V2I Queue Advisory/Warning Applications: Concept and Design

DESIGN VERIFICATION

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INTRODUCTION

BACKGROUND

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 proposed V2I QA/QW system utilizes data from multiple sources to detect the potential formation of queues on a per lane basis and provide relevant information about the queue to motorists. Data collected by typical technologies and systems (e.g., traffic sensors) deployed by infrastructure owner operators (IOOs), queue and congestion information provided by third-party data providers, and data provided by connected vehicles (CV) are combined to improve the accuracy and timeliness of queue detection. IOOs can use this queue information to provide alerts and warnings to motorists approaching the back of a queue. Queue warnings may be provided through both traditional traveler information devices (e.g., dynamic message signs) and advanced information dissemination devices (e.g., in-vehicle displays).

The concept of operations including user needs, the system requirements and high-level design of the V2I QA/QW system are discussed in the following project documents:

- *V2I Queue Advisory/Warning Applications: Concept and Design - Concept of Operations*[1].
- *V2I Queue Advisory/Warning Applications: Concept and Design –System Requirements*[2].
- *V2I Queue Advisory/Warning Applications: Concept and Design – High-Level Design*[3].

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

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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.
[3] *V2I Queue Advisory/Warning Applications: Concept and Design* - High-Level Design. Texas A&M Transportation Institute. Texas A&M University System, College Station, TX. January 2021.

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 the document titled *Event-Driven Configurable Messaging (EDCM) Queue Advisory & Queue Warning (QA/QW) System and In-Vehicle Application Requirements*[4].

DOCUMENT PURPOSE

The purpose of this technical memorandum is to verify that the high-level design satisfies the system requirements and fulfills the user needs documented in Task 3 and Task 4 of the project. This objective is achieved by developing a traceability matrix that links high-level design functionalities with system requirements and user needs.

The first part of this document provides a brief overview of user needs, system requirements, and high-level design of the proposed V2I QA/QW system. The second part provides design verification results.

[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].

V2I QA/QW HIGH-LEVEL DESIGN OVERVIEW

The intended operational environment for the proposed V2I QA/QW system is a high-speed, high-volume freeway. The V2I QA/QW system is communication-agnostic and 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.

