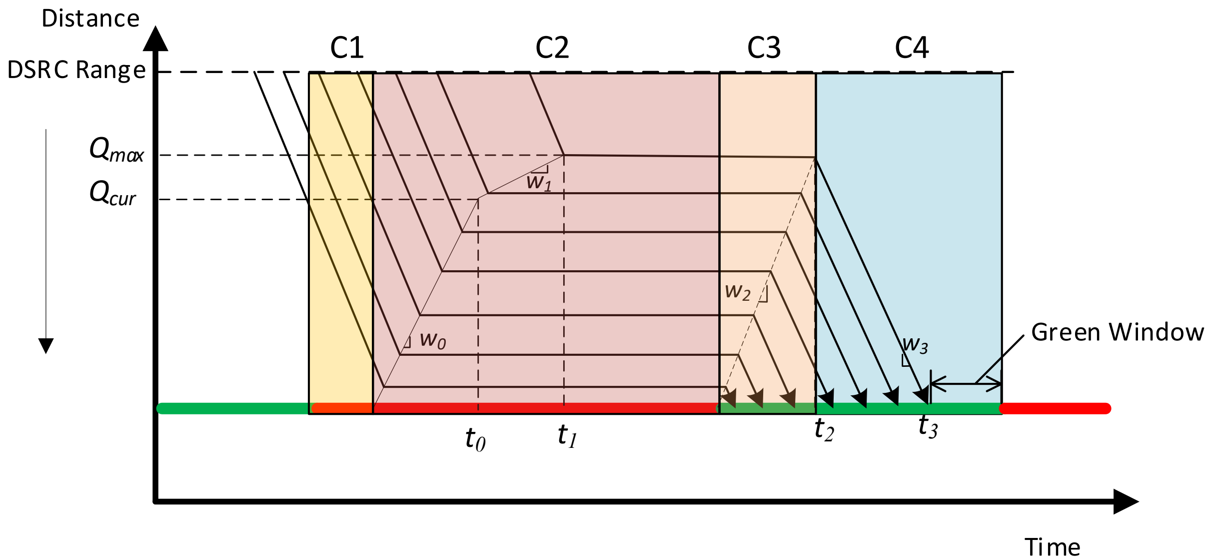
then

$$w_3 = \frac{Q_{max}}{t_3 - t_2} \qquad (4)$$

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

Figure 9: Speed of the Shockwave at which the Queue Disperses

The descriptions above provide a general approach to estimate the departure time t_3. However, the TOSCo-equipped vehicle may arrive at the intersection at any time with any number of downstream queuing vehicles. Vehicles downstream of the TOSCo-equipped vehicle may or may not stop based on current signal status and the remaining timing of the signal phase. As a result, four different cases are identified as shown in Figure 10.



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

Figure 10: Four Cases in Queuing Profile Prediction

In case 1, the signal is red, and there is no stopped vehicle downstream of the TOSCo-equipped vehicle. This case usually happens when the signal just transitioned to red. Whether the TOSCo-equipped vehicle stops or not depends on whether its preceding vehicle can pass the stop bar when the green signal starts (e.g., a very short red time). If the preceding vehicle stops, then case 1 turns to case 2.

In case 2, the signal is red, and there are stopped vehicles downstream of the TOSCo-equipped vehicle. This is the most common case when vehicles are waiting in the queue for the green light. The time of arrival at the end of the queue is compared with the time of discharge of the last vehicle in the queue, to determine whether the TOSCo-equipped vehicle stops or not.

In case 3, the signal is green, and there are stopped vehicles downstream of the TOSCo-equipped vehicle. It happens when an existing queue is dissipating. All stopped vehicles are discharging by saturation flow rate, and the approaching TOSCo-equipped vehicle is checked whether it joins the queue by comparing its arrival time with the discharge time of the last queuing vehicle

In case 4, the signal is green, and there is no stopped vehicle downstream of the TOSCo-equipped vehicle in the same lane. Whether the TOSCo-equipped vehicle stops or not depends on whether its preceding vehicle can pass the stop bar before the signal transitions to red. The TOSCo-equipped vehicle stops if its preceding vehicle stops. Otherwise, the time of arrival at the stop bar is compared with the remaining time of the green signal.

