Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design

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7. Author(s)
Kevin Balke, Hassan Charara, Srinivasa Sunkari

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Texas A& M Transportation Institute
Texas A&M University System
3135 TAMUS
College Station, Texas 77843-3135

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16. Abstract
This report provides a detailed description of the algorithms that will be used to generate harmonized recommended speeds and queue warning information in the proposed Intelligent Network Flow Optimization (INFLO) prototype. This document describes the functional requirements, design principles, and constraints controlling the development of enhanced queue warning and speed harmonization algorithms. Also presented in the report are the processes and procedures that are used to format and place the data into the INFLO database where it can be accessed by other components in the prototype. This report also presents the processes and procedures used by the queue warning algorithms to provide both infrastructure-based and vehicle-based queue warnings, how measured road weather condition information will be used to generate recommended link travel speeds appropriate for the prevailing weather conditions, and how harmonized speed recommendations will be derived from infrastructure-based information. Finally, the report also shows how the prototype will use the information produced by the algorithms to generate both infrastructure and vehicle-based warning messages.

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- Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO): Functional and Performance Requirements, and High-Level Data and Communication Needs), ITS JPO Publication Number FHWA-JPO-13-013.
- Report on Detailed Requirements for the INFLO Prototype, December 27, 2013.
- Report on Assessment of Existing Speed Harmonization/ Queue Warning Approaches, Revised – November 1, 2013.
- System Design Document for the INFLO Prototype (Draft), November 20, 2013.

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Chapter 1 Introduction

Speed harmonization is a process whereby transportation management operators dynamically adjust recommended travel speeds in a section of roadway in response to developing and/or diminishing congestion, incident, and road weather conditions. Queue warning/management focuses on providing warnings upstream of developing congestion in sufficient time to allow drivers to safely brake, change lanes or modify their routes before reaching the back of the queue; thereby reducing the likelihood for rear-end collisions at the back of the queue. The difference between speed harmonization and queue warning/management is that speed harmonization attempts to reduce the variability in speeds among vehicles prior to the onset of congestion, while queue warning/management focuses on how to manage vehicles after congestion has formed. Both are deemed to be critical traffic management functions.

The introduction of connected vehicles as a new data source has the potential to significantly alter the manner in which traffic management entities (TME), such as state and local departments of transportation, regional mobility authorities, etc., provide queue warning and recommended travel speeds. Data from connected vehicles has the potential to improve the accuracy of detecting when and where queuing and congestion forms; as well as reduce the time required to identify these conditions. Faster and more accurate detection has the potential to significantly reduce rear-end collisions common when congestion initially forms.

The purpose of this project is to develop a prototype dynamic speed harmonization/queue warning system that utilizes data from both typical infrastructure components and connected vehicles to enhance the capabilities of existing infrastructure-based algorithms. Objectives are to 1) detect when and where congestion forms, 2) formulate timely and accurate speed recommendations and warning responses to these conditions, and 3) disseminate such information to vehicles far enough upstream to allow effective compliance. This report focuses on the algorithms that are used to generate recommended travel speeds and to provide queue warning information that can be disseminated to travelers both inside their vehicle and on external infrastructure devices such as dynamic message signs (DMS).

Purpose of Document

The purpose of this report is to describe in detail the proposed enhancements to current queue warning and speed harmonization algorithms to overcome the limitation of infrastructure-only based algorithms. This document builds upon several other documents that have been prepared by the Battelle/TTI team up to this point, including the following:

- Report on Detailed Requirements for the INFLO Prototype, December 27, 2013.
- Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO): Functional and Performance Requirements, and High-Level Data and Communication Needs), ITS JPO Publication Number FHWA-JPO-13-013.

- Report on Assessment of Existing Speed Harmonization/ Queue Warning Approaches, Revised – November 1, 2013.
- System Design Document for the INFLO Prototype (draft), November 20, 2013.

Document Organization

This document is organized as follows:

- Chapter 2 provides a list of the assumptions and constraints used in developing the algorithms for the prototype deployment.
- Chapter 3 describes the functional requirements, design principles, and constraints controlling the development of enhanced queue warning and speed harmonization algorithms.
- Chapter 4 also describes the hardware and software components and system architecture developed for the prototype deployment.
- Chapter 5 presents the data sources and processing components of the proposed prototype system. This chapter also discusses the Data Aggregators associated with each data source. The Data Aggregators contains the processes and procedures used to manipulate, format and place the data into the INFLO database where it can be accessed by other components in the prototype.
- Chapter 6 of this report presents the processes and procedures used by the queue warning algorithm to provide both infrastructure-based and vehicle-based queue warnings.
- Chapter 7 documents the algorithms that are used to determine how measured road weather condition information will be used to generate recommended link travel speeds appropriate for the prevailing weather conditions.
- Chapter 8 contains the steps and processes that are used to provide harmonized speed recommendations derived from infrastructure-based information.
- Finally, Chapter 9 shows how information produced by the algorithms will be used in the generation of both infrastructure and vehicle-based warning messages.

Chapter 2 Assumptions and Constraints

It is anticipated that in the early stages of the adoption of connected vehicles technology, the percentage of connected vehicles of the overall vehicle fleet on the roadway network will be very small. Consequently, it is envisioned that the need for infrastructure-based traffic sensor data to monitor and manage the roadway network and infrastructure-based signs to disseminate information to drivers will continue for a while until the percentage of connected vehicles increases. These constraints will require the adoption of a modular and hybrid approach in the development of the INFLO bundle of applications where input data from multiple sources (infrastructure, connected vehicle, etc.) will be fused together to generate proper speed and queue warning recommendations. As time progresses and the penetration rate of connected vehicles increases, some of the algorithms might be able to rely on information collected from connected vehicles only without the need for data from infrastructure-based devices.

In developing the speed harmonization, weather responsive, and queue warning algorithms for the prototype, the following assumptions have been made:

- For the prototype, the front of queue (FOQ) is at a location of expected congestion caused by a known bottleneck. This represents a situation where recurring congestion exists.
- Each algorithm needs to be designed to function independently and in a modular fashion.
- The algorithms must continue to function in the absence of either infrastructure or connected vehicle information. The algorithm should produce a recommendation even if one of the sources of data is not available. The algorithms need to support a traffic mix of connected vehicles and non-connected vehicles.
- The information displayed to the driver must be consistent between the infrastructure and connected vehicles.
- The level of accuracy currently afforded by the GPS units in the vehicle does not support the accurate placement of the vehicle in travel lanes. Infrastructure data, however, can be used to support lane-by-lane detection and management of queues.
- For the prototype, the connected vehicles would not provide any data that would allow individual vehicles to be re-identified or tracked as they moved through the deployment corridor.
- Each connected vehicle can determine for itself whether or not it is in a queued state and can communicate this state to the TME cloud as part of the Basic Safety Message Part II. Although the process for determining whether a connected vehicle is in a queued state could theoretically reside physically in multiple locations, it is assumed that this process will be embedded in the mobile device for the prototype. It is logical that this determination would reside at the connected vehicle level as the

computations for determining if that vehicle is in a queued state are relatively straightforward. However, this process becomes more computationally intense the farther away the decision is made from the vehicle, especially at high levels of market penetration of connected vehicles.

- The forward looking collision avoidance system (or other system to measure range) would be available to calculate the separation distance. In the absence that this information is not available to the connected vehicle, only the speed will be used to determine if vehicle is in a queued state.
- The speed and separation distance thresholds used to determine whether a connected vehicle is in a queued state are parameters which are configured by the traffic management entity. This will allow the traffic management entity to set the criteria it uses for determining when a queued state exists. This will also allow the traffic management entity the ability to manipulate the parameters to adjust the responsiveness of the algorithm. It is assumed that these thresholds can be communicated (along with the linear referencing system information) to all connected vehicles when they first enter the deployment corridor.
- The connected vehicle has the ability to determine a mile marker location based on mile marker linear reference information.
- The connected vehicle can broadcast its SAE J2735:2009 Basic Safety Message (BSM), both Part I and Part II, including the vehicle's queued state and mile marker location every second. An unused portion of the BSM Part II will be used to convey the queued state and mile marker location of the vehicle.
- Only link based speed message will be generated. For the prototype, no lane-level speed harmonization is being included in the algorithm.
- The vehicle-based SPD HARM application that resides in the connected vehicle can receive recommendations from a SPD HARM application from a Traffic Management Entity (TME) and can display the messages to the driver.
- The vehicle-based Q-WARN application that resides in the connected vehicle can receive Q-WARN messages from the TME or cloud based Q-WARN applications and can display a custom message to the driver based on the vehicle's location from the back of the queue information sent in the Q-WARN message.
- Initial deployments of the speed harmonization and queue warnings will occur for defined segments of freeways, generally 5 to 15 miles in length. Each deployment will have its own instance of the algorithms providing queue warnings and speed recommendations The TME will have the ability to define the beginning and endpoint of the segment of freeway to be covered by each instance of the algorithm.
- The initial deployment segments can be divided into a series of links and sublinks. A link is defined as a segment of freeway between two consecutive detector stations. Sublinks are defined to be a segment of freeway 0.1 mile in the length, starting at the defined beginning milepoint of the deployment and ending at the defined endpoint of the deployment segment.
- Data from all infrastructure sensors (including traffic sensor systems, and environmental sensor stations) utilize National Transportation Communications for ITS Protocol for communicating with a TME.

- Data from all infrastructure sensors are providing valid data that accurately reflect current traffic conditions available 100 percent of the times. All data from the infrastructure sensors have been properly calibrated to local conditions.
- The TME has a system/database for providing historical traffic data. The algorithms are NOT responsible for collecting and storing historical traffic sensor data.

Chapter 3 Algorithm Requirements

To be successful, the prototype speed harmonization and queue warning algorithms have to be able to achieve the following:

- Reliably detect the location, type, and intensity of downstream congestion.
- Rapidly and reliably detect the location, duration, and length of queues impacting traffic flow operations.
- Formulate appropriate speed management and queue warning responses.
- Disseminate recommended speeds and/or queue warning messages to travelers through both infrastructure-based signs and in-vehicle displays.

This chapter describes the functional requirements, design principles, and constraints controlling the development of enhanced queue warning and speed harmonization algorithms.

Overview of Queue Warning/Speed Harmonization Process

Figure 3-1 shows the high-level view of the overall process for providing queue management/warnings and speed harmonization. Data from connected vehicles, infrastructure weather and traffic sensors, and mobile weather monitoring systems will be used in the development of queue warning and speed recommendations. These data include both infrastructure-based and connected vehicle-based systems. After obtaining the data from the various sources, the data are processed and aggregated into a form that can be used by the various components of the algorithm. The prototype is envisioned to first check whether the roadway is operating in queued state (i.e., after breakdown where stop-and-go operations exist) or congested state (i.e., before breakdown has occurred but where speeds are below free-flow conditions). The analysis will first focus on looking across all lanes (i.e., the link level). If no queues or congestion are detected at the link level, then the analysis will look for queuing at the lane level. Recommended travel speeds will be developed for each situation. Using the results of the analysis, messages will be generated that provide both queue warning and recommended travel speeds to motorist driving through the section. The information will be disseminated to a vehicle using both connected vehicles as well as infrastructure devices.

It should be noted that this is a prototype dynamic speed harmonization/queue warning system. This prototype is intended to demonstrate how connected vehicle data can be used to improve the level of accuracy and timeliness of generating traffic management responses. This prototype is intended to represent many different approaches that can be used to provide dynamic speed harmonization and queue warning. This prototype is not intended to represent the final solution. Other approaches for providing queue warning and dynamic speed recommendations in congested and queued states exist and may be viable in a full deployment scenario.

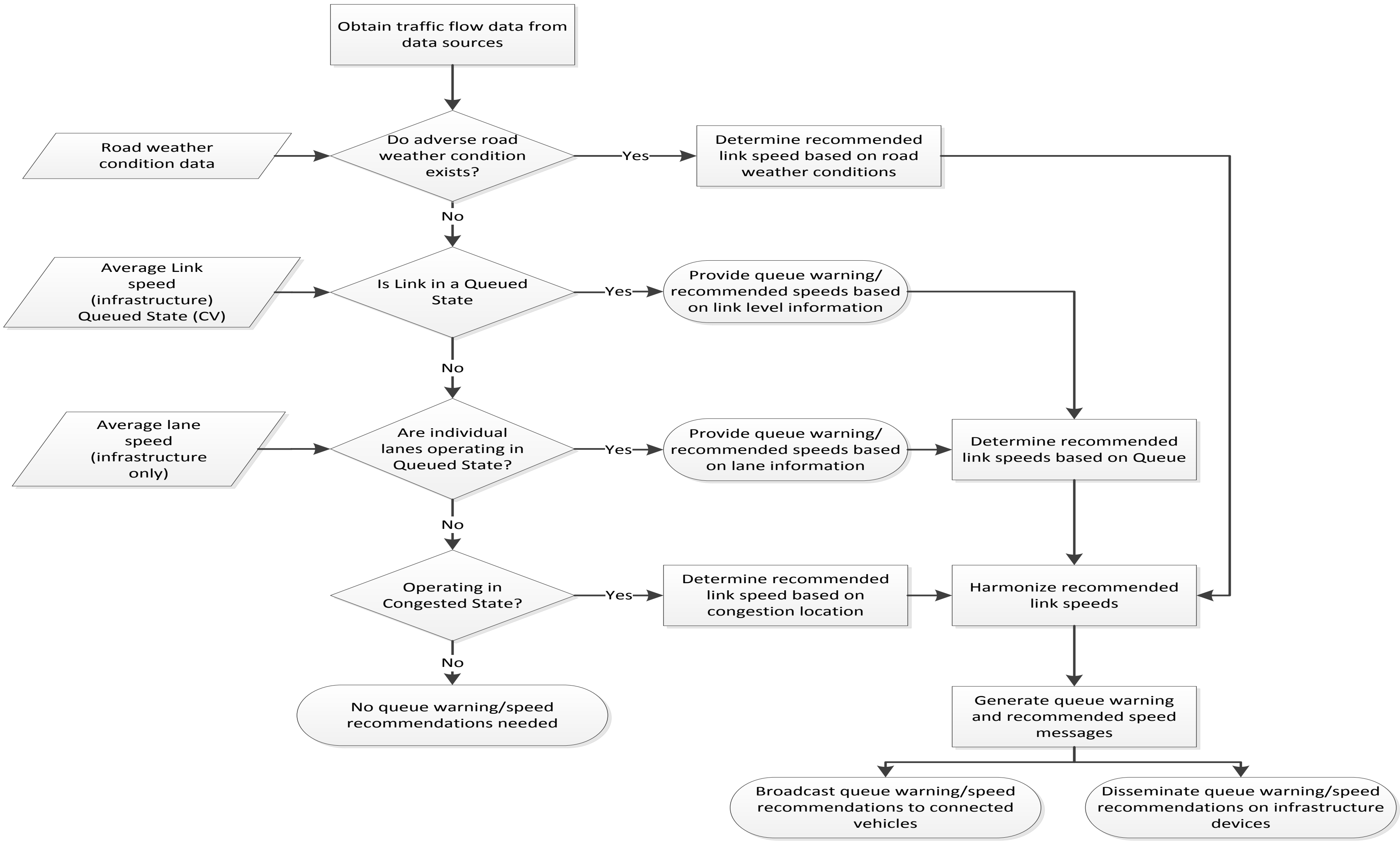

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Figure 3-1. Overview of Prototype Dynamic Speed Harmonization/Queue Warning Decisions Processes.

Algorithm Functional Requirements

Previous US DOT efforts with critical stakeholders identified the functional requirements for both speed harmonization/queue warning applications managed by a traffic management entity (called a TME-based application) as well as vehicle-based queue warning applications. These functional requirements were documented in *Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO): Functional and Performance Requirements, and High-Level Data and Communication Needs*.[1] The functional requirements specifically related to the development of the algorithms in the prototype environment were extracted and presented here for completeness.

Table 3-1 shows the functional requirements of the TME-based speed harmonization application. Table 3-2 shows the functional requirements of the TME-based queue warning application, while Table 3-3 shows the functional requirements of a connected vehicle based queue warning application. These functional requirements were used by the project team to structure and design the algorithms to be developed as part of the prototype system design.

It should be noted that these tables represent only those functional requirements that were anticipated to affect the design of the speed harmonization and queue management/ warning applications. Additionally, the scope of the prototype required that some of the requirements be revisited given the state of the technology available or the cost/complexity of fulfilling. These requirements are annotated as ‘Partial’ in the following tables. For a complete listing of the system functional requirements of the entire INFLO prototype system, the reader is encouraged to review the *Report on Detailed Requirements for the INFLO Prototype*.

[1] *Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO): Functional and Performance Requirements, and High-Level Data and Communication Needs)*, ITS JPO Publication Number FHWA-JPO-13-013.

Table 3-1. Functional Requirements for a TME-based Speed Harmonization Application.

Requirement Number	Requirement	User Need
RS-9.1	The Traffic Management Entity (TME)-based SPD-HARM application shall have a data collection capability for receiving real-time data from multiple sources.	S9
RS-9.1.1	The TME-based SPD-HARM application shall have a data collection capability for receiving real-time traffic, road conditions, and weather data from infrastructure-based systems.	S9
RS-9.1.2a	The TME-based SPD-HARM application shall have the capability to receive real-time traffic (including location and speed) from connected vehicles.	S9
RS-9.1.2b	The TME-based SPD-HARM application shall have the capability to receive road conditions (e.g. ice, wet, etc.) and weather data (clear, rainy and snowy) from connected vehicles where available.	S9
RS-9.2	The TME-based SPD-HARM application shall have the capability to access a data environment that includes historical traffic data (including speed, flow and density), road conditions data (e.g. ice, wet, etc.), and weather data (clear, rainy and snowy).	S9
RS-10.1	The TME-based SPD-HARM application shall be capable of fusing and processing data from various sources to make target speed recommendations.	S10
RS-10.1.1a	The TME-based SPD-HARM application shall utilize real-time traffic data when calculating the recommended target speed.	S10
RS-10.1.1b	The TME-based SPD-HARM application shall utilize historical data when calculating the recommended target speed.	S10
RS-10.1.2	The TME-based SPD-HARM application shall utilize real-time weather data when calculating the recommended target speed.	S10
RS-10.1.3	The TME-based SPD-HARM application shall utilize real-time road surface data when calculating the recommended target speed.	S10
RS-10.2	The TME-based SPD-HARM application shall have a shockwave detection capability for known fixed bottleneck locations.	S10
RS-10.2.1	The TME-based SPD-HARM application shall have a shockwave detection capability that identifies at least 95% of all shockwave occurrences for known fixed bottleneck locations.	S10
RS-10.2.2	The TME-based SPD-HARM application shall have a false positive identification rate of no more than 5% of all shockwave events at known fixed bottleneck locations.	S10
RS-10.2.3	The TME-based SPD-HARM application shall detect formed shockwaves within TBD seconds of formation at known fixed bottleneck locations.	S10
RS-10.2.4	The TME-based SPD-HARM application shall determine the lane(s) impacted by the formed shockwave based on infrastructure data.	S10
RS-10.2.4.1	The TME-based SPD-HARM application shall determine the lane(s) impacted by the formed shockwave within TBD seconds of shockwave detection.	S10

Table 3-1. Functional Requirements for a TME-based Speed Harmonization Application (Continued)

Requirement Number	Requirement	User Need
RS-10.2.5	The TME-based SPD-HARM application shall determine the length of the formed shockwave.	S10
RS-10.2.5.3	The TME-based SPD-HARM application shall update the current shockwave length estimation once every 5 second.	S10
RS-10.2.6a	The TME-based SPD-HARM application shall utilize real-time traffic data in shockwave detection algorithms.	S10
RS-10.2.6b	The TME-based SPD-HARM application shall utilize road condition and weather data in shockwave detection algorithms.	S10
RS-11.1	The TME-based SPD-HARM application shall have a target speed generation capability.	S11
RS-11.1.1	The TME-based SPD-HARM application shall generate target speed strategies for different segments of the roadway.	S11
RS-11.1.2a	The TME-based SPD-HARM application shall generate target speed strategies that consider downstream traffic conditions, weather, and local roadway surface conditions.	S11
RS-12.1	The TME-based SPD-HARM application shall have a target speed recommendation dissemination capability.	S12
RS-12.1.1	The TME-based SPD-HARM application shall disseminate target speed recommendations to SPD-HARM enabled connected vehicles on the facility via I2V communications.	S12
RS-12.1.2	The TME-based SPD-HARM application shall disseminate target speed recommendations to DMS locations.	S12

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Table 3-2. Functional Requirements of a TME-based Queue Warning Application.

