

V2I Queue Advisory/Warning Applications: Concept and Design

REVIEW OF PRIOR/CURRENT WORK

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

The purpose of this document is twofold:

- Gather input from stakeholders who can help identify gaps, constraints, and developing areas that need consideration in the systems engineering activities in subsequent tasks (Tasks 3 through 5) of the V2I Queue Advisory/Warning project. The next section provides details of specific information/feedback desired from the identified stakeholders.
- Review relevant prior work, including the Intelligent Network Flow Optimization (INFLO) project and recent and on-going developments of Queue Advisory/Warning systems by state DOTs and other state/local agencies. This review will focus primarily on those systems that have the potential to utilize multiple data sources, such as infrastructure sensor data (e.g., speed and occupancy), CV data (e.g., BSM messages) and/or traffic data from third party data providers (e.g., vehicle speeds from INRIX or estimated queues from Waze) that may be relevant to the concept development and design of V2I Queue Advisory/Warning applications.

The first part of this document includes a description of the stakeholder engagement process and a summary of stakeholder input. It is followed by a review of the INFLO Q-WARN documents and a section that identifies the INFLO components relevant to this effort. The review covers all major system components, communications flows, queue detection and message selection logic, and identifies key elements of the INFLO-QWARN system architecture that may serve as the basis for the Systems Engineering (SE) activities of the V2I Queue Advisory/Warning project. The last section of the document provides a review of recent and on-going developments of Queue Advisory/Warning systems. The review primarily focuses on those systems that have the potential to utilize multiple data sources such as infrastructure sensor data, CV data, or traffic data from third party data providers.

STAKEHOLDER ENGAGEMENT

The complexity of this project requires the need to engage a variety of transportation stakeholders throughout its duration. Initially, stakeholder interviews will be conducted to identify gaps, constraints, and developing areas that need consideration in the SE activities across the technical tasks. Appendix A provides a questionnaire that has been prepared for use to gather this information via telephone interviews. It includes technical questions related to the stakeholder's experience with, and interest in, queue warning systems, technical details about any past, existing, and/or planned systems, recommendations about additional agency staff that could be contacted, and their willingness to participate as a stakeholder in planned project activities (i.e., webinars, reviewing documents, etc.). Stakeholders who agree to participate in future activities will be asked to review draft documents as they are prepared and participate in periodic walkthroughs of specific deliverables, such as the draft Concept of Operations, the draft System Requirements, and the draft High-Level Design documents for vehicle-to-infrastructure (V2I) Queue Advisory/Warning applications. The intent is to ensure that the content developed addresses the identified gaps and provides effective guidance to agencies interested in implementing queue warning systems. Stakeholder involvement in latter tasks will be used to validate that their concerns are adequately addressed.

The research team has prepared a robust plan of action and interaction with the stakeholder group that clearly identifies the desired audiences, delineates the engagement goals, puts forth a comprehensive framework of how contact and communication take place, and sets a tentative schedule of when this contact occurs. Equally important, this engagement plan establishes a path to gather the information necessary for the effective completion of the research project. The research team has identified an initial list of stakeholders and will finalize the list based on feedback received from the CV PFS members. Selection criteria included, but were not limited to:

- Representatives from entities that are actively involved in the deployments or operation of Intelligent Transportation Systems (ITS) infrastructure and applications relevant to V2I Queue Warning;
- Members from organizations and working groups who have expertise with the latest version of the national ITS architecture, standards and joint efforts between transportation agencies, universities, auto manufacturers and freight industry; and
- Representatives of third-party data providers.

Organizations and entities considered for stakeholder selection included, but were not limited to, the following:

- State/local departments of transportation (DOTs);
- American Association of State Highway and Transportation Officials (AASHTO);
- ITS America;
- Cooperative Automated Transportation (CAT) Coalition AV Working Groups;
    - Policy, Legislative & Regulatory Working Group;
        - Planning Working Group;
        - Infrastructure /Industry Working Group;
    - V2I Groups;
        - Strategic Initiative Working Group;

- Technical Resources Working Group;
- Peer Exchange and Outreach Working Group;

Standards working groups;

- SAE DSRC Technical Committee; and
- Cellular Vehicle-to-Everything (CV2X) Committee.

These stakeholders will be engaged throughout the entire project. If needed, additional stakeholders will be identified in the course of the project.

As identified in Figure 1, the research team has established a comprehensive and logical process for stakeholder engagement.

Figure 1. The Stakeholder Engagement Process.

- Step 1 is the *identification* of potential participants. Participants will be identified through professional contacts, recommendations from the CV PFS, and other representatives and recognized industry experts.
- Step 2 will focus on the *invitation* to the potential participants. Where possible, this invitation will occur via personal contact from the research team member with the closest relationship. For those participants where a desired participant is not a known professional contact, the research team will attempt telephone and email communication to recruit participation. In all instances, the research team will develop a short 'pitch' or recruiting statement to generate interest in the challenge and participation.
- Step 3 will *initiate dialogue* with the recruited participants. Because these will not be paid participants, it is critical to clearly state to the participants what the project is tasked to do, what the expectations of the stakeholders are, and what the research objectives are. This will be communicated via a single page document that will essentially serve as a charter for the group. In this manner, all participants will know exactly what is being requested and in what timeframe.
- Step 4 will be the actual conduct of *stakeholder activities*. These activities are envisioned to include an introductory webinar for all participants. Materials will be prepared prior to the webinar and submitted to the CV PFS for review. Written feedback is expected within two weeks after the webinar. It is anticipated that throughout the course of stakeholder engagement, a range of potential activities may take place, including open discussions via webinar, walkthrough meetings in-person or via webinar, conference calls, or email, and requests for comments and feedback on specific documents.
- Step 5 is the *disbanding* of the stakeholder group. This is specifically called out as a step because it represents a concrete end to the stakeholder process. The stakeholders will

have the opportunity to see the final document prepared summarizing all activities and findings from the engagement process. Additionally, it is important to recognize that the stakeholders have provided valuable time and knowledge into this process and that should be appropriately recognized.

As part of Step 1, the research team has prepared a draft list of stakeholders whom they will approach to participate in this project, serving as the first step in the stakeholder engagement process. The initial list is presented in Table 1.

Table 1. Initial List of Stakeholders.

Association / Group of Organizations	Stakeholder Name	Organization	Role / Position
Cooperative Automated Transportation (CAT) Coalition	Blaine Leonard	UDOT	Chair of Strategic Initiatives Technical Working Group of CAT Coalition
	Joe Averkamp	PARSONS, McLean, VA	Vice Chair of Strategic Initiatives Technical Working Group of CAT Coalition
	Faisal Saleem	Maricopa County DOT	Chair of the Technical Resources Working Group of CAT Coalition
	Tom Timcho	WSP	Principal Connected/Automated Vehicle Consultant
	Roger Millar	WSDOT	Secretary of Transportation
	Jennifer Cohan	DelDOT	Chair of V2I Working Group of CAT
ITE	Siva Narla	ITE	Transportation Technology Senior Director of ITE
	Kevin G. Hooper	ITE	Strategic Projects, ITE
	Douglas E. Noble	ITE	Senior Director of Management and Operations
	Jeffrey A. Lindley	ITE	Associate Executive Director, ITE

AASHTO	Gummada Murthy	AASHTO	Associate Program Director, Operations
Society of Automotive Engineers (SAE) Infrastructure Working Group	Roy Goudy	CAMP/Nissan	Senior Principal Engineer
	Richard K. Deering	CAMP	Consultant
	Lee Mixon	Mixon Hill	President
	Justin McNew	JMC Rota Inc.	President
Third-Party Traffic Data Providers	Terri Johnson	INRIX	Solutions Director, ITS
	Jim Dale	City of Austin, TX	Assistant Director, Austin Transportation Department

To identify gaps, constraints, and new developing areas that should be considered in the SE activities of the V2I Queue Advisory/Warning project, the above list of potential stakeholders was expanded by including additional people who are expected to have first-hand experience with queue warning systems, sensor and detection technologies, and third-party traffic data. Table 2 identifies these stakeholders, all of whom have been requested to participate in a phone interview. It also identifies those who have already responded to the initial request and have been interviewed. Questions identified in Appendix A were used as a guide to seek feedback from the stakeholders.

Table 2. Additional Stakeholders.

Name	Agency	Title	Request Sent	Interviewed
Magdy Kozman, PE	Texas DOT	Transportation Operations Engineer	X	X
Erin Schoon, PE	Wisconsin DOT	Statewide Work Zone Operations Engineer	X	X
Faisal Saleem, PE	Maricopa County DOT (MCDOT)	ITS Branch Manager & MCDOT SMARTDrive Program Manager	X	X
April Wire, PE, PTOE	Maricopa County DOT	ITS Project Manager. County Rep for Pooled Fund	X	
Galen McGill, PE	Oregon DOT	ITS Program Manager	X	X

Nader Ayoub	Iteris	Regional Vice President, Roadway Sensors	X	X
Steven Torkelson	Iteris	Sr. Product Support Specialist, Roadway Sensors	X	X
Jianming Ma	Texas DOT	Traffic Operations Division	X	X
Virginia Lingham	WSP	Consultant, Advisory Services,	X	X
Mark Demidovich, PE	Georgia DOT	Assistant State Traffic Engineer	X	
Brian Kary	Minnesota DOT	Freeway Operations Engineer	X	
Shawn Yu	Colorado DOT	Standards and Specifications Engineer, Project Development Branch	X	
Anna K. Ching, PE	CalTrans	HQ Traffic Operations	X	
Vinh Dang, PE	Washington DOT	Freeway Operations Engineer	X	
Mark Sommerhauser	Missouri DOT	ITS Project Manger	X	
Gary Carlin, PMP, PE, PTP	INRIX	Director, Business Development	X	X
Rick Schuman	INRIX	VP Public Sector Business Development	X	
David Schrank	TTI	Senior Research Scientist, Mobility Analysis Program	X	X

Summary of Stakeholder Input

This section is a summary of stakeholder input that helped identify gaps, constraints, potential developments, and associated challenges that need consideration in the concept development and design of V2I Queue Advisory/Warning applications.

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. Locations of these sensors are mapped to the geographic network through mile marker referencing. Traditional infrastructure-based sensors collect lane-by-lane speed, volume and occupancy data at the sensor location and aggregate this data over 20- or 30-second intervals before sending it to the TMC. Once received at the TMC, these data must go through a quality assurance/quality control (QA/QC) process, which includes removing bad data items using predefined criteria, such as:

- Entries with error codes (typically values of -1 or 255) added by an in-field processor;

- Entries with zero speed, occupancy and volume;
- Check for consistency of elapsed time between data polls;
- Duplicate records where location identifier, date, and time stamp are identical;
- Date, time, and location identifier values that are not in the valid domain range;
- Data with values larger than possible (e.g., Volume > 3000 vphpl); and
- Multivariate consistency checks (e.g., Invalid if SPEED=0 and VOLUME>0 [and OCC>0]);

Once cleaned, queue warning systems (and other similar applications) 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 impossible to accurately estimate BOQ when it is located in between a pair of adjacent sensors. As a result, most current queue warning systems are unable to respond to sudden changes in traffic conditions.

Potential Developing Areas

Data from additional sources can be used to improve spatial and temporal accuracy and speed of queue detection algorithms by filling any holes in sensor data coverage and those created by the QA/QC process. These additional sources include:

- Segment speed data using Bluetooth sensors. Many agencies use these sensors, but do not retain any personally identifiable information (PII).
- Real-time CV data that includes GPS locations, speeds, and headings of individual vehicles. Even though research has shown the benefits of CV data for queue warning applications, it will take time before CV deployment reaches sufficient market penetration.
- A recent MCDOT investigation concluded that data from electronic logging devices (ELDs), installed in freight vehicles, can be leveraged to produce CV-type data. ELDs can provide vehicle location and heading information to a Roadside Unit (RSU) and can also receive information/message back from the RSU. CV data does not contain any PII.
- Subscription-based vehicle probe data from third parties (e.g., INRIX probe data) can either 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 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 till it is available for downloading via an API. Difference of speed data from adjacent segments can be used to identify queuing conditions. INRIX data does not contain any PII.
- 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 vehicle trajectory (location and speed) information for up to eight lanes. This sensor is capable of detecting stopped vehicles. At least two US vendors market products that use this sensor. This

sensor is also capable of providing vehicle classification. Vehicle trajectory data collected by this sensor does not include any PII.

Gaps and Constraints

Fusing data from multiple sources poses several challenges due the fact that there are differences in how the data is collected and disseminated. For instance:

- Traditional sensors provide average spot speeds, probe data provide space mean speeds over segments that may vary in length from location to location, and CV provide high-resolution trajectory data;
- Different geographical referencing schemes used by different sources (i.e., GPS coordinates, mile marker or another format used by an agency);
- Differences in latency of data (real-time trajectory data vs. aggregation intervals of different sizes);
- Potential differences in clocks between various sources of data;
- Roadway segment with overlapping sensor, probe-data, and/or RSU coverage; and
- Speed data for the same location reported by different sources not matching.

These challenges can be addressed by:

- Selecting a standard referencing scheme for geographic mapping of location data (vehicles position, sensors locations, segment boundaries) and transforming all data to that format;
- Synching clocks to ensure that all sources use a common time base;
- Incorporating procedures that resolve difference in data aggregation levels;
- Calibrating infrastructure-based sensors and incorporating QA/QC processes;
- Proactively maintaining these sensors; and
- Incorporating processes to enable handling of missing data due to sensor or communication failure.

Institutional Factors

In large metropolitan areas, a QWS 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). Any concerns with data privacy and security should also be addressed. Stakeholder feedback obtained as part of this task shows that data security and privacy is not of significant concern. Traditional infrastructure-based sensors do not collect any PII. In the case of 3rd party private-sector provision, data are cleaned at the provider point of origin and are not supplied with any PII (personally identifiable information). In the case of CV placements, personal and data privacy must be protected, which generally includes stripping out PII that could be traced to a person or vehicle. Standard message sets in use for que warning applications do not include PII elements in the data stream.

Finally, resources should be allocated and incorporated in the mid to long range agency/partner plan to provide for routine system maintenance and operation.

INFLO Q-WARN REVIEW

The objective of the INFLO project was to develop a prototype dynamic speed harmonization/queue warning system that utilizes data from both typical infrastructure components and CVs to enhance the capabilities of existing infrastructure-based algorithms. Thus, the INFLO system combines three applications:

- Queue Warning
- Speed Harmonization
- Weather Responsive Traffic Management

This section of the document includes a review of the queue-warning portion of the INFLO bundle. It provides a brief overview of the INFLO system architecture, the major system components, communications flows, queue detection and message selection logic, and identifies key elements that may serve as the basis for the Systems Engineering (SE) activities in the V2I Queue Advisory/Warning project.

