Technical Report on Prototype Intelligent Network Flow Optimization (INFLO) Dynamic Speed Harmonization and Queue Warning

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16. Abstract

This Technical Report on Prototype Intelligent Network Flow Optimization (INFLO) Dynamic Speed Harmonization and Queue Warning is the final report for the project. It describes the prototyping, acceptance testing and small-scale demonstration of the INFLO Prototype Speed Harmonization (SPD-HARM) and Queue Warning (Q-WARN) applications. This report also describes the programmatic and technical accomplishments of the program wherein the Small-Scale Demonstration fully confirmed the functionality of the INFLO Prototype System in an operational highway traffic environment. The system was proven to reliably

- Capture current location and telematics data from connected vehicles and vehicle speed data from infrastructure
- Analyze the data to detect congestion and determine the beginning and end of congestion queues
- Formulate speed harmonization recommendations
- Communicate queue location and speed harmonization recommendations to drivers.

The demonstration proved connected vehicle data capture and dissemination functionality using both cellular communications and DSRC communications. Furthermore, the Small-Scale Demonstration confirmed that the INFLO Prototype System has the latency and processing speed to support INFLO application functionality in an operational traffic environment.

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Executive Summary

This Technical Report on Prototype Intelligent Network Flow Optimization (INFLO) Dynamic Speed Harmonization and Queue Warning is the final report for the INFLO project. It describes the prototyping, acceptance testing and small-scale demonstration of the INFLO Prototype Speed Harmonization (SPD-HARM) and Queue Warning (Q-WARN) applications. This report also describes the programmatic and technical accomplishments of the program wherein the INFLO Prototype Seattle Small-Scale Demonstration fully confirmed the functionality of the INFLO Prototype System in an operational highway traffic environment.

The INFLO Prototype System consists of Q-WARN and SPD-HARM applications, in-vehicle components, roadside units, dedicated short-range communications (DSRC) and cellular communications, databases, a virtual traffic management entity and others. The primary functional components of the implemented INFLO Prototype System are the following:

- Connected Vehicle In-Vehicle System consisting of
  - In-Vehicle System User Interface Module (Android™ User Interface and Cellular Radio),
  - In-Vehicle System DSRC Radio Module (Processor and DSRC Radio),
  - In Vehicle Network Access System (Vehicle Controller Area Network (CAN) Network)
- Roadside Units (RSUs)
- Virtual Traffic Management Entity (TME) consisting of
  - INFLO Database
  - Traffic Sensor System (TSS) Data Aggregator
  - Connected Vehicle Data Aggregator
  - TME-Based Q-WARN Application
  - TME-Based SPD HARM Application with Weather Responsive Traffic Management (WRTM).

Its components are described in detail in the *INFLO Prototype System Design Document* and the *Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design*.

The principles of system engineering were applied in conducting INFLO Prototype System Acceptance Testing to verify that the developed prototype meets the system requirements defined in Chapter 6 of the *Report on Detailed Requirements for the INFLO Prototype (FHWA-JPO-13-TBD)*. The INFLO Prototype System was tested in three phases:

- Phase I – Component Acceptance Testing
- Phase IIa – Communications and Messaging System Integration Acceptance Testing
- Phase IIb – TME-Based Application System Integration Acceptance Testing
- Phase III – On-road Prototype System Acceptance Testing.

Phase I test cases and Phase II test cases were conducted within a laboratory environment using simulated or real data inputs. Phase III test cases were conducted using test vehicles in either a controlled (closed-course) environment or on streets and highways in Columbus, Ohio. The system passed all Acceptance Tests.

Following successful completion of Acceptance Testing, the U.S. DOT approved the Project Team to proceed with the next step in verifying the viability of applying connected vehicle technology for INFLO applications, which was to conduct a Small-Scale Demonstration in operational traffic conditions. In this Small-Scale Demonstration, the Project Team worked with Washington State Department of Transportation (WSDOT) to deploy connected vehicle systems at three Variable Speed Limit (VSL) gantries, and in twenty-one vehicles, in a scripted driving scenario circuiting a corridor on I-5 from Tukwila to Edmonds through downtown Seattle, during morning rush hour the week of January 12, 2015. The INFLO Prototype System collected vehicle speed data from both the WSDOT infrastructure-based speed detectors and the connected vehicles during the driving scenario. The System processed the data in real time and delivered Q-WARN and SPD-HARM messages to drivers. The Team captured system performance data as well as driver feedback to demonstrate the INFLO Prototype System in a fully operational highway traffic environment and to examine potential benefits of connected vehicle technology.

This Small-Scale Demonstration represented a number of accomplishments for the U.S. DOT and the Project Team. Firstly, the Small-Scale Demonstration fully confirmed the functionality of the INFLO Prototype System in an operational highway traffic environment. The system was proven to reliably

- Capture current location and telematics data from connected vehicles and vehicle speed data from infrastructure
- Analyze the data to detect congestion and determine the beginning and end of congestion queues
- Formulate speed harmonization recommendations
- Communicate queue location and speed harmonization recommendations to drivers.

The demonstration proved connected vehicle data capture and dissemination functionality in an operating environment using both cellular communications and DSRC communications.

Secondly, the Small-Scale Demonstration confirmed that the INFLO Prototype System has the latency and processing speed to support INFLO application functionality in an operational traffic environment.

Thirdly, the Small-Scale Demonstration developed data that helped confirm that the INFLO Prototype System can deliver more precise estimates of the location of the back of the queue and the length of the queue faster than an infrastructure-based system.

This demonstration and this project clearly confirmed that connected vehicle technology can deliver dynamic mobility benefits for transportation system operators and the traveling public.

Chapter 1 Introduction

Through the Dynamic Mobility Applications (DMA) Program, U.S. DOT desires to improve current operational practices and transform management of future surface transportation systems. The DMA program is designed to enhance deployment of the technologies and applications and promote collaboration in research and development (R&D) of the transformative mobility applications. The DMA program's current phase involves application prototype development and testing and coordinated research activities on a portfolio of selected high-priority mobility applications.

The Intelligent Network Flow Optimization (INFLO) bundle is one of these, a collection of high-priority, transformative applications that target maximizing roadway throughput, reducing crashes, and reducing fuel consumption through the use of frequently collected and rapidly disseminated multi-source data drawn from wirelessly connected vehicles, travelers' communication devices, and infrastructure.

The U.S. DOT funded a Team led by Battelle and the Texas A&M Transportation Institute (TTI) (the Project Team) to prototype and demonstrate Dynamic Speed Harmonization (SPD-HARM) with Queue Warning (Q-WARN), two component applications of the INFLO bundle. In this program the U.S. DOT and the Team advanced SPD-HARM and Q-WARN from concept formulation to prototype development, acceptance testing and demonstration in a controlled environment. The team then deployed the applications in Seattle, WA to conduct a Small-Scale Demonstration to confirm its functionality and performance in an operational traffic environment.

Document Identification

This Technical Report on Prototype Intelligent Network Flow Optimization (INFLO) Dynamic Speed Harmonization and Queue Warning is the final report for the project. It describes the prototyping, acceptance testing and small-scale demonstration of the INFLO Prototype SPD-HARM and Q-WARN applications. This report also describes the programmatic and technical accomplishments of the program wherein the Small-Scale Demonstration fully confirmed the functionality of the INFLO Prototype System in an operational highway traffic environment. The system was proven to reliably

- Capture current location and telematics data from connected vehicles and vehicle speed data from infrastructure
- Analyze the data to detect congestion and determine the beginning and end of congestion queues
- Formulate speed harmonization recommendations
- Communicate queue location and speed harmonization recommendations to drivers via in-vehicle systems.

The demonstration proved connected vehicle data capture and dissemination functionality using both cellular communications and dedicated short-range communications (DSRC). Furthermore, the Small-Scale Demonstration confirmed that the INFLO Prototype System has the latency and processing speed to support INFLO application functionality in an operational traffic environment.

Document Organization

This remainder of the report is organized into the following chapters:

- Chapter 2. Reference Documents
- Chapter 3. INFLO Prototype System Design and Development Overview
- Chapter 4. INFLO Prototype Component, System and Application Acceptance Testing
- Chapter 5. INFLO Prototype Seattle Small-Scale Demonstration
- Chapter 6. Summary of Accomplishments and Considerations for Future Work
- Appendix A. Acronyms and Abbreviations.

Chapter 2 Reference Documents

Table 2-1 identifies the INFLO Prototype Project Documents referred to herein.

Table 2-1. INFLO Prototype Project Documents.

Number	Document Title
FHWA-JPO-13-012	Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO)
FHWA-JPO-13-013	Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO); Functional and Performance Requirements, and High-Level Data and Communication Needs
FHWA-JPO-13-171	Report on Detailed Requirements for the INFLO Prototype
FHWA-JPO-13-170	Report on Architecture Description for the INFLO Prototype
FHWA-JPO-13-168	Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design
FHWA-JPO-13-169	System Design Document for the INFLO Prototype
FHWA-JPO-13-208	Intelligent Network Flow Optimization (INFLO) Prototype Acceptance Test Plan
FHWA-JPO-13-209	Intelligent Network Flow Optimization (INFLO) Prototype Acceptance Test Summary
FHWA-JPO-15-200	Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Plan
FHWA-JPO-15-223	Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Report

Source: Battelle

Chapter 3 INFLO Prototype System Design and Development Overview

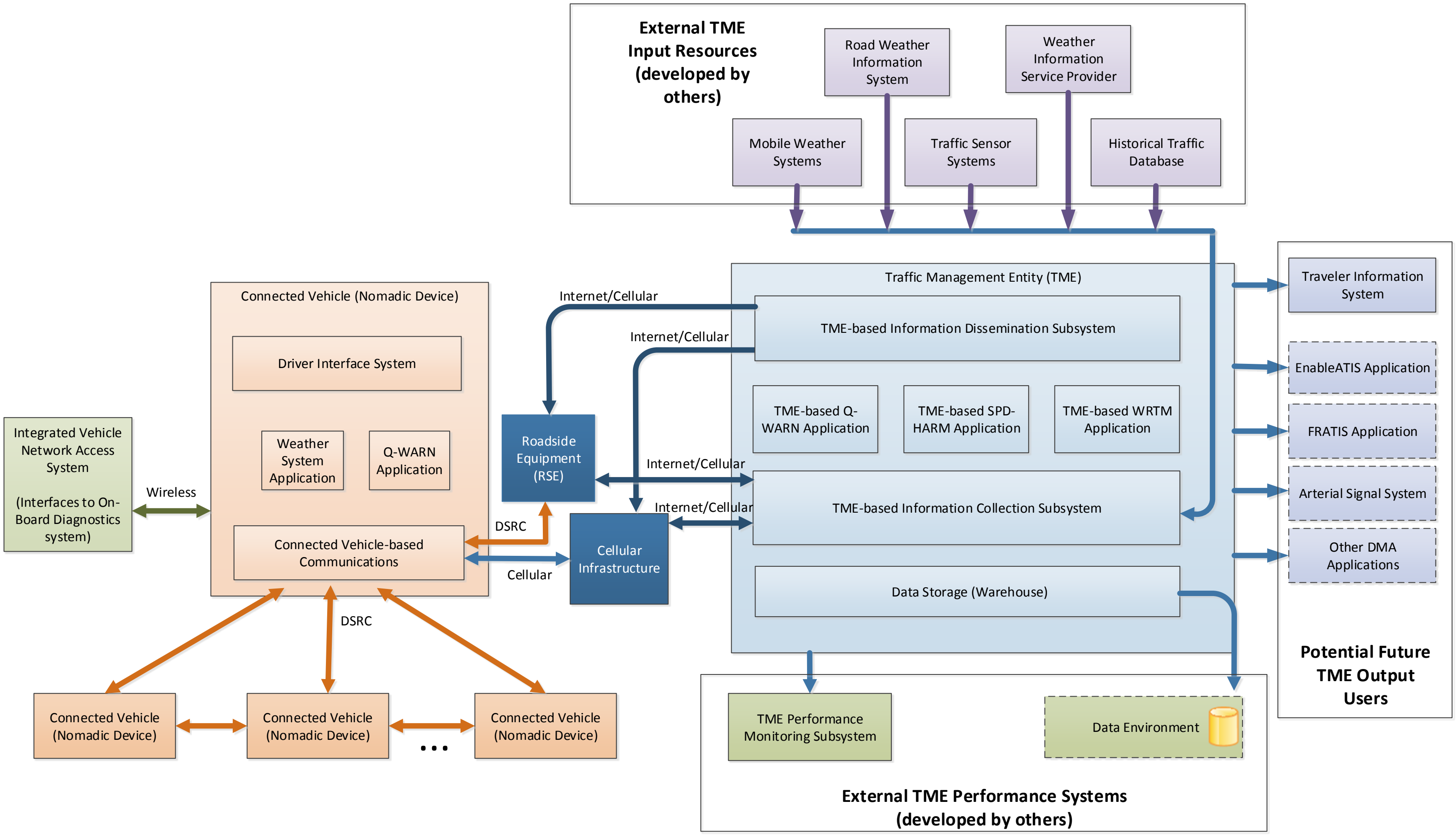
Overview of the INFLO Prototype System

The INFLO Prototype System consists of Q-WARN and SPD-HARM applications, in-vehicle components, roadside units, DSRC and cellular communications, databases, a virtual traffic management entity (TME) and others. Its components are described in detail in the *INFLO Prototype System Design Document* and the *Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design*. This chapter provides an overview of the system.

The system consists of multiple components which exchange data through messages using DSRC or cellular communication. Figure 3-1 shows a comprehensive INFLO Prototype System-level diagram which identifies the components, the communication methods and messages that flow between the components. This figure represents a comprehensive system and current and future capabilities that are described in detail in the *INFLO Architecture Description* Document. Figure 3-2 then provides a simplified view of the INFLO Prototype System as it has been implemented for the purposes of this project, including the Small-Scale Demonstration. This system has the functionality and capabilities necessary to support the demonstration and future potential pilot deployments. Figure 3-3 shows the same figure, with the addition of the messages that were exchanged between components necessary to support the multiple INFLO scenarios and applications.

The remainder of this chapter provides background and overview of the system components organized under the following headings:

- INFLO Prototype System Components
- DSRC Messages
- INFLO Applications
- Test Visualization Tools.



Source: Battelle

Figure 3-1. INFLO Prototype System Diagram from INFLO Design Report.

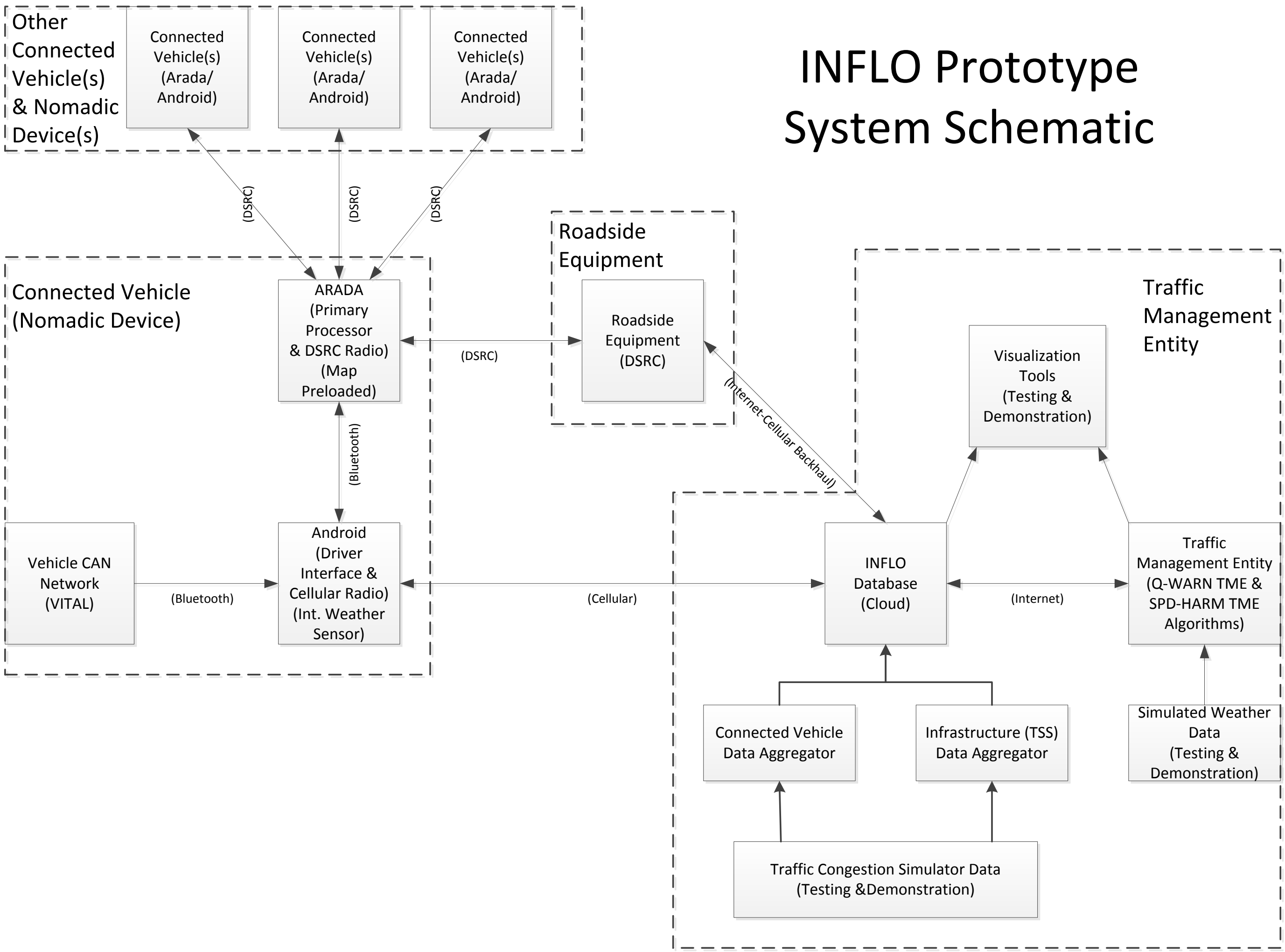


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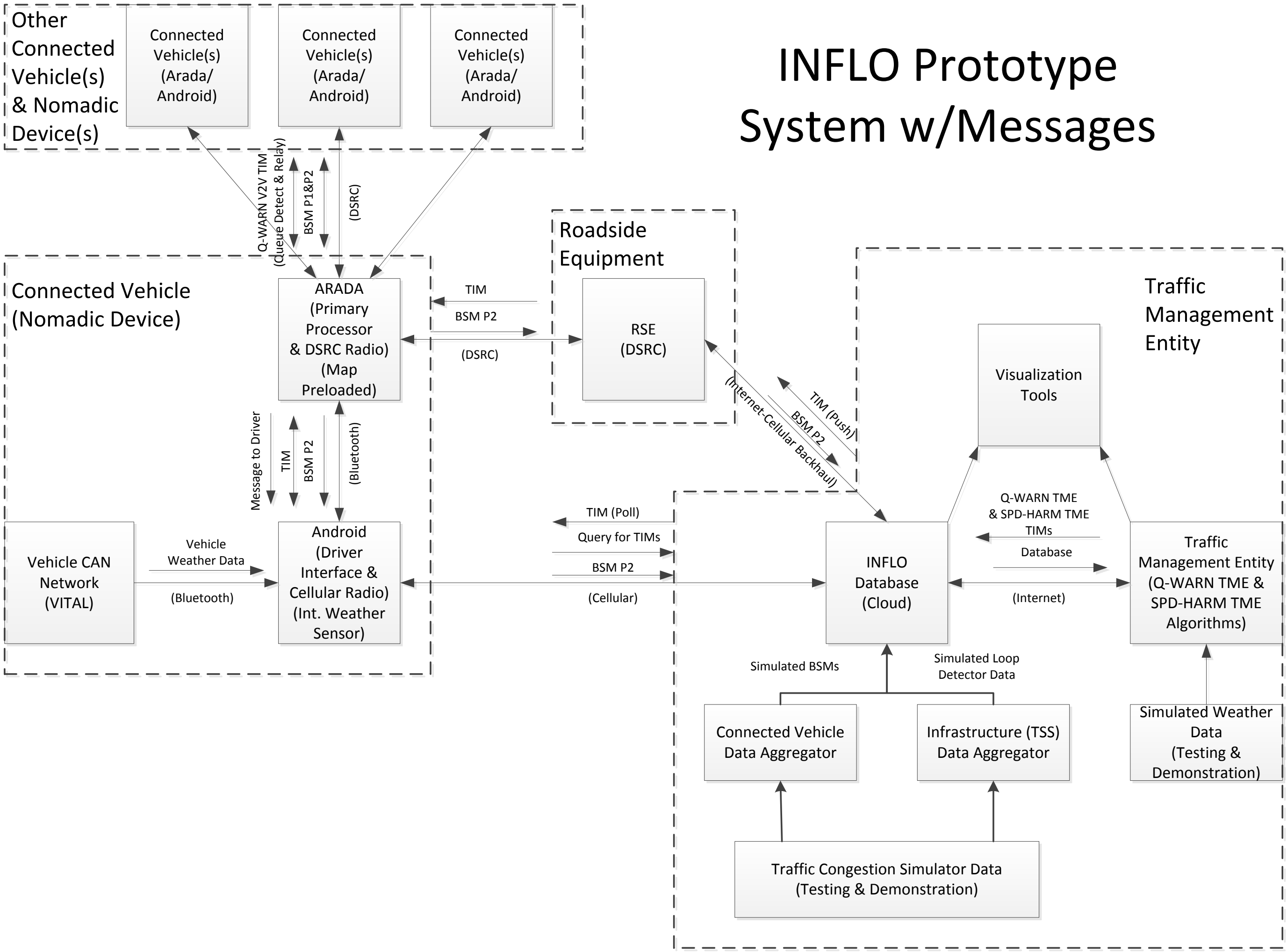
Figure 3-2. Schematic of the Implemented INFLO Prototype System.



Source: Battelle

Figure 3-3. Schematic of the Implemented INFLO Prototype System Showing Messages Transmitted between Components.

INFLO Prototype System Components

The primary functional components of the implemented INFLO Prototype System, shown in Figure 3-2 and Figure 3-3, are the following:

- Connected Vehicle In-Vehicle System consisting of
  - In-Vehicle User Interface Module (Android User Interface and Cellular Radio),
  - In-Vehicle DSRC Radio Module (Processor and DSRC Radio),
  - In Vehicle Network Access System (Vehicle Controller Area Network (CAN) Network)
- Roadside Units (RSUs)
- Cloud Computing Platform
- Virtual TME consisting of
  - INFLO Database
  - TSS Data Aggregator
  - Connected Vehicle Data Aggregator
- DSRC Messages
- INFLO Applications.

The following additional components were used for acceptance testing demonstration

- Test Visualization Tools
  - INFLO Database Map Viewer
  - TME Algorithm Queue Visualization Tool
- Traffic Congestion and Weather Simulation Data.

Following is an overview of each of these components.

In-vehicle User Interface Module

The In-Vehicle User Interface Module is a mobile device (smartphone) running the Android operating system. The features of this component include

- Provides an interface to the cellular network (i.e., the TME via the Internet)
- Manages the connection back to the Microsoft Azure™ Web Service hosting the TME
- Provides ambient weather sensor data (from mobile device sensors).

The mobile device display provides a graphical user interface which communicates the following to the driver:

- INFLO Prototype System operational status
- In-Vehicle System operational status
- SPD-HARM messages (e.g. recommended speed)
- Q-WARN messages (e.g. distance to back of queue, length of queue).

The mobile device interfaces with the DSRC radio module in the In-Vehicle System via Bluetooth® connections to send ambient weather data to the DSRC radio module and to receive TME-bound messages.

User Interface Message Examples

Figure 3-4 through Figure 3-13 provide example screen captures of the User Interface Messages on the In-Vehicle System User Interface Module for the INFLO Applications. These interfaces were implemented to be as simple and clear as possible with the goal of displaying:[1]

- SPD-HARM Recommended Speed
- Q-WARN Queue Ahead message with distance to the back of queue
- Q-WARN In-Queue message with distance and estimated time to the end of queue
- Vehicle weather and other data (on the Diagnostics Screen).

Note the following messages and indicators in the User Interface.

- Blank INFLO User Interface screen in Figure 3-4 indicating no queue detected ahead
- V2V Queued[2] red bullet in Figure 3-5 wherein V2V communications have determined that the vehicle is in a queued state.
- V2V Queue Ahead message in Figure 3-6 wherein V2V communications have determined that a queue is ahead with the distance to the back of queue (BOQ).
- TME Queue Ahead message in Figure 3-7 wherein TME algorithms have determined that a queue is ahead with the distance to the back of queue (BOQ).[3]
- TME In-Queue message in Figure 3-8 wherein TME algorithms have determined that the vehicle is in a queue and the distance and travel time to the front or end of the queue.
- TME Speed Harmonization message in Figure 3-9 wherein the TME algorithms have recommended a reduction in speed.
- TME Multiple messages in Figure 3-10 wherein both Speed Harmonization and Queue Ahead messages were issued and displayed simultaneously.
- Diagnostic and Test Verification messages shown in Figure 3-11, Figure 3-12, and Figure 3-13.

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[1] Note that Human factors or industrial design is outside the scope of this prototype

[2] V2V – vehicle-to-vehicle

[3] The distinction between Figure 3-6 (distance to the back of the queue determined using V2V communications) and Figure 3-7 (distance determined using TME algorithms) is primarily for testing.

Source: Battelle

Figure 3-4. User Interface Display.

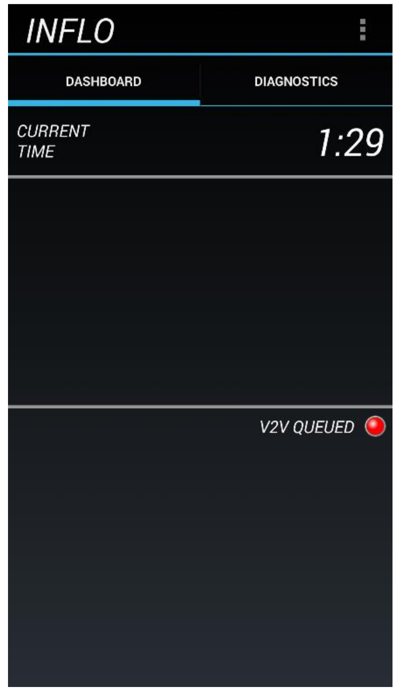

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Figure 3-5. Queue Detected V2V.

Source: Battelle

Figure 3-6. Queue Ahead (V2V).

Source: Battelle

Figure 3-7. Queue Ahead (TME).

Source: Battelle

Figure 3-8. In Queue (TME).

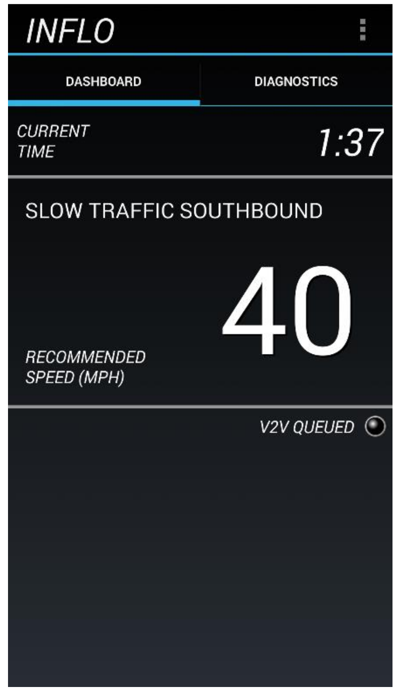

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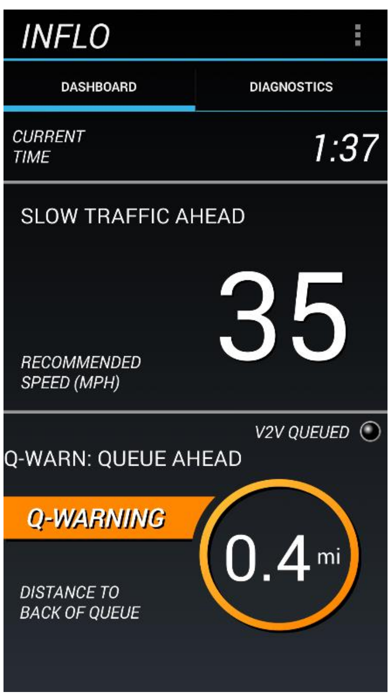
Figure 3-9. SPD-HARM (TME).

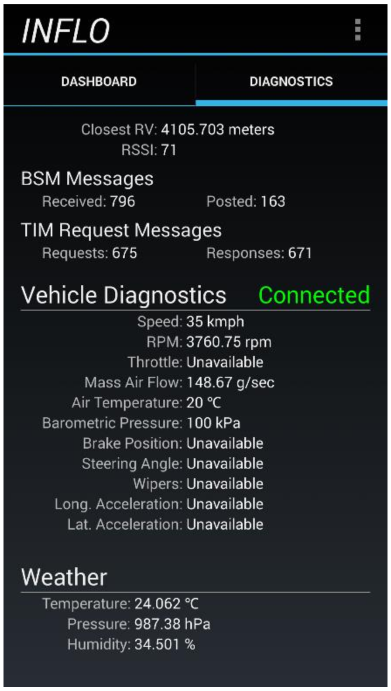


Source: Battelle

Figure 3-10. TME Multiple Warnings.

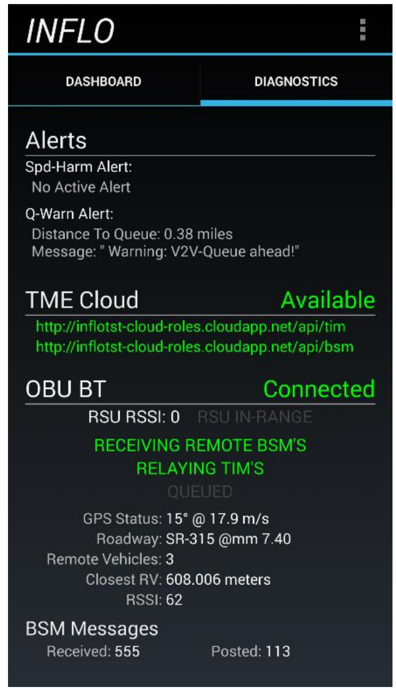
Source: Battelle

Figure 3-11. Not Connected.



Source: Battelle

Figure 3-12. Vehicle Data.



Source: Battelle

Figure 3-13. Diagnostic Display.

In-vehicle DSRC Radio Module

The DSRC Radio Module is a small portable unit that is the main computational processor for the In-Vehicle System. The unit interfaces to the User Interface Module via Bluetooth. The unit receives messaging from the (internal) DSRC radio and the cellular network (via the Bluetooth paired mobile device). It processes all messages and supplies any needed information for driver alerts and warnings. The DSRC Module is the primary processing unit for in-vehicle algorithms for the prototype.

The DSRC radio transmits Basic Safety Messages (BSMs), both Part 1 and Part 2, to other DSRC radios that are in communications range. The DSRC radio also hosts the connected vehicle-based Q-WARN Application which is the core in-vehicle application that processes real-time data and either makes individual queue warning determinations or responds to the queue warning messaging from the TME.

The BSM Part 2 (which also includes Part 1 data elements) is populated by data from the vehicle, data from the onboard GPS and data collected by weather sensors. The BSM Part 1 is transmitted at 10 Hz and Part 2 is transmitted at 1 Hz. The In-Vehicle System also transmits Q-WARN indicators calculated in the onboard Q-WARN Application (such as “this Vehicle Queued”) as part of the BSM Part 2.

The In-Vehicle System DSRC Radio Module receives messages from other vehicles and from the infrastructure. The In-Vehicle System will receive and process any BSMs from surrounding vehicles and supply the data to the onboard Q-WARN application. The In-Vehicle System also receives and processes, at a minimum, the Traveler Information Message (TIM) whether it is from a local DSRC radio or the cellular connection. TIM messages received by DSRC are rebroadcast by DSRC for reception by other In-Vehicle Systems within radio range and “relay” of vehicle queue information.