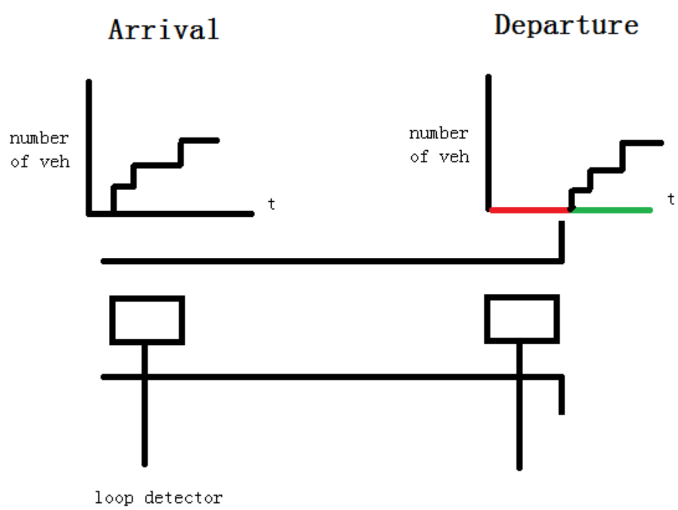
3.2.3 Input-Output Approach

The input-output model-based algorithm is designed to utilize both loop-detector and BSM data for queuing profile prediction. It is applied to mixed traffic conditions where the CV penetration rate is not 100%. In addition, coordinated actuated signal control is assumed to increase the uncertainty of the prediction. The following assumptions are made:

- Only a portion of vehicles are connected and broadcast BSMs

- Loop detectors are installed upstream of the intersection (entrance detector) and can provide lane by lane detection
- Loop detectors installed downstream of the intersection (exit detector) is optional
- Traffic signals operate under coordinated actuated control
- Traffic demand is not oversaturated

The input-output model (7) is used to estimate the number of vehicles within the link, shown in Figure 11. When a vehicle passes by the entrance loop detector, it updates the number of vehicles entering the link. When a vehicle passes by the exit loop detector, it updates the number of vehicles exiting the link. In this way, the number of vehicles in the link can be counted precisely. If the exit detector is not installed, the number of vehicles exiting the intersection during green time can be estimated by the shockwave speeds w_2 and w_3 from the SPM model.



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

Figure 11: The Input-output Model

However, the input-output model can only count the number of vehicles within a link. Detailed vehicle speed trajectories between the two detectors cannot be directly obtained from the data (e.g., whether a vehicle is stopped or not). Newell's linear car following model (*8*) is implemented to predict vehicle speed trajectories. By applying the car following model, when a vehicle passes the entrance detector, time of arrival at the end of the queue $t_1$is calculated and compared with t_2, the launch time of the preceding vehicle, to determine whether the vehicle will stop or not. Here, d_{stop} is the distance to stop bar from the entrance loop detector. q is the predicted queue length and v_{free} is the free-flow speed. A constant value, t_d, has been added to capture the deceleration process because Newell's model assumes infinite acceleration and deceleration rate. Once the algorithm knows whether a vehicle will stop or not, equations (5) through (7) can be used to calculate t_1, t_2, and t_3. The superscript of f denotes the preceding vehicle and t_g is the start time of the green signal.

BSMs from DSRC-equipped vehicles and TOSCo-equipped vehicles are used to update the predicted queue length to capture the lane-changing behavior. The distance between two stopped vehicles does not vary a lot in the queue. When a DSRC-equipped vehicle or TOSCo-equipped vehicle stops, its distance to the stop bar is compared with the predicted distance. The positive difference indicates the number of downstream vehicles changing to this lane, and the negative difference indicates the number of downstream vehicles leaving this lane.

$$\boldsymbol{t_1 = \frac{d^f_{stop} - q^f}{v_{free}} + t_d} \quad (5)$$

$$\boldsymbol{t_2 = t_g + Q_{max}/w_2} \quad (6)$$

$$\boldsymbol{t_3 = t_g + Q_{max}/w_3} \quad (7)$$

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

Figure 12: Equations for Arrival at the End of the Queue, Launch Time of the Preceding Vehicle and Speed of the Shockwave