Three types of INFLO queue warning algorithms were developed (1):

- Traffic Management Entity (TME) based queue warning
- Cloud-based queue warning
- Vehicle-to-vehicle (V2V) based queue warning

The TME- and cloud-based queue warning algorithms are relevant to the V2I Queue Advisory/Warning applications, and therefore these two systems are reviewed here.

TME-BASED QUEUE WARNING

INFLO System Architecture

Figure 2 shows the System Architecture of the INFLO Traffic Management Entity (TME) based Queue Warning/Speed Harmonization System (1).

A critical component of the virtual TME environment is the INFLO database. It can store various data and queue warning message logs, and can be used to document historical conditions, evaluate the performance of the algorithms, and to replay historical scenarios to evaluate new modifications to the algorithms. The INFLO database also provides a flexible mechanism to synchronize the operations of the various components in the TME virtual environment. For example, the queue warning algorithm fuses data from multiple sources including external sources like infrastructure-based sensor traffic data and CV traffic data. Each of these data sources is acquired or generated at a different frequency. For example, the infrastructure-based sensor data is acquired at 20 second to one-minute intervals while the CV data is acquired at one to five second intervals. All this data can be stored in the INFLO database in real-time; and depending on the frequency of running the queue warning algorithm, the algorithm will query the database for the data it needs and generate the proper warning messages.

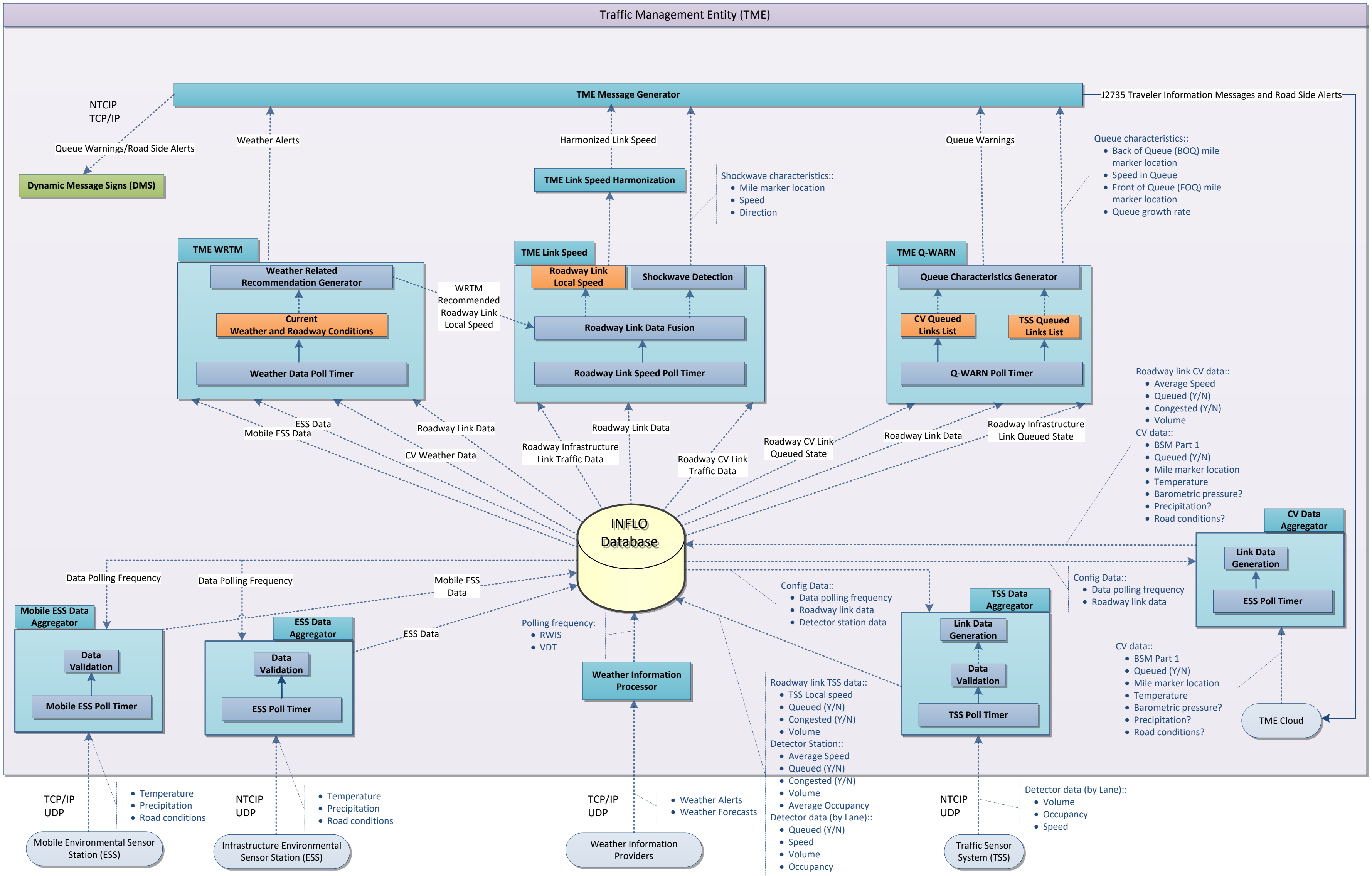

Figure 2. System Architecture of INFLO TME-Based Queue Warning/Speed Harmonization System (1).

Vehicle in Queued State

Determining when a vehicle has reached a queued state is critical in determining the location of the back of the queue. The 2016 Highway Capacity Manual (2) defines a queue as "a line of vehicles, bicycles, or persons waiting to be served because of traffic control, a bottleneck, or other reasons." According to the 2016 Highway Capacity Manual, a vehicle has reached a queued state when it is "within one car length of a stopped vehicle or the stop bar and is itself stopped." Figure 3 shows the approach used in the INFLO prototype to determine if a vehicle is in a queued state.

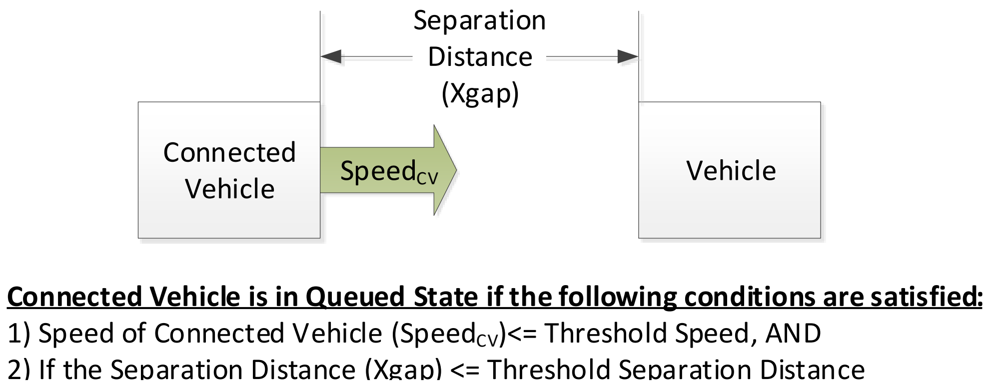

Figure 3. Conditions for Determining if Vehicle is in Queued State (1).

For the purposes of the INFLO Q-WARN prototype deployment, some assumptions have been made (1):

- Each CV can determine for itself whether it is in a queued state using the logic presented earlier and can communicate this state to the TME as part of the Basic Safety Message Part II.
- Data from the vehicle's on-board safety system (such as the forward-looking collision avoidance systems) can be used to measure the separation distance and speed of the vehicles ahead of the CV. If this data is not available, then just the speed of the CV itself can be used to determine whether it is in a queued state.
- The speed and distance thresholds used to determine whether a CV is in a queued state are parameters which are configured by the TME and can be communicated to all CVs when they first enter the deployment corridor.

Other technologies and queue warning applications use different definitions for queued state. For example, in the I-35 work zone project, traffic was defined to be in a "slow" state when average speeds over 5 minutes dropped below 40 mph and in a "stopped" state when the average speed dropped below 25 mph.

Figure 4 shows the logic for determining if a CV is traveling in a queued state.

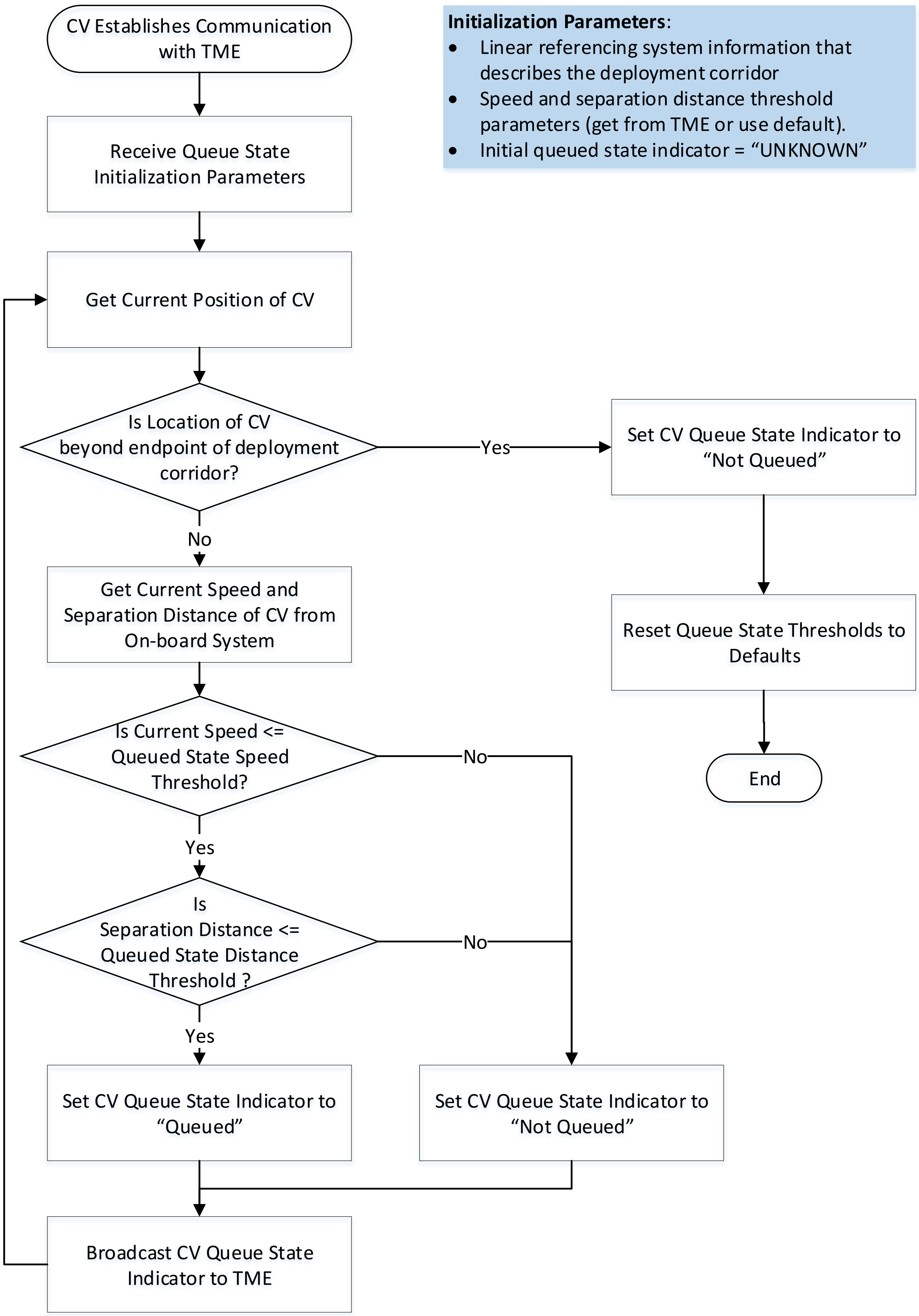

Figure 4. Process for Determining if CV is in Queued State (1).

Segment Operating State

The Connected Vehicle (CV) Data Aggregator shown in Figure 2 collects the data from all the CVs traveling in the deployment corridor and converts it into link-based information. In the prototype, each link in the network will be subdivided into approximately 0.1-mile long sub-links. The CV Data Aggregator is responsible for determining the average speed, congested state, and queued state of all sub-links. The Data Aggregator computes the average speed for each sub-link from all the CVs located in that sub-link. Using the average sub-link speed, the CV Data Aggregator will determine the operating state (free-flow, congested or queued) of each sub-link by comparing the percentage of CVs indicating that they are operating in a queued or congested state.

If a roadway segment includes multiple queued sub-links with congested sub-links between them (e.g., stop-and-go condition), the BOQ is defined as the farthest upstream sub-link operating in a queued state.

The CV data aggregation process to determine sub-link operating states (free-flow, congested or queued) is illustrated in Figure 5, and the output is summarized in Table 3.

Table 3. Output of CV Data Aggregation Process (1)

Data Element	Required	Type	Refresh Rate	Standard/ Reference	Description
Timestamp	Yes	Date Time	1-5 seconds	TMDD	The local time zone date and time when the message was generated by the nomadic device
Sub-link Identifier	Yes	Integer	5 seconds	--	A unique ID identifying a section of roadway
Sub-link Speed	Yes	Number-Integer t	5 seconds	TMDD	Average speed of the CV located in the sub-link
Congest State Indicator	Yes	Text	5 seconds	TMDD	A variable indicating whether the current operating state of the sub-link is congested
Queued State Indicator	Yes	Text	5 seconds	TMDD	A variable indicating whether the current operating state of the sub-link is queued
Sub-link Volume Count	Yes	Integer	5 seconds	--	The number of vehicles located in the sub-link during the computation interval.