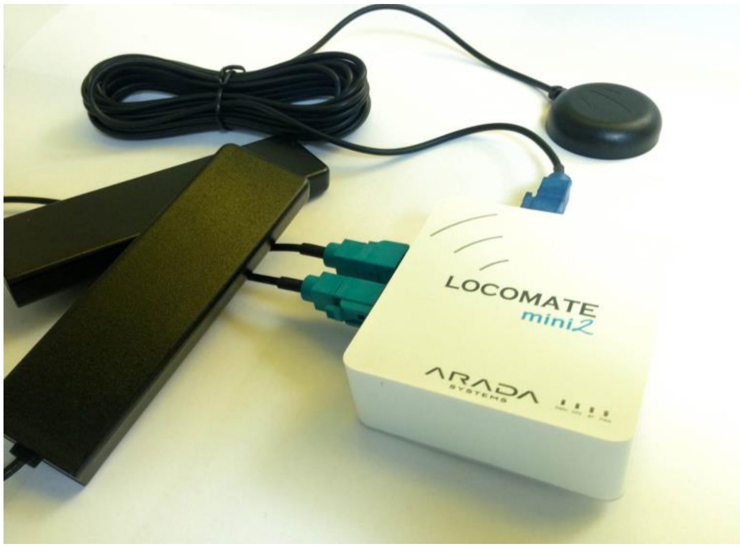
Along with TIMs, the In-Vehicle System DSRC Radio Module receives MAP messages for use in determining vehicle location on the roadway and applicability of Q-WARN and SPD-HARM messages. For Prototype demonstration purposes, maps of demonstration routes were preloaded on the In-Vehicle System.

For Acceptance Testing, the Project Team used the battery powered LocoMate™ ME on-board unit (OBU) with integral GPS and DSRC antenna, also known as the “Backpack”, shown in Figure 3-14. The backpack form factor is used with the Samsung Galaxy® S4 smartphone as an integrated “nomadic device”.[4] For the Small-Scale Demonstration, the Team used Arada System’s LocoMate Mini 2 OBU, which allowed the use of external GPS and DSRC antennas, as shown in Figure 3-15. Both units use the same radios, circuitry, and software, but are enclosed in a different external case.

Source: Arada/Battelle

Figure 3-14. Arada Locomate ME Battery Powered DSRC Communication Hardware, also known as the “Backpack.”

[4] For this investigation a nomadic device is a prototype dual-radio (cellular and DSRC) device that can be carried by a single person throughout a complete door-to-door trip, including pedestrian, transit and private vehicle modes. It includes the ability to collect weather data.



Source: Arada/Battelle

Figure 3-15. Arada Locomate “Mini2” DSRC Radio with External GPS and DSRC Antenna.

Source: Battelle.

Figure 3-16. VITAL™ OBD-II Module.

In-vehicle Network Access System

The In-vehicle Network Access System (IVNAS) is used to obtain data from the vehicle CAN bus through the OBD-II interface. This module allows the DSRC radio to receive vehicle telematics data to populate the Basic Safety Message Part 2. The In-Vehicle System uses the VITAL™ module, a proprietary Battelle module that plugs into the OBD-II port, to obtain a vehicle’s telematics data and forward it using Bluetooth to a connected device (see Figure 3-16). The availability of specific data elements is dependent upon the vehicle.

Roadside Units

The RSU used in testing and demonstration is the Arada LocoMate™ RSU, shown in Figure 3-17, which handles all DSRC communications from the TME to In-Vehicle Systems and DSRC communications from the vehicles to the TME. The RSU forwards any warnings from the TME to all devices within its range. The RSU also collects BSM Part 2 messages and forwards these messages to the TME for use by the infrastructure-based algorithms.

Cloud Computing Platform

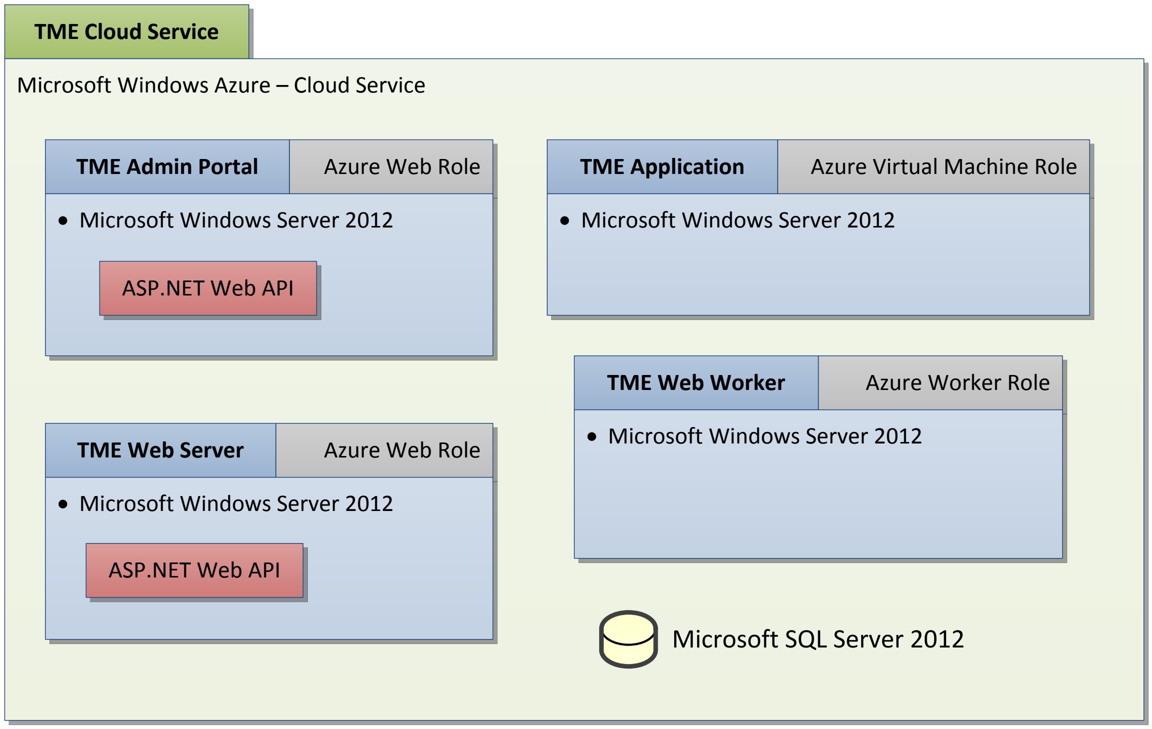
The computational platform used for the INFLO Prototype System is a Microsoft Azure Cloud Service that includes the following components:

- INFLO Database (SQL Azure)
- Web Role (TME Web Server)
- Web Role (Admin Portal)
- Worker Role (Database Worker).

The computing platforms for each virtual machine (VM) in the Azure Cloud Service are summarized in Figure 3-18. Cloud services provide a user interface to monitor the state of the underlying vehicle-data database, the web services used to facilitate the exchange of data from/to vehicles, to monitor the state of the connected vehicle network, and to allow configuration of parameters associated with this prototype. This interface is intended for use by the development team.

Source: Arada Systems

Figure 3-17. Road Side Equipment Arada LocoMate™ RSU.



Source: Battelle

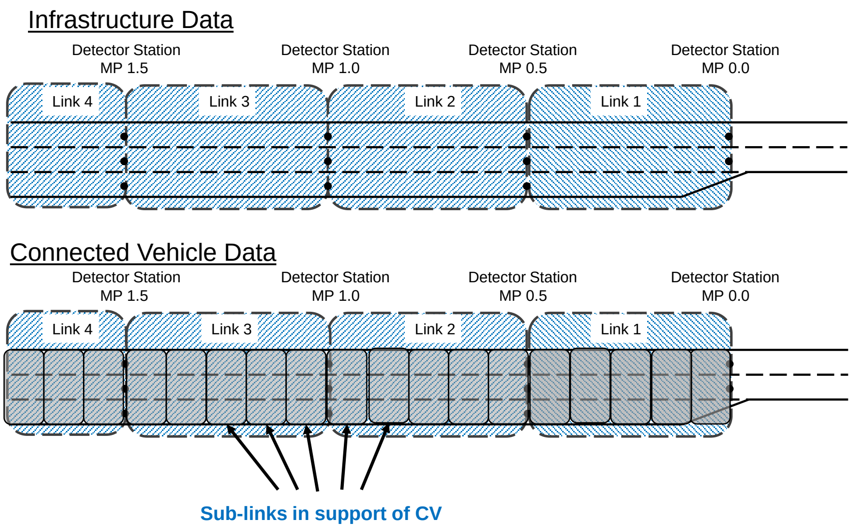
Figure 3-18. Cloud Service Computing Platforms.

Virtual Traffic Management Entity

The virtual TME consists of the hardware and software components required to implement the TME-based INFLO bundle of prototype applications. The TME is built using a modular approach including key components of Data Collector/Aggregators, INFLO Database, TME Link Speed Process, TME Queue Warning Process, TME WRTM Process, TME Link Speed Harmonization Process and TME Message Generator. The data aggregators were responsible for obtaining, processing, formatting, and distributing the data used by the various processes in the INFLO algorithm. The INFLO Database system is a critical component of the virtual TME environment that provides the flexibility needed in designing the algorithms. The INFLO Database is 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 that are made by each algorithm and sent to drivers and infrastructure-based signs are also stored in the database. The TME Link Speed Process is responsible for performing the speed harmonization analysis for the system. The TME Queue Warning Process is responsible for processing the traffic sensor data delivered by the Data Collector/Aggregator and determining which freeway segments were operating in a queue state. The TME WRTM Process is responsible for generating safe speeds for measured weather conditions. The TME Link Speed Harmonization Process receives the results of the various INFLO algorithms and selects the critical message to be sent out to the road users. The TME Message Generator is responsible for determining the appropriate speed messages to be displayed for each section of the freeway.

Link and Sublink Definitions

Roadways are divided into a series of links and sublinks, as illustrated in Figure 3-19, for efficient data aggregation and processing. A link is defined as a segment of roadway between two consecutive infrastructure based detector stations. Sublinks are defined to be a segment of roadway approximately 0.1 mile in the length. The number of sublinks in a link is a user-defined variable such that the length of each sublink should equal approximately 0.1 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.



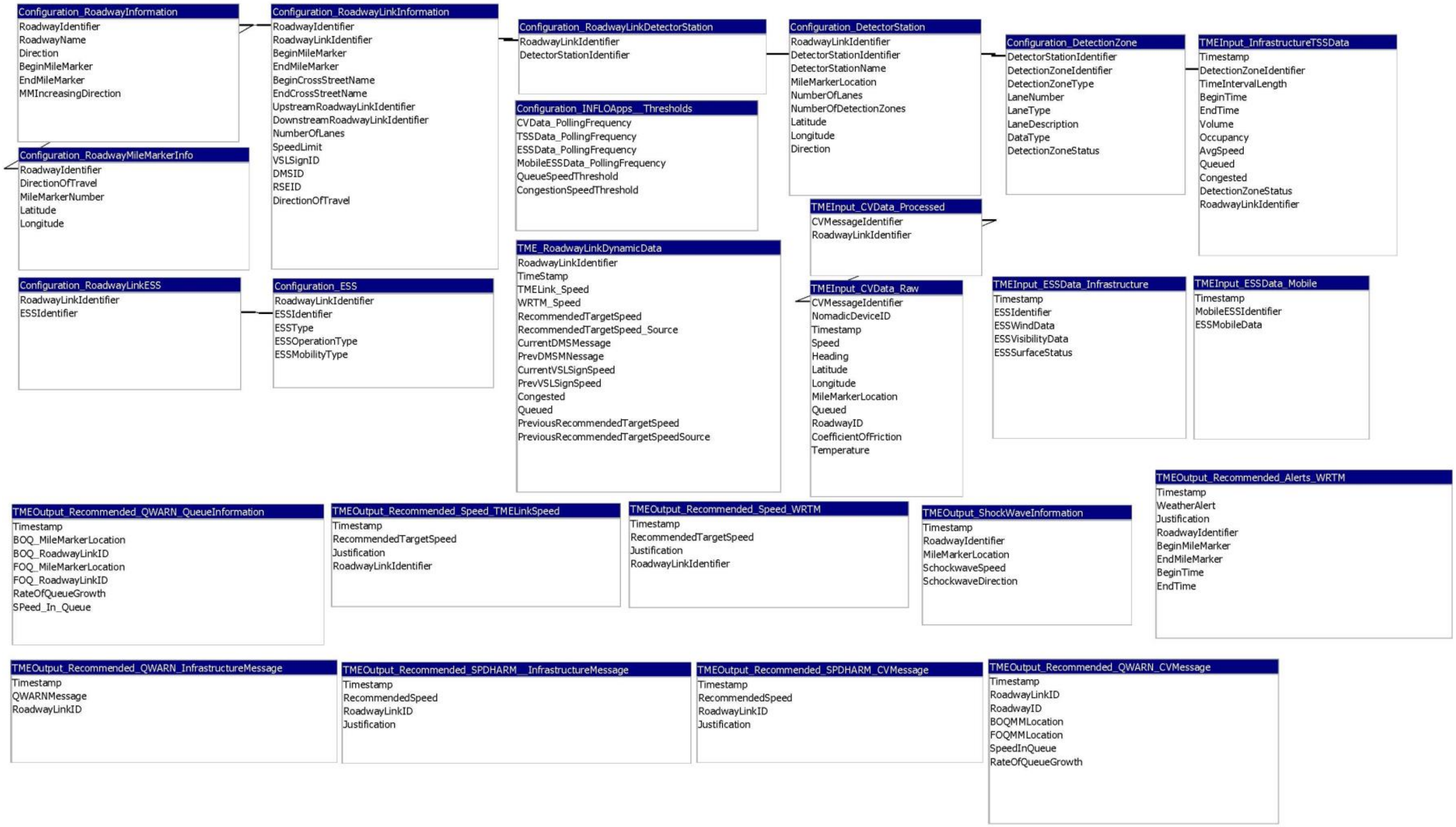
Source: TTI

Figure 3-19. Illustration of Segmenting Roadways into Links and Sublinks.

INFLO Database

The INFLO Database 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 WRTM algorithm. Each of these data sources is acquired or generated at a different frequency. 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 longer intervals. All of this data is stored in the INFLO Database in real time. Each of the algorithms query the database for the data it needs and then generates and posts the appropriate messages for each roadway link back to the database.

Figure 3-20 documents the data dictionary for the INFLO Database. It holds incoming data from the In-Vehicle Systems (BSM data), and incoming messages from the TME such as TIM-based Q-WARN and SPD-HARM messages.



Source: TTI

Figure 3-20. INFLO Database Tables.

Traffic Sensor System Data Aggregator

For the INFLO Prototype System, the TSS Data Aggregator collects the data from roadway sensors, aggregates the data according to user defined procedures and thresholds, and populates the INFLO Database. For the prototype, initially only speed data is used to determine operating states for the link and the lanes within the link.

Connected Vehicle Data Aggregator

For the INFLO Prototype System the Connected Vehicle Data Aggregator collects the data from all the connected vehicles traveling in the deployment corridor and converts it into link-based information. The Connected Vehicle Data Aggregator is responsible for processing the data from each connected vehicle and determining the average speed, congested state, and queued state of the sublink. The milepost reference in the connected vehicle data is used to determine the sublink in which the vehicle is located. Once the sublink location for each connected vehicle has been determined, the Connected Vehicle Data Aggregator computes the average speed for each sublink for all the connected vehicles located in each sublink. Using the average sublink speed, the Connected Vehicle Data Aggregator determines 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.

DSRC Messages

Two primary SAE J2735:2009 DSRC messages are transmitted and used to communicate data between components in the system, the Basic Safety Message (BSM) Part 2[5] and the Traveler Information Message (TIM).

For purposes of INFLO demonstration, the BSM Part 2 was used to communicate vehicle location, velocity (speed), heading, and external air temperature. When it is available from the vehicle telematics system Part 2 may also be used to communicate barometric pressure, lateral acceleration, longitudinal acceleration, yaw rate, rate of change of steering wheel, brake status, brake, boost status, impact sensor status, anti-lock braking status, wiper status, headlight status, traction control status, stability control status, and differential wheel speed. As shown in Figure 3-3, the BSM Part 2 message is primarily communicated from the In-Vehicle System to the INFLO Database to capture an individual vehicle's speed and congestion related data. The BSM Part 2 is transmitted by either DSRC through the RSU or by cellular communications when an RSU is not in communications range. This message is sent once per second.

The TIM message is primarily used to communicate TME-based Queue Warning and Speed Harmonization messages from the INFLO Database to the In-Vehicle System for processing and, if appropriate, display to the driver. The TIM message may also be transmitted by either DSRC through the RSU or by cellular communications when an RSU is not in range.

[5] When broadcast, the BSM Part 2 includes both Part 1 and Part 2 data elements.

INFLO Applications

Four applications, described in more detail in the Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design,[6] were implemented to demonstrate the functionality and performance of the INFLO Prototype System. These were

- TME-Based Queue Warning (Q-WARN)
- TME-Based Speed Harmonization (SPD-HARM) with Weather Responsive Traffic Management (WRTM)
- Cloud-Based Queue Warning
- V2V Queue Warning.

Following is a brief description of each of these applications.

TME-Based Q-Warning Application

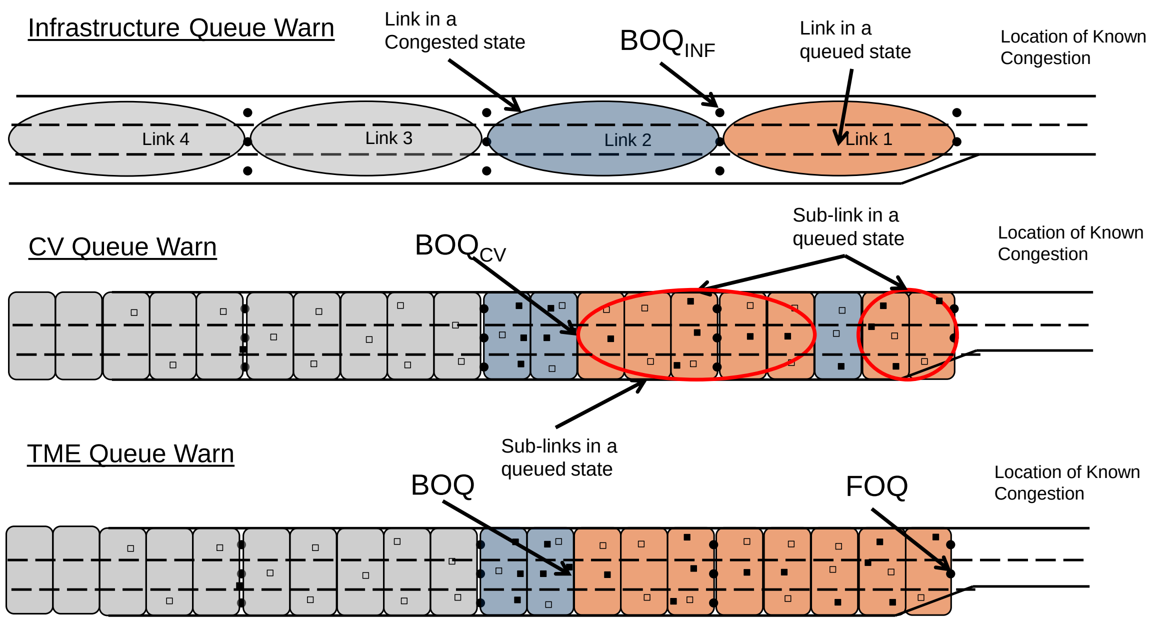
The purpose of the TME-based queue warning algorithm is to fuse the vehicle speed data from the infrastructure and the connected vehicles and generate queue warning messages that can be disseminated through both infrastructure signs[7] and connected vehicles. In this application, the decision-making processes reside primarily within the TME. The connected vehicles were not required to process any data other than determining their queue state and generating queue warning displays for the driver from the data provided by the TME.

The TME-based queue warning algorithm determines the back of queue (BOQ) from a fusion of infrastructure data and connected vehicle data. Figure 3-21 illustrates the process of determining the BOQ. It is assumed that the front of queue (FOQ) is at a bottleneck location which is routinely congested 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_{INF} 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 is also 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 connected vehicles in the sublink are in a queued state. The BOQ based on the connected vehicle data (BOQ_{CV}) is defined as the farthest upstream sublink operating in a queued state. The final BOQ is then determined by comparing the BOQ_{INF} from the infrastructure data and BOQ_{CV} from connected vehicle data and selecting the BOQ that is furthest upstream from the BOQ location.

[6] Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design – 100030614-251A (FINAL), March 28, 2014.

[7] While the Prototype system is architected to display Q-WARN and SPD-HARM messages through infrastructure signage as well as in-vehicle displays, the infrastructure display was not implemented in this demonstration.



Source: TTI

Figure 3-21. 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 connected vehicle 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.

TME-Based Speed Harmonization Application

The objective of speed harmonization is to minimize the turbulence in the traffic stream approaching a section of the roadway experiencing low speeds. Speed harmonization of traffic flows in response to downstream congestion, incidents, and weather or road conditions can help to maximize traffic throughput and reduce crashes. The INFLO SPD-HARM application concept aims to realize these benefits by utilizing connected vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication to detect the precipitating roadway or congestion conditions that might necessitate speed harmonization, to generate the appropriate response plans and speed recommendation strategies for upstream traffic, and to broadcast such recommendations to the affected vehicles. The INFLO SPD-HARM algorithm was designed to identify, produce, and establish a recommended speed for segments of the corridor. The algorithm identifies 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.[8] For the purpose of the prototype development, speed harmonization was based only in the TME.

[8] The Uniform Motor Vehicle Law indicates that state and local agencies are responsible for establishing recommended speeds on public roadway facilities.

The speed harmonization algorithm developed in this project 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 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.

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 updated at the resolution at which connected vehicle data is being received (e.g. 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 on overhead 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.

Weather-Responsive Traffic Management

The purpose of Weather Responsive Traffic Management (WRTM) algorithm is to determine the recommended travel speed for each link based on the prevailing road weather conditions. In this prototype development, WRTM is implemented as a subset of Speed Harmonization Algorithm in which recommended harmonization speeds may be adjusted based upon road weather conditions.

For the purposes of the prototype development, recommended travel speed is 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. This 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.

Cloud-Based Queue Warning Application

The cloud based queue warning algorithm is a subset of the TME-based Queue Warning Algorithm which is implemented 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 speed data is used. Similarly, any queue warning messages issued are only displayed inside a connected vehicle.

Vehicles in a cloud based queue warning system get the mile marker linear information (i.e., map information) from the cloud using cellular communication. 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 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 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 is 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. This information is then transmitted to the connected vehicles in the affected roadway segments via the cellular network.

V2V Queue Warning Application

The V2V Queue Warning Application determines independently if the subject vehicle is in a queued state, without input from infrastructure systems, and then uses DSRC to communicate the vehicle's queued state to nearby connected vehicles. 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. Each connected vehicle determines its milepost location and its queued state. The connected vehicle then transmits this information as part of BSM Part 2 to other vehicles. These messages enable nearby connected vehicles to determine if they are in a queued state and to locate the back of queue (BOQ).

Each connected vehicle receiving information from other connected vehicles identifies and locates all downstream connected vehicles. Based on the milepost location of the downstream connected vehicles, a non-queued vehicle identifies the BOQ, if present, from among the vehicles. The location of BOQ is then transmitted upstream by all non-queued vehicles. All upstream vehicles receiving the BOQ message will then display a Queue Ahead message to the driver and then retransmit the location of BOQ to vehicles further upstream. This relay process of receiving BOQ location and retransmitting it to upstream vehicles is continued for a user defined distance from the BOQ.

Test Visualization Tools

As shown in Figure 3-4 through Figure 3-10, INFLO messages to the driver are displayed directly on the In-Vehicle System and can be readily demonstrated and verified. However, the INFLO Database is a data repository in the Cloud that is not in readable form. Figure 3-1 identifies visualization tools that were used to demonstrate and verify the functionality of the INFLO database during Acceptance Testing described in Chapter 4. These tools include an INFLO Database Map Viewer and the TME Algorithm Queue Visualization Tool, each described below.

INFLO Database Map Viewer

To assist the Project Team and the U.S. DOT in observing the functionality of the INFLO Database, the Team assembled a Map Viewer in which key data from the database are overlaid on a map. Figure 3-22, Figure 3-23 and Figure 3-24 show three zoom levels of simulated congestion data from the Map Viewer. The figures show car icons for vehicle BSMs received and posted in the database. In this case the map viewer is showing the BSMs received from the traffic simulation. The Viewer uses red car icons for cars that meet the TME criteria for being queued and green icons for nonqueued vehicles. Hovering a mouse over any vehicle will display the contents of its BSM Part 1 and 2.

The traffic simulation data used for validation and demonstration is generic and not associated with a specific highway. For the purposes of these demonstrations the simulated traffic data was overlaid on a satellite image of Interstate 71 in Columbus OH, a frequently congested roadway.

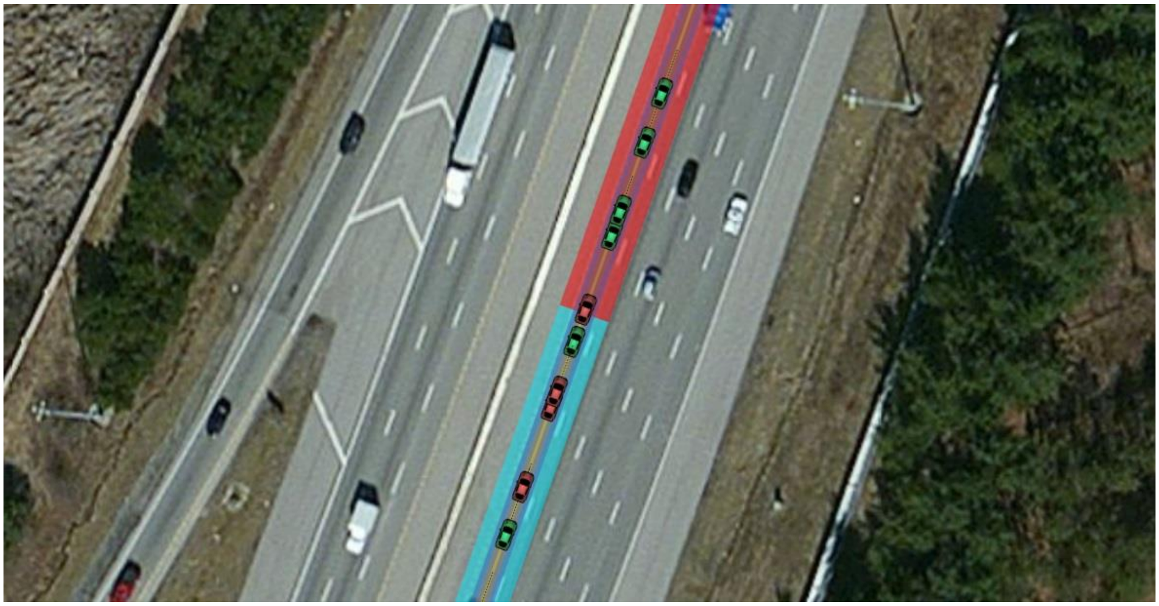
The Map Viewer displays TME-Based Queue region as a magenta highlight and TME-based Speed Harmonization segments as a Cyan (greenish-blue) highlight. This display is fully dynamic and was used during laboratory demonstrations of the TME algorithms to demonstrate the formation and deformation of queues and the formation and deformation of speed harmonization regions upstream. Viewer results were shown in parallel with Nomadic Device Queue Ahead message displays and with TME Algorithm Queue Visualization Tool.

Source: Battelle

Figure 3-22. INFLO Database Map Viewer Displaying Vehicle BSM Data with Queue Warning and Speed Harmonization Message Overlay on Satellite Image from Microsoft Bing®. Traffic is Flowing Northbound or Upwards in the Figure.

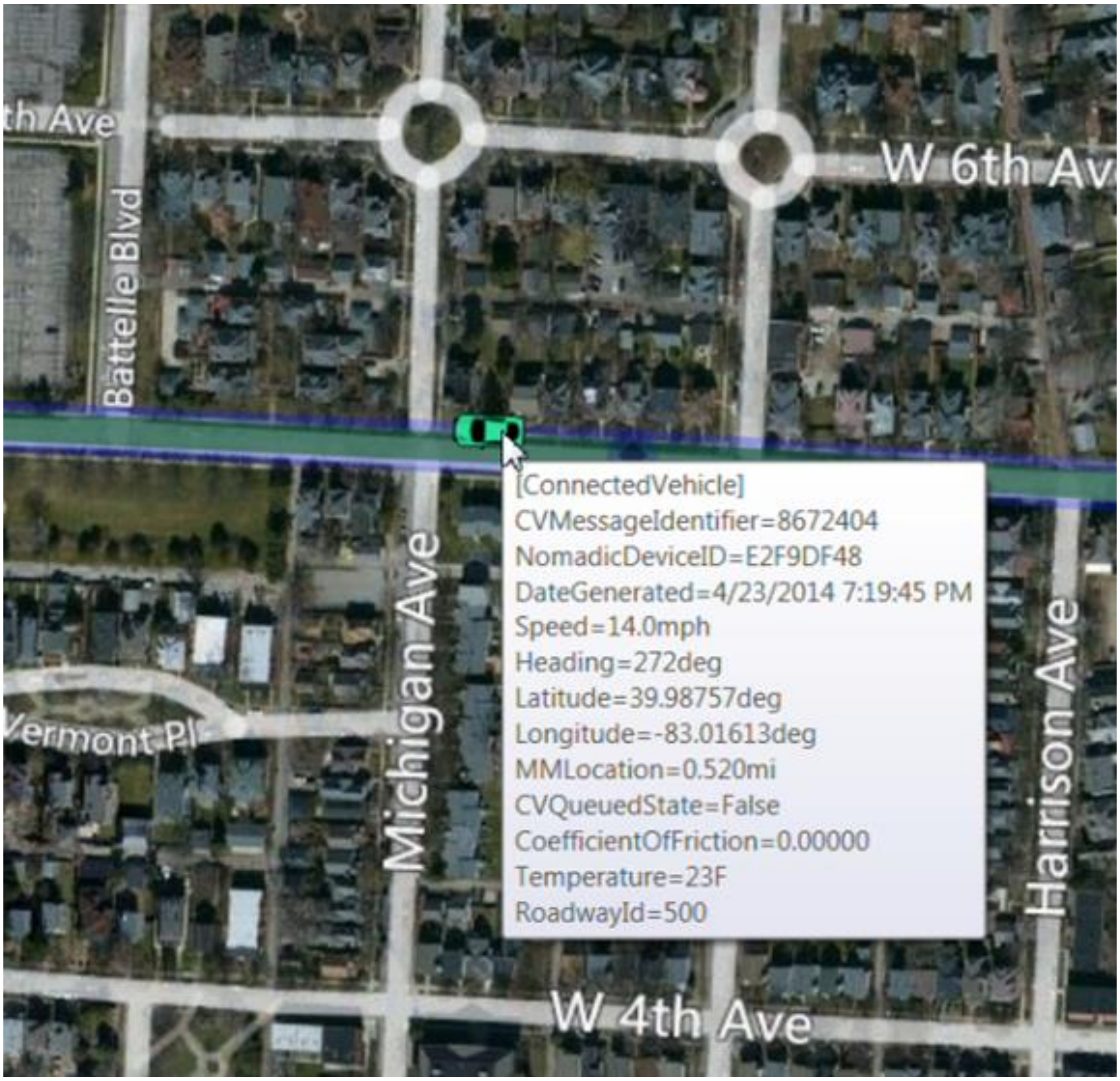
Source: Battelle

Figure 3-23. Medium Zoom View showing Queued Vehicles (Red) and Unqueued Vehicles (Green).



Source: Battelle

Figure 3-24. Close in Zoom Showing Database Vehicles (red and green) Overlaid on Satellite Image.