Because of the uncertainties associated with coordinated actuated signal control, this initial algorithm development work assumed that TOSCo functions are only enabled on coordinated phases. This assumption reduces that uncertainty. When the signal is green, the remaining time is accurate since the end of the green is the reference point, which is the beginning of the cycle. When the signal is red, the remaining time t_r is unknown because of actuation (e.g., early return to green), but it is bounded, as shown in equation (18). $\sum t^{other}_{min}$ is the summation of minimum green time of non-coordinated phases, and $\sum t^{other}_{max}$ is the summation of maximum green time of non-coordinated phases. The lower bound ($t_r = \sum t^{other}_{min}$) is now used when planning trajectory, so TOSCo-equipped vehicles are more likely to pass the intersection to improve mobility. To guarantee safety, when the TOSCo-equipped vehicle is planning an over-aggressive trajectory, an adaptive cruise control (ACC) model will be triggered to bring the vehicle to a stop. Basically, the TOSCo-equipped vehicle will choose a more conservative acceleration rate between the trajectory planning and the ACC model.

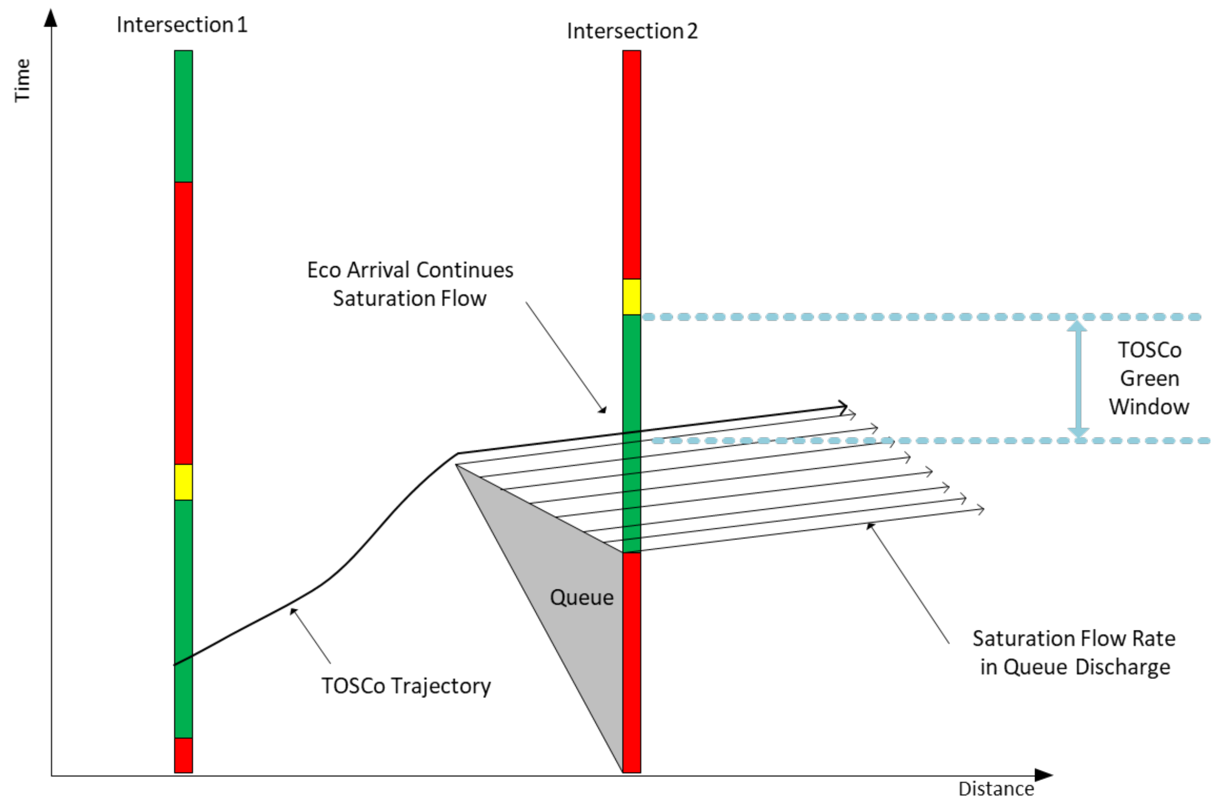
$$\boldsymbol{\sum t^{other}_{min} \le t_r \le \sum t^{other}_{max}} \quad (8)$$

