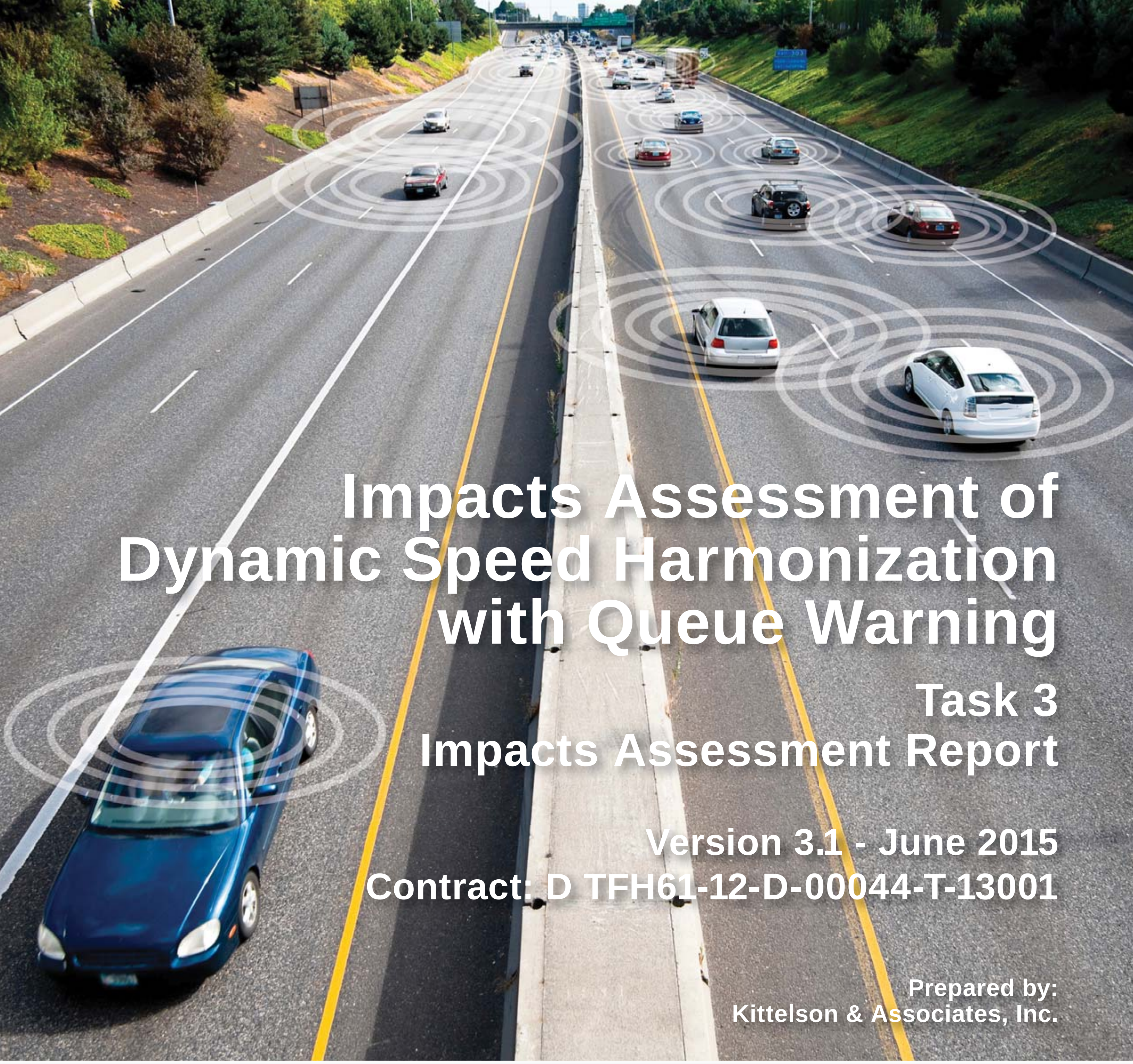

Impacts Assessment of Dynamic Speed Harmonization with Queue Warning

Task 3
Impacts Assessment Report

Version 3.1 - June 2015
Contract: D TFH61-12-D-00044-T-13001

Prepared by:
Kittelson & Associates, Inc.

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16. Abstract

This report assesses the impacts of a prototype of Dynamic Speed Harmonization (SPD-HARM) with Queue Warning (Q-WARN), which are two component applications of the Intelligent Network Flow Optimization (INFLO) bundle. The assessment is based on an extensive analysis of the Prototype using a Vissim simulation model for the US 101 freeway corridor in San Mateo, CA as well as an evaluation of a small-scale demonstration that was conducted in Seattle, WA.

Results from the simulation analysis found that the Prototype significantly reduces the magnitudes of the speed drops (shockwaves) between vehicles, even at the 10-percent market penetration level. This is considered to benefit safety by reducing the probability of collisions where free-flowing traffic meets the back of a queue. The trade-off for the improved safety is that the Prototype increases the geographic impact of existing bottlenecks on freeway speeds by expanding the upstream distance that is affected by congestion.

17. Key Words INFLO, Speed harmonization, queue warning, simulation, connected vehicles	**18. Distribution Statement**		
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CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

API	Application Programming Interface – custom software written to interface with a microsimulation model and perform a specialized function not currently in the microsimulation model.
Cellular	Cell phone transmission network communication method
ConOps	Concept of Operations
CV	Connected vehicle
DMA	Dynamic Mobility Applications
DOT	Department of Transportation
DSRC	Dedicated Short Range Communications
FHWA	Federal Highway Administration
IA Contractor	Impact assessment contractor
INFLO	Intelligent Network Flow Optimization
OBU	On-Board unit (receives or transmits DSRC)
PD Contractor	Prototype development contractor
Q-WARN	Queue warning algorithm or application
RSE	Roadside equipment installed to monitor conditions; collecting traffic flow, density, and speed data and transmitting this information to a data environment (which in turn is accessible by connected vehicles and the transportation management center). Transmission to connected vehicles may be through DSRC or cellular network.
RSSI	Received signal strength indicator
RSU	Roadside unit (a receiver or transmitter of DSRC).
RWIS	Road weather information system
SPaT	Signal phase and timing message sent to vehicle from infrastructure.
SPD-HARM	Speed Harmonization algorithm or application
TMC, TME	Traffic Management Center, Traffic Management Entity
TOPR	Task Order Proposal Request
V2I	Vehicle-to-infrastructure communications and the reverse
V2V	Vehicle-to-vehicle communications.
V2X	Vehicle-to-vehicle and vehicle-to-infrastructure communications and the reverse

EXECUTIVE SUMMARY

This document is the Task 3 deliverable, the Impacts Assessment Report, for the task order: Impacts Assessment of Dynamic Speed Harmonization with Queue Warning (Contract: DTFH61-12-D-00044). The purpose of this task order has been to:

(i) Assess the impacts of a prototype of Dynamic Speed Harmonization (SPD-HARM) with Queue Warning (Q-WARN), which are two component applications of the Intelligent Network Flow Optimization (INFLO) bundle (The prototype was developed by the Prototype Development, PD Contractor), and

(ii) Assess the impacts of the prototype at various levels of potential future market acceptance.

An Impact Assessment (IA) Plan was prepared to ensure that the assessment addressed the following topics identified in the project management plan:

- Hypotheses to be tested by simulation testing and through a small-scale demonstration to be conducted by the PD Contractor.
- Performance measures and targets.
- Assumptions that will be used for the impacts assessment.
- Performance and explanatory data (“before” and “after”) that need to be collected, and the process by which the data will be collected.
- Processes for verifying data quality and for cleaning data, and minimum thresholds for data quality.
- Methods for collecting feedback from stakeholders and demonstration/test drivers, processing and analyzing feedback, and integrating the results into the assessment of the impacts of the prototype as well as a large-scale deployment.
- Processes for estimating or simulating the impacts of the prototype demonstration/test.
- Processes for extrapolating, inferring, estimating, or simulating the impacts of a future deployment of the prototype system at various levels of potential future market acceptance.
- Identify which data are intended to be broadly shared on the RDE and which data elements are proprietary or include personally identifiable information (PII).

MEASURES OF EFFECTIVENESS

The measures of effectiveness identified in the INFLO Concept of Operations document, their associated issues, and the recommended performance measures for the Impact Assessment are summarized in (see Chapter 2 for details).

Table 1: Performance measures, issues, recommendations (summary).

ConOps Performance Measure	Issues	Recommendation
Shockwaves	Useful for diagnosis, but too detailed to compare across scenarios or CV market levels.	Examine shockwaves, but report only maximum speed drops between 5-minute periods and between sublinks.
Queues: Length and Duration	Useful for diagnosis, but too detailed to compare.	Examine queues, but report Vehicle-Hours in Queue (VHQ).
Throughput (veh per hour)	Should also be compared to demand.	Report Vehicle-Miles Traveled (VMT) (demanded and served).
Speed Variance	May increase or decrease with speed smoothing.	Report maximum speed drops between adjacent sublinks and between 5-minute time periods.
Average Travel Time	Good summary measure.	Report vehicle hours traveled/trip.
Reliability measure	Buffer time undependable.	Report 95th% Travel Time Index
Environmental Effects Estimated CO2 equivalent emissions Estimated fuel consumption (gallons)	Data intensive computations.	Discuss qualitatively.
User Acceptance Market penetration Compliance with speed messages	Available resources insufficient to test user acceptance.	Conduct sensitivity assessment of market penetration and compliance.
Safety Effects Number of Crashes Severity of Crashes	Microsim proxies are not well related to real safety effects.	Discuss qualitatively the likely safety effects of reduced speed variance and time in queue.

DEVELOPMENT OF THE EXPERIMENTAL PLAN

The development of the experimental plan considered the key questions identified in the Task Order Proposal Request (TOPR) (See Chapter 3 for details):

- When is the best time to implement SPD-HARM (solo or in combination)?
- Which communication process is best for nomadic devices?
- What are the impacts of near-, mid- and long-term deployment?
- What level of market penetration is required?
- What are the effects of communication errors and latency?
- What are the benefits of widespread RSE deployment?
- Is connected vehicle data required for success?

These questions were converted into hypotheses and the Impact Assessment Plan was developed to test them.

Given the multidimensional nature of the hypotheses, it was necessary to develop a strategic sampling and testing plan to cost-effectively employ study resources. The proposed testing plan groups, factors by causality chains so that variations in each individual factor do not have to be exhaustively simulated—only variations in the results of the several factors acting together are simulated.

For example, rather than simulate different market penetration rates, different communication loss rates (and latencies), and different compliance rates separately, these factors are combined into a single total response rate for simulation modeling. The different levels of total response are explicitly simulated. Then, the contributions of each factor (penetration, communication loss, latency, and compliance) are evaluated separately by post-processing the simulation results for each of the response levels simulated in the model runs.

THE EXPERIMENTAL PLAN

The Impact Assessment Experimental Plan is shown in Table 2 (see Chapter 4 for details). A total of 7 tests were planned to address the 7 questions posed in the TOPR.

- Test #2, the evaluation of under what operational conditions the applications are most beneficial, is the core test to be conducted under this Impact Assessment Plan.
- The remaining Tests (#1, 3, 4, 5, 6, 7, 8) consist of numerical evaluations, extrapolations, and application of probabilistic and combinatorial analysis to the simulation-generated results of Test #2.

Test #2 consists of a series of simulation experiments (model runs, each with multiple repetitions) to estimate the changes in the measures of effectiveness (MOEs) under a variety of operating conditions and response rates.

The response rates are, in turn, a function of market penetration, communication loss, communication latency, and compliance. Thus, we can meet the objectives of the Impact Assessment Plan by running the simulations for different levels of response rates, and then post-process the results to determine how different assumptions of market penetration, communication loss, and compliance affect the response rate and, therefore, the MOE results.

The simulation results were combined with the small-scale demonstration results to obtain a more-complete picture of the likely impacts of a connected vehicle implementation of SPD-HARM and Q-WARN.

Table 2: Impact assessment experimental plan (summary).

Test	Objective	Method	MOE's
1	Determine if SPD-HARM and Q-WARN bundles are more effective combined then individually.	Not feasible to test Q-WARN with current driver behavior knowledge and limited small-scale demonstration.	N/A
2	Under what operational conditions are the applications most beneficial?	IA contractor to design and conduct a multi-dimensional simulation test program. Small-scale demo to test communication effects.	See Table 3 in Performance Measures and Targets.
3	When is DSRC needed and when will cellular suffice?	Examine Test #2 simulation and small-scale demo results to obtain sensitivity to different communication latencies.	Loss or delay in acquisition and transmission of Basic Safety Messages (BSM).
4	Determine impacts of near, mid, long term deployment.	Examine numerically the Test #2 market penetration results.	Same as Test #2.
5	Determine required level of market penetration	Examine numerically the Test #2 market penetration results.	Same as Test #2.
6	Determine effects of communications errors and latency.	Examine Test #2 simulation and small-scale demo results to obtain sensitivity to communication errors and latencies.	Loss or delay in acquisition and transmission of BSMs.
7	Determine benefits of widespread RSE.	Examine numerically the Test #2 results. Consider Test #3 conclusions.	Same as Test #2.
8	Determine extent to which V2X is required.	Examine numerically the Test #2 results. Consider Test #3 conclusions.	Same as Test #2.

SMALL SCALE DEMONSTRATION

A small-scale demonstration deploying the INFLO Prototype System and applications was conducted to demonstrate their functionality and performance in an operational traffic environment and to capture data to help assess the hypotheses pertaining to system functionality, system performance, algorithm performance, and driver feedback. The material presented here is quoted from the Small Scale Demonstration Report by Battelle and Texas Transportation Institute. [1]

For the small-scale demonstration, Battelle and the Texas Transportation Institute (TTI) worked with the Washington State Department of Transportation (WSDOT). Battelle and TTI installed connected vehicle systems in 21 vehicles, and deployed them in a scripted driving scenario

[1] Battelle Memorial Institute / Texas A&M Transportation Institute, Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Report Draft, FHWA, Washington, DC, March 27, 2015

traversing both directions of a 23-mile stretch of the I-5 freeway from Tukwila to Edmonds through downtown Seattle, during morning rush hour the week of January 12, 2015.

Early in the week, the connected vehicles were released in pulses (two platoons, 5 minutes or 15 minutes apart). Later in the week, the connected vehicles were spaced out, one vehicle being released every 30 seconds or so.

Vehicle speed data was collected from both the WSDOT infrastructure-based speed detectors (loops) and the connected vehicles during the driving scenario. The connected vehicle data was transmitted and collected via both dedicated short-range communication (DSRC) and the cellular phone network.

The system received and processed loop detector and connected vehicle data in real time and delivered Q-WARN and SPD-HARM messages to drivers. Drivers were also informed as to when they were in queue and how long it would take to exit the queue (in-queue status).

The PD contractor captured system performance data as well as driver behavior and driver feedback on their experiences with the devices to demonstrate the INFLO Prototype System in a fully operational highway traffic environment and to examine potential benefits of connected vehicle technology.

CONCLUSIONS

The conclusions of the Impacts Assessment rely on the results of simulation testing as well as a small-scale demonstration of the prototype conducted by the PD Contractor. The results of the simulation tests of SPD-HARM and Q-WARN (the Prototype) are described in Chapter 6. The results of the small-scale demonstration are described in Chapter 7.

The combined conclusions of the simulation tests and the small-scale demonstration are as follows:

1. Simulation analysis found that:
   a) The Prototype significantly reduces the magnitudes of the speed drops (shockwaves) between vehicles, even at the 10% market penetration level. This is considered to benefit safety by reducing the probability of collisions where free-flowing traffic meets the back of a queue.
   b) The trade-off for the improved safety is that the Prototype increases the geographic impact of existing bottlenecks on freeway speeds by expanding the upstream distance that is affected by congestion.
      - The Prototype reduces average speeds on freeways by up to 20%, with the greatest impact occurring at the 50% connected vehicle level (higher percentages of connected vehicles were not tested).
      - Under severe-congestion conditions (such as during lane-closure incidents), reductions in speed still occur with the Prototype, but they are less significant than for less-severe conditions.
      - The Prototype probably also decreases the frequency of congestion caused by incidents and secondary crashes that arise when free-flowing traffic meets the back of a queue, but this could not be tested in the simulation analysis.

   - The Prototype had relatively little effect on vehicle stops. This is because the Prototype reacts to congestion rather than trying to predict and postpone congestion. In addition, the SPD-HARM Prototype was instructed to cease presenting speed recommendations when speeds are below 30 mph on the freeway. Thus, it makes no recommendations when the connected vehicle is in a "stop and go" situation. (The minimum threshold speed is user editable).

c) The Prototype increased the amount of lane changing on the freeway.
   - This effect increased with increasing percentages of connected vehicles.
   - This effect is no doubt created by the effect of splitting the vehicle fleet into two classes: one class (the connected vehicles) that is informed of and complying with the recommended speed, the other class that is uninformed and not complying with the recommended speed. The difference in the desired speeds between the two classes of vehicles incentivizes lane changing.
   - This effect may be enhanced by the reduced speed differentials between vehicles that is caused by the SPD-HARM Prototype, which facilitates easier lane changing.

d) The Prototype shows rapidly increasing benefits in the first 20% of the fleet that is both connected and complying with the SPD-HARM recommendations. After reaching 20% response rate for the entire vehicle fleet, the benefits increase less rapidly (but still continue to increase).

2. The small-scale demonstration found that:

a) There was no evidence in the small-scale demonstration of:
   - Loss of BSM data, whether DSRC or Cellular,
   - Disruption in the algorithms caused by loss of BSM data,
   - BSMs lost during the switch between cellular to DSRC and back, or,
   - Disruption in the algorithms caused by switching between cellular to DSRC and back.

b) In general, the cycle of capturing field data, transmitting it to the database, processing it, and delivering messages back to drivers took less than 10 seconds.
   - This confirms that drivers can be expected to receive queue warning messages approximately a mile in advance of the back of the queue.
   - The Q-WARN and SPD-HARM processors were able to capture BSM data from the database, analyze it and populate messages for drivers every 2 to 3 seconds.
   - The process of vehicles polling the database for new information every second and delivering messages to the driver took 2 to 3 seconds.

c) Q-WARN was able to detect the back of queues up to 3 minutes sooner and could pinpoint their geographic location more precisely (0.5 to 1.5 miles farther upstream) than the road loop detectors.
   - The road loop detectors are spaced 1/3 to 1/2 mile apart, and the connected vehicle reported speeds were compared to the average speeds across all lanes reported by the loop detectors.

  - The small scale demonstration I-5 test site experiences significant differences in lane-by-lane speeds in the northbound direction with one to two lanes free-flowing (because of one or more downstream left hand or right hand force offs) while the adjacent lanes were severely queued.

d) 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.

e) The current operation of the WSDOT overhead gantry variable speed limit signs (VSL) suggest that the number of SPD-HARM speed step downs and their length could be reduced from what is currently in the Prototype. Additionally, VSL results suggest that the frequency in updates of SPD-HARM recommendations might also be reduced.

f) The SPD-HARM recommendations based upon a field-simulated lower-level penetration (using the spread out connected vehicle departure patterns) are closer to the WSDOT VSL recommendations than are those with a field-simulated higher-level penetration (using pulsed departure patterns). The WSDOT 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 ability of the prototype to quickly spot and accurately identify the locations of the backs of queues.

CHAPTER 1. INTRODUCTION

The USDOT Dynamic Mobility Applications (DMA) Program focuses on exploiting new forms of data from wirelessly connected vehicles, travelers, and the infrastructure to enable transformative mobility applications including advanced information systems for travelers and freight, incident management systems, and advanced management systems for highway facilities, transit, and signal control systems. Dynamic Speed Harmonization (SPD-HARM) and Queue Warning (Q-WARN) are two component applications of the Intelligent Network Flow Optimization (INFLO) bundle of the (DMA) program.[2]

PURPOSE OF IMPACT ASSESSMENT

The purpose of the Impact Assessment is to employ the results of microsimulation testing and a small-scale demonstration to answer the following questions related to the prototype:

- When is the best time to implement SPD-HARM alone or in combination with Q-WARN?
- Which communication method is best for nomadic (cell phone) devices?
- What are the impacts of near-, mid- and long-term deployment?
- What level of market penetration of connected vehicles is required for success?
- What are the effects of communication errors and latency?
- What are the benefits of widespread roadside equiPMent (RSE) deployment?
- Is connected vehicle data required for SPD-HARM and Q-WARN to be successful?

The prototype algorithms, and the concepts behind them, are described below.

THE SPD-HARM APPLICATION CONCEPT

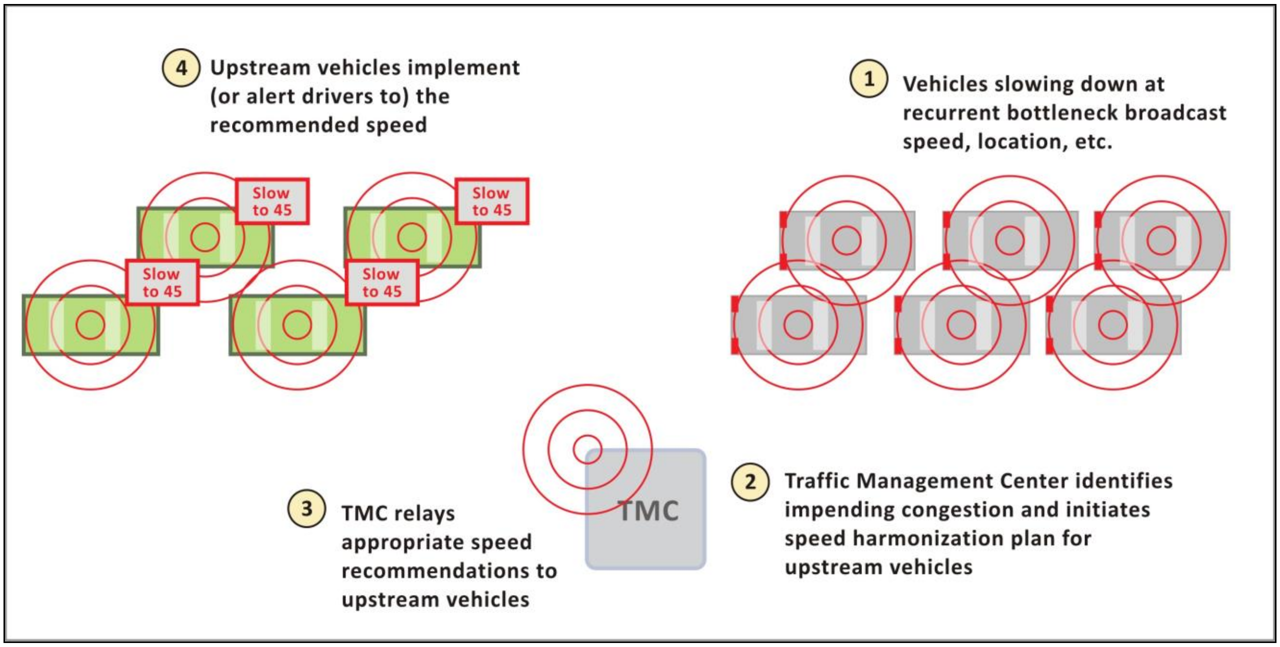
The concept of SPD-HARM is that harmonizing the speeds of traffic flows in response to downstream congestion, incidents, and weather or road conditions can greatly help to maximize traffic throughput and reduce crashes. The INFLO SPD-HARM application concept aims to realize these benefits by utilizing connected vehicle communication to detect the precipitating roadway or congestion conditions that might necessitate speed harmonization, to generate the appropriate response plans and speed recommendation strategies for upstream traffic, and to broadcast such recommendations to the affected vehicles.

The overall concept for the SPD-HARM application is illustrated in Figure 1. Roadway sensors and connected vehicles transmit information on vehicle speeds, flow rates, and occupancy to the traffic management center (TMC). A road weather information system (RWIS) transmits facility information on visibility, coefficient of pavement-tire friction, temperature (air and road

[2] "Concept DeveloPMent & Needs Identification for Intelligent Network Flow Optimization (INFLO): Concept of Operations," Final Report FHWA-JPO-13-012, June 2012.

surface), humidity, wind speed, pressure, and precipitation to the connected vehicle and/or the TMC.

The SPD-HARM application detects the presence of a mobility problem or predicts an imminent mobility problem based on heavy flow rates. A response-generating algorithm within the SPD-HARM application (housed at the TMC) recommends speeds for upstream vehicles and other recommended actions on the part of the TMC. This algorithm identifies the timing, location, and recommended speeds for transmission. The speed recommendations are transmitted to the vehicles on the facility.



Source: Concept of Operations, Concept DeveloPMent and Needs Identification for Intelligent network Flow Optimization, Final Report, FHWA-JPO-13-012, June, 2012.

Figure 1: Illustration. SPD-HARM concept with connected vehicles.

THE SPD-HARM PROTOTYPE TO BE EVALUATED

The SPD-HARM prototype to be evaluated in this Impact Assessment has the following features:[3]

- Existing average traffic speeds by direction for each 1/10th-mile-long sublink of the facility are gathered from both infrastructure sensors and connected vehicles.
    - In cases of conflicts between road sensors and connected vehicles, the lower speed controls.

[3] Kevin Balke, Hassan Charara, Srinivasa Sunkari; draft Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design, Texas A&M Transportation Institute, FHWA, Washington, DC, January 15, 2014.

- Adjacent sublinks with similar mean speeds (falling within a speed range specified by the agency operator) are grouped together into “troupes.”
- The recommended speed for each “troupe” is set at the average speed for that troupe rounded up to the nearest 5 mph increment, subject to:
    - Agency-specified maximum and minimum speed values for the sublinks cannot be exceeded.
    - The recommended speed cannot exceed the recommended maximum speed for weather conditions.
    - Differences in recommended speeds between adjacent troupes greater than 5 mph must be transitioned through the sublinks bordering the two adjacent troupes.
    - The recommended speed for any sublink cannot change more often than once every 15 seconds.
- The recommended connected vehicle speeds should be the same as that displayed on any roadway variable speed signs.
- Recommended speeds are advisory, not regulatory.

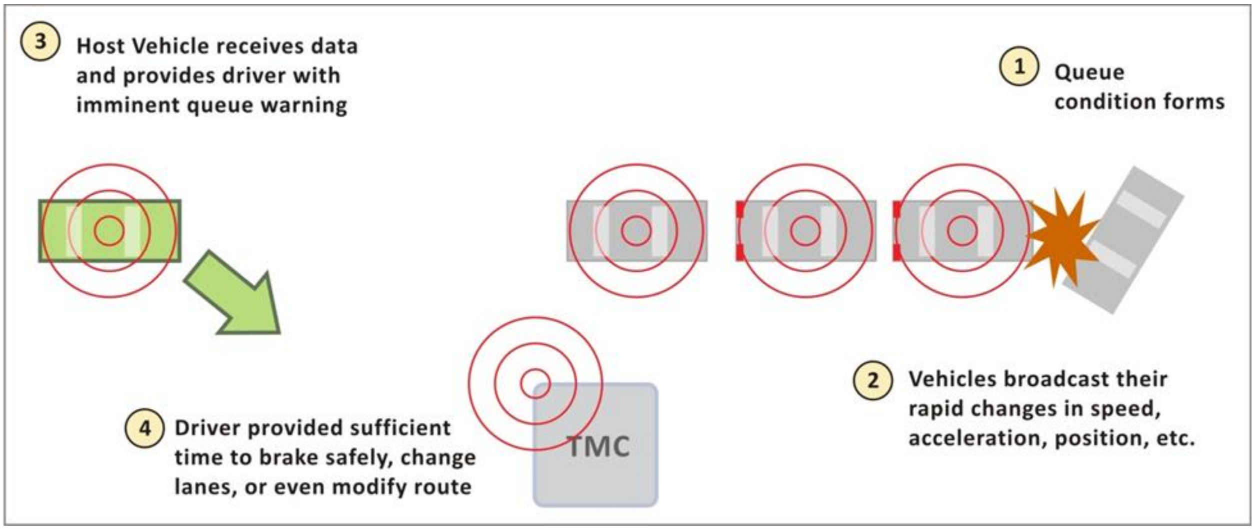
Note that there are slight differences between the SPD-HARM Application concept and its prototype.

- The SPD-HARM prototype is always operational. There is always a recommended speed displayed (which may be zero for links with low measured speeds) for every sublink of the facility.
- The SPD-HARM prototype does NOT predict events nor speeds, and only recommends a speed significantly different than the measured average speed in the case of bad weather.

THE Q-WARN APPLICATION IN CONCEPT

Queuing conditions present significant safety concerns, particularly with the increased potential for rear-end collisions. They also present disruptions to traffic throughput by introducing shockwaves into the upstream traffic flow. The INFLO Q-WARN application concept aims to minimize the occurrence and impact of traffic queues by utilizing connected vehicle technologies, including vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications, to enable vehicles within the queue event to automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to nearby upstream vehicles and to infrastructure-based central entities (such as the TMC) in order to minimize or prevent rear-end or other secondary collisions.

The overall concept for the Q-WARN application is illustrated in Figure 2.



Source: Concept of Operations, Concept DeveloPMent and Needs Identification for Intelligent network Flow Optimization, Final Report, FHWA-JPO-13-012, June, 2012.

Figure 2. Illustration. The Q-WARN application (concept).

Just as for the SPD-HARM application, under the Q-WARN application roadway sensors and connected vehicles transmit information on vehicle speeds, flow rates, and occupancy to the traffic management center (TMC).

THE Q-WARN PROTOTYPE TO BE EVALUATED

The Q-WARN prototype to be evaluated in this Impact Assessment has the following features:[4]

- Existing average traffic speeds by direction for each 1/10th-mile-long sublink of the facility are gathered from both infrastructure sensors and connected vehicles.
- If a sufficient number and percent of roadway lane sensors or connected vehicles meet a user-set maximum speed threshold for being in queue state for a user-set sufficient length of time (to avoid false alarms), then the sublink is determined to be in the queue state.
    - In the case of a conflict between roadway sensors and connected vehicles, the lower speed controls.
- For each queue, a queue warning message is broadcast to all connected vehicles within a user-specified distance upstream of the back of the queue.
- The message states the distance between the vehicle and the back of the queue.

One difference between the concept and the prototype for Q-WARN is that in the prototype, connected vehicles will NOT know in which lane they are operating.

[4] Kevin Balke, Hassan Charara, Srinivasa Sunkari; draft Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design, Texas A&M Transportation Institute, FHWA, Washington, DC, January 15, 2014.

CHAPTER 2. PERFORMANCE MEASURES AND TARGETS

The Concept of Operations document (ConOps) for INFLO lists several performance measures for SPD-HARM and Q-WARN to quantify the objectives of safety, mobility, and energy/environment. The objective of this Impact Assessment is to obtain these performance measures (or their proxies) from a combination of the small-scale demonstration test and microsimulation analysis.

No performance targets are set for the Impact Assessment. That is not the purpose of this assessment. Performance targets will be determined by the users of the Impact Assessment results.

The small scale demonstration was not designed for testing the impacts of the Prototype on traffic operations. Consequently the output from a microsimulation model will be the primary source of performance measures for evaluating the prototype. The microsimulation model also enables the evaluation of the effects of several factors in a controlled setting.

Table 3 lists the INFLO ConOps performance measures, the issues involved in their measurement, and suggested solutions for use in the Impact Assessment. The discussion below explains the entries in this table.

SHOCKWAVES

One of the objectives of SPD-HARM and Q-WARN is to improve safety by giving drivers advance warning of downstream queues and smoothing out the speeds of vehicles on the facility. Consequently, the ConOps recommended that reduction of the frequency and severity of speed shockwaves in the traffic stream be used as a direct measure of the speed-smoothing effects and, therefore, an indirect measure of the safety effects.

The shockwaves of interest for the SPD-HARM and Q-WARN impact assessment are generated when downstream traffic density is greater than upstream density. It is indicated by an abrupt change in the speeds of vehicles.

Loop detector data (or similar data from other detector technologies) can be used in the field and in the microsimulation model to identify bottlenecks[5], to determine the spatial and temporal extent of the congestion, and to obtain estimates of the shockwave speeds[6]

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[5] Chen, C., A. Skabardonis and P. Varaiya, “Systematic Identification of Freeway Bottlenecks,” Transportation Research Record #1867, Journal of the Transportation Research Board, 2004

[6] Wieczsorek, J, H. Li and R. Bertini, “Integrating an Automated Bottleneck Detection Tool into an Online Freeway Data Archive,” 88th TRB Annual Meeting, Washington DC, January 2009.

Table 3: Performance measures, issues, recommendations.

ConOps Performance Measure	Issues*	Recommendation for Impact Assessment
Shockwaves: Number of shockwaves formed, Length (duration), propagation speed	Useful for diagnostic work, but hard for reader to meaningfully compare across alternatives when varying number of shock waves present.	Report: 1. Distribution of speed drops between adjacent sublinks. 2. Distribution of speed drops between adjacent 5-minute periods within sublink.
Queues: Length and Duration	Useful for diagnosis, but hard to compare across alternatives when multiple queues present.	Report: Vehicle-Seconds in Queue per vehicle (VSQ).
Throughput (veh per hour)	Good summary measure. Should also be compared to demand.	Report: 1. Vehicle-Miles Traveled (VMT) served 2. VMT demanded
Speed Variance	See “Variance of Speed” discussion page 27	Report: 1. Lane Changes/vehicle. 2. Stops/vehicle.
Average Travel Time	Good summary measure	Report vehicle hours traveled (VHT) per vehicle, including entry delay.
Reliability measure: Buffer time or Planning time index--95th Percentile Travel Time Index	Buffer time can behave unexpectedly when comparing alternatives	Report 95th Percentile Travel Time Index (TTI).
Environmental Effects - Estimated carbon dioxide (CO_2) equivalent emissions - Estimated fuel consumption (gallons)	Emission modeling required to report quantitative results.	Report qualitative results.
User Acceptance & Compliance - Market penetration - Compliance with speed messages - Ratings in public opinion surveys	The available resources insufficient to test or survey user acceptance.	Conduct post-processing assessment of different penetration rates and compliance rates.
Safety Effects - Number of Primary and Secondary Crashes - Severity of Crashes	According to stakeholders, the proposed proxies are not well related to actual safety effects.	Discuss qualitatively the likely safety effects of reduced speed variance and time in queue.

**The issues are explained in the text.*

Identification and tallying of shockwaves (number, duration, propagation speed) is certainly feasible in a microsimulation environment through the processing of the vehicle trajectory data output. The size of the vehicle trajectory data files to be processed is not trivial, but probably the biggest challenge will be interpreting the multi-dimensional results. For example: Are fewer shockwaves of longer duration preferable to the reverse? What is an acceptable number of, and duration for, shockwaves? How should higher or lower shockwave propagation speeds be interpreted?

The detailed shockwave information is useful for achieving a better understanding of the mechanisms involved in producing the observed results with SPD-HARM and Q-WARN. However, detailed shockwave information is difficult to employ in summary form to readily assess the results of multiple simulation runs to determine if the prototype performed better under one set of conditions or the other. Consequently, it is recommended that two measures be used as the proxy performance measures for shockwaves:

1. The distribution of the decreases in mean 5-minute sublink speeds between adjacent sublinks.
2. The distribution of the decreases in mean vehicle speeds between adjacent 5-minute time periods within each sublink.

Lower values of speed drops indicate that the prototype is achieving its objective of reducing extreme speed variations, reducing shockwaves, and indirectly improving safety.

QUEUE LENGTH AND DURATION

Like shockwaves, queue lengths and durations are another example of detailed microsimulation output valuable for diagnosing the causes of observed phenomena, but potentially confusing for interpreting overall results. Consequently, it is recommended that for the purposes of comparing overall performance between alternatives, that Vehicle-Seconds in Queue (VSQ) per vehicle be reported for each simulation test. This summary measure should track the overall facility-wide effects of the algorithms. The VSQ is computed by summing the number of vehicle-seconds of travel spent when each vehicle first drops to speeds below 3 km/h (2 mi/h) and before it returns to speeds above 5 km/h (3 mi/h). The queued vehicle must also be within 20 meters (60 ft) of its lead vehicle in the queue. (This is the user-editable default definition of queuing in the VISSIM simulation model. The defaults were used in this analysis. See page 578, VISSIM 5.40-03 Users Guide, PTV AG, 2012).

Note that this definition diverges from the definition of “queued state” used by the Prototype. The Prototype default definition for a queue state is speeds below 5 mph, a value which is also user editable. The Prototype was run with its default definition of queuing, while VISSIM was run with its default definition of queuing. Neither definition affected the operation of SPD-HARM. Q-WARN was not tested within the simulation environment.

THROUGHPUT

It is recommended that throughput be reported for each test in terms of vehicle miles traveled (VMT). Two values of VMT should be reported—VMT demanded and VMT served.

VMT demanded is often determined by multiplying each cell in the facility's origin-destination (OD) table by the length of the shortest path between the two points and summing the results over the entire OD table. Because ramp flows were coded for the microsimulation analysis (rather than an OD table), the VMT demanded will be estimated as the maximum observed total peak-period VMT observed among the scenarios evaluated.

VMT served is obtained by tallying the distances the vehicles actually moved within each link and summing the results across all vehicles and links.

The difference between the VMT demanded and served indicates the unserved demand. This difference will also serve a valuable diagnostic function. Once VMT served equals VMT demanded, further increases in throughput cannot be expected, no matter the improvements to facility capacity or operation.

VARIANCE OF SPEEDS

Initial hypothetical tests of the SPD-HARM prototype suggest that the computed variance for the facility will increase with SPD-HARM, rather than decrease. This occurs because SPD-HARM increases the number of time periods and links when speeds are less than free-flow speeds. When free-flow speeds constitute the majority of the links and time periods in the overall study section and study period, the result of SPD-HARM is to increase the standard deviation of the link and time period speeds from the predominant free-flow speed. Consequently, simple statistical variance of speed may not be a desirable performance measure for the prototype. Figure 3 illustrates these effects for a theoretical bottleneck.

- The top drawing shows a theoretical freeway flowing from left to right with increasing time in the vertical dimension. Speeds in the bottleneck sublink gradually decrease until the bottleneck reaches capacity. At that point, speeds are 35 mph within the bottleneck. Once the bottleneck reaches capacity, a queue starts to build up, upstream of the bottleneck (as evidenced by speeds in the 15 mph to 30 mph range). Eventually, demand starts to drop off and the queue clears, at which point speeds within the bottleneck start to increase back up to the 70 mph free-flow speed for this hypothetical example.
- The bottom drawing shows the likely effects of the SPD-HARM prototype with speed differentials between adjacent sublinks limited to 5 mph. The effect is to spread the speed effects of the bottleneck further upstream of the bottleneck.
    - Note that there is still a significant time shear between recommended speeds for the same sublink between time slices (a rapid large magnitude change in recommended speed). This is unavoidable, because the SPD-HARM prototype cannot predict queueing, but must instead react to it. Reducing the time shearing effect would require increasing the geographic shearing effect between adjacent sublinks.

The net result of this hypothetical example is that SPD-HARM (in this particular instance) results in a net reduction in mean speed (from 66.5 to 61.7 mph) and a net increase in the standard deviation of speeds (11.1 to 13.7 mph) between sublinks and time slices. However, SPD-HARM has reduced the maximum speed difference between adjacent sublinks from 20 mph to 5 mph, a desired effect of the prototype.

Thus, this hypothetical example and additional hypothetical tests of much less aggressive SPD-HARM options by the IA team (not documented here) suggest that classical statistical variance of speed may NOT be a desirable performance measure for the prototype. Instead, the distribution of the differences in mean sublink speeds between adjacent sublinks (each on the order of 1/10th of a mile in length) is recommended as the superior performance measure. The distribution of vehicle speed differences for adjacent 5-minute time periods within each sublink should also be reported for the facility. Because the focus is safety, only speed drops from one sublink to the next from one time period to the next will be included in the calculations.