Source: Battelle

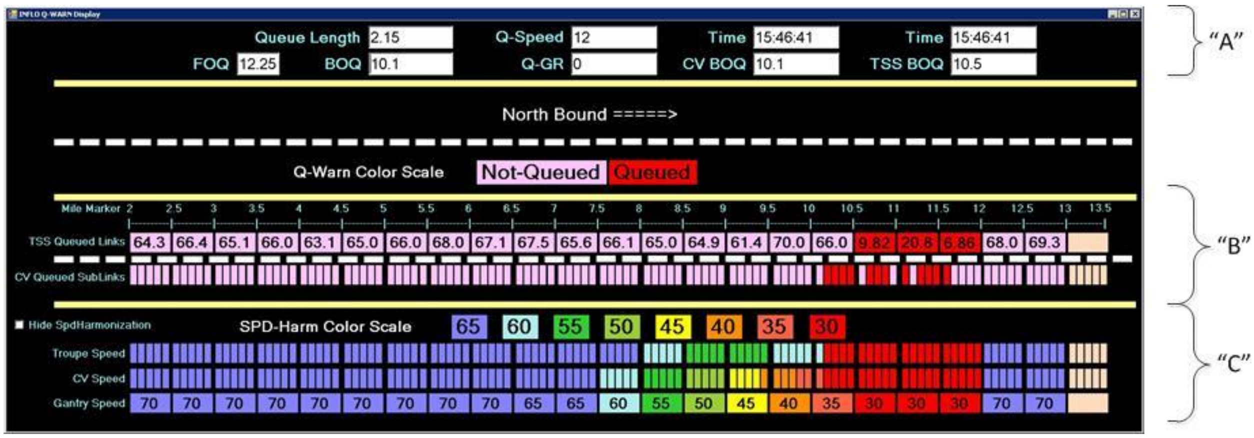
Figure 3-25. Display of BSM data for an Individual Vehicle in the Map Viewer (note Temperature = 23C).

TME Algorithm Queue Visualization Tool

To demonstrate the functionality of the algorithm, the Project Team developed the display shown in Figure 3-26. The display, which updates in real time, shows the output of the decision processes coded in the TME algorithms. The display is separated into the following three parts:

- The content of the algorithm output sent to the message generator (labeled as part "A" in the diagram)
- The results of the queue detection/queue warning portion of the algorithm (labeled as part "B" in the diagram)
- The results of the speed harmonization portion of the algorithm (labeled as part "C" in the diagram).

Each section is separately described below.



Source: TTI

Figure 3-26. TME Algorithm Display Tool showing Queue Parameters, Average Speed of Queued and Not-Queued Road Segments and Speed Harmonization Recommendations.

Algorithm Outputs. The top portion of the display (part "A") shows the output results produced by the algorithms. These outputs represent the information that is passed to the message generation process for broadcast either to the connected vehicle or to infrastructure displays (e.g., dynamic message signs). This output includes the following:

- The milepost location of the Front of the Queue (FOQ)
- The milepost location of the Back of the Queue (BOQ)
- The length of the queue (Queue Length) in miles
- The average speed of travel in the queue (Q-Speed) in mph
- The average rate of grow of the queue (in miles per second)
- The milepost location (CV BOQ) and the clock time (Time) of the Back of Queue determined using connected vehicle data only
- The milepost location (TSS BOQ) and clock time (Time) of the Back of Queue as determined using the traffic sensor system data only.

Queue Warning Results. Part "B" of the display shows the results of the queue detection/queue warning process. The top row of boxes (labeled TSS Queued Links) shows the outcome of the queue detection process for each link using the TSS data, while the bottom row of boxes (labeled CV Queue Links) shows the outcome of the queue detection process for each sublink using the connected vehicle data. Links (and sublinks) that were determined to be in a queued state are shown in red while those links and sublinks that were determined to be in an un-queued state are shown in lavender. Also shown on each link is the average speed as measured by the TSS detection systems. Links were determined to be in a queued state if the average link speed is less than 30 mph. Sublinks were determined to be in a queued state if 50 percent of the connected vehicles in those sublinks were reporting that they were in a queued state.

Speed Harmonization Results. Part "C" of the display shows the results of the speed harmonization process. Three speeds are displayed. The first speed is the Troupe Speed. This speed represents the unified speeds for each sublink after fusing link TSS speed and sublink connected vehicle data speed (calculated by averaging the speeds of all the connected vehicles in a sublink). Below the Troupe Speed is the CV Speed. The CV Speed is the recommended speed that is broadcast to the connected vehicle, while the Gantry speed represents the recommended speeds displayed on infrastructure based VSL signs.

Traffic Congestion and Weather Simulation Data

To develop, test and verify the INFLO applications for Acceptance Testing, a data set of simulated traffic sensor and connected vehicle data was developed. This data set captures the key features of traffic congestion and provides input to the applications to verify their functionality and performance during Acceptance Testing. The data set was developed using the VISSIM microscopic simulation mode. Each VISSIM run produced the following three output files:

- Connected vehicle data assuming all vehicles are “connected” (100 percent market penetration) and perfect data.
- 20-second lane-by-lane speeds, volumes, and occupancies obtained from data collection points located at half-mile separation.
- VISSIM-generated queuing statistics for validation purposes.

For the purposes of generating the data used for the testing, a seventeen mile section of two-lane freeway was coded into VISSIM. The section of freeway was coded as a two-lane freeway with no entrance and exit ramps. A lane closure bottleneck was coded for the right lane at Milepoint 12.25. The capacity of the bottleneck was coded to be 1900 vehicles per hour. Traffic sensors were “installed” at half mile intervals, beginning at Milepoint 2.0 through Milepoint 13.0. The traffic sensor data were coded to collect the following information in 20-second intervals for each lane:

- Simulation timestamp
- The number of vehicles passing the identified lane detector in each lane during the 20-second interval (lane volume)
- The average speed of all vehicles passing through the detection zone during the 20-second interval (travel speeds)
- The average amount of time the detection zone was occupied by vehicle during the 20-second interval (lane occupancy).

These data were aggregated in an output file which was fed into the Traffic Sensor System (TSS) data aggregator using a post-process application. The TSS data aggregator aggregated the lane-based data to provide the simulation detector station input. The data aggregation process converts the lane-by-lane detector data to produce the following detector station information:

- Station speed – the average speed for all lanes weighted by the recorded volume in each lane
- Total station volume – the sum of all the volumes recorded in each lane detector associated with a detection station
- Station Occupancy – the average of all reported lane occupancies from each lane detector associated with a detection station.

Connected vehicle data were generated using a built-in feature of VISSIM. This feature generates (emulates) and saves, second-by-second, the following data for each vehicle in the simulation:

- Vehicle identification number
- Location (X-Y coordinate)
- Lane number
- Current speed in the network.

The VISSIM output file was then post-processed to produce a simulated BSM file for each individual vehicle. This program parsed through VISSIM output, added a queue-state data field, and separated the data into one-second data streams (files) to emulate connected vehicle data.

VISSIM cannot directly produce impacts of adverse weather conditions. If desired, such conditions can be emulated by implementing reduced speeds. For this project, it was sufficient to test whether data flows based on certain emulated conditions lead to decisions about speed harmonization coming from the right source. To achieve this goal, a third data stream was developed to emulate weather data based on the following conditions:

- Visibility: ≤ 500 ft and > 500 ft
- Coefficient of Friction: < 0.3; In the interval (0.3, 0.7); and ≥ 0.7.

Chapter 4 INFLO Prototype Component, System and Application Acceptance Testing

This chapter summarizes the Prototype System Acceptance Test for the INFLO application bundle, with a focus on the Q-WARN and SPD-HARM with WRTM applications. This chapter summarizes the component, system integration and prototype acceptance testing conducted to verify that the system meets its functional and performance requirements. The results of the acceptance tests summarized here were used by the U.S. DOT as the basis for deciding to proceed with the Small-Scale Demonstration of the Prototype described in Chapter 5.

Scope of the Acceptance Test

The principles of system engineering were applied in conducting INFLO Prototype System Acceptance Testing to verify that the developed prototype meets the system requirements defined in Chapter 6 of the *Report on Detailed Requirements for the INFLO Prototype (FHWA-JPO-13-TBD)*. Specifically, this test summary addresses testing for the following systems and sub-systems, as described in the *Report on Architecture Description for the INFLO Prototype (FHWA-JPO-13-TBD)*:

- In-Vehicle System including
  - User Interface Module (Android User Interface and Cellular Radio),
  - DSRC Radio Module (Processor and DSRC Radio),
  - Vehicle Network Access System (Vehicle Controller Area Network (CAN) Network)
- RSUs
- Virtual TME consisting of
  - INFLO Database
  - TSS Data Aggregator
  - Connected Vehicle Data Aggregator
  - TME-Based Q-WARN Application
  - TME-Based SPD HARM Application with Weather Responsive Traffic Management (WRTM).

The INFLO Prototype System was tested in three phases:

- Phase I – Component Acceptance Testing
- Phase IIa – Communications and Messaging System Integration Acceptance Testing
- Phase IIb – TME-Based Application System Integration Acceptance Testing
- Phase III – On-road Prototype System Acceptance Testing.

Phase I test cases and Phase II test cases were conducted within a laboratory environment using simulated or real data inputs. Phase III test cases were conducted using test vehicles in either a controlled (closed-course) environment or on streets and highways in Columbus, Ohio. Following is an overview of the test cases conducted and their results.

Phase I Component Level Acceptance Test Summary

Phase I of the INFLO Prototype Acceptance Testing consisted of testing and verifying the functionality and performance of each of the components making up the INFLO System in the laboratory. This required testing the operational capabilities, data detection, retrieval and transmission capabilities, data logging capabilities and communication capabilities of each of the components. The DSRC components used in the development of INFLO Prototype were used by the Project Team and others in the development and implementation of the systems deployed in Safety Pilot Model Deployment in 2012 and 2013, where their functionality and performance was well established. Consequently, Phase 1 individual component test was completed quickly and often in conjunction with Phase II – System Integration Acceptance Testing. Demonstration of the Phase I component functionality for the U.S. DOT was performed as an integral part of the Phase II and Phase III Acceptance Test Demonstrations.

Phase 1 Laboratory tests were conducted on the following components as part of the identified test cases (TCs):[10]

- TC 1-01 – Connected Vehicle Nomadic Device Functionality
- TC 1-02 – Connected Vehicle Nomadic Device User Interface System (IU) Functionality
- TC 1-03 – Connected Vehicle Q-WARN Application Functionality
- TC 1-05 – Connected Vehicle Communication (CVC) System Functionality
- TC 1-06 – Connected Vehicle Weather System Functionality
- TC 1-07 – Integrated Vehicle Network Access System (INVAS) Communication
- TC 1-08 – Traffic Management Entity (TME) Functionality
- TC 1-09 – TME Q-WARN application Functionality
- TC 1-10 – TME SPD-HARM Application Functionality
- TC 1-11 – TME WRTM Application Functionality
- TC 1-12 – TME-Based Information Dissemination Sub-system (IDS) Functionality
- TC 1-13 – TME-based Communication System (CS) Functionality
- TC 1-14 – Roadside Equipment (RSE) Functionality.

[10] Because the final implementation of SPD-HARM does not have a component resident on the vehicle, TC 1-04 – Connected Vehicle SPD-HARM Application Functionality was not performed.

Testing was conducted on each to verify, as appropriate:

- Operational Capabilities
- Component's ability to perform the function(s) required to support the integrated INFLO Prototype System delivery of messages to the driver where appropriate.
- Data Detection, Retrieval and Transmission Capabilities
- Component's ability to retrieve required input data from the vehicle, the infrastructure and other components
- Component's ability to obtain geographic location (road segment), vehicle location (direction of travel and heading), and vehicle speed characteristics when required
- Component's ability to transmit output data to the vehicle, the driver and other components as required
- Data Logging Capabilities
- Component's ability to log all alerts issued to driver and associated parameters
- Component's ability to log all outbound messages generated by vehicle-based applications
- Component's ability to log travel data (GPS position, timestamp, device and trip IDs)
- Communication Capabilities
- Device's ability to communicate with other components, when required, to transmit required data, information and messages, data.

Phase II System Integration Acceptance Testing

Phase II testing in this program was focused on laboratory integration of the system components and verifying functionality and performance of the system using simulated vehicle and traffic data. Phase IIa consisted of laboratory system communications and message acceptance tests which test, verify and demonstrate the functionality of interfaces, communications and transmission of messages between all mobile components and the INFLO Cloud Database. Phase IIb consisted of laboratory INFLO TME algorithm system acceptance tests which test, verify and demonstrate the functionality of interfaces, communications and transmission of messages between the INFLO Cloud Database and the TME, including application algorithms. Phase IIa and IIb together represent testing and verification of the complete end-to-end INFLO system communications and messaging.

Phase II testing was organized in three two test cases, summarized below:

- Phase IIa Q-WARN and SPD-HARM System Communications and Messaging Test Case
- Phase IIa V2V Q-WARN System Communications and Messaging Test Case
- Phase IIb Q-WARN and SPD-HARM Algorithm System Integration Test Case.

Additional details may be found in the report *Intelligent Network Flow Optimization (INFLO) Prototype Acceptance Test Summary*.

Phase IIa Q-WARN and SPD-HARM System Communications and Messaging Test Case

Test Case Summary

In this test case, the INFLO Cloud Database is prepopulated with TME-based Q-WARN and SPD-HARM messages for a predetermined route for north and southbound travel on Ohio State Highway 315. A nomadic device is fed GPS data simulating travel along the highway. TME-Based Q-WARN and SPD-HARM Messages are delivered to the nomadic device via DSRC through the RSU and via cellular communications when the RSU is turned off. Researchers verified that all Q-WARN and SPD-HARM messages are received and displayed to the driver at the proper locations when travel is simulated in the specified direction. They also confirmed that the messages are received, but not displayed to the driver when travel is in the opposite direction.

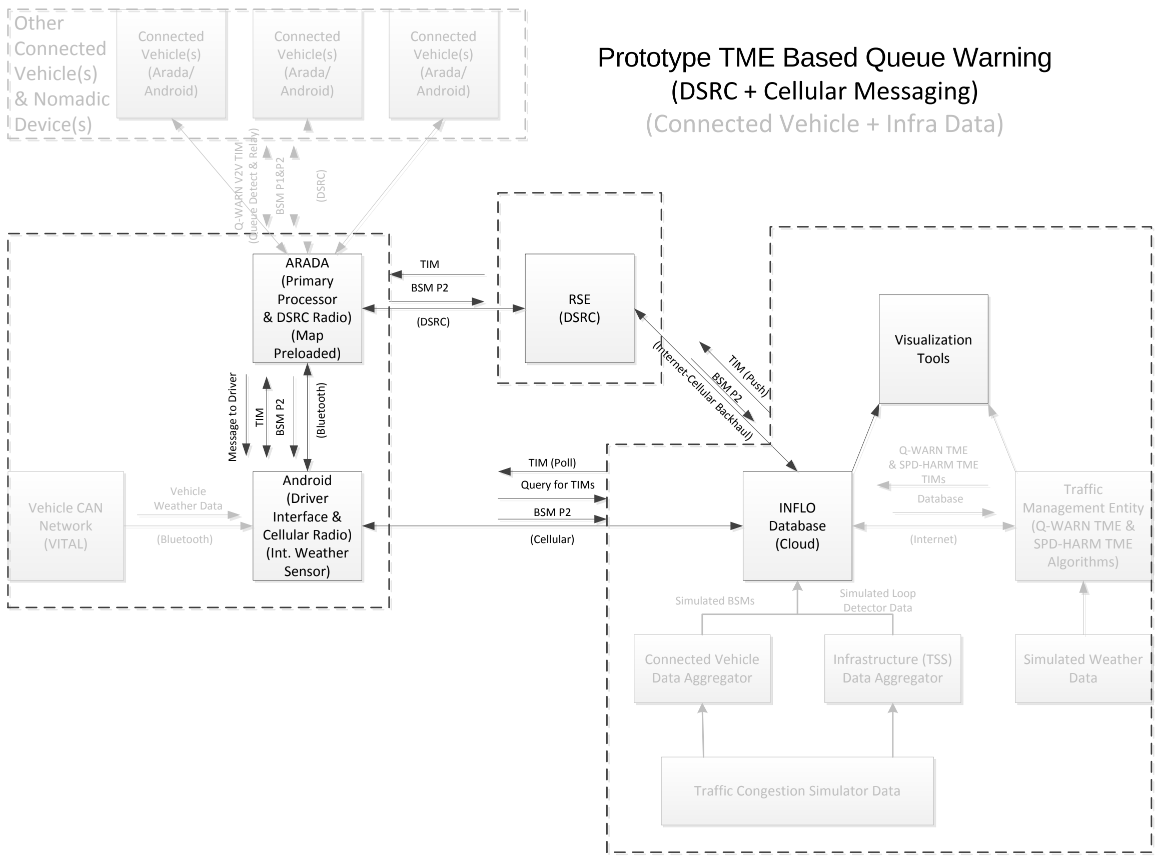
Test Case Objective

This Acceptance Test demonstrates the functionality of TME-based Q-WARN and SPD-HARM messaging from the Cloud Database to the Nomadic Devices via DSRC communications through the RSU and through cellular communications when DSRC is not available. This test case

- Verifies that Connected Vehicle System Elements are operational
- Verifies that the TME System Elements are operational
- Verifies that when a *simulated* queue is created, the following occurs:
- TME-based Q-WARN is disseminating the queue information to connected vehicles
- TME-based SPD-HARM is disseminating target speed recommendations to connected vehicles.

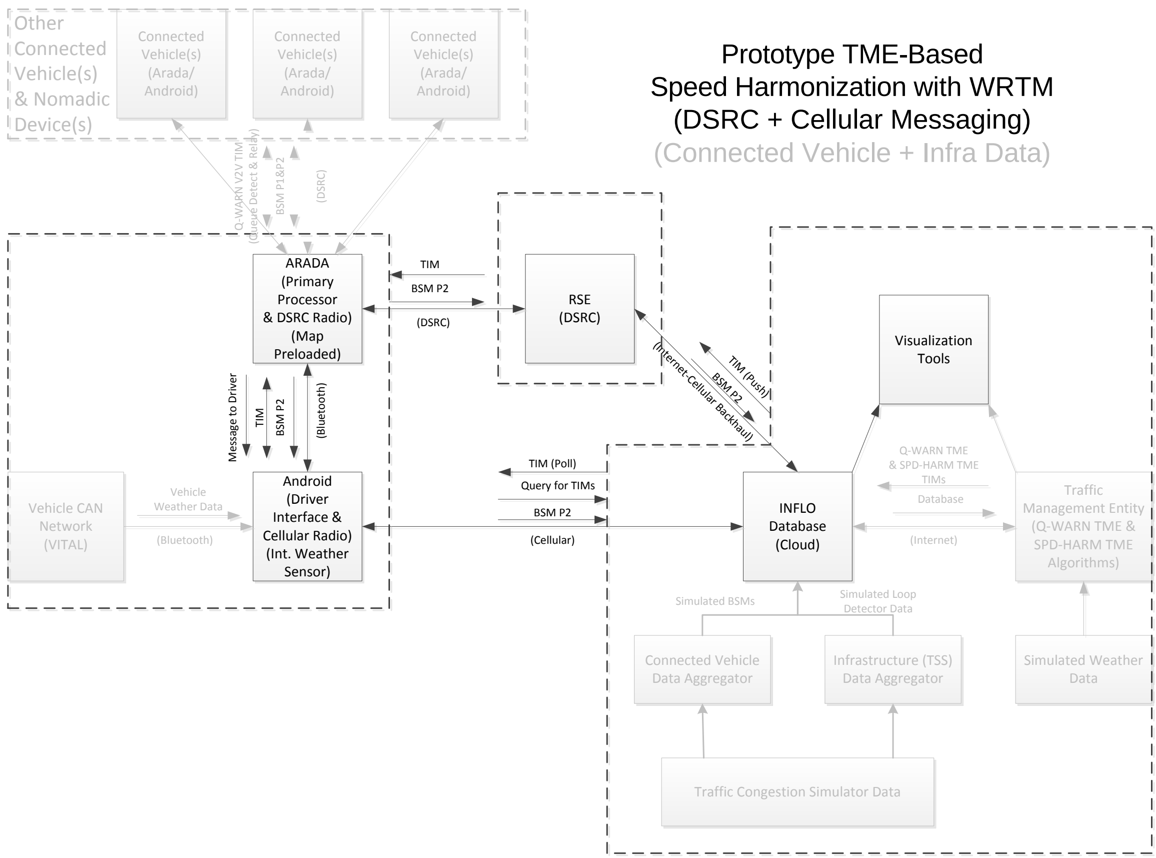
Test Case System Configuration

The INFLO System configuration for Q-WARN System Communications and Messaging Test Case is shown in Figure 4-1. The INFLO System configuration for SPD-HARM System Communications and Messaging Test Case is shown in Figure 4-2.



Source: Battelle

Figure 4-1. Prototype INFLO System Configuration Used in TME-Based Queue Warning Laboratory Testing.



Source: Battelle

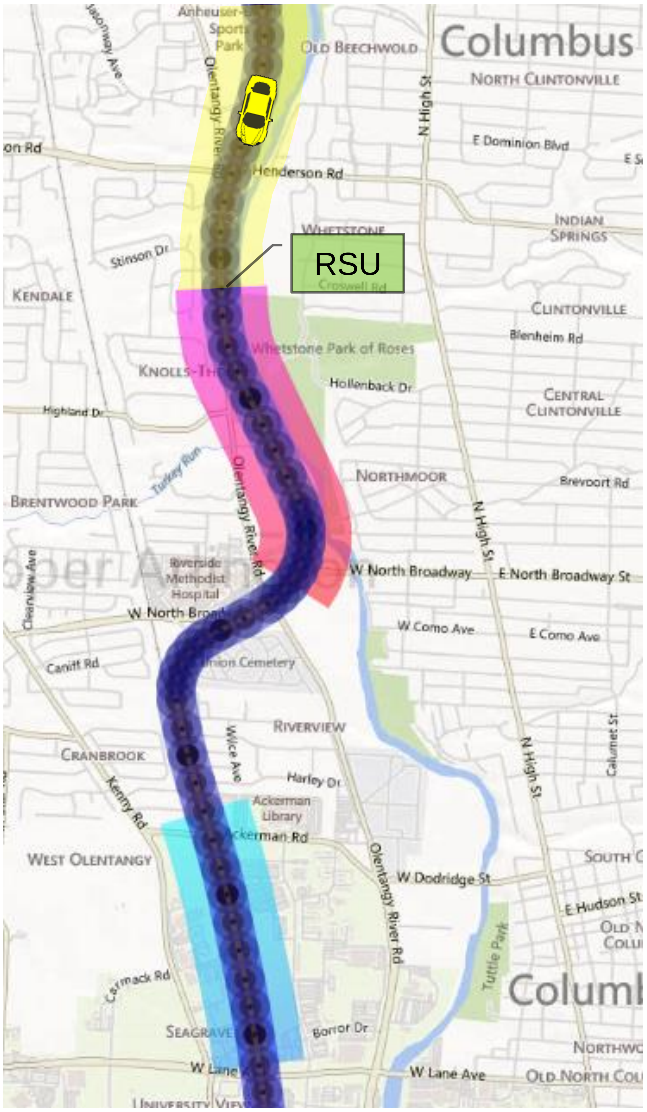
Figure 4-2. Prototype INFLO System Configuration Used in TME-Based Speed Harmonization Laboratory Testing.

Test Case Location

Project Team Connected Vehicle Laboratory. U.S. DOT Acceptance Test Demonstration conducted in Visitor Conference Room.

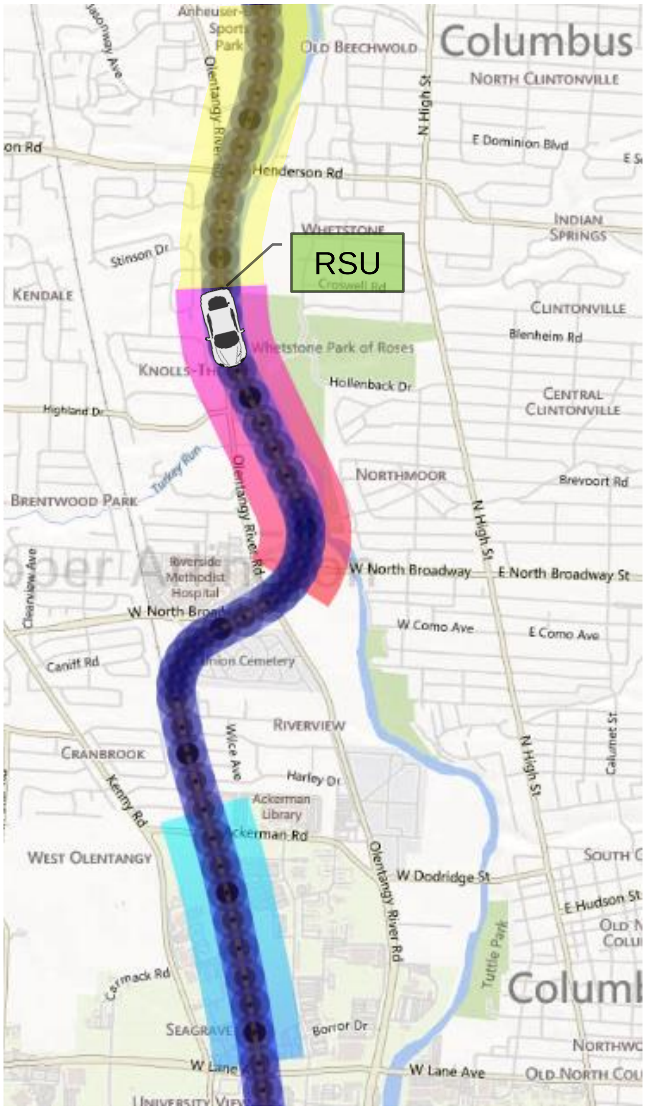
Test Case Setup (Route and Messaging)

The simulated routes traveled during this Prototype Acceptance Test are illustrated in Figure 4-3, Figure 4-4, Figure 4-5, and Figure 4-6 along with color coding to show the location of messages populated in the INFLO Database. Figure 4-3 shows the simulated southbound vehicle location when it displays the Queue Ahead Message indicated by yellow shading. The simulated RSU location is ahead of the vehicle at the boundary between the Queue Ahead and In-Queue messages. Figure 4-4 shows the simulated southbound vehicle location when it displays the In-Queue message indicated by red shading. Figure 4-5 shows the simulated southbound vehicle location when it displays the Speed Harmonization Queue message indicated by light blue shading. The simulated RSU location for this message is at the end of the Speed Harmonization location. Figure 4-6 shows the simulated northbound vehicle location when it displays the both the Speed Harmonization and Queue Ahead messages simultaneously, indicated by both yellow and light blue shading.



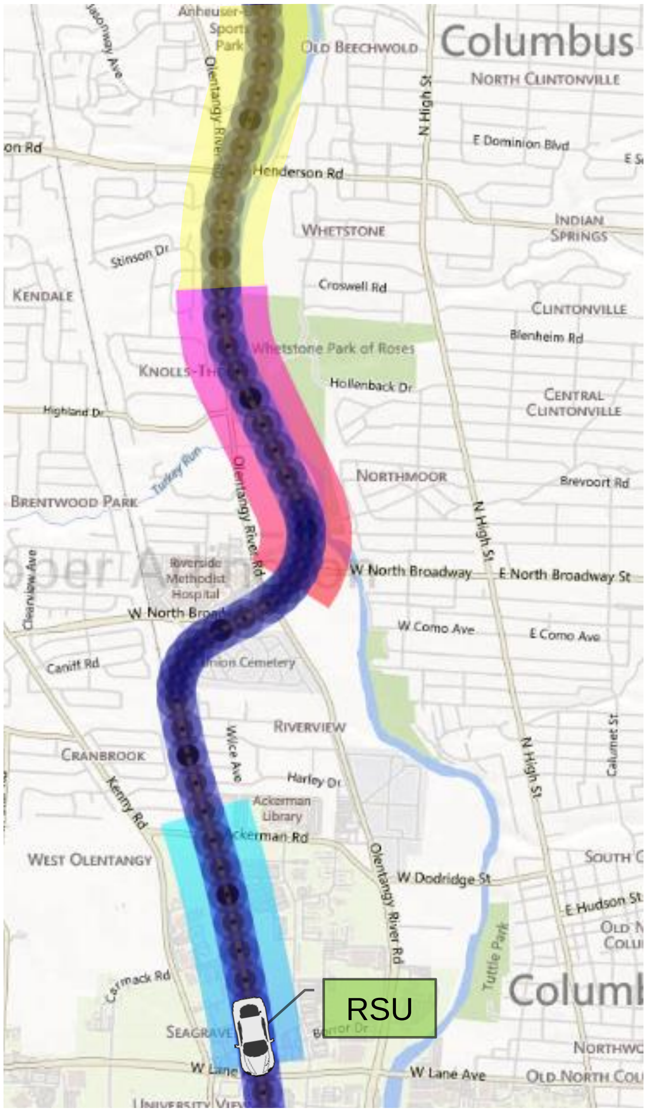
Source: Battelle

Figure 4-3. Simulated Travel Route Used for Queue Warning and Speed Harmonization Laboratory Testing with Vehicle in the Queue Ahead Message Region.



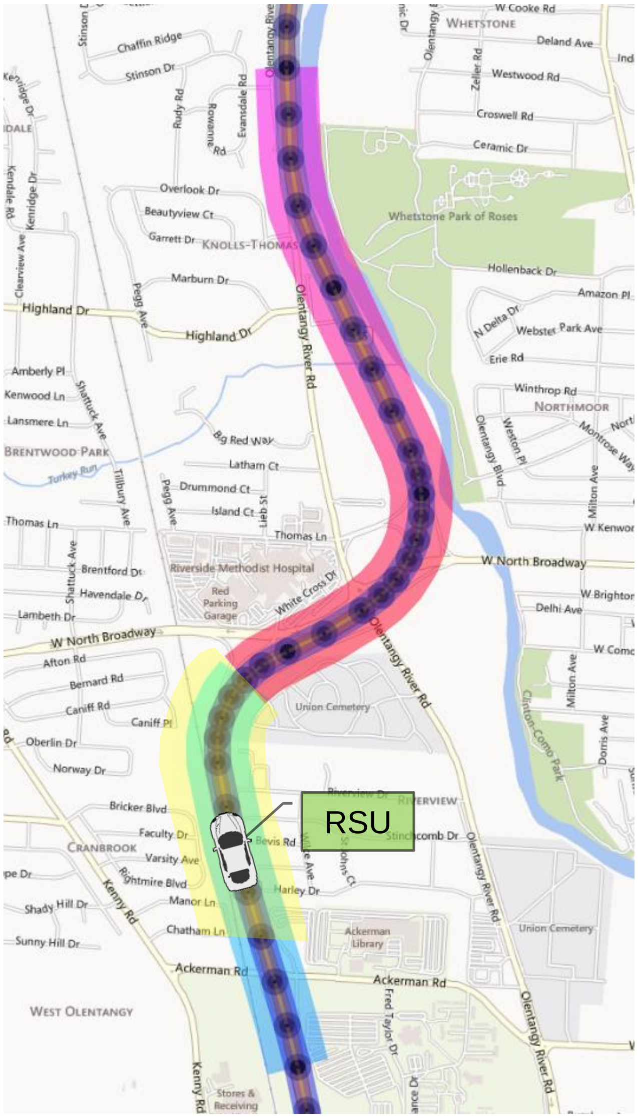
Source: Battelle

Figure 4-4. Simulated Travel Route Used for Queue Warning and Speed Harmonization Laboratory Testing with Vehicle in In-Queue Message Region.



Source: Battelle

Figure 4-5. Simulated Travel Route Used for Queue Warning and Speed Harmonization Laboratory Testing with Vehicle in Speed Harm Message Region.



Source: Battelle

Figure 4-6. Simulated Travel Route Used for Queue Warning and Speed Harmonization Laboratory Testing with Vehicle in Queue Ahead and Speed Harmonization Message Region.

Test Case Results

Researchers first confirmed that TME-based Q-WARN and SPD-HARM messages were received via DSRC and displayed correctly for both northbound and southbound travel during at least ten simulated circuits of each. The test series was repeating using cellular communications. The messages received were similar to those displayed in Figure 3-7 through Figure 3-10. The location of the message specification where displayed on both the Cloud Database Visualization Tool and the In-Vehicle System User Interface Module.

