Traffic Optimization for Signalized Corridors (TOSCo) Phase 2

Infrastructure System Requirements and Architecture Specification Final Report

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16. Abstract
This document is an update and refinement of the system architecture and specifications for the infrastructure components of the Traffic Optimization for Signaled Corridors (TOSCo) system. This document reflects the system architecture and functionality in the controlled environment testing at the Texas A&M University System's RELLIS campus deployed in Phase 2 of the project. The TOSCo infrastructure subsystem consists of five functional components: MAP message generation, Queue Estimation, Green Window Prediction, Signal Phase and Timing (SPaT) message generation, and differential correction message generation. This document also describes the processes and procedures used to verify the infrastructure subsystem components.

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List of Acronyms

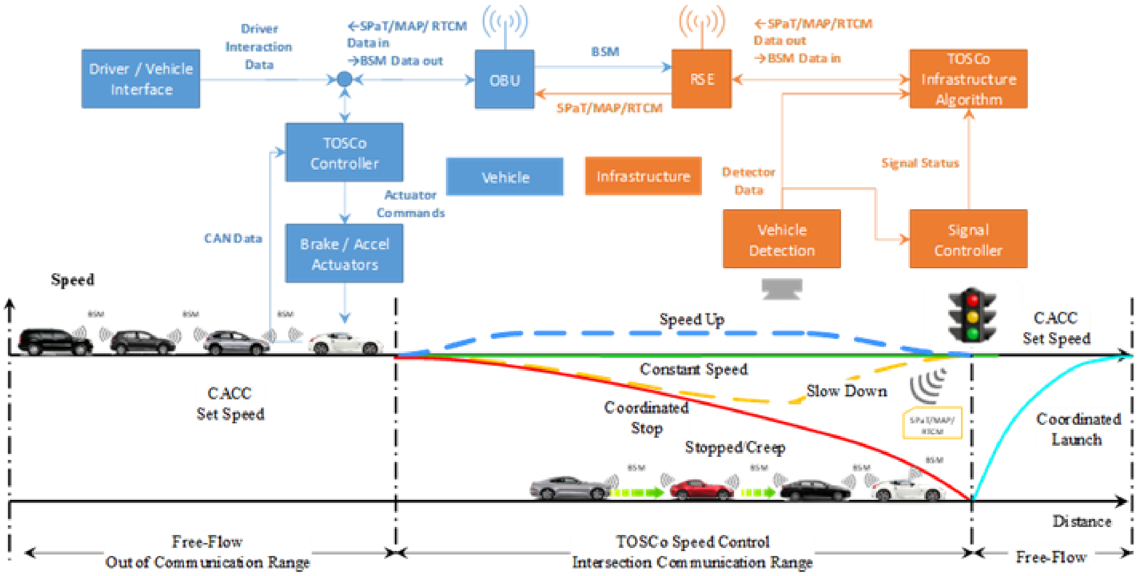
Acronym	Definition
ACC	Adaptive Cruise Control
ASN	Abstract Syntax Notation
ATC	Advance Traffic Controller
BOQ	Back of Queue
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAMP	Crash Avoidance Metrics Partners LLC
CORS	Continuous Operating Reference Station
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communication
ECEF	Earth-Centered-Earth-Fixed
FHWA	Federal Highway Administration
FOQ	Front of Queue
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IOOs	Infrastructure Owners and Operators
MAP	SAE J2735 Map Message
NOAA	National Oceanic and Atmospheric Administration
NTCIP	National Transportation Communications for Intelligent Transportation System Protocol
NTRIP	Network Transport of RTCM via Internet Protocol
OBU	On-board Unit
PRC	Pseudo-range Correction
PTLM	Phase-to-Lane-Movement
RRC	Range Rate Corrections
RSE	Roadside Equipment
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-time Kinematic
SAE	Society of Automotive Engineers

Acronym	Definition
SCSC	SubCarrier Systems Corp.
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
SCSC	SubCarrier System Corp.
SPaTTSC	Signal Phase and Timing Data Log
SSR	State Space Representation
TCP/IP	Transmission Control Protocol / Internet 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
UPER	Unaligned Packed Encoding Rules
USDOT	United States Department of Transportation
UTC	Coordinated Universal Time
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

Chapter 1. Introduction

The Traffic Optimization for Signalized Corridors (TOSCo) system is a series of innovative applications designed to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based connected-vehicle communications to assess the state of vehicle queues and cooperatively control the behavior of strings of equipped vehicles approaching designated 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 (CACC), 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 infrastructure also provides Radio Technical Commission for Maritime Services (RTCM) messages to allow the vehicle to assist the vehicle in determining lane-level map matching on a TOSCo approach. 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 application uses the SPaT regional extension to convey information about the “green window” to individual vehicles. The “green window,” computed by the infrastructure, is based on the estimated time 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 host vehicle's onboard longitudinal vehicle control capabilities to support partial automation. This vehicle control leverages previous work to develop CACC algorithms.



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

Figure 1. TOSCo Operating Concept

Scope

This document specifies the infrastructure design requirements, architecture, and data processes developed in Phase 2 of the TOSCo 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 a TOSCo-enabled intersection
- Descriptions of processes developed by the development team to produce those data elements

Organization of the Report

The organization of this report is as follows:

- Chapter 2 provides a high-level description of the system requirements and architectures for the TOSCo infrastructure components.
- Chapter 3 describes the processes used to provide queue information to the TOSCo vehicles.
- Chapter 4 describes the processes by which the TOSCo Infrastructure generates green window information.
- Chapter 5 describes how the TOSCo Infrastructure generates the enhanced Signal Phase and Timing (SPaT) information.
- Chapter 6 contains information on how the TOSCo system delivers differential correction information to the TOSCo vehicles.

- Chapter 7 describes the process for generating and delivering MAP information to the TOSCo vehicles.
- Chapter 8 provides a data dictionary of the logs generated by the TOSCo Infrastructure processes for use in verification testing.
- Chapter 9 provides as summary of the field test deployment In FM 1960 in Houston, Texas and lessons learned.

Chapter 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

TOSCo Infrastructure System Requirements

The following describes the functional requirements of the infrastructure systems needed to support the TOSCo operations at an intersection.

- 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 as 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.
    - 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.
    - 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 Dedicated Short-Range Communication (DSRC) messages as defined in the Society of Automotive Engineers (SAE) J2735 – 2016.

TOSCo Infrastructure Operating Assumptions and Requirements

The following describes the operating environment and assumptions in which TOSCo must operate:

- *Each TOSCo intersection will function independently of the other intersections in the corridor.* Each intersection will be equipped with its own TOSCo system and interact only with those TOSCo vehicles in immediate proximity to the intersection (i.e., within communications ranges of the intersection).
- *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).* At least for the foreseeable future, the 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 and 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.

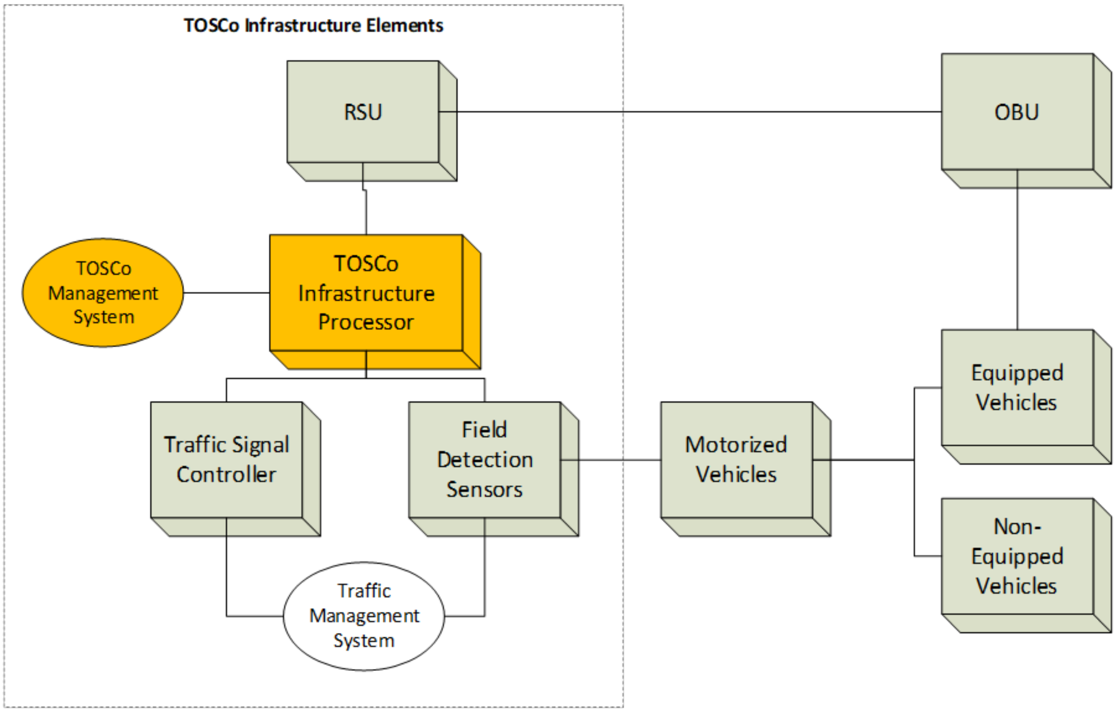
- *The TOSCo Infrastructure systems must be able to detect and gather information using commercial off-the-shelf detection technologies*. TOSCo requires that queue information be provided at the lane-level. Many agencies have already made significant investments in detection technologies at their intersection, particularly related to queue detection. Therefore, the TOSCo Infrastructure Team developed the TOSCo system around existing approaches and technologies for detecting intersection queues. For the system's initial deployment, the team used traditional approaches used by agencies to detect and measure queues.
- *TOSCo will be deployed on passenger vehicles only.* Theoretically, any vehicle class can use TOSCo. However, for demonstration purposes, the TOSCo Infrastructure Team assumed that only passenger vehicles have TOSCo functionality. This assumption allows the developers to apply industry-accepted values for the operating characteristics of the unequipped vehicles (such as vehicle lengths, vehicle acceleration and deceleration characteristics, perception/reaction times of drivers, etc.). The TOSCo Infrastructure 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. This section describes both the physical and software components of the TOSCo Infrastructure elements. The *Traffic Optimization for Signalized Corridors (TOSCo) Vehicle System Requirements and Architecture Specification Report* (2) provides a high-level description of the TOSCo vehicle elements.

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 system's physical components. 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, 2022

Figure 2. TOSCo Physical Components

The Roadside Unit (RSU) is a device that allows the TOSCo Infrastructure Processor to communicate to TOSCo-equipped vehicles. This device manages all the communications between the infrastructure and TOSCo-equipped vehicles including SPaT and digital roadway geographic design (MAP) messages containing TOSCo information elements. While not shown in the figure, the RSU can also support other functions to improve the performance of the TOSCo processes. Examples of these processes include real-time GPS correction information, RTCM, roadside service announcements, and other connected vehicle applications that may reside at the intersection. The RSU also contains the MAP which is the digital description of the intersection geometry and associated traffic control definitions.

The TOSCo Infrastructure Processor is a device that contains all the processes that the TOSCo vehicles need from the infrastructure. This processor could potentially reside on a card inserted into a traffic signal controller or embedded on a stand-alone device. The TOSCo Infrastructure Processor is expected to communicate with the traffic signal controller, the intersection detection sensor systems, and the RSU using Ethernet communications. The Project Team implemented the following for the Infrastructure Processor:

An industrial, field-hardened computer (without fan) with:

- 16 G of RAM
- 1 TB Solid-State Drive (SSD) with 4 Local Area Network (LAN) ports
- 4 serial communications ports
- 1 mini-PCIe port
- 4 USB ports
- 1 HDI port
- 1 Dell HDI port

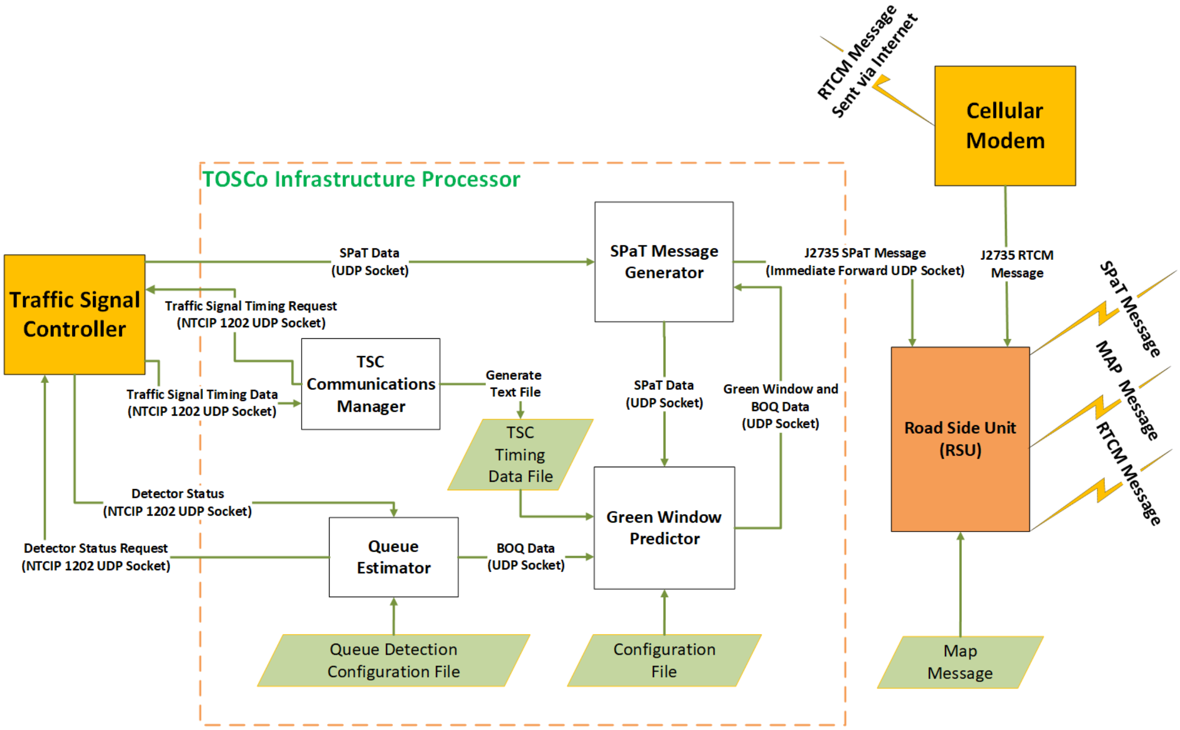
The computer was preloaded with Windows 10 Pro (64 BIT) and was powered with a 100-240V to 150W 24V AC to DC power supply (with power cord). The following section describes the processes that reside on the TOSCo Infrastructure Processor.

To support TOSCo functionality, both the traffic signal controller (TSC) and the vehicle detection sensors (Sensors) installed at the intersection connect to the TOSCo Infrastructure Processor. TOSCo Infrastructure Processor interfaces with a NEMA TS-2 TSC via NTCIP communications over Ethernet communications. The TSC is also required to support the generation of SPaT information directly.

The TOSCo Infrastructure Processor also communicates with the vehicle detection subsystem. The vehicle detection subsystem is 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 traditional control functions of the traffic signal controller and detect and monitor queue formation and dissipation.

Software Components

Figure 3 shows the software components of the TOSCo Infrastructure System. The boxes inside the dashed box represent processes explicitly developed for TOSCo. This section provides a high-level description of the purposes and functions of these software elements.



Source: Texas A&M Transportation Institute, 2022

Figure 3. TOSCo Infrastructure Software Components

TOSCo Infrastructure Processor

The TOSCo Infrastructure Processor is responsible for producing the infrastructure data elements needed by TOSCo-equipped vehicles to plan their speed profiles. Currently, the TOSCo Infrastructure Processor contains the following processes as described in the sections below.

SPaT Message Generator

The SPaT Message Generator is the process responsible for generating the SAE J2735 SPaT message. This module receives the SPaT data pushed by the TSC every 100 milliseconds, decodes the SPaT Data message, and extracts the data elements, like phase status, minimum and maximum time for each phase, and other information like intersection status, which are needed to enhance the SAE J2735 SPaT message. This module also receives from the Green Window Predictor module, Green Window information and queue length for each designated TOSCo lane at the intersection. The enhanced SPAT message includes both traditional signal phase and timing information (intersection status, phase status, minimum end times, maximum end times, etc.) and regional extensions that provide green window information and queue length for each movement to equipped vehicles via the RSU. The SPaT Message Generator utilizes information received from the TSC and the Green Window Predictor to enhance the SAE J2735 SPaT message and forwards the message to the RSU every 100 milliseconds to broadcast to equipped TOSCo vehicles at the intersection. The SPaT Message Generator also forwards the SPaT data to the Green Window Predictor, every 100 milliseconds, when received from the TSC. The SPaT Message Generator logs into log files the SPaT data it receives from the TSC and the contents of the generated SPaT messages when logging is activated.

TOSCo Queue Estimator

The TOSCo Queue Estimator is responsible for determining the current location of the back of the queue, the predicted maximum location of the back of the queue, and the time the maximum queue will reach the stop bar during each signal cycle. These estimates are on a lane-by-lane basis generated using the detector status information queried from the TSC every 100 milliseconds. The TOSCo Queue Estimator sends the per lane queue information to the Green Window Predictor module via a UDP socket. The TOSCo Queue Estimator module logs the detector status it received from the TSC and per lane queue length information it calculated into a log file when logging is activated.

TOSCo Green Window Predictor

This module is responsible for determining the start and end of the “green window” using data from the TOSCo Queue Estimator and SPaT data from the TSC. The beginning of the Green Window is the time in the cycle when the last vehicle in the queue will 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, typically the yellow phase's onset. The TOSCo Green Window Predictor updates the green window information at a frequency of 10 Hz. The Green Window Predictor logs into a log file the green window information it generates when logging is activated.

TOSCo TSC Communications Manager

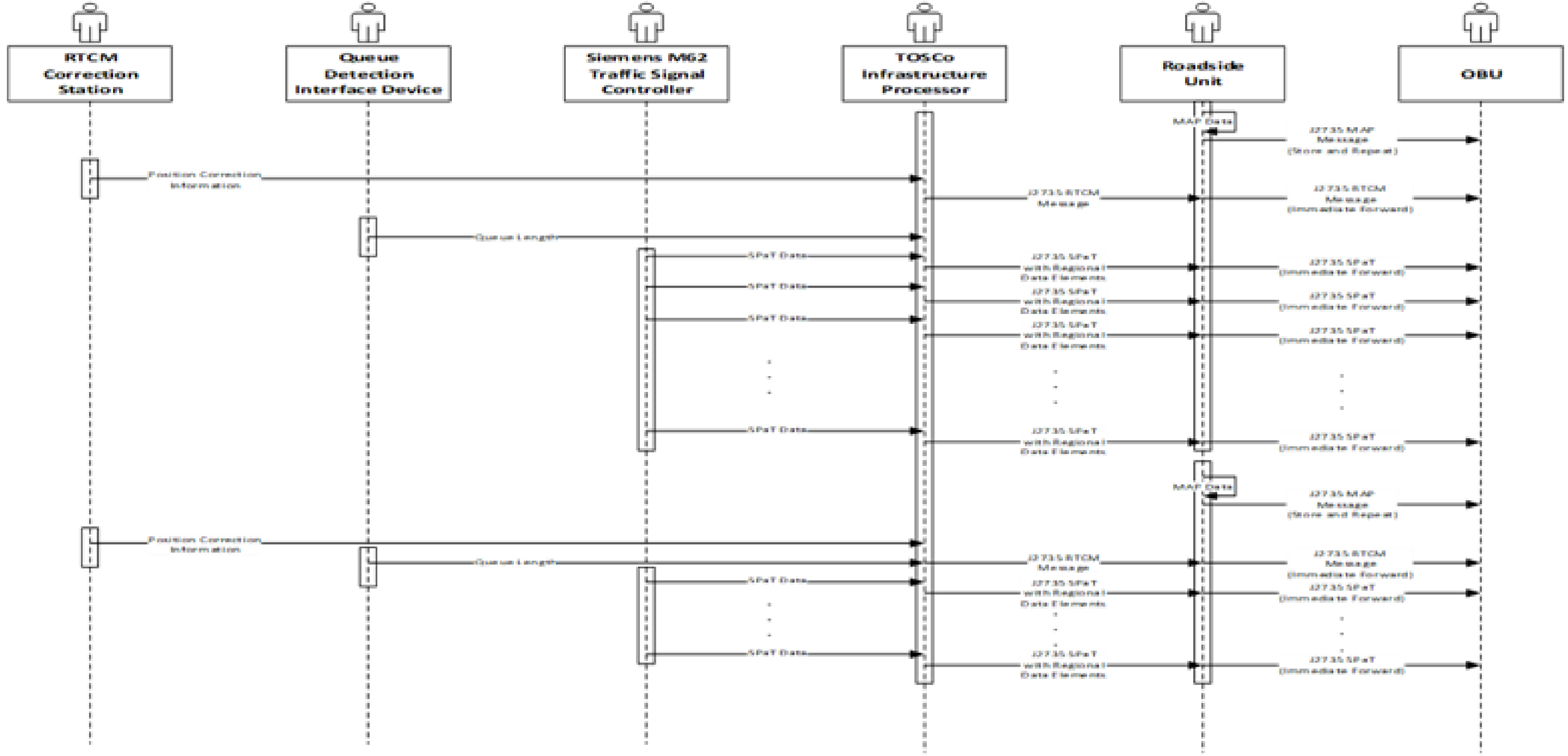
This module is responsible for querying the TSC and getting information about the available timing patterns programmed in the TSC by the responsible agency. The module generates a Timing Pattern file that is accessed and used by the TOSCo Green Window Predictor module. This file includes information about each pattern programmed in the TSC including pattern number, cycle length, offset, and split values. This module is run once anytime the TSC configuration is modified to get the latest timing pattern information from the TSC.

TOSCo System Configuration Files

The TOSCo System modules require configuration files that are generated manually by the user and stored in a predefined folder on the TOSCo Infrastructure processor. The system developers use configuration files to achieve this functionality. System developers use a simple user interface to view and edit configuration parameters to support system deployment for the demonstration.

Data Flows

Figure 4 shows the data flow between the TOSCo major infrastructure subsystems.



Source: Texas A&M Transportation Institute, 2022

Figure 4. Data Flow between TOSCo Infrastructure Subsystems

Chapter 3. TOSCo Queue Estimator

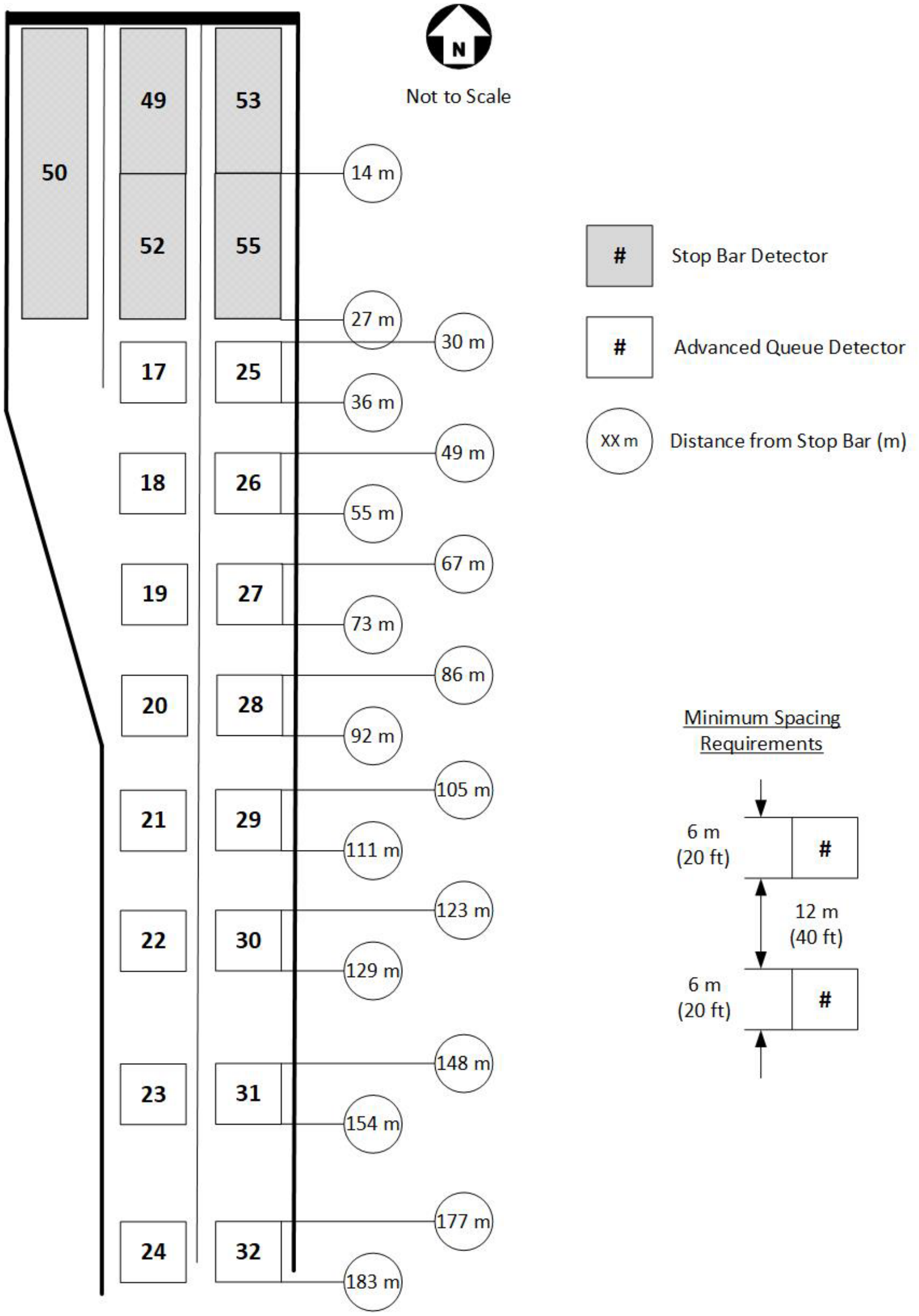
TOSCo requires an estimation of the queue length for the vehicles to identify a stop location and to adjust the green window start (a recommendation from the infrastructure of when vehicles should arrive at the stop bar). This chapter explains the method for estimating the queue length on TOSCo approaches.

Fundamental Queue Length Estimation Concept

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 in this case), 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 stop bar. The TOSCo Team configured 16 queue zones numbered from 17 to 32 on the approach, as illustrated in Figure 5. (It is assumed that the detectors 1 through 16 are used by the traffic signal controller as demand detectors for normal signal operations).

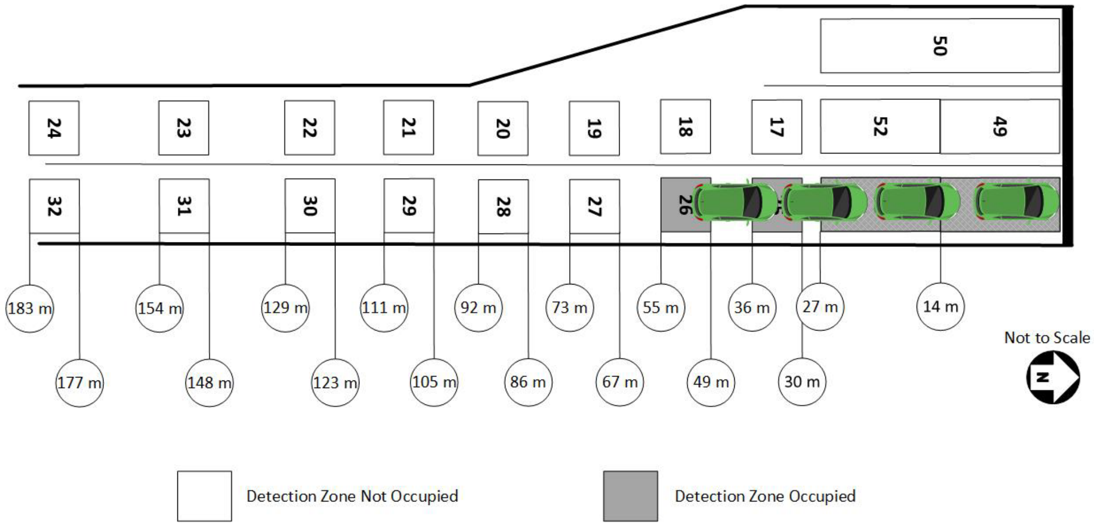
In addition to radar-based sensors, the TOSCo Team also included video-based sensors for detecting vehicles from the stop bar to 30 m. For instance, in Figure 5, zones 49, 52, 53 and 55 are configured as video-based. These sensors activiate as vehicles travel through them. Hence, their detections are not considered when the traffic signal is green and yellow.

The queue estimation algorithm estimates the back of the queue by assessing the states of all the detection zones “occupied” by stopped vehicles. As shown in Figure 6, the algorithm estimates the back of the queue to be the locations of the trailing edge of the first unoccupied queue detection zone upstream of the stop bar. This approach overestimates the actual queue length by providing an additional buffer between the TOSCo vehicles and the back of the queue.



Source: Texas A&M Transportation Institute, 2022

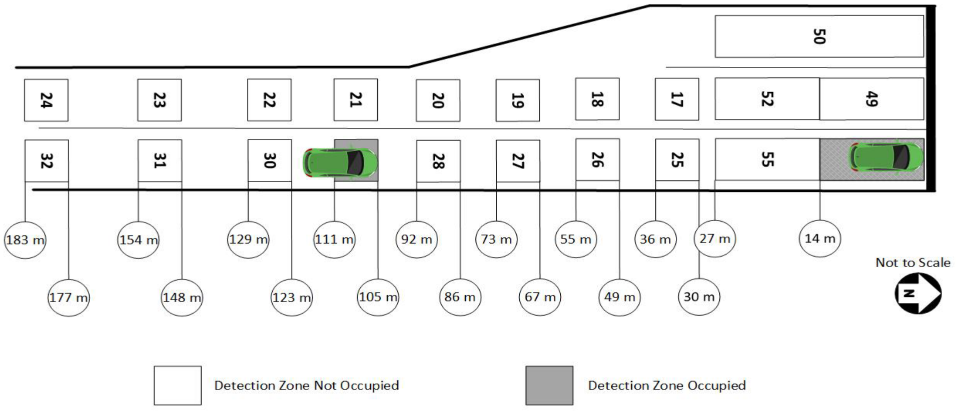
Figure 5. Typical Detection Zone Configuration for an Approach to a TOSCo Intersection



Source: Texas A&M Transportation Institute, 2022

Figure 6. Example of TOSCo Queue Detection

Lastly, queues at the intersection must grow and dissipate logically. The algorithm checks the status of the queue detectors every 100 ms. Based on vehicle dynamics, it is unlikely for a queue to grow more than one detection zone in 100 ms. Also, for signalized intersections, queues must grow and dissipate from the stop bar. That means the detection zones closest to the stop bar must clear before the queue can clear the detection zones farther away from the stop bar. The team has added logic checks in the algorithm to ensure that queues at the intersection grow and dissipate logically in the absence of vehicle breakdown. Figure 7 illustrates an illogical queue growth scenario. Because multiple detection zones are not occupied by the stopped vehicle, the algorithm ignores the stopped vehicle on detector 29. As a result, queue estimator would declare the back of queue to be located 14 m upstream of the stop bar (and not 129 m).



Illogical queue growth because intermediate detectors not occupied!

Source: Texas A&M Transportation Institute, 2022

Figure 7. Example of Illogical Queue Growth Scenario

Inputs

The queue estimation algorithm utilized a combination of video- and radar-based sensors. This sensor uses video for stop bar detection up to 30 m and radar for advanced detection up to 183 m. The placement and configuration of the detection zones have the following constraints:[1]

- The first queue zone for any lane must be placed at least 30 m beyond the stop bar.
- Each queue detection zone must be separated from the following queue detection zone by at least 12.5 m.
- Each queue detection zone has a minimum zone length of 6 m.

Each radar sensor is limited to a total of 16 detector channels per approach. In addition, these detection zones were evenly distributed across all lanes, conforming to the separation constraints specified above. Figure 5 shows the detection zone boundaries and detector numbers for the test intersection of the Texas A&M University Systems' RELLIS campus.

The Queue Detection algorithm uses the following convention for configuring the detection zones in each lane:

- Format: Lane No.
- Number of Detectors
- Detector No.
- Distance from Stop Bar

Note that the Lane No. in the Queue Detection Algorithm configure file is the same as the *LaneNo* data element in the MAP Message. For example, the northbound approach has two lanes coded as *LaneNo* 2 and *LaneNo* 3 in the MAP Message for the RELLIS test intersection. For this test intersection, *LaneNo. 2* (the inside lane) has a total of 10 detectors. For testing purposes, the research team configured this approach to have two 12 m long detection zones (i.e., Detector No. 49 and 52) at the stop bar and eight queue detection zones (Detector No. 17 to No. 24) spaced evenly between 30 m and 183 m. Figure 8 shows an example configuration file for *LaneNo*. 2 in Figure 5 above. Each TOSCo-supported lane must include these data elements in the configuration file.

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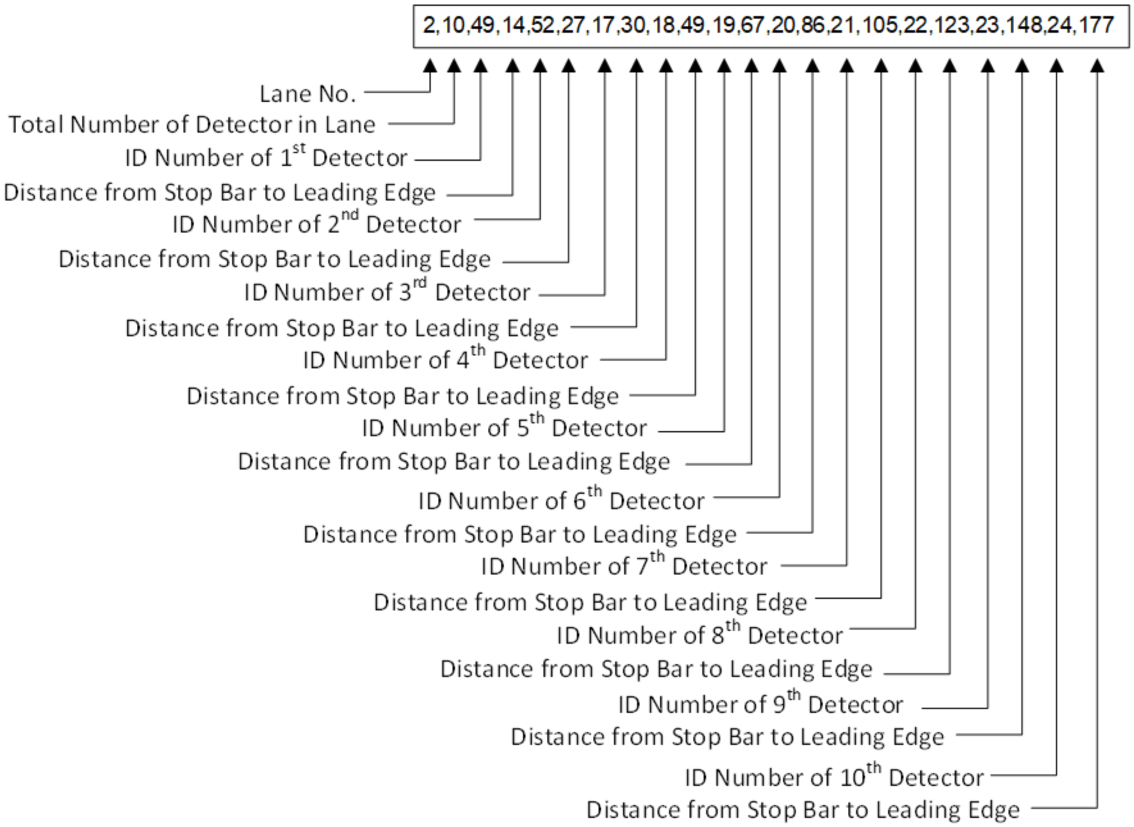
[1] These constraints are for the specific radar sensor used in the deployment. Different constraints may exit for different types of sensors used to provide queue detection.