Time		With SPD-HARM				Mean	64.1	mph		StDev	12.7	mph		CofV=	19.9%		MaxDecel =		5	mph			
19:30	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	
19:15	70	70	70	70	70	70	70	70	70	70	70	70	70	70	65	70	70	70	70	70	70	70	
19:00	70	70	70	70	70	70	70	70	70	70	70	70	70	65	60	70	70	70	70	70	70	70	
18:45	70	70	70	70	70	70	70	70	70	70	70	70	65	60	55	70	70	70	70	70	70	70	
18:30	70	70	70	70	70	70	70	70	70	70	70	65	60	55	50	70	70	70	70	70	70	70	
18:15	70	70	70	70	70	70	70	70	70	70	65	60	55	50	45	65	70	70	70	70	70	70	
18:00	70	70	70	70	70	70	70	70	70	65	60	55	50	45	40	60	70	70	70	70	70	70	
17:45	70	70	70	70	65	60	55	50	45	40	35	30	20	15	35	55	70	70	70	70	70	70	
17:30	70	70	70	65	60	55	50	45	40	35	30	20	15	15	35	55	70	70	70	70	70	70	
17:15	70	70	65	60	55	50	45	40	35	30	20	15	15	15	35	55	70	70	70	70	70	70	
17:00	70	70	70	65	60	55	50	45	40	35	30	20	15	15	35	55	70	70	70	70	70	70	
16:45	70	70	70	70	65	60	55	50	45	40	35	30	20	15	35	55	70	70	70	70	70	70	
16:30	70	70	70	70	70	70	70	70	70	65	60	55	50	45	40	60	70	70	70	70	70	70	
16:15	70	70	70	70	70	70	70	70	70	70	65	60	55	50	45	65	70	70	70	70	70	70	
16:00	70	70	70	70	70	70	70	70	70	70	70	65	60	55	50	70	70	70	70	70	70	70	
15:45	70	70	70	70	70	70	70	70	70	70	70	70	65	60	55	70	70	70	70	70	70	70	
15:30	70	70	70	70	70	70	70	70	70	70	70	70	70	65	60	70	70	70	70	70	70	70	
15:15	70	70	70	70	70	70	70	70	70	70	70	70	70	70	65	70	70	70	70	70	70	70	
15:00	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	
	0.30	0.60	0.90	1.20	1.50	1.80	2.10	2.40	2.70	3.00	3.30	3.60	3.90	4.20	4.50	4.80	5.10	5.40	5.70	6.00	6.30	6.60	miles
	MilePost					Direction of Flow -->									Bottleneck								

Source: Kittelson & Associates/USDOT

Figure 3: Chart. Impacts of SPD-HARM prototype on sublink speeds near a theoretical bottleneck.

Speed variance between links is likely to increase with speed smoothing; but variance within a link is likely to decrease with smoothing. The net result may be an overall increase or decrease in speed variance.

Two additional measures of speed variation are recommended in addition to the distributions of speed drops:

1. Number of Stops per vehicle.
2. Number of Lane Changes per vehicle (which are driven by differences between the desired speed of the following vehicle and the actual speed of the lead vehicle).

These measures provide additional perspectives on the speed-drop distributions.

AVERAGE TRAVEL TIME AND SPEED

The total number of vehicle-hours (VHT) accumulated by vehicles using, and attempting to use, the facility during the simulation period will be reported. Vehicles attempting to use the facility are those prevented from entering the facility due to queues backing up onto the on-ramps or onto the mainline entry point. The average travel time is the total VHT divided by the number of vehicles entering and attempting to enter the facility. The average speed is the ratio of the VMT served over the VHT.

RELIABILITY

The INFLO ConOps identified Buffer Time and the Planning Time Index as potential reliability performance measures.

- The Buffer Index is the difference between the 95^{th}-percentile travel time and the average (or median) travel time divided by the average travel time (or the median travel time).
- The Planning Time Index is the 95^{th}-percentile highest travel time divided by the free-flow travel time.

According to the SHRP2-L08 project, "The buffer index can be an unstable indicator of changes in reliability because it can move in a direction opposite to the mean and percentile-based measures. This occurs because it uses both the 95^{th}-percentile and the median or mean travel time, and the percent change in these values can differ annually." [7]

Accordingly, the Planning Time Index is recommended as the reliability performance measure for the purposes of the Impact Assessment.

ENVIRONMENTAL EFFECTS

Table 8-1 of the INFLO ConOps identified the estimated carbon dioxide equivalent emissions and estimated fuel consumption as potential environmental performance measures for SPD-HARM.

Emission rates for vehicles are affected by numerous environmental factors not directly related to speed harmonization or advanced queue warning. These environmental factors include: ambient temperature, vehicle mix (age and size of vehicle and fuel source), humidity, altitude, and the emission control requirements of the particular state in which the facility is located.

The vehicular emissions of hydrocarbons, carbon monoxide, and carbon dioxide then must be converted into their Carbon equivalent based on their comparative greenhouse warming effects.

To avoid devoting an extensive amount of evaluation resources to emissions analysis, it is recommended that a qualitative approach be adopted for the purposes of the Impact Assessment. The Impact Assessment results would then be reported in terms of changes in fuel consumption and carbon dioxide (CO_2) equivalent emissions, instead of actual tons or gallons.

[7] Kittelson, Wayne; Mark Vandehey; SHRP 2 Reliability Project L08, Incorporation of Travel Time Reliability into the HCM, Prepublication Draft, Unedited, Transportation Research Board, Washington, DC, August 2013.

USER ACCEPTANCE AND COMPLIANCE

The INFLO ConOps identified the desirability of measuring user acceptance in some manner. Compliance rate with posted or recommended speeds was one recommended measure. A second suggested measure was "ratings on public opinion surveys."

The available resources do not allow a marketing or public acceptance survey to be conducted, nor will they support recruitment of a sufficient sample of drivers to provide a reliable unbiased estimate of the likely compliance rate with speed harmonization messages by the general public.

Consequently, it is proposed for the Impact Assessment that sensitivity tests be conducted of different market penetration and compliance rates. It is likely that public opinions on the bundles will be discussed tentatively and qualitatively based on the feedback provided by the test drivers in the small-scale demonstration.

SAFETY EFFECTS

The INFLO ConOps identified several measures of the safety effects, including: number of primary crashes, severity of crashes, and number of secondary crashes. The typical microsimulation modeling environment is not suitable for predicting changes in crash rates and severity. In addition, quantifying the reduction of crashes before and after the implementation of the prototype in the field requires multi-year data collection (due to the highly stochastic nature of and relative infrequency of crashes). Therefore, our analysis must be based on metrics that can be correlated with increased risk of rear-end crashes.

Recent statistical analyses of crashes on urban freeways using limited real-time travel data has shown that the risk of rear-end crashes increases with variation in individual vehicle speeds, variation in individual vehicle headways, and vehicle spacing in the congested queue.

There are several surrogate measures that have been proposed and tested in the literature[8],[9],[10] including maximum decelerations, speed gradient, time-to-collision, crash potential (combination of speed variance at a point, traffic density, and speed gradient), and combination of speed and deceleration.

Two surrogate measures were initially considered as proxies for crashes:

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[8] Gettman, D. and L. Head, "Surrogate Safety Measures from Traffic Simulation Models, "Transportation Research Record #1840, Journal of the Transportation Research Board, 2003.

[9] Ozbay, K. et al, "Derivation and Validation of a New Simulation Based Surrogate Safety Measure," Transportation Research Record #2083, Journal of the Transportation Research Board, 2008.

[10] Lee, C., B. Hellinga and F. Saccomanno, "Assessing Safety Benefits of Variable Speed Limits," Transportation Research Record #1897, Journal of the Transportation Research Board, 2004.

- Number of instances in which adjacent vehicles have a speed difference of greater than 10 mph.
- Number of instances in which adjacent vehicles are within 2 seconds headways of each other.

Neither measure was considered a satisfactory surrogate measure for crashes by at least one of the stakeholder reviewers of the Impact Assessment Plan. In fact, given the available microsimulation tools and the short time frame for any field work, it was recommended that the Impact Assessment not attempt to make any safety claims beyond the capabilities of the proposed impact assessment methodology. Consequently, it was decided that the Impact Assessment should address qualitatively the likely safety effects based on simulation model predicted changes in the distributions of speed drops between links and time periods for traffic on the facility.

CHAPTER 3. DEVELOPMENT OF THE EXPERIMENTAL PLAN

This chapter explains the development of the recommended experimental plan to assess the impacts of SPD-HARM and Q-WARN. Seven sets of key questions were identified in the Task Order Proposal Request (TOPR) (page 13 under Task 2 in the O&ITS-13-07 TOPR Statement of Work). Hypotheses, assumptions, and suggestions are provided here regarding how they might be addressed within the framework of the Impact Assessment.

The objective of Impact Assessment (IA) of the SPD-HARM with Q-WARN is to address as many of the questions identified in the TOPR as feasible, given the resources available for the IA, and the limitations of the proposed small-scale demonstration of the SPD-HARM/Q-WARN prototype.

Note that this Impact Assessment is specific to the Prototype being developed and not to the SPD-HARM and Q-WARN concepts described earlier. Details of the Prototype to be evaluated are given in the report by Balke, Charara, and Sunkari. [11]

QUESTION 1: WHEN IS THE BEST TIME TO IMPLEMENT SPD-HARM SOLO OR IN COMBINATION WITH Q-WARN?

This first question set in the TOPR consisted of the following questions:

- (1a) Are speed harmonization and queue warning applications more beneficial when implemented in conjunction or in isolation?
- (1b) Under what operational conditions are the applications the most beneficial?
- (1c) Under what conditions is one application superior to the other?

The operational hypotheses here are:

- *SPD-HARM and Q-WARN will individually produce benefits even when implemented without the other application.*
- *SPD-HARM and Q-WARN will produce higher benefits, and perhaps synergistic benefits, when deployed in combination.*
- *There are some operational conditions under which SPD-HARM and Q-WARN are most effective, and these conditions might vary depending on whether each application is implemented solo or in combination.*

This is a multi-dimensional hypothesis that would require simulation testing of the two applications under differing traffic operation and weather conditions. These conditions may include varying recurrent congestion levels due to varying demand levels, varying visibility, varying pavement friction coefficients, varying non-recurrent congestion (incident, weather, etc.)

[11] Kevin Balke, Hassan Charara, Srinivasa Sunkari; draft Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design, Texas A&M Transportation Institute, FHWA, Washington, DC, January 15, 2014.

conditions, varying geometric conditions (sight distance, vertical and horizontal curvature, lane widths, shoulder widths), varying roadside and in-vehicle distractions, density of the roadside equiPMent (RSE) for detecting traffic conditions, varying communication errors and latency, degree and quality of guidance provided the connected vehicles, and varying market penetration rates for the connected vehicles.

One practical note must be made here. While questions 1a, 1b, and 1c make it desirable to test SPD-HARM and Q-WARN together and separately, one issue has been what to tell the simulation model about how drivers would respond to SPD-HARM and Q-WARN messages.

In the case of SPD-HARM, the issue was easily resolved by assuming that a certain percentage of connected drivers would comply with the recommended speeds issued by SPD-HARM (assuming successful and timely receipt of the guidance). Different percentage response rates (combining connected, message receipt, and compliance rates) could be tested within the simulation model in separate runs.

In the case of Q-WARN, there was–and still is–a lack of information or behavioral theory regarding how drivers would respond to advance notice of queues, one or more miles ahead. Will the drivers slow down? Will the drivers pay more attention to traffic? Will drivers leave the freeway and take an alternate route? Lacking information on how drivers would respond to Q-WARN messages, it was decided to assume for microsimulation-analysis purposes that drivers would respond according to the speeds recommended by SPD-HARM, but there would be no change in routes and no reduction of speeds in anticipation of the SPD-HARM messages.

The small-scale demonstration was potentially an alternate method for testing the effects of SPD-HARM and Q-WARN separately; however, the sample of drivers was insufficient to establish SPD-HARM compliance rates or Q-WARN responses. Institutional constraints (asking test drivers to obey SPD-HARM speeds rather than WSDOT VSL speeds) also prevented testing of SPD-HARM compliance rates. In addition, drivers were instructed to stay on the freeway regardless of the Q-WARN message. Therefore route diversion effects could not be tested.

Thus, while it was ultimately feasible to test SPD-HARM effects within the microsimulation environment, the effects of Q-WARN could not be tested either in simulation or in the field during the small-scale demonstration.

QUESTION 2: WHICH COMMUNICATION METHOD IS BEST FOR NOMADIC DEVICES?

This question set consists of:

- (2a) Will a nomadic device that is capable of communicating via both DSRC as well as cellular meet the needs of the two applications?
- (2b) When is DSRC needed and when will cellular suffice?

Dedicated short-range communication (DSRC) devices have low communication latencies and limited range (the specification for DSRC is a 300 meters—approximately 1,000 feet—range, but can be greater under favorable conditions). Cellular phone network has a much broader coverage range, but communications may be delayed (increased latency) under heavy cell traffic conditions.

The two questions lend themselves to the hypothesis that:

- Nomadic devices and the facilities may need to be DSRC-capable under certain conditions.

The microsimulation analysis portion of the Impact Assessment can provide information to help address these questions (without specifically answering the questions) through sensitivity testing of different communication latencies (delays in delivery of messages between the connected vehicles and the infrastructure).

The small-scale demonstration was able to test both DSRC and cellular communication methods and assess their effects on message loss and latency. However, the test was made in a single urban environment.

Thus, the microsimulation analysis and small-scale demonstrations will not be able to identify the specific environmental conditions in which one method of communication is superior to the other, but they will be able to identify the impacts of communication latencies on the performance of the Prototype.

QUESTION 3: WHAT ARE THE IMPACTS OF NEAR-, MID-, AND LONG-TERM DEPLOYMENT?

The full text of the question is: “What are the impacts of future operational deployments of speed harmonization and queue warning applications in the near, mid, and long term?” The focus of this question is on the specific facility where the INFLO applications are tested by the Prototype develoPMent (PD) contractor.

The hypotheses here are that:

- The performance of the Prototype will improve as more drivers opt to be connected (market penetration plus compliance).
- Consequently, the benefits of deployment will be different in the near, mid, and long term.

The answer to this question and these hypotheses can be obtained by evaluating the results of the Question 1b tests for different levels of compliance with the SPD-HARM messages.

QUESTION 4: WHAT LEVEL OF MARKET PENETRATION IS REQUIRED FOR SUCCESS?

The question is: “At what levels of market penetration of connected vehicle technology do speed harmonization and queue warning applications become effective?”

The answer to this question will be produced through examination of the Question 1b test results.

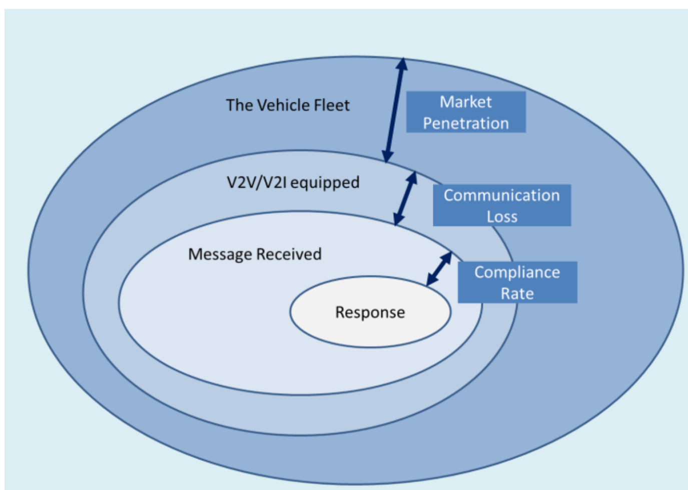
The associated hypothesis is that:

- Market penetration, communications delay (or loss),[12] and compliance rate are all tied together into the estimation of the overall driver response to INFLO guidance (Figure 4). All else being equal, higher levels of market penetration will result in greater benefits. There will be a critical region of market penetration where benefits will steeply increase.

Market penetration determines who is eligible to receive the guidance. Communications errors, delays, and loss determine which among the eligible receivers will get the message and by when. Compliance rate (which will be a function of external conditions and the message received) then determines the actual responses of the drivers. At the same time, we must take into account that drivers may receive the message from multiple non-connected vehicle sources (their direct perception of the problem, changeable message signs, commercial radio, highway advisory radio or a traveler information system). In this case, traveler information system (TIS) includes public and proprietary area-wide traffic information systems that the driver may already subscribe to in their vehicle.

This assessment also needs to take into account the additive effect of other drivers receiving information from unconnected vehicle sources. In addition, there will be an additive effect where uninformed drivers seeing vehicles in front of them slow down, change lanes, or exit early, may do the same thing because they think the other drivers know what they are doing (Figure 5).

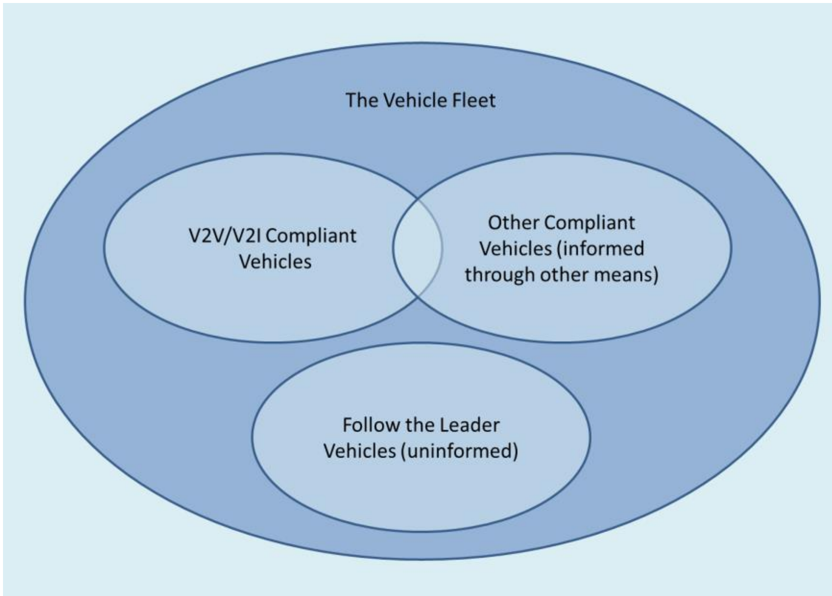
The microsimulation analysis will automatically take care of the behavior of unconnected drivers seeing connected vehicles slow down through standard car-following and lane-changing driver behavior models. The “follow the leader” effects of when unconnected drivers see connected drivers leaving the freeway will not be modeled.



Source: Kittelson & Associates/USDOT

Figure 4: Illustration. Market penetration, communication loss, compliance rate effect on response.

[12] Note that messages without a confirmation receipt are repeated until the confirmation is obtained. Thus, communication losses may translate into delays in transmission (latency) rather than actual lost messages. Losses occur, if the message does not arrive by a critical time point for action.



Source: Kittelson & Associates/USDOT

Figure 5: Illustration. Additive effects of other information sources and "follow the leader" effect.

QUESTION 5: WHAT ARE THE EFFECTS OF COMMUNICATION ERRORS AND LATENCY?

This question set consists of the following questions:

- (5a) How effective are the two applications when there are errors or loss in communication?
- (5b) What are the impacts of communication latency on benefits?

The working hypothesis is:

- Communication errors, losses, and latency all will reduce the effectiveness of SPD-HARM and Q-WARN. Some reduction in effectiveness may be acceptable.

This hypothesis will be directly tested in the small-scale demonstration in the field.

QUESTION 6: WHAT ARE THE BENEFITS OF WIDESPREAD RSE DEPLOYMENT?

This question set consists of the following questions:

- (6a) What are the benefits of widespread roadside equiPMent (RSE) deployment versus ubiquitous cell coverage?
- (6b) Which is more beneficial?
- (6c) What is the marginal benefit with data from existing sensors?

Roadside equiPMent (RSE) is installed to monitor conditions—collecting traffic flow, density, and speed data and transmitting it to a data environment (which in turn is accessible by connected vehicles and the transportation management center). Connected vehicles may access the data environment via dedicated short-range communications (DSRC) devices or via the cellular telephone network.

The working hypotheses in this case are:

- Roadside equiPMent (RSE) and cell phone coverage each have their unique detection benefits for SPD-HARM and Q-WARN, which may vary under certain conditions.
- Widespread RSE detection may be a partial substitute for connected vehicle detection of speeds and headways.
- Existing sensors may provide benefits to SPD-HARM and Q-WARN implementation.

These questions and hypotheses can best be addressed in the small-scale demonstration tests to answer Question 1b by investigating how different mixes of roadside equiPMent affect:

i. The ability to detect queues on the facility, and
ii. The ability to accurately predict congestion and queuing.

QUESTION 7: IS CONNECTED VEHICLE DATA REQUIRED FOR SUCCESS?

This question set consists of the following questions:

- (7a) To what extent are connected vehicle data instrumental to realizing a near-term implementation of the two applications?
- (7b) What are the impacts of dispersed vs. focused deployment of connected vehicles (i.e., nomadic devices)?

Working hypotheses include:

- V2X (that is V2I plus V2V) increases the effectiveness of SPD-HARM and Q-WARN when compared to a roadside equiPMent (RSE) only installation for monitoring conditions.
- A high market penetration of connected vehicles is more effective than a lower rate.

The small-scale demonstration will examine the timing and precision with which the backs of queues are determined via connected vehicles and road loop detectors at one site.

The microsimulation analysis will examine different levels of response to SPD-HARM speed messages. The level of response is a function of the market penetration rate for connected vehicles, the communication latency and loss, and the drivers' compliance rates with the received messages from SPD-HARM.

CONCLUSIONS

The Impact Assessment of the SPD-HARM with Q-WARN Prototype has to address several questions identified in the Task Order Proposal Request (TOPR) related to its effectiveness, data/communication technologies, user acceptance, and deployment potential.

Table 4 provides a list of the recommended tests to be conducted to answer the questions identified in the TOPR.

Table 5 cross references the tests to the original TOPR questions.

The hypotheses identified in Table 6 will be tested. The strike-out text indicates which hypotheses cannot be tested using the available microsimulation model or the small-scale demonstration.

Table 4: Experimental plan.

Test	Objective	Method	MOE's
1	Determine if SPD-HARM and Q-WARN bundles are more effective combined then individually.	Not feasible to test Q-WARN with current driver behavior knowledge and limited small-scale demonstration.	N/A
2	Under what operational conditions are the applications most beneficial?	IA contractor to design and conduct a multi-dimensional simulation test program. Small-scale demo to test communication effects.	See Table 3 in Performance Measures and Targets.
3	When is DSRC needed and when will cellular suffice?	Examine Test #2 simulation and small-scale demo results to obtain sensitivity to different communication latencies.	Loss or delay in acquisition and transmission of BSMs.
4	Determine impacts of near, mid, long term deployment.	Examine numerically the Test #2 market penetration results.	Same as Test #2.
5	Determine required level of market penetration.	Examine numerically the Test #2 market penetration results.	Same as Test #2.
6	Determine effects of communications errors and latency.	Examine Test #2 simulation and small-scale demo results to obtain sensitivity to communication errors and latencies.	Loss or delay in acquisition and transmission of BSMs.
7	Determine benefits of widespread RSE.	Examine numerically the Test #2 results. Consider Test #3 conclusions.	Same as Test #2.
8	Determine extent to which V2X is required.	Examine numerically the Test #2 results. Consider Test #3 conclusions.	Same as Test #2.

Table 5: Relation of tests to TOPR questions.

Test	Objective	TOPR Question
1	Determine if SPD-HARM and Q-WARN bundles are more effective combined then individually.	#1a, 1c
2	Determine under what operational conditions the applications are most beneficial.	#1b, 1c
3	When is DSRC needed and when will cellular suffice?	#2a, 2b
4	Determine impacts of near, mid, long term deployment.	#3
5	Determine required level of market penetration.	#4
6	Determine effects of communications errors and latency.	#5

Test	Objective	TOPR Question
7	Determine benefits of widespread RSE.	#6
8	Determine extent to which V2V and V2I are required.	#7

Table 6: Hypotheses to be tested.

TOPR Question	Hypothesis to be Tested
1	• There are some operational conditions under which SPD-HARM and Q-WARN are most effective.
2	• Nomadic devices and the facilities may need to be DSRC capable under certain conditions.
3	• The performance of the prototype will improve as more drivers opt to be connected (market penetration). • Consequently, the benefits of deployment will be different in the near, mid, and long-term.
4	• Market penetration, communications loss, and compliance rate are all tied together into the estimation of the overall driver response to V2X guidance.
5	• Communication errors, losses, and latency all will reduce the effectiveness of SPD-HARM and Q-WARN.
6	• Roadside equiPMent (RSE) and cell phone coverage each have their unique benefits for SPD-HARM and Q-WARN, which may vary under certain conditions. • Widespread RSE may be a partial substitute for connected vehicle detection. • Existing sensors may provide benefits to SPD-HARM and Q-WARN implementation.
7	• V2X increases the effectiveness of SPD-HARM and Q-WARN when compared to an RSE only installation. • A high market penetration of connected vehicles is more effective than a lower rate.

CHAPTER 4. EXPERIMENTAL PLAN

This chapter describes the processes for estimating or simulating the impacts of the Prototype demonstration/test. The simulation of the Prototype involves several steps described below including selecting the test bed, emulation software for simulation of the Prototype, and operating scenarios to be tested.

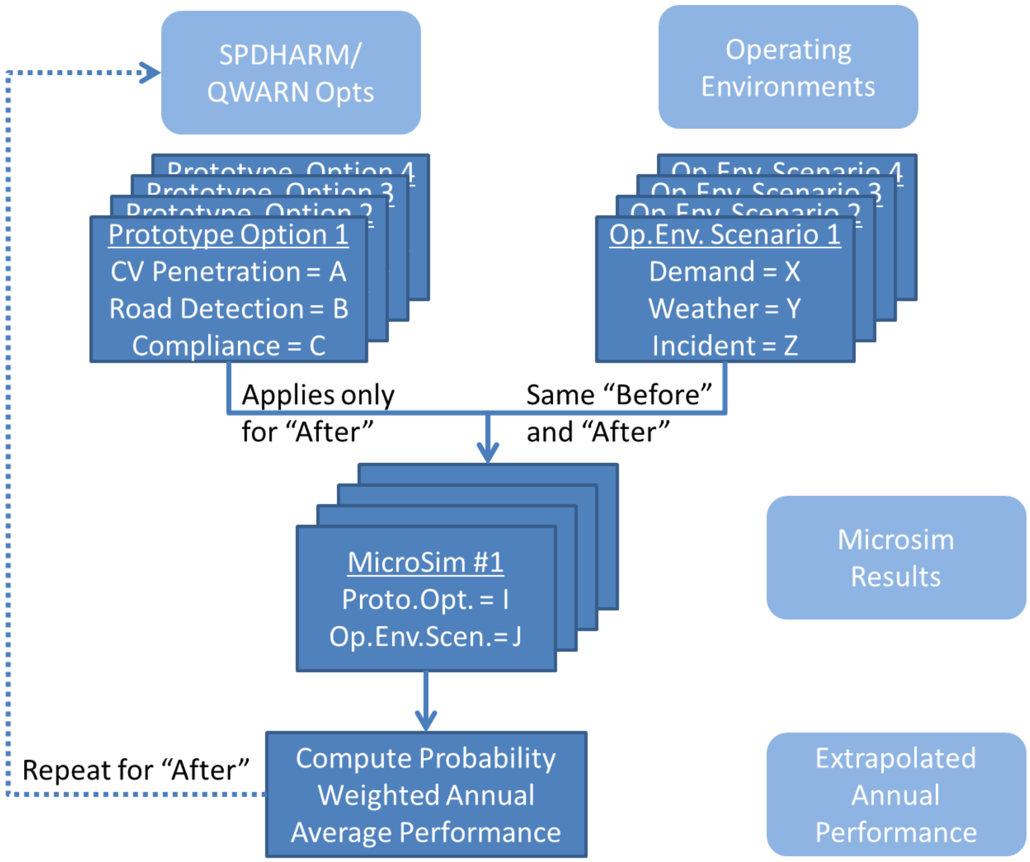
Tests #1, 3, 4, 5, 6, 7, 8 all involve examination and extrapolation of Test #2 results. This chapter focuses in detail on the design of Experiment #2 with brief descriptions of how the results of Experiment #2 will be extended to the other experiments.

OVERALL APPROACH TO EXPERIMENT #2

Experiment #2 will assess the effects of the SPD-HARM and Q-WARN applications using a "before and after" analysis approach. The performance measures for the selected test bed will be computed "before" application of the SPD-HARM and Q-WARN prototypes. The same measures will then be computed for the same test bed "after" application of the prototypes. Figure 6 provides an overview of the process for Experiment #2.

Because the effects of the prototypes are expected to vary according to the operating environment (high or low demand conditions, incident or non-incident conditions, and good or bad weather conditions), a set of operating environments (called scenarios) will be set up for testing the SPD-HARM and Q-WARN applications.

The SPD-HARM and Q-WARN applications however are also expected to affect the frequencies of occurrence for the scenarios. Both applications should reduce the frequency of incidents under high and low demand conditions, and under good and bad weather conditions. However, the state of the art in microsimulation is not currently able to support the prediction of crash frequencies as a function of changes in speed distributions caused by SPD-HARM or changes in demand caused by Q-WARN. Thus, these effects cannot be reported in this Impact Assessment.



Source: Kittelson & Associates/USDOT

Figure 6: Illustration. Overview of Experiment #2.

PURPOSE AND SCOPE OF EXPERIMENT #2

The purpose of Experiment #2 is to identify under what operational conditions are the SPD-HARM and Q-WARN applications (together or separately) the most beneficial?

The experiment will focus on how the guidance given, the connected vehicle response, and the actions of unconnected vehicles will affect facility performance. The effects of the factors contributing to the responses of connected and unconnected vehicles (for example market penetration and dynamic message sign density) will be examined in other tests conducted outside of Experiment #2, but building on the information gained from Experiment #2.

Simulation Test Bed Selection

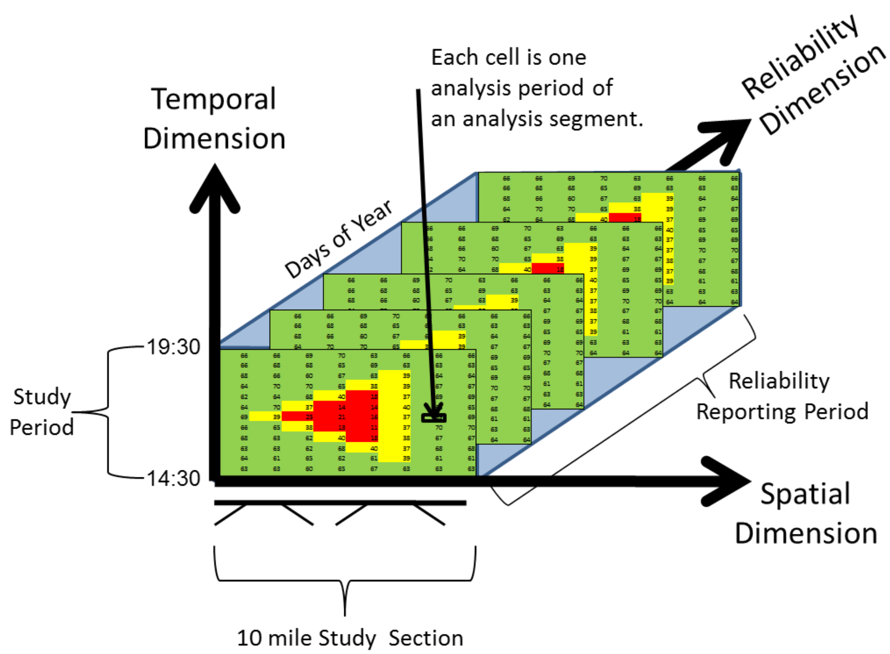
The test bed selection and the criteria upon which the selection was based are described in Appendix A. The result of this evaluation was that the 8.5-mile long San Mateo, California, US 101 freeway test site was selected for conducting the microsimulation Impact Assessment of the SPD-HARM/Q-WARN Prototype. The 8.5-mile study area fully captures the usual geographic extent of the recurring queues at the test site.

Software for Implementing SPD-HARM and Q-WARN Prototype

The impact assessment requires the use of a microsimulation software compatible version of the SPD-HARM/Q-WARN prototype. Appendix A discusses the identification and selection of the software implementation of the Prototype. Because the original Prototype was developed as a post-processor of VISSIM, and the selected test bed is also implemented in VISSIM, the original Prototype was used for simulation testing.

Selected Study and Reliabilty Reporting Periods

To capture the effects of SPD-HARM and Q-WARN on travel-time reliability, it is necessary to select the time period of the day, the days of the year, and the operational scenarios to be evaluated (see Figure 7 for terms used). Each operational scenario is modeled in a single simulation model run for the selected peak period, study section, and operating condition (demand, weather, incident). The single simulation model run is repeated 10 times and the results are averaged to obtain average performance for that scenario. The scenario results are then weighted according to their expected frequency over the course of a year to obtain annualized results.



Source: Kittelson & Associates/USDOT

Figure 7: Illustration. Reliability analysis terminology.

Reliability analyses are very demanding on resources, so in order to conserve study resources, days and hours of the year when demand is low and the effects of SPD-HARM and Q-WARN are likely to be negligible, will be neglected. Thus, the selected reliability reporting period for the analysis of Experiment #2 results will be approximately 250 non-holiday weekday peak periods of a single year.

To further conserve study resources, the focus of Experiment #2 will be on the PM peak period, under the assumption that AM peak period benefits would be similar for the facility.

The duration of the PM peak period selected for analysis will be the 5-hour peak from 2:30 PM to 7:30 PM. Recurring congestion usually begins around 3 PM and ends by 7 PM on the selected test site.

OPERATING ENVIRONMENT SCENARIOS FOR EXPERIMENT #2

In the simulation study, the impacts on facility performance of the SPD-HARM and Q-WARN algorithms will be evaluated for the following operating scenarios identified in the INFLO ConOps:

- **Fixed-point breakdown**: This relates to recurrent congestion, i.e., presence of fixed bottleneck(s) along the test facility that create queues upstream, which, in turn, is a function of variations in demand. The facility will be simulated before, during, and after the bottleneck activation. The impact depends on the severity of congestion, i.e., the level of traffic demand.
- **Non-fixed point (incident caused) breakdown**: This involves the modeling of incident conditions. The impact depends on the incident severity and duration, and prevailing operating conditions on the facility. We consider two levels of incident severity: 1-lane blocking incident lasting 30 minutes and another lasting 60 minutes.
- **Weather-related breakdown**: Inclement weather affects both the speeds and discharge flows along a highway facility that may trigger congestion and formation of shock waves. The impacts depend on the intensity of weather conditions. The weather options for the Prototype include three levels of pavement condition (dry, wet, icy/snowy) and two levels of visibility (good, poor).

The selection of the operating environments for testing of the SPD-HARM and Q-WARN Prototype is described in the next chapter.

The probability of each scenario occurring during the PM peak period over the course of a year of non-holiday weekdays will be determined by examining the incident and weather logs, and the demand profile for the test site.

As part of the post-processing of the Experiment #2 simulation results to obtain annual average (Full Year) performance results, an initial set of incident, weather, and demand level probabilities will be used for the test site based on actual real-world logs for the test site.

Operating environment scenarios with exceptionally low probabilities (the value to be determined through test computations, but generally those falling under one hundredth of one percent) will not be formally microsimulated because their results would not significantly affect the computed Full Year performance of the facility with or without SPD-HARM and Q-WARN.

SPD-HARM/Q-WARN PROTOTYPE OPTIONS

The SPD-HARM and Q-WARN Prototype options to be tested in Experiment #2 include:

- Evaluation of the impacts of SPD-HARM and Q-WARN implementations separately or in combination.
- The impacts of different user-selected values for the user-definable parameters in the two applications.
- The impacts of different densities of road sensors and dynamic message signs.
- The impacts of different market penetration rates.

Evaluation of SPD-HARM and Q-WARN in Combination or Separately

The current Prototype for Q-WARN involves detection and delivery of a queue warning message to connected vehicles and dynamic message signs (if available) to vehicles a user-specified distance upstream. The message will state the time or distance to the back of queue.

SPD-HARM will tell the driver when to slow down in tenth mile increments, making it unlikely that a Q-WARN notice of a back of queue “X” miles ahead will significantly affect driver behavior as the vehicle approaches the back of queue. The Q-WARN message may reinforce the SPD-HARM message in the driver’s mind, but the small scale demo and the microsimulation model are not well suited for testing this effect without data from a large sample of drivers to better quantify this effect.

Therefore Q-WARN effects on traffic operations were not explicitly modeled in the microsimulation environment. The small-scale demo was not of a magnitude to permit isolation of the Q-WARN effects from the SPD-HARM effects on traffic operations.

The other effect that Q-WARN may have will be to cause drivers to change routes. Neither the small-scale demo nor the selected microsimulation model will be able to test this “diversion” effect. In addition, the microsimulation model would require some data on driver behavior to be able to predict the “diversion” effect. Because a driver behavior study was not part of the Impact Assessment, the decision was made to not model the potential driver diversion effects of Q-WARN.

The small-scale demo evaluated SPD-HARM and Q-WARN together but never as separate applications. The microsimulation analysis evaluated SPD-HARM alone, but not Q-WARN.

Effects of User Definable Parameters

The user-definable parameters for the SPD-HARM and Q-WARN prototypes along with their recommended values for Experiment #2 are listed in Table 7.

They generally give the user the flexibility to define the queue state for the facility and to fine tune the sensitivity of the SPD-HARM and Q-WARN applications so as to minimize “false alarms” by the system.

Resources did not permit testing of different user-definable parameters for SPD-HARM and Q-WARN in either the small-scale demonstration or in the microsimulation analysis.

Effects of Market Penetration and Road Infrastructure

The effects of different market penetration rates and road infrastructure densities of detection and changeable message signs will be determined in Experiment #2 using the specific values shown in Table 7.

The following total response rates will be tested in Experiment #2: none, 10%, 25%, and 50%. Connected vehicles will be assumed to have 0% communication loss, zero communication latency, and 100% compliance for the purposes of the microsimulation runs within Experiment #2. Following completion of the microsimulation model runs a graph of the performance with SPD-HARM and Q-WARN is constructed based on the results. Then the market penetration can be depreciated for communication loss, latency, and less than 100% compliance to obtain the effects of those factors on performance.

Given that the density and frequency of information provided by connected vehicles to SPD-HARM and Q-WARN greatly exceed the density and frequency of information from road detectors spaced at half a mile, it was concluded that little value could be gained by testing higher densities of road detectors than were already present at the microsimulation site (generally half-mile spacing). Testing of different road detector densities at the small-scale demonstration site was not feasible.

MICROSIMULATION RUNS

To fully test all possible combinations of operating environment scenarios and possible levels of market penetration and infrastructure would require more microsimulation model runs then could be feasibly completed within the resources available for this project. In addition, not all of these potential combinations proved to be interesting for various reasons (extremely low likelihood, miniscule effects, etc.). The next chapter explains how the final set of scenarios was selected for analysis.

Table 7: User definable parameters for SPD-HARM/Q-WARN prototype emulator.

User Definable Q-WARN Parameter	Comment
1. Average Speed Threshold for Queued State	Set at 5 mph for all tests
2. Min/Seconds below speed threshold before Lane detector is considered to be in "Queue"	Use defaults selected by PD Contractor
3. Criteria for Link in "Queue" state a. Number Lane Detectors in "Queue". b. Percent Lane Detectors in "Queue".	Use defaults selected by PD Contractor
4. Min/Seconds below speed threshold before connected vehicle is considered to be in "Queue"	Use defaults selected by PD Contractor
5. Criteria for SubLink in "Queue" state a. Number connected vehicles in "Queue". b. Percent connected vehicles in "Queue".	Use defaults selected by PD Contractor
6. Upstream broadcast range for queue warning	Set at 1 mile for all tests
User Definable SPD-HARM Parameters	**Comment**
1. Recommended speeds by visibility and pavement condition type	Set at values shown in Table 30
2. Criteria for Valid Link Speed determination: a. Number Lane Detectors in operation b. Percent Lane Detectors in operation.	Use defaults selected by PD Contractor
3. Criteria for Valid SubLink Speed determination: a. Number connected vehicles present with comm. b. Percent connected vehicles present with comm. c. Smoothing period (min/secs) for speed estimates.	Use defaults selected by PD Contractor
4. Speed range for determining troupes for SPD-HARM	Use defaults selected by PD Contractor
5. Maximum and Minimum speeds for SPD-HARM	Set at 70 mph and 30 mph
Market Penetration and Infrastructure	**Comment**
Percent vehicles responding to SPD-HARM	Test range: none, 10%, 25%, 50%.
Road detector spacing	Use existing spacing

Note: The definition of Queue used in the Prototype varies from the definition of queue used by VISSIM to compute the queue statistics.

