RITA *Intelligent Transportation Systems Joint Program Office*

Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO)

Concept of Operations Walkthrough Workbook

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April 27, 2012

U.S. Department of Transportation

Research and Innovative Technology Administration

ITS Joint Program Office
Research and Innovative Technology Administration
U.S. Department of Transportation

Notice

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1 Introduction

This document is the Intelligent Network Flow Optimization (INFLO) Concept of Operations walkthrough workbook to be reviewed and updated by INFLO stakeholders participating in the April 27, 2012 ConOps walkthrough.

1.1 Walkthrough Objectives

The objective of this walkthrough is to obtain INFLO stakeholder feedback on the draft Concept of Operations (ConOps) from a functional, technical, management, and implementation perspective. The ConOps is intended to provide system concepts, operational scenarios, and the rationale for key concept decisions related to the deployment of the INFLO applications.

This workshop will build upon the stakeholder input received at the February 8, 2012 workshop on INFLO goals, performance measures, transformative performance targets, and user needs. In particular, the walkthrough will focus on:

- Confirming key INFLO operational scenarios
- Confirming performance measures and targets
- Confirming user needs and roles and responsibilities
- Identifying next steps for refining the INFLO ConOps

Feedback from this walkthrough will be used to finalize the INFLO Concept of Operations.

1.2 Walkthrough Preparation

This workbook has been structured to address key sections of the draft Concept of Operations document. With the time provided, the discussion will focus the objectives identified above, as well as provide for an opportunity to obtain additional input and insights.

The research team requests walk through participants to review the sections of the workbook and corresponding sections of the document prior to the discussion on April 27. This workbook is organized into the following sections:

1. Introduction
2. Walkthrough Workshop Agenda
3. INFLO Background

4. Justification for and Description of INFLO Changes
5. Goals, Performance Measures, and Transformative Performance Targets
6. INFLO Applications Operational Concepts
7. System Users and User Needs
8. INFLO Applications Operational Scenarios
9. Summary of Impacts
10. Analysis of Proposed System

2 Agenda

Intelligent Network Flow Optimization (INFLO)
Concept of Operations Walkthrough

Friday, April 27, 2012, 8:30 a.m. – 4:00 p.m.

Location:
Detroit Metro Airport Marriott
30559 Flynn Drive
Romulus, Michigan 48174

8:30-8:45	1. Welcome and Introductions 2. Meeting Objectives	Yousuf
8:45-9:15	3. INFLO Background and Methodology	Lukasik
9:15-9:45	4. Review of Justification for and Description of Desired Changes	Lukasik
9:45-10:30	5. Review of Goals, Performance Measures, and Targets	Hubbard
10:30-10:45	**Break**	
10:45-11:15	6. Operational Concept	Mahmassani Rakha Lukasik
11:15-12:00	7. Users and User Needs	Mahmassani Rakha Lukasik
12:00-1:00	**Lunch**	
1:00-2:30	8. Operational Scenarios and Evolution of the System	Mahmassani Rakha Lukasik
2:30-3:00	**Break**	
3:00-3:15	9. Summary of Impacts	Lukasik
3:15-3:45	10. Analysis of Proposed System	Lukasik
3:45-4:00	11. Wrap-up and Next Steps	Yousuf Lukasik
4:00	**Adjourn**	

3 INFLO Background and Methodology

In support of USDOT's Intelligent Transportation Systems' (ITS) Mobility Program, several of the Department's agencies are fully engaged in exploiting active interaction between fixed and mobile transportation system entities both in the way new forms of data are being exchanged and in the opportunities that are afforded to extend the geographic scope, precision and control of our Nation's surface transportation system. An important initiative within the framework of this strategic effort is the Dynamic Mobility Applications (DMA) program which, in part, seeks to create applications that fully leverage frequently collected and rapidly disseminated multi-source data gathered from connected travelers, vehicles and infrastructure, and that increase efficiency and improve individual mobility while reducing negative environmental impacts and safety risks. Under this program, the USDOT has identified a portfolio of ten high-priority mobility applications, including a common bundle collectively identified as Intelligent Network Flow Optimization, or INFLO.

