Transportation Research Procedia
Volume 15, 2016, Pages 459–470
ISEHP 2016. International Symposium on Enhancing Highway Performance

Performance Benefits of Connected Vehicles for Implementing Speed Harmonization

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Abstract

This paper reports on a microsimulation and small scale demonstration evaluation of the freeway performance effects of a specific connected vehicle implementation of speed harmonization.

Keywords: Connected Vehicles, Speed Harmonization, Freeway

1 Introduction

The advent of connected vehicle technology has made possible continuous real time monitoring and communication with drivers, which in turn enables the possibility of providing real-time guidance to drivers to promote safer driving. Speed harmonization and advanced queue warning are two examples of the types of real-time guidance that connected vehicle technology would enable agencies to apply in order to promote safer driving.

This paper reports on the results of an impacts assessment of one particular implementation of the dynamic speed harmonization concept with advanced queue warning (“The Prototype”). The Prototype was developed by Kevin Balke, Hassan Charara and Srinivasa Sunkari (Balke, Charara, & Sunkari, 2014) for the United States Federal Highway Administration. This particular implementation of dynamic speed harmonization and advanced queue warning will be abbreviated as SPD-HARM and Q-WARN in this paper. SPD-HARM and Q-WARN are two component applications of FHWA’s envisioned Intelligent Network Flow Optimization (INFLO) bundle (Mahmassani, Rakha, Hubbard, & Lukasik, 2012).

This paper:

(i) Assesses the mobility impacts of a SPD-HARM with Q-WARN,
(ii) Indirectly assesses the potential safety implications of SPD-HARM with Q-WARN, and

Selection and peer-review under responsibility of the Scientific Programme Committee of ISEHP 2016

doi:10.1016/j.trpro.2016.06.039

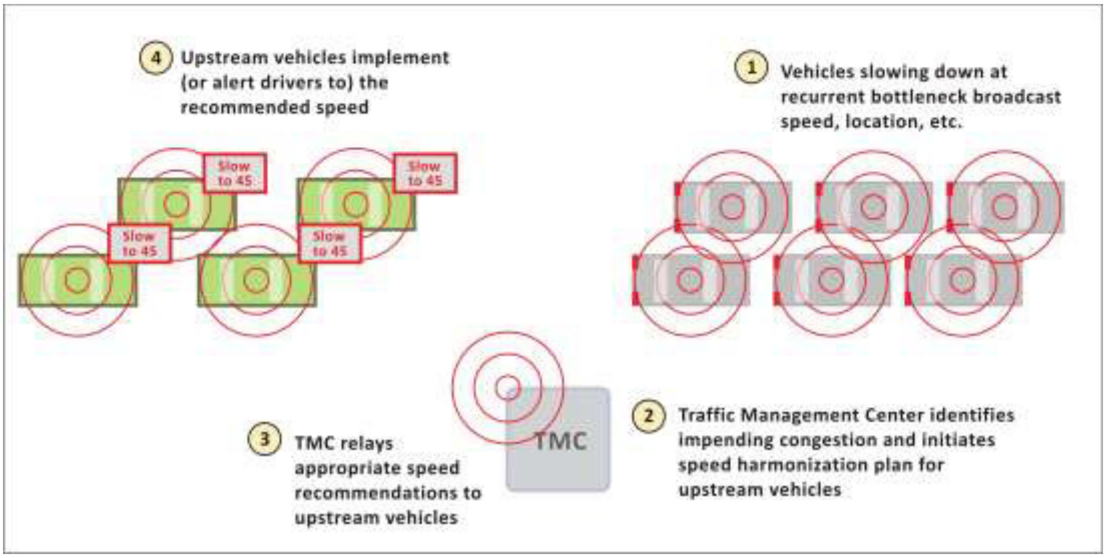
(iii) Investigates how these impacts vary for varying levels of potential future market acceptance for connected vehicle devices.

2 The Speed Harmonization Prototype

The concept of speed harmonization is that reducing the speed differences between vehicles in response to downstream congestion, incidents, and weather or road conditions can greatly help to maximize traffic throughput and reduce crashes. The Intelligent Network Flow Optimization (INFLO) SPD-HARM application concept selected by FHWA 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 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: (Mahmassani, Rakha, Hubbard, & Lukasik, 2012).