The operations of the prototype algorithm were demonstrated to FHWA as part of the INFLO Demonstration Workshop held in Columbus, OH, May 6-7 as illustrated in Figure 4-7.

Source: Battelle

Figure 4-7. Conference Room Demonstration of Laboratory Communications Testing (Arada Diagnostic Screen Shown on TV, RSU in Background).

Test Case Pass/Fail: Pass

Phase IIa V2V Q-WARN System Communications and Messaging

Test Case Summary

In this Phase II System Integration Acceptance Test Case, simulated GPS data is fed to multiple nomadic devices simulating travel approaching a queue. The second simulated vehicle approaches a stopped vehicle, and determines that it is in a queued state and issues a message indicating it is queued. A third following simulated vehicle approaches from the same direction and issues a Queue Ahead message to the driver. A fourth simulated vehicle approaching from the opposite direction does not display a message. Researchers verify that all messages are received and displayed to the driver at the proper locations when travel is simulated in the specified direction. They also confirmed that the messages are received, but not displayed to the driver when traveling is simulated in the opposite direction.

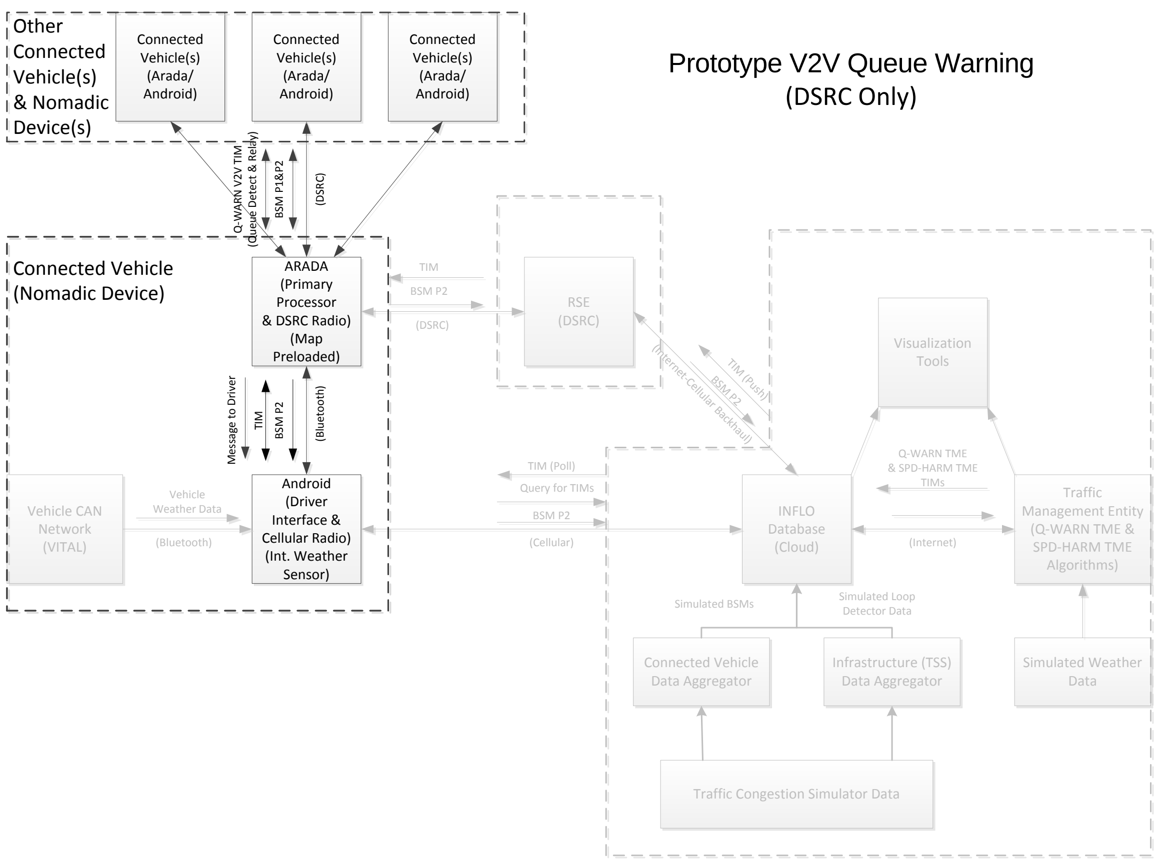
Test Case Objective

This Acceptance Test demonstrates the functionality of V2V DSRC based Queue detection and Queue warning in the laboratory environment as well as interfaces, communication and messaging. This test case

- Verifies that Connected Vehicle System Elements are operational
- Verifies that when a simulated queue is created, the following occurs:
- CV-based Q-WARN is detecting roadway location and queue state and passing information to other connected vehicles and infrastructure
- CV-based Q-WARN is providing recommendations to the User Interface which is communicating with driver
- CV-based Q-WARN is disseminating queue status alerts and information to other connected vehicles.

Test Case System Configuration

The INFLO System configuration for this Prototype Acceptance Test Case is shown in Figure 4-8 below.



Source: Battelle

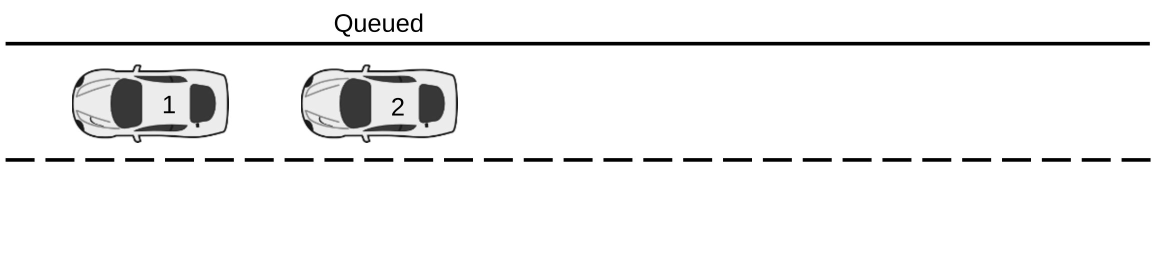
Figure 4-8. Prototype INFLO System Configuration Used in V2V Queue Warning Laboratory Testing.

Test Case Location

Project Team Connected Vehicle Laboratory. U.S. DOT Acceptance Test Demonstration conducted in Visitor Conference Room.

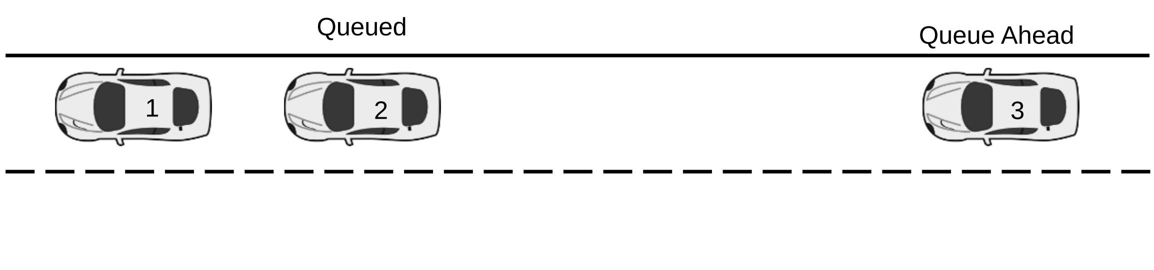
Test Case Setup (Route and Messaging)

The simulated route traveled during this Prototype Acceptance Test is illustrated in Figure 4-9, Figure 4-10, and Figure 4-11. Figure 4-9 illustrates the configuration when Vehicle 2 approaches Vehicle 1 and determines that it is queued. Figure 4-10 illustrates the configuration when Vehicle 3 approaches, receives the vehicle queued message and delivers the Queue Ahead message to the driver. Figure 4-11 illustrates the configuration when Vehicle 4 approaches from the opposite direction, receives the vehicle queued message and *does not* deliver the Queue Ahead message to the driver.



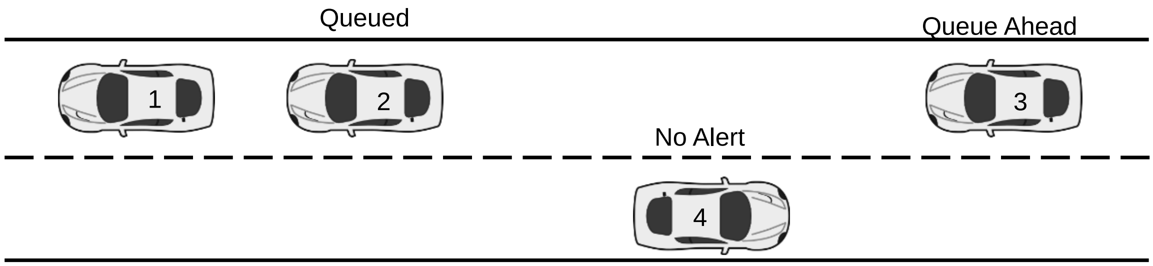
Source: Battelle

Figure 4-9. Simulated Vehicle/Nomadic Device Configuration for DSRC Based Queue Detection.



Source: Battelle

Figure 4-10. Simulated Vehicle/Nomadic Device Configuration for DSRC Based Communication of Queue Ahead.



Source: Battelle

Figure 4-11. Simulated Vehicle/Nomadic Device Configuration for Verification that Message is not Displayed to Vehicles Traveling in the Opposite Direction.

Test Case Results

Researchers first confirmed that vehicle 7 correctly detects that it is queued and issues a Queue Ahead message. They then confirmed that vehicle 8 received and displayed the message on the In-Vehicle System User Interface Module correctly for at least ten simulated trials. They also confirmed that the message was not received on vehicle 9. Messages received were similar to those shown in Figure 3-5 and Figure 3-6.

Test Case Pass/Fail: Pass

Phase IIb Q-WARN and SPD-HARM Algorithm System Integration Test Case

Test Case Summary

In this test case simulated traffic congestion data was fed into the INFLO Database at the rate that would be expected from Infrastructure-based and connected vehicle-based data collection systems. The algorithms were applied to detect and measure queue formation and evolution and to recommend speed harmonization results. The results were displayed visually. Four scenarios are illustrated.

- Queue warning with speed harmonization using TSS data and 100 percent of vehicles are connected
- Queue warning with speed harmonization using TSS data only
- Queue warning with speed harmonization using connected vehicle data only when 100 percent of vehicles are connected (Cloud Based Queue Warning)
- Queue warning with speed harmonization using TSS data and 50 percent of vehicles are connected.
- Speed harmonization in response to the formation of a shockwave.

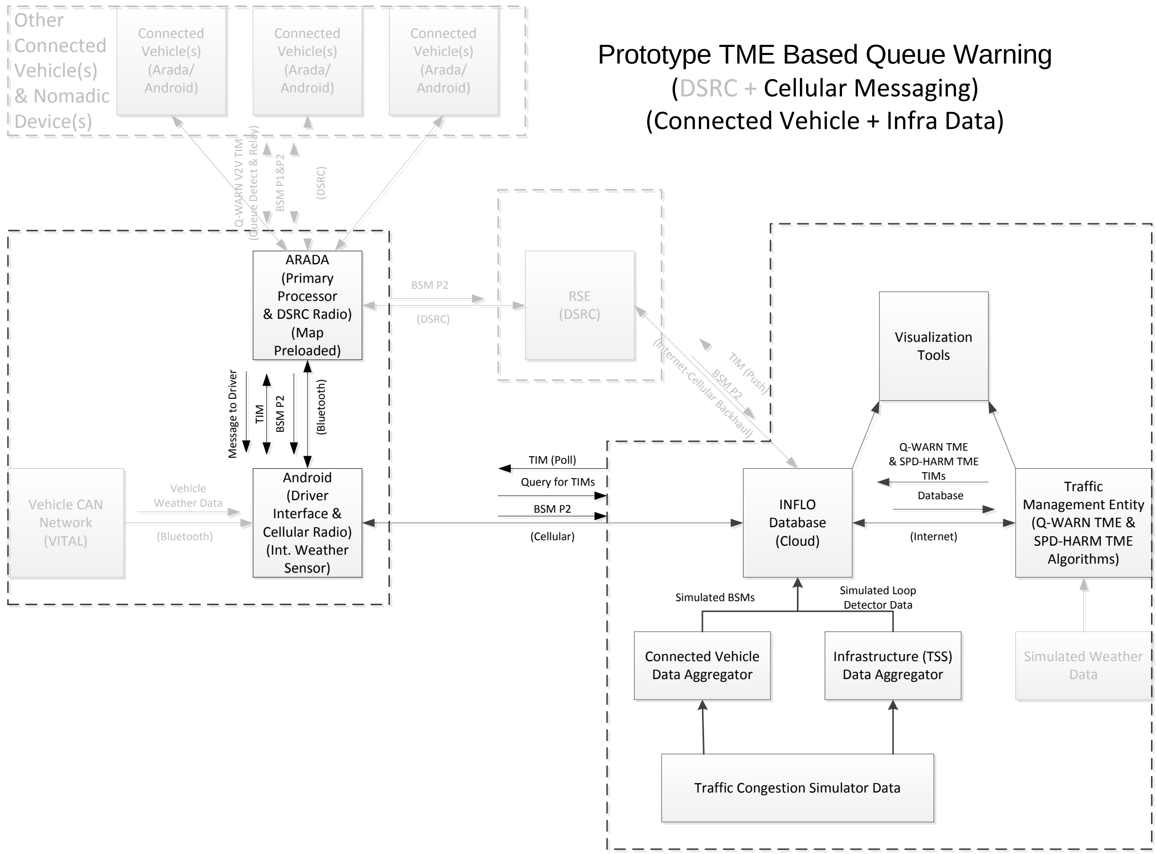
Test Case Objective

This test case illustrates the ability of the TME-based Queue Warning and Speed Harmonization algorithms to obtain infrastructure-based and connected vehicle-based data from the INFLO database, analyze and process the data and then transmit Queue Warning and Speed Harmonization messages in the database for display to the drivers. This test case

- Verifies that Connected Vehicle System Elements are operational
- Verifies that the TME System Elements are operational
- Verifies that when a *simulated* queue is created, the following occurs:
  - TME-based Q-WARN is receiving real-time conditions and queue information from various sources and fusing and processing the data to generate queue response strategies
  - TME-based Q-WARN is disseminating the queue strategies to connected vehicle network
  - TME-based SPD-HARM is receiving real-time traffic, road, and weather conditions from various sources and fusing and processing data to calculate speed target recommendations
  - TME-based SPD-HARM is disseminating target speed recommendations to connected vehicles and DMS locations.

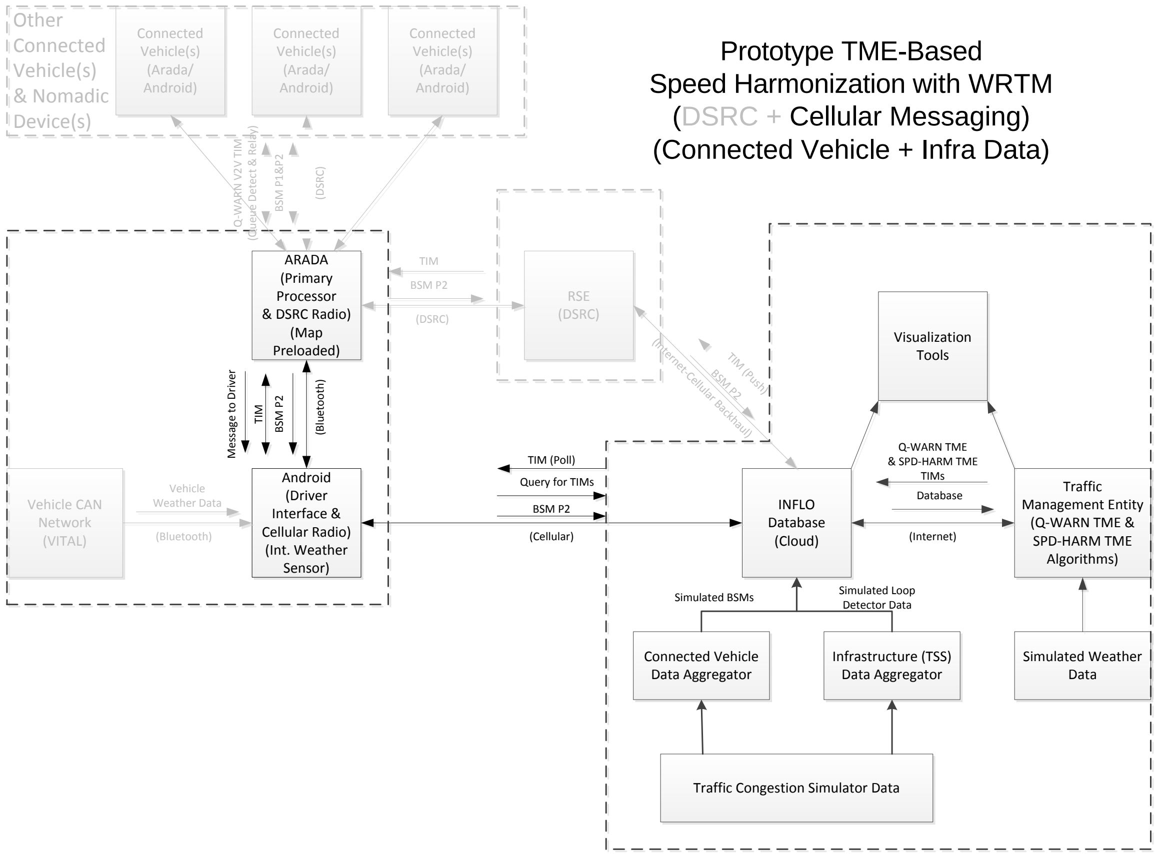
Test Case System Configuration

The INFLO System configuration for this Q-WARN and SPD-HARM Algorithm and System Test Case is shown in Figure 4-12 and Figure 4-13 below. Figure 4-14 illustrates the configuration for Cloud-Based Q-WARN in which no infrastructure data or infrastructure communications (DSRC) are utilized.



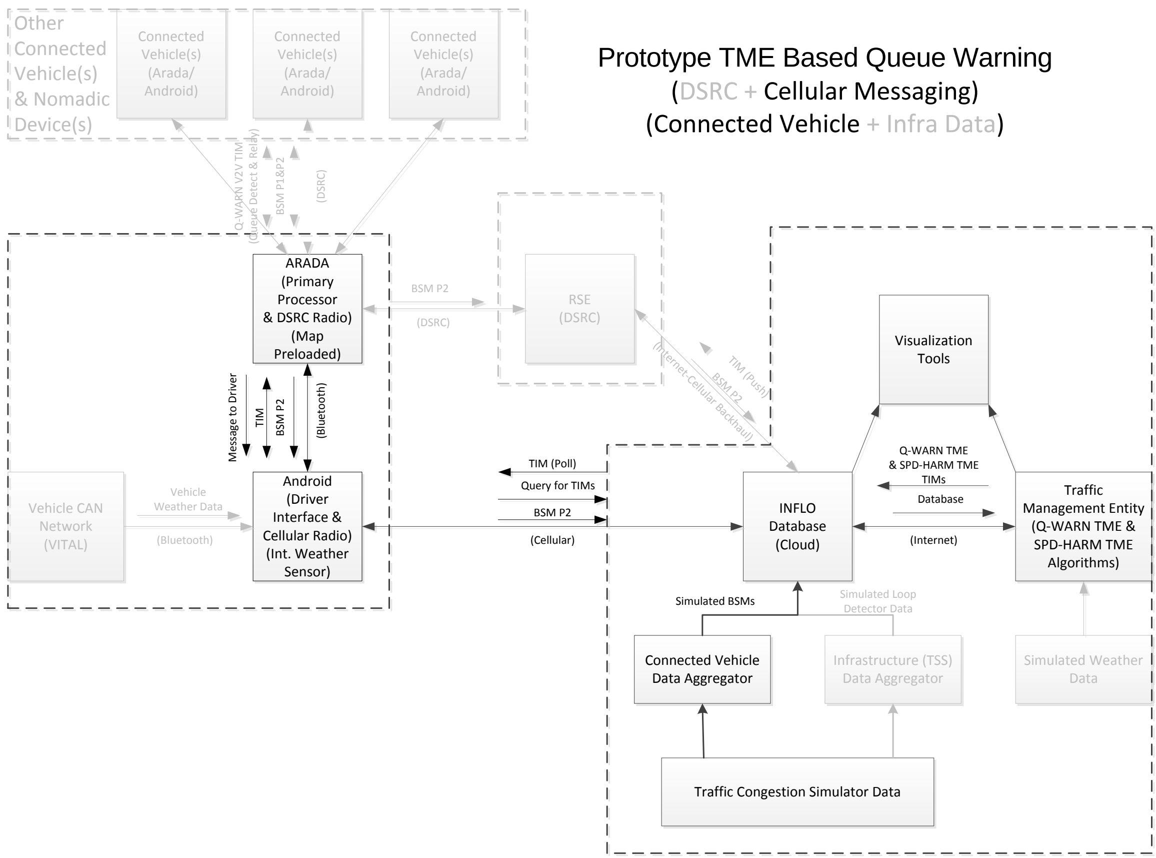
Source: Battelle

Figure 4-12. Prototype INFLO System Configuration Used in Laboratory TME-Based Queue Warning Testing.



Source: Battelle

Figure 4-13. Prototype INFLO System Configuration Used in Laboratory TME-Based Speed Harmonization Testing.



Source: Battelle

Figure 4-14. Prototype INFLO System Configuration Used in Laboratory Cloud-Based Queue Warning Testing.

Test Case Location

Project Team Connected Vehicle Laboratory. U.S. DOT Acceptance Test Demonstration conducted in Battelle Visitor Conference Room on May 6, 2014.

Test Case Setup (Route and Messaging)

The route is that described under Traffic Congestion and Weather Simulation Data in Chapter 3. For the purposes of generating the data used for the testing, a seventeen mile section of two-lane freeway was coded into VISSIM. The section of freeway was coded as a two-lane freeway with no entrance and exit ramps. A land closure bottleneck was coded for the right lane at Milepoint 12.25. The capacity of the bottleneck was coded to be 1900 vehicles per hour. Traffic sensors were "installed" at half mile intervals, beginning at Milepoint 2.0 through Milepoint 13.0.

Test Case Results

The Project Team demonstrated the following operation of the prototype algorithms:

- Queue warning with speed harmonization using TSS data and 100 percent connected vehicles
- Queue warning with speed harmonization using TSS data only

- Queue warning with speed harmonization using connected vehicle data only with 100 percent connected vehicles.
- Queue warning with speed harmonization using TSS data and 50 percent connected vehicles.
- Speed harmonization in response to the formation of a shockwave.

In each of the scenarios, the results of the demonstration showed that the algorithms were successful at meeting all Test Case Pass/Fail Criteria listed above.

Test Case Pass/Fail: Pass

Phase III INFLO Prototype System Acceptance Test Summary

Phase III testing in this program focused on vehicle-based on-road and closed-course testing and verification of functionality and performance of the system. This section describes the Phase III on-road system communications and message acceptance tests which test, verify, and demonstrate the functionality of interfaces, communications and transmission of messages between traveling mobile components and the INFLO Cloud Database. This section and the previous section together represent testing and verification of the functionality of the complete INFLO system, end-to-end using both DSRC and cellular communications.

The testing described in this chapter is organized in three test cases

- On-road Low Speed TME-Based Q-WARN and SPD-HARM Test Case
- On-road High Speed TME-Based Q-WARN and SPD-HARM Test Case
- V2V Queue Warning Test Case.

The first two test cases test, verify and demonstrate the functionality of interfaces, communications and transmission of messages via cellular communications between all mobile components and the INFLO Cloud Database. The last test case demonstrates on-road communications and transmission of messages via DSRC between all mobile components. This testing also demonstrated mobile V2I DSRC communications between vehicles and the RSE.

On-road Low Speed TME-Based Q-WARN and SPD-HARM Test Case

Test Case Summary

In this Prototype Acceptance Test Case, the INFLO Database is prepopulated with TME-based Q-WARN and SPD-HARM messages on a predetermined route operating in live traffic at speeds from 0 to 15 miles per hour, through multiple signalized intersections. Researchers drove the route and verified that all Q-WARN and SPD-HARM messages are received and displayed to the driver at the proper locations when traveling the specified direction. They also confirmed that the messages are received, but not displayed to the driver when traveling in the opposite direction.

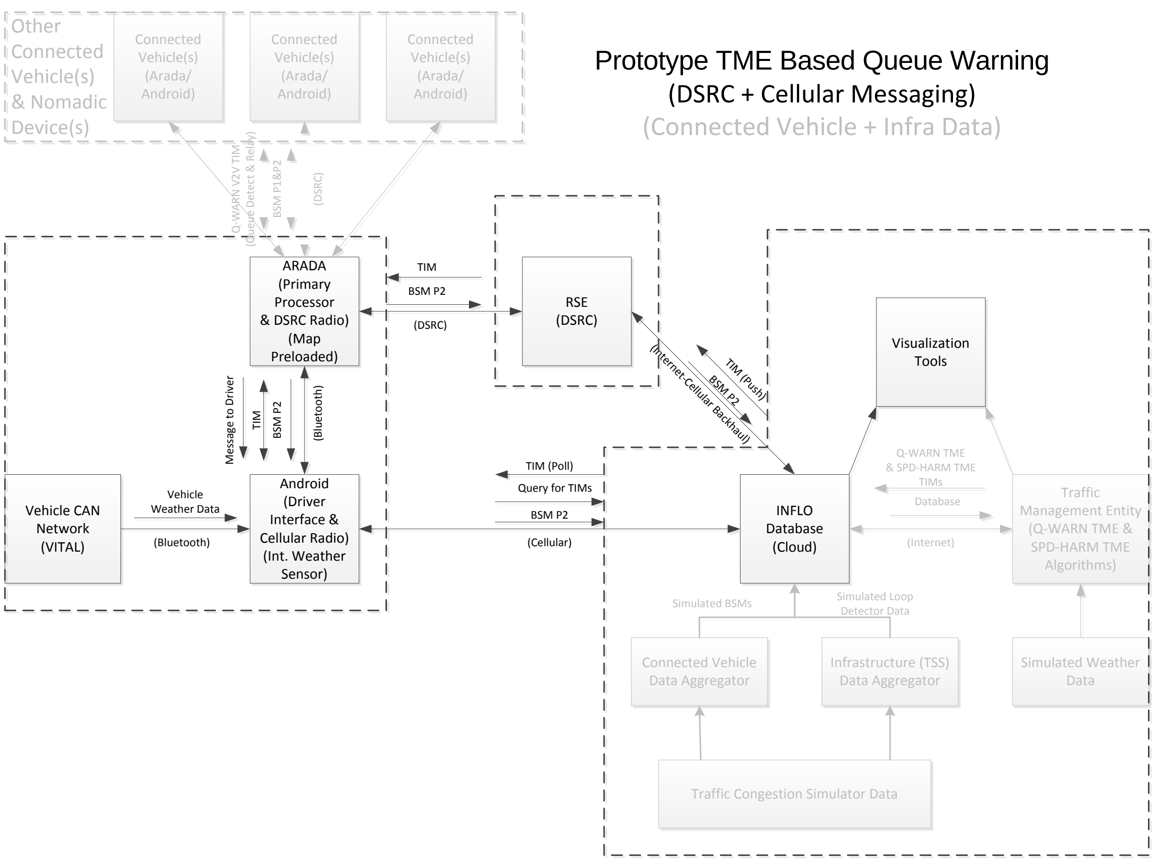
Test Case Objective

This Acceptance Test demonstrates the functionality of TME-based Q-WARN and SPD-HARM messaging from the INFLO Database to the Nomadic Devices when traveling at low speeds. This test case

- Verifies that Connected Vehicle System Elements are operational
- Verifies that the TME System Elements are operational
- Verifies that when a queue is created in the field, the following occurs:
  - TME-based Q-WARN is disseminating the queue information to connected vehicles
  - TME-based SPD-HARM is disseminating target speed recommendations to connected vehicles.

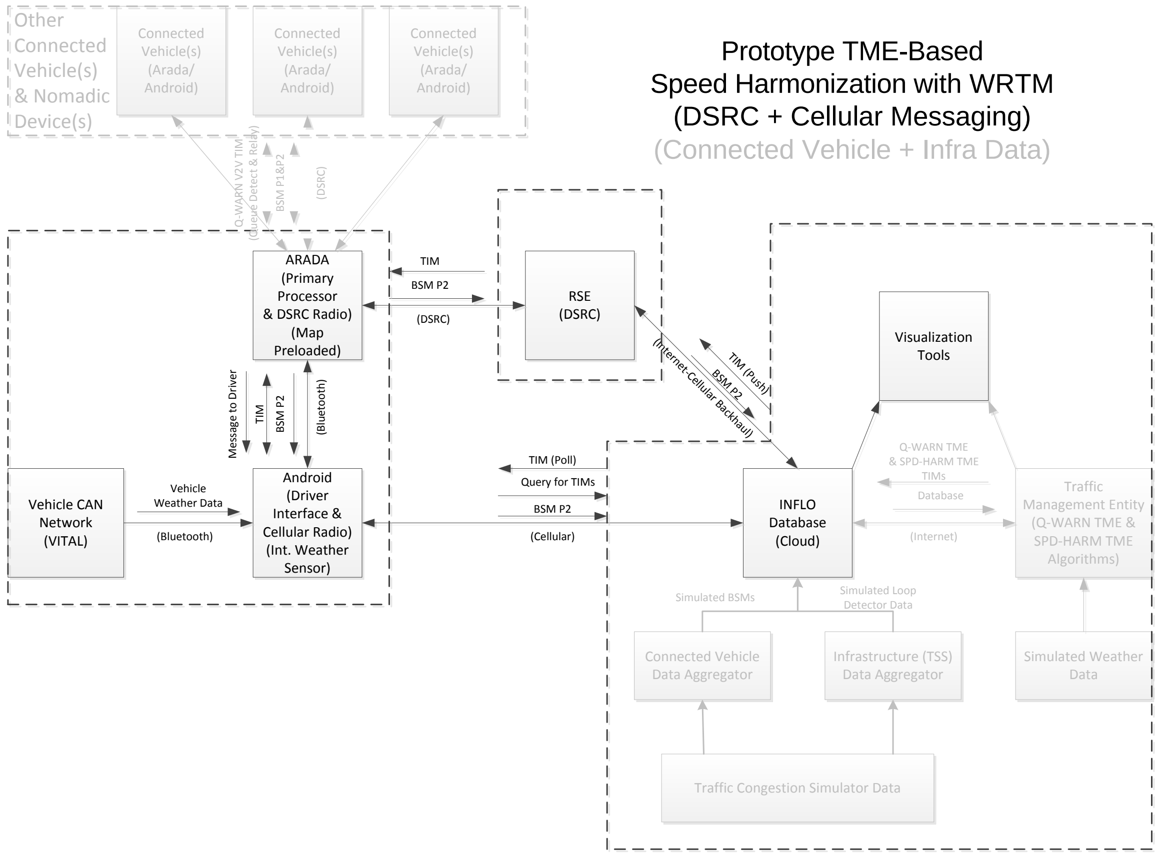
Test Case System Configuration

The INFLO System configuration for this Prototype Acceptance Test Case is shown in Figure 4-15 and Figure 4-16 below.



Source: Battelle

Figure 4-15. Prototype INFLO System Configuration Used in TME-Based Queue Warning On-road Testing.



Source: Battelle

Figure 4-16. Prototype INFLO System Configuration Used in TME-Based Speed Harmonization On-road Testing.

