V2I Queue Advisory/Warning Applications: Concept and Design

HIGH-LEVEL DESIGN

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TABLE OF CONTENTS

INTRODUCTION

The United States Department of Transportation (USDOT) Intelligent Transportation Systems Joint Program Office (ITS JPO) Vehicle-Infrastructure Program has been researching connected transportation systems. Part of this effort has focused on researching and prototyping applications to optimize the safety and mobility performance of the transportation network by integrating infrastructure-based technologies with connected systems.

This document is one of the deliverables prepared for the Vehicle-to-Infrastructure (V2I) Queue Advisory/Warning (QA/QW) Applications: Concept and Design project. The project is a collaborative effort between the USDOT, and the Connected Vehicle Pooled Fund Study (CV PFS) entitled *Program to Support the Development and Deployment of Connected Vehicle Applications*. This CV PFS was created by a group of state, local, and international transportation agencies, and the Federal Highway Administration (FHWA), with the Virginia Department of Transportation (VDOT) serving as the lead agency. The University of Virginia Center for Transportation Studies (UVA CTS) supports VDOT on the pooled fund study, serving as the technical and administrative lead for the effort, and manages all the projects on behalf of the CV PFS and the USDOT.

The purpose of this document is to provide details on the high-level design of a V2I QA/QW application and its key subsystems. The application utilizes typical technologies and systems deployed by infrastructure owner operators (IOOs)—traffic sensor data and queue and congestion information provided by third-party data providers, married with data provided by vehicles equipped with connected vehicle (CV) technologies—to detect the potential formation of queues on a per lane basis, and provide relevant information about the queue. IOOs can use this information to provide alerts and warnings to motorists approaching the back of a queue through both traditional traveler information devices (e.g., dynamic message signs) and advanced information dissemination devices (e.g., in-vehicle displays).

This document builds on the following documents developed previously in this project:

- *V2I Queue Advisory/Warning Applications: Concept and Design - Concept of Operations*[1].
- *V2I Queue Advisory/Warning Applications: Concept and Design –System Requirements*[2].

Readers are encouraged to consult these documents first to gain a high-level understanding of how the system is expected to operate and function.

The V2I QA/QW system also incorporates the concept of Event Driven Configurable Messaging (EDCM) developed by the Crash Avoidance Metrics Partners, LLC (CAMP) Vehicle-to-Infrastructure 2 (V2I-2) Consortium. The EDCM concept was developed as part of a project sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH6114H0002. Readers can find detailed description of the EDCM concept in a document

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[1] *V2I Queue Advisory/Warning Applications: Concept and Design - Concept of Operations*. Texas A&M Transportation Institute. Texas A&M University System, College Station, TX. December 2020.

[2] *V2I Queue Advisory/Warning Applications: Concept and Design* - System Requirements. Texas A&M Transportation Institute. Texas A&M University System, College Station, TX. December 2020.

titled *Event-Driven Configurable Messaging (EDCM) Queue Advisory & Queue Warning (QA/QW) System and In-Vehicle Application Requirements*[3].

V2I QA/QW SYSTEM OVERVIEW

This section provides a systems level overview of the proposed V2I QA/QW architecture, its key system components, and the interfaces between them.

The intended operational environment for the proposed V2I QA/QW system is a high-speed, high-volume freeway. The V2I QA/QW system may be implemented using short- or long-range communication. Figure 1 shows high-level system architecture for the scenario which uses dedicated short-range communication (DSRC) or cellular vehicle to everything (C-V2X) communication between CVs and the central system, the Traffic Management Entity (TME), where the queue warning application is running.

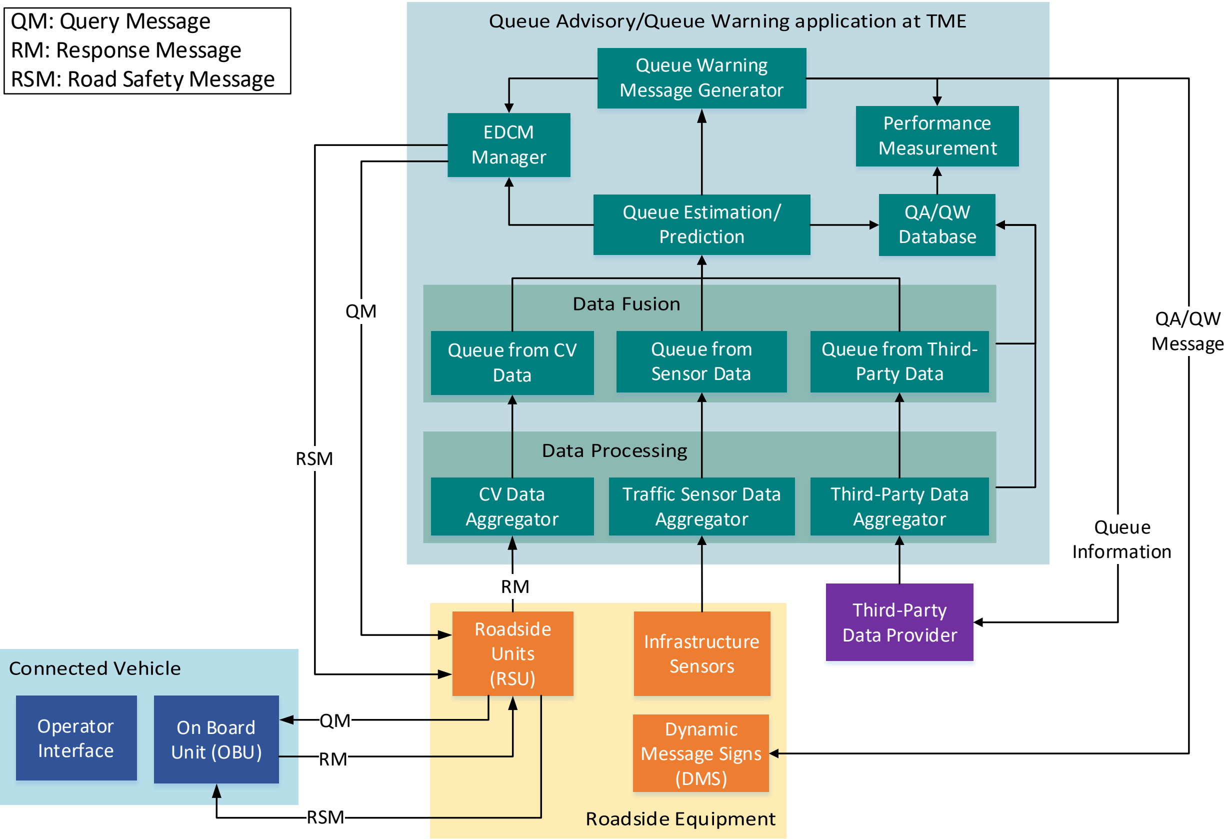

Figure 1. System Diagram of V2I QA/QW Application Using Short-Range Communication.

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[3] *Event-Driven Configurable Messaging (EDCM) Queue Advisory & Queue Warning (QA/QW) System and In-Vehicle Applications Requirements*. Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure 2 (V2I-2) Consortium. June 2020. [DRAFT].

The main system components include: 1) roadside equipment, 2) CVs, 3) third-party data providers, and 4) TME where data processing, data fusion, queue estimation/prediction, and queue warning actions take place. TME may reside at a Traffic Management Center (TMC), on a cloud-based server, or at a roadside facility.

The proposed QA/QW system uses the EDCM framework developed by CAMP. The EDCM framework operates within the larger CV environment, which includes supporting communication infrastructure, security protocols and privacy management techniques required for EDCM to function. EDCM provides a dynamically reconfigurable two-way messaging scheme between EDCM-equipped CVs and IOOs operating the roadways through a traffic management entity (TME). The TME is responsible for identifying events and road conditions that potentially impede the safety and mobility of the traveling public. EDCM enables a TME to request information from CVs in specified areas regarding current conditions at varying rates and times of day. In response, EDCM-equipped CVs provide vehicle dynamics and status data using a flexible messaging schema. The V2I QA/QW system combines this information with data from other sources to detect queues and queue characteristics.

Figure 2 shows the same system architecture with long-range cellular (e.g., 4G or 5G) communication between the TME and CVs. Figure 1 and Figure 2 also indicate the data and information flow between the key elements and system components. It is also possible to deploy a hybrid system using both short- and long-range communications.

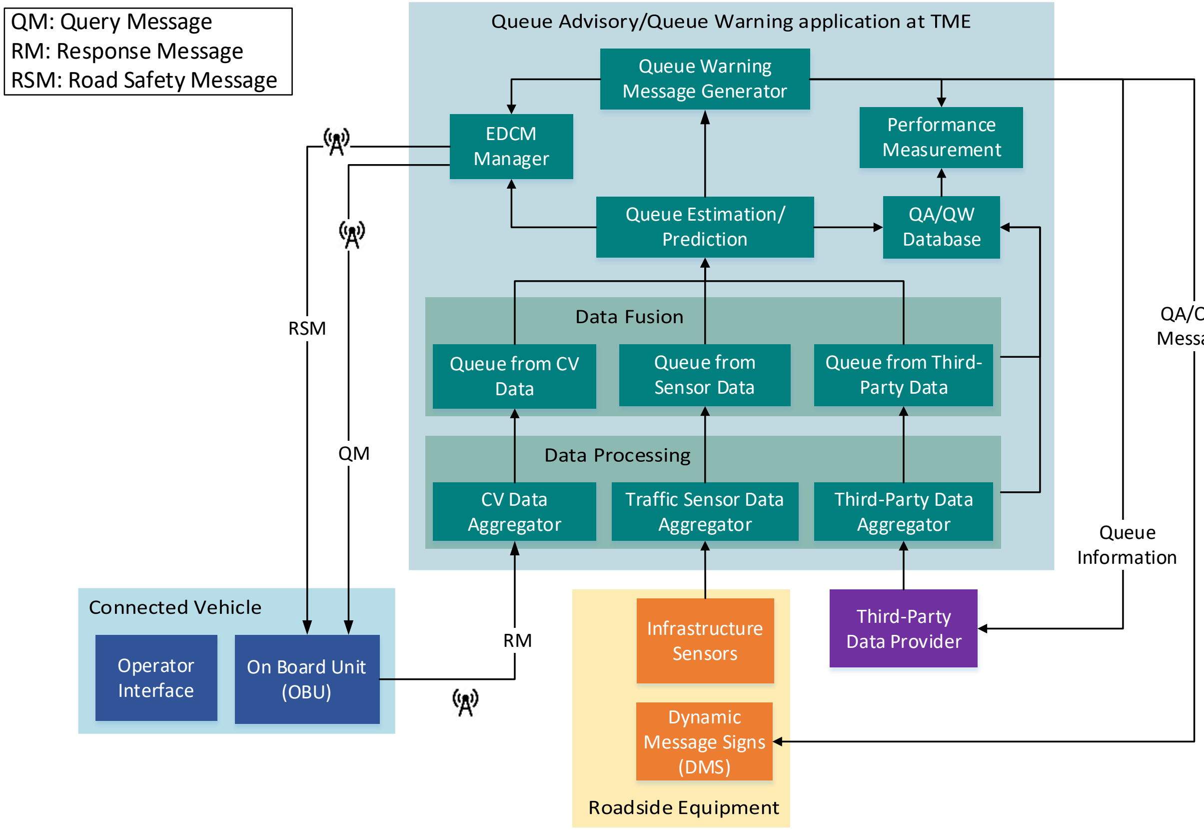


Figure 2. System Diagram of V2I QA/QW Application Using Long-Range Communication.

The system will use input from multiple data sources, process and combine data from all available sources to detect queues and warn operators of approaching vehicles about any downstream queues or slow traffic. As illustrated in Figure 1 and Figure 2, the key processes include data collection, data processing, queue estimation, queue warning, and performance measurement. Accordingly, the V2I QA/QW architecture includes the following subsystems:

- Data Collection Subsystem
- Data Processing Subsystem
- Queue Detection Subsystem
- Queue Warning Subsystem
- Performance Measurement Subsystem

The following sections of the document provide high-level description of these subsystems using the system architecture shown in Figure 1.

DATA COLLECTION SUBSYSTEM

Figure 3 highlights the components of data collection subsystem and associated data flows.

