

V2I Queue Advisory/Warning Applications: Concept and Design

METHODS AND METRICS FOR PERFORMANCE MEASUREMENT

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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 into connected systems.

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

The purpose of this technical memorandum is to identify methods and metrics for performance measurement for assessing both the functionality and the system performance of V2I QA/QW applications. The document may also serve as a basis for the initial version of a System Validation Plan to be used for validating whether a deployed V2I QA/QW system satisfies all user needs defined in the ConOps document.

The first part of this document provides a brief overview of V2I QA/QW system that needs to be tested and evaluated based on the evaluation methods and performance metrics identified in this document. The second part describes the methods and metrics that can be potentially used to validate the functionalities and evaluate the performance of a V2I QA/QW system.

SYSTEM OVERVIEW

Figure 1 shows a high-level graphical overview of the V2I QA/QW System. The system has 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 figure also indicates the data and information flow between system components.

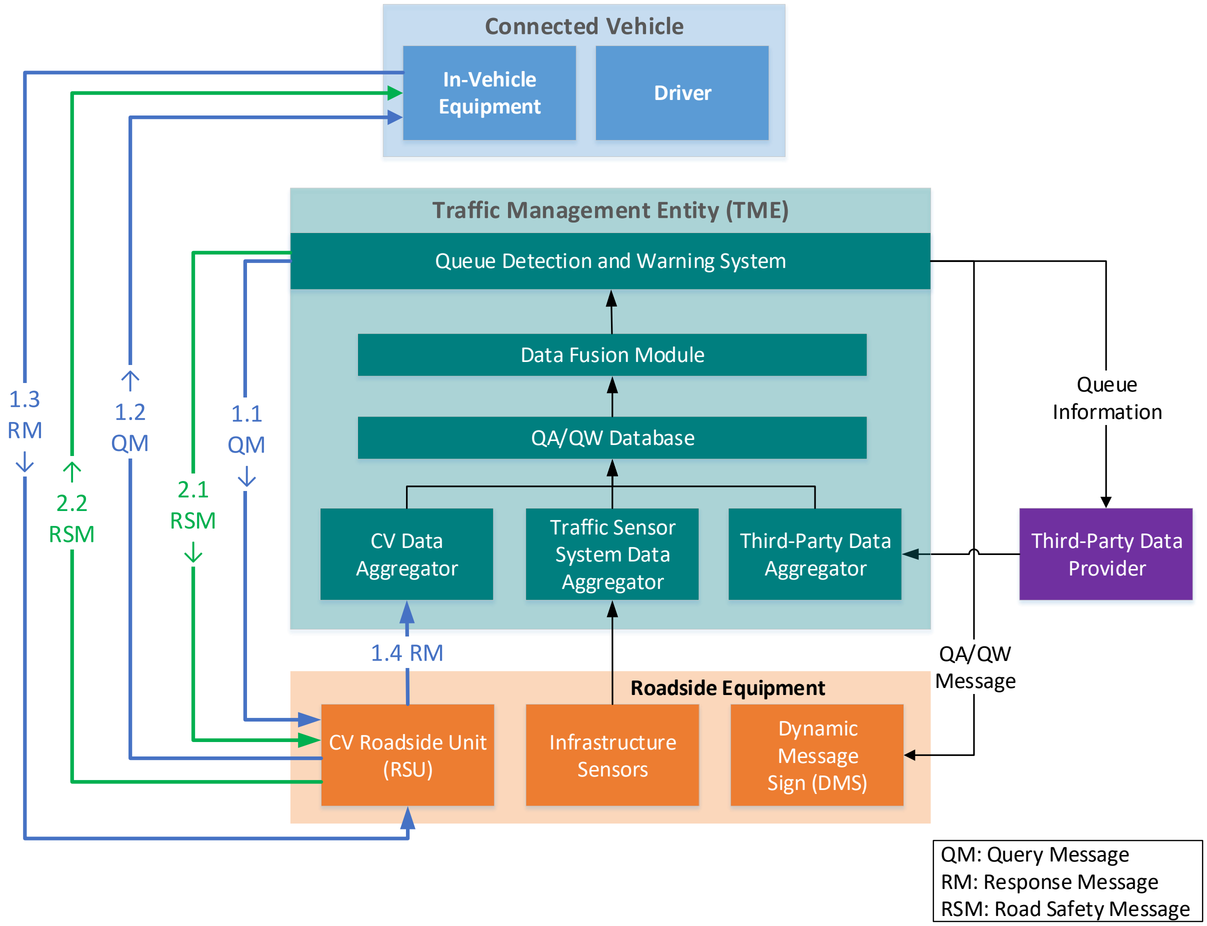


Figure 1. System Diagram of V2I QA/QW Applications Using Short-Range Communication.

