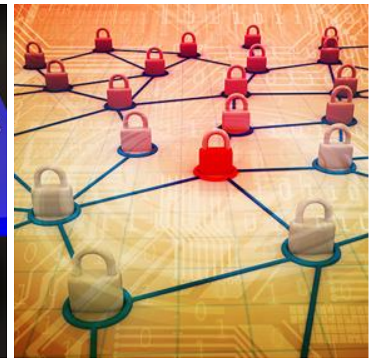




V2I Queue Advisory/Warning Applications: Concept and Design

CONCEPT OF OPERATIONS

Contract #: VTCR 114420
TTI Maestro Project #: M1901702

Submitted by:
Texas A&M Transportation Institute
College Station, TX 77843-3135

Submitted to:
University of Virginia Center for Transportation Studies
Connected Vehicle Pooled Fund Study

Date: 12/1/2020

Texas A&M Transportation Institute	Contract #: VTCR 114420	TTI Project #: 612141-00003	WBS #: 3.1
	Title: V2I Queue Advisory/Warning Applications - Concept of Operations		
	Document Date/revision Date: 12/1/2020		

Contract Start Date: 4/3/2019	Contract End Date: 1/15/2021	Appropriation:

Key TTI Contacts Geza Pesti, Ph.D., PE. Researcher Engineer System Reliability Division Texas A&M Transportation Institute 3135 TAMU College Station, TX 77843-3135 P: 979-317-2829 E: g-pesti@tti.tamu.edu	TTI Contract Administration *Pre-award Administrator*: Tim Hein Research Development Office Texas A&M Transportation Institute P: 979-317-2046 E: T-Hein@tti.tamu.edu *Post-Award Administrator*: Daniel Martinez Sponsored Research Services Texas A&M University P: 979-845-2901 E: d.mtz@exchange.tamu.edu
Customer Organization: University of Virginia Center for Transportation Studies	Key Customer Contacts: Brian Smith, Ph.D., P.E.

DOCUMENT REVISION HISTORY

Document Version	Document Sections	Description of Changes	Date	Approval
1	All	Initial draft	12/9/2019	
2	All	Revision #1	4/14/2020	
3	All	Revision #2	7/14/2020	
4	All	Final	12/1/2020	

TABLE OF CONTENTS

1. SCOPE

1.1 DOCUMENT IDENTIFICATION

This Concept of Operations (ConOps) document is a key deliverable of the research project "V2I Queue Advisory/Queue Warning Applications: Concept and Design" conducted for the Connected Vehicle Pooled Fund Study (CV PFS) entitled "Program to Support the Development and Deployment of Connected Vehicle Applications."

1.2 DOCUMENT OVERVIEW

Purpose

The purpose of this ConOps document is to communicate the research team's understanding of the concept and user needs of the desired V2I Queue Advisory/Warning System to stakeholders and developers for future deployment and testing of the system. The ConOps document can also serve the purpose of consensus building among developers from the vehicle side, infrastructure side, and third-party data provider side, who may be involved in the developments of future applications of the V2I Queue Advisory/Warning System.

Intended Audience

The intended audience of the ConOps document includes:

- Traffic engineers, traffic management center (TMC), and infrastructure operators responsible for traffic operations and safety on roadways where vehicle queues often form because of frequent recurring congestion, incidents, or road construction activities.
- Developers of future V2I Queue Warning systems who can use the ConOps document as a basis for their system development activities.

Document Organization

The standards document IEEE 1362-1998 (R2007) titled "IEEE Guide for Information Technology - System Definition - Concept of Operations (ConOps) Document" guided the research team in the development of the ConOps document. The remaining part of the document includes the following chapters that reflect the essential ConOps elements identified by the IEEE standard:

- Scope
- Referenced documents
- Current system or situation
- Justification for and nature of changes
- Concept for the proposed system
- Operational scenarios
- Summary of impacts

- Analysis of the proposed system
- Notes
- Appendices
- Glossary

1.3 SYSTEM OVERVIEW

Figure 1 provides a high-level graphical overview of the proposed V2I Queue Advisory/Warning System. It includes four key components: 1) roadside equipment, 2) connected vehicles (CV), 3) third-party data providers, and 4) traffic management entity. Each of these components has several elements. The system diagram in Figure 1 assumes the use of Roadside Units (RSU) and short-range communication between RSU and CV. CVs may be operated by humans and can also be controlled by Cooperative Adaptive Driving Systems (CADS).

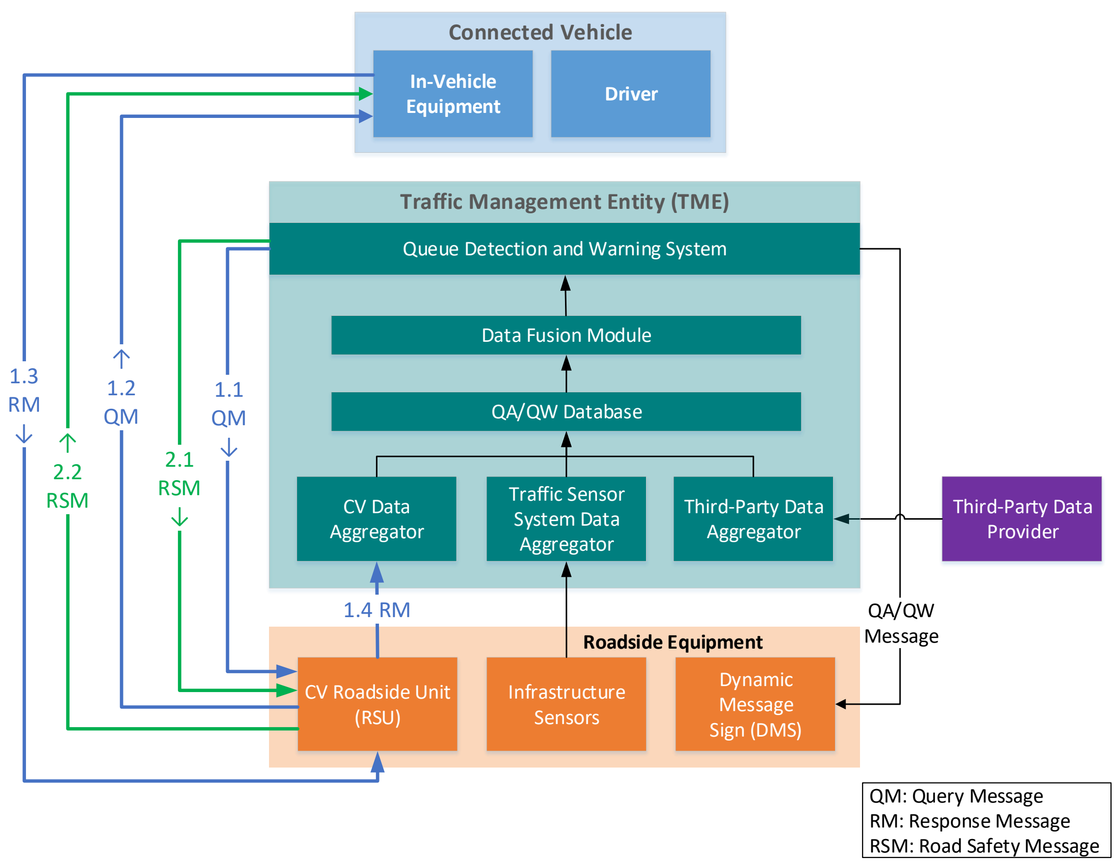


Figure 1. System Diagram of V2I Queue Advisory/Warning Applications Using Short-Range Communication

Figure 2 shows another implementation of the same system without RSUs using long-range communication between the TME and CV. The two figures also indicate the data and information flow between the key elements and system components. The section titled "Description of Proposed System" in Section 5.3 provides additional details on each system component.

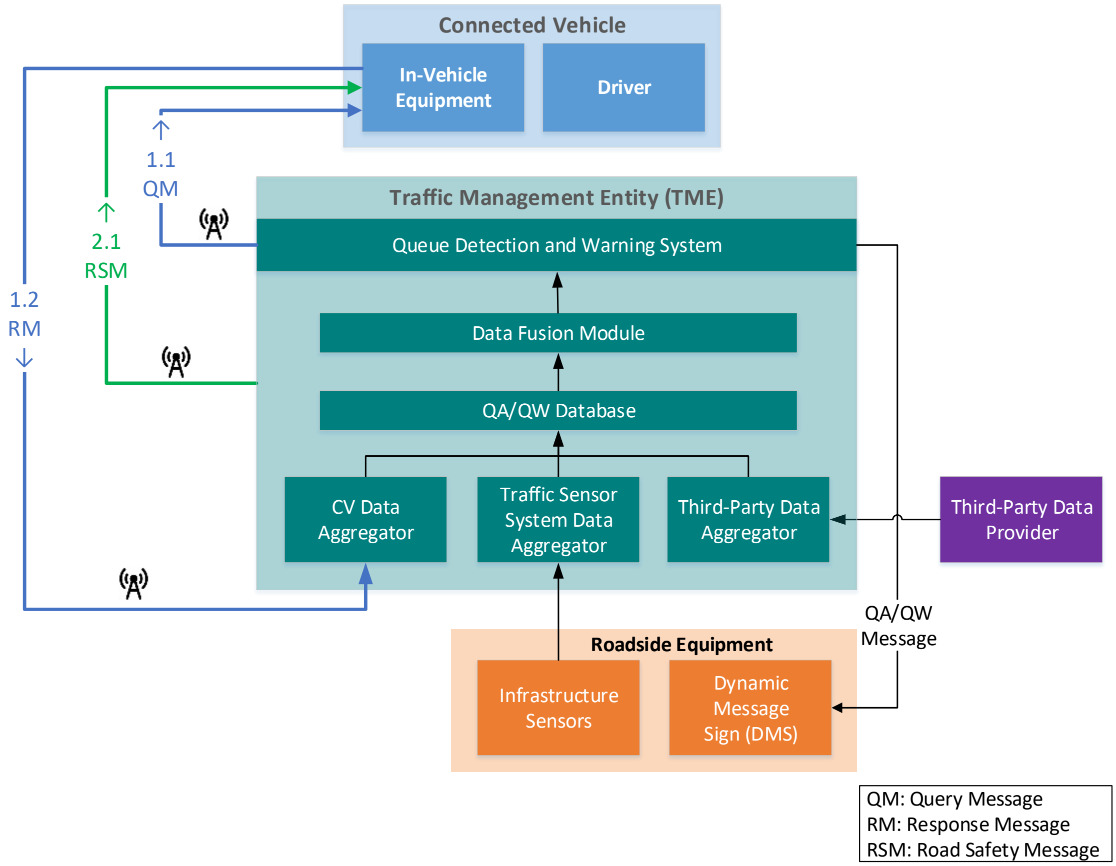


Figure 2. System Diagram of V2I Queue Advisory/Warning Applications Using Long-Range Communication

2. CURRENT STATE OF PRACTICE

This section introduces the problem domain of vehicle queues and provides a discussion of the current state of practice in queue warning.

2.1 BACKGROUND, OBJECTIVES, AND SCOPE

Vehicle queues frequently occur at locations where available roadway capacity cannot serve traffic demand. They commonly form upstream of bottlenecks caused by incidents, work zones, weaving traffic at freeway junctions, exit ramps that overspill onto freeway lanes, and on arterials upstream of traffic signals. In addition, they may be caused by adverse weather and poor visibility conditions that may significantly reduce vehicle speeds and roadway capacity.

Drivers approaching the end of queues without receiving any warning often have poor perception of the time and distance needed to safely slow down or stop to avoid rear-end collisions with slower or stopped vehicles in front of them. Thus, vehicle queues present significant safety concerns. Queues that form downstream of horizontal or vertical curves that limit drivers' sight distance are also potentially hazardous.