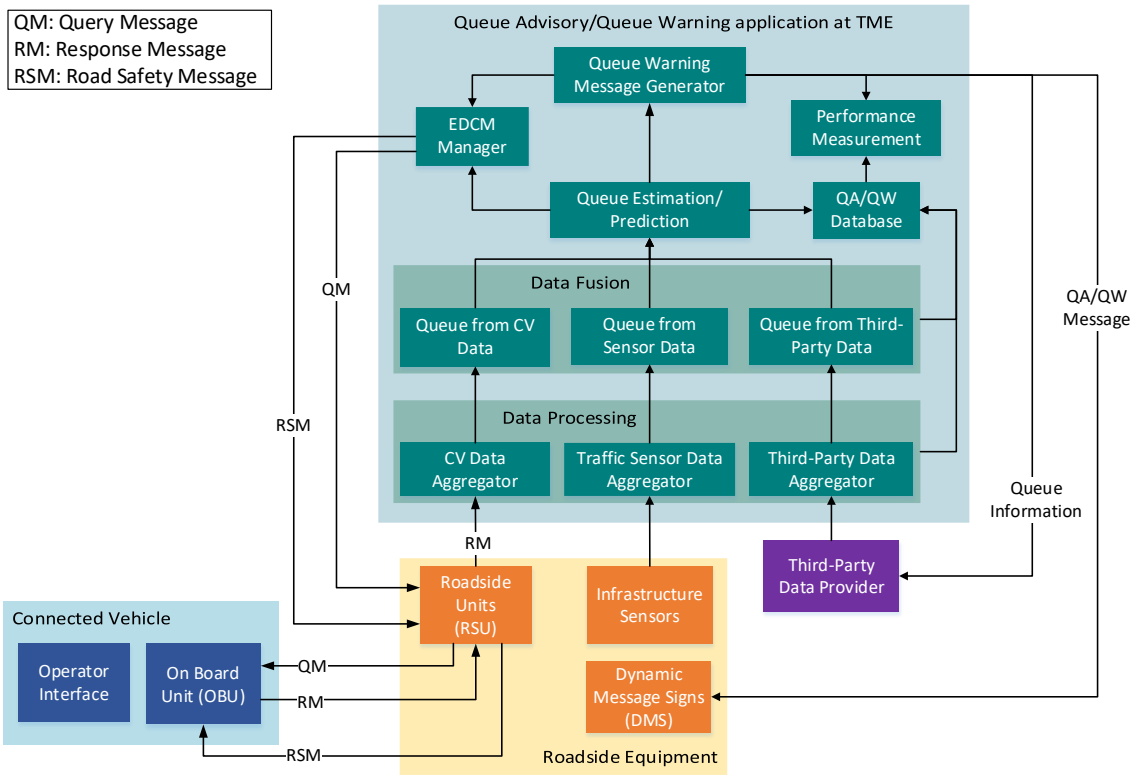

Figure 1. System Diagram of V2I QA/QW Application Using Short-Range Communication.

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 TME. 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.

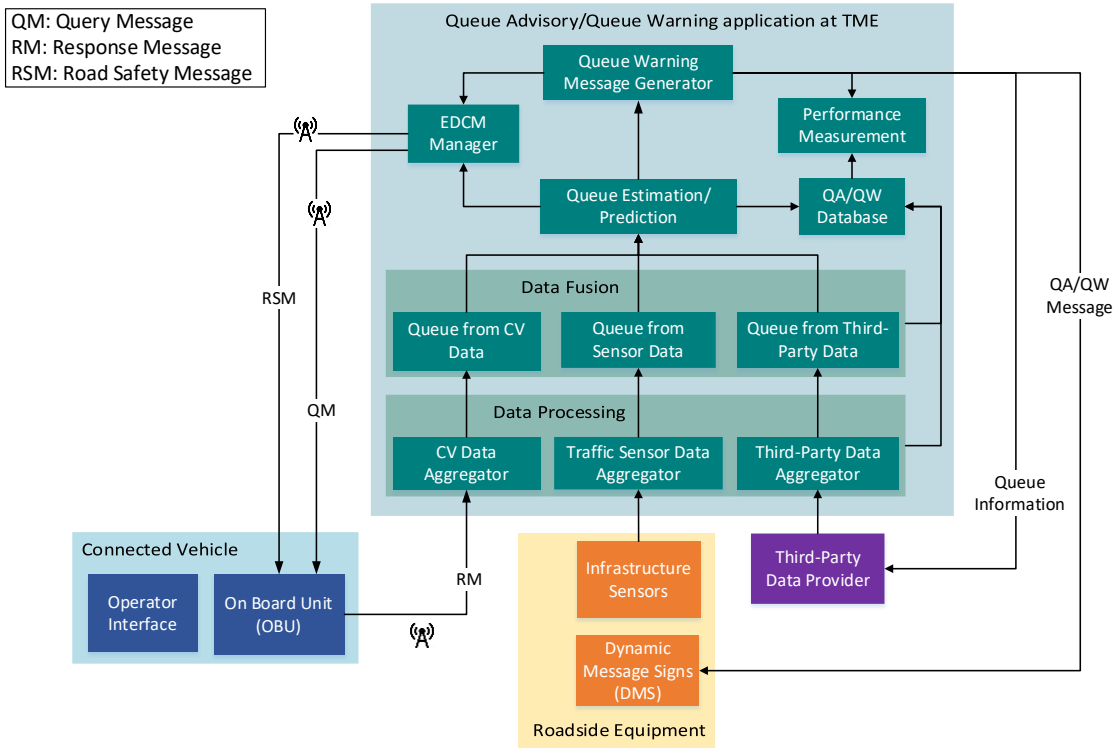

Figure 2. System Diagram of V2I QA/QW Application Using Long-Range Communication.

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.

USER NEEDS

User needs for the V2I QA/QW system were developed in Task 3 of this project as part of the Concept of Operations. Table 2 in the Concept of Operations document lists all identified user needs. For easy reference, this table is reproduced in Appendix A.

SYSTEM REQUIREMENTS

Requirements for the V2I QA/QW system were developed in Task 4 of this project. Tables 1 through 6 in the System Requirements document provide details of these requirements. For easy reference, these tables are reproduced in Appendix B.

