Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Report

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16. Abstract

This report describes the performance and results of the INFLO Prototype Small-Scale 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 system functionality, system performance, algorithm performance and driver feedback. In this Small-Scale Demonstration, Battelle and TTI worked with Washington State Department of Transportation to deploy connected vehicle systems in 21 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 queue warning and speed harmonization messages to drivers. The Team captured performance data as well as driver feedback. The Small-Scale Demonstration fully confirmed the functionality of the INFLO Prototype System using both cellular communications and DSRC communications. The Demonstration confirmed that the System has the latency, processing speed and communications bandwidth to support INFLO application functionality in an operational traffic environment.

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Chapter 1 Introduction

Purpose of this Demonstration Report

This report describes the performance and results of the Intelligent Network Flow Optimization (INFLO) Prototype Small-Scale Demonstration that was conducted as part of the U.S. DOT Prototype Development and Small-Scale Demonstration of Dynamic Speed Harmonization with Queue Warning Project. The purpose of the Small-Scale Demonstration was to deploy the INFLO Prototype System and applications to demonstrate its functionality and performance in an operational traffic environment and to capture data that can help assess hypotheses pertaining to system functionality, system performance, algorithm performance and driver feedback.

Following is a description of the demonstration conducted by Battelle, with the support of its subcontractor Texas A&M Transportation Institute (TTI), and Washington State Department of Transportation (WSDOT). This document summarizes the

- INFLO Prototype Small-Scale Demonstration Plan
- INFLO Prototype System Description
- INFLO Prototype Applications
- Implementation Of The INFLO Small-Scale Demonstration
- Data Analysis And Evaluation
- Summary Of Accomplishments

Scope of the Demonstration

The Battelle Team developed prototype INFLO Queue Warning (Q-WARN) and Speed Harmonization (SPD-HARM) applications and demonstrated their functionality and performance to U.S. DOT as part of controlled environment tests conducted on roadways around Battelle offices in Columbus, Ohio in May 2014. This report describes 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.

The Small-Scale Demonstration was intended to be an interim step between controlled environment demonstrations and a full-scale field test deployment of the application in highway traffic. It was intended to demonstrate that the system can function in an operational environment and can provide a basis for planning a more comprehensive field deployment of the technology.

In this Small-Scale Demonstration, Battelle and TTI worked with WSDOT to deploy connected vehicle systems in 21 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 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.

The scope of this effort focused on demonstrating the capabilities of connected vehicle technology to support a prototype INFLO system. The number of participants in the demonstration was limited to the number needed to demonstration the technology. The scope of the effort did not include capturing ground truth data.

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, processing speed and communications bandwidth 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.

Participation

All work described within this document was conducted by the Team of Battelle and TTI. This effort was supported by WSDOT who shared their professional expertise as well as data feeds from their Advanced Traffic Management (ATM) system. Battelle recruited 21 participants from the local area who served as drivers for the demonstration. Recruitment and identification of demonstration participants is described in Chapter 4.

Security

No testing related to security was planned for this prototype. While Arada Systems has implemented and verified over-the-air-security for DSRC radios used here as prescribed for the US DOT Safety Pilot Model Deployment in V3.0 of the Roadside Equipment specification, the necessary firmware modifications for the “Arada GO ME “backpack” and “Mini-2” form factors were still in development at the time this demonstration was conducted. Communications using cellular and other internet ‘standards’, used secure-socket layers, and as necessary, virtual private network connections.

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-14-171	Report on Detailed Requirements for the INFLO Prototype
FHWA-JPO-13-170	Report on Architecture Description for the INFLO Prototype
FHWA-JPO-14-168	Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design
FHWA-JPO-14-169	System Design Document for the INFLO Prototype
FHWA-JPO-15-208	Intelligent Network Flow Optimization (INFLO) Prototype Acceptance Test Plan
FHWA-JPO-15-209	Intelligent Network Flow Optimization (INFLO) Prototype Acceptance Test Summary
FHWA-JPO-15-TBD	Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Plan

Source: Battelle.

Chapter 3 Summary of the INFLO Prototype Small-Scale Demonstration Plans

This section provides an overview of the plan for conducting the INFLO Small-Scale Demonstration including

- Site Selection Criteria
- Introduction to the Seattle I-5 Corridor and ATM system
- Overview of the INFLO Prototype System
- I-5 Corridor Demonstration Route
- Hypotheses Examined
- Data Collected.

Site Selection Criteria

Upon completion of the Acceptance Testing, Battelle 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 Battelle staff providing rapid troubleshooting and routine maintenance support.

Battelle compared seven locations and recommended Seattle as the preferred location for the INFLO Small Scale Demonstration because it met the most 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 Battelle to proceed with the Small-Scale Demonstration in Seattle.

Source: Washington State Department of Transportation.

Figure 3-1. Locations of VMS and VSLS Devices in the Seattle, WA Area.

Introduction to the Seattle I-5 Corridor and ATM system

The Small-Scale Demonstration was conducted on I-5 between Tukwila and Edmonds Washington. The approach to downtown Seattle from the south is equipped with ATM Variable Message Signs (VMS) and Variable Speed Limit (VSL) signs on the northbound lanes. (See Figure 3-1 and Figure 3-2.)

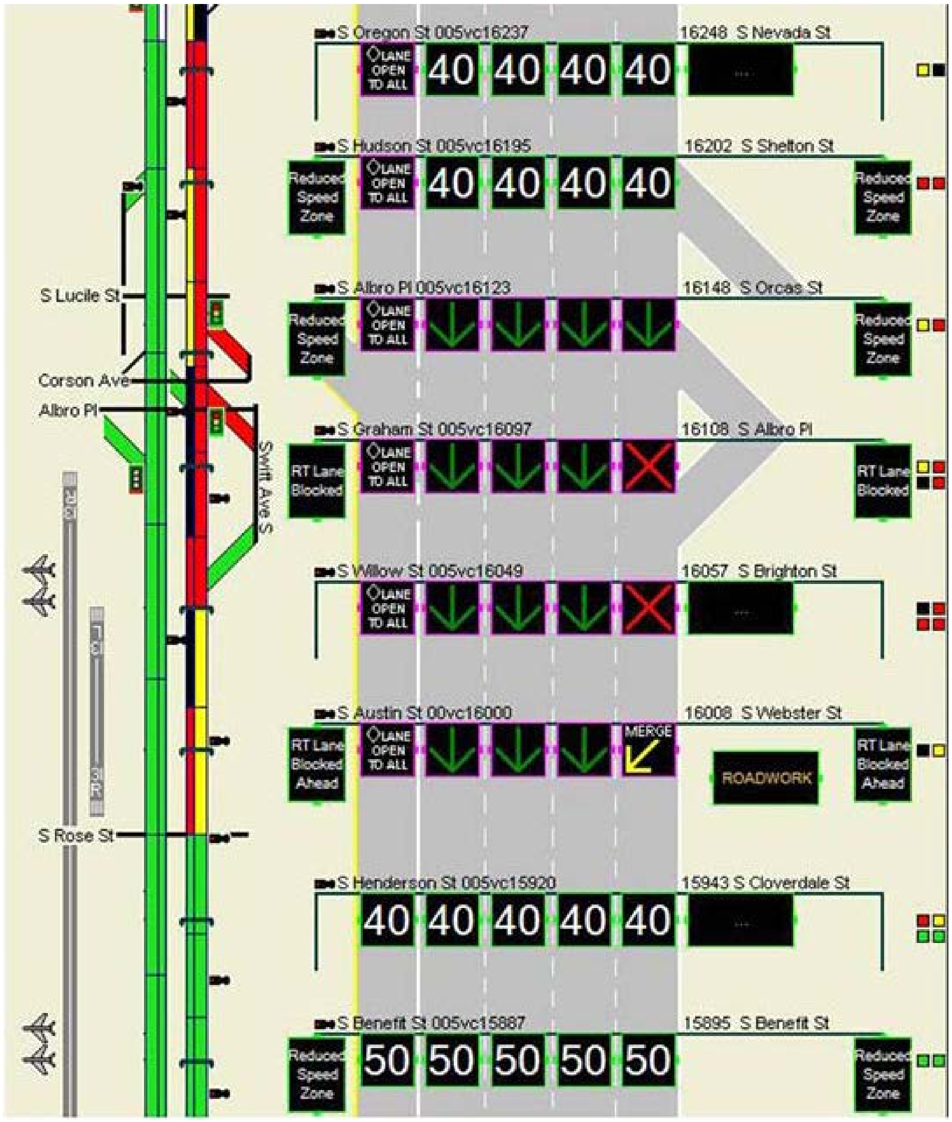
To date, three corridors in the Seattle area, branded "Smarter Highways," include ATM signage, which is used for congestion management and automatically posts regulatory VSLs to smooth traffic flow. The first corridor to begin ATM operations in Seattle is the seven-mile segment of Interstate 5 (I-5) northbound from the Boeing Access Road to Interstate 90 (I-90) in downtown Seattle. This corridor has dynamic message signs on sign bridges spaced roughly every half-mile. Along this segment, I-5 is reduced from five lanes to two lanes as it enters downtown Seattle. This corridor was part of the planned route for demonstration of the INFLO applications.

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 3-3) 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.

Source: Washington State Department of Transportation.

Figure 3-2. Example of Combined VMS and VSLS just South of Seattle, WA.



Source: Washington State Department of Transportation.

Figure 3-3. Seattle ATM Software User Interface showing VSL and Lane Closures Due to Roadwork.

Variable Speed Limits

In the Seattle region, ATM signage displays regulatory enforceable VSLs. As shown in Figure 3-2, 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.

As the system has evolved, changes have been made to the maximum and minimum posted VSLs. The maximum posted VSL was 50 miles per hour (mph). However, the system automatically displays the normal 60 mph speed limit on the ATM signs immediately upstream and also downstream of the reduced speed zone. Originally, WSDOT restricted the lower limit of the automatic VSL to a 40 mph minimum because of data instability at lower speeds, which resulted in frequent changes in posted VSLs under stop-and-go conditions. After adjustments to the algorithm, the automatic VSL minimum was lowered to 35 mph, and with additional refinements will likely be further reduced to 30 mph. The operating procedures currently allow for a manual input of the speed limit as low as 30 mph.

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. In fact, WSDOT has adapted the system since deployment to automatically activate additional signs in advance of congestion to begin reducing speeds sooner. As noted earlier, WSDOT also has the system automatically post a 60 mph speed on the ATM signage on the gantries immediately upstream and downstream of the reduced speed zone.

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. Instead, the highway patrol focuses almost exclusively on reckless driving with speeds greatly exceeding the posted speed. Thus, 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. However, three gantry locations along this proposed corridor were equipped with the roadside version of the DSRC radio. These roadside units (RSUs) were completely independent of the WSDOT ATM system including their own separate communications backhaul.

As described later, SPD-HARM messages were not displayed on highway segments with VSL to avoid potential conflict or confusion.

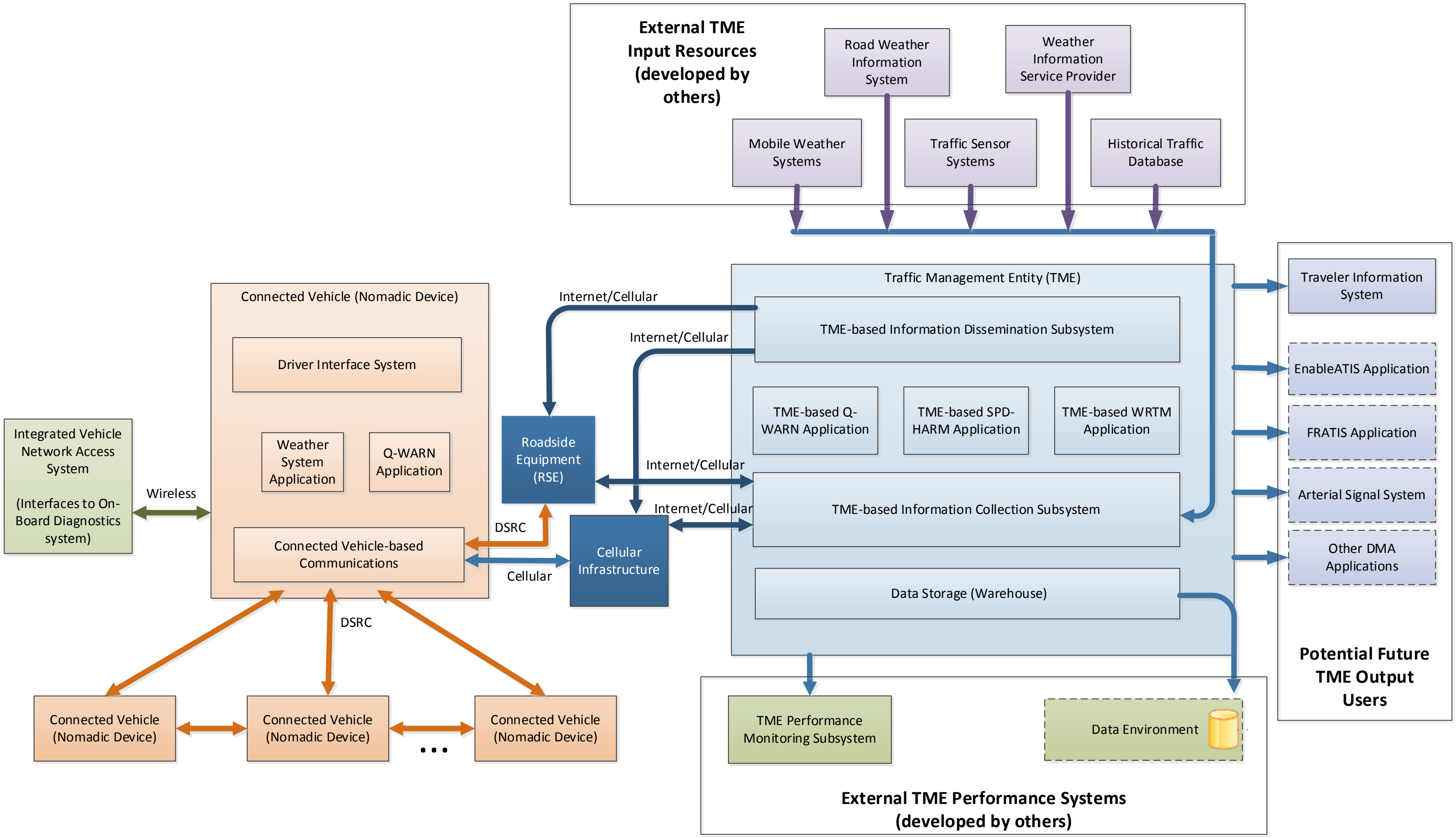
Overview of the INFLO Prototype System

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 and others. Its components are described in detail in the INFLO Prototype System Design Document. A brief synopsis is provided here for completeness and clarity of this demonstration summary.

The system consists of multiple components which exchange data through messages using DSRC or cellular communication. Figure 3-4 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 3-5 below is a simplified view of the INFLO Prototype System as it has been implemented for the purposes of this project and as it was implemented for the Small-Scale Demonstration. This system has the functionality and capabilities necessary to support this and other demonstrations. Figure 3-6 shows the same figure, with the addition of the messages that were exchanged between components necessary to support the multiple INFLO scenarios and applications.

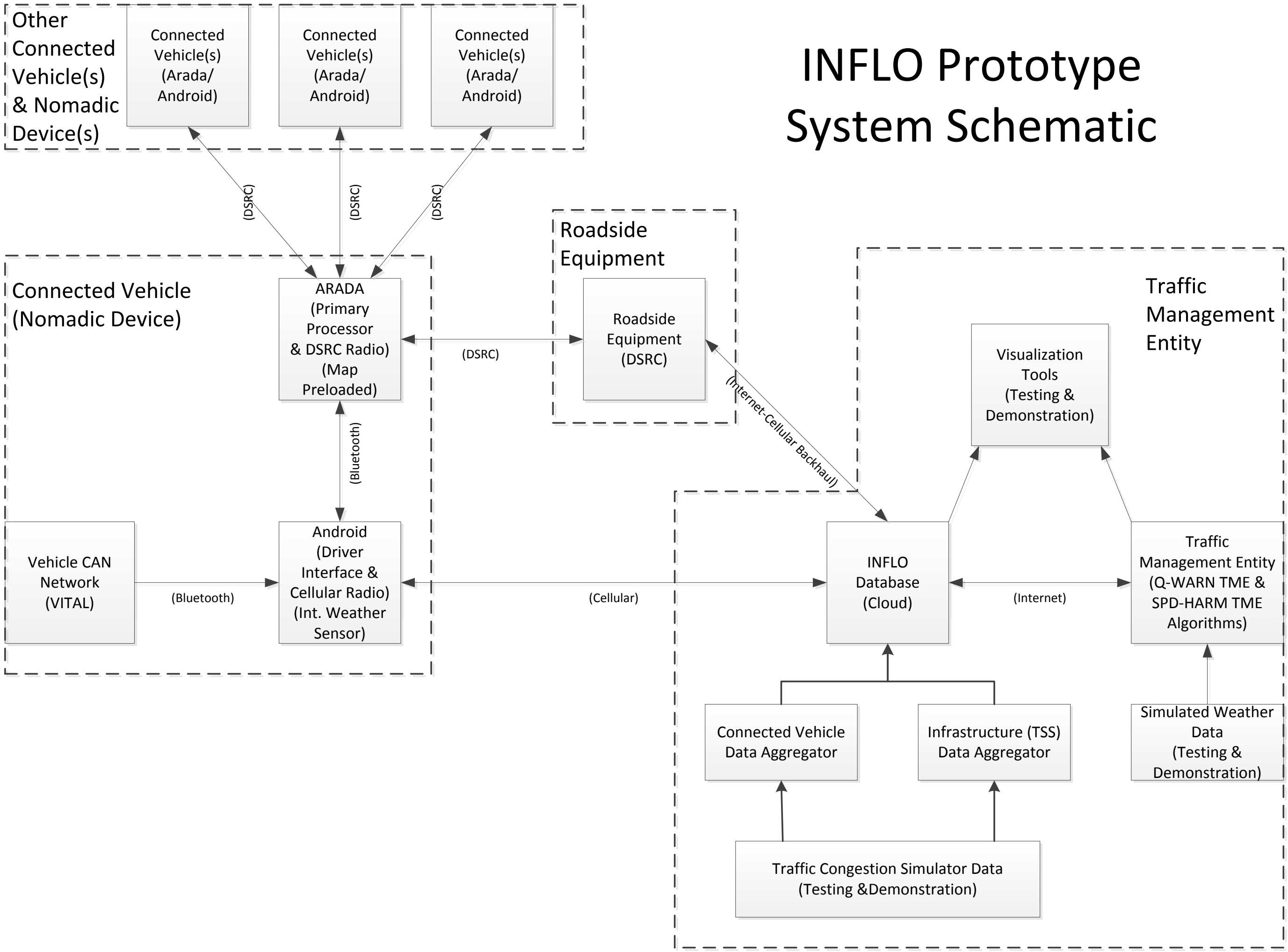
The remainder of this section of the report provides background and overview of the system components, the implemented INFLO Prototype System and the location and methods by which they were demonstrated. The remainder of this section is organized under the following headings:

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



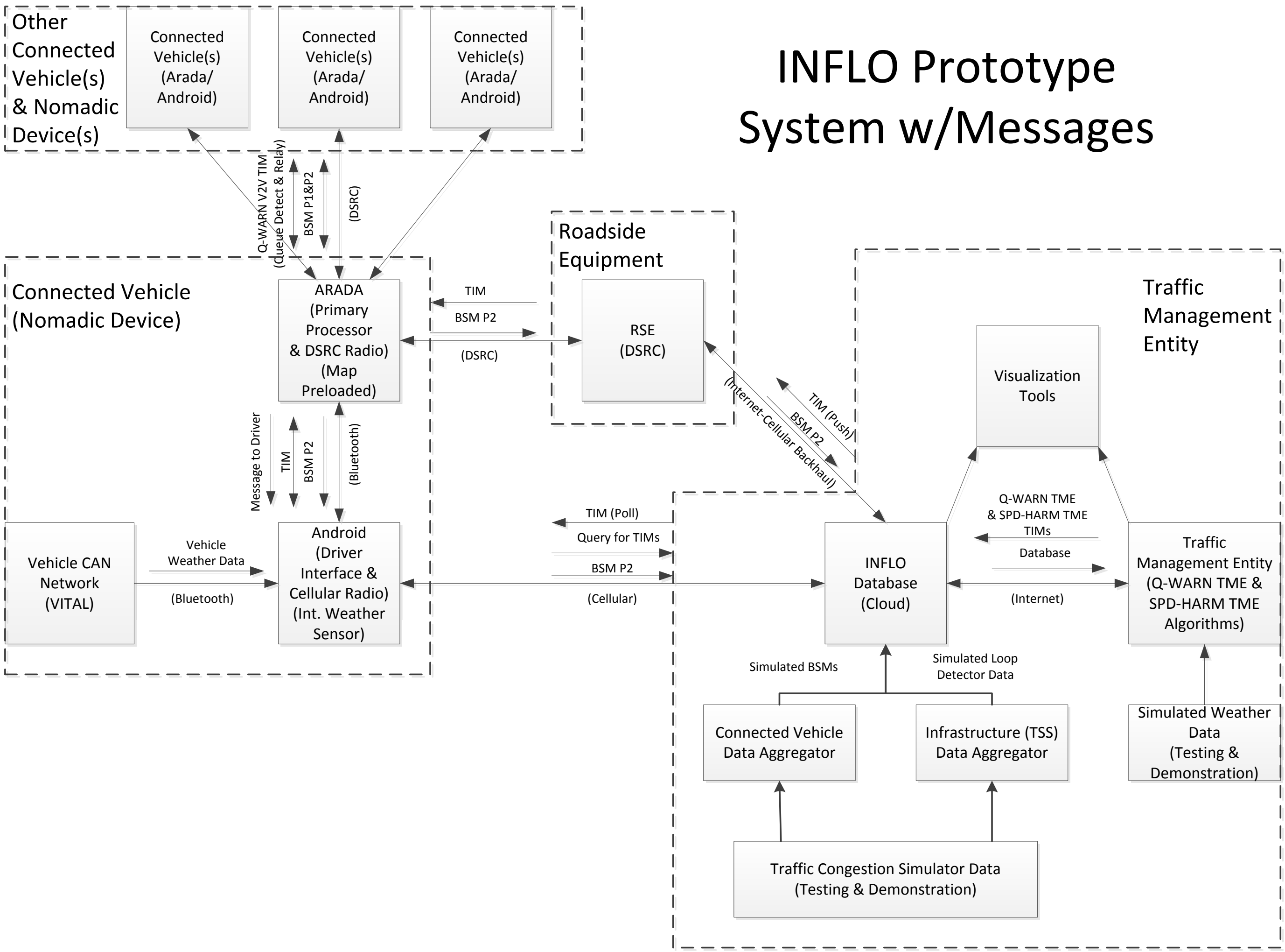
Source: Battelle.

Figure 3-4. INFLO Prototype System Diagram from INFLO Design Report.



Source: Battelle.

Figure 3-5. Schematic of the Implemented INFLO Prototype System.



Source: Battelle.

Figure 3-6. 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 3-5 and Figure 3-6 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)
- Cloud Computing Platform
- Virtual Traffic Management Entity (TME) consisting of TME applications and
  - INFLO Database
  - Infrastructure Traffic Sensor System (TSS) Data Aggregator
  - Connected Vehicle Data Aggregator
- DSRC Messages
- INFLO Applications

The following additional components were used for testing and demonstration

- Test Visualization Tools
  - TME Algorithm Queue Visualization Tool

Following is an overview of each.

In-Vehicle System User Interface Module

The In-Vehicle User Interface Module is a mobile device (cell phone) 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 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 state
- In-Vehicle System system state
- 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 3-7 through Figure 3-16 provide screen capture examples of the User Interface Messages on the Android Device for the INFLO Applications. The screens were implemented to be as simple and clear as possible with the goal of displaying[1]:

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

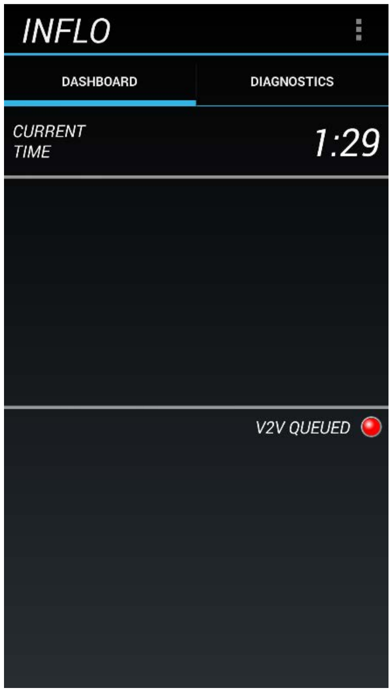
Note the following messages and indicators in the User Interface.

- V2V Queued red bullet in Figure 3-8 wherein V2V communications have determined that the vehicle is in a queued state.
- V2V Queue Ahead message in Figure 3-9 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 3-10 wherein TME algorithms have determined that a queue is ahead with the distance to the back of queue (BOQ).
- TME In-Queue message in Figure 3-11 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 3-12 wherein the TME algorithms have recommended a reduction in speed.
- TME Multiple messages in Figure 3-13 wherein both Speed Harmonization and Queue Ahead messages were issued and displayed simultaneously.
- Diagnostic and Test Verification messages shown in Figure 3-14, Figure 3-15, and Figure 3-16.

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

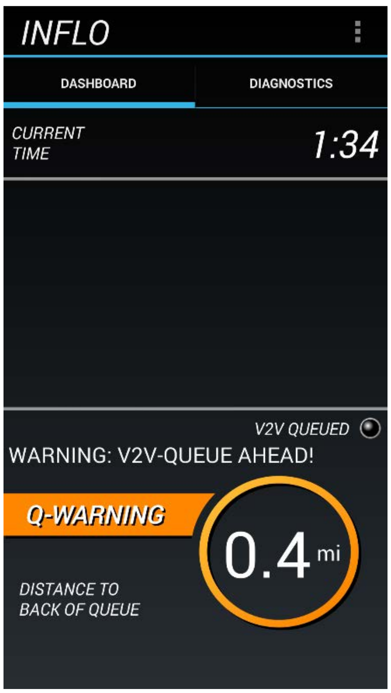
Source: Battelle.

Figure 3-7. User Interface Display.



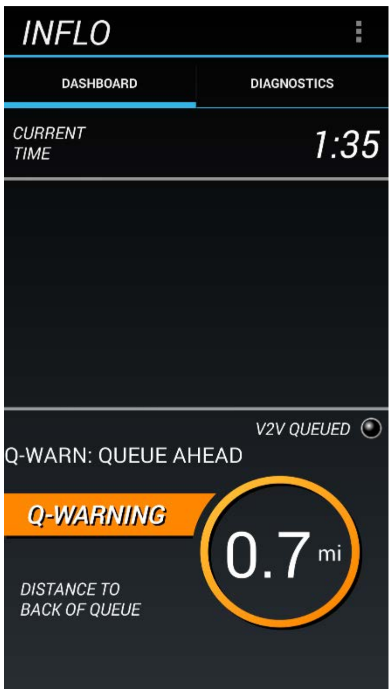
Source: Battelle.

Figure 3-8. Queue Detected V2V.



Source: Battelle.

Figure 3-9. Queue Ahead (V2V).

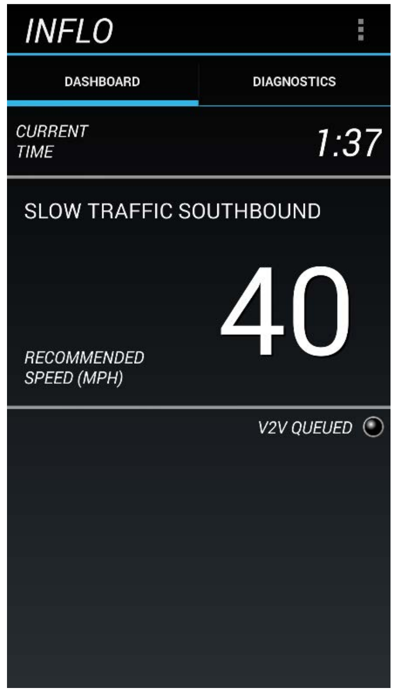


Source: Battelle.

Figure 3-10. Queue Ahead (TME).

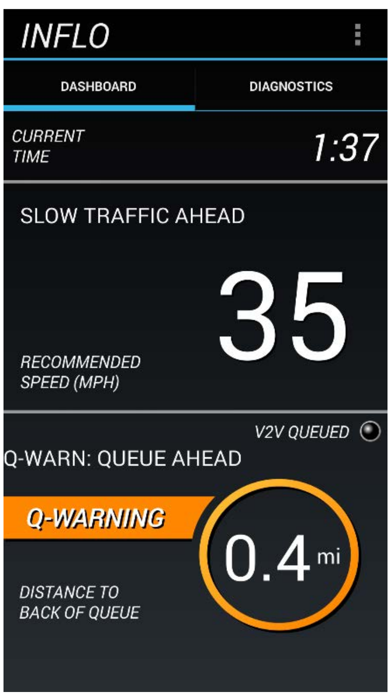
Source: Battelle.

Figure 3-11. In Queue (TME).



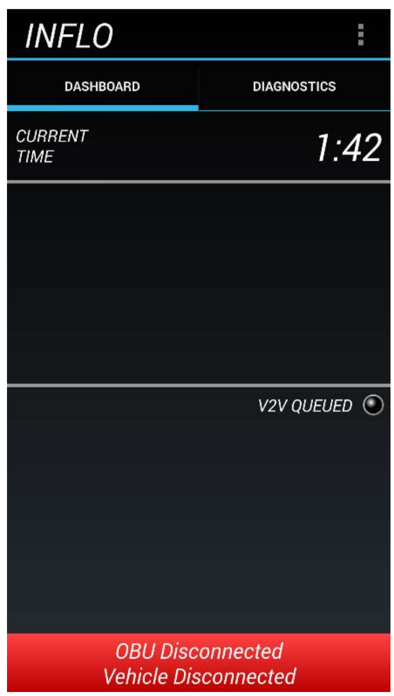
Source: Battelle.

Figure 3-12. SPD-HARM (TME).



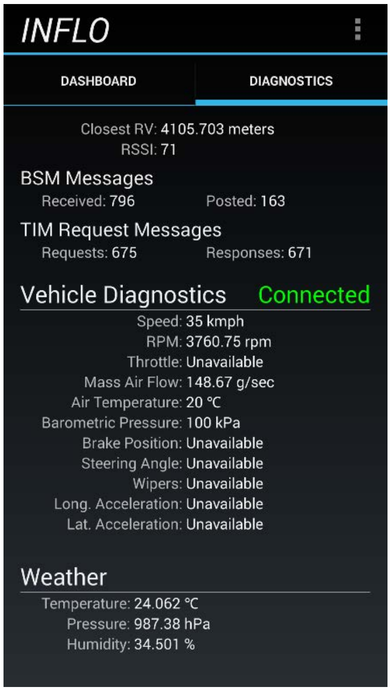
Source: Battelle.

Figure 3-13. TME Multiple Warnings.



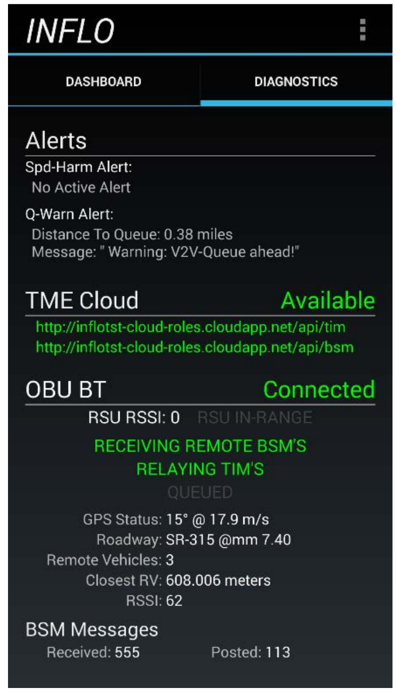
Source: Battelle.

Figure 3-14. Not Connected.



Source: Battelle.

Figure 3-15. Vehicle Data.



Source: Battelle.

Figure 3-16. Diagnostic Display.

In-vehicle System 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 radio receives both V2V and I2V communications. The DSRC radio transmits Basic Safety Messages (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 Basic Safety Message 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 1HZ. 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 (V2V) and from the infrastructure (I2V). 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 were rebroadcast by

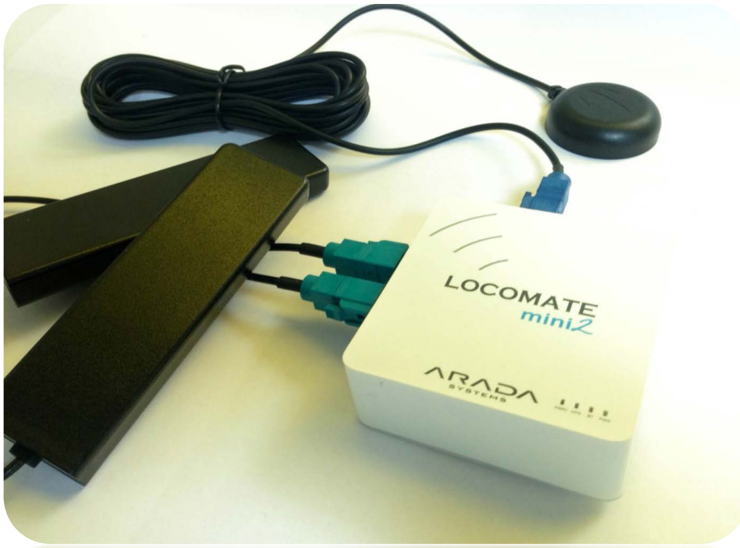
DSRC for reception by other In-Vehicle Systems within radio range and "relay" of vehicle queue information.

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, Battelle used the Battery Powered Locomate ME OBU with integral GPS and DSRC antenna, also known as the "Backpack", shown in Figure 3-17. The backpack form factor is used with the Samsung smart phone as an integrated "nomadic device." For the Small-Scale Demonstration, Battelle used Arada System's LocoMate™ Mini 2 OBU, which allowed the use of external GPS and DSRC antennas, as shown in Figure 3-18. Both units use the same radios, circuitry, and software, but are enclosed in a different external case.

Source: Arada/Battelle.

Figure 3-17. Arada Locomate ME Battery Powered DSRC Communication Hardware, also known as "The Backpack".



Source: Arada/Battelle.

Figure 3-18. Arada Locomate "Mini2" DSRC Radio with External GPS and DSRC Antenna.

In-vehicle Network Access System

The In-vehicle Network Access System (IVNAAS) is used to obtain data from the vehicle CAN bus through the OBD-II interface. The In-Vehicle System uses the VITAL module, a proprietary Battelle module that plugs into the OBD-II port, to obtain a vehicle's telemetry data and forward the messages using Bluetooth to a connected device (see Figure 3-19). This module allows the DSRC radio to receive vehicle dynamics to populate the Basic Safety Message Part II. The availability of specific data elements is dependent upon the vehicle.

Source: Battelle.

Figure 3-19. VITAL™ OBD-II Module.

Roadside Units

The RSU used in demonstration is the Arada LocoMate™ RSU, shown in Figure 3-20, which handles all DSRC communications from the TME to In-Vehicle Systems and DSRC communications from the vehicles to the TME. The Road Side Equipment forwards any warnings from the TME to all devices within its range. The RSU also collects BSM Part II messages and forwards these messages to the TME for use by the infrastructure-based algorithms.

Cloud Computing Platform

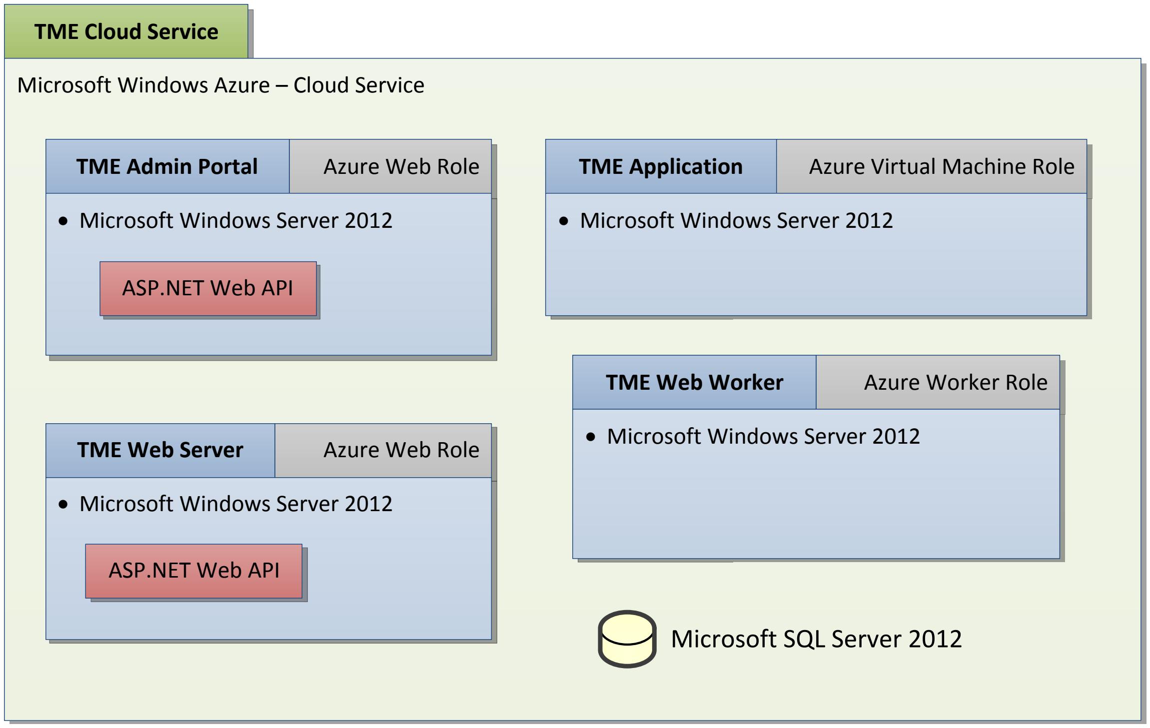
The computational platform use for the INFLO Prototype System is a Microsoft® Azure Cloud Service that includes the following components:

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

The computing platforms for each virtual machine in the Azure Cloud Service are summarized in Figure 3-21 Cloud service(s) 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 the development team.

Source: Arada Systems

Figure 3-20. Road Side Equipment Arada LocoMate™ RSU.



Source: Battelle.