Queue warning systems that constantly monitor traffic conditions (e.g., vehicle speeds, volumes and/or occupancies) can detect the formation and propagation of vehicle queues, and provide queue warning for the vehicles upstream.

The objective of queue warning systems is to provide advance warning to drivers approaching the back of vehicle queues, so that they can safely adjust their speeds and slow down or move to an adjacent lane to avoid the need for sudden braking and to prevent the occurrence, or significantly reduce the potential, of both primary and secondary rear-end collisions. If a queue warning is provided upstream of a potential diversion point to a less congested alternate route, drivers may also choose to divert and change their route.

2.2 OPERATIONAL POLICIES AND CONSTRAINTS

The operational policies of existing queue warning systems are discussed in this section. The majority of the recently developed and deployed queue warning systems use infrastructure-based speed sensors to detect changes in traffic conditions, and the formation and propagation of vehicle queues. Many of them are operated as part of a broader ITS traveler information system. They can be often found in major freeway construction projects where lane closures can significantly reduce roadway capacity and create long vehicle queues and greatly increase the potential for rear-end crashes.

In large metropolitan areas, a queue warning system may cross multi-jurisdictional boundaries. If this is the case, institutional agreements should be put in place to provide for sharing data and infrastructure (sensors, communication backbone, etc.) between all stakeholders (e.g., city, county, DOT).

2.3 DESCRIPTION OF THE CURRENT SYSTEM OR SITUATION

A typical infrastructure-based queue warning system is illustrated by Figure 3.

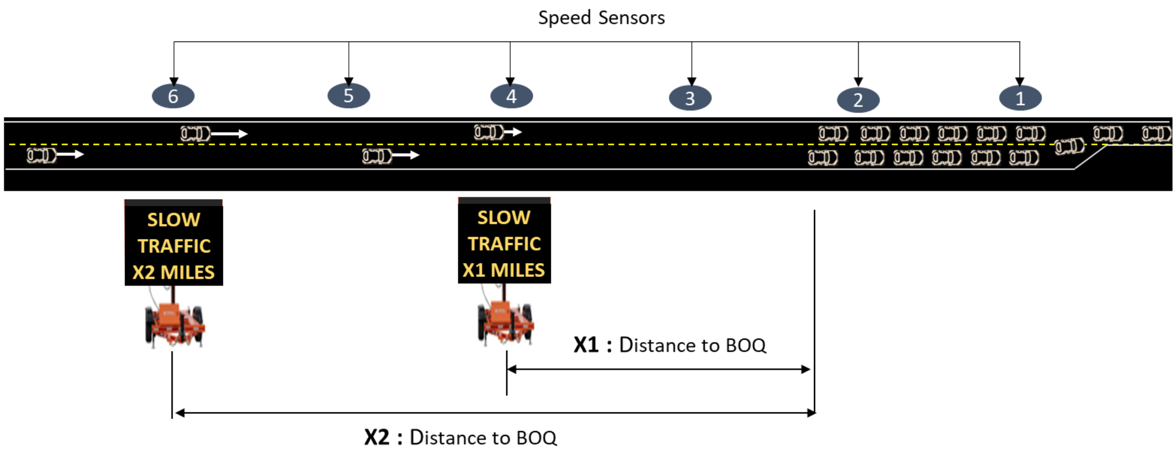


Figure 3. Sensor-Based Queue Warning System.

The main components of such systems include:

- Sensors to measure spot speeds and/or occupancies at multiple points upstream of a known bottleneck location.
- Traffic Management Center (TMC) or some other Traffic Management Entity (TME) to analyze the sensor data and select appropriate real-time queue warning messages based on some message selection logic/algorithm.
- Dynamic message sign(s) (DMS) or portable changeable message sign(s) (PCMS) to display queue-warning messages for drivers of approaching vehicles.

Traffic Sensor Deployment and Operation

In infrastructure-based queue warning systems, vehicle speeds (and volumes or occupancies) are measured by sensors deployed at multiple points along the roadway. The sensor data is processed by a TMC/TME to detect queues and determine the appropriate response/warning.

The accuracy of queue detection, including back of queue (BOQ) and front of queue (FOQ) estimation, greatly depends on the density of sensors along the roadway. The smaller the spacing between sensors, the greater the queue detection accuracy. The spacing between traffic sensors generally varies between 1/2 and 1 mile. Some queue warning systems may use shorter sensor spacing near the queue generation point for quicker detection of the beginning of traffic slowdown, and longer sensor spacing farther upstream. Queue warning systems with this type of non-uniform spacing have been deployed at locations with recurring queues upstream of fixed queue generation points, such as work zone lane closures.

Some sensors, such as loop detectors and high-definition radar units, are capable of collecting lane-by-lane traffic data (speed, volume, time headway, occupancy). These types of sensors are more appropriate for permanent deployments of queue warning systems at locations with frequent recurring congestion and imbalanced queues between lanes (e.g., exit ramp overspill to freeway lanes). Traffic sensors in temporary deployments of queue warning systems typically do not collect data at lane levels.

Some constraints that need to be considered in finding the right location for speed sensors include the availability of power source, roadside objects blocking the sensors' "field of measurement," presence of entrance/exit ramps, construction activities with concrete barriers that make sensor installation and maintenance difficult, and change in roadway alignment (e.g., lane shift) that may require sensor readjustment.

Queue Detection and Warning

The data collected by the sensors are averaged over pre-defined time intervals (e.g., 1-minute) and used by the TME to:

- detect the formation of queues,
- identify the location of the back of queue,
- estimate the speed of vehicles in the queue, and
- select appropriate queue warning messages.

Traffic slowdown and the formation of a queue at any sensor location is typically detected by comparing the time averaged sensors speed (v) to some speed thresholds. Table 1 illustrates a relatively simple queue detection logic with two speed thresholds (v_1 for slow traffic and v_2 for stopped traffic queues).

Table 1. Queue Detection Based on Speed Thresholds

	$v_1 < v$	$v_2 \leq v \leq v_1$	$v < v_2$
Traffic condition	Free-flow or uncongested	SLOW traffic	STOPPED traffic

Since speeds are measured at just a few discrete points (at the sensor locations), the BOQ location and its distance from the PCMS cannot be accurately determined. The system can detect that the BOQ is somewhere between two consecutive speed sensors, but it cannot determine the exact location. A simple but common approach is to assume the BOQ location at the mid-point between two consecutive sensors where the downstream sensor has already detected the queue, but the upstream sensor has not.

The speed sensor that triggers a queue-warning message is always the most upstream detector station among those where the average speed falls below one of the speed thresholds for slow or stopped traffic.

Message Signs for Queue Warning

The deployments of temporary queue warning systems are often preceded by a prediction of the longest queues that are expected to occur during time periods of the highest traffic demand. For this purpose, an input-output analysis can be performed using historical volumes and the estimated reduced roadway capacity. The locations and number of warning message signs and speed sensors are determined based on the longest expected queue length. At least one warning message sign should be deployed upstream of the longest expected queue to ensure that drivers are protected at all times.

Warning message signs should be deployed and positioned in such a way that they are clearly visible for all drivers traveling in any of the lanes. Adverse weather conditions with low visibility can significantly reduce the effectiveness of the queue warning system.

2.4 MODES OF OPERATION FOR THE CURRENT SYSTEM OR SITUATION

The typical modes of operation of existing queue warning systems are the following:

- Normal mode.
- Enhanced mode.
- Shadow mode.
- Maintenance mode.

Normal Mode

In the normal operation mode, the queue warning system works and performs as designed. All system components function as designed. As soon as the formation of a queue is detected, the system generates appropriate warning messages using a message selection algorithm, and disseminates them through available message signs to provide advance warning for vehicles approaching the back of the queue.

Enhanced Mode

In the enhanced mode, the queue warning system works similarly to the normal mode, but with extensions required to provide some additional functionality for a specific application/deployment. For example, queue-warning systems deployed as part of an integrated ITS work zone traffic control system, may need to work in combination with a dynamic late merge (DLM) control. In this enhanced operation, the queue warning and merge control systems may use the same sensors and share some warning message signs. Therefore, such combined systems may require a modified message selection logic that can provide all required functionalities of the queue warning and merge control subsystems.

Shadow Mode

In the shadow mode, all subsystems responsible for queue detection and warning message selection are active and working properly, but the subsystem responsible for disseminating the warning messages is deactivated. This mode can be useful for testing the performance of individual system components, conduct training activities and exercises, or calibrate and fine-tune some system parameters, such as speed thresholds and speed aggregation intervals for queue detection, and warning message update intervals.

Maintenance Mode

In the maintenance mode, some subsystems and/or components may be selectively deactivated in order to perform some testing, repair, and maintenance activity on them. During this time, some functionality may become unavailable, and therefore maintenance activities should be performed during uncongested off-peak periods when formation of queues is not expected. However, maintenance mode can always be switched back to normal operation mode, if needed (e.g., in case of an incident causing unexpected congestion and queues during maintenance activity).

2.5 USER CLASSES AND OTHER INVOLVED PERSONNEL

User classes of current queue warning systems can be divided into two main groups:

- Vehicle operators (road users who are expected to benefit from the queue warning messages),
- Personnel involved in the operation and maintenance of the system, and
- Management and decision makers.

Vehicle Operators

The first user group includes operators of the following:

- Passenger vehicles (e.g., cars, minivans and pickup trucks, motorcycles, and fleet vehicles such as taxis).
- Transit vehicles (buses for public transportation).
- Trucks (Corporately or privately-owned freight vehicles for transporting goods).

Figure 4 shows a more detailed vehicle category classification by FHWA.

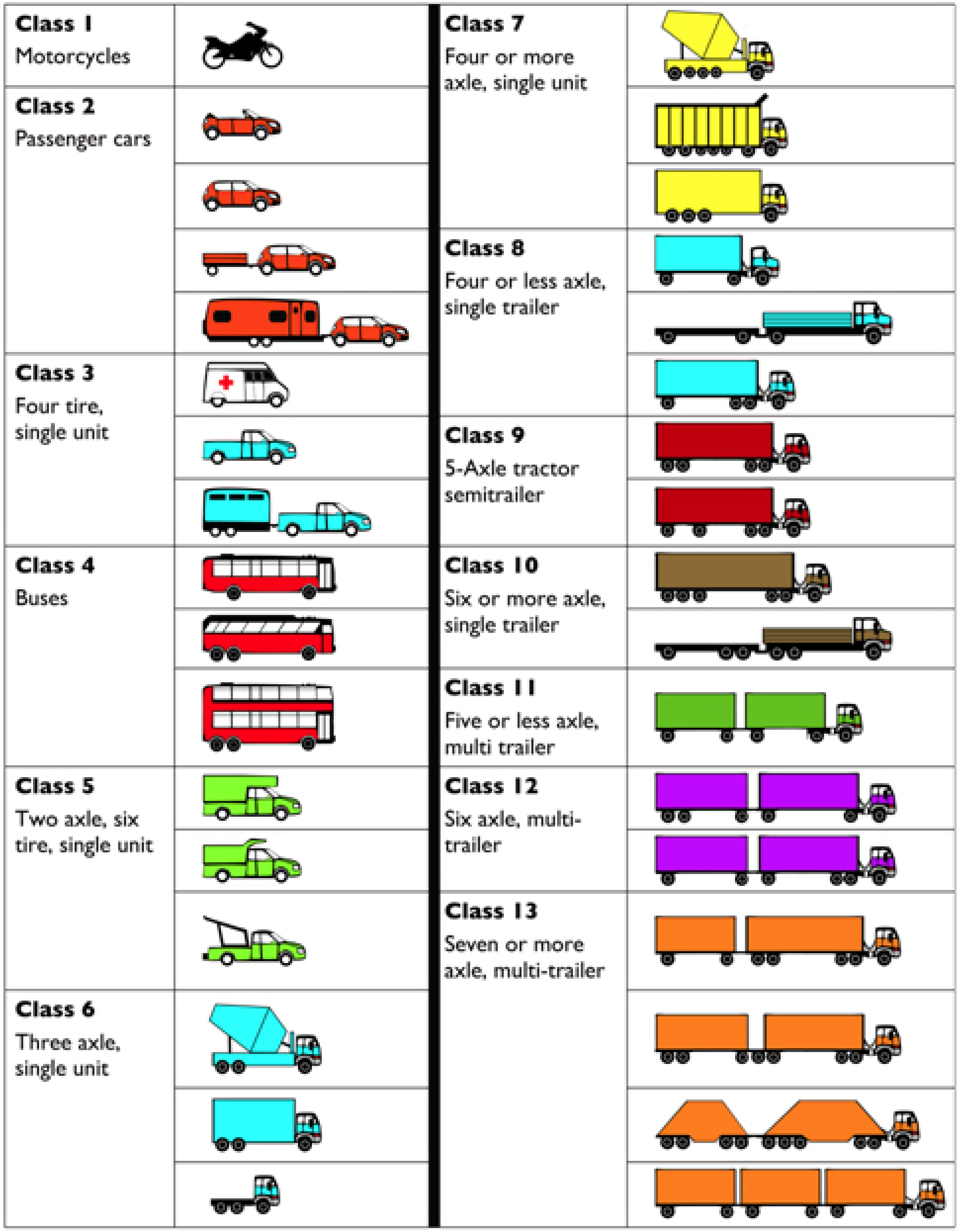


Figure 4. FHWA 13 Vehicle Category Classification (Source: FHWA).