The next section summarizes the results of the design verification process, which verifies that the high-level design satisfies all user needs and system requirements.

DESIGN VERIFICATION

It is essential that the overall system and its subsystems satisfy all previously identified user needs and system requirements. The design verification process ensures this by matching the functionalities of the following V2I QA/QW subsystems with relevant user needs and system requirements:

- Data Collection,
- Data Processing,
- Queue Detection,
- Queue Warning, and
- Performance Measurement.

Table 1 shows a traceability matrix that provides verification that all user-needs and system requirements are satisfied. Column 1 lists V2I QA/QW subsystems and provides page numbers of the High-Level Design Document (HLDD) containing detailed discussion of each subsystem. Column 2 provides a brief overview of subsystem functionalities. Columns 3 and 4 provide links to relevant system requirements and user needs.

Table 1. V2I QA/QW High-Level Design Verification.

Subsystem	Subsystem Description	System Requirement	User-Needs
Data Collection (Pages 4-13 in HLDD)	TME receives data from infrastructure sensors: • Per-lane spot speeds (volume and occupancy optional). • Per-lane trajectory data (optional). • Segment travel times and speeds (optional).	1.1 1.2	QW-N8
	TME receives data from 3rd party data providers: • Segment travel times and speeds.	1.3 1.7	QW-N9
	TME receives CV data: • TME generates query message (QM), which includes definition of geo-fence and trigger conditions for data collection. • TME sends QM to roadside unit (RSU). • RSU broadcasts QM. • CV receives and interprets QM. • CV generates response message (RM) containing requested CV data. • CV sends RM to RSU. • RSU transmits RM to TME.	1.4	QW-N10
		1.7	
		3.1	QW-N6 QW-N7
		3.2	QW-N6
		3.3	QW-N7
		3.4	QW-N6 QW-N7

Subsystem	Subsystem Description	System Requirement	User-Needs
Data Processing (Pages 13-15 in HLDD)	TME continuously processes data received from all sources and prepares it for use by queue detection algorithms: • Removes any personally identifiable information (PII). • Performs quality control checks and flags bad/missing data. • Prepares data for additional processing (i.e., resolves differences in formats, temporal/spatial referencing, and latencies). • Archives data in QA/QW database.	2.1	QW-N11
		2.2	QW-N11
		2.3	QW-N11
		2.4	QW-N3
Queue Detection (Pages 16-24 in HLDD)	System detects formation and dissipation of queues using data from multiple sources: • Detects locations of back-of-queue (BOQ) and front-of-queue (FOQ) in each lane. • Detects stop-and-go conditions within a queue. • Determines shockwave speeds of BOQ and FOQ. • Makes short-term queue predictions (changes in locations of BOQ and FOQ) using shock wave speeds. • Estimates other queue attributes (e.g., delay experienced by vehicles in queue).	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8	QW-N5 QW-N12
	System can use archived historical data to predict queues when real-time data is not available.	2.5	QW-N14
Queue Warning (Pages 25-28 in HLDD)	System provides up-to-date queue warning via dynamic message signs (DMS): • TME formulates/selects queue warning messages to display on upstream DMSs. • TME sends these messages to DMS. • TME generates and archives a log of warning messages.	1.5	QW-N15
		5.1	QW-N15
		5.2	QW-N1 QW-N13
		5.4	QW-N2
	System provides up-to-date queue warning to CVs:	5.3	QW-N4

Subsystem	Subsystem Description	System Requirement	User-Needs
	• TME formulates appropriate Road Safety Messages (RSM). • TME transmits RSMs to RSUs located upstream of BOQ. • TME generates and archives a log of RSMs. • RSU receives and broadcasts RSM to CV. • CV generates customized warning messages based on its current position and speed relative to the information (BOQ location and shockwave speed) contained in the RSM. • CV displays/conveys customized in-vehicle warning to CV operator.	5.4	QW-N2
	System shares queue information with other ITS systems in the corridor: • Traveler information systems. • Emergency response teams.	5.5	QW-N17
	TME shares queue information with third-party data provider(s).	5.6	QW-N18
Performance Measurement (Pages 29-31 in HLDD)	System archives available data from all sources for post-event processing: • CV trajectory data. • Infrastructure sensor data. • Third-party segment data.	6.1	QW-N16
	System archives time-stamped attributes of all detected queues at lane-level: • Coordinates of FOQ and BOQ. • Queue length and delay in queue.	6.2	QW-N16
	System archives the following messages and associated event times: • Queue warning messages displayed on DMS. • RSM messages broadcasted to CVs.	6.3	QW-N16

The design verification results in Table 1 prove that the high-level design of the proposed V2I QA/QW system satisfies all user-needs and system requirements.