CHAPTER 5. BASELINE SCENARIOS ANALYSIS – SIMULATION

This chapter describes the results of the baseline (no Prototype in operation) analyses using the simulation test bed. The results of the small-scale demo tests are described in a later chapter.

SELECTION OF BASELINE SCENARIOS

This subsection documents the development and selection of the baseline scenarios against which the benefits of the SPD-HARM and Q-WARN prototypes were evaluated under varying assumptions related to communication technology, market penetration, and driver response rates.

Approach to DeveloPMent and Selection of Baseline Scenarios

One of the hypotheses identified in the Impact Assessment Plan (finalized February 18, 2014) was that the traffic congestion and safety benefits of the speed harmonization (SPD-HARM) and advanced queue warning (Q-WARN) prototypes would vary for different levels of recurring congestion (congestion associated with high demand levels) and non-recurring congestion (congestion associated with incidents and bad weather, sometimes in combination with high demand levels). Study resources did not allow microsimulation of every possible combination of the factors. The consultant team employed the following ad-hoc cluster analysis-like approach to reduce the number of scenarios that had to be tested with full microsimulation analysis.

1. Examine real-world conditions at the test site.
2. Identify all of the possible combinations of demand, incidents, and weather that occurred on approximately 250 non-holiday weekday afternoon periods.
3. Evaluate the impacts of these factors (demand, incidents, weather) separately and in combination on travel times.
4. Remove from further consideration factors that appear to have little effect on observed travel times in the corridor.
5. Identify the frequency of occurrence for each scenario.
6. Defer to later consideration low-probability scenarios.
7. Assemble a set of baseline scenarios that span the range of observed congested conditions on the corridor.

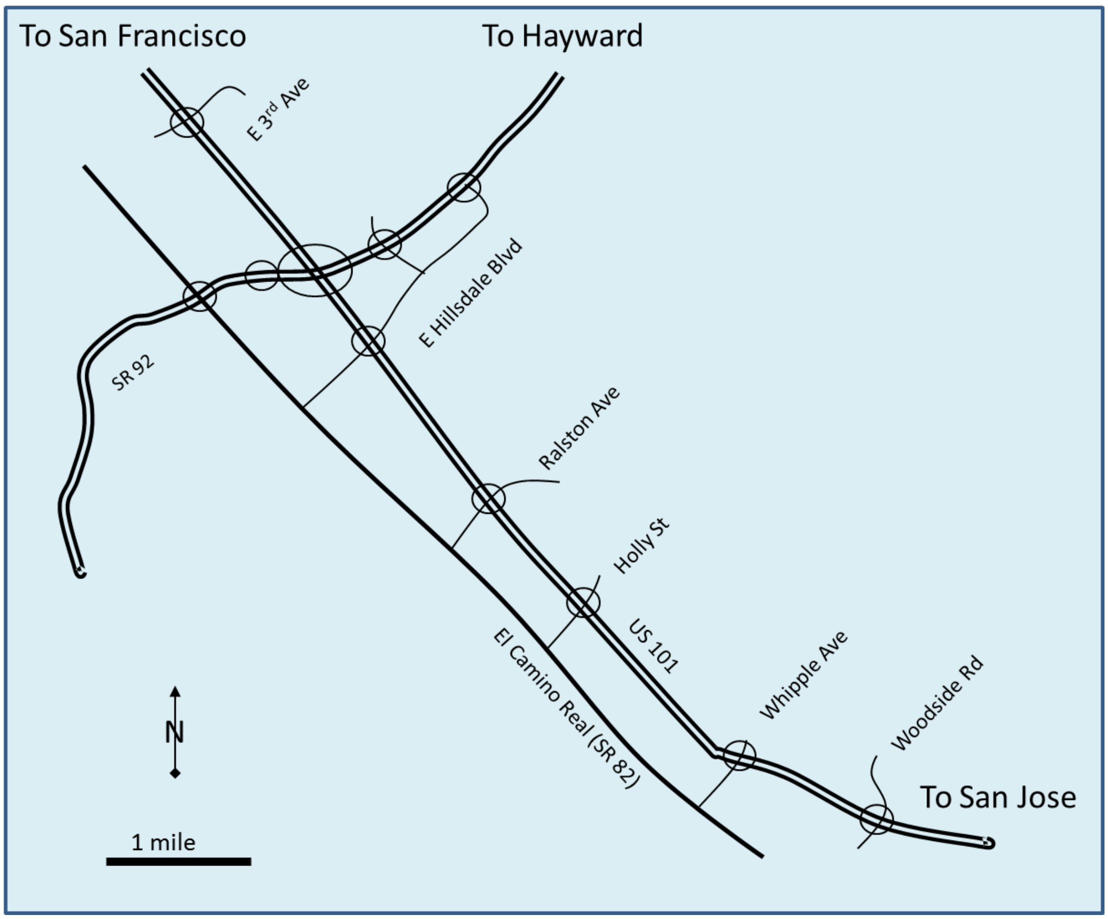
The number of members (scenarios) to be included in the final set of scenarios to be evaluated for the baseline analysis is determined with the twin objectives of:

- Identifying a full range of operational conditions for testing the prototypes, while
- Ensuring there remain sufficient project resources for adequate testing of the SPD-HARM and Q-WARN prototypes under a sufficiently wide range of technology, market penetration, and driver response options.

The Test Site

The test site is an 8.5-mile stretch of the US 101 freeway in San Mateo County located approximately 10 miles south of the San Francisco International Airport (SFO). The test site extends from the Woodside Road interchange in Redwood City to the Third Avenue interchange in San Mateo, California (Figure 8). The study period is five hours of the PM peak period extending from 2:30 PM to 7:30 PM.

This section of the US 101 freeway is an 8-lane freeway, transitioning to 6 mixed-flow lanes plus two peak-period HOV 2+ lanes south of Whipple Avenue. The HOV lanes are continuously accessible from the mixed-flow lanes, operating as mixed flow lanes outside of the PM peak period (3-7 PM) weekdays. The freeway carries between 200,000 and 250,000 AADT of which 15% are HOV 2+ vehicles. SamTrans currently operates two express bus routes on the freeway during the peak periods.



Source: Kittelson & Associates/USDOT

Figure 8: Map. The San Mateo US 101 test site.

The US 101 freeway is regularly congested in the northbound direction during weekday PM peak periods. The weaving section between the East Hillsdale interchange (just south of SR 92) and the SR 92 interchange is the bottleneck. The freeway-to-freeway connector ramps at SR 92 also regularly experience queuing, backing up from eastbound SR 92 approaching the San Mateo Bridge. Traffic is heavy in the southbound direction as well, but it is not usually congested during weekday PM peak hours.

Active Traffic Management Measures Already in Place

The US 101 freeway currently has freeway service patrols, highway advisory radio (HAR), and variable message signs. The Caltrans TMC monitors freeway operations using loop detectors to monitor lane volumes and speeds at approximately half-mile spacing. Local dynamic ramp metering currently is in operation on most on-ramps in both directions during the AM and PM peak periods.

Changeable Message Signs: Within the study section, for the selected analysis year of 2012, changeable message signs were in place at approximately two-mile spacing along the freeway: South of Hillsdale Blvd., South of Holly Street (near Brittan Ave.), and north of Woodside Drive.

Freeway Service Patrol: The US 101 freeway is covered by two freeway service patrol (FSP) beats (#6 and #10). The beat north of SR 92 has four trucks operating Monday-Friday from 6:00 AM to 7:00 PM. It services slightly under 500 incidents per month. The beat south of SR 92 has 3 trucks operating on weekdays from 6:00 AM to 10:00 AM and 3:00 PM to 7:00 PM. It services about 250 incidents per month.

Data Collection: The analysis required travel time, demand, weather, and incident data.

Travel Time Data

Travel-time data for 251 non-holiday weekday PM peak periods (2:00 PM - 8:00 PM) for the year 2012 were obtained from the Caltrans PeMS (Performance Measurement System) database[13] for nine miles of US 101 between Woodside Road (milepost 407) and Third Avenue (milepost 416).

The following PeMS defined holidays for 2012 were excluded from the travel-time data:

- 01/02/2012 New Year's Day Monday
- 01/16/2012 Martin Luther King, Jr. Day Monday
- 02/20/2012 Washington's Birthday Monday
- 05/28/2012 Memorial Day Monday
- 07/04/2012 Independence Day Wednesday
- 09/03/2012 Labor Day Monday
- 10/08/2012 Columbus Day Monday

[13] http://pems.dot.ca.gov/?redirect=%2F%3Fdnode%3DState#37.7743,-122.2023,10, Accessed June-July 2014.

- 11/12/2012 Veterans Day Monday
- 11/22/2012 Thanksgiving Day Thursday
- 12/25/2012 Christmas Day Tuesday

The PeMS database computes travel time for each direction of the freeway by examining the spot speeds reported by the various loop detectors located on the selected length of freeway. Five-minute average spot speeds for each lane loop detector are archived. The spot speeds are converted to travel time indices (TTIs) for each lane using a nominal 60 mph free-flow speed. The 5-minute lane-by-lane TTI's are then averaged across all lane detectors in the selection study section and direction of the freeway and are aggregated to the user's preferred temporal aggregation level. In this case, one-hour aggregations were selected.

For the nine-mile section of US 101 selected for data collection, there were 30 mainline loop detector stations in each direction (each station recording lane-by-lane speeds for four lanes)

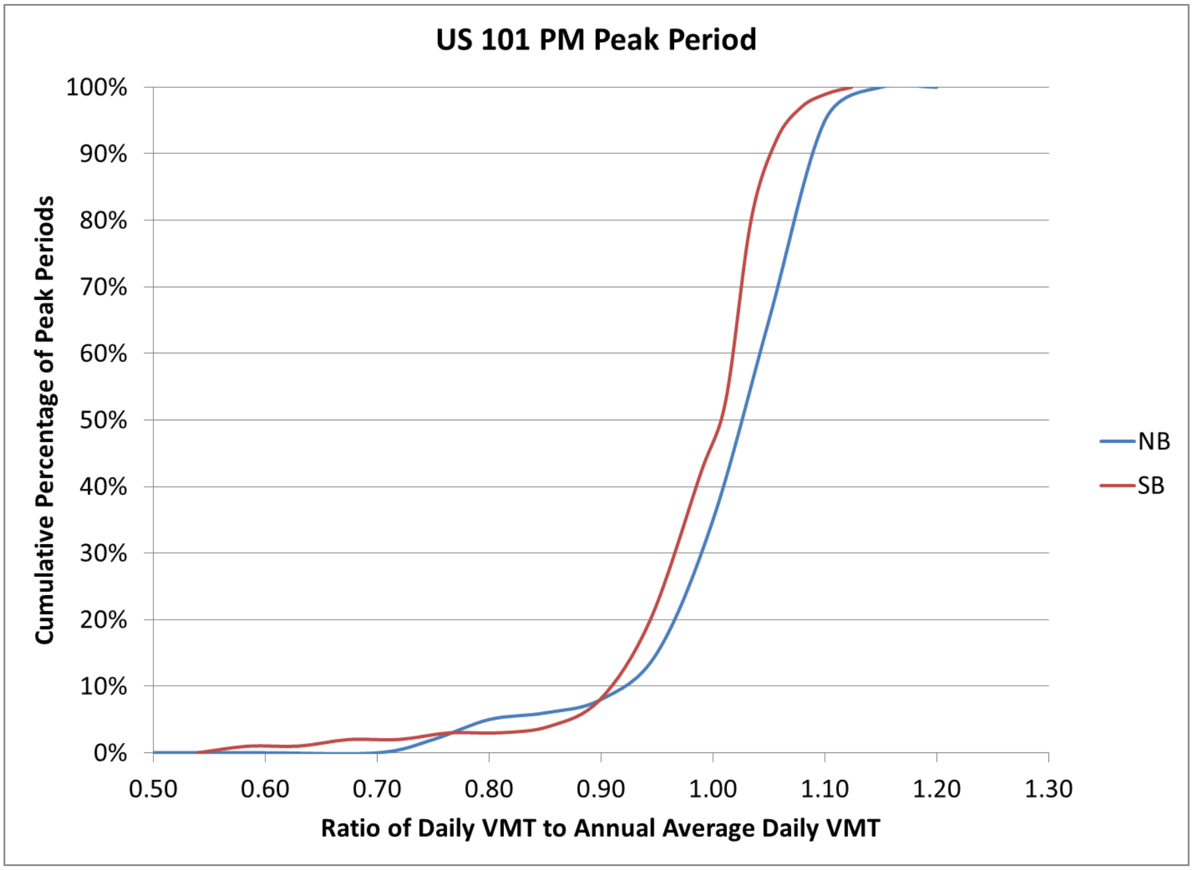
Demand Data

Demand data in the form of vehicle-miles traveled (VMT) was downloaded from the PeMS database for the subject freeway study section and directions for 2012. PeMS estimates the VMT by tallying the volume measured at each lane loop detector and multiplying that volume by the sum of the average distances to the nearest upstream and downstream detectors. The volumes, available at the 5-minute level of aggregation, were aggregated to full PM peak period VMT for each of the study days, by direction, over the length of the freeway study section. Figure 9 shows the variation in measured VMT by direction for weekday PM peak periods over the year 2012. The chart shows that the measured VMT varies by no more than plus or minus 10% from the annual average over 90% of the peak periods of the year. This suggests that the VMT being obtained in this manner is demand "served" not "demanded." There are significant capacity constraint effects in the computed VMT. It was, therefore, concluded that the variations in VMT observed for the study section of freeway for the PM peak period were more measurements of variations in throughput, than variations in demand.

Weather Data

Twenty-four hour weather data for the year 2012 was extracted from the University of Utah on-line database (http://mesowest.utah.edu/) for the San Francisco International airport, which is next to the test bed. Weather data was then examined for the weekday, non-holiday PM peak periods.

Twenty-six days of rainy weather were observed at the airport in 2012 during the weekday PM peak period. There was no snow, ice, or ground fog conditions during 2012.



Source: Kittelson & Associates/USDOT

Figure 9: Graph. Cumulative distributions of PM peak period VMT.

Incident Data

Incident logs from the California Highway Patrol (CHP) computer-aided dispatch (CAD) log were obtained from the PeMS database for the year 2012. This source provides starting time, duration, and location information on incidents by type, but does not indicate if or how many lanes were closed.

To help estimate which incidents might have involved lane closures, collision data was obtained from the Caltrans accident reporting system (TASAS) for the latest available year, 2010. This source provides greater detail on the accidents, including number of lanes closed.

These two sources were compared to determine if the lane closure data in TASAS could be used to identify the incidents in the CHP database that were likely to have involved lane closures. It was found that lane closure was correlated to accident duration. The correlation found in the TASAS database was applied to the accidents in the CHP database to identify which accidents probably resulted in the temporary closure of one or more lanes.

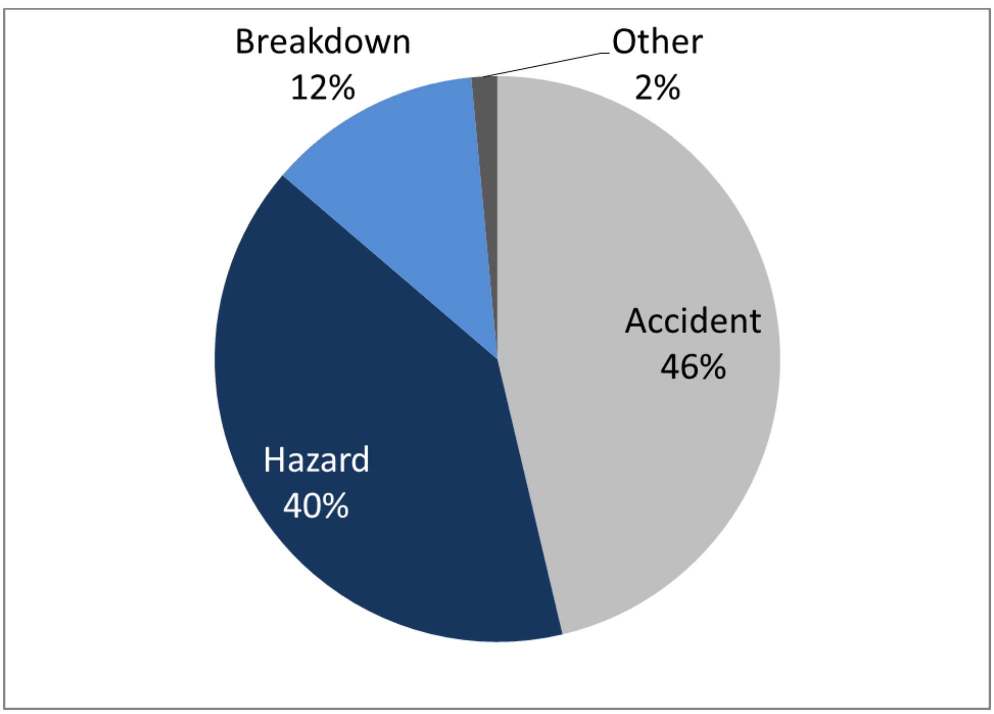
The following discussion of incident data focuses primarily on the northbound direction of travel (the peak direction of travel during the PM peak period on the study section of freeway).

According to the CHP Incident Log there were a total of 1,268 incidents in the northbound direction in the test corridor (from Woodside Rd to 3rd street) in all of 2012 (24 hours, 7 days a week). There were 473 incidents in the PM peak study period (2:00 to 8:00 PM) during weekdays. Figure 10shows the distribution of incidents.

By way of comparison, there were a total of 336 incidents recorded in the southbound direction of the US101 test bed, lower than the 473 incidents recorded in the northbound direction. The proportion of recorded incidents that were accidents in the southbound direction (42%) was slightly lower than the accident occurrence (47%) in the northbound direction.

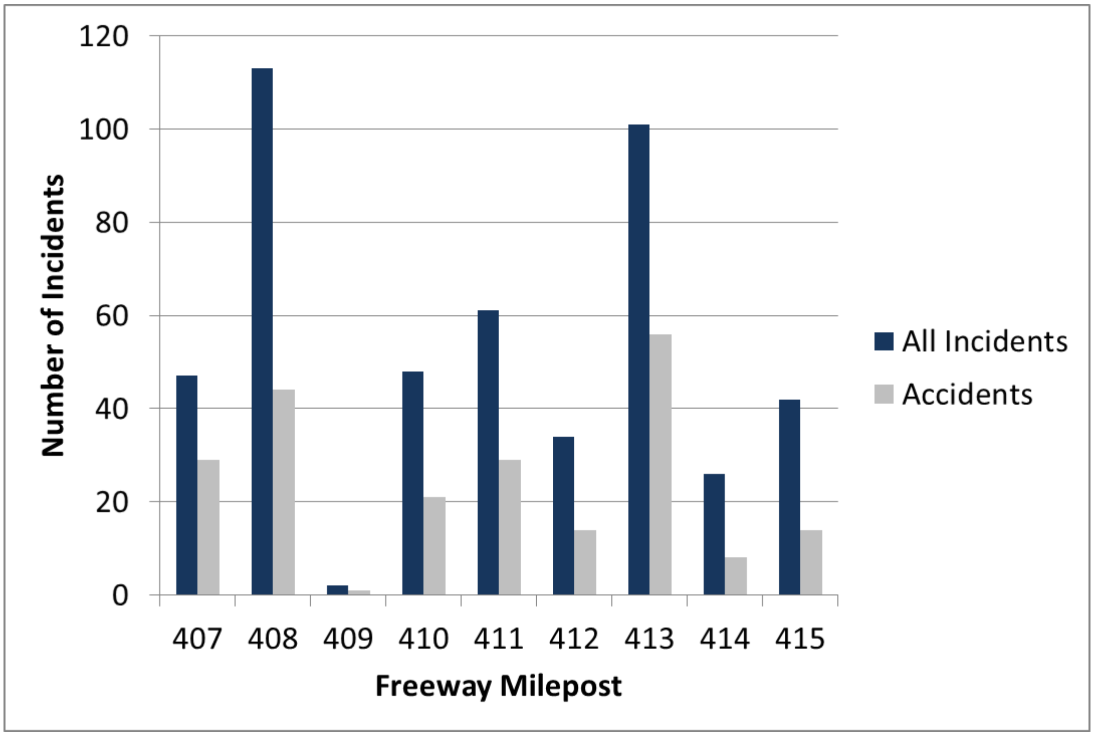
Figure 11 shows the spatial distribution of all the incidents and separately the accidents along the study corridor. The majority of events occur between mileposts 408 and409 (South of, or Upstream of, Whipple Avenue) and in between mileposts 413 and 414 (downstream of Hillsdale Blvd). The highest frequency of accidents occurs in these locations between 4:00PM and 6:00PM.

The distributions of accident durations for both the northbound and southbound directions are shown in Figure 12. Most reported accidents last less than 3 minutes, but there are several accidents with long durations. The average weekday PM peak period accident duration is 23.3 minutes for the northbound direction and 25.4 minutes for the southbound direction.



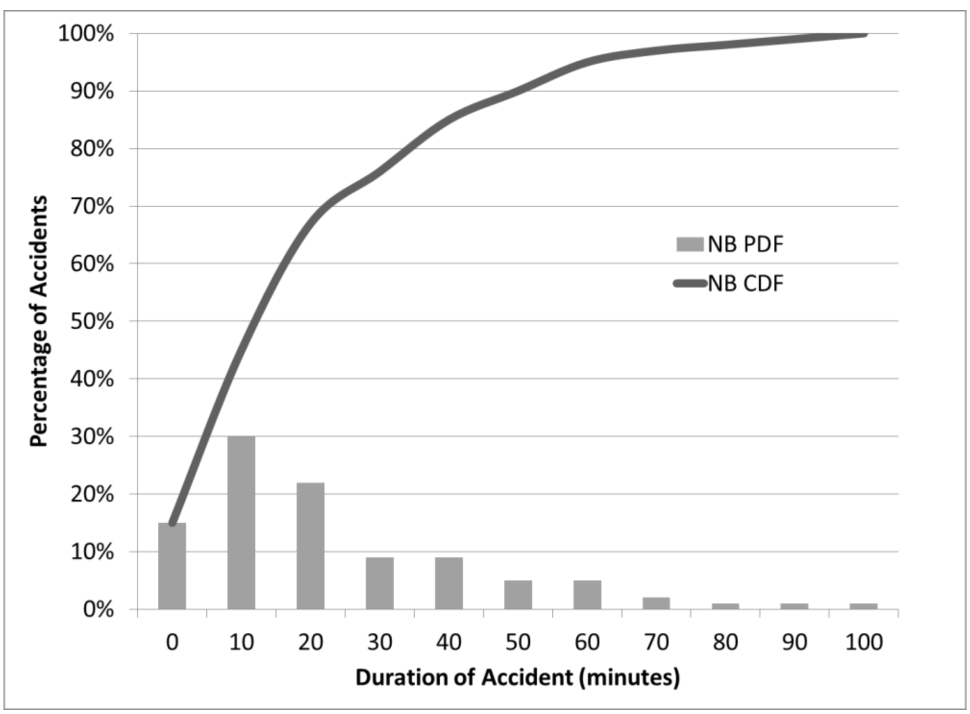
Source: Kittelson & Associates/USDOT

Figure 10: Graph. Incident classification, NB 101 PM peak 2012.



Source: Kittelson & Associates/USDOT *NB US 101 CHP Incidents, PM Peak, 2012*

Figure 11: Graph. Spatial distribution of incidents along NB US101.



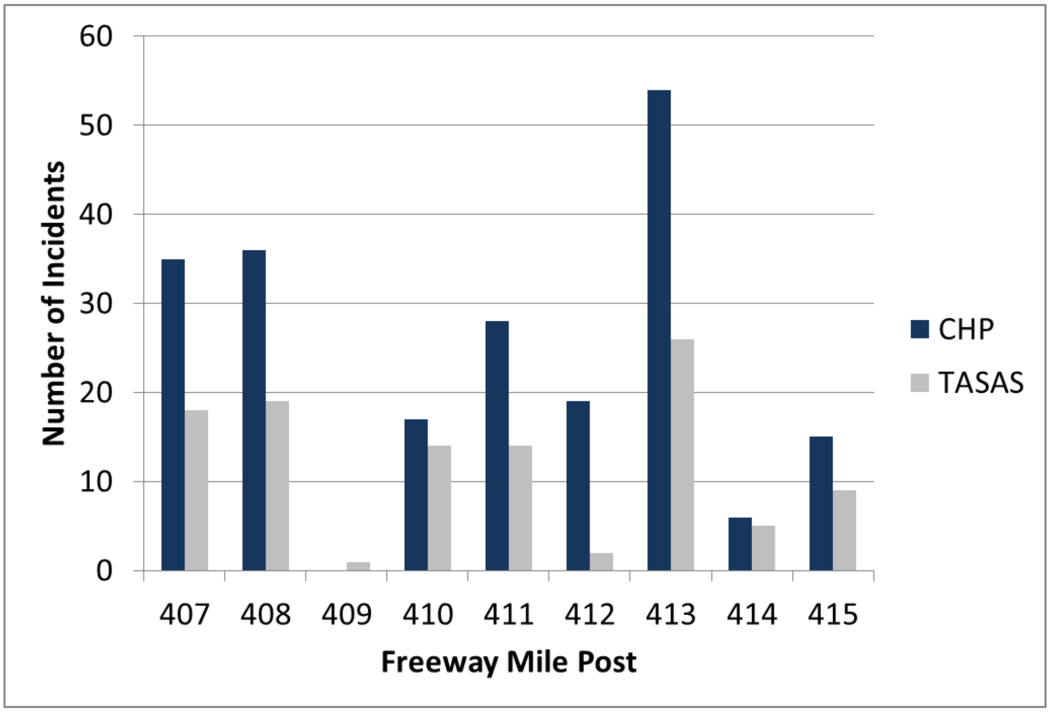
Source: Kittelson & Associates/USDOT

Figure 12: Graph. Distribution of accident durations (NB Only).

Comparison of CHP and TASAS Accidents for NB 101: The number and type of accidents reported on the CHP/CAD and TASAS databases were compared for the NB direction of the US101 test bed in the 2010 year (the latest year that TASAS data are available).

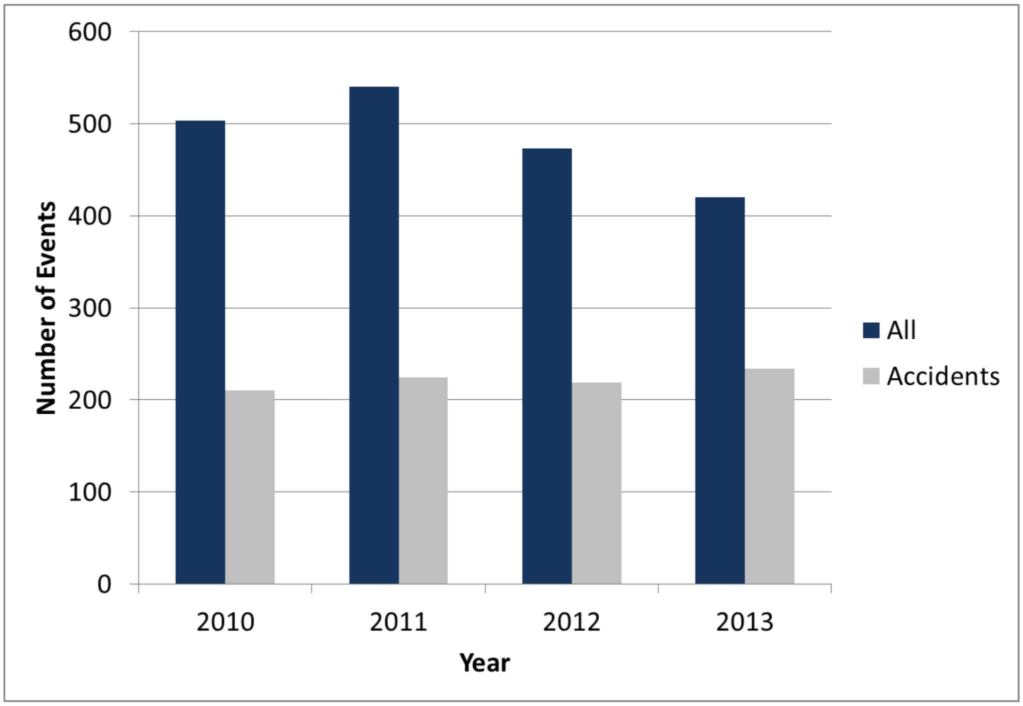
There were 210 CHP recorded accidents in NB 101 during the weekday PM peak period. The TASAS database reports 107 accidents for the same times. Thirteen percent are injury accidents and 78% are lane-blocking accidents.

The spatial distribution of accidents per reporting source is shown in Figure 13. The distribution is similar for both accident sources. Note that there is a higher frequency of accidents in post-mile 407-408 (Woodside Rd) and a lower frequency in post-mile 408-409 compared to the accident frequency in year 2012.



Source: Kittelson & Associates/USDOT

Figure 13: Graph. Comparison of CHP and TASAS reported accidents.



Source: Kittelson & Associates/USDOT

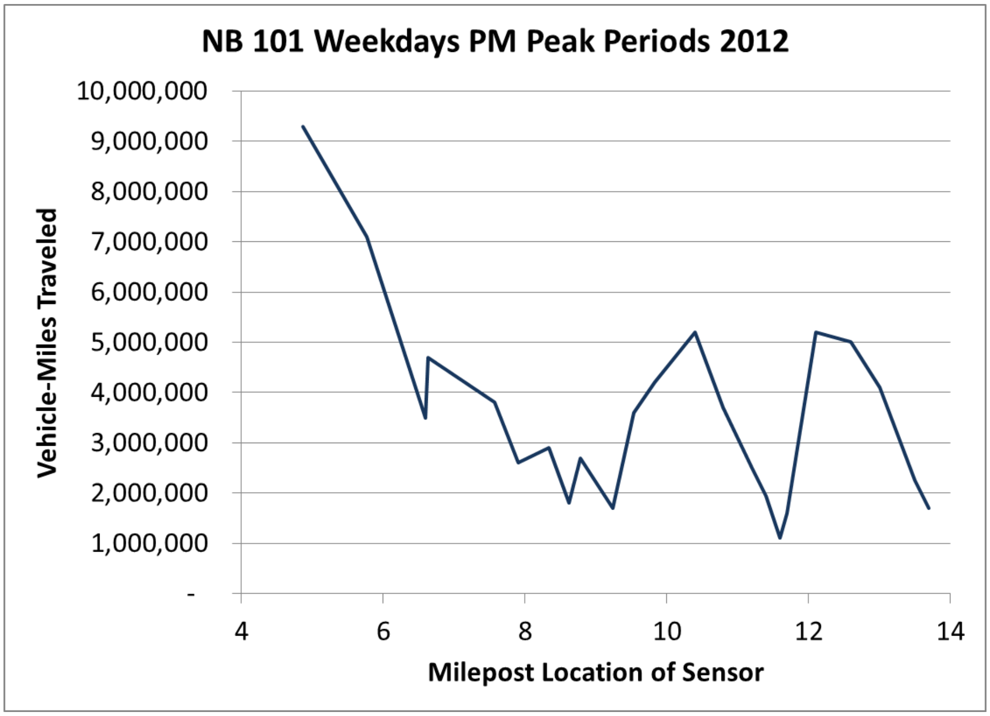
Figure 14: Graph. CHP reported incidents 2010-2013.

Figure 14 shows the number of all CHP-reported incidents and accidents from 2010 through 2013. The number of all incidents decreases from 540 in 2010 to 420 in 2013. However, the number of accidents remains about the same over the last four years. The maximum difference of about six-percent in the number of reported accidents is not statistically significant.

Determining Incident Rates: The incident rates were determined using incident and traffic information in the PeMS system for the 2012 year. The VMT data was downloaded for all weekdays in the PM peak (2:00 PM to 8:00 PM) along the test section of NB 101.

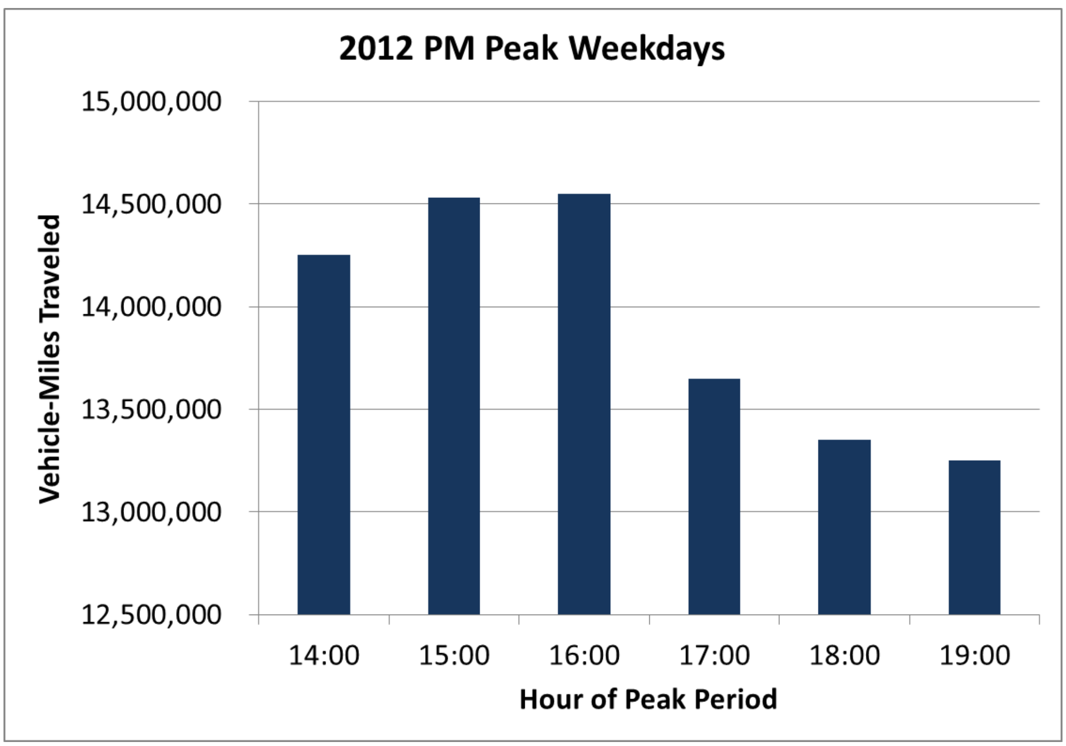
The traffic volumes and VMT from detector data are reported per detector station, as shown in Figure 15. Figure 16 shows the variation of the hourly VMT during the PM peak period.

To calculate the incident rates it was necessary to first calculate the VMT volumes per the one-mile roadway segment that the incidents are reported. The incident rates in #/events per million vehicle-miles of travel for all incidents and separately for accidents are shown in Figure 17. The average accident rate was 3.1 incidents/million vehicle miles.



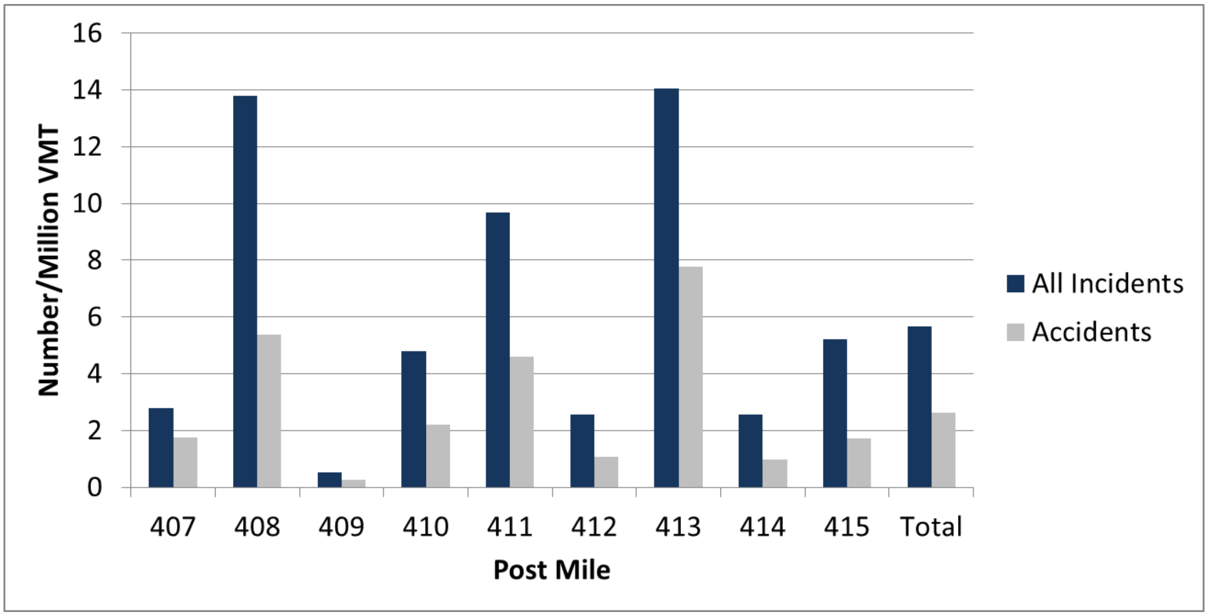
Source: Kittelson & Associates/USDOT

Figure 15: Graph. Geographic distribution of VMT for NB 101 weekdays PM peak 2012.



Source: Kittelson & Associates/USDOT

Figure 16: Graph. Hourly variation of traffic in the PM peak period –NB 101.



Source: Kittelson & Associates/USDOT

Figure 17: Graph. Geographic distribution of incidents NB 101 for 2012.

Data Exploration

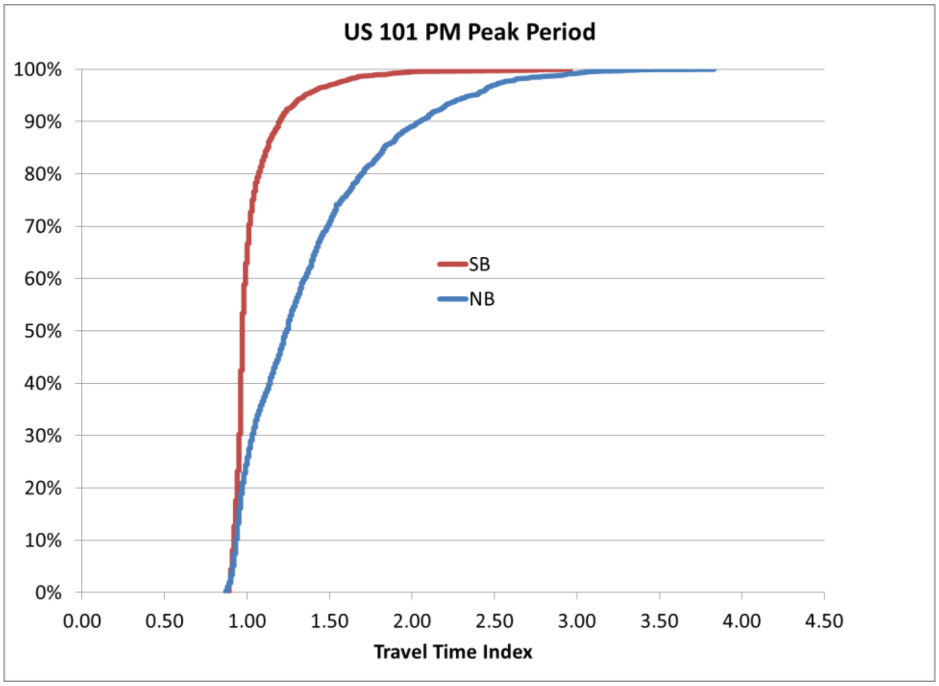
This section explores the structures apparent in the data set.