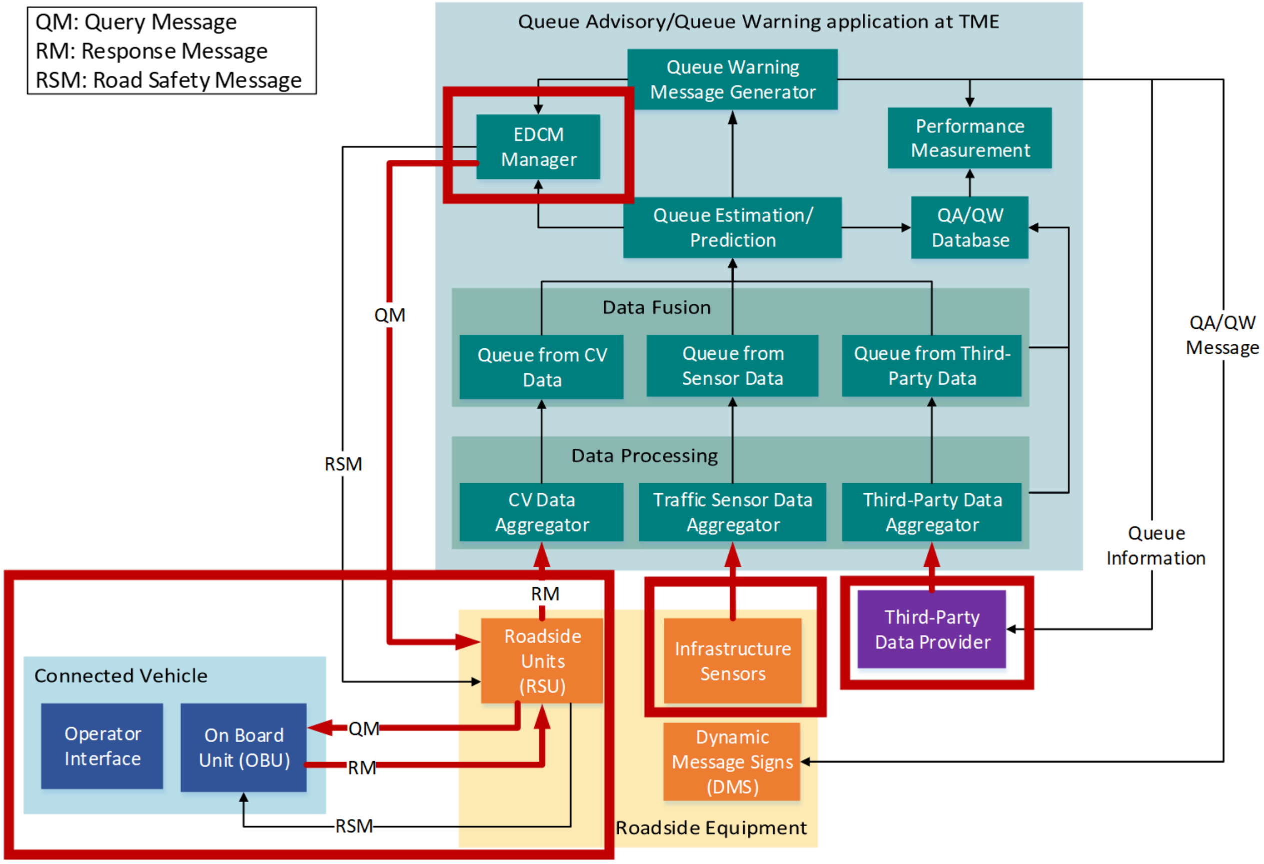


Figure 3. Data Collection Subsystem.

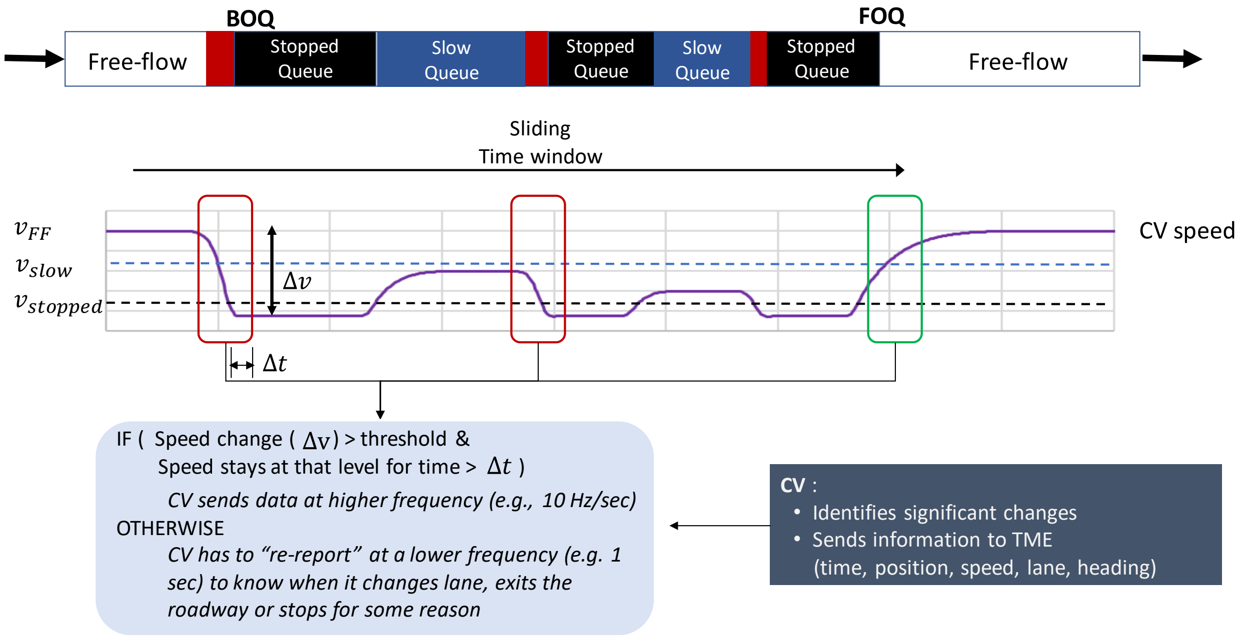
The data collection subsystem is responsible for getting available data from CVs, infrastructure sensors and third-party data providers. The following subsections provide details on the data collection process from these three sources.

CV DATA

The TME utilizes the EDCM manager to formulate and send Query Messages (QM) requesting data needed for queue detection. A QM can specify a geofenced area of interest, direction of travel, the type of vehicle dynamics data needed, trigger criteria for data collection frequency, and length of pre-sampling time interval. Each CV in the specified geofence then collects the requested data and sends it back to the TME in a Response Message (RM). The geofenced area is initially defined based on expected queue conditions along the roadway segment targeted by the V2I QA/QW application. Its boundaries can be dynamically changed if needed (e.g., if a queue is about to extend beyond the current geofenced area).

To enable a CV to provide its correct position (location and lane of travel), TME broadcasts roadway map which each CV downloads before entering the geofenced region applicable to the V2I QA/QW system. A GPS correction mechanism is also deployed to facilitate collection of accurate CV data.

EDCM makes it possible to dynamically adjust the frequency and content of two-way data exchange between a CV and a TME depending on changes in traffic conditions. Figure 4 illustrates an example where the frequency of CV data changes depending on the rate of speed change of the CV.



IF (Speed change (Δv) > threshold &
Speed stays at that level for time > Δt)
CV sends data at higher frequency (e.g., 10 Hz/sec)
OTHERWISE
CV has to "re-report" at a lower frequency (e.g. 1 sec) to know when it changes lane, exits the roadway or stops for some reason

CV :
- Identifies significant changes
- Sends information to TME (time, position, speed, lane, heading)

Figure 4. Queue Detection Using CV Data of Different Frequencies.

A sliding time window (pre-sampling interval) is used to check if the speed change is significant and sustained. If that is the case, high-frequency CV data is sent to the TME to identify the locations of BOQ, FOQ, and additional significant slowdowns within the queue. Otherwise, CV provides data at a lower frequency, which is sufficient to determine if a vehicle changes lane or exits the roadway.

Hardware and Software Requirements

Communication between TME and CVs

In the short-range communication scenario, roadside units (RSUs) provide the interface for two-way communication between the TME and the on-board unit (OBU) of the CV via DSRC or C-V2X equipment. The long-range communication scenario uses cellular communication between TME and CVs. These are described in more details below.

EDCM-Enabled CV

An EDCM-enabled CV is equipped with appropriate hardware and application software to support wireless information exchange with the TME. Two-way communication for data exchange is an integral part of the EDCM System for short-range and/or long-range communication. As shown in Figure 5, a typical in-vehicle system to enable EDCM consists of:

- Short-range communication device – DSRC or C-V2X PC5 interface,
- Long-range communication device – cellular (e.g., 4G, 5G),
- Global Positioning System (GPS),
- On-Board Unit (OBU) – computing platform for processing queries and application,
- Controller Area Network (CAN) for vehicle data, and
- Driver Vehicle Interface (DVI) system.

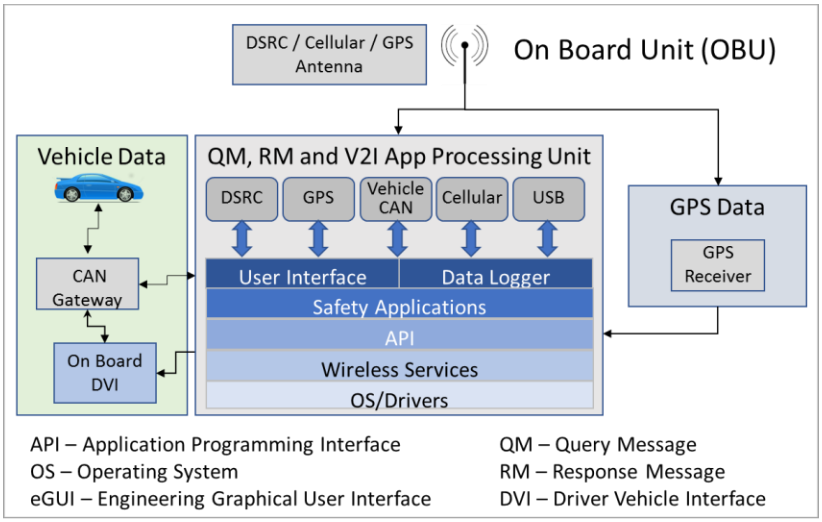


Figure 5. EDCM-Enabled Vehicle System (Source: CAMP).

Communication with CV

This subsection describes the currently available communication options between TME and EDCM-enabled vehicles. Based on the EDCM communication schema, the TME may communicate with EDCM-enabled CVs using different communications methods as shown in Figure 6. Short-range and/or long-range communication may be utilized to broadcast QMs and receive RMs as available and appropriate.

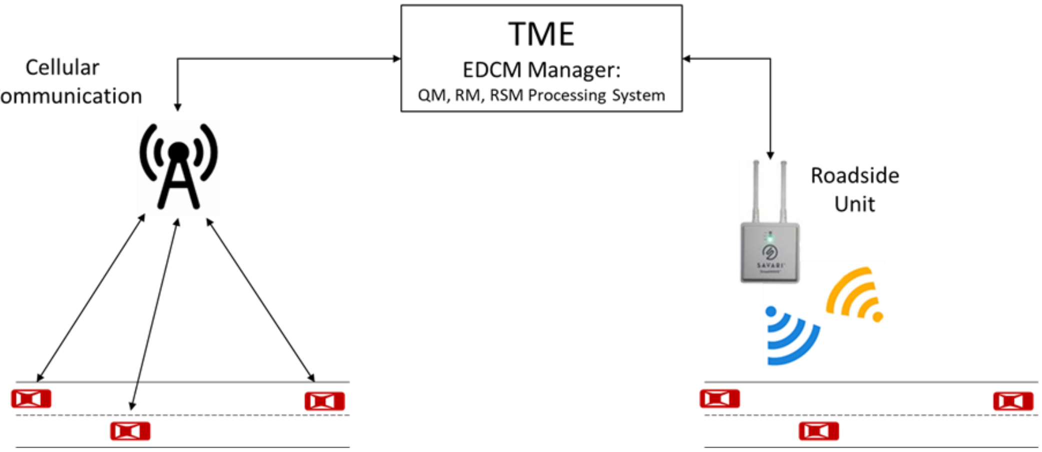


Figure 6. Communication between TME and CV.

Long-Range: Direct Communication between TME and CV

The EDCM manager in the TME may establish direct communication with the EDCM-enabled vehicle over a long-range using cellular communication for information exchange. When using this mode of communication, the TME may experience the delays/latencies in information exchange due to latency introduced by the cellular communication system, which could be up to a few seconds.

Short-Range: Direct Communication between RSU and CV

In this communication schema, information exchange between the TME and CV involves two steps. The TME communicates QMs to Roadside Units (RSUs) along a road segment using backhaul communications. The RSU then uses low latency short-range wireless communication to broadcast QMs to EDCM-enabled vehicles within its transmission range. In this mode, the TME may experience delay/latency due to the following reasons:

- Depending upon the type of communication backhaul between the TME and the RSU, the latency can be introduced in communicating the QM to the RSU including information processing in RSU.
- Similarly, latency can be introduced in forwarding the received RM from RSU to TME.

In addition to latency associated with communication, there can be in-vehicle processing delay. This delay can be caused by vehicle system processing priority for more safety critical system such as ABS or a traction control system and available resources to process QM from TME.

INFRASTRUCTURE SENSOR DATA

Existing infrastructure-based sensors fall into three categories depending on the type of vehicle data they collect and report. These categories are spot data, segment data, and vehicle trajectory data. The following subsections describe data collection systems in these three categories, with a focus on systems that can measure vehicular speeds.

Spot Data

Traditional freeway data collection systems fall into this category and may use any of several available technologies including, but not limited to inductive loops-, video-, and radar-based sensors. Figure 7 illustrates the traditional inductive loop-based data collection system, which uses time-stamped “On” and “Off" signals (contact closure information) from 6’×6’ individual loop to obtain desired data. Vehicle count is the number of “On” or “Off” signals over the desired interval (i.e., 20-second). Loop occupancy associated with an instance is the duration (time of “Off” signal minus Time of “On” signal) a loop is occupied. Sum of individual occupancies is divided by count to obtain average occupancy for the specified interval. Actuation times from pair of loops in a lane (called a speed trap, usually installed 10 feet apart) are processed to calculate speed and length of each detected vehicle.