Traffic Management Entity

The Traffic Management Entity (TME) is responsible for fusing the data from CVs, infrastructure sensors and third-party data providers and using the resulting data set for the detection of queues and generation of appropriate queue warning messages.

Data received from each source is cleaned (checked for potential outliers, missing data, errors and inconsistencies) and aggregated as needed. The cleaned and aggregated data are stored in a QA/QW database, and then processed by a data fusion application. The data fusion process considers the differences in data characteristics, spatial and temporal resolutions and location referencing between various data sources.

Based on these fused data, the TME determines the back of queue (BOQ) and front of queue (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 dynamic message signs (DMSs), and Query Messages (QM) and Road Safety Messages (RSM) for CVs.

Connected Vehicle

CV collects high-resolution vehicle operational data that can supplement infrastructure and third-party data, and thereby improve the accuracy 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 Roadside Unit (RSU).
- CV is also capable of long-range communication with TME and third-party data providers.
- CV can receive, interpret, and process Query Message (QM).
- CV can collect the data requested in the QM.
- Based on the QM received, the CV can generate appropriate Response Message (RM) and send it to the RSU or directly to the TME.
- CV can receive, interpret, and process/customize RSM.
- CV can provide in-vehicle queue warning with minimal distraction to the driver.
- CV requires V2I communication with RSU or TME.

One of the project objectives is to take advantage of a new flexible messaging scheme defined by the Event-Driven Configurable Messaging (EDCM) concept. EDCM makes it possible to dynamically adjust the frequency and content of two-way data exchange between a CV and a TME depending on changes in traffic conditions. Figure 2 illustrates an example where the frequency of CV data changes depending on the rate of speed change of the CV. A sliding time window is used to check if the speed change is significant and sustained. The high-resolution CV data is used by the TME to identify the locations of BOQ, FOQ, and additional significant slowdown within the queue. This low-resolution data is sufficient to determine if a vehicle changes lanes, exits the roadway, or stops.