Travel-Time Distribution

The cumulative hourly travel-time distributions by direction are shown in Figure 18 and in Table 8 in terms of the travel time index (TTI)—the ratio of the actual travel time to the theoretical travel time at 60 mph. The median TTI for the northbound direction is 1.23, implying a median speed of 49 mph during the PM peak period. In the reverse direction, the median TTI is 0.97, for a median speed of 62 mph. (The travel time index is computed in relation to a 60 mph free-flow speed.)

From this data it can be determined that the northbound direction is the peak direction during the PM peak period and that it is subject to both recurring and non-recurring congestion. The recurring congestion in the southbound direction is comparatively minor. Figure 19 shows by direction how average annual travel times during the PM peak periods vary by day of week and hour of the year. Thursdays and Fridays tend to be the most congested days of the week, with the greatest congestion (largest travel times) occurring at 5:00 PM (17:00).

This data suggests that recurring variations in demand are a significant contributing cause to congestion on the freeway. The 2:00 PM hour appears representative of generally uncongested conditions, especially on Mondays and Tuesdays.



Source: Kittelson & Associates/USDOT

Figure 18: Graph. Cumulative travel time distributions US 101.

Table 8: Cumulative travel time index statistics – US 101 PM peak period.

Statistic	Northbound	Southbound
5th Percentile	0.91	0.91
25th Percentile	1.00	0.95
Median (50%)	1.23	0.97
75th Percentile	1.56	1.03
95th Percentile	2.32	1.33

Source: Kittelson & Associates/USDOT

Figure 20 shows the hourly travel times (by hour of day) by direction over the course of a year. The charts indicate no strong seasonality in congestion. The northbound direction experiences several severe congestion events pretty much every season over the course of the year. The southbound direction experiences relatively few severe congestion events.

Effects of Demand, Weather, Incidents on Travel Time

Figure 20 shows how the average travel time for each hour within the peak period is affected by lane blocking incidents and weather. The effects of demand can be indirectly gauged by comparing how the travel times vary from the early hours to the later hours in the peak period. At presumably low demand levels (see 14:00 hour) incidents and rain have negligible effects on travel times. At presumably higher demand levels (see 17:00 hour), the effects of incidents and rain on travel times are significantly more pronounced.

Note that the effects of incidents and rain are significantly lower in the southbound direction (than the northbound direction) due to the presumably lower demands in the southbound direction.

The conclusion is that incidents and rain significantly affect travel times, but only at high demand levels. While the earlier attempt to use VMT to measure changes in demand was unsatisfactory, it is apparent from these charts that the effects of demand can be obtained by examining the microsimulation results in the northbound direction, hour by hour within the peak period.

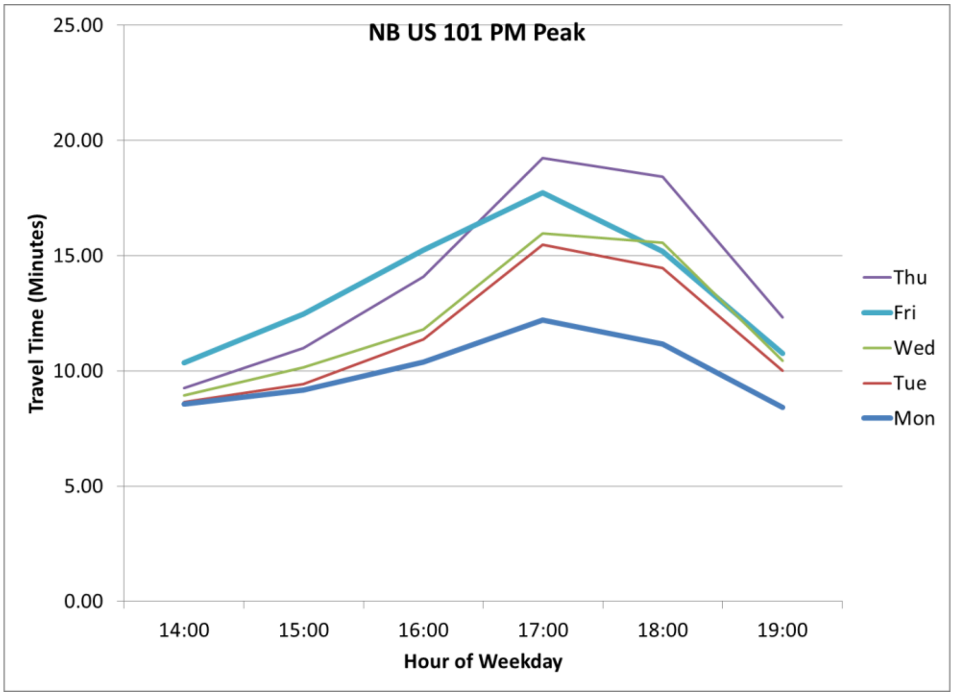
Combined Event Probabilities

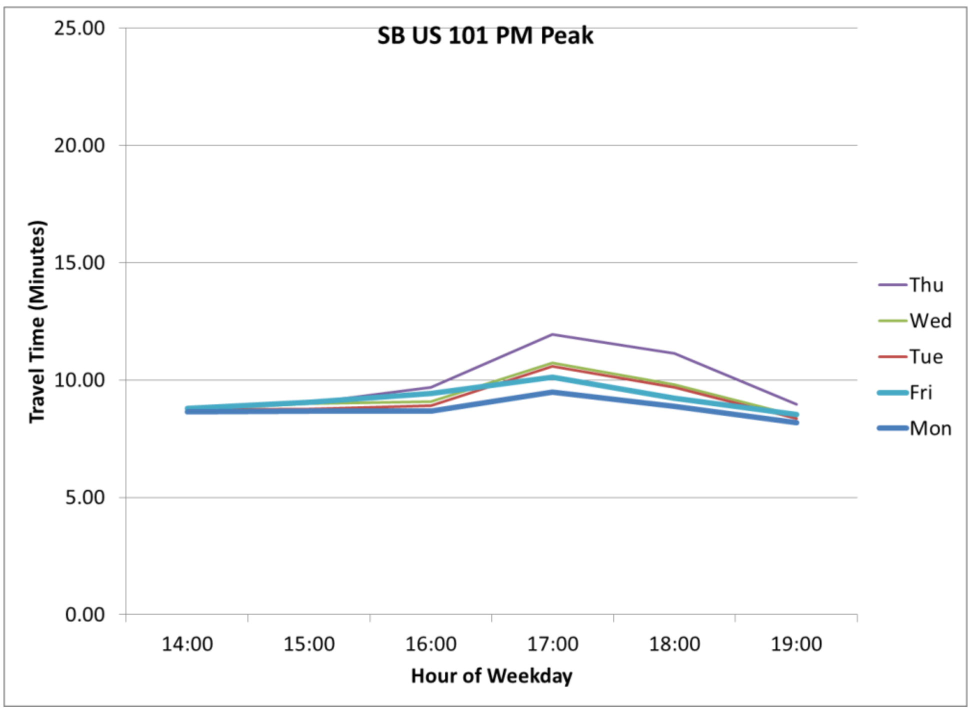
The frequencies of combinations of weather, incidents, and demand that were observed during the weekday PM peak periods on US 101 are shown in Table 9 for both directions.

The freeway experienced rainy weather approximately 10% (26 days) of the year during the 251 weekday PM peak periods in 2012. Fog (reduced visibility at ground level), snow, ice, high wind, low temperature, and other adverse weather conditions were not observed in 2012.

Lane-blocking incidents occurred sometime during the weekday PM peak periods, somewhere on the freeway, approximately 49% of the year in 2012 in the northbound direction, and 36% of the year in the southbound direction. In the northbound direction, approximately 13% of the PM peak periods of the year saw lane-blocking incidents lasting at least 30 minutes. In the southbound direction approximately five percent of the PM peak periods saw lane-blocking incidents lasting at least 30 minutes.

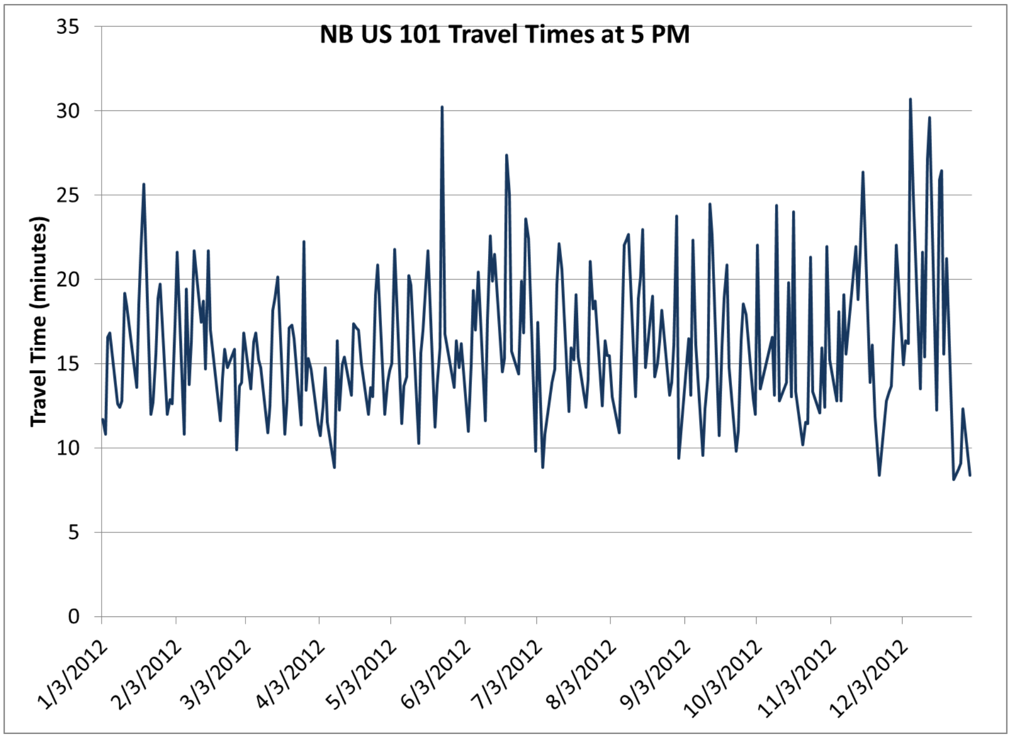
Although the probability of an incident during rainy weather is higher than during dry weather, the combined occurrence of incidents with rainy weather was only two percent in the northbound direction and four-tenths of one percent in the southbound direction. This is primarily because rainy weather is relatively infrequent in the corridor.

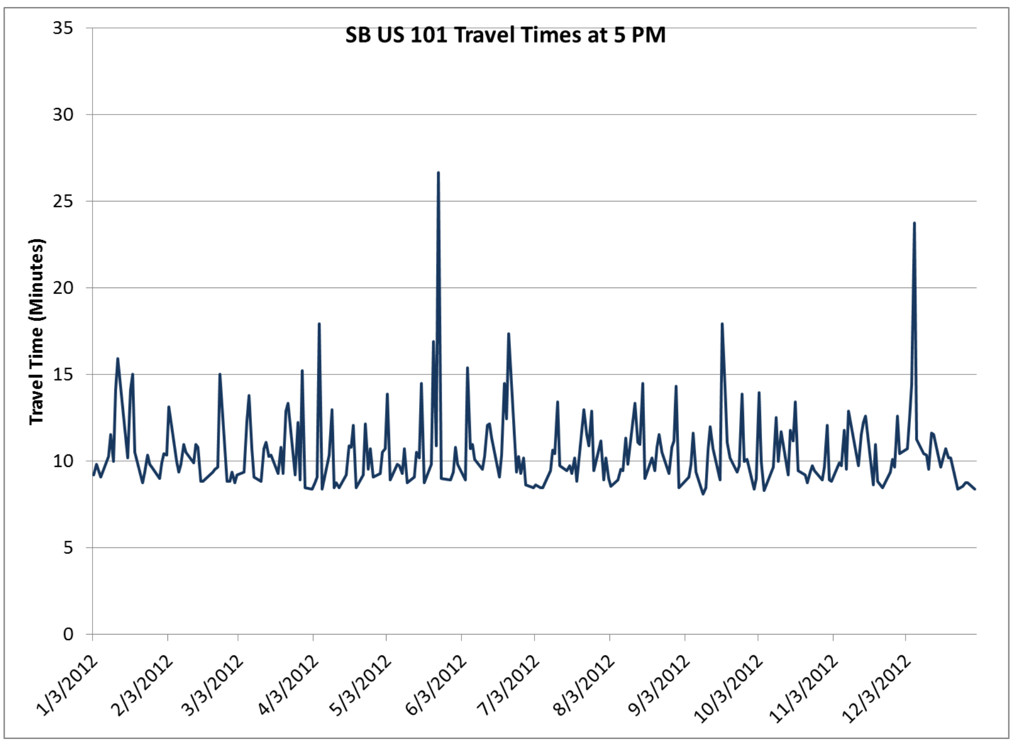




Source: Kittelson & Associates/USDOT

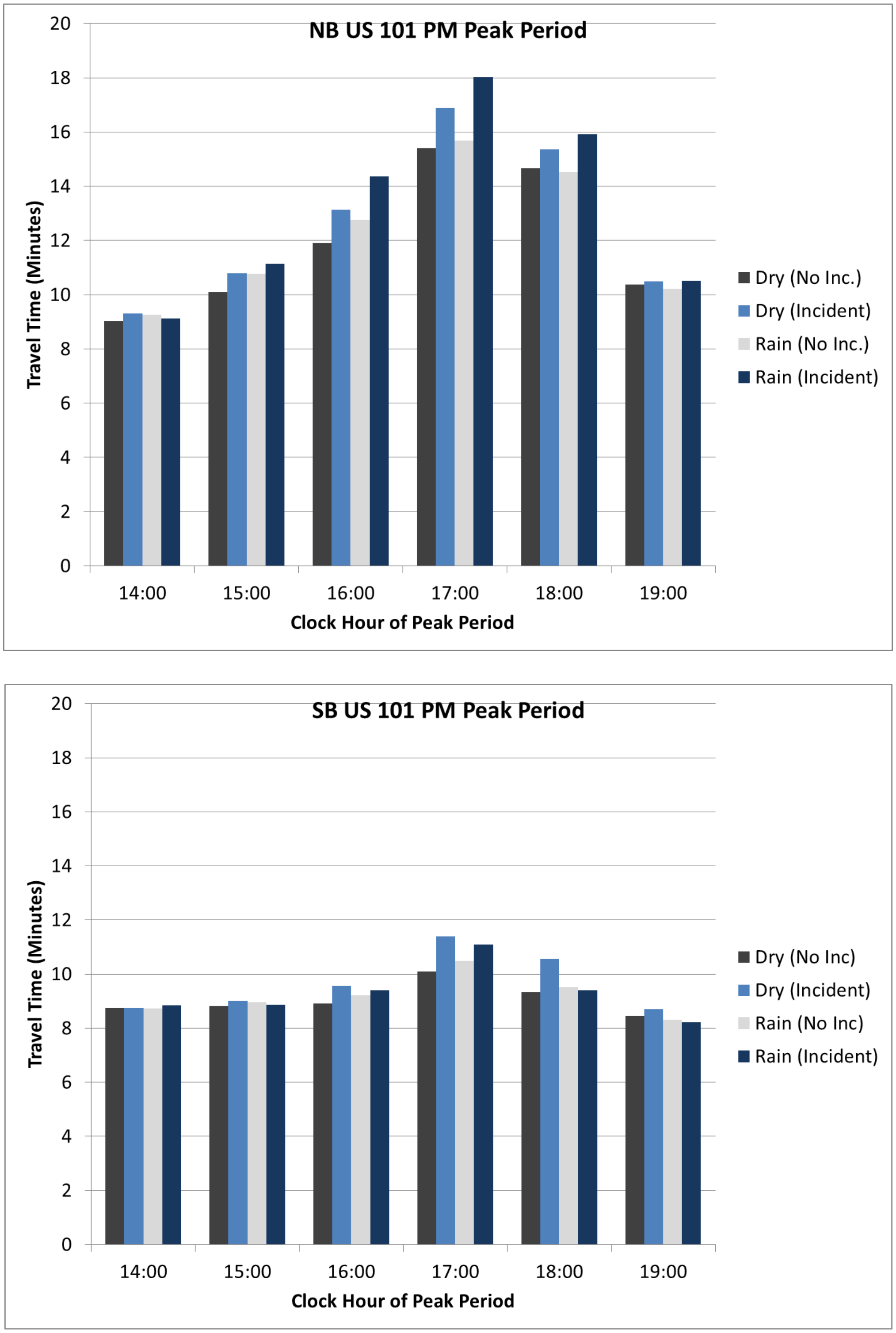
Figure 19: Graph. Weekday variation of mean travel times.





Source: Kittelson & Associates/USDOT

Figure 20: Graph. Seasonal variation in travel time.



Source: Kittelson & Associates/USDOT

Figure 21: Graph. Combined effects of weather and incidents on travel time.

Table 9: Combined frequencies of demand, weather, and incidents by duration.

Weather	Incidents	Northbound		Southbound	
		Frequency	Probability	Frequency	Probability
Dry	No Incidents	117	46.6%	140	55.8%
	Incidents 30 min	16	6.4%	7	2.8%
	Incidents 60 min	11	4.4%	5	2.0%
	Incidents Other	81	32.3%	73	29.1%
	Subtotal	*225*	*89.6%*	*225*	*89.6%*
Rain	No Incidents	11	4.4%	20	8.0%
	Incidents 30 min	3	1.2%	0	0.0%
	Incidents 60 min	2	0.8%	1	0.4%
	Incidents Other	10	4.0%	5	2.0%
	Subtotal	*26*	*10.4%*	*26*	*10.4%*
TOTAL		**251**	**100.0%**	**251**	**100.0%**

Frequencies are the number of non-holiday weekdays in 2012 when a condition occurred during the PM peak period.

Recommended Baseline Scenarios

There are 18 possible baseline scenarios combining three possible traffic demand levels, three possible severity levels of incidents and two possible weather types for the corridor. As discussed above, the data on the test bed was analyzed to:

1. Assess the relative importance of demand, weather, and incidents for predicting travel-time effects of connected vehicles, and
2. Determine the relative probabilities of different combinations of these factors into analysis scenarios.

Review of the travel-time distribution data determined that the northbound direction regularly experienced much greater recurring and non-recurring congestion during weekday PM peak periods. So data for this direction was used to select the scenarios.

Review of the VMT variability data suggested that it could not be effectively used as a proxy for demand. Consequently, it was decided to model only one overall peak-period demand level in the scenarios. Instead, the examination of effects by hour within the peak period suggested that a similar hour-by-hour examination of the microsimulation results for each scenario could be used to determine demand effects. The selected peak period is long enough to span both uncongested and congested conditions, providing a sufficiently robust demand basis for assessing the benefits of connected vehicles under varying demand conditions.

The probabilities of each of the initial 18 candidate scenarios occurring in the future (based on an assessment of 2012 frequencies) are shown in Table 10.

To preserve project resources for microsimulation analysis and evaluation, all baseline scenarios with under one-percent probability were dropped from further consideration. These scenarios are so infrequent that they are unlikely to significantly affect the results and conclusions. This resulted in the elimination of eight low probability scenarios from further consideration.

Dropping the different daily (VMT) demand variation levels from the analysis and dropping the exceptionally low probability scenarios resulted in six recommended baseline scenarios for full microsimulation analysis, as shown in Table 11.

Table 10: Initial set of operating environment scenarios for Experiment #2.

Op. Env. Scenario	Demand	Incident Type	Weather Type	Probability	
				NB	SB
1	25th% (Low)	None/short	Dry Pavement	6%	15%
2	50th% (Median)	None/short	Dry Pavement	68%	64%
3	95th% (V.High)	None/short	Dry Pavement	5%	6%
4	25th% (Low)	1 Ln – 30 min	Dry Pavement	<1%	1%
5	50th% (Median)	1 Ln – 30 min	Dry Pavement	6%	2%
6	95th% (V.High)	1 Ln – 30 min	Dry Pavement	1%	<1%
7	25th% (Low)	1 Ln – 60 min	Dry Pavement	<1%	<1%
8	50th% (Median)	1 Ln – 60 min	Dry Pavement	4%	1%
9	95th% (V.High)	1 Ln – 60 min	Dry Pavement	<1%	1%
10	25th% (Low)	None/short	Wet Pavement	1%	2%
11	50th% (Median)	None/short	Wet Pavement	7%	7%
12	95th% (V.High)	None/short	Wet Pavement	<1%	1%
13	25th% (Low)	1 Ln – 30 min	Wet Pavement	<1%	<1%
14	50th% (Median)	1 Ln – 30 min	Wet Pavement	1%	<1%
15	95th% (V.High)	1 Ln – 30 min	Wet Pavement	<1%	<1%
16	25th% (Low)	1 Ln – 60 min	Wet Pavement	<1%	<1%
17	50th% (Median)	1 Ln – 60 min	Wet Pavement	1%	<1%
18	95th% (V.High)	1 Ln – 60 min	Wet Pavement	<1%	<1%

Notes: 1 Ln – 30 min = one lane closed for 30 minutes.

Table 11: Recommended set of operating environment scenarios for Experiment #2.

Op. Env. Scenario	Demand	Incident Type	Weather Type	Probability NB
1	50^{th}% (Median)	None	Dry Pavement	79%
2	50^{th}% (Median)	1 Ln – 30 min	Dry Pavement	7%
3	50^{th}% (Median)	1 Ln – 60 min	Dry Pavement	4%
4	50^{th}% (Median)	None	Wet Pavement	8%
5	50^{th}% (Median)	1 Ln – 30 min	Wet Pavement	1%
6	50^{th}% (Median)	1 Ln – 60 min	Wet Pavement	1%
			Total	**100%**

Notes:

- *Incidents:*
    - *For the purposes of computing probabilities, "None" implies either no incidents, minor incidents not blocking a lane, or lane blocking incidents of 15 minutes or less. All will be represented in the microsimulation model by a single no incident model scenario.*
    - *1 Ln – 30 min = one lane closed for 30 minutes.*
    - *1 Ln – 60 min = one lane closed for 60 minutes.*
- *Variations in demand will be evaluated by examining variations in hourly performance within the peak*
- *Wet pavement will be evaluated as a light falling rain condition (0.1 inch per hour)*

ADAPTATION OF TEST BED FOR BASELINE SCENARIOS

The adaptations of the test bed to model the incidents and rainy weather scenarios are described in Appendix A.

COMPUTATION OF PERFORMANCE MEASURES

The methodologies used to compute the performance measures from the microsimulation model output for the test bed are described in Appendix A, Computation of Performance Measures (pg. 117).

BASELINE RESULTS

The microsimulation model results for the baseline (no connected vehicle) scenarios 1-6 are shown in Table 13 in the next chapter.

Speed Differential, Lane Change, and Stops Results

Four performance measures were used to measure the impacts of the scenarios on the speed differences between vehicles and lane changing:

- The distribution of speed drops between tenth-mile sublinks
  - The mean, 95th-percentile, maximum, and standard deviation are reported.
- The distribution of speed drops between 5-minute time periods within the sublinks.
  - The mean, 95th-percentile, maximum, and standard deviation are reported.
- The total number of lane changes per vehicle.
- Number of stops per vehicle.

Figure 22 shows how the inter-sublink speed drops vary by hour for each scenario. The figure shows the dry weather scenarios (1-3) starting with 95th-percentile speed differences around 10 mph, increasing to just under 40 mph during the middle hours of the peak. The rainy day scenarios (4-6) start higher (at around 20 mph difference), increasing to slightly over 40 mph during the middle hours of the peak.

Figure 23 shows how the inter-vehicular speed drops within the sublinks vary by hour and by baseline scenario. This figure shows that the 95th percentile highest speed drops fall in the range of 6 to 14 miles per hour at the start of the peak period, reach values of roughly 35 mph (for the rainy day scenarios) during the middle hours of the peak period, and with some random variation, drop slightly to 30 mph for most of the scenarios.

Figure 24 shows that the number of lane changes per vehicle starting out in the 0.35 to 0.40 range for the dry scenarios, peaking at around 0.45 before dropping to below 0.25 as congestion decreases towards the end of the peak period. For the rainy day scenarios, the lane changes per vehicle start at just under 0.45, dropping gradually to 0.40 before dropping below 0.35 at the end of the peak period. Severe congestion on the rainy days appears to be slightly dampening lane changing at 5:30 PM (17:30).

Figure 25 shows the number of stops per vehicle for all scenarios starting at near zero. The stops per vehicle increase slightly for scenarios 1 and 2 before dropping back to zero. The stops per vehicle for Scenario 3, the long incident scenario, increases, then drops slightly at 6:30 before greatly increasing at 7:30. This is probably due to demand that could not be served in this scenario. The rainy day scenarios show sharper increases in stops per vehicle.

Performance Results

A sixth hour (with zero demand) was added at the end of the 5-hour simulation period to enable traffic to clear out at the end of the scenarios. Table 12 shows the ratio of the input demand to the number of vehicles able to exit the system for each scenario. Generally, the dry scenarios (1-3) are able to serve all the demand. The rainy scenarios (4-6) are able to serve 97% to 98% of the coded demand, even when an extra zero-demand hour is added at the end of the simulation to allow all stored vehicles to exit.

Table 12: Comparison of departing vehicles to input demand.

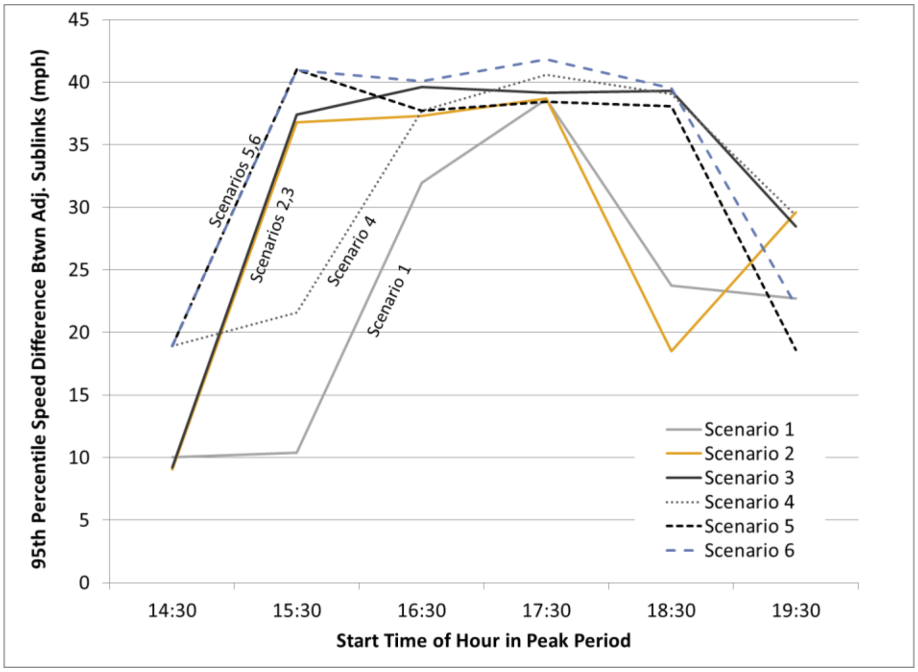
Scenario:	1	2	3	4	5	6
Repetition	Recurring	Short Incident	Long Incident	Rain	Rain+ Short Inc	Rain+ Long Inc
1	100.3%	100.4%	100.2%	97.8%	97.1%	96.3%
2	100.3%	100.4%	100.3%	98.3%	97.9%	97.1%
3	100.4%	100.4%	100.4%	97.3%	97.2%	97.1%
4	100.3%	100.4%	100.2%	98.0%	98.5%	97.8%
5	100.4%	100.4%	100.1%	96.7%	97.0%	96.0%
6	100.3%	100.4%	100.2%	97.5%	97.1%	95.5%
7	100.3%	100.4%	100.2%	98.4%	97.7%	97.1%
8	100.3%	100.4%	100.2%	98.6%	98.1%	97.4%
9	100.3%	100.3%	100.1%	98.4%	97.3%	97.3%
10	100.4%	100.3%	100.2%	98.8%	98.0%	97.5%
Average	**100.3%**	**100.4%**	**100.2%**	**98.0%**	**97.6%**	**96.9%**

Demands and departing vehicles accumulated over the peak period.

Figure 26 shows the served and unserved vehicle miles traveled (VMT) for each baseline scenario for the 6-hour simulation period. The extra hour enabled 98% of the demand to clear for the dry weather scenarios (1-3). For the rainy weather scenarios 89% to 94% of the demand was able to clear with the extra hour. It was not cost-effective to redo the simulations a third time with a 7th hour, so the final performance results for each scenario were adjusted by adding the VISSIM-reported latent delay (otherwise unrecorded delay to vehicles prevented from entering the network by queues) and the time necessary to clear the remaining unserved VMT from the network at an estimated speed of 60 mph to the VISSIM-reported vehicle-hours traveled (VHT) for each scenario.

Figure 27 shows the resulting VHT estimates by scenario and the computed average speed for the northbound freeway averaged over the entire peak period. Rainy weather has a significant effect on peak period congestion reducing average speed from the 40 to 45 mph range for dry weather, non-incident conditions to the 20 to 25 mph range for rainy weather conditions.

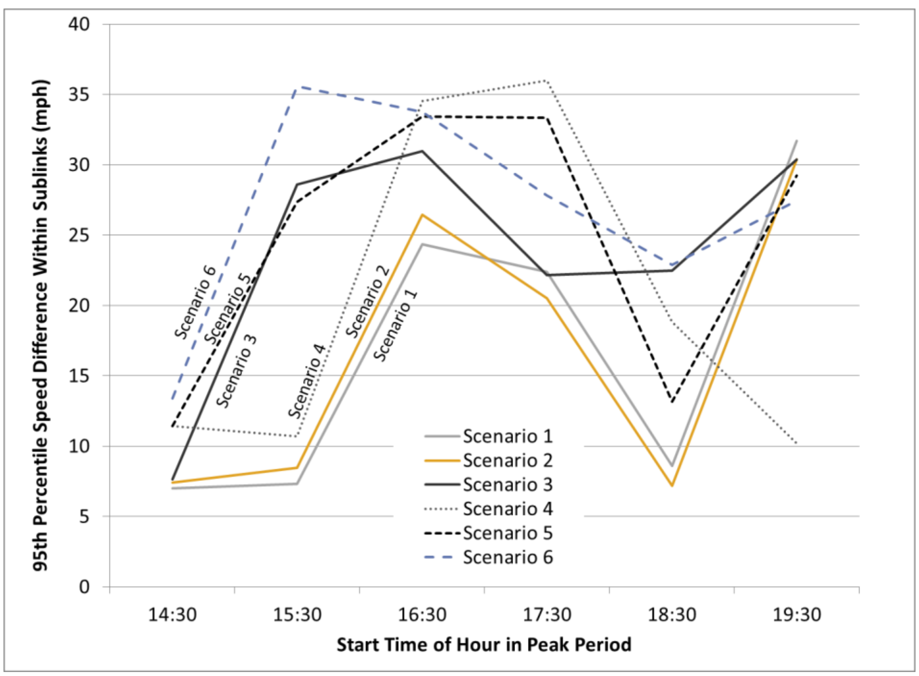
Total vehicle-hours traveled during the PM peak period were increased by 25% to 50% by rainy weather.



Scenario	Incident	Weather
1	None	Dry
2	30 minute	Dry
3	60 minute	Dry
4	None	Rain
5	30 minute	Rain
6	60 minute	Rain

Source: Kittelson & Associates/USDOT

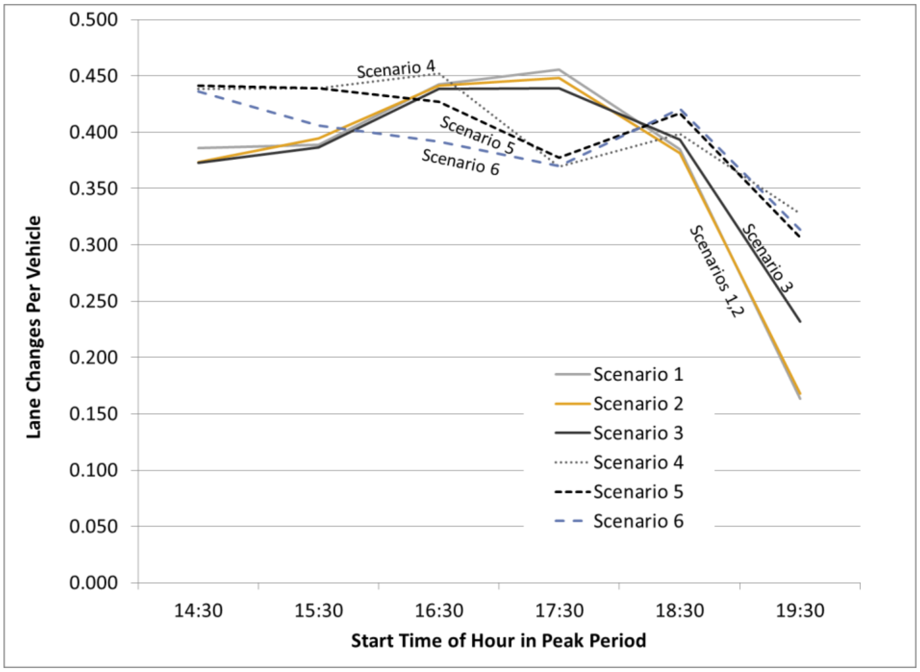
Figure 22: Graph. Comparison of inter-sublink speed drops – baseline scenarios.



Scenario	Incident	Weather
1	None	Dry
2	30 minute	Dry
3	60 minute	Dry
4	None	Rain
5	30 minute	Rain
6	60 minute	Rain

Source: Kittelson & Associates/USDOT

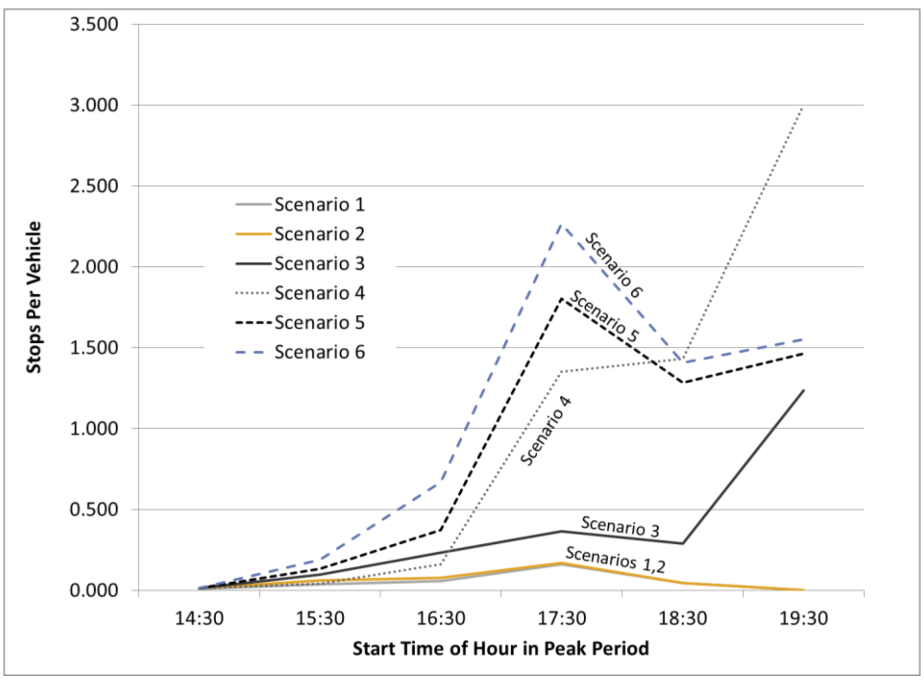
Figure 23: Graph. Comparison of inter-time period speed drops within sublinks–baseline scenarios.



Scenario	Incident	Weather
1	None	Dry
2	30 minute	Dry
3	60 minute	Dry
4	None	Rain
5	30 minute	Rain
6	60 minute	Rain

Source: Kittelson & Associates/USDOT

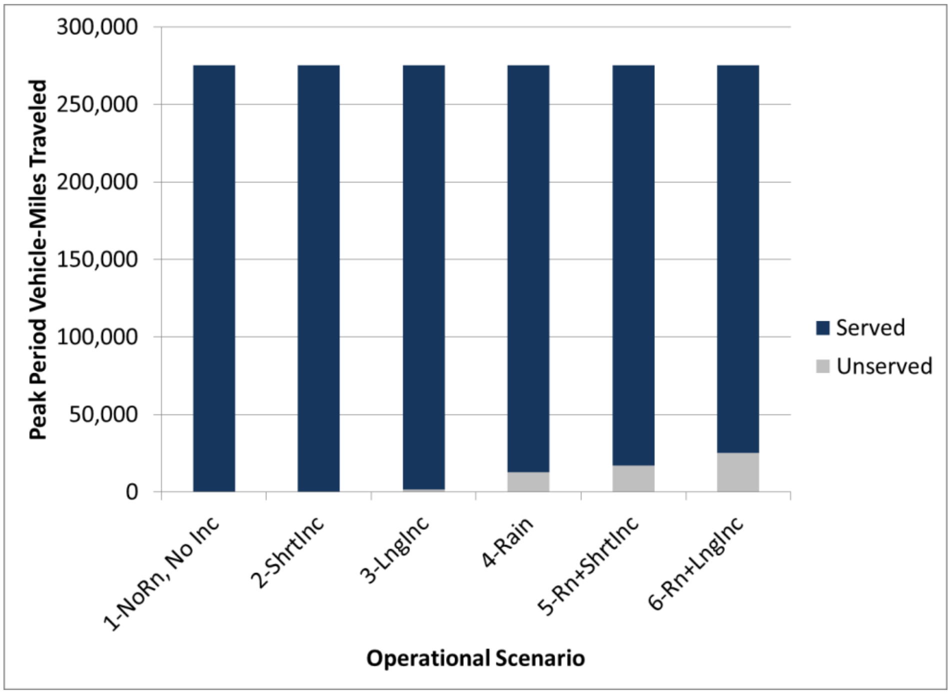
Figure 24: Graph. Comparison of lane changing for baseline scenarios.



Scenario	Incident	Weather
1	None	Dry
2	30 minute	Dry
3	60 minute	Dry
4	None	Rain
5	30 minute	Rain
6	60 minute	Rain

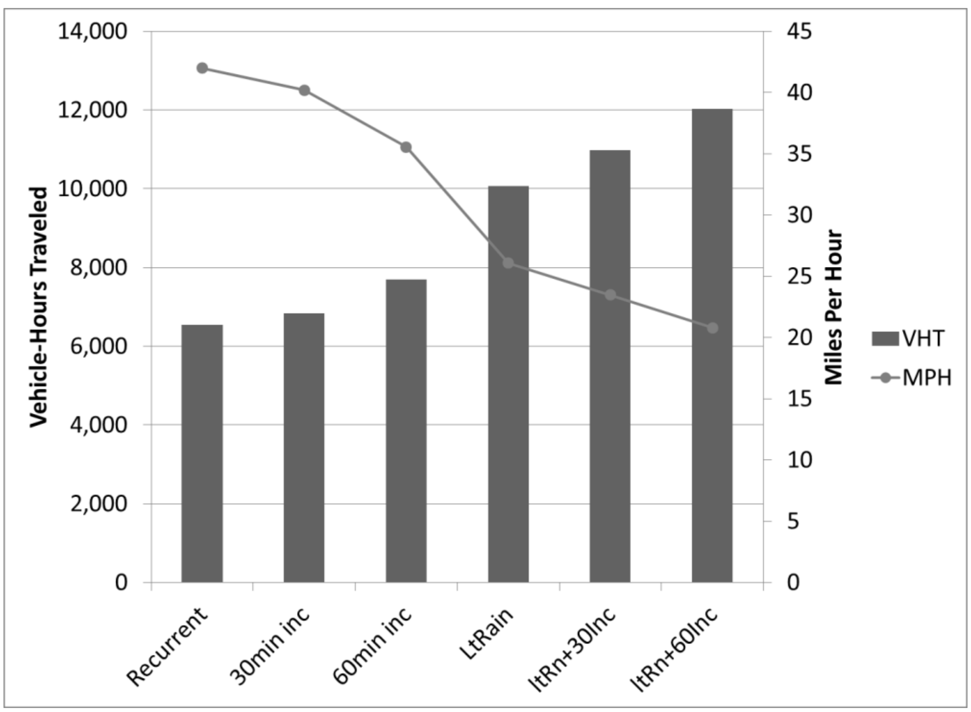
Source: Kittelson & Associates/USDOT

Figure 25: Graph. Comparison of stops for baseline scenarios.