These vehicle types are also very different in their vehicle dynamics and engine characteristics. For queue warning system applications, the most important differences are in their acceleration, deceleration and baking capabilities.

Personnel Involved in System Operation and Maintenance

The second user group includes ITS professionals, traffic engineers, electrical engineers and software developers, technicians and field personnel, law enforcement, and EMS personnel. They are involved in the development, deployment, operation, and maintenance of the queue warning system. They have different levels of access to the system. Field personnel are primarily involved in the field deployment, and day-to-day monitoring and maintenance of system components. They cannot override warning messages or change any functionality of the system.

Technicians and engineers with operator-level access can interact with the system by overriding warning messages and changing some parameters in the system configuration files. Law enforcement and EMS personnel may also have some limited operator-level access and can deactivate the system if required by an emergency. ITS, traffic, and electrical engineers with supervisory/administrative role have the highest level of access to the system. They can override the operator's decisions and actions and reconfigure system parameters (e.g., change speed thresholds for queue detection) if needed.

Management and Decision Makers

Users interested in and/or responsible for

- System performance assessment,
- Benefit-cost evaluation,
- Resource allocation, and
- Public information.

2.6 SUPPORT ENVIRONMENT

Some state and local agencies may have their own personnel including traffic engineers, ITS professionals and technicians with proper training to support operation and maintenance of their queue warning systems. However, in many cases, they use outside vendors for the setup, operation, and maintenance. It is particularly true for temporary deployments of queue warning systems in work zone applications. To minimize maintenance and staff training costs, agencies tend to implement similar queue warning system technologies (both hardware and software) developed by the same vendor, wherever it is possible.

3. JUSTIFICATION FOR AND NATURE OF CHANGES

3.1 JUSTIFICATION FOR CHANGES

Existing queue warning systems predominantly use infrastructure-based sensors (inductive loops, video cameras, radar, magnetometers, etc.) generally installed at one-half mile to one-mile spacings. Traditional infrastructure-based sensors collect lane-by-lane speeds and occupancy at the sensor location and aggregate this data over 20- or 30-second interval before sending it to the TME. Queue warning systems may further aggregate these data to one- or five-minute intervals to smooth out random fluctuations and prevent false positive/negative queue detection. This aggregation results in additional latency in detecting a queue. Spatial separation between sensors also makes it difficult to accurately estimate BOQ when it is located in between a pair of adjacent sensors.

From a driver's perspective, queue detection error is the difference between the estimated BOQ location provided in the warning message and the location where the vehicle actually arrives at the BOQ. The queue detection error ΔQ and its two components are illustrated in Figure 5.

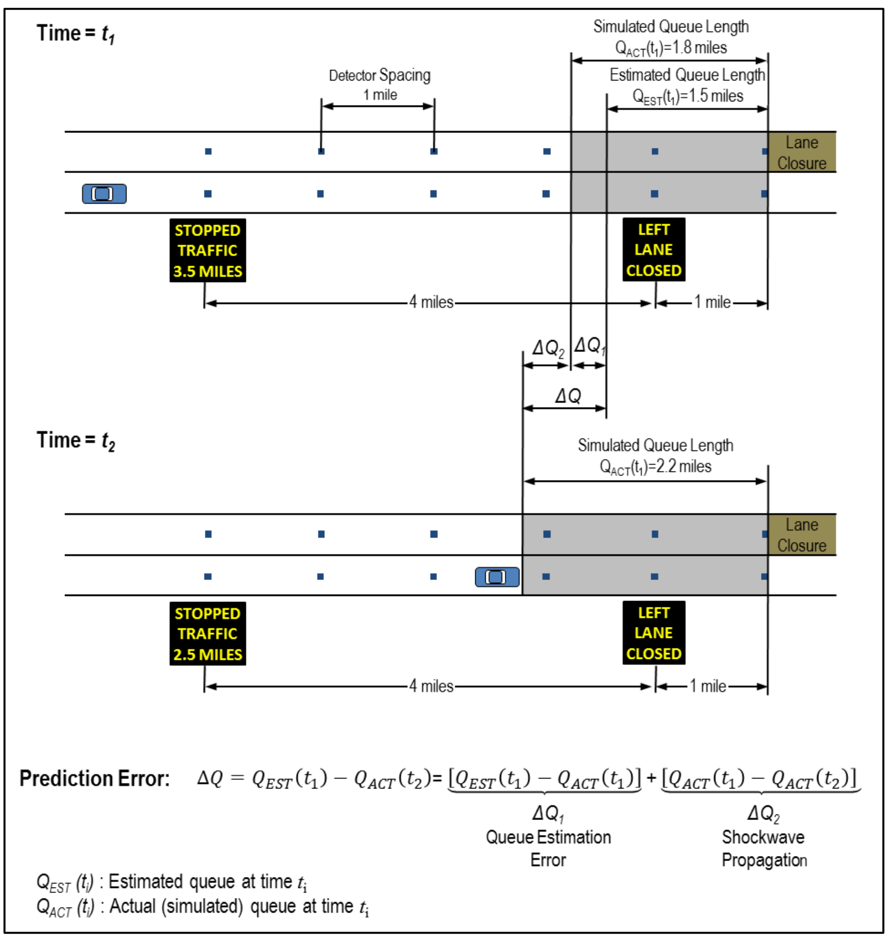


Figure 5. Queue Detection Error.

The error component ΔQ_1 is the queue estimation error at the time when the vehicle passes by the DMS. It is a function of detector spacing and speed aggregation interval. The error component ΔQ_2 is due to shockwave propagation during the time period when the vehicle travels from the DMS to the BOQ.

In addition to the queue detection error, there are vehicles that encounter queues without a warning message. At the time when a queue begins forming, there are vehicles between the queue generation point and the DMS that is typically located several miles upstream. These vehicles will not get any warning of the queue downstream. The number of such vehicles that approach the end of queue without being warned depends on the distance of the message sign upstream of the queue generation point. In addition, there are vehicles upstream of the message sign that may also encounter the queue without getting any warning. This is because the warning messages are displayed with some delay after traffic begins to slow. This delay primarily depends on the warning message update interval. The longer the message update interval, the more vehicles are expected to encounter a queue without warning.

As this overview shows, most currently deployed infrastructure-based queue warning systems are unable to accurately detect BOQ location and respond to sudden changes in traffic conditions.

3.2 DESCRIPTION OF DESIRED CHANGES

Lane-Level Queue Detection

There are cases when vehicle queues affect a subset of lanes only (e.g., exit ramp overspill to freeway) while traffic in adjacent lanes can move at near free-flow speeds. This imbalance in queues and speeds requires lane-by-lane queue detection and appropriate queue warning. In other cases when all lanes are equally affected by vehicle queues, lane-by-lane queue detection may not be needed.

BOQ and FOQ Detection

To determine which roadway segment is in a queued state, the queue detection algorithm should be able to identify the location of both the BOQ and FOQ in near real-time. BOQ location is needed to provide reliable queue warning for approaching traffic. FOQ location can be used to calculate the remaining distance and/or time needed for a vehicle to travel through a queued segment.

Shockwave Speed for BOQ and FOQ

An important variable that needs to be considered in queue warning system designs is shockwave speed of BOQ (i.e., the speed of queue propagation upstream). Higher shockwave speeds (faster queue propagation) require shorter update intervals of queue warning messages and shorter speed aggregation intervals in the queue detection algorithm of infrastructure-based systems. Knowing the shockwave speed can improve queue detection by making short-term prediction about the location of BOQ.

It is also important to know how vehicle queues dissipate. Vehicle queue dissipation starts when there is a reduction in traffic demand (flow rate) or increase in capacity, or both at the same time. For example, capacity can increase when a work zone lane closure is opened, or when an incident is cleared and vehicle(s) blocking the lane(s) are removed. The following three basic cases of queue dissipation can be distinguished:

- IF traffic demand decreases & capacity remains the same, THEN queue starts to dissipate from the back-of-queue.
- IF traffic demand does NOT decrease & capacity increases, THEN queue starts to dissipate from the front-of-queue.
- IF traffic demand decreases & capacity increases, THEN queue starts to dissipate from both the front- and back-of-queue.

In summary, queue detection and warning can be improved if the shockwave speeds for FOQ and BOQ are known.

User Needs of the V2I Queue Advisory/Warning System

Based on stakeholder input and review of recent work and developments in queue warning systems, user needs associated with the proposed V2I QA/QW system were identified. The user needs classified by user classes that will interact with the system (i.e., vehicle operator, CV operator, TME operator) are listed in Table 2. In addition to a brief description, the rationale for selecting the user need is also discussed in the last column of the table.

Table 2. V2I QA/QW System User Needs

No	ID	User	User Need	Rationale
1.	QW-N1	Vehicle operator	Needs advance information on the existence of slow or stopped traffic queue downstream.	Drivers must be made aware of downstream queues with sufficient notice to take into account typical human reaction times. Additionally, such information must be provided succinctly and in such a way that it is not overly distracting to the driver.
2.	QW-N2	Vehicle operator	Needs up-to-date information on key queue attributes to be able to choose the best action.	The information may include distance to the BOQ, queue length, average speed in queue, which lanes are queued, expected delay, etc. This information can help the vehicle operator to choose the best action (e.g., safely adjust its speed, change lane, or divert to an alternate route)

No	ID	User	User Need	Rationale
3.	QW-N3	Vehicle operator	Needs PII securely protected.	Data used by the queue warning system should not include personally identifiable information (PII) to protect the privacy of individuals and their vehicles traveling in the traffic stream.
4.	QW-N4	CV	Needs to be able to generate appropriate CV-specific queue warning based on queue information received from TME.	CV needs to be able to interpret and process queue and roadway information received in the form of Road Safety Messages (RSM), and generate appropriate CV-specific queue warning depending on the position of the vehicle relative to the BOQ. Human operated CVs must have appropriate hardware and software to effectively communicate queue warning to the driver. The information may be audio and/or visual and should be provided in a way that is not distracting to the driver.
5.	QW-N5	TME operator	Needs to be able to detect BOQ, FOQ, significant speed changes, and different queued states.	Data from infrastructure sensors and third-party data providers can be supplemented by high-resolution CV data that can improve the accuracy and latency of detecting the locations of BOQ, and segments with stop-and-go traffic conditions within the queue. The FOQ location is also needed to estimate the actual queue length, expected delay, or remaining distance and time in queue. This information enables the TME to provide more accurate (1) queue warning to non-CVs and (2) queue location information to CV, which then determine appropriate warning for the CV operator.