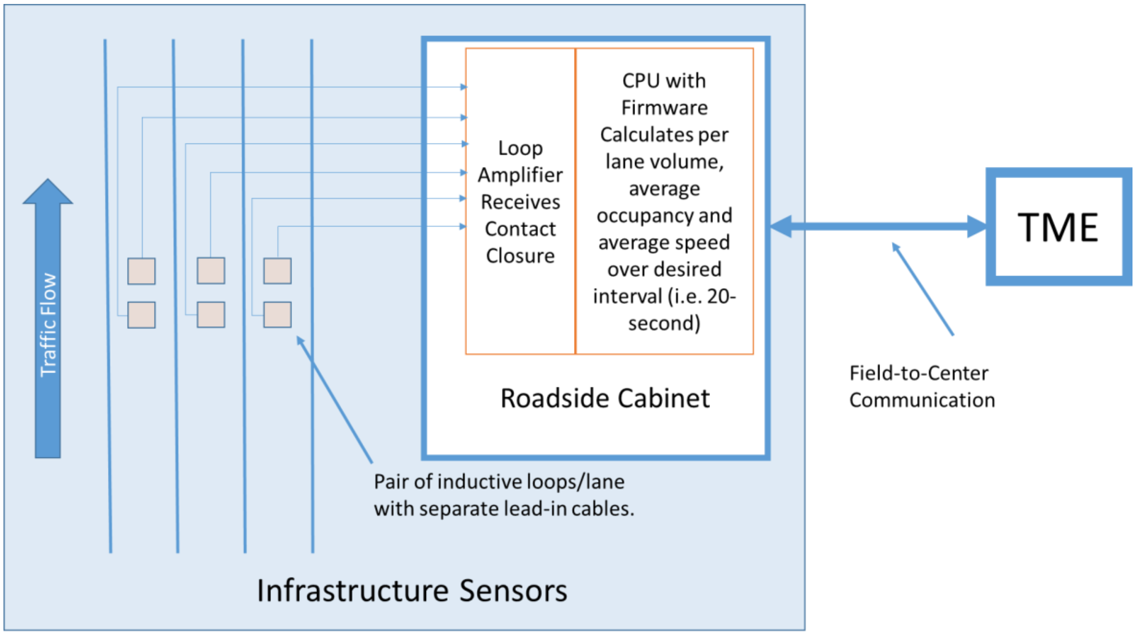


Figure 7. Inductive Loop Based Detection.

As illustrated in Figure 8 and Figure 9, the two other most common data collection technologies in this category are video- and radar-based sensors.

As shown in Figure 8, video-based systems emulate the loop-based system by using virtual loops created using a video-processing unit, which provides contact closure information for further processing. Detection data from virtual loops is processed in the same way as real loops to produce counts, speeds, and occupancies. At the data collection location, the camera can be installed on a roadside pole or on a structure directly above the lanes. Optimal camera placement (height and angle) is important to prevent data inaccuracies due to occlusion.

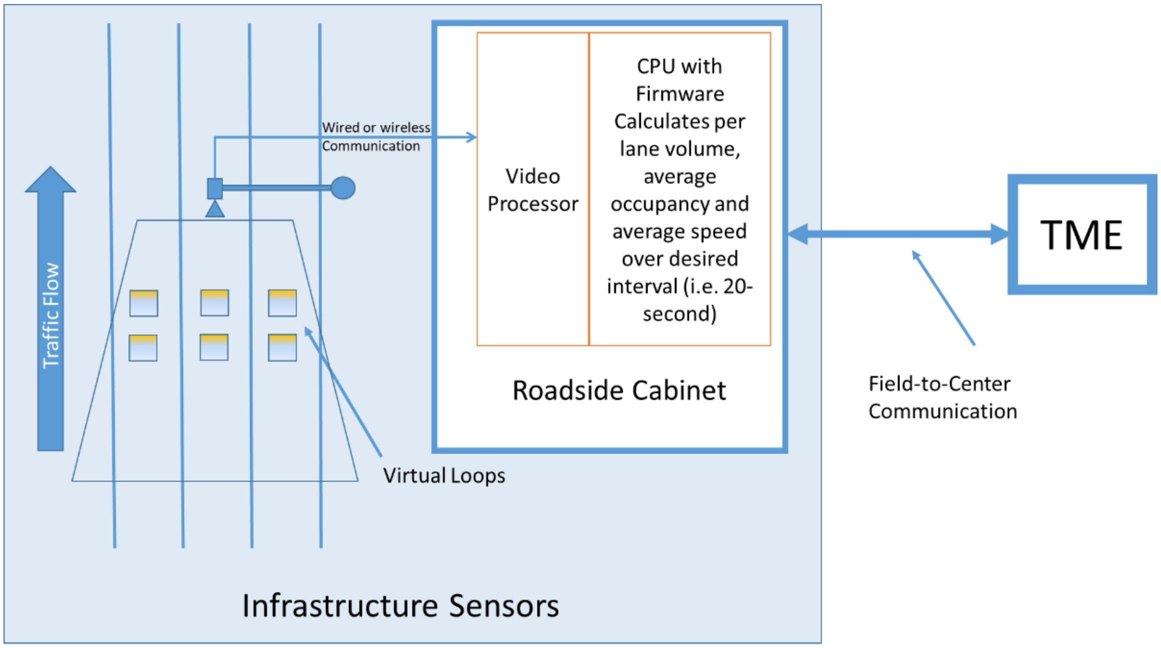


Figure 8. Video Camera Based Detection.

As shown in Figure 9, a radar-based spot data collection system uses a sensor installed on a roadside pole. The sensor uses a unique pair of radar beams (a speed trap) projected across each traffic lane to detect vehicles and calculate their speeds and lengths on a per lane basis. The most common brand of this type of sensors uses central software that receives sensor data transmitted through messages. Using an optional hardware device installed in the roadside cabinet, this data collection system can convert sensor messages into contact closure output as in a loop-based system.

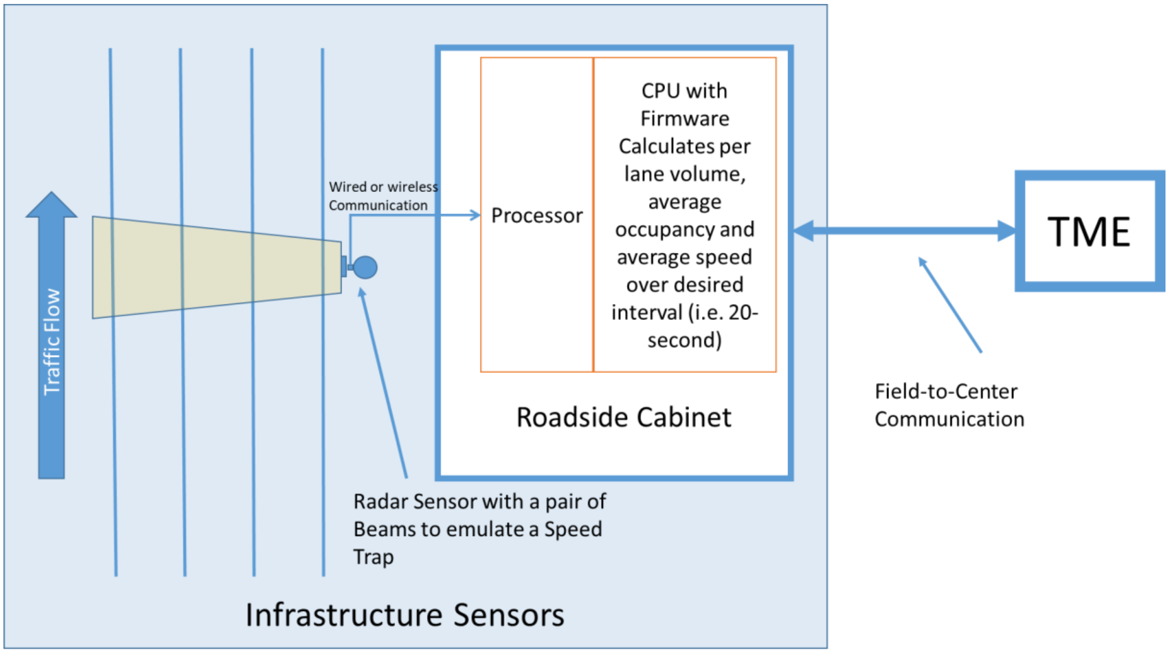


Figure 9. Radar-Based Detection.

Segment Data

Infrastructure-based segment data collection systems use a series of in-field Bluetooth (BT)-based devices along a roadway. Each roadside unit reads MAC addresses of passing-by mobile BT devices (vehicle-based or hand-held devices of occupants) and sends this information to the cloud or central location, typically via a cellular modem. The central computer software uses an address-matching algorithm to identify vehicles detected at adjacent stations and uses respective detection times and known distance between field devices to calculate the segment travel time for these vehicles. Travel times of vehicles are averaged to obtain average segment travel times over a predetermined interval. Travel times of vehicles are averaged to obtain average segment travel times over a predetermined interval. Many vendors provide BT-based segment data as a per-site monthly service, which includes cost of hardware installation/maintenance, communication, and data processing. An agency may choose to install its own system. This data is like third-party probe data. Figure 10 illustrates this system.

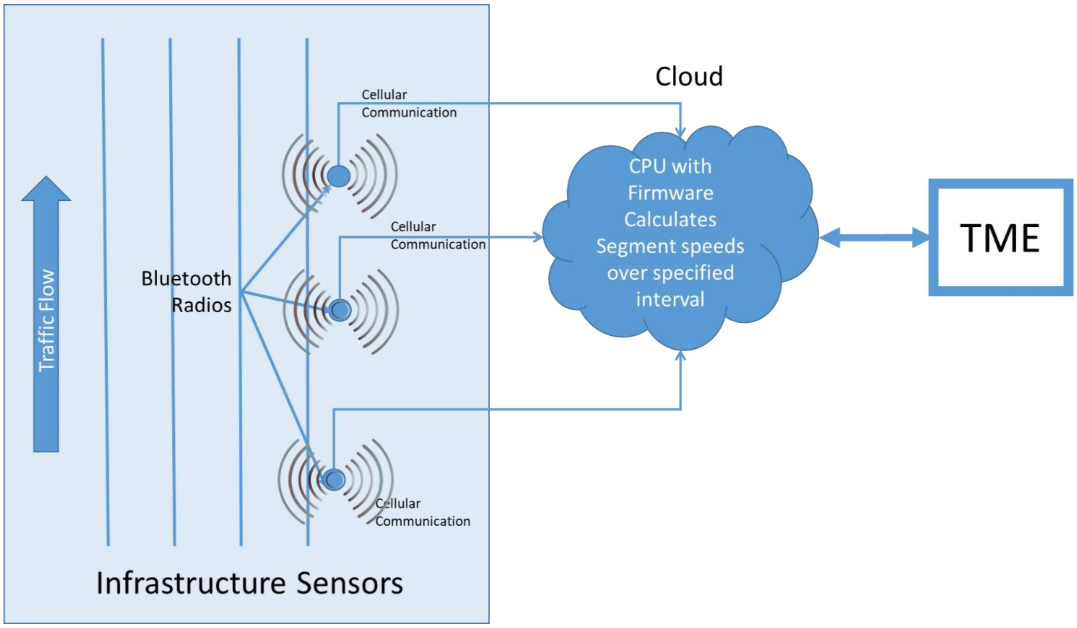


Figure 10. Infrastructure-based Segment Data Collection System.

Vehicle Trajectory Data

In recent years, several companies have developed radar-based traffic sensors capable of providing vehicle trajectory data. One of these companies markets two versions of a sensor which provide CV type vehicle trajectory data on a lane-by-lane basis. For each tracked vehicle, this data includes:

- X-position,
- Y-position,
- Absolute velocity,
- Heading angle,
- Length, and
- Object ID.

The higher-end version of this sensor can track up to 256 objects (passenger cars, trucks, bicycles, and pedestrians) in up to 12 lanes. It reports a list of all tracked objects in every measurement cycle, typically 50 or 100ms. This version of radar sensor can detect cars and trucks as far as 853 feet and 984 feet away from the sensor, respectively. The minimum range is 5 feet. The sensor can be installed either on a roadside pole or on a mast-arm or gantry. Figure 11 illustrates this type of system. Sensor-based vehicle trajectory data can be used in conjunction with spot data collection to improve accuracy of queue detection especially where market penetration of connected vehicles is low.

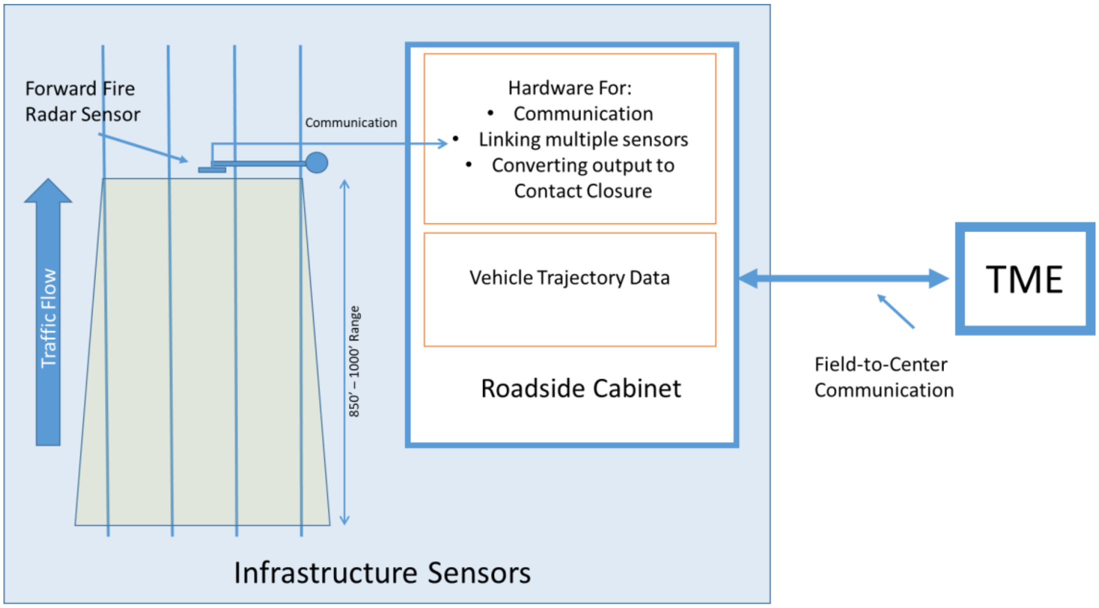


Figure 11. Infrastructure-Based Vehicle Trajectory Data Collection System.