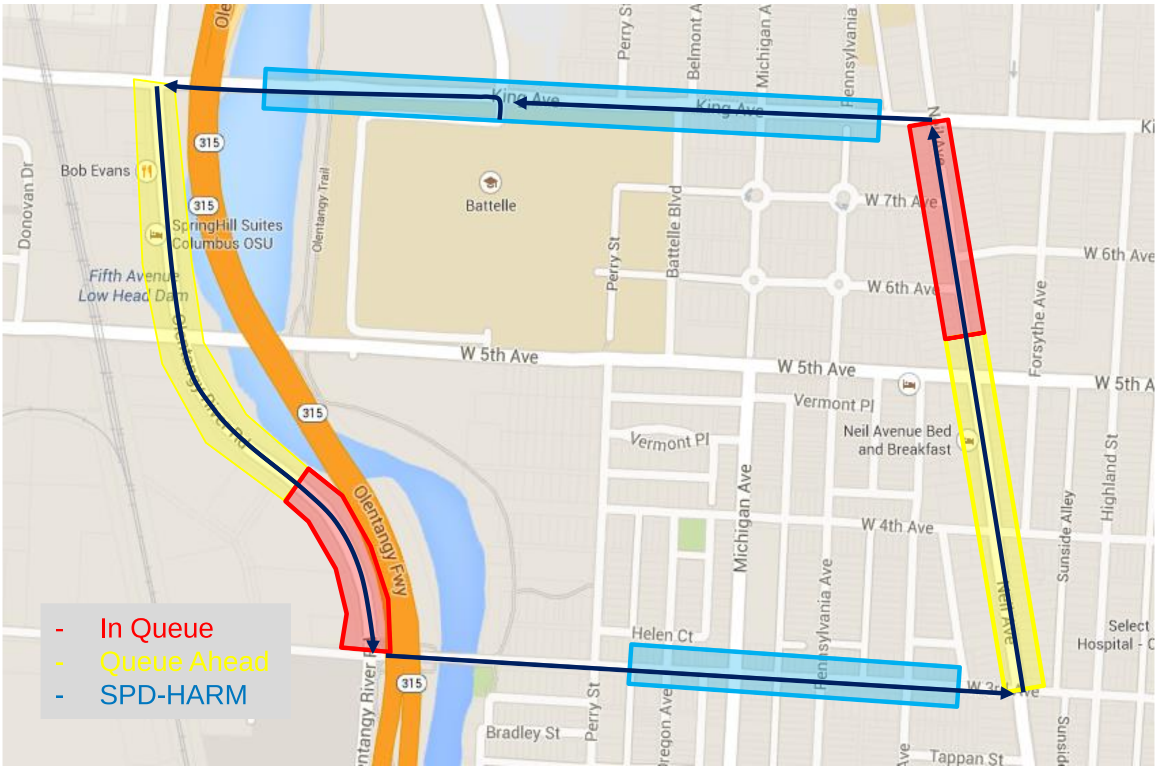
Test Case Location

This test case was conducted around the Project Team Connected Vehicle Test Loop. U.S. DOT Acceptance Test Demonstration was also conducted on the Project Team Connected Vehicle Test Loop.

Test Case Setup (Route and Messaging)

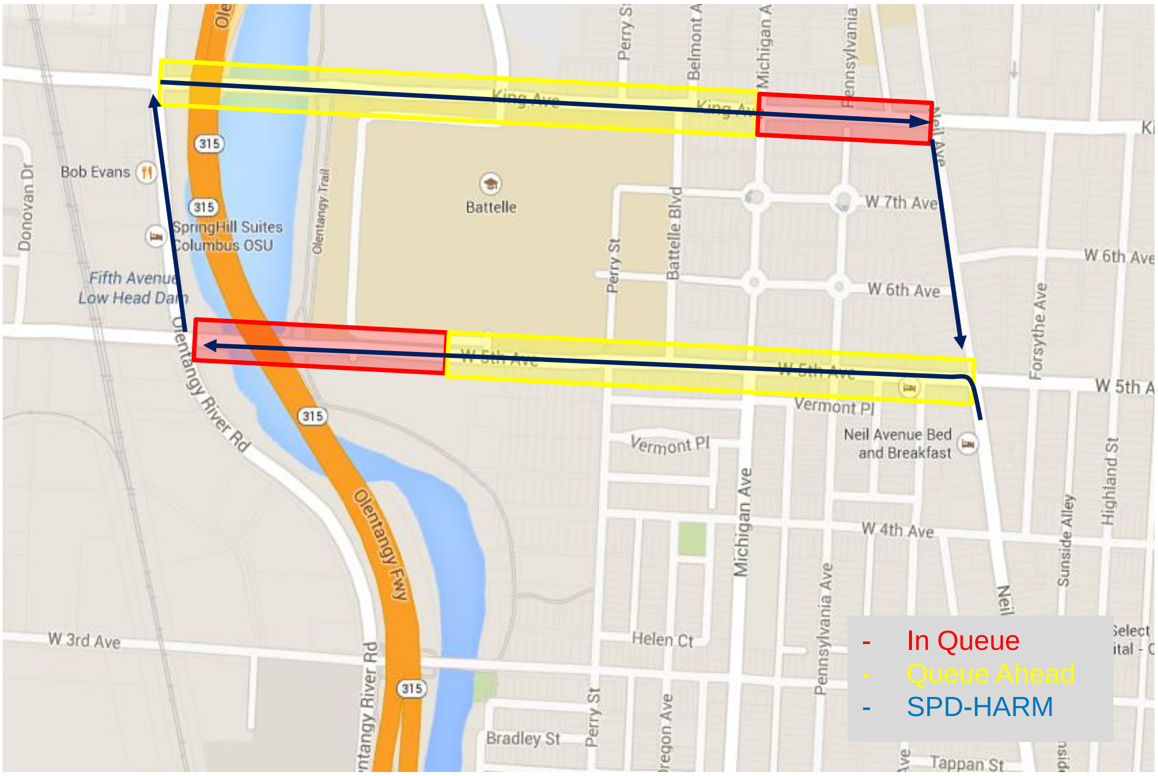
The Cloud Database was prepopulated with TME-based Q-WARN and SPD-HARM messages on a predetermined route around Battelle operating in live traffic. Researchers drive the route and verify that all Q-WARN and SPD-HARM messages are received and displayed to the driver at the proper locations when traveling the specified direction.

The routes traveled during this Prototype Acceptance Test are illustrated in Figure 4-17 and Figure 4-18 below along with color coding to show the location of messages populated in the Cloud Database. Figure 4-17 shows the messages populated for “counter-clockwise travel” and Figure 4-18 shows the messages populated for “clockwise travel”.



Source: Battelle

Figure 4-17. Project Team Connected Vehicle Test Loop Counter Clockwise TME Messages.



Source: Battelle

Figure 4-18. Project Team Connected Vehicle Test Loop Clockwise TME Messages.

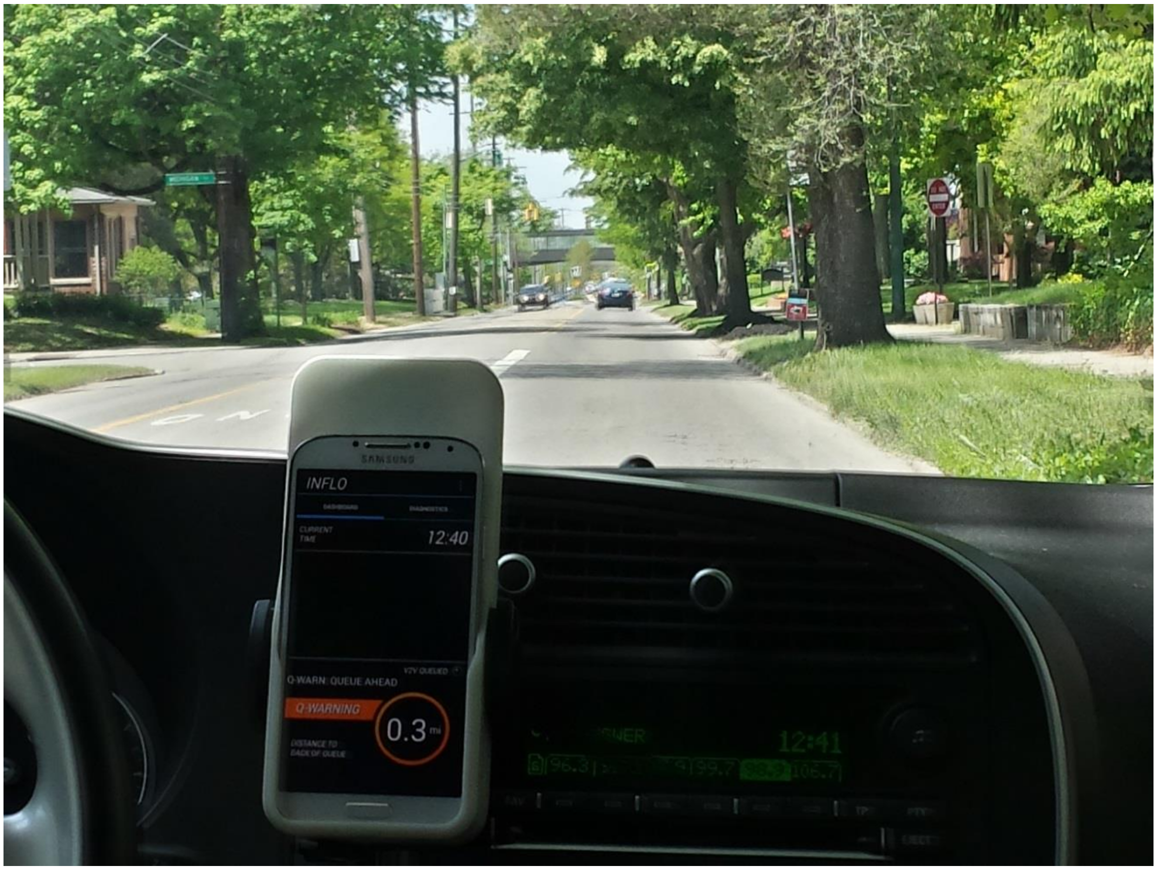
Test Case Results

Researchers first confirmed that TME-based Q-WARN and SPD-HARM messages displayed correctly for both counter-clockwise and clockwise travel during at least ten circuits of each. The location of the message specification where displayed on both the INFLO Database Map Viewer and the In-Vehicle System User Interface Module.

Figure 4-19 through Figure 4-23 below show pictures of the driver messages displayed while traveling the Project Team Connected Vehicle Test Loop.

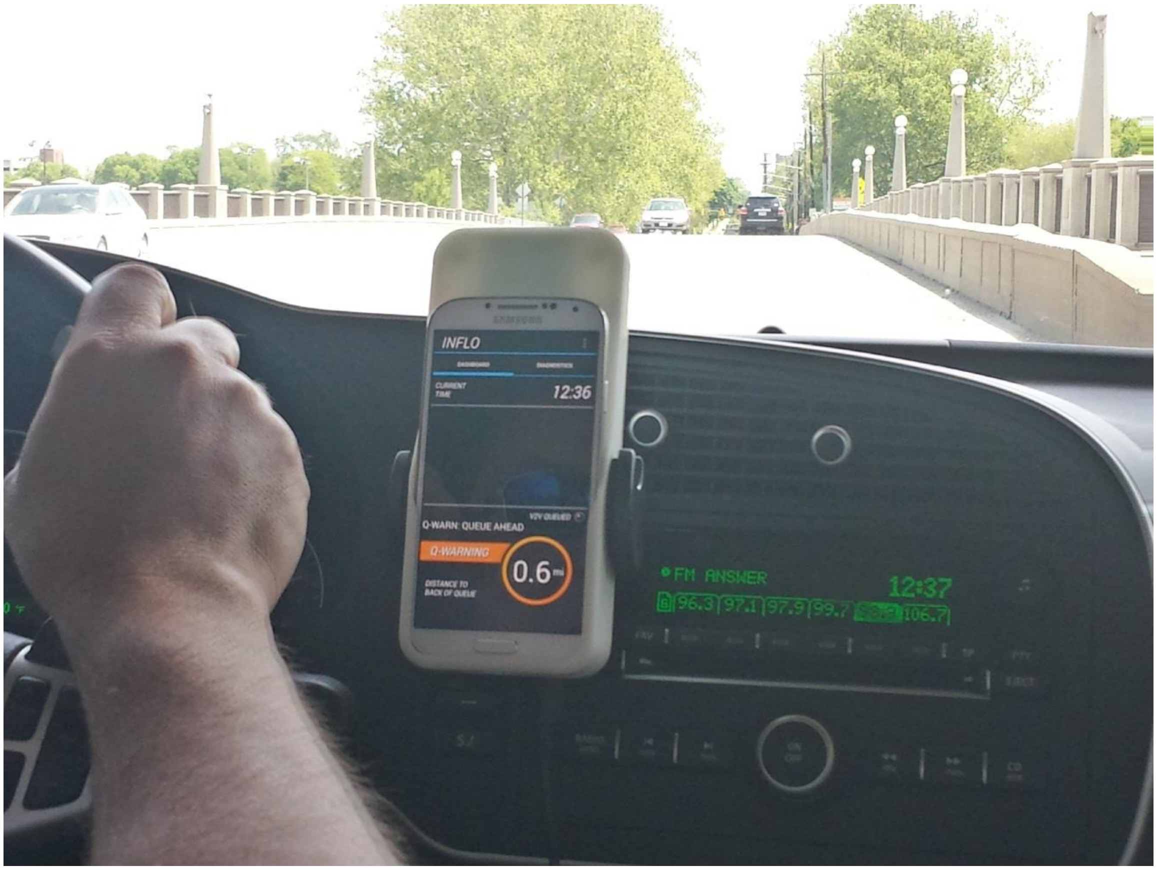
Source: Battelle

Figure 4-19. Nomadic Device Mounted in Vehicle showing Android Samsung Galaxy S4 Cellular Phone in Arada BackPack DSRC Radio.



Source: Battelle

Figure 4-20. Queue Ahead Message Displayed Correctly on Project Team Connected Vehicle Test Loop.

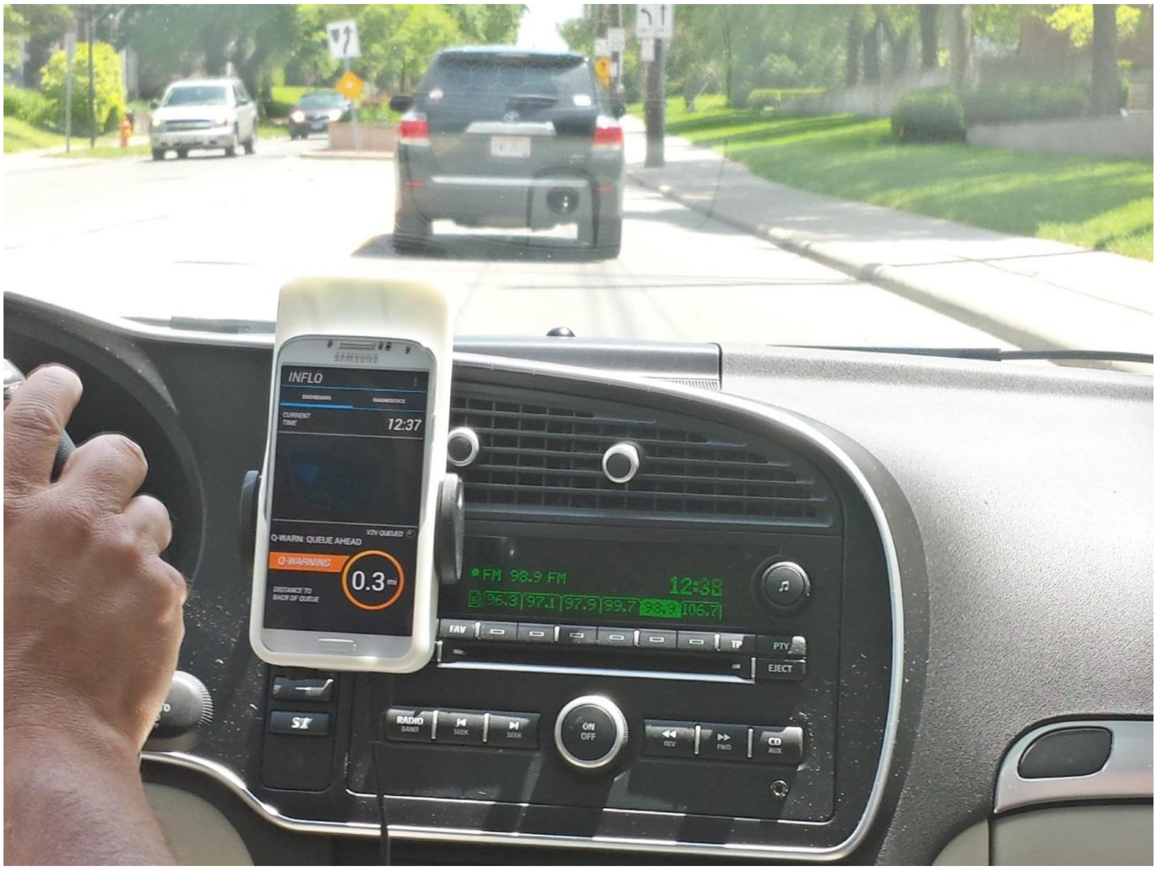


Source: Battelle

Figure 4-21. Queue Ahead Message Displayed Correctly on Project Team Connected Vehicle Test Loop.

Source: Battelle

Figure 4-22. In-Queue Message Displayed Correctly on Project Team Connected Vehicle Test Loop.



Source: Battelle

Figure 4-23. Queue Ahead Message Displayed Correctly on Project Team Connected Vehicle Test Loop.

Source: Battelle

Figure 4-24. Display of Vehicle Location on INFLO Database Visualization Tool While Conducting Acceptance Test Demonstration on Project Team Test Loop.

Test Case Pass/Fail: Pass

On-road High Speed TME-Based Q-WARN and SPD-HARM Test Case

Test Case Summary

In this Prototype Acceptance Test Case, the Cloud Database is prepopulated with TME-based Q-WARN and SPD-HARM messages on a predetermined route northbound and southbound on State Highway 315 through a commonly congested area, at speeds from 30 to 60 miles per hour. Researchers drive the route and verify that all Q-WARN and SPD-HARM messages are received and displayed to the driver at the proper locations when traveling the specified direction. They also confirmed that the messages are received, but not displayed to the driver when traveling in the opposite direction.

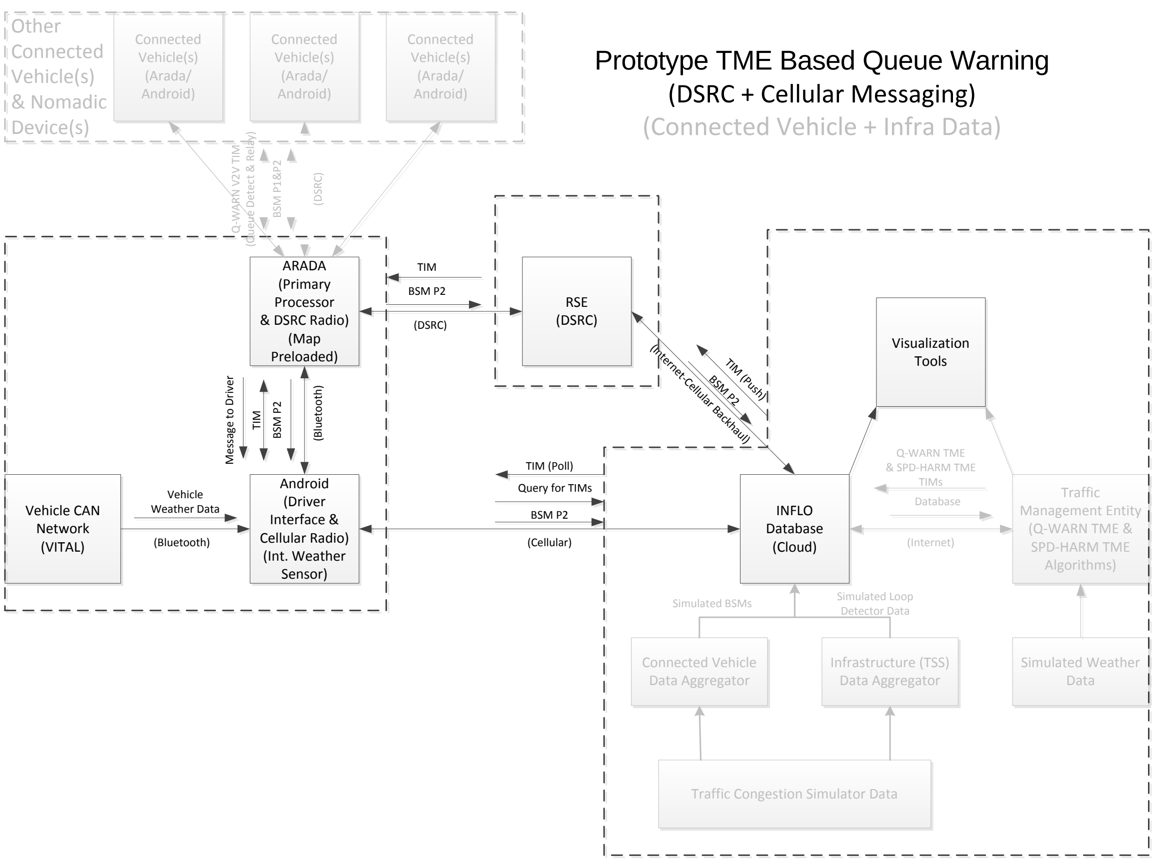
Test Case Objective

This Acceptance Test demonstrates the functionality of TME-based Q-WARN and SPD-HARM messaging from the Cloud Database to the Nomadic Devices when at highway speeds. This test case

- Verifies that Connected Vehicle System Elements are operational
- Verifies that the TME System Elements are operational
- Verifies that when a queue is created in the field, the following occurs:
  - TME-based Q-WARN is disseminating the queue strategies to connected vehicle network
  - TME-based SPD-HARM is disseminating target speed recommendations to connected vehicles.

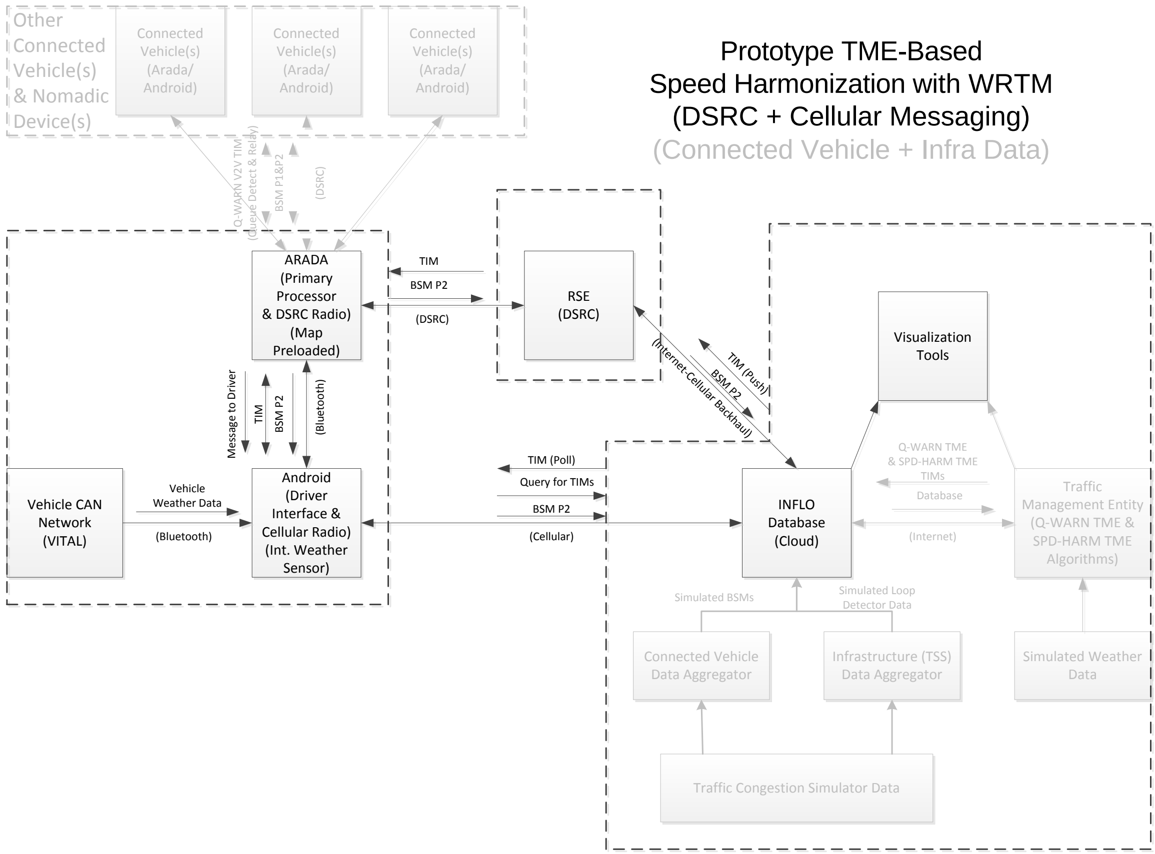
Test Case System Configuration

The INFLO System configuration for this Prototype Acceptance Test Case is shown in Figure 4-25 and Figure 4-26 below.



Source: Battelle

Figure 4-25. Prototype INFLO System Configuration Used in TME-Based Queue Warning On-road Testing.



Source: Battelle

Figure 4-26. Prototype INFLO System Configuration Used in TME-Based Speed Harmonization On-road Testing.

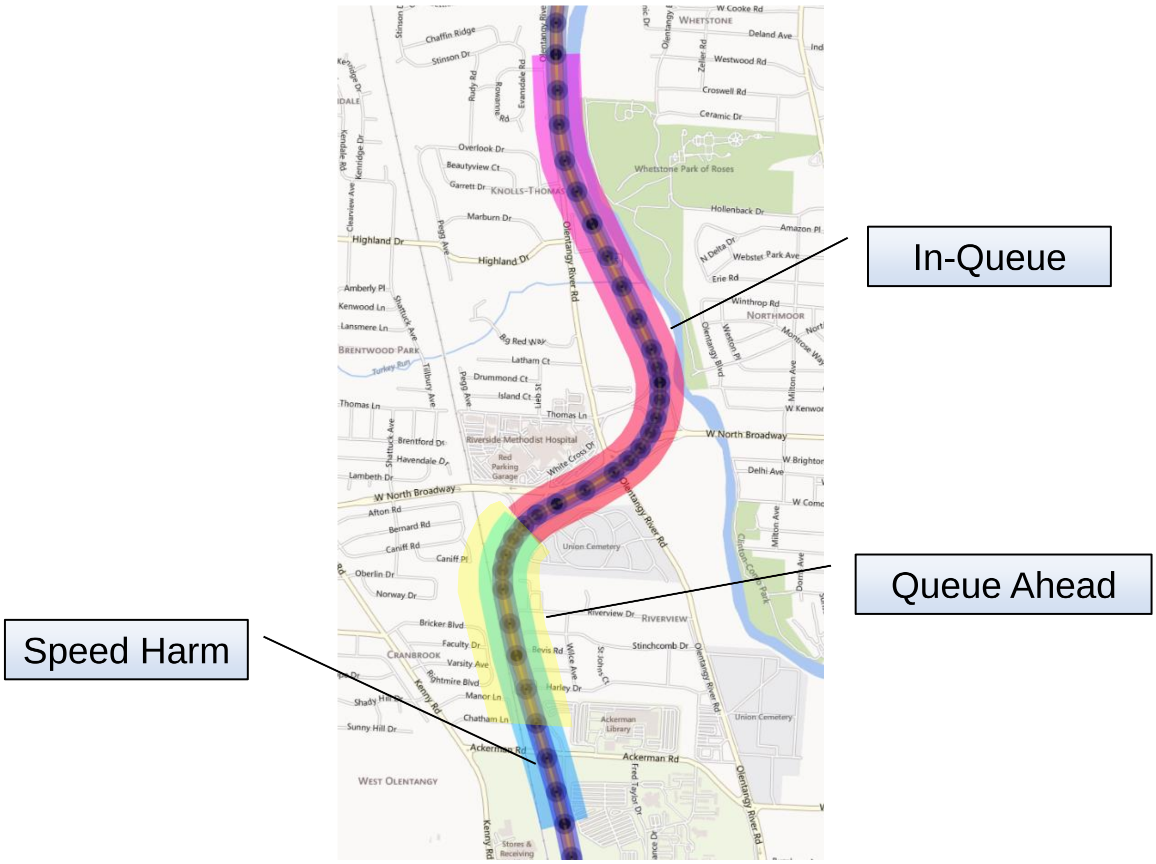
Test Case Location

This test case was conducted on State Route 315 north of Battelle. U.S. DOT Acceptance Test Demonstration was also conducted on the same State Route 315.

Test Case Setup (Route and Messaging)

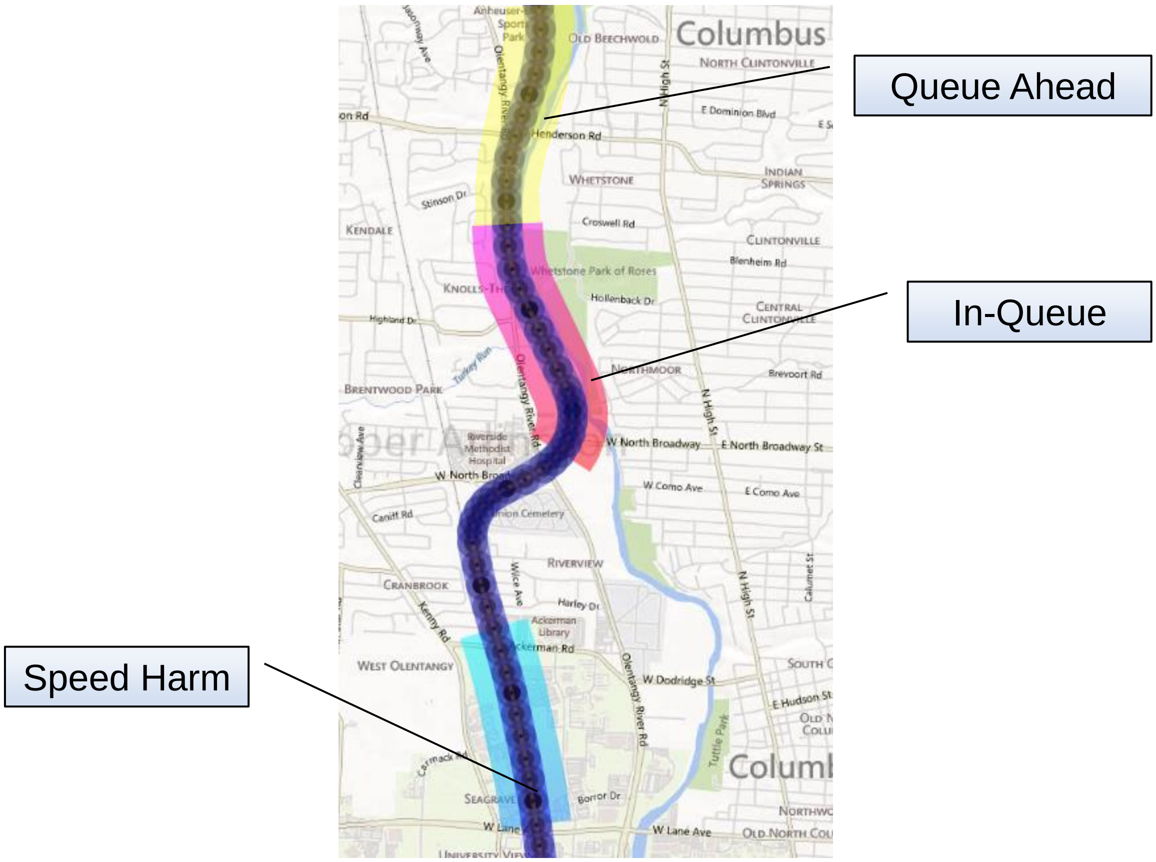
The Cloud Database was prepopulated with TME-based Q-WARN and SPD-HARM messages on a predetermined route near Battelle operating in live traffic. Researchers drive the route and verify that all Q-WARN and SPD-HARM messages are received and displayed to the driver at the proper locations when traveling the specified direction.

The routes traveled during this Prototype Acceptance Test are illustrated in Figure 4-27 and Figure 4-28 below along with color coding to show the location of messages populated in the Cloud Database. Figure 4-27 shows the messages populated for northbound travel and Figure 4-28 shows the messages populated for southbound travel.



Source: Battelle

Figure 4-27. State Route 315 Northbound.



Source: Battelle

Figure 4-28. State Route 315 Southbound.