No	ID	User	User Need	Rationale
6.	QW-N6	TME operator	Needs to be able to formulate CV data requests in the format of Query Message (QM).	The V2I QA/QW system will use a flexible messaging scheme defined by the Event-Driven Configurable Messaging (EDCM) concept. It makes it possible to dynamically adjust two-way data exchange between a CV and a TME. The QM defines the geo-fence boundaries and the types and frequency of required vehicle data (e.g., speed, position, heading, lane number) that the CV should send to the TME under certain conditions (e.g., vehicle experiences sudden speed drop exceeding some threshold, or performs a lane change). The QM can include trigger conditions that enable the TME to request CV data at higher-frequency only when desired vehicle dynamics have reached (e.g., speed drop of 65% or greater in a 10-second interval).
7.	QW-N7	TME operator	Needs appropriate Response Messages (RM) that includes the CV data requested in the QM.	The RM includes the CV data collected in response to the request defined by the QM. The frequency of CV data included in the RM is controlled by the trigger conditions defined in the QM.
8.	QW-N8	TME operator	Needs to receive and process infrastructure/ traffic sensor data.	Traffic data from infrastructure-based detection systems is one of the data sources for the V2I QA/QW system. Traffic sensors should collect lane-level data. Then the data are processed (cleaned and aggregated if needed) and stored in the QA/QW database.
9.	QW-N9	TME operator	Needs to receive and process third-party traffic data.	Third-party traffic data (e.g. segment speeds) is one of the data sources for the V2I QA/QW system. The data from third-party data feeds are processed (cleaned and aggregated if needed) and stored in the QA/QW database.
10.	QW-N10	TME operator	Needs to receive and process CV data.	CV-data is one of the data sources for the V2I QA/QW system.

No	ID	User	User Need	Rationale
11.	QW-N11	TME operator	Needs to be able to fuse data from the three data sources.	Infrastructure, CV, and third-party data significantly differ in spatial coverage, spatial and temporal resolution, latency, location referencing, and accuracy. A Data Fusion Module in the TME should be responsible for fusing the different data types (e.g., bring them to common reference), use them to detect the formation of queues, and calculate queue attributes (e.g., BOQ and FOQ locations, shock wave speeds for BOQ and FOQ, vehicle speed at BOQ and average speed in queue)
12.	QW-N12	TME operator	Needs to be able to make short-term predictions of changes in queue states.	BOQ and FOQ locations can be predicted using shock wave speeds determined from previously detected positions of BOQ and FOQ.
13.	QW-N13	TME operator	Needs to generate queue warning messages that help drivers choose the most appropriate response.	Another critical function of the V2I QA/QW system is to provide drivers of upstream vehicles with warning messages that help them chose appropriate responses to the detected queuing situations. The message type may depend on the distance of a vehicle from the BOQ, the speed differential between queued and non-queued vehicles, the availability of lanes that are not in a queued state, and the possibility for diversion to an alternate route. The message content may include distance to BOQ, vehicle speed at the BOQ, expected delay, remaining distance in queue, or other description of the queue condition. Thus, vehicle operators may decide to reduce their speed, change lane or divert and change their route.
14.	QW-N14	TME operator	Needs to be able to predict impending queues.	The V2I QA/QW system should also be able to predict the formation and expected length of impending queues based on archived historical traffic data and queue information.

No	ID	User	User Need	Rationale
15.	QW-N15	TME operator	Need to provide appropriate queue warning messages to upstream vehicles.	Queue information must be disseminated to vehicles upstream of the queue using DMS and CV technology. Non-CVs will be provided with queue warning messages displayed on DMS. CVs will use the queue information received from the TME to generate customized in-vehicle warning.
16.	QW-N16	TME operator	Needs to be able to monitor the performance of V2I QA/QW system and fine-tune if needed.	Based on data received from the field, the TME must be able to validate the reliability of data, analyze the performance of the Q-WARN system overall, and make changes to the algorithm or software to improve performance.
17.	QW-N17	TME operator	Needs to be able to share queue information with other ITS systems on the corridor.	The V2I QA/QW system may be operated as part of a broader ITS traveler information system. In such case, sharing queue information with other sub-systems can improve traffic conditions on a much longer segment of the corridor as well as the connecting roadway network.
18.	QW-N18	TME operator	Needs to be able to share queue information with third-party data provider(s).	Third-party data providers can help with broader dissemination of queue information to users.

3.3 PRIORITIES AMONG CHANGES

In the current version of the ConOps, all user needs listed in Table 2 are considered essential. Essential user needs must be met for the system to achieve its goals. User needs may also be classified as desirable or optional. Agencies with different priorities may decide to revise the current essential classification of some of the user needs.

4. CONCEPTS OF THE PROPOSED SYSTEM

4.1 BACKGROUND, OBJECTIVES, AND SCOPE

The objectives of the proposed systems are as followed:

1. Fuse traffic condition data in real-time from multiple sources including CV, infrastructure-based traffic sensors, and third-party data providers, to produce improved queue warning alert messages.
2. Using the fused data, compute queue boundary information at the lane level, including the location of the front and back of the queue, the speed in queue, estimated delay in queue, and level of confidence associated with the queue alert information. Although lane-level queue information is desired, it may be necessary to use segment-level information in cases when traffic data at the lane-level are not available.
3. Determine the speed differential between vehicles in the queue and vehicles approaching the back of queue.
4. Populate a J2945/4 Road Safety Message (RSM) containing information about the queue ahead.
5. Generate queue warning and traffic delay messages that traffic management entities can broadcast on dynamic message signs.

4.2 DESCRIPTION OF THE PROPOSED SYSTEM

This section provides a systems level overview of the proposed V2I QA/QW system. It provides information on the system users, the interfaces between system components, the planned capabilities, and the system architecture.

The intended operational environment for the proposed system is a high-speed, high-volume freeway. The V2I QA/QW system may be implemented using short- or long-range communication. Figure 6 shows the high-level graphical system overview when short-range communication is used. The main system components include: 1) roadside equipment, 2) CVs, 3) third-party data providers, and 4) TME. Figure 6 also shows the data and information flow between the key elements of the four main system components. Figure 7 shows the implementation of the same system without RSUs using long-range communication between the TME and CV. The two figures also indicate the data and information flow between the key elements and system components.

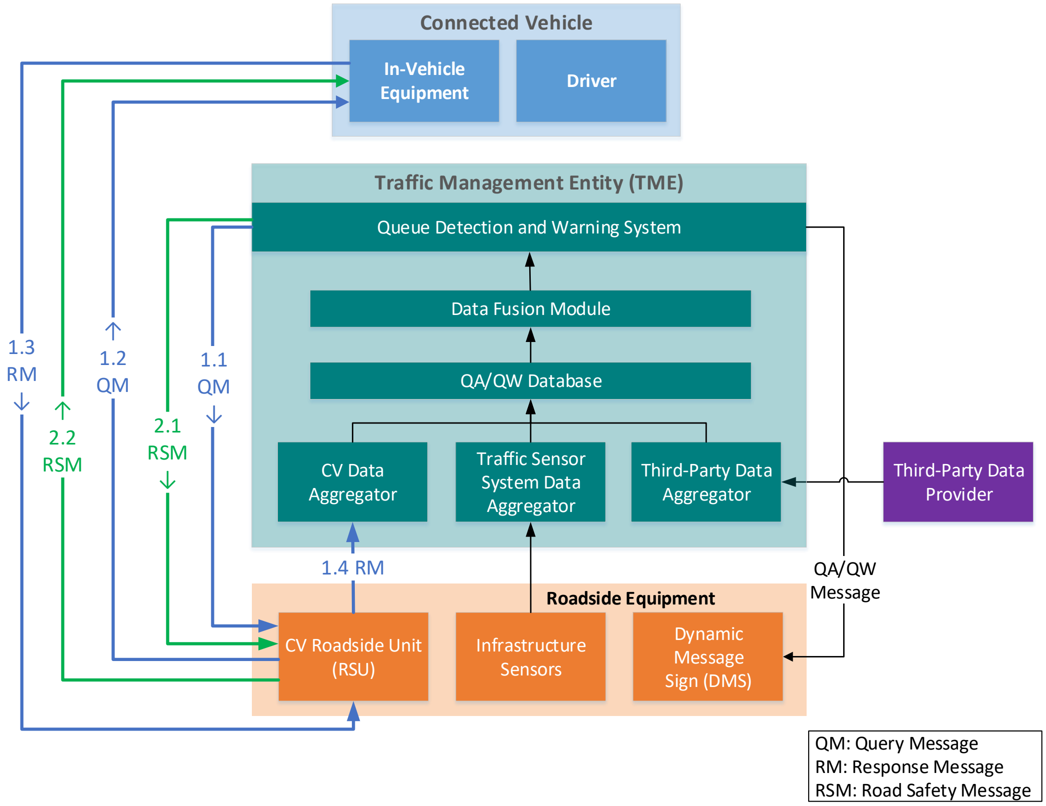


Figure 6. V2I QA/QW System using Short-Range Communication.

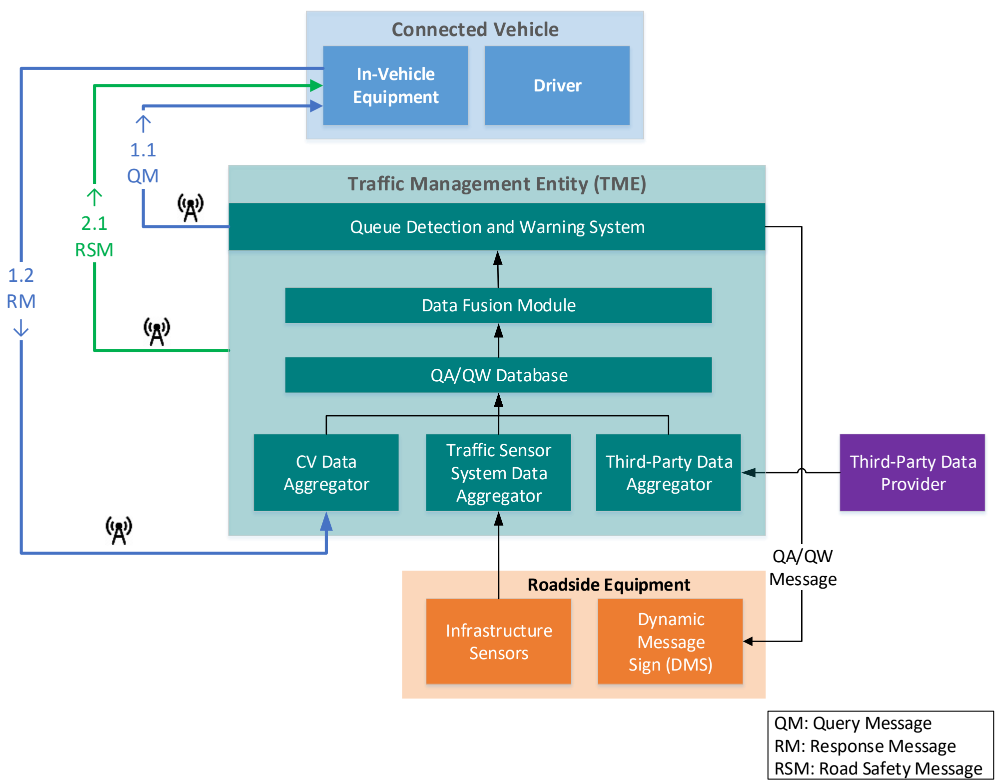


Figure 7. V2I QA/QW System using Long-Range Communication.