Requirements Number	Requirement	User Need
RQ-9.1	The Traffic Management Entity (TME)-based Q-WARN application shall have a data collection capability for receiving real-time traffic, road conditions, and weather data from multiple sources.	9
RQ-9.1.1	The Traffic Management Entity (TME)-based Q-WARN application shall have a data collection capability for receiving real-time traffic, road conditions, and weather data from infrastructure-based systems.	9
RQ-9.1.2	The TME-based Q-WARN application shall have the capability to receive real-time traffic (including location and speed), and weather data (barometric pressure and ambient temperature when outside the vehicle) from nomadic devices.	9
RQ-9.2	The TME-based Q-WARN application shall have the capability to access a data environment that includes historical traffic data (including speed, and flow), road conditions data (e.g. ice, wet, etc.), and weather data (clear, rainy and snowy).	9
RQ-11.1	The TME-based Q-WARN application shall be capable of fusing and processing data from various sources to perform queue detection.	11
RQ-11.1.1a	The TME-based Q-WARN application shall utilize real-time data in queue detection algorithms.	11
RQ-11.2	The TME-based Q-WARN application shall have a queue detection capability for known fixed queue generation locations.	11
RQ-11.3	The TME-based Q-WARN application shall determine the lane(s) impacted by the formed queue from infrastructure sensor data.	11
RQ-11.4	The TME-based Q-WARN application shall determine the length of the formed queue.	11
RQ-11.5	The TME-based Q-WARN application shall determine the number of vehicles in the formed queue.	11
RQ-11.6	The TME-based Q-WARN application shall determine the traveling speed and direction of the formed queue.	11
RQ-11.6.1	The TME-based Q-WARN application shall determine the traveling speed of the formed queue within two update cycles of the queue detection.	11
RQ-11.6.2	The TME-based Q-WARN application shall update the estimation of the traveling speed of the queue at regular intervals when queue is present.	11
RQ-11.6.3	The TME-based Q-WARN application shall determine the traveling speed of the formed queue to within 5 mph.	11
RQ-12.1	The TME-based Q-WARN application shall be capable of fusing and processing data from various sources to perform queue prediction.	12
RQ-12.1.1	The TME-based Q-WARN application shall utilize real-time and historical traffic data in queue prediction algorithms.	12

Table 3-2. Functional Requirements of a TME-based Queue Warning Application (Continued)

Requirements Number	Requirement	User Need
RQ-12.1.2	The TME-based Q-WARN application shall utilize real-time and predicted weather data in queue prediction algorithms.	12
RQ-12.1.3	The TME-based Q-WARN application shall utilize real-time road surface data in queue prediction algorithms.	12
RQ-12.4	The TME-based Q-WARN application shall determine the lane(s) impacted by the predicted queue.	12
RQ-12.5	The TME-based Q-WARN application shall determine the length of the predicted queue.	12
RQ-13.1.1	The TME-based Q-WARN application shall generate queue warning response strategies that include speed reduction recommendations.	13
RQ-13.1.1.1	The TME-based Q-WARN application shall interface with the TME-based SPD-HARM application to generate appropriate speed reduction targets.	13
RQ-13.1.2a	The TME-based Q-WARN application shall generate target speed strategies that consider distance to back of queue.	13
RQ-14.1	The TME-based Q-WARN application shall have a queue warning and queue information dissemination capability.	14
RQ-14.1.1	The TME-based Q-WARN application shall disseminate queue warnings and queue information to DMS locations.	14
RQ-14.1.2	The TME-based Q-WARN application shall disseminate queue warnings and queue information to connected vehicles.	14
RQ-14.1.3	The TME-based Q-WARN application shall disseminate queue warnings and queue information to traveler information systems (e.g., 511).	14

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Table 3-3. Functional Requirements of a Connected Vehicle-based Queue Warning Application.

Requirements Number	Requirement	User Need
RQ-2.1	The Connected Vehicle-based Q-WARN application shall pass individualized queue response strategies (based on vehicle's distance to back of queue) to the driver interface system (speed reduction, lane change, diversion recommendations).	2,8
RQ-3.1	The Connected Vehicle-based Q-WARN application shall utilize secure data transmission methods when disseminating any personally identifiable information.	3
RQ-4.1	The Connected Vehicle-based Q-WARN application shall have the ability to detect when the vehicle is in a queued state.	4
RQ-4.2	The Connected Vehicle-based Q-WARN application shall communicate with the Integrated Vehicle Network Access System to gather real-time vehicle-collected data from the vehicle network.	4
RQ-5.1	The Connected Vehicle-based Q-WARN application shall disseminate a queued status alert to other connected vehicles via V2V communication.	5
RQ-5.2	The Connected Vehicle-based Q-WARN application shall disseminate a queued status alert to infrastructure systems via V2I communication.	5
RQ-6.1	The Connected Vehicle-based Q-WARN application shall have the ability to receive queue warning messages via I2V communication channels.	6
RQ-6.2	The Connected Vehicle-based Q-WARN application shall have the ability to receive queue warning messages via V2V communication channels.	6
RQ-7.1	The Connected Vehicle-based Q-WARN application shall individualize generic queue warning message based on vehicle's position and distance to the end of the queue.	7
RQ-7.2	The Connected Vehicle-based Q-WARN application shall generate appropriate queue response strategies based on distance to back of queue.	7
RQ-7.2	The Connected Vehicle-based Q-WARN application shall generate appropriate queue response strategies based on local traffic, weather, and roadway conditions.	7
RQ-7.3.1	The Connected Vehicle-based Q-WARN application shall interface with the Connected Vehicle-based SPD-HARM application to generate appropriate speed reduction targets.	7

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Chapter 4 Virtual TME System Architecture

Figure 4-1 shows the proposed system architecture for a virtual TME that will be developed to support the prototype deployment of a combined Speed Harmonization/Queue Warning system. The virtual TME consists of the hardware and software components required to implement the TME-based INFLO bundle of applications prototype. A modular design approach that takes into consideration the design principles mentioned earlier, will guide the development of the prototype components. The reason for the modular approach is that some of the external input feeds (like the infrastructure-based sensor traffic data) might be dropped over time when newer, richer sources of data become available due to the increase in the connected vehicles penetration rate in the overall vehicle fleet. This will require a flexible architecture in the design of the algorithms components where adding or dropping of certain components to enhance algorithms performance would not affect other components of the system.

Figure 4-1 also shows the proposed components that envisioned for the prototype design. The purpose and function of each of these components are discussed below.

Data Collector/Aggregators

The prototype is envisioned to have four major data aggregator. The data aggregators are responsible for obtaining, processing, formatting, and distributing the data used by the various processes in the INFLO algorithm. The Data Collector/Aggregator will obtain speed, volume, and/or occupancy data from the Traffic Sensors, BSM data from Connected Vehicles, and road surface and weather condition information from Road Weather Information Sensor (RWIS) stations deployed in the corridor. The Aggregators will be also be responsible for performing quality assurances checks on the data before sending the data on to other processes.

INFLO Database

A critical component of the virtual TME environment that will provide the flexibility needed in designing the algorithms is the INFLO database system. The INFLO database will be used to store the processed input data collected from the various external sources required by the algorithms and any metadata generated from processing the input data by the data aggregators. The recommendations made by each algorithm and sent to drivers and infrastructure-based signs will also be stored in the database. The database 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 for sharing data between the various prototype components and to synchronize the operations of the various components in the TME virtual environment. For example, the speed harmonization algorithm fuses data from multiple sources including external sources like infrastructure-based sensor traffic data and connected vehicle traffic data besides metadata generated by other algorithms like the safe speed recommendations from the Weather-Responsive Traffic Management (WRTM) algorithm. 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 connected vehicle data is acquired at one to five second intervals. On the other hand the WRTM algorithm might generate weather safe speed recommendations every minute or at higher intervals. All of this data will be stored in the INFLO database in real-time and depending on the frequency of running the TME-speed harmonization algorithm, it will query the database for the data it needs and generate the proper speed recommendation for roadway links.

TME Link Speed Process

This process is responsible for performing the speed harmonization process for the system. This involves obtaining the both infrastructure-based and vehicle-based information from the Data Collector/Aggregator and processing this data to determine when the local speed should be in each freeway segment. The TME Link Speed contains the logic associated with providing smooth transitions of speed from free flow to congested flow regimes. The output of the TME Link Speed feeds to the Message Arbitrator where it is compared to the output of other processes to determine which speed governs individual freeway segments.

TMEQueue Warning Process

This process is responsible for processing the traffic sensor data delivered by the Data Collector/Aggregator and determining which freeway segments are operating in a queue state. The process is responsible for producing estimates of the queue location, the rate of growth/dissipation of the queue, the length of the queue, and other information necessary to produce a queue warning for both infrastructure devices as well as connected vehicles.

TME WTRM Process

This process is responsible for generating safe speeds for measured and/or forecasted weather conditions. This process will first use forecasted weather conditions to determine when weather information should be obtained from RWIS sensors. This process would then use real-time measures of road surface conditions, visibility, and precipitation to determine the safe travel speeds for the weather conditions.

TME Link Speed Harmonization Process

The TME Link Speed Harmonization Process is a process that receives the results of the various INFLO algorithms and selects the critical message to be sent out to the road users. The critical message is usually the lowest advisory speed from among the speeds recommended by the various INFLO algorithms. The TME Link Speed Harmonization Process will use user-defined rules to determine which of the speed recommendations has priority to be displayed to road users.

TME Message Generator

This process is responsible for determining the appropriate speed messages to be displayed for each section of the freeway. This process will start with the controlling section and then adjust speed message upstream to provide a smooth transition from free flow to congested speed. The message generator will also determine the content of the messages to be displayed dynamic message signs. Two separate processes will be used to generate the messages: one for infrastructure-based information dissemination system (such as dynamic message signs) and one for vehicle-based systems.

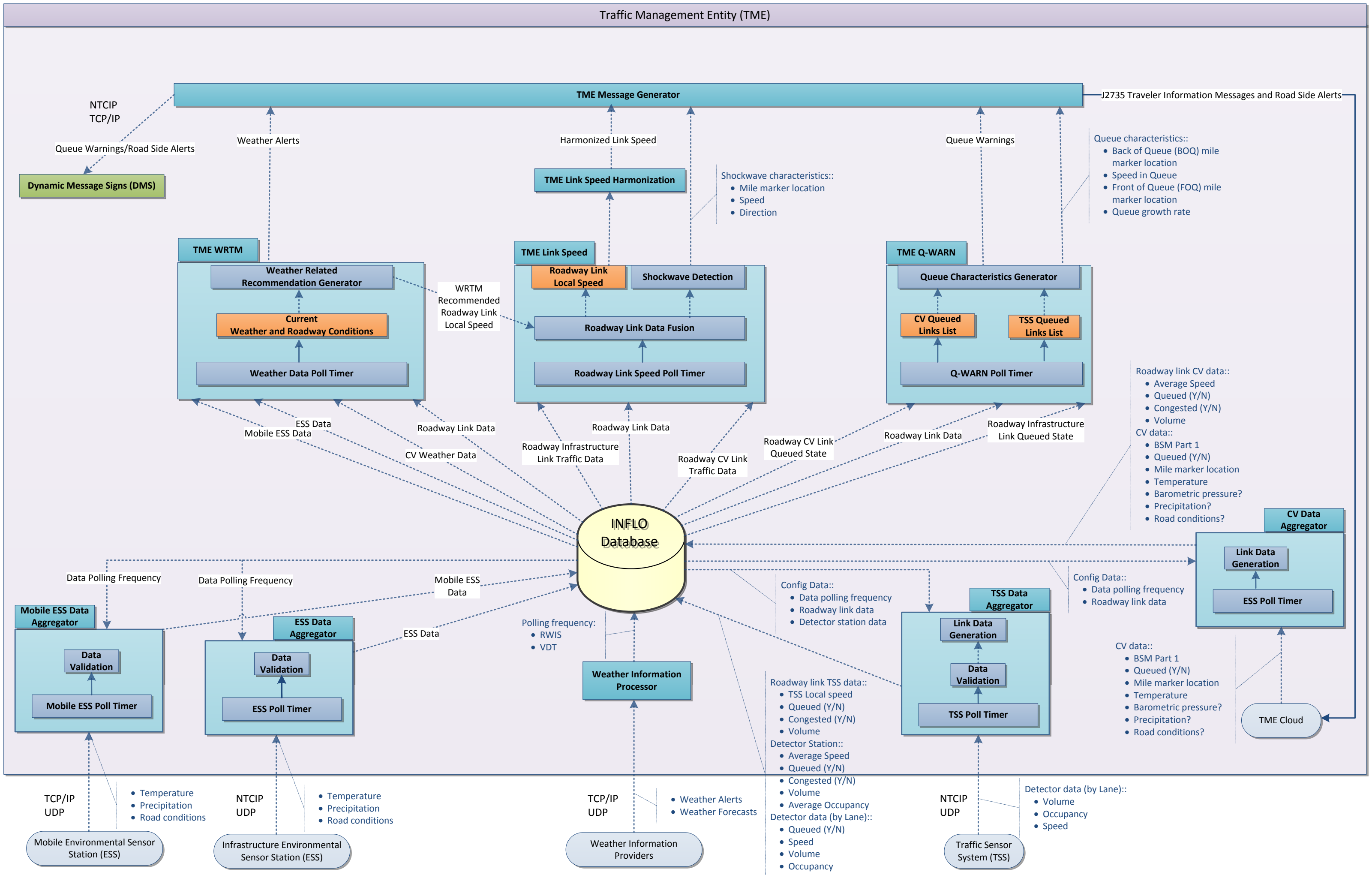

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Figure 4-1. System Architecture of TME-Based Queue Warning/Speed Harmonization System.

Chapter 5 Data Sources and Data Aggregation

This chapter describes the sources of infrastructure and connected vehicle data that will be used in the algorithms. The primary sources of data to be incorporated in the prototype include the following:

- Infrastructure-based fixed sensor data
- Wireless connected vehicle data/travelers' mobile devices
- Both public and private sources of weather data.

Each of these sources of data is discussed in detail below.

In addition to describing the structure and the particular data elements that will be used in the algorithms, this chapter also discusses the processes and procedures used to process and ready the data for use in the algorithms. These processes are called Data Aggregators. A Data Aggregator is associated with each data source. The Data Aggregators contain the processes and procedures used to manipulate, format, and store the data into the INFLO database where it can be readily accessed by other components in the prototype.

Infrastructure-based Data Sources

A number of different technologies can be used to produce traffic flow measures. Generally, transportation sensor technology can be classified as either intrusive or non-intrusive. Intrusive roadway sensors are those that are embedded in the pavement, embedded in the subgrade of the pavement, or adhered to the surface of the roadway. Vehicles are detected by passing over the sensor. Examples of these sensors include loop detectors and magnetometers. Non-intrusive sensors are those which are mounted either above or adjacent to the roadway. Examples of these types of sensors include video image processors, microwave radar, ultrasonic, and passive infrared sensors. Vehicles are detected by passing through the detection zones. Most transportation management entities will commonly deploy multiple types of detector technologies.

Regardless of the technology used, most traffic management entities rely on these sensors to provide the same basic level of data. The measurements typically used by traffic management entities to monitor traffic operations on roadways include the following:

- **Volume** – Used to measure the quantity of traffic. Volume is defined as the number of vehicles observed or predicted to pass over a given point or section of a lane or roadway during a given time. Volume is typically used to track historical trends and to predict the future occurrence of congestion on specified freeway sections.
- **Speed** – An important measurement in determining the quality of traffic operations. Speed is frequently used to describe traffic operations because it is easy to explain and understand. Speed measurements are typically taken for individual vehicles and

averaged to characterize the traffic stream as a whole. Measured speeds can be compared to optimum values to estimate the level of operations for a freeway or to detect incidents. For example, an alarm for an incident detection system might be triggered if average speeds fall below a target value.

- **Occupancy** – Defined as the percent of time a given section of roadway is occupied by a vehicle and can be used as a surrogate for density. Occupancy is measured using presence detectors and is easier to measure than density. Occupancy is measured on a lane-by-lane basis, with values ranging from 0 percent (no vehicles passing over a section of roadway) to 100 percent (vehicles stopped over a section of roadway).

Both the speed harmonization and queue warning algorithms utilize these traffic system sensor data elements.

Traffic Sensor System Data

For the purpose of this prototype deployment, it is assumed that all infrastructure-based roadway sensors will utilize *NTCIP 1209: Data Element Definitions for Transportation Sensor Systems*[2] to transfer traffic sensor data from the field. NTCIP 1209 is a national standard that describes how traffic sensor systems, regardless of the physical technology, communicate with traffic management centers (TMCs). These standards establish the communications protocol that allows transportation management entities to configure, manage, and collect data from traffic sensor systems deployed in the field. The algorithms will be designed using the NTCIP 1209 data elements shown in Table 5-1.

The algorithms will be designed to operate at both the link (defined below) and individual detector level. For this prototype, a link is defined as a section of roadway, measured longitudinally, between two detector stations. Figure 5-1 shows a schematic of the typical way traffic management agencies aggregate traffic sensor systems from individual detectors to provide “link” averages.[3] Detector readings from each lane are first combined across all through lanes in each direction to what is commonly referred to as the “station level”. Typically, slow-moving auxiliary lanes are not included when aggregating to the station level. Each detector station is then assigned a “zone of influence” which is intended to be a portion of the roadway considered to be represented by the information from the detector station. In most active management applications, these “zones of influence” for each detector station extend to the next downstream sensor.

[2] *National Transportation Communications for ITS Protocol – Data Element Definitions for Transportation Sensor Systems*. NTCIP 1209 v01.18 d. American Association of State Highway and Transportation Officials. April 2004.

[3] Margiotta, R. et al. *Guide to Effective Freeway Performance Measurement: Final Report and Guidebook.* NCHRP Web-Only Document 97. National Academy of Science, Transportation Research Board. Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w97.pdf. Accessed January 10, 2014.

Table 5-1. Description of NTCIP 1209 Transportation Sensor System Data Objects to be used in Prototype INFLO Algorithms.

Object Name	Syntax	Description
sensorZoneNumber	INTEGER (1..255)	The numerical label or number of the sensor zone. This value shall not exceed the maxSensorZones data element value.
endTime	Counter	Indicates the time at which the data collection period ended for the data contained in this row, the most recently completed sample period. If the clockAvailable data element indicates the presence of a clock, this time shall be expressed in local time as expressed in the controller-localTime data element (see NTCIP 1201); otherwise, this time shall be expressed in the number of seconds since the most recent device initialization.
volumeData	Integer (0..65535)	Counts per sample period, for the most recently completed sample period. Counts are expressed as an integer value in the volumeData data element. The value of 65535 shall be returned to represent a missing value. A missing value is reported when the zoneStatus is anything other than OK for the entire sampling period.
percentOccupancy	Integer (0..1000|65535)	Percent occupancy over the sample period for the most recently completed sample period. Occupancy is expressed in tenths of a percent, from 0 to 100.0 percent, in the percentOccupancy data element. The value of 65535 shall be return to represent an invalid or missing value. A missing value is reported when the zoneStatus is anything other than OK for the entire sampling period. Values 1001 through 65534 are reserved for future use.
speedData	INTEGER (0..2550 | 65535)	Arithmetic mean of speeds collected over the sample period with units of 1/10ths of km/h, for the most recently completed sample period. For a volume of zero during the sample period, the value of 65535 shall be returned to represent an invalid or missing value. A missing value is reported when the zoneStatus is anything other than OK for the entire sampling period. Values 2551 through 65534 are reserved for future use.

Table 5-1. Description of NTCIP 1209 Transportation Sensor System Data Objects to be used in Prototype INFLO Algorithms (Continued)

Object Name	Syntax	Description
zoneStatus	INTEGER { other (1), oK (2), initializing (3), noActivity (4), maxPresence (5), configurationError (6), erraticCounts (7), disabled (8), overrideActive (9), sensorFailure (10) }	Detailed status returned as result of diagnostics, as follows: other: Status returned indicating an error has occurred within the device for which there is no defined definition within this data element, oK: Status returned indicating OK, initializing: Status returned indicating an initialization or diagnostics procedure is in progress, noActivity: Status returned indicating no activity error condition, maxPresence: Status returned indicating max presence error condition, configurationError: Status returned indicating an error within the device configuration setup, erraticCounts: Status returned indicating erratic counts, disabled: Status returned indicating that the zone is disabled. overrideActive: Status returned indicating an override is active. sensorFailure: Status returned indicating a sensing element failure, If a condition occurs during the sample period, then that state remains for the duration of that sample period. If multiple conditions occur during a sample period, the last reported condition, other than OK, is retained.

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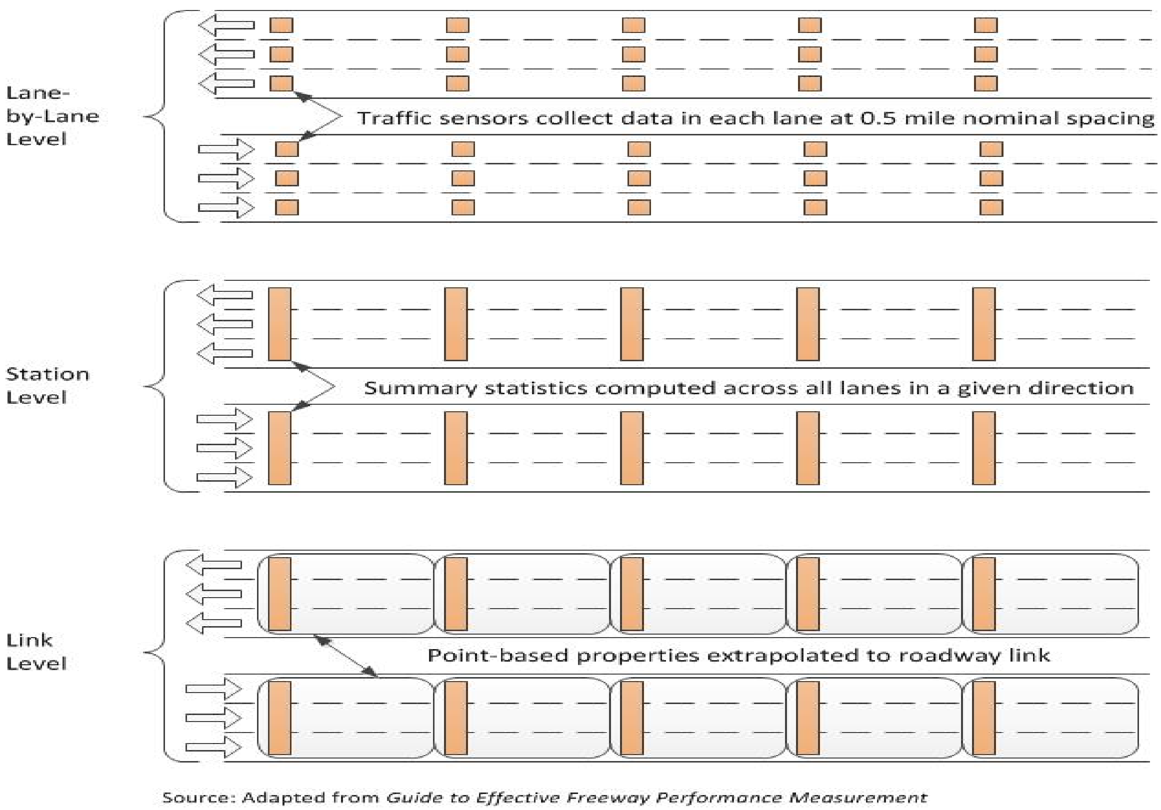

Figure 5-1. Spatial Aggregation of Traffic Sensor Data.