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

Figure 13: Time Remaining in Red Cycle

3.3 Green Window Determination

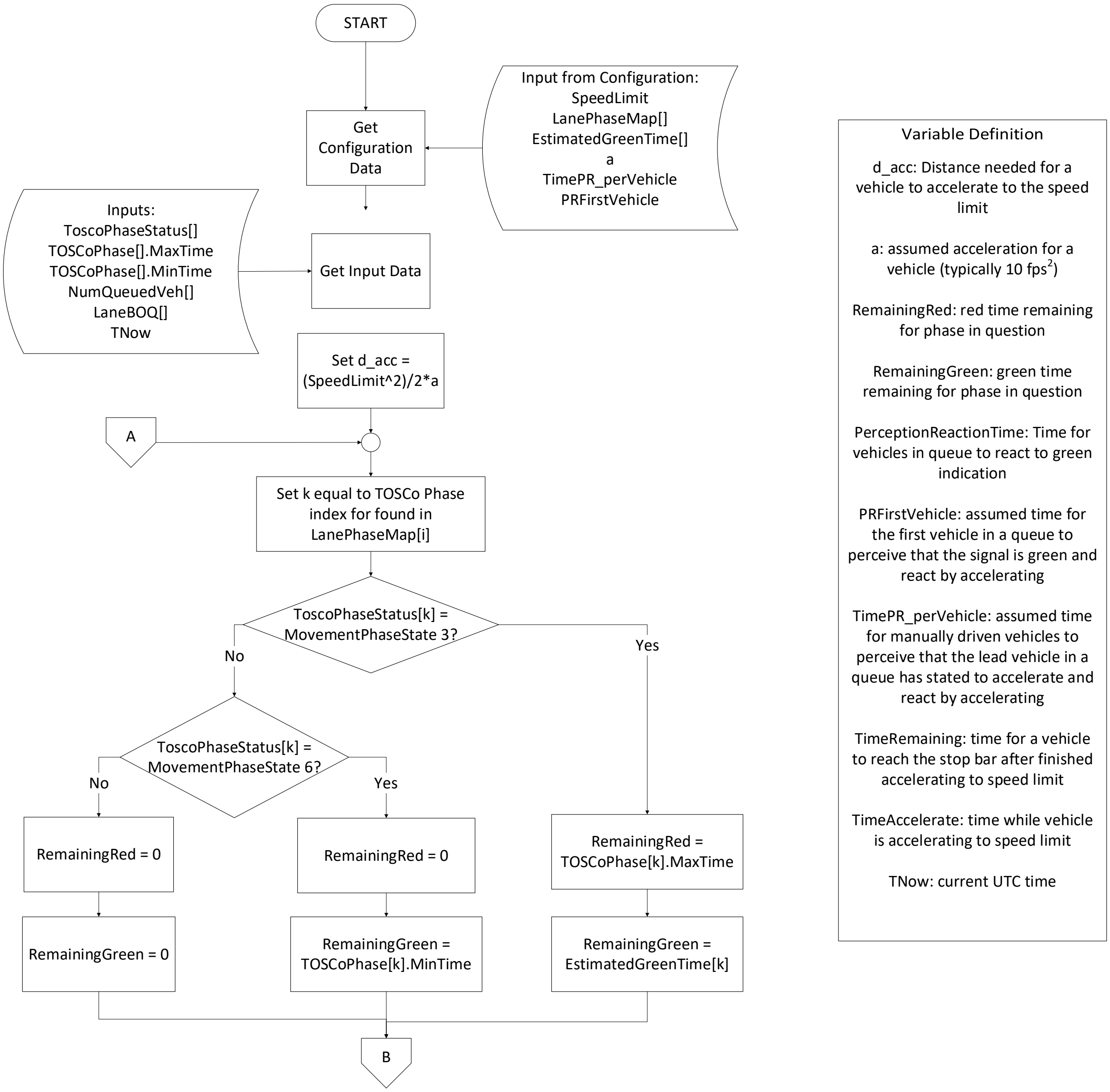
One critical function of the infrastructure in the TOSCo system is to estimate the green window. As shown in Figure 14, the "green window" represents the time during the green interval when the last vehicle in the queue clears the stop bar of the intersection and the end of the green interval. The "green window" is the time 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 having to stop.