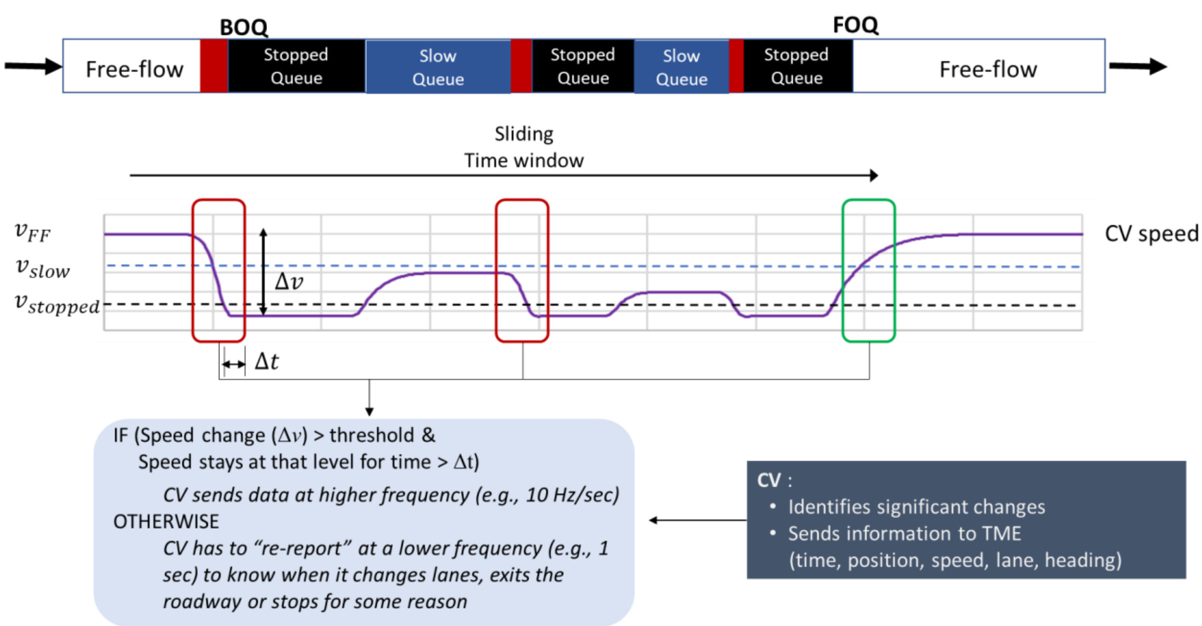


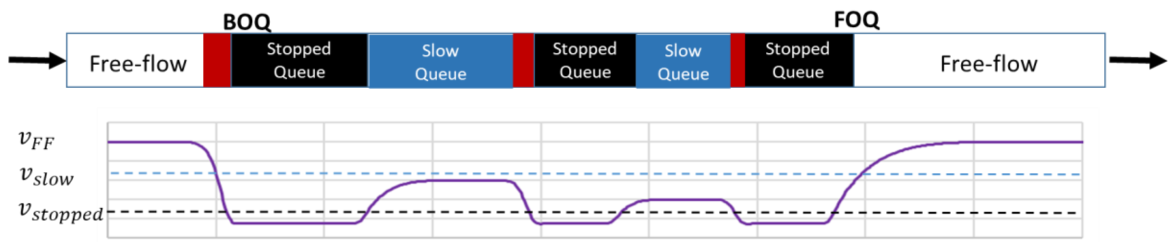
Figure 2. Queue Detection using CV Data of Different Frequencies.

Roadside Equipment

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 upstream of the queue generation point. The sensor data is processed by a TME to detect queues and determine the appropriate response/warning. Figure 3 illustrates a relatively simple queue detection logic with two speed thresholds defined as percentages of the free-flow speed. The speed threshold for slow traffic is 60% of the free-flow speed, and the speed threshold for stopped traffic is 20%. In the following illustration, free-flow speed is 75mph and the two thresholds are 45mph and 15 mph, respectively.



Speed (v)

Condition	Traffic state
$p_1 v_{FF} \le v$	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 3. Sensor-Based Queue Detection Logic

Dynamic Message Signs

DMSs are used for disseminating queue-warning messages for drivers approaching a downstream vehicle queue. They are primarily intended for drivers of unequipped vehicles, but will also be seen by drivers of CVs. If possible, queue warning messages should also be provided on DMS upstream of potential diversion points (e.g., exit ramps or freeway interchanges). This gives drivers the option to divert to a less congested alternate route, if available.

Roadside Unit

The RSU provides the interface for two-way communication between the TME and the on-board unit (OBU) of the CV.

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 and road construction, as well as segment travel times and speeds. For example, 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.

METHODS FOR PERFORMANCE MEASUREMENT

This section discusses potential methods for assessing the performance of V2I QA/QW applications, and the data to be collected and archived by the system to determine the performance metrics defined in the next section of the document.

EVALUATION METHODS

Potential performance assessment methods for the V2I QA/QW systems include:

- Modeling and Simulation
- Shadow Mode Operation
- Before/After study

Modeling and Simulation

Modeling and traffic simulation tools, such as Hardware in the Loop (HITL) and Software in the Loop (SITL) simulations may be used to evaluate the expected performance of a V2I QA/QW system before deployment. They offer cost-effective ways to perform:

- Sensitivity Analysis
- Subcomponent Testing

Sensitivity Analysis

Traffic simulations may be used to assess the sensitivity of queue detection accuracy and latency for various combinations of V2I QA/QW system parameters and their values, traffic conditions, traffic composition, and queueing scenarios. For example, it can be used to evaluate the expected impacts of different:

- Data source availability
- CV market penetration levels
- Infrastructure sensor spacings
- Speed thresholds for queue detection
- Speed aggregation intervals
- Queue warning message update intervals

Subcomponent Testing Using HITL

HITL simulation allows the evaluation of interactions between simulated vehicles and a small number of real connected vehicles. HITL can be used for testing all links/hardware needed for TME-2-CV communication and CV-2-TME communication. It can also be used to test the performance of queue detection algorithms and the appropriateness of in-vehicle queue warning messages provided to CV operators.

Shadow Mode Operation

Shadow mode operation may be useful for testing the queue detection portion of a deployed system in real-time, while queue waning messages are not communicated to the vehicle operators. The objective of this testing stage is to ensure that all system components are working as designed. In addition, this testing stage provides for calibration and fine-tuning of queue detection algorithm parameters in a real environment.