Hardware and Software Requirements

Regardless of the type of desired lane-level data (i.e., spot speeds or vehicle trajectories), the following components will be needed at each sensor location:

- Selected sensor installed as per specification:
  - If inductive loops, properly buried in ground at right spacing to create the speed trap and with separate lead-in wire.
  - If radar or camera, mounted on a structure at proper height and facing the right direction. Installation of these sensors may require additional mounting hardware (i.e., pole, mast arm, brackets) and cables to transmit raw data to roadside cabinet.
- Roadside cabinet with:
  - Appropriate hardware and firmware that is configurable from TME to provide desired data from the sensor.
  - Any additional hardware and firmware needed to aggregate raw sensor data to interval-based data.
  - CPU and utility (hardware/firmware) for local queue detection (Optional).
  - Communication hardware (i.e., Ethernet or cellular modem) for field-to-center communication of data from roadside cabinet to TME.

Depending on specific sensor, the data may be stored locally or pushed to vendor's utility located at the TME. For collecting optional segment-level data, two or more roadside cabinets will be required to house:

- Bluetooth (BT) radio,
- BT Antenna,
- CPU with firmware that uploads collected travel times to the cloud or central location,
- Cellular modem, and
- A pole if one is not available.

Additionally, a solar-based power source may need to be installed for each sensor cabinet that does not have ready access to a wired power source. A solar power system consists of:

- Cabinet with appropriate hardware (pole, brackets, etc.),
- Solar Panel,
- Electrical components,
- Batteries, and
- Cables.

THIRD-PARTY DATA

Third-party traffic data providers offer crowdsourced and probe vehicle data over a large portion of the roadway network. A major benefit of crowd-sourced traffic data is that they can be collected without the need for the deployment and operation of physical infrastructure. Third-party traffic data has broad coverage over the road network, especially on limited access roadways. There are several third-party providers such as WAZE, INRIX, HERE and TomTom. They can provide information on incidents, road construction, congestion information, segment travel times and speeds. Below are examples of two types of third-party data.

Incident and Congestion Alerts

WAZE provides crowd-sourced incident and congestion data through the WAZE for Cities (formerly Connected Citizens) Program. There is no cost, but agencies are expected to share their own incident and/or work zone data feed with WAZE. Data are available to partners through a localized XML or JSON data feed that is updated every two minutes. Users can define a data collection polygon to delineate the area where data must be collected. The Waze data feed contains the following data types:

- Traffic incidents (e.g., jams, accidents, hazards, construction, stopped vehicles, objects on road).
- System-generated traffic jams: location and speed data associated with slowdowns below average speed for a particular segment for the time of day/day of week identified by analyzing user GPS signals.

Each alert gets reliability and confidence scores (based on a scale of 0 to 10). Higher scores indicate more reliable reports. Waze generates traffic jam information by processing the following data-sources:

- GPS location-points sent from users’ phones (users who drive while using the WAZE app) and calculations of the actual speed vs. average speed (on specific timeslot) and free-flow speed (maximum speed measured on the road-segment).
- User-generated reports shared by WAZE users who encounter traffic-jams. These appear as regular alerts.

Segment Data

Several third-party data providers make available crowd-sourced or probe-based segment speed and/or travel time data that can be useful for QA/QW applications, especially when segment lengths are sufficiently short (one mile or shorter), and latency of data is relatively low. INRIX, for example, is one such provider. In urban areas, which are the primary targets for the V2I QA/QW applications, INRIX XD segments are as short as 0.1 mile. INRIX data latency is estimated to be around four minutes, which includes 1-minute data averaging interval and approximately three minutes for data transmission and processing. INRIX data download service provides for querying available data and downloading the desired data using their application programming interface (API). This is a subscription-based service that requires authentication. INRIX also uses segment speed information to identify potential queues and alert upstream drivers. This alert service is dubbed as Dangerous Slowdown (DSD). This application compares real-time speeds from consecutive upstream and downstream INRIX XD segments. A difference in segment speeds greater than some specified threshold (e.g., 45 mph) indicates a DSD at the connection point between the two segments. The acceptable range for speed differential threshold is from 15 to 50 mph.

One limitation of third-party segment data is the unavailability of lane-by-lane data. However, some third-party data providers are working to overcome this limitation.

DATA PROCESSING SUBSYSTEM

Figure 12 highlights the key components of data processing subsystem that includes the following:

- CV Data Aggregator,
- Traffic Sensor Data Aggregator, and
- Third-Party Data Aggregator.

These subsystem components are discussed in this section.

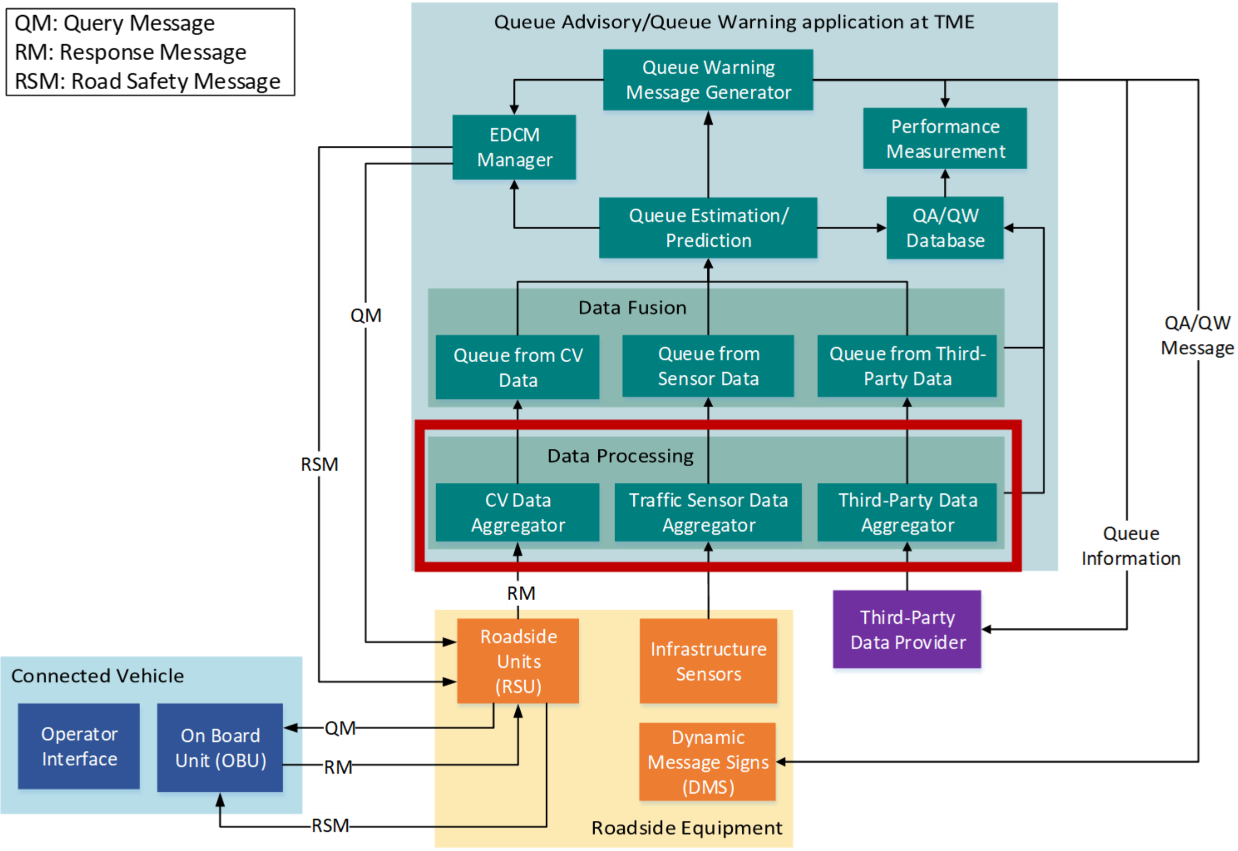


Figure 12. Data Processing Subsystem.

The data processing subsystem receives data from all three data sources and prepares it for use in the queue estimation process. CV data are received continually as provided by individual vehicles, sensor data are received every 20- or 30-seconds as per desired sensor configuration, and third-party segment (and any other data) are received in 1- to 3- minute intervals. Data sources may have significantly different latencies, which are accounted for in the data aggregation process.

CV DATA

CV data is received from EDCM-enabled vehicles as RM. The aggregator first transforms vehicle position data from GPS coordinates to mile-marker (MM)-based linear system which includes a longitudinal position and lane assignment for each vehicle. Determining a vehicle's lane requires that the availability of a lane-level digital map of the roadway segment. Other data included in the RM includes, vehicle ID, vehicle heading and its speeds over a predefined pre-sampling interval (e.g., past 10 seconds).

INFRASTRUCTURE SENSOR DATA

At a minimum, the data processing system receives (20- or 30-second) time-averaged lane-by-lane spot speed, volume, and occupancy data from all sensor stations. A configuration file is used to assemble the data in right order (e.g., upstream to downstream) for use in queue detection, which only uses speed information from adjacent stations. Volume and occupancy information is only used for error checking in data to identify any sensor or communication malfunctions. This process identifies missing values and outliers and records these occurrences in a data quality log. The processed data and error logs are stored in the QA/QW database for use in performance measurement (including identification of sensor or communication malfunctions) and historical data analysis and long-term predictions.

THIRD-PARTY DATA

The data processor uses vendor's application programming interface (API) to pull segment data for the specified region from their live (XML or JSON) data feed. If necessary, segment data are reordered in proper sequence (e.g., upstream to downstream). The process also converts geographical coordinates of segment boundaries to MM-based linear reference system. The system also keeps statistics on data latency.

QUEUE DETECTION SUBSYSTEM

Figure 13 highlights the key components of queue detection subsystem that include data fusion and queue estimation/prediction. These subsystem components are discussed in this section.

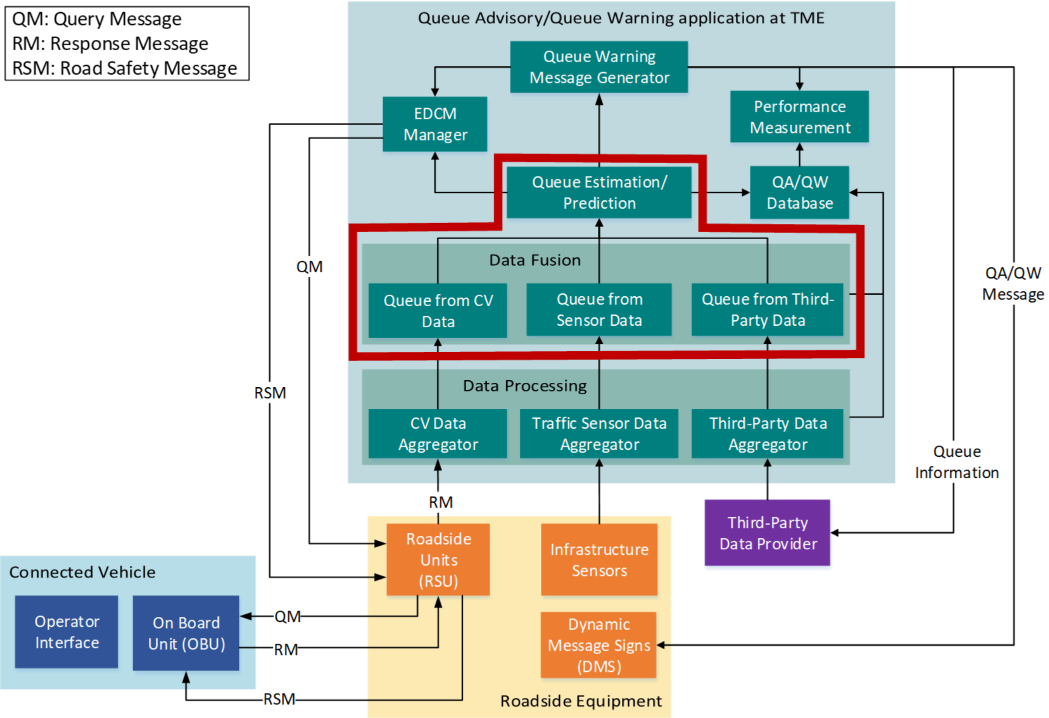


Figure 13. Queue Detection Subsystem.