Test Case Results

Researchers first confirmed that TME-based Q-WARN and SPD-HARM messages displayed correctly for both northbound and southbound travel during at least five circuits of each. The location of the message specification where displayed on both the INFLO Database Map Viewer and the In-Vehicle System User Interface Module.

Figure 4-29 through Figure 4-35 below show pictures of the driver messages displayed while traveling on State Route 315.

Source: Battelle

Figure 4-29. Nomadic Device Display Traveling on State Route 315.

Source: Battelle

Figure 4-30. TME Unavailable Message While Traveling State Route 315.

Source: Battelle

Figure 4-31. Speed Harmonization Message Display with Recommended Speed While Traveling on State Route 315.

Source: Battelle

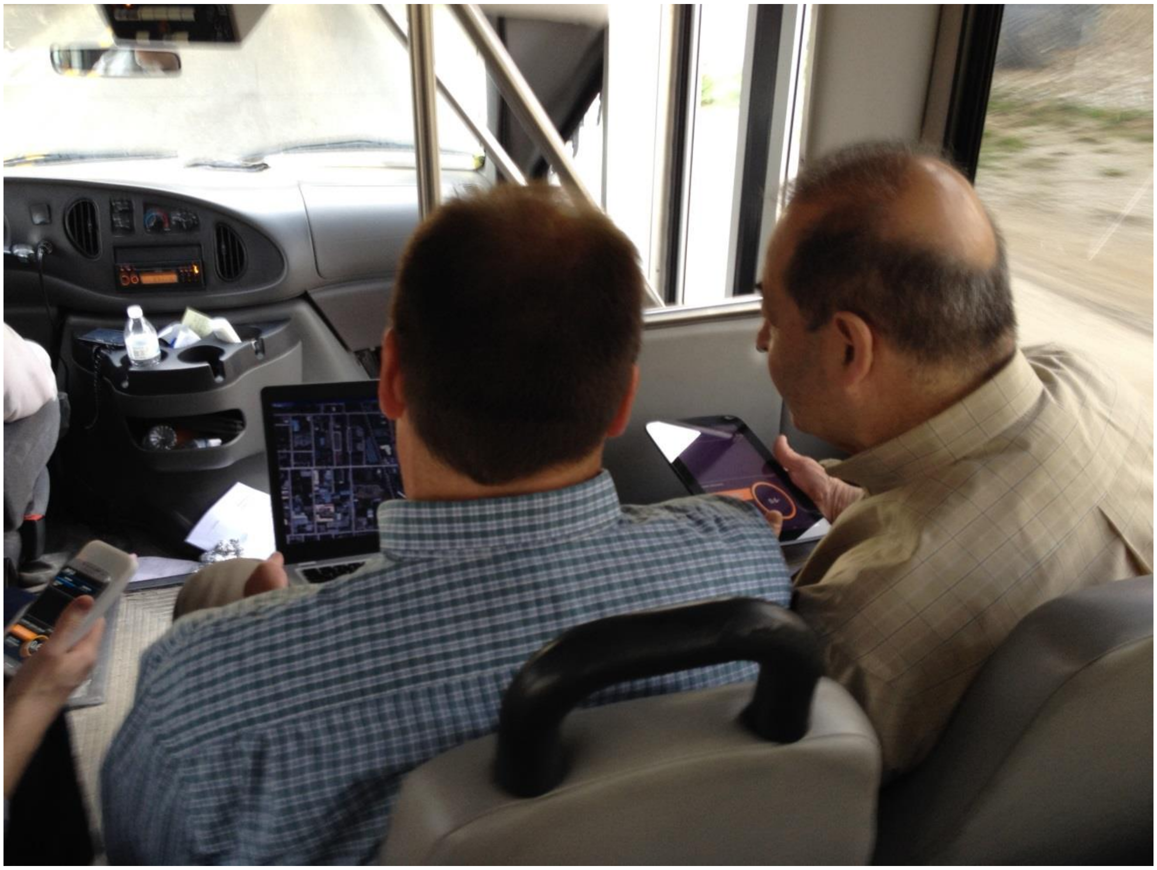
Figure 4-32. Queue Ahead Message While Traveling State Route 315 Indicating Back of Queue 0.1 mile Ahead.

Source: Battelle

Figure 4-33. Queue Ahead and Speed Harmonization Recommended Speed Message While Traveling State Route 315.

Source: Battelle

Figure 4-34. In-Queue Message While Traveling State Route 315 indicating Queue is 1 Mile in Length and Will Take 11 Minutes to Traverse.



Source: Battelle

Figure 4-35. Queue Ahead Warning Displayed on Android Device and Laptop Visualization Tool while Traveling on SR 315.

Test Case Pass/Fail: Pass

V2V Queue Warning Test Case

Test Case Summary

In this on-road Prototype Acceptance Test Case, a single vehicle slows and stops on a test road. The second vehicle approaches the stopped vehicle, and determines that it is in a queue and issues a message indicating it is queued. A third vehicle approaches from the same direction and issues a Queue Ahead message to the driver. Researchers verify that all messages are received and displayed to the driver at the proper locations when travel is in the specified direction. They also confirmed that the messages are received, but not displayed to the driver when traveling in the opposite direction.

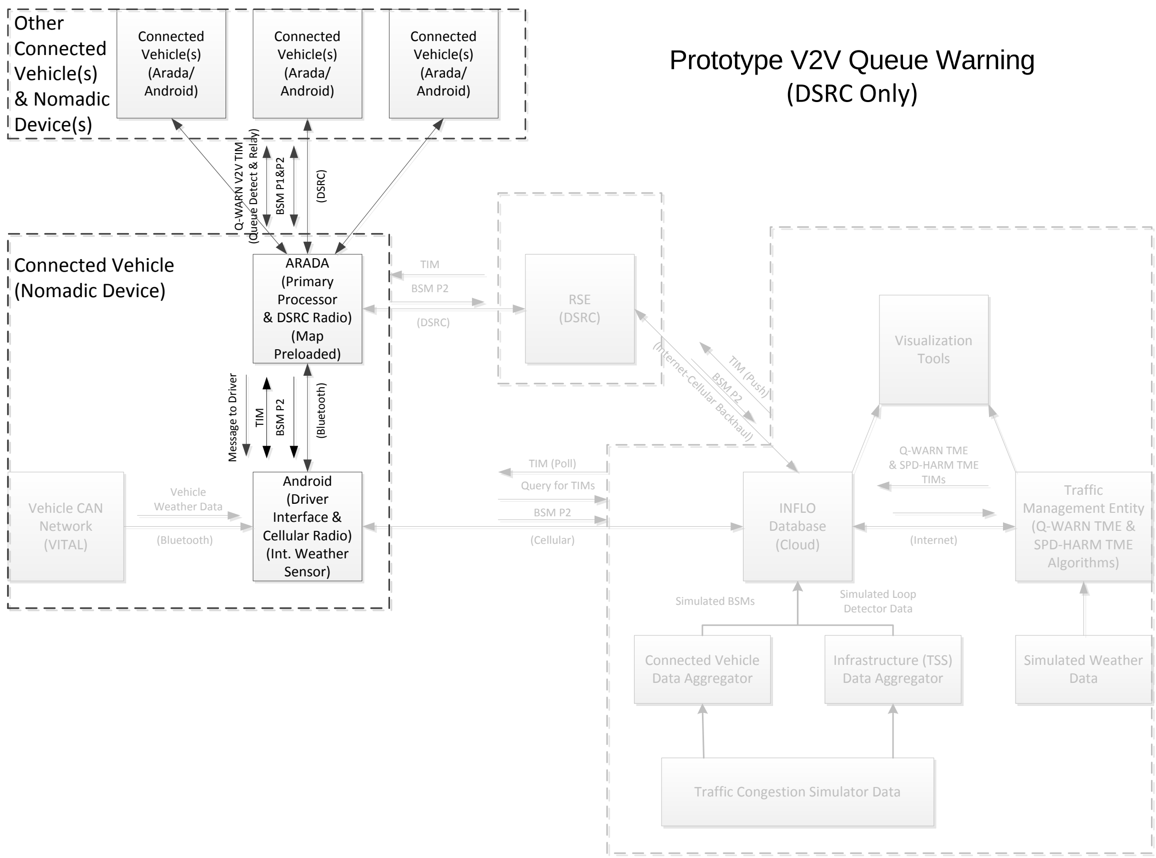
Test Case Objective

This Acceptance Test demonstrates the functionality of V2V DSRC based Queue detection and Queue warning in the on-road environment including all interfaces, communication and messaging. This test case

- Verifies that Connected Vehicle System Elements are operational
- Verifies that when a simulated queue is created, the following occurs:
- CV-based Q-WARN is detecting roadway location and queue state and passing information to other connected vehicles and infrastructure
- CV-based Q-WARN is receiving queue warnings and information from other connected vehicles and the TME-based Q-WARN application and using data to generate individualized queue response strategies
- CV-based Q-WARN is providing recommendations to the User Interface which is communicating with driver
- CV-based Q-WARN is disseminating queue status alerts and information to other connected vehicles.

Test Case System Configuration

The INFLO System configuration for this Prototype Acceptance Test Case is shown in Figure 4-36 below.



Source: Battelle

Figure 4-36. Prototype INFLO System Configuration Used in V2V DSRC Queue Warning On-road Testing.

Test Case Location

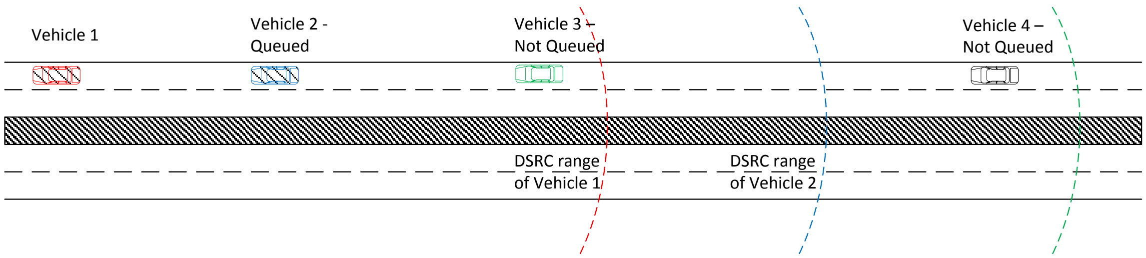
This test was conducted on the Ohio DOT Delaware Test Pavement north of Columbus. U.S. DOT Acceptance Test Demonstration was also conducted on the same ODOT Delaware Test Pavement.

Test Case Setup (Route and Messaging)

The scenario for this Prototype Acceptance Test is illustrated in Figure 4-37 through Figure 4-38. Figure 4-37 illustrates the configuration when Vehicle 2 approaches Vehicle 1 and determines that it is queued. Vehicle 3 approaches, receives the vehicle queued message and delivers the Queue Ahead message to the driver. Vehicle 3 also rebroadcasts the Queue Ahead message, which is received and displayed by Vehicle 4. Vehicle 4 is within DSRC range of Vehicle 3, but is not within DSRC range of Vehicle 3.

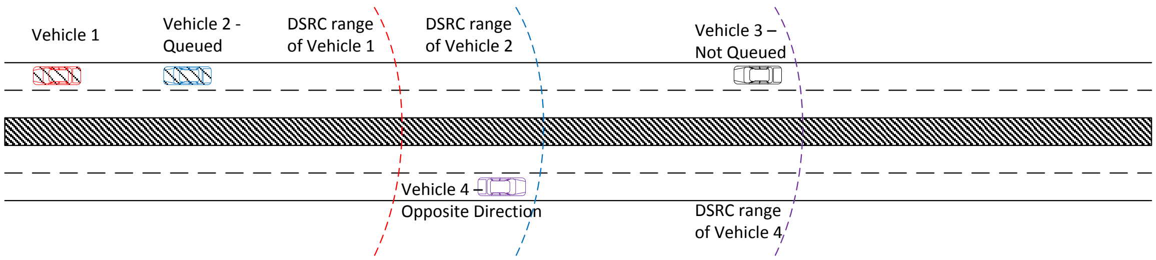
The scenario for V2V Message Relay through vehicles approaching from the opposite direction is illustrated in Figure 4-38. Figure 4-38 illustrates the configuration when Vehicle 2 approaches Vehicle 1 and determines that it is queued. Vehicle 4 approaches from the opposite direction, receives the vehicle queued message, *does not* display it to the driver and rebroadcasts the Queue Ahead message. Vehicle 3 receives the Queue Ahead message from Vehicle 4 and displays it to the driver. Vehicle 3 is within DSRC range of Vehicle 4, but is not within DSRC range of Vehicle 2.

Figure 4-38 illustrates the configuration when vehicle/nomadic device 9 approaches from the opposite direction, receives the vehicle queued message and *does not* deliver the Queue Ahead message to the driver.



Source: Battelle

Figure 4-37. Q-WARN V2V Message Relay through Following Vehicles



Source: Battelle

Figure 4-38. Q-WARN V2V Message Relay with Opposing Vehicles

Test Case Results

Researchers verify that all messages are received and displayed to the driver at the proper locations when travel is in the specified direction. They also confirmed that the messages are received, but not displayed to the driver when traveling in the opposite direction.

Figure 4-39 through Figure 4-44 below show vehicles and components used for testing and demonstration.

Source: Battelle

Figure 4-39. Stopped and Queued Vehicle on Delaware Test Pavement and RSU.

Source: Battelle

Figure 4-40. Android Samsung Cellular Phone Being Inserted in Arada Backpack.

Source: Battelle

Figure 4-41. External DSRC and GPS Antenna Used for V2V DSRC Communications.

Source: Battelle

Figure 4-42. RSU to Demonstrate V2I Communications.

Source: Battelle

Figure 4-43. Shuttle Bus Used as Subject Vehicle for Acceptance Test Demonstration.

Source: Battelle

Figure 4-44. Test Vehicles at the Roadside.

Test Case Pass/Fail: Pass

Chapter 5 INFLO Prototype Seattle Small-Scale Demonstration

Following successful completion of Acceptance Testing, the U.S. DOT approved the Project Team to proceed with the next step in verifying the viability of applying connected vehicle technology for INFLO applications, which was to conduct a Small-Scale Demonstration in operational traffic conditions. In this Small-Scale Demonstration, the Project Team worked with Washington State Department of Transportation (WSDOT) to deploy connected vehicle systems at three VSL gantries, and in twenty-one vehicles, in a scripted driving scenario circuiting a corridor on I-5 from Tukwila to Edmonds through downtown Seattle, during morning rush hour the week of January 12, 2015. The INFLO Prototype System collected vehicle speed data from both the WSDOT infrastructure-based speed detectors and the connected vehicles during the driving scenario. The System processed the data in real time and delivered Q-WARN and SPD-HARM messages to drivers. The Team captured system performance data as well as driver feedback to demonstrate the INFLO Prototype System in a fully operational highway traffic environment and to examine potential benefits of connected vehicle technology.

Objectives of the Demonstration

The purpose of the Small-Scale Demonstration was to deploy the INFLO Prototype System to demonstrate its functionality and performance in an operational traffic environment and to capture data that can help assess hypotheses pertaining to

- INFLO Prototype System functionality
- INFLO Prototype System performance
- INFLO algorithm performance
- Driver feedback.

The first objective was to demonstrate functionality, including

- Demonstration of the basic functionality of the INFLO Prototype System in an operational highway traffic environment, including its ability to
  - Capture current location and telematics data, including location and speed, from the demonstration participants vehicles and vehicle speed data from infrastructure
  - Analyze the data to detect congestion and determine the beginning and end of congestion queues
  - Formulate speed harmonization recommendations
  - Communicate congestion and speed recommendations to drivers.

- Demonstration of connected vehicle data capture and dissemination using both cellular communications and dedicated short-range communications (DSRC) communications.

The second objective was to demonstrate that the INFLO Prototype System has the latency and processing speed to support this functionality in an operational traffic environment.

The third objective was to develop measures that can help assess if the INFLO Prototype System can deliver more precise estimates of the location of the back of the queue and the length of the queue faster than infrastructure-based systems.

Finally, the Team captured driver impressions and feedback concerning the system, its performance and its benefits through a written survey.

The remainder of this chapter provides a summary of the Chapter 5 INFLO Prototype Seattle Small-Scale Demonstration, including

- Site Selection
- I-5 Corridor Demonstration Route
- Implementation of the INFLO Small-Scale Demonstration
- Recruitment and Identification of Demonstration Participants
- Daily Demonstration Vehicle Deployment
- Highlights of the Data Analysis and Evaluation.

Site Selection Criteria

The Project Team worked with the U.S. DOT to assess candidate sites for the Small-Scale Demonstration. In considering the needs and objectives of the program, the Team identified the following criteria for selecting a candidate site for demonstration:

- Has freeway segment with recurring congestion
- Route is a primary route for a targeted participant base
- Existing infrastructure-based queue detection
- Existing Variable Speed Limit (VSL) policy and accompanying signage
- Installed inventory of Dynamic Message Signs
- 4G LTE Coverage
- Local employer(s) with shift-based schedule
- Local operator familiar with ITS Research
- Area subject to varying weather conditions
- Accessible RWIS
- Historical Traffic Data (Baseline)
- Local or Nearby Project Team staff providing rapid troubleshooting and routine maintenance support.

The Project Team compared seven locations and recommended Seattle as the preferred location for the INFLO Small-Scale Demonstration because it met all criteria and because there were multiple VSL installations in the area (I-5, I-90, SR-520) that offer different traffic and incident conditions with varying signage distances. According to U.S. DOT's Bureau of Transportation Statistics publication National Transportation Statistics (Tables 1-69 & 1-70), Seattle, Washington is 12th in the nation in terms of annual person-hours of delay on the highway, and is ranked 4th in terms of the travel time index. As a demonstration site, the city of Seattle offers some unique advantages to this important research. After reviewing the assessments, the U.S. DOT concurred with the recommendation and approved the Project Team to proceed with the Small-Scale Demonstration in Seattle.

I-5 Corridor Demonstration Route

The first corridor to begin Advanced Traffic Management (ATM) operations with variable speed limits (VSL) in Seattle is the seven-mile segment of Interstate 5 (I-5) northbound from the Boeing Access Road to Interstate 90 (I-90) in downtown Seattle. This corridor has 97 electronic signs on 15 sign bridges (gantries) spaced roughly every half-mile. Along this segment, I-5 is reduced from five lanes to two lanes as it enters downtown Seattle. It was this corridor that was selected as the route for demonstration of the INFLO applications.

Demonstration vehicles were driven in a loop on I-5, beginning approximately 9 miles south of downtown. They proceeded north on I-5 through downtown and on to approximately 14 miles north of downtown where they exited and returned southbound, returning to their original starting point. This loop encompassed two highway segments with known congestion points, I-5 North going into downtown from the south and I-5 South going into downtown from the north.

Figure 5-3 shows a Google Earth™ view of the I-5 corridor demonstration route. Red pins show the location of the North and South I-5 entrance and exits for the route (Exit 156 and 179). Light Green Pins show the location of the Edmunds and Tukwila vehicle staging areas which are large parking lots near the entrances. Yellow Pins show the locations of three RSUs at mileposts 159, 159.4 and 160.1. Dark Green Pins show South and North Ends of the I-5 Northbound ATM corridor. Table 5-1 below summarizes key characteristics of the four segments of the roadway. Q-WARN messages were displayed throughout the entire route when warranted. SPD-HARM messages were

Source: WSDOT

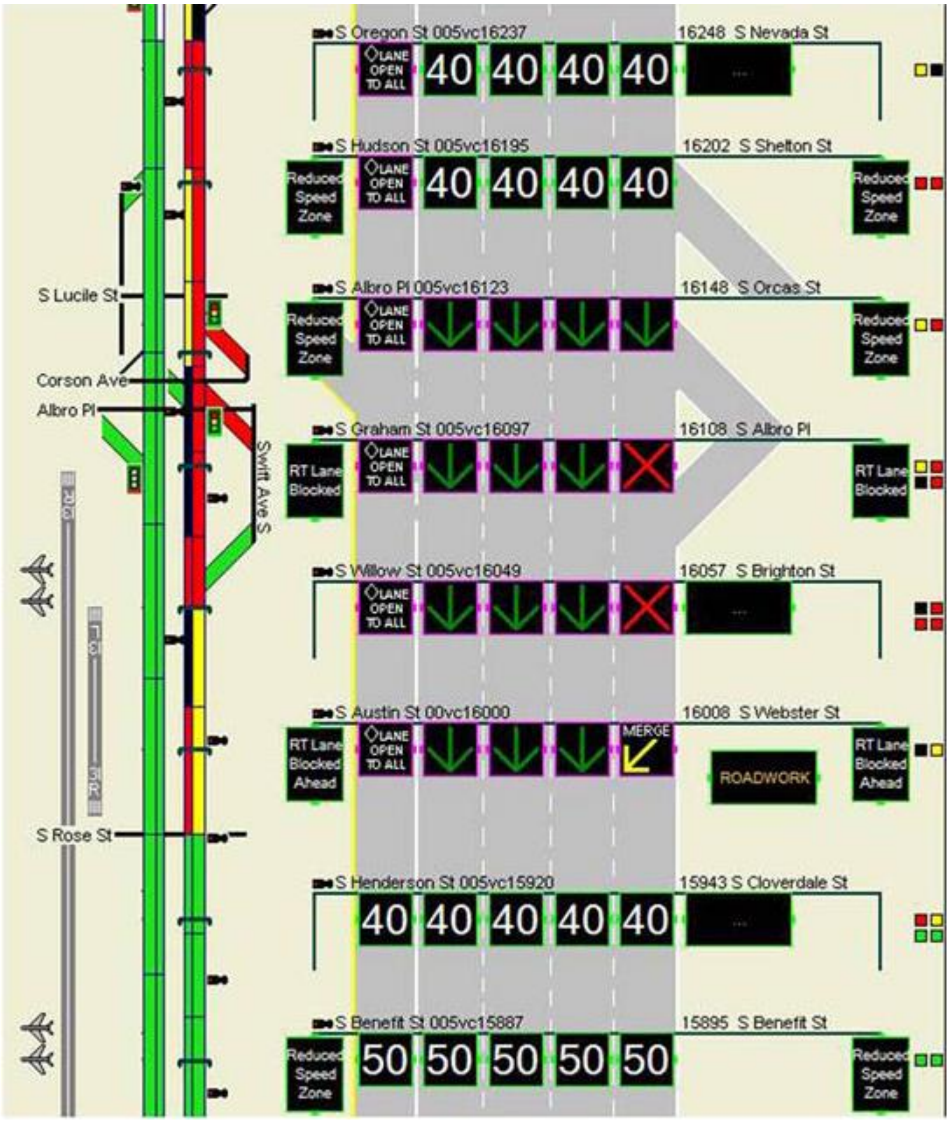
Figure 5-1. Example of Combined VMS and VSLS just South of Seattle, WA.

displayed, with the exception of Northbound I-5 where VSL messages were displayed by the infrastructure.[11]

For this ATM deployment, WSDOT gathers real-time traffic information using existing inductive loop detectors and fills the gaps with additional radar-based speed detectors. Side-mounted dynamic message signs (DMS) are typically installed on every other gantry on both the left and right side of the highway, with remaining gantries having a standard, larger overhead DMS.

The ATM signage system is operated from the WSDOT Northwest Regional Traffic Management Center in Shoreline, Washington just north of Seattle. The software user interface (shown in Figure 5-2) has a control view showing current displays and a preview view on which the operator clicks signs manually based on incident location. In Seattle, the ATM signage is actively managed 24 hours a day.

[11] ATM VSL message display data are not currently available in real time to support real-time coordination with INFLO messaging, but are available after the fact for post-demonstration analysis.



Source: WSDOT

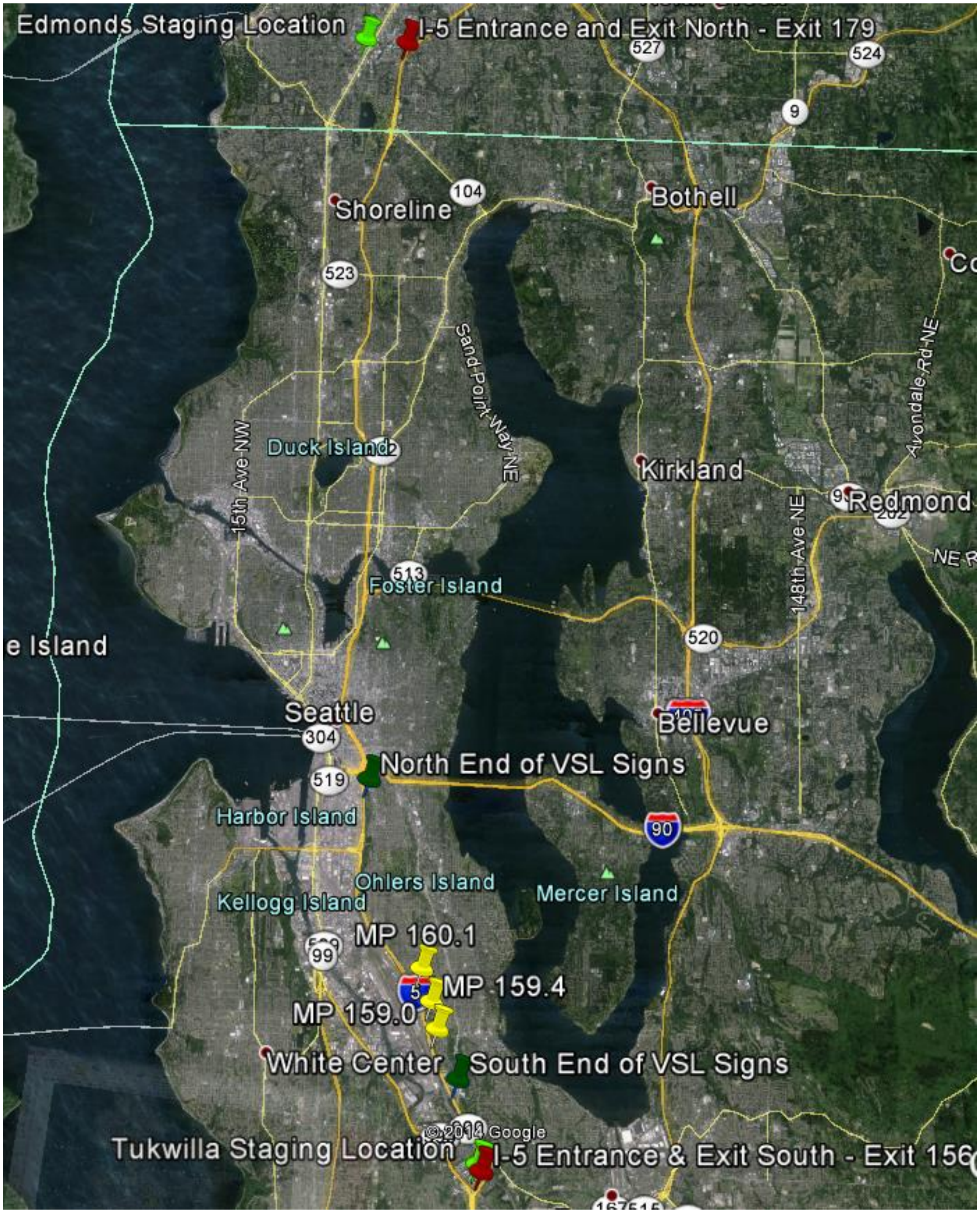
Figure 5-2. Seattle ATM Software User Interface showing VSL and Lane Closures Due to Roadwork.

Table 5-1. Characteristics and Messaging along the Demonstration Route.

Road Segment Number	Road Segment Description*	Mile Post	Beginning of Congestion	Speed Detectors	ATM VSL Signage	Q-WARN Messages	SPD-HARM Messages
1	NB I-5 from South into Downtown	MP 156 to 165	Fixed	Approx. 0.5 mile spacing	Signs spaced approx. 0.5 miles	Yes	No
2	NB I-5 from Downtown North	MP 165 to 179	Variable	Approx. 1 mile spacing	None	Yes	Yes
3	SB I-5 from North into Downtown	MP 179 to 165	Fixed	Approx. 1 mile spacing	None	Yes	Yes
4	SB I-5 from Downtown South	MP 165 to 156	Variable	Approx. 1 mile spacing	None	Yes	Yes

*NB-Northbound, SB-Southbound

Source: Battelle



Source: Google Earth™

Figure 5-3. Google Earth™ View of I-5 Demonstration Route showing Entrance and Exit and RSU Locations.

Variable Speed Limits

In the Seattle region, ATM signage displays regulatory enforceable VSLs. As shown in Figure 5-1, these signs are displayed in the configuration of a typical speed limit sign. VSLs are entirely automated and are activated by the system in advance of congested areas, including those caused by incidents. The VSL algorithm uses 20-second averages of current speed to assess congestion levels on the corridor at stations ¼- and ½-mile downstream, and posts speeds roughly based on 85th percentile speed. Thus, operators need not deploy the variable speeds, although they can manually override the signs if needed to better reflect current speed on the highway. WSDOT notes that the system automatically detects slowing traffic and posts a lower speed limit roughly 5 minutes before the slowdown would be manually detected.

WSDOT posts speeds for each lane on a single gantry. Speeds may differ up to 15 mph between the general purpose and the HOV lanes. However, note that speeds never vary between individual general purpose lanes at a single gantry. Between gantries, the maximum drop in speed is 15 mph.

VSLs work in groups of three gantries to reduce speeds for a smooth speed transition. However, variable speeds are displayed through the congested area and there is no limit to the number of consecutive gantries that display VSLs. Because each gantry in the Seattle area contains either an overhead or a set of side-mounted DMS, WSDOT typically posts messages to supplement the VSLs. WSDOT posts a specific message about speed reductions due to a work zone or incident, instead of a generic “CONGESTION AHEAD” message for heavy traffic conditions. The message will typically read “REDUCED SPEED ZONE.”

Although the VSLs posted on the ATM signage are technically enforceable, the highway patrol generally does not tightly enforce minor speeding infractions of individual variable speed postings. WSDOT describes the VSLs in the Seattle region as essentially “self-enforcing.”

No changes to the operations of the current ATM system were planned as a result of this demonstration.

Infrastructure- and Connected Vehicle-based Speed Detection

The demonstration route includes a section of highway roughly seven miles in length along I-5 from milepost 157.23 to 164.46 that has inductive loop speed detectors in each lane spaced approximately ½ mile apart, which provided speed and occupancy data every 20 seconds. Detectors elsewhere in the corridor are spaced approximately one mile apart.

The connected vehicle OBUs provided BSM data every second. For the purposes of using the connected vehicle data from equipped vehicles more accurately, each link (segment between consecutive detector stations) was divided into smaller links of approximately 0.1 mile. This was accomplished by defining the boundaries of the sublinks at a milepost marker every 0.1 mile. For example the first sublink within the first link can be from 157.3 to 157.4 and so on. The last sublink within the corridor can be from 164.3 to 164.4.

DSRC Communications along Route

In the Small-Scale Demonstration, the Team equipped demonstration vehicles with OBUs that have the capability to transmit BSMs either using DSRC radio or cellular radio when a DSRC RSU is not present. Three DSRC RSUs were installed along the demonstration route. These roadside units (RSUs) were completely independent of the WSDOT ATM system including their own separate communications backhaul. The RSUs were used to demonstrate the capability of the In-Vehicle

System to automatically switch between sending and receiving messages via DSRC and sending and receiving messages via cellular communications and to demonstrate that both methods provide the latency needed to support SPD-HARM and Q-WARN functionality.

INFLO Messages

During the conduct of this demonstration, the Project Team ran the TME-based Q-WARN and SPD-HARM algorithms. The algorithms generated Q-WARN and SPD-HARM messages based upon

- WSDOT infrastructure data only
- Connected vehicle data only
- Integrated WSDOT infrastructure and connected vehicle data.

The messages delivered to drivers were generated from integrated WSDOT Infrastructure and connected vehicle data. The infrastructure only and vehicle only messages were captured in the database for subsequent comparison and analysis.

Where congestion was detected the Q-WARN algorithm generated two messages:

- Q-Ahead with distance to back of queue (congestion) for vehicles approaching a queue
- In-Queue with distance and time to the beginning of the queue for vehicles in a queue.

SPD-HARM messages were recommended speeds for drivers before areas of congestion to maintain flow and reduce risk of collisions due to speed differentials.