Traffic Sensor System (TSS) Data Aggregator

The Traffic Sensor System (TSS) Data Aggregator collects the data from the roadway sensors, aggregates the data according to user defined procedures and thresholds, and populates the INFLO Database. The roadway sensor data typically collected includes the speed data from speed sensors in each lane along with a time stamp. The data is then aggregated to obtain average station speeds across all lanes. Average station speeds are then compared to user-defined speed thresholds to determine if the speeds by link are operating in a clear, congested, or queued state. If detector data are available at the lane level, the TSS Data Aggregator will also determine which lanes within the link are operating in a congested and/or queued state. The thresholds to determine whether a link and/or lane are in a queued state or congested state are user defined. For the prototype, initially only speed data will be used to determine operating states for the link and the lanes within the link.

While typical speed harmonization systems collect data (only from infrastructure) at a frequency of 2 to 3 minutes, data from the infrastructure sensors will be collected every 20 to 60 seconds and updated in the INFLO database at this same interval. The infrastructure data aggregation process is illustrated in Figure 5-2.

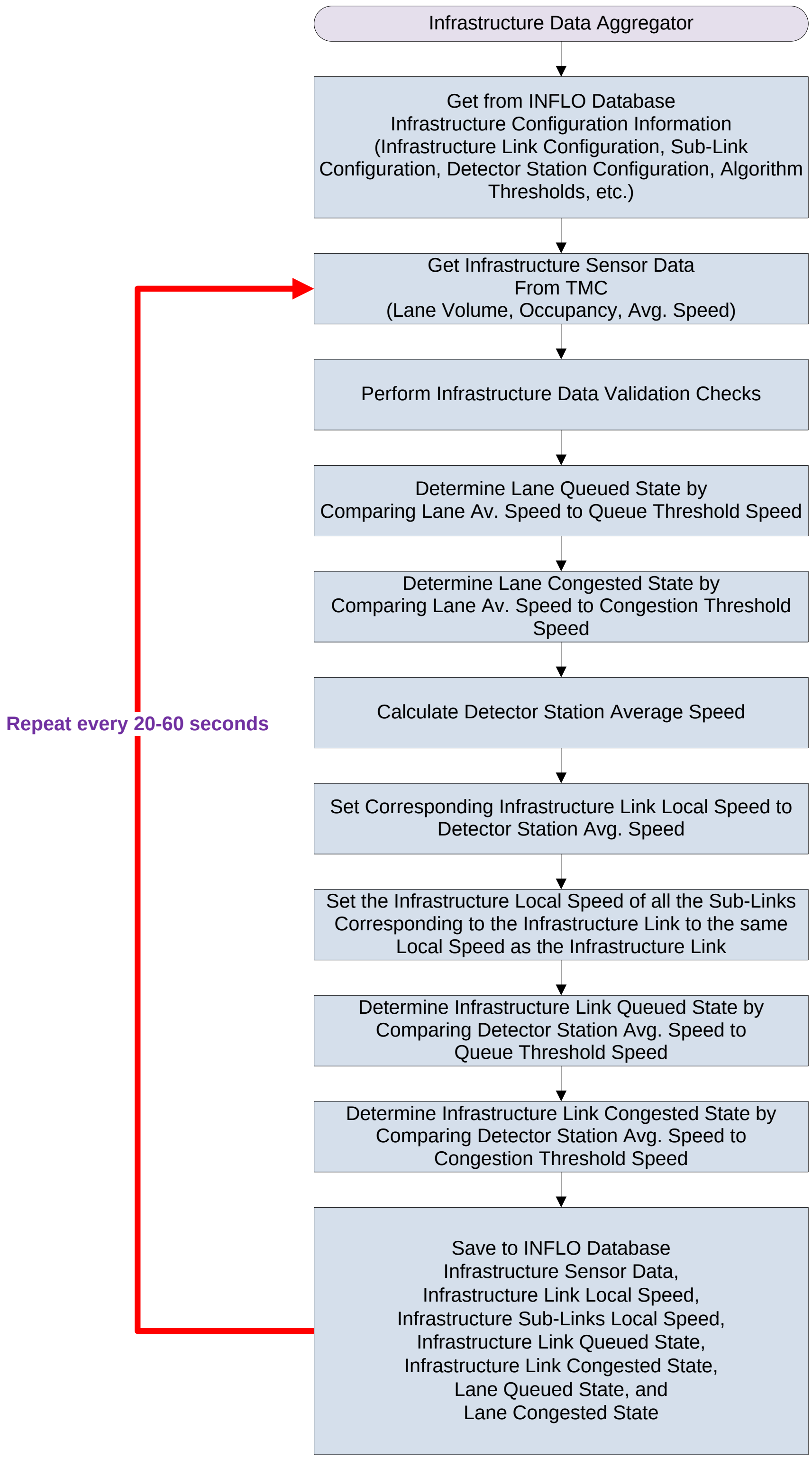

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Figure 5-2. Process of Infrastructure Data Aggregation.

The output of the TSS Data Aggregator process is shown in Table 5-2.

Table 5-2. TSS Data Elements in the INFLO Database.

Data Element	Required	Type	Refresh Rate	Standard/ Reference	Description
Timestamp	Yes	DateTime	20-60 seconds	TMDD	Local time zone date and time when the recommendation was generated
Roadway Link Identifier	Yes	Text	static	TMDD	A unique ID identifying a section of roadway
TME Lane_Speed	Yes	Number-Integer	20-60 seconds	TMDD	Roadway lane local speed measured by the infrastructure-based sensors
Lane Congested State	Yes	Text	20-60 seconds	NA	The state of the lane by comparing the current lane speed to the congestion threshold speed (Yes/No)
Lane Queued State	Yes	Text	20-60 seconds	NA	The state of the lane by comparing the current link speed to the queue threshold speed (Yes/No)
TME Link_Speed	Yes	Number-Integer	20-60 seconds	TMDD	Roadway link local speed measured by the infrastructure-based sensors
Link Congested State	Yes	Text	20-60 seconds	NA	The state of the link by comparing the current link speed to the congestion threshold speed (Yes/No)
Link Queued State	Yes	Text	20-60 seconds	NA	The state of the link by comparing the current link speed to the queue threshold speed (Yes/No)

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Vehicle-Based Data Sources

The SAE J2735:2009 Basic Safety Message (BSM) is one of the critical messages broadcast by vehicles in a connected vehicle environment. The BSM provides information about the vehicle state with a variety of data content that is critical for safety, mobility and other applications. The BSM message is usually broadcast by the vehicle via DSRC at a rate of 10 times per second. The BSM consists of Part I and Part II data. The BSM Part I data provide information about the vehicle's location, motion, and state and consist of the following data elements:

- Message ID
- Timestamp represented as the time within the minute when the message was broadcast
- Vehicle Position (Latitude, Longitude, Elevation, Accuracy)

- Vehicle Motion (Speed, Heading, SteeringWheelAngle, AccelerationSet4Way)
- Vehicle Brake System Status
- Vehicle Size.

BSM Part II consists of data elements that provide more information about the vehicle state and the surroundings in case the vehicle was equipped with sensors to detect surrounding conditions like weather sensors. BSM Part II elements are typically sent as requested by other vehicles, infrastructure, or applications. However for this prototype, BSM Part II will also be broadcast at a recurring frequency, currently planned for 1Hz. For a full listing of the possible data elements that can be sent in the Part II BSM message, refer to the SAE J2735:2009standard data frames Vehicle Safety Extension and Vehicle Status.

Connected Vehicle Data

Vehicles in a connected vehicles environment will exchange the BSM Part I message with other vehicles on the roadway and within DSRC range 10 times per second. Each vehicle will use BSM data from other vehicles to determine its locations with respect to other surrounding vehicles, i.e. their location upstream or downstream of other vehicles, their direction of travel (either with the same heading or opposite heading), and their separation distance from other downstream vehicles. Connected vehicles will use their separation distance in determining their queued state and the location of other queued vehicles in their vicinity. In addition to the BSM Part I data, vehicles equipped with a nomadic device for the INFLO prototype will also have the ability to determine their queued state and their mile marker location on the roadway network. These two data elements, queued state and mile marker location, will be broadcast by the vehicle in the BSM Part II message to other vehicles in conjunction with the BSM Part I. Table 5-3 shows the data elements which will be collected from each individual connected vehicle.

The following sections describe how a vehicle will use information from other vehicles and configuration data to determine the additional two data elements: vehicle’s queued state and mile marker location.

Determining Mile Marker Location of Connected Vehicles

One of the critical data elements for the vehicle-based V2V queue warning application is the ability of the vehicle to determine its mile marker location on the roadway network. Upon initially entering the deployment corridor, the connected vehicle will receive linear referencing system information. Similar to the MAP message that is broadcast by the roadside equipment (RSE) to vehicles in intersection related safety and mobility applications, the linear reference system information would enable the vehicle to locate itself between two adjacent mile markers in the corridor and consequently enable it to calculate its mile marker location using either upstream or downstream mile marker locations. The linear reference system consists of the following information:

- Roadway ID
- Roadway Name
- Mile Marker Location
- Heading
- Mile Marker Latitude, Longitude, and Elevation.

Table 5-3. Connected Vehicle Data Elements Used the INFLO Processes.

Data Element	Required	Type	Refresh Rate	Standard/ Reference	Description
CV Message Identifier	Yes	Number Integer	Second	SAE J2735 2009	An automatic unique number assigned to each message received from connected vehicle by the TME
Nomadic Device Identifier	No	Text	Second	SAE J2735 2009	The nomadic device unique identifier. This data element is tracked and used only in the prototype testing for evaluation purposes.
Timestamp	Yes	Date Time	Second	TMDD	The local time zone date and time when the message was generated by the nomadic device
Speed	Yes	Number-Integer t	Second	TMDD	Speed of the vehicle when the message was generated
Heading	Yes	Number-Double	Second	TMDD	Heading of the vehicle when the message was generated
Latitude	Yes	Number-Double	Second	TMDD	Geographical location of the vehicle when the message was generated
Longitude	Yes	Number-Double	Second	TMDD	Geographical location of the vehicle when the message was generated
Coeff. of Friction	No	Number-Double	Second	NA	Either calculated by the CV or in the TME using data elements sent by the CV
Temperature	No	Integer	Second	TMDD	The air temperature measured by weather sensors on the connected vehicle
Barometric Pressure	No	Integer	Second	NA	The barometric pressure measured by weather sensor on the connected vehicle.
Mile Marker Location	Yes	Number-Double	Second	TMDD	Mile marker location when the message was generated
Queued State	Yes	Text	Second	NA	The queued state (Yes/No) of the vehicle when the message was generated
Roadway Identifier	Yes	Text	Second	TMDD	Identifier of the roadway where the vehicle was traveling when the message was generated

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Using the linear reference system information, a vehicle will calculate its mile marker location using the following steps:

- Using its current location latitude and longitude and comparing it to the latitude and longitude of the mile markers, the vehicle will determine the two adjacent mile markers between which it is located.
- Using its current location latitude and longitude, the vehicle will calculate its distance from either one of the adjacent mile markers.
- Depending on the direction of increasing/decreasing order of the mile markers, the vehicle will use the distance it calculated to one of the mile markers to determine its mile marker location.

Determining Queued State of Connected Vehicles

Critical to the INFLO prototype is the determination that a vehicle is in a queued state. The *2010 Highway Capacity Manual*[4] defined a queued state as follows:

> *A condition when a vehicle is within one car length (20 ft.) of a stopped vehicle and is itself in a stopped state (i.e., has slowed to speed of less than 5 mi/h).*

Using this definition, two conditions in the HCM must be satisfied in order for the connected vehicle to declare itself to be in a queued state:

- The instantaneous speed of the vehicle must be measured to below a predefined queued state speed threshold, and
- The separation distance (or gap) between itself and the vehicle immediately downstream must be less than a predefined separation distance threshold.

These conditions are illustrated in Figure 5-3.

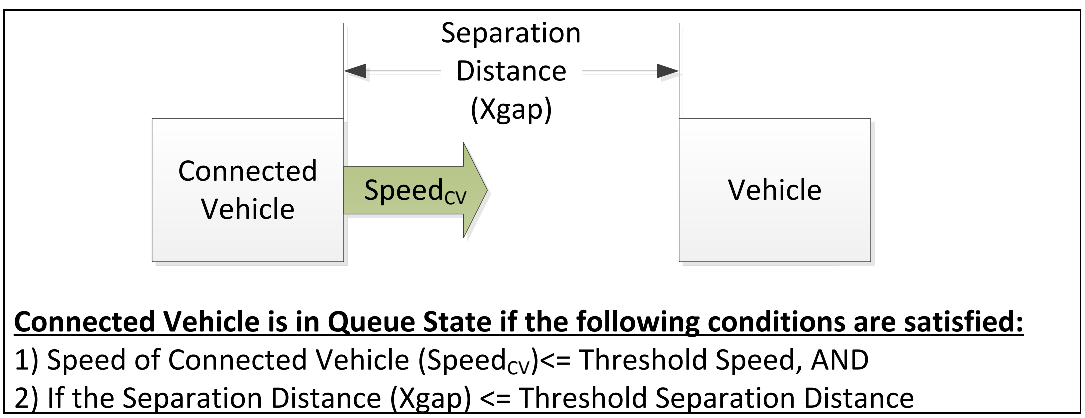

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Figure 5-3. Conditions for Determining if Queue is in Queued State

[4] *HCM 2010 Highway Capacity Manual*. Volume 1: Concepts. National Academy of Science, Transportation Research Board. 2010.

Note: it is not critical that the vehicle downstream of the connected vehicle be a connected vehicle itself. The upstream vehicle only needs to be able to determine that it is within the threshold separation distance of the downstream vehicle, and that the travel speed of the vehicle is at or below the threshold speed. Other systems, such as the vehicle's collision avoidance system could possibly be used to provide separation distance information.

Figure 5-4 shows the proposed logic for determining if a connected vehicle is traveling in a queued state. The steps in performing this determination are as follows:

- Upon initially entering the deployment corridor, the connected vehicle will receive linear referencing system information that describes the deployment corridor as well as the speed and distance threshold parameters from the TME. The connected vehicle should also set its initial queued state indicator to reflect an "UNKNOWN" state. If the connected vehicle does not receive an initial set of speed and distance threshold parameters, default values will be used.
- Once inside the deployment corridor, the vehicle would repeat the following steps every second until it determines its location to be beyond the end of the deployment corridor:
    - The connected vehicle should get its current speed and the separation distance to the next downstream vehicle, if available, from its on-board systems.
    - The connected vehicle would then compare its current speed and separation distance to the queued state speed and separation distance threshold parameters. IF the speed of the connected vehicle is less than or equal to queued state speed threshold AND if the distance to the next downstream vehicle is less than the queued state separation distance threshold, THEN the connected vehicle should set its queued state indicator to represent that the vehicle is in a "QUEUED" state; ELSE the queued state indicator should be set to represent that the vehicle is in a "NOT QUEUED" state.
    - The connected vehicle should then broadcast its queued state indicator as part of its BSM.
- Upon exiting the deployment corridor, the queued state indicator should be reset to the "UNKNOWN" state and the queue state speed and separation distance thresholds should be reset to their default conditions.

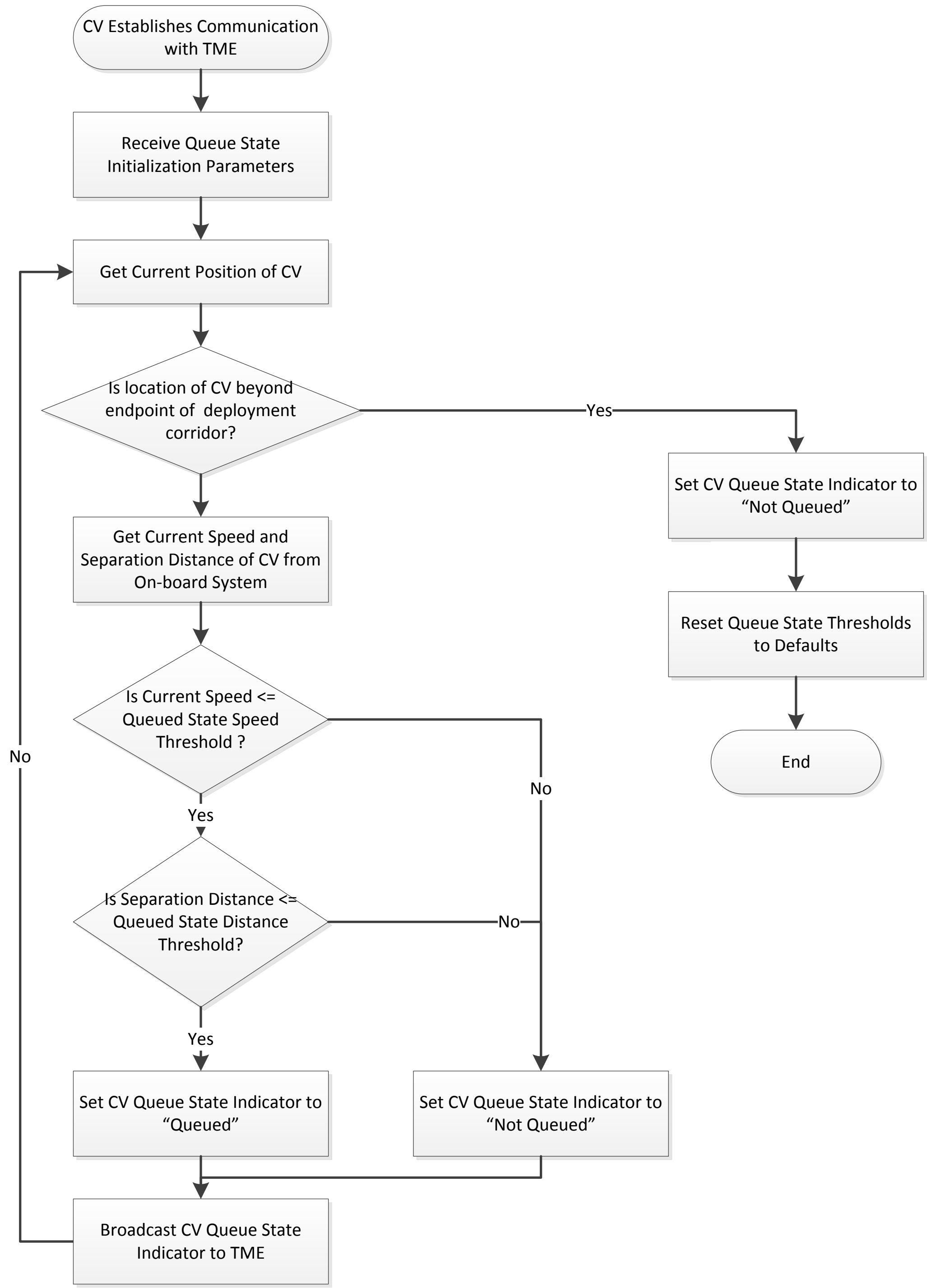

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Figure 5-4. Process for Determining if Connected Vehicle is in Queued State.

Connected Vehicle Data Aggregator

The Connected Vehicle (CV) Data Aggregator collects the data from all the connected vehicles traveling in the deployment corridor and converts it into link-based information. In the prototype, each link in the network will be subdivided into sublinks. The number of sublinks in a link should be a user-defined variable such that the length of each sublink should equal approximately 1/10th of a mile. For example, if the length of a link (as defined as the distance between infrastructure sensors) is 0.5 miles, then the link should be divided into 5 sublinks, each with an approximate length of 0.1 mile.

The CV Data Aggregator is responsible for processing the data from the each connected vehicle and determining the average speed, congested state, and queued state of the sublink. The mile marker reference in the CV Data will be used to determine the sublink in which the vehicle is located. Once the sublink location for each connected vehicle has been determined, the CV Data Aggregator will compute the average speed for each sublink for all the connected vehicles located in each sublink. Using the average sublink speed, the CV Data Aggregator will determine the operating state (congested and queued) of each sublink by comparing the percentage of connected vehicles indicating that they are operating in a queued or congested state.

The connected vehicle data aggregation process is illustrated in Figure 5-5. The output of the Connected Vehicles Data Aggregator process is shown in Table 5-4.

Table 5-4. Output of Connected Vehicle Data Aggregator Process.

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
Sublink Identifier	Yes	Integer	5 seconds	--	A unique ID identifying a section of roadway
Sublink Speed	Yes	Number-Integer t	5 seconds	TMDD	Average speed of the connected vehicle located in the sublink
Congested State Indicator	Yes	Text	5 seconds	TMDD	An variable indicating whether or not the current operating state of the sublink is congested
Queued State Indicator	Yes	Text	5 seconds	TMDD	An variable indicating whether or not the current operating state of the sublink is queued
Sublink Volume Count	Yes	Integer	5 seconds	--	The number of vehicles located in the sublink during the computation interval.