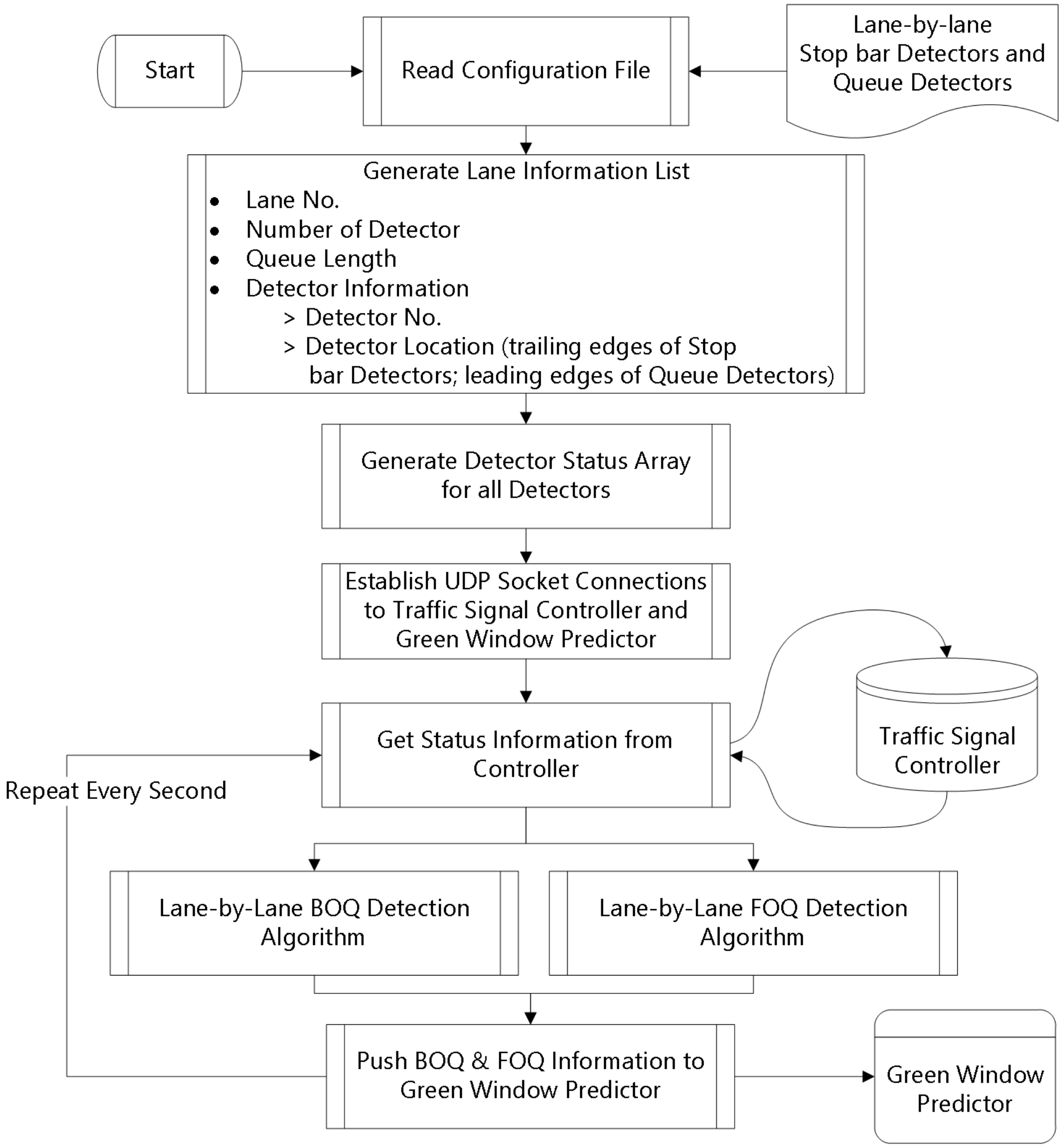


Source: Texas A&M Transportation Institute, 2022

Figure 8. Example of Data Elements in Queue Detection Zone Configuration File

Process Description

The Queue Estimator reads the prepared detection layout listed in the configuration file per intersection, generates lane information list and status arrays, and queries the TSC for the detector calls for all detectors and signal phase status as illustrated in the flowchart (Figure 9). The module includes two algorithms which are the back of queue detection (i.e., queue length detection), and the front of queue detection.



(UDP: User Datagram Protocol, BOQ: Back of Queue, FOQ: Front of Queue)

Source: Texas A&M Transportation Institute, 2022

Figure 9. Queue Length Detection Module

Determining Back of Queue (BOQ)

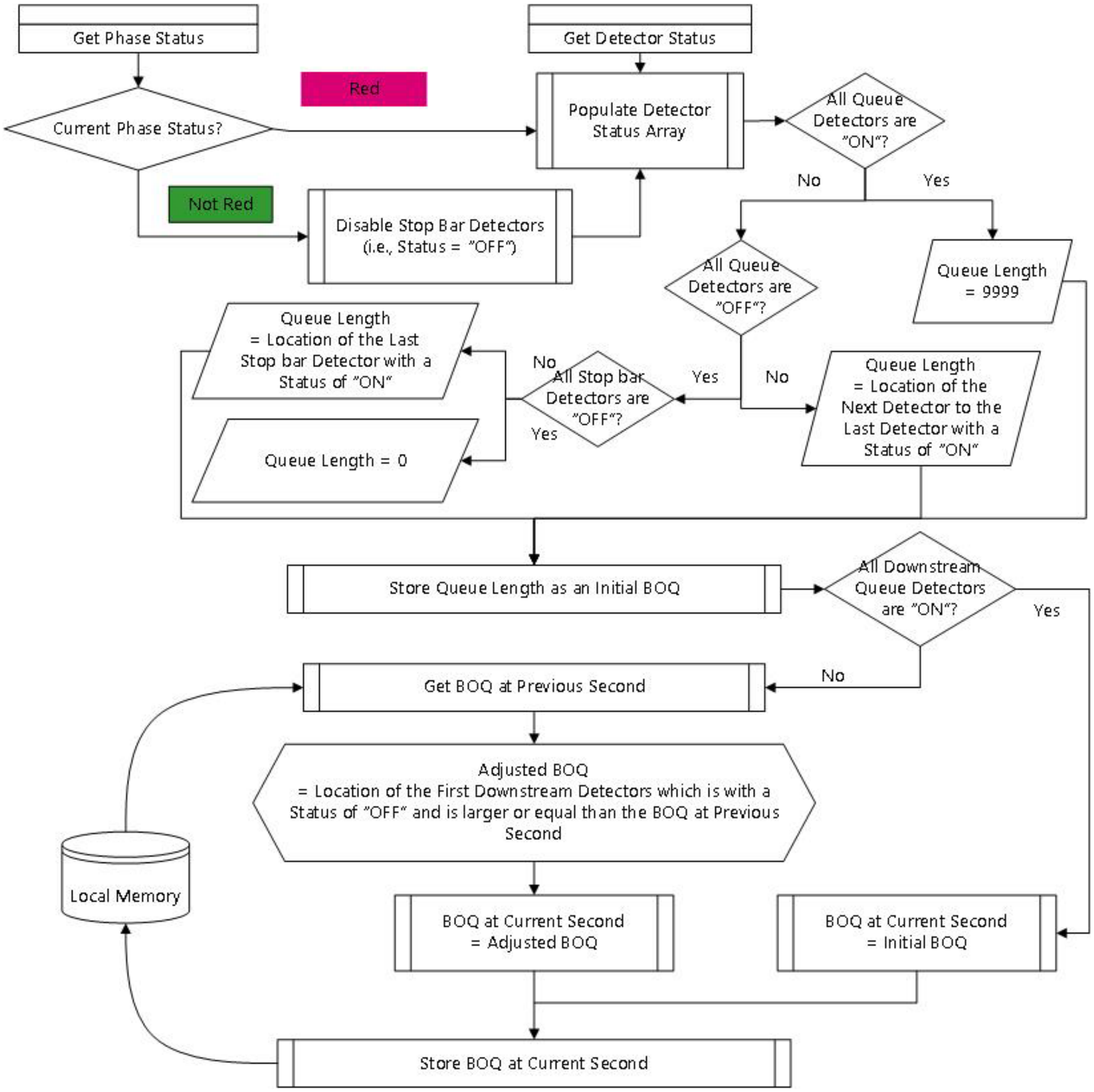
Figure 10 shows the logic diagram for determining the back of the queue. The algorithm uses the status of the stop bar detection zones and the status of queue detection zones to identify the location of the back of the queue. The stop bar detection zones are video based. When a vehicle is present, the detection zone is activated. The queue detection sensors measure the speed of traffic in each detection zone. The sensor has its defined detection range from 30 m to 183 m away from stop bar. When the sensors detect that vehicle speeds are below five mph, the detection system activates the detection zone (i.e., turns it "ON"). The algorithm checks the status of the detection zones every 100 ms. If no detection zones are "ON," the algorithm assumes that no queue exists. If the status of one or more detection zone is "ON," the algorithm checks the status of each detection zone starting at the detection zone closest to the stop bar. It sets the back of the queue parameter equal to the leading edge of the next unoccupied detection zone. If the queue covers the last detector in a lane, the algorithm assumes that the queue extends beyond the range of the detection systems and reports a queue length value of "9999." The system developers have added checks to ensure that the queue grows logically between time steps. When the queue is shorter than the available queue detection range, video-based stop bar detection zones are implemented to report queue length. The algorithm applies the same logic for the video-based detection system, except at the beginning of green, a hold and a queue dissipation timer is included. Because the video-based sensor is presence based, stop bar detection zones are kept as "ON" as vehicles traverse them. Hence, at the beginning of green, the short queue length is held using a hold and the hold is removed when queue dissipation timer goes to zero.

Determining Front of Queue (FOQ)

Simultaneously, the queue length detection module also determines the front of the queue. The green window prediction system uses information about the front of the queue to refine the estimate of when the queue will clear (see Figure 11). When the signal phase is not green, the process always sets the front of the queue equal to the stop bar (0 meters). When the signal phase turns green, the algorithm determines the front of the queue by assessing the status of the detectors as the queue dissipates. The algorithm determines the front of the queue to be the location of the back of the first queue detection zone upstream of the stop bar with an "ON" status.

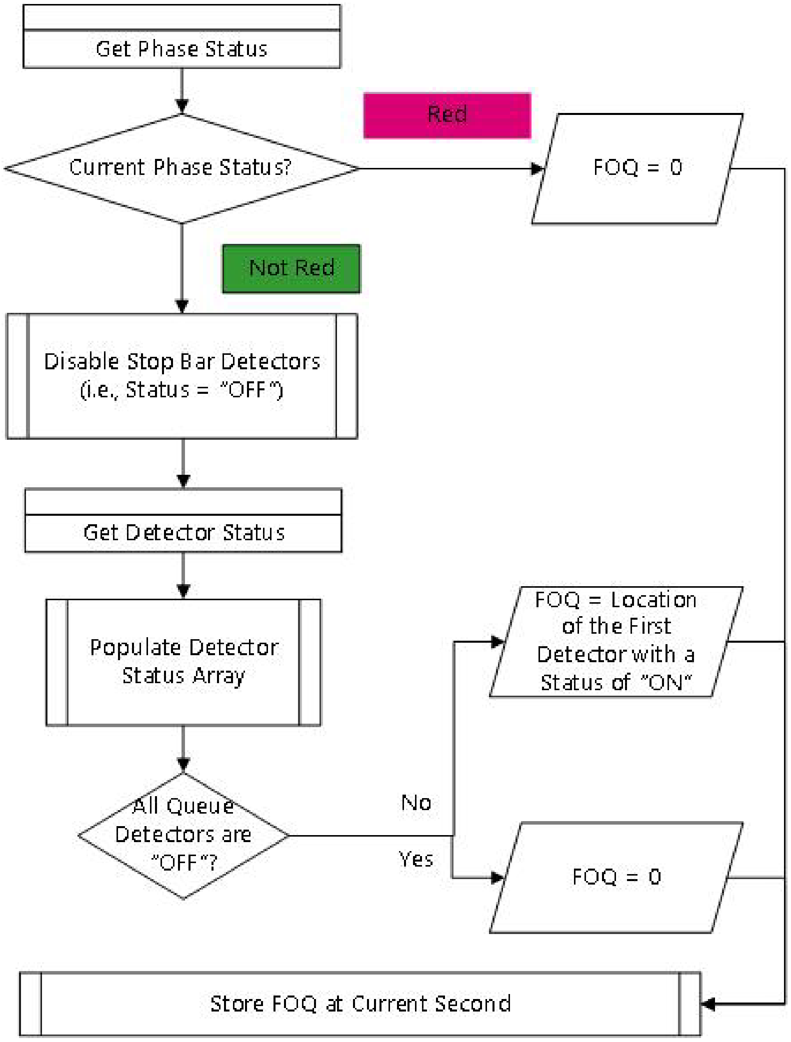
Outputs

After the Queue Detection algorithm has determined both the back and the front of the queue, the Queue Detection algorithm pushes this information to the Green Window Predictor through a User Diagram Protocol (UDP) socket connection.



Source: Texas A&M Transportation Institute, 2022

Figure 10. Logic Diagram for the Back of Queue Detection Algorithm



Source: Texas A&M Transportation Institute, 2022

Figure 11. Logic Diagram for the Front of Queue Detection Algorithm

Alternate Queue Detection Strategy

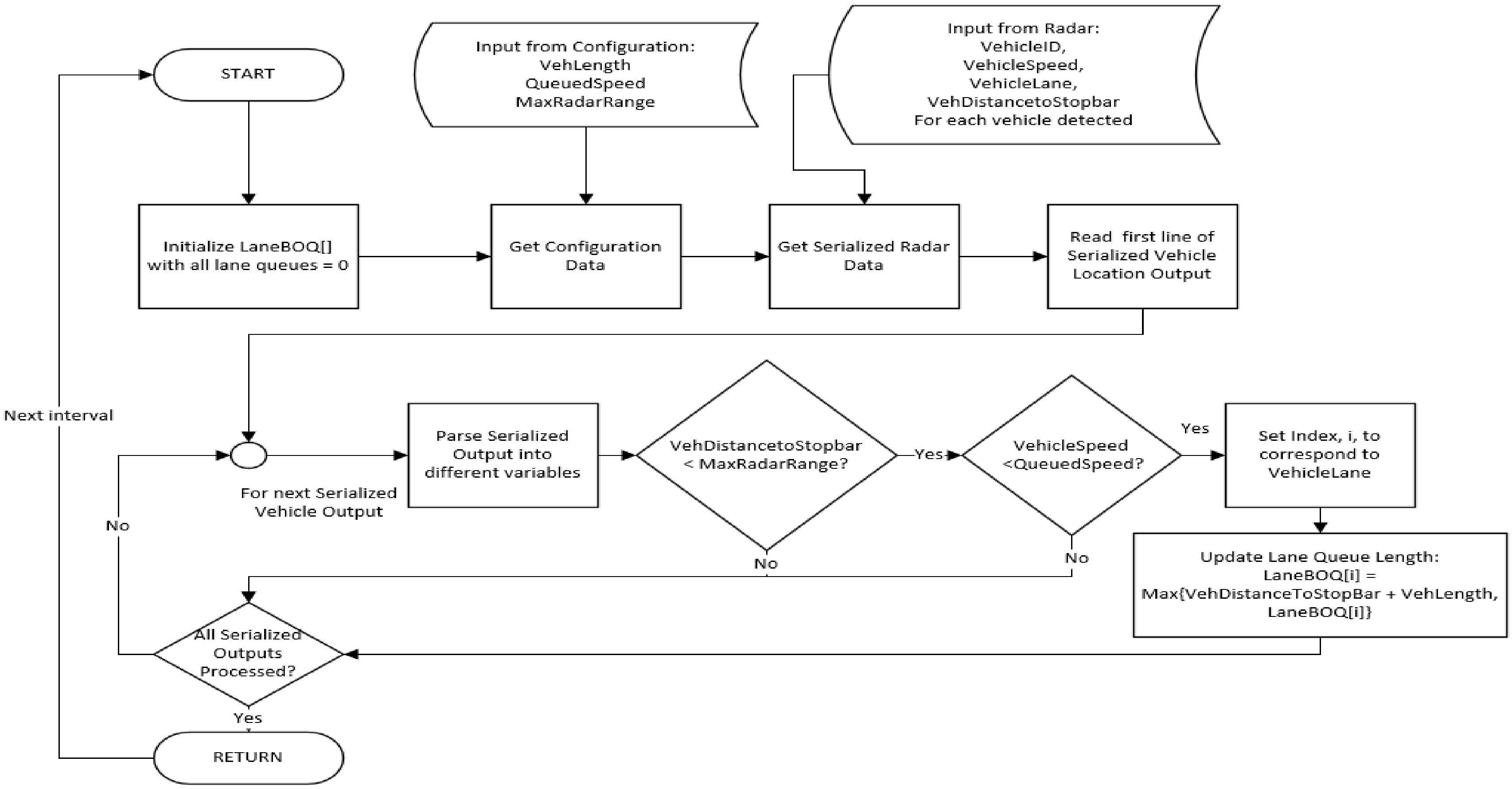
The Iteris Vantage Radar detector can generate a serial data stream of each vehicle approaching the intersection. This data stream contains the vehicle speed and vehicle distance from the sensor. TOSCo developers have developed an alternate approach for estimating queue length by lane. Figure 12 provides a logic diagram illustrating this approach.

The first input is the serialized vehicle output produced by the sensors. The serialized output records the speed and distance of each vehicle approaching the queue in each lane to enable special functions. For this application, the serialized detector output must contain 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 bounds the data to be the maximum range of an approach to filter out detector inputs from adjacent intersections. 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 and is applied to all vehicles regardless of their types.

Next, the algorithm begins to read each line of vehicle data from the detector radar packet. The infrastructure algorithm converts each line of text into usable variables 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 algorithm does not include the input from that vehicle in the queue length determination. For those vehicles within the detection zone, the algorithm then uses the vehicle speed to determine if 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 it has evaluated all the vehicle data from the detector radar. The algorithm then returns a queue length value for each lane.

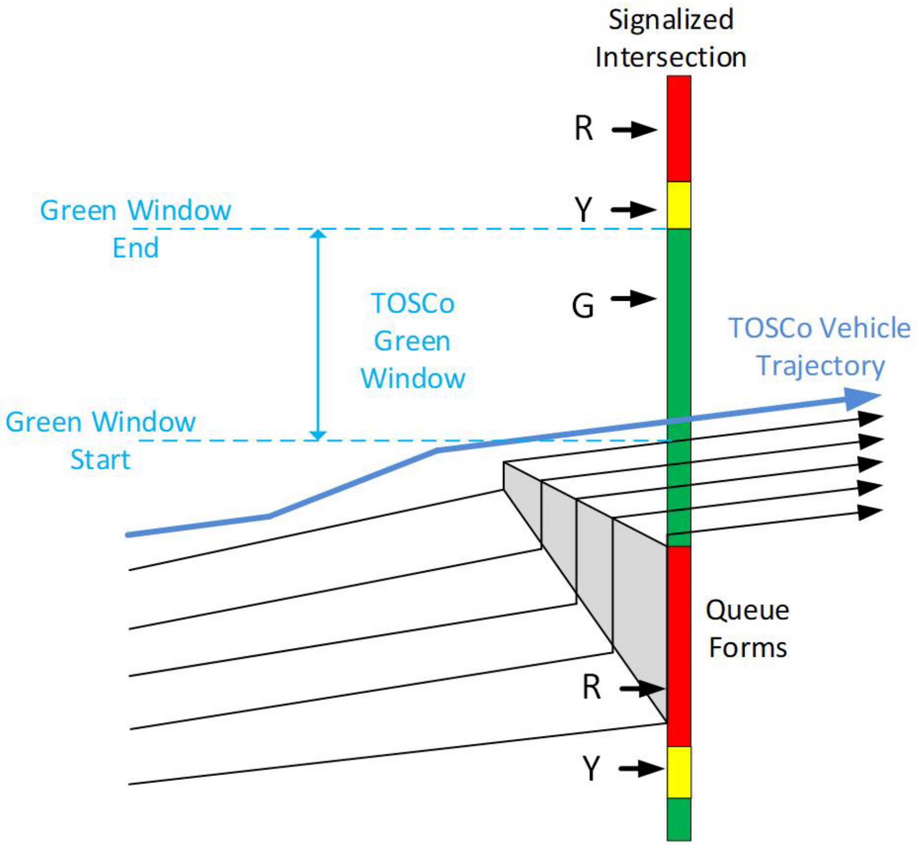


Source: Texas A&M Transportation Institute, 2022

Figure 12. Proposed Queue Calculation from Serialized Vehicle Data from Radar Sensor

Chapter 4. TOSCo Green Window Predictor

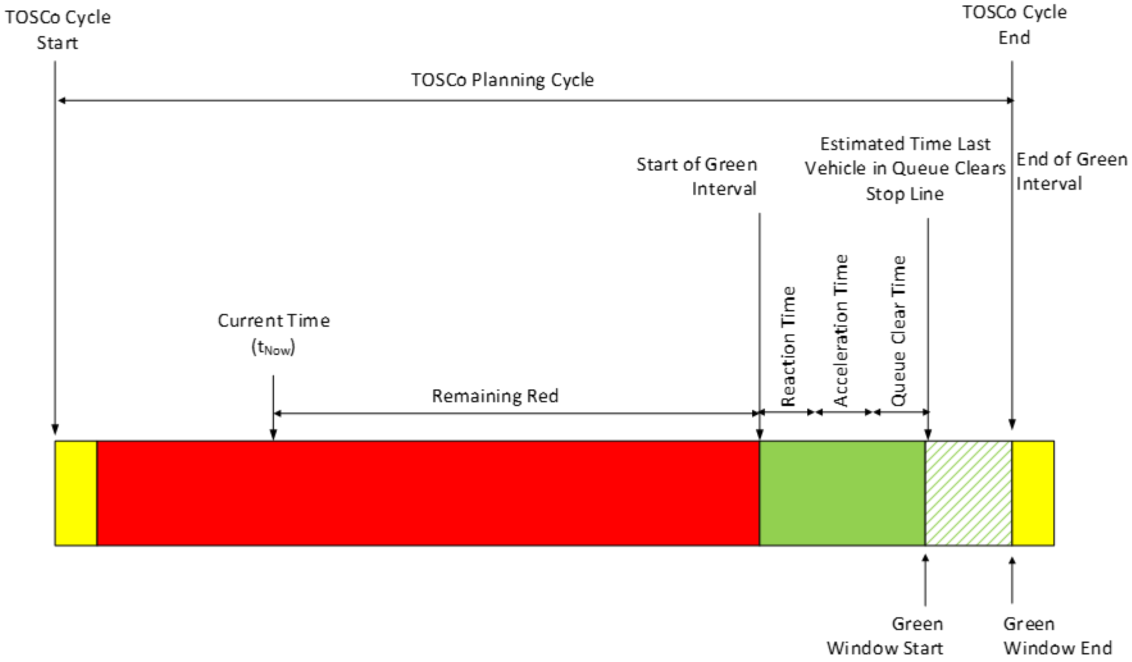
One critical function of the TOSCo Infrastructure System is to predict the green window. As shown in Figure 13, the “Green Window” represents the time during the green interval when the last vehicle in the queue clears the stop bar of the intersection and the end of the green interval. The “Green Window” 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, 2022

Figure 13. Definition of Green Window

For the vehicle trajectory planning purpose, 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. Figure 14 also shows the various elements in determining the Green Window.



Source: Texas A&M Transportation Institute, 2022

Figure 14. Definition of TOSCo Planning Cycle

If the time required for the back of the queue to reach the stop bar is greater than the allocated green time (i.e., *GreenWindowStart ≥ GreenWindowEnd)*, then queue spillover is expected. In this case, the Green Window Predictor declares the Green Window start and end to be equal to the end of the green phase to communicate that there is no Green Window.

Configuration Parameters

Several inputs into the Green Window Predictor algorithm come from configuration data stored in a file. These configuration parameters do not change during TOSCo regular operation. The configuration parameters are as follows:

- *IntersectionID*: The identification number of the intersection corresponding to the configuration file. Use for logging and error checking.
- *VehLength*: The *VehLength* parameter represents the total distance (in feet) occupied by a vehicle in a queue. The Green Window Predictor assumes that all queue vehicles are passenger cars. This parameter includes both the physical length of the car and the gap between vehicles. The Green Window Predictor uses this parameter to estimate the number of vehicles in a queue. This value is stored in the configuration file in units of feet, and the value is converted to meters as the Green Window Predictor reads the configuration file.
- *SpeedLimit*: This parameter is the speed limit of the roadway converted into meters-per-second. The speed limit of all the TOSCo lanes is assumed to be the same in the current algorithm.
- *DistanceLastVideoDetectorFeet*: This parameter corresponds to the location where the queue length converts from video to radar-based detection. The variable is used to hold the queue

length until after the queue is expected to clear for the distance where the detectors are only presence based, video based in the case of this research effort. The value should be set to the distance of the upstream location of the furthest presence-based detector.

- a: This parameter is the assumed acceleration for a vehicle as it accelerates from a stop to its desired speed. The Green Window Predictor assumes that a vehicle's acceleration is constant. Deployers can use this parameter to fine-tune the time required to clear the queue based on field observations.
- Time*PR_FirstVehicle*: This parameter is 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 amount of time for the first vehicle in a queue to perceive and respond to a protected movement is typically longer than subsequent vehicles. The default value for this parameter is 2 seconds. Deployers can use this parameter to fine-tune the queue clearance times based on field observations.
- *TimePR_perVehicle*: This configuration parameter is 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. This value is typically 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.
- *NumTOSCoLanes*: This configuration parameter represents 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*: This configuration array represents 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*: This configuration array contains the phases corresponding to each TOSCo approach, *i*. The value at element i^{th} corresponds to the TOSCo phase, *k*, for that lane.
- *PatternNumber*: This configuration represents the coordination patterns (or coordination plan) stored in the traffic signal controller. The Green Window Predictor references the pattern number, *l*, to identify the active timing plan so the Green Window Predictor can select the appropriate cycle length and phase split times.
- *CycleLength*: This parameter describes 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.

Input Parameters

The Green Window Predictor uses the following variables 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. These dynamic inputs are as follows:

- *TOSCoPhaseStatus*: This array contains the phase status of the TOSCo-enabled phases at the intersection. The phase status is represented by the MovementPhaseState ASN.1 value (from the SAE J2735 Standard). The SPaT information from the traffic signal controller contains the current MovementPhaseState for each programmed signal phase. A MovementPhaseState equal to “3” means the signal indications governing the TOSCo movement are displaying a “red” indication and that vehicles should “Stop-And-Remain” until the movement phase state changes. [(red) and “8” means Protected Clearance (yellow).]
- *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 intersection as the time remaining for the active phase state and is converted into the DE_maxEndTime data element in the J2735 SPaT message.
- *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 time remaining for the active phase state and is converted to the DE_minEndTime data element in the J2735 SPaT message.
- *NumQueuedVeh*: This array provides the number of queued vehicles estimated for each TOSCo lane, i, in the queue calculation. The Green Window Predictor uses this variable to calculate the amount of time required for the back of the queue to start accelerating.
- *LaneBOQ:* This array contains the distance (in meters) from the stop bar to the back of the queue. The Green Window Predictor uses LaneBOQ to calculate the amount of time required for the rear of the last vehicle in the queue to reach the stop bar.
- *TNow*: This value is the current UTC. 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 Green Window Predictor uses this value to refine the beginning of the Green Window and detect when the queue clears.

Process Description

Figure 15 shows a high-level process diagram developed to calculate the start and end of the Green Window for the TOSCo regional elements. 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* in Figure 14*)* and the time when the TOSCo phase will end for the lane (shown as the *GreenWindowEnd* in Figure 14).

The steps to calculate the start and end of the green window are discussed below. APPENDIX F provides a detailed flowchart of the computation process for determining the green window.

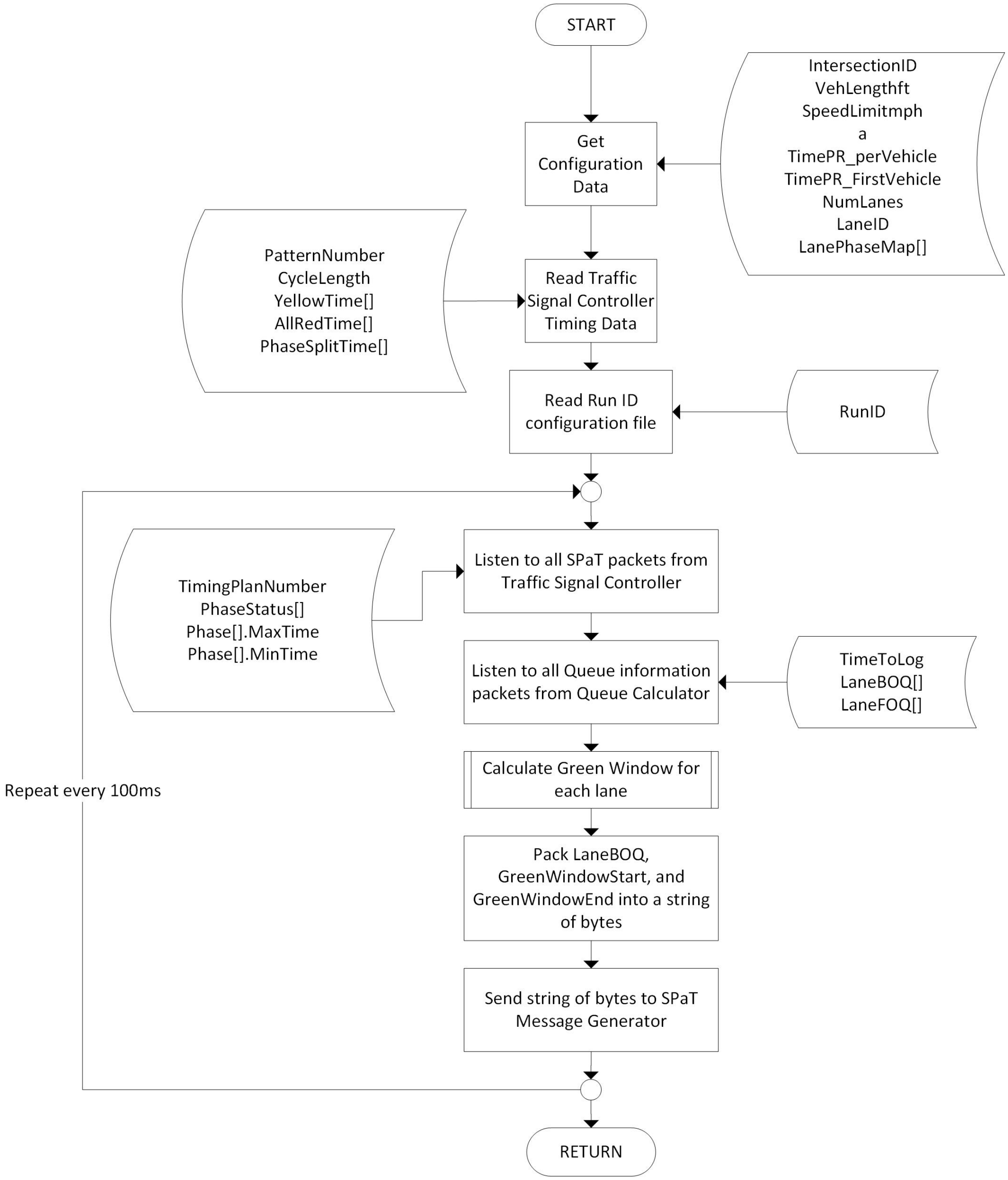


Figure 15. High Level Process Diagram of Green Window Predictor

Computing Variables Used in Calculation

The first step in the process is to compute some variables to help calculate the green window. The first is the distance required to accelerate a vehicle from a stop to the posted speed limit (d_{acc}). 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. Next, the predictor calculates the estimated number of vehicles in the queue (*NumVehQueued*). The algorithm estimates the number of vehicles in the queue by subtracting the front of queue measurement from the back of queue measurement and dividing by the vehicle length. The algorithm rounds the resulting value down to acquire the *NumVehQueued*. Finally, the predictor calculates the *EstimatedGreenTime*. This parameter contains the estimated duration of the green interval of the TOSCo phase, based on the base signal timing plan programmed in the controller. The algorithm calculates this value using the following equation:

$$EstimatedGreenTime = [Split\ Time - (Yellow\ Interval + All\ Red)]_{TOSCo\ Approach\ Phase}$$

Figure 16. Equation

The Green Window Predictor must estimate this value because the traffic controller does not provide data for the expected duration of the green state while it is in a red state. The Green Window Predictor uses this process to compute the *EstimatedGreenTime* only when the TOSCo phase is red. Once the TOSCo phase is in a green state, the Green Window Predictor uses the *minEndTime* value produced by the controller to determine the time remaining in the green interval.

Estimating *RemainingRed* and *RemainingGreen* Times

The remaining red and remaining green time calculations vary based on the current signal state of the TOSCo phase because the signal controller only provides information about the currently displayed signal status. Therefore, Green Window Predictor uses different values based on the active status. A red, or StopAndRemain, status uses the SPaT data from the controller to populate the *RemainingRedMax* and *RemainingRed* values and the *EstimatedGreenTime* for the phase to populate the *RemainingGreen* value. The *RemaingRedMax* is populated from the *maxEndTime* data element in the SPaT and the *RemaingRed* is populated from the *minEndTime* data element in the SPaT. If the phase status is green, both the *RemainingRedMax* and *RemainingRed* values are set to zero and, the *RemainingGreen* value is set to the *minEndTime* data element. Note, while the signal is green, the *minEndTime* and *maxEndTime* data elements are equal for the TOSCo approach phase. If the signal is in another phase, the software assumes the phase is yellow and calculated the *RemainingRedMax* and *RemainingRed* with the following equations:

$$\begin{aligned} RemainingRed = {} & CycleLength \\ & - [(EstimatedGreenTime - Yellow\ Interval + de\_MaxTime)]_{TOSCo\ Approach\ Phase} \end{aligned}$$

$$RemainingRedMax = RemainingRed$$

Figure 17. Equation

For this portion of the cycle, the RemaingRedMax and RemainingRed are set equal to each other with a large value because the TOSCo vehicles are assumed to need to stop regardless of the duration of red. The *RemainingGreen* is set to the *EstimatedGreenTime* for the phase.