Before/After Study

The main purpose of a before/after study is to evaluate the performance of the V2I QA/QW system. This evaluation is done when the system is deployed and fully operational. The method requires the following steps:

1. Collect data before the V2I QA/QW system is turned on, and compute selected performance measures.
2. Collect data after the system is turned on, and compute selected performance measures.
3. Compare the two sets of performance measures.

Step 1 data collection can be done prior to system deployment or after deployment without activating the system. The before/after data collection for a roadway segment should be conducted under similar traffic conditions.

Since the primary purpose of the V2I QA/QW system is to improve safety by reducing rear-end crashes upstream of vehicle queues, the most preferable safety performance measures are the changes in the number and severity of rear-end crashes as a result of queue warning. However, the sample size needed to obtain statistically significant results may require very long data collection periods. Although crash data may be available over a sufficiently long period before V2I QA/QW deployment (e.g., at locations with frequent recurring congestion), crash data over a comparable time period is also needed after deployment.

If enough crash data are not available, surrogate safety measures may be used. Examples of surrogate safety measures for queue warning systems may include:

- Changes in the number of erratic maneuvers (e.g., excessive braking and/or sudden lane changes to avoid rear-end collision) at the BOQ.
- Changes in speed profiles of vehicles approaching the BOQ.

In case of erratic maneuvers, the safety impact of the V2I QA/QW system is evaluated based on the change in the number of vehicles performing sudden braking or lane changes comparing the periods before and after system deployment. Note that collection of such erratic maneuvers requires video detection with enough coverage of the roadway upstream of the BOQ location at any time when queues form or dissipate.

The change in vehicle speed profiles in response to queue warning is another potential surrogate safety performance measure. Smoother speed profiles over a longer roadway segment indicate safer traffic conditions where vehicles gradually decelerate as they approach the BOQ. To evaluate the change in vehicle speed profiles, special detectors that can track the movement of individual vehicles are needed.

If queue warning messages are displayed on DMSs or Portable Changeable Message Signs (PCMS) located upstream of exit ramps, before/after studies can also be used to assess the impact of queue warning messages on the percentage of vehicles exiting the roadway to take alternate routes.

DATA TO BE COLLECTED AND ARCHIVED

To evaluate the performance of the V2I QA/QW system, several data types that are collected or generated by the system need to be archived for post-event processing. These data types include the following:

- Traffic and vehicle data from multiple data sources
- Attributes of detected queues
- Generated warning messages

Traffic and vehicle data from multiple data sources to be archived include:

- CV data: high-resolution vehicle position, speed, heading data for each vehicle within the defined geo-fenced area.
- Sensor Data: time-averaged speed, occupancy (if available), volume at all sensor locations. Lane-level data are preferable.
- Third party data: segment travel times from live data feeds.

Note that some infrastructure-based radar sensors can provide lane-by-lane vehicle trajectory data like CV data. When they are part of the system, data from such sensors will also be used and archived.

Attributes of detected queues to be archived include:

- Time and location where queue is formed (FOQ)
- Time and location of BOQ at specified time intervals (i.e., every 20-seconds)
- Length of queue at specified time intervals (i.e., every 20 seconds)
- Delay in queue as time progresses (recorded every 20 seconds)
- Lanes in which queues exists (store lane by lane)

Message logs to be archived include queue warning messages generated at TME for the following:

- Displaying on DMSs.
- Broadcasted in the form of RSM to CVs directly or through RSU’s.

Additional data for performance evaluation may also include the following:

- Speed and volume data from temporarily deployed sensors.
- Queue verification data/information from video detection or other sensors.
- Probe vehicle data (data collected inside a CV or another probe vehicle).

METRICS FOR PERFORMANCE MEASUREMENT

This section identifies potential performance metrics that may be used for testing and evaluation of V2I QA/QW applications. The performance metrics are divided into the following four groups:

- Metrics for Functionality Test (M-F-#).
- System performance related metrics (M-SP-#).
- Safety related metrics (M-S-x).
- Metrics related to expected future impacts (M-FI-#).

METRICS FOR FUNCTIONALITY TEST

Metrics that may be used for system functionality testing are identified in Table 1. The purpose of this group of performance metrics is to check if all required functions of the V2I QA/QW system perform as desired. The required functions are related to the following:

- Data/information flow between system components.
- Data processing.
- Queue detection and warning.

The functionality test gives a Yes or No answer to the question in the second column of Table 1. If the answer is No, the percent time when the functionality fails during the test can also be determined.