The purpose of the INFLO project is to facilitate concept development and needs refinement for the INFLO applications and to assess their readiness for development and testing. The three applications under the INFLO bundle will ultimately help to maximize roadway system productivity, enhance roadway safety and capacity, and reduce overall fuel consumption. These three applications are:

- Queue Warning (Q-WARN);
- Dynamic Speed Harmonization (SPD-HARM); and
- Cooperative Adaptive Cruise Control (CACC).

In selecting these applications, the USDOT sought applications that have the potential to be transformative (i.e., that they result in substantial roadway mobility and safety improvements), that are achievable in the near-term, and that leverage the opportunities provided through connected entities. This philosophy of identifying applications that can be deployed in the near-term is in keeping with the USDOT's goals of quickly moving these applications from the research stage to adoption in the field.

The Concept of Operations (ConOps) document, which this walkthrough workbook will help to develop, provides a conceptual overview of the proposed INFLO applications. The ConOps is intended to support the development and eventual near-term deployment of subsets of or the entire INFLO application bundle. Moreover, the ConOps is a living document and will be coordinated in a collaborative manner with agency, industry, and public stakeholders to ensure the viability of the concepts represented.

Once completed, the INFLO ConOps will be used to develop the functional and performance requirements and high-level data and communication needs for INFLO. Further, this ConOps will facilitate the identification and assessment of key technical and non-technical issues related to field-testing the INFLO bundle and its individual component applications.

4 Justification for and Description of Desired Changes

4.1 Justification for Changes

Speed Harmonization
Current speed harmonization implementations are fundamentally limited by their exclusive reliance upon infrastructure-based detection and alerting. This imposes a number of limitations on the system, impacting its ability to:

- Target appropriate speed limit recommendations to specific portions of the facility
- Ensure that generated speed recommendations are received by drivers
- Obtain sufficient traffic and road weather data to be able to produce accurate speed recommendations
- Operate for sufficient periods in the day to provide speed guidance whenever the need may arise
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Queue Warning
Like with speed harmonization, queue warning's reliance upon infrastructure-based detection and alerting imposes a number of limitations on the system, impacting its ability to:

- Locate and distribute queue warnings sufficiently along a facility
- Ensure that generated warnings are received by drivers
- Obtain sufficient traffic and road weather data to be able to produce accurate warnings
- Operate for sufficient periods in the day to provide warnings whenever queues occur
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Cooperative Adaptive Cruise Control

No operational CACC implementations currently exist since CACC is reliant upon yet-to-be-deployed connected vehicle technologies. However, an operational CACC system would benefit the current transportation system in terms of:

- Increased facility throughput
- Delayed breakdown formation
- Reduced shockwave propagation
- Increased travel time reliability
- Reduced number and severity of crashes
- Reduced energy consumption and emissions
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4.2 Speed Harmonization Proposed Changes and Prioritization

Recommended Changes	Comments
1. Develop a SPD-HARM application An application that makes use of frequently collected and rapidly disseminated multi-source data drawn from connected travelers, vehicles, and infrastructure	
2. Develop enhanced speed limit recommendation algorithms Speed limit selection algorithms must be enhanced in order to achieve the mobility, safety, and environmental goals of dynamic speed harmonization	
3. Develop a data collection system To obtain all of the necessary SPD-HARM data, in real-time, from vehicles, on-board sensors, wireless devices, roadway traffic sensors, weather systems, message boards, and other related systems	
4. Develop a performance measurement system To measure relevant performance measures to identify whether the system goals and performance targets for the application are being achieved	
5. Improve dissemination capabilities for communicating speed limit and related information Developing methods for communicating speed information to drivers, so as to maximize compliance and effectiveness	