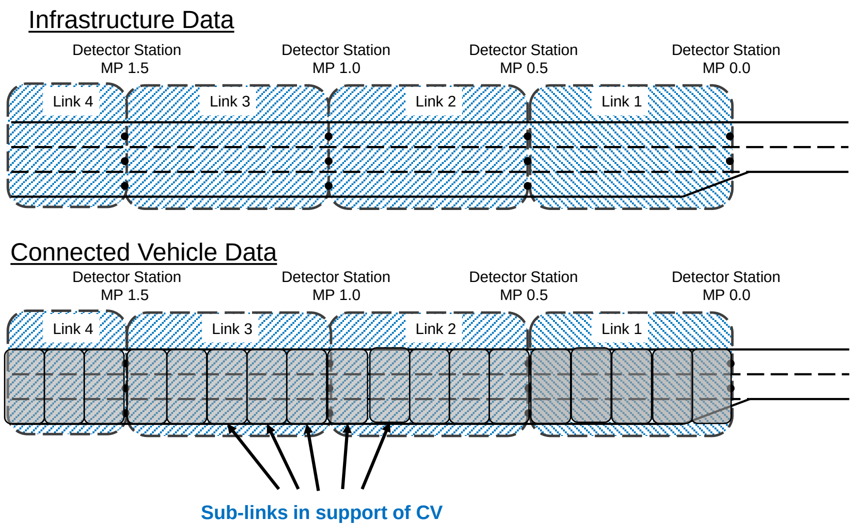
Figure 3-21. Cloud Service Computing Platforms.

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. A critical component of the virtual TME environment that provides the flexibility needed in designing the algorithms is the INFLO Database system. 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 made by each algorithm and sent to drivers and infrastructure-based signs were also stored in the database. The TME Link Speed Process is responsible for performing the speed harmonization process 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 3-22, 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.



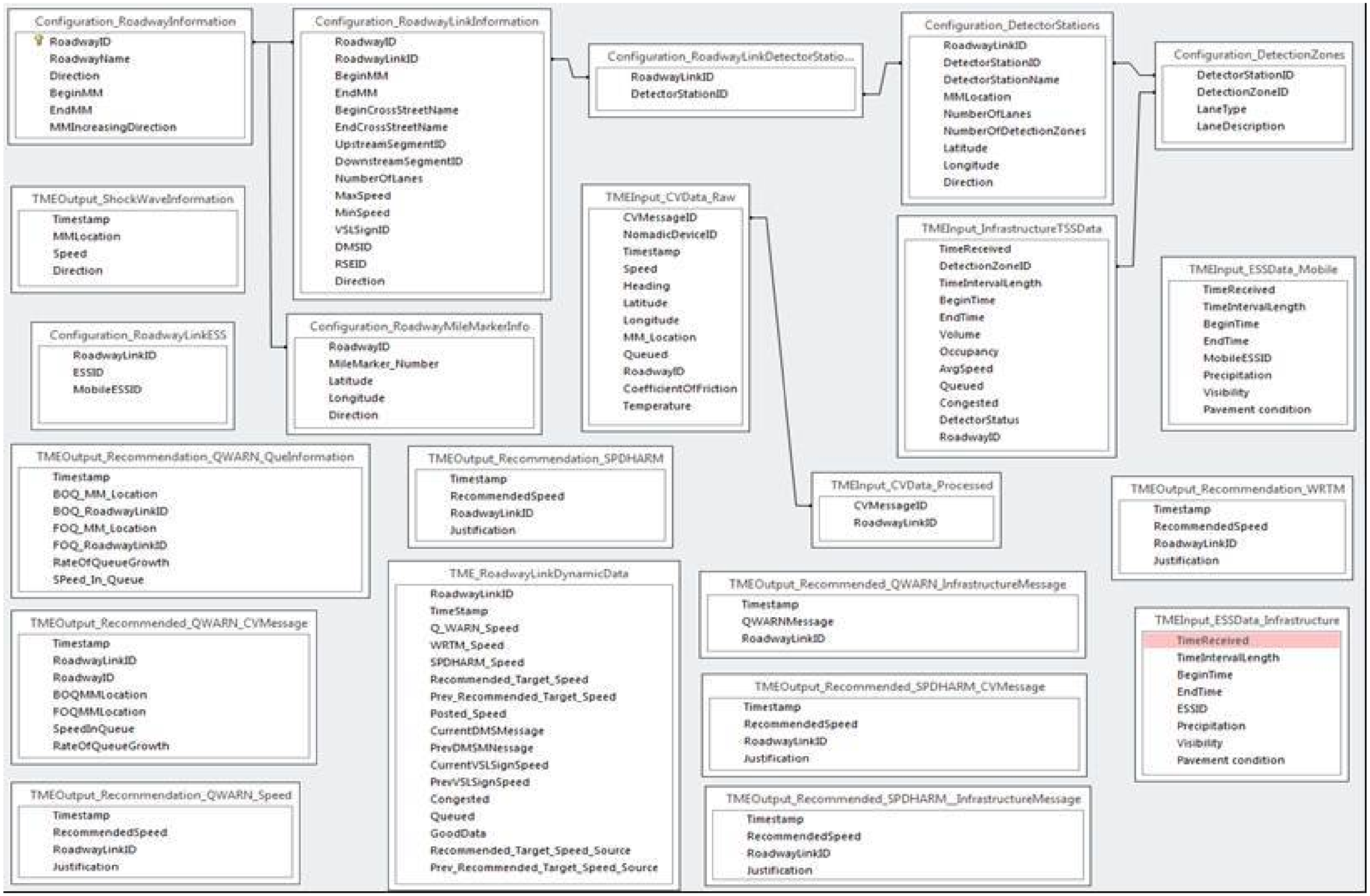
Source: TTI.

Figure 3-22. 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. For example, the infrastructure-based sensor data is acquired at 20 second to one minute intervals while the connected vehicle data is acquired at one to five second intervals. On the other hand the WRTM algorithm might generate weather safe speed recommendations every minute or at longer intervals. All of this data will be stored in the INFLO Database in real-time and depending on the frequency of running the TME-speed harmonization algorithm, it will query the database for the data it needs and generate the proper speed recommendation for roadway links.

Figure 3-23 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 3-23. INFLO Database Tables.

Infrastructure Traffic Sensor System (TSS) Data Aggregator

For the INFLO Prototype System, the Infrastructure Traffic Sensor System (TSS) Data Aggregator collects the data from simulated 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 (CV) Data Aggregator collects the data from all the connected vehicles traveling in the deployment corridor and converts it into link-based information. The CV Data Aggregator is responsible for processing the data from the each connected vehicle and determining the average speed, congested state, and queued state of the sublink. The milepost reference in the CV 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 CV Data Aggregator computes the average speed for each sublink for all the connected vehicles located in each sublink. Using the average sublink speed, the CV 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 DSRC messages were transmitted and used to communicate data between components in the system, the Basic Safety Message (BSM) Part 2[2] 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 3-6, 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.

No modifications were made to the TIM message. Three elements were added to the BSM Part 2: Roadway Identification Number for current location, Mile Marker for the current location, and an indicator that the vehicle is in a Queued state.

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

INFLO Applications

Four INFLO Application scenarios, described in more detail in the Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design[3], 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 the 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 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 its queue state and generating queue warning displays for the driver from the data provided by the TME.

The TME Q-WARN application is responsible for detecting queues in the traffic stream and for generating appropriate queue warning messages. The TME Q-WARN application interfaces with the INFLO Database to extract both connected vehicle data and infrastructure-based traffic data to determine information about the queue. The application consists of two processes running in parallel: one process for detecting queues using connected vehicle data and the other for detecting queues using information based on infrastructure based traffic data. The TME Q-WARN application uses the queue state data element in both the connected vehicle and infrastructure-based traffic data to determine which links in the network were operating in a queue state. The TME Q-WARN application then produces information about the queue (i.e., the location of the back of the queue, the speed and direction of the queue growth, etc.) by monitoring the links and sublinks defined to be operating in a queued state. The TME Q-WARN application then forwards information about the queue to the TME Message Generator, which uses the information to generate appropriate queue warning alerts for display on infrastructure-based dynamic message signs and for broadcast to connected vehicles. The TME Q-WARN application reports the longest queue length, from either from connected vehicle or infrastructure based traffic data.

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 greatly 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

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

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

Weather-Responsive Traffic Management

The purpose of Weather Responsive Traffic Management algorithm is to determine the recommended travel speed for each link based on the prevailing road weather conditions. In this prototype development, Weather Responsive Traffic Management 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.

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 were being used. Specifically, no infrastructure detectors were present to provide vehicle data and no infrastructure signs (dynamic message signs) were deployed. This means that only connected vehicle speed data is used. Similarly, any queue warning messages issued are only displayed inside a connected vehicle.

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 uses DSRC to communicate their queued state to nearby connected vehicles. Each connected vehicle determines its milepost location and its queued state (Yes or No). 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 locate the back of queue (BOQ). Typically, queued state depends on the speed of the vehicle as well as the separation distance from the vehicle immediate downstream. If however, a vehicle is unable to determine its distance from vehicles immediately downstream, only the vehicle speed may be used to determine its queued state.

Each connected vehicle receiving information from other connected vehicles identifies and locates all downstream connected vehicles. Based on the milepost location of the connected vehicles, a non-queued vehicle identifies the BOQ, if present, from among the downstream vehicles. The location of BOQ is then transmitted 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

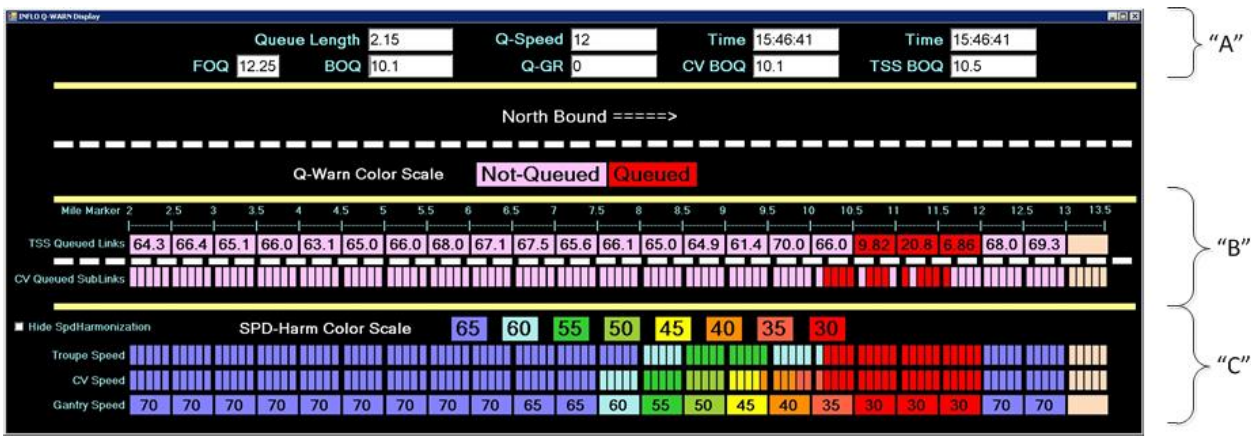
As shown in Figure 3-7 through Figure 3-13, INFLO messages to the driver are displayed directly on the In-Vehicle System and can be readily demonstrated and verified. However, the INFLO Database is a data repository in the Cloud that is not easily read and understood. Visualization tools were used to demonstrate and verify the functionality of the INFLO Database. This includes the TME Algorithm Queue Visualization Tool described below.

TME Algorithm Queue Visualization Tool

To demonstrate the functionality of the algorithm, TTI developed the display shown in Figure 3-24. 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 3-24. 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 CV 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 sate 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 CV data speed (calculated by averaging the speeds of all the connected vehicles in a sublink). For this prototype the "fused speed" for a sublink is the CV data speed where it is available and is the TSS speed where not. 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.

I-5 Corridor Demonstration Route

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 travel through two highway segments with known congestion points, I-5 North going into downtown and I-5 South going into downtown.

Table 3-1 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 displayed, with the exception of Northbound (NB) I-5 where ATM VSL messages were displayed by the infrastructure[4]. The table notes whether the beginning of the congestion is at a fixed location, such as a lane closure, or if it is variable, due to traffic turbulence.

The INFLO algorithm contains numerous configuration and threshold parameters. These parameters need to be configured for the each specific demonstration corridor. Appendix B shows lists these parameters and the value used in the Small-Scale Demonstration.

[4] 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.

Table 3-1. 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 165 to 179	Fixed	Approx. 1 mile spacing	None	Yes	Yes
4	SB I-5 from Downtown South	MP 156 to 165	Variable	Approx. 1 mile spacing	None	Yes	Yes

NB-Northbound, SB-Southbound

Source: Battelle.

Figure 3-25 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

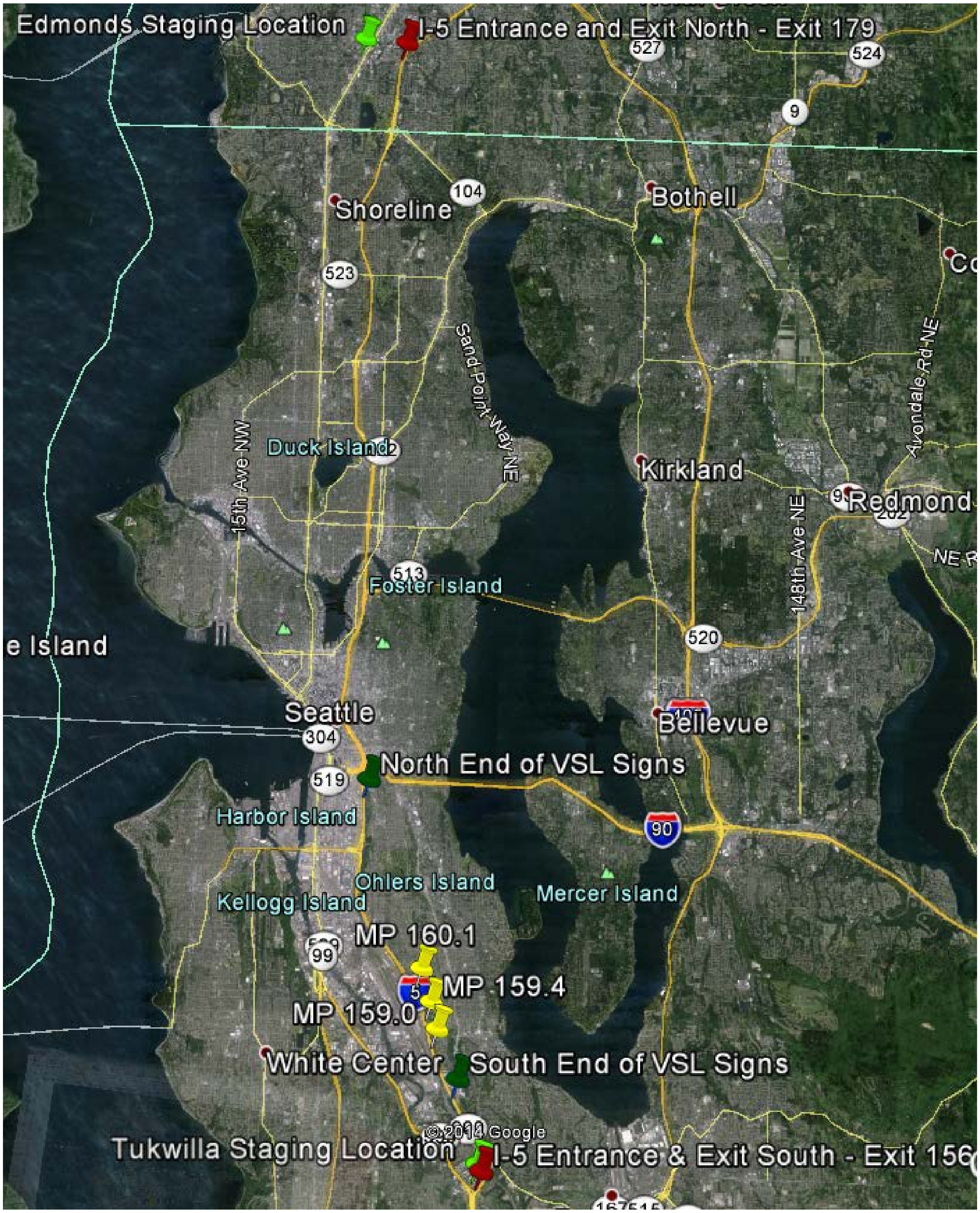
Exit 156 and 179). Light Green Pins show the location of the Edmunds and Tukwila vehicle staging areas which are large parking lots near the entrances. Yellow Pins show the locations of three RSUs at mileposts 159, 159.4 and 160.1. Dark Green Pins show South and North Ends of the I-5 Northbound ATM VSL corridor.

Infrastructure- and Connected Vehicle-based Speed Detection

The demonstration route includes a section of highway roughly seven miles in length along I-5 from MP 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 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 sub-links at a milepost marker every 0.1 mile. For example the first sub-link within the first link can be from 157.3 to 157.4 and so on. The last sub-link 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. 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.



Source: Google Earth™.

Figure 3-25. Google Earth™ View of I-5 Demonstration Route showing Entrance and Exit and RSU Locations.

Hypotheses Examined

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 system functionality and performance, measured driver behaviors and driver feedback. The demonstration vehicles and drivers traveled the deployment corridor as part of loosely organized platoons of vehicles. The data resulting from this demonstration was analyzed to examine the following hypotheses. The results of the data analyses are described Chapter 5 Data Analysis and Evaluation.

System Functionality and Performance

1. INFLO DSRC-only and cellular-only communications capture 98 percent of broadcast BSMs.
2. INFLO communications capture greater than 96 percent of BSM data when switching between DSRC and cellular communications.
3. INFLO Prototype System delivers Q-WARN and SPD-HARM messages to the drivers at least 1 mile in advance of congestion.
4. INFLO Prototype System delivers messages to drivers within 5 seconds of detection of congestion (using both DSRC and cellular communications).

Algorithm Performance

5. Integrating connected vehicle data with infrastructure data will result in improved time of detection/notification that queues are present in the deployment corridor when compared to infrastructure data only.
6. Integrating connected vehicle data with infrastructure data will result in improved resolution in the location of the back of queue when compared to infrastructure data only.
7. Integrating connected vehicle data with infrastructure data will result in improved precision in estimating vehicle speeds in the queue when compared to infrastructure data only.
8. Integrating connected vehicle data with infrastructure data will result in a difference in the recommended speeds in the corridor when compared to infrastructure data only.
9. With adequate market penetration, connected vehicle-based speed data by itself can provide estimates of the location of the back of the queue and the length of the queue that are comparable to the estimates provided by infrastructure-based speed sensors only.

Measured Driver Behavior

10. On average, drivers slow down further in advance of congestion when provided Q-WARN notification of distance to beginning of queue.
11. On average, driver speeding (greater than 10 MPH over the ATM VSL or SPD-HARM recommended speed) is reduced when Q-WARN indicates a queue ahead.
12. On average, drivers speed is within 10 MPH of the SPD-HARM and ATM recommended speeds.
13. On average, there are fewer panic stops as indicated by longitudinal deceleration.

Driver Feedback

14. On average, drivers report that they find Q-WARN and SPD-HARM messages useful, valuable and appropriate for traffic conditions.
15. On average, drivers report that they believe Q-WARN and SPD-HARM messages will improve safety by notifying them of slowed and congested traffic ahead.
16. On average, drivers report that they reduce speed when they are notified by Q-WARN and SPD-HARM messages of congestion ahead.

Data Collected

Data was collected from multiple sources and captured in the INFLO Database. All data was captured as a function of milepost location along the route northbound or southbound and a function of time. Key data included infrastructure data, vehicle data and INFLO messages summarized below.