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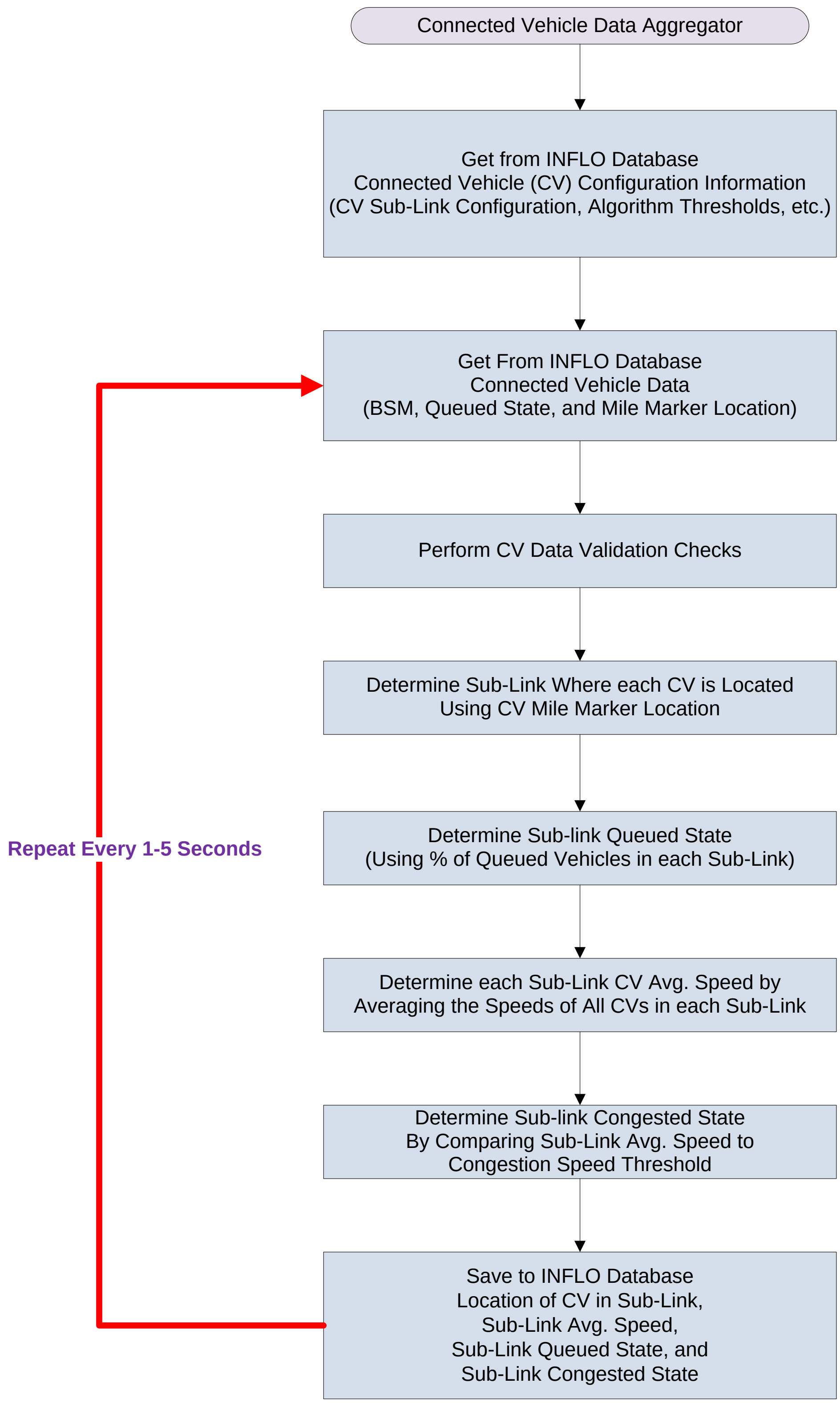


Figure 5. CV Data Aggregation Process to Determine Sub-Link Operation State (1).

TME-Based Queue Warning Process

The TME-based queue warning algorithm fuses data from the infrastructure and the CVs and generates queue warning messages that can be disseminated through both infrastructure signs and CVs. In this application, the decision-making processes reside primarily within the TME. The CV is not required to process any data other than determining its queue state and generating queue warning displays from the data provided by the TME.

The TME-based queue warning algorithm fuses the infrastructure data with the CV data to determine the back of queue (BOQ). Figure 6 illustrates the process of determining the BOQ.

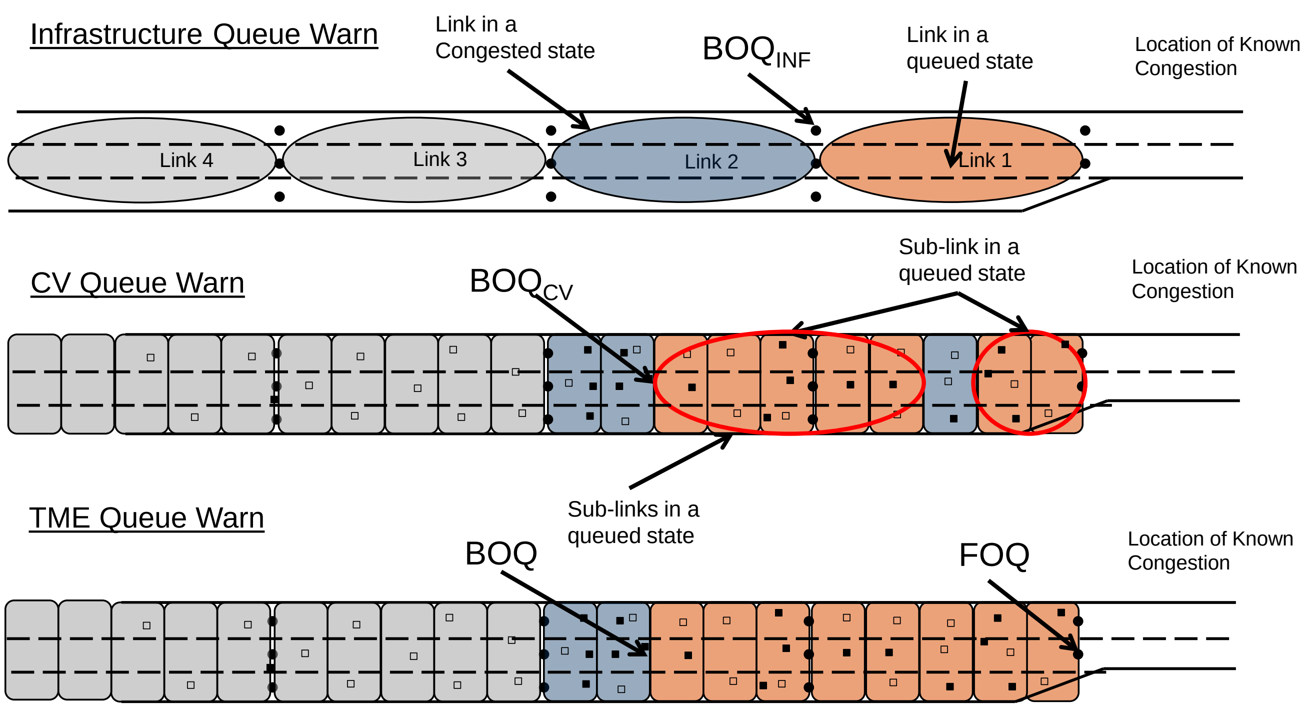


Figure 6. Queue Detection in INFLO (1).

Because the INFLO project also provided speed harmonization information built around recurring bottleneck locations, the researchers assigned the known bottleneck locations to be the front of queue (FOQ). Data from infrastructure sensors were used to determine which links are operating in a free-flow, congested, or queued state. Using this information, the BOQ was determined and located at the mile marker reference point of the detector station where the state of the link transitions from a free-flow or congested state to a queued state. Figure 6 illustrates that while Link 1 is in a queued state, Link 2 is in a congested state, and the rest of the links are in a free-flow state. The BOQ from infrastructure traffic data is defined to be the mile marker reference associated with the Link 1 detector station.

Figure 6 also illustrates how the sub-link information from the CVs can be used to locate the BOQ. A sub-link is in a queued state if a user-specified percentage of the CVs in the sub-link are in a queued state. The BOQ from CV traffic data is at the upstream end of sub-link 8. The BOQ based on the CV data is defined as the farthest upstream sub-link operating in a queued state. The final BOQ is then determined by comparing the BOQ from the infrastructure data and CVs data and selecting the BOQ that is furthest upstream as the BOQ location.

Once the BOQ is determined, additional details including speed in queue, length of queue, and rate of change of queue are calculated. Speed in queue is calculated by averaging the CV sub-link speeds from the FOQ to the BOQ. The rate of change in queue is calculated when the BOQ changes from one interval to the other and is equal to the change in the location of BOQ divided by the time intervals taken for the change to occur. The sign (negative or positive) of the rate of change in queue will indicate the direction the queue is moving, i.e., if it is dissipating or growing.

CLOUD-BASED QUEUE WARNING

The cloud-based queue warning algorithm is a subset of the TME-based Queue Warning Algorithm. It is implemented when infrastructure components (detectors and dynamic message signs) are not available and only CV speed data can be used. Consequently, any queue warning messages issued are only displayed inside a CV. In such cases, a cloud-based queue warning system can minimize the workload of computing the queue warning data within a vehicle and provide a broader view of the facility. A cloud-based queue warning system is illustrated in Figure 7 (1).

Vehicles in a cloud-based queue warning system get the mile marker linear information from the cloud using cellular communication. The vehicles provide the BSM, queued state (Yes or No), and mile marker location of the vehicle to the cloud. The cloud-based algorithm then places the CV data into the appropriate sub-links and determines the queued state of the sub-links based on the percentage of queued vehicles to non-queued vehicles a sub-link. Based on the queued state of the sub-links, the FOQ and the BOQ are determined. For the purposes of the prototype development, the FOQ was defined as the location of a fixed queue generation point (e.g., lane closure). Based on the location of the BOQ, the speed in queue, length of queue, as well as rate of growth of queue (i.e., shock wave speed) is calculated. This information is then transmitted to the CVs in the affected roadway segments via cellular network. During the operation of the cloud-based queue warning system, CVs communicate with each other (V2V) by transmitting and receiving the BSM data. This V2V communication is used by individual vehicles to determine their queued state by comparing their speeds and their distances from the vehicles immediately downstream of them (1).

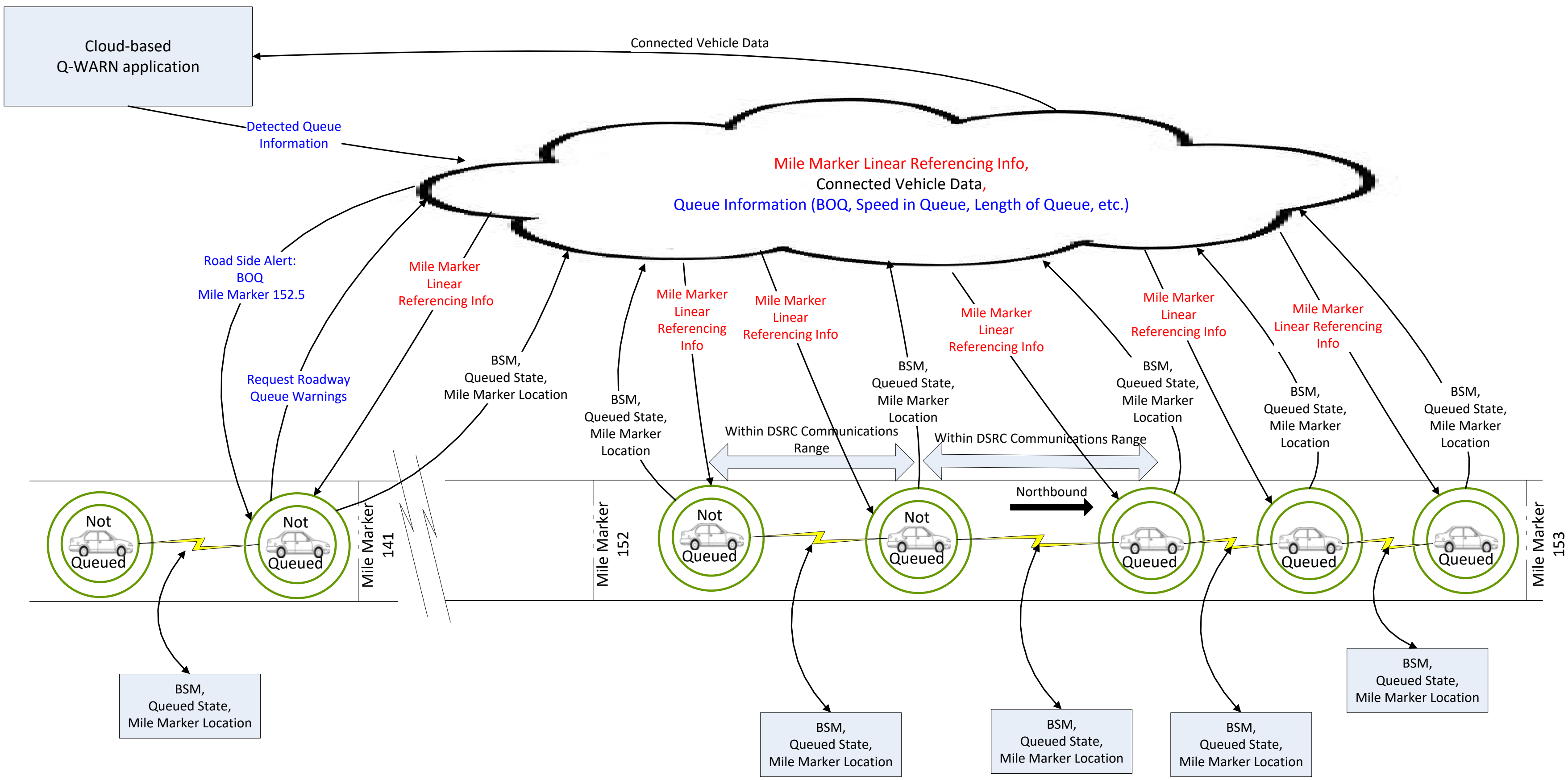


Figure 7. Cloud-Based Queue Warning System (1).

RELEVANCE TO THE V2I QUEUE ADVISORY/WARNING PROJECT

There are some significant differences between the INFLO bundle and the V2I Queue Advisory/Warning concept and design to be developed in this project. They are summarized in Table 4.

Table 4. INFLO Bundle vs. V2I QWARN (this project).

INFLO Bundle	V2I QWARN (This project)
Combines three applications • Queue Warning • Speed Harmonization • Weather Responsive Traffic Management	Only one application • Queue Warning
Queue Warning application developed using two data sources • CV • infrastructure sensor data	Queue Warning application will be developed with additional data sources • CV • infrastructure sensor data • third-party data
Queue Warning application did not identify FOQ. FOQ was always a known location (recurring congestion).	Queue Warning application should be able to determine FOQ.
Queue Warning application not compatible with EDCM approach.	Queue Warning application should be compatible with EDCM.

Regardless of these differences, there are several components of the INFLO system that can serve as bases for the development of the concept and design of V2I Queue Advisory/Warning System Applications. Relevant components of the INFLO System Architecture are identified by a red polygon in Figure 8. It is envisioned that a similar system architecture will be used for the hybrid V2I queue warning system with modifications to accommodate an additional queue warning sub-system module that uses third-party traffic data.