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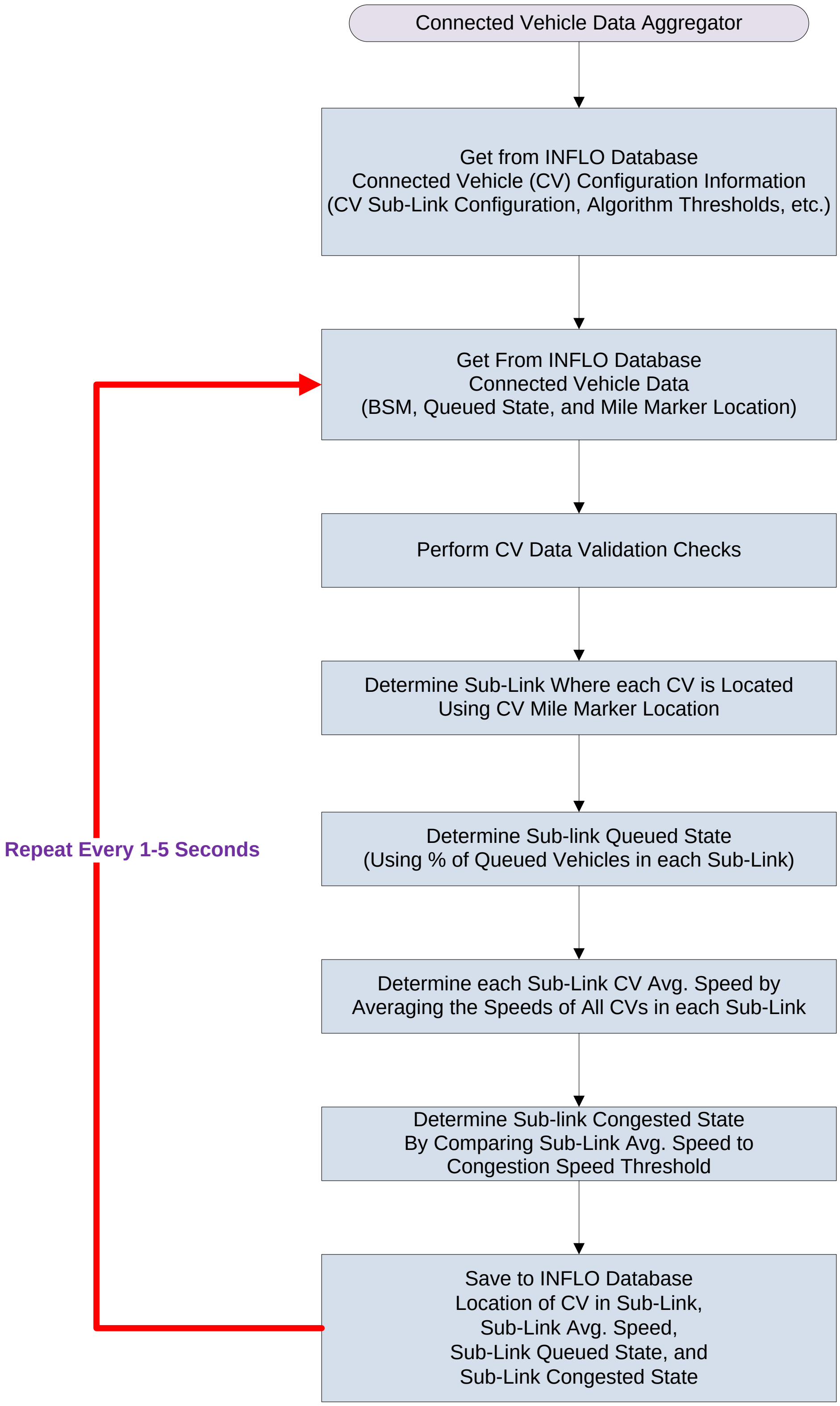

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Figure 5-5. Connected Vehicle Data Aggregation Process.

Road Weather Information

The algorithm will be designed to provide recommended travel speed and road condition advisories and alerts based on measured road weather conditions in the corridor. It is anticipated that road weather data will be available from a number of sources. This section discusses how these sources of data will be managed and integrated for use in the prototype system.

Sources of Weather Data

The prototype system will be designed to use data from the following road weather data sources:

- Stationary Environmental Sensor Station
- Mobile Environmental Sensor Stations
- Connected Vehicle Data
- External Weather Information Providers

It is anticipated that data from all of these sources may not be available at all times. The Road Weather Data Aggregator will be responsible for merging the data from all the available data sources.

Stationary Environmental Sensor Station

The algorithm will be developed to use road weather data from stationary environmental sensor stations (ESS) deployed in the corridor. For the prototype, it is assumed that at least one stationary ESS will be deployed in the corridor. If data from multiple ESS are available, then the prototype will use the data from the sensor that represents the worst-case weather conditions in the corridor.

For the purposes of the prototype development, it is assumed that weather data will be provided from ESS using NTCIP 1204: *National Transportation Communications for ITS Protocol: Environmental Sensor Station (ESS) Interface Protocols*:[5] The prototype will use the data available through the Weather and the Pavement Sensor blocks of the data stream. The Weather Block contains the atmospheric, wind, temperature, precipitation, and visibility data objects associated with most environmental sensor stations. Pavement surface condition objects are contained in the Pavement Sensor block. Latitudinal and longitudinal information of the ESS can be used to associate the weather information generated by the system with sections of roadway.

Pavement Surface Condition

Pavement surface conditions are the prime factors that will be used to determine recommended travel speeds in the corridor. Two approaches are being incorporated for determining pavement surface conditions from stationary ESS. One approach involves the direct measurement of the coefficient of friction from the pavement surface. A number of pavement sensors are readily available on the market that can provide some direct measurement of coefficient of friction. These sensors generally express coefficient of friction as a unitless parameter. For the prototype development, it is assumed that the coefficient of friction will be available for these sensors; however, coefficient of friction is NOT a standard NTCIP 1204 data element.

[5] *National Transportation Communications for ITS Protocol Environmental Sensor Station (ESS) Interface Protocol.* NTCIP 1204, Version v03. American Association of State Transportation and Highway Officials. 2009

Most pavement monitoring systems also provide a status indication of the observed pavement surface. Most sensors are able to provide indicators of the following pavement surface states: dry, wet, snow, and ice. The pavement surface state conditions supported by the NTCIP are shown in Table 5-5. Coefficient of friction values will be estimated based on the observed states of the pavement surface using the following:

- 0.6 for wet pavement surface conditions
- 0.25 for when snow and ice are present on the pavement surface.

These values are consistent with the recommendations provided in FHWA's *Guidelines for the Use of Variable Speed Limit Systems in Wet Weather.*[6]

Visibility

Visibility is another critical data element that will be used in determining the weather-based recommended speeds. A number of manufacturers produce optical sensors that measure the "clarity" of the air. These sensors measure the amount of light scatter through the air. Objects suspended in the air – such as fog, mist, rain, snow, dust, etc. – cause light particles to scatter. Visibility sensors detect the amount of scattered light to compute visibility distances

Table 5-6 shows the visibility data elements supported by NTCIP. Most visibility sensors support both direction measurements of visibility and well as a status data element indicating the state of visibility. The prototype algorithm is being designed to support both direct measurements of visibility and well state indicators associated with visibility. These state indicators can then be converted to estimates of visibility using visibility factors.

[6] Katz,B, et. al. *Guidelines for the Use of Variable Speed Limit Systems in Wet Weather.* FHWA-SA-12-022. US Department of Transportation, Federal Highway Administration. August 2012. Available at http://safety.fhwa.dot.gov/speedmgt/ref_mats/fhwasa12022/fhwasa12022.pdf. Accessed December 2013.

Table 5-5. NTCIP Pavement Surface Condition Data Element.

Object Name	Syntax	Description
essSurfaceStatus	INTEGER {other (1), noReport (2), errorReport (3), dry (4), trace (5), absorption (6), wet (7), chemicallyWet (8), dew (9), frost (10) freezeAdvisory (11), slushAdvisory (12), iceAdvisory (13) freezeHazard (14) slush (15) ice(16) }	This is a value indicates the status of the pavement surface conditions as measured by the pavement sensor. **other** – The value reported by the sensor is not defined by the standard. See the manufacturer's documentation for more information. **noReport** – The sensor is not providing any reading for surface status and may not be responding. **errorReport** – The sensor is providing a reading for surface status, but either the reading indicates an error code or the data has been deemed invalid or suspect **dry** – The sensor does not detect any moisture or unusual conditions. **trace** – The sensor detects some moisture, but it is suspected to be isolated **absorption** – A salt chemical is present that is not fully dissolved in water. As a result, the conductivity readings will result in erroneous calculations for amount of chemical in the mix. **wet** – The sensor detects a significant amount of moisture indicating a wet roadway. **chemicallyWet** – The sensor detects a significant amount of moisture mixed with a de-icing or anti-icing chemical. **dew** – The sensor detects moisture that is suspected to be from the formation of dew. **frost** – The sensor detects the formation of frost. **freezeAdvisory** – The risk of the formation of some sort of frozen moisture on the roadway is elevated, but its occurrence, location, and/or timing is still uncertain. **slushAdvisory** – The risk of the accumulation of snow or slush on the roadway is elevated, but its occurrence, location, and/or timing is still uncertain. **iceAdvisory** – The risk of the formation of ice or black ice on the roadway is elevated, but its occurrence, location, and/or timing is still uncertain. **freezeHazard** – The sensor detects some sort of frozen moisture but is unable to classify as slush or ice. **slush** – The sensor detects snow or slush. **ice** – The sensor detects ice or black ice.

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Table 5-6. NTCIP 1204 Visibility Data Elements.

Object Name	Syntax	Description
essVisibility	Integer (0…1000001)	This is a value indicates the amount of visibility available at the surface measured in one tenth of a meter. The value 1000001 indicates an error condition or missing value.
essVisibilitySituation	INTEGER {other (1), unknown (2), clear (3), fogNotPatchy (4), patchyFog (5), blowingSnow (6), smoke (7), seaSpray (8), vehicleSpray (9), blowing DustOrSand (10), sunGlare(11), swarmsOfInsects (12)}	These integer values are intended to provide an indication of the prevailing visibility conditions.

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Mobile Environmental Sensor Station

The prototype will also be designed to integrate information from mobile environmental sensor stations (or mobile ESS). Mobile ESS are ESS deployed on vehicles – usually a maintenance vehicle, or snowplow used to spread pavement treatments during inclement weather events. Most mobile ESS deployments include atmospheric and pavement sensors which gather information about snow and ice conditions, pavement conditions, and other similar data as the vehicle traverses the network. These data are generally communicated back to a TMC or maintenance facility (via a trunk radio system) to allow roadway operators and maintenance crew to monitor pavement conditions and determine application rates of pavement treatments. Data from mobile ESS are used to complement data obtained from stationary ESS also deployed along the roadway. The following shows the standard data elements for the mobile sensors specified in NTCIP 1204:

```
EssMobileData ::= SEQUENCE {
    essLatitude.0                              OPTIONAL, -- @NTCIP1204-v03
    essLongitude.0                             OPTIONAL, -- @NTCIP1204-v03
    essReferenceHeight.0                       OPTIONAL, -- @NTCIP1204-v03
    essVehicleSpeed.0                          OPTIONAL, -- @NTCIP1204-v03
    essVehicleBearing.0                        OPTIONAL, -- @NTCIP1204-v03
    essVehicleOdemeter.0                       OPTIONAL, -- @NTCIP1204-v03
    essMobileFriction.0                        OPTIONAL, -- @NTCIP1204-v03
    essMobileObservationGroundState.0          OPTIONAL, -- @NTCIP1204-v03
    essMobileObservationPavement.0             OPTIONAL, -- @NTCIP1204-v03
    essPaveTreatmentAmount.0                   OPTIONAL, -- @NTCIP1204-v03
    essPaveTreatmentWidth.0                    OPTIONAL -- @NTCIP1204-v03}
```

Latitude and longitude along with vehicle bearing can be used to locate the position of the mobile ESS in the network. The essMobileFriction data element indicates the coefficient of friction (measured in percent) measured by the vehicle at its current location. The essMobileObservationPavement data element defines the prevailing state of the condition of the driving surface (as determined by an observer). These two data elements can be used to characterize the pavement surface condition in the algorithm.

Connected Vehicles Weather Data Component

Information about pavement surface condition is also potentially available directly from the connected vehicles. J2735 defines a data element – DE_CoefficientOfFriction – that could potentially be used to help determine locations of deteriorating pavement surface conditions due to weather.[7] This object defines the coefficient of friction between the wheels of the vehicle and the pavement surface. For connected vehicles, coefficient of friction is measured in micros. This data element is part of the vehicle status data frame and is included in Part II of the Basic Safety Message (BSM – Part II). Position data available in the BSM – Part I can be used to determine the location of the vehicle on the network. As the vehicle position is updated every 1 to 5 seconds, information about the location of deteriorating pavement surface conditions can be determined by monitoring these data elements from vehicles.

[7] *Dedicated Short Range Communications (DSRC) Message Set Dictionary*. SAE J2735. Society of Automotive Engineers. 2009.

Vehicle Data Translator

The Vehicle Data Translator represents another potential source of weather information that could be used to determine weather-based speed recommendations and warnings. The Vehicle Data Translator (VDT) is a system that is currently being developed by the University Corporation for Atmospheric Research's (UCAR) National Center for Atmospheric Research (NCAR) that ingests and processes mobile data resident on the vehicle along with ancillary weather data to derive pavement and visibility conditions for sections of roadway.[8] This work is currently exploring several techniques for estimating pavement and visibility conditions using information from both vehicle and non-vehicle sources. Efforts are currently underway to develop algorithms that predict road surface conditions using the following vehicle data: air temperature, road temperature, front wiper status, ratio of vehicle speed to road segment speed limit, anti-lock brake/traction control/stability control equipment, lateral and longitudinal acceleration, yaw rate, steering angle, steering angle rate, headlight status and more.

Although this work is currently underway, it is not likely to be completed in time to be fully integrated as a potential source of weather data from this prototype development. However, the data aggregator is being designed such that information from the source, if available, could be integrated and incorporated into the INFLO algorithms.

Road Weather Data Aggregator

The Weather Data Aggregator is responsible for receiving the data from the various sources of weather data, integrating the information from the systems, and producing a single set of road weather condition information that can be used by the other algorithms to generate weather-based recommend link speeds and weather-related vehicle warning messages. As part of the prototype deployment, the Road Weather Data Aggregator will perform the following functions:

1. Retrieve data from each of the various sources contributing weather information to the system.
2. Perform minimal data quality checks on the received information to verify its validity and structure.
3. Process state and direct measurement data to a common data format.
4. Select the data defining the "worst case" weather conditions for the corridor.
5. Publish a table showing the measured visibility and coefficient of friction values to be used in determining weather-based recommended link travel speeds and weather-related warning messages.

The output of the Road Weather Data Aggregator process is shown in Table 5-7. These data elements reflect the data which is updated in the INFLO database. This table includes the road weather data elements that can be used to produce recommended link speeds for the prevailing road conditions. During periods of inclement weather, this table is envisioned to be updated at least every 5 minutes.

[8] Drobot, S. M. Chapman, B. Lambi, G. Wiener, and A. Anderson. *The Vehicle Data Translator V3.0 System Description*. FHWA-JPO-11-127. University Corporation for Atmospheric Research. May, 2011.

Table 5-7. Road Weather Data Elements in the INFLO Database

Data Element	Required	Type	Refresh Rate	Standard/ Reference	Description
Roadway Link Identifier	Yes	Text	static	TMDD	A unique ID identifying a section of roadway
Timestamp	Yes	DateTime	5 minutes	TMDD	Local time zone date and time when weather data was received from the Infrastructure ESS
Visibility	Yes	Integer	5 minutes	NTCIP 1204 Weather Block	This is a measure/estimate of the currently available line of sight visibility (miles)
Visibility state	Yes	Text	5 minutes	NTCIP 1204 Weather Block	This is an indicator of the current state of the visibility (Fair, Poor)
Coefficient of Friction	Yes	Integer	5 minutes	NTCIP 1204 Weather Block	The NTCIP 1204 Visibility data will be used to calculate the current visibility
Pavement Surface State	Yes	Text	5 minutes	NTCIP 1204 Pavement Sensor	This is an indicator of the current state of the pavement (dry, wet, ice/snow)

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Chapter 6 Queue Warning (Q-WARN)

The Queue Warning application is intended to provide advance notification to drivers that a queue exists ahead. This queue may result from many causes, but its ultimate effect is a significant reduction in expected speed. Sudden braking by drivers can contribute to a decrease in safety. The queue warning system is designed to address this effect. The primary purpose of the queue warning application is to significantly reduce the number of crashes, especially the rear-end type, that are likely related to unpredictable traffic jams throughout the corridor. Infrastructure-based queue warning messages should be shown any time there is an end-of-queue condition ahead and dynamic message signs are not already displaying a higher priority message. Queue warning messages are of immediate importance to drivers and should have a priority equal to adverse weather conditions and just below an incident or crash message.

The prototype system will include three types of queue warning algorithms: TME Based Queue Warning, Cloud Based Queue Warning, and Vehicle Based Queue Warning Algorithms. Each of these algorithms is described in this chapter.

TME Based Queue Warning Algorithm

The following section describes the processes and procedures for developing TME-based queue warning messages.

Purpose of Algorithm

The purpose of the TME-based queue warning algorithm is to fuse the data from the infrastructure and the connected vehicles and generate queue warning messages that can be disseminated through both infrastructure signs and connected vehicles. In this application, the decision-making processes will reside primarily within the Traffic Management Entity (TME). The connected vehicle will not be required to process any data other than determining its queue state and generating queue warning displays from the data provided by the TME.

Algorithm Concept/Theory

The TME-based queue warning algorithm fuses the infrastructure data with the CV data to determine the back of queue (BOQ). Figure 6-1 illustrates the process of determining the BOQ. It is assumed that the front of queue (FOQ) is at a location of expected congestion and is thus known. Data from infrastructure sensors are used to determine which links are operating in a queued, congested or in a free flow state. Using this information, the BOQ is 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. The figure 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.

The figure also illustrates how the sublink information from the connected vehicles can also be used to locate the BOQ. The figure illustrates the sublinks which are in queued states. A sublink is in a queued state if a user specified percentage of the CVs in the sublink are in a queued state. The BOQ from CV traffic data is at the upstream end of sublink 10. The BOQ based on the connected vehicle data is defined as the farthest upstream sublink operating in a queued state. The final BOQ is then determined by comparing the BOQ from the infrastructure data and connected vehicles data and selecting the BOQ that is furthest upstream as the BOQ location.

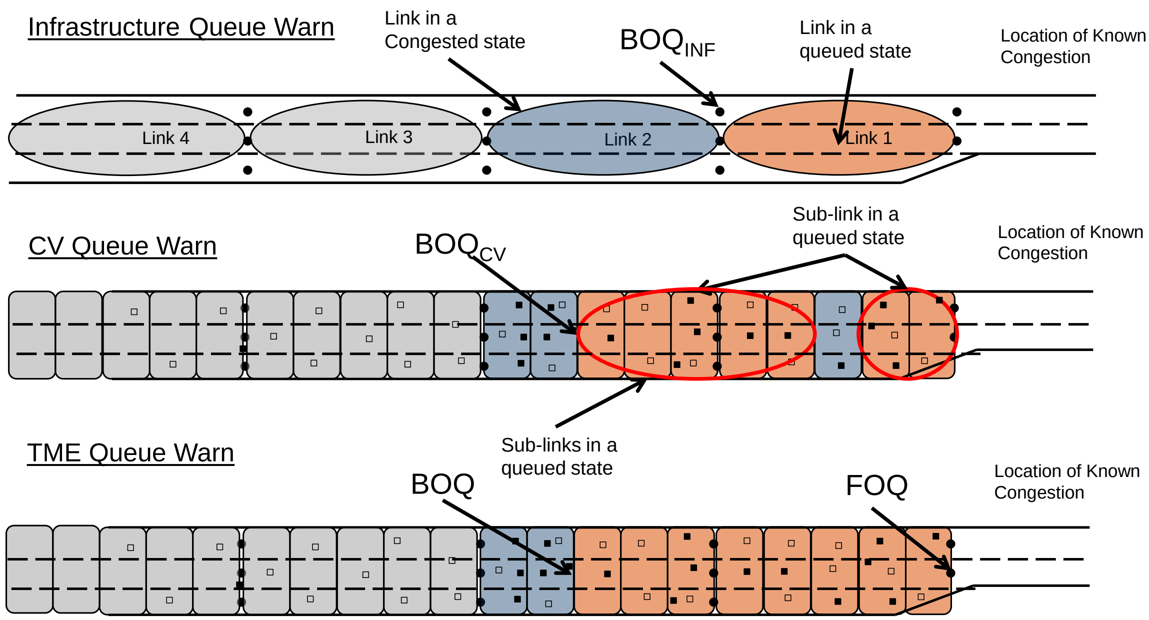

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Figure 6-1. TME Queue Warn Algorithm.

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 sublink 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. The TME based Q-Warn application is illustrated in Figure 6-2.