Estimating Queue Clearance Times

One feature of the green window as developed is to manage the short queue lengths coming from the queue estimator. This process involves determining if the video detection is unable to detect a queue. The process involves checking if the queue estimator is sending a queue length of zero and if the signal is green (or “ProtectedMovementAllowed”), if the current time is past an expected time for the queue to clear, and if the queue is shorter than the configured distance of the end of the last video-based detector from the stop bar. If all the conditions are met, the *LaneBOQ* is overridden with the previous iteration queue length, *LastQ*. Otherwise, the green window predictor uses the queue length from the queue estimator. Note, the research team recommends that a future implementation of TOSCo would move this function to the queue estimator. This implementation put this function in the green window predictor due to the flexibility offered by the green window predictor already reading the signal status.

Next, the Green Window Predictor estimates time associated with the clearance of any reported queues. If the *LaneBOQ* element is greater than zero, the Green Window Predictor calculates the *PerceptionReactionTime, AtSpeedTravelTime*, and *TimeAccelerate* values. Otherwise, it sets each of these components to zero. The *PerceptionReactionTime* is the amount of time needed for each vehicle to perceive and react to the opportunity to begin to accelerate. If the *LaneFOQ* is equal to zero, the algorithm estimates the *PerceptionReactionTime* by summing the Time*PR_FirstVehicle* and the product of the *NumQueuedVeh* minus one multiplied by *TimePR_perVehicle*. If the *LaneFOQ* is not equal to zero, the algorithm does not add the Time*PR_FirstVehicle* to the queue clearance time. 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. The Green Window Predictor estimates the *AtSpeedTravelTime* by dividing the difference between the *LaneBOQ* and the d_{acc} by the approach speed limit. The representation of 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}, the algorithm sets the *AtSpeedTravelTime* to zero and calculates the *TimeAccelerate* using the lane’s *LaneBOQ* element.

Confirming Valid Information

The final step in the process is to confirm that the algorithm is generating valid information for TOSCo. The algorithm uses temporary variables to store information for the potential green window start and end which are called *TempStart* and *TempEnd*, respectively. The first validation check is to see if there are any reasons to invalidate or correct the information. The first step is to calculate the *TempStart and TempEnd* time marks. The *TempStart* is the sum of the *RemainingRed*, the *PerceptionReactionTime,* the *TimeAccelerate,* the *AtSpeedTravelTime*, and the *TNow* components. The *TempEnd* is the sum of the *RemainingRed, the RemainingGreen*, and the*TNow* data elements. If the *LaneBOQ* is reported as a valid value from the queue calculator and the *TempStart* is greater than the *TempEnd,* the Green Window Predictor equates the *TempStart* to the *TempEnd*. Next, the Green Window Predictor checks if the time marks are in the next hour (e.g., over 36,000). If either value is greater than 36,000, then the Green Window Predictor subtracts 36,000 from the temporary value.

Finally, the Green Window Predictor checks if the *LaneBOQ* is a valid measurement, the controller is in coordination, and both *TOSCoPhase.MinTime* and *TOSCoPhase.MaxTime* values are valid. If all of these parameters are valid, the Green Window Predictor sets the *GreenWindowStart* equal to the *TempStart* and the *GreenWindowEnd* equal to the *TempEnd*. If the *LaneBOQ* is invalid but the controller is in coordination, the *LaneBOQ* is set to the maximum valid reading of 9,999. The *GreenWindowStart* is then set equal to the *GreenWindowEnd* which signifies that the queue is beyond detection limits, there is no green window, but TOSCo can still operate. If the signal is out of coordination or there is bad SPaT data, the Green Window Predictor will set the *LaneBOQ* equal to 10,000, and the *GreenWindowStart* and *GreenWindowEnd* equal to “-1,” signifying that an error condition exists. Once the Green Window Predictor calculates the *GreenWindowStart* and *GreenWindowEnd* for each TOSCo lane, the function is complete.

Outputs

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.

Chapter 5. TOSCo Signal Phase and Timing (SPaT) Message

The SPaT Message Generator provides 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 and time change values to the equipped vehicles. 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 statuses of the 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.

Configuration Parameters

As mentioned earlier, the TSC pushes SPaT data that includes the status and remaining time for each one of the 16 phases, 16 overlaps, and 16 pedestrian signals in the TSC. The SAE J2735 encoded SPaT message provides information about the status of movements available from each lane at the intersection controlled by the TSC. 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. APPENDIX A provides an example of a PTLM Configuration file for the RELLIS Smart Intersection.

Input Parameters

The three main inputs to the SPaT module are as follows:

- The TSC data pushed by the TSC
- The Green Window information pushed by the Green Window Predictor
- The PTLM configuration file for the intersection. The TSC and the Green Window Predictor push their data to the SPaT Message Generator every 100 milliseconds.

The TSC pushes signal phase and timing information to the TSC Simple Network Management Protocol (SNMP) objects. These objects include the time to change values for each vehicle, pedestrian, and overlap programmed in the controller. It also includes data objects on the status of controller operations at the intersection. APPENDIX B shows the byte-map structure of the SPaT data coming from the TSC.

In addition to the signal phases and timing information, the TSC data also contains a data element called the “Action Plan.” The SPaT Message Generator uses this data element to synchronize the PTLM configuration to the signal timing information. The SPaT Message Generator also uses this data element to ensure that the RSU broadcasts the proper MAP message that correlates to the traffic signal timing plan.

The green window data pushed by the Green Window Predictor provides the following data elements:

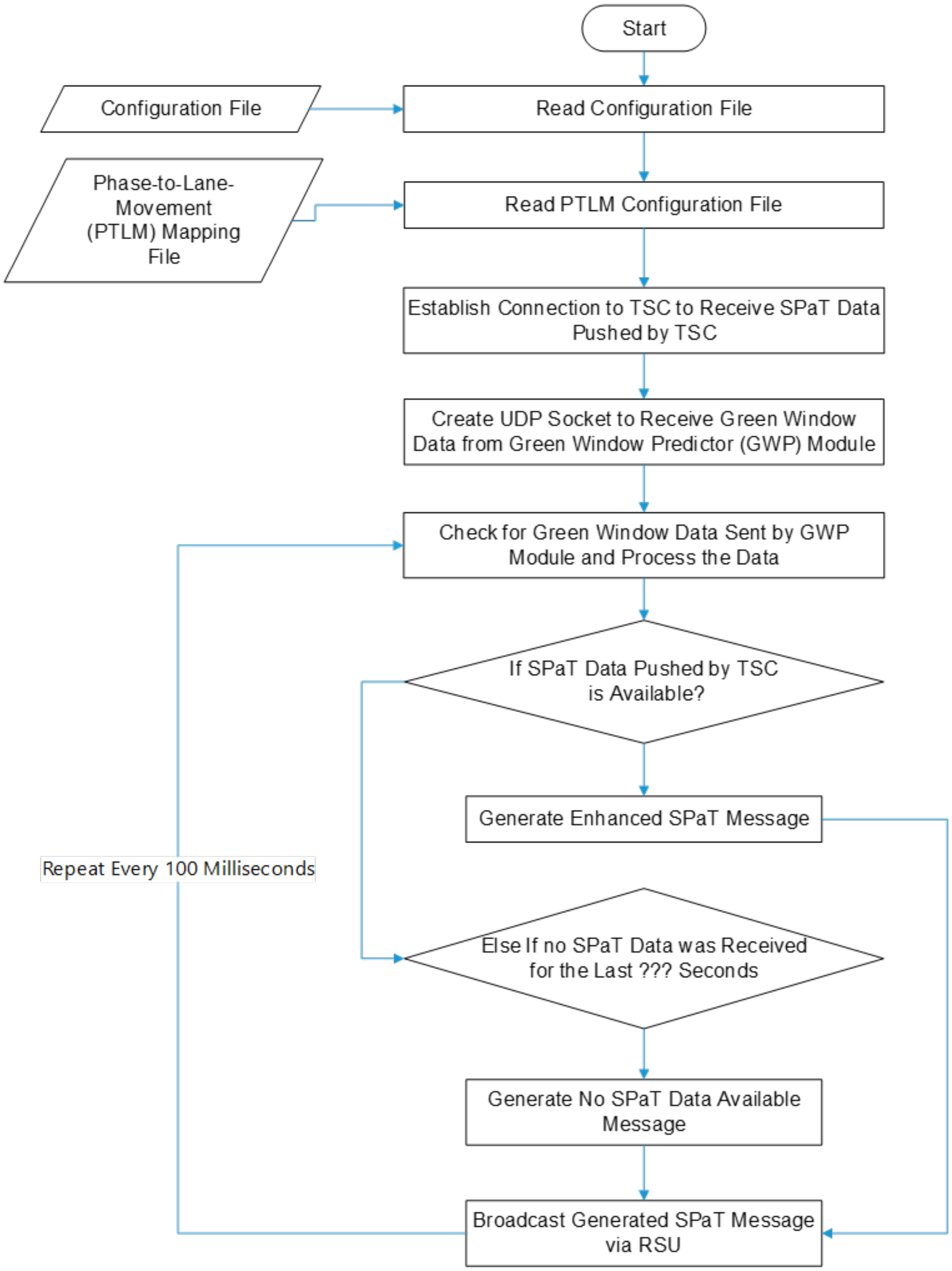
- Log detector status: During validation and evaluation studies, the TOSCo team uses a specific detector to start and stop data logging in the TOSCo computer. This value records the status of the detector that begins the logging process. The log detector status has a value of “0,” which means do not log data or “1” to indicate the need to log data generated by the infrastructure modules.
- Green window message number: This is a counter that increments each time the Green Window Predictor pushes new Green Window information to the SPaT Message Generator.
- Green window flag: This flag has a value of “0” or “1.” Zero (“0”) indicates that there have been no changes in the green window information from the previous message. One (“1”) indicates that the green window information includes new green window information since the last message.
- Number of TOSCo lanes: Indicates the number of lanes for which the Green Window Predictor will provide information in the remainder of the message. The Green Window Predictor sends information about the queue length, Green Window Start, and Green Window End for each TOSCo lane at the intersection to the SPaT Message Generator.
- Lane number: Indicates the lane number associated with the information that follows next.
- Queue length, Green Window Start, Green Window End: Identifies information for the lane number just specified.

The Green Window Predictor provides the lane number and green window information for each TOSCo lane at the intersection.

Process Description

Figure 18 shows the steps involved in generating the SAE J2735 2016 SPaT message for broadcasting to the TOSCo vehicles at the intersection. The SPaT Message Generator checks the UDP socket interface with the Green Window Predictor for any new messages every 100 milliseconds. If a message is received, the SPaT Message Generator reads the message contents, processes its content, and stores the information for use by the TOSCo subsystems in generating the SPaT message. The SPaT Message Generator uses the same green window information until it receives a new message from the Green Window Predictor.

The SPaT Message Generator also checks for any new SPaT data that the TSC pushes. If a new message is received, the SPaT Message Generators reads the message contents, decodes the message, and stores it in the SPaT data structures to be used later in generating the J2735 SPaT message. In decoding the SPaT data message pushed by the controller, the SPaT Message Generator includes checks to validate the information.



Source: Texas A&M Transportation Institute, 2022

Figure 18. TOSCo SPaT Message Generator

Once the SPaT Message Generator receives and processes the information from the Green Window Predictor and the TSC, it uses the information along with the PTLM configuration file to determine the status for each movement available in the lanes at the intersection and the minimum and maximum time to change for that movement. The SPaT Message Generator adds the queue length, the Green Window Start, and the Green Window End for the TOSCo lanes at the intersection. The Green

Window Start and End are added to the lane movement as part of the regional elements of the J2735 SPaT message.

Once all the movements available in the lanes at the intersection are processed, the SPAT Message Generator uses a third-party ASN.1 library to compile and generate the SAE J2735 encoded SPaT message in unaligned packed encoding rules (UPER).

Outputs

After generating the SPaT message, the SPaT Message Generator sends the encoded SPaT message to the RSU via a UDP socket interface established with the RSU at the start of the application. The RSU immediately forwards the SPaT Message to vehicles in the vicinity. The TOSCo team has configured specific UDP ports on the RSU in the immediate-forward-mode. The RSU immediately broadcasts any messages it receives to these UDP ports from external devices. For this testing, security was not enabled. The TOSCo team has configured UDP Ports 1516 and 1517 on the RSU in the immediate-forward mode. Appendix C shows the message profile for the SPaT message produced by the SPaT Message Generator.

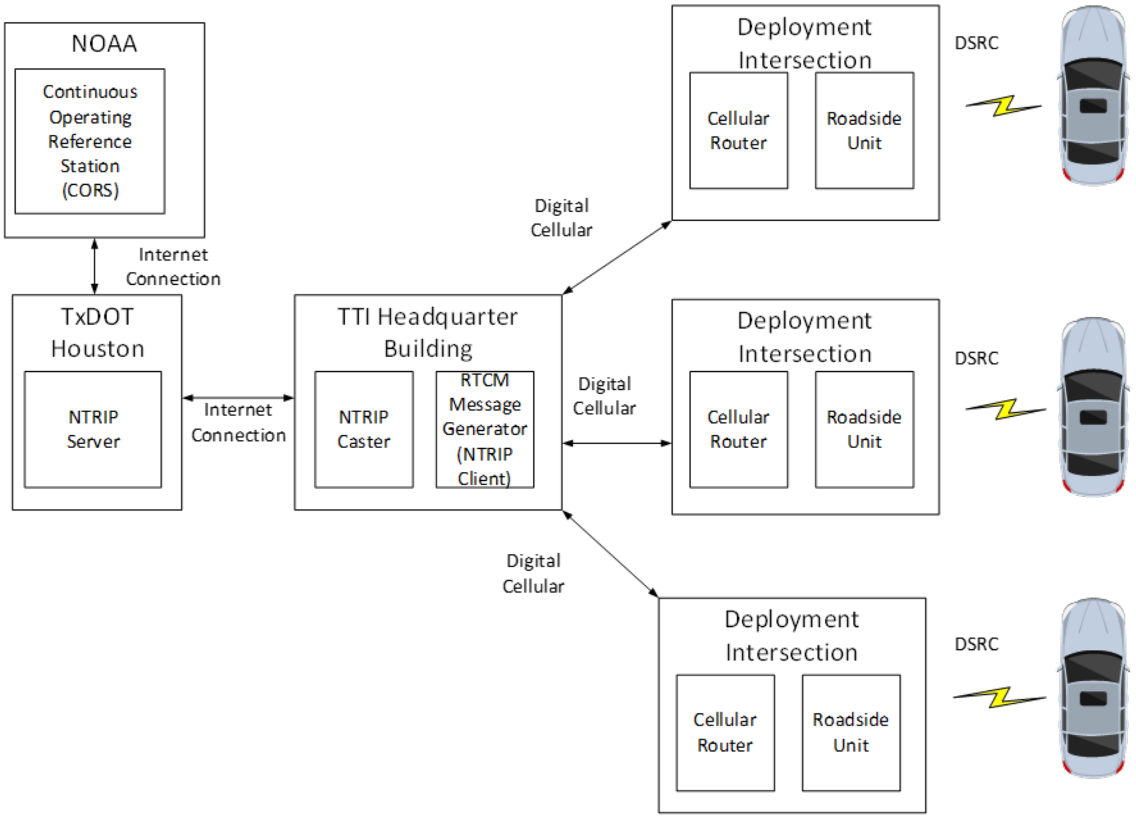
Chapter 6. TOSCo Differential Position Corrections

The TOSCo Infrastructure is also responsible for providing correction messages to the vehicles as defined by the Radio Technical Commission for Maritime Services (RTCM) Special Committee Number 14. The J2735 RTCM messages encapsulate 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 DSRC media. The receiving application (in this case, the TOSCo vehicle) is responsible for reconstructing the content of the message into the final expected format defined by the RTCM 10402.3 *RTCM Recommended Standard for Differential GNSS (Global Navigation Satellite System) Service, Version 2.3 Amendment 1 (May 2010).*

Figure 19 shows the basic architecture for generating the RTCM correction data. The TOSCo system obtains correction position information from a Continuous Operating Reference Station (CORS) operated by National Oceanic and Atmospheric Administration (NOAA) and accessed under authorization by Texas Department of Transportation (TxDOT) through its Network Transport of RTCM via an Internet Protocol (NTRIP) Server. The closest CORS near the deployment corridor is in Conroe, Texas. To minimize the number of connections to the CORS, TTI accesses the correction data from an NTRIP Server using a computer located in the TTI Headquarters building in Bryan, Texas. The TxDOT’s NTRIP Server forwards the Global Navigation Satellite System (GNSS) data stream to an NTRIP Caster using HTTP over TCP/IP. The NTRIP Caster, installed on a computer in the TTI Headquarters building located in Bryan, Texas, takes the data stream from the CORS Station and provides the correction data to an application that builds the J2735 RTCM Message set. This client forwards the formed J2735 RTCM message to each TOSCo intersection via a cellular router at each intersection. The cellular router connects to the RSU which immediately forwards the information for broadcast to the TOSCo vehicle over a DSRC link.

As part of this deployment, TTI contracted with SubCarrier Systems Corp. (SCSC) to develop the process for generating J2735 RTCM messages. The process uses SCSC’s SNIP® NTRIP Caster to extract appropriate correction information from the CORS to place in the RTCM message for broadcast to the vehicles. New RTCM messages are sent to the RSU every second. SCSC developed an application that converts the correction information from the caster into a J-2735-2016 RTCM message. The on-board unit (OBU) is then responsible for deconstructing the correction information and applying the corrections to improve the vehicle’s positioning and map-matching functions.

The OBU in the TOSCo vehicle uses an UBlox module to provide GPS positioning information. The UBlox module in the TOSCo vehicle uses standard RTCM 10402.3 codes [as opposed to RTCM 10403.1 standard that supports Real-Time Kinematic (RTK) or State Space Representation (SSR) corrections] to provide positioning correction information. RTCM 10402.3 provides 64 types of messages used to provide correction information for different applications. The TOSCo Infrastructure provides RTCM Message Types 1, 2, 3, and 9 to the TOSCo vehicle through the RTCM message. Table 1 provides a summary of these message types.



Source: Texas A&M Transportation Institute, 2022

Figure 19. Architecture for Providing RTCM Correction Information from TOSCo Infrastructure

Table 1. RTCM Message Types Provided in RTCM Message for TOSCo Vehicles

Message Type Identifier	Message Name	Description
1	Differential GPS Corrections	This message is the primary message type containing the pseudo-range correction (PRC (t)) for any user receiver GPS measurement time.
2	Delta Differential GPS Corrections	This message contains the difference in the PRC and range rate corrections (RRC) caused by the change in satellite navigation data. The reference station uses the difference in the corrections to determine the DELTA PRC and DELTA RRC needed for the Type 2 message.
3	Reference Station Parameters	This message contains information about the reference station. It includes the GPS coordinates (Earth -Centered-Earth-Fixed (ECEF)) of the reference station antenna to the nearest centimeter.
9	Partial Satellite Set Differential Corrections	This message type serves the same purpose as the Type 1 message as it contains the primary differential GPS corrections. However, Type 9 messages do not require a complete satellite set.

Source: J2735 DSRC Standard, 2016.

Chapter 7. TOSCo 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.

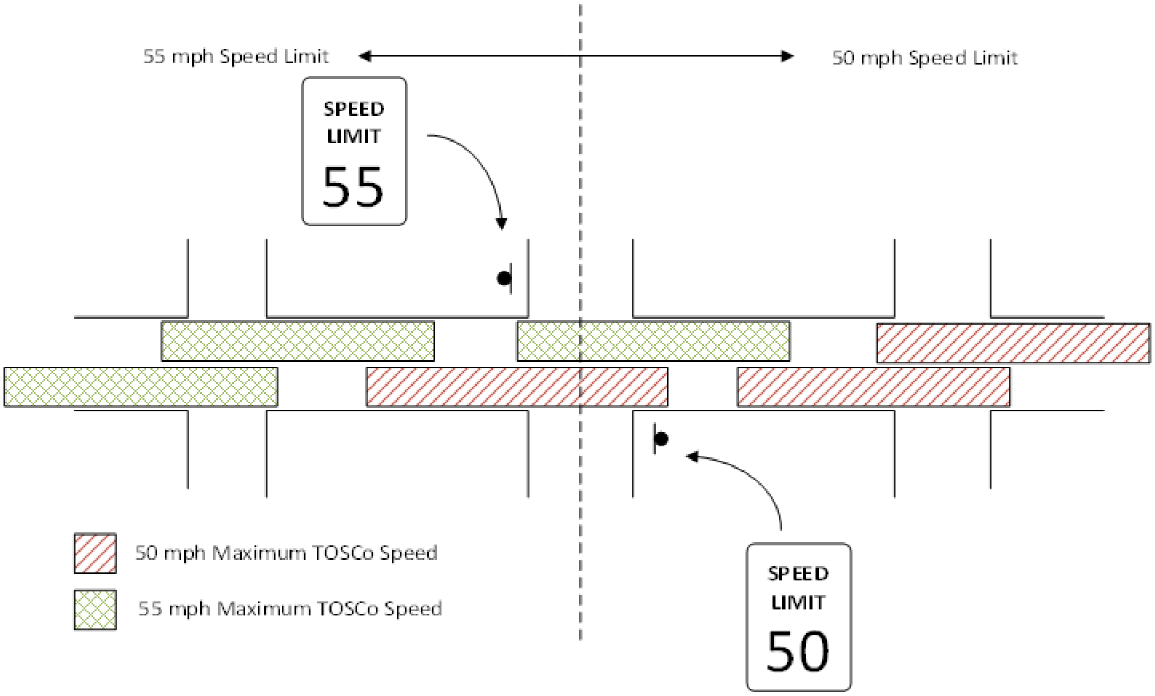
Structure of MAP Message

APPENDIX D shows the final MAP message profile used by TOSCo. These data elements are consistent with SAE J2735-2016. An asterisk (*) indicates those optional data fields that TOSCo requires. TOSCo also requires that the entire intersection fits within a single MAP message.

For TOSCo, the minimum length of the ingress lanes on the TOSCo approach should be as long as possible, which is ideally 300 m, the minimum range of the DSRC radio. Setting the TOSCo ingress lanes as long as possible maximizes the opportunity for the TOSCo vehicle to plan its trajectory.

The other important MAP element needed for TOSCo is the speed limit on each TOSCo approach. TOSCo vehicles are not allowed to exceed the speed limit and use the speed limit to define their maximum approach speed to the intersection. TOSCo vehicles also require speed limits for each lane. There are two ways to set speed limits through the MAP message. The first is to use an intersection-level speed limit parameter that applies to all lanes approaching the intersection. The second is to use lane-level attributes to set the speed limits for each lane. As a general rule, the TOSCo team uses the intersection-level approach to set the speed limit of the lanes under TOSCo control and uses the lane-level approach to set the speed limits for all cross-streets that have different speed limits from the TOSCo lanes.

In some cases, speed limits can change just after an intersection (see Figure 20). In these cases, the maximum TOSCo speed will be set to the speed of the downstream link so that the vehicles will not violate the speed limit requirements when they enter the downstream link.



Source: Texas A&M Transportation Institute, 2022

Figure 20. TOSCo Maximum Speeds at Intersection Where Speed Limit Changes Occur

MAP Creation Process

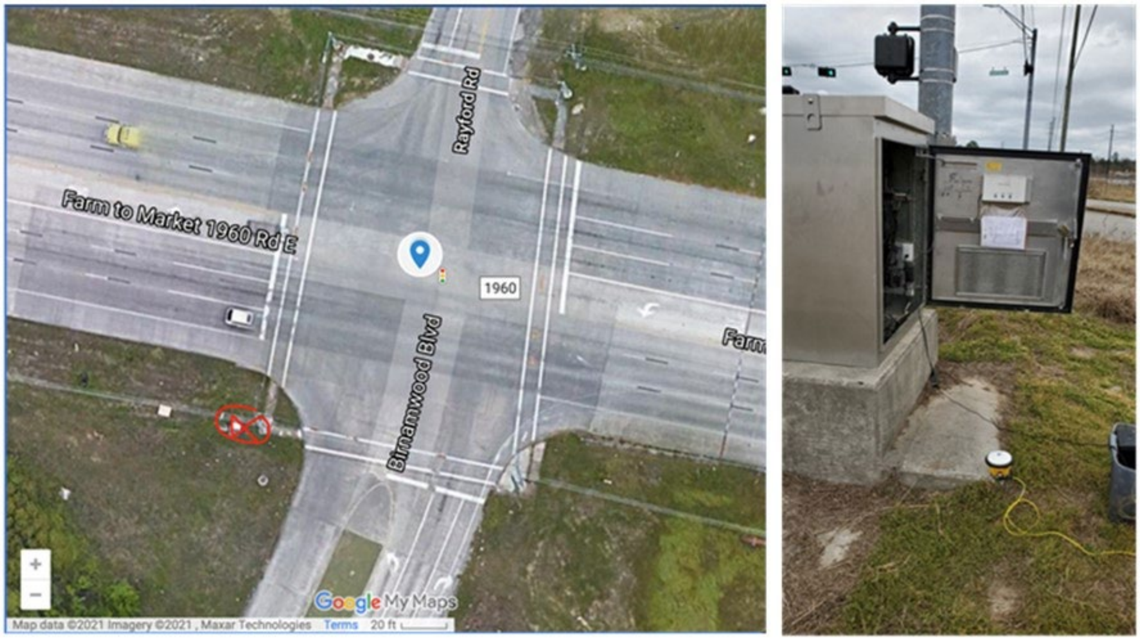
The TOSCo team used the ISD Message Creator tool available at the United States Department of Transportation (USDOT) Connected Vehicle Tool Library to generate the initial MAP message. USDOT developed this tool to assist users in producing the basic SAE J2735 MAP message for an intersection. Because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

- Establish Reference Point at Intersection
- Create Initial MAP Configurations
- Add Speed Limit by lane MAP Elements

Establish Reference Point at Intersection

The first step in the MAP generation process is establishing a reference point at the intersection to build the MAP. Generally, the reference point is the center of the intersection. The tool then defines the intersection geometries as offsets from this referent point. If the coordinates of the center of the intersection are known, the MAP developer can use those to build the MAP message. However, in many cases, it is not possible to obtain high-precision coordinate measurements of the center of the intersection without closing the intersection. The tool allows the MAP developer to set a verified point marker near the intersection. The verified point marker is a location near the intersection where the geographic coordinates can be accurately measured. APPENDIX E tabulates the measured geographic coordinates of verified point markers at 14 intersections along FM 1960. The tool uses the relationship between this verified point marker and the reference point of the intersection to adjust the lane geometries.

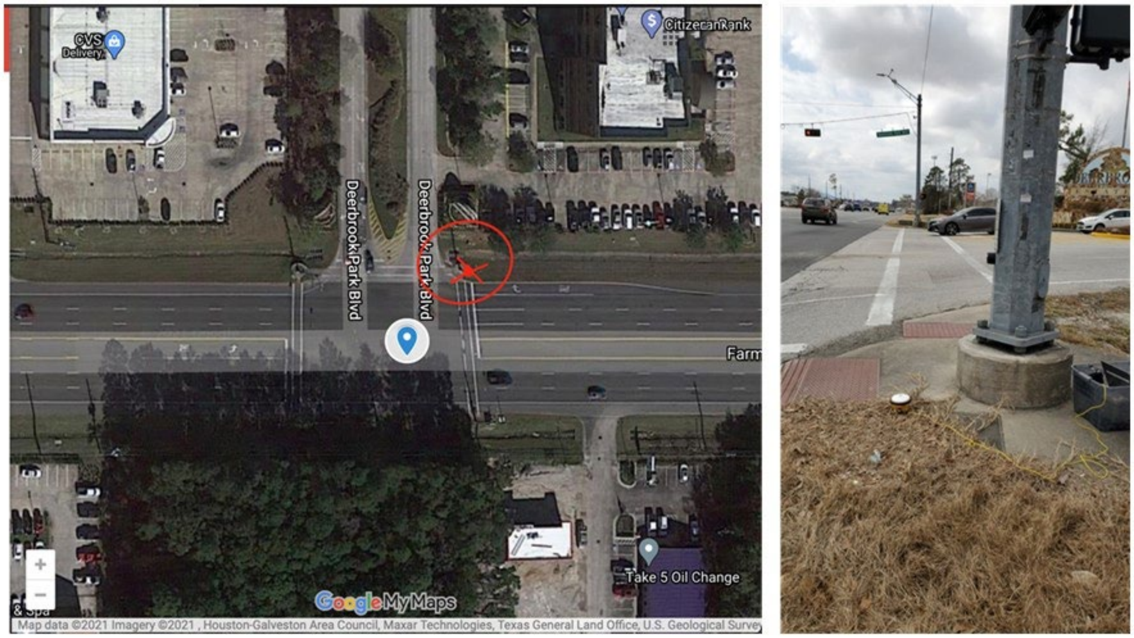
The verified reference point must be visible in the *ISD Message Creator* tool. As a general rule, the TOSCo team will use a point on the traffic signal cabinet pad as the verified point at the intersection (see Figure 21). The MAP developer can then use a high-precision GPS device to obtain the coordinates of this point. This process works well when the verified marker location is visible in the *ISD Message Creator* tool. However, some intersections exist where the traffic signal cabinet is not visible. Figure 22 provides an example of where vegetation obstructs the view of the traffic signal cabinet. When a traffic signal cabinet is not visible in the tool, the MAP developer identifies an alternative point near the cabinet to serve as the verified point marker. Usually, the alternate location is a location that is visible in the tool (e.g., the traffic signal pole foundation on the upper right side of the intersection).



(a) Overhead view (b) Field collector view

Source: a) Google Map Data Imagery ©2021, Maxar Technologies b) Texas A&M Transportation Institute, 2022

Figure 21. Verified Marker Point Located at Traffic Signal Cabinet Pad



(a) Overhead view

(b) Field collector view

Source: a) Google Map Data Imagery ©2021, Houston-Galveston Area Council, Maxar Technologies, Texas General Land Office, U.S. Geological Survey b) Texas A&M Transportation Institute, 2022

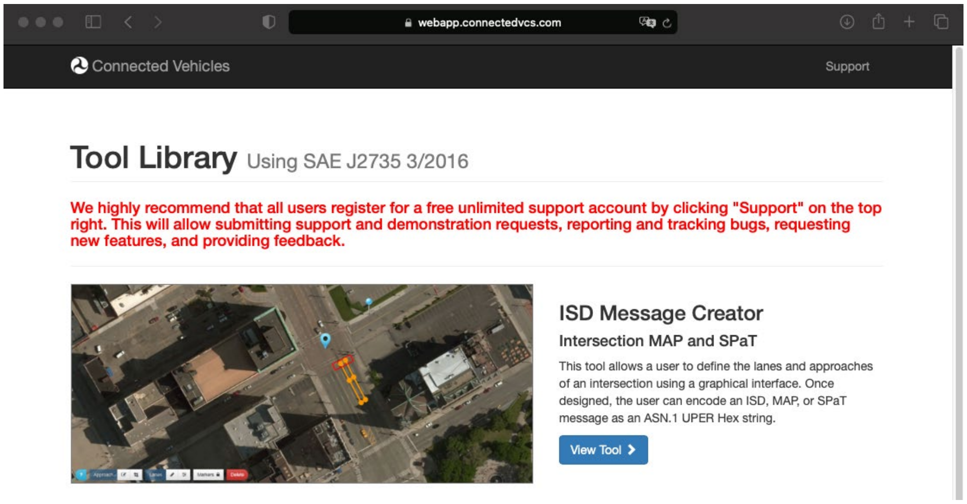
Figure 22. Example of Traffic Signal Cabinet Pad not Visible in ISD Message Creator Tool

Generate Initial MAP Configurations

The tool requires the user to create two maps: a parent map and a child map. The parent map provides information associated with the physical nature of the intersection (such as widths of the approach lanes, the approach angles, etc.) while the child map defines attributes associated with the use of the intersection approaches (such as the lane configurations per approach, movements per lane, etc.). Every intersection may have only one parent map but can have multiple child maps to reflect different lane use configurations by time of day.

The following describes the steps the team followed to generate MAP messages for TOSCo.

Step 1: Open the ISD Message Creator from the USDOT Connected Vehicle Tool Library (https://webapp.connectedvcs.com) by clicking the “View Tool” button (see Figure 23).



Tool Library Using SAE J2735 3/2016

We highly recommend that all users register for a free unlimited support account by clicking "Support" on the top right. This will allow submitting support and demonstration requests, reporting and tracking bugs, requesting new features, and providing feedback.

ISD Message Creator

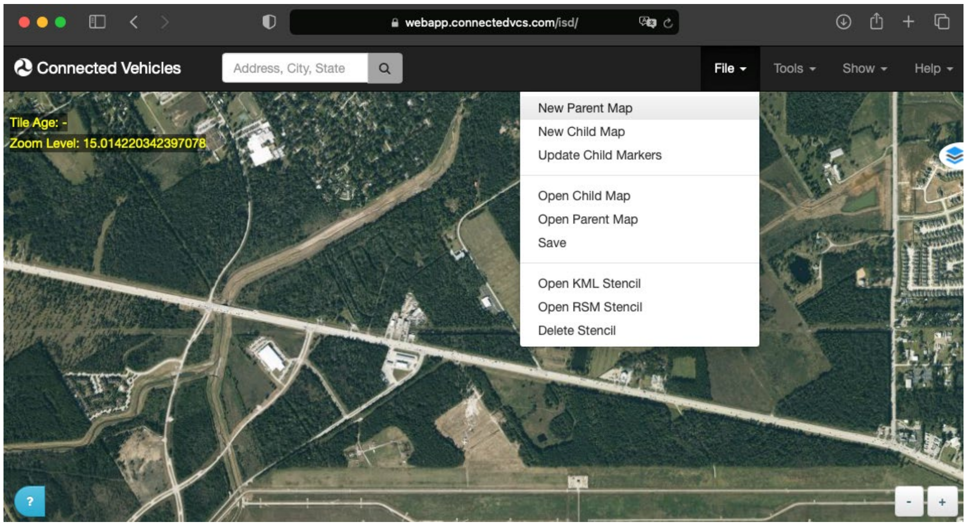
Intersection MAP and SPaT

This tool allows a user to define the lanes and approaches of an intersection using a graphical interface. Once designed, the user can encode an ISD, MAP, or SPaT message as an ASN.1 UPER Hex string.