Connected Vehicle

The blue-shaded boxes in Figure 6 and Figure 7 represents the CV in the proposed V2I QA/QW system. A CV can collect high-resolution vehicle operational and location data at different frequencies depending on trigger conditions defined by the TME request. Then the TME can use these CV data to supplement infrastructure and third-party data, and thereby improve the accuracy of, and latency in, queue detection. Development of the ConOps for V2I QA/QW applications is based on the following CV-related assumptions:

- CV is capable of short-range communication with RSU (e.g., DSRC).
- CV may also be capable of long-range cellular communication (e.g., 4G-LTE, 5G) with TME and/or third-party data providers.
- CV can receive, interpret, and process QM.
- CV can collect information about the vehicle's location, direction, speed, and other vehicle operational data at the frequency requested in the QM.
- Based on the QM received, the CV can generate appropriate RM and send it to the RSU using short-range communication or directly to the TME using long-range communication.
- CV can receive, interpret, and process RSM to generate appropriate queue warning messages depending on the position of the vehicle relative to the BOQ.
- In-Vehicle Equipment in CV can provide the driver with customized queue warning with minimal distraction to the driver.
- If there is any V2V communication between CVs, it does not involve the transmission of queue related information. Any V2V communication is limited to the transmission of BSMs outside of the functionality of this QA/QW design.

Roadside Equipment

The orange-shaded boxes in Figure 6 and Figure 7 shows the three main elements of roadside equipment and their interfaces with other components of the V2I QA/QW system. The roadside equipment elements include infrastructure sensors, CV roadside equipment, and dynamic message signs.

Infrastructure Sensors

Traffic sensors in the V2I QA/QW system will measure spot speeds and/or occupancies at multiple points. The sensor data is processed by a TME to detect queues and determine the appropriate response/warning. The accuracy of queue detection and BOQ estimation greatly depends on the density of sensors along the roadway. Half mile spacing or less between traffic sensors is desirable.

Some sensors, such as loop detectors and high-definition radar units, are capable of collecting lane-by-lane traffic data (speed, volume, time headway, occupancy). These types of sensors are more appropriate for deployments of queue warning systems at locations with frequent recurring congestion and imbalanced queues between lanes (e.g., exit ramp overspill to freeway lanes).

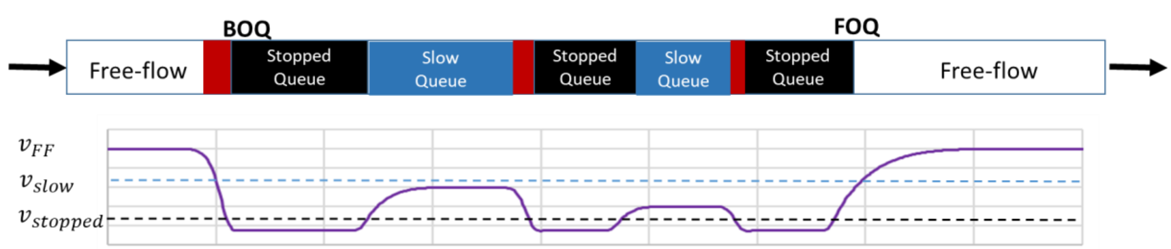
Some constraints that need to be considered in finding the right location for speed sensors include the availability of power source, roadside object blocking the sensors "field of measurement," road construction activities with concrete barriers that make sensor installation and maintenance difficult, and change in roadway alignment (e.g., lane shift) that may require sensor readjustment.

The data collected by the sensors are averaged over pre-defined time intervals (e.g., 1-minute) and used by the TME to:

- Detect the formation of queues,
- Identify the location of the back of queue,
- Estimate the speed of vehicles in the queue, and
- Select appropriate queue warning messages.

Vehicle queues and significant slowdowns can be detected by comparing the time-averaged sensor data to thresholds defined for different queue conditions. Agencies may define their own queue detection thresholds depending on the queue warning application, roadway type and geometry, typical traffic conditions and vehicle composition, potential sight distance limitations, and other factors.

Figure 8 illustrates a relatively simple queue detection logic with two speed thresholds defined as percentages of the free-flow speed. In this example, the speed threshold for slow traffic is 60% of the free-flow speed, and the speed threshold for stopped traffic is 20%. In this illustration, free-flow speed is 75 mph and the two thresholds are 45 mph and 15 mph, respectively. The deceleration zones between segments of different traffic states are indicated by red color. Here "No Queue" condition is true when the average speed is 45 mph or higher, a "Stopped Queue" condition is true when the average speed is below 15 mph, and a "Slow Queue" condition is true otherwise.



	Condition	Traffic state
Speed (v)	$p_1 v_{FF} \le v$	No Queue
	$p_2 v_{FF} \le v < p_1 v_{FF}$	Slow Queue
	$v < p_2 v_{FF}$	Stopped Queue

E.g., Freeway: $v_{FF} = 75\ mph$, $p_1 = 0.6$, $p_2 = 0.2$

Condition	Traffic state
$45\ mph \le v$	No Queue
$15\ mph \le v < 45\ mph$	Slow Queue
$v < 15\ mph$	Stopped Queue

Figure 8. Sensor-Based Queue Detection Logic.

Recent developments in sensor technology make it possible to track vehicles and collect trajectory data instead of spot speeds. For example, the Smart Micro Radar developed by a European company provides an infrastructure-based sensor option for producing CV-type vehicle trajectory data. The most advanced version of this sensor has a range of over 1100 feet with an ability to provide vehicles trajectory (location and speed) information for up to eight lanes. This sensor is also capable of detecting stopped vehicles. At least two US vendors market products that use this sensor. Therefore, the use of this type of sensor data will also be considered in the development of V2I QA/QW system design.

Dynamic Message Signs

Dynamic message signs (DMS) are used for disseminating queue-warning messages for drivers approaching a vehicle queue. They are primarily intended for drivers of unequipped vehicles but can also be seen by drivers of CV.

The locations and number of DMSs included in a V2I QA/QW system should be determined based on the longest expected queue lengths. At least one warning message sign should be deployed upstream of the longest queue to ensure that drivers are protected at all times. If DMS is not available, portable changeable message signs (PCMS) may also be used. Warning message signs should be deployed and positioned in such way that they are clearly visible for all drivers traveling in any of the lanes. Adverse weather conditions with low visibility can significantly reduce the effectiveness of the queue warning system.

If possible, queue warning messages should also be provided upstream of potential diversion points (e.g., exit ramps or freeway junctions/interchanges). This gives drivers the option to divert to a less congested alternate route, if available.

CV Roadside Unit

The RSU provides the interface with two-way communication between the TME and the on-board unit (OBU) of the CV. As much as possible, the V2I QA/QW system will follow the communication standards (SAE J2735) developed by the USDOT for data exchanges between RSU and OBU. However, one of the project objectives is to take advantage of a revised flexible messaging scheme defined by the Event-Driven Configurable Messaging (EDCM) concept that is currently being developed by CAMP. 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.

In the EDCM framework, the TME generates CV data requests in the format of Query Messages (QM). The QM includes conditions that define the types and frequency of required vehicle data (e.g., vehicle position, speed, heading, lane number and queue status) that the CV should send to the TME, and a geo-fence that defines the boundaries where the CV should start acting on the QM. The QM can include trigger conditions that enable the TME to request CV data at higher-frequency only when desired vehicle dynamics have been reached, such as speed drop of 65% or greater in a 10-second interval.

It should be noted that determination of lane number and queue status requires additional sensing/processing of data in CV. The current implementation of EDCM flexible messaging system does not consider additional sensor/processing in CVs. Although the QM can be extended in the future to enable TMCs to request and get such information, the current implementation does not support these additional parameters.

After interpreting the QM content, the CV generates a Response Message (RM) that includes all requested data elements and sends it at the required frequency to the TME via the RSU or directly.

Figure 9 illustrates an example where the frequency of CV data changes depending on the rate of speed change of the CV. A sliding time window (e.g., 20 seconds) is used to check if the speed change is significant and sustained (not just momentary). If the speed change within the time window exceeds a threshold and stays at that level, the CV sends the requested data (e.g., position, speed, direction) at high frequency (e.g., 10 Hz). This high-resolution CV data is used to identify the locations of BOQ, FOQ and additional significant slowdown within the queue. If the speed change within the sliding time window is not significant (i.e., does not exceed the specified threshold), the CV sends the data at much lower resolution (e.g., 1 sec). This lower resolution data is necessary to determine if a vehicle changes lane, exits the roadway or stops.

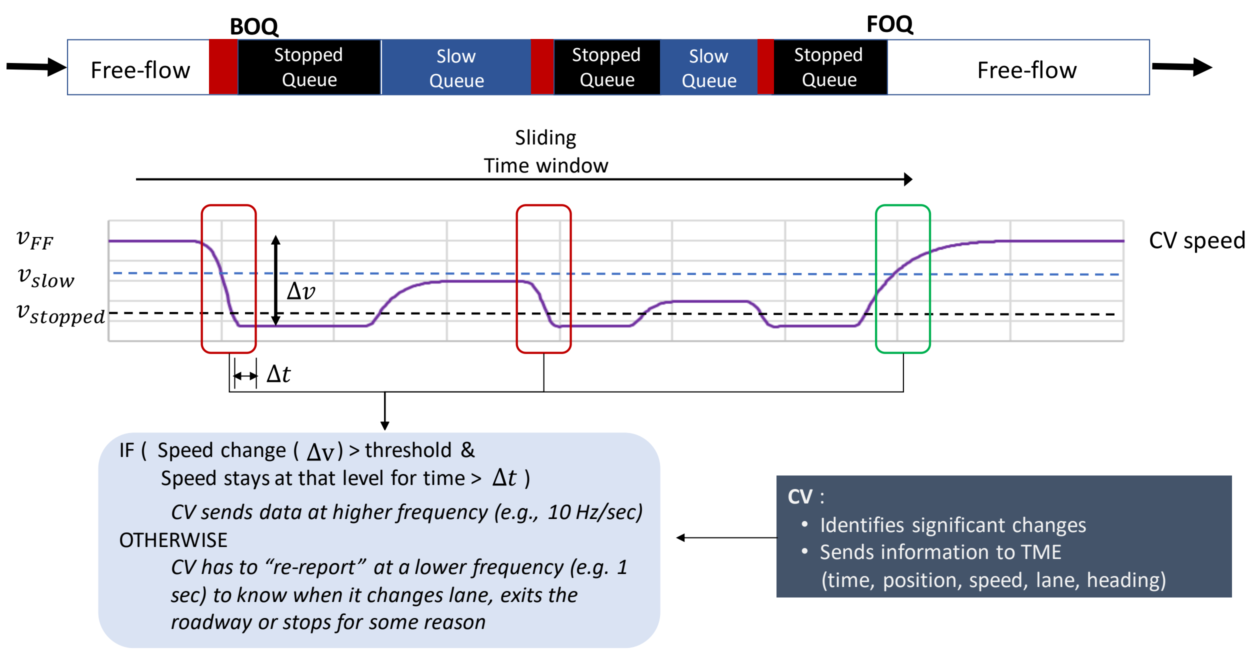


Figure 9. Queue Detection Using CV Data of Different Frequencies.

The TME also generates RSM and sends it to the RSU that forwards it to the CV OBU. In case of long-range communication, the TME sends the RSM to the CV via a cellular network. The RSM may include lane-level roadway map to support high-fidelity QA/QW application that allows the OBU to correctly position the CV in the roadway environment and locate the BOQ and FOQ. The information contained in the RSM is also needed for the CV to select and generate the appropriate queue warning message depending on the CV's actual position and speed.

The CV may also receive position correction information so that the in-vehicle equipment can correct any data received from Global Navigation Satellite System (GNSS) equipment before utilizing it for other purposes.