APPENDIX A: USER NEEDS

Table A1. 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 account for 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).
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.
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.

No	ID	User	User Need	Rationale
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.
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.

APPENDIX B: SYSTEM REQUIREMENTS

Table B1. Requirements for Data Aggregation.

Requirement Number	Requirement Description	User Need Traceability
1.	**DATA AGGREGATION**	
1.1	The V2I QA/QW system shall interface with the Traffic Sensor Subsystem of a TME to receive traffic monitoring information in each lane for each detector station.	QW-N8
1.1.1	The traffic sensor system shall publish a timestamp associated traffic sensor data for each detection station.	
1.1.1.1	The traffic sensor system shall publish the average speed in each lane for each detector station.	
1.1.1.2	The traffic sensor system shall publish the measured volume in each lane for each detector station.	
1.1.1.3	The traffic sensor system shall publish the percent time occupancy in each lane for each detector station.	
1.1.1.4	The traffic sensor system shall publish the average time headway between vehicles.	
1.1.2	The traffic sensor systems shall publish the operational status of each traffic sensor.	
1.1.3	The traffic sensor system shall publish the geographic locations of center of each detection zone.	
1.2	The V2I QA/QW system may interface with radar-based traffic sensors capable of measuring vehicle trajectories. (Optional)	QW-N8
1.2.1	The radar-based system shall provide measured vehicle movements on each link on a lane-by-lane basis.	
1.2.2	The radar-based system shall provide a trajectory of travel for each vehicle traveling in each lane.	
1.2.3	The vehicle trajectory shall provide the position and speed of each individual vehicle for the duration that the vehicle is traveling in the detection zone.	
1.3	The V2I QA/QW system shall interface with the Third-Party Data Provider Subsystem of a TME to receive congestion information at segment level and on a lane-by-lane basis, if available.	QW-N9
1.3.1	The Third-Party Data Provider Subsystem shall provide any available queue information using Traffic Management Data Dictionary (TMDD) data formats.	
1.3.2	The Third-Party Data Provider Subsystem shall provide timestamp data.	
1.3.3	The Third-Party Data Provider Subsystem shall provide segment travel times.	
1.3.4	The Third-Party Data Provider Subsystem shall provide BOQ location if available.	
1.4	The V2I QA/QW system shall interface with an agency's Connected Vehicle Subsystem.	QW-N10
1.4.1	The RSU shall be able to receive RMs from all equipped vehicles within its range.	
1.4.2	The RSU shall be able to receive RMs at a frequency of 10 Hz.	
1.4.3	The RSU shall be able to broadcast RSMs to all equipped vehicles within its range.	QW-N4
1.4.4.	The RSU shall be able to broadcast RSMs at a frequency of 1 Hz.	
1.4.5	The RSU shall be able to broadcast QM (including MAP Message) to all equipped vehicles within its range.	
1.4.6	The RSU shall broadcast QM at a frequency of 1 Hz.	

Requirement Number	Requirement Description	User Need Traceability
1.5	The V2I QA/QW system shall interface with agency's Traveler Information System.	QW-N4
1.5.1	The V2I QA/QW system shall interface with agency's Dynamic Message signs.	
1.5.2	The V2I QA/QW system shall interface with other Traveler Information System devices.	
1.6	The V2I QA/QW shall interface with the agency's traffic sensor system data as defined by the TMDD requirement for providing roadway network data.	See TMDD V3.1 Requirement # 3.3.4
1.7	The V2I QA/QW system shall interface with a configuration file that allows the operator to enter data elements needed.	

Table B2. Requirements for Data Fusion.