Source: Federal Highway Administration (https://webapp.connectedvcs.com), 2022

Figure 23. Initial Entry Screen of ISD Message Creator Tool

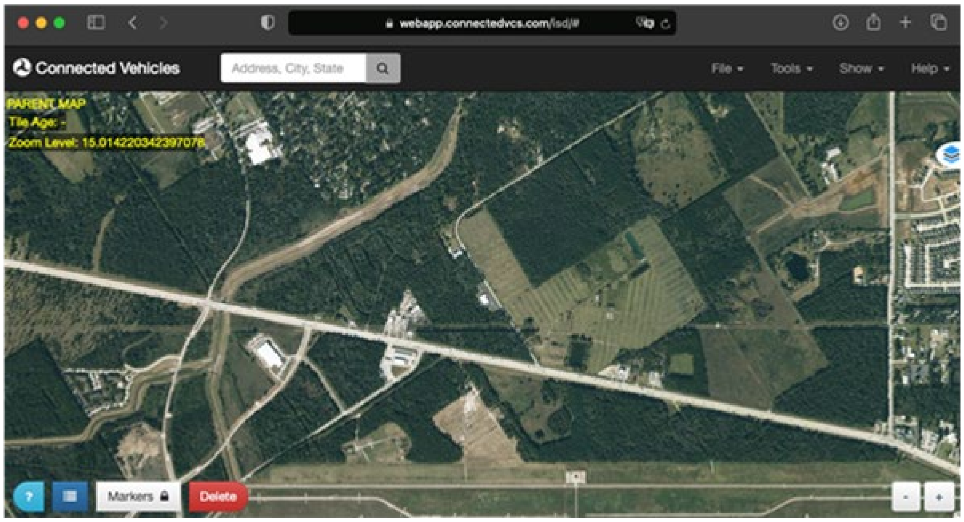
Step 2: Start to create a new parent map by selecting the “File” tab and clicking the “New Parent Map” button (see Figure 24).



Source: Federal Highway Administration, 2022

Figure 24. Creating a New Parent Map

Step 3: Confirm that it is under the layer of a parent map by viewing the yellow legend, “PARENT MAP” appeared on the left top corner (see Figure 25).

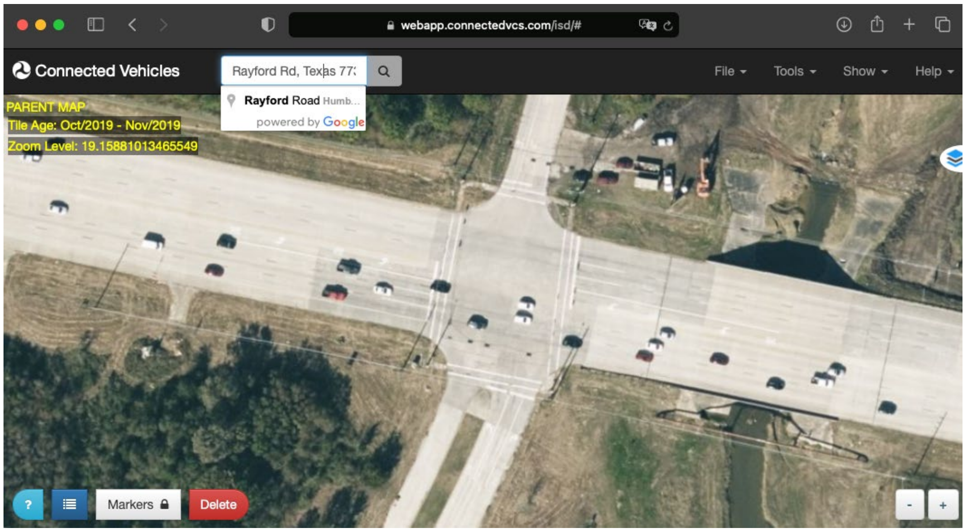


PARENT MAP
Tile Age: -
Zoom Level: 15.014220342397078

Source: Federal Highway Administration, 2022

Figure 25. Confirmation Screen of Parent Map Creation

Step 4: Locate the intersection by typing its address in the search bar and by using the mouse to zoom in and out to provide an initial location of the intersection's center (see Figure 26).



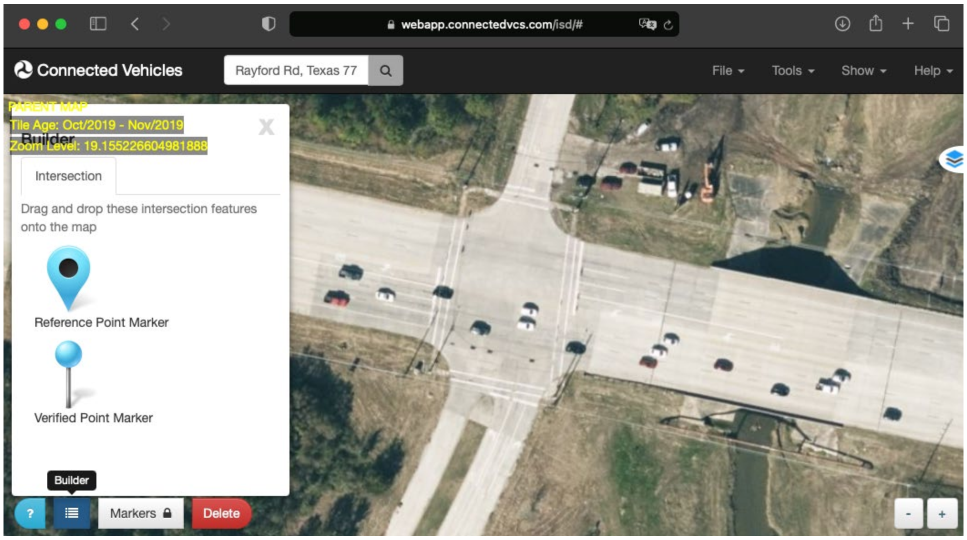
Rayford Rd, Texas 77:

PARENT MAP
Tile Age: Oct/2019 - Nov/2019
Zoom Level: 19.15881013465549

Source: Federal Highway Administration, 2022

Figure 26. Searching for Intersection Location using Address

Step 5: Use the pulldown feature to define the basic information (e.g., intersection ID) of the “Reference Point Marker” and “Verified Point Marker” (see Figure 27).



Drag and drop these intersection features onto the map

Source: Federal Highway Administration, 2022

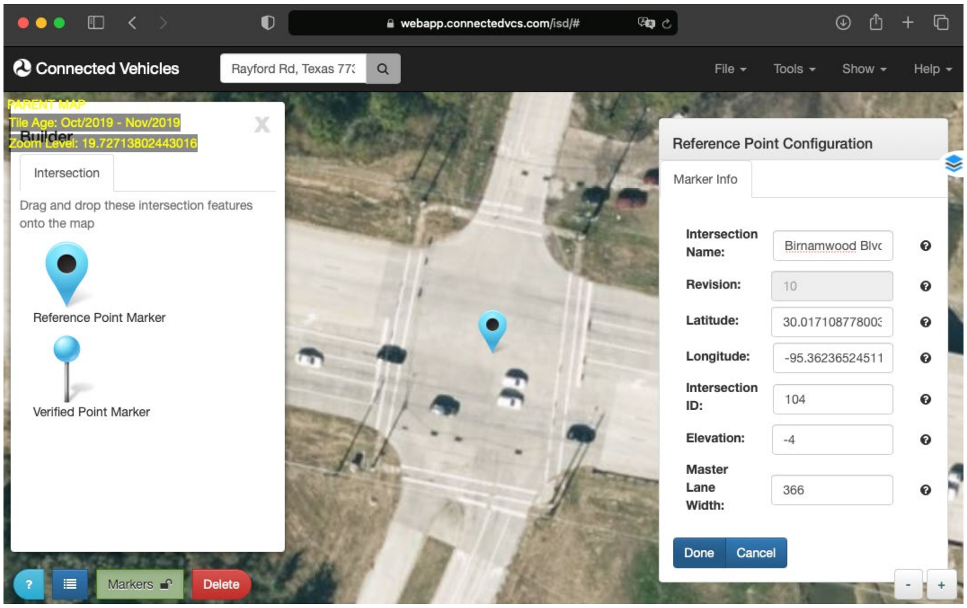
Figure 27. Establishing Reference Point Marker

Step 6: Place the “Reference Point Marker” at the center of the intersection and the reference point configuration window will pop up simultaneously (see Figure 28).

The reference point configuration window contains and auto-fills the following information in the marker information tab:

- Intersection Name
- Revision Number
- Latitude
- Longitude
- Intersection ID
- Elevation
- Master Lane Width

The intersection name is unchangeable and determined by the embedded map. The revision number is unchangeable within the window but can change when saving the parent map between 0 and 255. The latitude and longitude are unchangeable if the location of the point is fixed. The TOSCo Team changes the intersection ID to follow the naming convention of the project. Click the “Done” button to save all changes made in the configuration window.



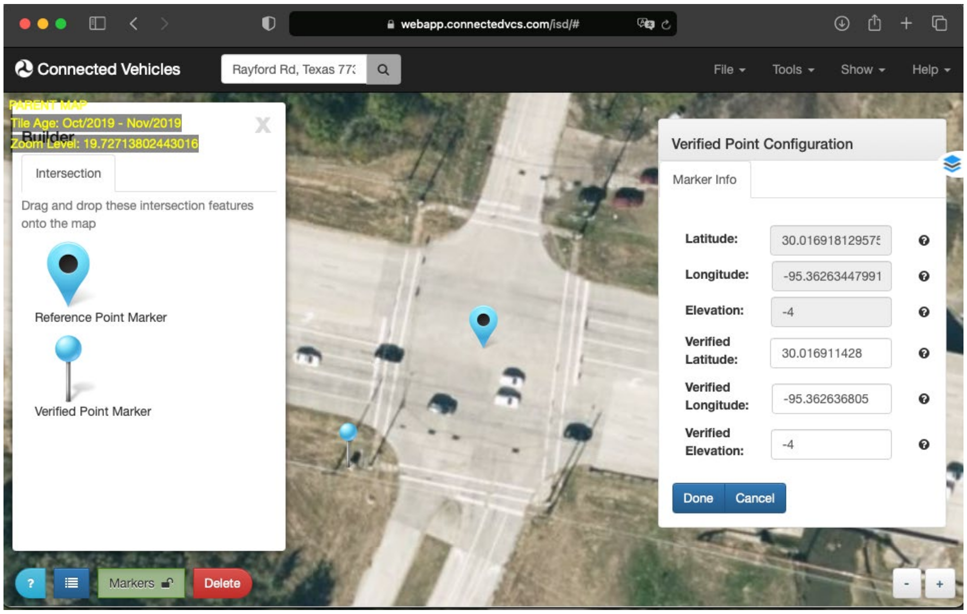
Reference Point Configuration

Intersection Name: Birnamwood Blv
Revision: 10
Latitude: 30.01710877800
Longitude: -95.36236524511
Intersection ID: 104
Elevation: -4
Master Lane Width: 366

Source: Federal Highway Administration, 2022

Figure 28. Adding Location Data for Reference Point Marker

Step 7: Place the “Verified Point Marker” at the location where the survey point is collected in the field. Replace the auto filled “Verified Latitude” and “Verified Longitude” with the collected coordinates in the verified point configuration window (see Figure 29). Click the “Done” button to save all changes made in the configuration window.



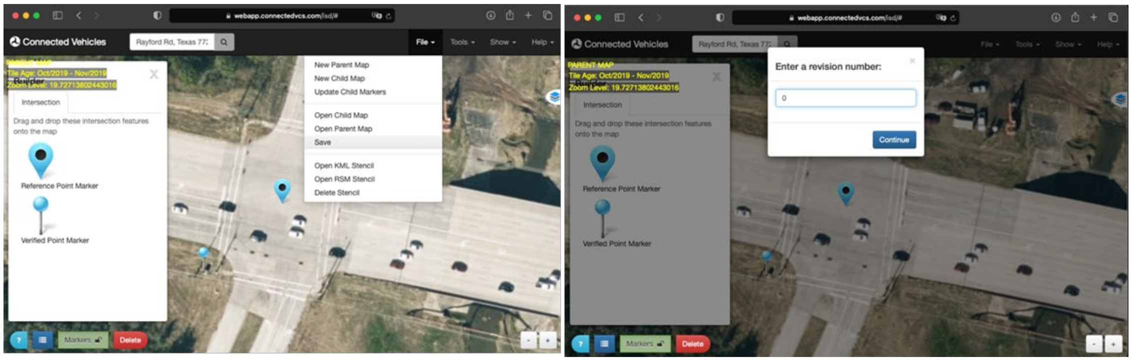
Verified Point Configuration

Latitude: 30.01691812957
Longitude: -95.36263447991
Elevation: -4
Verified Latitude: 30.016911428
Verified Longitude: -95.362636805
Verified Elevation: -4

Source: Federal Highway Administration, 2022

Figure 29. Establishing Verified Point Marker

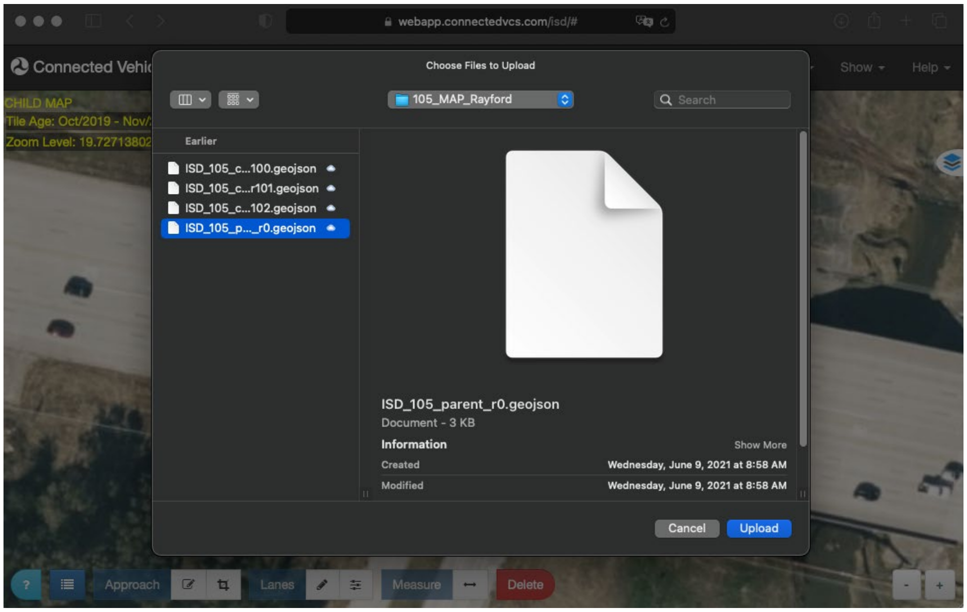
Step 8: Save the parent map by selecting the “File” tab and clicking the “Save” button (see Figure 30). Enter a revision number between 0 and 255 for a version control purpose, e.g., 0, and click the button, “Continue.”



Source: Federal Highway Administration, 2022

Figure 30. Saving Parent Map Information

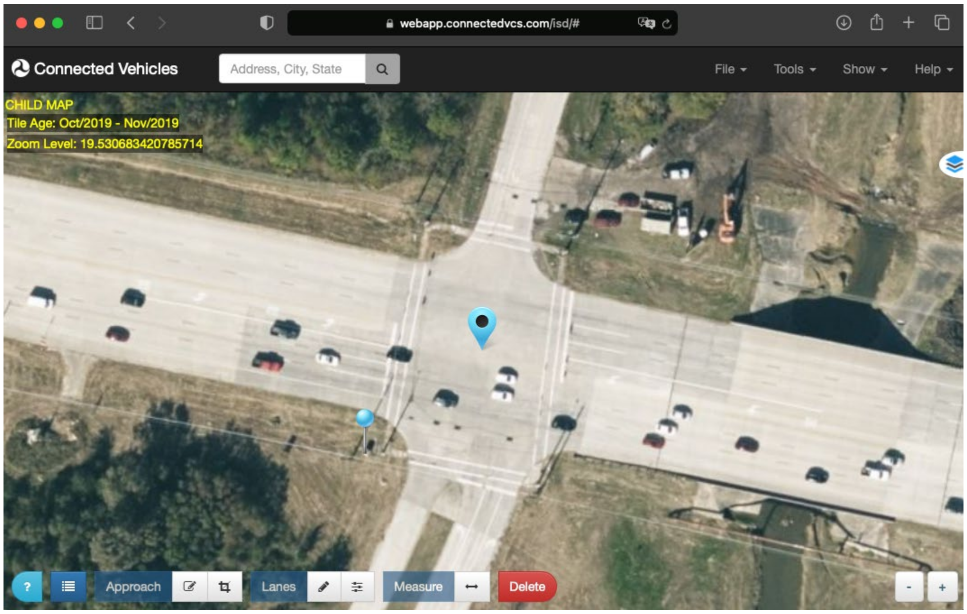
Step 9: Start to create a new child map by selecting the “File” tab and clicking the “New Child Map” button (see Figure 31). It is noted that the following two windows pop up before the selection of the parent map. This will reset the map and delete any progress. Click on Continue? using the file dialog to open a parent map. The response for the first window is to click “Ok,” and the response for the second window is to click “Close.” The following file dialog will allow the users to select the parent map by clicking the “Upload” button.



Source: Federal Highway Administration, 2022

Figure 31. Uploading Parent Map

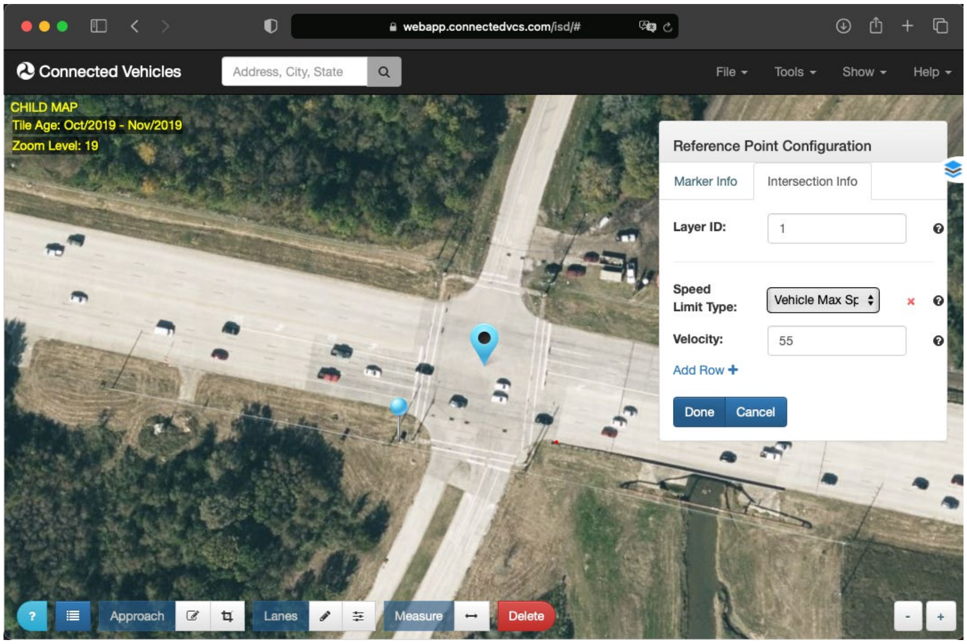
Step 10: Confirm that it is under the layer of a child map by viewing the yellow legend, “CHILD MAP,” which appears on the left top comer (see Figure 32). This layer is on the top of the parent map and the previously created points are viewable in the child map.



Source: Federal Highway Administration, 2022

Figure 32. Confirmation Screen for Adding Child Map

Step 11: Add a speed limit to the intersection by clicking the reference point, selecting the “Vehicle Max Speed” under the “Intersection Info” tab, and including the speed limit (e.g., 55 mph). Click the “Done” button to save all changes made in the reference point configuration window (see Figure 33).



Layer ID: 1

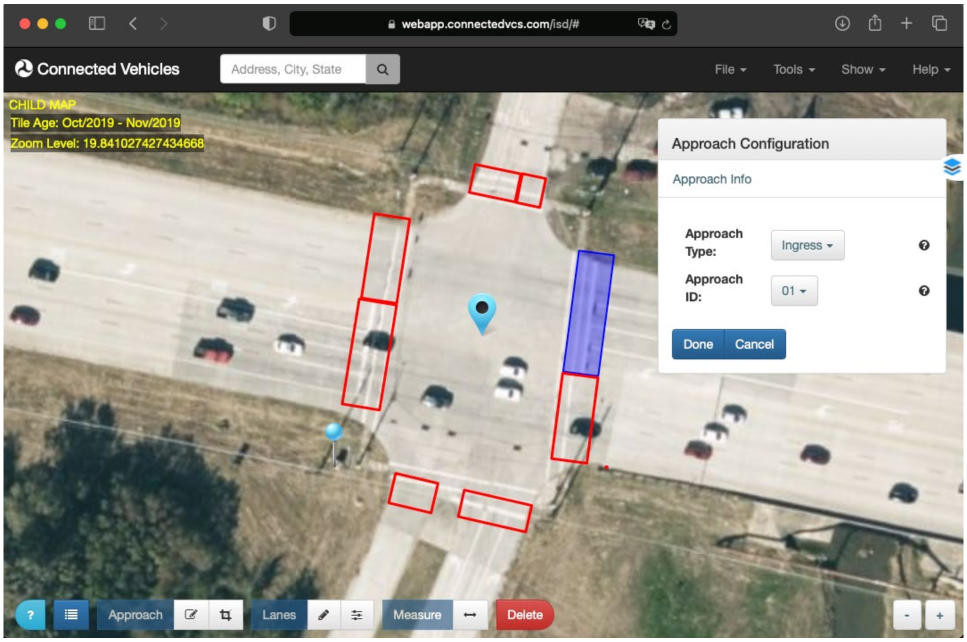
Speed Limit Type: Vehicle Max Sp

Velocity: 55

Source: Federal Highway Administration, 2022

Figure 33. Adding Intersection-Level Speed Limits to Child Map

Step 12: Draw “Approach” over the stop bar for every ingress and egress direction by clicking the Approach edit icon (see Figure 34). Adjust the size or orientation of each approach by clicking the cropping icon. Identify the approaches accordingly as ingress or egress and number them, respectively. The TOSCo Team numbered the lanes in order of east, north, west, and south. Click the “Done” button to save all changes.



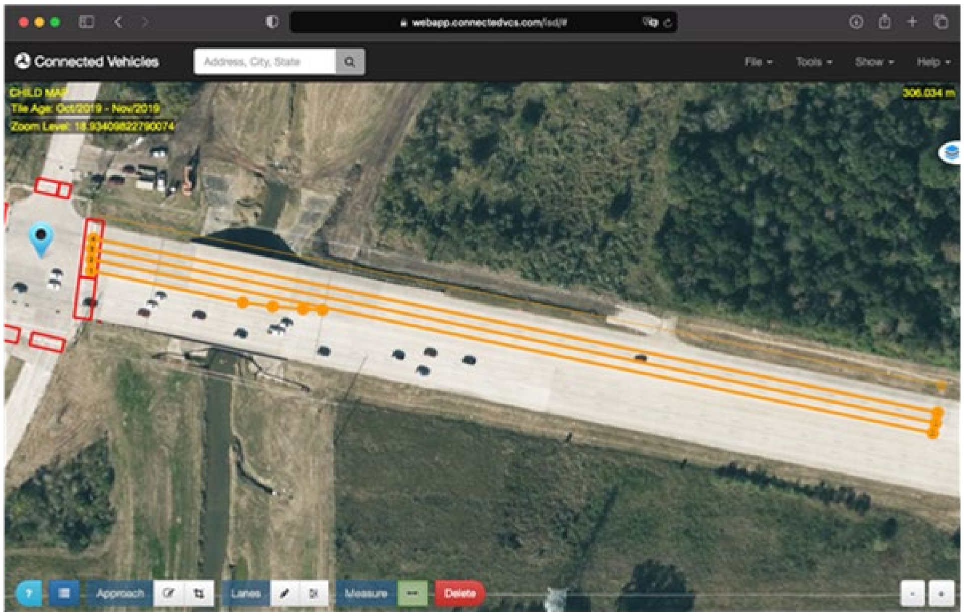
CHILD MAP
Tile Age: Oct/2019 - Nov/2019
Zoom Level: 19.841027427434668

Approach Type: Ingress
Approach ID: 01

Source: Federal Highway Administration, 2022

Figure 34. Configuring Intersection Approaches in Child Map

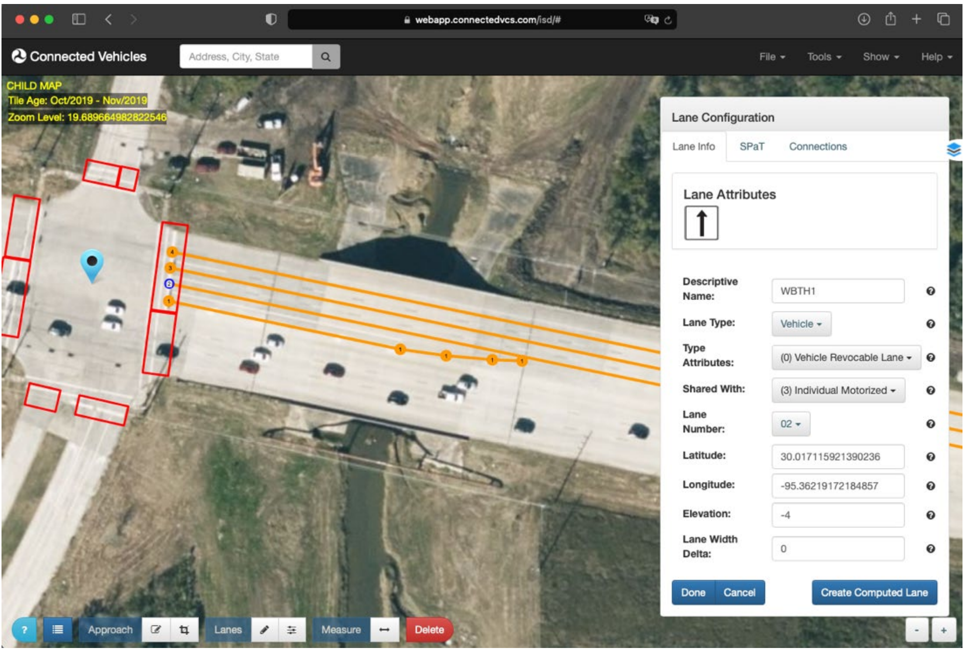
Step 13: Draw “Lanes” for every lane by clicking the Lane edit icon (see Figure 35). Every lane should begin within its corresponding approach and end at its appropriate length. Users can adjust the length of a lane or add more nodes to fit the curvature of a lane by clicking the cropping icon. Ingress lanes should be at least 300 meters. When coding left turn bays, the two lanes should not overlap. Also, the number of nodes per lane should be kept to a minimum so that the message size does not exceed 1400 bytes (i.e., the maximum payload size of an RSU). The ISD Message Creator only permits a maximum distance of 320 meters between two nodes.



Source: Federal Highway Administration, 2022

Figure 35. Configuring Approach Lanes

Step 14: Input “Lane Info” under the lane configuration window by clicking over the first node of each lane (see Figure 36). Under the “Lane Info” tab, the information, such as latitude, longitude and elevation are auto filled based on the coordinates given in the parent map (see Figure 36). The screen is where the user enters lane attribute information and a descriptive name for the lane.

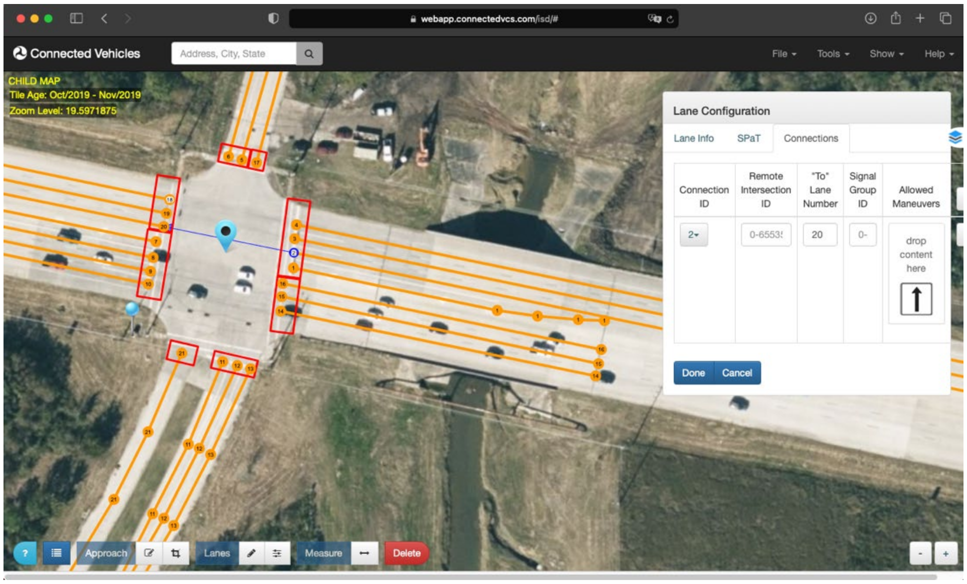


Descriptive Name:	WBTH1
Lane Type:	Vehicle
Type Attributes:	(0) Vehicle Revocable Lane
Shared With:	(3) Individual Motorized
Lane Number:	02
Latitude:	30.017115921390236
Longitude:	-95.36219172184857
Elevation:	-4
Lane Width Delta:	0

Source: Federal Highway Administration, 2022

Figure 36. Configuring Lane Attributes

Step 15: Create “Connections” under the lane configuration window for every ingress lane by clicking over the first node of each lane (see Figure 37). The allowed maneuvers are defined under the “Connections” tab. The “Connection ID” should be the lane number of the ingress lane, and “‘To’ Lane Number” is the number of the egress lane.

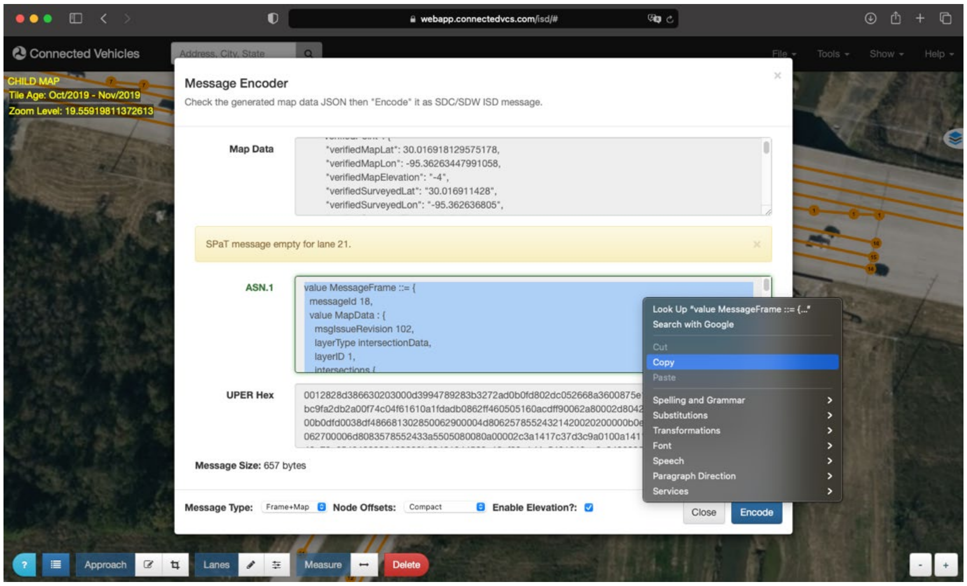


Connection ID	Remote Intersection ID	"To" Lane Number	Signal Group ID	Allowed Maneuvers
2	0-65535	20	0-	

Source: Federal Highway Administration, 2022

Figure 37. Connecting Ingress Lanes to Egress Lanes

Step 16: Create and encode in abstract syntax notation one (ASN.1) of the child map by clicking the “Tools” tab and selecting “Encoder” to display the “Message Encoder” window (see Figure 38). Select the message type as “Frame + Map,” the Node offsets as “Compact,” and click “Encode” button to encode the message.



Message Encoder

Check the generated map data JSON then "Encode" it as SDC/SDW ISD message.

Map Data

```
"verifiedMapLat": 30.016918129575178,
"verifiedMapLon": -95.36263447991058,
"verifiedMapElevation": "-4",
"verifiedSurveyedLat": "30.016911428",
"verifiedSurveyedLon": "-95.362636805",
```

SPaT message empty for lane 21.

ASN.1

```
value MessageFrame ::= {
  messageId 18,
  value MapData : {
    msgIssueRevision 102,
    layerType intersectionData,
    layerID 1,
    intersections {
```

UPER Hex

```
0012828d386630203000d3994789283b3272ad0b0fd802dc052668a3600875e
bc9fa2db2a00f74c04f61610a1fdadb0862ff460505160acdff90062a80002d8042
00b0dfd0038df48668130285006290000 4d80625785524321420020200000b0e
062700006d8083578552433a5505080080a00002c3a1417c37d3c9a0100a141
```

Message Size: 657 bytes

Message Type: Frame+Map **Node Offsets:** Compact **Enable Elevation?:** ☑

Source: Federal Highway Administration, 2022

Figure 38. Encoding Initial MAP Message

Add TOSCo MAP Elements

The FHWA MAP tool allows the user to set a single speed limit for all approach lanes at each intersection. Because speed limits on the cross-street are often significantly lower than the main street, and to accommodate different speed limits on different directions of travel, the TOSCo Team had to edit the MAP message with additional information (i.e., speed limit for lanes on cross street) and encode it in UPER Hex for the RSU.

Chapter 8. TOSCo Infrastructure Data Logs

TOSCo Infrastructure Team has 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 following sections describe the content of each of the logs. The following section also provides samples of the data contained in each log.

Detector Status Log (DetStatusLogFile)

The TOSCo Infrastructure produces a log of the status of all the vehicle detectors available to the controller. This log includes both those detectors programmed to call phases in the controller and those detectors used by the queue detection algorithm. The log contains the following information:

- The status of each of the 64 detectors available to the controller (1= "ON" or occupied, 0 = "OFF" or not occupied).
- The status of each of the 16 vehicle phases available for use in the controller ("G" if the phase is displaying a green indication, and "NG" if the phase is not showing a green indication). TTI uses this log to verify the inputs into the queue detection process.

Table 2 describes the data elements contained in the TOSCo Detector Status log. Table 3 shows a sample of the data contained in this log, imported into Microsoft Excel. These data are stored in a comma-delimited text file. The traffic signal controller queries the traffic signal controller every 100 milliseconds to obtain the detector and phase status information contained in this log.

Table 2. Description of the Data Elements Contained in the TOSCo Detector Status Log

Data Element Name	Description
Run#	An indicator parameter identifying the run number associated with the data. This number links the infrastructure data logs and the vehicle data logs together.
IntersectionID	The identification number of the TOSCo intersection associated with the log entry. The *IntersectionID* is the same as the intersection identification number in the MAP message.
Date	The month, day, and year that the TOSCo system generated the entry in the Detector Status Log.
Time	The minutes and seconds in the hour that the detector status application generated the data. The format for the data entry is in mm:ss.0.
CurrentTimeMark	The minutes and seconds in the hour that the TOSCo System generated the entry in the Detector Status log. The format for the data entry is in mm:ss.0.
MSecsEpochTime	The time mark of the current time in seconds (x10) since the beginning of the present hour.
LogDetectorStatus	An indicator flag denoting that detector status logging is active: “1” means the detection logger is active, and “0” means that the detection logger is not active.
QueueDataID	The identification number associated with the queue detection algorithm for which the data were used.
Det(#)	The current status of each detector (1 through 64). A value of “0” in this field indicates that a vehicle is not occupying the detection zone, while a value of “1” indicates that a vehicle is occupying the detection zone.
Phase(#)	The current status of each signal phase (1 through 16) programmed in the controller. A value of “G” indicates that the controller is currently displaying a green indication. A value of “NG” indicates that the current indication of the signal is not green.