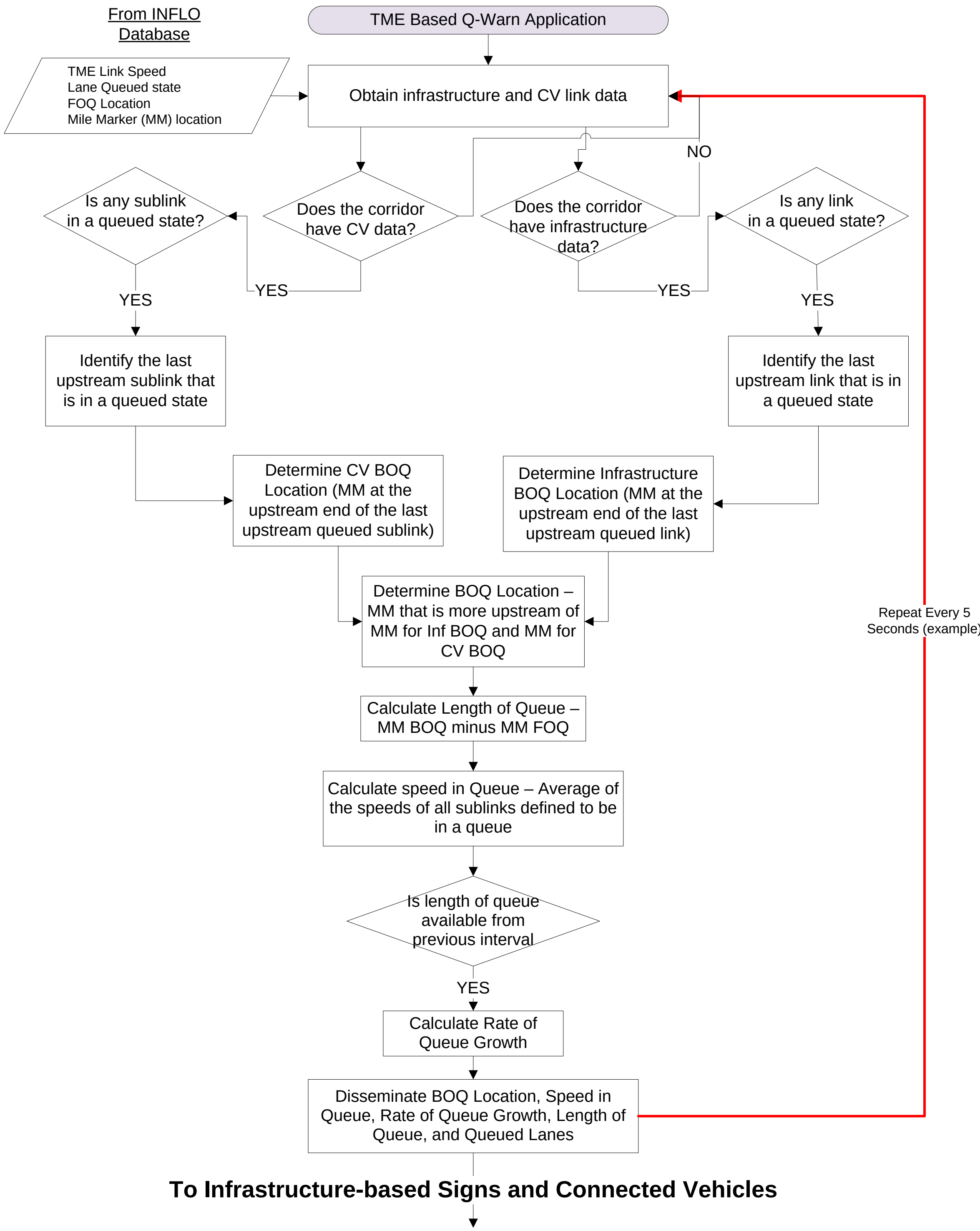

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Figure 6-2. TME Based Q-Warn System.

Connected Vehicle Based Queue Warn Algorithms

The connected vehicle based queue warn algorithm uses connected vehicle data only. The data for the algorithm is provided by connected vehicles and the queue warning is provided to the connected vehicles. The overall premise is to provide warning about the location of BOQ to upstream vehicles. There are two ways for implementing the connected vehicle-based queue warn algorithm. One methodology uses cellular communication and the other uses DSRC communication to transmit the states of the vehicle as well as the location of BOQ.

Cloud Based Queue Warn System

The cloud based queue warning algorithm is deployed when no infrastructure elements are being used. Specifically, no infrastructure detectors are present to provide vehicle data and no infrastructure signs (dynamic message signs) are deployed. This means that only connected vehicle data is available from the facility. Similarly any queue warning messages will only be displayed inside a connected vehicle. In such a scenario, a cloud based queue warning system is more applicable to minimize the computing workload of all the queue warning data within a vehicle as well as to have a broader view of the facility. The Cloud Based Queue Warn System is illustrated in Figure 6-3.

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 (Y or N), and mile marker location of the vehicle to the cloud. The cloud based algorithm then places the connected vehicle data into the appropriate sublinks and determines the queued state (Y or N) of the sublinks. The queued state of the sublinks is determined based on the percentage of queued vehicles to non-queued vehicles in a sublink which can be user defined. Based on the queued state of the sublinks, the FOQ and the BOQ are determined for every queue that is detected in the segment. For the prototype system, the FOQ is determined at the mile marker of the known bottleneck location. The BOQ for a queue is determined to be at the mile marker of the most upstream sublink. Based on the location of the BOQ, the speed in queue, length of queue, as well as rate of growth of queue is calculated. The speed in queue is calculated by averaging the speeds of all the connected vehicles between the FOQ and BOQ. The length of queue is calculated from the mile marker location of the FOQ and BOQ. Finally, the rate of growth of queue is calculated by recording the change in the location of BOQ over a certain number of intervals and dividing by time. This information is then transmitted to the connected vehicles in the affected roadway segments via cellular network. However, while the cloud based queue warning system is operational, all the connected vehicles continue to 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. The processes within a cloud based queue warning algorithm are illustrated in a flow chart in Figure 6-4.

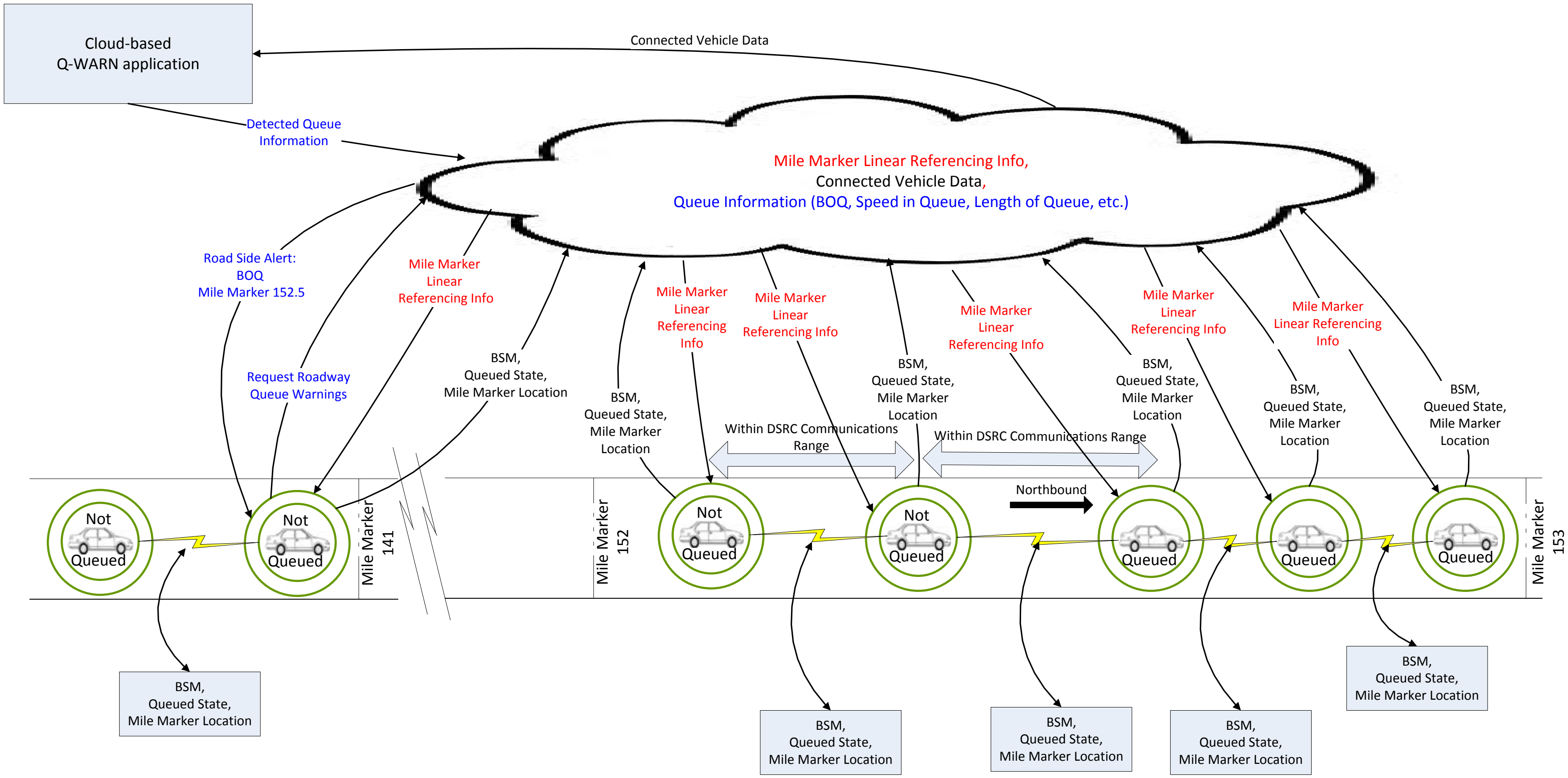

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Figure 6-3. Cloud Based Queue Warn System.

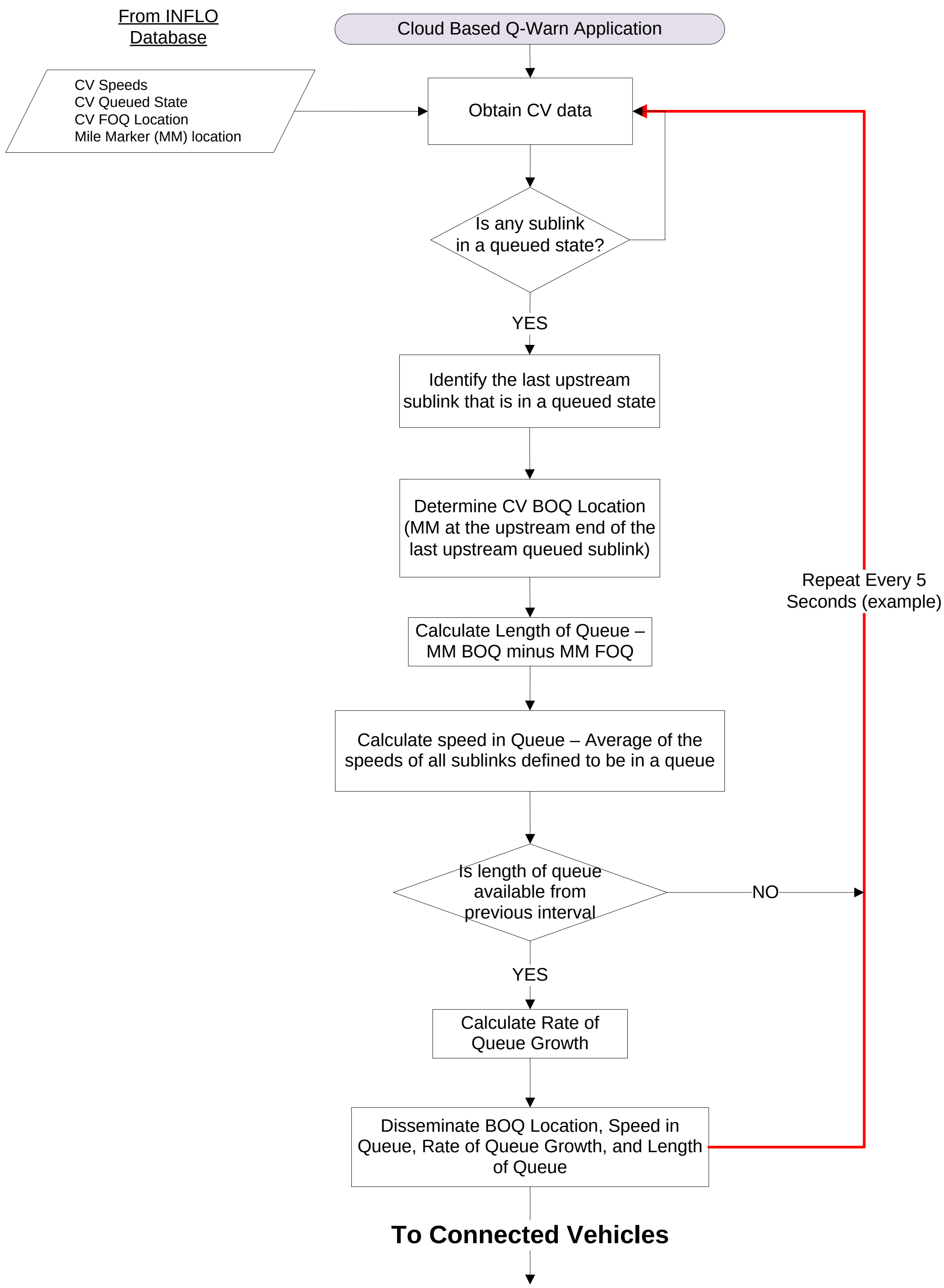

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Figure 6-4. Process to Illustrate Cloud-Based Queue Warn System.

V2V Queue Warn System

Vehicles in a V2V Queue Warn System use DSRC to communicate with other connected vehicles every 1/10th of a second. Each connected vehicle will determine its mile marker location and queued state (Y or N). The connected vehicles will then transmit this information along with BSM to other vehicles. The V2V Queue Warn System is illustrated in Figure 6-5.

The V2V Queue Warn System relies upon DSRC communication to send and receive BSM messages. The primary purpose of these messages is to enable connected vehicles to determine if they are in a queued state and locate the BOQ. Typically queued state depends on the speed of the vehicle as well as the separation distance from the vehicle immediate downstream. If however, a vehicle is unable to determine its distance from vehicles immediately downstream, only the vehicle speed may be used to determine its queued state. The queued state along with BSM is then transmitted to other vehicles.

Each connected vehicle receiving information from other connected vehicles identifies and locates all downstream connected vehicles. Based on the mile marker location of the connected vehicles, a non-queued vehicle identifies the BOQ if present from among the downstream vehicles. The location of BOQ is then transmitted by all non-queued vehicles. All upstream vehicles receiving the BOQ message will then display a proper message to the driver and retransmit the location of BOQ. This process of receiving BOQ location and retransmitting it to upstream vehicles is continued for a user defined distance from the BOQ and then ignored as that information may become irrelevant at large distances from the BOQ. If the vehicle is beyond a user-defined distance upstream of the BOQ (e.g., 10-mile for the prototype testing), then the warning information would not be displayed. The V2V Queue Warn Application process is illustrated in Figure 6-6.

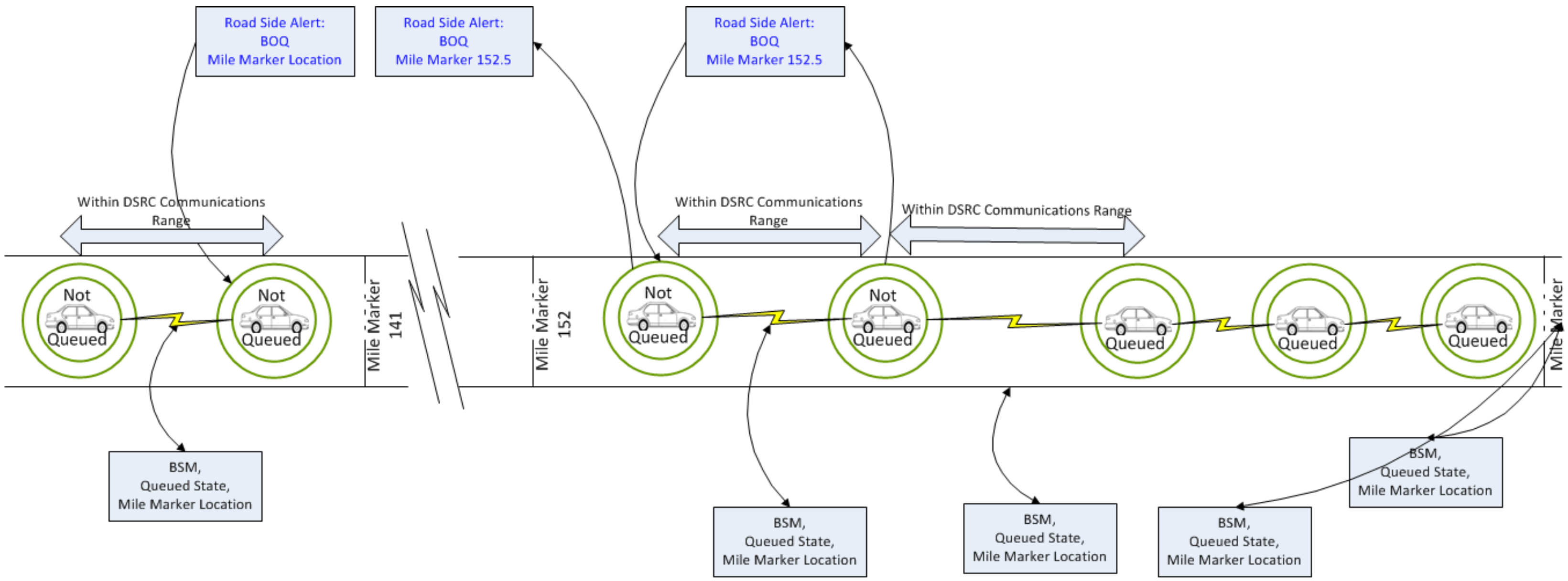

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Figure 6-5. V2V Based Queue Warn System.

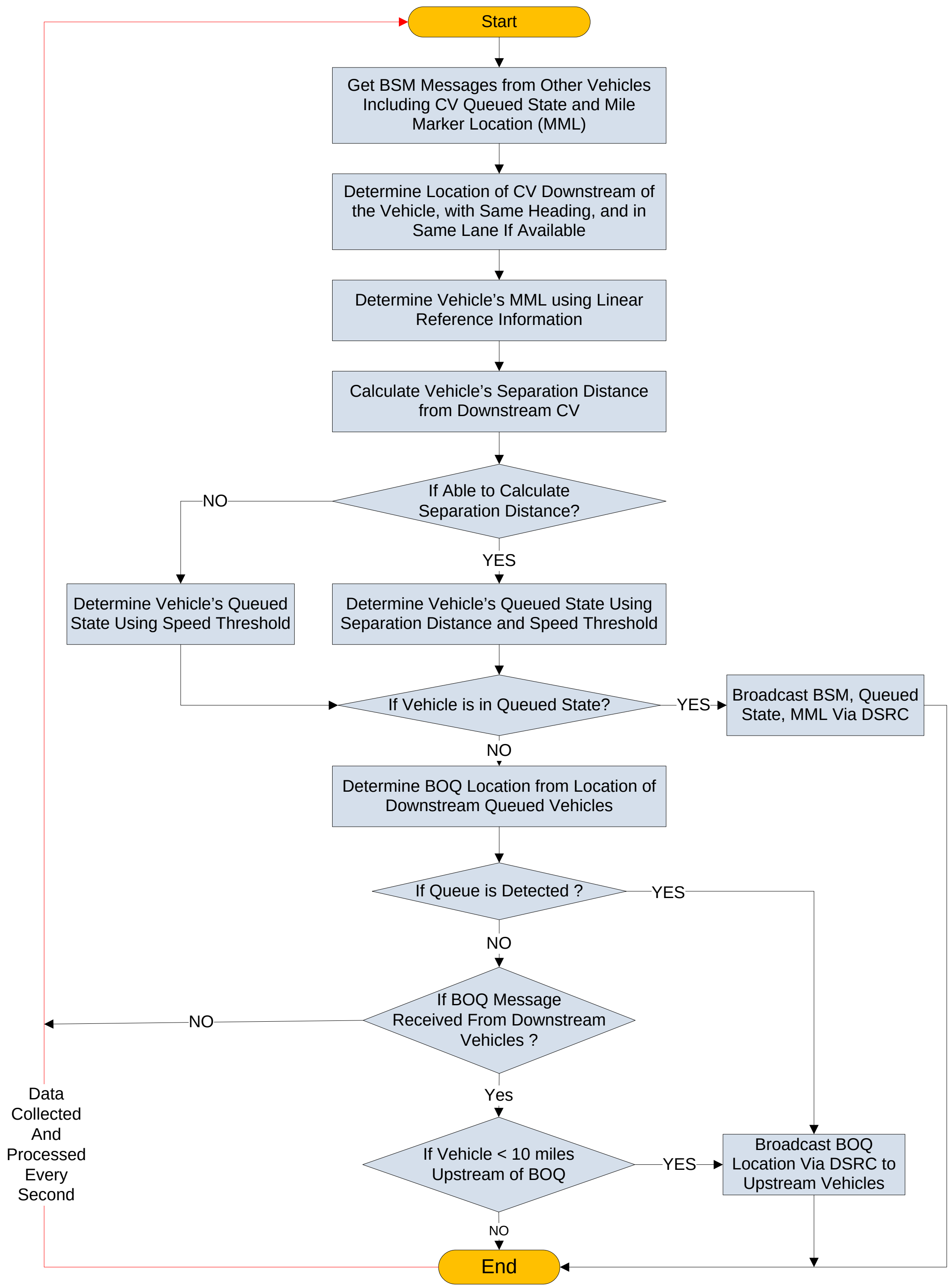

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Figure 6-6. Process to Illustrate V2V Queue Warn Application.

Chapter 7 Weather-Responsive Traffic Management

This chapter documents the algorithms that are used to determine the recommended link travel speeds based on road weather conditions. Road weather data will also be used to develop traveler advisories and alerts consistent with the recommended speed.

Purpose of Algorithm

The purpose of this algorithm is to determine the recommended travel speed for each link based on the prevailing road weather conditions. For the purposes of the prototype development, recommended travel speed will be based upon visibility and pavement surface conditions. While transportation management agencies will implement reduced travel speed recommendations for high wind conditions, similar concepts could be used to produce recommended travel speeds based on high wind conditions.