Source: Kittelson & Associates/USDOT

Figure 26: Graph. Served and unserved VMT baseline scenarios.



Source: Kittelson & Associates/USDOT

Figure 27: Graph. Vehicle hours traveled and speed by baseline scenario.

CHAPTER 6. PROTOTYPE TESTING – SIMULATION

This chapter describes the process and results of the simulation model testing of the Prototype.

IMPLEMENTATION AND VALIDATION OF PROTOTYPE IN TEST BED

Implementation of the SPD-HARM/Q-WARN prototype required several steps:

- Add new connected vehicle types to the VISSIM model that will transmit and receive speed and location information to/from the SPD-HARM/Q-WARN Prototype created by TTI.
- Create tenth-mile checkpoints (with artificial loop detectors) to represent the connected vehicle reporting and guidance segmentation in SPD-HARM/Q-WARN.
- Write a software interface to transmit SPD-HARM/Q-WARN guidance to the connected vehicles in VISSIM (The Prototype already had the capability to read VISSIM output files to obtain connected vehicle positions and speeds.).
- Write custom software to process the VISSIM batch run output files and compute the custom performance measures required for the evaluation.

Additional details on these steps are provided in Appendix A, Simulation Test Bed Selection (pg.98).

TESTS OF DIFFERENT RESPONSE RATES

The microsimulation model by default assumes that all drivers will comply with instructions. Consequently different response rates were tested in the simulation model with the implicit assumption that the connected vehicle combined response rate used in the simulation model runs is the market penetration rate depreciated for communication loss, and driver compliance effects. Thus a 50% combined response rate can only be achieved with a higher than 50% market penetration rate.

Three different response rates were tested in the simulation model, 50%, 25%, and 10% of the total passenger-vehicle fleet.

The Analysis of Factors Affecting Response section, addresses how different combinations of driver compliance rates, communication loss or latency rates, and market penetration rate can combine to yield the connected vehicle response rates input into the simulation model runs.

MODEL RESULTS

This section presents the simulation model results.

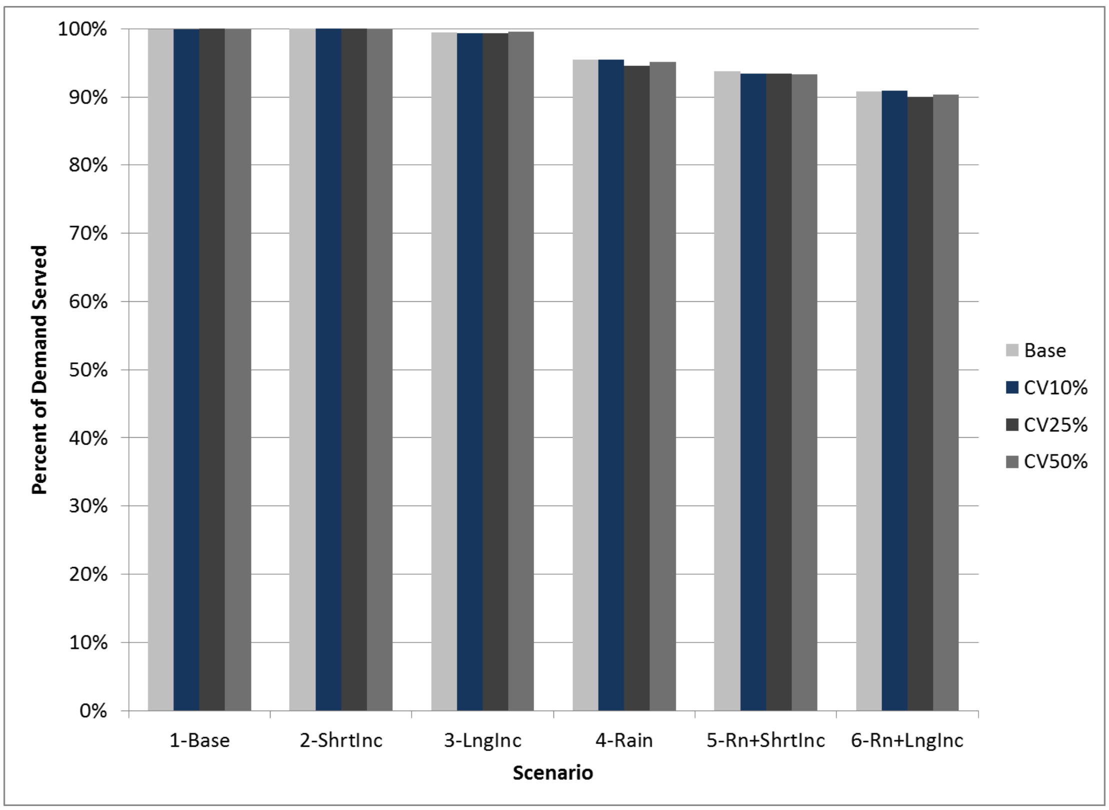
Served Demand versus Coded Demand

In Figure 28, the freeway was generally able to serve nearly 100% of the demand coded for the model. The vehicle-miles traveled (VMT) throughput generally fell within 1% of the coded demand for all of the non-rain scenarios, regardless of the percentage of connected vehicles with SPD-HARM activated.

The lower capacities associated with rain caused significant peak period backups in the 5-hour simulation period that still could not be completely cleared out in the extra cool-down hour (with zero new demand coded for that hour). The percent of demand that could be served ranged from 90% under the most-severe scenario combining rain and a one-hour long incident (Long Incident), to 96% when there was rain but no incidents.

There is some slight variation between scenarios with and without connected vehicles but the differences are minor and within the expected random variation between model-runs.

This result gives us confidence that we can compare performance measures between the scenarios with connected vehicles and those without connected vehicles.



Source: Kittelson & Associates/USDOT

Figure 28: Graph. Comparison of VMT throughput to VMT demand.

Demand is measured in terms of vehicle-miles traveled. The percent demand served is the ratio of the throughput to the coded demand for the simulated peak period.

Speed Differential, Lane Change, and Stops Results

Four performance measures were used to measure the impacts of the scenarios on the speed drops between adjacent sublinks, between adjacent time periods, stops, and lane changing:

- The distribution of speed drops between tenth-mile sublinks.
  - The mean, 95th-percentile, maximum, and standard deviation are reported.
- The distribution of speed drops between adjacent time periods within the sublinks.
  - The mean, 95th-percentile, maximum, and standard deviation are reported.
- The total number of lane changes per vehicle.
- Number of stops per vehicle.

Performance Results

The performance results for each of the 6 scenarios and the four different levels of connected vehicles that were tested are summarized in Table 13.

This table also includes the probability of each scenario occurring over the course of a year. The non-incident, fair weather scenario (#1) is highly probable during the non-holiday, weekday PM peak period. The incident and adverse weather scenarios (#2-#6) are less probable.

The figures and text below highlight some of the results shown in Table 13.

Impacts of Prototype on Between Segment Shockwaves

The SPD-HARM/Q-WARN Prototype definitely reduces the variation of speeds between freeway segments (Figure 29). There is a big payoff (in terms of reduced speed drops) with the first 10% connected vehicles. The reduction in the magnitude of the speed drops continues to improve but at a slower rate, for 25% and 50% connected vehicles. Between 25% and 50% connected vehicles the improvements appear to be occasionally bottoming out, depending on the specific circumstances.

Impacts of Prototype on Within Segment Shockwaves

The Prototype also reduces speed drops between adjacent 5-minute time-periods within a freeway sublink (Figure 30). The effect is most pronounced with the first 10% connected vehicles, decreasing in effectiveness with 25% and 50% connected vehicles. The effects occasionally bottom out at 50% (only for the Base scenario in our particular tests). Under exceptionally severe conditions (rain plus a long incident, scenario 6), the payoff of going from 10% to 25% connected vehicles is as great as going from 0% to 10%.

Table 13: Results of connected vehicle combined response tests.

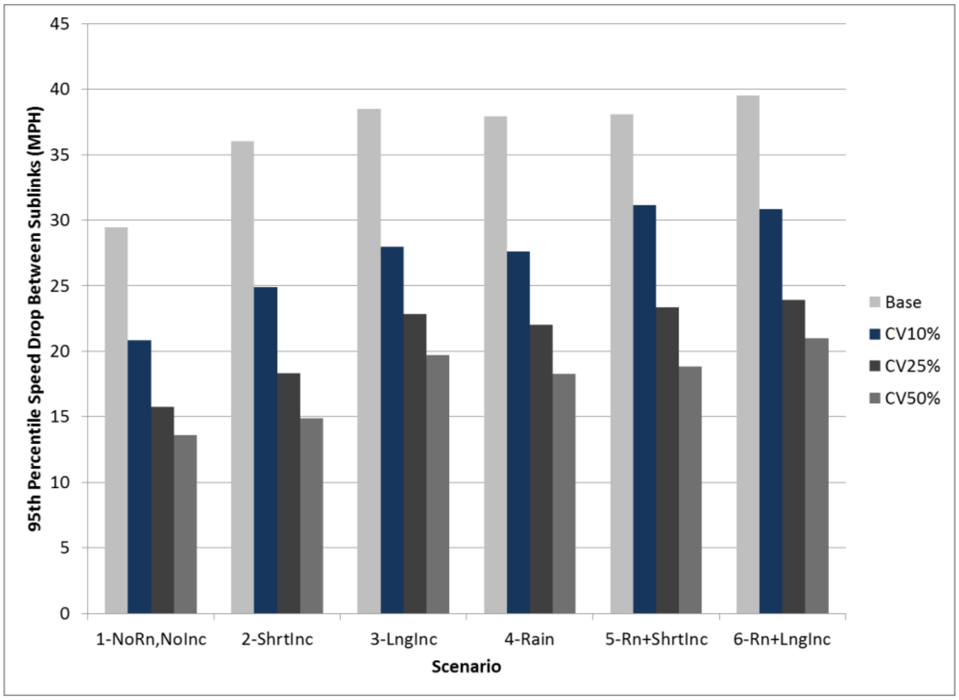
CV Level	Scenario	Prob.	Interlink Shock (mph)	Intralink Shock (mph)	VMT Served (1,000s)	VHT (veh-hr)	Speed (mph)	VSQ (secs/veh)	95th %ile TTI	Lane Change/ 1000 veh	Stops/ 1000 vehs
0% CV	1. Dry, No Incident	79%	29 (2.9)	18 (2.1)	275 (0.2)	6,453 (32.8)	43 (0.2)	52 (2.5)	1.66 (0.03)	449 (1.6)	71 (4.6)
	2. Short Incident	7%	36 (3.4)	20 (2.2)	275 (0.2)	6,755 (65.7)	41 (0.4)	55 (3.4)	1.63 (0.04)	446 (2.3)	83 (7.1)
	3. Long Incident	4%	39 (4.0)	26 (2.6)	274 (0.4)	7,587 (150.2)	36 (0.8)	117 (15.2)	1.99 (0.21)	455 (2.8)	255 (47.1)
	4. Rain, No Incident	8%	38 (3.5)	27 (2.7)	262 (2.2)	9,765 (154.4)	27 (0.6)	290 (22.2)	3.85 (0.18)	489 (2.7)	850 (79.1)
	5. Rain + Shrt Inc.	1%	38 (3.8)	28 (2.8)	258 (1.8)	10,614 (84.3)	24 (0.4)	304 (15.6)	4.11 (0.16)	493 (2.9)	914 (63.6)
	6. Rain + Lng Inc.	1%	40 (4.0)	30 (3.0)	250 (2.3)	11,509 (242.7)	22 (0.6)	363 (26.9)	4.56 (0.25)	486 (3.9)	1,167 (121.3)
10% CV	1. Dry, No Incident	79%	21 (2.1)	16 (1.9)	275 (0.2)	6,050 (46.6)	45 (0.3)	46 (3.3)	1.70 (0.03)	428 (2.5)	60 (6.5)
	2. Short Incident	7%	25 (2.6)	18 (1.9)	275 (0.2)	6,938 (71.9)	40 (0.4)	62 (3.9)	1.81 (0.04)	430 (3.0)	99 (8.6)
	3. Long Incident	4%	28 (2.9)	19 (2.1)	273 (0.4)	7,994 (128.1)	34 (0.6)	133 (15.0)	2.22 (0.21)	429 (2.1)	313 (52.7)
	4. Rain, No Incident	8%	28 (2.6)	21 (2.0)	263 (1.3)	10,030 (84.5)	26 (0.3)	271 (15.1)	3.91 (0.14)	468 (3.7)	795 (58.8)
	5. Rain + Shrt Inc.	1%	31 (3.1)	22 (2.1)	257 (2.0)	10,838 (217.5)	24 (0.7)	314 (19.2)	4.18 (0.13)	466 (2.4)	983 (72.7)
	6. Rain + Lng Inc.	1%	31 (3.1)	24 (2.3)	250 (1.6)	11,728 (332.5)	21 (0.9)	356 (23.3)	4.58 (0.21)	461 (2.9)	1,168 (105.7)
25% CV	1. Dry, No Incident	79%	16 (1.8)	13 (1.8)	275 (0.2)	6,956 (33.5)	40 (0.2)	52 (2.5)	1.78 (0.04)	456 (2.2)	73 (5.5)
	2. Short Incident	7%	18 (2.0)	15 (1.9)	275 (0.2)	7,171 (93.1)	38 (0.5)	61 (4.2)	1.90 (0.04)	463 (2.1)	96 (9.2)
	3. Long Incident	4%	23 (2.4)	18 (2.0)	273 (0.4)	8,251 (126.7)	33 (0.5)	134 (15.4)	2.27 (0.21)	470 (2.2)	312 (54.1)
	4. Rain, No Incident	8%	22 (2.3)	19 (1.9)	260 (1.0)	10,450 (114.5)	25 (0.4)	291 (16.2)	4.26 (0.12)	498 (2.7)	879 (58.9)
	5. Rain + Shrt Inc.	1%	23 (2.5)	19 (1.8)	257 (2.1)	11,223 (179.3)	23 (0.5)	309 (18.7)	4.08 (0.13)	491 (2.3)	960 (68.9)

CV Level	Scenario	Prob.	Interlink Shock (mph)	Intralink Shock (mph)	VMT Served (1,000s)	VHT (veh-hr)	Speed (mph)	VSQ (secs/veh)	95th %ile TTI	Lane Change/ 1000 veh	Stops/ 1000 vehs
	6. Rain + Lng Inc.	1%	24 (2.5)	17 (1.9)	248 (1.5)	12,285 (121.9)	20 (0.3)	356 (18.6)	4.59 (0.14)	482 (2.8)	1,194 (80.9)
50% CV	1. Dry, No Incident	79%	14 (1.7)	13 (1.7)	275 (0.2)	7,171 (101.2)	38 (0.5)	53 (4.1)	1.95 (0.06)	488 (1.8)	74 (9.5)
	2. Short Incident	7%	15 (1.9)	14 (1.8)	275 (0.2)	7,298 (94.9)	38 (0.5)	63 (5.8)	2.00 (0.06)	485 (2.1)	102 (14.4)
	3. Long Incident	4%	20 (2.1)	14 (1.7)	274 (0.5)	8,415 (212.7)	33 (1.0)	123 (17.0)	2.30 (0.22)	492 (2.5)	287 (57.8)
	4. Rain, No Incident	8%	18 (2.1)	17 (1.7)	262 (1.6)	10,654 (102.1)	25 (0.4)	273 (11.8)	4.04 (0.07)	513 (2.0)	826 (37.2)
	5. Rain + Shrt Inc.	1%	19 (2.1)	18 (1.8)	257 (1.9)	11,179 (135.4)	23 (0.4)	297 (13.8)	4.11 (0.09)	505 (2.1)	946 (59.9)
	6. Rain + Lng Inc.	1%	21 (2.2)	16 (1.6)	249 (2.1)	12,115 (219.1)	21 (0.5)	350 (18.9)	4.57 (0.15)	502 (2.5)	1,165 (82.1)

Numbers in parentheses show standard deviation of the mean of the simulation runs.

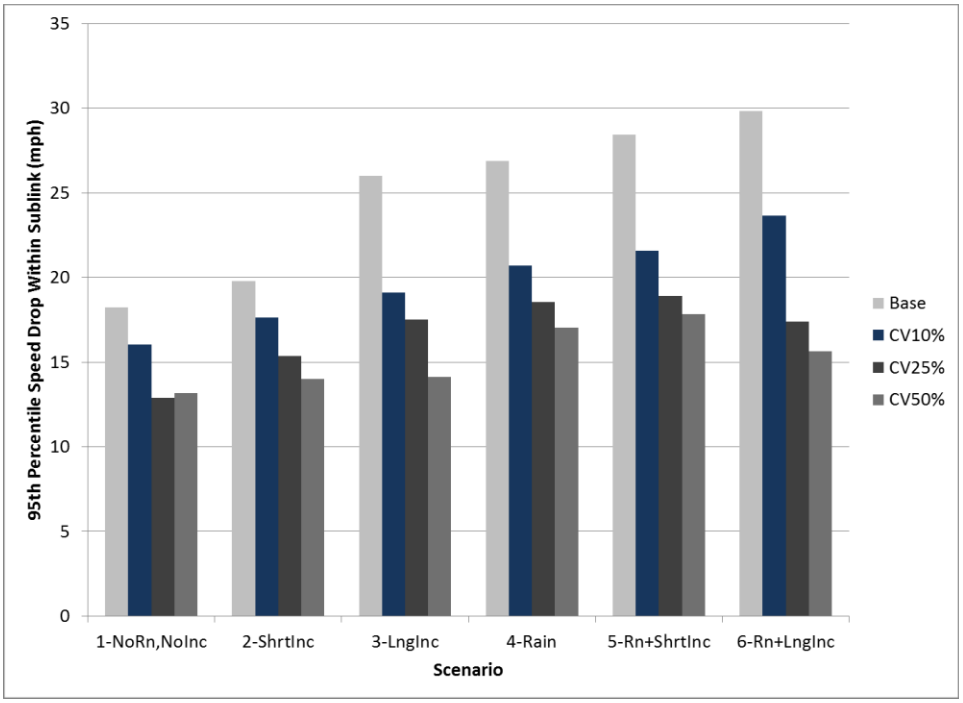
Notes to Table 13:

1. *All values in table are accumulated or averaged over the 6-hour simulation period.*
2. *CV Level is % of the entire vehicle fleet that: a) has CV capabilities, b) successfully receives the message, AND c) complies with the SPD-HARM guidance.*
3. *Prob. is the probability of the scenario occurring in a year of non-holiday weekday PM peak periods.*
4. *Interlink Shock is the maximum drop in average speeds between adjacent sublinks, counted only when the downstream average is lower than the upstream average (see section 0 for details). This table reports the 95th percentile highest values.*
5. *Intralink Shock is the maximum observed drop in average sublink speeds between adjacent 5-minute time periods for the same sublink. This table reports the 95th percentile highest sublink values. (see section 0 for details).*
6. *VMT = vehicle-miles traveled. The average VMT across all 10 runs for a scenario.*
7. *VHT = vehicle-hours traveled.*
8. *VSQ = vehicle-seconds in queue per vehicle.*
9. *95th %TTI = the 95th percentile highest travel time index for the facility.*
10. *Speed is computed as the average vehicle miles traveled (across all runs) divided by the average vehicle-hours traveled (across all runs).*
11. *Stops per thousand vehicles is the average stops per vehicle across the 10 simulation repetitions*
    Lane Change per vehicle is the average lane changes per vehicle across the 10 simulation repetitions. Additional details are provided in Appendix A, Computation of Performance Measures (pg. 117).
12. *The standard deviations of the means are computed across the 10 simulation repetitions performed for each scenario.*
    The standard deviations are shown in parentheses following each mean.



Source: Kittelson & Associates/USDOT

Figure 29: Graph. Impacts on speed drops between adjacent sublinks.

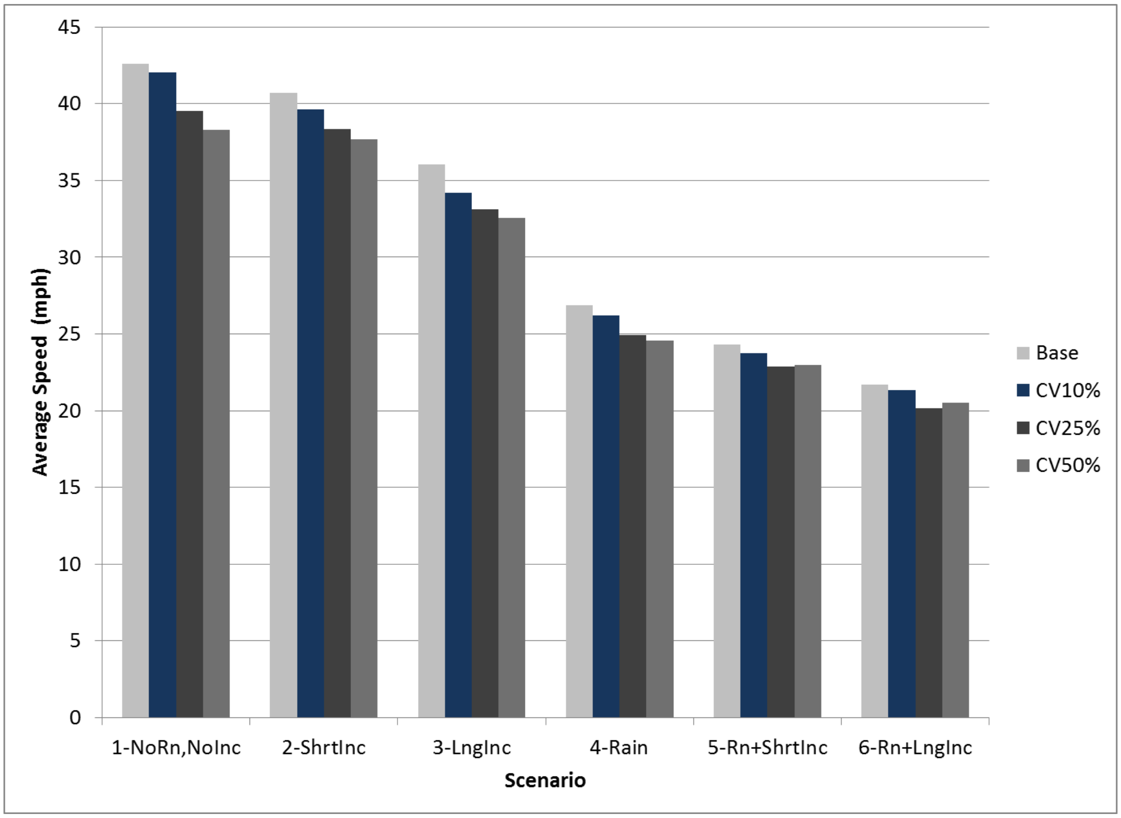


Source: Kittelson & Associates/USDOT

Figure 30: Graph. Impacts on speed drops between adjacent time periods of same sublink.

Impacts of Prototype on Average Speed

The price for the safety effects of SPD-HARM/Q-WARN is slightly lower average speeds on the freeway under all scenarios (Figure 31).[14] The effect is generally linear between 0%, 10%, 25%, and 50% connected vehicles. For the more severe scenarios (see Scenarios 5 and 6 in Figure 31), the speeds are already so low that 25% and 50% connected vehicles make little difference.



Source: Kittelson & Associates/USDOT

Figure 31: Graph. Impact on average freeway speed.

Impacts of Prototype on Stops

The stops per vehicle (another indirect measure of safety) are generally unaffected by SPD-HARM (Figure 32). Note that SPD-HARM effectively shuts down at speeds below 30 mph (a user-editable default in the Prototype), not issuing any recommendations when speeds are below that threshold. The differences in the chart among the different levels of connected vehicles appear to be mostly random effects associated with the randomness built into the simulation runs.

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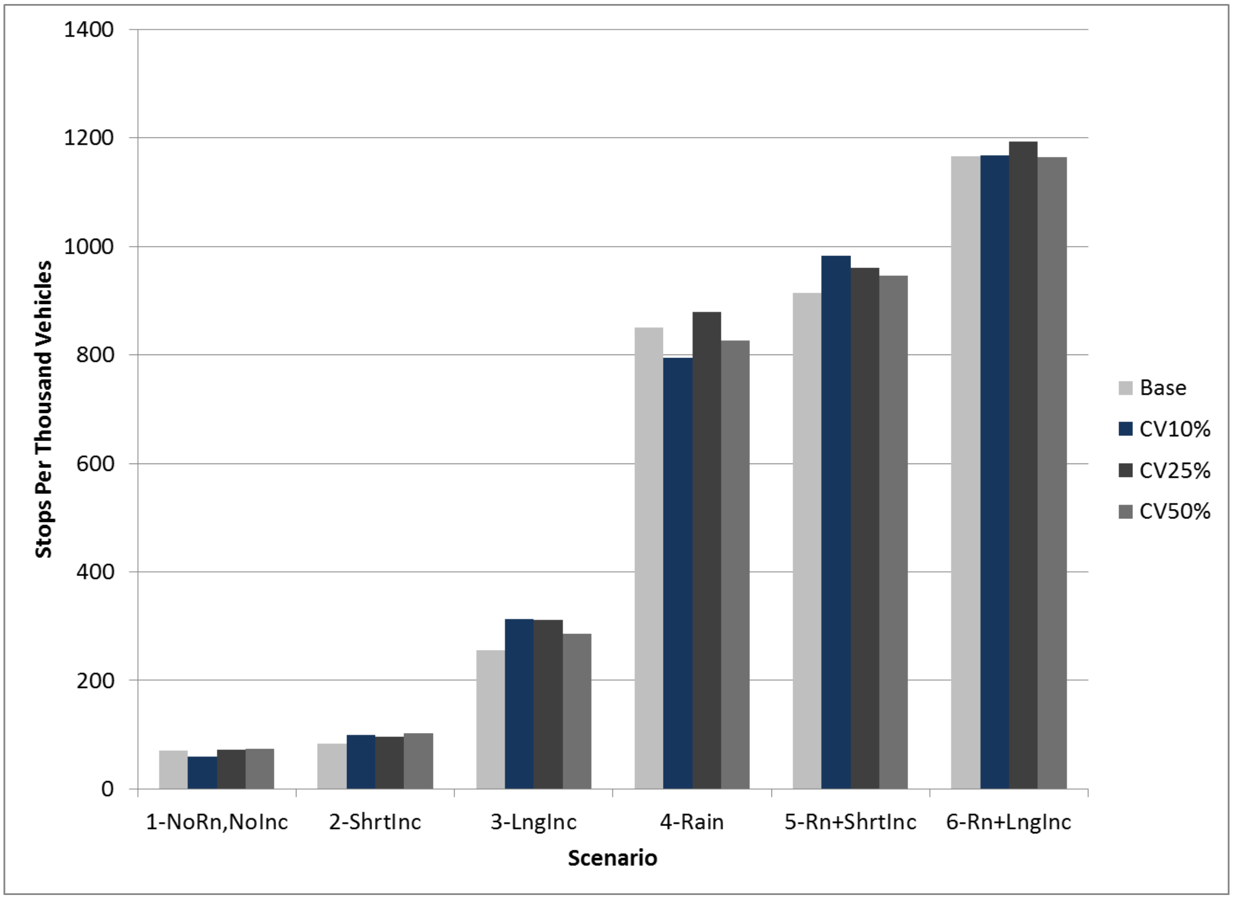
[14] *Readers may note that the average speed for the Base shown in Figure 31 differs from the field measured average speed given in the section on Travel-Time Distribution. The figure includes the results of an extra hour of simulation for the base that were not included in the data exploration step.*



Source: Kittelson & Associates/USDOT

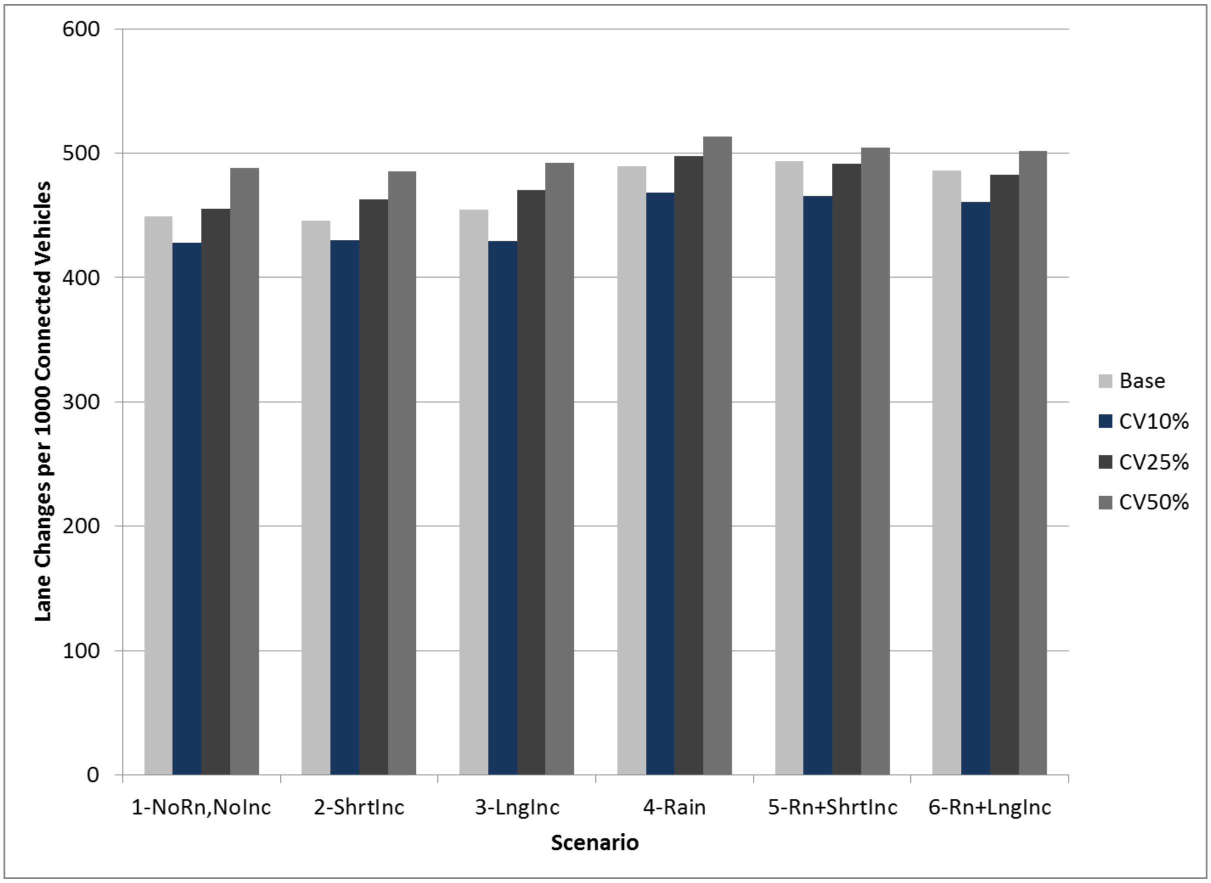
Figure 32: Graph. Impacts on stops per thousand vehicles.

Impacts of Prototype on Lane Changing

The number of lane changes per thousand vehicles, another indirect indicator of safety effects, does increase with SPD-HARM implemented with connected vehicles (Figure 33). The effect increases with the percent connected vehicles. This may be due to the fact that only a portion of the vehicle fleet (the connected vehicles) is aware of the recommended speed, which causes the unconnected drivers behind the connected vehicles to change lanes. Even 50% connected vehicles does not appear to be high enough to dampen this effect.

The effect of SPD-HARM on reducing the speed differential between vehicles may facilitate more, safer lane changes. Therefore, the increase in lane changing may not be a 100% adverse indicator of safety when SPD-HARM is implemented.

For the two most-severe scenarios (#5 and #6) randomness appears to become more important, with 25% connected vehicles better than 0% but 50% connected vehicles worse than 0%.



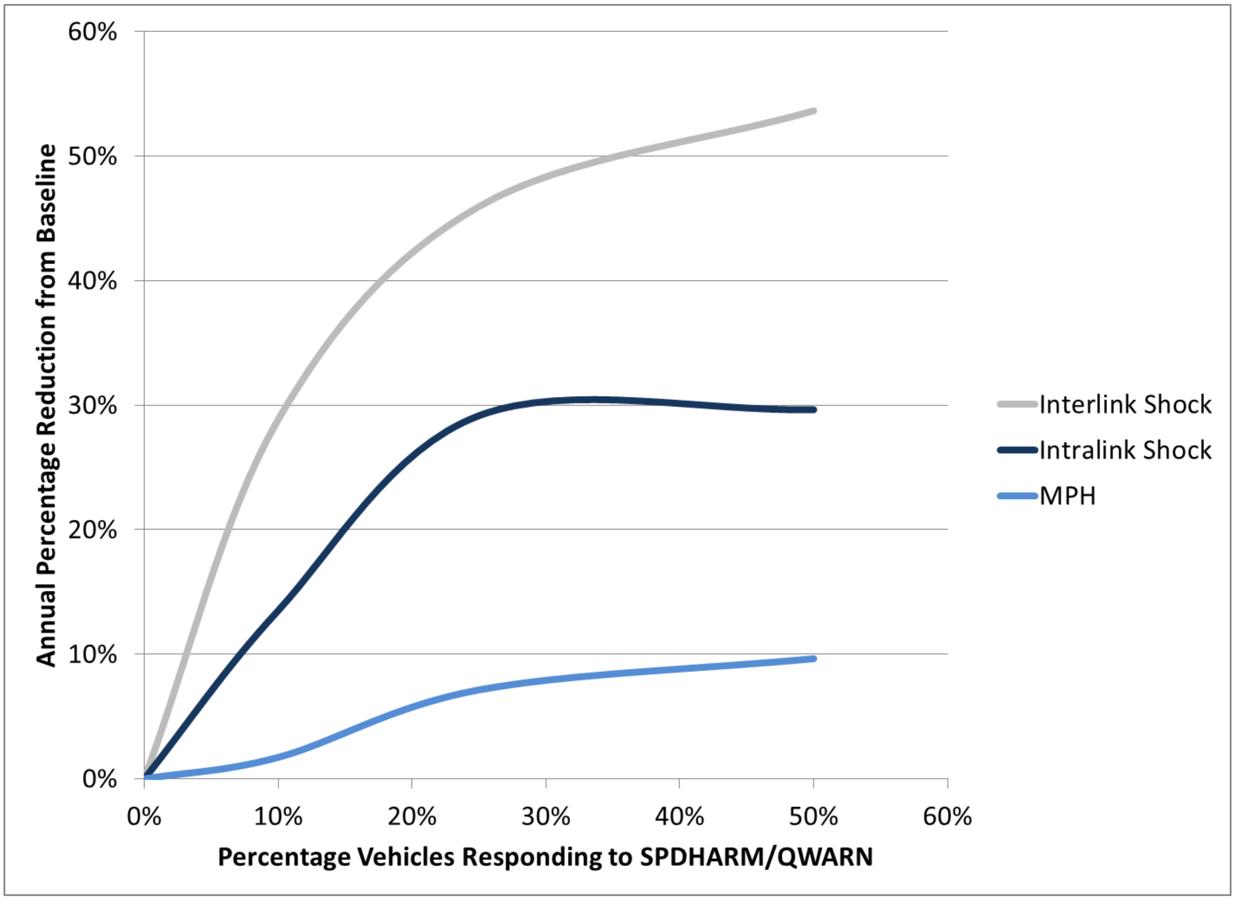
Source: Kittelson & Associates/USDOT

Figure 33: Graph. Impacts on lane changes per thousand connected vehicles.

Note that for the Base there are no connected vehicles, so reported result in the above figure is per thousand unconnected vehicles. The Base results may, therefore, not be directly comparable to the other results in the chart for connected vehicles.

Annualized Impacts of Prototype on Shockwaves and Average Speed

Taking the above scenario-specific results and weighting them by their probability of occurrence over the course of a year’s worth of non-holiday, weekday PM peak periods, results in the annual benefits chart shown in Figure 34. This chart shows how the percentage of connected vehicles affects the predicted annual reduction in speed differentials between freeway segments (interlink shockwaves) and within freeway segments (intralink shockwaves). The chart compares the percentage reduction in speed drops to the predicted reduction in average travel speed on the freeway needed to achieve those benefits. In this chart, increases in the reductive effects of SPD-HARM on shockwaves is desirable, while increase in the reductive effects of SPD-HARM on speeds in general (MPH in the chart) are undesirable.



Source: Kittelson & Associates/USDOT

Figure 34: Graph. Annualized impacts on shockwaves and average speed.

The chart shows that the biggest payoff (interlink and intralink shockwave speed reductions are steepest) occurs with the first few connected vehicles until the level is reached where about 20% of the vehicles in the traffic stream are responding to the SPD-HARM/Q-WARN guidance.

Meanwhile, the penalty in terms of reductions in overall speed (the black line labeled MPH) is comparatively modest (under 8%) in the range of 20% vehicles responding to the SPD-HARM/Q-WARN guidance.

The gains in reducing between-link (interlink) shockwave speed drops continue to climb with over 20% of the vehicles responding to SPD-HARM/Q-WARN, but not as quickly. The reductions in intralink speed drops seem to level off above 20% connected vehicles.

Effects of Demand on Results

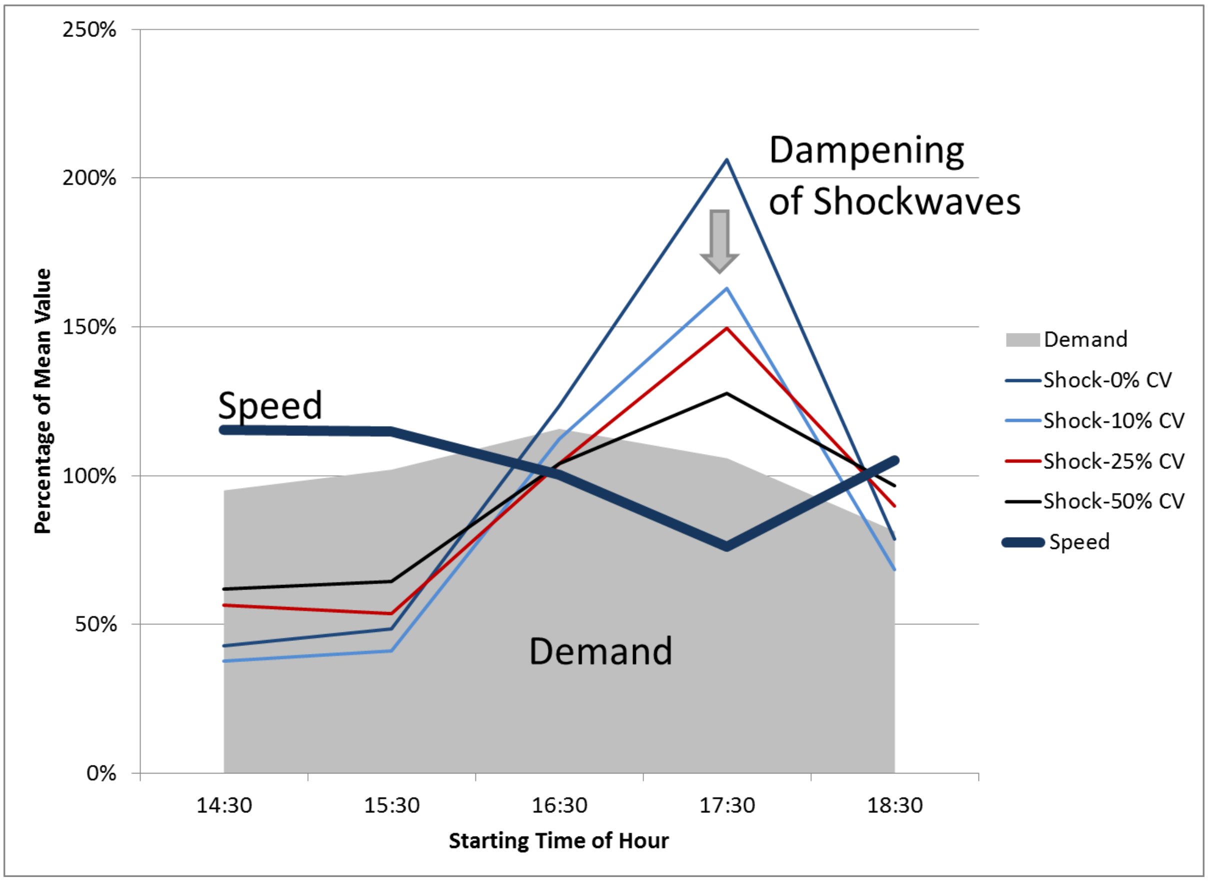
Figure 35 shows the effects of changes in hourly demand for the US 101 freeway on the shockwave and speed dampening effects of the Prototype.