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

Table 3. Sample of Data Contained in the TOSCo Detector Status Log

Run#	IntersectionID	LogDetectorStatus	QueuDataID	Date	Time	MSecsEpochTime	Det1	Det2	Det3	Det4	Det5	Det6	Det7	Det8	Det9	Det10	Phase1	Phase2	Phase3	Phase4	Phase5	Phase6	Phase7	Phase8
2018	7	1	41532	6/17/2021	03:27.8	1623949407823	0	0	0	0	0	0	0	0	0	0	G	G	G	G	G	G	G	G
2018	7	1	41533	6/17/2021	03:27.9	1623949407932	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41534	6/17/2021	03:28.4	1623949408410	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41535	6/17/2021	03:28.2	1623949408151	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41536	6/17/2021	03:28.3	1623949408260	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41537	6/17/2021	03:28.4	1623949408369	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41538	6/17/2021	03:28.5	1623949408479	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41539	6/17/2021	03:28.6	1623949408588	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41540	6/17/2021	03:28.7	1623949408697	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41541	6/17/2021	03:28.8	1623949408807	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41542	6/17/2021	03:28.9	1623949408916	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG
2018	7	1	41543	6/17/2021	03:29.3	1623949409260	1	1	0	0	1	0	0	1	0	0	G	NG	NG	NG	G	NG	NG	NG

NOTE: For brevity, the table shows the status of the first 10 detectors and the first 8 phases only.

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

Queue Data Log

The Queue Data Log File (abbreviated as QDataLogFile) contains the output of the queue detection algorithm. The queue detection algorithm uses the status of the multiple detectors in each lane to determine how far upstream the queue extends upstream of the stop bar. Table 4 describes the data elements contained in this log, while Table 5 provides a sample of the TOSCo Queue Data log data.

Table 4. Description of the Data Elements Contained in the TOSCo Queue Data Log

Data Element Name	Description
GWMsgNo	The identification number of the iteration of the green window prediction algorithm. Each number represents a unique iteration of the algorithm.
IntersectionID	The identification number of the TOSCo intersection associated with the log entry. The *IntersectionID* is the same as the intersection identification number in the MAP message.
Date	The month, day, and year that the TOSCo system generated the entry in the Queue Data Log.
Time	The minutes and seconds in the hour that the queue detection application generated the data. The format for the data entry is in mm:ss.0.
CurrentTimeMark	The minutes and seconds in the hour that the TOSCo System generated the entry in the Queue Data log. The format for the data entry is in mm:ss.0.
MSecsEpochTime	The time mark of the current time, in seconds (x10) since the beginning of the present hour.
LogDetectorStatus	An indicator flag denoting that detector status logging is active: “1” means the detection logger is active, and “0” means that the detection logger is not active.
NumberofLanes	The total number of lanes for which the TOSCo system will provide queue data.
LaneID	The identification number of the lane associated with the TOSCo approach. The *LaneNo* is the same as the lane identification number in the MAP message.
frontofQueue	The distance of the front of the queue extending upstream from the stop bar, in meters.
BackofQueue	The distance of the back of the queue extending upstream from the stop bar, in meters.
EndIndicator	A special character indicating the end of this queue data.

Source: Texas A&M Transportation Institute, 2022

Table 5. Sample of Data Contained in the TOSCo Queue Data Log

Run #	InersectionID	Date	Time	MsecsEpochTime	LogDetectorStatus	QueueDataID	NumberofLanes	LaneID	frontofQueue	backofQueue	LaneID	frontofQueue	backofQueue	EndIndicator
2018	7	6/17/2021	03:27.8	1623949407823	1	41532	2	2	0	0	3	0	0	?
2018	7	6/17/2021	03:27.9	1623949407932	1	41533	2	2	0	27.387	3	0	0	?
2018	7	6/17/2021	03:28.4	1623949408410	1	41534	2	2	0	27.387	3	0	0	?
2018	7	6/17/2021	03:28.2	1623949408151	1	41535	2	2	0	27.387	3	0	0	?
2018	7	6/17/2021	03:28.3	1623949408260	1	41536	2	2	0	27.387	3	0	0	?
2018	7	6/17/2021	03:28.4	1623949408369	1	41537	2	2	0	27.387	3	0	0	?
2018	7	6/17/2021	03:28.5	1623949408479	1	41538	2	2	0	27.387	3	0	0	?
2018	7	6/17/2021	03:28.6	1623949408588	1	41539	2	2	0	27.387	3	0	0	?
2018	7	6/17/2021	03:28.7	1623949408697	1	41540	2	2	0	27.387	3	0	0	?

Source: Texas A&M Transportation Institute, 2022

Green Window Data Log

The Green Window Data Log (abbreviated GW-Data) contains the output of the Green Window Predictor process. The Green Window Predictor ingests status and time remaining values for the TOSCo computer and queue length data from the Queue Estimator to predict the beginning and end of the Green Window. Table 6 describes the data elements contained in the Green Window Data log, while Table 7 provides a sample of data in the Green Window Log, imported into Microsoft Excel. The Green Window Predictor updates this log every 100 ms.

Table 6. Description of the Data Elements Contained in the TOSCo Green Window Data Log

Data Element Name	Description
GWMsgNo	The identification number of the iteration of the green window prediction algorithm. Each number represents a unique iteration of the algorithm.
Date	The month, day, and year that the TOSCo system generated the Green Window Data Log entry.
Time	The minutes and seconds in the hour that the TOSCo System generated the entry in the Green Window Data log. The format for the data entry is in mm:ss.0.
CurrentTimeMark	The time mark of the current time, in seconds (x10) since the beginning of the present hour.
MSecsEpochTime	The current time in milliseconds since January 1, 1970.
IntersectionID	The identification number of the TOSCo intersection associated with the log entry. The *IntersectionID* is the same as the intersection identification number in the MAP message.
LaneID	The identification number of the TOSCo approach lane associated with the data entry. The *LaneID* is the same as the lane identification number in the MAP message.
TSCDataCoordActive	A parameter indicating if the traffic signal is in coordination. “1” means the traffic signal controller is in coordination while “0” means the traffic signal controller is not in coordination. If the traffic signal controller is not in coordination, the TOSCo system will not produce green window information.
PhaseStatus	The parameter indicates the current status of the signal indication associated with the TOSCo approach lane.
MinTime	The minimum amount of time (in tenths of seconds) until the signal phase indication will transition to a new state. The traffic signal controller provides this value directly. (*This value should not be confused with the de_MinEndTime in the J2735 SPaT message standard.)*
MaxTime	The maximum amount of time (in tenths of seconds) until the signal phase indication will transition to a new state. The traffic signal controller provides this value directly. (*This value should not be confused with the de_MaxEndTime in the J2735 SPaT message standard.)*
RemainingRed	The time (in seconds x10) that the traffic signal expects to continue to display a red indication. If the signal is currently showing a green indication, this value is “0.” The *RemainingRed* is based on the current active traffic signal plan and does not reflect the actual amount of time that the traffic signal indication will remain in red.
RemainingGreen	The time (in seconds x10) that the traffic signal expects to display the green indication when the TOSCo approach enters into a “green” state. This value is based on the current active traffic signal timing plan. The TOSCo system uses the combination of the *RemainingRed* and *RemainingGreen* to set the *GreenWindowEnd* value.

Data Element Name	Description
EstimatedNumVehInQ	The estimated number of vehicles in the queue. This value is a computed value using an assumed average vehicle length for a passenger vehicle. This assumed vehicle length is a configurable parameter and contained in the Green Window Predictor configuration file.
QueueDataID	The identification number of the data in the queue data log entry that the Green Window Predictor used to produce the green window data.
frontofQueue	The distance of the front of the queue extending upstream from the stop bar, in meters.
queueLength	The distance of the back of the queue extending upstream from the stop bar, in meters.
PRTime	The estimated amount of time (in tenths of seconds) for the last vehicle in the queue to begin moving towards the stop bar.
TimeAccelerate	The estimated amount of time (in tenths of seconds) for the last vehicle to accelerate to a stop to reach the set speed or to reach the stop bar.
AtSpeedTravelTime	The time (in tenths of seconds) that the Green Window Predictor estimates for the last vehicle in the queue to travel to the stop bar after accelerating and reaching its set speed.
TempStart	The time mark (in seconds x 10 since the top *of* the hour) representing the sum of the *RemainingRed*, the *PerceptionReactionTime,* the *TimeAccelerate,* the *AtSpeedTravelTime*, and the *TNow* components. The Green Window Predictor uses this value to determine if the predicted start of the green window occurs in the next hour.
TempEnd	The time mark (in seconds x 10 since the top of the hour) representing the sum of the *RemainingRed, the RemainingGreen*, and the*TNow* data elements. The Green Window Predictor uses this value to determine if the predicted start of the green window occurs in the next hour.
GWStart	The time mark (in seconds x 10 since the top of the hour) when the TOSCo system expects the green window to “open” (i.e., become available for TOSCo vehicles).
GWEnd	The time mark (in seconds x 10 since the top of the hour) when the TOSCo system expects the green window to “close” (i.e., become unavailable for TOSCo vehicles).
GWDFlag	A Boolean parameter indicating that a change in the green window data has occurred.

Source: Texas A&M Transportation Institute, 2021

Table 7. Sample of Data Contained in the TOSCo Green Window Data Log

GreenWindowID	TimeStampDay	TimeStampHour	CurrentTimeMark	IntersectionID	LaneID	TSCdataCoordActive	PhaseStatus	MinTime	MaxTime	RemainingRed	RemainingGreen	EstimatedNumVehInQ	QueueDataID	frontofQueue	queueLength	PRTime	TimeAccelerate	TimeRemaining	QueueDispersionTime	Tempstart	Tempend	GreenWindowStart	GreenWindowEnd	DiscontinuousFlag
28931	6/17/2021	03:27.8	2078	7	2	1	4	70	179	179	350	0	41532	0	0	0	0	0	2257	2325	2606	2325	2606	0
28931	6/17/2021	03:27.8	2078	7	3	1	4	70	179	179	350	0	41532	0	0	0	0	0	2257	2256	2606	2256	2606	0
28932	6/17/2021	03:28.0	2079	7	2	1	4	70	177	177	350	4	41533	0	27.432	32	37	0	2288	2325	2606	2325	2606	1
28932	6/17/2021	03:28.0	2079	7	3	1	4	70	177	177	350	0	41533	0	0	0	0	0	2256	2256	2606	2256	2606	1
28933	6/17/2021	03:28.2	2081	7	2	1	4	70	176	176	350	4	41534	0	27.432	32	37	0	2289	2325	2606	2325	2606	0
28933	6/17/2021	03:28.2	2081	7	3	1	4	70	176	176	350	0	41534	0	0	0	0	0	2257	2256	2606	2256	2606	0
28934	6/17/2021	03:28.3	2083	7	2	1	4	70	175	175	350	4	41536	0	27.432	32	37	0	2290	2325	2606	2325	2606	0
28934	6/17/2021	03:28.3	2083	7	3	1	4	70	175	175	350	0	41536	0	0	0	0	0	2258	2256	2606	2256	2606	0
28935	6/17/2021	03:28.5	2084	7	2	1	4	70	173	173	350	4	41537	0	27.432	32	37	0	2289	2326	2606	2326	2606	1
28935	6/17/2021	03:28.5	2084	7	3	1	4	70	173	173	350	0	41537	0	0	0	0	0	2257	2257	2606	2257	2606	1
28936	6/17/2021	03:28.6	2086	7	2	1	4	70	171	171	350	4	41539	0	27.432	32	37	0	2289	2326	2606	2326	2606	1

Source: Texas A&M Transportation Institute, 2022

SPaT Message Log

The SPaT Message Log (abbreviated Spat_Msg) contains the data the TOSCo system uses to generate the SPaT message. Table 8 describes the data elements contained in this log. Table 9 provides a sample of the data contained in the SPaT Message Log.

Table 8. Description of the Data Elements Contained in the TOSCo SPaT Message Log

Data Element Name	Description
Run#	An indicator parameter identifying the run number associated with the data. This number links the infrastructure data logs and the vehicle data logs together.
IntersectionID	The identification number of the TOSCo intersection associated with the log entry. The *IntersectionID* is the same as the intersection identification number in the MAP message.
Revision#	A standard J2735 2016 data element that contains the message counter associated with the SPaT Message. The revision number increments every time the SPaT message includes new information. Revision numbers remain fixed during a stream of messages when the content of the SPaT message has not changed from the last message sent.
GWMsgNo	The identification number of the iteration of the green window prediction algorithm. Each number represents a unique iteration of the algorithm.
GWDFlag	A Boolean parameter indicating that a change in the green window data has occurred.
Date	The month, day, and year that the TOSCo system generated the entry in the SPaT Message Log.
Time	The minutes and seconds in the hour that the TOSCo System generated the SPaT Message. The format for the data entry is in mm:ss.0.
MSecsEpochTime	The current time in the milliseconds since January 1, 1970.
SignalGroupID	The identification number in the J2735 2016 SPaT message signal group. It is an index used to map traffic signal indications to allowable vehicle movements at an intersection.
MPS	The content of the standard *DE_MovementPhaseState* data element in the J2735 2016 SPaT message. This data element provides the overall current state of the movement governed by the signal indication.
MinEndTime	The standard *DE_minEndTime* data element in the J2735 2016 SPaT message. It represents the minimum time (expressed as a time mark) that the signal indication will remain in its current state. This data element is taken directly from the traffic signal controller.
MaxEndTime	The standard *DE_maxEndTime* data element in the J2735 2016 SPaT message. It represents the maximum time (expressed as a time mark) that the signal indication can remain in its current state. This data element is taken directly from the traffic signal controller.
ConnectionID	The standard *DE_LaneConnectionID* data element in the J2735 2016 SPaT message. This value is a connection index for a lane-to-lane connection. TOSCo uses this data element to associate queue information to specific lanes in the SPaT message.
QueueLength	The value of the length of the queue for the lane identified in the *ConnectionID*. This value represents the distance, in meters, from the stop bar to the leading edge of the first detection zone not registering to be in a queued state. This value comes from the *backofQueue* data element contained in the Queue Data log.

Data Element Name	Description
RegionID	A data element used to indicate that the following data elements in the SPaT message are specific to a region or application. TOSCo uses the value of “130” to indicate that the SPaT message contains data elements to support TOSCo. This data element allows the vehicle to determine that the following data elements include the *GWStart* and *GWEnd* data elements associated with a particular *ConnectionID*.
GWStart	The time mark (in seconds x 10 since the top of the hour) when the TOSCo system expects the green window to “open” (i.e., become available for TOSCo vehicles).
GWEnd	The time mark (in seconds x 10 since the top of the hour) when the TOSCo system expects the green window to “close” (i.e., become unavailable for TOSCo vehicles).

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

Table 9. Sample of Data Contained in the TOSCo SPaT Message Log

Run#	IntersectionID	Revision#	GWMsgNo	GWDFlag	Date	Time	MSecsEpochTime	SignalGroupID	MPS	MinEndTime	MaxEndTime	ConnectionID	QueueLength	RegionID	GWStart	GWEnd
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	1	ProtectedMovementAllowed	2099	2206	1				
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	6	StopAndRemain	2149	2256	2	0	130	2325	2606
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	6	StopAndRemain	2149	2256	3	0	130	2256	2606
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	8	StopAndRemain	2299	2656	4				
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	3	StopAndRemain	2299	2656	4				
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	5	ProtectedMovementAllowed	2099	2206	5				
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	2	StopAndRemain	2149	2256	6	0	130	0	0
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	4	StopAndRemain	2299	2656	7				
2018	7	118	28931	0	6/17/2021	03:27.9	1623949407916	7	StopAndRemain	2299	2656	7				
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	1	ProtectedMovementAllowed	2099	2205	1				
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	6	StopAndRemain	2149	2255	2	0	130	2325	2606
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	6	StopAndRemain	2149	2255	3	0	130	2256	2606
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	8	StopAndRemain	2299	2655	4				
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	3	StopAndRemain	2299	2655	4				
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	5	ProtectedMovementAllowed	2099	2205	5				
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	2	StopAndRemain	2149	2255	6	0	130	0	0
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	4	StopAndRemain	2299	2655	7				
2018	7	118	28931	0	6/17/2021	03:28.0	1623949407995	7	StopAndRemain	2299	2655	7				

Source: Texas A&M Transportation Institute, 2022

SPaTTSC Data Log

The Signal Phase and Timing (SPaTTSC) Data Log (abbreviated as SPaTTSCData) contains the two data sets that are combined to generate the SPaT message. It consists of two data sets merged into one file, the green window information and the state data from the traffic signal controller. Table 10 describes the content of the Green Window portion of the TOSCo SPaTTSC Data Log. Table 11 describes the contents of the SPaT part of the SPaTTSC Data Logs. Table 12 shows a sample of the SPaTTSC Message Log that contains the information about the queue, and Table 13 shows the signal phase and timing portion of the SPaTTSC Message log.

Table 10. Description of the Data Elements Contained in Green Window Portion of the TOSCo SPaTTSC Data Log

Data Element Name	Description
Run#	An indicator parameter identifying the run number associated with the data. This number links the infrastructure data logs and the vehicle data logs together.
IntersectionID	The identification number of the TOSCo intersection associated with the log. The *IntersectionID* is the same as the intersection identification number in the MAP message.
GWMsgNo	The identification number of the iteration of the green window prediction algorithm. Each number represents a unique iteration of the algorithm.
GWDFlag	A Boolean parameter indicating that a change in the green window data has occurred.
Date	The month, day, and year that the TOSCo system generated the SPaT TSC Data Log entry.
Time	The minutes and seconds in the hour that the TOSCo System generated the data. The format for the data entry is in mm:ss.0.
MSecsEpochTime	The current time in milliseconds since January 1, 1970.
SignalGroupID	The identification number in the J2735 2016 SPaT message signal group. It is an index used to map traffic signal indications to allowable vehicle movements at an intersection.
DataType	The type of data contained in this row of data. “GWData” refers to data related to the green window used to produce the enhanced SPaT message. “SpatData” refers to the signal phase and timing data from the controller used to produce the enhanced SPaT message.
LogDetectorStatus	An indicator flag denoting that detector status logging is active: “1” means the detection logger is active, and “0” means that the detection logger is not active.
GWMsgNo	The identification number of the iteration of the green window prediction algorithm. Each number represents a unique iteration of the algorithm.
GWDFlag	A Boolean parameter indicating a change in the green window data has occurred.
Number of Lanes	The total number of lanes for which the TOSCo system will provide queue data.

Data Element Name	Description
LaneNo	The identification number of the lane associated with the TOSCo approach. The *LaneNo* is the same as the lane identification number in the MAP message.
QueueLength	The value of the length of the queue for the lane identified in the *ConnectionID*. This value represents the distance, in meters, from the stop bar to the leading edge of the first detection zone not registering to be in a queued state. This value comes from the *backofQueue* data element contained in the Queue Data Log.
GWStart	The time mark (in seconds x 10 since the top of the hour) when the TOSCo system expects the green window to “open” (i.e., become available for TOSCo vehicles).
GWEnd	The time mark (in seconds x 10 since the top of the hour) when the TOSCo system expects the green window to “close” (i.e., become unavailable for TOSCo vehicles).

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

Table 11. Description of the Data Elements Contained in SPaTData Portion of the TOSCo SPaTTSC Data Log

Data Element Name	Description
Run#	An indicator parameter identifying the run number associated with the data. This number links the infrastructure data logs and the vehicle data logs together.
IntersectionID	The identification number of the TOSCo intersection associated with the log. The *IntersectionID* is the same number as the intersection identification number in the MAP message.
GWMsgNo	The identification number of the iteration of the green window prediction algorithm. Each number represents a unique iteration of the algorithm.
GWDFlag	A Boolean parameter indicating that a change in the green window data has occurred.
Date	The month, day, and year that the TOSCo system generated the SPAT TSC Data Log entry.
Time	The minutes and seconds in the hour that the Green Window Predictor generated the data. The format for the data entry is in mm:ss.0.
MSecsEpochTime	The current time in milliseconds since January 1, 1970.
SignalGroupID	The identification number in the J2735 2016 SPaT message signal group. It is an index used to map traffic signal indications to allowable vehicle movements at an intersection.
DataType	The type of data contained in this row of data. “GWData” refers to data related to the green window used to produce the enhanced SPaT message. “SpatData” refers to the signal phase and timing data from the controller used to produce the enhanced SPaT message.
Ph/Ov/Ped#	The number of the phase, overlap, or pedestrian indications represented in the data.

Data Element Name	Description
Grn	A logic indicator reflecting the state of the green indication associated with the phase. "TRUE" means the green signal indication associated with the signal phase is active, while "FALSE" means the green signal indication is not active.
Yel	A logic indicator reflecting the state of the yellow indication associated with the phase. "TRUE" means the yellow signal indication associated with that signal phase is active, while "FALSE" means the yellow signal indication is not active.
Red	A logic indicator reflecting the state of the red indication associated with the phase. "TRUE" means the signal indication associated with the signal phase is active, while "FALSE" means the red signal indication is not active.
Status	The status of the signal indications associated with the signal phase. This value is determined based on the *Grn, Yel,* and *Red* status objects.
MinTime	The least amount of time (in seconds x 10) remaining until the signal phase indication will transition to a new state. The traffic signal controller provides this value directly. *(This value should not be confused with the de_MinEndTime in the J2735 SPaT message standard.)*
MaxTime	The maximum amount of time (in seconds x10) remaining until the signal phase indication will transition to a new state. The traffic signal controller provides this value directly. (*This value should not be confused with the de_MaxEndTime in the J2735 SPaT message standard.)*
OGrn	A logic indicator reflecting the state of the green indication associated with an overlap. "TRUE" means the green signal indication associated with the overlap is active, while "FALSE" means the green signal indication is not active.
Oyel	A logic indicator reflecting the state of the yellow indication associated with an overlap. "TRUE" means the yellow signal indication associated with the overlap is active, while "FALSE" means the yellow signal indication is not active.
Ored	A logic indicator reflecting the state of the red indication associated with an overlap. "TRUE" means the red signal indication associated with the overlap is active, while "FALSE" means the red signal indication is not active.
OStatus	The status of the signal indications associated with the signal overlap. This value is determined based on the *Ogrn, Oyel,* and *Ored* status objects.
OMinTime	The minimum amount of time (in seconds x 10) remaining until the signal overlap will transition to a new state. The traffic signal controller provides this value directly.
OMaxTime	The maximum amount of time (in seconds x 10) until the signal overlap will transition to a new state. The traffic signal controller provides this value directly.
PedWalk	A logic indicator reflecting the state of the "WALK" pedestrian indication associated with the phase. "TRUE" means the "WALK"

Data Element Name	Description
	indication associated with the pedestrian signal phase is active, while “FALSE” means the “WALK” pedestrian signal indication is not active.
PedDontWalk	A logic indicator reflecting that the indication associated with the pedestrian indication is flashing “DON’T WALK.” “TRUE” means that the pedestrian signal is currently displaying a flashing “DON’T WALK” indication, while “FALSE” means the traffic signal is not showing a flashing “DON’T WALK” indication.
PedClear	A logic indicator reflecting that the indication associated with the pedestrian indication is in a cleared or solid “DON’T WALK” state. “TRUE” means the pedestrian signal is currently displaying a steady “DON’T WALK” indication, while “FALSE” means the pedestrian signal is not showing a steady “DON’T WALK.”
PedStatus	The status of the pedestrian signal indications. This value is determined based on the *PedWalk, PedDontWalk,* and *PedClear* logic indicators.
PedMinTime	The minimum amount of time (in tenths of seconds) remaining until the pedestrian signal indication will transition to a new state. The traffic signal controller provides this value directly.
PedMaxTime	The maximum amount of time (in tenths of seconds) remaining active until the pedestrian indication will transition to a new state. The traffic signal controller provides this value directly.
PhsFlashing	A logic flag indicating if the phase is in a flashing mode. “TRUE” means that the current traffic signal phase is flashing, while “FALSE” means that the phase is not flashing currently.
OvlpFlashing	A logic flag indicating if the overlap is in a flashing mode. “TRUE” means that the overlap is flashing, while “FALSE” means that the overlap is not flashing currently.
StopTimeActive	A logic flag indicating if the stop time function in the traffic signal controller is active. “TRUE” means that the stop time function is in effect, while a value of “FALSE” indicates that the stop time function is not in effect.
FaultFlashActive	A logic flag indicating if the traffic signal cabinet is in a fault flash. “TRUE” indicates that the controller detects a fault flash, while “FALSE” means that the controller is not in a fault flash.
PreemptActive	A logic flag indicating if the traffic signal controller is actively servicing a preempt request. “TRUE” means that the controller is servicing a preemption request, while “FALSE” means that the controller is not servicing a preemption request currently.
TSPActive	A logic flag indicating if the traffic signal controller is actively servicing a transit signal priority request. “TRUE” means that the traffic signal controller is servicing a transit signal priority request, while “FALSE” means that the controller is not servicing a transit signal priority request currently.
CoordinationActive	A logic flag indicating if the traffic signal controller is running a coordination timing plan. “TRUE” means that the traffic signal controller is actively running a coordination timing plan, while

Data Element Name	Description
	"FALSE" means that the traffic signal controller is not actively running a coordination timing plan.
CoordinationInTransitionActive	A logic flag indicating if the controller is transitioning from one coordination plan to another or from a "free" mode to a coordination plan mode. "TRUE" means that the controller actively in transition, while "FALSE" indicates that the controller is <u>not</u> actively in transition.
ProgrammedFlashActive	A logic flag indicating if the traffic signal controller is running a planned flash operation (such as during late night hours). "TRUE" means that the controller is actively in a programmed flash mode, while "FALSE" indicates that the controller is <u>not</u> actively in a programmed flash mode.

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

Table 12. Sample of Data Contained in the Green Window Data Portion of the TOSCo SPaTTSC Data Log

Run#	IntersectionID	GWMsgNo	GWDFlag	Date	Time	MSecsEpochTime	DataType	LogDetStatus	GWMsgNo	GWDFlag	NumberOfLanes	LaneNo	QueueLength	GWStart	GWEnd	LaneNo	QueueLength	GWStart	GWEnd
2018	7	28931	0	6/17/2021	03:27.9	1623949407916	GWData	1	28931	0	2	2	0	2325	2606	3	0	2256	2606
2018	7	28931	0	6/17/2021	03:28.0	1623949407995	GWData	1	28931	0	2	2	0	2325	2606	3	0	2256	2606
2018	7	28933	0	6/17/2021	03:28.2	1623949408182	GWData	1	28933	0	2	2	27.432	2325	2606	3	0	2256	2606
2018	7	28933	0	6/17/2021	03:28.3	1623949408276	GWData	1	28933	0	2	2	27.432	2325	2606	3	0	2256	2606
2018	7	28934	0	6/17/2021	03:28.4	1623949408369	GWData	1	28934	0	2	2	27.432	2325	2606	3	0	2256	2606
2018	7	28934	0	6/17/2021	03:28.5	1623949408479	GWData	1	28934	0	2	2	27.432	2325	2606	3	0	2256	2606
2018	7	28935	1	6/17/2021	03:28.6	1623949408557	GWData	1	28935	1	2	2	27.432	2326	2606	3	0	2257	2606
2018	7	28936	1	6/17/2021	03:28.7	1623949408651	GWData	1	28936	1	2	2	27.432	2326	2606	3	0	2257	2606
2018	7	28936	1	6/17/2021	03:28.7	1623949408744	GWData	1	28936	1	2	2	27.432	2326	2606	3	0	2257	2606
2018	7	28937	0	6/17/2021	03:28.8	1623949408838	GWData	1	28937	0	2	2	27.432	2326	2606	3	0	2257	2606
2018	7	28937	0	6/17/2021	03:28.9	1623949408932	GWData	1	28937	0	2	2	27.432	2326	2606	3	0	2257	2606
2018	7	28938	1	6/17/2021	03:29.0	1623949409026	GWData	1	28938	1	2	2	27.432	2326	2606	3	0	2257	2606
2018	7	28939	1	6/17/2021	03:29.1	1623949409135	GWData	1	28939	1	2	2	27.432	2325	2606	3	0	2256	2606
2018	7	28939	1	6/17/2021	03:29.2	1623949409213	GWData	1	28939	1	2	2	27.432	2325	2606	3	0	2256	2606
2018	7	28940	0	6/17/2021	03:29.3	1623949409307	GWData	1	28940	0	2	2	27.432	2325	2606	3	0	2256	2606

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

Table 13. Sample of Data Contained in the Signal Phase and Timing Portion of the TOSCo SPaTTSC Data Log

DataType	Ph/Ov/Ped#	Grn	Yel	Red	Status	MinTime	MaxTime	OGrn	Oyel	Ored	OStatus	OMinTime	OMaxTime	PedWalk	PedDontWalk	PedClear	PedStatus	PedMinTime	PedMaxTime
SpatData	1	TRUE	FALSE	FALSE	Green	20	127	FALSE	FALSE	FALSE	Red	127	0	FALSE	TRUE	0	8	0	0
SpatData	2	FALSE	FALSE	TRUE	Red	70	177	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	70	65535
SpatData	3	FALSE	FALSE	TRUE	Red	0	0	FALSE	FALSE	FALSE	Red	127	0	FALSE	TRUE	0	8	0	0
SpatData	4	FALSE	FALSE	TRUE	Red	220	577	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	220	65535
SpatData	5	TRUE	FALSE	FALSE	Green	20	127	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	0	8	0	0
SpatData	6	FALSE	FALSE	TRUE	Red	70	177	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	70	65535
SpatData	7	FALSE	FALSE	TRUE	Red	0	0	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	0	8	0	0
SpatData	8	FALSE	FALSE	TRUE	Red	220	577	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	220	65535
SpatData	1	TRUE	FALSE	FALSE	Green	20	126	FALSE	FALSE	FALSE	Red	126	0	FALSE	TRUE	0	8	0	0
SpatData	2	FALSE	FALSE	TRUE	Red	70	176	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	70	65535
SpatData	3	FALSE	FALSE	TRUE	Red	0	0	FALSE	FALSE	FALSE	Red	126	0	FALSE	TRUE	0	8	0	0
SpatData	4	FALSE	FALSE	TRUE	Red	220	576	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	220	65535
SpatData	5	TRUE	FALSE	FALSE	Green	20	126	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	0	8	0	0
SpatData	6	FALSE	FALSE	TRUE	Red	70	176	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	70	65535
SpatData	7	FALSE	FALSE	TRUE	Red	0	0	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	0	8	0	0
SpatData	8	FALSE	FALSE	TRUE	Red	220	576	FALSE	FALSE	TRUE	Red	0	0	FALSE	TRUE	16	8	220	65535

Note: The table does not show the first seven data elements (*Run#, Intersection ID, GWMsgNo., GWDFlag, Date, Time,* and *MSecsEpochTime*).

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

Table 13. Sample of Data Contained in the Signal Phase and Timing Portion of the TOSCo SPaTTSC Data Log (continued)

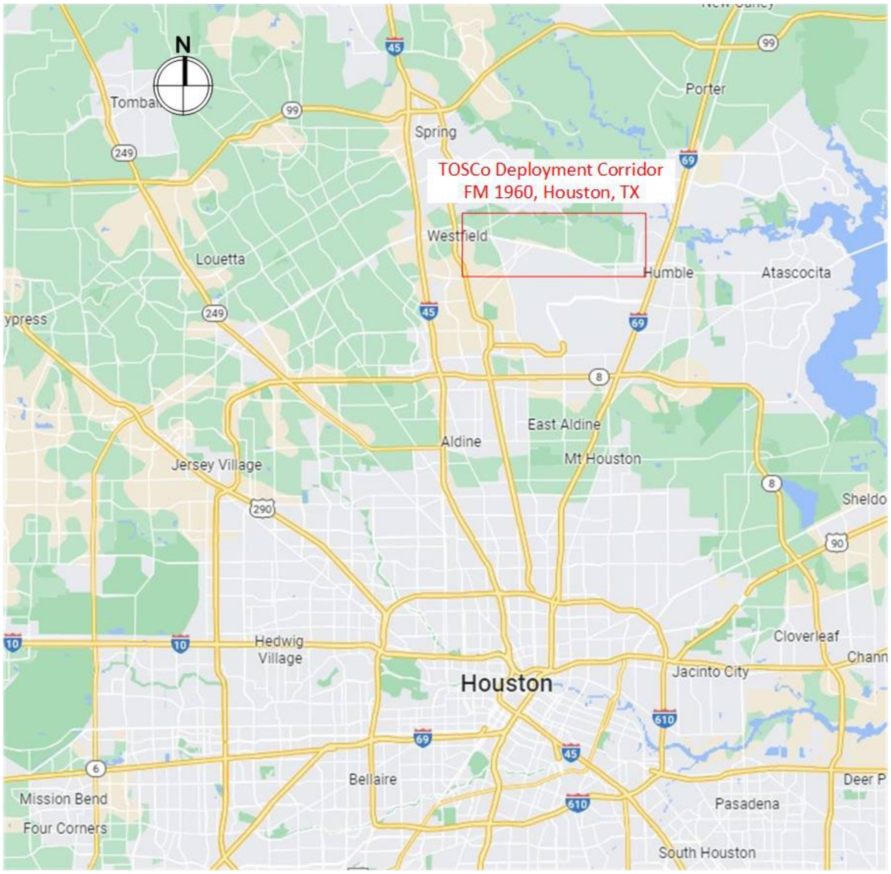
PhsFlashing	OvlpFlashing	ManualControl Active	StopTimeActive	FaultFlashActive	PreemptActive	TSPActive	Coordination Active	CoordinationIn Transition Active	ProgrammedFlash Active
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE

Note: The table does not show the first seven data elements (*Run#, Intersection ID, GWMsgNo., GWDFlag, Date, Time,* and *MSecsEpochTime*).