Requirement Number	Requirement Description	User Need Traceability
2.	**DATA FUSION**	
2.1	The V2I QA/QW system shall fuse queue data from multiple sources.	QW-N11
2.1.1	The Data Fusion subsystem shall obtain data from agency's Traffic Sensor System.	
2.1.2	The Data Fusion subsystem shall obtain desired CV data.	
2.1.3	The Data Fusion subsystem shall obtain queue and/or travel-time data from Third-Party Data Providers.	
2.2	The V2I QA/QW system shall transform the data from multiple sources to a common reference.	QW-N11
2.2.1	The Data Fusion subsystem shall transform data from all sources to a common geographical reference using the agency's Roadway Link Inventory.	
2.2.2	The Roadway Link inventory shall provide the name of the roadway network as assigned by the owner organization for each link. (TMDD V3.1 Req. #3.3.4.3.1.5.2.2)	
2.2.3	The Roadway Link inventory shall provide the name of the link as assigned by the owner organization for each link. (TMDD 3.3.4.3.1.5.2.3)	
2.2.4	The Roadway Link inventory shall provide all other name(s) of the link as assigned by the owner organization for each link. (TMDD 3.3.4.3.1.5.2.4)	
2.2.5	The Roadway Link inventory shall provide the primary route designator information for each link. (TMDD 3.3.4.3.1.5.2.5)	
2.2.6	The Roadway Link inventory shall provide other route designator information associated with the link. (TMDD 3.3.4.3.1.5.2.6)	
2.2.7	The Roadway Link inventory shall provide the linear reference location information for each link. The linear reference version information may also be included. (TMDD 3.3.4.3.1.5.2.3.7)	
2.2.8	The Roadway Link inventory shall provide the length of the link, in meters, for each link. (TMDD 3.3.4.3.1.5.2.8)	
2.2.9	The Roadway Link inventory shall provide posted speed limit along the link for each link. Unless indicated otherwise by the Speed Limit Units data element, the unit for posted speed limit is in kilometers per hour. (TMDD 3.3.4.3.1.5.2.10)	
2.2.10	The Roadway Link inventory shall provide the normal direction of travel on the link as part of the link inventory for each link. Supported values shall include northbound, northeast bound, eastbound, southeast bound, southbound, southwest bound, westbound, northwest bound, not directional, positive direction, negative direction, both directions, and any other. (Patterned after TMDD 3.3.5.1.2.1.2.10)	
2.3	The V2I QA/QW system shall merge the data from multiple sources to a common temporal reference.	QW-N11
2.3.1	The V2I QA/QW system shall synchronize all time elements to UTC time.	
2.3.2	The V2I QA/QW system shall use GPS timestamp as the temporal reference.	
2.4	The V2I QA/QW system shall remove all PII (if any) from all data sources.	QW-N3
2.5	The V2I QA/QW system shall integrate archived historical traffic data and queue information.	QW-N14

Table B3. Requirements for EDCM Manager.

Requirement Number	Requirement Description	User Need Traceability
3	**EDCM MANAGER**	
3.1	The V2I QA/QW system shall have the ability to perform Event-Driven Configurable Messaging to equipped CVs.	QW-N6 QW-N7
3.2	EDCM shall be capable of sending QMs to equipped CVs.	QW-N6
3.2.1	QM shall specify the conditions under which equipped CVs shall provide an RM.	
3.2.1.1	QM shall specify the geo-fenced location of interest.	
3.2.1.2	QM shall specify the direction of travel.	
3.2.1.3	QM shall specify the sample time interval.	
3.2.2	QM shall specify the type of information that equipped vehicles shall provide in response.	
3.2.2.1	QM can request the vehicle to provide basic information.	
3.2.2.2	QM can request that the vehicle provide vehicle position and dynamic information.	
3.2.2.3	QM can request that the vehicle provide the status of its safety systems.	
3.2.2.4	QM can request the vehicle provide the status of vehicle-based systems.	
3.2.3	QM shall specify how equipped vehicles shall provide an RM.	
3.2.3.1	QM shall be capable of requesting instantaneous values from equipped vehicles.	
3.2.3.2	QM shall be capable of requesting composite or averaged data from equipped vehicles.	
3.2.3.2.1	QM can specify that data be averaged over a given time-period.	
3.2.3.2.2	QM can specify that data be average over a defined distance traveled.	
3.2.3.3	QM shall be capable of requesting data from equipped vehicle based on specific criteria.	
3.2.3.3.1	QM can specify that data from equipped vehicles be provided based on certain vehicle status.	
3.2.3.3.2	QM can specify that data from equipped vehicles be updated at specified intervals.	
3.2.3.3.3	QM can specify that data from equipped vehicles be provided based on demand.	
3.2.3.3.4	QM can specify that data from equipped vehicles be provided based on pre-samples.	
3.2.3.4	QM shall be capable of requesting data from equipped vehicles located within a specified region of interest (geo-fenced).	
3.3.	EDCM shall be capable of processing Response Messages (RM) from equipped connected vehicles.	QW-N7
3.3.1	RM shall contain basic information about the vehicle.	
3.3.1.1	Basic information shall include the vehicle type.	
3.3.1.2	Basic information shall include a pseudo identifier for the vehicle.	
3.3.2	RM shall contain information about the vehicle position and dynamic information.	
3.3.2.1	The position and dynamic information shall include the coordinates (latitude/longitude) of the vehicle.	