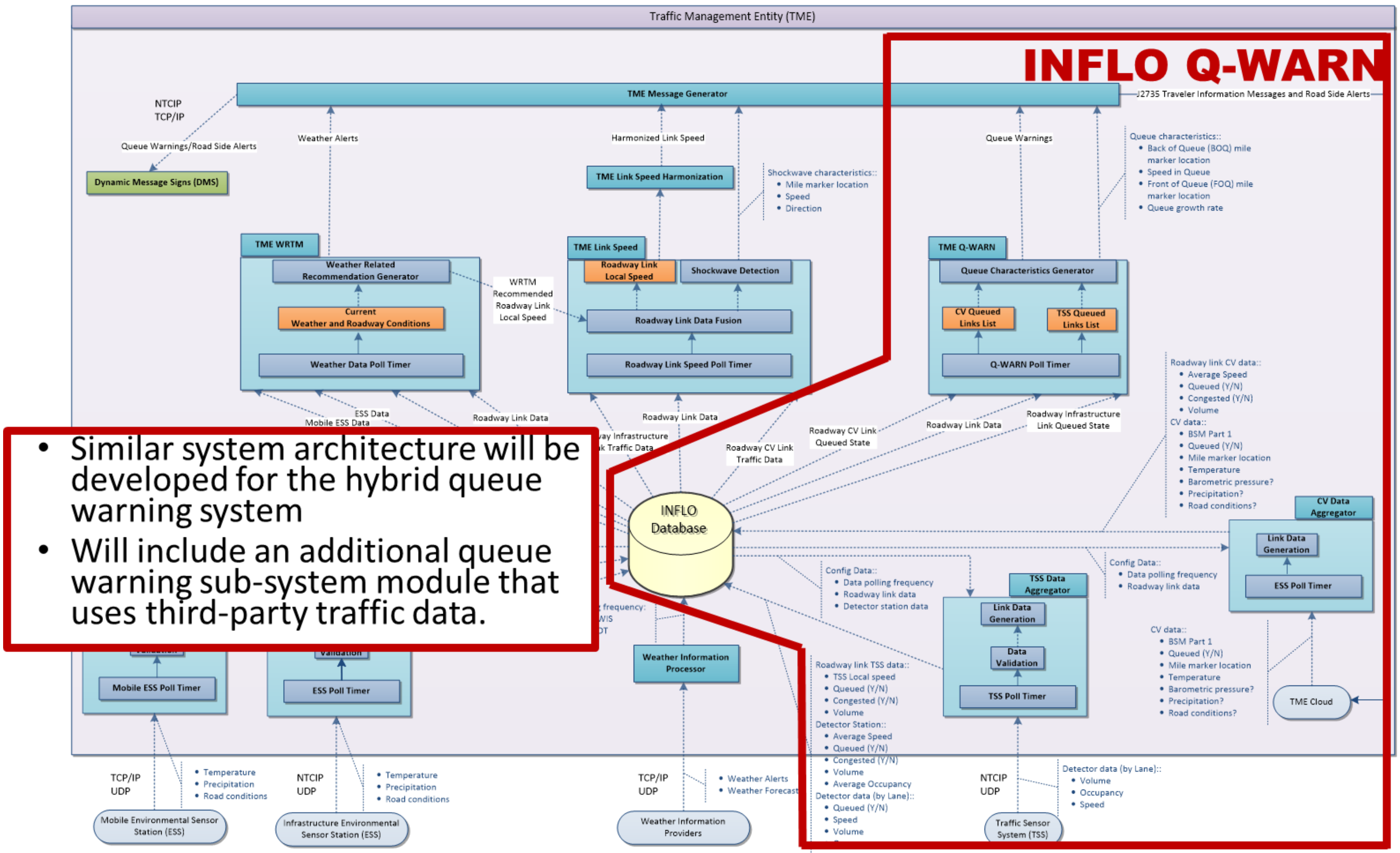


Figure 8. Relevant INFLO System Architecture Components.

RECENT QUEUE ADVISORY/WARNING DEVELOPMENTS

Queue warning systems using three different data types were reviewed:

- Queue warning systems using infrastructure/sensor data
- Queue warning systems using CV data
- Queue warning systems using third-party traffic data
- Queue warning systems using multiple data sources (any combinations of the above three data types)

The following sections provide an overview of recent developments in each of these queue warning system types.

QUEUE WARNING SYSTEMS USING INFRASTRUCTURE/SENSOR DATA

System Configuration

System Components

The main components of a sensor-based queue warning system include:

- Sensors to measure spot speeds and/or occupancies at multiple points upstream of a bottleneck location (e.g., on the approach to a work zone lane closure).
- Central Processing Unit (CPU) 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 provide real-time queue warning messages (e.g., slow/stopped traffic ahead) to the drivers of approaching vehicles.

A typical sensor-based queue warning system is illustrated by Figure 9.

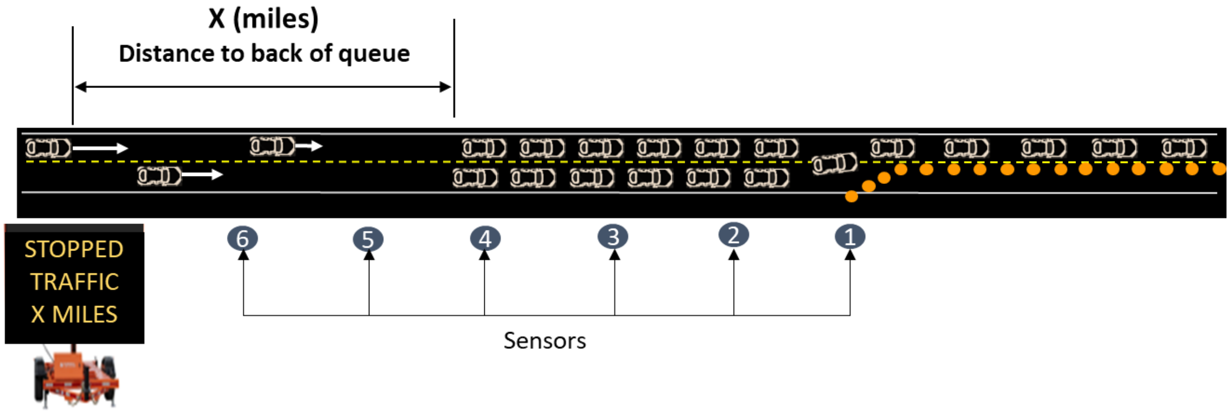


Figure 9. Sensor-Based Queue Warning System.

Traffic Sensors

In infrastructure-based queue warning systems, vehicle speeds and/or occupancies are measured by sensors deployed at multiple points upstream of queue generation points (e.g., lane drop, lane closure, exit ramp, freeway junction). The typical spacing between traffic sensors is around ½ to 1 mile. Some queue warning systems use shorter spacing (e.g. ½ mile) near the queue generation point for quicker detection of traffic slowdown and longer spacing for sensors farther upstream. The data collected by the sensors are averaged over pre-defined time intervals (e.g., 1-minute) and used for triggering certain warning messages based on a message selection algorithm. Some sensors such as loop detectors and high-definition radar units collect lane-by-lane speed, volume and occupancy data. 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. The following section of this document includes examples for both permanent and temporary deployments of infrastructure-based queue warning systems.

Queue Warning Message Selection

Queue warning messages are selected based on sudden changes in traffic conditions indicating the formations of slow or stopped vehicle queues. These traffic condition changes are identified by comparing the sensor data to pre-defined thresholds. A relatively simple message selection logic with two speed thresholds (v_1 for slow traffic and v_2 for stopped traffic) is shown in Table 5.

Table 5. Message Selection based on Speed Conditions.

	v: lowest time-mean speed among all sensor locations		
	$v_1 < v$	$v_2 \leq v \leq v_1$	$v < v_2$
Message	Default Message for Free-Flow Conditions	**SLOW TRAFFIC X MILES**	**STOPPED TRAFFIC X MILES**

As speed drops and congestion begins to develop, the first message that drivers will commonly see is “SLOW TRAFFIC X MILES”. When speeds further drop, drivers will see the queue warning message “STOPPED TRAFFIC X MILES”. In situations when speeds very suddenly drop to near zero (e.g., in case of major accidents), the SLOW TRAFFIC warning message may be skipped entirely, and drivers of approaching vehicles are immediately warned of STOPPED TRAFFIC ahead. 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. The objective is to provide all drivers with either of the two messages when traffic slows and a queue forms.

Back-of-Queue Location

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. In such cases, the distance between the PCMS and the estimated location of the BOQ is calculated as

$$\boldsymbol{X} = \boldsymbol{x_{PCMS}} - \underbrace{\left[\boldsymbol{x_{DET}}(\boldsymbol{i}) + \frac{1}{2}\Delta \boldsymbol{x_{DET}}\right]}_{\text{Estimated location of BOQ}} \tag{1}$$

where X_{PCMS} : distance of PCMS from lane closure (miles)
$X_{DET}(i)$: distance between lane closure and speed sensor i that activates a message
ΔX_{DET} : detector spacing (miles)

The queue length and BOQ estimation can be improved if data for reliable calculation of shockwave speeds is available.

Recent Deployments

The majority of recently deployed infrastructure-based queue warning systems used speed sensors to detect changes in traffic conditions, and the formation and propagation of vehicle queues. Many of them were operated as part of the ITS traveler information systems deployed for major road construction project. They were intended to reduce the potential for rear-end crashes upstream of lane closures that can significantly reduce roadway capacity and often create long vehicle queues.

The Texas Department of Transportation (TxDOT) in collaboration with the Texas A&M Transportation Institute (TTI) deployed several portable queue warning systems for work zones in a major reconstruction of the I-35 Central Texas corridor (3). The deployment procedure started with the prediction of queues that a lane closure was expected to create. An input-output analysis was performed using traffic demands from historical volumes measured on the approach to the work zone and the estimated reduced capacity of the lane closure. If a queue was expected to occur, then a queue warning system was deployed at that location. The queue warning systems were deployed in two configurations depending on the expected lengths of the longest queues. The first configuration consisted of speed sensors placed at the lane closure taper and at 0.5, 1.5, and 2.5 miles upstream of the taper; a PCMS was placed at 3.5 miles upstream of the taper, as illustrated by Figure 10. When queues longer than 3 miles were expected, additional sensors were placed at 3.5, 4.5, 5.5 and 6.5 miles upstream of the taper, and an additional PCMS was placed at 7.5 miles upstream of the taper. Message selection logics for the two queue warning system configurations are shown in Figure 11 and Figure 12, respectively.

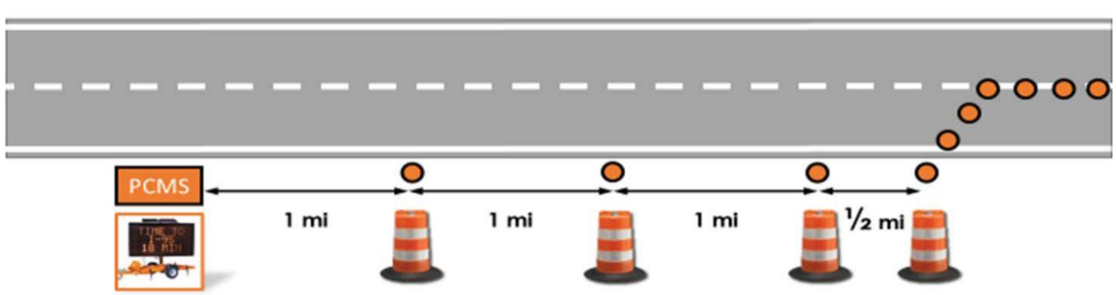
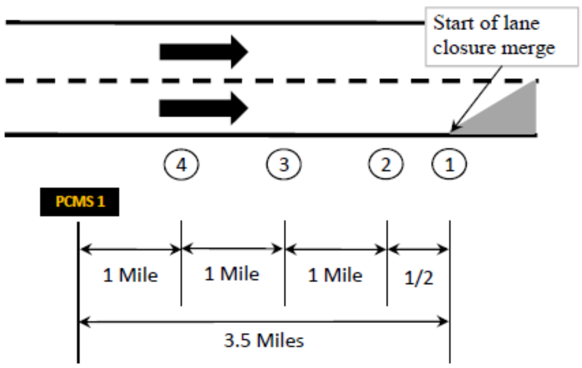


Figure 10. iCone Deployment Configuration Layout (4).



PCMS 1	Q	④	③	②	①
{Blank}	= 0	F	F	F	F
SLOW TRAFFIC 3 MILES	= 0.25	F	F	F	M
SLOW TRAFFIC 2 MILES	= 1	F	F	M	!S
SLOW TRAFFIC 1 MILE	= 2	F	M	!S	!S
SLOW TRAFFIC AHEAD	= 3	M	!S	!S	!S
STOPPED TRAFFIC 3 MILES	= 0.25	F	F	F	S
STOPPED TRAFFIC 2 MILES	= 1	F	F	!F S	S A
STOPPED TRAFFIC 1 MILE	= 2	F	!F S	S A	A
STOPPED TRAFFIC AHEAD	>= 3	!F S	S A	A	A

① iCone Traffic Sensor

PCMS Portable Changeable Message Sign

Notes

- Location of the iCones and the PCMS can be adjusted based on site conditions (ramp locations, other static signing, overpasses, etc.)
- Free Flow/Slow/Stopped traffic trigger speeds are adjustable on a per iCone basis
- Displayed message text is configurable on a per PCMS basis
- "Q" is the calculated queue length from iCone-1, in miles, and resolves to the mid-points between iCones.
- **Condition tables may not cover all possible cases.** Please refer to the specific deployment's logic and settings for details.

Symbol	Condition	Avg Speed (V)
F	Free Flow	40mph < V
!F	Non Free Flow	V <= 40mph
M	Moderate / Slow	25mph <= V <= 40mph
!S	Non Stopped	25mph <= V
S	Stopped	V < 25mph
A	Any	0 <= V

iCone
End Of Queue Warning
(Type 1)

Figure 11. Message Selection for Queues up to 3 miles (Source: iCone).