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

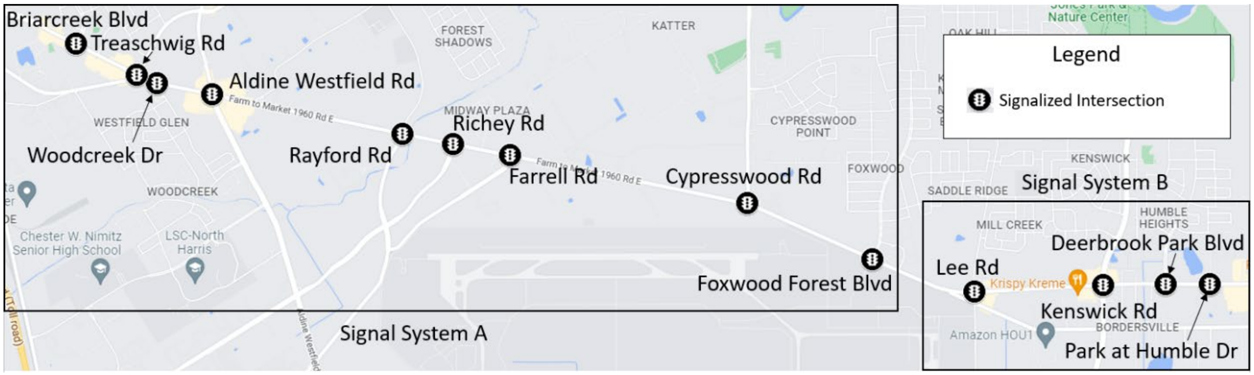
Chapter 9. Field Deployment on FM 1960

The TOSCo system was deployed and tested under live traffic conditions at 13 intersections on 12 miles of FM 1960 in Houston, Texas, near the city of Humble. The corridor is a major arterial at the northern edge of the Bush Intercontinental Airport. Figure 39 shows the general site map of the location while Figure 40 shows the location of the signalized intersections considered FM 1960. The posted speed limit in most of the analysis corridor is 55 mph, with the easternmost two miles posted at 50 mph. The annual average daily traffic (AADT) in the corridor ranges from 38,398 vehicles per day on the west end to 43,098 vehicles per day on the east end. The travel time through the corridor is approximately twelve to fifteen minutes, depending on traffic volumes and time of day. Table 14 and Table 15 list the characteristics of each segment and each intersection in the FM 1960 corridor. Note that although there are not dedicated right turn lanes at each intersection, this roadway has large shoulders along the entire length of this segment which allows for vehicles to make right turns off the shoulder.



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

Figure 39. Site Map of TOSCo Deployment Corridor—FM 1960, Houston Texas



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

Figure 40. Location of Signalized Intersections on the FM 1960 Corridor

Table 14. Characteristics of Road Segments on the FM 1960 Corridor in Houston, Texas

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

Source: Texas A&M Transportation Institute, 2022

Table 15 also notes the intersection numbers assigned to the intersections along the corridor by the research team. These intersection numbers were introduced to increase the ease of understanding the order of intersections and documentation for field implementation. Although the field implementation is not covered in this document, the numbering convention for intersections is maintained for brevity.

Table 15. Characteristics of Intersections on the FM 1960 Corridor

Intersection Name	Assigned Intersection Number	Exclusive Left Turn Lane	Exclusive Right Turn Lane
Briarcreek Blvd.~~,~~	101	EB	None
Treaschwig	102	EB and WB	EB Only
Woodcreek Dr.~~,~~	103	EB and WB	None
Aldine Westfield Rd.	104	EB and WB	EB and WB
Rayford Rd.	105	EB and WB	None
Richey Rd.	106	WB Only	None
Farrell Rd.	107	WB Only	None
Cypresswood Dr.	108	EB Only	WB Only
Foxwood Forest Blvd.	109	EB and WB	WB Only
Lee Rd.	110	EB and WB	WB Only
Kenswick Dr.	111	EB and WB	WB Only
Deerbrook Park Blvd.~~,~~	112	EB Only	None
Park at Humble Dr.	113	EB and WB	None

Source: Texas A&M Transportation Institute, 2022

Traffic Signal Operations

The Texas Department of Transportation (TxDOT) operates all the intersections on this length of FM 1960. TxDOT uses TS-2 controllers operating in TS-2 cabinets in all but one intersection (which uses a TS-2 controller in a TS-1 cabinet), As shown in Figure 40, the signals are grouped into two systems with Signal System A operating the signals on the west end of the corridor and Signal System B operating the four intersections on the east end of the corridor.

The systems operate in actuated coordinated mode using a time-of-day schedule. Table 16 shows the base timing coordination scheme for each signal system. To limit the impact of testing on traffic operations, testing was constrained to 9:00 AM to 3:00 PM. All cross-street and main-street left-turn phase were programmed with a minimum recall to ensure that all phases in the signal were activated for their minimum duration in the normal phase sequence.

Table 16. Base Time of Day Coordination Plans for FM 1960 Corridor

Signal System A			Signal System B		
Briarcreek to Foxwood			Lee Road to Townsend		
Pattern	Time	Cycle	Pattern	Time	Cycle
99	0:00	Free	4	0:00	90
4	5:45	90	2	5:30	150
2	6:30	120	7	9:30	150
4	9:00	90	6	14:30	165
1	11:30	105	3	16:30	165
3	16:00	135	1	19:30	135
1	19:00	105	4	22:30	90
4	20:30	90			
99	22:00	Free			

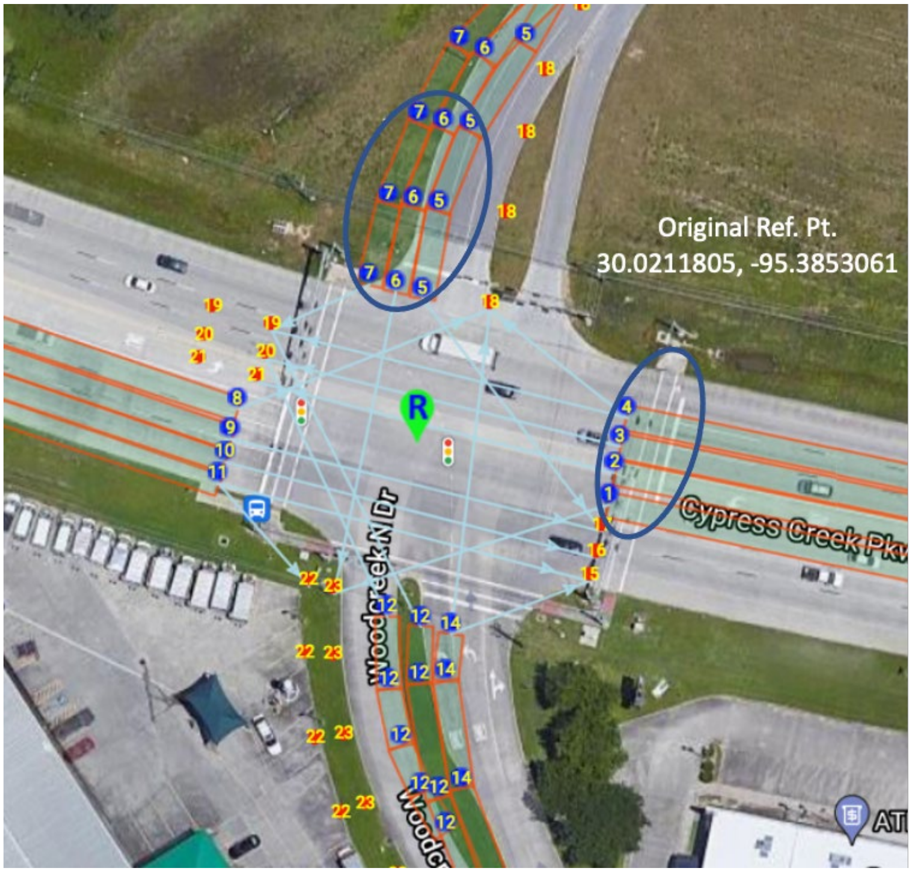
Source: Texas A&M Transportation Institute, 2022

The TOSCo corridor was along FM 1960 in Houston from the intersection of Briarcreek Boulevard in the west to the intersection of Park at Humble in the east. Most of the intersections were span-wire installation and required the sensor to be installed on a pole in the corner. A few intersections were mast-arm installation where the optimum location to install the sensor was on the mast arms. Table 17 lists the configuration of each intersection.

MAP Recalibration

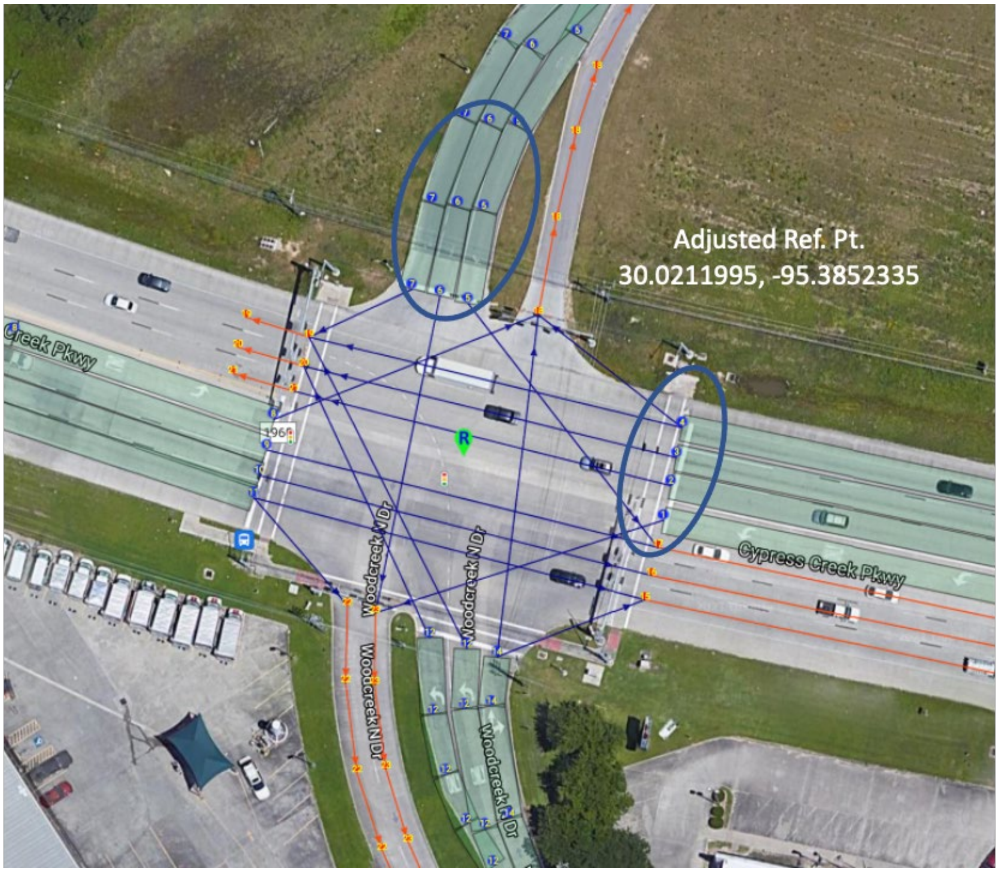
The MAP message broadcast by the TOSCo Infrastructure provides lane geometry used by the TOSCo vehicles to determine their lane position needed to associate SPaT for the lane and position of stop point for vehicles to stop when appropriate (e.g., CSTOP). The Intersection geometry was developed using the USDOT ISD tool. The lane geometry node points in the MAP message were defined starting with reference point as X-Y offsets. The placement of reference point was critical since the incorrect reference point causes shift in mapped lanes leading to incorrect lane determination by the vehicle.

The on-road field testing test data indicated incorrect lane position by the vehicle due to shift in lane position when the intersection MAP is overlaid on Google satellite view. As shown in Figure 41 with the original reference point generated by the mapping tool, the physical lane markers and the stop points were shifted. Figure 42 shows the same intersection with the adjusted reference points where the lane marker and the stop points were properly aligned. After the adjustment, the TOSCo vehicles successfully determined the intended lane position.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium, 2022
Imagery ©2022 Google. Map Data ©2022 Google

Figure 41. Offset in Original MAP Before Adjusting Reference Point



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle to Infrastructure (V2I) Consortium, 2022
Imagery ©2022 Google. Map Data ©2022 Google

Figure 42. MAP Realignment after Adjusting Reference Point

Table 17. Intersection Configurations in the Corridor

Intersection Number	Intersection Name	Intersection Type
101	Briarcreek Blvd.	Mast Arm
102	Treaschwig Rd.	Span Wire
103	Woodcreek N. Dr.	Mast Arm
104	Aldine Westfield	Span Wire
105	Rayford/Birnamwood	Span Wire
106	Richey Rd.	Span Wire
107	Farrell Rd.	Span Wire
108	Cypresswood Dr.	Span Wire
109	Foxwood Forest Blvd.	Span Wire
110	Lee Rd.	Mast Arm
111	Kenswick Dr.	Span Wire
112	Deerbrook Park Blvd.	Span Wire
113	Park at Humble	Span Wire

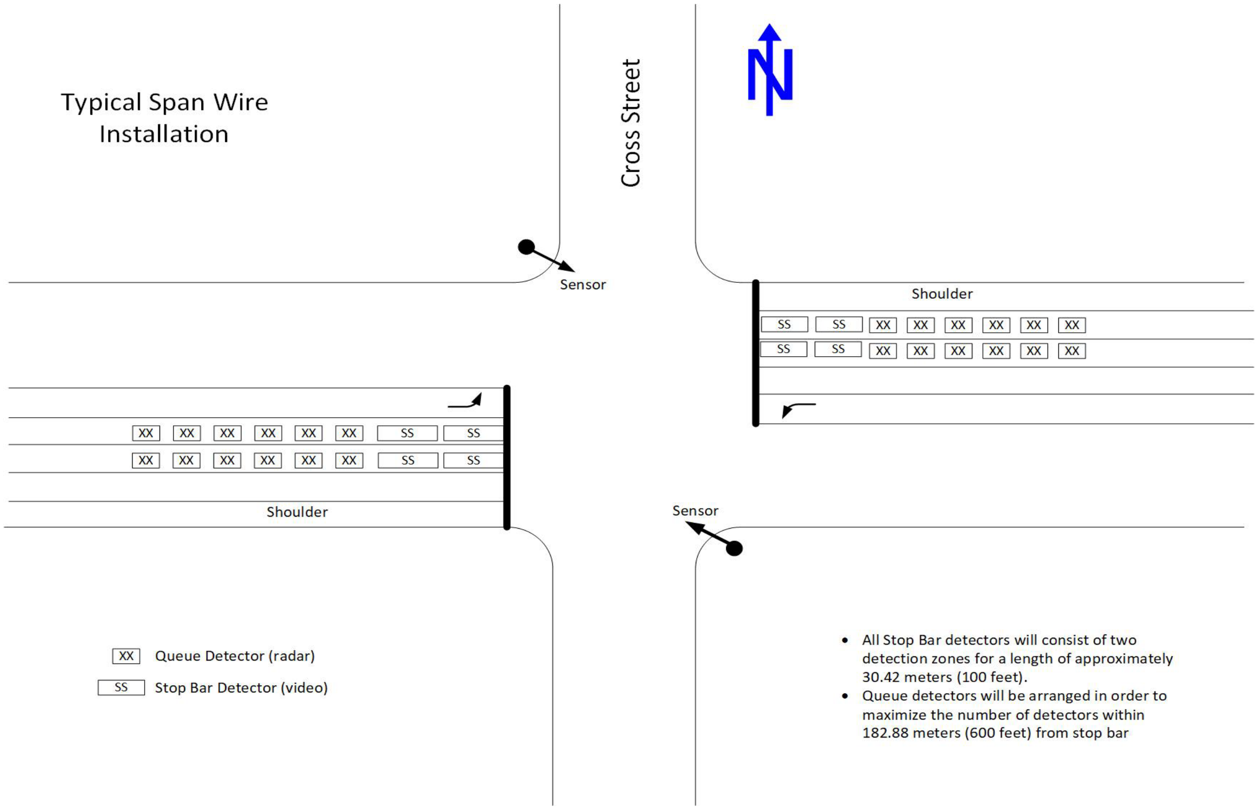
Source: Texas A&M Transportation Institute, 2022

Queue Detection

The TOSCo Team used a combination video and radar detector similar to the unit shown in Figure 43 to provide queue detection for the major street movements for all intersections. Separate units were installed to detect queues on both the eastbound and westbound approaches. Video detection was used to provide queue detection near the stop bar, while radar detection was used for upstream queue detection zones. Figure 44 and Figure 45 show the typical detection zone configuration used at span wire and mast arm installation, respectively. Detections zones were established in two through lanes in each direction for the TOSCo corridor.

Source: Texas A&M Transportation Institute, 2022

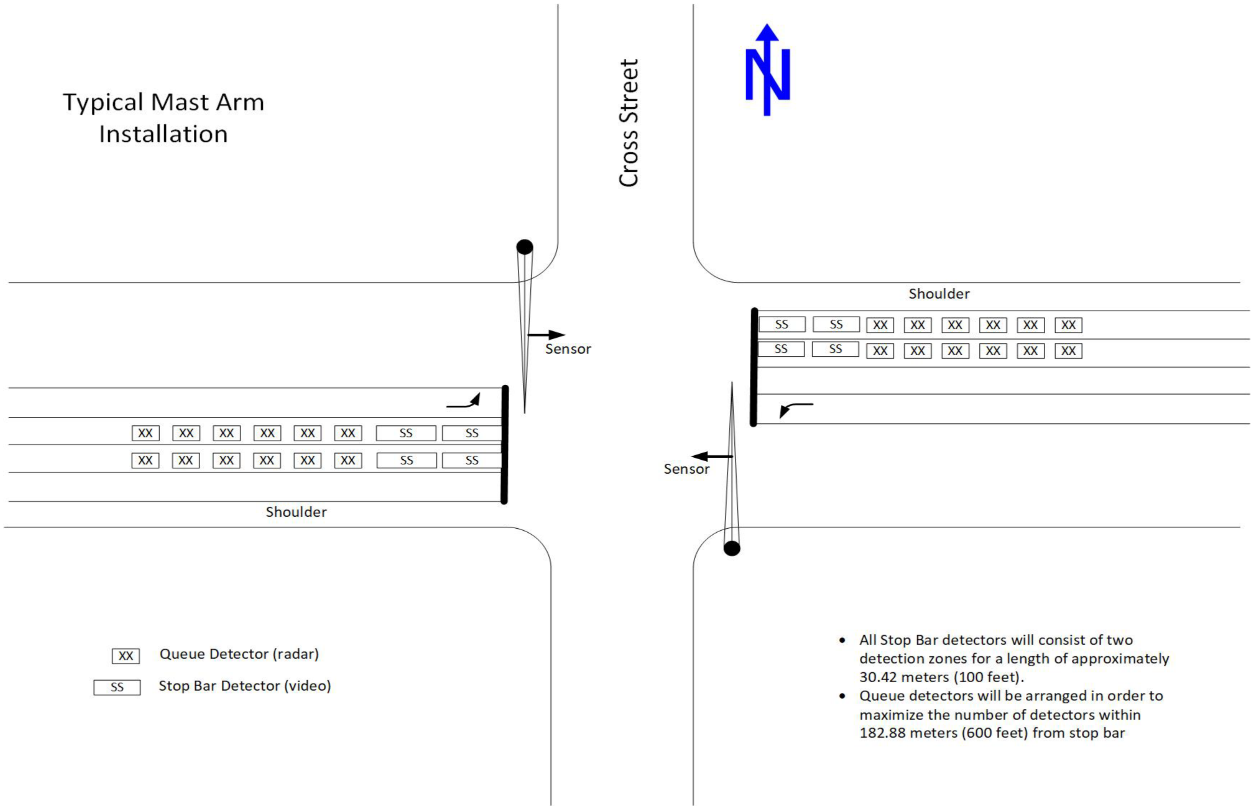
Figure 43. Queue Detection Sensor Used with TOSCo



- All Stop Bar detectors will consist of two detection zones for a length of approximately 30.42 meters (100 feet).
- Queue detectors will be arranged in order to maximize the number of detectors within 182.88 meters (600 feet) from stop bar

Source: Texas A&M Transportation Institute, 2022

Figure 44. Typical Span Wire Installation



- All Stop Bar detectors will consist of two detection zones for a length of approximately 30.42 meters (100 feet).
- Queue detectors will be arranged in order to maximize the number of detectors within 182.88 meters (600 feet) from stop bar

Source: Texas A&M Transportation Institute, 2022

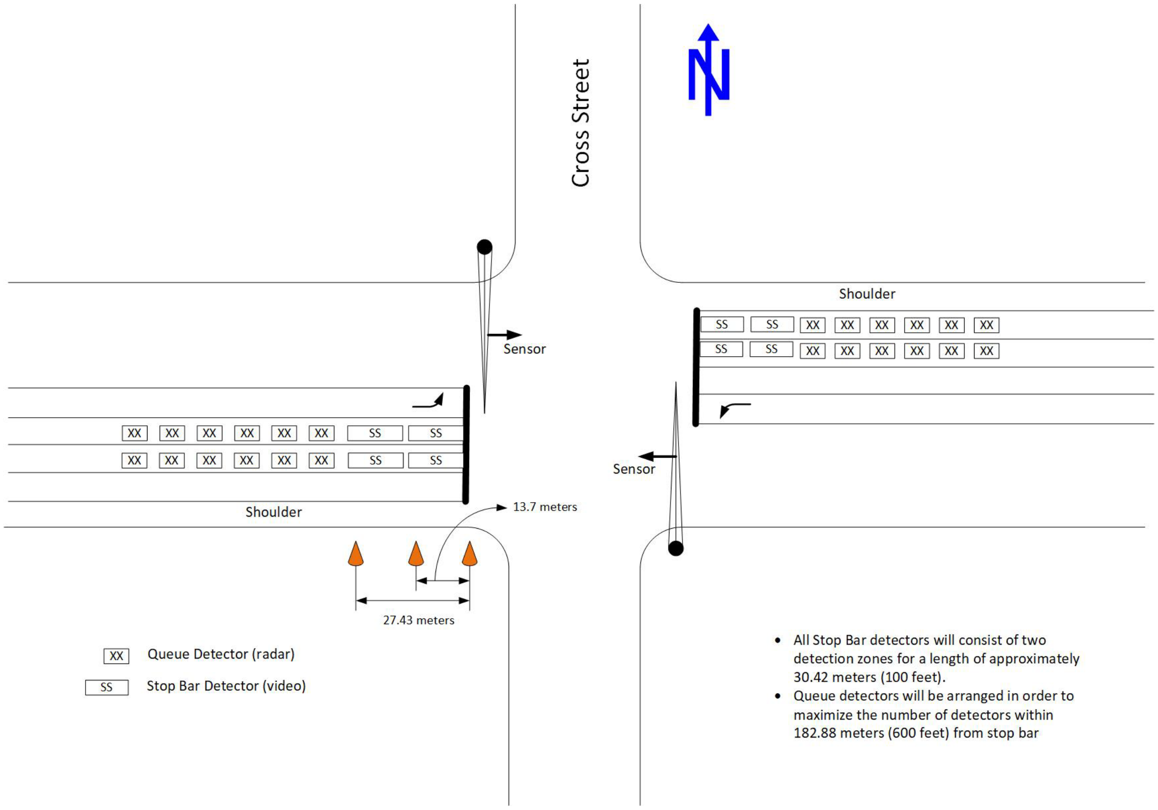
Figure 45. Typical Mast-Arm Installation

Detector Zone Configurations and Calibration

Once the sensors were installed, some basic configuration information such as height, angle, and distance from installation location to stop bar was input into the detection application. In addition to the normal demand detection system, a combination radar-video based detection system was used to provide queue detection at each intersection. Input modules were added to the cabinet to provide a total of 16 additional detection zone for each TOSCo approach. TOSCo was deployed on the main street approaches only.

Stop Bar Video Detection

The TOSCo Team configured the detection zones near the stop bar (two zones) to cover a specific distance (specific numbers of passenger cars) from the stop bar as noted in Figure 46. This was accomplished by placing cones on the shoulder at a distance of 14 meters (45 feet) and 27 meters (90 feet) from stop bar. TTI researchers then observed the vehicles being queued in that area while in communication with researchers at the signal controller cabinet. The researchers at the cabinet would confirm when each of detection zone was occupied by a vehicle at the stop bar. The zones lengths were also adjusted to detect the correct number of vehicles. When a single vehicle was at the stop bar, only the downstream stop bar zone should be actuated. The second zone would be actuated when a second vehicle was present at the stop bar. The upstream zone was adjusted so that the rear bumper of the third vehicle was at the leading edge of the upstream zone.



- All Stop Bar detectors will consist of two detection zones for a length of approximately 30.42 meters (100 feet).
- Queue detectors will be arranged in order to maximize the number of detectors within 182.88 meters (600 feet) from stop bar

Source: Texas A&M Transportation Institute, 2022

Figure 46. Configuration of Stop Bar Detection Zones

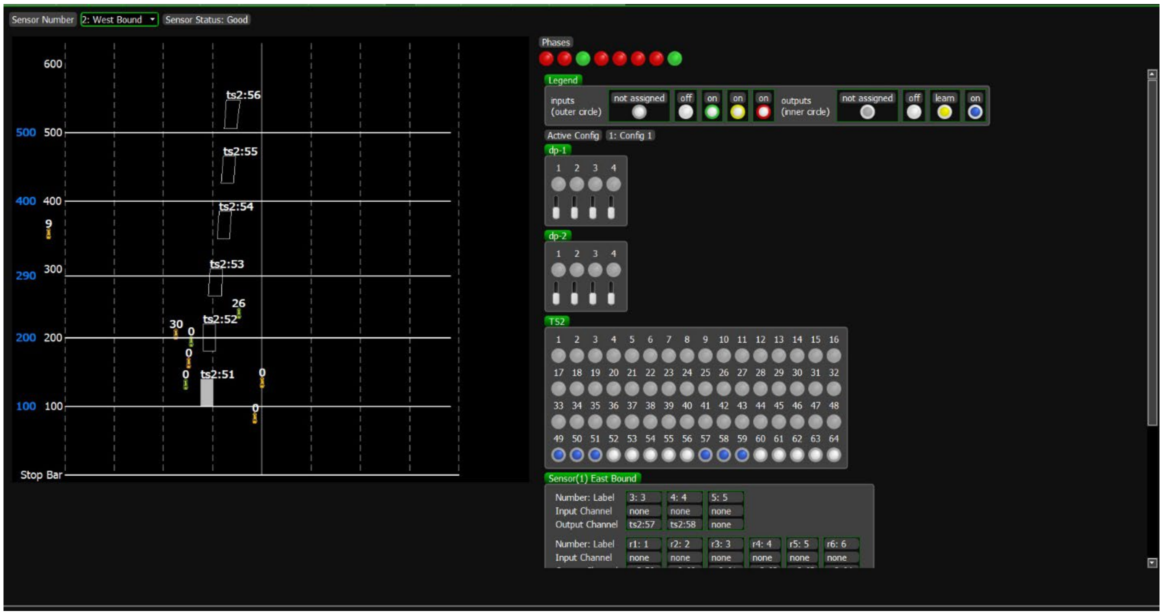
Speed-based Detection Zones

After the stop bar detection zones were configured, speed-based radar detection zones to measure queue lengths were configured to be 12 meters (40 feet) in length with a minimum spacing of 12 meters (40 feet) between them. The trailing edge of the speed detection zone closest to the stop bar was placed 30 meters (100 ft) from the stop bar. Table 18 shows the initial configuration for each detection zone. Each zone was 40 feet long and had a spacing of 40 feet, which is the minimum allowed spacing by the configuration software. The software to configure the distances of these zones is illustrated in Figure 47.The TOSCo Team then adjusted the detection distances associated with each detection zone laterally and/or longitudinally by driving through each lane under a light traffic (e.g., late night) using a TOSCo vehicle. Operators would record the distance until the stop bar for each detection zone. Multiple runs were performed until a consistent distance was reached. The teams then updated the distance parameters based on the measurements.

Table 18. Initial Speed-Based Distance From Stop Bar Configuration

Zone Count from Stop Bar	Sample Detector Channel Number	Initial Distance of Trailing Edge of Detector Zone (feet)
3	51	100
4	52	180
5	53	260
6	54	340
7	55	420
8	56	500

Source: Texas A&M Transportation Institute, 2022


Sensor Number: 2: West Bound
Sensor Status: Good
Active Config: 1: Config 1

Sensor(1) East Bound

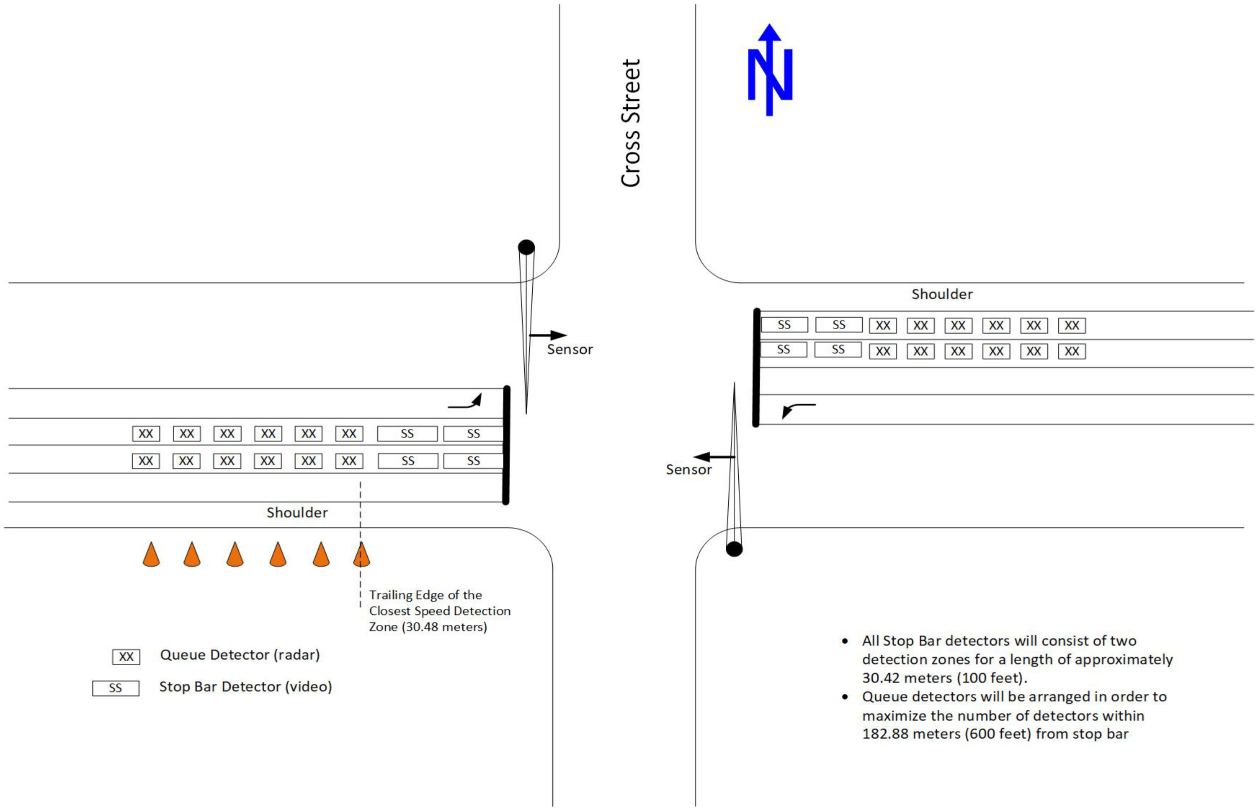
Number: Label	3: 3	4: 4	5: 5
Input Channel	none	none	none
Output Channel	ts2:57	ts2:58	none

Number: Label	r1: 1	r2: 2	r3: 3	r4: 4	r5: 5	r6: 6
Input Channel	none	none	none	none	none	none

Source: ITERIS, 2022

Figure 47. Detector Software to Configure the Distances of the Queue Zones

To verify proper detected queue lengths, the TOSCo Team conducted observations at each intersection under normal traffic conditions. To verify, proper queue length detection, the TOSCo Team placed cones at the defined detection zone parameters and compared field observations to reported queues. Queue detection distances where then adjusted to agree with observed queue conditions.



Source: Texas A&M Transportation Institute, 2022

Figure 48. Configuration of Queue Detection Zones

Green Window Predictor

The last step in the TOSCo installation process is to install the Green Window calibration parameters. These parameters were saved in a text file with the variable name, a comma, and the value in each line of the configuration file. Table 19 shows the default values for the manually configured calibration parameters.

Table 19. Green Window Predictor Default Configuration Values

Parameter Name	Default Value	Units
IntersectionID	Varied by Intersection	Count
VehLength	20	Feet
SpeedLimit	55	Miles-per-hour
DistanceLastVideoDetectorFeet	100	Feet
a	10	Feet per second squared
TimePR_FirstVehicle	2.5	Seconds
TimePR_perVeihcle	1.0	Seconds
NumTOSCoLanes	2	Count
LanePhaseMap	Varied by Intersection	None

Source: Texas A&M Transportation Institute, 2022

Some of the parameters were extracted from the traffic signal controller and saved into a file. This was designed so that the signal timing information could be updated quickly and accurately based on what the traffic signal controller was actually operating in the field. The parameters with values read from the traffic signal controller are as follows:

- *PatternNumber*
- *CycleLength*
- *YellowTime*
- *RedTime*
- *PhaseSplitTime*

The research team primarily calibrated the *DistanceLastVideoDetectorFeet* parameter as the queue zone configuration was adjusted in search for better queue detection performance. The default values for the other parameters functioned well on FM 1960. The parameters that varied by intersection were signal timing variables that remained stagnant between the daily operations for the deployed intersections.

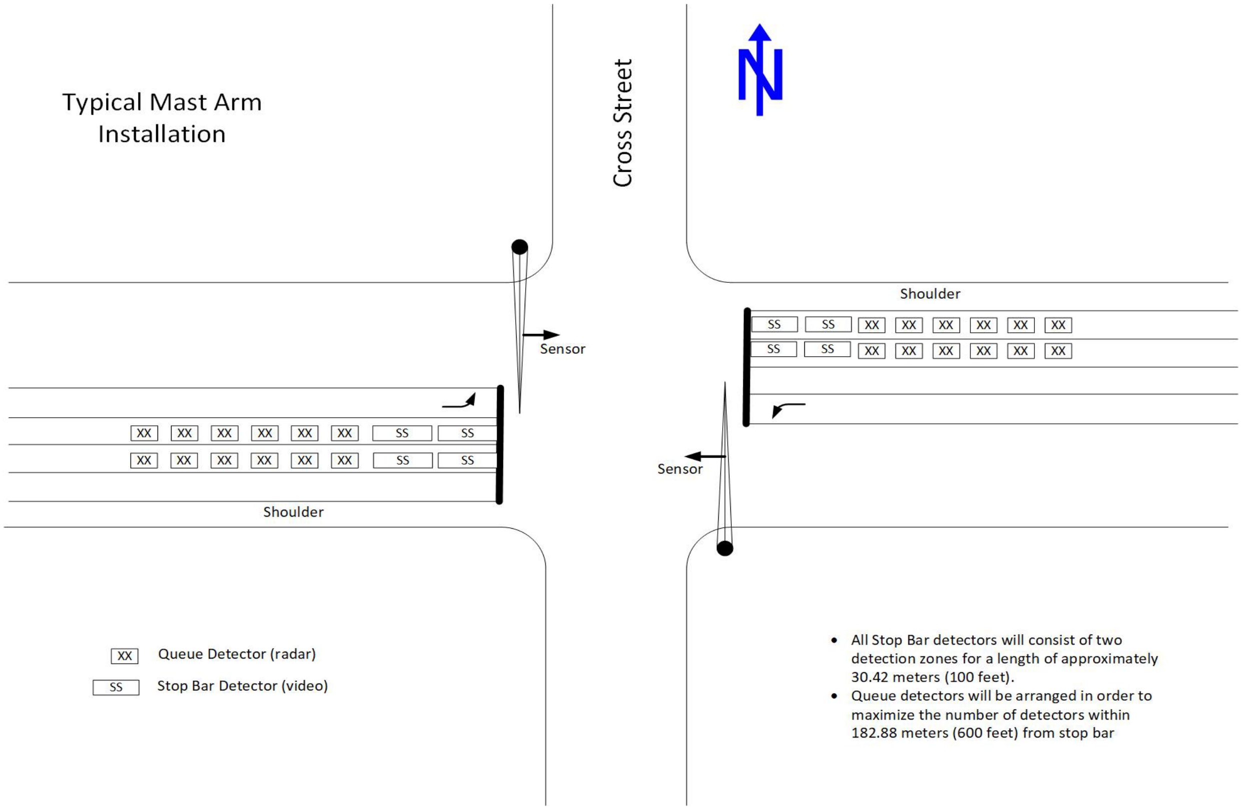
Deployment Lessons Learned

The following captures some of the critical lessons learned associated with deploying the TOSCo infrastructure in the corridor.