Table 1. Potential Performance Metrics for Testing V2I QA/QW System Functionality

ID	Functionality Related Performance Metrics Description	Category
M-F-1	Does TME receive data from infrastructure sensors? Items to check: • System receives per-lane data from each data station • Flag if data not received on time	Data Flow
M-F-2	• Is system (TME) receiving data from 3rd party sources?	Data Flow

ID	Functionality Related Performance Metrics Description	Category
M-F-3	Does TME receive CV data? Items to check: • Correctly formatting QM (including definition of geo-fence) • Successfully sending QM to RSU • RSU is broadcasting the QM • CVs are receiving QM and correctly interpreting its contents • CVs in the subject geo-fence area broadcasting requested data (e.g., their heading, position, speed, etc.) at the request frequency • RSU unit is receiving data from CV and transmitting back to TME	Data Flow
M-F-4	Does TME continually process data received from all sources? Items to check: • Removes any PII information • Performs quality control checks and flags bad data • Aggregates data from each source to the desired level and archives it • Maps data from all sources to physical location using an appropriate (predefined) referencing scheme (i.e. mile markers) • Flags missing data • Calculates and saves statistics on missing, bad, and/or late-arriving data and notifies operator when preestablished criteria are met (i.e., data from a sensor station bad or missing for several consecutive time slices, CV data expected at current time of day, and market penetration is not received from an RSU for a specified time threshold)	Data Processing

M-F-5	Does TME prepare data for use by queue detection algorithms?
	
	Items to check:
	• Fuses available data from all three sources
	  ○ handles missing/bad data
	  ○ handles different formats of data
	  ○ handles differences in temporal and spatial resolutions/referencing
	  ○ handles different latencies
	• Archives fused data
	• Formats data and flags missing/bad data for input to the queue detection algorithm
		Data Processing

ID	Functionality Related Performance Metrics Description	Category
M-F-6	Does the system detect any existing and impending queues and their current characteristics within the subject roadway? Items to check: • Can determine locations of BOQ and FOQ, and average speed (or expected travel time) within a queue? • Can make short-term prediction for change in BOQ and FOQ locations using shock wave speeds?	Queue Detection
M-F-7	Does the system provide appropriate queue warning? Items to check: • TME formulates/selects queue warning messages to display on upstream DMSs and sends/activates these messages • TME formulates appropriate Road Safety Messages (RSMs) and transmits these messages to upstream RSUs for local broadcast • TME archives message logs/generated QW messages	Queue Warning
M-F-8	Does RSU receive and broadcast RSM to CV?	Queue Warning

M-F-9	Does CV correctly interpret RSM and generate appropriate warning message?
	
	Items to check:
	• If CV within geofence and traveling in the direction of downstream queue:
	  o Uses its current location to generate message content
	  o Displays/conveys customized message to CV operator
		Queue Warning

M-F-10	CV detects BOQ, FOQ, and locations of significant speed changes between different queued states. Items to check: • CV detects when it joins the back of a queue • CV detects when it clears the front of queue • CV detects speed changes while in different queued states • CV passes this information to TME	Queue Detection

ID	Functionality Related Performance Metrics Description	Category
M-F-11	TME shares information with other ITS systems in the corridor? Examples include: • Traveler information systems • Emergency response teams	Queue Detection and Warning
M-F-12	Is TME successfully sharing queue information with third-party data provider(s)?	Data Flow

SYSTEM PERFORMANCE RELATED METRICS

Metrics that may be used for the evaluation of system performance are identified in Table 2. The purpose of this group of performance metrics is to assess the accuracy, responsiveness, latency and reliability of the V2I QA/QW system.

Table 2. Metrics for Evaluating V2I QA/QW System Performance

ID	System Performance Related Metrics Description
M-SP-1	Queue detection accuracy • Difference in detected and actual location of BOQ and FOQ
M-SP-2	Queue warning accuracy • Difference between the BOQ location provided to the driver by the queue warning message and the actual location where the driver joins the BOQ
M-SP-3	System responsiveness • How quickly initial queue formation, queue growth/propagation and queue dissipation are detected
M-SP-4	Latencies in • Data acquisition from various sources • Data processing and queue detection • Queue-related message transmittal
M-SP-5	Reliability of the system and its components • Percent of undetected queues (False Negative) - a queue exists and is not identified (In this case the system is not working as intended) • Percent of false alarms (False Positive) - a queue is identified when one does not exist (If too many such cases, drivers may stop trusting the system) • Objective is to minimize instances of false positive and false negative

ID	System Performance Related Metrics Description
M-SP-6	Mobility impact • Delay due to queue • Duration of queued/congested state

SAFETY RELATED METRICS

Metrics that may be used for the evaluation of safety impacts of the V2I QA/QW system are identified in Table 3.