Third-Party Traffic Data Providers

Third-party traffic data providers offer crowdsourced probe vehicle data over a large portion of the roadway network. The data may include information on incidents, road construction, segment travel times and segment speeds. For example, agencies can access the WAZE crowd-sourced incident data through the Waze for Cities (formerly: Connected Citizen) Program. In exchange, cities/agencies are expected to share their own incident and/or work zone data feeds with WAZE. Details on the mechanism of data sharing with partners of the Waze for Cities program is discussed in the Task 2 Technical Paper. Other third-party data providers such as INRIX, HERE, and TomTom can provide agencies with access to their segment travel time and speed data feeds and some specific product features that can be useful for queue warning applications.

A major benefit of crowd-sourced third-party traffic data is that they can be collected without the need for the deployment and operation of physical infrastructure. They have broad coverage over the road network, especially on limited access roadways.

It is envisioned that a subscription-based third-party vehicle probe data will be used as one of the data sources for the V2I QA/QW system. These data may be requested for preconfigured linear segments or can be obtained from live data feeds of a data collection polygon defined by GPS coordinates. The spatial resolution of third-party data has significantly improved over the past several years. For example, the lengths of INRIX eXtreme Definition (XD) segments range from less than one-tenth of a mile in urbanized areas to a maximum of one mile. Currently, real-time INRIX data has a latency of three minutes from the time data is collected until it is available for downloading via an API. Difference of speed data from adjacent segments can be used to identify queuing conditions.

Traffic Management Entity

The TME is responsible for fusing the data from CV, infrastructure sensors and third-party data providers and use the resulting data set for the detection of queues and generation of appropriate queue warning messages.

Once data are received from one of the data sources, it is checked for potential outliers, missing data, errors, and inconsistencies. After the removal of the erroneous items, the data are aggregated as needed. For example, sensor data collected at 20-second intervals are often aggregated into longer time intervals (e.g., 1 to 5 min). There is a data aggregation module for each data source. The cleaned and aggregated data are stored in a QA/QW database, and then processed by a data fusion application that takes into account the differences in the spatial coverage, spatial and temporal resolution and location referencing of the data from CV, infrastructure sensors, and third-party data.

Based on these fused data, the TME determines the BOQ and FOQ locations and some additional queue attributes (e.g., speed at the BOQ, average speed in queue and boundaries of zones with stopped, slow and stop-and-go traffic). The TME is also responsible for the generation of queue warning messages for the DMS, and Query Messages (QM) and RSMs for CVs.

The interactions between the main system components, the three data sources and the TME are illustrated by the V2I QA/QW use case diagram shown in Figure 10. It represents a use case where all three data sources – sensor data, CV-data and third-party data – are available and used by the V2I QA/QW system. Additional use cases with different combinations of data availability are discussed under Operational Scenarios in Chapter 6.

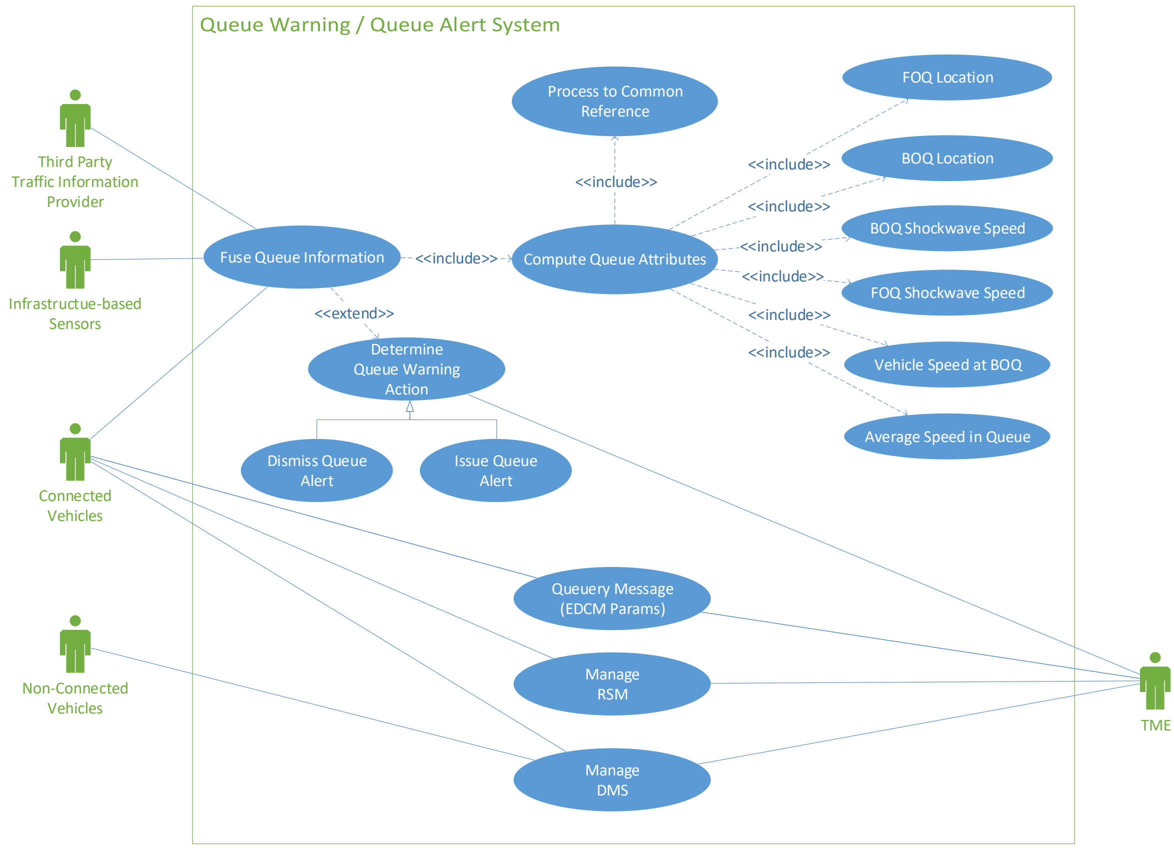


Figure 10. Use Case Diagram for V2I QA/QW System Combining CV, Infrastructure, and Third-Party Data.

As the percentage of CV in the traffic stream increases, the need for roadside sensors for queue and congestion detection is expected to diminish, and at sufficiently high CV penetration, it might be completely eliminated.

4.4 MODES OF OPERATION

The typical modes of operation of the V2I Queue Advisory/Warning system are the following:

- Normal mode.
- Enhanced mode.
- Shadow mode.
- Maintenance mode.

Normal Mode

In normal operation mode, the queue warning system works and performs as designed. All system components function as designed. As soon as the formation of a queue is detected, the system generates appropriate warning messages using a message selection algorithm, and then disseminates them to CVs and DMS to provide warning for vehicles approaching the back of the queue. CV may customize the generic warning message depending on its own location and speed.

Enhanced Mode

In enhanced mode, the queue warning system works similarly to the normal mode, but with extensions required to provide some additional functionality for a specific application/deployment. For example, queue-warning systems deployed as part of an integrated ITS work zone traffic control system may need to work in combination with a DLM traffic control. In this enhanced operation, the queue warning and merge control systems may use the same sensors and share some warning message signs. Therefore, such combined systems may require a modified message selection logic that can provide all required functionalities of the queue warning and merge control subsystems.

Shadow Mode

In shadow mode, all subsystems responsible for queue detection and warning message selection are active and working properly, but the subsystem responsible for disseminating the warning messages is deactivated. This mode can be useful for testing the performance of individual system components, conducting training activities and exercises, or calibrating and fine-tuning some system parameters, such as speed thresholds and speed aggregation intervals for queue detection and warning message update intervals.

Maintenance Mode

In maintenance mode, some subsystems and/or components may be selectively deactivated in order to perform some testing, repair, and maintenance activity on them. During this time, some functionality may become unavailable, and therefore maintenance activities should be performed during uncongested off-peak periods when formation of queues is not expected. However, maintenance mode can always be switched back to normal operation mode if needed (e.g., in case of an incident causing unexpected congestion and queues during maintenance activity).

4.5 USER CLASSES AND OTHER INVOLVED PERSONNEL

User classes of a V2I QA/QW systems can be divided into two main groups:

- Vehicle operators (road users who are expected to benefit from the queue warning messages).
  - CV operators
  - Non-CV operators
- Personnel involved in the operation and maintenance of the system.
- Management and decision makers.

Vehicle Operators

The first user group includes operators of the following vehicle classes:

- Passenger vehicles (e.g., cars, minivans and pickup trucks, motorcycles, and fleet vehicles such as taxis).
- Transit vehicles (buses for public transportation).
- Trucks (Corporate or private freight vehicles for transporting goods).

Vehicles in any of the above classes can be EDCM-enabled CVs.

Personnel Involved in System Operation and Maintenance

The second user group includes ITS professionals, traffic engineers, electrical engineer and software developers, technicians and field personnel, law enforcement, and EMS personnel. They are involved in the development, deployment, operation and maintenance of the queue warning system. They have different levels of access to the system. Field personnel are primarily involved in the field deployment and day-to-day monitoring and maintenance of system components. They cannot override warning messages or change any functionality of the system.

Technicians and engineers with operator-level access can interact with the system by overriding warning messages and changing some parameters in the system configuration files. Law enforcement and EMS personnel may also have some limited operator-level access and can deactivate the system if required by an emergency. ITS, traffic, and electrical engineers with supervisory/administrative role have the highest level of access to the system. They can override the operator's decisions and actions and reconfigure system parameters (e.g., change speed thresholds for queue detection) if needed.

Management and Decision Makers

Users interested in and/or responsible for:

- System performance assessment,
- Benefit-cost evaluation,
- Resource allocation, and
- Public information.

4.6 SUPPORT ENVIRONMENT

Some state and local agencies may have their own personnel including traffic engineers, ITS professionals, and technicians with proper training to support operation and maintenance of their queue warning systems. However, in many cases, they use outside vendors for the setup, operation, and maintenance. It is particularly true for temporary deployments of queue warning systems in work zone applications. To minimize maintenance and staff training costs, agencies tend to implement similar queue warning system technologies (both hardware and software) developed by the same vendor, wherever it is possible.

5. OPERATIONAL SCENARIOS

This section presents operational scenarios that explain and illustrate how the proposed V2I QA/QW system can serve the needs of its users under various modes of operation. The operational scenarios are discussed under five use cases that vary based on the availability of different data sources at the facility.

5.1 USE CASE 1: QUEUE WARNING USING INFRASTRUCTURE SENSORS ONLY

The base condition assumes that the roadway facility has sensors to detect traffic conditions and dynamic message signs (DMS) to issue warnings and advisories about the queues detected by the sensors. The sensors may be deployed every mile or half mile along the facility. Depending on the type of sensors deployed, they may provide lane-by-lane or aggregate queueing information. The system must detect the queues and calculate its attributes based solely on the spot speeds collected by the sensors. The system architecture diagram of this operational scenario is shown in Figure 11.