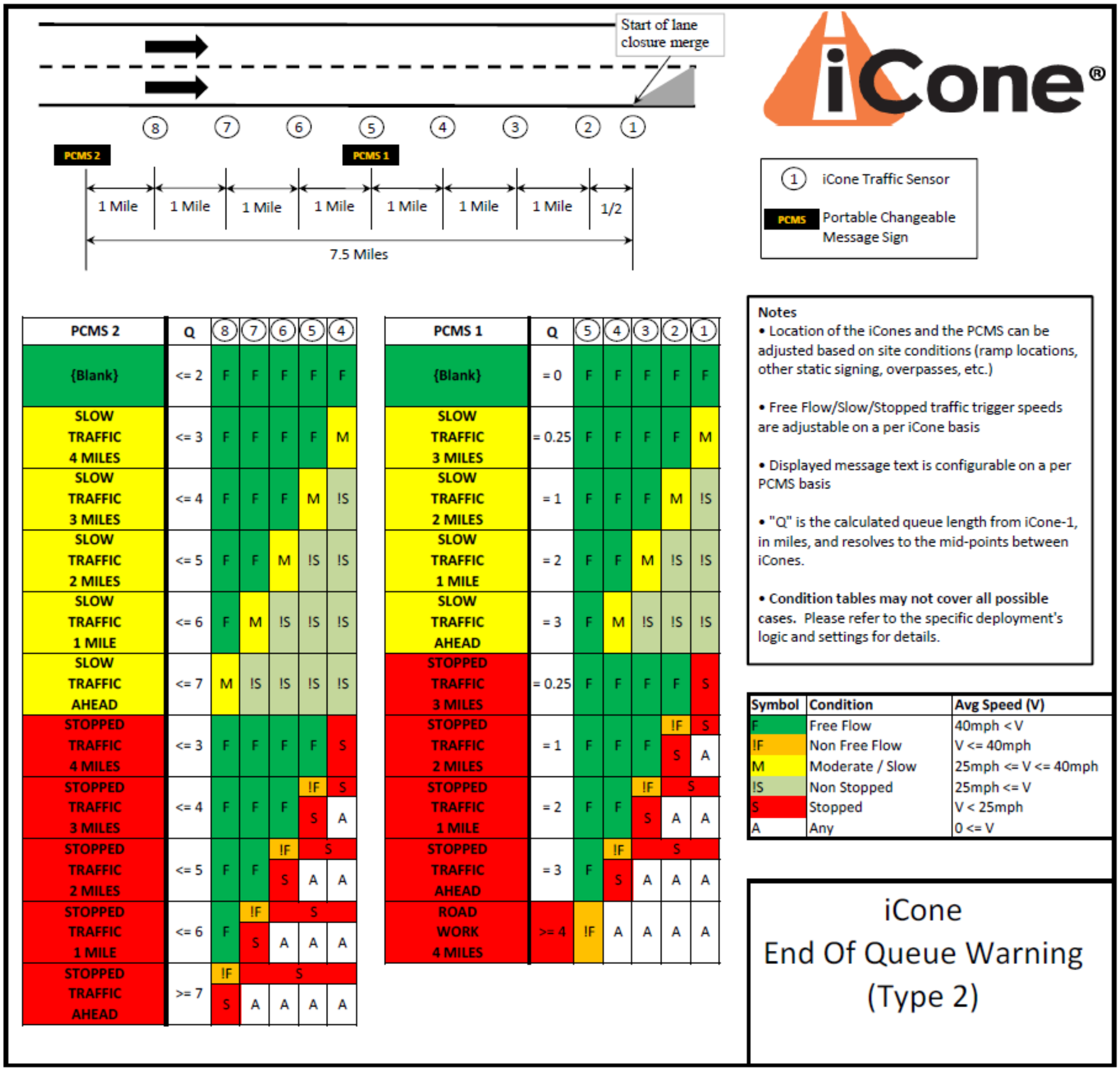


Figure 12. Message Selection for Queues up to 7 miles (Source: iCone).

The Illinois Department of Transportation (IDOT) deployed two commercial off-the shelf ITS systems that provided motorists with both queue warning and delay information. They deployed the two systems on two different road construction projects on interstate highways I-70 and I-57. Both freeway corridors had four lanes (2 lanes in each direction), and they were located in a rural area near central Illinois. The road construction activities required temporary lane closures, shoulder closures, lane shifts and/or reduction of lane width, which resulted in the formation of vehicle queues during periods of high traffic demand. The increased potential for rear-end crashes was the primary safety concern at both project locations, but the delays generated by the queues were also concerns for IDOT. The work zone ITS system was expected to achieve the following objectives (4):

- Reduce the frequency and severity of rear-end collisions in slowed or stopped traffic,
- Provide real-time delay information to travelers, and
- Direct traffic onto alternate route detours when necessary (i.e., for full interstate closures).

The system requirements included:

- Should automatically detect slow/queued traffic.
- Should warn approaching motorists of slow/queued traffic.
- Should encourage diversion by informing motorists of current delays.
- Should compute travel times and delays for each direction and update frequently.
- Should determine messages based on a predetermined algorithm.
- Should display predetermined messages on appropriate PCMS.
- Should allow operators (including IDOT staff) to override the system to post messages as needed.
- Should operate automatically on a continuous (24/7) basis.

For the road construction project on I-70, a work zone ITS system provided by Ver-Mac®, Inc. was deployed. It covered a 12-mile long freeway segment upstream of the construction project in each direction. The ITS system included the following components (4):

- 25 PCMS remotely controlled by a central base station.
- 25 Wavetronix sensors linked to the central base station.
- 20 video cameras remotely controlled by the central base station.
- Central base station with software and dedicated communication devices that would link with traffic management system components.
- Password-protected website accessible to personnel to monitor the project conditions.
- PCMS messages were selected based on the logic summarized in Table 6.

Table 6. Message Selection Logic for I-70/I-57 Interchange Project. (Source: IDOT).

Traffic Condition Logic		Phase I Message	Phase II Message
No traffic congestion detected		NO DELAY TO *<I-57 or I-70>*	ROADWORK XX MILES AHEAD
Speeds less than 40 mph detected		SLOW SPEEDS AHEAD	PREPARE TO STOP
Significant delays detected (presented on PCMS farther upstream from the congestion)		XX MIN DELAY	NEXT XX MILES
Even more significant delays detected		XX MIN DELAY	CONSIDER ALT ROUTE
Delays exceeding a maximum threshold value detected (i.e., 20 minutes)	Certain signs	MAJOR DELAYS > 20 MIN	ALT ROUTE EXIT XX
	Other signs	EXPECT MAJOR DELAYS	*<Direction>* BOUND *<I-57 or I-70>*

- Evaluations found that the system provided sufficient advance notification of queues and provided timely information on available alternative routes for motorists who chose to divert in response to the messages (4).

For the construction project on I-57, a system using iCone® portable traffic monitoring devices was deployed. The iCone® is a self-contained, battery-powered unit that consists of a radar detector, GPS antenna, cellular and backup satellite communication capabilities, and processor. Figure 13 shows the locations of iCone devices in the project.

The system included the following components:

- 32 iCone® devices with approximately 1-mile spacing.
- 15 PCMS.
- Web portal to monitor the devices, traffic conditions, and messages displayed.

A multi-layer PCMS message selection logic was applied depending on the sign location:

- Signs closer to the project displayed slow or stopped traffic messages to help prevent rear-end crashes at the back of the queue.
- Signs farther upstream displayed messages based on delays estimated from detected queue lengths.

Table 7 explains the message selection based on the traffic status detected by the system. As congestion begins to develop, vehicle speeds drop and queues begin forming, messages warning of slow or stopped traffic ahead are displayed. The distance to the BOQ is estimated by the distance from each PCMS to the last downstream sensor that was detecting travel speeds below 45 mph. If the detected queue length exceeds 2 miles, messages encouraging drivers to divert to alternate routes are displayed on PCMs located farther upstream.

Table 7. PCMS Messages Displayed for Different Traffic Statuses, I-57/I-64 Project, Mount Vernon, Illinois. (Source: IDOT).

PCMS closest to the project	Criteria to Display Message	*Lowest speed downstream > 45 mph*	*Lowest speed downstream 30 to 45 mph*	*Lowest speed downstream < 30 mph*	
	Phase 1 Message	ROADWORK NEXT XX MILES	CAUTION SLOWING TRAFFIC	CAUTION STOPPED TRAFFIC	
	Phase 2 Message	XX MIN THRU ROADWORK	SLOWING XX MILES AHEAD	STOPPED XX MILES AHEAD	
PCMS farther upstream from the project	Criteria to Display Message	*Delay < 5 minutes*	*Delay 5 to 25 minutes*	*Delay 26 to 45 minutes*	*Delays > 45 minutes*
	Phase 1 Message	ROADWORK NEXT XX MILES	XX MIN DELAY AHEAD	XX MIN DELAY AHEAD	XX MIN DELAY AHEAD
	Phase 2 Message	XX MIN THRU ROADWORK	N/A*	CONSIDER ALT RTE EXIT XX	FOLLOW ALT RTE EXIT 77

*One-phase message that would periodically flash

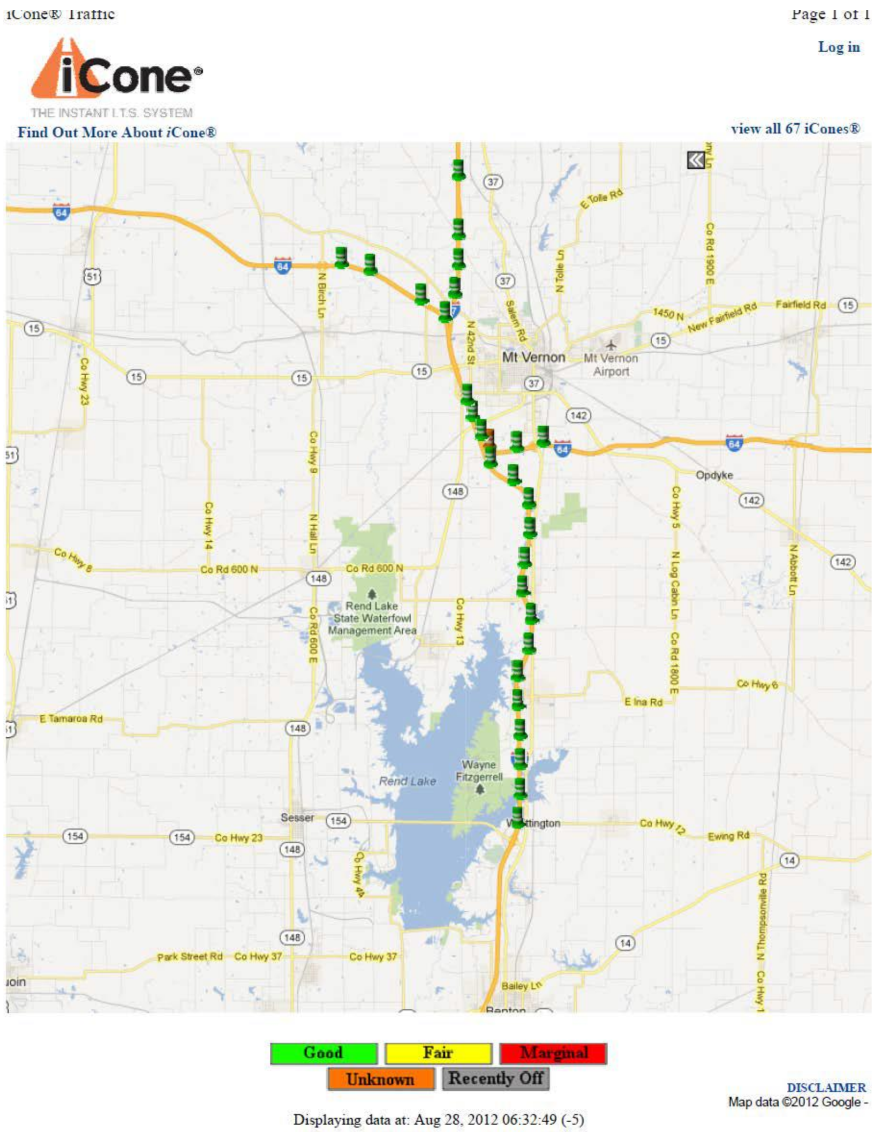


Figure 13. Map Layout of the iCone® Sensors (4).

Liu et al. (5) designed, implemented, and evaluated a freeway queue warning system for recurring queues forming in the right lane of a 1.7-mile long freeway segment of I-94 WB in Minnesota. They developed a unique queue warning algorithm using a multi-metric traffic evaluation model to identify dangerous traffic conditions based on measured speeds and estimated crash probability. Queue warnings were displayed on two signs located upstream of the detection zone. The multi-layer system architecture of the queue warning system is shown in Figure 14.

The crash event frequency prior to the system installation was 11.9 crashes per million vehicles traveled and 111.8 near crashes per million vehicles traveled. A three-month investigation of the operations of the queue warning system showed the crash event frequency reduced to 9.34 crashes per million vehicles traveled and 51.8 near crashes per million vehicles traveled.

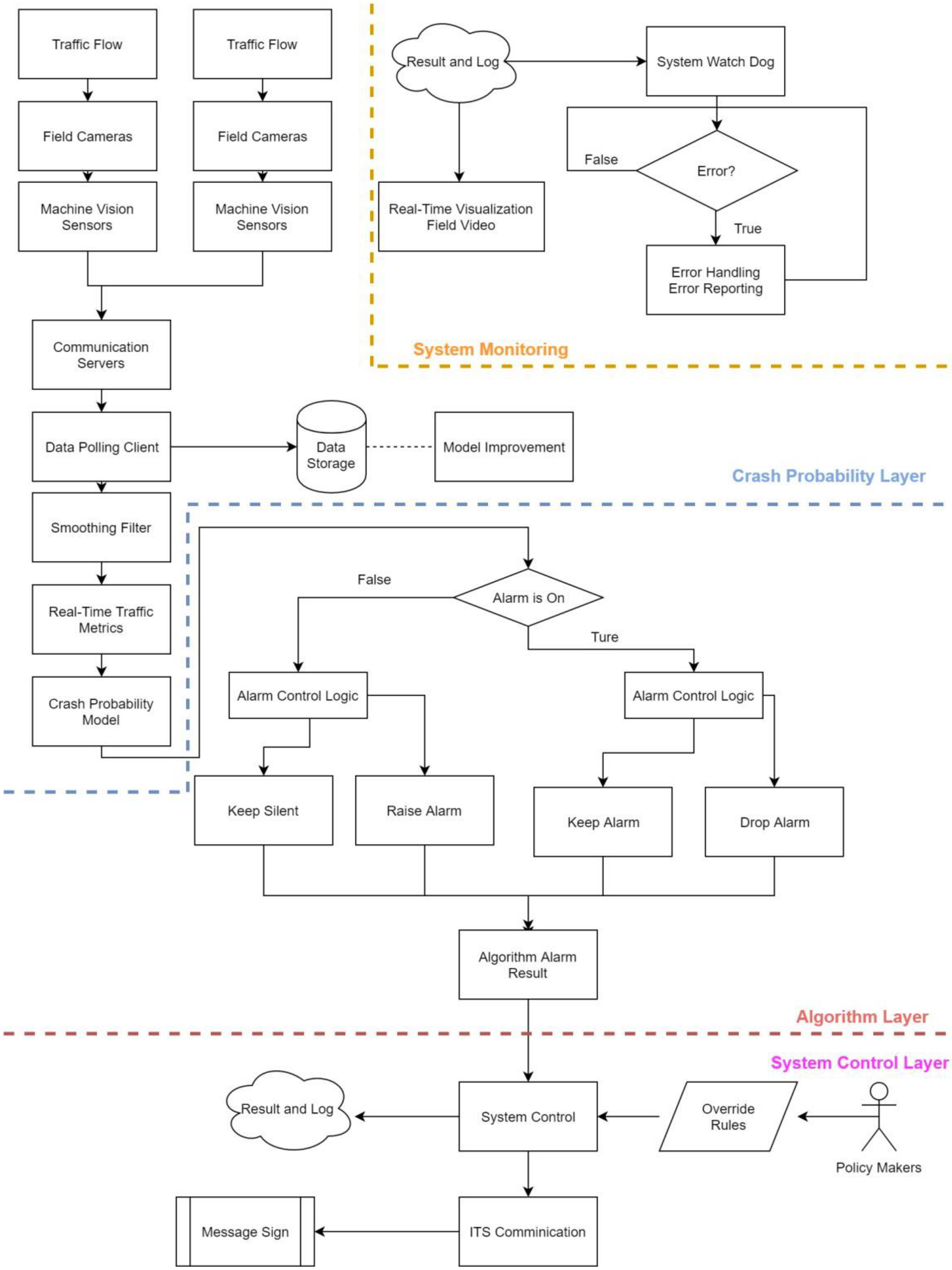


Figure 14. Multi-Layer System Architecture of the Queue Warning system on I-94 in Minnesota (5).