Recommended Changes	Comments
6. Include more data sources and more accurate data • Real-time traffic data • Weather condition data • Visibility data • Pavement condition data • Vehicle data • Historical data	
7. Improve compliance of speed limit recommendations Through more intelligent speed recommendation communication to drivers and expanded tracking and enforcement capabilities of system operators (balanced against user acceptance and privacy concerns)	

4.3 Queue Warning Proposed Changes and Prioritization

Recommended Changes	Comments
1. Develop a Q-WARN application An application that makes use of frequently collected and rapidly disseminated multi-source data drawn from connected travelers, vehicles, and infrastructure	
2. Develop enhanced queue warning algorithms Algorithms for queue determination (detection and prediction) and response strategies must be enhanced in order to achieve the safety and mobility goals of next-generation queue warning	
3. Develop a data collection system To obtain all of the necessary Q-WARN data, in real-time, from vehicles, on-board sensors, wireless devices, roadway traffic sensors, weather systems, message boards, and other related systems	
4. Develop a performance measurement system To measure relevant performance measures to identify whether the system goals and performance targets for the application are being achieved	
5. Improve dissemination capabilities for communicating queue warnings and relevant queue information Developing methods for communicating information on the characteristics of the upstream queue, potential safety issues, and response scenario options to specific portions of the traffic flow or even to individual vehicles	

Recommended Changes	Comments
6. Include more data sources and more accurate data • Real-time traffic data • Weather condition data • Visibility data • Pavement condition data • Vehicle data • Historical data	

4.4 CACC Proposed Changes and Prioritization

Recommended Changes	Comments
1. Develop a CACC application An application that makes use of frequently collected and rapidly disseminated multi-source data drawn from connected travelers, vehicles, and infrastructure	
2. Develop enhanced vehicle following algorithms Capable of generating general traffic condition predictions, platoon movement predictions, and response scenarios in real time	
3. Develop a data collection system To obtain all of the necessary CACC data, in real-time, from vehicles, on-board sensors, wireless devices, roadway traffic sensors, weather systems, message boards, and other related systems	
4. Develop a performance measurement system To measure relevant performance measures to identify whether the system goals and performance targets for the application are being achieved	
5. Improve real-time speed and gap communication capabilities Conventional communication methods are inadequate to achieve dynamic and automatically coordinated vehicle movements in a CACC platoon. CACC requires high-speed, low-latency vehicle-to-vehicle communication in order to function	

Recommended Changes	Comments

5 Goals, Performance Measures, and Transformative Performance Targets

The following goals, performance measures, and transformative performance targets, which are presented in the draft Concept of Operations, reflect stakeholder feedback received during the February 8, 2012 face-to-face workshop on INFLO goals, performance measures, and user needs.

Note: For a discussion of some of the key terms used in this section (including terminology related to goals, performance measures, performance targets, crashes, shockwaves, and queues), see *Appendix A – Goals and Performance Measures Glossary*.

5.1 SPD-HARM Goals, Performance Measures, and Targets

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
1. Reduce occurrence of significant traffic shockwaves	Number of significant shockwaves formed	• Reduce number by 25% (near) • Reduce number by 50% (mid) • Reduce number by 75% (long)	
2. Reduce severity of traffic shockwaves	Propagation speed of formed shockwaves relative to wave front	• Reduce shockwave propagation speed relative to wave front to below 10 mph for 25% of formed shockwaves (near) • Reduce shockwave propagation speed relative to wave front to below 10 mph for 50% of formed shockwaves (mid) • Reduce shockwave propagation speed relative to wave front to below 10 mph for 90% of formed shockwaves (long)	