Source: Texas A&M Transportation Institute (TTI)

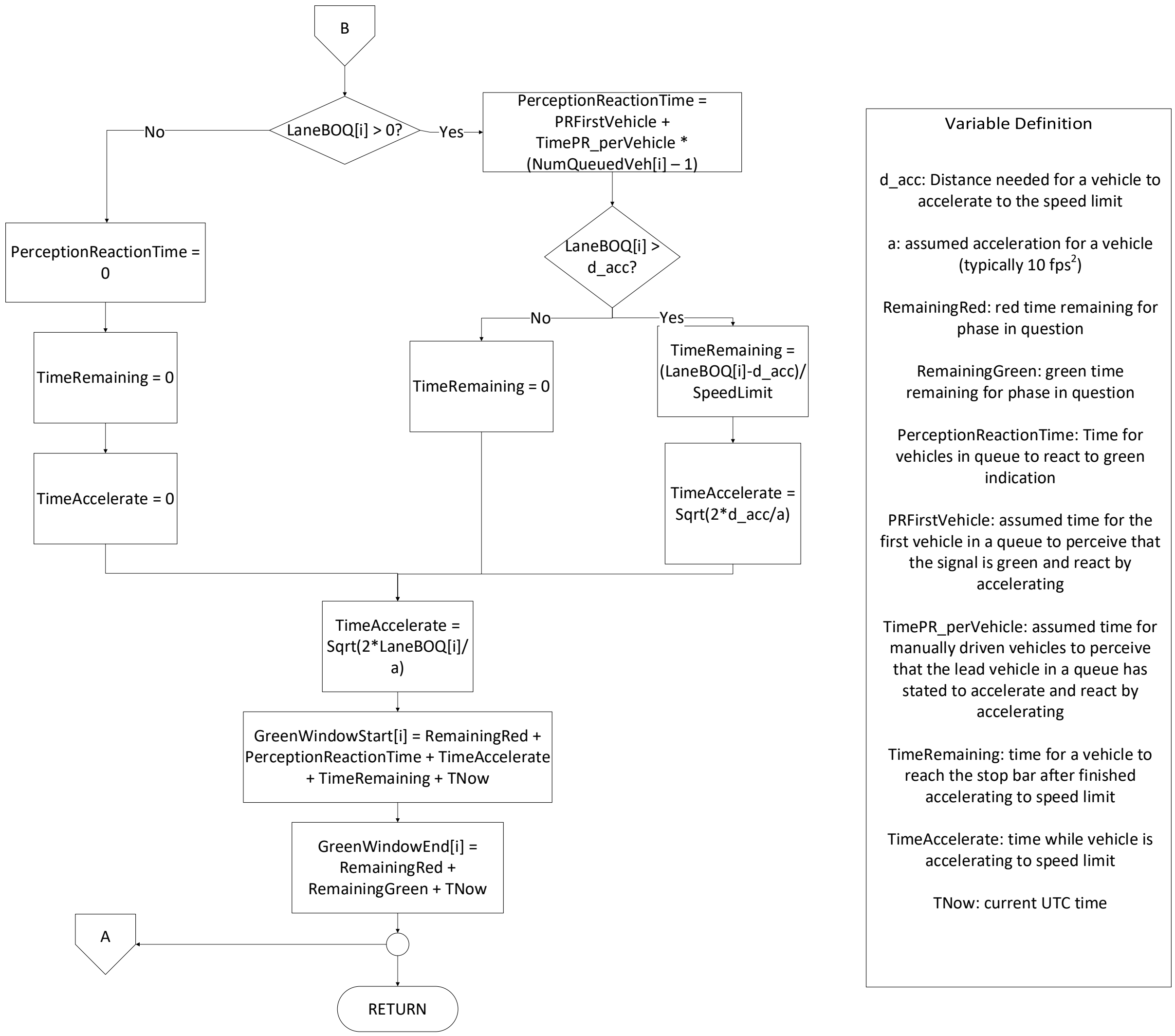
Figure 14: Definition of Green Window

Figure 15 shows the process used to calculate the start and end of the Green Window for the TOSCo regional extension in the SPaT. The process uses signal timing and kinematics to estimate the start and end of the green window. These elements dynamically represent the times at which the queue might clear the intersection, GreenWindowStart, and when the TOSCo phase will end for the lane, GreenWindowEnd. Note, the GreenWindowStart could be larger than the GreenWindowEnd if the queue is sufficiently large. A GreenWindowStart larger than the GreenWindowEnd indicates that the phase in not expected to be long enough for the queue to clear. A cycle for an intersection is defined as the start of red for each TOSCo approach, since different approaches could have different starts of red. The green window determination algorithm requires several variables and parameters.