Infrastructure Data

Speed and occupancy data were collected from the WSDOT loop detector system every 20 seconds. ATM recommended speeds displayed on the VSL were captured in the database at 20 second intervals. ATM recommended speed data were captured after the demonstration as these data were not available in real time.

Vehicle Telematics Data[5]

The following vehicle data were captured every second (1 Hz):

- GPS Latitude and Longitude, at approximately road level accuracy
- Speed
- Heading.

INFLO Messages

During the conduct of this demonstration, the Battelle 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.

[5] Battelle attempted to capture vehicle longitudinal and lateral accelerations, which are not standard data elements available through the vehicles OBD-II port, but available from some vehicles using Battelle's VITAL IVNAS. Battelle was unable to recruit sufficient drivers with vehicles from which this data could be captured.

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 and
- In-Queue with distance and time to the beginning of the queue for vehicles in a queue.

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

Process for Verifying Data Quality and Minimum Thresholds

The INFLO data aggregators verified that the infrastructure detector data (volume, occupancy, and speed) received from WSDOT were valid before using the real-time traffic data in the INFLO algorithms (SPD-HARM and Q-WARN). The Team adopted some of the infrastructure detector data checks used by WSDOT into the INFLO algorithms. Similarly, validity checks were conducted on the connected vehicle data received from vehicles to determine that the data was valid for use in making decisions for the roadway segment being monitored. For example, the location of the vehicle was compared to the boundaries of the roadway segment being monitored to determine if the vehicle information could be used or not.

The Infrastructure data thresholds that were adopted from the WSDOT algorithm include:

- Occupancy = 8 percent
- Volume = 10 vehicles per minute
- Max Speed = 65 mph
- Min Speed = 35 mph.

Some of the infrastructure data checks that were adopted from the WSDOT algorithm to insure data quality include:

- If occupancy and volume are less than thresholds, use the Max Speed
- If occupancy or volume are less than thresholds, use calculated speed[6]
- If neither occupancy or volume are less than thresholds, use trap speed[7]
- If speed = 0.0, use Max Speed
- Any Local Speed[8] above Max Speed is set to Max Speed.

[6] "Calculated speed" is a speed at a detector station where speed cannot be measured directly (e.g., at a station where only one detector exists). The speed is computed using measured volume and occupancy at the location.

[7] "Trap speed" is the speed measured by the traffic detection system. Generally, this speed is measured by using two loop detectors.

[8] "Local speed" is a term used by WSDOT to indicate the prevailing speed at a given detection station. It can be the calculated speed, the trap speed, or the max speed.

The Team evaluated the messages that were received from the connected vehicles during the early stages of the deployment to set thresholds for connected vehicles data quality. These thresholds include:

- Minimum number of vehicles in a sub-link for use of the connected vehicle data to calculate the speed of a sub-link[9] and
- Percentage of queued vehicles in a sub-link to declare a sub-link as queued.[10]

[9] Because the demonstration had a limited number of connected vehicles, this value was set to 1.0.

[10] For the purposes of the demonstration, this value was set to 50 percent.

Chapter 4 Implementation of the INFLO Small-Scale Demonstration

This section of the report summarizes the implementation of the demonstration, including

- Recruitment and Identification of Demonstration Participants
- Vehicle System Readiness Acceptance Criteria
- Driver Support During the Demonstration
- Daily Demonstration Vehicle Deployment.

Recruitment and Identification of Demonstration Participants

Participants were recruited using internet classified advertisements, based upon prior success. Battelle 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. Although the project does not include a parametric analysis of driving with regard to age or gender, Battelle attempted to recruit a reasonably balanced population demographically in order to achieve a representative sample of drivers in the Seattle area.

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). Recruiting materials were a key component of the IRB approval process, so those were developed as soon work began on the IRB submission. Recruiting began following the 2014 Thanksgiving Holiday and continued until the week before 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. The initial list of screening variables is shown in Table 4-1 below. The screening questions below were updated to reflect additional constraints identified as the IRB process was completed.

Table 4-1. Variables Included in the Participant Screening Questionnaire.

Proposed Variable	Type	Purpose
Driver age	Continuous	Used for filling experimental groups
Driver gender	M / F	Used for filling experimental groups
Own and / or regularly drive an insured vehicle?	Yes / No	Participant Requirement
Available to drive during specified demonstration periods?	Yes / No	Participant Requirement
Commuting Vehicle is a 2004 or later Ford, GM or Toyota?	Yes / No	Desirable for obtaining vehicle telematics data, but not required
Is the primary driver of this vehicle?	Yes / No	Participant Requirement
Is the vehicle in good operating condition?	Yes / No	Participant Requirement
Able to complete questionnaire?	Yes / No	Participant Requirement
Have and regularly use internet and e-mail?	Yes / No	Participant Requirement

Source: Battelle.

Participant Intake and Institutional Review Board Approval (IRB)

Once recruited, the Team scheduled an appointment with the participants at the Battelle Seattle Research Center. On arrival, the participants were provided with the informed consent form that describes the demonstration, participant requirements and the risks associated with the demonstration. In addition, participants were also given specific instructions about the demonstration and then asked to fill out a demographic questionnaire. All participants received a demonstration check-list that would serve as a reach-back tool throughout the demonstration period. The demonstration check-list contained specific instructions for events such as "What to do if you are in an accident?" or "How do you know if your equipment is working?" and other such topics. Team members assisted the participants with the intake process and answered any questions/concerns that they had about the demonstration and/or the check-lists that were provided.

Protecting driver privacy and confidentiality was a key requirement in the current project because, while not likely, we could potentially record behavior that is in violation of law. Risk to participants such as being subject to prosecution because of recorded behavior needs to be minimized. Full disclosure of this litigation risk was given to participants during the recruiting and the informed consent processes. Another reason for focusing on confidentiality is to discourage participants from changing their behavior and responses to make them more socially acceptable (e.g., by driving slower than they normally would), thus impairing our ability to answer the key research questions.

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.

Another issue that required special consideration is that the installed equipment must not pose a safety risk to drivers. We addressed this by ensuring that the device was positioned well outside of the driver's normal field of view, and it is fastened securely to the vehicle so that it does not cause undue distraction by sliding around the driver's dashboard.

Driver Support during the Demonstration

This section addresses:

- Vehicle System Preparation and Acceptance
- Onboarding of Participants and System Installation
- Monitoring and Operational Support
- Equipment De-installation and Closeout.

Vehicle System Preparation and Acceptance Testing

Battelle acquired components and assembled connected vehicle installation kits that were provided to system installers. As part of the kit assembly process the appropriate firmware and applications were installed on each component. They were placed in a benchtop acceptance test system in which their functionality was verified, before they were placed in the kit for installation. Upon installation in a participant's vehicle, a test application was run to verify that the system was functional and was sending and receiving appropriate messages via DSRC and via cellular communications.

Prior to conducting the demonstration, TTI conducted a comparison of the SPD-HARM recommendation messages to WSDOT ATM VSLS speed recommendations and refined the SPD-HARM algorithms for consistency and to provide a baseline for comparison.

Onboarding of Participants and System Installation

Prior to the data collection period, the Team developed written procedures for participant intake and installation and testing the equipment installation.

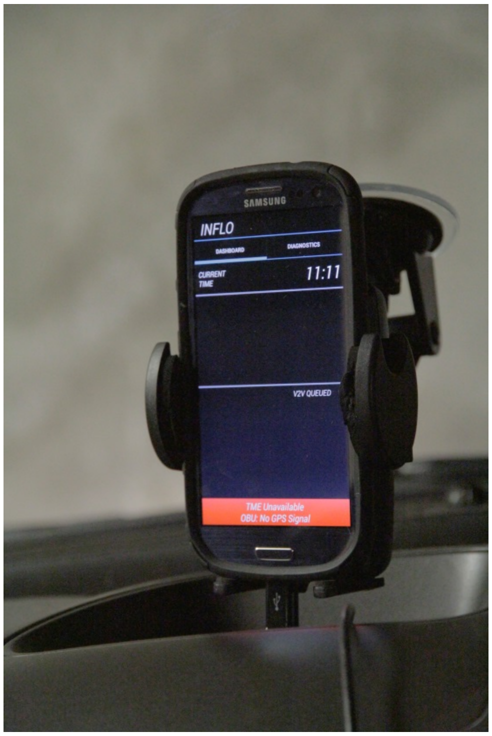
The participant consent, participant briefing and equipment installation was performed at the Battelle Seattle Research Center. Once the participant had completed the intake process, the installer accompanied the participant to his or her vehicle for installation of the connected vehicle equipment. The 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. It was important the driver be able to remove the device when the vehicle is not moving in order to minimize the risk of break-in and theft of the device. Figure 4-1 shows a part of the installation process.

Source: Battelle.

Figure 4-1. 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.

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. The test also included a check of the power adapter and cable to ensure that the device was charging when plugged into the APP and active. Figure 4-2 shows the drive display unit (Samsung smartphone) during post-installation testing.

For quality control purposes, a checklist was developed to facilitate documentation of the installation. The installer marked each step of the installation and testing procedure to make sure the device was properly installed and the participant received all instructions and materials.



Source: Battelle.

Figure 4-2. Initial Display of the INFLO Application in a Participant Vehicle during Post Installation Testing.

Monitoring and Operational Support

Consistent engagement with demonstration participants and continual monitoring of the connected vehicle equipment that support the applications was maintained during the operational period. The status of the installed devices was checked before deployment each day to determine if the In-Vehicle Systems were functioning as designed, identifying why it is not functioning properly and taking corrective actions to ensure proper functionality during each driver's period of participation.

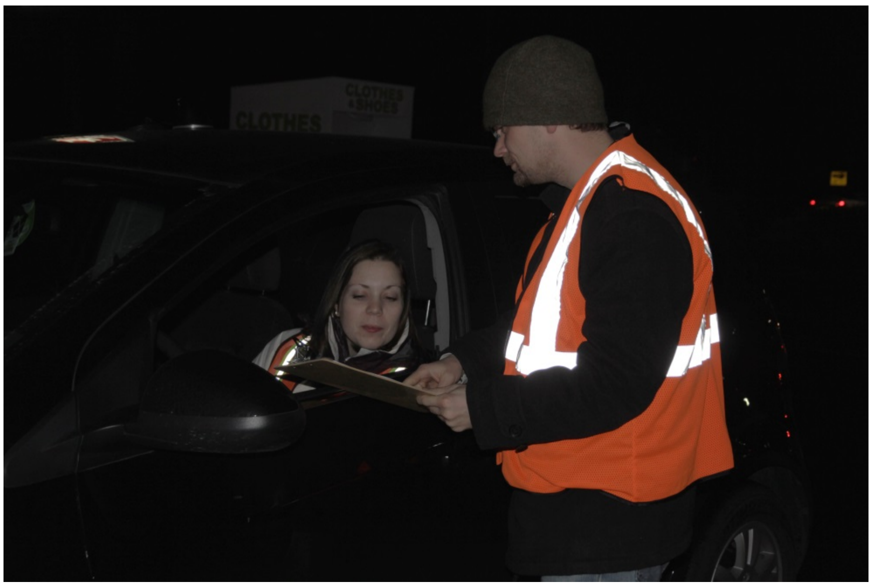
Daily Demonstration Vehicle Deployment

The Battelle Team recruited 21 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 7 drivers, and platoon two had 14 drivers. Each platoon concentrated the number of vehicles within a link and sublink to provide relatively compact groupings of CV 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 3-25. 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. Figure 4-3 shows a simulation of Battelle staff providing instructions to drivers prior to departure. Figure 4-4 shows a simulation of participant vehicles lined up and ready, prior to departure.[11]



Source: Battelle.

Figure 4-3. Simulation of Driver Instruction Prior to Departure.

[11] Simulations using Battelle staff are used here to protect the privacy of the participants.

Source: Battelle.

Figure 4-4. Simulation of Drivers Lined up Prior to Departure from the Tukwila Parking Lot.

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.

Monday through Wednesday, participants did not have time to make the second Edmonds to Tukwila leg due to time constraints (participants agreed to drive until 10:00 a.m.). Thursday participants drove two full round trips. Friday, the southbound, leg ended at Battelle offices where the equipment was removed from their vehicles and they completed the post-drive questionnaire.

Participant Summary

Twenty-one participants enrolled and completed the demonstration. Two participants were unable to make the Thursday demonstration due to unexpected scheduling conflicts. Two participants did not drive on Friday because of equipment issues. One participant arrived late and started the drive 20 minutes after the last platoon member left.

Participants were generally enthusiastic about the study and remained so for the duration of the study. Participants largely followed instructions, although a few may have taken the express lanes on Wednesday when there was heavy traffic due to three crashes along the driving route.

Hardware

DSRC radios had to be replaced in 8 of the 21 vehicles during the course of the week. Battelle notes that “first-generation” DSRC components are commercially available from multiple suppliers, but the number of units sold is currently limited to relatively small research and development deployments. This appears to be too few deployments in the field for the technology to be considered “field-hardened”.

Equipment De-installation and Closeout Driver Survey

At the conclusion of the data collection, a Team member contacted the participants to schedule the closeout appointment at the Battelle Seattle Research Center. 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.

Chapter 5 Data Analysis and Evaluation

The scope of the 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 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, and
- 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. Furthermore, the Small-Scale Demonstration confirmed that the INFLO Prototype System has the latency, processing speed and communications bandwidth 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 description of the data comparisons and analyses that were performed to help assess the hypotheses introduced earlier. 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. The data, analysis, and observations provided below are considered preliminary and subject to revision when the system is refined and more rigorous testing is conducted.

The scope of this effort focused on demonstrating the capabilities of connected vehicle technology to support a Prototype INFLO System. The number of participants in the demonstration was limited to the number needed to demonstrate the technology. The scope of the effort did not include capturing ground truth data.

System Functionality and Performance

Hypothesis 1. Vehicle BSM Data Capture

Connected vehicle communications are designed with the expectation that all broadcast BSMs may not be received, particularly at the edge of DSRC communication range. Hypothesis 1 for the demonstration evaluation was to confirm that the system reliably captures the majority of vehicle BSMs when in range. The specific hypothesis is that

INFLO DSRC-only and cellular-only communications capture 98 percent of broadcast BSMs.

Limited onboard logging capability prevented performing direct comparisons of messages sent and messages received to determine the exact percentage received, however, as shown in later graphs and analysis, the system and algorithms performed as expected and had sufficient BSM data to assess traffic congestion and deliver Q-WARN and SPD-HARM messages to drivers. No evidence was found of loss of BSM data, whether DSRC or Cellular, 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 meet the needs for reliably capturing BSMs.

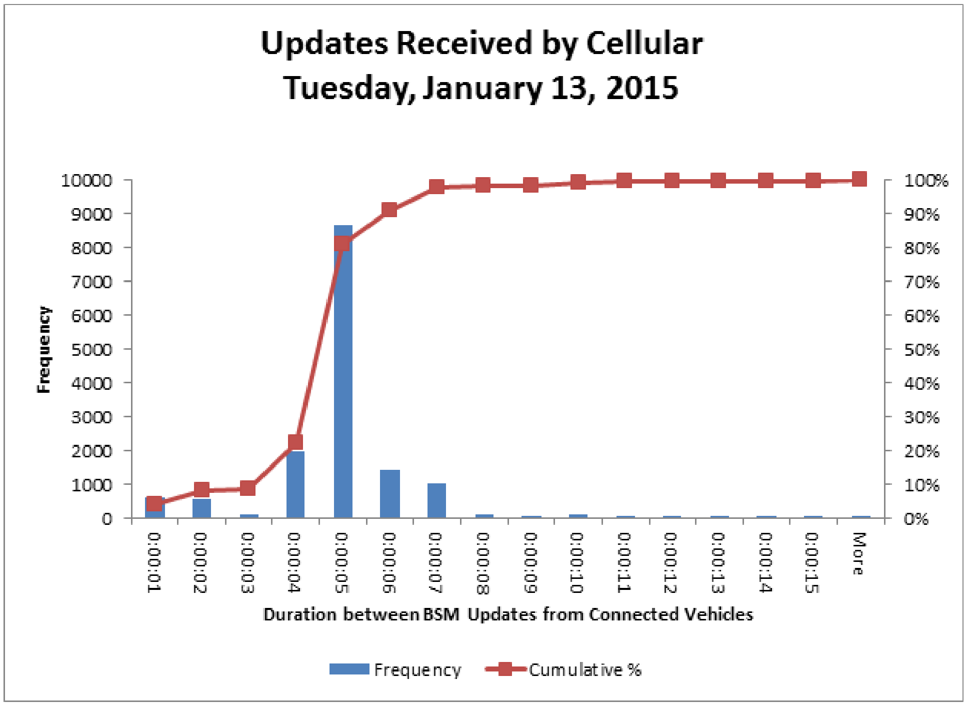
Hypothesis 2. Data Loss When Switching Communication Modes

It is expected that DSRC infrastructure will grow as the number of DSRC enabled vehicles on roads and highways grow. Until DSRC infrastructure is widespread, it is expected that cellular communications may be used for V2I exchange of connected vehicle data. This hypothesis and brief analysis is focused on determining if there are any fundamental issues with automatic switching between DSRC and cellular communications. The specific hypothesis is that

INFLO communications capture greater than 96 percent of BSM data when switching between DSRC and cellular communications.

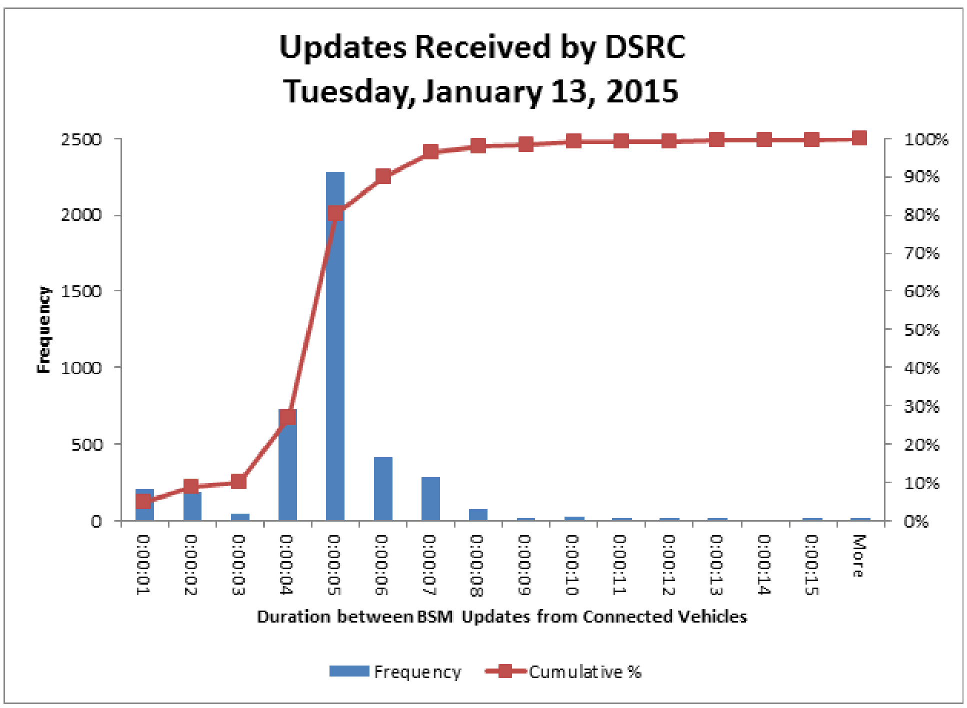
Again, limited onboard logging capability prevented performing direct comparisons of messages sent and messages received to determine the exact percentage received via cellular and via DSRC. Figure 5-1 through Figure 5-4 compare differences between the duration of BSM bundle updates received from all vehicles as they traversed through Segment 1 northbound on I-5, from milepost 157 to 166 for two days of the demonstration. BSMs were generated every second. BSMs were then bundled and sent via DSRC or Cellular communications every 5 seconds. As described earlier, the applications were developed such that BSMs are sent via DSRC when there is adequate RSU to OBU DSRC signal strength for communication (as measured by RSSI) or via cellular communications when not. These figures compare vehicle BSM bundle update differences between when they are in range of RSUs and when they are at least a mile away from RSUs. Figure 5-2 and Figure 5-4 encompass the data received from all three deployed RSUs.