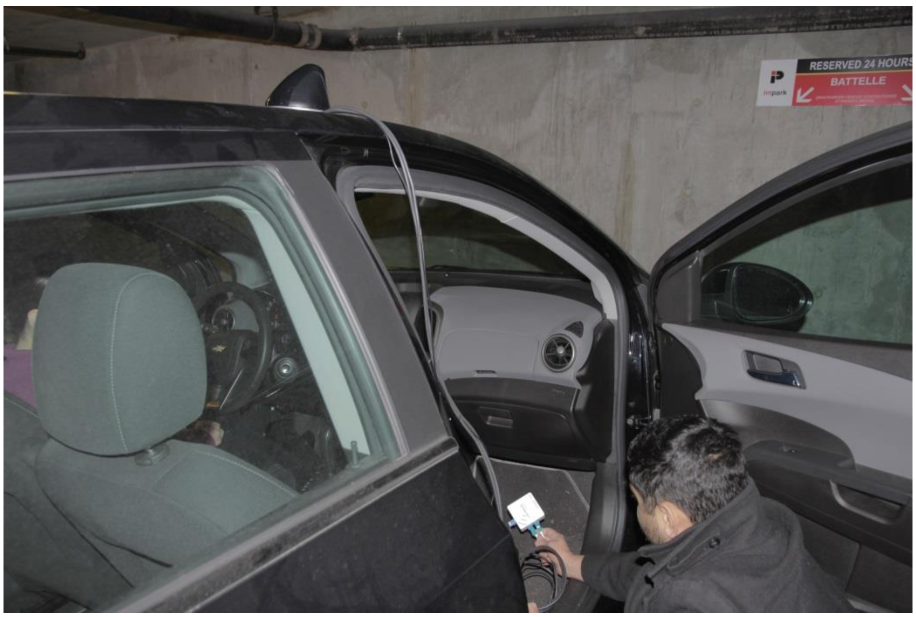
Recruitment and Identification of Demonstration Participants

Battelle's Institutional Review Board (IRB) reviews and approves all human subjects research in accordance with the provisions of 45 CFR Part 46 and maintains a Federal wide Assurance, FWA00004696 (approval to 25 February 2018) with the Department of Health and Human Services' (DHHS) Office of Human Research Protections (OHRP). All elements of this demonstration involving human subjects were reviewed and approved in advance by Battelle's IRB.

Participants were recruited using internet classified advertisements, based upon prior success. The Project Team also coordinated with WSDOT to advertise for recruits using WSDOT's Twitter® account. The classified advertisements directed interested participants to an informational website that contained detailed information about the demonstration, participant eligibility requirements, contact information and what they could expect to do during the demonstration. The informational website provided potential participants with a phone number and e-mail address that they could contact if they were eligible and interested in participating. A trained administrative staff person fielded these calls and e-mail inquiries, and used a pre-designed screening questionnaire to identify eligible participants.

Once recruited, the Team scheduled an appointment with the participants at the Battelle Seattle Research Center. The participant consent, participant briefing and equipment installation was performed at the Battelle Seattle Research Center. Once the participant had completed the intake process, the installer accompanied the participant to his or her vehicle for installation of the connected vehicle equipment.[12] The installer discussed the installation procedure with the participant, and they mutually decided on the best placement of the device. The placement of the connected vehicle equipment was based on criteria such as dashboard configuration, available mounting hardware, location of the vehicle's accessory power port (APP), placement for optimum GPS signal availability, routing of power cables from the APP to the connected vehicle equipment, ease of inserting and removing the device, and participant concerns. Once the best location was determined, the installer installed the mounting hardware and instructed the participant on how to insert and remove the device. Figure 5-4 shows a part of the installation process.

After installing the devices, the installer performed a testing procedure that exercised the connected vehicle equipment, in order to ensure that the device was working before leaving the installation facility. The testing protocol included verifying that the connected vehicle equipment was operational, the DSRC communications were functional and cellular communication was working.



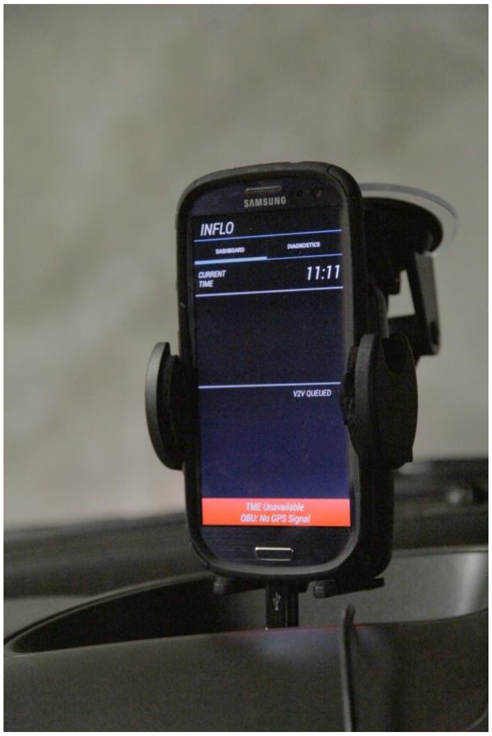
Source: Battelle

Figure 5-4. Installation of the In-vehicle System showing the Placement of the GPS/DSRC Antenna on the Vehicle Roof and the DSRC Module under the Passenger Seat.

Protecting driver privacy and confidentiality was a key requirement in the current project. Participant information and responses to questionnaires were identified by confidential code. To address the issue of driver privacy, no data identifying the vehicle or the driver were captured electronically or uploaded to the INFLO Database. Requirements ensuring the anonymity of the BSM were adhered to, with one exception. For the purposes of the demonstration, the MAC address of the DSRC radio was not regularly changed, as it will be in actual deployments. The MAC address was held constant so that data could be analyzed consistently. The record of which DSRC radio was installed in each vehicle was kept secure during the demonstration and was destroyed following the demonstration.

[12] Battelle acquired components and assembled connected vehicle installation kits that were provided to system installers.

Figure 5-5 shows the drive display unit (Samsung smartphone) during post-installation testing.



Source: Battelle

Figure 5-5. Initial Display of the INFLO Application in a Participant Vehicle during Post Installation Testing.

Daily Demonstration Vehicle Deployment

The Project Team recruited twenty-one drivers with vehicles to participate in the Small-Scale Demonstration. As described earlier, the demonstration was conducted the week of January 12, 2015. For Monday through Wednesday demonstration runs, the participants were divided in two platoons: platoon one had seven drivers, and platoon two had fourteen drivers. Each platoon concentrated the number of vehicles within a link and sublink to provide relatively compact groupings of connected vehicle data flowing through the congested area for both comparison with and enhancement of loop detector data. Platoons were intended to be spaced so that the Q-WARN and SPD-HARM messages received by the second platoon were based upon connected vehicle data from the first platoon, integrated with infrastructure data. On Monday, the second platoon was released 15 minutes after the last member of the first platoon left. On Tuesday and Wednesday, the second platoon was released 5 minutes after the last member of the first platoon left. On Thursday and Friday cars were not grouped, but were released individually approximately 30 seconds apart.

Drivers were instructed to drive as they normally would, naturalistically, passing each other and changing lanes as desired. They were not expected to remain in sequential order or in the same lane.

Participants assembled each morning during the demonstration week, Monday through Friday, and were asked to drive two round-trip traversals along the I-5 corridor between Tukwila and Edmonds shown in Figure 5-3. One round trip was 48.8 miles. They were given instructions to not use the express lanes or alternate routes unless instructed by law enforcement in the event of a traffic incident.

Drivers were asked to assemble in a parking lot in Tukwila at 6:00 am while the installed equipment was checked to ensure it was fully operational.

Participants drove north on I-5, exited the freeway at 220th street (exit 179), and drove to a parking lot in Edmonds. When all members of their respective platoons were assembled, the drivers were released as a platoon and drove south on I-5 to Tukwila. The platoons were released 15 minutes apart on Monday and 5 minutes apart on Tuesday and Wednesday. Participants were again staged in Tukwila and released as platoons.

Equipment De-installation and Closeout Driver Survey

Upon arrival for closeout, participants were requested to fill out a post demonstration questionnaire. Following completion of the questionnaire, a Team member accompanied the participant to their car, de-installed the connected vehicle equipment and answered any questions that the participants have. Finally, the participants were compensated for their participation in the study.

Highlights of the Data Analysis and Evaluation

The scope of the Small-Scale Demonstration was to deploy the prototype in an operational traffic environment to demonstrate that it has the functionality and capacities needed to support development and hardening into a production-level application for regional deployment. The Small-Scale Demonstration was successful in achieving these objectives. The system was proven to reliably

- Capture current location and telematics data from connected vehicles and vehicle speed data from infrastructure
- Analyze the data to detect congestion and determine the end of congestion queues
- Formulate speed harmonization recommendations
- Communicate queue location and speed harmonization recommendations to drivers.

The Small-Scale Demonstration proved connected vehicle data capture and dissemination functionality in an operating environment using both cellular communications and DSRC communications. Furthermore, the Small-Scale Demonstration confirmed that the INFLO Prototype System has the latency and processing speed to support INFLO application functionality in an operational traffic environment.

Data was captured as part of the demonstration to understand system and algorithm performance and to suggest areas for refinement in future work. Following is a summary of highlights from the data comparisons and analyses that were performed. More detailed background and discussion may be found in the *Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Report*. Note that the scope of these activities was the first demonstration of the functionality of a prototype in an operational environment. As such, it was not a rigorous test and evaluation of a production-level system.

System Functionality and Performance Observations

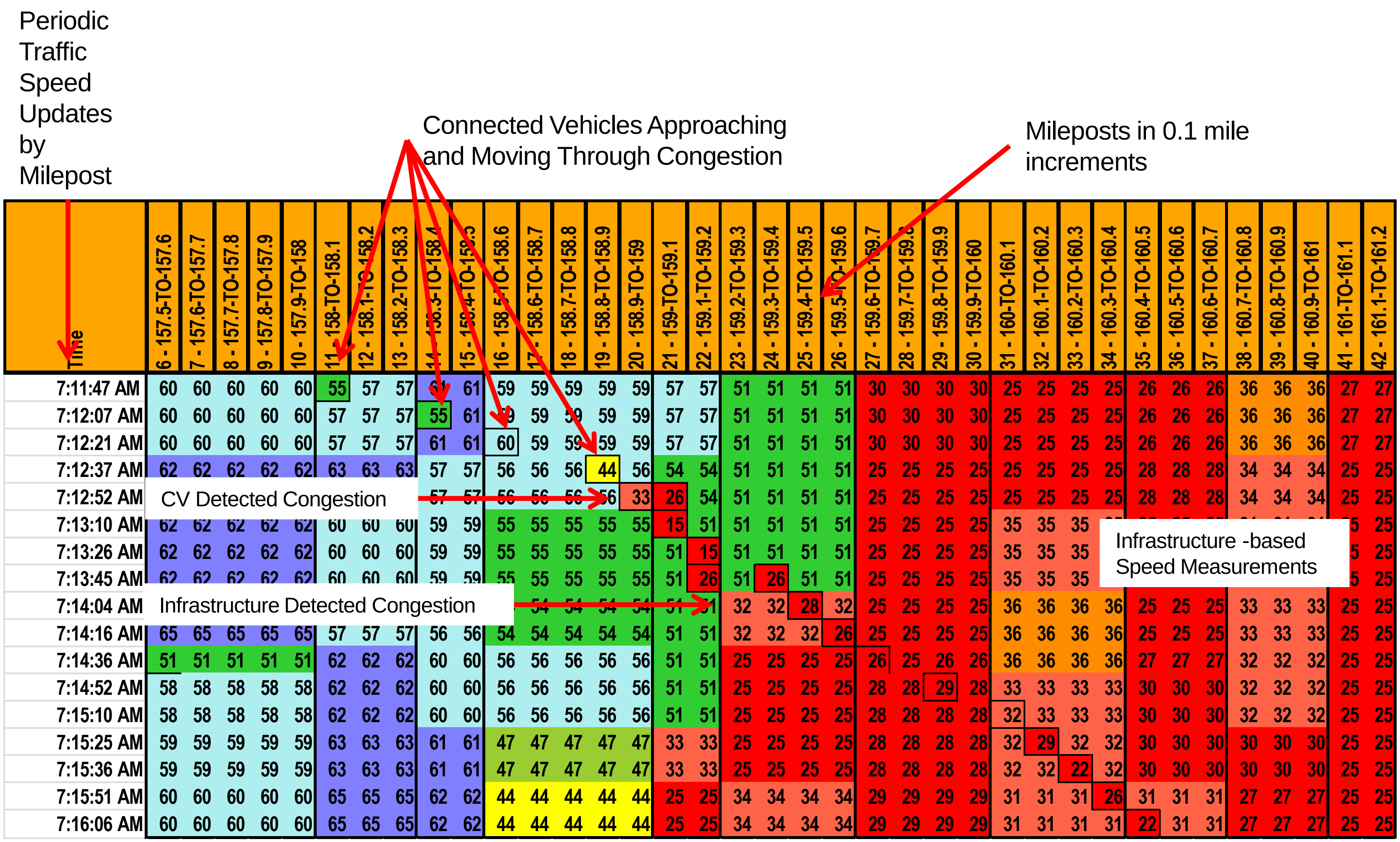
While the demonstration was not a comprehensive test, the system and algorithms performed as expected and had sufficient BSM data to assess traffic conditions and deliver messages to drivers. No evidence was found of loss of BSM data, whether by DSRC or cellular communications, or of disruption in the algorithms caused by loss of BSM data. DSRC and cellular coverage was sufficient to capture BSMs from the deployed vehicles. The system, as designed, appears to fully meet the needs for reliably capturing BSMs during this demonstration.

No evidence was found that BSMs were lost during the switch between cellular communications to DSRC and back. No evidence was found of disruption in the algorithms caused by switching between cellular to DSRC and back.

INFLO Prototype System testing and demonstrations found that the system was very capable of capturing vehicle and infrastructure speed data, analyzing and processing the data and delivering messages to drivers well before they would need to take suitable action. In general, the cycle of capturing data from vehicles, storing it in the database, processing it and delivering messages back to drivers took less than 10 seconds. In practice, the process of delivering messages to the drivers *after detection* by Q-WARN and SPD-HARM algorithms took 2 to 3 seconds. Drivers could be expected to receive messages at least a mile in advance of the back of the queue.

Algorithm Performance Observations

The example below shows one case where the INFLO Prototype System detected a queue 3 minutes earlier using connected vehicle data than was achieved with infrastructure only data. Figure 5-6 shows a portion of INFLO operations logs where the connected vehicle data and the traffic sensor data have been fused together. The figure shows a connected vehicle platoon approaching the back of an existing queue. Large blocks of similar colors represent data received from the infrastructure-based speed detectors. These data are collected approximately every half mile, and, for illustration, are assumed to apply to each 0.1 segment. In this example, infrastructure sensors estimate the back of the queue is located at milepost 159.6 at 7:11:47 a.m. and then moves upstream to milepost 159.2 at 7:14:36 a.m. and then to milepost 159.0 at 7:15:51 a.m. Small blocks of a single color (like that shown at milepost 158 at 7:11:47 a.m.) indicate the speed of a connected vehicle platoon (55 mph) approaching the back of the queue. Note that as the connected vehicle platoon approaches the back of the queue, the reported speed of the connected vehicles begins to decrease (44 mph at 7:12:37 a.m., 33 mph at 7:12:52 a.m., etc.). This reduction in speed is detected much sooner than that reported by the infrastructure sensor system. The connected vehicle platoon indicates that the back of the platoon had reached milepost 159.0 at 7:12:52 a.m. The infrastructure sensor system does not detect the back of the queue until 7:15:51 a.m. – almost 3 minutes after the connected vehicle platoon. This is one example that demonstrates the ability of the INFLO Prototype System to detect a queue earlier using connected vehicle data than can be achieved with infrastructure only data. Because connected vehicles can provide vehicle speed data almost continuously along a roadway, queues can be detected earlier than when using speeds from periodic infrastructure sensor locations. As shown in a later example, connected vehicle data can also be used to determine the back of the queue more precisely.

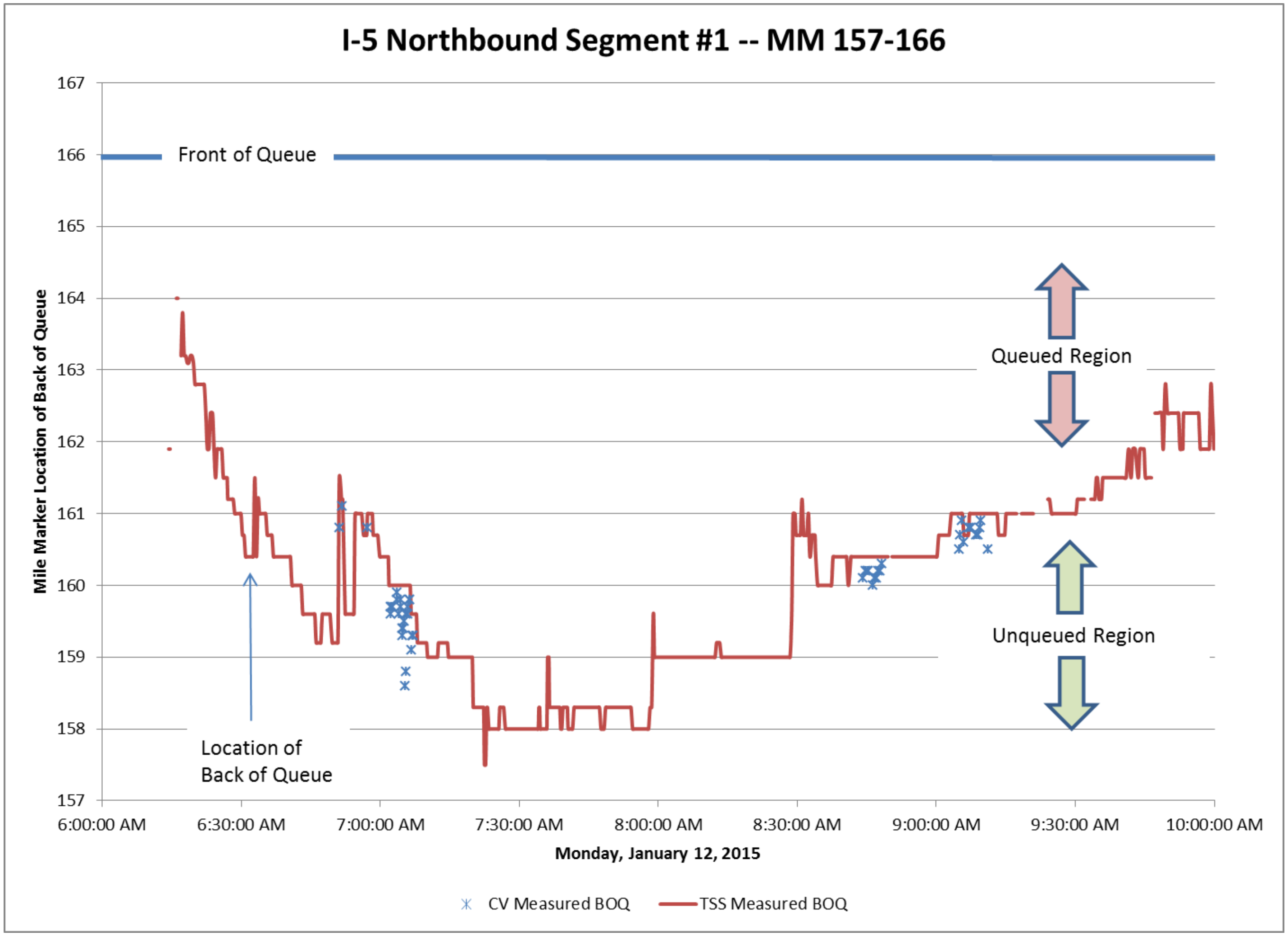


Source: TTI

Figure 5-6. Example Data Showing Infrastructure and Connected Vehicle-based Speed Measurements every 0.1 Mile as Connected Vehicles Approach the Back of the Queue.

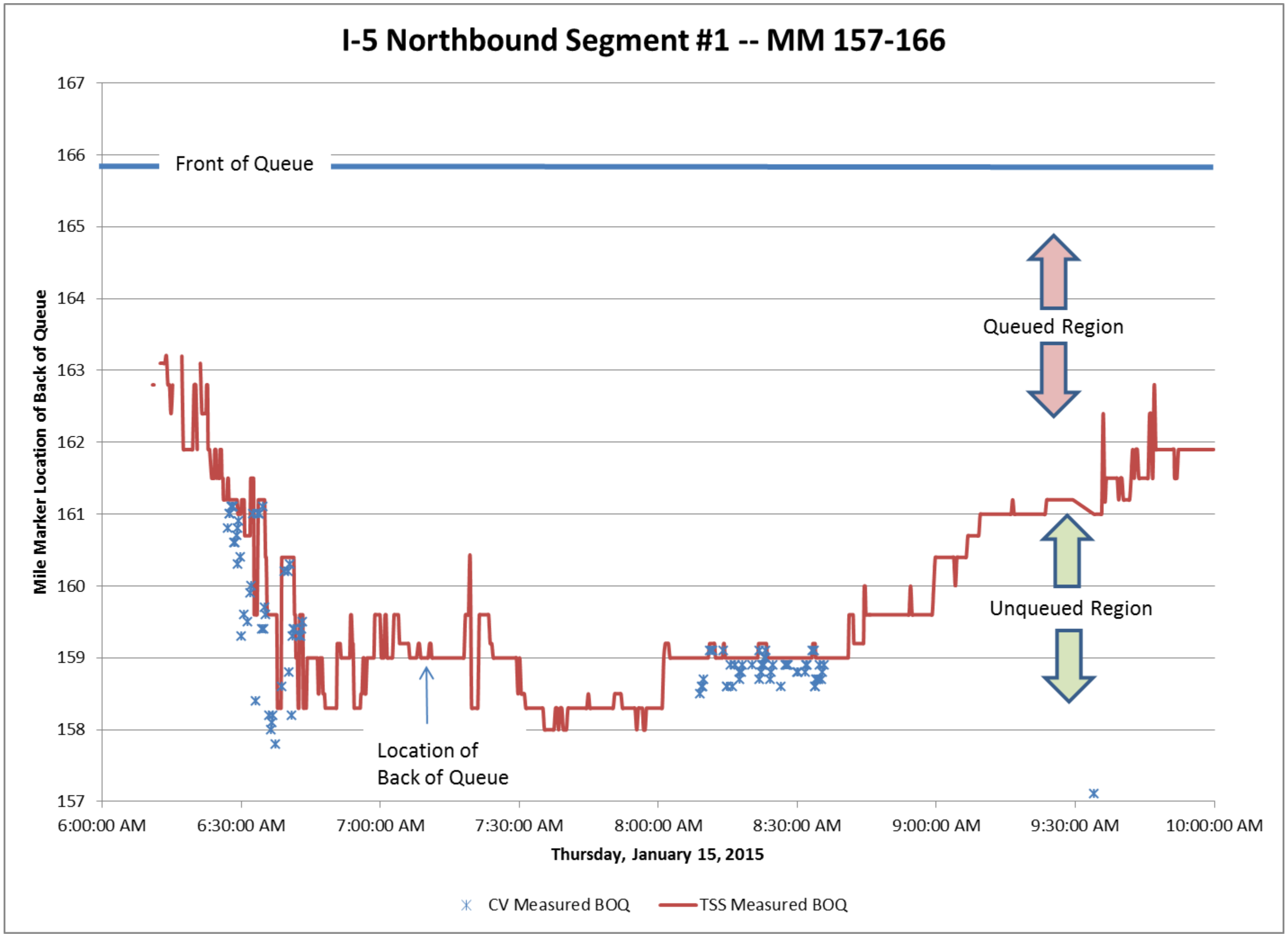
Two examples below show where connected vehicles reported being in a queued state between a 0.5 mile and 1.5 miles further upstream than that determined by using traffic sensor data alone. For this analysis, the research team used a series of time-space plots comparing the estimated location of the back of the queue derived by INFLO algorithms using WSDOT traffic sensors data only with the estimated location of the back of the queue derived using connected vehicle data. In this deployment, a section of roadway was declared to be in a queue state when the average speed in the section was reported to be 30 mph or less. The same speed threshold was used for both the connected vehicles and the traffic sensor data.

Figure 5-7 and Figure 5-8 compare the location of the back of queue in the first northbound segment on I-5, from milepost 157 to 166, for two days that the INFLO Prototype System was deployed in Seattle. These figures show the location of the back of queue as measured by the various INFLO inputs from 6:00 a.m. to 10:00 a.m. The solid line near the top of each figure represents the predefined location of the bottleneck (or the front of the queue). The jagged (red) line represents the location of the back of queue using the traffic sensor data only. The stars represent the location of the back of queue as determined by the connected vehicles. These figures show that the connected vehicles reported being in a queued state between a 0.5 mile and 1.5 miles further upstream than that determined by using traffic sensor data alone. This suggests that because connected vehicle speed data is spread nearly continuously, rather than spaced periodically, it can substantially improve the resolution in detecting the back of the queue, compared to infrastructure only information.



Source: TTI

Figure 5-7. Comparison of Back of Queue Estimates for I-5 Northbound Segment 1 on Monday, January 12, 2015.



Source: TTI

Figure 5-8. Comparison of Back of Queue Estimates for I-5 Northbound Segment 1 on Thursday, January 15, 2015.

The Team explored the precision of vehicle speed estimates in the queue. For this assessment, we refer back to Figure 5-6 above. This figure shows infrastructure and vehicle-based speed data every 0.1 mile as connected vehicles approach and progress through the queue. We note boxes showing connected vehicle speeds among the blocks of infrastructure measured speed. In this case the INFLO algorithms captured speed from connected vehicles at 0.1 mile intervals, while the infrastructure-based sensors captured vehicle speeds every 0.5 mile. While the infrastructure-based sensors are spaced periodically and must estimate the speeds between sensors, connected vehicles can provide speeds almost continuously along a path, thereby providing more precise estimates of vehicle speeds in the queue.

The next example in Figure 5-9 provides a comparison of the infrastructure speeds measured by WSDOT infrastructure-based speed detectors to the WSDOT VSL speeds and the INFLO SPD-HARM recommended speeds. The data shown in the figure is a sample of the speed harmonization data produced by the algorithm on Friday, January 16, 2015. The speeds are color coded with speed greater than 50 mph shown in purple to light blue, speeds between 50 mph and 40 mph shown in shades of green, speeds between 40 mph and 30 mph being yellow and orange, and speeds 30 mph or less shown in red. In this deployment, the freeway was defined to be queued when speeds reached 30 mph or less, and congested when speeds are between 30-50 mph.

The top chart in Figure 5-9 shows the travel speeds as measured by the WSDOT infrastructure-based speed detectors. The middle chart shows the WSDOT VSL speeds. The bottom chart shows the harmonized speed recommended by the INFLO algorithm. The top chart shows that travel speed, as measured by the WSDOT detectors, remained relatively high (greater than 50 mph) in advance of the congestion point, creating a large speed differential approaching the back of the queue. The bottom two charts show that the VSL and INFLO algorithms both recommended speeds that provided a smooth transition in advance of the back of the queue, but were different in their details.

From 6:20 to 6:21 AM on the detector data, we see slow down from 52 to 33 MPH beginning at milepost 161, followed by a brief speedup and then slowdown again to 27 MPH at milepost 161.5. During this time, the WSDOT VSL speeds recommend 30 MPH at milepost 161.0, preceded by speed reduction steps beginning at milepost 158 from 60 to 55, 50, 40 and finally 30 MPH at milepost 161. Detector speeds continue to decrease between 161.0 and 161.5 through 6:22 AM. At 6:21 AM, the VSL speed reduction step down shifts to 60, 50, 35 and finally 30 at milepost 161.0. This pattern remains constant until 6:23 where the speed at milepost 161.0 is adjusted to 35 MPH, even though measured speeds there were below 30 MPH.

During this same time, the INFLO SPD-HARM application is more dynamic. This algorithm shows the back of the queue and congestion is updated every 20 to 30 seconds and the SPD-HARM recommendation changes with each update and varies more widely than that specified by VSL. The step down in speed recommended by SPD-HARM is consistently in 5 MPH increments. The beginning of the SPD-HARM speed reduction varied from milepost 159 to 157 and changed frequently.

The comparison of the figure below is enlightening and confirms that the SPD-HARM recommendations are different from VSL. The VSL system and SPD-HARM algorithms are both intended to achieve the same objectives and appear to provide a smooth transition in speed. The VSL system has been in place for a few years and has been refined as WSDOT has gained experience. Furthermore, the VSL speeds are regulatory and enforceable. SPD-HARM is advisory only and this is its first demonstration.

The results shown here are promising, but, as expected, more refinement is needed. The VSL results suggest that the number of SPD-HARM speed step downs and their length could be reduced. Additionally, VSL results suggest that the frequency in updates of SPD-HARM recommendations may also be reduced. This is a subject area where empirical connected vehicle data and driver feedback is needed to guide adjustment of the algorithms and their control parameters.