Generating Weather-based Recommended Link Travel Speeds

The algorithm will support two approaches for determining weather-based recommended link speeds. The first approach involves using measured visibility and pavement surface condition to directly compute recommended link speeds. The other approach involves performing a table look-up of recommended travel speeds based on ranges in travel speeds. Each of these approaches is described below.

Direct Computation of Recommended Travel Speed

This method involves implementing the method proposed for determining recommended safe travel speed in FHWA's *Guidelines for the Use of Variable Speed Limit Systems in Wet Weather.*[9] The algorithm is built on the premise that direct measurements of pavement surface friction (or coefficient of adhesion) and available sight distance from environmental sensors systems can be used to directly compute a recommended travel speed required to provide safe stopping under the prevailing conditions. The algorithm determines the maximum safe travel speed based on real-time measurements of visibility and pavement surface friction using the following equation:

[9] Katz, B. et. al. *Guidelines for the Use of Variable Speed Limit Systems in Wet Weather.* Report No. FHWA-SA-12-022. US Department of Transportation, Federal Highway Administration. August, 2012. Available at http://safety.fhwa.dot.gov/speedmgt/ref_mats/fhwasa12022/fhwasa12022.pdf. Accessed December 26, 2013.

$$V = \frac{\left(-3.67 + \sqrt{13.47 + \frac{0.12}{\mu \ \pm G} * S}\right)}{\frac{0.06}{\mu \pm G}}$$

Where

V= Recommended safe travel speed (mph)
S= Available sight distance (feet)
μ = coefficient of road adhesion (unit less)
G= roadway grade (percent expressed as a decimal)

The guidelines recommend that site-specific coefficient of roadway can be applied directly from pavement sensors that can measure pavement friction, regardless of whether pavement surface quality is known. This would require the deployment of a pavement monitoring system that directly measures pavement surface friction at the site. Several manufacturers produce pavement sensors that directly measure pavement surface friction; however, direct measurement of pavement friction is not a data element supported by the *NTCIP 1204 Environmental Sensor System* standards. If actual values of coefficient of road adhesion are not available, the guidelines recommend that the following values for coefficient of road adhesion can be used:

- 0.6 for wet pavement surface conditions
- 0.25 for when snow and ice are present on the pavement surface

Table Look-Up of Recommended Travel Speed

Another strategy commonly used to provide recommended travel speeds is through a table look-up. The table look-up method uses visibility and pavement conditions to determine the cell in the table representing the prevailing conditions in the corridor. Each cell in the table would correspond to a particular recommended travel speed for the prevailing conditions. The cells in the table would be the bound by a minimum and maximum recommended travel speed. The maximum recommended travel speed would correspond to the most favorable conditions – high coefficients of friction with high visibility conditions. The minimum recommended travel speed would correspond to the least favorable condition – limited visibility with poor coefficients of friction.

While multiple levels of visibility and pavement friction conditions could be supported through this method, our deployment will consist of only two visibility levels (defined by one visibility threshold) and three pavement surface conditions (defined by two coefficient of friction thresholds). Table 7-1 shows an example of how the table of recommended speeds would be configured for this deployment. The user would also need to define the recommend maximum and minimum travel speeds for the specific corridor as well as the recommended travel speed for the different levels of visibility and pavement condition. Recommended speed levels would correspond to agency defined recommended speeds for various visibility and pavement surface conditions. A total of six recommended speed levels would exist. Recommended travel speeds would need to conform to the following criteria:

- Maximum Recommended Speed> Recommend Speed Level 1 > Recommended Speed Level 2 $\geq$ Minimum Recommended Speed
- Minimum Recommended Speed < Recommended Speed Level 4 <Recommended Speed Level 3 $\leq$ Maximum Recommended Speed

Table 7-1. Structure of Look-Up Table for Determining Recommended Speed based on Prevailing Road Weather Conditions.

Visibility Conditions		**Observed Pavement Surface State**		
		Dry	**Wet**	**Ice/Snow**
Measured Visibility	**Measured Visibility State**	**Measured Coefficient of Friction**		
		≥Upper Coefficient of Friction threshold	**Between upper and lower Coefficient of Friction threshold**	**≤ Lower coefficient of friction threshold**
> Visibility Threshold	**Good**	Maximum Recommended Speed	Recommended Speed Level 1	Recommended Speed Level 2
≤ Visibility Threshold	**Poor**	Recommended Speed Level 3	Recommended Speed Level 4	Minimum Recommended Speed

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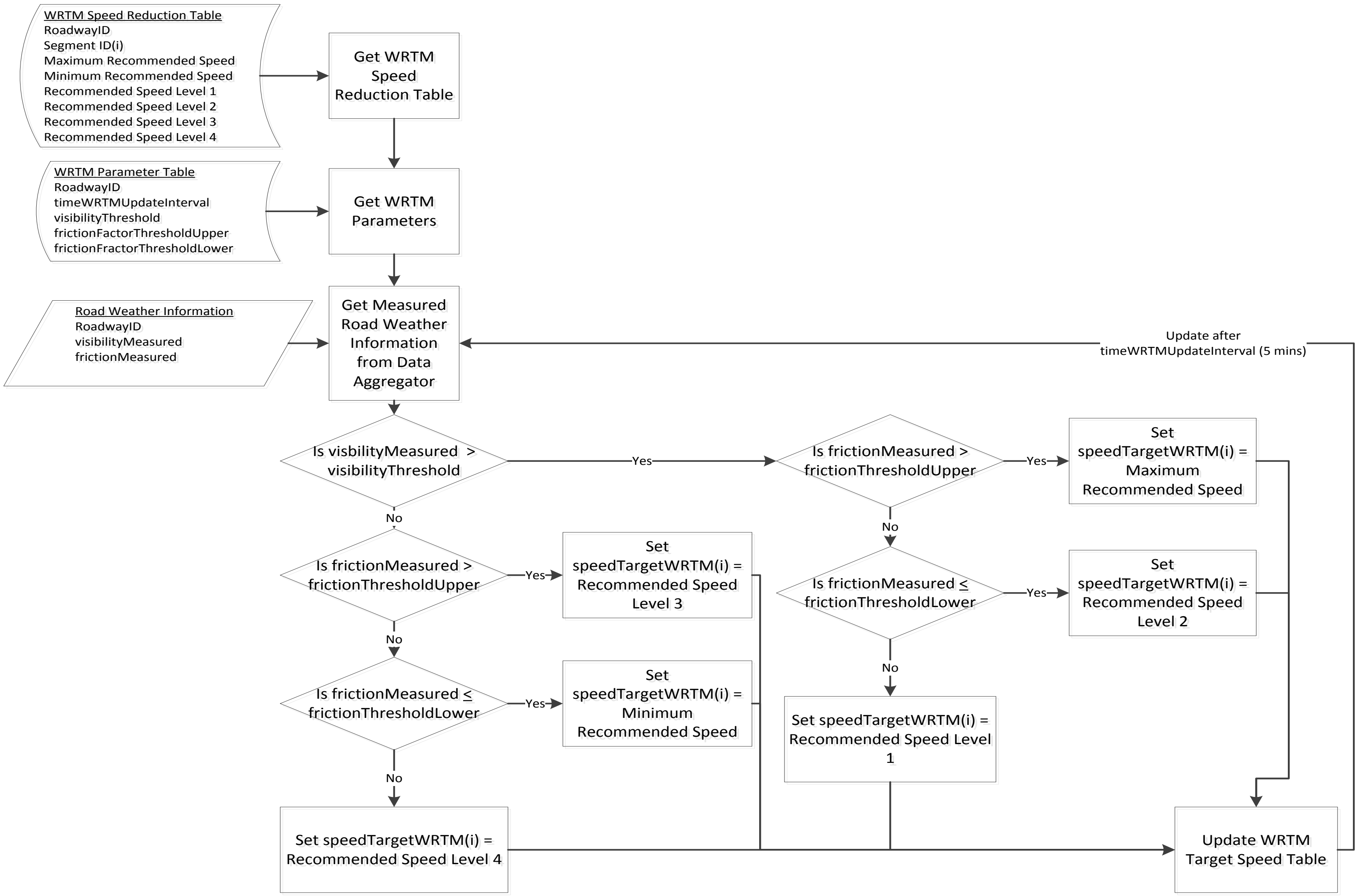
Recommended travel speeds for each segment would be determined using the following logic:

- If the measured visibility is greater than the visibility threshold, then the following conditions apply:
    - If the measured surface friction factor of the roadway is greater than the friction factor upper threshold, then the recommended target speed for each segment is equal to the maximum speed defined for the segment.
    - If the measured surface friction factor of the roadway is less than the friction factor lower threshold, then the recommended target speed for each segment is equal to the recommended travel speed adopted by the agencies corresponding to visibility conditions but deteriorating pavement surface conditions.
    - If the measured surface friction factor of the roadway is between the upper and lower friction factor thresholds, then the recommended travel speed for each segment is equal to the recommended travel speed adopted by the agencies corresponding to visibility conditions but poor pavement surface conditions.
- If the measured visibility is less than the visibility threshold, then the following criteria should be applied for determining the recommended target speed for each section of roadway:
    - If the surface friction factor of the roadway is greater than surface friction factor upper threshold, then the recommended target speed for each segment is equal to the Recommended Speed Level 3.
    - If the measured surface friction factor is less than the surface friction factor lower threshold, then the recommended target speed for each segment of roadway is equal to the minimum speed defined for each segment

- o If the measured surface friction factor of the roadway is between the upper and lower surface friction factor thresholds, then the recommended target speed for each segment of roadway is equal to Recommended Speed Level 4.

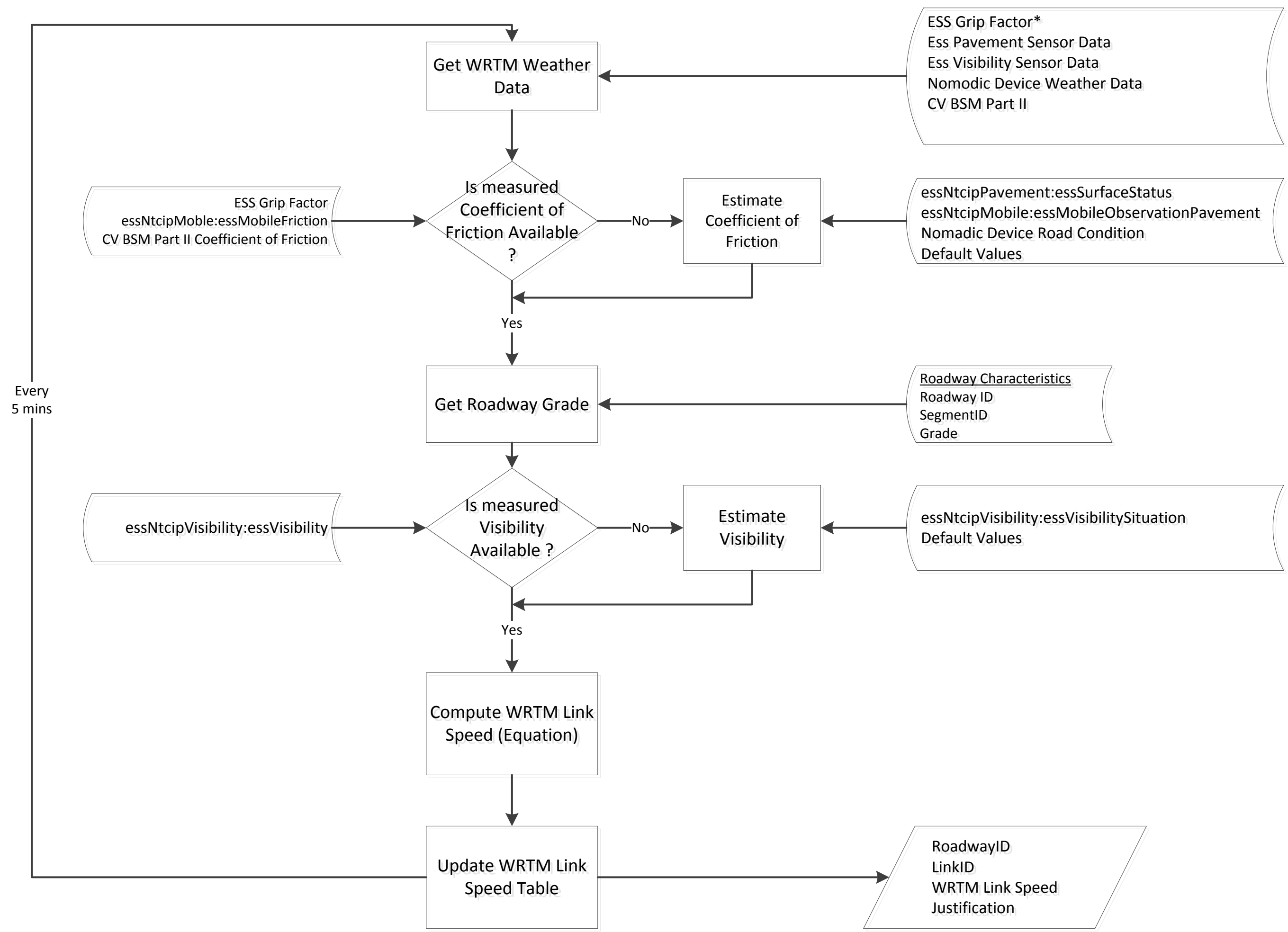
Algorithm Logic Description

Figure 7-1 shows the proposed logic which will be used to determine the recommended segment travel speed based on weather information via the table look-up method and Figure 7-2 shows the proposed logic which will be used to determine weather-related recommended segment travel speeds direct calculations. The algorithm will deploy the forward the minimum of the two speeds for use in the speed harmonization process. Both the direct calculation and table look-up method will be supported by the algorithm.



Source: Texas A&M Transportation Institute

Figure 7-1. Process for Determining Weather-based Recommended Link Speed via Table Look-up .



Source: Texas A&M Transportation Institute

Figure 7-2. Process for Determining Weather-based Recommended Link Speed.

Chapter 8 TME-Based Speed Harmonization

This chapter describes the processes and procedures that will be used to produce harmonized recommended travel speeds in the corridor. The harmonized travel speeds will integrate the recommended travel speeds from all the potential sources to produce a final recommended travel speed. The output of this process will define speed zones based on recommended speeds from each of the potential data sources.

Purpose of Algorithm

The objective of speed harmonization is to minimize the turbulence in the traffic stream approaching a section of the roadway experiencing low speeds. The algorithm is being designed to identify, produce, and establish a recommended speed for segments of the corridor. The algorithm will identify the beginning and ending mile point over which the recommended speed is applicable. These speeds may be advisory or regulatory speeds based upon agency policy.

For the purpose of the prototype development, speed harmonization will be based only in the TME. The Uniform Motor Vehicle Law indicates that state and local agencies are responsible for establishing recommended speeds on public roadway facilities.

Algorithm Concept/Theory

The speed harmonization algorithm developed in this task attempts to fuse data from infrastructure-based sensors with data from connected vehicles, identify sections of the roadway that exhibit common speed characteristics and then develop recommended speeds for various segments in a gradual manner. This is accomplished by developing recommended speeds for successive upstream roadway segments in small increments. Researchers broke down the links of the roadway into lengths of 0.1 miles called sublinks. This length was considered small enough to capture unique traffic characteristics from connected vehicle data while having a unique identity in the form of mileposts. Researchers applied the criteria stipulated by AASHTO for the time/distance required to observe, comprehend, react, and respond to a speed change message on the roadway to minimize driver work load. This criterion is indicated in the recommendations of the decision sight distance values for various speeds which are based on a travel time of 14 to 14.5 seconds. A critical value of 14.5 seconds of travel time is being considered for this algorithm.

Algorithm Logic Description

As indicated earlier, roadway segments have been divided into sublinks of length 0.1 miles. The harmonization process starts once the recommended speed is known for each sublink. The recommended link speed for each sublink is being updated at the resolution at which connected vehicle data is being received (for example every five seconds). These speed values for each sublink are compared with speed values of adjacent sublinks to form troupes. An average speed is then calculated for each troupe. The connected vehicle recommended speeds are then calculated for all the sublinks. While the calculations are based on the average troupe speeds, recommended speed values are adjusted to achieve a gradual change in speed between adjacent sublinks, and to ensure that a change in speed at a particular location is implemented in such a way to minimize driver workload. Typically, recommended speed values are incremented in 5 mph increments and the speed values are not modified for about 15 seconds. Once the connected vehicle recommended speeds are calculated for the entire section, infrastructure recommended speeds are determined. Infrastructure speeds are recommended speeds that are displayed in gantries. Since the gantry spacing is not standard in all places, a procedure was developed to determine the suitable infrastructure recommended speeds based on the connected vehicle recommended speeds and driver work load. This section describes the algorithm in greater detail.

Determining TME-based Recommended Link Speed

The objective of the TME Link Speed module is to generate a link speed that is representative of the existing conditions along the roadway. The TME Link Speed module uses information from the INFLO Database for roadway and traffic data to generate TME Link Speeds from Roadway Link Data, Roadway Infrastructure Link Traffic Data, Roadway CV Link Traffic Data, and the WRTM Recommended Roadway Link Local Speeds. These local speeds are applicable for links and sublinks as defined earlier. TME Link Speed is then estimated by fusing the data from WRTM, infrastructure data from TSS data aggregator, connected vehicle data from CV data aggregator and historical sublink speed. The data fusion process is illustrated in Figure 8-1.

The data fusion process starts by getting the average infrastructure link speeds, average CV sublink speeds, recommended WRTM speeds, and historical speeds from the INFLO database. Within the database, infrastructure link speeds are updated at a frequency of 20 to 30 seconds which usually depends on the policies of the facility operator and the communication infrastructure. Link level infrastructure data speeds can be directly assigned to the sublinks within the respective links. The average of the CV sublink speeds are updated at a frequency of approximately 5 seconds and is a function of limitations of the communication infrastructure. Due to the small size of the sublink, there may be some intervals where some sublinks may not have any CV data. Under such conditions, the CV sublink link speeds are replaced by the infrastructure link speeds as shown in Figure 8-2.

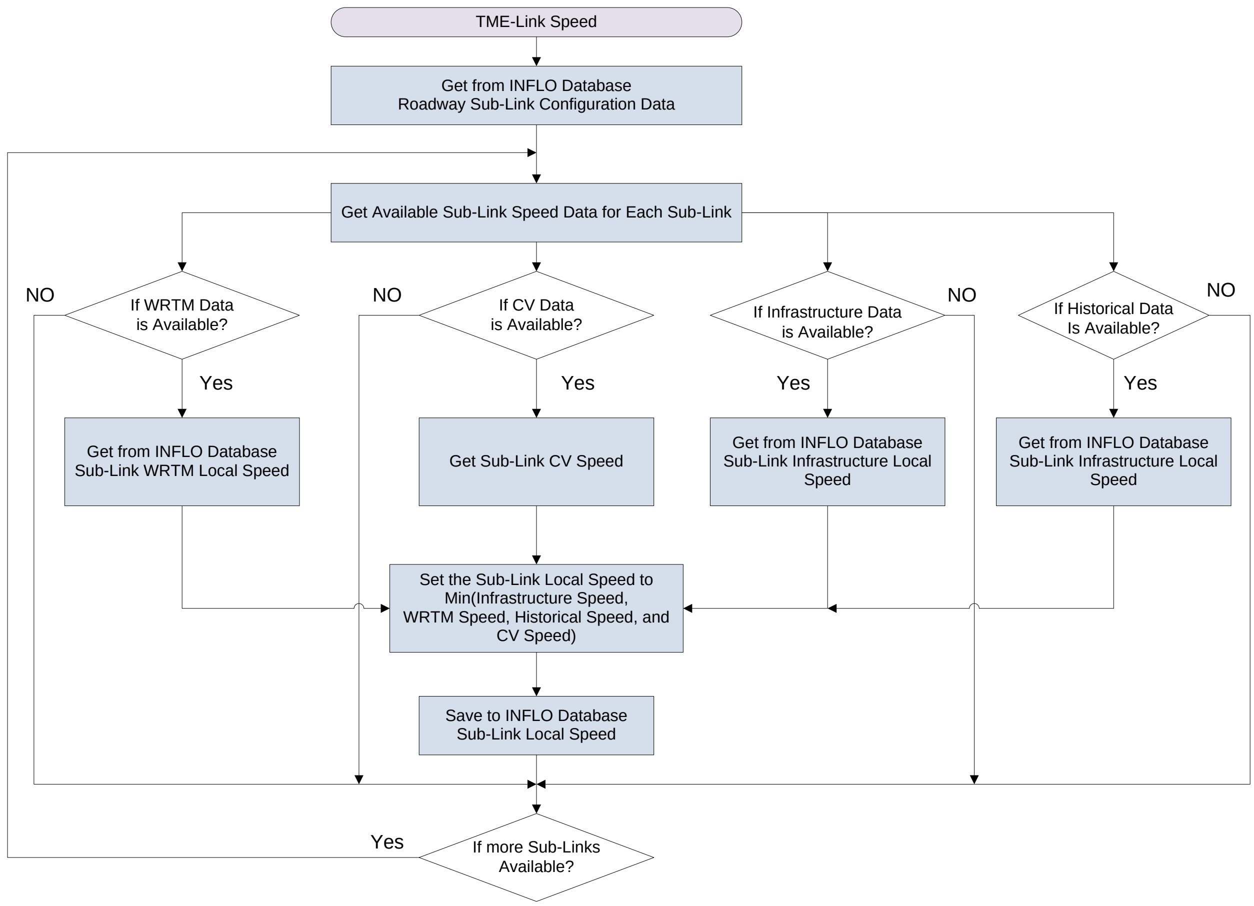


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Figure 8-1. Data Fusion to get TME-Link Speed.