Table 3. Metrics for Evaluating the Safety Impact of the V2I QA/QW System

ID	Safety Related Performance Metrics
M-S-1	Change in the number of rear-end accidents
M-S-2	Number of sudden braking/stops
M-S-3	Number of sudden lane changes to avoid rear-end collision
M-S-4	Differentials between average speed of congested segment and immediately upstream uncongested segment
M-S-5	Speed differentials between adjacent lanes in a queued segment
M-S-6	Speed profile (maximum and average deceleration) upstream of BOQ
M-S-7	Speed differentials between zones of different queued states (e.g., slow and stopped queues)
M-S-8	Differential between speeds of approaching vehicles and shockwave speed
M-S-9	Number of weaving maneuvers in a congested/queued segment

METRICS FOR EXPECTED FUTURE IMPACTS

Metrics that may be used for assessing the expected future impacts of a V2I QA/QW system are identified in Table 4.

Table 4. Metrics for Expected Future Impacts of the V2I QA/QW System

ID	Safety Related Performance Metrics
M-FI-1	Long-term safety improvement (e.g., reduction in rear-end crashes)

ID	Safety Related Performance Metrics
M-FI-2	Reduction in network-level travel times and delays if V2I QA/QW is connected to other ITS applications (e.g., regional traveler information systems, speed harmonization)

TRACEABILITY OF PERFORMANCE MEASURES TO USER NEEDS

To ensure that a V2I QA/QW application satisfies all user needs a traceability matrix that connects the user needs to the relevant performance metrics was created. The traceability matrix is shown in Table 5.

Table 5. V2I QA/QW System User Needs Mapping to Identified Performance Metrics

No	ID	User	User Need	Relevant Metrics
1.	QW-N1	Vehicle operator	Needs advance information on the existence of slow or stopped traffic queue downstream.	M-F-9
2.	QW-N2	Vehicle operator	Needs up-to-date information on key queue attributes to be able to choose the best action.	M-F-7 M-F-8 M-F-9
3.	QW-N3	Vehicle operator	Needs PII securely protected.	M-F-4
4.	QW-N4	CV operator	Needs to be able to generate appropriate CV-specific queue warning based on queue information received from TME.	M-F-9
5.	QW-N5	TME operator	Needs to be able to detect BOQ, FOQ, significant speed changes, and different queued states.	M-F-10
6.	QW-N6	TME operator	Needs to be able to formulate CV data requests in the format of Query Message (QM).	M-F-3
7.	QW-N7	TME operator	Needs appropriate Response Messages (RM) that includes the CV data requested in the QM.	M-F-3
8.	QW-N8	TME operator	Needs to receive and process infrastructure/ traffic sensor data.	M-F-1 M-F-4
9.	QW-N9	TME operator	Needs to receive and process third-party traffic data.	M-F-2 M-F-4
10.	QW-N10	TME operator	Needs to receive and process CV data.	M-F-3 M-F-4

No	ID	User	User Need	Relevant Metrics
11.	QW-N11	TME operator	Needs to be able to fuse data from the three data sources.	M-F-5
12.	QW-N12	TME operator	Needs to be able to make short-term predictions of changes in queue states.	M-F-6
13.	QW-N13	TME operator	Needs to generate queue warning messages that help drivers choose the most appropriate response.	M-F-7 M-F-8 M-F-9
14.	QW-N14	TME operator	Needs to be able to predict impending queues.	M-F-6
15.	QW-N15	TME operator	Need to provide appropriate queue warning messages to upstream vehicles.	M-F-7 M-F-8 M-F-9
16.	QW-N16	TME operator	Needs to be able to monitor the performance of V2I QA/QW system and fine-tune if needed.	M-SP-1 M-SP-2 M-SP-3 M-SP-4 M-SP-5 M-SP-6 M-S-1 M-S-2 M-S-3 M-S-4 M-S-5 M-S-6 M-S-7 M-S-8 M-S-9 M-F1-1 M-FI-2
17.	QW-N17	TME operator	Needs to be able to share queue information with other ITS systems on the corridor.	M-F-11
18.	QW-N18	TME operator	Needs to be able to share queue information with third-party data provider(s).	M-F-12