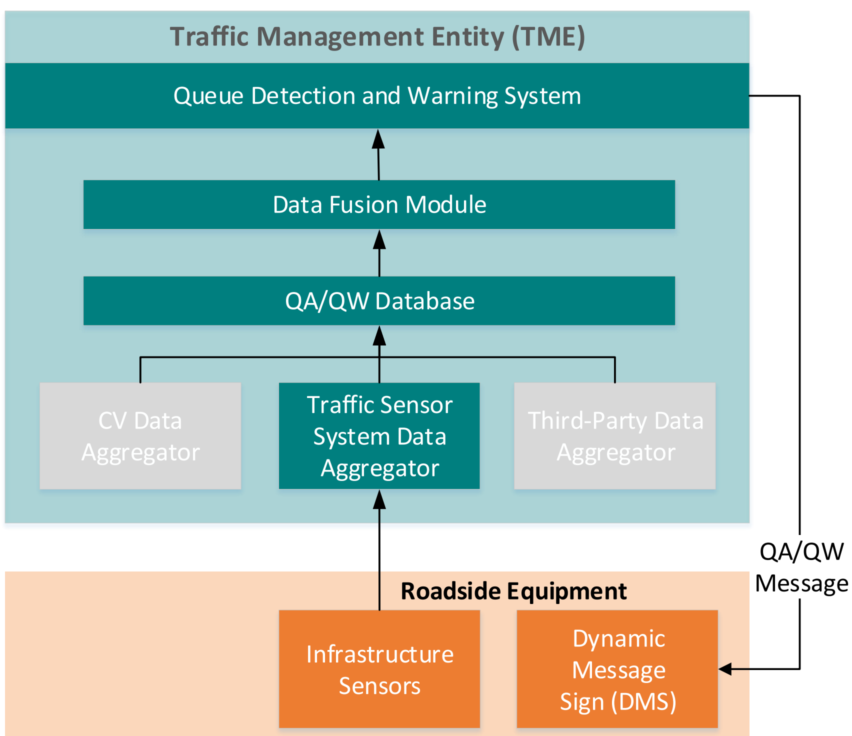


Figure 11. Use Case 1: Queue Warning Using Infrastructure Sensors.

Steps:

1. Sensors installed to monitor conditions on the facility collect traffic data and transmit them to the TME.
2. TME performs quality checks, aggregates the data, detects any queue, and calculates the characteristics of the queue.

3. TME-operated application generates queue warning messages.
4. DMS displays appropriate queue warning messages.
5. TME archives information about the queue, generated warning messages, actions taken, and results for subsequent performance evaluations.

Discussion

This scenario depends upon detection placed every ½ or 1 mile along the facility. Since speed information is available only at the sensor locations, the BOQ location and its distance from the DMSs cannot be accurately determined. The system can assume that the back of queue is somewhere between two consecutive speed sensors, but it cannot determine the exact location. A common approach is to assume the BOQ location at the mid-point between two consecutive sensors where the downstream sensor has already detected the queue, but the upstream sensor has not. A more conservative approach is to assign the BOQ location to the upstream sensor. The queue estimation accuracy of such systems is expected to be around ½ to 1 mile, and the queue warning messages may be updated at 1 to 5 minutes intervals.

5.2 USE CASE 2: QUEUE WARNING USING THIRD-PARTY DATA ONLY

The V2I QA/QW should also be able to operate using third-party traffic data only. This operational scenario can enable the TME to detect and describe queues in locations where sensors are not available. The system still requires a DMS or PCMS to provide information to travelers in the field. This scenario allows the system to identify queues and provide warning to motorists at unexpected locations in areas where infrastructure sensors are not available. The system architecture diagram of this operational scenario is shown in Figure 12.

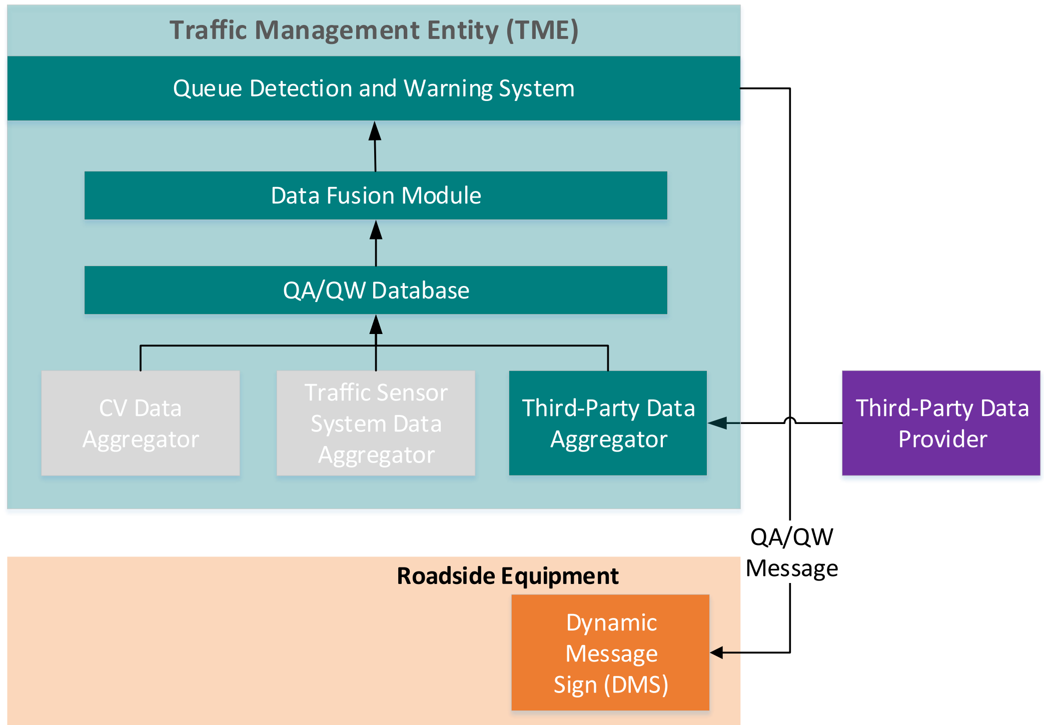


Figure 12. Use Case 3: Queue Warning Using Third-Party Data Only.

Steps:

1. TME requests and receives traffic condition data and information from third-party data provider.
2. TME application determines the existence queues and their characteristics.
3. TME application generates queue warning messages.
4. DMS or PCMS displays appropriate queue warning messages.
5. TME archives information about the queue, generated warning messages, actions taken, and input data for subsequent performance evaluation.

Discussion

This scenario utilizes third-party segment travel time or congestion data to detect and warn about queues on a facility that has no traffic sensors but has DMS or PCMS. The third-party data may include values aggregated over all lanes or provided at lane-level. Data aggregation/update interval of 3 minutes or more causes inherent latencies in queue detection. Furthermore, queue detection accuracy is lower in the absence of lane-level information from the data provider. The Queue Detection and Warning application running in TME determines the queueing parameters based on near real-time, third-party data. Queue warning messages are disseminated via DMS or PCMS. Queue estimation accuracy of such systems is expected to be around 1 mile, and the queue warning messages may be updated at 3- to 5-minute intervals.

5.3 USE CASE 3: QUEUE WARNING USING SENSOR AND THIRD-PARTY DATA

Traffic management entities have an option to subscribe to third-party traffic information and obtain segment travel time and speed data from their data feeds. This information could complement the sensor-based traffic data. Some third-party information (e.g., INRIX XD-segment data) often marks the congested condition at a higher resolution than the available infrastructure sensor data. Depending on the type of sensors deployed, they may provide lane-by-lane or aggregate queueing information. The system architecture diagram of this operational scenario is shown in Figure 13.

Steps:

1. Sensors installed to monitor conditions on the facility collect traffic data and transmit them to the TME.
2. TME requests and receives traffic condition data and information about congestion on the same facility from select third-party data provider.
3. TME-operated application detects the queue and determines queue characteristics based on data received from sensors.
4. Queue warning application at TME combines information from the two data sources and determines the presence of any queue and characteristics (e.g., FOQ and BOQ locations and shockwave speeds, etc.)
5. TME-operated application generates queue warning messages.
6. Upstream DMSs display appropriate queue warning messages based on their distance from the BOQ.
7. TME archives information about the queue, generated warning messages, actions taken, and results for subsequent performance evaluation.

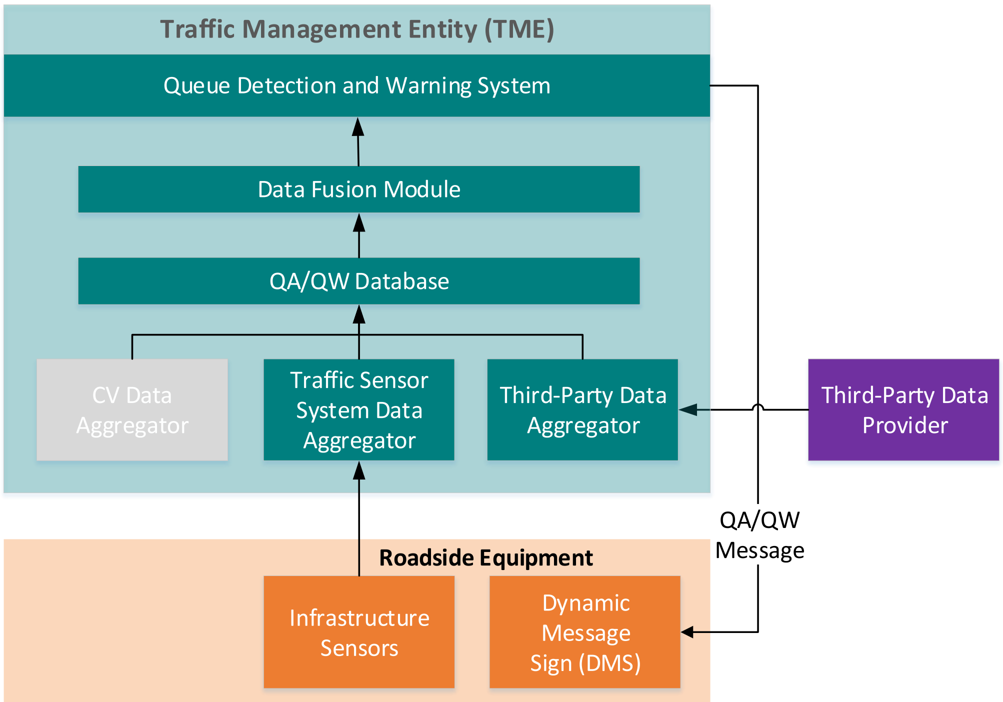


Figure 13. Use Case 2: Queue Warning Using Sensor and Third-Party Data.

Discussion

This scenario utilizes traffic sensors placed every ½ or 1 mile along the facility and third-party traffic data. The third-party data may include values aggregated over all lanes or provided at lane-level. The application running in the Data Fusion Module is responsible for fusing the information from multiple data sources and calculates queue parameters. This fusion must determine which data to keep in the case of conflicting queue information. Queue warning messages are disseminated via DMS.

The queue estimation accuracy of such systems is expected to be around ½ to 1 mile, and the queue warning messages may be updated in every 1 to 5 minutes.

5.4 USE CASE 4: QUEUE WARNING USING SENSOR AND CV DATA

This V2I QA/QW operational scenario uses lane-by-lane data from traffic sensors. In addition, it incorporates CV data into the queue estimation process to improve the accuracy and timeliness of queue detection. The system continues to use DMSs for disseminating queue warnings. In addition, CV operators receive customized queue warning messages based on their positions relative to the BOQ. Figure 14 shows the system architecture for a V2I QA/QW using infrastructure sensors and CV data. The figure shows a system architecture with DSRC-based, short-range communication between CVs and RSU.