Generally, the magnitude of the benefits of SPD-HARM for dampening shockwaves is greatest when the average speed of traffic on the freeway is lowest (in other words, when congestion is greatest). This is illustrated by the large percentage drop in the mean speed drops between vehicles (a proxy for shockwaves) with increasing levels of connected vehicles at 5:30 in the simulation analysis. Outside of this hour, the effects of connected vehicles on shockwaves are significantly diminished.

The peak effect of SPD-HARM lags behind the peaking of demand by one hour. The demand peaks at 4:30 but the peak benefits of SPD-HARM are at 5:30.

The peak effect of SPD-HARM is much more-closely tied to dips in freeway speeds. The freeway speed dips at the same time that the benefits of connected vehicles and SPD-HARM peak, 5:30.

There is an approximate one-hour lag between the peak demand (at 4:30) and the maximum dip in speed (at 5:30). Demand peaking causes dips in speed, but the effect lags the cause by about one hour in this simulation. Thus, there is a similar lag between peak demand and the peak benefits of SPD-HARM with connected vehicles.



Source: Kittelson & Associates/USDOT

Figure 35: Graph. Sensitivity of SPD-HARM performance to demand.

STATISTICAL SIGNIFICANCE TESTS

Statistical significance tests were conducted to determine the extent to which the observed differences in productivity (as measured by vehicle-miles served – VMT) and performance (as measured by vehicle-hours traveled) for the different levels of connected vehicle might have arisen by pure random chance.

The null hypothesis was adopted to the effect that the different levels of connected vehicles had no effect on mean VMT or mean VHT. A 95% confidence level was selected. A two-sided test was performed to test whether the means were significantly different from the base (no connected vehicle mean). The NIST/SEMATECH e-Handbook of Statistical Methods procedures were employed for comparing the means of two independent samples from the same population, with a pooled estimate of the standard deviation. Since the standard deviation is estimated from the data, a Student's 't' statistic is used to determine the degree of significance.

The results of the VMT tests are shown in

Table 14. None of the levels of connected vehicles tested had a statistically significant effect on the productivity of the freeway (as measured by VMT served).

The results of the VHT tests are shown in

Table 15. SPDHARM and QWARN increased VHT in all scenarios tested, but for most of these scenarios the increase was not statistically significant. The 25% and 50% connected vehicle levels did have a significant effect on VHT for Scenario #1, the recurring congestion scenario (fair weather, no incidents) and Scenario #4, the rainy weather and no incidents scenario.

Table 14: Statistical significance test for effect on productivity (VMT).

VMT Scenario	CV0% Mean	CV0% StdDev	CV10% Mean	CV10% StdDev	Pooled StdDev	Diff of means	"t" statistic	95.0% Sig Diff?
1	274.89	0.66	274.95	0.62	0.64	0.06	0.10	No
2	275.07	0.58	274.99	0.67	0.63	-0.08	0.12	No
3	273.64	1.39	273.28	1.32	1.36	-0.36	0.27	No
4	262.49	7.03	262.71	4.23	5.81	0.23	0.04	No
5	258.03	5.74	257.09	6.18	5.96	-0.94	0.16	No
6	249.89	7.30	250.08	9.82	8.65	0.18	0.02	No
VMT Scenario	CV0% Mean	CV0% StdDev	CV25% Mean	CV25% StdDev	Pooled StdDev	Diff	"t" statistic	95.0% Sig Diff?
1	274.89	0.66	274.99	0.60	0.63	0.09	0.15	No
2	275.07	0.58	274.98	0.67	0.63	-0.09	0.14	No
3	273.64	1.39	273.35	1.24	1.32	-0.29	0.22	No
4	262.49	7.03	260.22	6.25	6.66	-2.27	0.34	No
5	258.03	5.74	256.96	6.70	6.24	-1.06	0.17	No
6	249.89	7.30	247.70	4.79	6.17	-2.19	0.35	No
VMT Scenario	CV0% Mean	CV0% StdDev	CV50% Mean	CV50% StdDev	Pooled StdDev	Diff of means	"t" statistic	95.0% Sig Diff?
1	274.89	0.66	274.80	0.64	0.65	-0.09	0.14	No
2	275.07	0.58	274.96	0.73	0.66	-0.11	0.17	No
3	273.64	1.39	273.94	1.63	1.51	0.30	0.20	No
4	262.49	7.03	261.72	5.12	6.15	-0.77	0.13	No
5	258.03	5.74	256.64	5.89	5.82	-1.39	0.24	No
6	249.89	7.30	248.60	6.53	6.93	-1.29	0.19	No

Notes:

1. *The standard deviations shown in table are for the mean of 10 simulation runs.*
2. *Three tests are shown – 10% Connected Vehicles, 25% Connected Vehicles, 50% Connected Vehicles. CV = connected vehicle. VMT = vehicle-miles traveled. "t" is the Student's "t" statistic. For two sided test at 95%, the significant "t" at 18 degrees of freedom is 2.44.*
3. *Reference: NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/, Accessed May 29, 2015, Section 7.3.1. Do two processes have the same mean?*

Table 15: Statistical significance test for effect on freeway performance (VHT).

VHT Scenario	CV0% Mean	CV0% StdDev	CV10% Mean	CV10% StdDev	Pooled StdDev	Diff of means	"t" statistic	95.0% Sig Diff?
1	5,854	107	5,945	142	126	91	0.73	No
2	6,183	199	6,359	201	200	176	0.88	No
3	6,925	437	7,317	356	398	393	0.99	No
4	7,276	158	7,544	99	132	269	2.03	No
5	7,833	259	7,948	307	284	114	0.40	No
6	7,934	305	8,121	335	320	187	0.58	No
VHT Scenario	CV0% Mean	CV0% StdDev	CV25% Mean	CV25% StdDev	Pooled StdDev	Diff of means	"t" statistic	95.0% Sig Diff?
1	5,854	107	6,358	116	112	503	4.50	Yes
2	6,183	199	6,588	282	244	405	1.66	No
3	6,925	437	7,577	363	402	652	1.62	No
4	7,276	158	7,749	124	142	473	3.33	Yes
5	7,833	259	8,253	201	232	420	1.81	No
6	7,934	305	8,553	266	286	619	2.16	No
VHT Scenario	CV0% Mean	CV0% StdDev	CV50% Mean	CV50% StdDev	Pooled StdDev	Diff of means	"t" statistic	95.0% Sig Diff?
1	5,854	107	6,558	289	218	704	3.23	Yes
2	6,183	199	6,713	294	251	530	2.11	No
3	6,925	437	7,769	613	532	844	1.59	No
4	7,276	158	8,032	170	164	756	4.61	Yes
5	7,833	259	8,286	330	297	452	1.52	No
6	7,934	305	8,572	324	315	637	2.03	No

Notes:

1. *The standard deviations shown in table are for the mean of 10 simulation runs.*
2. *Three tests are shown – 10% Connected Vehicles, 25% Connected Vehicles, 50% Connected Vehicles. CV = connected vehicle. VMT = vehicle-miles traveled. "t" is the Student's "t" statistic. For two sided test at 95%, the significant "t" at 18 degrees of freedom is 2.44.*
3. *Reference: NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/, Accessed May 29, 2015, Section 7.3.1. Do two processes have the same mean?*
4. *Note that the VHT shown in this table has not been corrected for latent delay (vehicles delayed from entering the network by queues on entry links to the simulation network).*

ANALYSIS OF FACTORS AFFECTING RESPONSE

This section discusses the likely effects of market penetration rate, communication latency, communication loss, and driver compliance on the effectiveness of the SPD-HARM/Q-WARN Prototype.

Market Penetration, Communication Latency/Loss, Driver Cooperation

It is projected that communication to/from the connected vehicles via DSRC may result in up to 10% communication loss. DSRC communication would have negligible latency, assuming no-handshake implementation. Cellular phone communications are not anticipated to result in communication losses. Cellular communications latencies of 0 to 5 seconds were selected for evaluation. [15]

Figure 36 illustrates the relative importance of driver compliance and communication loss on the resulting combined response rate of drivers to the SPD-HARM speed recommendations. While communication loss may reduce the combined response by 10%, uncertainty as to driver response to the SPD-HARM guidance is much greater. The graph illustrates the effect of driver compliance rates ranging from 50% to 100%.

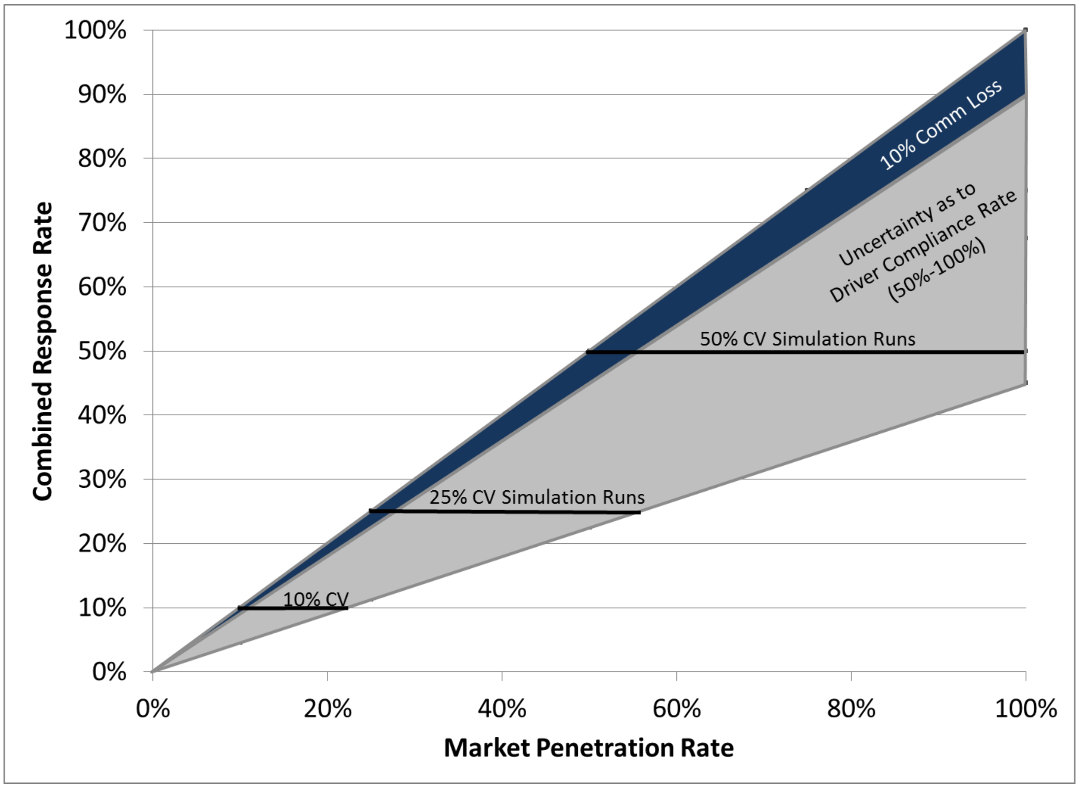
The wide range in the predicted driver compliance rate with successfully received SPD-HARM guidance reflects the lack of data on driver compliance, rather than a prediction that 50% of drivers might ignore or delay compliance with SPD-HARM guidance until they see the reason for the guidance in front of them.

Presuming that the assumptions upon which the graph is based are valid, then the simulation runs for 10%, 25%, and 50% connected vehicles would be applicable to the following ranges of market penetration:

- The 10% connected vehicle simulation runs would be valid for market penetration rates ranging from 10% (when there is no communication loss and 100% driver compliance) to 22%.
- The 25% connected vehicle simulation runs would be valid for market penetration rates ranging from 25% (when there is no communication loss and 100% driver compliance) to 55%.
- The 50% connected vehicle simulation runs would be valid for market penetration rates ranging from 50% (when there is no communication loss and 100% driver compliance) to 100%.

In essence, the simulation runs provide performance results for market penetrations rates from 10% to 100%, depending mostly on driver compliance and a little bit on communication loss.

[15] Communication from Noblis Technical Services Support team, December 1, 2014.



Source: Kittelson & Associates/USDOT

Figure 36: Graph. Sources of uncertainty affecting combined response rates.

As found in the small-scale demonstration, processing time and communication latency together typically added up to about a five-second delay between queue detection, processing, and message receipt in the vehicle, whether using DSRC or cellular communication. At these levels, the small-scale demonstration found no apparent effect on the performance of SPD-HARM and Q-WARN. Indeed, the small-scale demo concluded that SPD-HARM and Q-WARN recommendations could be updated less frequently than every 15 seconds.

Table 16 illustrates the effects of 5 seconds of communication latency in detection of an incident and another 5 seconds of communication latency for successful receipt of the SPD-HARM advisory by the connected vehicle for a one-minute long incident. The constraints imposed on SPD-HARM by human factors (recommended speed cannot change more frequently than once every 15 seconds, and the recommended speed cannot change by more than 5 mph) significantly dampen the potential effects of communication latency on SPD-HARM performance. The net effect of the communication latency on this simple example was to change the average recommended speed by SPD-HARM by eight-tenths of one percent. Different incident durations and severities would probably show different effects from this example.

Table 16: Effects of communication latency.

Latency	Detected		SPD-HARM Advisory	
	0 secs	5 secs	0 secs	5 secs
16:00:00	65	65	65	65
16:00:05	65	65	65	65
16:00:10	65	65	65	65
16:00:15	65	65	65	65
16:00:20	65	65	65	65
16:00:25	65	65	65	65
16:00:30	65	65	65	65
16:00:35	65	65	65	65
16:00:40	65	65	65	65
16:00:45	65	65	65	65
16:00:50	65	65	65	65
16:00:55	65	65	65	65
16:01:00	35	65	60	65
16:01:05	35	35	60	65
16:01:10	35	35	60	60
16:01:15	35	35	55	60
16:01:20	35	35	55	60
16:01:25	35	35	55	55
16:01:30	35	35	50	55
16:01:35	35	35	50	55
16:01:40	35	35	50	50
16:01:45	35	35	45	50
16:01:50	35	35	45	50
16:01:55	35	35	45	45
16:02:00	45	35	45	45
16:02:05	45	45	45	45
16:02:10	45	45	45	45
16:02:15	45	45	45	45
16:02:20	45	45	45	45
16:02:25	45	45	45	45
16:02:30	55	45	50	45
16:02:35	55	55	50	50
16:02:40	55	55	50	50
16:02:45	55	55	55	50
16:02:50	55	55	55	55
16:02:55	55	55	55	55
16:03:00	55	55	55	55
16:03:05	65	55	60	55
16:03:10	65	65	60	60
16:03:15	65	65	60	60
16:03:20	65	65	65	60
16:03:25	65	65	65	65
16:03:30	65	65	65	65
16:03:35	65	65	65	65
16:03:40	65	65	65	65
16:03:45	65	65	65	65
16:03:50	65	65	65	65
16:03:55	65	65	65	65
Ave Spd	50.14	50.14	56.14	56.60
		100.0%		100.8%

This example illustrates the impacts of 5 seconds of communication latency on the timing of the detection of an incident and a 5 second delay in delivering the SPD-HARM recommended speed to the connected vehicle.

The first column gives the time every 5 seconds between 16:00 and 16:04, for an example four minute period.

The second column shows the speeds detected with zero seconds latency when there is a slow down to 35 mph for a roadside incident that lasts for one minute.

The third column shows a five-second delay in SPD-HARM becoming aware of the slow down.

The fourth column shows the SPD-HARM speed advisory delivered to the driver with zero-seconds latency between detection and receipt by the vehicle. This column reflects the constraints on SPD-HARM – updates to driver limited to once every 15 seconds, and recommended speed cannot change by more than 5 mph.

The final column shows the SPD-HARM advisories with both a five-second detection delay and a five-second receipt by vehicle delay.

QUALITATIVE ANALYSIS OF SAFETY AND ENVIRONMENTAL EFFECTS

The simulation showed a significant reduction in speed drops between vehicles on the freeway. This is highly likely to result in reduced frequencies and severities of crashes on the freeway.

The simulation also showed 10% to 20% reductions in average speed for the freeway with SPD-HARM.

- Given that NOx and CO emissions per vehicle-mile at high speeds (in the range of 60 to 20 mph) decrease with speed, [16] then those two emission types are likely to be improved with SPD-HARM.
- Given that volatile organic compounds (VOC) emissions increase with speed decreases, VOC emissions per vehicle-mile are likely to be increased by SPD-HARM.
- Given that fuel economy improves when speeds above 40 mph are reduced to closer to 40 mph,[17] then the result is likely to be reduced fuel consumption per vehicle-mile traveled with SPD-HARM.

[16] Transportation Air Quality Facts and Figures, Federal Highway Administration, January 2006. Accessed April 2, 2015, http://www.fhwa.dot.gov/environment/air_quality/publications/fact_book/page00.cfm

[17] "Driving More Efficiently," http://www.fueleconomy.gov/feg/driveHabits.jsp, accessed April 2, 2015

CHAPTER 7. SMALL-SCALE DEMONSTRATION RESULTS

A small-scale demonstration deploying the INFLO Prototype System and applications was conducted to demonstrate their 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.

This chapter is extracted with minor edits from the Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Report Draft by Battelle and TTI.[18] That report should be consulted for additional details and supporting information regarding the methodology, results, and conclusions of the small-scale demonstration.

METHODOLOGY

In this small-scale demonstration, Battelle and TTI worked with WSDOT to deploy connected vehicle systems in 21 vehicles in a scripted driving scenario traversing both directions of a 23-mile stretch of the I-5 freeway from Tukwila to Edmonds through downtown Seattle, during morning rush hour the week of January 12, 2015.

Early in the week, the connected vehicles were released in pulses (two platoons, 5 minutes or 15 minutes apart). Later in the week, they were spaced out, with one vehicle being released approximately every 30 seconds.

The system collected vehicle speed data from both the WSDOT infrastructure-based speed detectors (loops) and the connected vehicles during the driving scenario (via DSRC and cellular).

The system processed the data in real time and delivered Q-WARN and SPD-HARM messages to drivers. Drivers were also informed as to when they were in queue and how far ahead and how long it would take to exit the queue (in-queue status).

The PD contractor 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.

RESULTS

The small-scale demonstration yielded the following results.

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 the DSRC (Dedicated Short Range Communications) communication range.

[18] Battelle Memorial Institute / Texas A&M Transportation Institute, Intelligent Network Flow Optimization (INFLO) Prototype Seattle Small-Scale Demonstration Report Draft, FHWA, Washington, DC, March 27, 2015

Limited onboard logging capability prevented direct comparisons of messages sent and messages received to determine the exact percentage received; however, the system and algorithms performed as expected and had sufficient BSM (Basic Safety Message) 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.

Data Loss When Switching Communication Modes

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. BSMs were generated every second. BSMs were then bundled and sent via DSRC or Cellular communications every five seconds. The applications were developed such that BSMs are sent via DSRC when there is adequate RSU (Roadside Unit) to OBU (On-board Unit) DSRC signal strength for communication (as measured by RSSI – Received Signal Strength Indicator) or via cellular communications when not.

The results 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.

Advance Delivery of Messages

The Q-WARN and SPD-HARM processors were designed to capture BSM data from the database, analyze it, and populate messages for drivers every five seconds. In practice, this process was found to take two to three 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 take two to three 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.

Latency of Message Delivery

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.

Time to Detection/Notification of Back of Queue

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.

In the small-scale demo, it was noted that as the connected vehicle platoon approaches the back of the queue, the reported speed of the connected vehicles begins to decrease. This reduction in speed is detected much sooner than that reported by the infrastructure sensor system. The infrastructure sensor system does not detect the back of the queue until almost 3 minutes after the connected vehicle platoon. The small scale demo found that the INFLO Prototype System is able 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.

Locating the Back of Queue

The Battelle/TTI 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.

The demo found 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 having connected vehicle speed data available between loop detector locations can substantially improve the resolution in detecting the back of the queue, compared to infrastructure-only information. The benefits of connected vehicle speed data would be less in situations where road detectors are more densely spaced, or in cases where the back of queue coincides with a road detector location. . At lower connected vehicle market penetration rates, bunching of connected vehicles may also reduce the benefits.

Estimating Vehicle Speed in Queue

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.

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 INFLO SPD-HARM application is more dynamic than the WSDOT VSL algorithm. The SPD-HARM algorithm back of the queue and congestion is updated every 20 to 30 seconds. Its recommendations change with each update and vary more widely than those specified by VSL. The step down in speed recommended by SPD-HARM is consistently in 5 MPH increments.

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 in the small scale demonstration 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.

The differences between VSL and SPD-HARM varied between Monday and Friday, which was 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 is 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 spaced 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 the detailed meaning of these results.

Market Penetration

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

During the evaluation, two different patterns were used to control how the connected vehicles moved through the study area. Early in the week, the connected vehicles were grouped in two tight platoons—a six-vehicle platoon was released first followed by a 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 estimated to be more indicative of the arrival patterns of a high market penetration while the second release pattern was estimated to be more indicative of an arrival pattern with a lower level of market penetration.

Following this logic, the Battelle/TTI research team examined the differences in which the algorithm determined the back of queue under the two release patterns. It was found that the CV data locates the back of the queue earlier in both time and distance than the infrastructure based data and is more precise. A reasonable estimate of the back of the queue can be obtained with connected vehicles spaced about 30 seconds apart. For comparison, the infrastructure-based estimate of the back of queue is updated every 20 seconds. Overall, this suggests that market penetration which achieves vehicle spacing of no more than 20 to 30 seconds may be needed. Of course, more definitive work is needed to draw firm conclusions. However, the results suggest reasonable estimates of the location of the back of the queue (identifying the back of queue to the nearest half or third mile, similar to what can be obtained from similarly spaced loop detectors) may be possible with medium to low market penetrations.

Driver Speed Reduction in Advance of a Queue

Most connected vehicles were observed to slow gradually as they approach the end of the queue, but a few did arrive at the back of the queue at high speeds. The first connected vehicle in the platoon would not receive Q-WARN messages so its deceleration rate was compared to that of the connected vehicles behind it. No observable differences were found between the first vehicle in the queue and the later arriving vehicles. 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.

Driver Speeding Behavior

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.

Scatter plots were prepared comparing actual vehicle speeds to SPD-HARM recommended speeds on Southbound I-5 Segment 3 and to WSDOT VSL speeds on Northbound Segment 1. Both SPD-HARM and WSDOT VSL do not recommend speeds below 30 mph. There is a large population of actual speeds that was found to fall below the diagonal line suggesting slow speeds leading up to the congestion queues. The scatter plots showed what appears to be a stronger correlation between the WSDOT regulatory VSL speeds and actual speed than with the recommended SPD-HARM speeds.

Keeping in mind that detailed assessment of driver behavior is outside the scope of this project, results suggest that participating drivers followed VSL speeds more closely than SPD-HARM speeds, which may be due to the VSL being enforceable speeds. Subsequent driver comments indicated that, in congested and queued traffic, they found it necessary to match their speed to the surrounding traffic, rather than follow SPD-HARM recommended speeds. The results here cannot be used to draw any further observations concerning driver response to VSL and SPD-HARM recommendations and the corresponding impact on safety and mobility.

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 fifth 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.

- On average, drivers report that they find Q-WARN and SPD-HARM messages useful, valuable, and 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.

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

CONCLUSIONS

The small-scale demonstration yielded the following conclusions:

1. 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.
2. 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.
3. The Q-WARN and SPD-HARM processors were able to capture BSM data from the database, analyze it and populate messages for drivers every 2 to 3 seconds. The process of vehicles polling the database for new information every second, and deliver messages to the driver 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 queue warning messages approximately a mile in advance of the back of the queue.
4. Q-WARN was able to detect the back of queues up to 3 minutes sooner and could pinpoint their geographic location more precisely (0.5 to 1.5 miles farther upstream) than the road loop detectors (which are spaced 1/3 to ½ mile apart, and average the speeds across all lanes, even when some lanes are queued and others are not).
5. 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.
6. 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.

7. The SPD-HARM recommendations based upon a simulated lower level penetration are closer to the WSDOT VSL recommendations than are those with a simulated higher level penetration. The WSDOT 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 the detailed meaning of these results.

CHAPTER 8. CONCLUSIONS – ANSWERING THE QUESTIONS

This chapter addresses the original research questions posed for this impact assessment.

QUESTION 1: WHEN IS THE BEST TIME TO IMPLEMENT SPD-HARM AND Q-WARN (SOLO OR IN COMBINATION)?

The simulation runs tested SPD-HARM exclusively. Thus, no simulation results were generated for Q-WARN. This is because of several difficulties testing Q-WARN in a simulation environment:

- The Q-WARN Prototype is not designed to support tactical driving decision making. It does not specify the lane where the queue is present, but does warn that the queue is one-tenth of a mile or several miles ahead.
- There is little or no data (and the small-scale demonstration was not able to generate the data) on how drivers will reroute in response to advanced queue warning.
- There is little or no data on how drivers might slow down (or not) in advance of actually seeing the queue. This simulation analysis took the conservative perspective that there would be no “strategic” slowing in advance of sighting the queue. Once the queue was sighted, then standard microsimulation car following behavior would come into play.

The small-scale demo tested both applications together, but not separately.

Question 1a: Are speed harmonization and queue warning applications more beneficial when implemented in conjunction or in isolation?

Answering this question hypothetically, there appears to be no conflict between the functions of Q-WARN and SPD-HARM. Because SPD-HARM does not recommend a freeway speed below 30 mph (by user-editable default), reinforcing that minimum recommended speed with advance warning of queues downstream should probably reinforce the compliance with the SPD-HARM speed advisories.

Question 1b: Under what operational conditions are the applications the most beneficial?

Simulation analysis showed that SPD-HARM particularly shines under recurring-congestion conditions. There are also benefits under adverse weather and incident conditions. Under exceptionally severe congestion, the benefits are still present, but they are less significant.

This analysis did not evaluate the impacts of SPD-HARM on the number of crashes, but the indirect measures of reduced shockwaves suggest there would be safety benefits and reduced numbers of crashes as well.

Question 1c: Under what conditions is one application superior to the other?

The simulation analysis could not inform the response to this question. Both SPD-HARM and Q-WARN are likely to show their best advantages under similar conditions. Thus, hypothetically, there does not appear to be a congestion condition in which one would be superior to the other.

It is possible that under less than ideal instrumentation conditions, it might be that a simple Q-WARN indication might require less-precise measurement of speeds than needed to generate a specific speed recommendation under SPD-HARM. However, this was not tested.

QUESTION 2: WHICH COMMUNICATION METHOD IS BEST FOR NOMADIC DEVICES?

Question 2a: Will a nomadic device that is capable of communicating via both DSRC as well as cellular meet the needs of the two applications?

The small-scale demonstration showed that both communication methods could be made to work together seamlessly from the perspective of the driver.

Question 2b: When is DSRC needed and when will cellular suffice?

Cellular with latencies of 5 seconds or less will suffice. DSRC is not needed except in the absence of cellular coverage, or where latencies are excessive. The majority of the small-scale demonstration functioned satisfactorily under exclusively cellular coverage. More connected vehicles may place greater demands on the cellular network, thereby, increasing communication latencies, but it is reasonable to anticipate that cell phone providers will increase their network capacity to handle the additional cell traffic, as long as the increase in connected vehicles is gradual.

QUESTION 3: WHAT ARE THE IMPACTS OF NEAR, MID, AND LONG-TERM DEPLOYMENT?

Speed harmonization and advanced queue warning will reduce shockwaves on a congested freeway. This should also reduce crashes, but by what amount, was not tested. Significant advantages (in terms of reduced speed differentials) accrue at even the 10% response rate, so there should be significant benefits in the near term to a SPD-HARM/Q-WARN installation. Longer term, as the percentage of connected vehicles increases, there should be continuing benefits, but the benefits will increase at a slower rate as the percent of connected vehicles exceeds 20%.

QUESTION 4: WHAT LEVEL OF MARKET PENETRATION IS REQUIRED?

The question is: “At what levels of market penetration of connected vehicle technology do speed harmonization and queue warning applications become effective?”

Significant benefits (in terms of reduced speed differentials) occur within the first few percent of the vehicle fleet complying with SPD-HARM recommendations delivered via connected vehicles. Simulation found high level of benefits in the first 10% of the fleet participating in and complying with the connected vehicle SPD-HARM messages.

QUESTION 5: WHAT ARE THE EFFECTS OF COMMUNICATION ERRORS AND LATENCY?

The effects of communication errors and latency appear to be mostly irrelevant for SPD-HARM and Q-WARN. The small-scale demonstration found no loss of functionality with 5 second delays between detection, processing, and delivery of the SPD-HARM/Q-WARN messages. This is because these applications of INFLO are strategic in approach, and advisory in nature to the driver. The limits of having the driver "in the loop" mean that advisories cannot come too frequently and they cannot differ too much from the previous advisory. The limits of GPS position assumed in the SPD-HARM/Q-WARN prototype mean that the advisories cannot be lane specific.

Question 5a: How effective are the two applications when there are errors or loss in communication?

The simulation and hypothetical analyses suggest, and the small-scale demonstration confirms, that five-second latencies and 10% communication loss, individually (and not together) should have no noticeable effects on the performance and benefits of SPD-HARM and Q-WARN.

Question 5b: What are the impacts of communication latency on benefits?

A hypothetical analysis found that five-second latencies would be likely to have a less than 1% effect on benefits. The small-scale demonstration confirmed this conclusion.

QUESTION 6: WHAT ARE THE BENEFITS OF WIDESPREAD RSE DEPLOYMENT?

Generally, the more communication and detection equipment, the better it is for performance.

Question 6a: What are the benefits of widespread roadside equipment (RSE) deployment versus ubiquitous cell coverage?

SPD-HARM and Q-WARN appear to be fairly tolerant of modest communication loss and latency. As confirmed by the small-scale demonstration, it appears that one communication method can substitute for the other with little harm to the performance of SPHARM and Q-WARN. Other sites with different geography and DSRC/cellphone tower infrastructure and capacities might obtain different results. More extensive presence of connected vehicles may pose communication capacity challenges that were not present at the small scale demonstration site.

Question 6b: Which is more beneficial?

As confirmed in the small-scale demonstration, SPD-HARM and Q-WARN would operate equally well with either means of communication and detection.

Question 6c: What is the marginal benefit with data from existing sensors?

SPD-HARM and Q-WARN are designed to work with existing sensors. The small-scale demonstration found that the use of connected vehicles significantly improved the detection of queues, providing earlier notice of queues, and a more-precise location for the back of the queue.

QUESTION 7: IS CONNECTED VEHICLE DATA REQUIRED FOR SUCCESS?

While the current variable speed limit system in Seattle works well with road sensors at half-mile spacing, the small-scale demonstration showed that SPD-HARM and Q-WARN would operate much better (with earlier detection, and more precise detection of queues) using connected vehicle data.

Connected vehicle data would be instrumental to realizing the maximum benefits of SPD-HARM and Q-WARN. While Seattle demonstrates that connected vehicles are not required (if significant investment in roadside sensors is made by the agency), the small-scale demonstration showed that the operation of SPD-HARM and Q-WARN would be much improved with connected vehicle data.

APPENDIX A

SELECTION AND DEVELOPMENT OF SIMULATION TEST BED

This appendix describes the selection of the recommended simulation model test site, the adaptation of the simulation model for testing the SPD-HARM/Q-WARN prototype. A high level description of the operation of the prototype is provided as well.

SIMULATION TEST BED SELECTION

Criteria for Test Bed Selection

The requirements for selecting the test bed include:

- Freeway facilities that are between 5 and 10 miles long,
- The freeway facilities experience recurrent and non-recurrent congestion
- The freeway facilities are coded and calibrated into microscopic simulation models.
- The simulation model should include interchanges and/or signalized intersections at the foot of the ramps as well as the freeway mainline

The focus on freeways is because they provide a more-controlled environment for examining the benefits of SPD-HARM and Q-WARN, and are likely, because of the high speeds involved, to show the greatest benefit of SPD-HARM and Q-WARN.

The 5- to 10-mile length was selected to ensure adequate distance to adequately track and trap the benefits of SPD-HARM and Q-WARN without overburdening the Impact Assessment with analysis of exceptionally long facilities.

The presence and availability of a previously calibrated and validated commercial microsimulation model is vital for cost-effectively generating the MOE's under the varying conditions necessary to answer the questions posed in the TOPR for this Impact Assessment. In addition, the software used to operate the simulation model must be capable of interfacing with custom developed API's for emulating SPD-HARM and Q-WARN.

The presence of recurring and non-recurring congestion is necessary to be able to observe the benefits of SPD-HARM and Q-WARN.

Candidate Test Beds

Table 17 lists the simulation test beds available to the research team. We did additional searches to identify simulation test beds that have been used in the analysis of SPD-HARM algorithms in recently completed and/or ongoing research. None additional were found that were readily available to the research team.

We reviewed the available test beds listed in Table 17 seeking facilities with the presence of recurring bottlenecks, and the availability of real-world detector coverage to obtain real-time data on operating conditions. The two sites that best met these and the previously described criteria were:

- I-210 in Southern California.
- US 101 in the San Francisco Bay Area, close to the California Test Bed for Connected Vehicles.

Both test sites have been coded and calibrated in the VISSIM model. The I-210 site has been used to evaluate alternative ramp metering strategies, and the US 101 site has been used to test alternative traffic management schemes.

Note that the US 101 site could be extended to include parallel arterial (El Camino Real), which is part of the California Test Bed if an arterial demonstration test were needed for future impact assessments.

Table 17: Available calibrated simulation model test sites.

Location	Facility	Limits	Miles	Peaks	Software
Freeways					
S. Clara Co, CA	US 101	Gilroy to San Jose	25.0	AM/PM	CORSIM
Alameda Co, CA	I-580	I-680 to I-205	20.0	AM/PM	Paramics
Raleigh, NC	I-40**	NC 147 to Gorman Street	16.0	PM	VISSIM
Philadelphia, PA	I-95	PA/Delaware to Schuylkill River	15.0	AM/PM	VISSIM
Milwaukee, WI	I-43/I-894	Loomis Rd to Greenfield Ave	7.0	PM	VISSIM
Berkeley, CA	I-80 WB	Carlson Blvd. to I-580	6.5	AM	VISSIM
Harford Co, MD	I-95	MD 543 to MD 152 (Mountain Rd)	6.0	AM/PM	Aimsun
Alameda Co, CA	I-880	SR 92 to Marina Blvd.	6.0	AM/PM	VISSIM
Pasadena, CA	I-210	Vernon to I-710	14.0	AM	Paramics
San Mateo, CA	SR 92	De Anza to Foster City Blvd.	5.2	AM/PM	VISSIM
St. Louis, MO	I-20	Dougherty Ferry Rd to Gravois Rd	4.8	PM	VISSIM
San Mateo, CA	US 101	Hillsdale to Mariner Island	4.7	AM/PM	VISSIM
St. Louis, MO	I-44	Marz Ln to Big Bend Rd	4.5	PM	VISSIM
Arterials					
Whistler, BC	Sea to Sky	Function Junction Stat. to Lorimer	5.5	PM	VISSIM
Waterloo, IA	University	SH 27 to Sargent Road	5.0	AM/PM	VISSIM
Broward Co, FL	SH 842	US 1 to US 44/SH7	4.0	AM/PM	VISSIM
Anthem, AZ	Daisy Mtn.	Galvin Pk to W. Anthem Wy	2.0	AM/PM	VISSIM/ASC
Networks					
Raleigh, NC	Research Triangle**	1000 links, 200 zones, 54 signals, 681 detectors	112.0 Ctr-Line	PM	Aimsun

SELECTED TEST BED – SAN MATEO US 101 FREEWAY

Following further review of the leading candidates I-210 and US101/SR92, we propose the use of the US101/92 test bed to perform the impact assessment through simulation. Additional information is given below.

Background

The US-101 and SR-92 test bed modeled in VISSIM platform was developed in a project (2009-2013) funded by Metropolitan Transportation Commission (MTC), San Mateo County Transportation Authority and City and County Association of Governments of San Mateo County. The model year is 2010 and the simulation time period is from 2:30 PM to 7: 30 PM. The traffic modes modeled in this test bed consist of the passenger car and truck. This test bed had been fully calibrated based on observed traffic conditions in the field, such as volumes, travel time, bottleneck location and duration of congestion. MTC approved the calibrated and validated VISSIM model for the study in 2010/2011. A series of operational and traffic management improvements were analyzed including ramp metering, auxiliary lanes, lane expansions, ramp closures due to short weaving/diverging/merging, and multimodal travel information.

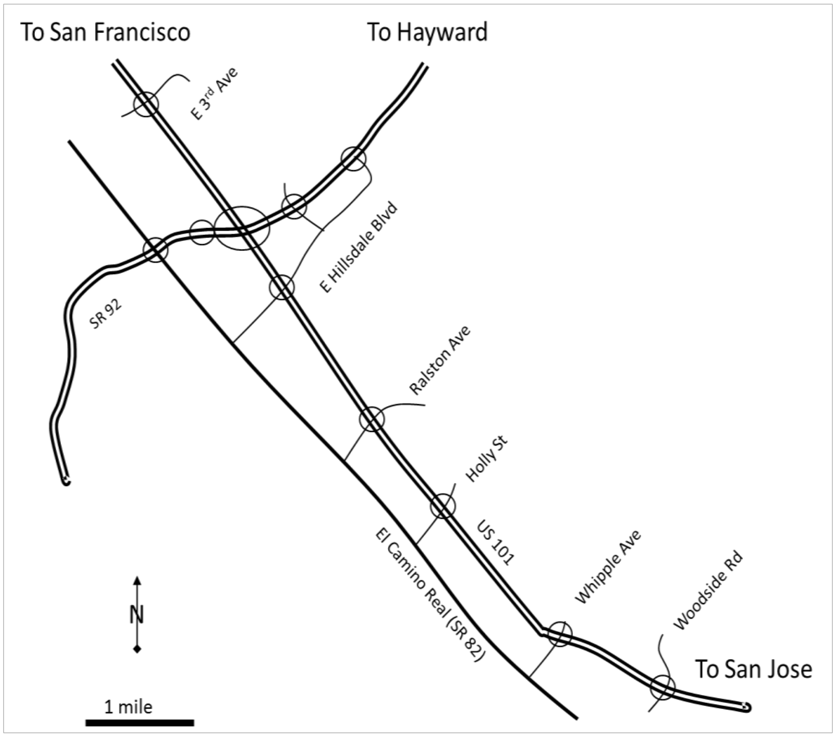
Test Bed Characteristics

The original US-101/SR-92 test bed is shown in Figure 37. The test bed is located approximately 10 miles south of the San Francisco International Airport (SFO). The highlighted purple line in Figure 37 represents the limits of US-101 corridor as originally modeled; the green line represents the limits of SR-92 corridor.