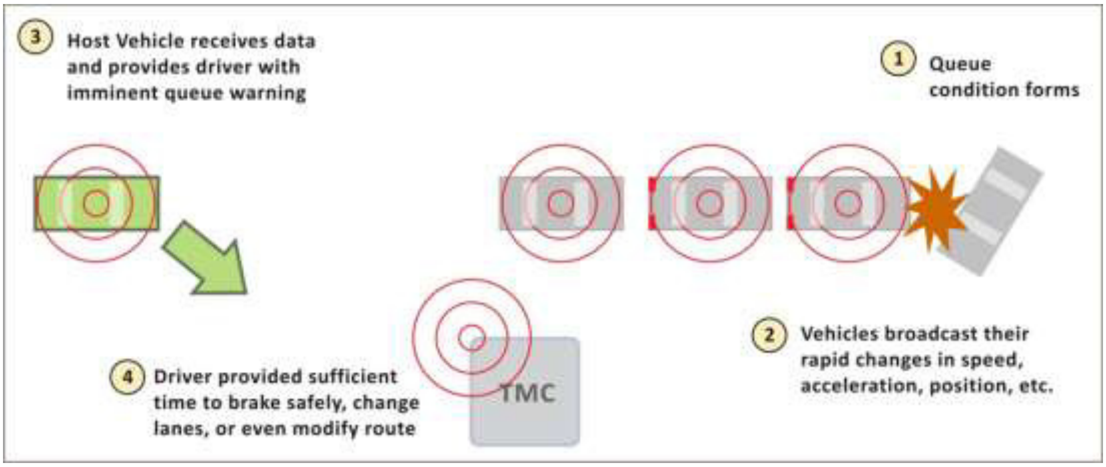
Figure 1: Illustration. SPD-HARM concept with connected vehicles

The SPD-HARM prototype developed by Balke et al. implements specific aspects of the speed harmonization concept. In particular, the SPD-HARM prototype does not predict traffic conditions; it only reacts to observed congestion. More specifically, the prototype has the following features:

- 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.
- 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 (to avoid unduly distracting the driver from his or her driving task).
- The recommended connected vehicle speeds should be the same as that displayed on any roadway variable speed signs (if any present).
- Recommended speeds are advisory, not regulatory.
- There is always a recommended speed displayed for each sublink (which may be the agency specified maximum speed in the absence of vehicle or road detector data).

3 The Advanced Queue Warning Prototype

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: (Mahmassani, Rakha, Hubbard, & Lukasik, 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 implemented by Balke et al. has the following features:

- 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 an agency user-set maximum speed threshold for being in queue state for an agency 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. Thus queue warnings cannot be lane specific in the Q-WARN prototype. This reflects the expected limitations in the precision of the GPS devices used to geo-locate the vehicles.

4 Development of the Experimental Plan

An Impact Assessment (IA) Plan was developed to ensure that the microsimulation experiments addressed the key research questions:

- Which communication process is best for nomadic devices (cellular or dedicated short range communications)?
- What level of market penetration is required?
- What are the effects of communication errors and latency?

- What are the benefits of widespread roadside equipment deployment (RSE) deployment to support dedicated short range communications (DSRC) to the mobile devices?
- Is connected vehicle data required for success?

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

The Concept of Operations for SPD-HARM and Q-WARN identified the desired performance measurements to assess the effectiveness of the Prototype (Mahmassani, Rakha, Hubbard, & Lukasik, 2012). Specific measures of effectiveness were then identified in the Impact Assessment Plan to address the desired performance measurements (see Table 1).

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.

Based on an assessment of historic traffic demand, incident, and weather patterns for the facility a total of 6 scenarios were selected for microsimulation analysis of the effects of SPD-HARM (See Table 2).

The Impact Assessment Plan specified the experimental plan to be pursued during the microsimulation tests.

Table 1: Selected Measures of Effectiveness

ConOps Performance Measurement	Comments	Selected Measure of Effectiveness
Traffic Shockwaves	Useful for diagnosis, but too detailed to compare across scenarios.	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 (vehicles/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: GHG emissions and fuel consumption	Data intensive computations.	Discuss qualitatively.
User Acceptance: Market penetration and compliance with speed messages	Available resources insufficient to test user acceptance.	Conduct sensitivity assessment of market penetration and compliance.
Safety Effects: Number and 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.