The results in the figures show consistent receipt of BSM bundles via both DSRC and cellular communications. No evidence was found that BSMs were lost during the switch between cellular to DSRC and back. No evidence was found of disruption in the algorithms caused by switching between cellular to DSRC and back. The use of RSSI as a measure of RSU to OBU DSRC signal strength appeared to satisfy the criterion for switching between communication modes.



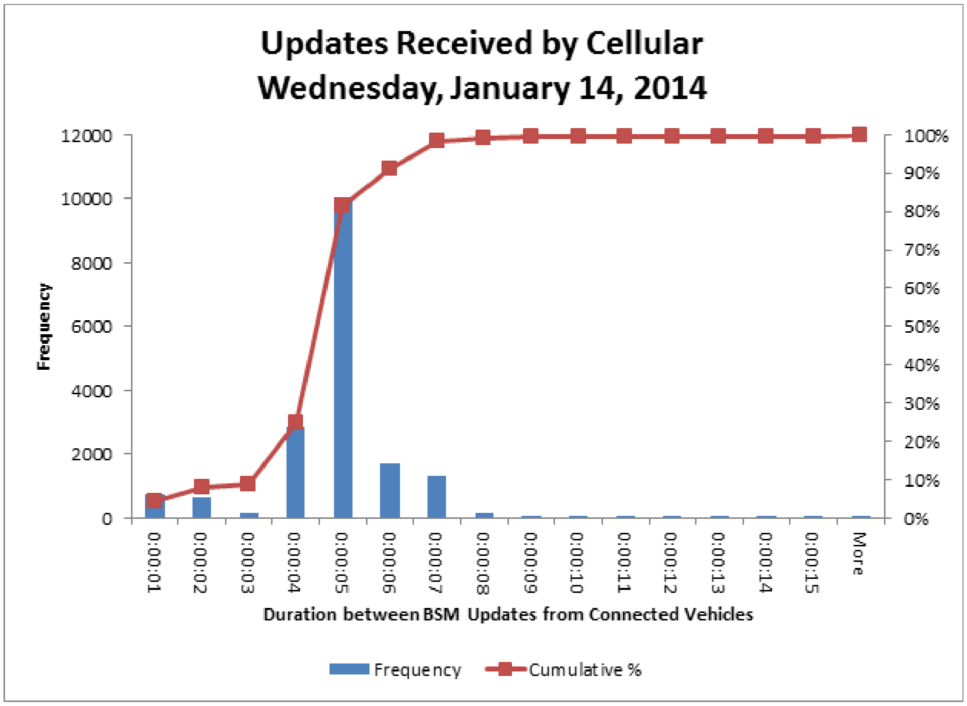
Source: TTI.

Figure 5-1. Duration between BSM Bundle Updates via Cellular on Tuesday, January 13, 2015.



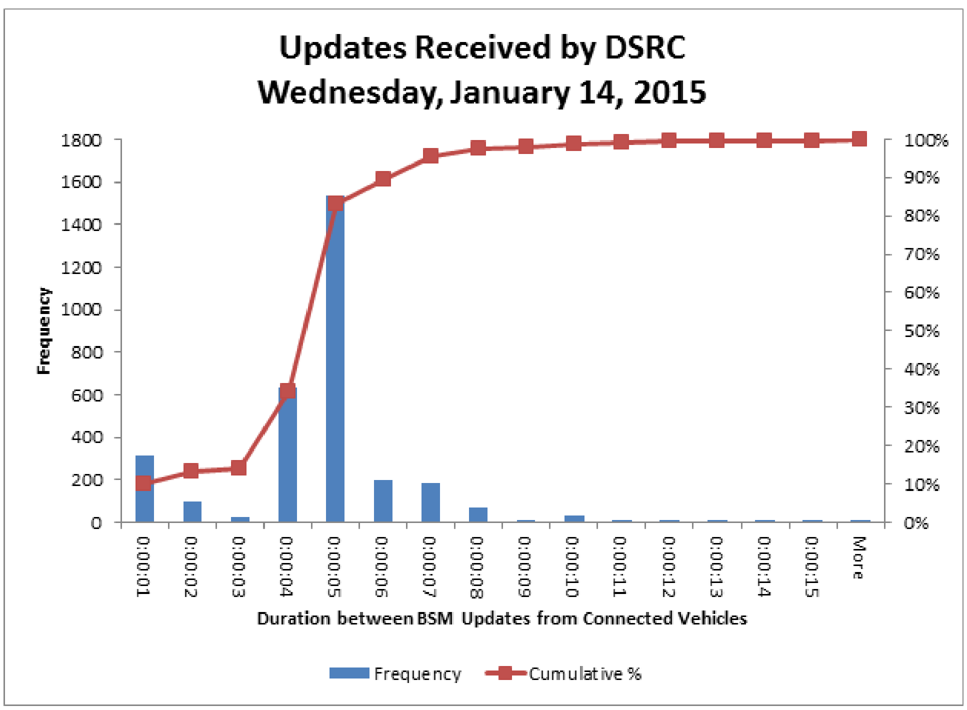
Source: TTI.

Figure 5-2. Duration between BSM Bundle Updates via DSRC on Tuesday, January 13, 2015.



Source: TTI.

Figure 5-3. Duration between BSM Bundle Updates via Cellular on Wednesday, January 14, 2015.



Source: TTI.

Figure 5-4. Duration between BSM Bundle Updates via DSRC Wednesday, January 14, 2015.

Hypothesis 3. Advance Delivery of Messages

A key INFLO user need is that drivers receive Q-WARN and SPD-HARM messages in time for them to take suitable action. The specific hypothesis is that

> *INFLO Prototype System delivers Q-WARN and SPD-HARM messages to the drivers at least 1 mile in advance of congestion.*

This hypothesis was addressed by inspection of the system and algorithm design. The Q-WARN and SPD-HARM processors were designed to capture BSM data from the database, analyze it and populate messages for drivers every 5 seconds. In practice, this process was found to take 2 to 3 seconds. Vehicles would similarly poll the database for new information every second, and deliver messages to the driver when they are within 1 mile of the back of the queue. In practice, this process took 2 to 3 seconds. In general, the cycle of capturing data in the database, processing it and delivering messages back to drivers took less than 10 seconds. This confirms that drivers can be expected to receive messages approximately a mile in advance. INFLO Prototype System testing and demonstrations found that the system is very capable of data capture, data processing and delivery of messages to drivers well before they would need to take suitable action. Design of production level INFLO Prototype Systems will need to consider the processing speed and bandwidth required to support capturing and processing data from the large population of connected vehicles on the roadway when the technology is essentially fully deployed.

Hypothesis 4. Latency of Message Delivery

Similar to the previous hypothesis, this one is focused on addressing the user need that drivers receive messages in time for them to take suitable action. The hypothesis is

> *INFLO Prototype System delivers messages to drivers within 5 seconds of detection of congestion (using both DSRC and cellular).*

The Q-WARN and SPD-HARM processors were designed to analyze data to detect congestion and populate messages for drivers every 5 seconds. Vehicles poll the database for new information every second and deliver messages to the driver immediately (when they are within 1 mile of the back of the queue). In practice, this process of delivering messages to the drivers after detection by Q-WARN and SPD-HARM algorithms took 2 to 3 seconds. INFLO Prototype System testing and demonstrations found that the system is very capable of data capture, data processing and delivery of messages to drivers well before they would need to take suitable action.

Algorithm Performance

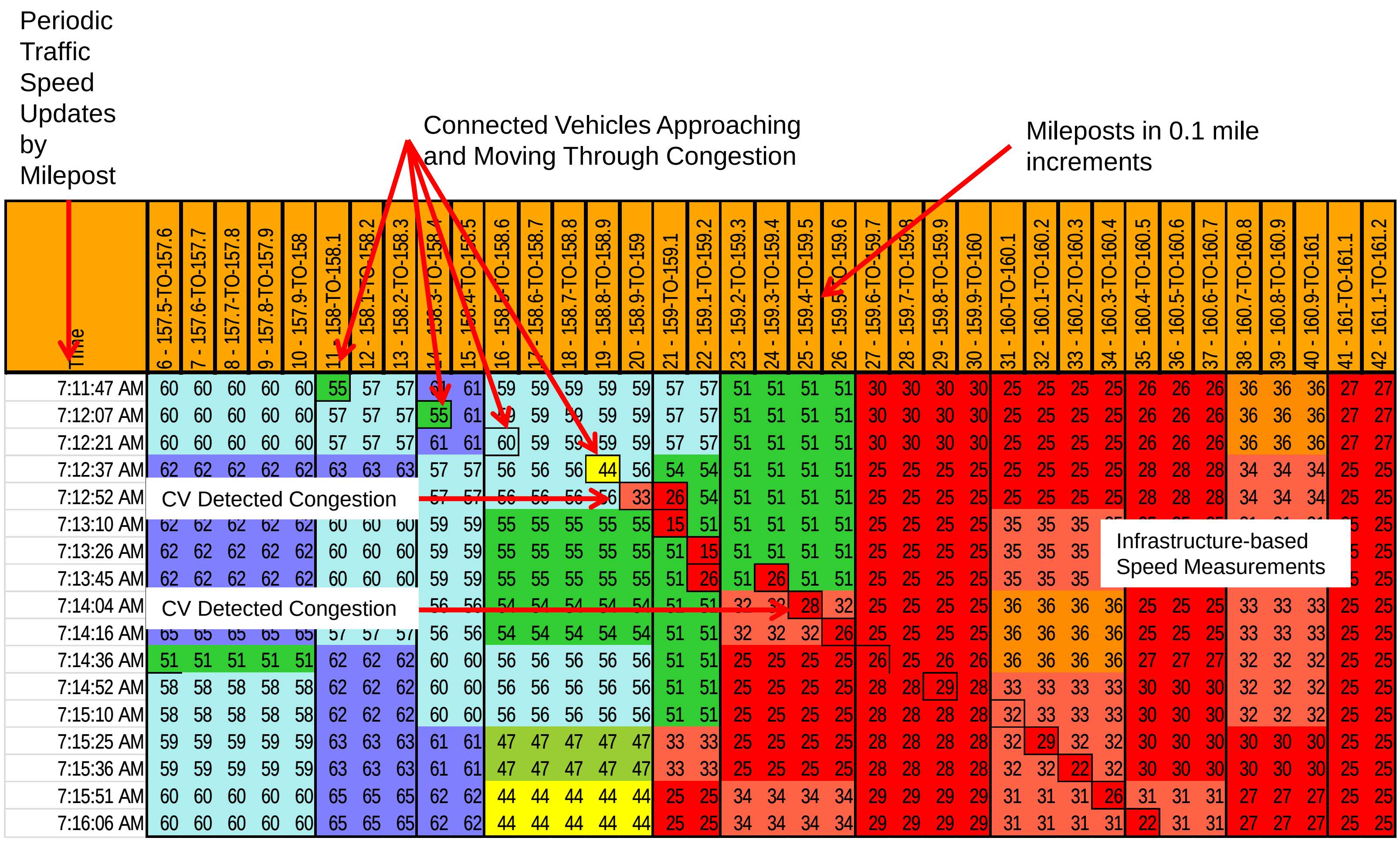
Hypothesis 5. Time to Detection/Notification of Back of Queue

Hypothesis 5 for the demonstration focuses on the degree to which connected vehicles could help improve the time of detection and notification of the back of the queue. The specific evaluation hypothesis is:

> *Integrating connected vehicle data with infrastructure data will result in improved time of detection/notification that a queue is present in the deployment corridor when compared to infrastructure data only.*

In each of the study days, queues had already formed in the corridor by the time the connected vehicles entered the traffic stream. However, insight into the extent to which integrating connected vehicle data changes the time to detection is provided by comparing the time a connected vehicle platoon detects the back of the queue to when the infrastructure traffic sensor system detects the back of the queue.

Figure 5-5 shows a portion of the 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 already 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 using speeds at periodic infrastructure sensor locations. As shown in the following hypothesis, connected vehicle data can also be used to determine the back of the queue more precisely.



Source: TTI.

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

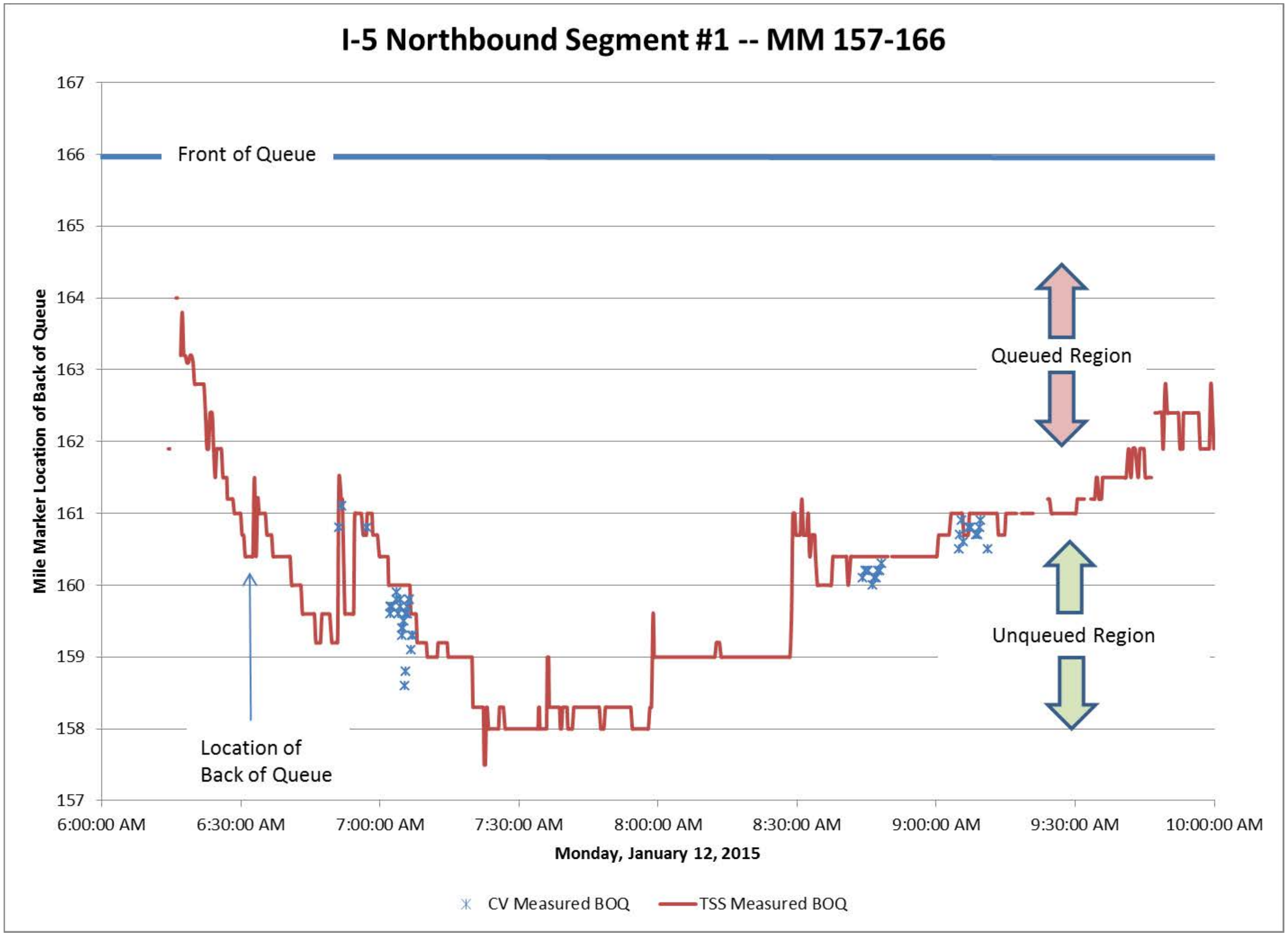
Hypothesis 6. Locating the Back of Queue

Hypothesis 6 focuses on the degree to which integrating data from connected vehicles can improve the accuracy and resolution of the estimated back of queue. The specific hypothesis under consideration in this analysis is:

> *Integrating connected vehicle data with infrastructure data will result in improved resolution in the location of the back of the queue after each iteration when compared to infrastructure only information*.

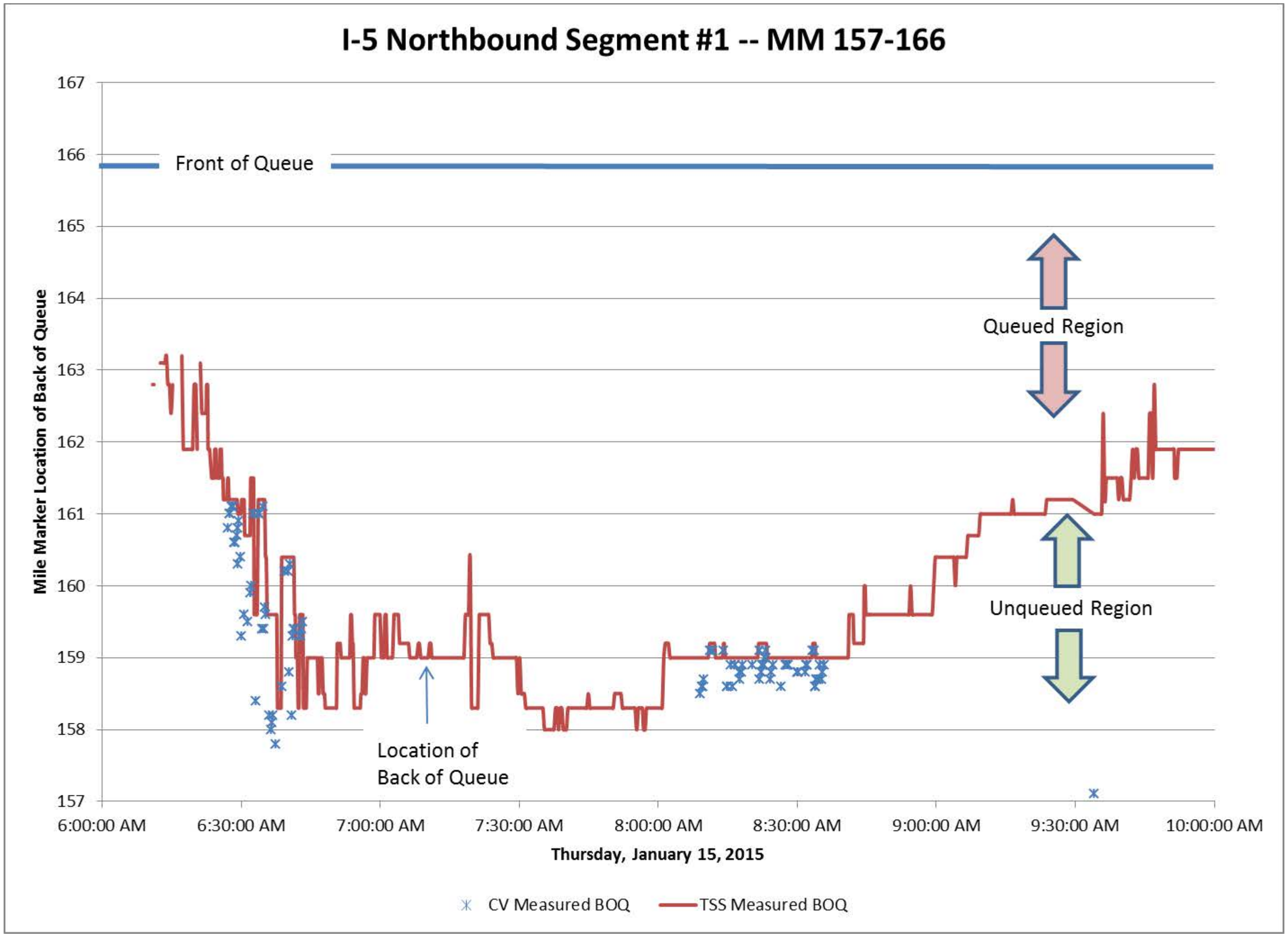
For this analysis, the research team used a series of time-space plots showing the estimated location of the back of the queue derived by INFLO algorithms using data from the WSDOT traffic sensors only compared with data from the INFLO algorithms with information from the connected vehicles included in the back of queue estimate. 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 5-6 and Figure 5-7 compare the location of the back of queue in the first northbound segment on I-5, from milepost 157 to 166, for each day 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 5-6. Comparison of Back of Queue Estimates for I-5 Northbound Segment 1 on Monday, January 12, 2015.