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
	Duration of shockwave-induced queues*	• Reduce average queue duration by 25% (near) • Reduce average queue duration by 50% (mid) • Reduce average queue duration by 75% (long)	
3. Improve speed limit compliance	Compliance rate of posted or recommended speed limit	• 75% compliance (near) • 95% compliance (mid) • 100% compliance (long)	
4. Improve smoothness of traffic flow	Variability (spread) of speeds within traffic stream (in-lane, between-lane, and over time)	• 1/2/3 (near/mid/long) standard deviations of traffic speeds are within 2 mph of average stream speed	
5. Improve expected travel time	Average travel time	• Reduce average travel time delay by 10% (near) • Reduce average travel time delay by 25% (mid) • Reduce average travel time delay by 50% (long)	
	Travel time reliability (over time)	• Reduce buffer/planning time index by 25% (near) • Reduce buffer/planning time index by 55% (mid) • Reduce buffer/planning time index by 75% (long)	
6. Achieve user acceptance and support of system	Ratings on public opinion surveys	• 75% positive ratings of system (near) • 85% positive ratings of system (mid) • 95% positive ratings of system (long)	
7. Reduce number of primary crashes	Number of primary crashes	• Reduce number by 25% (near) • Reduce number by 50% (mid) • Reduce number by 75% (long)	
8. Improve safety outcomes of crashes	Severity of crashes	• Reduce fatalities by 25% (near) • Reduce fatalities by 50% (mid) • Reduce fatalities by 75% (long) • Reduce serious injuries by 25% (near) • Reduce serious injuries by 50% (mid) • Reduce serious injuries by 75% (long)	

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
9. Reduce number of secondary crashes	Number of secondary crashes	• Reduce number by 50% (near) • Reduce number by 75% (mid) • Zero secondary crashes (long)	
10. Improve environmental impact of roadway	Level of CO_2 (equivalent) emissions	• Reduce total roadway emissions levels by 25% (near) • Reduce total roadway emissions levels by 33% (mid) • Reduce total roadway emissions levels by 50% (long)	
	Amount of energy consumed	• Reduce total roadway MPG/fuel efficiency by 25% (near) • Reduce total roadway MPG/fuel efficiency by 50% (mid) • Reduce total roadway MPG/fuel efficiency by 75% (long)	
11. Reduce speed harmonization-related system costs	Cost of SPD-HARM infrastructure and related systems construction	• Reduce infrastructure costs by 25% (near) • Reduce infrastructure costs by 50% (mid) • Reduce infrastructure costs by 75% (long)	
	Cost of SPD-HARM infrastructure and related systems operations and maintenance	• Reduce infrastructure costs by 25% (near) • Reduce infrastructure costs by 50% (mid) • Reduce infrastructure costs by 75% (long)	

5.2 Q-WARN Goals, Performance Measures, and Targets

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
1. Reduce secondary crashes at fixed queue points (Border crossings, ramp spillover locations, construction zones, etc.)	Number of secondary crashes at fixed queue point locations	• Reduce number by 50% (near) • Reduce number by 75% (mid) • Zero secondary crashes (long)	
2. Reduce secondary crashes at variable locations (Due to incidents, weather, traffic stops, etc.)	Number of secondary crashes at non-fixed queue point locations	• Reduce number by 50% (near) • Reduce number by 75% (mid) • Zero secondary crashes (long)	
3. Improve safety outcomes of queue-related crashes	Severity of crashes	• Reduce fatalities by 25% (near) • Reduce fatalities by 50% (mid) • Reduce fatalities by 75% (long) • Reduce serious injuries by 25% (near) • Reduce serious injuries by 50% (mid) • Reduce serious injuries by 75% (long)	
4. Reduce intensity of formed queues	Length (distance) of formed queues at variable locations	• Reduce average length of formed queues by 50% (near) • Reduce average length of formed queues by 75% (mid) • Queue formation at variable locations eliminated (long)	
	Duration of formed queues at variable locations	• Reduce average queue duration by 25% (near) • Reduce average queue duration by 50% (mid) • Reduce average queue duration by 75% (long)	
5. Reduce occurrence of traffic shockwaves upstream of queue	Number of shockwaves formed	• Reduce number by 25% (near) • Reduce number by 50% (mid) • Reduce number by 75% (long)	