GHG = greenhouse gas

Table 2: Operating Environment Scenarios for Testing SPD-HARM

Op. Env. Scenario	Demand	Incident Type	Weather Type	Probability
1	Hourly variation	None	Dry Pavement	79%
2	Hourly variation	1 Ln – 30 min	Dry Pavement	7%
3	Hourly variation	1 Ln – 60 min	Dry Pavement	4%
4	Hourly variation	None	Wet Pavement	8%
5	Hourly variation	1 Ln – 30 min	Wet Pavement	1%
6	Hourly variation	1 Ln – 60 min	Wet Pavement	1%
			Total	**100%**

Notes:

- *Demand:*
  - *Due to the severe capacity constraints in the corridor, reliable measurements of variations in peak period demand could not be obtained from freeway mainline counts (measured variations in volumes were actually variations in capacity due to unrecorded incidents). Consequently, the effects of SPD-HARM under different levels of demand were assessed by examining variations in hourly performance of SPD-HARM within the median peak period for the year. The coded demands ranged from 30,000 vehicles per hour (during the last hour of the peak period) to 43,000 vehicles per hour (during the peak hour of the peak period). These same demands were used for simulation model validation.*
- *Incidents:*
  - *None: 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.*
  - *1 Ln – 30 min = one lane closed for 30 minutes.*
  - *1 Ln – 60 min = one lane closed for 60 minutes.*
- *Wet pavement was evaluated as a light falling rain condition (0.1 inch per hour)*
- *Probabilities were estimated based on historic experience for the approximately 250 non-holiday weekday peak periods in a year.*

5 Prototype Testing Using Simulation

The SPD-HARM prototype was tested using microsimulation modeling of a real world freeway. It was determined that Q-WARN could not realistically be tested in a microsimulation environment at this time because of the lack of information in the literature on how drivers would respond to notices of queues one to ten miles ahead, without information on which lane the queue would be in or the anticipated delay due to the queue and the status of alternative routes. Thus the microsimulation analysis evaluated the impacts on freeway performance of only the SPD-HARM speed recommendations.

The test site was 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 3). The study period is five hours of the PM peak period extending from 2:30 PM to 7:30 PM. SPD-HARM was tested in only the northbound direction of the freeway due to the lack of recurring congestion in the southbound direction on this section of US 101 during the PM peak period.

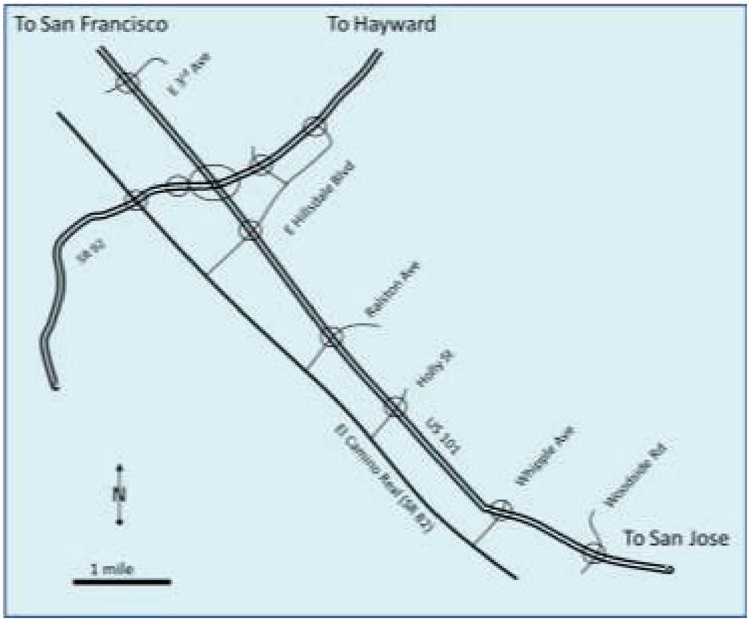


Figure 3: Map. The San Mateo US 101 test site

The SPD-HARM/Q-WARN prototype was written by Balke et al. as a VISSIM com interface. This interface would take the VISSIM reported vehicle status (speed and position) and the VISSIM reported road detector data (vehicle occupancy and speed) and apply the SPD-HARM algorithm at 20 second intervals to compute a recommended speed. A second VISSIM com interface was then written by Dr. Jia to deliver the recommended speed to the appropriate vehicles in VISSIM. The percent of vehicles sending and receiving connected vehicle data was varied for each run. The com interfaces assumed that 100% of the vehicles receiving the SPD-HARM recommendations would comply with the recommended speeds coming from SPD-HARM.

Figure 4 illustrates some of the results obtained regarding the impacts of SPD-HARM on freeway speeds. More details can be found in the full report (Dowling, Skabardonis, Barrios, Jia, & Nevers, 2015) and in the conclusions of this paper. As shown in this figure the SPD-HARM prototype reduced the 95th percentile highest speed difference between vehicles on a link (intralink shockwave) by up to 30% (see Figure 4). It reduced the 95th percentile highest difference between the mean speeds of adjacent links (interlink shockwave) by up to 50% (in the range of responding vehicles tested). These reductions in shockwaves came at the expense of an overall 5% to 10% reduction in the mean speed of all vehicles on the freeway.