Queue Detection

- The TOSCo Team had to make modifications to the queue detection zones sensor placement due to issue discovered during the installation process. At two of the mast-arm installations, the conduit was broken. Hence a sensor could not be placed on the appropriate mast-arm. At these two intersections, both sensors were installed on the same mast arm. This resulted in not being able to use the video detectors for the sensor located to the nearside approach as seen in Figure 49. Similarly, one of span-wire installations was a very wide intersection due to a skew. The sensors were installed on the nearside poles instead of the far side poles as illustrated Figure 50. Even this installation required the use of TxDOT detectors for the stop bar detection as the sensors were installed very close to the stop bar.
- 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 sights. Because of deployment limitations, occlusion by high profile vehicles or from traffic in adjacent lanes may cause over reporting of queues lengths at some intersections. Figure 51 shows an example of a false detection from traffic in an adjacent lane. These errors were caused primarily because of the need to place the detection unit off to the side of the travel lanes. Positioning the detector unit in line with the travel lanes may help reduce these types of false detections but may not solve occlusion issues.
- The placement of the queue detector sensors (e.g., mounting height, detection angle, placement at intersections with mast arms vs. with span wires, etc.) dramatically impacts the effectiveness of the sensors to detect queues. Care should be taken when sensors have a direct line of sight on the roadway as possible for detecting queues. The installer should make sure that overhead wires do not block the line of sight of the detectors at the intersection.
- Calibration radar-based zones (i.e., 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 that traditionally used for stop-line detection. With traditional stop-line 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 of detection impacted the overall performance of the TOSCo system. Persistency of detection refers to detectors retaining calls (remaining in the “ON” state) as long as a vehicle occupies the detection zone. Some intersection had issues with unstable detection where certain detection zones would drop calls, even though the detector was occupied (see Figure 52). Unstable detection was problematic at intersections that experienced long queues (greater than 90 meters (300 feet)). To overcome this situation, the TOSCo 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.

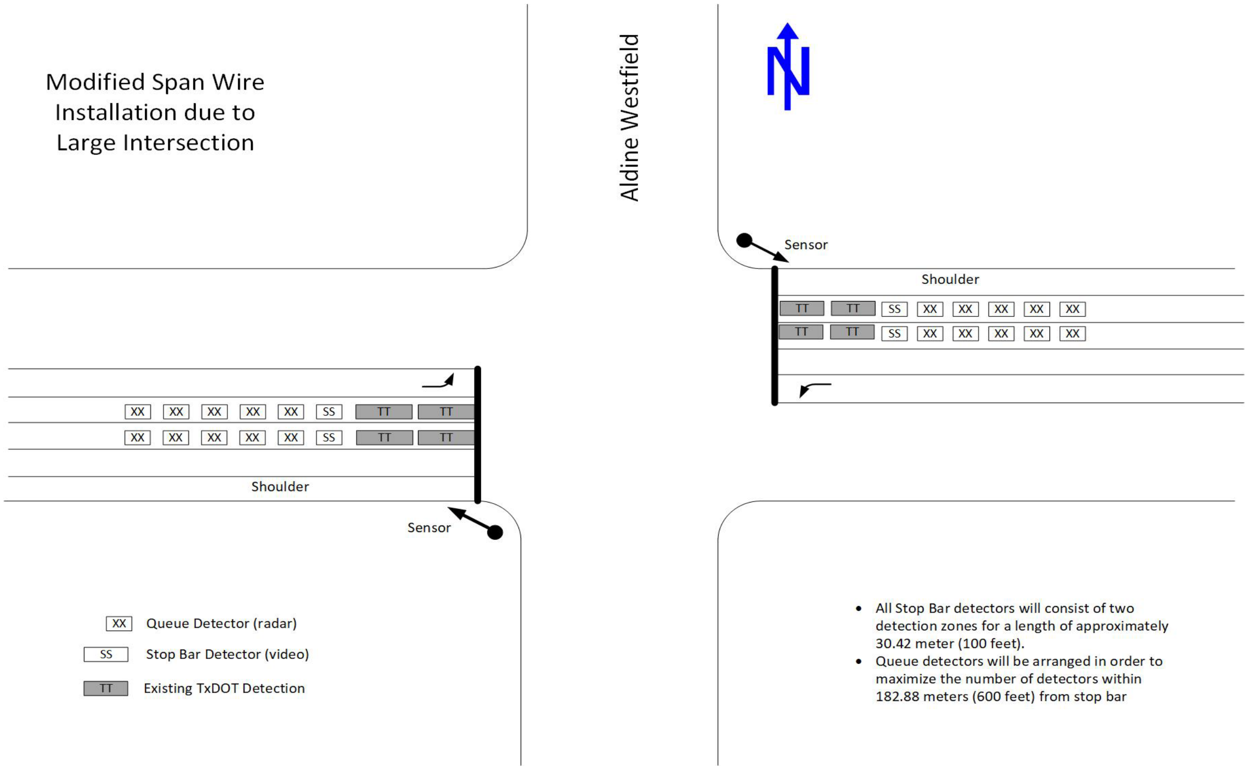
- The queue detection technology experienced accuracy issues when detection queue lengths over 122 meters (400 feet) occurred from the stop bar. To address detection accuracy issues, the deployment team had to adjust the speed threshold defining a stopped vehicle to 10 mph. This impacted the stability of the estimated queue lengths.



- All Stop Bar detectors will consist of two detection zones for a length of approximately 30.42 meters (100 feet).
- Queue detectors will be arranged in order to maximize the number of detectors within 182.88 meters (600 feet) from stop bar

Source: Texas A&M Transportation Institute, 2022

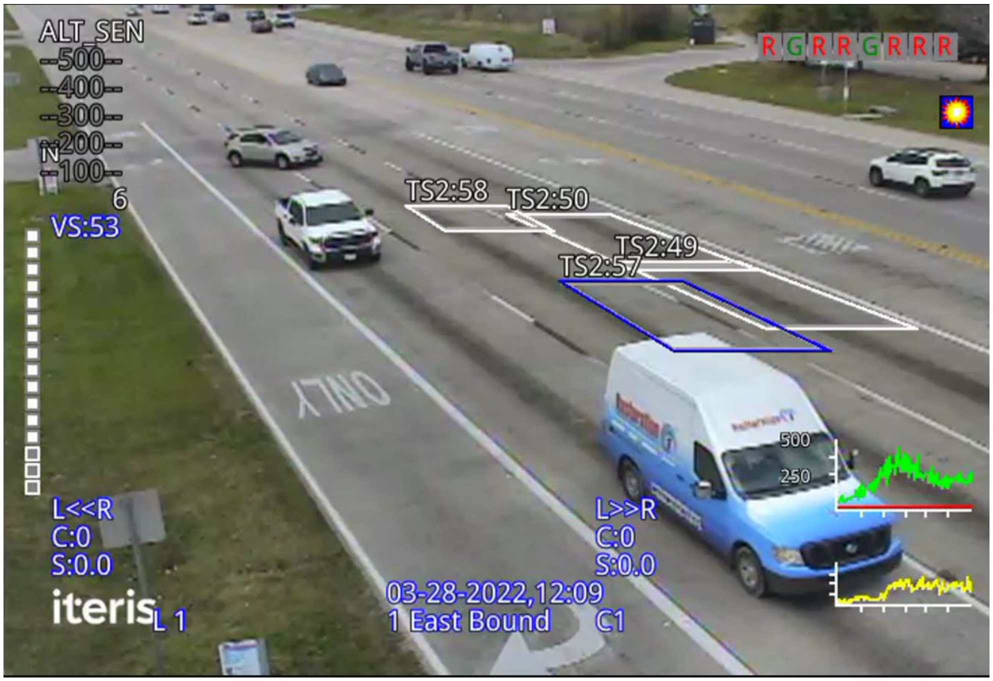
Figure 49. Modified Mast Arm Installations



- All Stop Bar detectors will consist of two detection zones for a length of approximately 30.42 meter (100 feet).
- Queue detectors will be arranged in order to maximize the number of detectors within 182.88 meters (600 feet) from stop bar

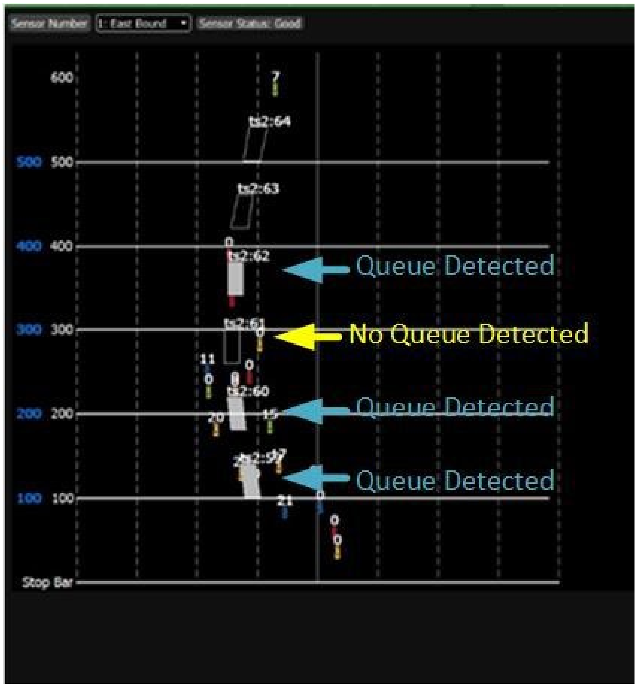
Source: Texas A&M Transportation Institute, 2022

Figure 50. Modified Span Wire Installation



Source: Texas A&M Transportation Institute, 2022

Figure 51. Example of a Vehicle in an Adjacent Lane Actuating a TOSCo Detector

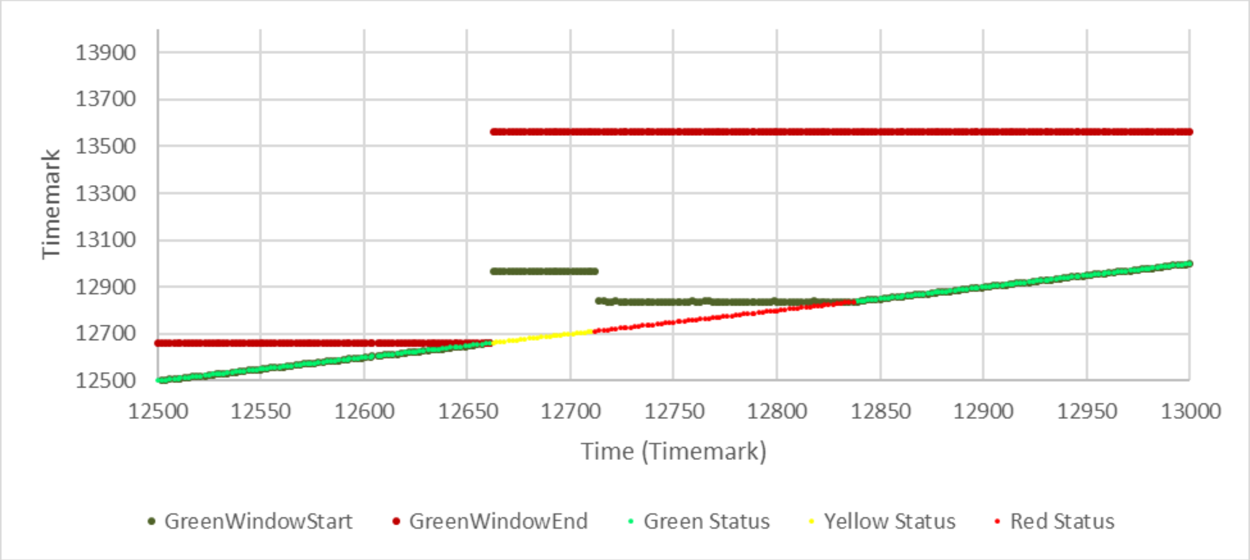


Source: Texas A&M Transportation Institute, 2022

Figure 52. Example of a Detection Zone Dropping a Call

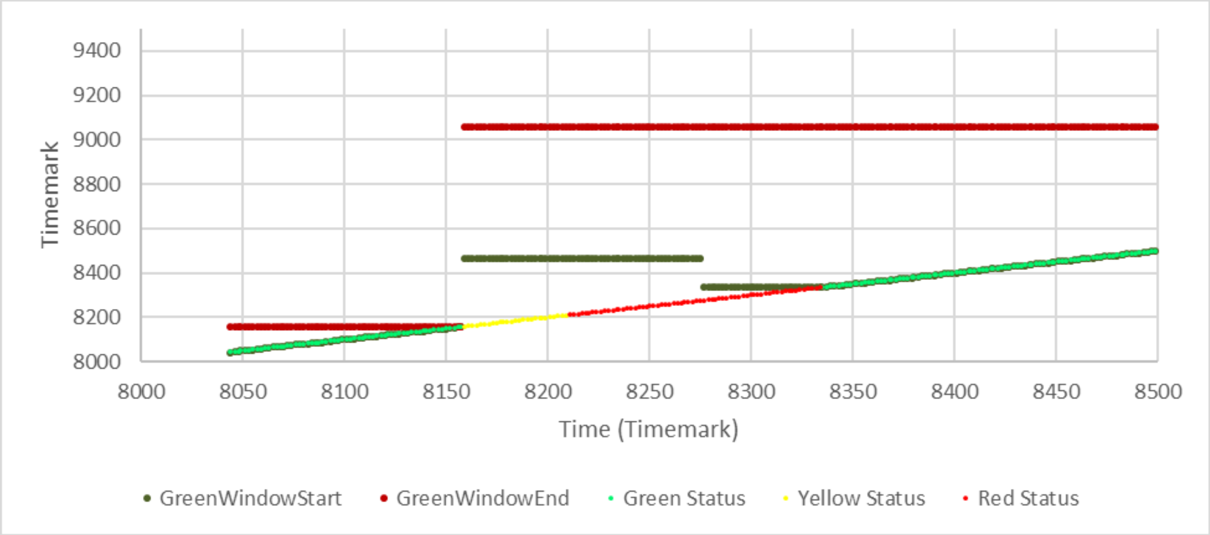
Green Window Prediction

The research team found that the Green Window Predictor produced extremely conservative estimates for when the signal would change, especially for intersections with low volumes on the cross street. With coordinated-actuated control on the cross streets, the red interval for the main street (coordinated) phase varied from cycle to cycle. The research team originally designed the green window predictor to base the green window on the maximum potential red duration, in favor of a single correction in the green window close to the time when the green phase becomes active. With the improvements to the vehicle algorithm's ability to function with multiple updates to the trajectory planning, the research team explored using the minimum timer in the SPaT data as the reference in the green window. Figure 53 and Figure 54 show some of the key differences in the green window with the different timer options when the TOSCo phase is red for the minimum potential duration at Intersection 107 as an example.



Source: Texas A&M Transportation Institute, 2022

Figure 53. Intersection 107 Phase Status and Green Window Information Where Red Phase is Minimal – Green Window Reference of Min Timer

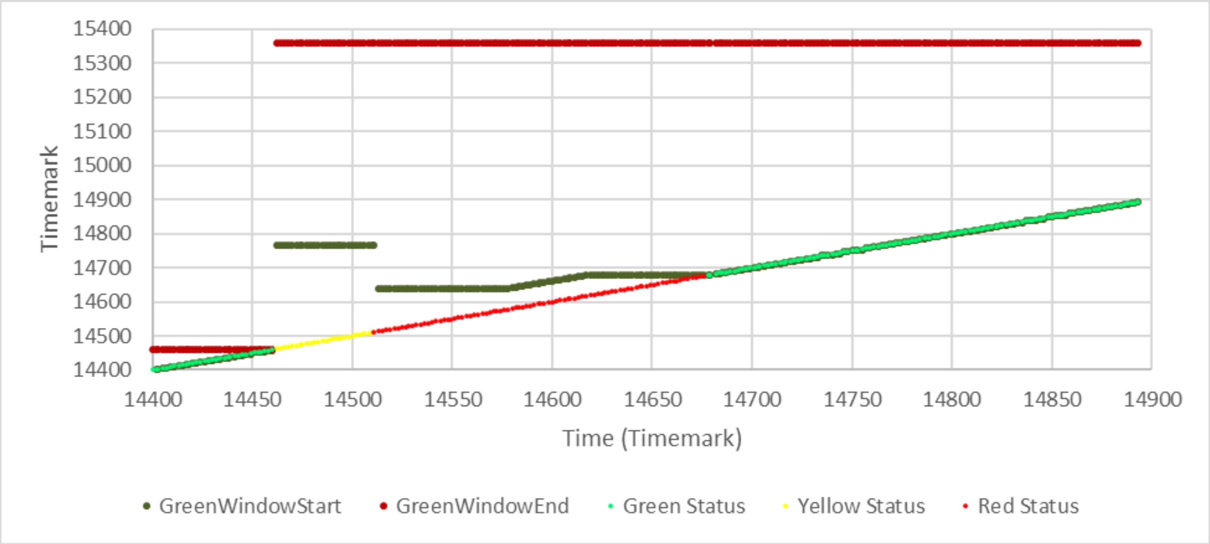


Source: Texas A&M Transportation Institute, 2022

Figure 54. Intersection 107 Phase Status and Green Window Information Where Red Phase is Minimal – Green Window Reference of Max Timer

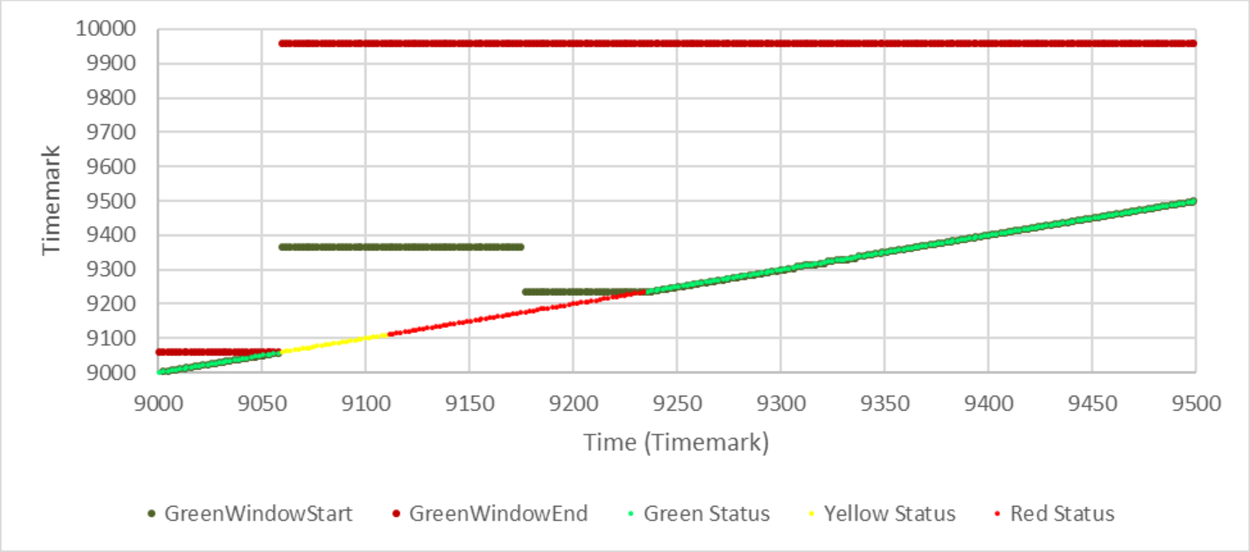
In these figures, the lowest diagonal lines represent the current time and the color represents the signal status. The larger and darker lines above the diagonal lines represent the green window time mark predicted in the future. As expected, the minimum timer reference is more accurate than the maximum time reference in describing when the green phase will begin. In this case, the green window is accurately predicted for the entire red duration with the minimum SPaT timer as a reference and the red duration is only accurately predicted after a correction six seconds before the onset of green.

Figure 55 and Figure 56 show the green window information where the red interval for the TOSCo phase is extended but does not run its maximum time.



Source: Texas A&M Transportation Institute, 2022

Figure 55. Intersection 107 Phase Status and Green Window Information Where Red Phase is Shortened – Green Window Reference of Min Timer

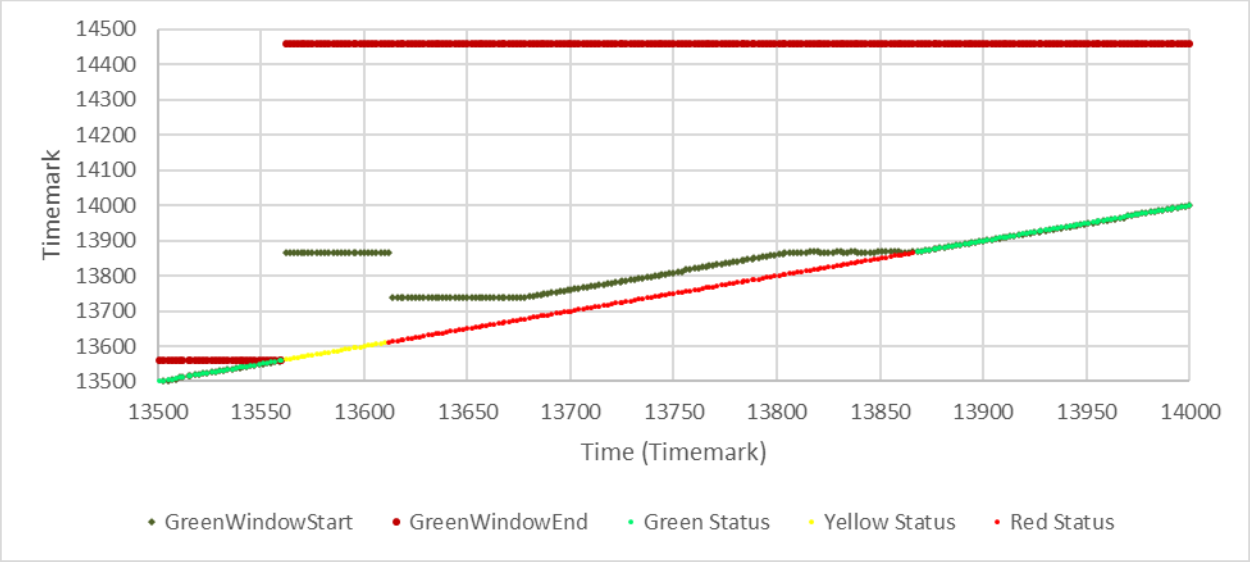


Source: Texas A&M Transportation Institute, 2022

Figure 56. Intersection 107 Phase Status and Green Window Information Where Red Phase is Shortened – Green Window Reference of Max Timer

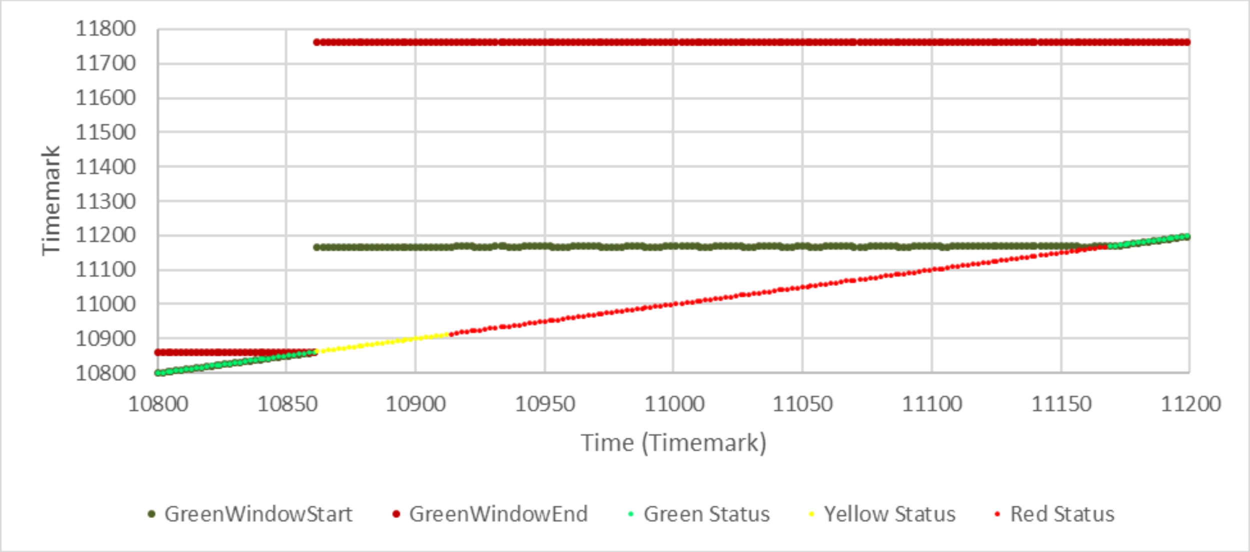
The green window prediction with the min timer prediction now has a point in the red interval where the green window start is constantly updating and is seen as a section of the green window line that is parallel to the current timeline in Figure 55. This effectively is the point where the green interval is going to continue at least six additional seconds, but the traffic on the cross street is extending the time which means that the green window updates until the signal controller begins to transition green to the TOSCo phase. The max timer reference for the green window behaves similar to before, where there is an initial conservative prediction and then a single correction to the green window six seconds before the onset of green.

Figure 57 and Figure 58 show the green window information when the red interval lasts the maximum potential duration.



Source: Texas A&M Transportation Institute, 2022

Figure 57. Intersection 107 Phase Status and Green Window Information Where Red Phase is Maximized – Green Window Reference of Min Timer



Source: Texas A&M Transportation Institute, 2022

Figure 58. Intersection 107 Phase Status and Green Window Information Where Red Phase is Maximized – Green Window Reference of Max Timer

The green window with the minimum time reference experiences continuous corrections to a large portion of the red interval if the red interval lasts the maximum duration. The green window based on the maximum timer is correct the entire duration of the red interval.

The research team decided to deploy the green window estimated based on the minimum timer in the field and found that the revision worked with the TOSCo vehicles and required few corrections for intersections with low volumes on the cross streets. The team also concluded that intersections with higher volumes on the cross streets would benefit with the maximum timer reference for the green window since that initial estimate would be more accurate. However, the min timer 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 reference from the SPaT data should be used for each intersection.

MAP Generation

- TTI generated the initial FM 1960 MAP messages using FHWA's ISD Message Creator tool. The TOSCo Team found that in some situations, the underlying map image to be out of date and inconsistent with the current configuration of the intersection. Furthermore, the zoom level supported by the map images was insufficient to allow the accurate placement of the reference point on the image.
- 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 (stop bars, center of lanes, etc.) Up-to-date satellite imagining tools provided valuable in assessing the accuracy of the broadcast maps.

SPaT and Green Window Determination

- The implementation relied on SPaT Data to be pushed from 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 controller 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 calculated with 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 it is updated regularly during the TOSCo phase’s red interval.
- 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 RSU. In 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 multiple intersections.
- Hardware that generates messages to support TOSCo needs to be configured to ensure that it maintains continuous operations. IT 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.

References

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APPENDIX A. Example of Phase-to-Lane-Movement (PTLM) Configuration File

```xml
<?xml version="1.0" encoding="utf-8"?>
<PhasetoLaneMovementMapping>

        <Intersection>
                <Name>RELLIS Smart Intersection</Name>
                <ID>7</ID>
                <City>College Station</City>
                <State>TX</State>
        </Intersection>
        <SPATMovement>
                <Movement>left</Movement>
                <Lane>1</Lane>
                <LaneType>Vehicle</LaneType>
                <Phase>1</Phase>
                <PhaseType>protected</PhaseType>
                <Signalgroupid>1</Signalgroupid>
                <ToscoMvmnt>no</ToscoMvmnt>
        </SPATMovement>
        <SPATMovement>
                <Movement>left</Movement>
                <Lane>1</Lane>
                <LaneType>Vehicle</LaneType>
                <Phase>2</Phase>
                <PhaseType>permitted</PhaseType>
                <Signalgroupid>1</Signalgroupid>
                <ToscoMvmnt>no</ToscoMvmnt>
        </SPATMovement>
        <SPATMovement>
                <Movement>straight</Movement>
                <Lane>2</Lane>
                <LaneType>Vehicle</LaneType>
                <Phase>6</Phase>
                <PhaseType>protected</PhaseType>
                <Signalgroupid>6</Signalgroupid>
                <ToscoMvmnt>yes</ToscoMvmnt>
        </SPATMovement>
        <SPATMovement>
                <Movement>straight</Movement>
                <Lane>3</Lane>
                <LaneType>Vehicle</LaneType>
                <Phase>6</Phase>
                <PhaseType>protected</PhaseType>
                <Signalgroupid>6</Signalgroupid>
```

```
        <ToscoMvmnt>yes</ToscoMvmnt>
</SPATMovement>
<SPATMovement>
        <Movement>straight</Movement>
        <Lane>4</Lane>
        <LaneType>Vehicle</LaneType>
        <Phase>8</Phase>            <PhaseType>protected</PhaseType>
        <Signalgroupid>8</Signalgroupid>
        <ToscoMvmnt>no</ToscoMvmnt>
</SPATMovement>
<SPATMovement>
        <Movement>left</Movement>
        <Lane>4</Lane>
        <LaneType>Vehicle</LaneType>
        <Phase>8</Phase>
        <PhaseType>permitted</PhaseType>
        <Signalgroupid>3</Signalgroupid>
        <ToscoMvmnt>no</ToscoMvmnt>
</SPATMovement>
<SPATMovement>
        <Movement>left</Movement>
        <Lane>5</Lane>
        <LaneType>Vehicle</LaneType>
        <Phase>5</Phase>
        <PhaseType>protected</PhaseType>
        <Signalgroupid>5</Signalgroupid>
        <ToscoMvmnt>no</ToscoMvmnt>
</SPATMovement>
<SPATMovement>
        <Movement>left</Movement>
        <Lane>5</Lane>
        <LaneType>Vehicle</LaneType>
        <Phase>6</Phase>
        <PhaseType>permitted</PhaseType>
        <Signalgroupid>5</Signalgroupid>
        <ToscoMvmnt>no</ToscoMvmnt>
</SPATMovement>
<SPATMovement>
        <Movement>straight</Movement>
        <Lane>6</Lane>
        <LaneType>Vehicle</LaneType>
        <Phase>2</Phase>
        <PhaseType>protected</PhaseType>
        <Signalgroupid>2</Signalgroupid>
        <ToscoMvmnt>yes</ToscoMvmnt>
</SPATMovement>
<SPATMovement>
        <Movement>straight</Movement>
        <Lane>7</Lane>
        <LaneType>Vehicle</LaneType>
        <Phase>4</Phase>
        <PhaseType>protected</PhaseType>
```

```
        <Signalgroupid>4</Signalgroupid>
        <ToscoMvmnt>no</ToscoMvmnt>
</SPATMovement>
<SPATMovement>
        <Movement>left</Movement>
        <Lane>7</Lane>
        <LaneType>Vehicle</LaneType>
        <Phase>4</Phase>
        <PhaseType>permitted</PhaseType>
        <Signalgroupid>7</Signalgroupid>
        <ToscoMvmnt>no</ToscoMvmnt>
</SPATMovement>
</PhasetoLaneMovementMapping>
```

APPENDIX B. Byte-Map Structure of the SPaT Data from the Traffic Signal Controller

byte 0: DynObj13 response byte (0xcd)	
byte 1: number of phase/overlap blocks below (16)	
bytes 2-14:	
0x01 (phase#)	*(1 byte)*
VehMinTimeToChange.1	*(2 bytes)*
VehMaxTimeToChange.1	*(2 bytes)*
PedMinTimeToChange.1	*(2 bytes)*
PedMaxTimeToChange.1	*(2 bytes)*
OvlpMinTimeToChange.1	*(2 bytes)*
OvlpMaxTimeToChange.1	*(2 bytes)*
...	
< repeat for each phase and overlap – bytes 15-196 >	
...	
bytes 197-209:	
0x10 (phase#)	*(1 byte)*
VehMinTimeToChange.16	*(2 bytes)*
VehMaxTimeToChange.16	*(2 bytes)*
PedMinTimeToChange.16	*(2 bytes)*
PedMaxTimeToChange .16	*(2 bytes)*
OvlpMinTimeToChange .16	*(2 bytes)*
OvlpMaxTimeToChange .16	*(2 bytes)*
bytes 210-215:	
PhaseStatusReds	*(2 bytes bit-mapped for phases 1-16)*
PhaseStatusYellows	*(2 bytes bit-mapped for phases 1-16)*
PhaseStatusGreens	*(2 bytes bit-mapped for phases 1-16)*
bytes 216-221:	
PhaseStatusDontWalks	*(2 bytes bit-mapped for phases 1-16)*
PhaseStatusPedClears	*(2 bytes bit-mapped for phases 1-16)*
PhaseStatusWalks	*(2 bytes bit-mapped for phases 1-16)*
bytes 222-227:	
OverlapStatusReds	*(2 bytes bit-mapped for overlaps 1-16)*
OverlapStatusYellows	*(2 bytes bit-mapped for overlaps 1-16)*
OverlapStatusGreens	*(2 bytes bit-mapped for overlaps 1-16)*
bytes 228-229:	
FlashingOutputPhaseStatus	*(2 bytes bit-mapped for phases 1-16)*
bytes 230-231:	
FlashingOutputOverlapStatus	*(2 bytes bit-mapped for overlaps 1-16)*
byte 232:	
IntersectionStatus (1 byte)	*(bit-coded byte)*

Byte 233:	
TimebaseAscActionStatus (1 byte)	*(current action plan)*
byte 234:	
DiscontinuousChangeFlag (1 byte)	*(upper 5 bits are msg version #2, 0b00010XXX)*
byte 235:	
MessageSequenceCounter (1 byte)	*(lower byte of up-time deciseconds)*
Byte 236-238:	
SystemSeconds (3 byte)	*(sys-clock seconds in day 0-84600)*
Byte 239-240:	
SystemMilliSeconds (2 byte)	*(sys-clock milliseconds 0-999)*
Byte 241-242:	
PedestrianDirectCallStatus (2 byte)	*(bit-mapped phases 1-16)*
Byte 243-244:	
PedestrianLatchedCallStatus (2 byte)	*(bit-mapped phases 1-16)*

Source: DeVoe, D. *SPAT MIB Support Document*. Econolite. July 23, 2012.