The WRTM recommended speeds are typically designated for segments of the facility. These recommended speeds are then directly assigned to the links within the segment and their respective sublinks for a specific time period and depend on weather related events. These three speeds within the database are compared with average historical sublink speeds and the minimum of these values is designated as the TME link speed. Since the average CV sublink speed is likely to be updated every 5 seconds, a new TME link speed is generated at similar frequency. The TME link speed is then smoothed over time by calculating a rolling average of the TME link speeds over “n” number of intervals which can be user defined. For the prototype, the value of “n” will be a function of the update frequency of the infrastructure data and CV data. The objective is to have the value of “n” equal to the number of CV data updates within an infrastructure data update interval. If the update interval for the infrastructure data is 20 seconds and the update interval for CV data is 5 seconds, the value of “n” will be four. This is primarily done to iron out any significant variations in the speeds due to random variations in average CV sublink speeds.

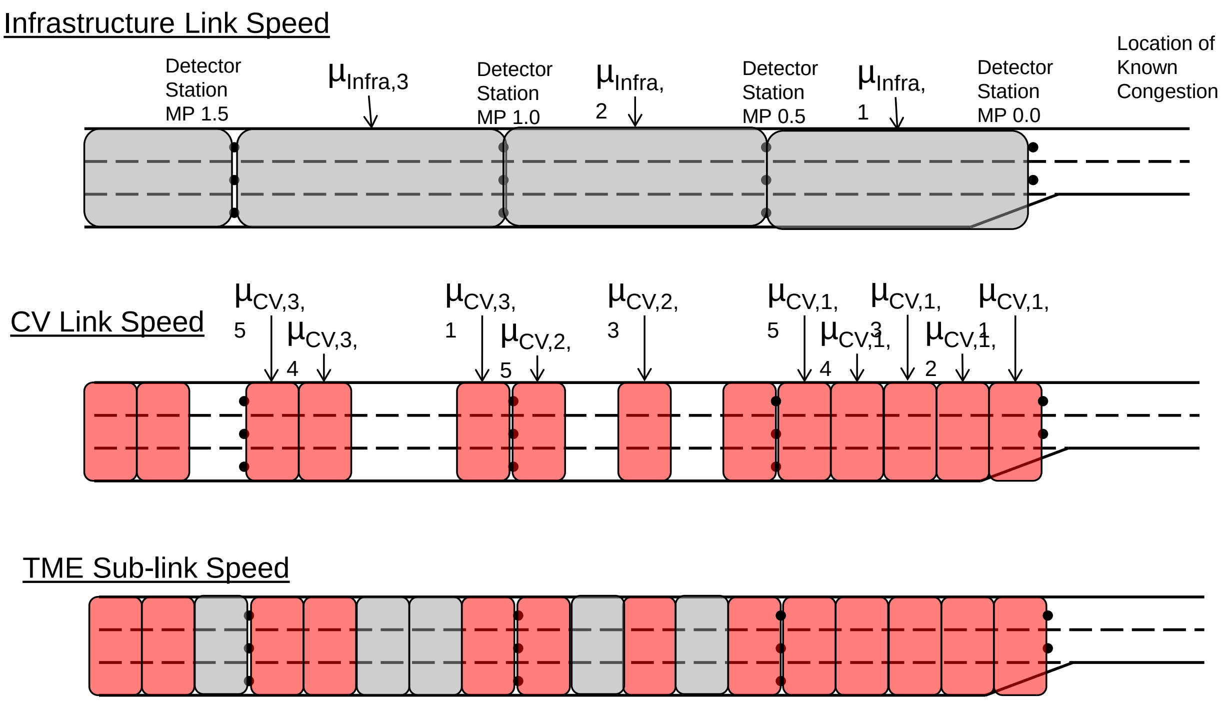

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Figure 8-2. Fusion of Infrastructure Link Speeds and CV Link Speeds.

Formation of Troupes

A troupe is a section of the roadway having common speed characteristics and is used by the speed harmonization algorithm in Seattle by Washington Department of Transportation[10]. The primary parameter in the formation of troupes is troupe range (TR). Seattle uses a troupe range of 12 mph while using a standard gantry spacing of 0.5 miles. Seattle also calculates the speeds of a troupe by averaging the speeds within the troupe and "rounding up" to the nearest 5 mph.

The SPD-HARM algorithm uses the same methodology as the Seattle approach to estimate troupes. The formation of troupes starts at the upstream end of the roadway section under consideration. A sublink is selected to become the starting block of a troupe and has a defined critical sublink speed. The immediate downstream sublink is then evaluated to see if its critical link speed is close enough to the first sublink so that it can join the troupe. The troupe formation process is illustrated in Figure 8-3 and further described in this section.

Let us assume that the critical sublink speed for the first sublink is VCRi where i is the ID of the first sublink. The critical sublink speed for the next sublink is VCRj where j is the ID of the second sublink and the critical sublink speed for the subsequent sublink VCRk where k is the ID of the next sublink and so on. The maximum value of ALL the critical sublinks speeds within a troupe (Troupe A) is identified (MaxVCR-A). The minimum value of ALL the critical sublinks speeds within a troupe (Troupe A) is identified (MinVCR-A). If the critical sublink speed for a sublink (VCRj to n) is between (MaxVCR-A - TR) and (Min VCR-A - TR), VCRj to n joins the troupe, otherwise check the troupe for

[10] Morse, Mark. "RE: VSL Algorithm in Seattle." Email to Srinivasa Sunkari. August 14th 2013.

minimum troupe length. The process of formation of troupes in the SPD-HARM algorithm is illustrated in Figure 8-4.

The freeway facility is divided into sublinks of 0.1 mile which are marked with Mile Markers (MM) from MM 1.1 and shown till MM 3.6. The critical smoothed sublinks speeds in miles per hour for each sublink are illustrated in the row below the MM. Starting from MM 1.1 which is in Troupe A, MM 1.2 is evaluated to see if it can join troupe A. Since there is only sublink in Troupe A i.e., i, the maximum value and the minimum value of the smoothed sublink speeds is 65 mph. The maximum value minus the Troupe Range (5 mph) is 65 – 5 mph and is equal to 60 mph. The minimum value plus the Troupe Range (5 mph) is 65 + 5 mph and is equal to 70 mph. These values are shown in the rows for Max – Troupe Range and Min + troupe range and form the range in which the subsequent smoothed sublink speed has to fall in order to join the troupe. Since the smoothed sublink speed for sublink j is 70 and is within the range, sublink j is added to Troupe A.

The process is repeated for sublink k and the subsequent sublinks. The Max – troupe range values and the Min + troupe range values calculated for each sublink and are used to evaluate if a sublink can join a troupe. Sublinks j, k, and l join sublink i to form Troupe A. However the smoothed sublink speed for sublink m falls outside the min and max range. Hence, before the second troupe is formed, a check is performed to ensure that troupe meets the minimum length requirement.

The algorithm requires that troupes meet a minimum length requirement as a troupe is considered to have common speed characteristics along the roadway. Since troupes will have an impact on the calculation of the advisory speeds, and having a very small troupe may have an impact on the objective to have a gradual change in speed, it was decided to adjust the troupe length by adding an additional sublink to the troupe. Thus when a sublink does not qualify to join an existing troupe, the average of the smoothed sublink speeds within the troupe is calculated and rounded up to the nearest 5 mph (troupe Speed). Then the decision sight distance for the troupe Speed is determined by calculating the decision sight distance for that speed (14.5 seconds of travel time). If the length of the troupe is greater than the decision sight distance, then a new troupe can be created. Otherwise, add the sublink that was not qualified to be added to the troupe, to the troupe and check the minimum troupe length requirement. It is more than likely that the minimum troupe length requirement will be met.

In Figure 8-4, the troupe Speed for Troupe A has been calculated as 70 mph. The decision sight distance for 70 mph is 1,445 feet. However, the length of Troupe A is four sublinks, each of which is 0.1 mile in length which is equal to about 2,100 feet (4 X 528). Hence the minimum troupe length requirement is met and a new troupe (Troupe B) is formed. This process is continued until Troupes, C, D, and E are formed as illustrated in Figure 8-4.

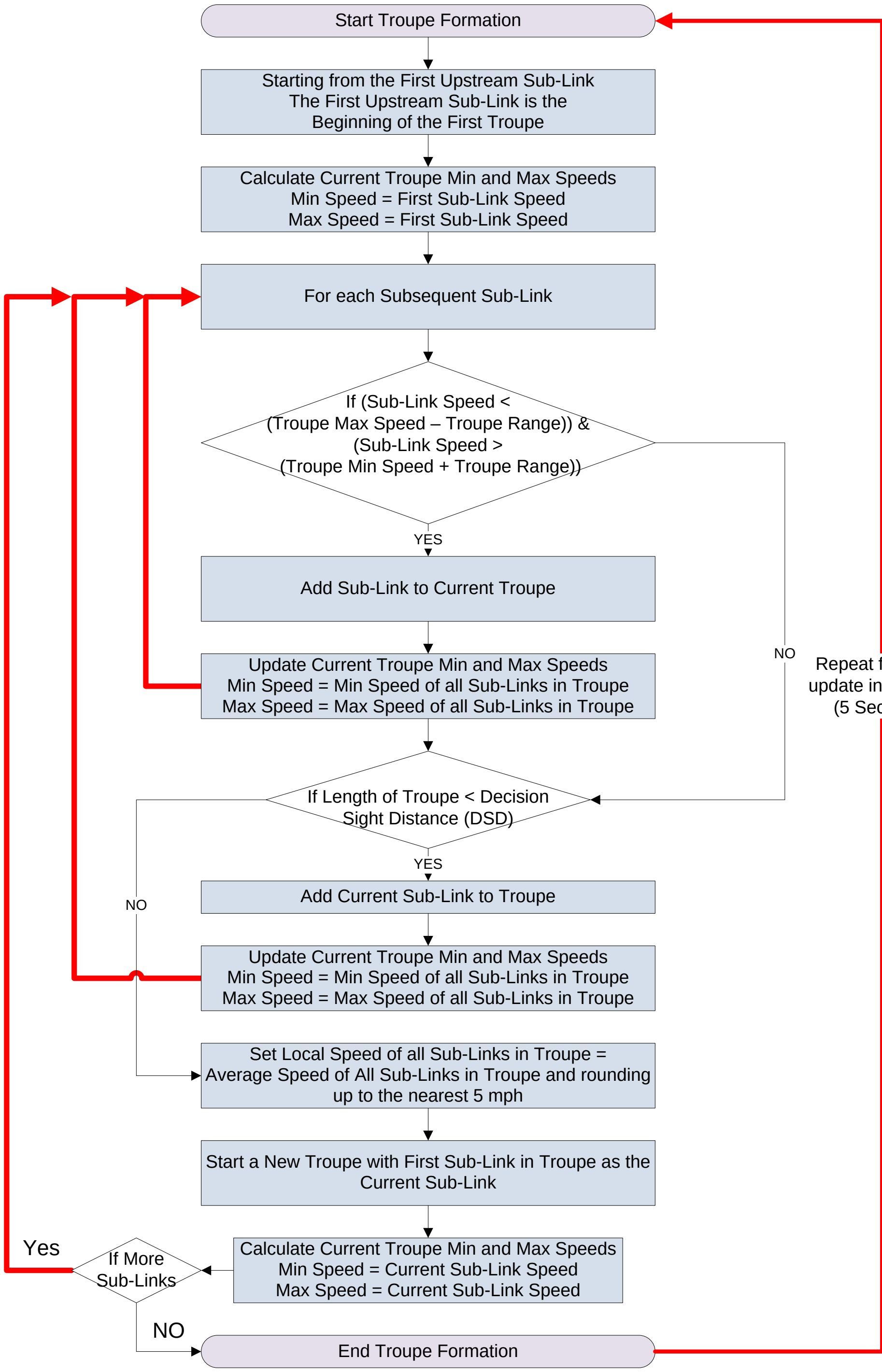

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Figure 8-3. Troupe Formation Process.

	Direction of travel →																									
Mileposts	MM 1.1	MM 1.2	MM 1.3	MM 1.4	MM 1.5	MM 1.6	MM 1.7	MM 1.8	MM 1.9	MM 2.0	MM 2.1	MM 2.2	MM 2.3	MM 2.4	MM 2.5	MM 2.6	MM 2.7	MM 2.8	MM 2.9	MM 3.0	MM 3.1	MM 3.2	MM 3.3	MM 3.4	MM 3.5	MM 3.6
Smoothed sub-link speed (mph)	65	70	70	60	60	60	60	60	60	60	50	55	50	55	50	40	45	40	45	40	40	40	35	35	35	30
Sub-link ID	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a1	b1	c1	d1	e1	f1	g1	h1
Max - Troupe Range		60	65	65	65	55	55	55	55	55	55	45	50	50	50	50	35	40	40	40	40	40	35	35	35	35
Troupe ID	A	A	A	A	B	B	B	B	B	B	C	C	C	C	C	D	D	D	E	E	E	F	F	F	F	F
Min + Troupe Range		70	70	70	65	65	65	65	65	65	65	55	55	55	55	55	45	45	45	50	45	45	45	40	40	40
Troupe Speed (mph)	70				65						55					45			45			40				
Troupe Range =	5	mph																								

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Figure 8-4. Illustration of Formation of Troupes in the SPD-HARM Algorithm.

Determining Connected Vehicle Advisory Speeds

Next, the Connected Vehicle Advisory Speeds are calculated every time a smoothed sublink speed is calculated. The troupe speed for each troupe is applied as the Connected Vehicle Advisory Speed for each sublink starting from the downstream end. Figure 8-4 has been amended with the calculated Connected Vehicle Advisory Speeds and illustrated in Figure 8-5.

	Direction of travel →																									
Mileposts	MM 1.1	MM 1.2	MM 1.3	MM 1.4	MM 1.5	MM 1.6	MM 1.7	MM 1.8	MM 1.9	MM 2.0	MM 2.1	MM 2.2	MM 2.3	MM 2.4	MM 2.5	MM 2.6	MM 2.7	MM 2.8	MM 2.9	MM 3.0	MM 3.1	MM 3.2	MM 3.3	MM 3.4	MM 3.5	MM 3.6
TME Link Speed (mph)	66	71	67	69	63	64	67	62	64	63	58	56	54	57	53	44	44	46	42	39	40	36	40	33	32	35
Sub-link ID	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a1	b1	c1	d1	e1	f1	g1	h1
Max - Troupe Range		61	66	66	66	58	59	62	62	62	62	53	53	53	53	53	39	39	41	37	37	37	31	35	35	35
Troupe ID	A	A	A	A	B	B	B	B	B	B	C	C	C	C	C	D	D	D	E	E	E	F	F	F	F	F
Min + Troupe Range		71	71	71	71	68	68	68	67	67	67	63	61	59	59	58	49	49	49	47	44	44	41	41	38	37
Troupe Speed (mph)	70				65						60					45			45			40				
Troupe Range =	5	mph																								
CV Recommended Speed	70	70	70	65	65	65	60	60	60	55	55	55	50	50	50	45	45	45	45	45	45	40	40	40	40	40

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Figure 8-5. Calculation of Connected Vehicle Recommended Speeds.

The algorithm uses four steps to determine the CV recommended speeds. First, the algorithm applies the troupe speeds for each segment as the Connected Vehicle Recommended Speeds to each sublink within the segment starting from the downstream end. Second, the algorithm ensures that the change in sublink speeds between any adjacent sublinks does not exceed a user defined threshold, for example 5 mph. Third, the algorithm ensures that a length of the segment of the facility having the same Connected Vehicle Recommended Speed is not shorter than the decision sight distance for that speed. Finally, the algorithm ensures that a change in the Connected Vehicle Recommended Speed for a sublink does not occur at a frequency of less than 15 seconds. These steps are to ensure minimizing work load on the driver by reducing the number of speed changes.

In the example in Figure 8-5, troupe speed for Troupe F is applied to sublinks d1 to h1 as 40 mph. The troupes immediately upstream, Troupe E and Troupe D, have a common troupe speed of 45 mph and these speeds are applied to sublinks x to c1. Then the immediate upstream troupe, Troupe C, had a troupe speed of 60 mph which is a 15 mph increment over the sublink x. The connected vehicle recommended speed should then be set at 50 mph (5 mph increment over the downstream sublink). This speed limit, however, should be set for a number of sublinks such that the combined length of the roadway at 50 mph should not be less than decision sight distance for 50 mph. The decision sight distance for 50 mph is 1,066 feet which is just over two sublinks. Hence, the connected vehicle recommended speed is set at 50 mph for the three sublinks from u to w. This process is repeated for the remainder of the sublinks till the upstream boundary is reached as is illustrated in Figure 8-6.

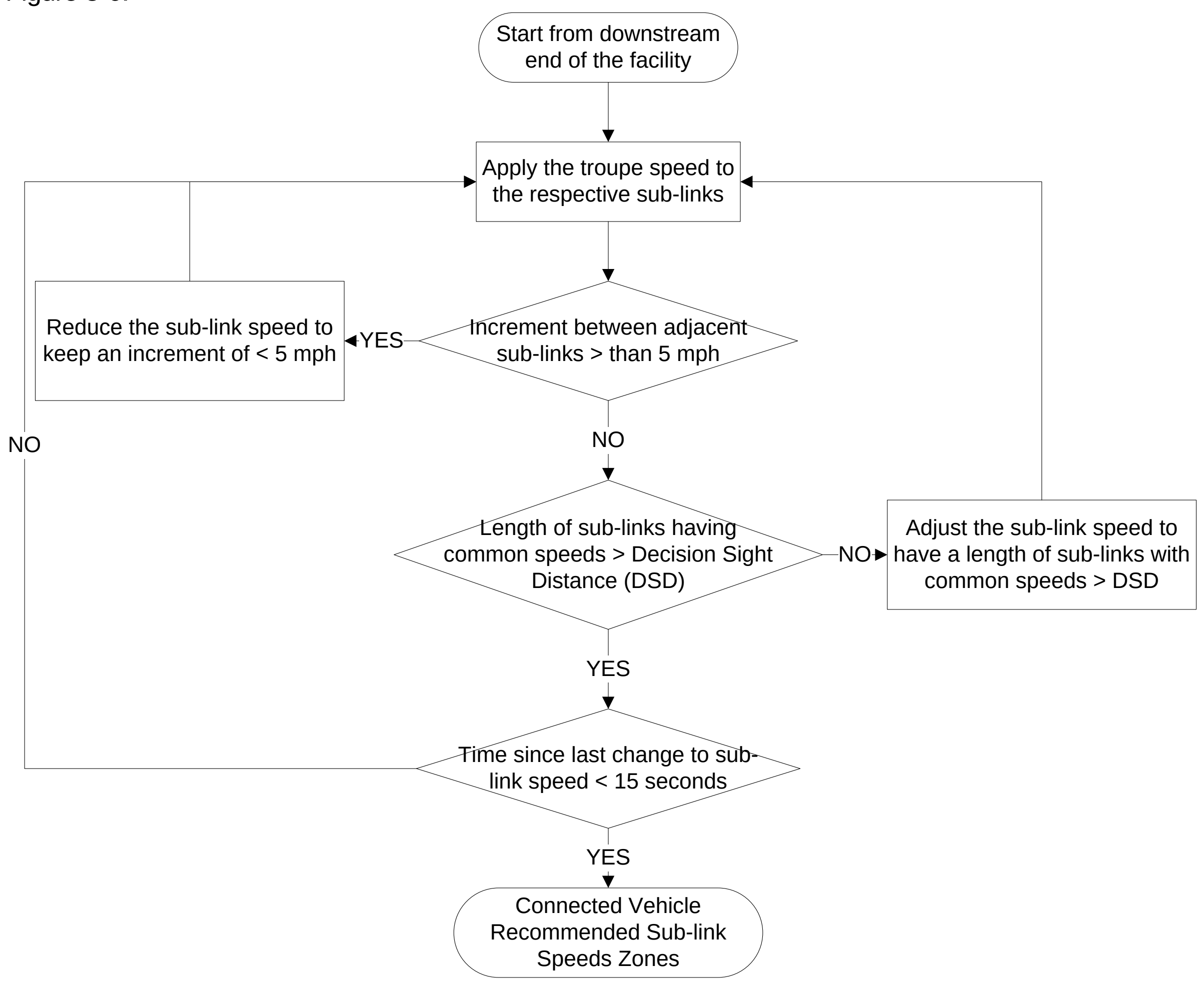

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Figure 8-6. Illustration of the Determination of Connected Vehicle Recommended Sublink Speeds.

Determination of Infrastructure Recommended Speeds

As stated earlier, infrastructure speeds on any gantries will be determined based on their location within the connected vehicle recommended speed zone or segment. Figure 8-5 has been amended by adding four gantries for the example and their speeds calculated as illustrated in Figure 8-7.

Direction of travel →

Mileposts	MM 1.1	MM 1.2	MM 1.3	MM 1.4	MM 1.5	MM 1.6	MM 1.7	MM 1.8	MM 1.9	MM 2.0	MM 2.1	MM 2.2	MM 2.3	MM 2.4	MM 2.5	MM 2.6	MM 2.7	MM 2.8	MM 2.9	MM 3.0	MM 3.1	MM 3.2	MM 3.3	MM 3.4	MM 3.5	MM 3.6
TME Link Speed (mph)	66	71	67	69	63	64	67	62	64	63	58	56	54	57	53	44	44	46	42	39	40	36	40	33	32	35
Sub-link ID	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a1	b1	c1	d1	e1	f1	g1	h1
Max - Troupe Range		61	66	66	66	58	59	62	62	62	62	53	53	53	53	53	39	39	41	37	37	37	31	35	35	35
Troupe ID	A	A	A	A	B	B	B	B	B	B	C	C	C	C	C	D	D	D	E	E	E	F	F	F	F	F
Min + Troupe Range		71	71	71	71	68	68	68	67	67	67	63	61	59	59	58	49	49	49	47	44	44	41	41	38	37
Troupe Speed (mph)	70				65						60					45			45			40				
Troupe Range =	5	mph																								
CV Recommended Speed	70	70	65	65	65	60	60	60	60	55	55	55	50	50	50	45	45	45	45	45	45	40	40	40	40	40
Infrastructure Recommended Speeds					Gantry 4	60	mph					Gantry 3	50	mph			Gantry 2	45	mph				Gantry 1	40	mph	

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Figure 8-7. Calculation of Infrastructure Recommended Speeds.