Requirement Number	Requirement Description	User Need Traceability
3.3.2.2	The position and dynamic information shall include the current heading of the vehicle.	
3.3.2.3	The position and dynamic information shall include the instantaneous speed of the vehicle.	
3.3.2.4	The position and dynamic information shall include the current acceleration of the vehicle.	
3.3.2.5	The position and dynamic information shall include the current yaw of the vehicle.	
3.3.2.6	The position and dynamic information shall include the current steering wheel angle of the vehicles.	
3.3.3	RM shall contain information about the status of vehicle's safety systems.	
3.3.3.1	The status of the vehicle's safety systems shall include the activation of the brake.	
3.3.3.2	The status of the vehicle's safety systems shall include the activation of the traction control.	
3.3.3.3	The status of the vehicle's safety systems shall include the activation of the stability control.	
3.3.4	RM shall contain information about the status of other systems in the vehicle.	
3.3.4.1	The status of other vehicle systems shall include the status of the exterior lights.	
3.3.4.2	The status of other vehicle systems shall include current position of the wiper switch.	
3.3.4.3	The status of other vehicle systems shall include the external air temperature.	
3.3.5.	RM shall provide information based on the aggregation interval specified in QM.	
3.3.5.1	The RM shall provide instantaneous values from equipped vehicles when requested in QM.	
3.3.5.2	RM shall provide composite or averaged data from equipped vehicles when requested in QM.	
3.3.5.3	RM shall report data from equipped vehicle based on the conditions specified in QM.	
3.3.5.3.1	RM shall report data from equipped vehicles based on vehicle status specified in QM.	
3.3.5.3.2	RM shall report the requested data from equipped vehicles at the intervals specified in QM.	
3.3.5.3.3	RM shall report the requested data from equipped vehicles on demand when specified in QM.	
3.3.5.3.4	RM shall report the requested data from equipped vehicles based on pre-samples specified in QM.	
3.3.6	RM shall provide the requested data from equipped vehicles when located within a specified region of interest (geo-fenced).	
3.4	EDCM shall use an eXtensible Markup Language (XML) messaging schema.	QW-N6 QW-N7

Table B4. Requirements for Queue Estimation/Prediction.