DATA FUSION

There are several challenges in combining data from infrastructure sensors, CV and third party-data providers. Most challenges arise from the fact that data from these three sources have different spatial coverage, temporal resolutions, and latencies because of the way they are collected, aggregated, and transmitted. For instance:

- Traditional sensors provide average spot data (speed, volume, and occupancy), third party sources provide space mean speeds over predefined segments of varying lengths without lane-level detail, and CVs provide continual trajectory (position, heading, speed, etc.) data as they traverse through the roadway section of interest.
- Different sources have varying latencies and biases based on how data is collected and processed. CV data is continual but current market penetration of CVs is minimal. Sensor data has a minimum latency of 20 or 30 seconds depending on the aggregation level. Third party crowd-sourced or probe data latency ranges from 3 to 4 minutes.
- There are potential differences in clocks between various sources of data.
- Roadways often have partial overlapping data segments for different data-sources.
- Different data sources use different geographical referencing schemes.
- Sensor data may have errors because of malfunction or calibration issues.

Some of these challenges can be addressed relatively easily, for instance by:

- Converting geographical coordinates to a common linear referencing system as proposed here.
- Synching clocks to ensure that all sources use a common time base.
- Calibrating infrastructure-based sensors and incorporating quality assurance and quality control processes to filter out bad data.
- Proactively maintaining and calibrating infrastructure sensors.
- Incorporating processes to enable handling of missing data due to sensor or communication failure.

Other issues are much more difficult to address. These include different latencies and biases in data from the three sources. These challenges can be most effectively addressed by using the following two-step approach:

1. Estimate queue parameters (BOQ and FOQ) using available data from each data source separately. In any given time-step, estimated positions of BOQ and FOQ may be calculated by using:
    a. Current time-step data from the three sources, or
    b. Predicted values of BOQ, FOQ, and shockwave speeds determined in previous time steps.
2. Choose the best BOQ and FOQ estimates from the results of Step 1 calculations. The best estimates of these parameters are those that have the highest likelihood of accurately detecting the queues in each calculation time-step.

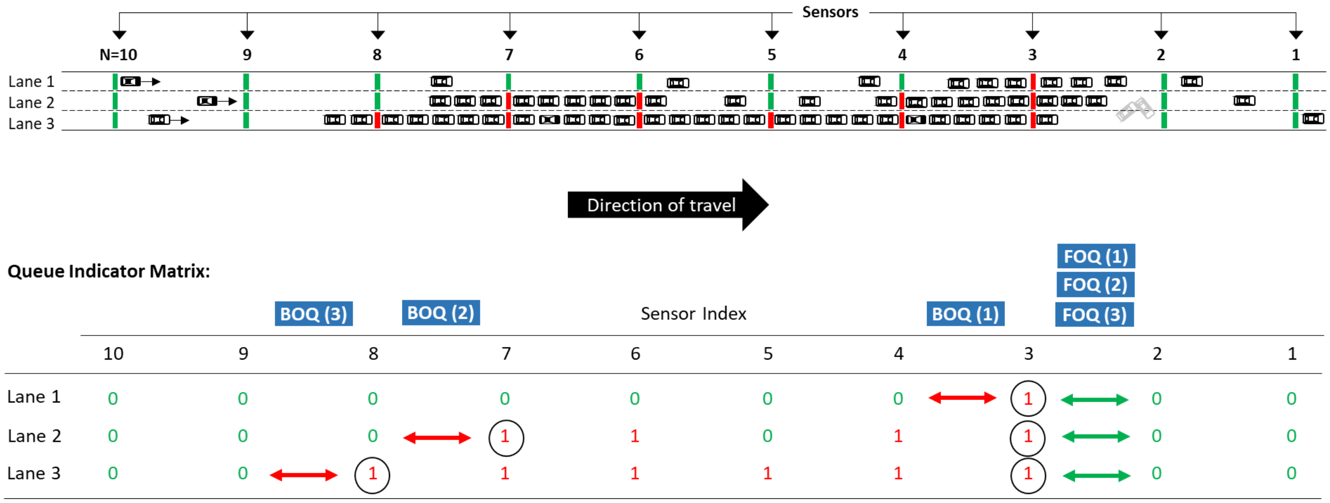
The configurable calculation time-step (e.g., 10 seconds) is also dictated by the time it takes to receive and process input data. Details of this simple and robust approach are described below.

Queue Estimation from Sensor Data

Estimation of BOQ and FOQ from infrastructure sensor data is illustrated in Figure 14. The top part of this figure shows a three-lane freeway segment with ten sensor stations (SS), which measure lane-by-lane speeds. An incident just upstream of SS #2 blocks the two right lanes (lanes 2 and 3) causing the formation of a queue propagating upstream. Figure 14 captures the time when the BOQ in lane 3 has extended beyond SS#8. Average speeds measured at individual sensors are compared to a pre-defined queue threshold (e.g., 15 mph) to determine if traffic flow at that location is queued or not. Red colored bars indicate sensors where traffic is queued. Green colored bars are used for sensors where the average speed is above the queue threshold. Figure 14 shows a situation with differing queue characteristics in the three lanes, as described below.

- Lane 1 has the shortest queue, which extends upstream of SS 3.
- In Lane 2, the BOQ is located upstream of SS 7. However, at this instant in time, average speeds of vehicles at SS 5 are above queue threshold. Thus, there are two distinct queues in this lane.
- In lane 3, the queue has reached upstream of SS 8.

For numerical processing, this information can be stored in a matrix (called queue indicator matrix here). The bottom part of Figure 14 shows the queue indicator matrix. In this matrix, rows represent lanes, and columns represent sensor stations. Cell values of 1 and 0 indicate queued and non-queues states, respectively. The matrix is depicting the current state of the roadway system shown in the top part of the figure. For queue warning purposes, BOQ in each lane is the most upstream position (cell) with a value of 1. The red lines with double arrowheads indicate that the actual queue at this time can be anywhere between this location and the next upstream sensor. The FOQ in each lane is the most downstream cell with a value of 1. The horizontal green lines with double arrowheads indicate that the actual FOQ position at this time can be anywhere between this location and the next downstream sensor. For algorithmic purposes, it is essential to record each time when a cell value changes from zero to one and one to zero. It is also essential to record which one of these changes occurred. These times would indicate when a queue has reached or cleared a SS location in each lane. This information can be combined with same information (times of change) from an adjacent upstream or downstream sensor to estimate shockwave speed. It should be noted that there will be calculation time steps with no change in detected traffic conditions.



	10	9	8	7	6	5	4	3	2	1
Lane 1	0	0	0	0	0	0	0	1	0	0
Lane 2	0	0	0	1	1	0	1	1	0	0
Lane 3	0	0	1	1	1	1	1	1	0	0

Figure 14. Queue Detection Using Infrastructure Sensor Data.

The flow chart shown in Figure 15 captures the above-described process for a single time-step for BOQ and FOQ estimation using infrastructure-sensor-based spot speeds. This logic consists of two nested loops. The outer loop steps through all lanes, while the inner loop steps through all detector stations for the current lane. It determines the queued state of each sensor and updates cell values of the queue indicator matrix. BOQ and FOQ for the current lane are updated when all calculations for the corresponding row are complete.

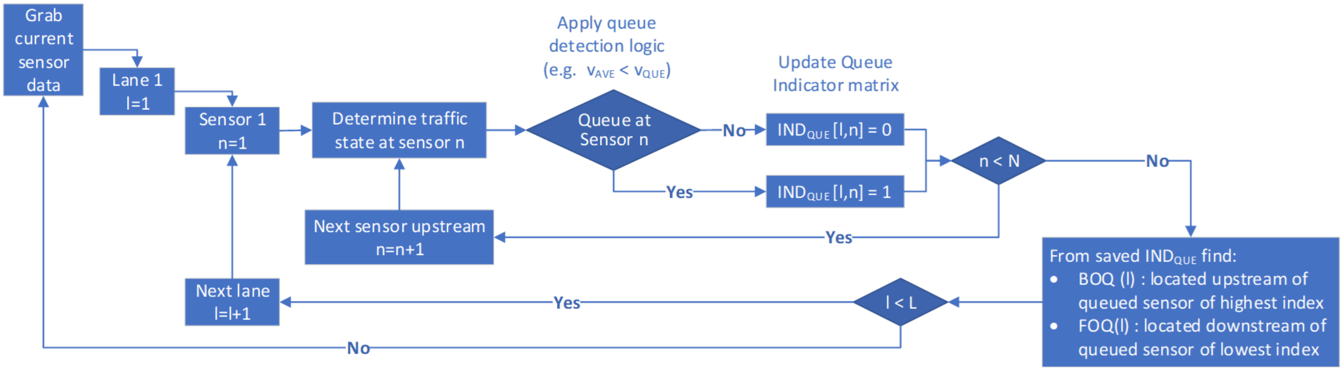


Figure 15. Flowchart for Queue Detection Algorithm Using Infrastructure Sensor Data.

Queue Estimation from Third-Party Data

Estimation of BOQ and FOQ using third-party data is illustrated in Figure 16. Here, there are eight third-party data segments. Vertical lines depict boundaries of these segments. Horizontal arrows above the roadway identify segment number and queued (arrow with red color) or non-queued (arrow with green color) status of each segment. The figure shows the same freeway and queueing conditions as in Figure 14. However, since segment data is based on travel times of a subset of vehicles on the roadway (i.e., probe vehicles detected by the third-party provider), which are averaged across all lanes, queue detection at lane-level is not possible, and it is less accurate than sensor-data-based queue detection. Furthermore, higher data latency of third-party data delays queue detection.

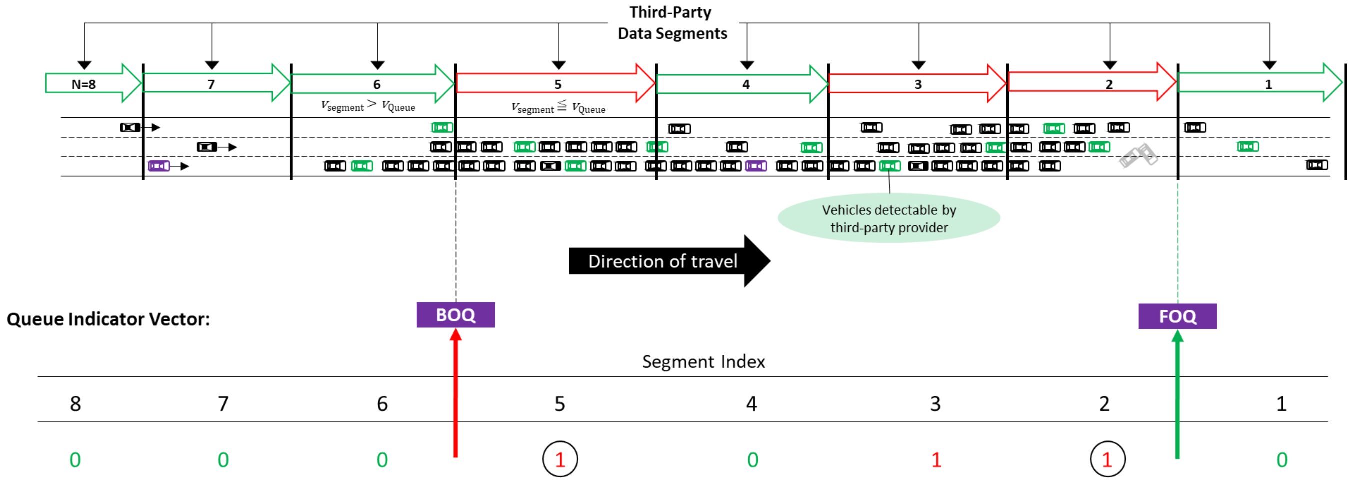


Figure 16. Queue Detection Using Third-Party Data.

In processing segment data, average speeds are compared to a pre-defined queue threshold to determine if traffic in that segment is queued or not. In Figure 16, segments 2, 3, and 5 are in a queued state. These segments are shown using red-colored arrows.

For numerical processing, a vector is used to store queued state (cell value of 1) of segments and the BOQ is estimated at the upstream end of the most upstream queued segment. The FOQ is placed at the downstream boundary of the most downstream queued segment. The bottom portion of Figure 16 shows the queue indicator vector for third-party data. Here, three cells, corresponding to the segments indicated by red arrows, have values of one. The BOQ and FOQ are identified by upper and lower boundaries of the two segments identified by circled entries (1’s). As in the case of sensor data, this information may be combined with positions of previously detected BOQ and FOQ locations to calculate shockwave speeds. Figure 17 shows a flow chart of calculations to determine BOQ and FOQ locations using third-party segment speed data. This logic is similar but simpler than the one described above for spot sensors. In certain time steps, segment data analysis may not detect any change. In fact, there might be several contiguous time steps without any detected change in queue conditions.