APPENDIX C. SPaT Message Profile

This appendix profiles the variables of the SPaT message. The SPaT message contains the standard J2735-2016 data elements with a regional extension to communicate the green window information. All of these data elements must be included in the SPaT message in order for the vehicle to perform TOSCo functionality.

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
Intersections	IntersectionStateList	1	32	Sequence of IntersectionState	Sets of SPaT data (one per intersection).
— IntersectionState	IntersectionState	-	-	-	To convey all the SPaT information for a single intersection. Both current and future data can be sent.
—— id	IntersectionReferenceID	-	-	-	A globally unique value set, consisting of a regionID and intersection ID assignment
——— id	IntersectionID	0	65535	0-255 for testing purposes	Unique ID of intersection. Random number. It has to be ensured that the same ID is not used by neighboring intersections to avoid ambiguity for matching between SPaT and MAP messages.

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
—— revision	MsgCount	0	127	-	Shall be incremented for every SPaT generated with updated content with respect to the last SPaT (e.g., SPaT will have the same revision within a current green phase).
—— status	IntersectionStatusObject	-	-	Bit String (Size (16)) • (5) is used for fixedTimeOperation • (6) is used for traffic dependent operation (actuated mode)	General status of the controller (s).
—— states	MovementList	1	255	-	Sequence of MovementState
———MovementState	MovementState	-	-	-	To convey every active movement in a given intersection so that vehicles, when combined with certain map information, can determine the state of the signal phases.
——— signalGroup	SignalGroupID	0	255	• 0 when not available/known	The *signalGroupID* is used to indicate the lane connections that

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
				- **255 used for permanent green movement state**	are signalized by the same traffic light. If multiple lanes have to obey the same traffic light, the same *signalGroupID* shall be allocated to multiple lanes.
———state-time-speed	MovementEventList	1	16	Sequence of MovementEvent	Consists of sets of movement data with SignalPhaseState, TimeChangeDetails, and AdvisorySpeeds (optional).
——— MovementEvent	MovementEvent	-	-	-	Contains details about a single movement. It is used by the movement state to convey one of possible of movements (typically occurring over a sequence of times) for a SignalGroupID.
———— eventState	MovementPhaseState	-	-	**-- unavailable (0)** -- This state is used for unknown or error. **-- dark (1)** -- The signal head is dark (unlit). **-- Reds (enum 2,3)**	Provides the overall current state of the movement (in many cases a signal state), including its core phase state and an indication of whether this state is permissive or protected.

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
				Stop-Then-Proceed (**2**), -- Often called 'flashing red' in US -- Driver Action: -- Stop vehicle at stop bar. -- Do not proceed unless it is safe. Stop-And-Remain (**3**), -- e.g., called 'red light' in US -- Driver Action: -- Stop vehicle at stop bar. -- Do not proceed. **-- Greens (enum 5,6)** Permissive-Movement-Allowed (**5**), -- Often called 'permissive green' in US -- Driver Action: -- Proceed with caution, -- must yield to all conflicting traffic. -- Conflicting traffic may be present. -- in the intersection conflict area protected-Movement-Allowed (**6**), -- Often called 'protected	

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
				green' in US. -- Driver Action: -- Proceed **-- Yellows / Ambers (enum 7,8)** Permissive-clearance (**7**), -- Often called 'permissive yellow' in US -- Driver Action: -- Prepare to stop. -- Proceed if unable to stop. -- Clear Intersection. -- Conflicting traffic may be present -- in the intersection conflict area Protected-clearance (**8**), -- Often called 'protected yellow' in US -- Driver Action: -- Prepare to stop. -- Proceed if unable to stop, -- in indicated direction (to connected lane) -- Clear Intersection.	
———— timing	TimeChangeDetails	-	-	-	Timing Data for signal provided from the top of the hour.

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
———— minEndTime	TimeMark	0	36001	• The values 35991…35999 are used when a leap second occurs. • The value 36000 is used to indicate time >3600 seconds. • 36001 is to be used when value undefined or unknown.	Expected shortest end time of a phase; a moment in UTC-based time when a signal phase is predicted to change, with a precision of 100 ms.
———— maxEndTime					•
——— maneuverAssistList	ManeuverAssistList	1	4	-	The maneuverAssistList shall be used on the MovementState level. Do not confuse with maneuverAssistList on IntersectionStateLevel!
———— maneuverAssist	ConnectionManeuverAssist	1	16	-	-
———— connectionID	LaneConnectionID	0	255		This connectionID refers to the connection of a particular lane in the MAP message and matches the data in this maneuverAssist DF to the particular ingress

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
					lane. Matches to the *connectionID* in the *Connection* DF of the Map (! not the connectingLane!)
———— queueLength	ZoneLength	0	10000	0 = no queue 1 = 1 meter	The queue length of the ingress lane to which this connectionID refers to.
———— regional	SIGNAL-APPROACH-SUPPLEMENTAL-INFORMATION-REGION.SignalPhaseTimingMessage-regExt				The TOSCo specific regional extension to provide green window information.
————— regionID	DSRC.RegionId	0	255	130 shall be used for TOSCo green window information.	The regional ID that shall be used to identify the extension container. Shall be set to 130.
————— greenWindowInformation	GreenWindowInformation	-	-	-	Provides green window information.
—————— greenWindowStart	TimeMark	0	36001	• The values 35991...35999 are used when a leap second occurs. • The value 36000 is used to indicate time >3600 seconds.	Start of the green window.

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
				• 36001 is to be used when value undefined or unknown.	
———————— greenWindowEnd	TimeMark	0	36001	• The values 35991...35999 are used when a leap second occurs. • The value 36000 is used to indicate time >3600 seconds. • 36001 is to be used when value undefined or unknown.	End of the green window.
—— maneuverAssistList	maneuverAssistList	1	16	Sequence of ConnectonManeuverAssist	The maneuverAssistList on the intersectionState level shall not be used!

APPENDIX D. MAP Message Profile

This appendix shows the MAP message profile used by TOSCo. These data elements are consistent with SAE J2735-2016. An asterisk (*) indicates those optional data fields that TOSCo requires. TOSCo also requires that the entire intersection fits within a single MAP message.

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
msgIssueRevision	MsgCount	0	127	-	Shall be set to the same (random) value between 0 and 127 if the entire map data fits in one message. Value shall persist for an intersection. Used by Denso Map matching to indicate that consecutive messages have the same content.
intersections	IntersectionGeometryList	1	32	-	List of intersection geometries. A single geometry shall be used per intersection. This DF may be added multiple times in case more than one intersection is described in the MAP message.
— intersectionGeometry	IntersectionGeometry	-	-	-	The description of the intersection geometry. This is one element of the intersections DF list.
—— id	IntersectionReferenceID	-	-	-	

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
——— region	RoadRegulatorID				
——— id	IntersectionId	0	65535	0 - 255 for testing purposes	Unique ID of intersection. Assigned unique number. It has to be ensured that the same ID is not used by neighboring or other intersections to avoid ambiguity for matching between SPaT and MAP messages.
—— revision	MsgCount	0	127		Shall be set to the same random number for this project.
—— refPoint	Position3D	-	-	-	Position (Lat / Long) of the reference position of the intersection. This can be any arbitrary point in the vicinity of the intersection as long as all initial lane offsets can be described. The required level of precision for the reference point shall be within 5 cm.
——— lat	Latitude	-900000000	900000001	900000001 for unavailable	Latitude of reference point in WGS84 reference frame in 1/10 micro degree.
——— long	Longitude	-1799999999	1800000001	1800000001 for unavailable	Longitude of reference point in WGS84 reference frame in 1/10 micro degree.
—— (speedLimits)	SpeedLimitList	1	9	-	List of global speed limits. Node-level speed limits overwrites intersection-level speed limit.

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
——— type	SpeedLimitType			vehicleMaxSpeed	enum vehicleMaxSpeed set to indicate global speed limit that shall apply to all subsequent lanes in the laneSet. This global speed limit for the intersection can be superseded by speed limits on a lane level (provided as part of the GenericLane).
——— speed	Velocity	0	8191	8191: speed unavailable	This is the global speed limit value that applies to all subsequent GenericLanes, unless superseded by a lane-specific speed limit.
—— laneSet	LaneList	1	255	-	Lane descriptions for this intersection geometry.
——— genericLane	GenericLane	-	-	-	Generic description of lane node points for a lane. This element is added to the *laneSet* list for every lane at the current intersection.
———— laneID	LaneID	0	255	0: laneID is unknown 255: reserved for future use	Unique ID within this intersection. The ID may be re-used for other intersection IDs but may not be repeated for this intersectionGeometry.
———— laneAttributes	LaneAttributes	-	-	-	List of global attributes that apply to the entire lane.
————— directionalUse	LaneDirection	-	-	0: ingressPath 1: egressPath	If set to 0, this indicates that this GenericLane is leading towards the intersection (ingress). If set to 1, this indicates that this GenericLane is

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
					leading away from the intersection (egressing).
——— sharedWith	LaneSharing	-	-	-	Indicates to the road users that this lane is shared with (equal rights of sharing the lane, e.g., cyclists and vehicles).
——— laneType	LaneTypeAttributes	-	-	-	Shall be set to *LaneAttributes-Vehicle* for TOSCo, indicating bit string value 0: *isVehicleRevocableLane.*
——— nodeList	NodeSetXY	2	63	-	List of nodePoints with offsets provided in a Cartesian Coordinate System (x-Axis towards east). The first nodePoint is interpreted as the offset from the referencePosition. All following nodePoints are offsets from the previous point in m. For ingress lanes, the first nodePoint in the list is also interpreted as the location of the stop bar. For egress lanes, the first nodePoint in the list is the beginning of the lane leading away from the intersection. **The minimum length for ingress lanes shall be 300 m or maximum length not overlapping with surrounding intersections.**

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
——— attributes	NodeAttributeSetXY	-	-	-	Attributes for a specific nodePoint
———— data	LaneDataAttributeList	-	-	-	Attributes that require a specific value, such as providing a speed limit. Multiple laneDataAttributes can be added to this list for a nodePoint.
————— laneDataAttribute	LaneDataAttribute	-	-	-	Attribute that belongs to this nodePoint for the laneDataAtribute.
—————— speedLimits	RegulatorySpeedLimits	-	-	-	List of speedLimits for this nodePoint. **In TOSCo, the provided speedLimit persists for all following nodePoints until another speed limit is provided for a different nodePoint of the current lane (i.e., if a speed limit shall apply for the entire lane, it shall be provided for the first node point). This speedLimit supersedes the global speed limit of the intersection.**
——————— type	SpeedLimitType	-	-	-	enum vehicleMaxSpeed set to indicate speed limit that shall apply to all subsequent node points of the current lane in the in the nodeList. This speed limit supersedes the global intersection speed limits, if provided.
——————— speed	Velocity	0	8191	8191: speed unavailable	This is the lane-specific speed limit value that applies to all subsequent

Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
					node points for this GenericLane until a subsequent node point defines a different speed limit value.
——— connectsTo*	ConnectsToList	-	-	-	Contains a list of connection between ingress and egress lanes. These connections indicate allowed connections from one ingress to (multiple) egress lanes. Multiple connections are added to this list per lane for each egress lane that an ingress lane connects to.
———— connectingLane	ConnectingLane	-	-	-	List of connecting lanes (i.e., the following lane that can be reached from a specific lane).
————— lane	LaneID	0	255	0: laneID is unknown 255: reserved for future use	ID of lane this particular GenericLane is connected to.
———— signalGroup*	SignalGroupID	0	255	0: signalGroupID is unknown 255: permanent green movement phase	
———— connectionID*	LaneConnectionID	0	255	Shall be set to the same ID as the laneID of the	This indicates the ID of this particular connection. It is used to link dynamic maneuverAssist

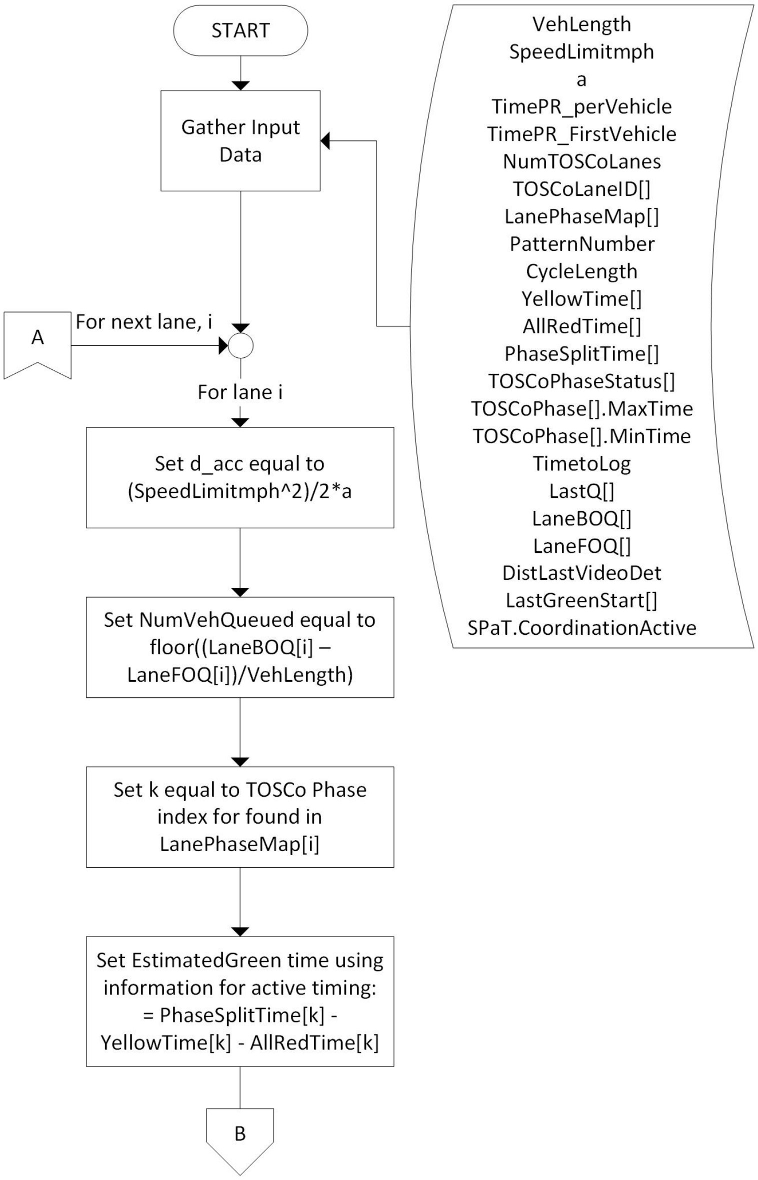
Variable	Type (J2735 ASN.1)	Min	Max	Special Values	Description and use within TOSCo
				current GenericLane in the laneSet.	information from the SPaT such as queue length and green window information.

APPENDIX E. Verified Marker Points on FM 1960 Deployment Intersections

This appendix shows the verified latitude and longitudinal points of the reference locations stored in the MAP messages after verification.

Intersection ID	Intersection Name	Latitude	Longitude
101	Briarcreek	30.024173808	-95.393097561
102	Treaschwig	30.021697148	-95.387456351
103	Woodcreek	30.020917720	-95.385052398
104	Aldine Westfield	30.019955398	-95.379744565
105	Rayford	30.016911428	-95.362636805
106	Richey	30.016090237	-95.357854059
107	Farrell	30.015155632	-95.352509812
108	Cypresswood	30.011237723	-95.330484511
109	Foxwood Forest	30.006658897	-95.318336991
110	Lee	30.004069002	-95.308797790
111	Kenswick	30.005103413	-95.297096500
112	Deerbrook Park	30.005160021	-95.290945220
113	Park at Humble	30.004739976	-95.286817684
114	Townsen Blvd	30.005209256	-95.282567043

APPENDIX F. Detailed Flowchart of Green Window Predictor Algorithm



Variable Definition

d_acc: Distance needed for a vehicle to accelerate to the speed limit

a: assumed acceleration for a vehicle (typically 10 fps^2)

RemainingRed: red time remaining for phase in question based on minEndTime from SPaT

RemainingRedMax: red time remaining for phase in question based on maxEndTime from SPaT

RemainingGreen: green time remaining for phase in question

PerceptionReactionTime: Time for vehicles in queue to react to green indication

TimePR_FirstVehicle: assumed time for the first vehicle in a queue to perceive that the signal is green and react by accelerating

TimePR_perVehicle: assumed time for manually driven vehicles to perceive that the lead vehicle in a queue has started to accelerate and react by accelerating

TimeRemaining: time for a vehicle to reach the stop bar after finished accelerating to speed limit

TimeAccelerate: time while vehicle is accelerating to speed limit

TNow: current UTC time

Figure 59. Green Window Estimation Process (Part I)

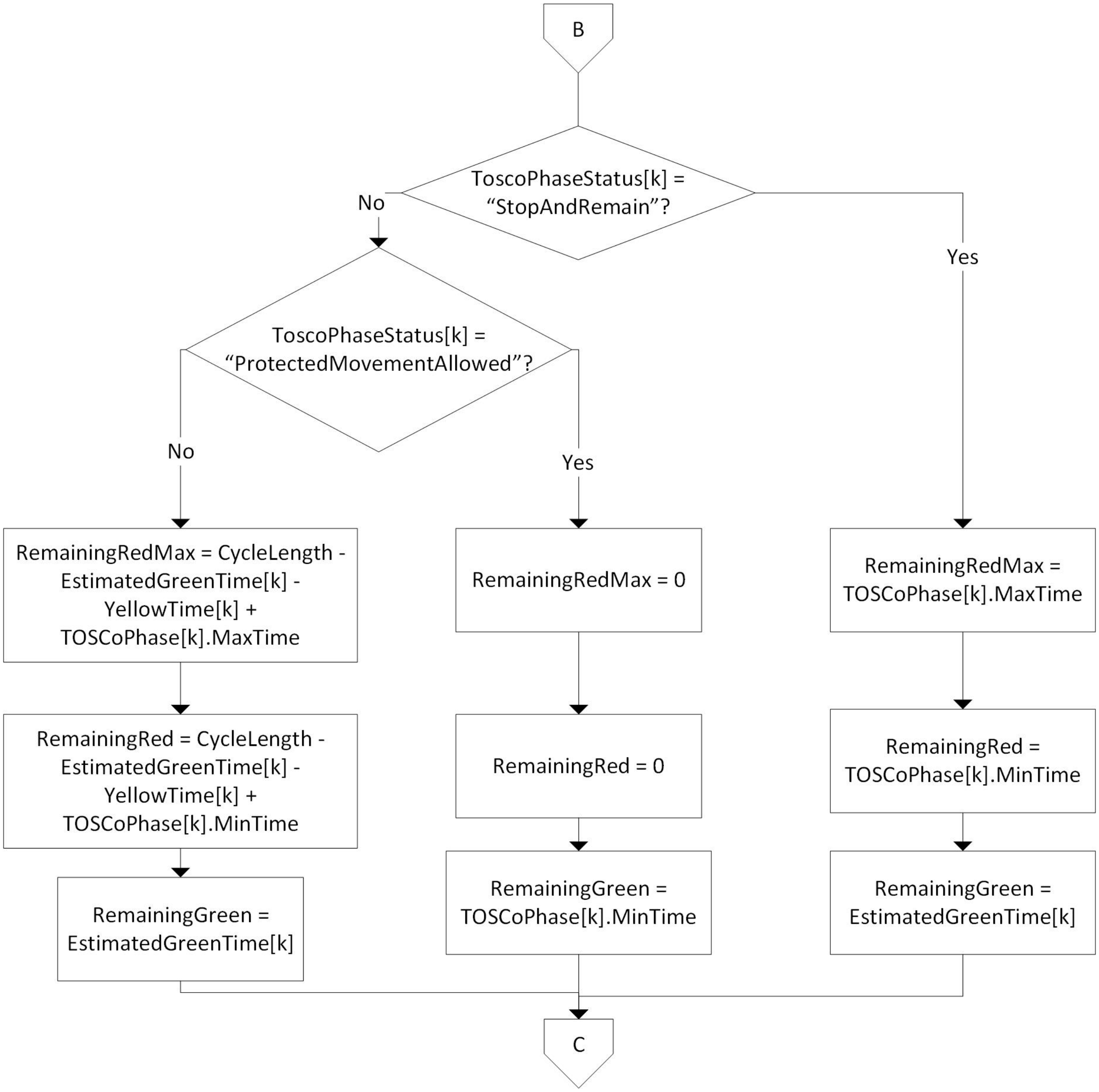


Figure 60. Green Window Estimation Process (Part II)

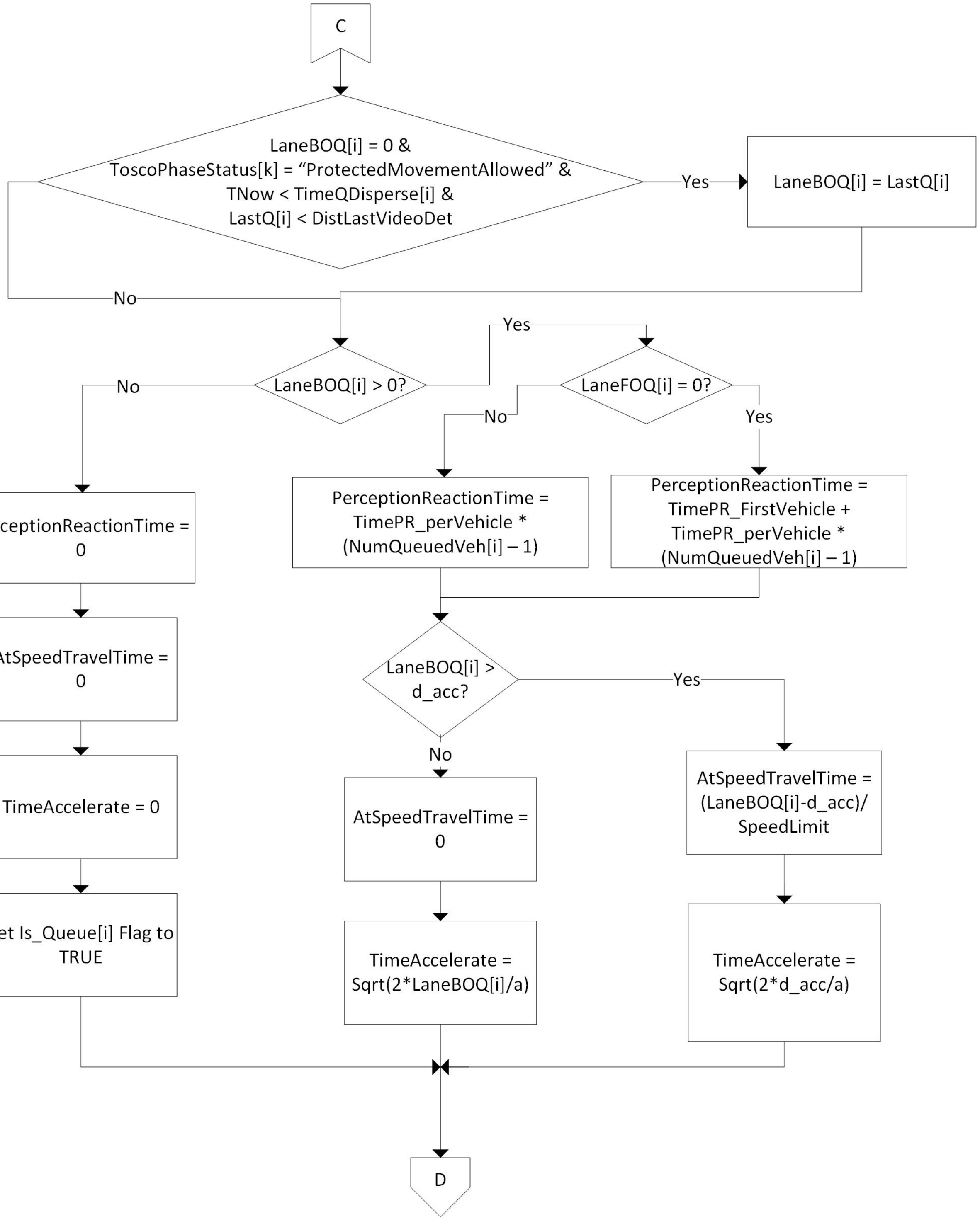


Figure 61. Green Window Estimation Process (Part III)

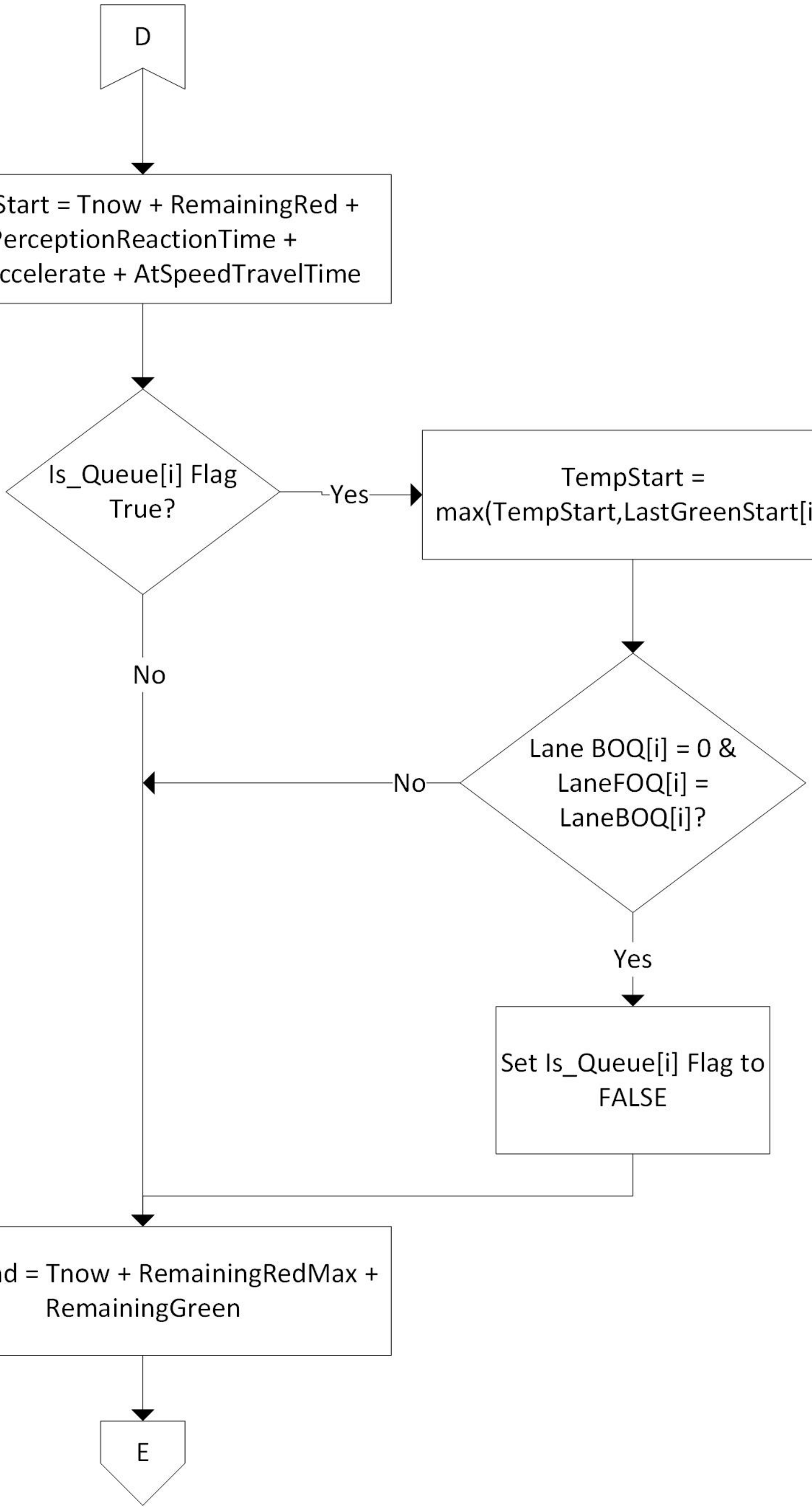


Figure 62. Green Window Estimation Process (Part IV)

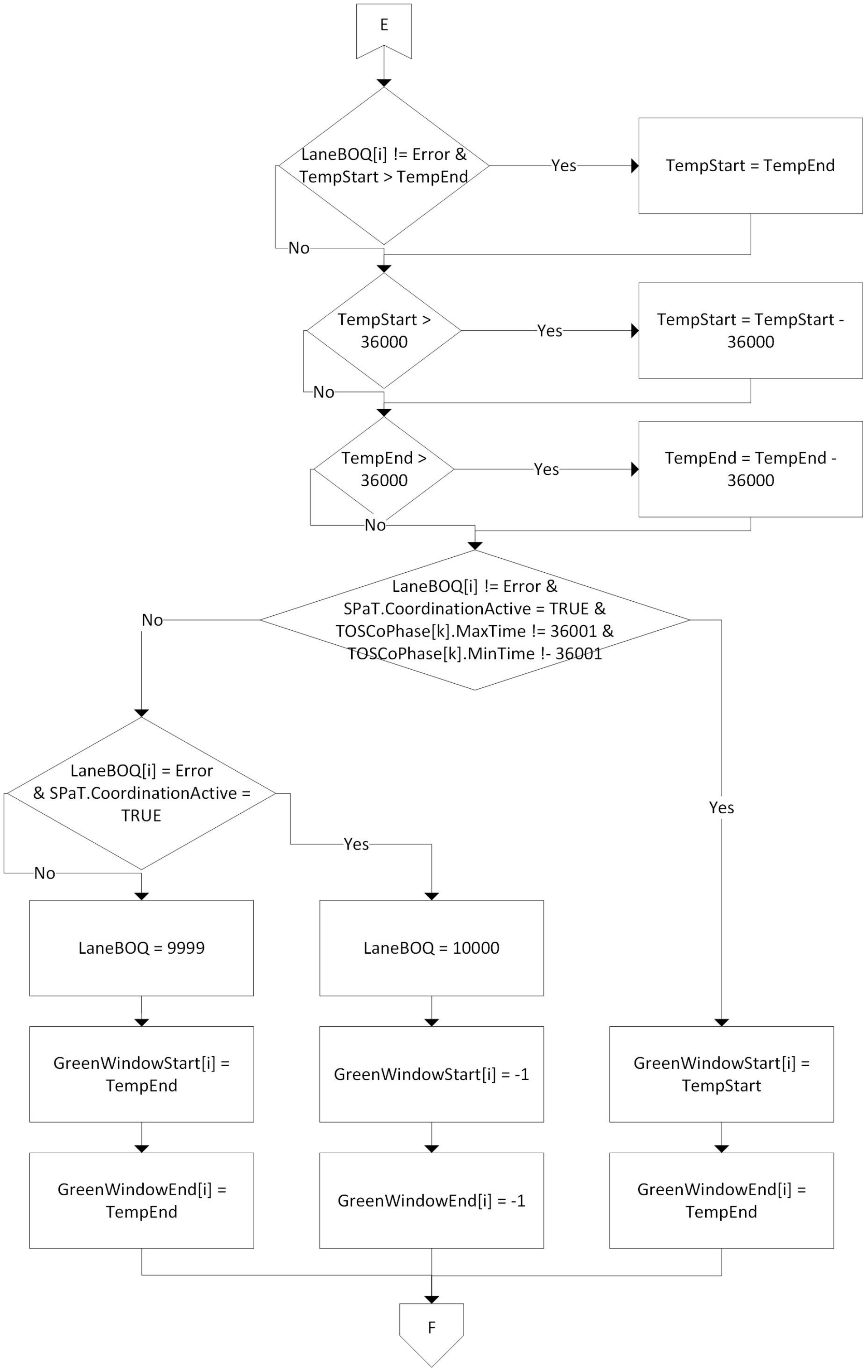


Figure 63. Green Window Estimation Process (Part V)

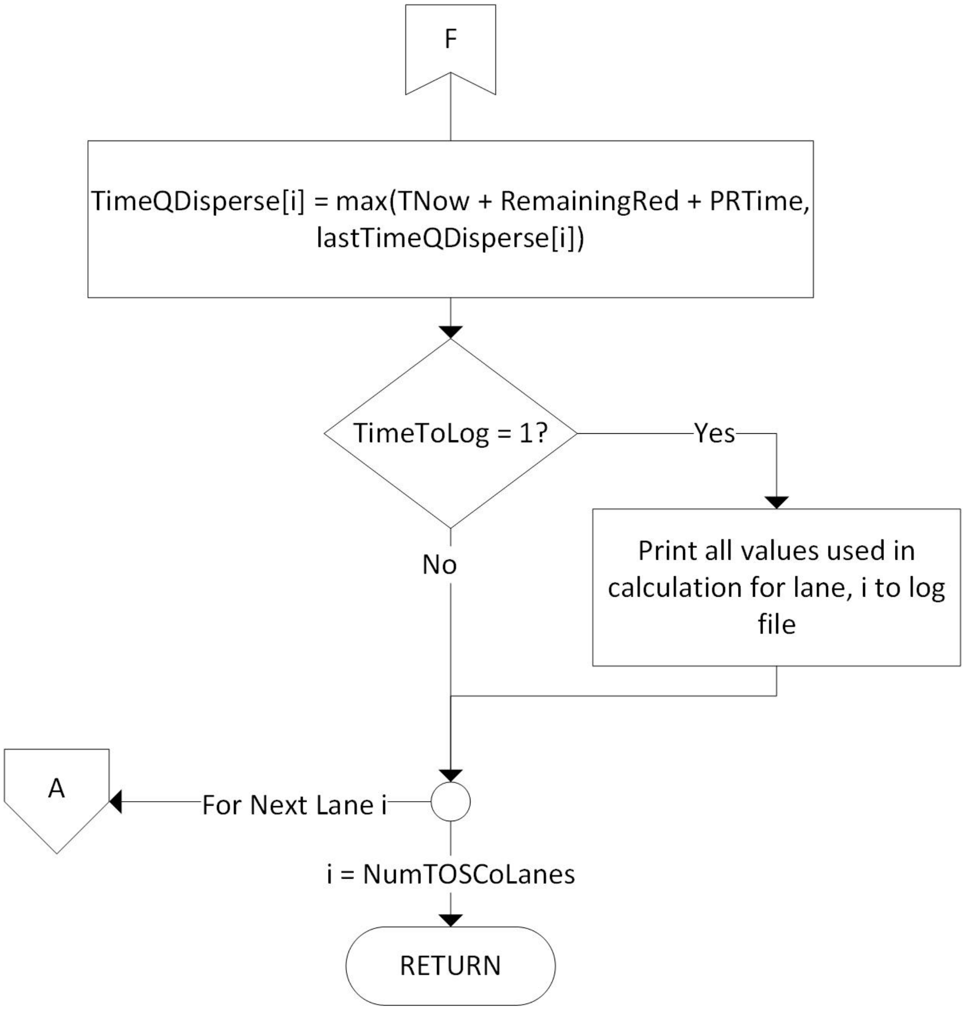


Figure 64. Green Window Estimation Process (Part VI)

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