Source: Texas A&M Transportation Institute (TTI)

Figure 15: Flowchart of Green Window Estimation Process



Source: Texas A&M Transportation Institute (TTI)

Figure 16: Flowchart of Green Window Estimation Process (Continued)

The following variables are provided as inputs into the algorithm:

- *TOSCoPhaseStatus*: this array contains the phase status of the TOSCo-enabled phases at the intersection. The phase status is represented by the MovementPhaseState ASN value (from the SAE J2735 standard[1]). A MovementPhaseState for the lane equal to 3 means Stop-And-Remain (red) and 8 means Protected Clearance (yellow). If the signal is not red or yellow the algorithm assumes it is green. This assumption can be lifted for deployment.
- *TOSCoPhase.MaxTime*: This variable returns the maximum time remaining for the current phase status of the TOSCo phase, k. This value comes from the traffic controller at the

[1] SAE International. *Dedicated Short Range Communications (DSRC) Message Set Dictionary*. March 2016.

intersection as the same value used to produce a SPaT message. Note that the data provided from the traffic controller is in units of time remaining for the active phase state.

- *TOSCoPhase.MinTime*: This variable returns the minimum time remaining for the current phase status of the TOSCo phase, k. This value comes from the traffic controller at the intersection as the same value used to produce a SPaT message. Note that the data provided from the traffic controller is in units of time remaining for the active phase state.
- *NumQueuedVeh*: This array provides the number of queued vehicles counted in the queue calculation for each TOSCo lane, i. This value is used to calculate the amount of time required for the vehicle at the back of the queue to start accelerating.
- *LaneBOQ*: This array contains the distance from the stop bar to the back-of-queue, a measurement of distance, which is used for calculating the amount of time required for the vehicle at the end of the queue to reach the stop bar and determining the distance of travel when a TOSCo-equipped vehicle is planning a "stop" trajectory.
- *TNow*: This value is the current UTC time used to convert data into a future point in time that the green window is expected to start or end.

The remaining inputs into the algorithm come from configuration data stored in a file. These parameters are considered configuration because the value does not change during normal operation. The parameters are as follows:

- *SpeedLimit*: This parameter is the speed limit of the roadway converted into meters-per-second. The speed limit of all the TOSCo lanes are assumed to be the same in the current algorithm. This can be updated for deployment.
- *LanePhaseMap*: This configuration array contains the phases corresponding to each TOSCo approach, i, represented by the order of the elements. The value at element i corresponds to the TOSCo phase, k, for that lane.
- *EstimatedGreenTime*: This parameter contains the estimated green time for the current cycle. This value is needed because the traffic controller does not provide data for the expected duration of the green state while the signal is still in a red state. Recall the cycle starts in a red state. This variable is only needed while the TOSCo phase is still in a red state.
- a: This parameter is the assumed acceleration for a vehicle as it accelerates from a stop to its desired speed. The algorithm assumes that a vehicle's acceleration is constant.
- *PRFirstVehicle*: This parameter is the assumed 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 amount of time for the first vehicle in a queue to perceive and react to a protected movement is typically longer than subsequent vehicles in the queue.
- *TimePR_perVehicle*: This parameter is the assumed amount of time for manually driven vehicles to perceive that the lead vehicle in a queue has started to accelerate and react by accelerating. This value is typically assumed to be less than PRFirstVehicle. Note that this value assumes all vehicles in the queue are manually driven. A string of TOSCo-equipped vehicles performing a coordinated launch would lead to an overestimation of the amount of time required for the last vehicle in the queue to begin to accelerate.

Once these input variables and parameters are loaded into the algorithm, the steps to calculate the start and end of the green window can begin.

First, d_{acc} is calculated. This variable represents the distance required for a vehicle to go from a stopped position (a speed of zero) to the speed limit using the assumed acceleration, a. Once

d_{acc} is calculated, the algorithm begins to cycle through each TOSCo lane and calculate the individual green windows.