Requirement Number	Requirement Description	User Need Traceability
4	**QUEUE ESTIMATION/PREDICTION**	
4.1	The V2I QA/QW system shall be able to detect when a queue forms in each direction of travel.	QW-N5, QW-N12
4.1.1	The V2I QA/QW system shall be able to detect when a queue forms on a lane-by-lane basis.	
4.2	The V2I QA/QW system shall be able to determine the lane(s) which are operating in queued state.	QW-N5, QW-N12
4.2.1	The V2I QA/QW system shall be able to determine when travel in the lane has reached a "slow" queue state.	
4.2.2	The V2I QA/QW system shall have a user-defined threshold for each lane defining the transition between a "slow" queue state and a "stopped" queue state.	
4.2.3	The V2I QA/QW system shall have a user-defined threshold for each lane defining the transition from a free-flow state to a "slow" state.	
4.3	The V2I QA/QW system shall determine the geographic location of the queue.	QW-N5, QW-N12
4.3.1	The V2I QA/QW system shall be able to determine the geographic coordinates of the location of the FOQ in each lane.	
4.3.2	The V2I QA/QW system shall be able to determine the geographic coordinates of the location of the BOQ in each lane.	
4.4	The V2I QA/QW system shall be able to determine the length of the queue in each lane.	QW-N5, QW-N12
4.5	The V2I QA/QW system shall be able to determine the average speed of vehicles within the queue in each lane.	QW-N5, QW-N12
4.6	The V2I QA/QW system shall estimate the expected delay experienced by travelers in the queue.	QW-N5, QW-N12
4.7	The V2I QA/QW system shall be able to estimate queue propagation/dissipation.	QW-N5, QW-N12
4.7.1	The V2I QA/QW system shall be able to determine or predict the speed at which the BOQ propagates/dissipates in each lane.	
4.7.2	The V2I QA/QW system shall be able to determine or predict the speed at which the FOQ propagates/dissipates in each lane.	
4.8	The V2I QA/QW system shall be able to detect when a queue dissipates (i.e., when travel conditions return to free flow).	QW-N5, QW-N12

Table B5. Requirements for Queue Alerts and Warning Messages.

Requirement Number	Requirement Description	User Need Traceability
5	**MESSAGE GENERATION**	
5.1	The V2I QA/QW system shall disseminate queue information to vehicles through multiple sources of information dissemination technology.	QW-N15
5.1.1	The V2I QA/QW system shall produce a queue warning message when traffic is in the "slow" state.	
5.1.2	The V2I QA/QW system shall produce a queue alert message when traffic is in the "stopped" state.	
5.1.3	The V2I QA/QW system shall remove warning and alert messages when traffic is in the "free-flow" state.	
5.1.4	The V2I QA/QW system shall automatically select the appropriate information dissemination devices (e.g., DMS or PCMS) based on the current location of the back of the queue.	
5.2	The V2I QA/QW system shall generate appropriate messages for displaying on agency's DMSs.	QW-N1, QW-N13
5.2.1	The V2I QA/QW system shall identify to a TME operator the appropriate DMSs associated with each queue detected.	
5.2.2	The V2I QA/QW system shall recommend to a TME operator the appropriate message to be displayed on each identified DMS with each queue detected.	
5.2.2.1	For DMSs located upstream of the back of queue, the V2I QA/QW system shall generate a message indicating the travel distance (in one-tenth of a mile increment) to the back of the queue.	
5.2.2.2	For DMSs located within the queue region, the V2I QA/QW system shall be able to provide messages indicating the expected time (or delay) to reach the front of the queue.	
5.2.2.3	For DMSs located within the queue region, the V2I QA/QW system shall be able to provide messages indicating the remaining travel distance to the front of the queue.	
5.2.3	The V2I QA/QW system shall be able to alter the update interval of the queue warning messages based on the speed of BOQ propagation upstream (shockwave speed).	
5.3	The V2I QA/QW system shall send information to connected vehicle for producing queue alerts and warnings.	QW-N
5.3.1	The V2I QA/QW system shall automatically generate a Road Safety Message (RSM) containing the queue information in the Queue Container.	
5.3.1.1	The queue container shall include a *Road Surface Condition Data Element* describing the current road condition (e.g., dry, wet, snow). (Optional)	
5.3.1.2	The Queue Container shall include a *Queue Status List* data element which lists the queue status for each applicable lane.	
5.3.1.3	The Queue Container shall include an *Associated Lane* data element which identifies the lane for which the information in *Queue Status* is relevant.	
5.3.1.4	The Queue Container shall include a *Queue Ahead Warning* data element indicates the presence or absence of a queue ahead.	
5.3.1.5	The Queue Container shall include a *BOQ Position* data element providing the estimated position of the last vehicle in the queue.	
5.3.1.6	The Queue Container shall include a *BOQ Position Update Time* data element	