Queue Warning Using Video Detection

Some agencies use video detection in their queue-warning systems. For example, Houston has video-based queue detection on two freeway corridors with frequent recurring congestion. The location of the two queue warning systems is shown in Figure 15. One of them was deployed on US 59 in the eastbound direction in advance of the junction with IH 610. The other system was deployed on IH 610 (West Loop) in the northbound direction before the US 59 and IH 610 interchange. Significant congestion and relatively long queues and stop-and-go conditions were observed at both sites at several times during any typical weekday. The congestion was commonly related to the high volume of exiting traffic, and therefore queues typically began forming in the right-most lanes. TxDOT decided to install a queue warning system to provide advance warning to drivers approaching the end of slow or stopped queues, thereby reducing the potential of severe rear-end collisions (6).

Figure 15. Layout of Video-Based Queue Warning Systems in Houston, TX (6).

The queue warning systems used video detection to determine vehicle speeds in all freeway lanes. The video detection system included video cameras mounted on sign bridges and an Autoscope® unit with image processing software that was able to detect individual vehicles and determine their speeds in all freeway lanes. The advance-warning signs included a static message board displaying the queue warning messages shown in Figure 15 and two flashing beacons that were activated when congested traffic conditions and queues were detected. One of the warning signs is located on the crest of a vertical curve to provide effective queue warning to drivers who otherwise would not be able to observe slow moving or stopped queues forming on the other side of the vertical curve.

The queue warning system on IH 610 used a single video camera for video detection, as illustrated by a blue camera symbol in Figure 15. There were two queue warning message signs deployed about 1 and 2 miles upstream of the camera location. The yellow flashing beacons were activated on both signs when the speed of three consecutive vehicles observed in any of the lanes at the camera location dropped below 25 mph. This logic works well until the bottleneck location is at or downstream of the camera location. However, in the case of an incident occurring between the camera and sign locations, the forming queues could not be detected by the video detection system, and therefore the flashers on the queue warning signs would not be activated even during severe congested conditions.

The queue warning system on US 59 included two video cameras for video detection. One of them was located on a sign bridge just before the exit to IH 610, and another camera was installed at the location of the first queue warning sign about 1 mile upstream of the first camera, as illustrated by the two blue camera symbols in Figure 15. There were two queue warning message signs 1 mile and 3 miles upstream of the first camera location. The yellow flashing beacons on the first sign, the one closest to the US 59 and IH 610 interchange, were activated when the speed of three consecutive vehicles observed in any of the lanes at either the first or second camera location dropped below 25 mph. The yellow beacons on the second sign began flashing when the speed of three consecutive vehicles observed in any of the lanes at the second camera location dropped below the 25-mph threshold.

A limited before-and-after study showed no significant difference between average speeds, but a significant reduction in speed variation on both approaches.

According to one of the participants in our stakeholders interview, the video-based queue detection/warning at both locations is non-operational, and the warning flashers have been switched to continuous operation. Current maintenance resources are being directed to other higher priority issues. TxDOT Houston district is not planning to install additional queue warning systems in its jurisdiction. In recent years, the department’s priority has been to install systems for warning trucks approaching curves at unsafe speeds.

TMCs in all major cities use some form of video surveillance of freeway traffic operation. When congestion and vehicle queues are observed at some location on the roadway system, TMC operators may manually activate queue-warning and alternate route messages to be displayed on dynamic message signs upstream of the congested roadways segments.

Performance of Sensor-Based Queue Warning Systems

Pesti et. al, (7) evaluated the performance and reliability of a sensor-based queue warning system using traffic simulations. They used queue detection error and percent of vehicles without warning as performance measures. From a driver’s perspective, queue detection error is the difference between the estimated BOQ location displayed on the PCMS and the location where the vehicle actually arrives at the back of the queue. The queue detection error ΔQ and its two components are illustrated in Figure 16.

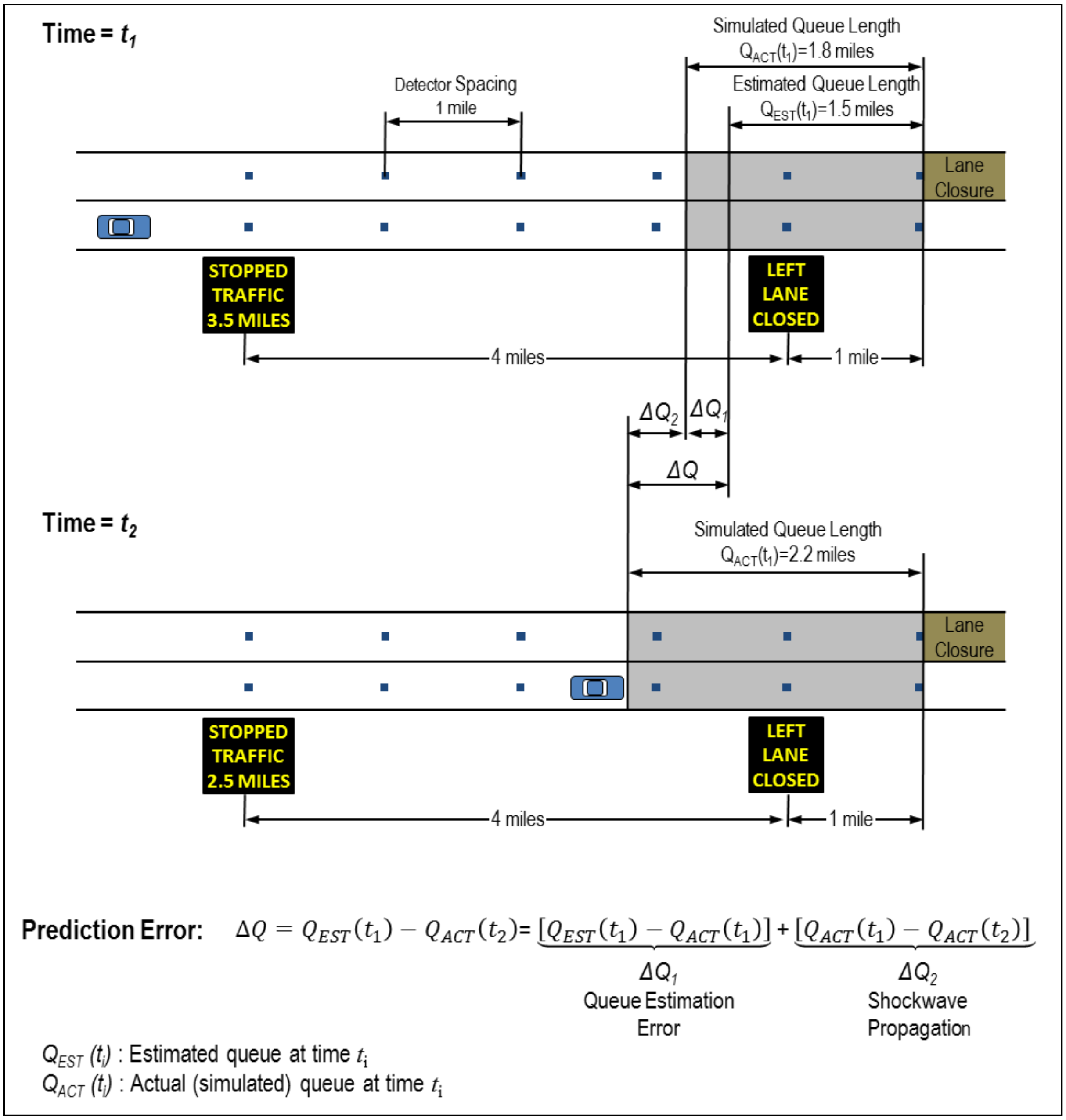


Figure 16. Queue Detection Error.

The error component ΔQ_1 is the queue estimation error at the time when the vehicle passes by the PCMS. 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 PCMS to the back of the queue.

Distributions of the queue estimation error of a queue warning system using ½-mile and 1-mile detector spacing and different intervals for speed aggregation and warning message update are shown in Figure 17.

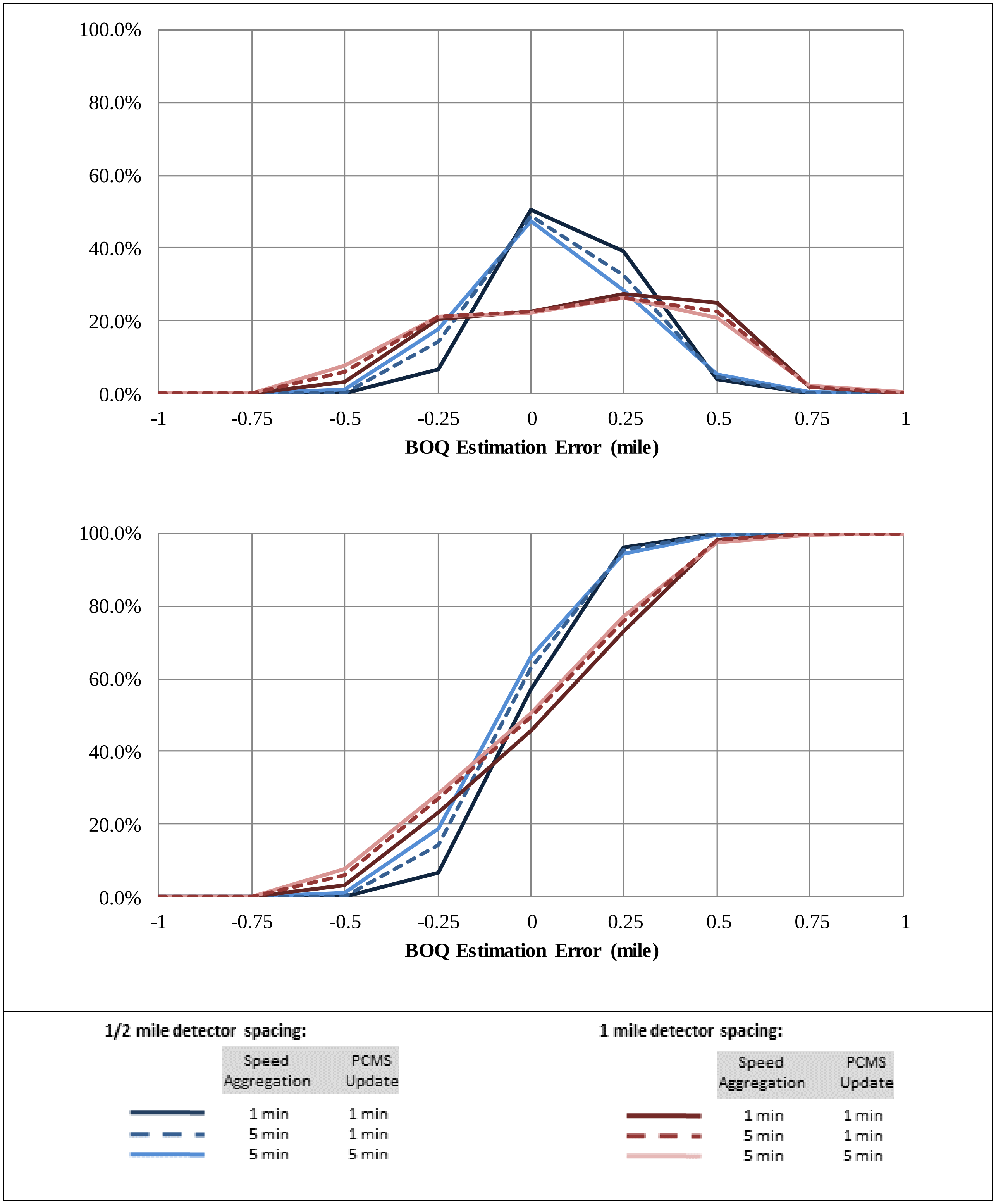


Figure 17. Queue Detection Error Distribution.

In addition to the queue detection error, the researchers also looked at the percent of vehicles without warning message. At the time when a queue begins forming there are vehicles between the queue generation point and the message sign that is typically located several miles upstream. These vehicles will encounter a queue without getting any warning. For a given volume level, the number of such vehicles that approach the BOQ 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. The percentages shown in Figure 18 correspond to a speed threshold of 35 mph for "stopped traffic" and a 50-mph threshold for "slow traffic" detection.