The green window is partially dependent on the signal timing. The algorithm uses the Vehicle Localization algorithm to find the TOSCo phase corresponding to the lane. Then the algorithm calculates two values from the signal phase and timing data: *RemainingRed* and *RemainingGreen*. *RemainingRed* and *RemainingGreen* represent the amount of red and green time, respectively, remaining in the cycle. The data source for these values vary based on the phase status. If the phase status is red, i.e., the *MovementPhaseState* is 3, then *RemainingRed* is set to the maximum remaining duration of the current phase state and the *RemainingGreen* is set to the *EstimatedGreenTime* corresponding to the TOSCo phase, k. The maximum remaining time is used for the *RemainingRed* in this case to ensure a conservative estimate. If the phase status is green, i.e., the *MovementPhaseState* is 6, the *RemainingRed* is set to zero and the *RemainingGreen* is set to the minimum remaining duration of the current phase. The minimum remaining duration is used for *RemainingGreen* in this case as a conservative estimate. If the signal is not red or green then the signal is assumed to be yellow, meaning there is no green window remaining. In this case *RemainingRed* and *RemainingGreen* are both set to zero.

The algorithm calculates queueing information next. If there is a queue indicated by the lane's *LaneBOQ* element being greater than zero, the *PerceptionReactionTime, TimeRemaining*, and *TimeAccelerate* values are calculated. Otherwise, each of these components are set to zero. The *PerceptionReactionTime* is calculated by adding together the amount of time needed for each vehicle to perceive and react to the opportunity to begin to accelerate. Specifically, the *PRFirstVehicle* is added to the *TimePR_perVehicle* multiplied by the *NumQueuedVeh* in that lane minus one (because the first vehicle's perception reaction time is accounted for by PRFirstVehicle). Then the algorithm determines which equation to use for the other queue clearance variables by checking if the subject lane's *LaneBOQ* element is greater than d_{acc}. If so, the vehicle can accelerate to the speed limit before crossing the stop bar. TimeRemaining is calculated using the *LaneBOQ* minus d_{acc} divided by the SpeedLimit. To represent the amount of time for a vehicle at speed to reach the stop bar after accelerating and *TimeAccelerate* is calculated using d_{acc}. If the lane's *LaneBOQ* element is less than or equal to d_{acc}, *TimeRemaining* is set to zero and *TimeAccelerate* is calculating using the lane's *LaneBOQ* element.

Finally, the *GreenWindowStart* is calculated by adding together the *RemainingRed*, *PerceptionReactionTime, TimeAccelerate, TimeRemaining*, and *TNow* components. The *GreenWindowEnd* is calculated by adding *RemainingRed, RemainingGreen*, and *TNow* together. Once all the TOSCo lanes are computed the function is complete.

4 TOSCo Messages

This chapter describes content of the message used by TOSCo-equipped vehicles to plan their speed profiles. The messages including the SPaT and MAP messages. The SPaT message is broadcast at 10 Hz while the MAP information is broadcast at 1 Hz.

4.1 Signal Phase and Timing (SPaT) Message

The infrastructure is required to provide SPaT and intersection geometry (MAP) data to the TOSCo vehicle. SPaT can be obtained from the traffic signal controller and provides information about the current operating status of the traffic signal as well as information about the time until the next change in the signal indication state. SPaT also provides information about the length of queue and the start and end times for the green window as provided in a regional extension to the message.

4.2 MAP Message

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 allows the vehicle to determine the lane in which it is located and what queue and signal timing information pertains to it. Both SPaT and MAP messages are standard SAE J2735-2016.

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List of Acronyms

ACC	Adaptive Cruise Control
ASN	Abstract Syntax Notation
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAMP	Crash Avoidance Metrics Partners LLC
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communication
FHWA	Federal Highway Administration
GID	Geometric Intersection Description
GPS	Global Positioning System
MAP	SAE J2735 Map Message
NTCIP	National Transportation Communications for Intelligent Transportation System Protocol
RSE	Roadside Equipment
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
SPaT	Signal Phase and Timing
SPM	Shockwave Profile Model
TOSCo	Traffic Optimization for Signalized Corridors
TSC	Traffic Signal Controller
TTI	Texas Transportation Institute
USDOT	United States Department of Transportation
UTC	Coordinated Universal Time
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VISSIM	Verkehr In Städten – SIMulationsmodell