Requirement Number	Requirement Description	User Need Traceability
	providing the date and time at which the BOQ position was last updated. (Optional)	
5.3.1.7	The Queue Container shall include a *BOQ Shockwave Speed* data element providing the rate at which the BOQ is moving. A negative value indicates the queue is growing toward the upstream traffic.	
5.3.1.8	The Queue Container shall include a *FOQ Position* data element providing the estimated position of the front bumper of the first vehicle in the queue.	
5.3.1.9	The Queue Container shall include a *FOQ Shockwave Speed* data element providing the rate at which the FOQ is moving. The rate of zero indicates the FOQ is stationary. (Optional)	
5.3.1.10	The Queue Container shall include a *Queue Confidence* data element providing the average confidence (in %) of the estimation, queue speed, FOQ and BOQ position, and shockwave speeds.	
5.3.2	The V2I QA/QW system shall identify to a TME operator the appropriate RSUs associated with each queue detected.	
5.3.3	The V2I QA/QW system shall update the RSM based on current queue information.	
5.4	The V2I QA/QW System should automatically update the appropriate information dissemination devices as the queue information is updated.	QW-N2
5.4.1	The V2I QA/QW System shall automatically update the messages displayed on dynamic message signs as the queue information is updated.	
5.4.2	The V2I QA/QW System shall automatically update the RSM message as the queue information is updated.	
5.5	The V2I QA/QW system shall share queue information with other ITS subsystems using a TMDD message structure.	QW-N17
5.6	The V2I QA/QW system shall be able to share queue information with third-party data providers.	QW-N18

Table B6. Requirements for Generating System Performance Measures.

Requirement Number	Requirement Description	User Need Traceability
6.	**Performance Measurement**	
6.1	The V2I QA/QW system shall archive traffic and vehicle data collected from multiple sources for post-event processing.	QW-N16
6.1.1	The V2I QA/QW system shall archive the data collected from the connected vehicles used to estimate queues.	
6.1.1.1	The V2I QA/QW system shall archive the coordinates (latitude and longitude) of the position of the connected vehicles within a defined geo-fenced area used in the queue estimation process.	
6.1.1.2	The V2I QA/QW system shall archive the instantaneous speed of the connected vehicles within a defined geo-fenced area used in the queue estimation process.	
6.1.1.3	The V2I QA/QW system shall archive the heading of the connected vehicles within a defined geo-fenced area used in the queue estimation process.	
6.1.1.4	The V2I QA/QW system shall archive the connected vehicle data for each user-defined geo-fenced area.	
6.1.2	The V2I QA/QW system shall archive the data collected from all traffic sensors used by the system.	
6.1.2.1	The V2I QA/QW system shall archive the time-averaged speed from all traffic sensors used to estimate queues.	
6.1.2.2	The V2I QA/QW system shall archive the percent time occupancy of all traffic sensors used to estimate queues.	
6.1.2.3	The V2I QA/QW system shall archive the volume measured by all traffic sensors used to estimate queues.	
6.1.3	The V2I QA/QW system shall archive all data from third-party providers used to estimate queues.	
6.1.4	The V2I QA/QW system shall archive all infrastructure-based vehicle trajectory data used.	
6.1.5	The V2I QA/QW system shall archive all traffic and vehicle data on a per lane basis.	
6.1.6	The V2I QA/QW system shall archive all traffic and vehicle data at a user defined interval (e.g., 20-seconds)	
6.1.7	The V2I QA/QW system shall provide a timestamp associated with each archived entry.	
6.2	The V2I QA/QW system shall archive all the queue estimation attributes computed for each lane at a user-defined interval.	QW-N16
6.2.1	The V2I QA/QW system shall archive the coordinates (latitude/longitude) of the FOQ.	
6.2.2	The V2I QA/QW system shall archive the coordinates (latitude/longitude) of the BOQ.	
6.2.3	The V2I QA/QW system shall archive the length of the queue.	
6.2.4	The V2I QA/QW system shall archive the delay in queue.	
6.2.5	The V2I QA/QW system shall provide a timestamp associated with each archived entry.	
6.3	The V2I QA/QW system shall archive all queue warning messages and RSM generated by TME.	QW-N16

Requirement Number	Requirement Description	User Need Traceability
6.3.1	The V2I QA/QW system shall archive all queue warning messages displayed on all DMSs for each geo-fenced area.	
6.3.2	The V2I QA/QW system shall archive all RSM broadcasted to CVs through each RSU for each geo-fenced area.	
6.3.3	The V2I QA/QW system shall provide a timestamp associated with each archived entry.	