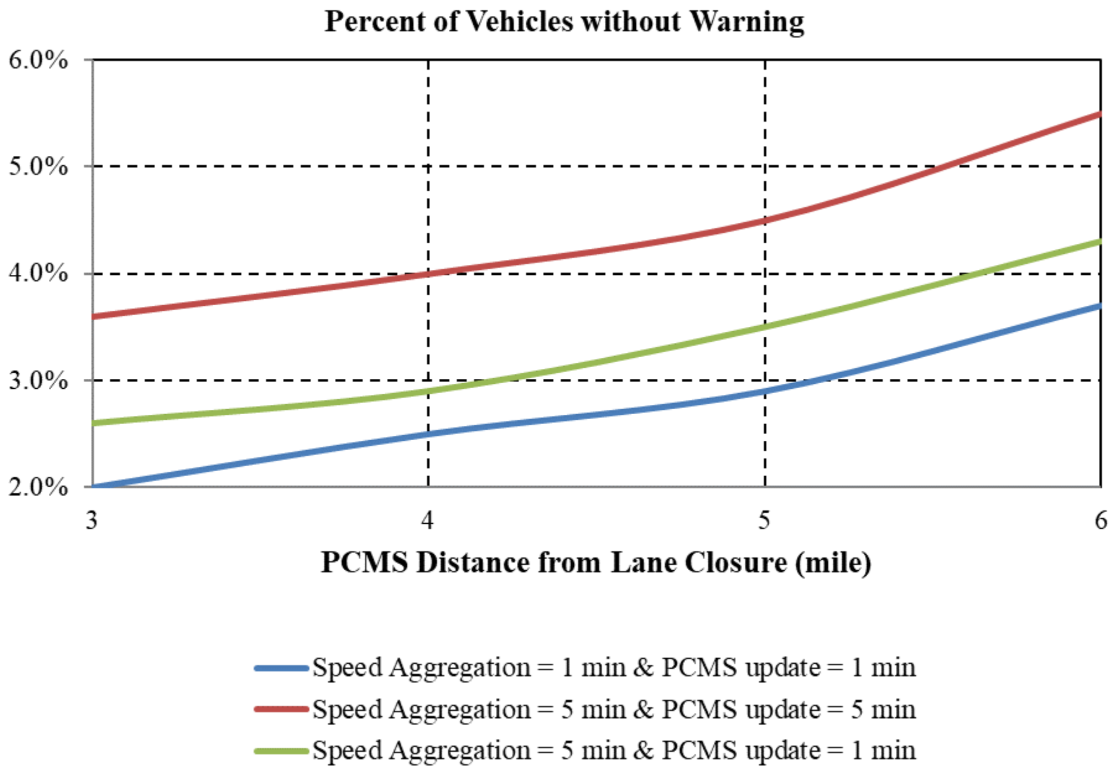


Figure 18. Percent of Vehicles Encountering Queues without Warning.

QUEUE WARNING SYSTEMS USING CV DATA

CVs, acting as probes within the traffic stream, can continuously provide information about their location, speed, acceleration, heading, and queued state. With the exception of the INFLO system, other studies focusing on CV-based queue warning application were simulation based. While a few of them discussed detection of queues on freeway facilities, many articles focused on utilizing probe vehicle data to determine the queue length at a signalized intersection.

In a freeway environment, CV-based data can cover a larger area than any detector system. Khazraeian et al. investigated the accuracy of a queue warning system utilizing the "Verkehr In Städten – SIMulationsmodell" (VISSIM) microscopic traffic simulation (8). Their methodology for detecting a queue involved organizing probe vehicle data based on location into small segments along the freeway and checking the speeds within these small segments to see if the speed was below a threshold speed. They also simulated a point detector-based BOQ algorithm to compare against probe vehicle detection. The simulation results showed that CV-based queue detection can outperform the detector-based queue detection at market penetrations as low as three to six percent. It was also found that CV data allowed faster detection of the bottleneck and queue formation around four minutes sooner than the detector-based algorithm.

Rayamajhi et al. (9) designed a distributed computing framework called "Things in a Fog (TGIF)" and illustrated it through a CV-based queue warning application. The system was implemented and deployed at Clemson University campus, Clemson, SC. The framework is based on an edge computing system where the applications processing is distributed to system computing nodes that are close to where the data is collected leveraging locality and computing resources to support system interactions and data collection activities that potentially have real-time constraints. The proposed framework for the CV-based queue warning application defines a hierarchical set of nodes (some mobile, some fixed) that run the TGIF middleware, and a set of external nodes, referred to as machine nodes, which do not run the TGIF code. For example, a mobile node could be a DSRC OBU running in a car and a fixed node could be an RSU at the side of the road. The queue warning application using CV data was designed to:

- rapidly detect the location, duration, and the length of a queue propagation,
- formulate an appropriate response plan for approaching vehicles, and
- disseminate such information to the approaching vehicles and in an actionable manner.

Figure 19 illustrates a high-level design of the queue warning services the authors developed in their framework.

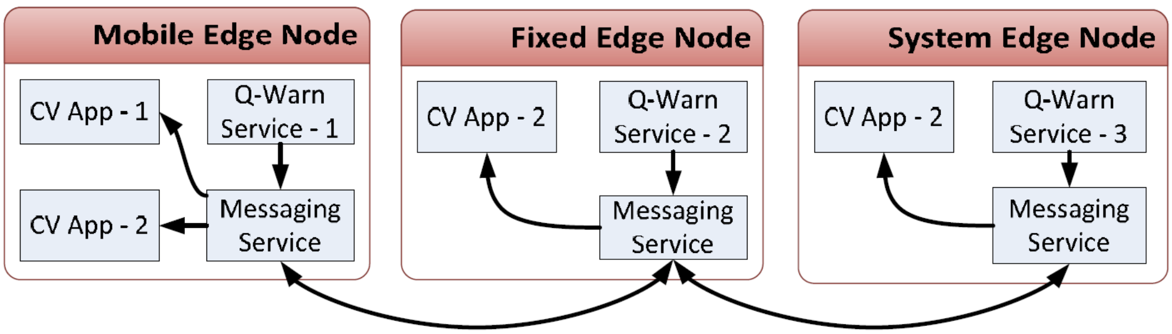


Figure 19. High-Level Design of Queue Warning Services (9).

The physical system consists of system edge node, fixed edge node, and mobile edge node. There are three different perspectives of queue warning in the system: Q-Warn service at the vehicle level (CV OBU), Q-Warn service at the fixed edge node (i.e., RSU), and Q-Warn service at system edge node (i.e., TMC). The three nodes can publish or subscribe to required information through the messaging services provided by the system.

Figure 20 illustrates the system the authors implemented and deployed on a perimeter road at Clemson University campus, Clemson, SC.

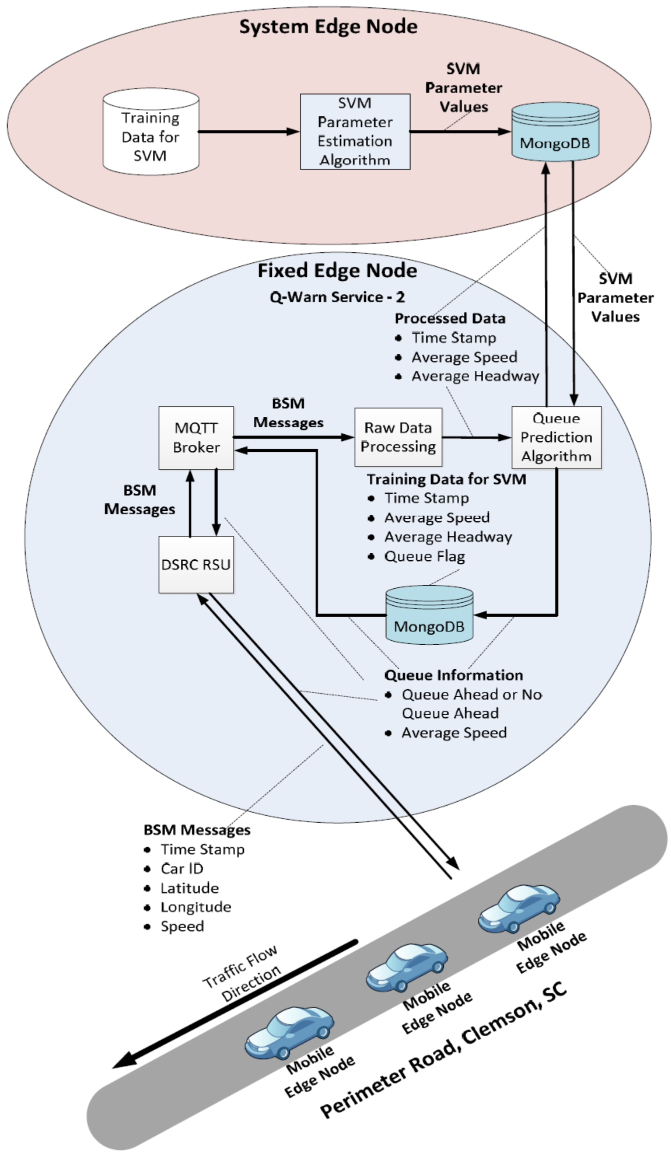


Figure 20. CV-Based Queue Warning System Deployment at Clemson Campus.

They implemented a machine learning based queue warning service at Fixed Edge. The queue warning algorithm is distributed between the Fixed Edge and System Edge Nodes in order to minimize the computing workload of processing, aggregating, and predicting queues using data from each CV within a DSRC communication range of a Fixed Edge Node. The authors simulated a similar CV environment on the perimeter road using VISSIM to get CV data for training the machine learning algorithm for queue detection.

Although the primary focus of this review is to assess prior work related to queue warning on freeways and high-speed roadways, several studies focused on the detection of queues at signalized intersections using CV data. These were mostly simulation-based studies that investigated how CV data may be used to improve queue detection on arterials. For example, Zhao et al. (10) utilized the probe vehicle and estimation of the market penetration rate to determine queue lengths at an intersection. They used the probe vehicle information to set a lower bound for the queue length and utilized an assumption of the local market penetration rate to estimate the intersection queue length. Several papers utilize a shockwave methodology with the probe vehicle data to estimate queue length, which utilizes a shockwave for queue formation assuming an initial queue formation shockwave, updating based on CV arrival rate, and using a queue dissipation shockwave at the onset of the corresponding green phase (11). Tiaprasert et al. (12) took the shockwave method a step further by applying a discrete wavelet transform (DWT) to address noise in the queue estimation at low market penetration rates. The application of DWT to a shockwave estimation of queue length enabled the algorithm to remove erroneous spikes in queue length estimation caused by detected moving vehicles far from the last stopped vehicle. Christofa et al. (13) considered CV technology for arterial queue spillback detection and explored two queue length methodologies.

QUEUE WARNING SYSTEMS USING THIRD-PARTY TRAFFIC DATA

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, and segment travel times and speeds. For example, agencies can access WAZE's crowd-sourced incident data through the Waze for Cities (formerly: Connected Citizen Program). In exchange, they are expected to share their own incident and/or work zone data feed with WAZE. Data sharing with partners of the Waze for Cities program has the following mechanisms:

- Data are available for partners through a localized XML or JSON data feed that is updated every two minutes.
- Partners can define a data collection polygon to delineate the area where data must be collected from.
- A web-interface called Traffic View Tool is available. Using this web-interface partners can access real-time user-reported incidents and estimated travel times along preselected routes.
- Waze also offers email updates on unusual traffic that can be sent to anyone in the partner organization.

The Waze data feed contains the following data types:

- Traffic incidents: jams, accidents, hazards, construction, potholes, roadkill, stopped vehicles, objects on road, missing signs reported by our community of mobile users.

- System-generated traffic jams: location and speed data associated with slowdowns below average speed for a particular segment for the time of day/day of week identified by analyzing user GPS signals.

Each alert gets reliability and confidence scores (based on a scale of 0 to 10) based on other user's reactions (e.g., 'Thumbs up', 'Not there' etc.). Higher scores indicate more reliable reports.

Waze generates traffic jam information by processing the following data-sources:

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

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 traffic data is that they can be collected without the need for the deployment and operation of physical infrastructure. Third-party traffic data has broad coverage over the road network, especially on limited access roadways. The segment travel times and speeds are provided as averages over predefined time intervals (e.g., 1, 5, 10 or 15 minutes).

Until recently, the use of third-party traffic in queue warning applications has been limited for the following main reasons:

- Speeds and travel times at lane level were not available.
- INRIX Traffic Message Channel (TMC) segments may be too long and often overlapping.

The use of INRIX XD segments and the development of some new features in the INRIX AI Traffic application have the potential to remove these limitations. INRIX XD can provide segment travel times and speeds for shorter roadway segments, and INRIX AI Traffic is capable of providing the data at lane level.

Dangerous Slowdowns

Dangerous Slowdowns (DSD) is a product feature under the INRIX safety alerts umbrella. It provides advance warning for drivers if the BOQ for a dangerous traffic slowdown is detected downstream. The application determines the location of DSD based on segment level speeds. DSD is available for all limited access roadways. It is calculated/re-evaluated every minute using real-time segment speeds from INRIX XD segments. INRIX compares real-time speeds from consecutive upstream and downstream segments. A difference in segment speeds greater than some threshold (e.g., 45 mph) indicates a DSD at the connection point between the two segments. Agencies can set the speed differential threshold from 15 to 50 mph. Each DSD is assigned a severity level based on the actual difference between the speeds from the two segments (14).

Congested conditions do not necessarily create a DSD where gradual speed reductions occur over adjacent segments. In this sense, DSD alert is different from a Congestion Alert. DSD identifies a point in space between the congested queued traffic and the uncongested traffic (14).

INRIX Traffic version 7 enhanced the alerts for dangerous traffic slowdowns by including distance to the BOQ and speed in the queue. Figure 21 shows an example of the DSD alert (15).

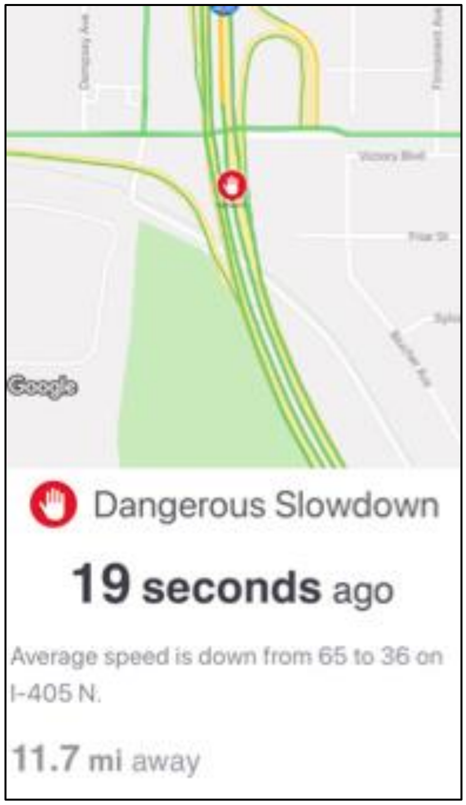


Figure 21. INRIX Traffic Dangerous Slowdown Alert (15).

Iowa Department of Transportation was among the first to utilize INRIX Dangerous Slowdowns to monitor and manage the state's road network. They were followed by several other states such as Indiana and Florida. INDOT and Purdue University have developed a series of dashboards and processing tools for INRIX data. They applied them to monitor traffic operations (travel times, speeds and queueing) in several case studies, including freeway crashes, a major interstate detour, and snow and ice storms (16).