Source: TTI.

Figure 5-7. Comparison of Back of Queue Estimates for I-5 Northbound Segment 1 on Thursday, January 15, 2015.

Hypothesis 7. Estimating Vehicle Speed in Queue

The INFLO algorithm also provided the connected vehicles with an estimate of the average speed in the queue. Hypothesis 7 focused on the estimated speed in queue. The specific hypothesis under consideration in this analysis is as follows:

> *Integrating connected vehicle data with infrastructure data will result in improved precision in estimating vehicle speeds in the queue when compared to infrastructure data only.*

For this hypothesis, we refer back to Figure 5-5 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.

Hypothesis 8. Recommended Travel Speeds

One function of the INFLO Prototype System was to provide SPD-HARM recommendations, the process of dynamically and automatically reducing speed limits in and/or before areas of congestion, accidents, or bottleneck locations in order to maintain flow and reduce the risk of collisions due to speed differential. The INFLO SPD-HARM algorithm was specifically designed to step speed down by 5 mph increments in advance of the queue as well as manage speeds within areas of congestion. The INFLO algorithm used both speeds from connected vehicles as well as speeds from WSDOT detector data to provide SPD-HARM recommended speeds. The specific hypothesis under consideration in this analysis is as follows:

> *Integrating connected vehicle data with infrastructure data will result in a difference in the recommended speeds in the corridor when compared to infrastructure data only.*

Figure 5-8 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 5-8 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 MP 161, followed by a brief speedup and then slowdown again to 27 MPH at MP 161.5. During this time, the WSDOT VSL speeds recommend 30 MPH at MP 161.0, preceded by speed reduction steps beginning at MP 158 from 60 to 55, 50, 40 and finally 30 MPH at MP 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 MP 161.0. This pattern remains constant until 6:23 where the speed at MP 161.0 is adjusted to 35 MPH, even though measured speeds there were below 30 MPH.

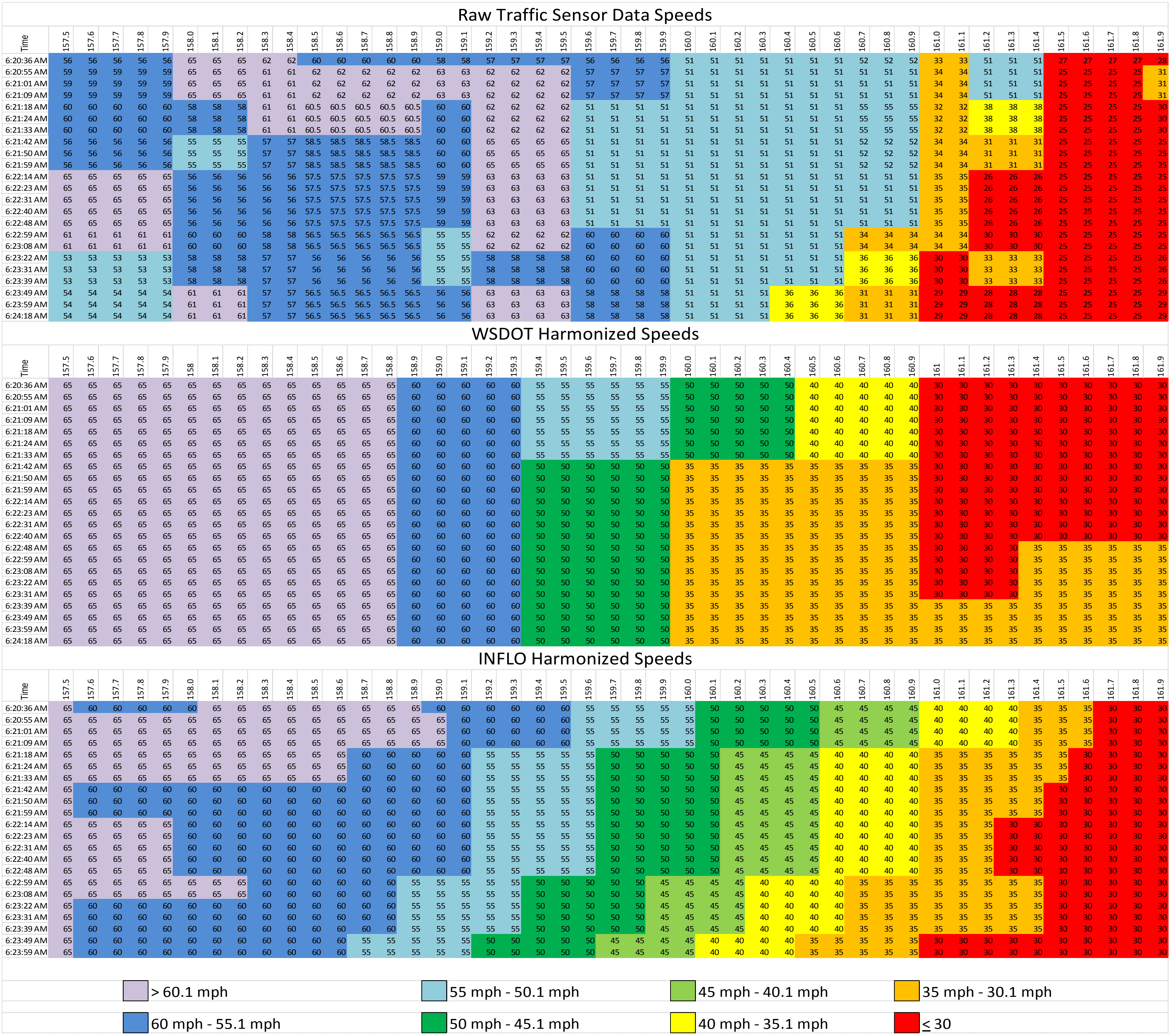
During this same time, the INFLO SPD-HARM application is more dynamic. This algorithm shows the back of the queue and congestion is updated every 20 to 30 seconds and the SPD-HARM recommendation changes with each update and varies more widely than that specified by VSL. The step down in speed recommended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

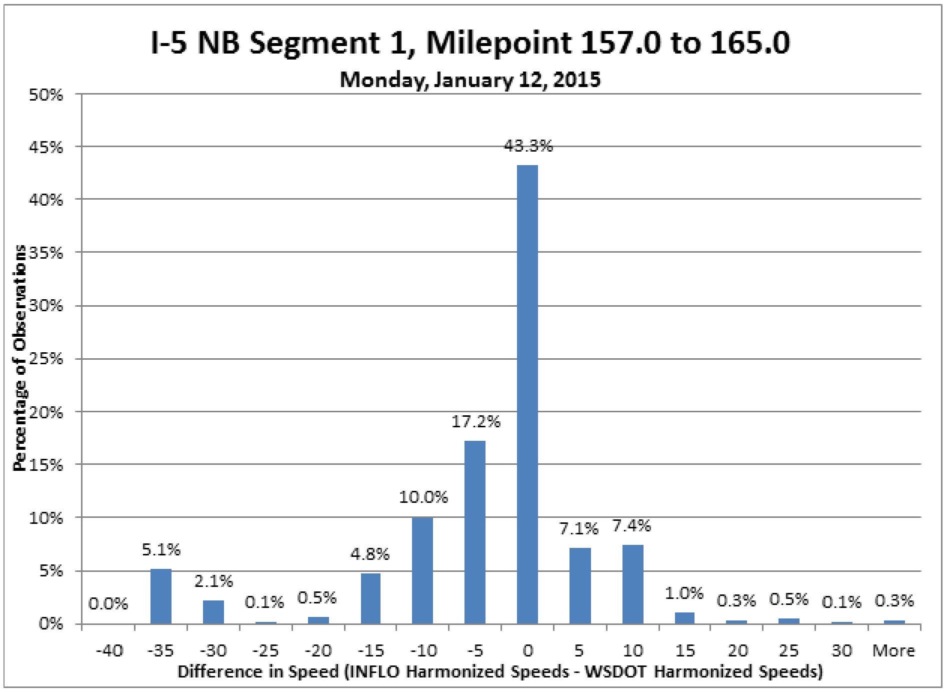
To provide further insights, Figure 5-9 and Figure 5-10 are histograms comparing SPD-HARM recommended speeds with VSL speeds on the first northbound segment on I-5, from milepost 157 to 166 on Monday and Friday. The histograms provide some interesting comparisons. In both cases, the peaks in the histogram shows that SPD-HARM recommendations are consistent with VSL speeds the largest fraction of the time, 43.3 percent on Monday and 67.8 percent on Friday. The SPD-HARM recommendations are within ±5 MPH of the VSL speed more than 65 percent of the time on Monday and 90.2 percent of the time on Friday. The SPD-HARM recommendations are within ±10 MPH of the VSL speed more than 85 percent of the time on Monday and more than 97.3 percent of the time on Friday. The SPD-HARM recommendations are equal to or below the VSL speed more than 80 percent of the time on Monday and 91.8 percent of the time on Friday.

The differences in results for Monday (Figure 5-9) and Friday (Figure 5-10) are attributed to the difference in vehicle deployment strategy at the beginning of the week and the end of the week. Early in the week, the connected vehicles were grouped in two tight platoons – a six-vehicle platoon was released first followed by a 12- vehicle platoon released approximately 15 minutes later. Later in the week, the release pattern was changed to 1 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. Interestingly, the SPD-HARM recommendations based upon a simulated lower level penetration are closer to the VSL recommendations than are those with a simulated higher level penetration. The VSL speeds are based upon periodically based sensors, while the SPD-HARM recommendations are based upon more continuously distributed vehicle speeds. These results suggest that market penetration may influence the SPD-HARM recommendations. More rigorous modeling, testing and analysis are needed to assess these issues.



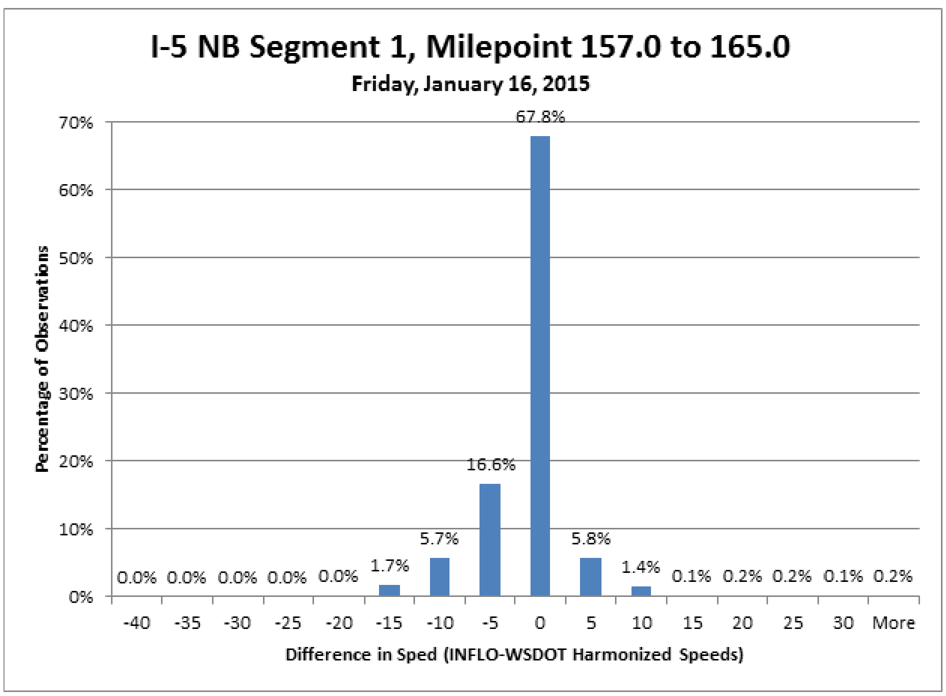
Source: TTI.

Figure 5-8. Example Comparison of SPD-HARM Recommended Speeds to Infrastructure Speeds.



Source: TTI.

Figure 5-9. Histogram comparing INFLO Recommended Speeds to WSDOT VSL Speeds on I-5 Northbound Segment 1 on Monday, January 12, 2015.



Source: TTI.

Figure 5-10. Histogram comparing INFLO Recommended Speeds to WSDOT VSL Speeds on I-5 Northbound Segment 1 on Friday, January 16, 2015.

Hypothesis 9. Market Penetration

The term "market penetration" is used to loosely denote the percentage of vehicles on the roadway that are connected vehicles. Hypothesis 9 considers the level of market penetration needed to estimate the location of the back of the queue. The specific hypothesis under consideration in this analysis is as follows:

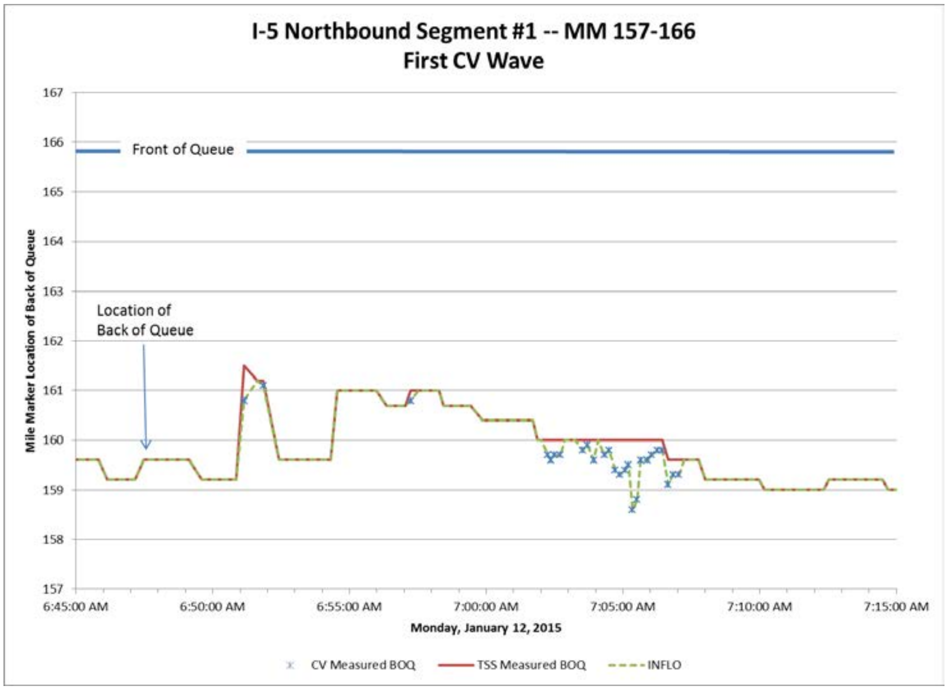
> *With adequate market penetration, connected vehicle-based speed data by itself can provide estimates of the location of the back of the queue and the length of the queue that are comparable to that provided by infrastructure-based speed sensors only.*

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 12- vehicle platoon released approximately 15 minutes later. Later in the week, the release pattern was changed to 1 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.

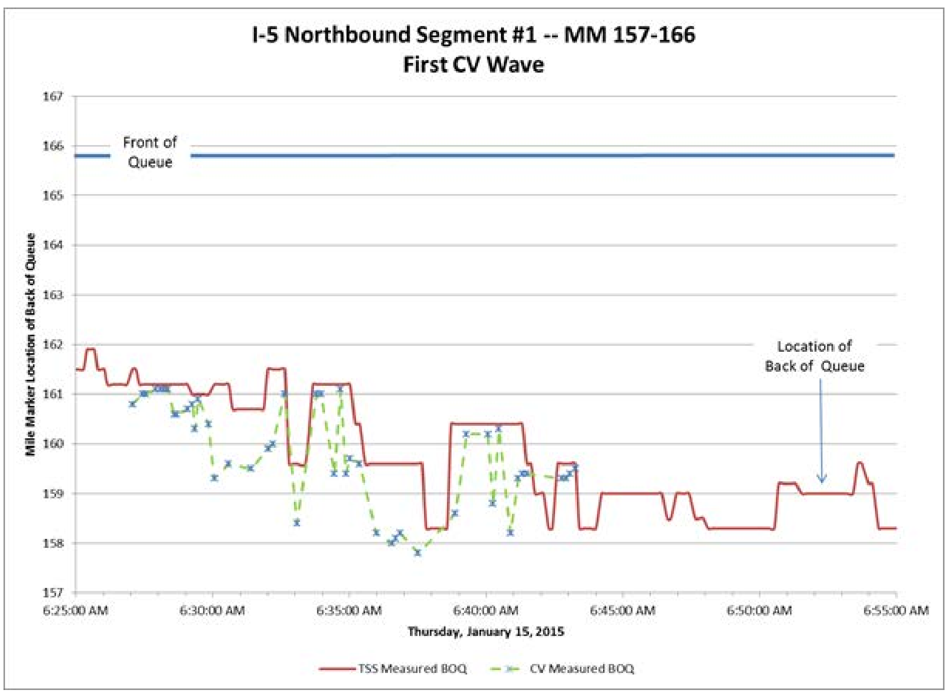
Following this logic, the research team examined the differences in which the algorithm determined the back of queue under the two release patterns. Figure 5-11 shows an example of the performance of the INFLO algorithm for a 30-minute window with short headways between connected vehicles and Figure 5-12 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 CV-only data and based upon infrastructure-only data. As shown in Hypothesis 5, Figure 5-5, the CV 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 5-12 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 that includes measurement of "ground truth" is needed to draw firm conclusions.



Source: TTI.

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



Source: TTI.

Figure 5-12. Determination of Back of Queue with Longer Headways between Connected Vehicles Representing a Low Market Penetration.

Measured Driver Behavior

Hypothesis 10. Driver Speed Reduction in Advance of a Queue

One of the key tenets of the INFLO Q-WARN and SPD-HARM applications is that they will notify drivers of slowed vehicles ahead so that drivers may slow down to smooth traffic flow and reduce the likelihood of collision. The relevant hypothesis is that:

> *On average, drivers slow down further in advance of congestion when provided Q-WARN notification of distance to beginning of Queue.*

For the demonstration, drivers were instructed to drive safely and consistent with their normal driving behavior. While, as noted later, drivers found the Q-WARN information valuable, the scope and size of this demonstration was not sufficient to be able to tease out driver speed reductions.