Traffic congestion in the network occurs in the northbound direction of US-101 northbound during the PM peak periods. Figure 38 also shows typical PM peak traffic conditions based on Google maps. These plots clearly show the presence of a bottleneck at the US-101 and SR-92 interchange, which is a recurring bottleneck during PM peak hour. Note that queues extend part the original US101/92 test bed boundary. Therefore, to properly analyze ATDM and/or DMA scenarios we extended the original network into VISSIM to capture the spatial and temporal effects of the congestion along US-101. The network extension along US101 is shown in Figure 37.

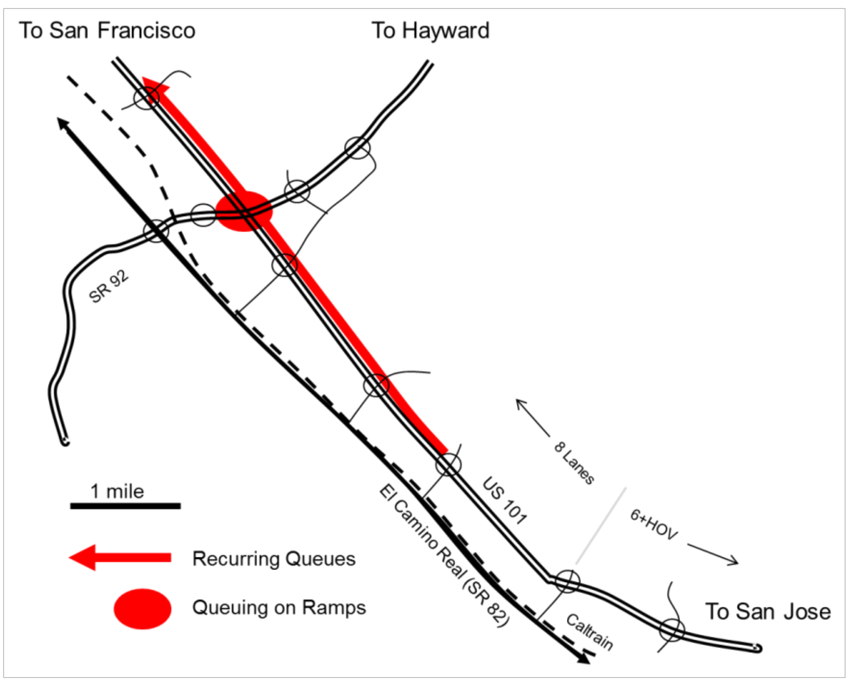
Because this US-101 and SR-92 network was modeled in the microscopic VISSIM simulator (version 5.40), the model can provide time-dependent performance measures, such as time-dependent volume, speed, travel time, delay, and queuing at different levels (individual vehicle, lane, link and subarea).

The built-in functions and Application Programming Interface (API) in VISSIM enable various strategies to be modeled in the test bed, including but not limited to: ramp metering, speed harmonization, queue warning, HOV/HOT lanes, variable lane use, shoulder lanes/reversible lanes, adaptive signal control, connected vehicles, etc. Moreover, the travelers’ response can be modeled by adjusting their behavior based on user-defined threshold(s), decision rule(s), and dynamic network performance.



Source: Kittelson & Associates/USDOT

Figure 37: Map. San Mateo US-101 test site.



Source: Kittelson & Associates/USDOT

Figure 38: Map. Recurring traffic conditions on US 101 PM peak.

There are comprehensive data sources within the US-101 and SR-92 test bed area, which can be used for model inputs, model calibration and validation for future studies. Table 18: Available real world data within San Mateo US 101 test site Table 18 summarizes the data sources and the corresponding data.

Table 18: Available real world data within San Mateo US 101 test site.

Sources	Data
Loop Detector Data (PeMS system) Detector spacing: 0.4 mile Detectors located on each travel lane and ramps	Volumes, Speeds, Densities (Occupancies) at various time resolutions Travel times along links/route
Inrix	Travel time statistics
Workzones (locations and operational details)	Caltrans District 4
SFO Airport Station and Caltrans Database	Weather information
California Highway Patrol and Bay Area Freeway Service Patrol	Incidents CHP data readily available in the PeMS system
SamTrans, CalTrain	Transit information

TRAVEL DEMANDS INPUT

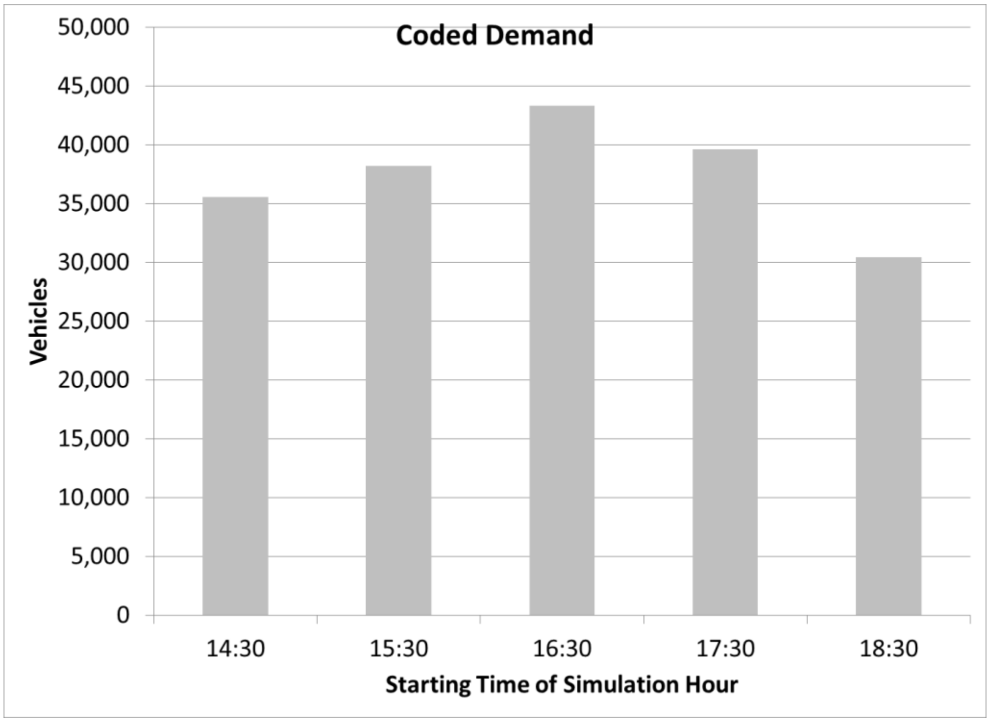
Table 19 shows the vehicle demands by ramp coded into VISSIM for each of the scenarios. The same demand was used for all baseline and connected vehicle scenarios. The only difference between scenarios is the proportion of connected vehicles assumed in the traffic stream.

Figure 39 shows how the input vehicle demands varied by simulation hour. The coded hourly demands peaked at 115% of the average hourly demand.

Note that only input demands are coded. VISSIM is allowed to use proportioning to allocate the demands at each mainline in and on-ramp (origin) to each mainline out and off-ramp (destination). The proportioning is based on the mainline out and off-ramp flows downstream of each origin.

Note that VISSIM was not required to load exactly the input number of vehicles each hour for each scenario.[19] There is some random variation between the coded demands by ramp and hour and the actual demand generated and loaded by VISSIM onto the network. In addition, queues backing up onto the mainline entry points and on-ramps would constrain the amount of VISSIM-generated traffic at each entry point and on-ramp that is actually able to enter the network each hour and overall for the simulation period.

[19] This avoids forcing VISSIM to make up the missing, ungenerated demand in the last hour, which can distort the hour by hour results.



Source: Kittelson & Associates/USDOT

Figure 39: Graph. Peaking of hourly demands coded into VISSIM.

Table 19: Demands coded into VISSIM model.

Link No.	Input Name	Warm Up	14:30	15:30	16:30	17:30	18:30	19:30
130	101 SB	2,552	4,254	4,675	4,868	4,263	4,257	0
1	92 WB	1,317	2,195	2,671	3,071	2,943	1,981	0
393	92 EB	1,564	2,606	3,173	3,622	3,212	2,233	0
297	Foster City WB	781	1,301	1,447	1,946	1,838	1,335	0
81	Foster City EB	209	349	507	800	740	495	0
26	Edgewater Blvd EB	94	157	230	340	324	252	0
315	Mariners Island Blvd WB	518	864	877	1,251	1,117	896	0
333	Delaware EB	350	584	673	699	597	471	0
438	Delaware WB	361	602	665	746	701	449	0
167	El Camino NB loop to 92 WB	100	166	188	224	221	165	0
340	El Camino SB loop to 92 EB	473	789	822	870	727	611	0
356	El Camino NB direct to 92 EB	357	595	559	608	560	427	0
178	El Camino SB direct to 92 WB	230	384	439	505	527	356	0
182	Alameda to 92 WB	333	555	485	624	627	315	0
367	Alameda to 92 EB	423	705	688	561	568	378	0
362	Hillsdale EB Loop to 101 NB	365	608	582	596	505	471	0
Link No.	Input Name	Warm Up	14:30	15:30	16:30	17:30	18:30	19:30
262	Hillsdale WB Direct to 101 NB	274	456	408	416	430	423	0
264	Hillsdale to SB 101	342	570	526	628	699	551	0
97	Hillsdale Loop to 101 SB	274	456	450	471	422	408	0
147	Kehoe to NB 101	98	164	155	152	200	152	0
390	3rd WB direct to NB 101	158	264	306	544	562	369	0
141	3rd EB loop to NB 101	301	501	552	566	518	442	0
368	3rd EB direct to SB 101	567	945	913	882	835	688	0
124	3rd WB loop to SB 101	265	442	460	443	420	328	0
63	Fashion Island to SB 101	197	328	321	392	441	292	0
73	Fashion Island to NB 101	206	344	391	497	410	339	0
206	NB Ralston Loop from EB	213	355	368	359	300	248	0
207	NB Ralston Loop from SB	213	355	367	359	300	247	0
189	NB Ralston Direct	335	558	739	1,434	1,320	460	0
492	Woodside NB Ramp	405	675	725	696	662	578	0
497	Woodside SB Ramp	208	347	374	359	341	298	0
530	Whipple SB	44	73	67	91	83	30	0
528	Whipple NB	782	1,303	1,329	1,283	937	813	0
467	Brittan Ave Onramp	284	474	515	517	380	327	0
479	Whipple SB onramp	52	87	85	86	78	54	0
533	Whipple-NB Onramp	370	616	685	769	614	488	0

505	Woodside Onramp	875	1,458	1,394	1,519	1,539	1,329	0
459	Holly EB Onramp	266	444	469	609	436	189	0
85	Holly WB Onramp	314	524	501	573	412	166	0
463	Holly St Onramp	65	108	92	88	64	64	0
196	Marine WB Onramp	148	247	257	250	226	213	0
199	Ralston EB	55	92	95	93	84	79	0
219	Harbor EB Onramp	38	64	66	64	58	55	0
545	US101 NB Extension	3,963	6,605	6,896	7,840	7,373	5,720	0
	HOURLY TOTAL	**21,339**	**35,569**	**38,187**	**43,311**	**39,614**	**30,442**	**0**
	SIM PERIOD TOTAL (excl. warm up)	**187,123**						

ADAPTATION OF TEST BED FOR USE IN IMPACT ANALYSIS

Selection of Analysis Hours, Warmup Period, Cool Down Period

The simulation was run for 5 hours (from 14:30-19:30). A one-hour warm up period was coded with 60% of the first hour's demand.

A one-hour cool-down period was coded with zero demand to enable more of the unserved demand in the simulation period (which reached 20% of the coded demand for the more severe scenarios) to clear the network.

Coding of Connected Vehicles

Vehicle type "C_Car" (i.e., connected vehicle) were created with the same characteristics as vehicle type "Car" (i.e., normal passenger car). The connected types were the source of the data for the SPD-HARM prototype and were the only vehicles affected by the recommendations of the prototype.

Coding of Detection System And Decision Points

Nineteen data collection stations are placed on US 101 northbound from the south of the Woodside Road interchange to the south of the State Route 92 interchange. The space between the adjacent data collection stations is 0.5 mile. Each detection station can represent a "sublink" of the roadway for the SPD-HARM prototype. The data collection stations collect the volume, speed, and occupancy.

Desired speed decision points were also placed on US 101 northbound from the south of the Woodside Road interchange to the south of the State Route 92 interchange. The space between the adjacent desired speed decision points is 0.1 mile. As soon as a connected vehicle reaches the speed decision points, it will adjust its traveling speed if the SPD-HARM prototype recommends one different from its previous desired speed.

Programming the Interface

An Excel interface was developed to transfer the data between VISSIM and SPD-HARM prototype. The working flow is summarized as follows:

1. The interface retrieves the outputs at 20 second interval from detection stations (volume, speed and occupancy) and the outputs from the vehicle record database (vehicle id, location, timestamp, speed);
2. The interface transfers the above information into the database of the SPD-HARM prototype;
3. The SPD-HARM prototype evaluates the outputs from VISSIM and then recommends the speed for each speed decision points along the study corridor;
4. The interface retrieves the recommended speed from the SPD-HARM prototype and updates the desired speed at each speed decision point in the VISSIM network;
5. The VISSIM simulation continues with the updated desired speed.

The compliance of the connected vehicles with SPD-HARM speed advisories was assumed to be 100%. Q-WARN advisories were assumed to have no effect on driver behavior. (These advisories are not intended to affect tactical behavior. The advisories are not lane specific and are intended to come long before the driver sees the actual queue.)

Validation of Extended Model

The extended model was calibrated and validated to the traffic data (traffic counts and travel time) collected in 2010 and 2012. In sum, the extended VISSIM model was calibrated to an acceptable level in terms of hourly flow rates and travel time of various routes. All criteria defined by the FHWA Microsimulation Guidelines were met. Table 20 provides a summary of model simulated versus observed traffic volumes on the freeway mainline, on-ramp and off-ramp locations throughout the network. Table 21 provides a summary of model simulated versus observed travel times through various segments of both US 101 and SR 92 corridors. Visual audits of the VISSIM model animation was also conducted to compare against field observed conditions in terms of observed freeway bottleneck locations and queue lengths. In general, the VISSIM model replicated field conditions reasonably well.

Table 20: VISSIM model volume calibration summary.

Criteria					
Individual Link Flows	**Target**	**Cases**	**Cases Met**	**% Met**	**Target Met?**
Within 15%, for 700 vph<Flow<2700 vph	>85%	115	115	100%	Yes
Within 100 vph, for Flow<700 vph	>85%	170	170	100%	Yes
Within 400 vph, for Flow>2700 vph	>85%	100	95	95%	Yes
Sum of All Link Flows	**Sum Counts**	**Sum Link Flows**		**% Met**	**Target Met?**
Within 5% of sum of all link counts	728,992	730,207		100%	Yes
GEH Statistic < 5 for Individual Link Flows	**Target**	**Cases**	**Cases Met**		**Target Met?**
	85%	385	381	99%	Yes
GEH Statistic for Sum of All Link Flows	**Sum Counts**	**Sum Link Flows**	**GEH**		**Target Met?**
GEH <4 for sum of all link counts	728,992	730,207	1.4		Yes

Table 21: VISSIM model travel time calibration summary.

Time Interval		101 SB	101 NB	Hillsdale to Foster City	Foster to Hillsdale	Foster to 3rd	Foster to Ralston	101 SB to Foster	101 SB to Hillsdale	Hillsdale to Ralston	Hillsdale to 3rd	Ralston to Foster	Ralston to Hillsdale	101 NB Woodside to Ralston	Cases with Diff <-15%	Cases with Diff >15%
2:30PM to 3:30PM	Simulated	227	236	270	269	195	255	194	259	330	310	225	326	246		
	STD	0.6	0.6	1.5	0.9	0.4	0.5	0.4	0.7	1.0	1.2	1.7	1.8	0.8		
	Observed	238	239	275	291	180	246	214	298	335	279	235	327	259		
	Diff	-11	-3	-5	-22	15	9	-20	-39	-5	31	-10	-1	-13		
	% Diff	-5%	-1%	-2%	-8%	8%	3%	-9%	-13%	-1%	11%	-4%	0%	-5%	0	0
3:30PM to 4:30PM	Simulated	227	240	290	277	197	256	228	269	340	321	235	341	248		
	STD	0.4	2.6	4.0	3.8	0.7	0.4	26.0	5.0	3.8	4.9	3.0	5.5	1.1		
	Observed	263	267	289	275	188	290	208	277	343	333	266	343	263		
	Diff	-36	-27	1	2	9	-34	20	-8	-3	-12	-31	-2	-15		
	% Diff	-14%	-10%	1%	1%	5%	-12%	10%	-3%	-1%	-3%	-12%	-1%	-6%	0	0
4:30PM to 5:30PM	Simulated	227	335	338	307	222	269	326	309	385	368	333	477	273		
	STD	0.6	16.9	32.4	18.6	4.3	0.9	82.4	19.2	33.2	33.4	16.6	57.7	8.0		
	Observed	259	374	316	324	247	327	256	373	403	333	356	470	265		
	Diff	-32	-39	22	-17	-25	-58	70	-64	-18	35	-23	7	8		
	% Diff	-12%	-10%	7%	-5%	-10%	-18%	27%	-17%	-5%	11%	-6%	1%	3%	2	1
5:30PM to 6:30PM	Simulated	227	408	317	285	222	258	256	285	370	355	402	525	431		
	STD	1.2	23.8	39.5	5.3	4.0	0.5	55.7	20.6	39.2	40.8	23.5	40.0	44.6		
	Observed	287	353	286	320	239	301	230	331	368	316	416	473	359		
	Diff	-60	55	31	-35	-17	-43	26	-46	2	39	-15	52	72		
	% Diff	-21%	16%	11%	-11%	-7%	-14%	11%	-14%	1%	12%	-4%	11%	20%	1	2
6:30PM to 7:30PM	Simulated	225	297	269	269	198	255	194	256	327	306	281	397	290		
	STD	0.7	33.6	1.3	1.8	3.1	0.5	0.6	0.8	1.3	1.1	34.0	35.2	17.1		
	Observed	233	256	266	275	194	262	205	277	317	287	235	326	283		
	Diff	-8	41	3	-6	4	-7	-10	-21	10	19	46	71	7		
	% Diff	-3%	16%	1%	-2%	2%	-3%	-5%	-8%	3%	7%	20%	22%	3%	0	3
															Total Cases	65
															Cases Within 15%	56
															% Cases Within 15%	86%
															Meet Criteria?	Yes

CODING WEATHER AND INCIDENTS

The selected baseline scenarios for evaluating the impacts of SPD-HARM and Q-WARN include:

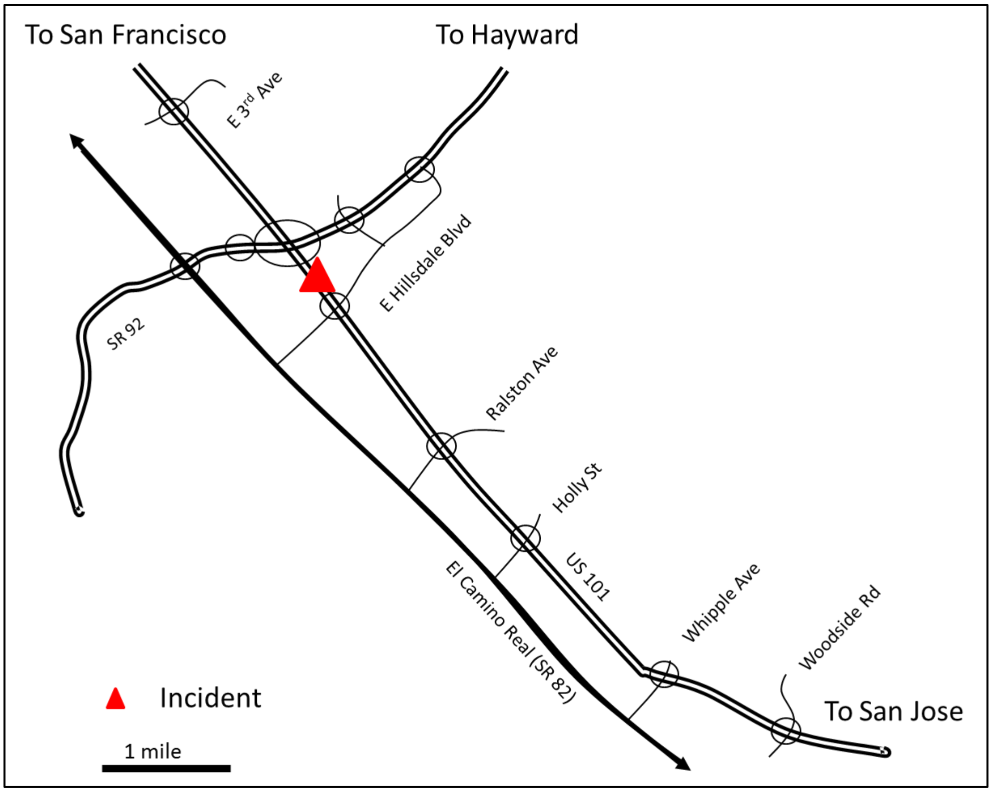
- Light rain
- An incident blocking one lane for 30 minutes
- An incident blocking one lane for 60 minutes

Selection of Start Time and Location for Incidents

The incident (1 lane closure) will be modeled at the bottleneck of the study corridor, i.e., the US-101 northbound segment between E Hillsdale Blvd and SR-92. Figure 40 demonstrates the incident location on the US 101/State Route 92 test bed. The lane closure will occur at the left-most lane.

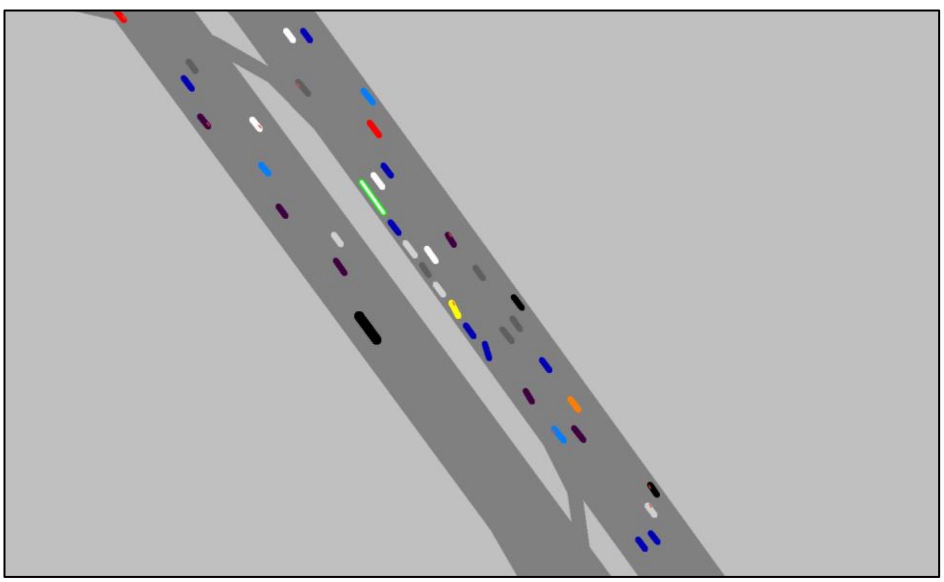
There is no incident function readily available in VISSIM. Therefore, the team used the bus stop to approximate the lane-block effect of the incident. The basic idea is to block the left-most lane by making the bus stop at the incident location for 30 minutes or 60 minutes. In VISSIM, this can be done by adjusting the dwell distribution of the bus.

Figure 41 demonstrates the implementation of the lane-blockage by the bus. As shown in this figure, artificial left-side on-ramp and off-ramp were coded near the bottleneck for the bus to enter and exit the network. The left-side on-ramp enables the bus to arrive at the incident location on time. At the end of the incident period, the bus will leave the facility from the left-side off-ramp (coded as a bus-only facility) without impacting other vehicles. The incident starts at 3:30 and ends at 4:00 (for the 30 minute incident) or 4:30 (for the 60 minute incident).



Source: Kittelson & Associates/USDOT

Figure 40: Map. Incident location on US-101/SR-92 test bed.



Source: Kittelson & Associates/USDOT

Figure 41: Illustration. Lane-block approximation for incident scenario.

Selection of Start Time and Location for Adverse Weather

Adverse weather was applied to both directions of the entire freeway for the entire multi-hour simulation period, including the warm-up and cool-down periods. Only light rain was modeled.

Selection of Capacity Adjustments for Incidents and Weathers

According to the 2010 Highway Capacity Manual (see Table 22 and Table 23), the light rain will impact both capacity and free-flow-speed (FFS) of the freeway facility, and the incident event will impact the capacity.

- The capacity reduction factor due to light rain is 0.98 (a 2% reduction in the dry weather capacity). The free-flow speed reduction is assumed to be the same as the capacity reduction.
- The capacity reduction factor for the lane closing incident will vary according to the remaining number of lanes at the selected site for the incident.

The selected capacity and free-flow speed adjustment factors are shown in Table 24. The factors are multiplied together to represent the effects of incidents on a rainy day.

Various locations and starting times were tested in the simulation model for the incidents. It was found that locating the incident outside of the bottleneck or too early in the peak period would result in incident related congestion clearing before the recurring congestion started. The result was negligible differences in the performance of the facility with and without the incident. Given that the objective of modeling the incidents was to better understand how SPD-HARM and Q-WARN could mitigate congestion under more severe conditions than under the recurring congestion (no incident, fair weather) scenario, the incident was relocated so as to get a more representative result for incidents causing significant congestion over and above that of recurring congestion.

The final location selected for the incidents was the northbound bottleneck between the East Hillsdale Blvd on-ramp and the SR 92 off-ramp, starting at 3:30 PM. The lane blocking incidents are all coded in the VISSIM model as a bus stopping in the left hand lane of the freeway, in the northbound direction, between the East Hillsdale Blvd. on-ramp and the SR 92 off-ramp. The bus stops there for either 30 minutes or 60 minutes, starting precisely at 3:30 PM each time. This is not randomly varied between repetitions of the simulation.

Table 22: Freeway incident capacity adjustment factors based on "before incident" conditions.

Number of Lanes (One Direction)	No Incident	Shoulder Closed	One Lane Closed	Two Lanes Blocked	Three Lanes Blocked
2	1.00	0.81	0.70	0.00	n/a
3	1.00	0.83	0.74	0.50	0.00
4	1.00	0.85	0.77	0.50	0.50
5	1.00	0.87	0.81	0.67	0.50
6	1.00	0.89	0.85	0.75	0.52
7	1.00	0.91	0.88	0.80	0.63
8+	1.00	0.93	0.89	0.84	0.66

Adapted from Exhibit 10-17, and 36-16, 2010 HCM. Entries are used to factor the estimated baseline "before incident" capacity of the remaining open lanes.

Table 23: Freeway capacity and free-flow speed adjustment factors for weather.

Weather Type		CAF	SAF
Clear	Dry Pavement	1.00	1.00
	Wet Pavement	0.98	0.95
	Potentially Icy Conditions (Temp < -4 deg. F)	0.92	0.93
Rain	<= 0.10 in/h	0.98	0.95
	<= 0.25 in/h	0.93	0.93
	> 0.25 in/h	0.86	0.92
Snow	<= 0.05 in/h	0.96	0.87
	<= 0.10 in/h	0.91	0.86
	<= 0.50 in/h	0.89	0.84
	> 0.50 in/h	0.78	0.83
Reduced Visibility (not due to snow or rain)	< 1 mi	0.90	0.94
	<= 0.50 mi	0.88	0.92

Adapted from Exhibits 36-15 and Exhibits 10-15 of the 2010 HCM. CAF = capacity adjustment factor, SAF = the free-flow speed adjustment factor.

Table 24: Weather and incident effects of six baseline scenarios.

Scenario	Weather Effects		Incident Effects	Combined Effect	
	CAF_W	SAF	CAF_I	CAF_T	SAF
1	1	1	1	1	1
2	1	1	0.81	0.81	1
3	1	1	0.81	0.81	1
4	0.98	0.98	1	0.98	0.98
5	0.98	0.98	0.81	0.79	0.98
6	0.98	0.98	0.81	0.79	0.98

Note: CAF_W is the capacity adjustment factor for weather effect; CAF_I is the capacity adjustment factor for incident effect; CAF_T is the capacity adjustment factor for the scenario ($CAF_T = CAF_W * CAF_I$)

CALIBRATION OF VISSIM PARAMETERS FOR WEATHER AND INCIDENTS

According to an FHWA RITA report[20] on adapting microsimulation models to represent weather conditions, two model constants in VISSIM's car-following model must be adjusted, CC0 (standstill distance) and CC1 (headway time). They are calculated as follows:

$$CC0 = \frac{5280}{K_j} - \bar{L} \qquad \text{Equation (1)}$$

Where:

- CC0 (Standstill distance) = the desired distance between stopped cars.
- K_j = Jam density (pc/mile)
- $\bar{L}$ = average vehicle length (25 ft is used in this study)

$$CC1 = 3600\left(\frac{1}{q_c} - \frac{1}{K_j u_f}\right) \qquad \text{Equation (2)}$$

Where:

- CC1 (Headway time) = the time (second) that a driver wants to keep. The higher the value, the more cautious the driver is.
- qc = capacity (pcphpl)
- uf = free flow speed (mph)

As shown in the above two equations, CC0 and CC1 can be determined by the three macroscopic traffic stream model parameters: jam density, capacity, and FFS. Within Scenario 1, the FFS is 65 mph and the capacity is 2350. According to Table 24, the capacity and FFS of scenario 2-6 can be calculated by multiplying the capacity and FFS of scenario 1 by the corresponding CAF_T and SAF. Therefore, the only missing parameter is the jam density. Because no modifications were made on Scenario 1, the jam density of Scenario 1 can be calculated based on the value of CC0 in the baseline VISSIM model. If a constant wave speed is assumed for the congested region of the flow-density curve of all scenarios, the jam density of Scenario 2-6 can be determined. In Scenario 1, CC0 (standstill distance) is set as 4.92 ft and, therefore, the jam density is 176 pc/mile based on Equation (1). The wave speed (*w*) of the congested region is the slope of the flow-density curve in the congested region (see Figure 42). It can be calculated as

$$w = \frac{(0 - q_c)}{(K_j - 45)} = \frac{(0 - 2350)}{(176 - 45)} = -17.9\ mph$$

Where,

- 45 pc/mile is the density at capacity, which is 2350 pcphpl in Scenario 1.

[20] FHWA FITA, Microscopic Analysis of Traffic Flow in Inclement Weather, Part 2, http://ntl.bts.gov/lib/38000/38000/38026/matfiw.pdf (Accessed on 08/06/2014)

Based on the wave speed calculated above, the jam density for scenario 2-6 can be easily estimated and the values of CC0 and CC1 can be determined. The jam density can be calculated as:

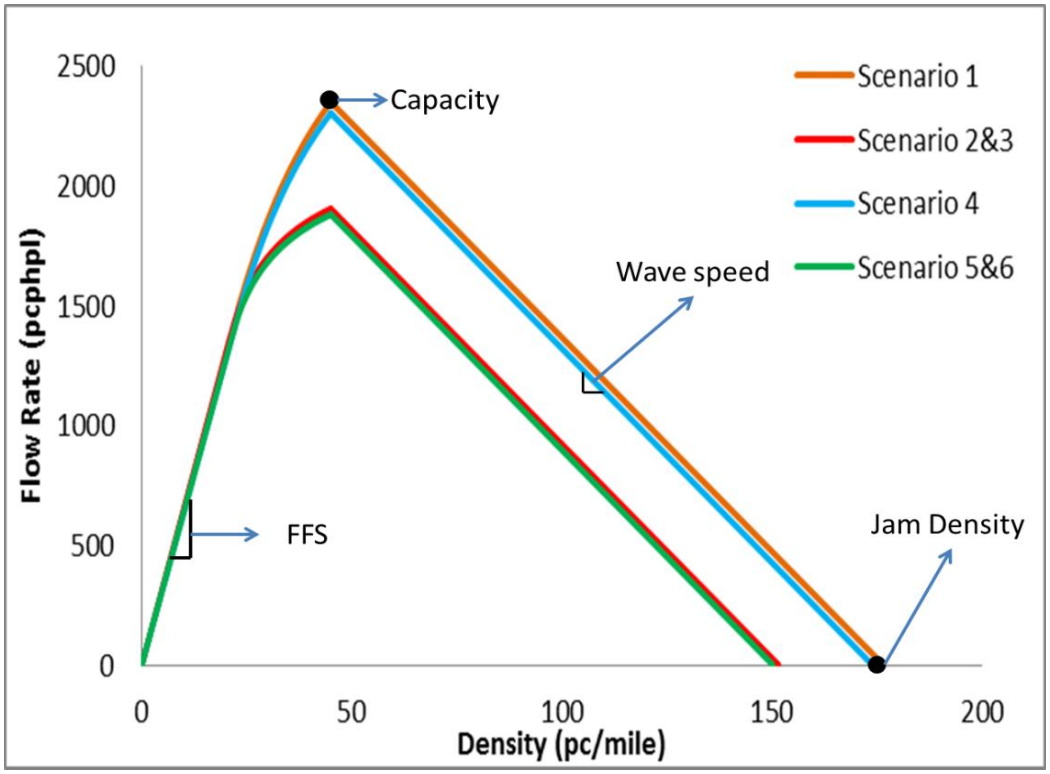
$$K_j = \frac{(0 - q_c)}{w} + 45$$

Table 25 summarizes the calibrated parameters of the macroscopic traffic stream model and the car-following model.

Table 25: Summary of calibrated parameters by scenarios.

Scenario	Capacity (pc/h/ln)	FFS (mph)	Jam Density (pc/mile)	CC0 (ft)	CC1 (s)
1	2350	65	176	4.92	0.9
2	1904	65	152	9.85	1.5
3	1904	65	152	9.85	1.5
4	2303	64	174	5.37	1.2
5	1880	64	150	10.16	1.5
6	1880	64	150	10.16	1.5

Figure 42 illustrates the emergent flow-density curves for different scenarios. The uncongested region is developed in a way similar to Exhibit 10-18 in HCM 2010, Chapter 10. The same flow breakpoint (i.e., 1400 pcphpl) is used for all scenarios. Note that these flow-density curves are put here just for illustration purpose. The development of flow-density curve is not necessary to calibrate the above car-following parameters. The values of Capacity, FFS, and Jam density are sufficient to complete the calibration process.



Source: Kittelson & Associates/USDOT

Figure 42: Graph. Flow-density curves for different scenarios.

The interim results of NCHRP 3-107 (ongoing work-zone capacity research project) also recommend some changes in the lane-change model in VISSIM for modeling work zone lane closure based on running several hundred scenarios. These values can be applied for various lane closure configurations. Considering the similarity between the work-zone scenario and the proposed incident scenario in this study (left-most lane closure), the following values of parameters (recommend by NCHRP 3-107) will be applied in the lane-changing model for modeling the incident impact.

- Lane change max deceleration = 20ft/sec^2 (own vehicle ONLY)
- Lane change slope per 1 ft/sec^2 = 100' (own AND trailing vehicles)
- Cooperative lane change = YES

Validation of Adjustment Paramenters Selected for Weather

This section documents the observed impacts of rain on the capacity and free-flow speeds of US 101 freeway. The US 101 freeway is regularly congested in the northbound direction during weekday PM peak periods near the SR 92 interchange. The NB section of US 101 just north of the SR 92 interchange was selected for validating the assumed capacity and speed effects of rainy weather.

Data analyzed include flows and speeds from loop detector data as archived and processed in the PEMS system for the baseline year 2012. The data for 48 non-holiday weekday PM peak periods (5:30-6:30 PM) for the year 2012 were obtained from the Caltrans PeMS database[21] for 1 mile of US 101 between Third Avenue (milepost 416) and the SR 92 interchange. It should be noted that these 48 days represent dry (fair-weather) incident free days.

Twenty-four hours of weather data was extracted for the year 2012 from the University of Utah on-line database (http://mesowest.utah.edu/) for the San Francisco International airport, which is next to the test bed. Weather data was then examined for the weekday, non-holiday PM peak periods (5:30-6:30 PM). Twenty six (26) days of rainy weather were observed at the airport in 2012 during the weekday PM peak period. There was no snow, ice, or ground fog conditions during 2012. The data show that adverse weather conditions were infrequent during the analysis period. Of these 26 rainy days, only 9 rainy weather days were incident free and with moderate traffic demand.

In order to assess the impact of rain on capacity for the test bed, the maximum and mean observed flows were examined for dry days and rainy days (see Table 26). The maximum observed flow on a rainy day during the PM peak hour was lower than that on a dry day by approximately 10%. There was no significant difference in mean observed flows for dry days when compared to rain days (Indicating that demand was not significantly different on rainy days).

Table 26: Measured rainy maximum speeds and maximum volumes on US 101.

Weather	Max Observed Flow Rate (veh/h)	Max Observed Speeds (mi/h)
Dry	5617	68.83
Rain	5039	61.35
Ratio Rain/Dry	0.90	0.89

The impact of rain on free-flow speeds was assessed by comparing the maximum speeds on dry days and rainy days. The maximum observed speed on a rainy day during the PM peak hour was lower than that on a dry day by approximately 11% (Table 26).

The implications for the VISSIM analysis of weather and incidents is that the capacity and free-flow speed adjustment factors of 0.98 appear to underestimate the impacts of rain on facility capacity and speeds. However, examination of the simulation runs for rainy weather conditions showed significant back-ups for all the rainy weather scenarios (using the 0.98 adjustment factors), back-ups exceeding the ability of the simulation model to clear the traffic within the original five-hour simulation period plus an extra hour of zero demand to enable the model to clear out the backed up traffic. These backups extending beyond the temporal and geometric limits of the simulation threaten the robustness of the simulation results. Consequently, the 0.98 adjustment factors for rain were retained for assessing the benefits of SPD-HARM and Q-WARN under mild rainy conditions.

[21] http://pems.dot.ca.gov/?redirect=%2F%3Fdnode%3DState#37.7743,-122.2023,10, Accessed June-July 2014.

COMPUTATION OF PERFORMANCE MEASURES

Several of the performance measures, being non-standard, will require post processing of microsimulation output files. Four different VISSIM output files will be used to calculate the nine performance measures (as identified in the rightmost column of Table 27). Within each output file, the following information/measurements are obtained from VISSIM:

Table 27: VISSIM output files post-processed for performance measures.

No.	Performance Measures	Recommendation for IA Plan	VISSIM output
1a 1b 1c	Shockwaves: Number of shockwaves formed, Length (duration), propagation speed	1a. Report mean and maximum speed drop between adjacent sub-links. 1b. Report mean and maximum speed drop between adjacent 5-minute periods within each sublink. 1c. Examine shockwaves,	Data Collection
2a 2b	Queues: Length and Duration	2a. Examine queues, 2b. Report Vehicle-Seconds in Queue per connected vehicle (VSQ).	Vehicle Record
3	Throughput (vehicles per hour)	Report Vehicle-Miles Traveled (VMT).	Data Collection
4	Speed Variance	See Performance Measures #1a-c.	Data Collection
5	Average Travel Time	Report vehicle hours traveled (VHT)	Data Collection
6	Reliability measure: Planning time index--95th Percentile Travel Time Index	Report 95th Percentile Travel Time Index (TTI).	Travel Time Measurement
7	Average number of lane changes	Report the average number of lane changes per connected vehicle	Vehicle Record
8	Average number of stops	Report the average number of stops per connected vehicle	Vehicle Record
9	Latent Demand and Delay	Report the number of vehicles denied entry to the network, as well as their delay.	Network Performance Evaluation

VISSIM Output Files

VISSIM outputs the following files: Data Collection, Vehicle Record, Travel Time Measurement and network performance measures.

The Data Collection features in VISSIM were set to output:

- Measurement points: **19** data collection stations are placed on US-101 northbound from the south of the Woodside Road interchange to the south of the State Route 92 interchange. The space between the adjacent data collection stations is 0.5 mile.[22]
- Start time of the aggregation interval and end time of the aggregation interval: these two parameters depend on the user-defined aggregation interval. For this study, a 20 second interval was used, with beginning and end times of 3,600 (14:30) seconds and 21,600 seconds (19:30), respectively.
- Number of vehicles (Q): total number of vehicles passing the data collection stations during the aggregation interval.
- Speed (V): average vehicle speed (mph) during the aggregation interval.