INRIX AI Traffic

The most recent evolution of INRIX's Traffic applications is the INRIX AI Traffic launched during the summer of 2019. This latest version leverages artificial intelligence and deep learning to provide instantaneous updates to traffic conditions and pinpoint traffic speeds in different lanes. It can provide this information for all road types such as interstates, arterials, state and country roads. Figure 22 illustrates a situation when INRIX AI Traffic detects the blockage of the right two lanes of a freeway segment and advises drivers to use the left lane where traffic still flows freely (17).

Figure 22. Lane-by-Lane Traffic Conditions in INRIX AI Traffic (17).

The lane-by-lane precision means that drivers approaching the BOQ in the blocked right lanes can be provided with advance queue warning. If they need to stay in right lanes to exit the freeway, they can be advised in time to safely slow down. Otherwise they can be advised to move into the less congested left lane. The lane-level detection capability of INRIX AI Traffic is a very useful feature that can also be used to provide queue warning to motorists approaching the back of the queue.

Driver Interaction with Third-Party Applications

There are a number of third party applications that drivers can use to obtain information on congested roadway segments where vehicle queues and delays are expected. The information may include warning messages alerting drivers about:

- Accidents, work zones (with or without lane closures), hazards, potholes, stopped vehicles, debris on road, traffic diversions, etc.
- delays and travel times longer than normal over a particular roadway segment, reduced speed zone, sudden traffic slowdown, and slow, stopped or stop-and-go traffic ahead, etc.

In response to these pieces of information, drivers may choose different actions depending on the type of alert, their longitudinal distance and lateral position on the roadway, traffic density in adjacent lanes and availability of alternate routes. In case of en route information, they can adjust their speeds to the traffic conditions ahead, safely change lanes, or divert to alternate routes. If they receive advance information prior to a planned departure, they may select a different route or choose a different departure time.

Drivers can access these third-party applications through their mobile phones or in-vehicle displays. Accessing traveler information through mobile phone applications generally provides better user experience, more features, and customization options than in-vehicle applications. This realization has been pushing drivers to use their cell phones more often than the factory-installed in-vehicle technology in their car. According to research by AT&T, seven out of ten US costumers regularly use their cell phones while driving. These distracted drivers on the roads pose major safety concerns. Although, there are laws that prohibit cell phone use while driving, OEMs are also developing driver monitoring systems to address the distracted driving problem related cell-phone use (18).

QUEUE WARNING SYSTEMS USING MULTIPLE DATA SOURCES

Some researchers have explored fusing data from sensors with probe vehicle data from CVs to enhance the performance of probe vehicle-based detection systems in low market penetrations. Li et al. propose an event-based approach to estimate the real-time queue length (19). Their algorithm uses either a change in signal state to green, red, or reception of probe vehicle information to update the queue length estimation. To estimate the queue length, they used the Kalman filtering formulation to fuse the probe vehicle and loop detector data in the event-based approach and compared the performance to an input-output model (20, 21, 22). The researchers tested their queue estimation approach using microsimulation and found that the event-based method with data fusion method slightly improved the performance of the event-based method without probe vehicle data and performed better than the input-output model with ideal loop detector data (19).

Badillo et al. (23) developed another system called IntelliFusion to fuse loop detector data with probe vehicle data using shockwave analysis. The IntelliFusion algorithm uses vehicle trajectory data from CVs and applies a linear car-following model. When the signal turns red the algorithm evaluates a growing queue shockwave until it meets a queue recovery shockwave which starts when the signal turns green to track the front of the queue. IntelliFusion uses the probe vehicle data to correct errors in the back and front of queue calculations. Badillo et al. tested their algorithm using microscopic traffic simulation and found that the algorithm can be accurate to a single vehicle at a market penetration level as low as 20 percent (23).

The Texas A&M Transportation Institute is working in partnership with the Consortium of Crash Avoidance Metrics Partners LLC (CAMP) and University of Michigan Transportation Institute (UMTRI), and the University of California-Riverside (UCR), on a system that attempts to optimize an equipped CV’s approach to an intersection called Traffic Optimization for Signalized Corridors (TOSCo). This project is in the second phase where the team will build a prototype version of the system. The first phase of the TOSCo project was to develop the system in a simulation model and analyze potential impacts. The TOSCo system has two components; vehicle and infrastructure. The vehicle component controls the vehicle’s throttle and brake as it approaches the intersection. The infrastructure component utilizes probe vehicle data and sensor data within two different approaches to estimate the queue length at an intersection, so it can generate an estimation of when the last vehicle in the queue clears the intersection and send the information to approaching TOSCo vehicles. One version of the queue estimation within the TOSCo system uses shockwave profile model proposed by Wu and Liu to estimate a queue growth shockwave (24) and compliments the probe vehicle data with a fixed detector input similar to Badillo et al. with their IntelliFusion algorithm (23). This infrastructure component of the TOSCo algorithm utilizes the Newell linear car following model to include non-CVs that actuate a vehicle detector in the shockwave profile model (25). This version of the TOSCo infrastructure algorithm also uses an input-output algorithm to estimate the maximum queue length (26). A separate instance of the TOSCo infrastructure algorithm considers an intersection with a radar sensor installed at the intersection to track the queue length. This system simulates the capabilities of a radar unit that creates a per-vehicle record for each vehicle approaching the intersection. The system determines the location and speed of the vehicle to estimate the queue length from the stop bar based on a 5-mph speed threshold to correspond with the HCM.

CONCLUSION

This effort was part of the V2I Queue Advisory/Warning Applications: Concept and Design project and this review document is one of the key deliverables that provides input for the SE activities in subsequent project tasks.

Stakeholders with relevant experience in queue warning system design and operations, sensor and detection technologies, and the use of third-party traffic data were identified and interviewed. The questionnaire in Appendix A was used as a guide to seek queue warning related stakeholder input that helped identify gaps, constraints, and new developing areas that need to be considered in the development of concept of operations, system requirements, and high-level design of V2I Queue Advisory/Warning applications.

All INFLO documents that cover the major system components, communications flows, queue detection, and message selection logic were reviewed. There are some elements of the INFLO system that can serve as bases for the development of the concept and design of V2I Queue Advisory/Warning System Applications in this project. The relevant components of the INFLO System Architecture are identified in Figure 8. It is envisioned that a similar system architecture can be used for the hybrid queue warning system in this project with modifications to accommodate an additional queue warning sub-system module that uses third-party traffic data. Some key differences between the INFLO system and the V2I Queue Advisory/Warning system to be developed in this project were also identified and summarized in Table 4.

Recent developments of queue warning applications using infrastructure sensor data, CV data, and third-party traffic data were also reviewed. There are significant differences between these systems in terms of their data sources, data types, queue detection logic, expected accuracy, prediction ability, spatial coverage, and queue warning dissemination method. Table 8 provides a comparison of these key characteristics for the three types of queue warning systems.

Table 8. Comparison of Key Characteristics of Queue Detection and Warning Systems

System characteristics	Queue Warning Systems		
	Infrastructure/Sensor Data	**CV Data**	**Probe vehicle/Third Party Data**
Implementations	Has been widely used	INFLO Prototype Demonstration Project	Very limited. INDOT & Purdue used INRIX data to detect BOQ in work zones
Data sources	Sensors deployed along the roadway (e.g., loop detector, microwave radar, video cameras & image processor)	The CV itself	INRIX, HERE, WAZE, TomTom and other third-party traffic data providers

System characteristics	Queue Warning Systems		
	Infrastructure/Sensor Data	**CV Data**	**Probe vehicle/Third Party Data**
Data types	Spot speed, Volume, and Occupancy aggregated over selected time intervals (e.g., 1 min, 5 min)	Basic Safety Message (BSM)	Segment travel times and speeds (INRIX, HERE) Approximate queue locations and estimated time in queue (Waze)
Queue detection logic	Queued state of a sensor location is determined using pre-defined speed or occupancy thresholds BOQ is detected by comparing threshold-based queued states of consecutive sensor locations	Queued state of a CV is determined comparing its speed and separation distance from its lead vehicle to pre-defined thresholds Queued state of a road section is determined based on percentage of queued CVs BOQ and FOQ locations are found at the upstream and downstream boundaries between queued and non-queued sections	Proprietary Queue Detection logic developed by the third-party data provider Agencies can develop their own queue detection logic that uses the segment speeds obtained from a third-party data provider
Lane-by-lane queue detection	YES – using high-definition microwave radars, loop detectors, or video image processing.	Yes, if lane-level mapping of the roadway is available	Until recently it was not possible, but new developments of INRIX AI Traffic has lane-level detection capability
Queue detection accuracy	Accuracy depends on sensor spacing and data aggregation interval If shockwave speed is known, accuracy can be improved	Accuracy depends on CV percentage in traffic stream Length of road sections used in determining queued states Higher CV market penetration and shorter section length improves accuracy	Can provide approximate locations of traffic slow-downs but cannot detect the real-time locations of BOQ and FOQ.
Queue information timeliness	Near real-time - depends on length of time intervals for data aggregation and warning	Real-time	Information may have a lag of 5, 10, 15 minutes.

System characteristics	Queue Warning Systems		
	Infrastructure/Sensor Data	**CV Data**	**Probe vehicle/Third Party Data**
	message update.		
Queue prediction ability	Locations, times and length of queues under recurring congestion can be predicted using historical data archived by TMC. Some limited short-term prediction using shock wave estimates is also possible	Very short-term prediction of BOQ and FOQ location may be possible based on shockwave speed observed during queue formation.	Locations, times and length of queues under recurring congestion can be predicted using historical data archived by the third-party data provider or TMC
Spatial coverage	Covers only few miles of selected roadway segments	Can cover those roadways where percent of CVs is sufficiently high. Spatial coverage is expected to improve significantly with increasing market penetration of CVs.	Covers the entire roadway network where third-party provides service and collects traffic related data
Queue information dissemination	DMS: Dynamic Message Signs VMS: Variable Message Signs	In-vehicle queue warning messages DMS or VMS through RSU and TMC	Mobile devices and in-vehicle navigation displays

The three types of queue warning systems have some non-overlapping benefits, and therefore have the potential to effectively supplement each other. Combining them in a modular hybrid queue warning system design is expected to significantly improve the accuracy of queue detection and reliability of queue warning.

Based on the stakeholder input and review of previous queue warning applications and data sources, the following specific gaps and constraints were identified that have to be considered when going through the SE process in developing a V2I Queue Warning System. Most of them are challenges that fusing data from multiple sources may pose due the differences in the spatial and temporal resolution of the data and the way they are collected, transmitted, and utilized. For instance:

- Traditional sensors provide average spot speeds, probe data provide space mean speeds over segments that may vary in length from location to location, and CVs provide high-resolution trajectory data;

- Different geographical referencing schemes used by different sources (i.e., GPS coordinates, mile markers or another referencing format used by an agency);
- Differences in the latency of data (real-time trajectory data vs. data aggregated over time intervals of different sizes);
- Potential differences in clocks between various sources of data;
- Roadway may have partially overlapping segments for sensors, probe-data and/or RSUs; and
- Speed data from different sources for the same location and time period are not matching.

These challenges can be addressed by:

- Selecting a standard referencing scheme for geographic mapping of location data (vehicles position, sensors locations, segment boundaries) and transforming all data to that format;
- Synching clocks to ensure that all sources use a common time base;
- Incorporating procedures that resolve difference in data aggregation levels;
- Calibrating infrastructure-based sensors and incorporating QA/QC processes;
- Proactively maintaining these sensors; and
- Incorporating processes to enable handling of missing data due to sensor or communication failure.

Constraints related to institutional factors also need consideration. In large metropolitan areas, a QWS 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).

If data privacy and security is a concern, it should also be addressed in the SE process of developing a V2I Queue Warning System. Based on information gathered from stakeholder input, data security and privacy is not of significant concern in this case. Traditional infrastructure-based sensors do not collect any PII. In the case of third party private-sector provision, data are cleaned at the provider point of origin and are not supplied with any PII. In the case of CV, personal and data privacy must be protected which generally includes stripping out PII that could be traced to a person or vehicle. Standard messages set in use for que warning applications do not include PII elements in the data stream.

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APPENDIX A: INTERVIEW INTRODUCTION AND QUESTIONS

Sample of Message to Potential Stakeholder

Dear xyz:

We are currently working on a Connected Vehicle (CV) Pooled Fund Study (PFS) project. The goal of this project is to perform system engineering to produce high-level design for V2I Queue Advisory/Warning Applications that use data from multiple sources, including infrastructure, vehicle and third-party providers. A key project task is to gather stakeholder input to assess prior work to identify gaps and additional user needs. Input about innovative uses of data from non-traditional sources is also desired.

I am contacting you to request your participation in this information gathering process. Please reply to my message to let me know if you will be able to participate in this volunteer effort.

Thank you,
(Name of Research Team Member)

Interview Preamble

- Thank you for agreeing to participate in this volunteer effort.
- Do you wish to proceed?
- The focus of this information gathering process is on Queue Warning Systems, but some of the questions are also relevant to other systems.

Interview Questions

1. What is your agency's experience with queue warning system?
    a. Past
    b. Existing
    c. Planned
2. What is the target application?
    a. Daily recurring congestions
    b. Work zone
    c. Incidents
    d. Weather conditions
    e. Exit ramp spillover
    f. Queueing at traffic signals
3. What was/is the data source, spatial coverage, and data gathering/accumulation frequency?
    a. Infrastructure-bases sensors
        i. Loops (single, trap, spacing)

   ii. Magnetometers, pucks etc.
   iii. Side fire radar
   iv. Forward facing radar
   v. Video
   vi. Bluetooth (Any Privacy/Data Security issues)
   vii. Hybrid
  b. Connected Vehicle data
  c. Probe data from third-party providers
  d. Combination of data from multiple sources
4. What infrastructure is used for and how is it located/installed
  a. DMS
  b. Overhead gantries
  c. Flashing beacons
  d. Signs
  e. Use of emerging technologies
5. Is queue detection human based (TMC)? How does it work? How is queue defined
6. Is queue detection/warning Automated. How does it work? How is queue defined?
7. Is the current system adequate? How can it be improved?
  a. Improved data collection and use?
  b. Data from additional sources?
  c. Better characterization of states at different locations within in a queue?
8. Are there any data privacy issues (current or planned systems)?
9. Are there any data security issues (current or planned systems)?

Interview Closing

- Is it OK if we contact you for any follow up questions?
- Can you provide any relevant documents (ConOps, algorithm details, etc.)
- What level of future participation would you be willing to commit to?
  - Review and comment on notes from today's call
  - Review and comment on project document (i.e., Tech Memo)
  - Participation in project webinars
- Is there anyone else, at the following levels, in your agency or partner agency that should be involved in this information gathering process
  - TMC operator
  - System design
  - Operations/maintenance
  - Executive level
- Thank you for your participation. If you have any questions, please feel free to contact me at staff@tti.tamu.edu or 979-317-####