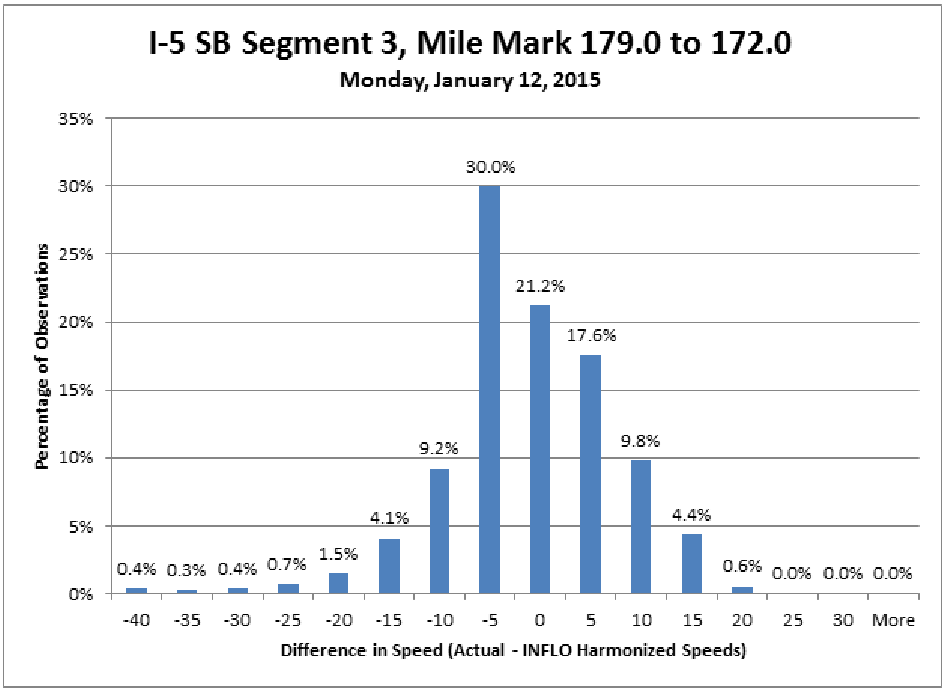
Hypotheses 11 and 12. Driver Speeding Behavior

Hypothesis 11 and 12 address driver speeding behavior in relation to the VSL speeds and SPD-HARM recommended speeds. The two hypotheses are

> *On average, driver speeding (greater than 10 MPH over the ATM VSL or SPD-HARM recommended speed) is reduced when Q-WARN indicates a queue ahead.*
>
> *On average, driver speed is within 10 MPH of the SPD-HARM and ATM recommended speeds.*

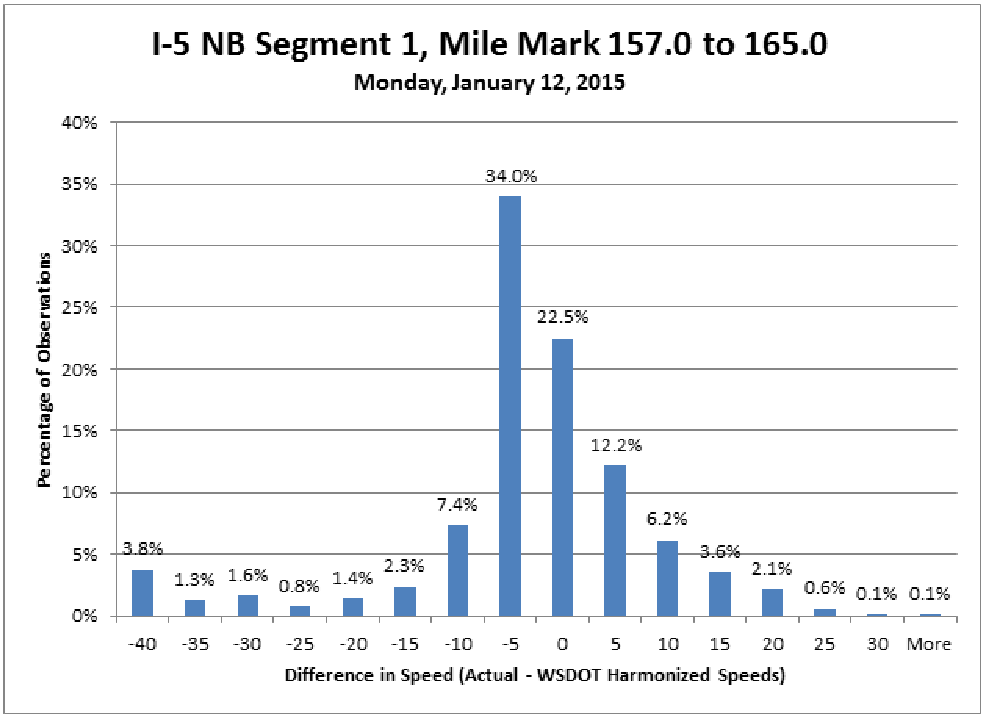
For the demonstration, drivers were instructed to drive safely and consistent with their normal driving behavior. Recognizing that VSL speeds are regulatory limits while SPD-HARM is not, it was postulated that there may be an observable difference in behavior between the two.

Figure 5-13 shows a histogram of the difference between actual speeds and SPD-HARM recommended speeds on Southbound I-5 Segment 3 (without VSL). Figure 5-14 show a histogram of the difference between actual speeds and WSDOT VSL speeds on Northbound Segment 1. The histograms both show a peak at 5MPH below the SPD-HARM and WSDOT VSL recommendations. The histograms then show an incremental decay in difference up to about 20 MPH over the SPD-HARM/VSL speeds and 20 MPH below. The behavior is fairly consistent between the two with no discernable differences. More comprehensive investigations addressing both human factors and traffic flow is necessary to address this issue. The results shown here do indicate that connected vehicles can be used as a valuable tool to collect the necessary data.



Source: TTI.

Figure 5-13. Histogram Comparing Actual Speeds to INFLO Recommended Harmonized Speeds on I-5 Southbound Segment 3 on Monday, January 12, 2015.



Source: TTI.

Figure 5-14. Histogram Comparing Actual Speeds to WSDOT VSL Speeds on I-5 Northbound Segment 1 on Monday, January 12, 2015.

Hypothesis 13. Panic Stops

It was planned to capture driver acceleration and deceleration data in an attempt to determine if there were fewer panic stops as indicated by longitudinal deceleration. Regrettably, the collected data were not sufficient to discern acceleration, deceleration or stopping behavior. No observations are made concerning panic stops.

Driver Feedback

At the conclusion of the five day of demonstration data collection, drivers were asked to fill out a brief survey. Following is a summary of their observations, as they relate to the hypotheses.

Hypothesis 14. Driver Value Perceptions

Drivers were asked questions concerning their perception of the value of Q-WARN and SPD-HARM to address the hypothesis:

> *On average, drivers report that they find Q-WARN and SPD-HARM messages useful, valuable and appropriate for traffic conditions.*

Sixty two (62) percent of participants agreed or strongly agreed that the Queue Ahead Message and the In-Queue Message was useful and valuable, while 52 percent agreed or strongly agreed that the Queue Ahead Message and the In-Queue Message was appropriate for traffic conditions. Twenty nine (29) percent of participants agreed or strongly agreed that the Speed Harmonization Message was useful and valuable, while 24 percent agreed or strongly agreed that the Speed Harmonization Message was appropriate for traffic conditions.

Overall, it appears that 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. One reason that participants may not understand the value of SPD-HARM was that this is the first deployment in the field of prototype applications. The scope of the project did not provide an opportunity to conduct field tests and refine the algorithms and application over time. Hence, drivers did not have the opportunity to observe an application refined for the local operating conditions. Another is that only participants received the SPD-HARM recommendations. Heavy traffic required that participants respond to surrounding traffic conditions, and not adjust to the recommended SPD-HARM recommendations. They did not have an opportunity to observe benefits of SPD-HARM. Future work may want to consider conducting closed course tests which enable drivers to follow SPD-HARM recommendations and observe potential benefits.

Hypothesis 15. Driver Safety Perceptions

Drivers were asked questions related to their perceptions of safety benefits of Q-WARN and SPD-HARM and the following hypothesis:

> *On average, drivers report that they believe Q-WARN and SPD-HARM messages will improve safety by notifying them of slowed and congested traffic ahead.*

Sixty seven (67) percent of participants agreed or strongly agreed that the Queue Ahead Message was presented far enough in advance for them to take action (i.e., reduce speed, change lanes), and 57 percent agreed or strongly agreed that the Queue Ahead Message helped reduce the need to slow down or to stop suddenly. Forty three (43) percent of participants agreed or strongly agreed that the Speed Harmonization Message was presented far enough in advance for the participant to take action, while 33 percent agreed or strongly agreed that the Speed Harmonization Message helped reduce the need to slow down or to stop suddenly.

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.

Hypothesis 16. Driver Behavior Perceptions

Lastly, drivers were queried concerning changes in driving behavior and the following hypothesis.

> *On average, drivers report that they reduce speed when they are notified by Q-WARN and SPD-HARM messages of congestion ahead.*

Thirty three (33) percent of participants agreed or strongly agreed that the Queue Ahead Message changed their driving behavior and Thirty eight (38) percent of participants agreed or strongly agreed that the Speed Harmonization Message changed their driving behavior.

This demonstration was limited to 21 participants driving in heavily congested Seattle traffic. 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.

Summary of Observations

Following is a summary of the key observations from analysis of the data from the Seattle Small-Scale Demonstration.

- While the testing was not comprehensive, 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 DSRC or Cellular, 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 meet the needs for reliably capturing BSMs.
- No evidence was found that BSMs were lost during the switch between cellular 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 is very capable of data capture, data processing and delivery of messages to drivers well before they would need to take suitable action.
- In general, the cycle of capturing data in the database, processing it and delivering messages back to drivers took less than 10 seconds. Drivers traveling at 50 mph or less are expected to receive messages at least a mile in advance of the back of the queue.
- In practice, the process of delivering messages to the drivers after detection by Q-WARN and SPD-HARM algorithms took 2 to 3 seconds.
- An example was shown where the INFLO Prototype System detected a queue 3 minutes earlier using connected vehicle data than was achieved with infrastructure only data.
- Two examples are shown 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.
- An example is shown where connected vehicles provide more precise estimates of vehicle speeds in the queue than can traffic sensor data alone.
- An example is shown where 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. 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.
- Although driver behavior was outside the scope of the project, efforts were made to identify changes electronically. However, no conclusions could be drawn from the available data.

- Overall, it appears that 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 see anecdotal 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 see 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.

Data Transfer

One of the objectives of the INFLO and other DMA demonstrations was gather data in a real world setting for both the immediate impact assessment and future operations and user behavior research. Data logging was core aspect of the INFLO Prototype System architecture. The data elements described here were transmitted with appropriate metadata to U.S. DOT's contractors and the Research Data Exchange. Prior to submission, any data that could possibly compromise PII or similar was scrubbed.

Chapter 6 Summary of Accomplishments

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 Battelle Team applied the latest developments in technology to successfully design, implement, and demonstrate prototype of INFO 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 vehicle-to-vehicle (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

In the Small-Scale Demonstration described in this report, Battelle and TTI worked with WSDOT to deploy connected vehicle systems in 21 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 behavior and 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, processing speed and bandwidth 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. These algorithms also determine the speed in the queue and issue 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 vehicle-to-vehicle 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.

Considerations for Future Refinements

The implementation of INFLO applications developed and demonstrated here focuses on current traffic conditions. As noted in earlier documents, it is expected that future enhancements will incorporate historical data, forecasted or predicted events and current and forecasted road weather conditions in the algorithmic assessments. The work performed here also demonstrated that connected vehicle technology needs a comprehensive and efficient strategy for developing, maintaining and broadcasting relevant maps.

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. While the computing capacity needed to initially support the applications may be modest, the computing capacity demands will grow as the number of connected vehicles on the road increases. Once the applications are deployed, it is expected that they will be applied to an increasing number of roadways across a larger geographic area, resulting in a geometric increase in computing capacity demands. Battelle addressed this issue for the INFLO prototype development through the use of cloud computing, which supports parallel processing and on-demand increases in computing capacity. The deployed INFLO Prototype System will need to be implemented for scalability and to smoothly support the ever-increasing need for growth.

Future work will also need to consider the requirements and testing that ensure ruggedness and durability of the connected vehicle components in automotive and highway environments.

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 data can be integrated with existing traffic monitoring data to support and potentially enhance traffic management systems. Finally, this project has demonstrated that connected vehicle technology can be efficiently and effectively implemented and that it has the potential to 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
CV	Connected Vehicle
CVC	Connected Vehicle Communication
DMA	Dynamic Mobility Application
DMS	Dynamic Message Sign
DSRC	Dedicated Short-Range Communications
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

APPENDIX B. INFLO Algorithm Parameters

Parameter Name	Value	Units	Description
Database Configuration Parameters			
DBInterface	sqlserver, oledb (Microsoft Access File)	-	Either a SQL server database or Microsoft Access database
DB Connection Configuration Parameters			
sqlserver ipaddress	xxx.xxx.xxx.xxx	-	IP address of the SQL server machine
sqlserver database	Name of SQL server database	-	Name of the SQL server database used to store input data and recommendations of the INFLO algorithm
sqlserver userid	User ID	-	User id to access the SQL server database
sqlserver password	Password	-	password to access the SQL server database
AccessDB File name	Microsoft Access database file name and path	-	Name and path of the Microsoft access database file in case Access was used instead of a SQL server database. This option was provided mainly to test the algorithm on a local machine.
Roadway Segment Information			
Roadway Name	-	-	Name of the roadway where the monitored segment is located. Examples: I5, I35,
Roadway ID	-	-	A user defined alphanumeric ID for the roadway. Example: 15
Roadway Direction	-	-	Direction of travel in the roadway segment being monitored. Examples: NB, SB,EB, WB, etc.
Beginning Mile Marker	-	-	Mile marker location of the beginning of the monitored roadway segment
Ending Mile Marker	-	-	Mile marker location of the end of the monitored roadway segment
Mile Marker Numbering Increasing Direction	-	-	The direction of the roadway in which the mile marker numbers are increasing
Recurring Congestion Location	-	-	Mile marker location of the recurring congestion in the monitored roadway segment

Parameter Name	Value	Units	Description
Algorithm Configuration Parameters			
Minimum Display Speed	30	mph	Minimum speed in mph that can be recommended to vehicles or displayed on DMS
Troupe Range	5	miles	The distance in miles used to group roadway links with similar speeds into troupes in the Speed Harmonization INFLO algorithm
Three Gantry Speed	15	miles	The maximum difference in miles between the speeds of any three consecutive gantries or DMS's
TSSData Polling Frequency	20	seconds	Frequency in seconds of polling the infrastructure sensor data from the database by the INFLO algorithms
CVData Polling Frequency	5	seconds	Frequency in seconds of polling the CV data from the database by the INFLO algorithm
ESSData Polling Frequency	5	minutes	Frequency in minutes of polling the environmental sensor data from the database by the INFLO algorithm
Mobile ESS Data Polling Frequency	15	minutes	Frequency in minutes of polling the Mobile environmental data from the database by the INFLO algorithm
Queue Speed Threshold	30	mph	Speed threshold in mph for classifying links and sublinks as queued
Congestion Speed threshold	50	mph	Speed threshold in mph for classifying links and sublinks as congested
Sublink Percent Queued CV	10	percent	Percent of queued vehicles in a sublink used to classify a link as Queued/NotQueued
Sublink Length	0.1	miles	Sublink length in miles used to divide a link into smaller segments.
Maximum Display Speed	65	mph	Maximum speed in mph that can be recommended to vehicles or displayed on DMS
COF Lower Threshold	0.3	unitless	Roadway surface coefficient of friction lower threshold
COF Upper Threshold	0.7	unitless	Roadway surface coefficient of friction upper threshold
Road Surface Status Dry COF	0.9	unitless	Dry roadway surface coefficient of friction
Road Surface Status Wet COF	0.5	unitless	Wet roadway surface coefficient of friction
Road Surface Status Snow COF	0.2	unitless	Snowy roadway surface coefficient of friction
Road Surface Status Ice COF	0.1	unitless	Icy roadway surface coefficient of friction
WRTM Max Recommended Speed	65	mph	WRTM maximum recommended speed

Parameter Name	Value	Units	Description
WRTM Max Recommended Speed Level 1	55	mph	WRTM level1 maximum recommended speed
WRTM Max Recommended Speed Level 2	30	mph	WRTM level2 maximum recommended speed
WRTM Max Recommended Speed Level 3	50	mph	WRTM level3 maximum recommended speed
WRTM Max Recommended Speed Level 4	40	mph	WRTM level4 maximum recommended speed
WRTM Min Recommended Speed	30	mph	WRTM minimum recommended speed
Visibility Status Blowing Sand	2600	feet	Visibility threshold for blowing sand
Visibility Status Smoke	2700	feet	Visibility threshold for smoke
Visibility Status Blowing Dust	2800	feet	Visibility threshold for blowing dust
Visibility Status Sun Glare	2900	feet	Visibility threshold for sand glare
Visibility Status Swarms Of Insects	3000	feet	Visibility threshold for swarms of insects
Visibility Status Blowing Snow	3100	feet	Visibility threshold for blowing snow
Visibility Status Sea Spray	3200	feet	Visibility threshold for sea spray
Visibility Status Vehicle Spray	3300	feet	Visibility threshold for vehicle spray
Visibility Status Patchy Fog	3400	feet	Visibility threshold for patchy fog
Visibility Status Fog Not Patchy	3900	feet	Visibility threshold for not patchy fog
Visibility Threshold	4200	feet	Visibility Threshold
Visibility Status Clear	5700	feet	
Volume Threshold	10	veh./min.	Threshold for infrastructure sensor traffic volume counts
Occupancy Threshold	8	percent	Threshold for infrastructure sensor occupancy