Raw Traffic Sensor Data Speeds

Time	157.5	157.6	157.7	157.8	157.9	158.0	158.1	158.2	158.3	158.4	158.5	158.6	158.7	158.8	158.9	159.0	159.1	159.2	159.3	159.4	159.5	159.6	159.7	159.8	159.9	160.0	160.1	160.2	160.3	160.4	160.5	160.6	160.7	160.8	160.9	161.0	161.1	161.2	161.3	161.4	161.5	161.6	161.7	161.8	161.9
6:20:36 AM	56	56	56	56	56	65	65	65	62	62	60	60	60	60	60	58	58	57	57	57	57	56	56	56	56	51	51	51	51	51	51	51	52	52	52	33	33	51	51	51	27	27	27	27	28
6:20:55 AM	59	59	59	59	59	65	65	65	61	61	62	62	62	62	62	63	63	62	62	62	62	57	57	57	57	51	51	51	51	51	51	51	51	51	51	34	34	51	51	51	25	25	25	25	31
6:21:01 AM	59	59	59	59	59	65	65	65	61	61	62	62	62	62	62	63	63	62	62	62	62	57	57	57	57	51	51	51	51	51	51	51	51	51	51	34	34	51	51	51	25	25	25	25	31
6:21:09 AM	59	59	59	59	59	65	65	65	61	61	62	62	62	62	62	63	63	62	62	62	62	57	57	57	57	51	51	51	51	51	51	51	51	51	51	34	34	51	51	51	25	25	25	25	31
6:21:18 AM	60	60	60	60	60	58	58	58	61	61	60.5	60.5	60.5	60.5	60.5	60	60	62	62	62	62	51	51	51	51	51	51	51	51	51	51	51	55	55	55	32	32	38	38	38	25	25	25	25	30
6:21:24 AM	60	60	60	60	60	58	58	58	61	61	60.5	60.5	60.5	60.5	60.5	60	60	62	62	62	62	51	51	51	51	51	51	51	51	51	51	51	55	55	55	32	32	38	38	38	25	25	25	25	30
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6:23:59 AM	54	54	54	54	54	61	61	61	57	57	56.5	56.5	56.5	56.5	56.5	56	56	63	63	63	63	58	58	58	58	51	51	51	51	36	36	36	31	31	31	29	29	28	28	28	25	25	25	25	29
6:24:18 AM	54	54	54	54	54	61	61	61	57	57	56.5	56.5	56.5	56.5	56.5	56	56	63	63	63	63	58	58	58	58	51	51	51	51	36	36	36	31	31	31	29	29	28	28	28	25	25	25	25	29

WSDOT Harmonized Speeds

Time	157.5	157.6	157.7	157.8	157.9	158	158.1	158.2	158.3	158.4	158.5	158.6	158.7	158.8	158.9	159.0	159.1	159.2	159.3	159.4	159.5	159.6	159.7	159.8	159.9	160.0	160.1	160.2	160.3	160.4	160.5	160.6	160.7	160.8	160.9	161	161.1	161.2	161.3	161.4	161.5	161.6	161.7	161.8	161.9
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6:22:48 AM	65	65	65	65	65	65	65	65	65	65	65	65	65	65	60	60	60	60	60	50	50	50	50	50	50	35	35	35	35	35	35	35	35	35	35	30	30	30	30	35	35	35	35	35	35
6:22:59 AM	65	65	65	65	65	65	65	65	65	65	65	65	65	65	60	60	60	60	60	50	50	50	50	50	50	35	35	35	35	35	35	35	35	35	35	30	30	30	30	35	35	35	35	35	35
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INFLO Harmonized Speeds

Time	157.5	157.6	157.7	157.8	157.9	158.0	158.1	158.2	158.3	158.4	158.5	158.6	158.7	158.8	158.9	159.0	159.1	159.2	159.3	159.4	159.5	159.6	159.7	159.8	159.9	160.0	160.1	160.2	160.3	160.4	160.5	160.6	160.7	160.8	160.9	161.0	161.1	161.2	161.3	161.4	161.5	161.6	161.7	161.8	161.9
6:20:36 AM	65	60	60	60	60	60	65	65	65	65	65	65	65	65	65	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	30	30	30
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6:21:18 AM	65	65	65	65	65	65	65	65	65	65	65	65	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	30	30	30	30
6:21:24 AM	65	65	65	65	65	65	65	65	65	65	65	65	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	30	30	30	30
6:21:33 AM	65	65	65	65	65	65	65	65	65	65	65	65	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	30	30	30	30
6:21:42 AM	65	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	30	30	30	30	30
6:21:50 AM	65	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	30	30	30	30	30
6:21:59 AM	65	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	30	30	30	30	30
6:22:14 AM	65	65	65	65	65	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	30	30	30	30	30	30	30
6:22:23 AM	65	65	65	65	65	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	30	30	30	30	30	30	30
6:22:31 AM	65	65	65	65	65	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	30	30	30	30	30	30	30
6:22:40 AM	65	65	65	65	65	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	30	30	30	30	30	30	30
6:22:48 AM	65	65	65	65	65	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	30	30	30	30	30	30	30
6:22:59 AM	65	65	65	65	65	65	65	65	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	35	35	30	30	30	30	30
6:23:08 AM	65	65	65	65	65	65	65	65	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	35	35	30	30	30	30	30
6:23:22 AM	65	60	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	35	35	30	30	30	30	30
6:23:31 AM	65	60	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	35	35	30	30	30	30	30
6:23:39 AM	65	60	60	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	35	35	35	30	30	30	30	30
6:23:49 AM	65	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	30	30	30	30	30	30	30	30	30	30
6:23:59 AM	65	60	60	60	60	60	60	60	60	60	60	60	55	55	55	55	55	50	50	50	50	50	45	45	45	45	40	40	40	40	35	35	35	35	35	30	30	30	30	30	30	30	30	30	30

> 60.1 mph	55 mph - 50.1 mph	45 mph - 40.1 mph	35 mph - 30.1 mph
60 mph - 55.1 mph	50 mph - 45.1 mph	40 mph - 35.1 mph	≤ 30

Source: TTI

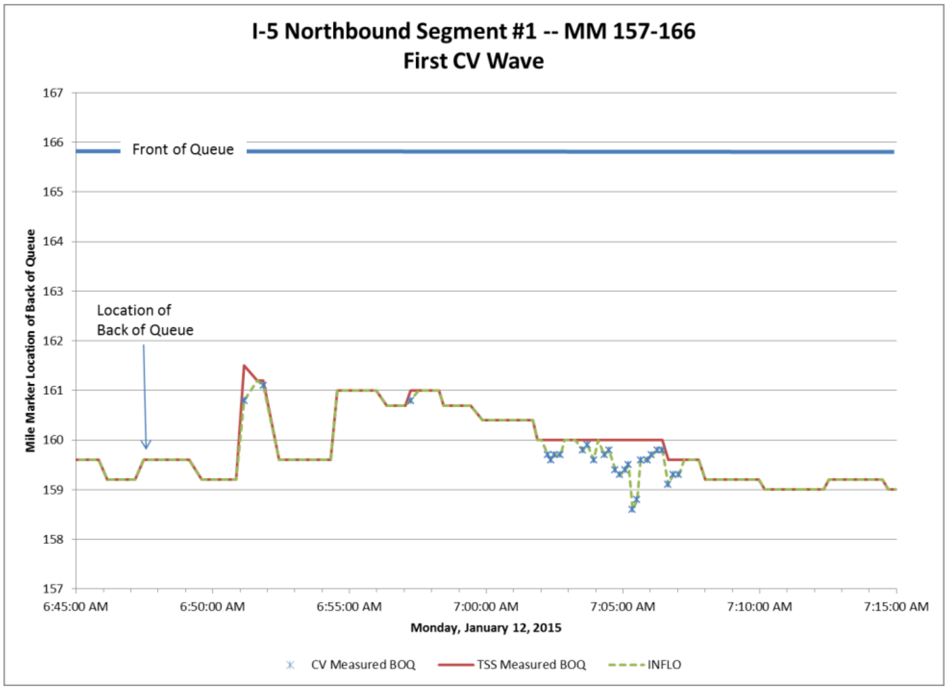
Figure 5-9. Example Comparison of SP-HARM Recommended Speeds to Infrastructure Speeds.

The next example explores potential influences of market penetration on queue detection. Here "market penetration" is used to loosely denote the percentage of vehicles on the roadway that are connected vehicles. While the number of connected vehicles deployed was not intended to be sufficient to provide a comprehensive assessment of market penetration, insight into the issue can be obtained by examining how the algorithm determined the back of queue under different release patterns.

During the evaluation, two different patterns were used to control how the connected vehicles moved through the study area. Early in the week, the connected vehicles were grouped in two tight platoons – a six-vehicle platoon was released first followed by a twelve-vehicle platoon released approximately 15 minutes later. Later in the week, the release pattern was changed to one vehicle released every 30 seconds. In the first release pattern, the connected vehicles experienced shorter headways between individual vehicles within a platoon, while the second release pattern had longer headways between individual vehicles. The first release pattern was assumed to be more indicative of the arrival patterns of a high market penetration while the second release pattern was assumed to be more indicative of an arrival pattern with a lower level of market penetration.

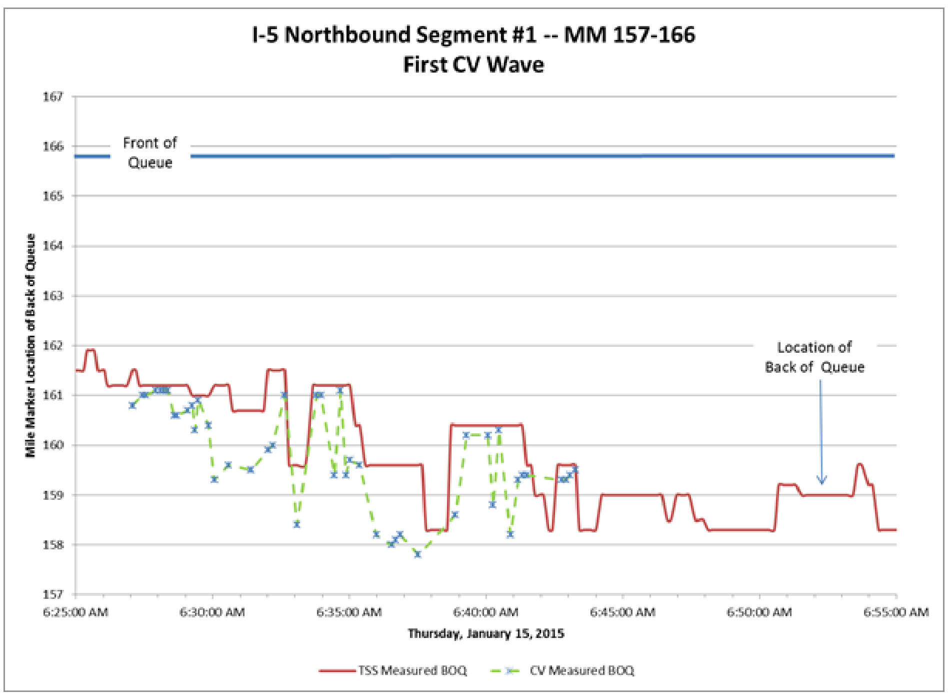
Following this logic, the research team examined the differences in which the algorithm determined the back of queue under the two release patterns. Figure 5-10 shows an example of the performance of the INFLO algorithm for a 30-minute window with short headways between connected vehicles and Figure 5-11 shows the performance of the INFLO algorithms for a similar 30-minute window where the release pattern results in longer headways between individual vehicles.

The figures compare the back of the queue estimates based upon connected vehicle-only data and based upon infrastructure-only data. As shown previously in Figure 5-6, the connected vehicle data locates the back of the queue earlier in both time and distance than the infrastructure based data and is more precise. The plot in Figure 5-11 shows that a reasonable estimate of the back of the queue is obtained with vehicles spaced about 30 seconds apart. For comparison, the infrastructure-based estimate of the back of queue is updated every 20 seconds. Overall, this suggests that market penetration which achieves vehicle spacing of no more than 20 to 30 seconds may be needed. Of course, more definitive work is needed to draw firm conclusions. However, the results suggest reasonable estimates of the location of the back of the queue may be possible with medium to low market penetrations.



Source: TTI

Figure 5-10. Determination of Back of Queue with Short Headways between Connected Vehicles Representing a High Market Penetration.



Source: TTI

Figure 5-11. Determination of Back of Queue with Longer Headways between Connected Vehicles Representing a Low Market Penetration.

Measured Driver Behavior Observations

Although driver behavior was outside the scope of the project, efforts were made to identify behavior changes electronically. However, no conclusions could be drawn from the available data.

Driver Feedback Observations

Assessing driver survey results, it appears that, overall, drivers saw immediate value in the Queue Ahead and In-Queue messages that informed them of the location and duration of congestion and queues. The value of SPD-HARM was not clear to participants.

Participating drivers appeared to observe safety benefits of the Queue Ahead message, allowing them to take action in advance of congestion and in reducing the need to slow down or stop suddenly. Drivers did not appear to observe the same level of benefits from SPD-HARM.

Although drivers saw immediate value in the Queue Ahead and In-Queue messages that informed them of the location and duration of congestion and queues, the size and scope was not sufficient to fully evaluate the short and long-term benefits of the technology on driver behavior. A more comprehensive human factors assessment will be necessary to characterize potential driver behavior effects.

Chapter 6 Summary of Accomplishments and Considerations for Future Work

This chapter concludes the report providing:

- Overview of the INFLO Application Bundle
- Summary of Programmatic Accomplishments
- Summary of Technical Accomplishments
- Considerations for Future Work
- Summary of the Value and Benefits of this Work.

INFLO Application Bundle Overview

The INFLO bundle is a collection of applications that target maximizing roadway throughput, reducing crashes, and reducing fuel consumption by collecting and processing data from wireless connected vehicles, travelers' communication devices, and infrastructure and rapidly disseminating useful information and recommendations to drivers. As part of the INFLO project, the Project Team applied the latest developments in technology to successfully design, implement, and demonstrate prototype of INFLO Dynamic Speed Harmonization and Queue Warning applications. Following acceptance testing of the applications in May 2014, the Team conducted a Small-Scale Demonstration of prototype applications in Seattle, Washington in January 2015.

Dynamic Speed Harmonization (SPD-HARM): The INFLO SPD-HARM application aims to maximize throughput and reduce crashes by utilizing infrastructure-to-vehicle (I2V) and V2V communication to detect impending congestion that might necessitate speed harmonization; generating appropriate target speed recommendation strategies for upstream traffic; and communicating the recommendations to the affected vehicles using either I2V or V2V communication. SPD-HARM is deployed in an operational environment in which speed recommendation decisions are made at a Traffic Management Center (TMC) or a similar infrastructure-based entity, and then communicated to the affected traffic.

Queue Warning (Q-WARN): The INFLO Q-WARN application aims to minimize or prevent impacts of rear-end or secondary collisions by utilizing I2V and V2V communication to detect existing queues and/or predict impending queues; and communicate advisory queue warning messages to drivers in advance of roadway segments with existing or developing vehicle queues. The Q-WARN concept reflects an operational environment in which two essential tasks are performed: queue determination (detection and/or prediction) and queue information dissemination. In such an environment, the Q-WARN application may reside in the vehicle or within an infrastructure-based entity, or utilize a combination of both. The queue warning messages may either be communicated by the infrastructure-based entity using I2V communication or broadcast by vehicles that are in a queued state to nearby vehicles and infrastructure based entities.

Programmatic Accomplishments

The principles of system engineering were applied in conducting INFLO Prototype System Acceptance Testing to verify that the developed prototype meets the system requirements defined in Chapter 6 of the Report on Detailed Requirements for the INFLO Prototype (FHWA-JPO-13-TBD). Acceptance testing was conducted for the following systems and sub-systems:

- In-Vehicle System including
  - User Interface Module (Android User Interface and Cellular Radio),
  - DSRC Radio Module (Processor and DSRC Radio),
  - Vehicle Network Access System (Vehicle Controller Area Network (CAN) Network)
- Roadside Units (RSUs)
- Virtual TME consisting of
  - INFLO Database
  - TSS Data Aggregator
  - Connected Vehicle Data Aggregator
  - TME-Based Q-WARN Application
  - TME-Based SPD HARM Application with Weather Responsive Traffic Management (WRTM).

The INFLO Prototype System was tested in three phases:

- Phase I – Component Acceptance Testing
- Phase IIa – Communications and Messaging System Integration Acceptance Testing
- Phase IIb – TME-Based Application System Integration Acceptance Testing
- Phase III – On-road Prototype System Acceptance Testing.

Phase I test cases and Phase II test cases were conducted within the laboratory environment using simulated or real data inputs. Phase III test cases were conducted using test vehicles in either a controlled (closed-course) environment or on streets and highways in Columbus, Ohio.

In the Small-Scale Demonstration described in Chapter 5, the Project Team worked with WSDOT to deploy connected vehicle systems in twenty-one vehicles in a scripted driving scenario circuiting the congested Seattle I-5 corridor northbound and southbound during morning rush hour Monday through Friday during the week of January 12, 2015. The Team collected vehicle speed data from both the WSDOT infrastructure-based speed detectors and the connected vehicles during the driving scenario. The Team processed the data in real time and delivered Q-WARN and SPD-HARM messages to drivers. The Team captured system performance data as well as driver feedback to demonstrate the INFLO Prototype System in a fully operational highway traffic environment and to examine potential benefits of connected vehicle technology. The Team also compared speed harmonization recommendations based upon connected vehicle data with those recommended by WSDOT system to help refine the INFLO algorithms.

This Small-Scale Demonstration represented a number of accomplishments for the U.S. DOT and the project team. Firstly, the Small-Scale Demonstration fully confirmed the functionality of the INFLO Prototype System in an operational highway traffic environment. The system was proven to reliably

- Capture current location and telematics data from connected vehicles and vehicle speed data from infrastructure
- Analyze the data to detect congestion and determine the beginning and end of congestion queues
- Formulate speed harmonization recommendations
- Communicate queue location and speed harmonization recommendations to drivers.

The demonstration proved connected vehicle data capture and dissemination functionality in an operating environment using both cellular communications and DSRC communications.

Secondly, the Small-Scale Demonstration confirmed that the INFLO Prototype System has the latency and processing speed to support INFLO application functionality in an operational traffic environment.

Thirdly, the Small-Scale Demonstration developed data that helped confirm that the INFLO Prototype System can deliver more precise estimates of the location of the back of the queue and the length of the queue faster than infrastructure-based system.

This demonstration and this project clearly confirmed that connected vehicle technology can deliver dynamic mobility benefits for transportation system operators and the traveling public.

Technical Accomplishments

A number of technical challenges were overcome in the course of this project to deliver the functionality and accomplishments outlined above. Some of the key challenges and technical accomplishments include design, implementation, deployment, testing and demonstration of:

- A comprehensive connected vehicle V2I system with end-to-end vehicle-to-TME-and-back data communications. This system
  - Captures relevant vehicle position and telematics data, packages and communicates the data to the infrastructure.
  - The infrastructure collects the vehicle data, sends it to a database/data warehouse system which parses it appropriately and stores it for backend analysis and processing.
  - Backend processors capture and assess relevant data from the database, determine if warnings and recommendations are warranted and, if so, issue messages with appropriate identifiers back through the database.
  - In-vehicle devices download messages, determine if they are relevant for the vehicle location and time and, if so, display those messages to the drivers.
- An integrated DSRC and cellular communication system that seamlessly sends and receives connected vehicle messages via DSRC when it is available or via cellular communication if not.

- A versatile nomadic integrated DSRC and cellular connected vehicle communications device. The device
  - Integrates a DSRC and cellular messaging system in a single portable package.
  - Seamlessly sends and receives connected vehicle messages via DSRC infrastructure when it is available or via cellular communication if not.
  - Is portable and operates on battery power when not located in a vehicle.
  - Can be installed in a vehicle and be fully functional in less than 5 minutes.
  - Captures vehicle telematics data wirelessly through the VITAL OBD-II CAN data module.
  - Displays connected vehicle messages and warnings to the driver through the cell phone display.
- A “link/sublink” methodology for integrating infrastructure-based and connected vehicle based vehicle speed and road weather data in a cloud database for efficient use by backend processors.
- An advanced TME-based Q-WARN data analysis algorithm that detects congestion, locates the back of the Queue and issues messages to drivers warning them of a Queue Ahead and the distance to the back of the queue. This algorithm also determines the speed in the queue and issues messages to drivers with the estimated time to exit the queue.
- An advanced Connected Vehicle only Q-WARN data analysis methodology that detects congestion, locates the back of the Queue and issues messages to drivers warning them of a Queue Ahead and the distance to the back of the queue without DSRC infrastructure.
- A V2V Queue Warning (TIM) Message Relay that relays messages to nearby affected vehicles without DSRC or cellular infrastructure.
- An advanced SPD-HARM data algorithm that recommends speeds to smooth speed reduction ahead of congestion based upon traffic and road surface conditions.

Systems engineering documentation, source code, and code documentation were shared with the U.S. DOT and the community via the Open Source Application Development Portal (OSADP).

Considerations for Future Work

This project has demonstrated that connected vehicle technology has the functional and performance capacity to meet the needs of INFLO Q-WARN and SPD-HARM applications. It has set the stage for future work needed to refine and enhance the INFLO applications for broader implementation. Following are suggestions to consider for future work that may be needed to support widespread deployment of these important applications. The suggestions address the following key topic areas.

- Connected Vehicle Technology
- Connected Vehicle Standards
- Nomadic and Personal Mobile Device Applications
- Human Factors Compliance and Design
- INFLO Algorithm Enhancement

- Comprehensive Field Testing and Evaluations
- Next Generation INFLO Applications
- Connected Vehicle Market Penetration Needs for INFLO
- Policy Issues.

Connected Vehicle Technology

Develop a Practical Positioning System For Connected Vehicles Which Reliably Delivers Road Level And Lane Level Position Accuracy. The accuracy specifications given by GPS chip manufacturers don’t reliably translate into repeatable vehicle positions when deployed in connected vehicles in the field. This results from a variety of factors, including dynamic drift due to atmospheric disturbances and changing satellite constellations. Rigorous testing and development is needed for a practical vehicle positioning system which reliably delivers road level and lane level latitude, longitude and elevation position accuracy.

Integrate Cellular and DSRC Connected Vehicle Data Communications. With the potential for implementing connected vehicle applications on personal mobile devices as well as in vehicles, relevant technical and policy issues need to be addressed pertaining to the integration of the capture and dissemination of connected vehicle data using both cellular and DSRC communications.

Connected Vehicle Standards

Develop Regional and Highway Map Messages. Current SAE J2735 map messages define road and lane geometries as sequences of latitude, longitude, and elevation points that are extensions of the map configurations developed for intersections. INFLO and other “highway” applications require a map message that efficiently and compactly describes highway geometries in terms of latitude, longitude, and elevation, as well as common reference methods such as route, direction and milepost. In addition, states vary widely in their GIS coding of roadway networks. A tool is needed which efficiently generates compact, but complete, highway and other road map messages from state GIS databases.

Implement INFLO Queued State Data in the Proposed Vehicle Situation Data Message or Other SAE J2735 Messages. Implementation of INFLO applications requires the addition of data elements such as Queued State in V2I messages. Investigation is needed on where best to implement them in SAE J2735 messages.

Develop V2I Message Strategy That Does Not Require Closely Spaced DSRC RSUs. INFLO and other applications rely on capturing traffic speed data from vehicles everywhere along roadways. BSM data are broadcast via DSRC as soon as they are generated, and “lost” if vehicles are not in range of an RSU. In order to capture vehicle BSMs for use by traffic mobility applications, RSUs must be spaced closely, overlapping at the edge of their range, to ensure vehicles are always within RSU range. This could be a costly requirement. In the absence of RSUs, INFLO’s needs may be also met using cellular technology, however this comes at a cost to the consumer for a cellular data plan. As such, a DSRC V2I temporary message storage and packaging strategy, wherein vehicle ‘probe’ data is retained, and then bundled into single, ‘most current’ messages for delivery when connectivity is available, is a recommended and necessary strategy for INFLO and other DMA and V2I applications that require this information, but where some latency is acceptable. This has been identified as a feature of the proposed Vehicle Situation Data Message.

Develop Physical and Environmental Ruggedness Test Requirements for Connected Vehicle Components. As the technology is still developing, connected vehicle components are in limited production and are sold in small quantities for use in development and testing. Sometimes these components are based upon electronic equipment used in protected environments, such as offices. They are not always adequately ruggedized for automotive and roadside environments. Physical and environmental ruggedness test requirements are needed to achieve more reliable performance in field deployments.

Nomadic and Personal Mobile Device Applications

Implement INFLO Applications on Personal Mobile Devices. While it is expected to be forthcoming, connected vehicle technology has not yet been mandated on new cars. It will take some number of years before a sufficient number of vehicles with connected vehicle technology will be on road to achieve the benefits of INFLO and other connected vehicle applications. However, many benefits could be achieved more rapidly through deployment of the applications on personal mobile devices (e.g. smartphones) in the near term.

Develop a Nomadic Personal Mobile Device with Integrated DSRC Radio. Such a device is needed for development and testing of personal safety and personal mobility DSRC messages and applications. A proof of concept has been demonstrated in this project with the smartphone and Arada "backpack". This development should include automatic coordination of DSRC communications when the owner of the personal mobile device is traveling within a DSRC enabled vehicle.

Human Factors Acceptance and Compliance

Investigate Driver Compliance with SPD-HARM Recommendations. SPD-HARM can theoretically reduce traffic flow turbulence and improve traffic throughput in congested areas. However, it is dependent upon driver adherence to the SPD-HARM recommendations. NHTSA work on Motivations for Speeding[13] showed evidence for four different types of speeding behaviors among individual drivers including (1) infrequent or incidental speeding, which may be unintentional; (2) trip-specific situational speeding; (3) taking many trips with a small amount of speeding per trip (i.e., casual speeding); and (4) habitual or chronic speeding. This work confirms speeding will occur even when speed limits are enforced. Human factors investigations are needed to assess potential driver compliance with SPD-HARM recommendations and to identify methods to maximize compliance. Subsequent work is suggested to refine the INFLO algorithms to accommodate associated variability in compliance.

Design a Driver Vehicle Interface (DVI) for INFLO. The value of the information delivered to drivers by the INFLO applications can be maximized through display in a carefully designed, intuitive interface that provides the most useful content. Human factors testing and development is recommended to develop and implement a clear and intuitive DVI for INFLO applications.

Assess Advanced Notification Requirements for INFLO Messages. A Human factors investigation is recommended to determine the advance notification time and distance needed by drivers to enable them to adjust their speed and lanes to support smooth traffic flow.

[13] http://www.nhtsa.gov/Driving+Safety/Research+&+Evaluation/Motivations+for+Speeding+I+II+III

INFLO Algorithm Enhancement

Capture Lessons Learned from State and Local VSL Deployments. Capturing and documenting the experience of State and local DOTs in refining their VSL systems after deployment would be valuable in helping refine INFLO implementations and algorithms.

Refine Models to Detect the Front of the Queue and Dynamics of Queue Formation and Dissolution. The model developed in this program assumed a fixed front of queue. Data captured suggests that queues formed and dissolved dynamically before and within the congested areas. Future work is recommended on the detection of the front of the queue and the dynamic formation and dissolution of queues. This effort should integrate macroscopic and microscopic perspectives of congestion.

Refine Connected Vehicle Criteria for Front of the Queue, In-Queue and Back of the Queue. The proposed definitions and criteria for the BOQ and In-Queue worked as intended for the small-scale demonstration. Further work is recommended to evaluate and refine them for broader application. The definitions need to be refined for infrastructure measured vehicle speeds, for connected vehicle measured vehicle speeds and for integrated infrastructure and vehicle measured speeds. Furthermore, different definitions may be needed for use in analysis by traffic control managers, in analysis by the algorithms and for display to drivers.

Enhance INFLO Algorithms to Support Work Zones and Accidents. As part of the enhancements to address dynamics of queue formation and dissolution, it is recommended that the system and algorithms be enhanced to consider unique aspects of congestion behavior at work zones and at accident scenes.

Develop Predictive Models for Queue Formation. Future work leveraging the results above is suggested to enhance, refine and implement models that predict queue formation and to implement SPD-HARM and other algorithms to reduce their likelihood and mitigate their effects.

Implement the Impacts of Adverse Weather in the SPD-HARM Algorithms. More development and implementation of the impacts of adverse weather on SPD-HARM algorithms is recommended.

Enhance INFLO to Leverage Third Party Traffic Data. Many DOTs have subscriptions to use traffic mobility data from third party sources. The system and algorithms could be enhanced to integrate this data with infrastructure-based and connected-vehicle based traffic mobility data.

Optimize INFLO Algorithm Performance for Large Scale Deployment. Large scale deployment of INFLO systems will be computationally intensive. Enhancements are recommended to optimize the algorithm's computational and data storage resources to support large scale deployments.

Develop a Robust Methodology for V2V Message Relay. This project established a foundation that demonstrates the feasibility of message relay. Further development is suggested to develop a robust implementation that avoids clogging DSRC communications and distributing outdated or irrelevant data.

Comprehensive Field Testing and Evaluations

Plan and Implement a Comprehensive Field Deployment, Test and Evaluation of INFLO Applications. The Seattle Small-Scale Demonstration showed that connected vehicle technology can support the communications and processing needs for INFLO applications and it provides a foundation for planning and implementation of a comprehensive field test and evaluation. The objective of the field test would be to conduct experiments, modeling and a full-scale field deployment to assess what works and what doesn't in INFLO deployment and to refine and optimize the applications to achieve the goals of improved throughput, mobility and safety. This program would implement a large deployment of connected vehicle technology in cars and in personal mobile devices to:

- Capture "ground truth" on traffic flow and conditions leading up to and including breakdown in flow for a diverse set of road geometries and traffic conditions causing congestion
- Apply captured data to calibrate traffic congestion and flow breakdown models
- Exercise calibrated models to explore and test different strategies for application deployments
- Deploy, implement and calibrate promising strategies in operational traffic environments
- Assess results and refine the implementation over time to improve throughput, mobility and safety
- Refine models based upon implementation experience to apply in future deployments.

Plan and Implement a Comprehensive Field Deployment, Test and Evaluation of INFLO-based WRTM Applications. Speed harmonization holds promise in smoothing traffic flow, improving throughput and reducing accidents during adverse weather events. A comprehensive field deployment and test of INFLO-based WRTM in areas prone to adverse weather impacts on traffic mobility would help determine how best to implement connected vehicle technology to mitigate these effects.

Next Generation INFLO Applications

Develop and implement the Next Generation of the INFLO Application Bundle with Speed and Lane Harmonization at Bottlenecks. In addition to providing speed recommendations to smooth flow and reduce the likelihood of incidents, this next generation application is expected to recommend lanes changes in advance that will further smooth and speed the flow of traffic and prevent last minute lane changes which disrupt flow and cause accidents. It is suggested that the Next-Generation INFLO applications be developed and applied to traffic bottlenecks such as bridge and tunnel entrances.

Develop and implement a Next Generation INFLO Application Bundle for Commercial Vehicles. In addition to improving traffic mobility in general, INFLO applications can also help improve freight mobility. It is suggested that Next-Generation INFLO applications be developed and applied to challenges of commercial vehicle mobility, including the implementation of SPD-HARM and Cooperative Adaptive Cruise Control (CACC) in commercial vehicles operating in truck-only lanes.

Plan and Implement a Comprehensive Field Deployment, Test and Evaluation of CACC to Improve Throughputs at Bottlenecks. Recognizing that some levels of vehicle autonomy are gaining acceptance, CACC has great promise in increasing throughput at bottlenecks such as the entrance to bridges and tunnels by matching vehicle speeds and reducing headways between vehicles. A comprehensive field test is suggested which includes conducting experiments, modeling and a full scale field deployment to assess what works and what doesn't in CACC deployment and to refine and optimize the application to maximize throughput, mobility and safety at bottlenecks.

Connected Vehicle Market Penetration Needs for INFLO

Conduct Modeling, Testing and Analysis to Determine the Level of Connected Vehicle Deployment Necessary to Capture Benefits of INFLO Applications. More information is needed on the number and spacing of connected vehicles necessary in the traffic stream to measure congestion and deliver accurate results to drivers.

Policy Issues

Establish Data Ownership Policies for Multijurisdictional Implementations of INFLO. Substantial questions exist concerning sharing, ownership and usage of connected vehicle data when it is captured and used by multiple jurisdictions across multiple communications networks. Investigations are suggested to address unresolved data ownership issues that have the potential to slow, or even block the implementation of promising connected vehicle applications.

Value and Benefits of this Work

Traffic congestion represents a number of safety and mobility challenges for transportation system managers and the traveling public. Congestion is dynamic, as slow moving queues form and disappear, while upstream traffic approaches at highway speeds. Approaching drivers do not know the location of the back of the queue and may approach too fast, creating a safety hazard as well as further disruptions in the smooth flow of traffic. Connected vehicle technology offers substantial safety and mobility benefits for highways by significantly improving drivers' situational awareness and delivering information that drivers can use to smooth traffic flow and reduce the likelihood of accidents. Improvements in situational awareness will support more informed and prepared driver behavior and response to traffic congestion.

The work summarized in this report presents an important foundation for capturing the safety and transportation mobility benefits of connected vehicle technology, particularly for traffic congestion. First, this work demonstrates application of connected vehicle technology is fully feasible and that the technology can reliably deliver information, alerts and warnings in sufficient time for travelers to the public to take mitigating measures. Secondly, this work demonstrates *how* connected vehicle technology can be integrated with existing traffic monitoring and management systems without increasing the cognitive workload of drivers or traffic system managers. Finally, this project has demonstrated how connected vehicle technology can be efficiently and effectively implemented with the potential to help improve the safety and mobility of travelers in our roads and highways.

APPENDIX A. Acronyms and Abbreviations

ATM	Advanced Traffic Management
BOQ	Back of queue
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CV	Connected Vehicle
CVC	Connected Vehicle Communication
DMA	Dynamic Mobility Application
DMS	Dynamic Message Sign
DSRC	Dedicated Short-Range Communications
DVI	Driver Vehicle Interface
ESS	Environmental Sensor Station
FHWA	Federal Highway Administration
FOQ	Front of Queue
I2V	Infrastructure-to-Vehicle
IDS	Information Dissemination Sub-system
IEEE	Institute of Electrical and Electronics Engineers
INFLO	Intelligent Network Flow Optimization
IRB	Institutional Review Board
IVNA	Integrated Vehicle Network Access
mph	Miles per hour
NB	Northbound
OBU	On-board Unit
PII	Personally Identifiable Information
Q-WARN	Queue Warning application
RSU	Roadside Unit
RSSI	Received Signal Strength Indicator
SAE	Society of Automotive Engineers
SPD-HARM	Speed Harmonization application
TC	Test Case
TIM	Traveler Information Message
TME	Traffic Management Entity
TMO	Traffic Management Operator

TSS	Traffic Sensor System
TTI	Texas Transportation Institute
UI	User Interface
U.S. DOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VMS	Variable Message Signs
VSL	Variable Speed Limit
WSDOT	Washington State Department of Transportation
WRTM	Weather Responsive Traffic Management

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