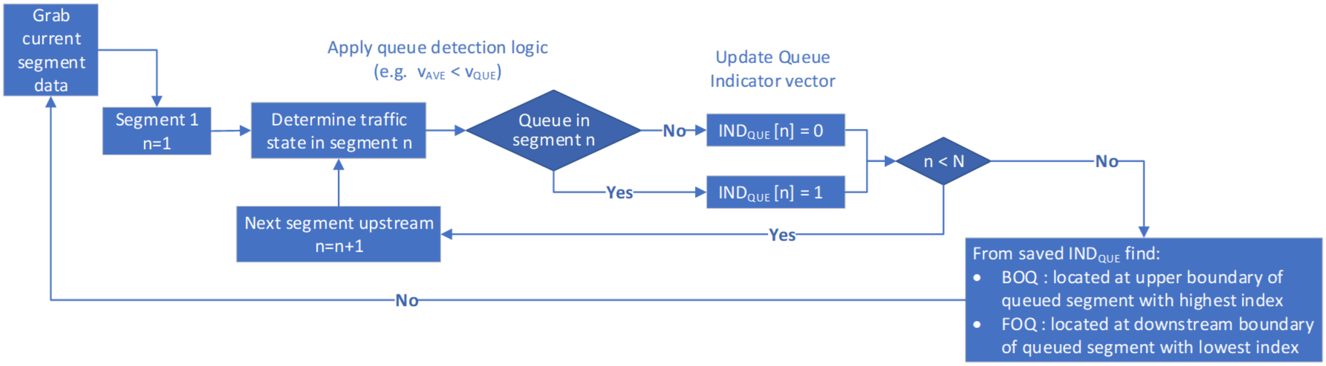


Figure 17. Flowchart for Queue Detection Algorithm Using Third-Party Data.

Queue Identification from CV Data

Figure 18 shows the queuing situation used above but assumes that a subset of vehicles in the system are EDCM-enabled CVs. As described previously, these vehicles can provide trajectory data at one-tenth of a second resolution in certain specified conditions such as sudden acceleration or deceleration. In Figure 18, these vehicles are identified using red color.

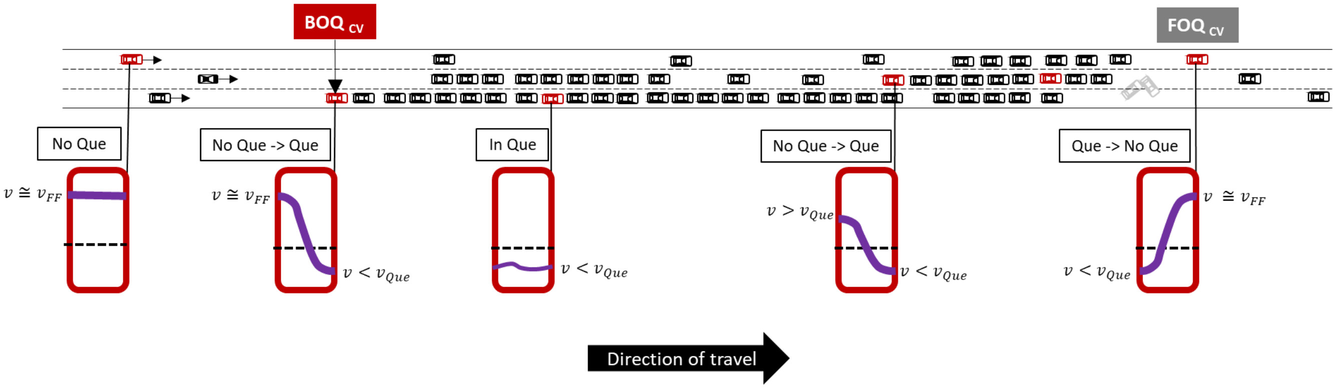


Figure 18. Queue Detection Using CV Data.

For the following description, we assume identification numbers of these vehicles as 1, 2, 3, 4, 5, and 6.

- Vehicles 1 is located downstream of the front of the queue. Because its speed changes from below queue threshold to above queue threshold (Que -> No-Que condition), its location can be considered a potential FOQ location.
- The speed of Vehicle 3 decreased and crossed the queue threshold (No-Que -> Que condition), its location is a potential BOQ.
- Vehicle 4 is in a queued state, where its speed remains below the queue threshold. Because there is no sudden change, it provides data at a specified lower frequency (e.g., 1 to 10 second). Vehicle 2 is also in queue and reports similarly.
- Vehicle 5 just joined the queue as identified by its sudden deceleration from free-flow speed to below queue threshold speed (No-Que -> Que condition).
- Vehicle 6 is traveling at free-flow speed upstream of the queue and reports at a specified lower frequency.

In each calculation time step, potential BOQ and FOQ locations are saved together with times of these events. The most upstream BOQ and the most downstream FOQ from these saved estimates are selected as final positions of BOQ and FOQ. It should be noted that this information is on a lane-by-lane basis. Figure 19 provides a flow-chart of these calculations. These BOQ and FOQ position and associated times, together with same data from previous time step can be used to calculate shockwave speeds for BOQ and FOQ predictions.

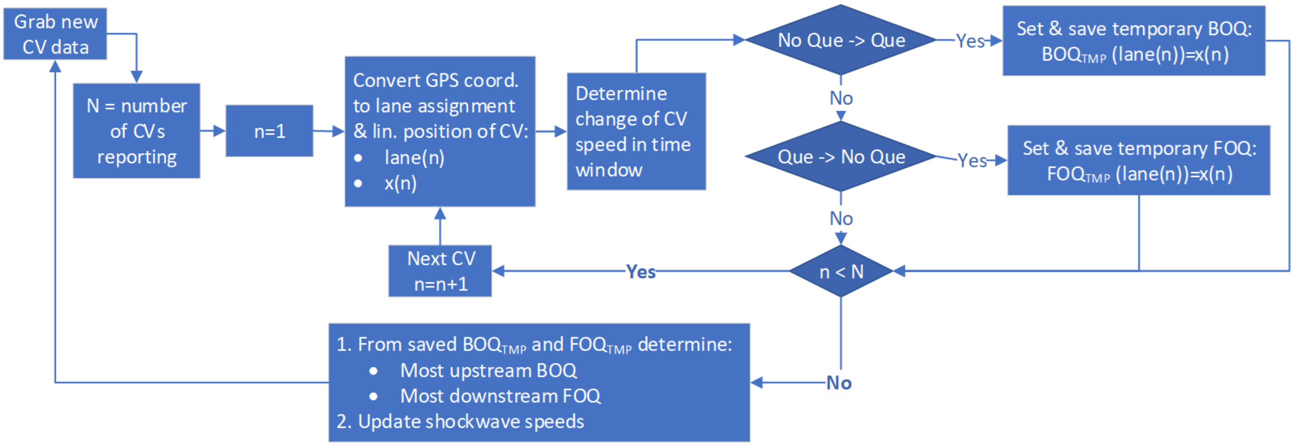


Figure 19. Flowchart for Queue Detection Algorithm Using CV Data.

QUEUE ESTIMATION AND PREDICTION

This is the second step of the previously described two-step queue estimation process. It is carried out at each time step after individual queue estimates have been updated using data from the three data sources individually. These calculations assume the following:

- CV data provides the most accurate and timely queue estimation at lane-level.
- When all sensors are working as intended, data from these sensors is considered second best for queue detection/estimation.
- Third-party segment data should be used when timely queue estimates from the above sources are not available. It is because of lack of lane-level data and longer latencies associated with third-party data.

Table 1 provides recommendations for BOQ estimation based on above assumptions and the availability of queue estimates from the three sources at any given calculation time step. As column labels show, these include estimated and predicted values of BOQ from the three data sources. Table rows represent different cases of BOQ estimate and prediction availability in a calculation time step.

Table 1. Scenarios for BOQ Estimation from Multiple Sources.

BOQ from			Predicted BOQ using data from			Comment
CV	Sensors	3rd Party	CV	Sensors	3rd Party	
BOQ_{CV}	BOQ_{SEN}	BOQ_{3RD}	Pred-BOQ_{CV}	Pred-BOQ_{SEN}	Pred-BOQ_{3RD}	
🟩 X	Any	Any	Any	Any	Any	If only BOQ_{CV} is available in the current time-step, a confirmation may be required that at least another CV, sensor, or third-party segment downstream is already in a queued state.
-	X	Any	🟩 X	Any	Any	Time since last detected CV < Sensor data latency (e.g., 30 seconds)
-	🟩 X	Any	X	Any	Any	Time since last detected CV ≥ Sensor data latency
-	🟩 X	Any	-	X	Any	
-	-	X	🟩 X	Any	Any	Time since last detected CV < Latency in 3rd party data (e.g., 4 minutes)
-	-	🟩 X	X	Any	Any	Time since last detected CV ≥ Latency in 3rd party data (e.g., 4 minutes)
-	-	X	-	X	Any	Time since last sensor data < Latency in 3rd party data (e.g., 4 minutes)
-	-	🟩 X	-	-	X	
-	-	-	🟩 X	Any	Any	
-	-	-	-	🟩 X	Any	
-	-	-	-	-	🟩 X	
-	-	-	-	-	-	Do nothing

X	Estimate available for current time step
🟩 X	User this estimate for BOQ determination
-	Estimate not available for current time step
Any	Estimate either available or not available

A legend provided in the last row of this table describes the meanings of cell entries. Below are some examples of the interpretations of these scenarios.

- The first row represents all cases where CV-based queue estimates are available for the current time-step, and estimates from other data sources may or may not be available. In such cases, use CV-based estimates for BOQ and shockwave speeds for prediction. If only BOQ_{CV} is available for the current time-step, it may not be accepted without confirming the existence of a downstream queue in the same lane. Queue data from previous time-steps, or additional CV data from the current and future time-step, can be used for this purpose.
- Rows 2 and 3 desribe situations when CV-based BOQ estimate is not available, but CV-based BOQ prediction is available for the current time step. In such cases, the following logic is recommended for BOQ selection:
    - If time since last detected CV is less than sensor data latency (e.g., 30 seconds), then used CV-based predicted BOQ.
    - Otherwise, use sensor-based BOQ etimate.
- Similarly, other rows describe scenarios with different combinations of available queue estimates and predictions from various data sources, and the green shaded cells indicate recommended BOQ selection.
- The last row of the above table accounts for the scenario where there is no queue estimate available for the current time slice from any of the three data sources. This scenario can occur under the following conditions:
    - Uncongested condition without any queue.
    - Queue has started forming but not yet detected by either of the three data sources.

Figure 20 shows a flow chart of the BOQ estimation logic in a single time-step using data availability scenarios identified in Table 1. As shown in Figure 21, these calculations steps are repeated over the entire time period when the V2I QA/QW application is running. In this illustration, the V2I QA/QW application runs from T_Begin through T_End, using a calculation time-step of Δt. As mentioned previously, the length for Δt should not be less than the time it takes to receive and process input data. Processing time includes the time required for data checks, data aggregation, queue detection/prediction and queue warning message generation. Daily operation times of the V2I QA/QW application could be implemented as a time-of-day schedule with a manual override capability to allow operator intervention. Note that the dashed red box in Figure 21 shows a simplified representation of the single-time-step logic in Figure 20. FOQ estimation process is similar to the BOQ estimation process discussed here.

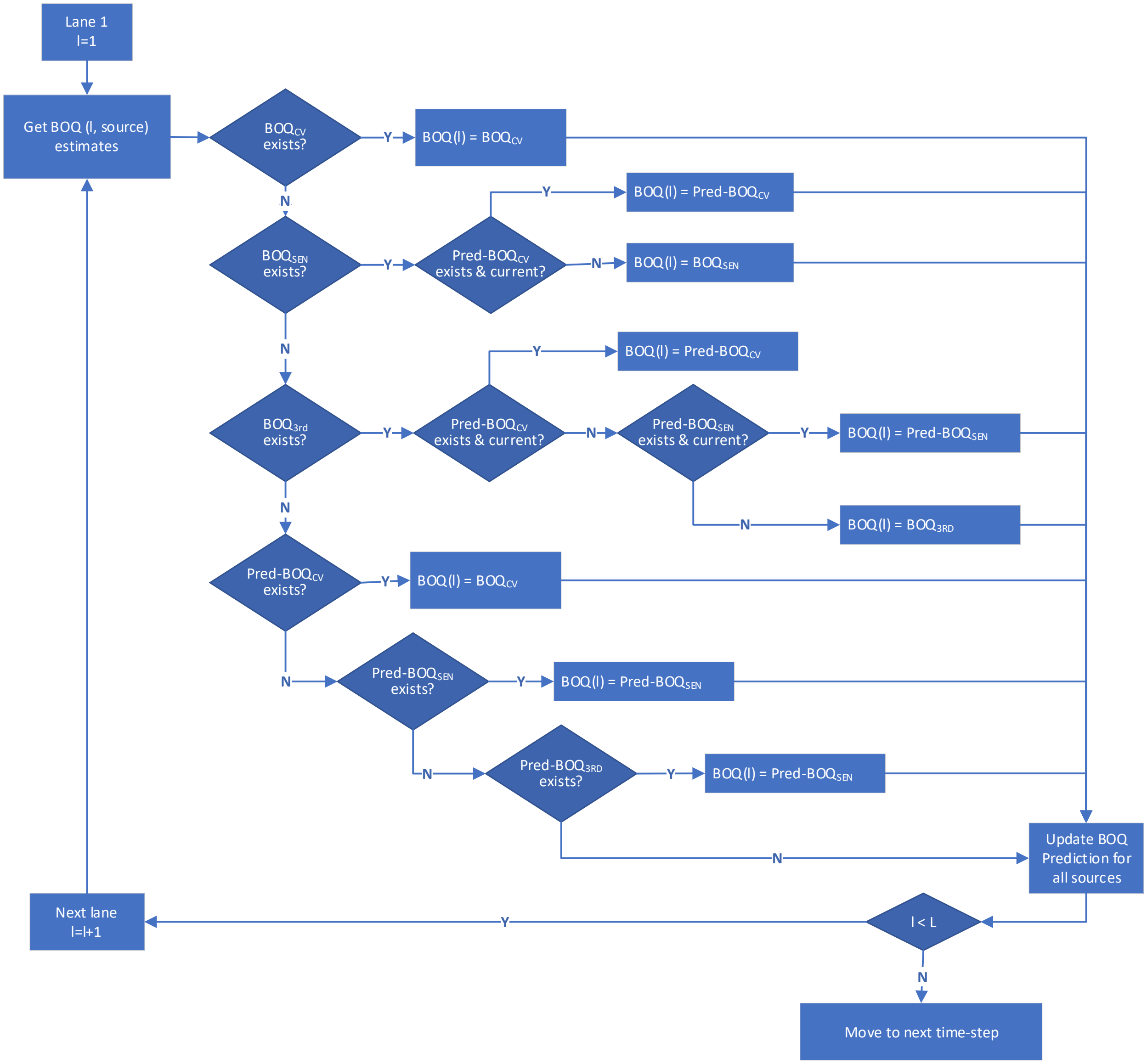


Figure 20. Flow Chart of Single-Step BOQ Estimation.