APPENDIX C. INFLO Network Configuration Parameters—I-5 Northbound

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
156.5	156.6	1	4	Northbound	S 129th St	005es15652:_MN_Stn	47.4898	-122.2643
156.6	156.7							
156.7	156.8							
156.8	156.9							
156.9	157.0							
157.0	157.1							
157.1	157.2							
157.2	157.3							
157.3	157.4							
157.4	157.5	2	4	Northbound	MLK Jr Way-NB	005es15742:MMN_Stn	47.5004	-122.2747
157.5	157.6							
157.6	157.7							
157.7	157.8							
157.8	157.9							
157.9	158.0	3	4	Northbound	Boeing Access- SB	005es15792:MMN_Stn	47.5067	-122.2805
158.0	158.1							
158.1	158.2							
158.2	158.3	4	4	Northbound	S Victor St	005es15821:_MN_Stn	0	0
158.3	158.4							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
158.4	158.5	5	4	Northbound	S Norfolk St	005es15845:_MN_Stn	47.5135	-122.2857
158.5	158.6							
158.6	158.7							
158.7	158.8							
158.8	158.9							
158.9	159.0	6	4	Northbound	S Benefit St	005es15892:_MN_Stn	47.5197	-122.2896
159.0	159.1							
159.1	159.2							
159.2	159.3	7	4	Northbound	Henderson St	005es15920:_MN_Stn	0	0
159.3	159.4							
159.4	159.5							
159.5	159.6	8	4	Northbound	S Thistle St	005es15957:_MN_Stn	47.5288	-122.293
159.6	159.7							
159.7	159.8							
159.8	159.9							
159.9	160.0	9	4	Northbound	S Holden St	005es15996:_MN_Stn	47.5342	-122.2956
160.0	160.1							
160.1	160.2							
160.2	160.3							
160.3	160.4							
160.4	160.5	10	4	Northbound	S Myrtle St	005es16040:_MN_Stn	0	0
160.5	160.6							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	**Ending Milepoint**						**Latitude**	**Longitude**
160.6	160.7	11	4	Northbound	S Holly St	005es16064:_MN_Stn	47.5423	-122.304
160.7	160.8							
160.8	160.9							
160.9	161.0	12	4	Northbound	S Graham St	005es16097:_MN_Stn	0	0
161.0	161.1							
161.1	161.2							
161.2	161.3	13	4	Northbound	Swift Ave-NB	005es16120:MMN_Stn	47.5485	-122.3116
161.3	161.4							
161.4	161.5	14	4	Northbound	Michigan St-NB	005es16147:MMN_Stn	47.5511	-122.3158
161.5	161.6							
161.6	161.7							
161.7	161.8							
161.8	161.9	15	4	Northbound	S Pearl St	005es16186:_MN_Stn	47.5562	-122.3195
161.9	162.0							
162.0	162.1							
162.1	162.2							
162.2	162.3							
162.3	162.4	16	4	Northbound	S Oregon St	005es16237:_MN_Stn	47.5633	-122.3217
162.4	162.5							
162.5	162.6							
162.6	162.7							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
162.7	162.8	17	3	Northbound	Columbian Way-SB	005es16272:_MN_Stn	47.5683	-122.3206
162.8	162.9							
162.9	163.0							
163.0	163.1	18	3	Northbound	S Spokane St	005es16302:_MN_Stn	47.5726	-122.3198
163.1	163.2	19	3	Northbound	Columbian Way-NB	005es16319:MMN_Stn	47.5753	-122.3197
163.2	163.3							
163.3	163.4							
163.4	163.5							
163.5	163.6							
163.6	163.7							
163.7	163.8	20	4	Northbound	S Walker St	005es16377:_MN_Stn	0	0
163.8	163.9							
163.9	164.0	21	4	Northbound	S Holgate St	005es16395:_MN_Stn	0	0
164.0	164.1							
164.1	164.2							
164.2	164.3	22	4	Northbound	S Atlantic St	005es16426:_MN_Stn	0	0
164.3	164.4							
164.4	164.5							
164.5	164.6							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
164.6	164.7	24	2	Northbound	4th/Dearborn-NB	005es16466:MMN_Stn	47.5961	-122.3202
164.7	164.8							
164.8	164.9							
164.9	165.0							
165.0	165.1							
165.1	165.2	25	4	Northbound	Yesler Way	005es16513:_MN_Stn	47.6019	-122.3252
165.2	165.3							
165.3	165.4							
165.4	165.5							
165.5	165.6	26	2	Northbound	Marion St	005es16551:_MN_Stn	47.6068	-122.3294
165.6	165.7							
165.7	165.8							
165.8	165.9	27	4	Northbound	University St-NB	005es16583:MMN_Stn	47.611	-122.3313
165.9	166.0							
166.0	166.1							
166.1	166.2							
166.2	166.3							
166.3	166.4							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
166.4	166.5	28	5	Northbound	Olive Way-NB	005es16640:MMN_Stn	47.6191	-122.3282
166.5	166.6							
166.6	166.7							
166.7	166.8							
166.8	166.9							
166.9	167.0							
167.0	167.1	29	4	Northbound	Mercer St-NB	005es16704:MMN_Stn	47.6283	-122.3276
167.1	167.2							
167.2	167.3							
167.3	167.4	30	4	Northbound	E Galer St	005es16732:_MN_Stn	47.6317	-122.3245
167.4	167.5							
167.5	167.7	31	4	Northbound	Boylston Ave-SB	005es16756:_MN_Stn	47.6349	-122.3236
167.6	167.7							
167.7	167.8							
167.8	167.9							
167.9	168.0							
168.0	168.1	32	3	Northbound	E Roanoke St	005es16802:_MN_Stn	47.6417	-122.3233
168.1	168.2							
168.2	168.3							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
168.3	168.4	33	4	Northbound	E Hamlin St	005es16831:_MN_Stn	47.646	-122.3224
168.4	168.5							
168.5	168.6							
168.6	168.7							
168.7	168.8							
168.8	168.9	34	4	Northbound	Ship Canal Br	005es16885:_MN_Stn	47.6538	-122.3226
168.9	169.0							
169.0	169.1							
169.1	169.2							
169.2	169.3	35	4	Northbound	NE 42nd St NB	005es16920:_MN_Stn	47.6587	-122.3221
169.3	169.4							
169.4	169.5	36	4	Northbound	NE 45th St-NB	005es16944:MMN_Stn	47.6622	-122.3219
169.5	169.6							
169.6	169.7							
169.7	169.8							
169.8	169.9							
169.9	170.0	37	4	Northbound	NE 50th St-NB	005es16977:MMN_Stn	47.667	-122.3217
170.0	170.1							
170.1	170.2							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
170.2	170.3	38	4	Northbound	NE 63rd St	005es17025:_MN_Stn	47.6739	-122.3209
170.3	170.4							
170.4	170.5							
170.5	170.6							
170.6	170.7							
170.7	170.8	39	3	Northbound	NE 70th St-NB	005es17076:MMN_Stn	47.6813	-122.3207
170.8	170.9							
170.9	171.0							
171.0	171.1							
171.1	171.2							
171.2	171.3							
171.3	171.4	40	3	Northbound	NE 85th St-SB	005es17131:_MN_Stn	47.6878	-122.3278
171.4	171.5							
171.5	171.6							
171.6	171.7	41	3	Northbound	NE 80th St-NB	005es17163:MMN_Stn	47.6923	-122.3291
171.7	171.8							
171.8	171.9							
171.9	172.0							
172.0	172.1							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
172.1	172.2	42	4	Northbound	N 97th St	005es17215:_MN_Stn	47.6998	-122.3292
172.2	172.3							
172.3	172.4							
172.4	172.5							
172.5	172.6							
172.6	172.7	43	4	Northbound	N 107th St-SB	005es17264:_MN_Stn	47.7067	-122.33
172.7	172.8							
172.8	172.9	44	4	Northbound	Northgate-NB	005es17289:MMN_Stn	47.7103	-122.3295
172.9	173.0							
173.0	173.1							
173.1	173.2							
173.2	173.3	45	5	Northbound	NE 120th St	005es17328:_MN_Stn	47.7154	-122.3261
173.3	173.4							
173.4	173.5							
173.5	173.6							
173.6	173.7							
173.7	173.8	46	4	Northbound	NE 130th St-SB	005es17375:_MN_Stn	47.722	-122.3245
173.8	173.9							
173.9	174.0							
174.0	174.1							
174.1	174.2							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
174.2	174.3	47	4	Northbound	NE 137th St	005es17416:_MN_Stn	47.728	-122.3242
174.3	174.4							
174.4	174.5							
174.5	174.6	48	4	Northbound	NE 145th St-NB	005es17458:MMN_Stn	47.7341	-122.3248
174.6	174.7							
174.7	174.8							
174.8	174.9							
174.9	175.0							
175.0	175.1	49	4	Northbound	NE 155th St	005es17508:_MN_Stn	47.7409	-122.329
175.1	175.2							
175.2	175.3							
175.3	175.4							
175.4	175.5							
175.5	175.6	50	4	Northbound	N Metro Base-SB	005es17551:_MN_Stn	47.7468	-122.3291
175.6	175.7							
175.7	175.8							
175.8	175.9							
175.9	176.0							
176.0	176.1							
176.1	176.2							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
176.2	176.3	51	3	Northbound	NE 175th St-NB	005es17627:MMN_Stn	47.7576	-122.3282
176.3	176.4							
176.4	176.5							
176.5	176.6							
176.6	176.7							
176.7	176.8	52	4	Northbound	NE 185th St	005es17674:_MN_Stn	47.7635	-122.3235
176.8	176.9							
176.9	177.0							
177.0	177.1							
177.1	177.2							
177.2	177.3	53	4	Northbound	NE 195th St	005es17722:_MN_Stn	47.7704	-122.3214
177.3	177.4							
177.4	177.5							
177.5	177.6							
177.6	177.7							
177.7	177.8	54	3	Northbound	NE 205th St-SB	005es17774:_MN_Stn	47.7773	-122.3181
177.8	177.9							
177.9	178.0							
178.0	178.1							
178.1	178.2							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
178.2	178.3	55	3	Northbound	SR 104-NB	005es17826:MMN_Stn	47.7847	-122.3161
178.3	178.4							
178.4	178.5							
178.5	178.6							
178.6	178.7							
178.7	178.8	56	3	Northbound	228th St SW	005es17875:_MN_Stn	47.7917	-122.3166
178.8	178.9							
178.9	179.0							
179.0	179.1							
179.1	179.2							
179.2	179.3	57	3	Northbound	220th St SW-NB	005es17927:MMN_Stn	47.7992	-122.3144
179.3	179.4							
179.4	179.5							
179.5	179.6							
179.6	179.7							
179.7	179.8	58	4	Northbound	213th St SW	005es17976:_MN_Stn	47.8052	-122.3092
179.8	179.9							
179.9	180.0							

APPENDIX D. INFLO Network Configuration Parameters—I-5 Southbound

Sublink Mile							Station Coordinates	
Starting Milepoint	Ending Milepoint	Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Latitude	Longitude
179.7	179.6	1	3	Southbound	213th St SW	005es17976:_MS_Stn	47.8052	-122.309
179.6	179.5							
179.5	179.4							
179.4	179.3							
179.3	179.2							
179.2	179.1	2	3	Southbound	220th St SW-SB	005es17926:MMS_Stn	47.7991	-122.315
179.1	179.0							
179.0	178.9							
178.9	178.8							
178.8	178.7							
178.7	178.6	3	3	Southbound	228th St SW	005es17875:_MS_Stn	47.7917	-122.317
178.6	178.5							
178.5	178.4							
178.4	178.3							
178.3	178.2							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
178.2	178.1	4	3	Southbound	SR 104-NB	005es17826:_MS_Stn	47.7847	-122.316
178.1	178.0							
178.0	177.9							
177.9	177.8							
177.8	177.7							
177.7	177.6	6	3	Southbound	NE 205th St-SB	005es17774:MMS_Stn	47.7773	-122.318
177.6	177.5							
177.5	177.4							
177.4	177.3							
177.3	177.2							
177.2	177.1	7	3	Southbound	NE 195th St	005es17722:_MS_Stn	47.7704	-122.321
177.1	177.0							
177.0	176.9							
176.9	176.8							
176.8	176.7							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
176.7	176.6	8	3	Southbound	NE 185th St	005es17674:_MS_Stn	47.7635	-122.324
176.6	176.5							
176.5	176.4							
176.4	176.3							
176.3	176.2							
176.2	176.1							
176.1	176.0							
176.0	175.9	9	3	Southbound	NE 175th St-SB	005es17601:MMS_Stn	47.7541	-122.33
175.9	175.8							
175.8	175.7							
175.7	175.6							
175.6	175.5							
175.5	175.4	10	3	Southbound	N Metro Base-SB	005es17551:MMS_Stn	47.7468	-122.329
175.4	175.3							
175.3	175.2							
175.2	175.1							
175.1	175.0							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	**Ending Milepoint**						**Latitude**	**Longitude**
175.0	174.9	11	3	Southbound	NE 155th St	005es17508:_MS_Stn	47.7409	-122.329
174.9	174.8							
174.8	174.7							
174.7	174.6							
174.6	174.5	12	3	Southbound	NE 145th St SB	005es17460:_MS_Stn	47.7344	-122.325
174.5	174.4							
174.4	174.3							
174.3	174.2							
174.2	174.1							
174.1	174.0	13	4	Southbound	NE 137th St	005es17416:_MS_Stn	47.728	-122.324
174.0	173.9							
173.9	173.8							
173.8	173.7							
173.7	173.6	14	4	Southbound	NE 130th St-SB	005es17375:MMS_Stn	47.722	-122.325
173.6	173.5							
173.5	173.4							
173.4	173.3							
173.3	173.2							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
173.2	173.1	15	4	Southbound	NE 120th St	005es17328:_MS_Stn	47.7154	-122.326
173.1	173.0							
173.0	172.9							
172.9	172.8							
172.8	172.7	16	4	Southbound	N 110th St-SB	005es17288:MMS_Stn	47.7102	-122.33
172.7	172.6							
172.6	172.5	17	3	Southbound	N 107th St-SB	005es17264:MMS_Stn	47.7067	-122.33
172.5	172.4							
172.4	172.3							
172.3	172.2							
172.2	172.1							
172.1	172.0	18	4	Southbound	N 97th St	005es17215:_MS_Stn	47.6998	-122.329
172.0	171.9							
171.9	171.8							
171.8	171.7							
171.7	171.6							
171.6	171.5	19	3	Southbound	N 88th St	005es17162:_MS_Stn	47.6921	-122.33
171.5	171.4							
171.4	171.3							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
171.3	171.2	20	3	Southbound	NE 85th St-SB	005es17131:MMS_Stn	47.6878	-122.328
171.2	171.1							
171.1	171.0							
171.0	170.9							
170.9	170.8							
170.8	170.7							
170.7	170.6	21	3	Southbound	Lake City Wy SB	005es17075:_MS_Stn	47.6812	-122.321
170.6	170.5							
170.5	170.4							
170.4	170.3							
170.3	170.2							
170.2	170.1	22	4	Southbound	NE 63rd St	005es17025:_MS_Stn	47.6739	-122.321
170.1	170.0							
170.0	169.9							
169.9	169.8	23	4	Southbound	Ravenna Blvd-SB	005es16990:MMS_Stn	47.6688	-122.322
169.8	169.7							
169.7	169.6							
169.6	169.5							
169.5	169.4							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
169.4	169.3	24	4	Southbound	NE 50th St-SB	005es16942:MMS_Stn	47.6619	-122.322
169.3	169.2							
169.2	169.1							
169.1	169.0	25	4	Southbound	NE 45th St-SB	005es16919:MMS_Stn	47.6586	-122.323
169.0	168.9							
168.9	168.8							
168.8	168.7	26	4	Southbound	Ship Canal Br	005es16885:_MS_Stn	47.6538	-122.323
168.7	168.6							
168.6	168.5							
168.5	168.4							
168.4	168.3							
168.3	168.2	27	4	Southbound	E Hamlin St	005es16831:_MS_Stn	47.646	-122.322
168.2	168.1							
168.1	168.0							
168.0	167.9	28	4	Southbound	E Roanoke St	005es16802:_MS_Stn	47.6417	-122.323
167.9	167.8							
167.8	167.7							
167.7	167.6							
167.6	167.5							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
167.5	167.4	29	5	Southbound	Boylston Ave-SB	005es16756:MMS_Stn	47.6349	-122.324
167.4	167.3							
167.3	167.2	30	5	Southbound	E Galer St	005es16732:_MS_Stn	47.6317	-122.325
167.2	167.1							
167.1	167.0							
167.0	166.9	31	4	Southbound	LakeviewBlvd SB	005es16701:_MS_Stn	47.6279	-122.328
166.9	166.8							
166.8	166.7							
166.7	166.6							
166.6	166.5	32	4	Southbound	Mercer St-SB	005es16661:MMS_Stn	47.6222	-122.329
166.5	166.4							
166.4	166.3	33	4	Southbound	Olive Way-NB	005es16640:_MS_Stn	47.6191	-122.328
166.3	166.2							
166.2	166.1							
166.1	166.0							
166.0	165.9							
165.9	165.8							
165.8	165.7	34	4	Southbound	University St-NB	005es16583:_MS_Stn	47.611	-122.331
165.7	165.6							
165.6	165.5							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
165.5	165.4	35	2	Southbound	Marion St	005es16551:_MS_Stn	47.6068	-122.329
165.4	165.3							
165.3	165.2							
165.2	165.1							
165.1	165.0	36	2	Southbound	Yesler Way	005es16513:_MS_Stn	47.6019	-122.325
165.0	164.9							
164.9	164.8							
164.8	164.7							
164.7	164.6							
164.6	164.5	37	2	Southbound	4th/Dearborn-NB	005es16466:_MS_Stn	47.5961	-122.32
164.5	164.4							
164.4	164.3							
164.3	164.2							
164.2	164.1	38	2	Southbound	SBCD-SB	005es16429:MMS_Stn	47.5908	-122.321
164.1	164.0							
164.0	163.9							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
163.9	163.8	39	4	Southbound	S Holgate St	005es16396:_MS_Stn	0	0
163.8	163.7							
163.7	163.6							
163.6	163.5							
163.5	163.4							
163.4	163.3							
163.3	163.2							
163.2	163.1							
163.1	163.0							
163.0	162.9	40	3	Southbound	S Spokane St	005es16302:_MS_Stn	47.5726	-122.32
162.9	162.8							
162.8	162.7							
162.7	162.6	41	4	Southbound	Columbian Way-SB	005es16272:MMS_Stn	47.5683	-122.321
162.6	162.5							
162.5	162.4							
162.4	162.3							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
162.3	162.2	42	4	Southbound	S Oregon St	005es16237:_MS_Stn	47.5633	-122.322
162.2	162.1							
162.1	162.0							
162.0	161.9							
161.9	161.8							
161.8	161.7	43	4	Southbound	S Pearl St	005es16186:_MS_Stn	47.5562	-122.32
161.7	161.6							
161.6	161.5							
161.5	161.4							
161.4	161.3							
161.3	161.2							
161.2	161.1							
161.1	161.0							
161.0	160.9	44	4	Southbound	Michigan St-SB	005es16107:MMS_Stn	47.547	-122.31
160.9	160.8							
160.8	160.7							
160.7	160.6							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
160.6	160.5	45	4	Southbound	S Holly St	005es16064:_MS_Stn	47.5423	-122.304
160.5	160.4							
160.4	160.3							
160.3	160.2							
160.2	160.1							
160.1	160.0							
160.0	159.9							
159.9	159.8	46	4	Southbound	S Holden St	005es15996:_MS_Stn	47.5342	-122.296
159.8	159.7							
159.7	159.6							
159.6	159.5							
159.5	159.4	47	4	Southbound	S Thistle St	005es15957:_MS_Stn	47.5288	-122.293
159.4	159.3							
159.3	159.2							
159.2	159.1							
159.1	159.0							
159.0	158.9							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
158.9	158.8	48	4	Southbound	S Benefit St	005es15892:_MS_Stn	47.5197	-122.29
158.8	158.7							
158.7	158.6							
158.6	158.5							
158.5	158.4							
158.4	158.3	49	4	Southbound	S Norfolk St	005es15845:_MS_Stn	47.5135	-122.286
158.3	158.2							
158.2	158.1							
158.1	158.0							
158.0	157.9							
157.9	157.8	50	4	Southbound	Boeing Access-NB	005es15792:_MS_Stn	47.5067	-122.281
157.8	157.7							
157.7	157.6							
157.6	157.5							
157.5	157.4							
157.4	157.3							
157.3	157.2							

Sublink Mile		Link No	Number of Lanes	Direction of Travel	Cross-Street Identifier	Detector Station Name	Station Coordinates	
Starting Milepoint	Ending Milepoint						Latitude	Longitude
157.2	157.1	51	4	Southbound	MLK Jr Way-SB	005es15723:MMS_Stn	47.4982	-122.273
157.1	157.0							
157.0	156.9							
156.9	156.8							
156.8	156.7							
156.7	156.6							
156.6	156.5							
156.5	156.4	52	4	Southbound	S 129th St	005es15652:_MS_Stn	47.4898	-122.264
156.4	156.3							
156.3	156.2							
156.2	156.1							
156.1	156.0							

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