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
6. Reduce severity of upstream shockwaves	Propagation speed of formed shockwaves relative to wave front	• Reduce shockwave propagation speed relative to wave front to below 10 mph for 25% of formed shockwaves (near) • Reduce shockwave propagation speed relative to wave front to below 10 mph for 50% of formed shockwaves (mid) • Reduce shockwave propagation speed relative to wave front to below 10 mph for 90% of formed shockwaves (long)	
	Duration of upstream shockwave-induced queues	• Reduce average queue duration by 25% (near) • Reduce average queue duration by 50% (mid) • Reduce average queue duration by 75% (long)	
7. Achieve user acceptance and support of system	Ratings on public opinion surveys	• 75% positive ratings of system (near) • 85% positive ratings of system (mid) • 95% positive ratings of system (long)	
8. Accurately detect queue formation	Number of false positive queue detection alerts	• 5% rate of false positive queue detection alerts (near) • 1% rate of false positive queue detection alerts (mid) • Zero false positive queue detection alerts (long)	

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
	Number of non-detected queue events	• 10% rate of non-detected queue events (near) • 5% rate of non-detected queue events (mid) • Zero non-detected queue events (long)	
9. Reduce queue warning-related system costs	Cost of Q-WARN infrastructure and related systems construction	• Reduce infrastructure costs by 25% (near) • Reduce infrastructure costs by 50% (mid) • Reduce infrastructure costs by 75% (long)	
	Cost of Q-WARN infrastructure and related systems operations and maintenance	• Reduce infrastructure costs by 25% (near) • Reduce infrastructure costs by 50% (mid) Reduce infrastructure costs by 75% (long)	

5.3 CACC Goals, Performance Measures, and Targets

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
1. Improve throughput	Vehicles per hour	• 50% increase in number of vehicles per hour for the CACC lane (near) • 100% increase in number of vehicles per hour for the CACC lane (mid) • 100% increase in number of vehicles per hour for all lanes (long)	
	Average vehicle headways	• 25% decrease in average vehicle headways for the CACC lane (near) • 50% decrease in average vehicle headways for the CACC lane (mid) • 50% decrease in average vehicle headways for all lanes (long)	
2. Reduce occurrence of significant traffic shockwaves	Number of significant shockwaves formed	• Reduce number by 25% (near) • Reduce number by 50% (mid) • Reduce number by 75% (long)	
3. Reduce severity of traffic shockwaves	Propagation speed of formed shockwaves relative to wave front	• Reduce shockwave propagation speed relative to wave front to below 10 mph for 25% of formed shockwaves (near) • Reduce shockwave propagation speed relative to wave front to below 10 mph for 50% of formed shockwaves (mid) • Reduce shockwave propagation speed relative to wave front to below 10 mph for 90% of formed shockwaves (long)	
	Duration of shockwave-induced queues	• Reduce average queue duration by 25% (near) • Reduce average queue duration by 50% (mid) • Reduce average queue duration by 75% (long)	