The algorithm develops the Infrastructure Recommended Speeds by ensuring that the gantries display a speed that is consistent with the speed being displayed inside a connected vehicle. When this is done, if the Connected Vehicle Recommended Speed does not match the Infrastructure for at least the decision sight distance downstream of the gantry, the Connected Vehicle Recommended Speeds are adjusted to ensure that this distance is maintained.

In Figure 8-7, Gantry 1 is located in the 40 mph connected vehicle recommended speed zone at MM 3.3. Before the speed is selected for the infrastructure recommended speed, a check is made to ensure that the speed selected is being displayed for at least the decision sight distance for the respective speed. Since the decision sight distance for a 40 mph vehicle is 853 feet (2 sublinks) and there are three more sublinks before the connected vehicle recommended speed zone ends, the recommended speed to be displayed on Gantry 1 will be 40 mph. The same rationale is used to estimate the remaining gantries. Since Gantry 2 is in the middle of the 45 mph connected vehicle recommended speed zone, it is selected as the speed to be displayed. Gantry 3 is at the border of the 55 mph and 50 mph speed zones. Hence, 50 mph is the selected speed limit to be displayed on Gantry 3 as that would be the recommended speed for motorists travelling downstream of the gantry. Finally while Gantry 4 is located in the 65 mph speed zone, it is just one sublink upstream of the 60 mph recommended speed zone. Since the decision sight distance for 65 mph is almost 1,400 feet and hence greater than one sublink (as indicated in Figure 8-5), the CV Recommended Speeds are changed for sublink n and k from 65 mph to 60 mph and from 70 mph to 65 mph respectively, and a value of 60 mph is selected for Gantry 4.

This process is repeated at a frequency equal to the frequency at which connected vehicle data is received which could be as low as five seconds. However, it is not advisable to change a displayed speed limit at the same frequency. The Battelle team recommends that the decision sight distance be used as a criterion to determine the frequency with which the speed limit displayed can be changed and recommends at least 14.5 seconds between successive changes to minimize excessive workload on the driver. The algorithm also recommends that when a change occurs in the recommended speed, the magnitude of change should not be greater than 5 mph so that drivers respond gradually. The process of determination of the recommended infrastructure speed is illustrated in Figure 8-8.

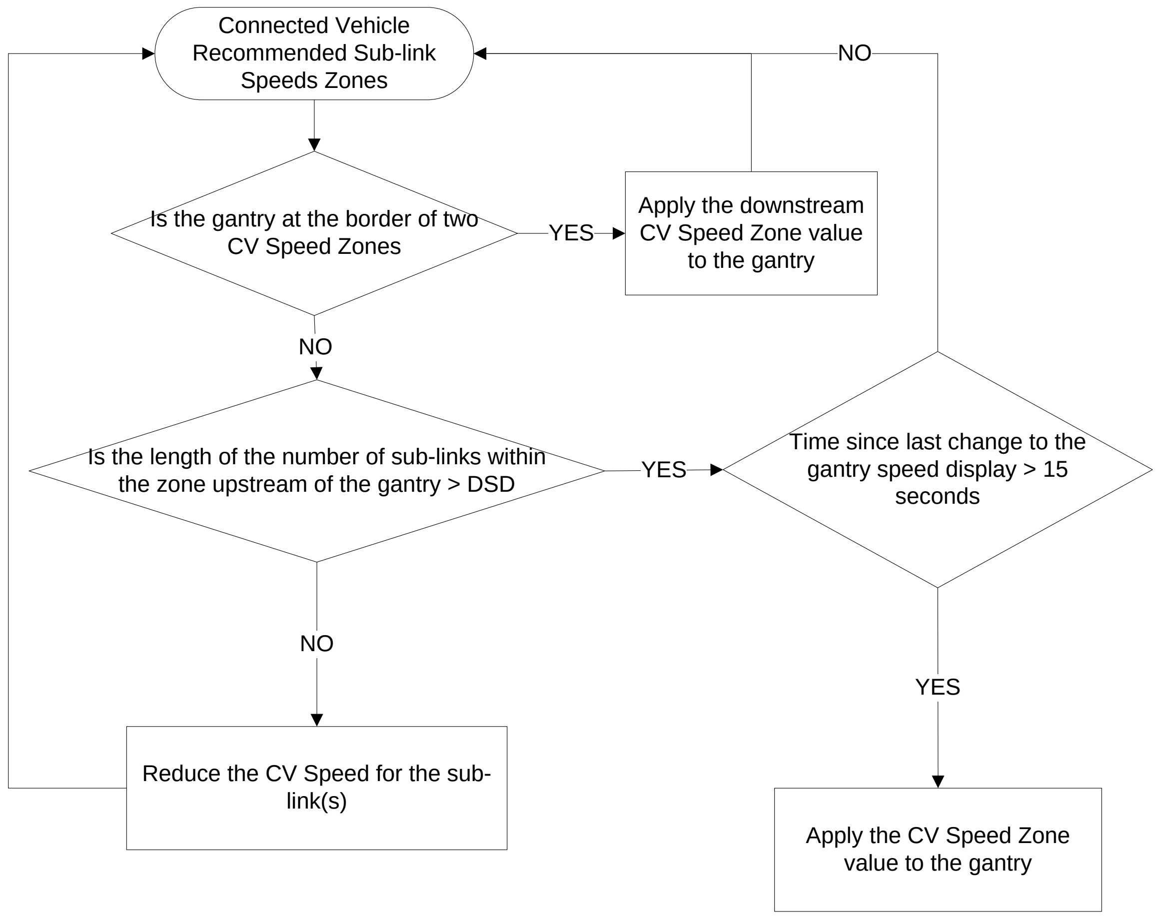

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Figure 8-8. Illustration of the Determination of the Recommended Infrastructure Speeds.

Chapter 9 Message Generation

This chapter describes the processes that will be used to generate the queue warning and recommended speed messages from the output of the speed harmonization and queue warning algorithms.

Generation of Queue Warning Message

The TME-based and Cloud-based Queue Warning algorithms generate the following data elements for detected queues:

- Front of queue (FOQ) mile marker location,
- Back of queue (BOQ) mile marker location,
- Speed in Queue, and
- Rate of Queue Growth.

On the other hand, the Vehicle-based V2V Queue Warning algorithm generates only the location of the BOQ and broadcast it to the vehicles.

The type of queue warning message that will be displayed to the motorists, be it in the vehicle or on an infrastructure DMS, will be a function of the location of the motorists or the sign with respect to the back of queue. Motorist closer to the BOQ, will receive a more urgent message. This distance can be a function of the stopping sight distance and decision sight distance. When the motorist is within the stopping distance, the collision avoidance messages will be generated to ensure that the vehicle stops before colliding with the vehicles in the queue. However, upstream of the stopping distance, if the vehicle is in its decision sight distance from the BOQ, an example of the queue warning message could be “Stopped Traffic Ahead, Reduce Speed”. Finally, if the vehicle is upstream of its decision sight distance from the BOQ, two types of messages, either distance-based or time-based, can be displayed on the DMS signs or in the vehicle. Figure 9-1 illustrates the rationale used to display the queue warning messages.

- Distance-based: Based on the distance of the DMS sign or the vehicle from the back of queue, a message could be displayed indicating the distance to the back of queue. An example of distance-based queue warning message could be “Stopped Traffic X Miles Ahead.”
- Time-based: The time-based queue warning message provides the driver with information about the time to the back of queue. An example of time-based queue warning message could be “Two Minutes to Back Of Queue”. In the case of the vehicle-based queue warning application, the application will use the vehicle’s distance from the back of queue and the vehicle’s current speed to calculate the time to the back of queue and display it to the driver. In the case of DMSs, the TME-based queue warning application will use the distance of the sign from the back of

queue and the current recommended speed for the roadway segment where the sign is located to calculate the time to the back of queue and display it on the DMS.

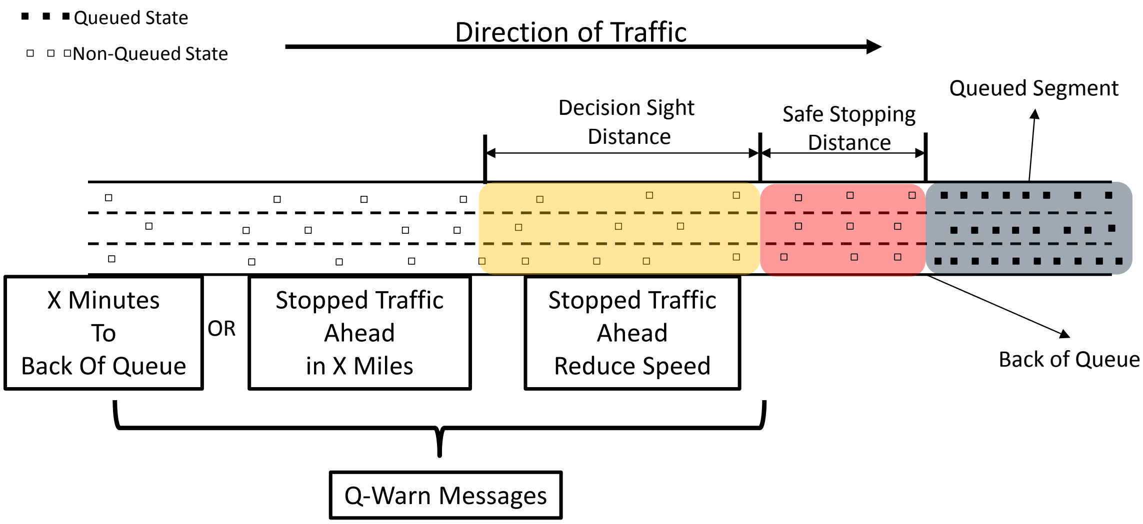

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Figure 9-1. Displaying Queue Warning Messages.

The queue warning messages module will process the detected queue information to generate appropriate queue warning messages to display on the infrastructure-based signs located in the affected roadway segments and also the information about the detected queue that will be sent to connected vehicles. The vehicle-based queue warning applications will receive the detected queue information sent from the TME using either an SAE J2735 TIM or RSA message and will display appropriate queue warning messages to the motorist based on the location of the vehicle from the BOQ. The same principles discussed earlier in displaying queue warning messages will be used by both the TME-based and vehicle-based queue warning applications to display queue warning messages on infrastructure signs or to the motorist.

Queue Warning Messages for Infrastructure Signs

Queue warning messages are usually displayed at a maximum of X miles upstream of a back of queue location to alert drivers to the presence of queues downstream. This distance is a user defined parameter and will be set to 10 miles for the prototype type testing. The process to select the infrastructure signs that can be used to display the queue warning messages and the generation of the custom messages to display on each sign include the following steps:

1. Retrieve the detected queue information from the INFLO database including: BOQ mile marker location, FOQ mile marker location, speed in queue, and rate of queue growth.
2. Determine the lower and upper mile marker boundaries of the roadway segment where queue warning messages should be displayed to alert drivers to the presence of queues downstream. The lower mile marker boundary is usually equal to the BOQ mile marker location. The roadway segment upper mile marker boundary is equal to the BOQ minus the X miles distance upstream of the BOQ where queue warning messages should be provided.
3. Using the lower and upper mile marker boundaries of the affected roadway segment, retrieve from the INFLO database the infrastructure signs that are located within the

boundaries of the identified roadway segment and can be used to display queue warning messages.

4. Depending on the distance of each infrastructure sign from the BOQ, generate a custom warning message for the sign. The following rules will be used in generating the custom queue warning messages for the selected infrastructure signs:
    a. If the infrastructure sign is within the stopping sight distance from the BOQ, the a message will be displayed to the driver through driver interface device:
    b. If the infrastructure sign is located within the decision sight distance from the BOQ but upstream of the stopping sight distance, the following provides an example of the queue warning message that could be displayed: “Stopped Traffic Ahead Reduce Speed”
    c. If the sign is located upstream of the decision sight distance, two possible queue warning messages can be generated: time-based or distance based.
        i. For time-based queue warning message, use the sign distance from back of queue and the recommended speed for the roadway segment where the sign is located to calculate the time to queue in minute. A possible time to queue warning message could be, “XX Minutes To Back Of Queue”
        ii. For distance-based queue warning message, depending on the infrastructure sign distance from the back of queue, a possible distance to queue warning message could be, “Stopped Traffic X Miles Ahead.”:

Queue Warning Messages for Connected Vehicle

The queue warning message to be displayed in the vehicle for the motorist will be a function of the location of the motorist with respect to the back of queue. The TME Generation of Queue Message module will send the queue information to vehicles in the affected roadway segments via either a TIM or RSA SAE J2735 message. The following data elements will be included in the message:

- Roadway name and ID,
- BOQ mile marker location,
- FOQ mile marker location,
- Heading,
- Speed in queue,
- Rate of queue growth, and
- Validity duration ” interval for the message in case no new updates were received.

The validity duration is a user-defined interval that is intended to represent the maximum amount of time that a message is considered to be valued. A timer is used to countdown the amount of time that defined to be valid. If the new message has not been generated before the validity duration counter reaches zero, then message is declare to be invalid and the algorithm deletes the message from the message generator.

The vehicle-based queue warning application will receive the queue information and display custom queue warning messages to the driver based on the location of the vehicle to the back of queue. The rules discussed earlier in the Queue Warning Messages for Infrastructure Signs section can be used by the vehicle-based queue warning application to generate the custom queue warning messages to be displayed in the vehicle.

Generation of Recommended Speed Messages

The TME-based Speed Harmonization algorithm generates a recommended speed for each connected vehicle sublink and infrastructure-based link in the area upstream of the known congestion location. The sublinks and links are usually grouped together if they have similar speeds resulting in a table with the following properties for each roadway segment:

- Roadway segment ID
- Roadway segment beginning mile marker
- Roadway segment ending mile marker
- Roadway segment recommended speed

The module also generates the recommended speed for each infrastructure link that is available in the freeway corridor.

Recommended Speed Messages for Infrastructure Signs

As mentioned earlier the TME-based Speed Harmonization application will generate the recommended speed to be displayed on infrastructure signs if any is available in the freeway corridor being monitored. The appropriate messages to be displayed on the infrastructure signs will use the recommended speed and formulate a NTCIP 1203 message to display on each sign. A possible recommended speed message could be, “Speed Limit XX MPH”.

Recommended Speed Message for Connected Vehicles

The recommended speed message to be displayed in the vehicle for the motorist will depend on the roadway segment where the vehicle is located. The TME Generation of Recommended Speed Messages module will send the roadway segment recommended speed information to vehicles in the affected roadway segments via either a TIM or RSA SAE J2735 message. The following data elements will be included in the message:

- Roadway name and ID,
- Beginning mile marker of roadway segment,
- Ending mile marker of roadway segment,
- Heading,
- Recommended speed for roadway segment,
- And time to live interval for the data in case no new updates were received.

The vehicle-based speed harmonization application will receive the roadway segment recommended speed information and generate a recommended speed message to the driver based on the roadway segment where the vehicle is located at a given time.

List of Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ADA	Advanced Driver Assistance
ATIS	Advanced Traveler Information System
ATM	Active Traffic Management
ATMS	Advanced Traffic Management System
ConOps	Concept of Operations
DMA	Dynamic Mobility Application
DMS	Dynamic Message Sign
DSRC	Dedicated Short-Range Communications
HCM	U.S. Highway Capacity Manual
IDM	Intelligent Driver Model
INFLO	Intelligent Network Flow Optimization
ITS	Intelligent Transportation System
NHTSA	National Highway Traffic Safety Administration
Q-WARN	Queue Warning application
RWIS	Roadway Weather Information System
SPD-HARM	Speed Harmonization application
TMC	Traffic Management Center
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure/Infrastructure-to-Vehicle
V2V	Vehicle-to-Vehicle
VC	Vehicular Communications
VMS	Variable Message Sign
VSL	Variable Speed Limit
VSS	Variable Speed Sign

Glossary of Terms

Term	Definition
Back of Queue	The farthest upstream location of the queue. Generally, the location where the traffic transitions from a free-flow state to a queued state.
Bottleneck	A system element or location on a freeway on which demand exceeds capacity.
Congested State	A condition when a vehicle is traveling in low-flow, high-occupancy traffic conditions that arises when demand approaches or exceeds a system element's capacity.
Downstream	The direction of traffic flow.
Free-Flow	A flow of traffic unaffected by upstream or down-stream conditions.
Freeway	A fully access-controlled, divided highway with a minimum of two lanes (and frequently more) in each direction.
Front of Queue	The farthest downstream point of the queue. Generally, the location where the traffic conditions transitions from a queued state to a free flow state.
Gap	The space or time between two vehicles, measured from the rear bumper of the front vehicles to the front bumper of the second vehicle.
Link	A length of roadway between two consecutive detector stations.
Non-recurring Congestion	Congestion that forms dues to temporary reduction in capacity caused be incidents, temporary lane blockages, or collection. The time and location of the congestion is not known.
Queue	A line of vehicle, bicycles , or persons waiting to be served due to traffic control, a bottleneck, or other causes.
Queue Length	The distance between the upstream and downstream end of the queue.
Queued State	A condition when a vehicle is within one car length (20 ft.) of a stopped vehicle and is itself in a stopped state (i.e., has slowed to less than 5 mph)
Recurring Congestion	Congestion that forms when routine traffic volumes exceed the available capacity of a known bottleneck location.
Segment	For uninterrupted flow facilities (such as a freeway), a portion of a facility between two user-defined points.
Separation Distance	See **Gap**
Shock Wave	A change or discontinuity in traffic conditions.
Stopped State	A condition when a vehicle is traveling less than 5 mph.
Sublink	A section of roadway equal in distance to 0.1 mile length.
Upstream	The direction of flow from which traffic is flowing.

List of User-Defined Parameters and Default Values

Algorithm Parameter	Subsystem	Range	Default	Description
Separation Distance	CV-based Q-Warn	0-100 ft.	20 ft.	Used by connected vehicle together with queued speed threshold to determine if it is in queued state
Queued Speed Threshold	CV-based Q-Warn TSS Data Aggregator	0 – 50 mph	10 mph	Used by connected vehicle together with separation distance to determine if it is in queued state
Troupe Range	TME SPD HARM	5 – 10 mph	5 mph	Used by TME SPD HARM to group adjacent links and sub-links with speeds within the troupe range speed
SPD HARM Minimum Speed	TME SPD HARM	0 – 50 mph	30 mph	The minimum speed that can be recommended to drivers or displayed on DMS
Interval between a change in Recommended Speed	TME SPD HARM	15 – 60 seconds	15 seconds	This is the minimum interval between a change in the recommended speed in TME SPD HARM application
CV Data Polling Frequency	CV Data Aggregation	1 – 60 seconds	5 seconds	Frequency of processing CV data
Infrastructure Data Polling Frequency	TSS Data Aggregator	1 – 300 seconds	30 seconds	Frequency of processing infrastructure traffic data
ESS Data Polling Frequency	ESS Data Aggregator	1 – 60 minutes	5 minutes	Frequency of processing weather data from fixed sensors
Mobile Weather Data Polling Frequency	Mobile ESS Data Aggregator	1 – 60 minutes	5 minutes	Frequency of processing weather data from mobile sensors
Percentage of Vehicles in Queued State in a Sub-Link	CV Data Aggregator	0 – 100	20	Used to determine if a roadway sub-link is in a queued state

Algorithm Parameter	Subsystem	Range	Default	Description
Visibility Thresholds	WRTM	200 – 2000 ft.	500 ft.	The distances below which visibility is determined to require a reduction in recommended speed.
Maximum WRTM Recommended Speed	WRTM	30-85 mph	70 mph	The maximum recommended safe during good visibility conditions and pavement surface conditions.
Minimum WRTM Recommended Speed	WRTM	30- 85 mph	30 mph	The minimum recommended safe speed during poor visibility conditions and pavement surface conditions.
Pavement Surface Friction Factor Upper Threshold	WRTM	0-1.0	0.7	The coefficient of friction above which pavement conditions are determined to be "good."
Pavement Surface Friction Factor Lower Threshold	WRTM	0-1.0	0.3	The coefficient of friction that exists on the pavement surface when conditions are "poor".
Recommended Speed Level 1 through 4	WRTM	30-85 mph	Level 1: 45 mph Level 2: 40 mph Level 3: 40 mph Level 4: 35 mph	Recommended safe speeds for different levels of visibility and pavement surface conditions.
Roadway Sub-link length	TME SPD HARM TME Q-WARN Cloud-based Q WARN	0.1 – 1 mile	0.1 miles	Minimum distances for subdividing roadway segment in for aggregating connected vehicle data.
V2V Upstream Distance from Back-of-Queue for Queue Warning	V2V Q-WARN Cloud-based Q-WARN		10 miles	The distance upstream of the back-of-queue in V2V Q WARN where a CV does not to rebroadcast the Q-WARN message to upstream vehicles
Adjacent Sub-links Maximum Speed Difference Threshold	TME SPD HARM	2 – 10 mph	5 mph	The maximum difference in speed between adjacent sub-links
Validity Duration	CV Q-WARN CV SPD HARM	0 – 600 seconds		The time to live for a SPD HARM or Q-WARN message broadcast to CVs
Queued Link Speed Threshold	TME Q-WARN	0 – 50 mph	30 mph	The speed value used to determine if a roadway link is queued based on infrastructure speed data
Congested Link Speed Threshold	TME SPD HARM	0 – 50 mph	45 mph	The speed value used to determine if a roadway link is congested based on infrastructure speed data

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