There are currently 30 real-world mainline detector stations each direction (each station consisting of a set of lane detectors) on the study section of US 101. For the purposes of simulating the SPD-HARM prototype, these real world detectors have been overlain with an artificial set of 19 detector stations spaced exactly 0.5 mile apart in the northbound direction only (Each artificial detector station defines a "sublink" of the freeway associated with it). The artificial detector stations will be the source of the speed and volume data used to evaluate the effects of SPD-HARM/Q-WARN.

Each artificial station output a record of the number of vehicles crossing the lane detectors at the station and the arithmetic average speed of those vehicles for the selected aggregation period (in this case, each hour of the simulation period, exclusive of the warm up period: the hours starting at 14:30, 15:30, 16:30, 17:30, 18:30)

All of the output described above was output by VISSIM to its "data collection" file.

The Vehicle Record features in VISSIM were set to output:

- Simulation Time: the simulation timestamp (second)
- Vehicle ID
- Link ID
- Total Queue Time (T_q): cumulative time for a single vehicle staying in a queue
- Direction of current lane change: the parameter indicates whether the vehicle is making a lane-change, which could be treated as a binary variable (C): 1 – lane change and 0 – no lane change.
- Number of stops: A stop is counted if the speed of the vehicle was greater than zero at the end of the previous time step and is zero at the end of the current time step.

Due to data storage limitations, the vehicle record output file will be set to only output data for connected vehicles. Connected vehicles will comprise between 10 and 50 percent of the vehicle population, depending on the setup of the different test scenarios. In the baseline scenarios (i.e., those without speed harmonization), 20 percent of the vehicle population will be labeled as

[22] Note that data collection detectors are spaced every half mile, while desired speed decision points are spaced one tenth of a mile apart.

connected vehicles for purposes of reporting data. However, in these scenarios these vehicles will behave identically to the non-connected vehicles.

To enable apples-to-apples comparisons among scenarios with different sample sizes, all performance measures obtained from the vehicle record output are normalized to a per-vehicle basis (i.e., VSQ, number of lane changes, and number of stops).

The travel time (TT) measurement is conducted on US-101 northbound in two parts:

- Part 1: from the south of the Woodside Road interchange to the south of the State Route 92 interchange.
- Part 2: from south of the State Route 92 interchange to north of the Third Avenue interchange.

The travel time (in seconds) is reported based on user-defined time interval (in this case, each hour of the simulation period, exclusive of the warm up period: the hours starting at 14:30, 15:30, 16:30, 17:30, 18:30, 19:30).

The Network Performance Evaluation evaluates several parameters that are aggregated for the whole simulation run and the whole network to an *.NPE file. Therefore, the outputs from this file will not be able to be reported on an hour-by-hour basis or on a link-by-link basis.

The following parameters are selected for output:

- Number of active vehicles: total number of vehicles on the network at the end of the simulation.
- Number of arrived vehicles: total number of vehicles that have left the network during the simulation.
- Latent demand: number of vehicles which could not immediately enter the network.
- Latent delay time: total waiting time of vehicles which could not immediately enter the network.

Latent delay time is a cumulative metric that includes waiting time of vehicles which have entered the network before the end of the simulation.

Performance Measures From Vehicle Records

Three performance measures—Vehicle Seconds in Queue (VSQ), number of lane changes, and number of stops—need be obtained from the vehicle record database from VISSIM. Ideally, these performance measures should be reported for all vehicles for the scenarios where connected vehicles were present. However, these performance measures will be reported only for connected vehicles for two reasons:

1. The SPD-HARM prototype uses the vehicle record database as an input to generate the recommended speeds for the connected vehicles. Unfortunately, the SPD-HARM prototype only needs the outputs for connected vehicles. Consequently, it was difficult to report these performance measures for all vehicles.

2. The SPD-HARM prototype requires the vehicle records reported at 20 second interval, which will generate significant amounts of data. If incorporating all vehicles into the database, the simulation will crash due to the data storage limitations.

Shockwave

The shockwaves in each scenario are quantified in terms of the speed drops between adjacent sublinks (for the same 5-minute time period) and the speed drops between adjacent 5-minute periods within each sublink for each hour simulated. The speed drops are calculated based on the outputs from data collection stations placed on the US-101 northbound.

Speed Drops between Adjacent Sub-links

Nineteen data collection stations, spaced at 0.5 miles, represent 19 sub-links along US-101 northbound from the south of the Woodside Road interchange to the south of the State Route 92 interchange. For each hour, the speed drop between sub-links is calculated as:

Equation 1

$$W_{(\mathrm{i},\,\mathrm{i}+1,\,h)} = Max[0,(V_{(i,\,t,\,n)} - V_{(i+1,\,t,\,n)})]_{t\in h, n\in N}$$

Where,

- $W_{(\mathrm{i},\mathrm{i}+1,h)}$ = the maximum difference in 5-minute average speeds for adjacent freeway sublinks within the selected hour (*h*) observed across "*N*" simulation repetitions. Only decelerating speed differences are counted. Downstream speed increases are NOT counted.
- *i* = upstream sublink number (must be northbound freeway mainline sublink)
- *i+1* = adjacent downstream sublink number (must be northbound freeway mainline sublink)
- *h* =simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30, 19:30
- *t* = 5 minute period within simulation hour (*h*)
- *V* = average speed (mph) during "*t*" in simulation repetition "*n*".

The distribution of maximum link speed differences by hour will be tabulated and the mean, max, standard deviation, and 95th percentile values will be reported for each hour of the simulation. The distribution will also be graphically reported. Note that all vehicle types across all lanes will be included in the link speed averages and only the freeway mainline links in the northbound direction will be evaluated. The first and last freeway mainline links (the simulation model entry and exit links on the freeway where vehicles are first loaded on or extracted from the network) will be excluded to minimize potential fringe effects on the results.

Note also that for the purposes of the speed difference computation the 19 artificial detector overlay (described earlier) will be used to define the freeway sublinks (each sublink linked to a specific artificial detector). VISSIM links will not be used in this computation.

Temporal Speed Drops within Sub-links

Following similar procedures as described above for between sublink speed differences, the speed drops between adjacent 5 minute periods within each sublink is computed as follows for the 19 northbound sublinks for each hour of the simulation period:

Equation 2

$$W_{(\mathrm{i},h)} = Max[0,(V_{(i,t,n)} - V_{(i,t+1,n)})]_{t\in h,n\in N}$$

Where,

- $W_{(\mathrm{i},h)}$ = the maximum difference in 5-minute average speeds within each freeway sublink (*i*) within the selected hour (*h*) observed across "*N*" simulation repetitions. Only decelerating speed differences from *t* to *t+1* are counted. Speed increases are NOT counted.
- *i* = sublink number (must be northbound freeway mainline sublink)
- *h* =simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30, 19:30
- *t* = 5 minute period within simulation hour (*h*)
- *t+1*=next 5 minute period
- *V* = average speed (mph) during "*t*" in simulation repetition "*n*".

The results for all sublinks in the northbound direction were reported for each hour of the simulation in terms of the mean, maximum, standard deviation (of the sublink variances), and the 95th percentile highest sublink result.

Average Vehicle Seconds in Queue (VSQ)

The vehicle seconds in queue is computed as follows. Set ***L*** as all the links coded in VISSIM on US-101 northbound from the south of the Woodside Road interchange to the south of the State Route 92 interchange. For each simulation hour, the VSQ per connected vehicle can be calculated as:

Equation 3

$$VSQ_h = \left(\frac{1}{N \times Q_{cv,h}}\right) \times \sum_{n} \sum_{j,l\in L} T_{q(j,l,h)} - T_{q(j,l,h-1)}$$

Where,

- VSQ_h = Average system (freeway northbound only) vehicle-seconds in queue per connected vehicle during hour "h" across "*N*" simulation repetitions
- *j* = vehicle index
- *l* = link index
- *h* = simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30

- $T_q(j,l,h)$ = total time (seconds) for vehicle, j, staying in a queue on link at the end of hour "h".
- $T_q(j,l,h-1)$= total time (seconds) for vehicle, j, staying in a queue on link at the end of hour h - 1.
- *N* = number of simulation runs
- $Q_{cv,h}$ = Average number of connected vehicles in hour *h*.

VISSIM gives the user the freedom to define what constitutes a queued vehicle[23]. Rather than change the default parameters, the following default criteria in VISSIM for determining when a vehicle is in queue have been retained:[24]

- A vehicle first enters queue when its speed drops below the default value of 5.0 km/h (approximately 3 mph)
- Once in a queued state, the vehicle remains in queue until its speed exceeds the default value of 10.0 km/h (approximately 6 mph)
- Adjacent lanes, by default, are taken into account in the evaluation

VSQ(h) is computed for each hour (h) of the peak period (excluding the warm up period) for freeway mainline links in northbound direction only. Only connected vehicles will be sampled for the calculation of this performance measure. The first and last freeway links are excluded to avoid fringe effects.

Note that VSQ is computed for VISSIM links (not the 19 artificial detector links created for the speed analysis).

Special Note: Due to file limitations of the VISSIM/SPD-HARM interface, the vehicle-seconds queued is computed only for the connected vehicles and is therefore reported in terms of the number of seconds in queue per connected vehicle.

[23] Page 650, The Queue Counters window, PTV VISSIM 6 User Manual, PTV AG, Karlsruhe, Germany, November 2013.

[24] For the purposes of computing queue lengths (not used in the VHQ computation, but provided here for completeness), two additional parameters are available to the user (default values given below):

- If the distance between any pair of vehicles exceeds the default value of 20.0 meters (approximately 60 feet) the queue is split into two (or more) queues.

- If the length of the entire queue exceeds 500.0 meters (approximately 1500 feet), the queue is split into multiple queues. This limit facilitates faster simulation run times.

Throughput – Vehicle Miles Traveled (VMT)

For each simulation hour, the VMT is calculated from the VISSIM Data Collection file using the following formula:

Equation 4

$$VMT_h = \frac{1}{N}\sum_{n}\sum_{i}(0.5 * Q_{(i,h,n)})$$

Where,

- VMT_h = Total vehicle miles traveled during hour *h* averaged across "*N*" simulation repetitions
- *i* = sub-link index
- *h* = simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30
- $Q_{(i,h)}$: Volume on sub-link measured at detector *i* (sublink length = 0.5 mile) during hour *h*
- *N* = number of simulation run repetitions

Note that 0.5 in the above equation is the distance between sublink detectors in miles.

Note that all vehicle types across all lanes are included in the VMT calculation and only the freeway mainline sublinks in the northbound direction were evaluated. The first and last freeway mainline links (the simulation model entry and exit links on the freeway where vehicles are first loaded on or extracted from the network) are excluded to minimize potential fringe effects on the results.

Post Processing Adjustment of VISSIM Reported VMT for Unserved Demand

The VISSIM reported VMT decreased for the rainy day scenarios even though the same total trips were loaded for each scenario. The decrease was due to the severe congestion in the rainy day scenarios preventing VISSIM from loading all of the input vehicle flows onto the network during the simulation period. An extra hour of zero demand was added to the simulation to clear the excess demand, which significantly reduced the unserved demand in the system for the rainy day scenarios.

To better understand the significance of the unserved VMT the VISSIM reported "Latent Demand" (the number of vehicles that were not allowed to enter the network from the input flows during the simulation)[25] was compared for each scenario.

[25] Page 637, PTV VISSIM 6 User Manual.

Average Travel Time - Vehicle Hours Traveled (VHT)

For each simulation hour, the VHT is calculated from the VISSIM Data Collection Output file of sublink detectors according to the following equation:

Equation 5

$$VHT_h = \frac{1}{N}\sum_n \sum_i \left(Q_{(i,h,n)} \frac{0.5}{V_{(i,h,n)}} \right)$$

Where,

- VHT_h = Average vehicle hours traveled during hour *h* across "*N*" simulation repetitions
- *i* = sub-link index (only northbound freeway sublinks included)
- *h* = simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30
- $Q_{(i,h)}$: Volumes on sub-link *i* (length = 0.5 mile) during hour *h*
- $V_{(i,h)}$: Average traveling speed on sub-link *i* during hour *h*
- *N*: number of simulation runs

Note that 0.5 in the above equation is the distance between sublink detectors in miles.

Note that all vehicle types across all lanes are included in the VHT calculation and only the freeway mainline sublinks in the northbound direction are evaluated. The first and last freeway mainline links (the simulation model entry and exit links on the freeway where vehicles are first loaded on or extracted from the network) were excluded to minimize potential fringe effects on the results.

Post Processing Adjustment of VISSIM Reported VHT for Unserved Demand

The VISSIM reported VHT for each scenario does not include the delays incurred by vehicles denied entry to the network because of excessive congestion. In addition, the time it would take to clear out the unloaded vehicles at the end of the simulation period is not included in the VISSIM reported VHT. Consequently, two post processing adjustments are made to the VISSIM reported delay. First the VISSIM reported Latent Delay[26] in vehicle-hours is added to the VISSIM reported VHT. Second the time required for the unloaded vehicles to complete their trip is added to the VISSIM reported VHT. The time to complete the trip is estimated for the average trip length of 5 miles within the network at a speed of 60 mph.

[26] VISSIM reports "latent delay" as the "Total waiting time of vehicles from input flows and parking lots that were not used at their actual start time in the network. This value may also include the waiting time of vehicles that enter the network before the end of the simulation." Source: Page 638, PTV VISSIM 6 User Manual.

Reliability Measure - 95th Percentile Travel Time Index (TTI)

For each simulation hour, the 95th Percentile TTI is calculated from VISSIM's Travel Time Measurement Output file according to the following equation.

Equation 6

$$TTI_h = \frac{TT_h^{95th}}{TT_h^{FF}}$$

Where,

- TTI_h = the 95th percentile travel time index of the study corridor during hour *h*
- *h* = simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30
- TT_h^{95th} = 95th percentile travel time (seconds) of the study corridor during hour *h*, calculated based on the *N* simulation repetitions
- TT_h^{FF} = Free-Flow travel time (seconds) of the study corridor during hour *h*

Travel time is only measured for the northbound direction on the freeway mainline for the study corridor. Three results are reported:

- Part 1: US-101 northbound from the south of the Woodside Road interchange, to the south of the State Route 92 interchange.
- Part 2: US-101 northbound from south of the State Route 92 interchange to north of the Third Avenue interchange.
- Combined: Combination of Part1 and 2 travel times.

Average Number of Lane Changes

The average number of freeway lane changes per connected vehicle in the northbound direction for each hour of the peak period is computed from the VISSIM Vehicle Record Output File. Set ***L*** as all the VISSIM freeway mainline links on US-101 northbound. For each simulation hour, the number of lane changes (*LC*) were calculated as follows:

Equation 7

$$LC_h = \frac{1}{N \times Q_{cv,h}} \times \sum_{n} \sum_{j,l \in L} C(j,l,h)$$

Where,

- LC_h = Average number of lane changes per connected vehicle during hour *h* across "*N*" simulation repetitions
- *j* = vehicle index

- *l* = link index
- *h* = simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30
- $C(j,l,h)$: Lane change variable for vehicle, *j*, traveling on link *l* during hour *h* for repetition "n".
- *N*: number of simulation runs
- $Q_{cv,h}$ = Average number of connected vehicles in hour *h*.

Note that only connected vehicles across all lanes will be included in the lane change calculation and only the freeway mainline links in the northbound direction will be evaluated. Only connected vehicles will be sampled for the calculation of this performance measure. The first and last freeway mainline links (being simulation model loading and extraction links) will be excluded to minimize potential fringe effects on the results.

Special Note: Due to file limitations of the VISSIM/SPD-HARM interface, the number of lane changes is computed only for the connected vehicles and is therefore reported in terms of the number of lane changes per connected vehicle

Three results are reported:

- Part 1: US-101 northbound from south of the Woodside Road interchange to south of the State Route 92 interchange.
- Part 2: US-101 northbound from south of the State Route 92 interchange to north of the Third Avenue interchange.
- Combined: Combination of Part 1 and 2.

Average Number of Stops

The average number of stops per connected vehicle in the northbound direction for each hour of the peak period will be computed from the VISSIM Vehicle Record Output File. Set ***L*** as all the VISSIM freeway mainline links on US 101 northbound. For each simulation hour, the number of stops (*S*) will be calculated as follows:

Equation 9

$$S_h = \frac{1}{N \times Q_{cv,h}} \sum_{n} \sum_{j,l \in L} S(j,l,h) - S(j,l,h-1)$$

Where,

- S_h = Average number of stops per connected vehicle during hour *h* across "*N*" simulation repetitions
- *j* = vehicle index
- *l* = link index
- *h* = simulation hours starting at 14:30, 15:30, 16:30, 17:30, 18:30
- *S (j ,l, h)*: Number of stops variable for vehicle, *j*, traveling on link *l* during hour *h.*

- $S(j, l, h\text{-}1)$: Number of stops variable for vehicle, *j*, traveling on link *l* during hour *h - 1.*
- *N*: number of simulation runs
- $Q_{cv,h}$ = Average number of connected vehicles in hour *h*.

In VISSIM, the number of stops is counted by summing the number of times that the vehicle speed reaches a speed of zero from a non-zero value. Only connected vehicles will be sampled for the calculation of this performance measure. The first and last freeway mainline links (being simulation model loading and extraction links) will be excluded to minimize potential fringe effects on the results.

Three results will be reported:

- Part 1: US 101 northbound from south of the Woodside Road interchange to south of the State Route 92 interchange.
- Part 2: US 101 northbound from south of the State Route 92 interchange to north of the Third Avenue interchange.
- Combined: Combination of Part 1 and 2.

Latent Demand and Delay

The total number of unserved vehicles—those denied entry to the network—will be obtained from the VISSIM Network Performance Evaluation output. The latent delay—the waiting time of vehicles which could not immediately enter the network—is cumulative and accounts for vehicles which were delayed, but entered the network prior to the end of the simulation.

As previously mentioned, the VISSIM output for latent demand and latent delay is reported for the whole simulation run and the whole network, such that hour-by-hour or link-by-link reporting is not possible.

THE SPD-HARM AND Q-WARN PROTOTYPE

This section describes the features and functionality of the SPD-HARM/Q-WARN prototype algorithm. This description focuses on the parameters, variables, and user interface required to operate the algorithm in a microsimulation environment.

These specifications are for a microsimulation model operation of the Battelle/TTI prototype Dynamic Speed Harmonization and Queue Warning Algorithm (the TTI Prototype), as documented in the January 15, 2014 draft Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design, by Kevin Balke, Hassan Charara, Srinivasa Sunkari of the Texas A&M Transportation Institute (Balke Report).

Overview of the TTI Prototype

This overview of the TTI Prototype is taken from the Balke report.

"Data from multiple sensors will be used in the development of queue warning and speed recommendations. These data include both infrastructure-based and connected vehicle-based systems. After obtaining the data from the various sources, the data are processed and aggregated into a form that can be used by the various components of the algorithm. The prototype is envisioned to first check whether the roadway is operating in queued state (i.e., after breakdown where stop-and-go operations exist) or congested state (i.e., before breakdown has occurred but where speeds are below free-flow conditions). The analysis will first focus on looking across all lanes (i.e., the link level). If no queues or congestion are detected at the link level, then the analysis will look for queuing at the lane level. Recommended travel speeds will be developed for each situation. Using the results of the analysis, messages will be generated that provide both queue warning and recommended travel speeds to motorist driving through the section. The information will be disseminated to a vehicle using both connected vehicles as well as infrastructure devices." Figure 43 provides a flow chart for the prototype.

Microsimulation Model Coding Requirements

Network Coding Requirements

The locations of in-road loop detectors (if any) must be specified in the microsimulation model.

The locations of changeable message signs (if any) and variable speed limit signs (if any) must be specified in the microsimulation model.

Vehicle Subtypes Required

The following five specialized vehicle sub-types can be coded in the microsimulation model for each major vehicle type (auto, bus, single unit truck, semi-trailer truck):

a) Unconnected Vehicles
b) Connected Vehicle1 (Not equipped with nomadic device or weather sensor)
c) Connected Vehicle2 (equipped with weather sensor, but no nomadic device)
d) Connected Vehicle3 (equipped with nomadic device, but no weather sensor)
e) Connected Vehicle4 (equipped with nomadic device and weather sensor)

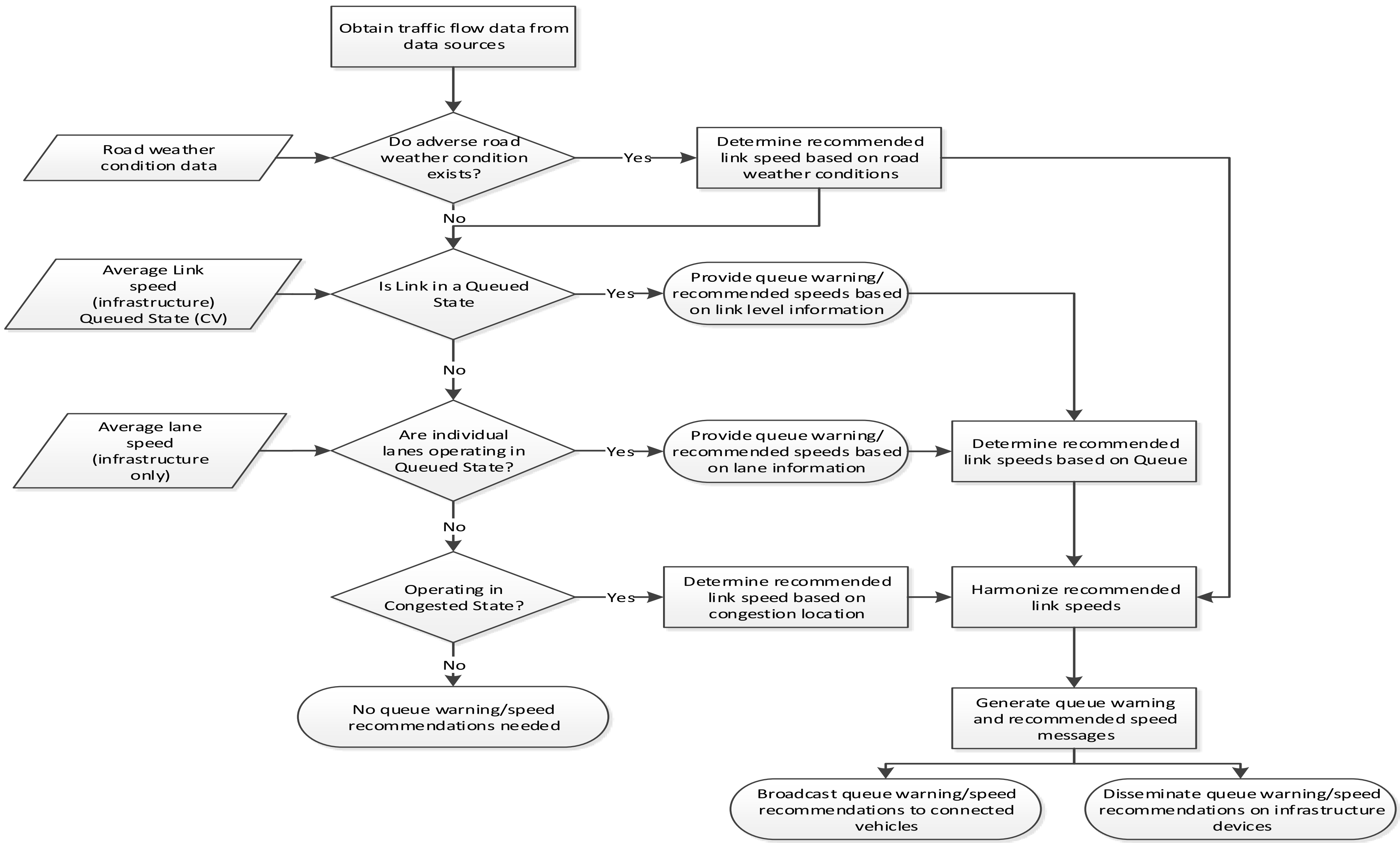
The proportions of each vehicle subtype within each major vehicle type are specified by the analyst.

Link Correspondence Table for Prototype

Directional DMA Links for the purposes of the Prototype are defined as starting a certain distance upstream of one detector and extending a certain distance upstream of the downstream detector (see page 18, Figure 3-1 of Balke report).

Each directional DMA link in the network must be subdivided into sublinks of equal length of approximately, but no less than 1/10th of a mile long. For example, if the length of a DMA link (as defined by the distance between two adjacent infrastructure-sensor stations) is 0.59 miles, then the link is divided into five sublinks, each with an approximate length of 0.12 mile each.

The Prototype requires a correspondence table between its internal DMA links and sublinks, the VISSIM detectors, and the VISSIM links.



Source: Balke, Charara, Sunkari

Figure 43: Overview of the TTI INFLO prototype.

Sources of Traffic Volume and Speed data for Prototype

The TTI Prototype draws traffic volume and vehicle state (speed, and queue status) data from in-road detectors and the connected vehicles in the microsimulation model.

Infrastructure Sources

The TTI Prototype is designed to work with "infrastructure-based roadway sensors utilizing *NTCIP 1209: Data Element Definitions for Transportation Sensor Systems*[27] "

Detectors collect data at the lane-by-lane level, which are aggregated to the station level (by averaging or summing across all lanes). The traffic status measured at the station is assumed to apply to the entire link.

Average station speeds and lane-by-lane speeds are compared to user-defined speed thresholds to determine if the speeds by link or by lane are operating in a "clear," "congested," or "queued" state. According to page 18 of Balke, "*For the prototype, initially only speed data will be used to determine operating states for the link and the lanes within the link*."

The Prototype requires the user to define speed thresholds for "clear", "congested,' and "queued" detector station and lane status. The suggested defaults at this time are shown in Table 28.

Table 28: Definition of Traffic condition status (recommended defaults).

Congestion State	Average Road Detector Station Speed
Queued	<= 5 mph
Congested	> 5 mph and <=40 mph
Clear	> 40 mph

Data from the infrastructure sensors is collected every 20 seconds.

The Prototype is designed to work in the field, so it does not currently provide for generating random lane sensor and station sensor failure rates centered on values entered by the user. Failures consist of loss of data associated with that sensor for the duration. For the simulation testing 100% lane and station sensor operation will be assumed.

If sensor failure rates were to be modeled then the suggested default value for average percent failed sensors at any one time would be 25%. Agencies with superior detector maintenance programs might select a lower value.

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

Vehicle Sources

Connected vehicles are assumed to broadcast data according to SAE J2735:2009 Basic Safety Message (BSM). Connected Vehicles will be polled by the Prototype every 0.1 second (pg 20-21 Balke) for:

- Direction of travel,
- Latitude and Longitude,
- Speed (mph),
- brake status (on, off), and
- Length (feet)

In the TTI Prototype connected vehicles will be polled for visibility (miles) and pavement surface coefficient every 1.0 second (pg. 21 Balke). However, since the prototype will also get weather data from stationary sources, this particular source does not need to be modeled in the Prototype for microsimulation modeling purposes.

The Prototype is designed to work in the field, thus it does not currently have a random factor centered on a user defined value to add random error to the Latitude and Longitude reported by the vehicle. For the simulation testing it will be assumed that there is no error in the GPS positions.

If GPS error were to be modeled then the suggested user range of error in GPS position (for a civilian unit) is 5 to 15 meters (15 feet to 50 feet). The lower values apply to optimal clear sky, dry conditions.[28] A default value of 30 feet is suggested. The user should increase this value for facilities near tall buildings and mountains under humid conditions. Thus, the lane position of a connected vehicle cannot be known by the Prototype.

The Prototype calculates the linear position of the vehicle within the link based on its latitude and longitude.

The queued state of the connected vehicles is determined based on the user set minimum threshold speed (pg 24 Balke). Five mph is suggested as the default (pg. 23 Balke). The distance to adjacent downstream vehicle is not always available (because of unconnected vehicles in the stream), so speed will be the only indicator of queue state.

Table 29: Definition of traffic condition status (recommended defaults).

Vehicle Queue State	Vehicle Speed
Queued	<= 5 mph
Not Queued	> 5 mph

[28] Wikipedia. (n.d.). *Error Analysis for the Global Positioning System*. Retrieved January 24, 2014, from Wikipedia: http://en.wikipedia.org/wiki/Error_analysis_for_the_Global_Positioning_System

Road Weather Condition Data for Prototype

The TTI prototype draws weather information from four sources: stationary sensor stations, mobile sensor stations, connected vehicles, and external weather providers (pg. 29 Balke). For simulation testing purposes, the weather will be dictated by the user. The user provides the Prototype with the weather data to be modeled, specifying the directional DMA links and five-minute time periods to which each weather condition applies.

The weather data, which is sublink specific and updated every five minutes (pg. 34 Balke), consists of:

- Pavement coefficient of friction factors (pg. 30 Balke)
  - 0.80 for dry pavement (est.),
  - 0.60 for wet pavement, and
  - 0.25 for snow/ice on pavement.
- Visibility in miles.[29]
  - Good > 0.50 miles
  - Poor <=0.50 miles

For the weather speed recommendation the Prototype uses the look-up table approach described on page 45 of Balke. This provides for three pavement conditions (dry, wet, ice/snow) and two visibility conditions (good, poor).

The weather data is assumed to be applicable uniformly to the entire sublink across all lanes for the five-minute period. It can vary between sublinks on the facility, but to simplify user input requirements, only link level weather will be input. Thus, weather will be uniform across all sublinks of the link, within the simulation implementation of the Prototype.

Queue Warning Prototype

The queue warning Prototype has two functions:

1. Detection of queues from road infrastructure and connected vehicles, and
2. Delivery of queue warnings to connected vehicles and changeable message signs.

The TTI prototype generates queue warning messages using three different algorithms operating in parallel: A TME (transportation management entity) Based Algorithm, a Cloud Based Algorithm, and a Vehicle Based Algorithm. Since for microsimulation modeling purposes the vehicle will be indifferent to the source of the queue warning, the simulation implementation of the Prototype is designed to generate queue warning messages regardless of the source of information upon which they are based.

Every 1/10th of one second (page 42 Balke), at time "t", the Prototype checks the queue status of all sublinks. A sublink is defined by the Prototype as "queued" if:

[29] Values taken from Exhibit 10-15, 2010 Highway Capacity Manual

1. There is a detector station located within the sublink AND a user specified minimum percentage of the lane detectors at the detector station are in “Queue” status. In-operational lane detectors count against the percentage. See earlier description of how queue status is determined for detector stations; OR
2. There are a user specified minimum number of connected vehicles located within the sublink at time “t” AND a user specified minimum percentage of those connected vehicles are in “Queued” status. Communication losses (temporarily disconnected connected vehicles) count against the minimum number and percentage of connected vehicles. See earlier description of how queue state is determined for connected vehicles; or

If a sublink is determined to be “queued,” that status applies to all lanes within that sublink. In the case of detector stations that are determined to be “queued,” that status applies to all sublinks for the link associated with that detector station.

Although not currently in the prototype, future simulation testing of the Prototype should have user-selectable toggle switches to:

- Turn on and off the ability to obtain queue status from all detector stations (so that an un-instrumented facility can be easily modeled), or to
- Turn on and off the ability to obtain queue status from all connected vehicles (for modeling an instrumented facility without connected vehicles).

The Prototype has user-specifiable parameters for:

- Setting the minimum number of functional lane sensors in the sublink at time “t” for it to trigger “queued” status for the sublink;
- Setting the minimum percent of lanes at a detector station that must be in “queue” to trigger a detector station “queue” status;
- Setting the minimum number of connected vehicles that must be present in the sublink at time “t” for it to trigger “queued” status for the sublink;
- Setting the minimum percent of connected vehicles that must be in “queued” status to trigger “queued” status for the sublink.

The back of queue is the farthest upstream sublink of a continuous set of sublinks in “queued” status regardless of whether the status was determined via detectors or connected vehicles. There can be several back-of-queues sublinks on a facility or a link.

Queue warning messages are delivered to all connected vehicles and changeable message signs located within a user specified distance upstream of the back of queue at time “t”. Page 40 of Balke suggests the distance be 10 miles.

How the driver should respond to them is not currently specified for the TTI Prototype. For the purposes of the current round of simulation testing the approach has been to let VISSIM use its own internal driver behavior model decide when drivers are aware of queues and how they respond. In essence, the advance information of downstream queues before they are visible to the driver will not be modeled.

For future tests, it is suggested that Q-WARN be modeled as follows. The TTI prototype message (which includes the number of miles to the back of queue) repeats the queue warning each mile (but there is no change in driver behavior) until the vehicle is within one mile of the back of queue at which point:

1. The driver's target car-following headways for all speeds are increased in the microsimulation model by a user-defined percentage (perhaps 10% for starters).
2. The driver's desired travel speed is reduced in the microsimulation model by a user defined percentage (perhaps 10% for starters).

The Prototype would need to provide for user-specified percentage increases in car following headways and decreases in desired speed, perhaps 10% default values for now.

Weather Speed Recommendations Prototype

The TTI Prototype provides for generating weather recommended speeds for two levels of visibility (good and poor) and three levels of pavement condition (dry, wet, icy/snow) (page 45 Balke) using a table of values input by the user.

The Prototype provides for a user-definable 2x3 look-up table of speed recommendations by pavement condition and visibility. Table 30 shows table with initial recommended default values for consideration.

Table 30: Weather speed recommendations look-up table (recommended defaults shown).

Visibility	Pavement Condition		
	Dry	Wet	Ice/Snow
Good (>.50 miles)	Driver's Desired Speed for link under ideal conditions	Minimum of 55 mph or 90% of ideal	Minimum of 45 mph or 70% of ideal*
Poor (<=0.50 miles)	Minimum of 45 mph or 75% of idea	Minimum of 35 mph or 60% of ideal	Minimum of 25 mph or 55% of ideal*

**Assumes plowed road.*

Speed Harmonization Recommendations Prototype

The TTI Prototype updates speed harmonization recommendations once every 5 seconds. The recommended speeds may change no more than 5 mph every 15 seconds (page 49 Balke). Since the recommended speeds cannot be changed more frequently than once every 15 seconds, the Prototype computes speed harmonization recommendations only once every 15 seconds and round the recommendations down to the nearest 5 mph divisible value.

Note that the infrastructure detector speeds are updated every 20 seconds.

The TTI Prototype makes use of historic speeds to fill in missing data. The simulation implementation of the Prototype will NOT make use of historic data because the quality of such data is site and situation specific, and would cloud the comparison results.

Determination of Existing Sublink Speed

The determination of existing sublink speeds follows the algorithm:

1. For each link with a user defined minimum number and minimum percentage of lane detectors in operation, the Prototype will compute the simple average speed across lanes. This same observed average speed is assigned to all sublinks within the link.
2. For each sublink with a user defined minimum number of connected vehicles the Prototype should compute the simple average speed across all connected vehicles in the sublink over the 15 second time period.
3. The connected vehicle speeds will override the detector speeds for all sublinks where a detector is NOT present.
4. For sublinks where a detector is present AND both connected vehicle speeds and detector speeds are available, the lower of the two speeds is the selected speed. (Figure 6-1, page 50 of Balke).
5. Sublinks without observed speeds from the prior 4 steps are assigned a "No Data" status for speed.

The Prototype provides for smoothing of the connected vehicle speeds over a user specified "N" 5-second periods. The simulation of the Prototype will automatically address this by computing average 15 second speeds (where N = 3) for connected vehicles. The number of periods for smoothing will not be user adjustable.

Calculation of Recommended Sublink Speeds for Speed Harmonization

Following the general approach described on pages 48-57 of Balke for the speed harmonization prototype, the Prototype will use the following algorithm to determine the recommended speeds for the connected vehicles and the gantry signs.

For each 15-second period, the Prototype identifies adjacent sublinks with similar enough observed speeds that should be grouped together for speed harmonization purposes.

1. Start with first upstream sublink.
    a. Set maximum and minimum speed thresholds for the first group of sublinks based on this first sublink.
    b. Add and subtract ½ of user specified acceptable range of speeds to the observed mean speed for grouping sublinks together. Use Seattle range of 12 mph as default. Thus, if mean observed speed is 57 mph, the acceptable range for adding downstream sublinks to this group for speed harmonization purposes is 51 mph to 63 mph.
2. Continue to downstream sublink
    a. If candidate downstream sublink has "no data," add it to the speed harmonization group, go to next sublink downstream
    b. If observed mean speed of downstream sublink falls within acceptable range, add it to the speed harmonization group.

            i. Recompute mean speed and max/minimum range for augmented group of sublinks.

        c. if candidate downstream sublink's observed mean speed falls outside the speed range for the group then:

            i. Check to see that group of sublinks can be traversed at the mean speed for the group in less than 15 seconds.

                1. If less than 15 seconds, add next downstream sublink (regardless of its mean speed), recompute average and range and continue on.

                2. If greater than or equal to 15 seconds,

                    a. stop adding sublinks to this group.

                    b. Start new group (go back to step 1)

3. Repeat steps 1 and 2 until all sublinks in analysis direction have been grouped.

    a. If last group is less than 15 seconds to traverse, add last group to second to last group.

4. Set recommended speeds for connected vehicles within each sublink group

    a. Round mean speed of group up to nearest 5 mph, subject to not exceeding the user specified posted speed limit or falling below the user specified minimum speed for the facility.

        i. This is the initial recommended speed for all connected vehicles within the group of sublinks.

    b. Check initial recommended speeds for transitions between adjacent groups of sublinks.

        i. If the upstream speed is more than 5 mph greater than the downstream speed, transition in 5 mph increments for upstream sublinks within the upstream group.

5. Set recommended speeds for gantries located within each sublink group

    a. The gantry speed in the sublink in which the gantry is located should match the recommended connected vehicle speed for the same sublink.

Note that this logic allows the recommended speeds between gantries to differ by more than 5 mph if they are more than ½ mile apart. This provides flexibility to accommodate more widely spaced gantries. Regardless, the logic does not allow speed changes of greater than 5 mph for every ½ mile of facility.

User Definable Parameters for Prototype

Table 31 provides a list of the user definable parameters that must be provided in the Prototype. Table 32 identifies the microsimulation model parameters required to test the prototype under varying conditions.

Table 31: User definable parameters for TTI prototype.

User Definable Q-WARN Parameter	Comment
6. Average Speed Threshold for Queued State	Set at 5 mph for all tests
7. Min. Seconds below speed threshold before Lane detector is considered to be in "Queue"	Perform side tests to find best values under varying equipment error rates.
8. Criteria for Link in "Queue" state a. Number Lane Detectors in "Queue". b. Percent Lane Detectors in "Queue".	Perform side tests to find best values under varying equipment error rates.
9. Min. Seconds below speed threshold before connected vehicle is considered to be in "Queue"	Perform side tests to find best values under varying equipment error rates.
10. Criteria for SubLink in "Queue" state a. Number connected vehicles in "Queue". b. Percent connected vehicles in "Queue".	Perform side tests to find best values under varying equipment error rates.
11. Upstream broadcast range for queue warning	Set at 1 mile for all tests
User Definable SPD-HARM Parameters	**Comment**
12. Recommended speeds by visibility and pavement condition type	Set at values shown in Table 30
13. Criteria for Valid Link Speed determination: a. Number Lane Detectors in operation b. Percent Lane Detectors in operation.	Perform side tests to find best values under varying equipment error rates.
14. Criteria for Valid SubLink Speed determination: a. Number connected vehicles present with comm. b. Percent connected vehicles present with comm. c. Smoothing period (min/secs) for speed estimates.	Perform side tests to find best values under varying equipment error rates.
15. Speed range for determining troupes for SPD-HARM	Perform side tests to find best values under varying equipment error rates.
16. Maximum and Minimum speeds for SPD-HARM	Set at 70 mph and 30 mph

Table 32: Parameters for testing of TTI prototype in microsimulation model.

User Definable Microsim Parameter	Comment
1. Percent Connected Vehicles	Net percent connected vehicles that receive the SPD-HARM message and comply with it.
2. Road Detector Spacing	Average miles between traffic state detection (volume and average speed by lane)
3. Changeable or Dynamic message sign spacing	Average miles between dynamic or changeable message signs capable of displaying recommended speed.