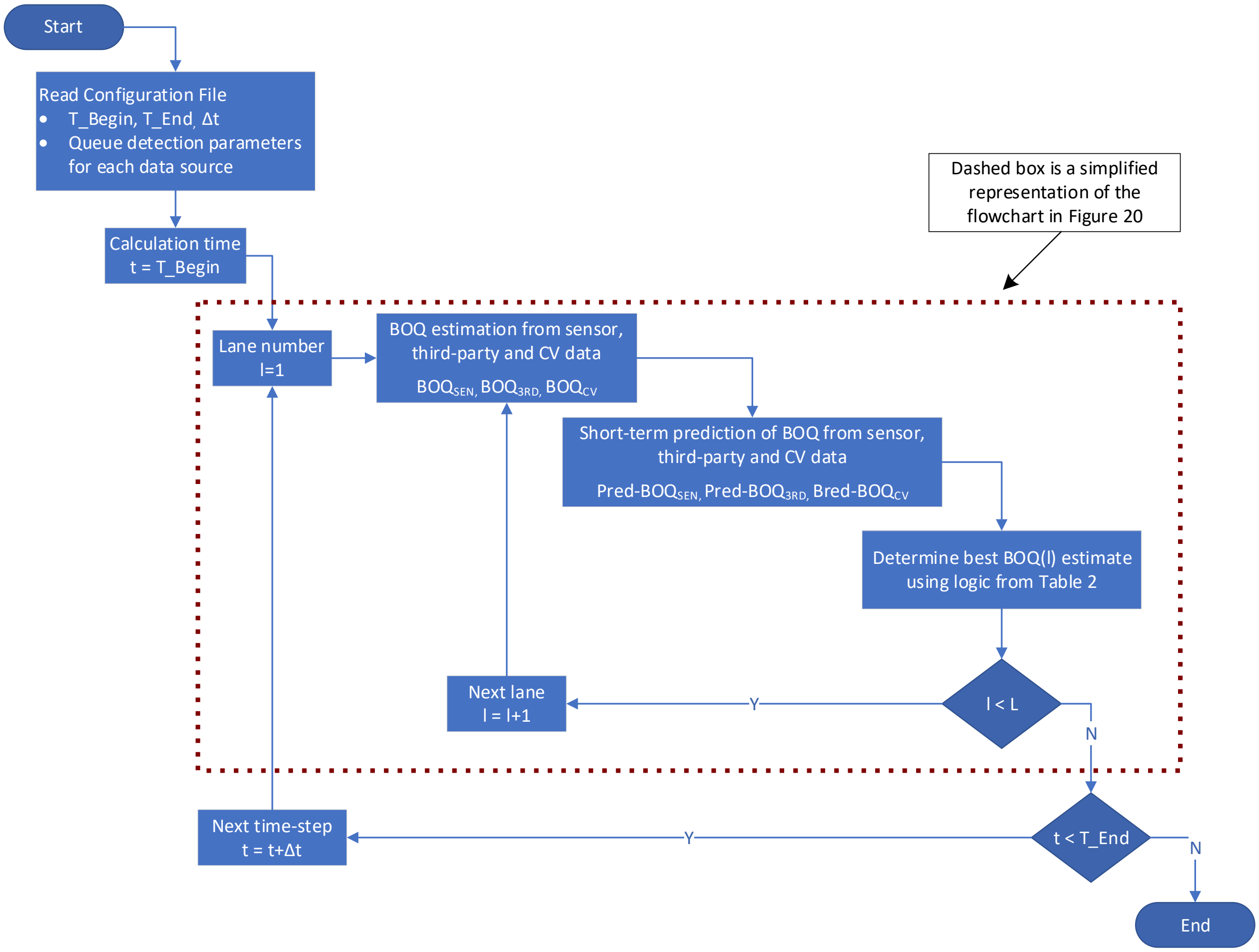


Figure 21. Flow Chart of Overall BOQ Estimation.

QUEUE WARNING SUBSYSTEM

Figure 22 highlights the key components of queue warning subsystem that includes the following:

- CV-based Queue Warning.
- DMS-based Queue Warning.
- Queue Information Sharing with Third-Party Providers.

These subsystem components are discussed in this section.

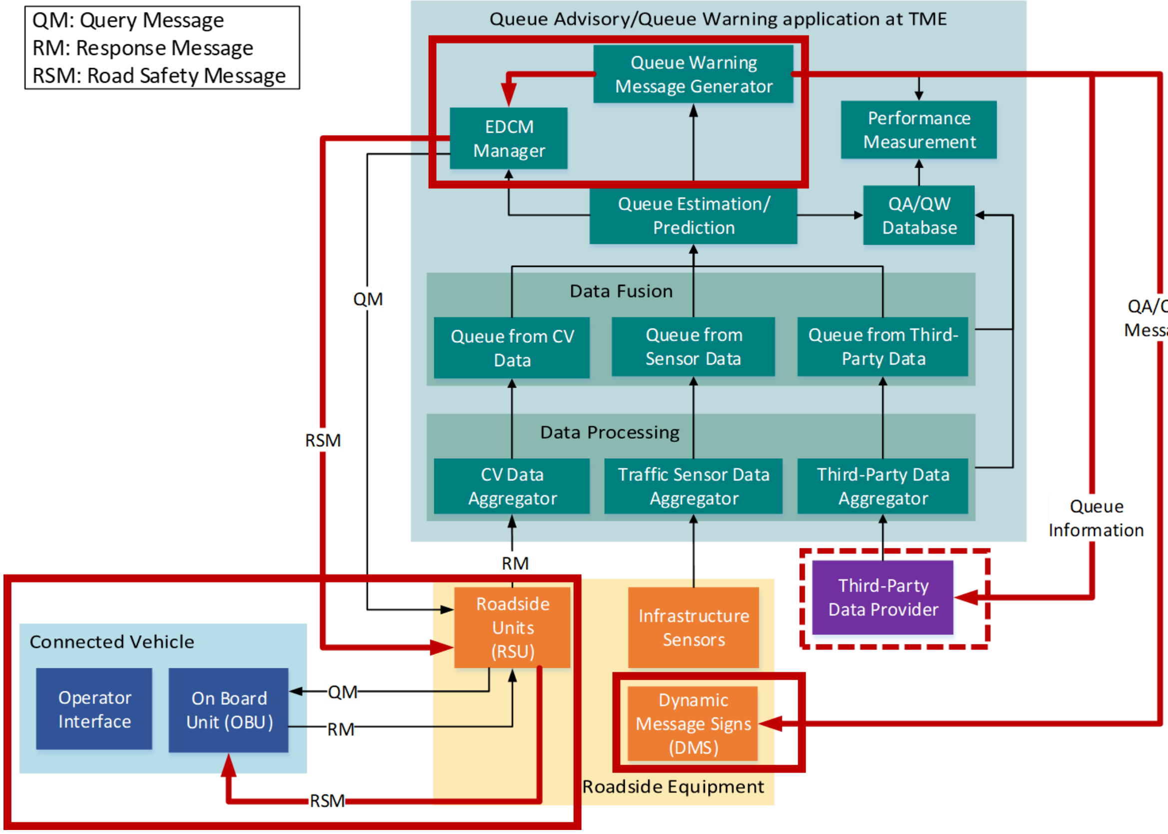


Figure 22. Queue Warning Subsystem

CV-BASED QUEUE WARNING

In the V2I QA/QW application, when the TME detects the formation of a queue, it transmits lane-level BOQ locations and shock wave speeds to all CVs using RSMs. A requirement for lane-level queue warning is that a CV should be able to download a digital lane-level map of the roadway before entering a pre-defined zone containing the geofenced area targeted by the V2I QA/QW application. CVs can download this map through an internet or cellular connection. The RSM data elements required to support the in-vehicle QA/QW application are described in document *Event-Driven Configurable Messaging (EDCM) Queue Advisory & Queue Warning (QA/QW) System and In-Vehicle Application Requirements*[4].

Based on the queue information contained in the RSM, and the CVs current speed and position, an in-vehicle QA/QW application generates relevant alerts for the vehicle operator in a timely manner. The alert consists of two stages. The first stage informs the driver about the presence of a queue downstream. The second stage provides a stronger warning. It allows the operator to take appropriate action (e.g., slow down, change lane, etc.) prior to reaching the BOQ. Figure 23 shows a flowchart of the in-vehicle queue warning application.

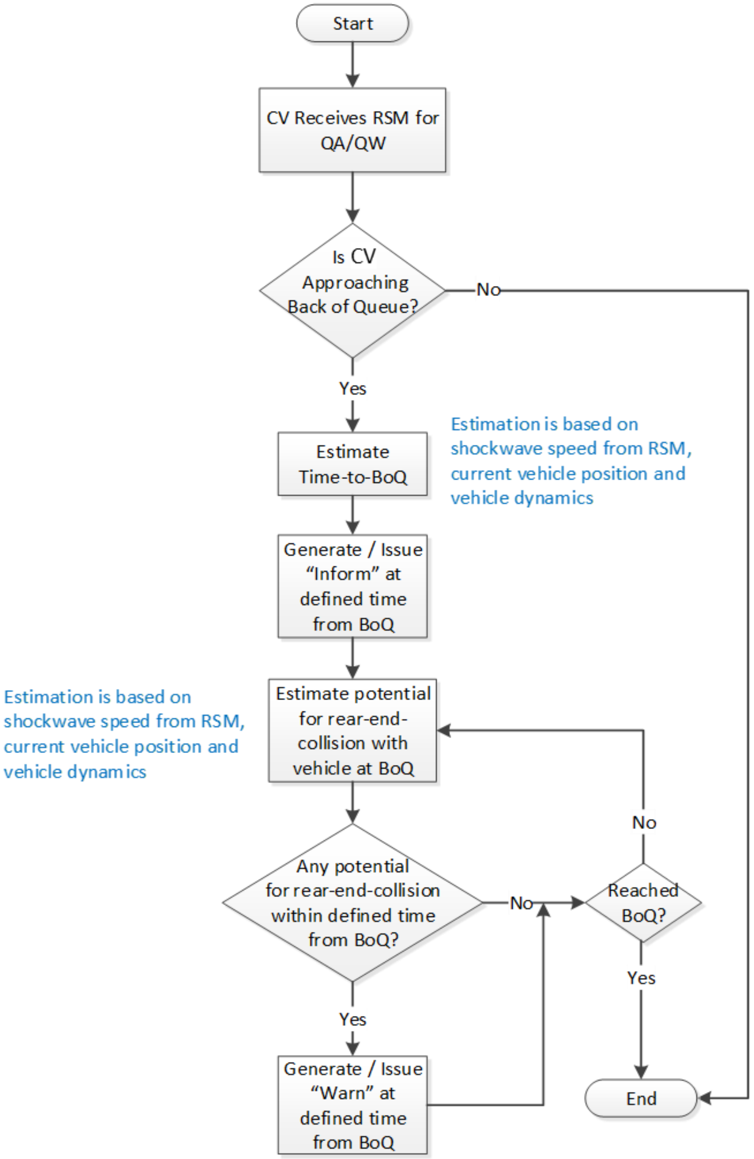


Figure 23. Flow Diagram for In-Vehicle QA/QW Application (Source: CAMP).

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[4] *Event-Driven Configurable Messaging (EDCM) Queue Advisory & Queue Warning (QA/QW) System and In-Vehicle Applications Requirements*. Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure 2 (V2I-2) Consortium. June 2020. [DRAFT].

As a CV approaches a queue, the in-vehicle QA/QW application continuously calculates and updates the following infromation:

- Estimated time needed for the CV to reach the BOQ ((t_{eBOQ}).
- Estimated distance needed for the CV to reach the BOQ (d_{eBOQ}).
- Estimated position where the CV will join the queue (P_{eBOQ}).
- Distance from P_{eBOQ} to start of “Inform” zone (d_{inf}).
- Distance from P_{eBOQ} to start of “Warn” zone to (d_{warn}).

Figure 24 illustrates the concept of “Inform” and “Warn” zones.