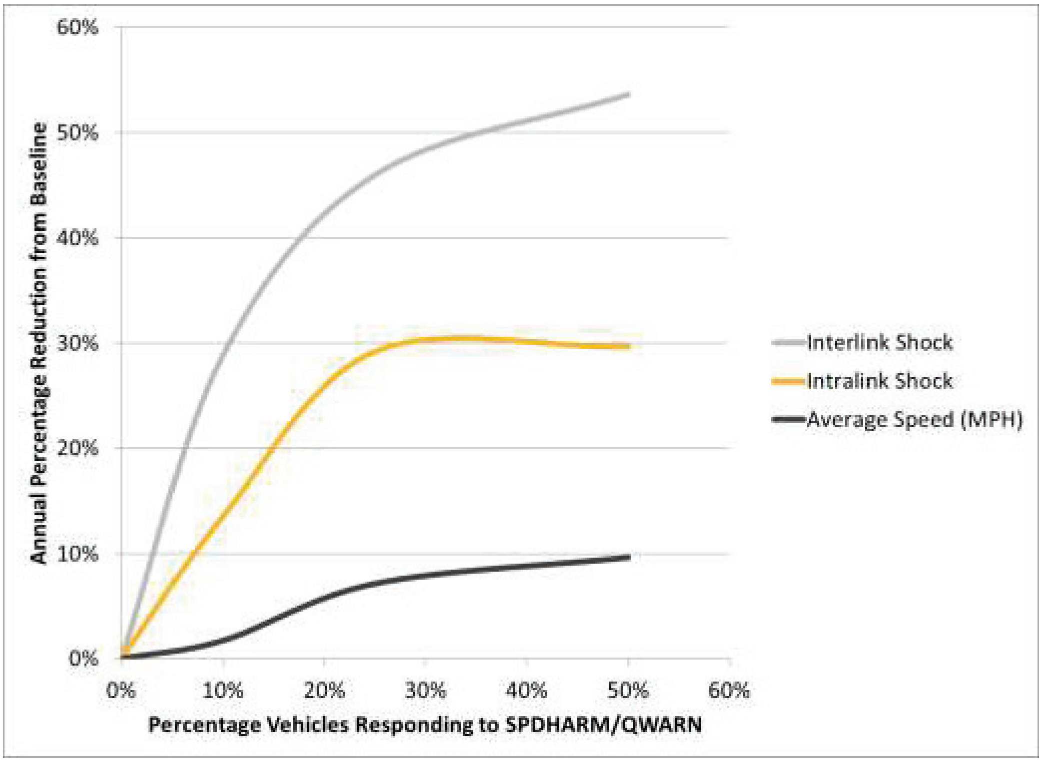


Figure 4: Annualized Impacts of SPD-HARM on Shockwaves and Average Speed.

6 Small Scale Field 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 Stephens et al. (Stephens, Timcho, Smith, Balke, Charara, & Sunkari, 2015).

For the small-scale demonstration, Stephens et al. worked with the Washington State Department of Transportation (WSDOT). Stephens et al. installed connected vehicle systems in 21 vehicles, and deployed them 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, 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 small scale field demonstration 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.

7 CONCLUSIONS

The combined conclusions of the simulation tests and the small-scale demonstration are presented below.

The microsimulation analysis found that:

a) The Prototype significantly reduces the magnitudes of the speed drops (shockwaves) between vehicles, even at the 10% (of the total vehicle fleet) response level. Although not tied directly to crash reductions, this reduction of shockwaves 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% (of the total vehicle fleet) response 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 might 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 agency 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. The reduced speed differences between vehicles 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).

As reported by Balke et al. (Balke, Charara, & Sunkari, 2014) the small-scale field demonstration found that:

e) There was no evidence in the small-scale demonstration of:
  - Loss of Basic Safety Message (BSM) data (US Department of Transportation), whether DSRC (dedicated short range communication) or cellular telephone was used,
  - 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.

f) 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.

g) 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.

h) 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.

i) The current operation of the Washington State Department of Transportation (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.

j) 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.

8 Acknowledgements

This paper is based upon work supported by the Federal Highway Administration under contract number DTFH61-12-D-00044. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the Federal Highway Administration.

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