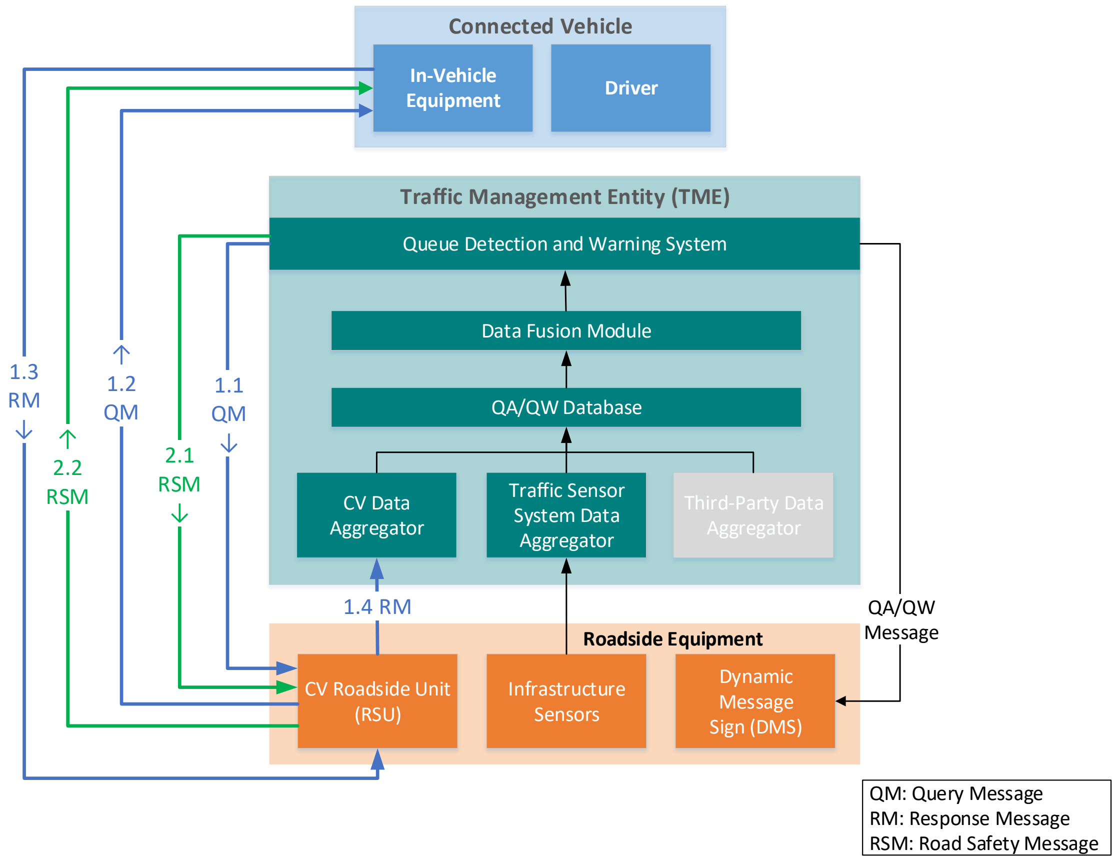


Figure 14. Use Case 4: Queue Warning Using Sensor and CV Data

Steps:

1. Infrastructure sensors collect traffic data and transmit them to the TME.
2. TME generates QM and sends it to the RSU that transmits it to the CV.
3. The CV collects the required data and generates RM.
4. RSU receives the RM and transmits it to the TME.
5. The TME fuses the data from infrastructure sensors and CV.
6. A queue detection application running in the TME detects the queue and determines queue characteristics based on data received from CV and traffic sensors.
7. The TME generates appropriate queue warning messages for DMSs.
8. The DMS displays the queue warning messages received from the TME.
9. CV receives RSM that includes queue information from TME.
10. In-vehicle queue warning application generates and displays individualized warning messages based on the CV's location and speed with respect to BOQ.
11. TME archives queue information and generated warning messages for subsequent performance evaluations.

Discussion

This scenario uses both CV and infrastructure data for queue detection and disseminates warning messages through in-vehicle and infrastructure devices (DMS). The queue estimation accuracy of such systems is expected to be around 100-300 feet. The in-vehicle queue warning messages for CVs are constantly updated based on their changing positions with respect to BOQ. The queue warning messages displayed on roadside DMS may be updated every minute. In the long-term, with increased CV market penetration, CV-based data collection would eliminate the need for infrastructure-based data.

5.5 USE CASE 5: QUEUE WARNING USING SENSOR, CV AND THIRD-PARTY DATA

The V2I QA/QW system can accept data from all three data sources presented in the previous scenarios. The system architecture for a system with all three data sources is shown in Figure 15. The figure shows a system architecture with DSRC-based, short-range communication between CVs and RSU.

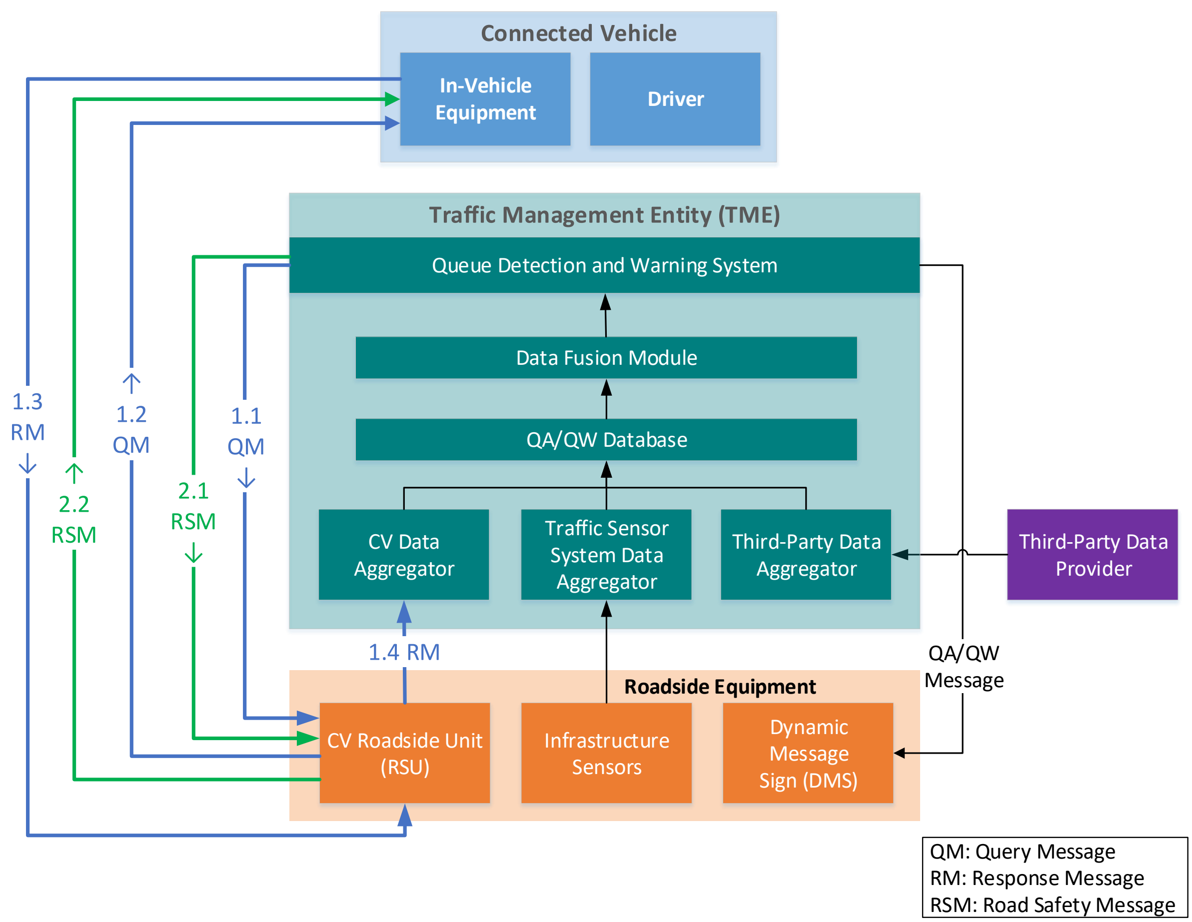


Figure 15. Use Case 5: Queue Warning Using Sensor, CV and Third-Party Data.

Steps

1. Infrastructure sensors collect traffic data and transmit them to the TME.
2. TME generates QM and sends it to the RSU that transmits it to the CV.
3. The CV collects the required data and generates RM.
4. RSU receives the RM and transmits it to the TME.
5. TME requests and receives traffic data and information about congestion from third-party data provider.
6. The TME fuses the data from the three data sources.
7. A queue detection application running in the TME detects the queue and determines queue characteristics based on data received from all three data sources.
8. The TME generates appropriate queue warning messages for DMSs.
9. The DMS displays the queue warning messages received from the TME.
10. CV receives RSM that includes queue information from TME.
11. In-vehicle queue warning application generates and displays individualized warning messages based on the CV's location and speed with respect to BOQ.
12. TME archives queue information and generated warning messages for subsequent performance evaluations.

Discussion

This operational scenario utilizes three different data sources and fuses the information to generate queue advisory/warning. Warning messages are generated based on the locations of DMSs and CVs in relation to BOQ. This approach to queue warning could be deployed in the near-term and operate in a mixed technology environment, since it does not depend solely on CV data for queue detection. Once sufficient CV market penetration has occurred, CV-based data collection would replace infrastructure-based sensors. Initially, the queue estimation accuracy of such systems is expected to be around 100-300 feet. The in-vehicle queue warning messages for CV are constantly updated. The queue warning messages displayed on roadside DMS may be updated every minute.

6. SUMMARY OF IMPROVEMENTS

The proposed V2I QA/QW system makes queue detection and warning more accurate, reliable, and accessible to a broader area within the roadway system. Queue detection accuracy can be measured by the difference in detected and actual location of BOQ and FOQ. Queue warning accuracy is the difference between the BOQ location provided to the vehicle operator in the form of a queue warning message and the actual location where the vehicle joins the BOQ. The reliability of the QA/QW system can be measured by the percent of false negatives and false positive errors. Examples of false negative and false positive in queue detection are not detecting an actual queue and detecting one when there is none. The objective is to minimize instances of both false positive and false negative errors.

CVs provide data at much higher spatial and temporal resolution than traffic sensor data used in traditional infrastructure-based queue warning systems. CV-based, high-resolution trajectory data can significantly improve accuracy and timeliness of BOQ and FOQ detection on a lane-by-lane level. In addition, CV data can be used to determine the shock wave speeds associated with the propagation of both BOQ and FOQ.

Inclusion of third-party traffic data makes it possible to deploy queue warning systems on roadways where/when data from infrastructure traffic sensors and CVs are not available. Third-party traffic data can also enhance the operation of infrastructure-based queue warning systems where sensor coverage is sparse, or locations where some traffic sensors are not working properly or have failed. They can also supplement hybrid infrastructure- and CV-based queue warning systems with very low percentage of CVs in the traffic stream. Archived third-party traffic and queue data may also be used to predict the formation and expected length of impending queues on roadway segments with frequent recurring congestion.

The improved accuracy and reliability of the proposed V2I QA/QW system is expected to reduce the potential of rear-end crashes upstream of vehicle queues typically forming at known locations and times (e.g., work zone lane closures, exit ramp overspill locations, freeway junctions, toll booth, border crossing points), as well as unexpected locations and times (e.g., incidents, debris on road, adverse weather conditions, sand storm, conditions with limited visibility/sight distance).

Considering the cost and resources required for the deployment, operation, and regular maintenance of typical sensor-based queue warning systems, the incorporation of more accurate CV data and relatively inexpensive third-party traffic data into the V2I QA/QW system can offer a cost-effective way to enhance queue warning systems and improve traffic safety.

APPENDIX A. LIST OF ACRONYMS

The following is a list of the acronyms described in this document:

AASHTO	American Association of State Highway and Transportation Officials
BOQ	Back of Queue
BSM	Basic Safety Message
CAMP	Crash Avoidance Metrics Partners LLC
ConOps	Concept of Operations
CV	Connected Vehicle
CV PFS	Connected Vehicle Pooled Fund Study
DLM	Dynamic Late Merge
DMS	Dynamic Message Sign
DSRC	Dedicated Short-Range Communications
EDCM	Event-Driven Configurable Messaging
FHWA	Federal Highway Administration
FOQ	Front of Queue
IOO	Infrastructure Owner operators
ITS	Intelligent Transportation System
OBU	On-Board Unit
QM	Query Message
QA/QW	Queue Advisory / Queue Warning
Q-WARN	Queue Warning
RM	Response Message
RSM	Road Safety Message
RSU	Roadside Unit
TMC	Traffic Management Center
TME	Traffic Management Entity
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2I QA/QW	Vehicle-to-Infrastructure Queue Advisory/Queue Warning