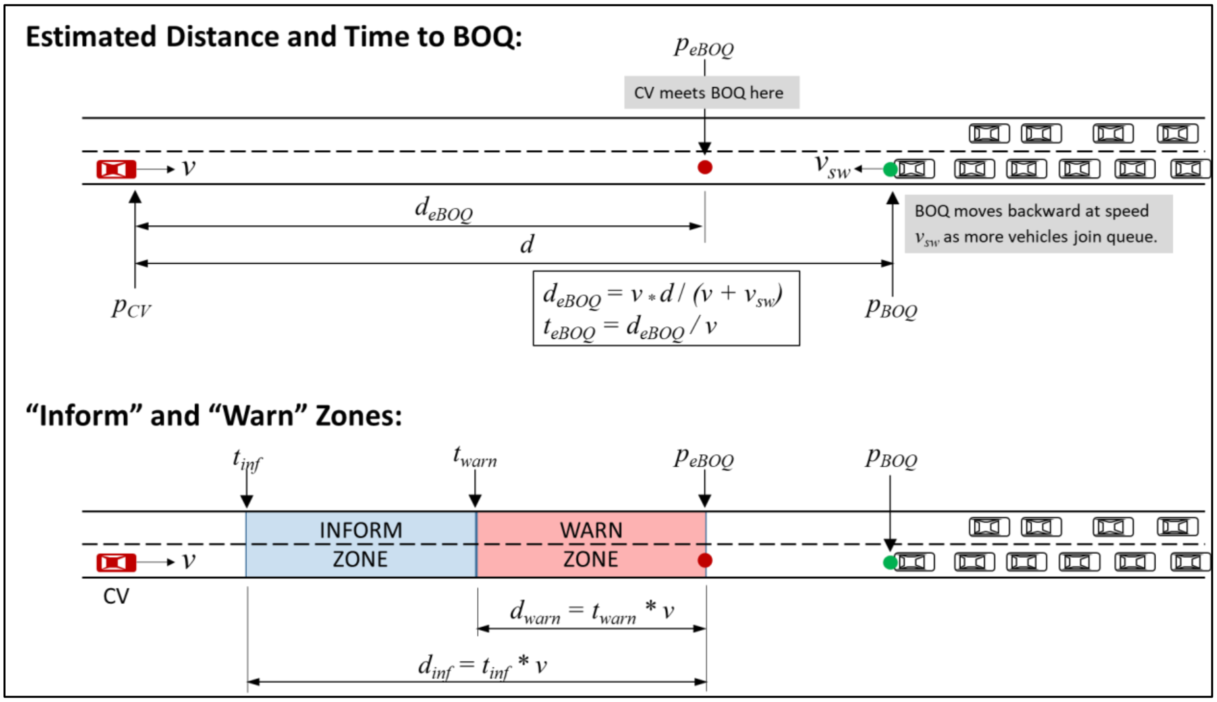

Figure 24. In-Vehicle QA/QW Warning Based on "Inform" and "Warn" Zones.

“Inform” and “Warn” zones are calculated segments of the roadway where the in-vehicle application issues and maintains “Inform” or “Warn” alerts for the operator according to the following logic:

```
IF ( $d_{eBOQ} < d_{inf}$ ) THEN
    IF ( $d_{eBOQ} < d_{warn}$ ) THEN
        IF ( $d_{eBOQ} > 0$ ) THEN
            Issue “WARN” message
        ENDIF
    ELSE
        Issue “INFORM” message
    ENDIF
ENDIF
```

The starting points of “Inform” and “Warn” zones are defined based on configurable pre-defined travel times (t_{inf}, t_{warn}) for the CV to reach the estimated position of BOQ (P_{eBOQ}). Calculations of t_{inf} and t_{warn} consider vehicle dynamics (e.g., vehicle speed, vehicle type, laden vs. unladen, appropriate deceleration rate, etc.), and an estimate of operator perception reaction time. The position where the CV is expected join the queue (P_{eBOQ}) is calculated using the shockwave speed v_{sw} for the BOQ.

DMS-BASED QUEUE WARNING

DMSs are used for disseminating queue-warning messages for drivers approaching a downstream vehicle queue. They are primarily intended for drivers of non-CVs but will also be seen by drivers of CVs. TME generates appropriate queue warning messages for all DMSs depending on their distances to the BOQ location. The message content may include:

- General queue information (e.g., Queue Ahead)
- Lane specific Queue information (e.g., Right Lane Queued)
- Approximate distance to the BOQ (e.g., Queue 1 mile)
- Type of queue and distance to queue (e.g., Slow Traffic 1 mile ahead, Stopped Queue 1 mile ahead, etc.)

If possible, queue warning messages should also be provided on DMSs upstream of potential diversion points (e.g., exit ramps or freeway interchanges) to give drivers the option to divert to available alternate routes.

INFORMATION SHARING WITH THIRD-PARTY PROVIDERS

Information on congested roadway segments and queue characteristics detected by the V2I QA/QW system can also be shared with third-party data providers. For example, this can be achieved by setting up a data feed in a standard format (e.g., XML or JSON) that third-party providers can access and disseminate to a wider audience.

PERFORMANCE MEASUREMENT SUBSYSTEM

DESCRIPTION

Figure 25 highlights the performance measurement subsystem, which uses data stored in a database by other subsystems. Information stored by these systems in real-time includes data received from all sources, results of data aggregation and error checking, outputs from data fusion process, information about detected queues, and queue warning messages generated by the message generator.

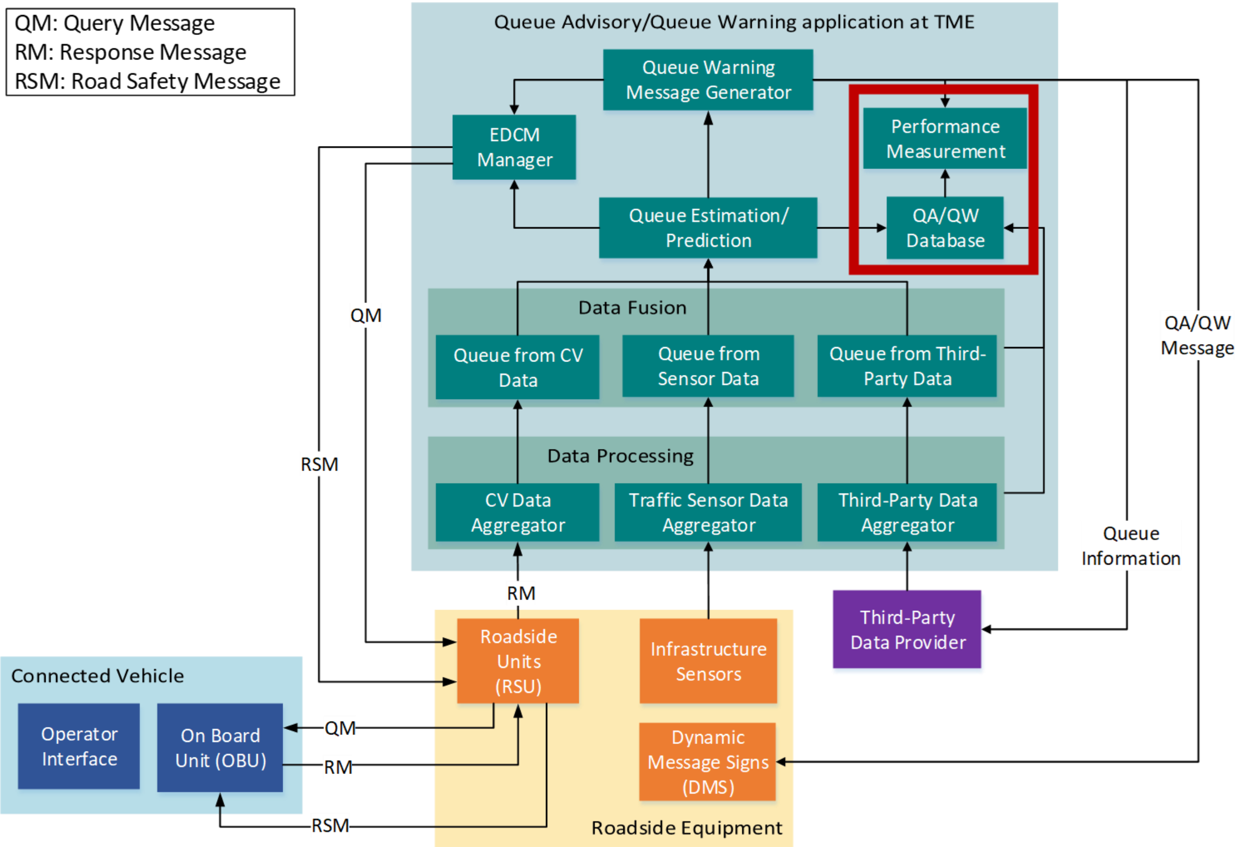

Figure 25. Performance Measurement Subsystem.

Detailed operational performance and long-term safety evaluations of the proposed V2I QA/QW system requires significant additional data, collection of which is not within the scope of this system. The objective of performance evaluation subsystem is to make system operational data available for such evaluations on an as needed basis. This subsystem can provide real-time and off-line performance measures for assessing the performance of input data streams and some system components.

POTENTIAL PERFORMANCE MEASURES

Sensor Data

Sensor data stored in the database includes average speeds, volumes, and occupancies for all data collection intervals for all sensors. Depending on storage limitations, these data may be retained for short durations (e.g., one month). Long-term data storage may require aggregation of these data to 5-minute or longer intervals (e.g., 5- or 60-minute), which could be done in the data aggregator in real-time or in a separate off-line process. Sensor data aggregator also performs data quality checks, and flags missing and erroneous data. It also keeps track of communication-related latencies (time when sensor data was received compared to data time stamp). Once this data is stored in the QA/QW database, the following performance metrics can be generated through data queries:

1. Identification of sensors or stations which are consistently providing questionable data.
2. Identification of sensors or stations from which data is missing either part of time or all the time.
3. Identification of any duplicate records for same sensor ID and same time.
4. Mean and standard deviations of latencies for different sensor stations.
5. Comparison of speeds at pairs of adjacent stations during queue propagation.

Items 1 and 2 can be implemented in real-time to alert operators about sensor and/or communication link malfunctions. Item 3 may identify configuration errors. Data in item 4 may be used to adjust queue detection parameters. For locations with recurring congestion, data from item 5 can be used for post-event analysis of queue formation and dissipation to estimate shockwave speeds. This historic information can be used for queue estimation in cases when real-time data for BOQ and FOQ detection and/or prediction is not available.

CV Data

The system saves individual vehicle trajectories for selected periods of time (e.g., one week) to calculate the following statistics about CVs:

- Number of CVs within the geofence in a specified time interval (e.g., 30 seconds).
- Number of CVs in queue.
- Percent of CVs in traffic stream. This would require the use of volume data from sensors.
- Queue length measured by the distance between detected FOQ and BOQ positions.
- Average time CVs spend in queue.
- Maximum, mean, and standard deviation of CV decelerations.

The first three statistics are indicators of market penetration of CV that can help establish confidence in the use of CV data in queue detection. With increased market penetration, FOQ and BOQ estimation will significantly improve. Maximum and average queue lengths are also useful performance measures. Time in queue is an indicator of queue-related delay. Deceleration statistics may be used as surrogate safety measures.

Third-Party Data

Data aggregator uses vendor-specific APIs to obtain segment travel time and speed data at vendor-specified update intervals (e.g., 1 to 3 minutes). In addition to saving these data to the QA/QW database for future use, third-party data aggregator also computes and keeps track of the following information:

- Statistics on data latencies.
- Frequency of identical records in data stream.
- Latency in third-party queue/congestion detection compared to CV-based and sensor-based queue-detection.

APPLICABLE DOCUMENTS

This section lists documents applicable to the V2I QA/QW high-level design.

V2I QA/QW DOCUMENTS

- V2I Queue Advisory/Warning Applications: Concept and Design: Review of Current Work, December 2020.
- V2I Queue Advisory/Warning Applications: Concept and Design: Concept of Operation, December 2020.
- V2I Queue Advisory/Warning Applications: Concept and Design: Methods and Metrics for Performance Measurement, December 2020.
- V2I Queue Advisory/Warning Applications: Concept and Design: High-Level System Requirements, December 2020.
- Event-Driven Configurable Messaging (EDCM): Queue Advisory & Queue Warning (QA/QW) System and In-Vehicle Application Requirements. Crash Avoidance Metric Partners, LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium. June 2020 (Draft).

STANDARDS

- NTCIP 1209, Version v02: Object Definitions for Transportation Sensor Systems (TSS), AASHTO, ITS, and NEMA, May 2014. https://www.ntcip.org/wp-content/uploads/2018/11/NTCIP1209v0218jp.pdf.
- NTCIP 1203, Version v03: Object Definitions for Dynamic Message Signs (DMS), AASHTO, ITS, and NEMA, September 2014. https://www.ntcip.org/wp-content/uploads/2018/11/NTCIP1203v03f.pdf.
- Extensible Markup Language (XML) 1.0 (Fifth Edition), https://www.w3.org/TR/2008/REC-xml-20081126/.
- SAE J2735: Dedicated Short-Range Communications (DSRC) Message Set Dictionary, SAE International, March 2016.

OTHER DOCUMENTS

- Waze Traffic Data Specification Document Ver 2.8.2 (https://www.scribd.com/document/430592482/Waze-Traffic-data-Spec-v2-8-2).
- Waze for Cities (https://www.waze.com/ccp).
- INRIX data download service (http://docs.inrix.com/datadownload/datadownload/).
- RTCM 10410.1 Standard for Networked Transport of RTCM via Internet Protocol (Ntrip) (https://rtcm.myshopify.com/collections/differential-global-navigation-satellite-dgnss-standards/products/rtcm-10410-1-standard-for-networked-transport-of-rtcm-via-internet-protocol-ntrip-version-2-0-with-amendment-1-june-28-2011).