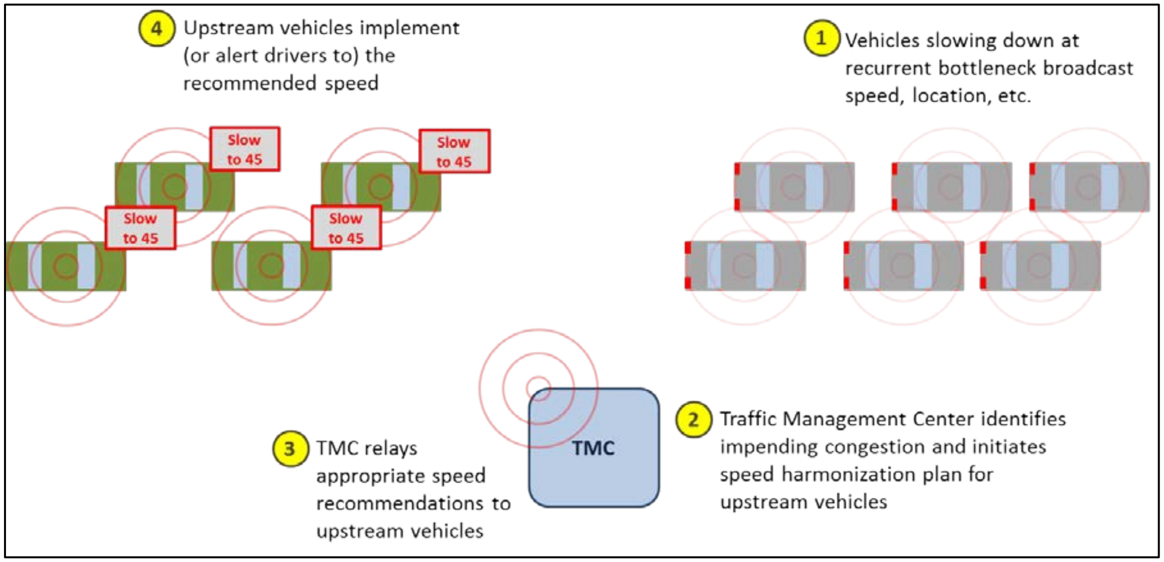
Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
4. Improve smoothness of traffic flow	Variability (spread) of speeds within traffic stream (in-lane, between-lane, and over time)	• 1/2/3 (near/mid/long) standard deviations of traffic speeds are within 2 mph of average stream speed	
5. Improve expected travel time	Average travel time	• Reduce average travel time delay by 10% (near) • Reduce average travel time delay by 25% (mid) • Reduce average travel time delay by 50% (long)	
	Travel time reliability (over time)	• Reduce buffer/planning time index by 25% (near) • Reduce buffer/planning time index by 55% (mid) • Reduce buffer/planning time index by 75% (long)	
6. Achieve user acceptance and support of system	Ratings on public opinion surveys	• 75% positive ratings of system (near) • 85% positive ratings of system (mid) • 95% positive ratings of system (long)	
7. Reduce number of primary crashes	Number of primary crashes	• Reduce number by 25% (near) • Reduce number by 50% (mid) • Reduce number by 75% (long)	
8. Improve safety outcomes of crashes	Severity of crashes	• Reduce fatalities by 25% (near) • Reduce fatalities by 50% (mid) • Reduce fatalities by 75% (long) • Reduce serious injuries by 25% (near) • Reduce serious injuries by 50% (mid) • Reduce serious injuries by 75% (long)	
9. Reduce number of secondary crashes	Number of secondary crashes	• Reduce number by 50% (near) • Reduce number by 75% (mid) • Zero secondary crashes (long)	
10. Improve environmental impact of roadway	Level of CO_2 (equivalent) emissions	• Reduce total roadway emissions levels by 25% (near) • Reduce total roadway emissions levels by 33% (mid) • Reduce total roadway emissions levels by 50% (long)	

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Comments
	Amount of energy consumed	• Reduce total roadway MPG/fuel efficiency by 25% (near) • Reduce total roadway MPG/fuel efficiency by 50% (mid) • Reduce total roadway MPG/fuel efficiency by 75% (long)	
11. Reduce active traffic management-related system costs	Cost of ATM infrastructure and related systems construction	• Reduce infrastructure costs by 25% (near) • Reduce infrastructure costs by 50% (mid) • Reduce infrastructure costs by 75% (long)	
	Cost of ATM infrastructure and related systems operations and maintenance	• Reduce infrastructure costs by 25% (near) • Reduce infrastructure costs by 50% (mid) • Reduce infrastructure costs by 75% (long)	

6 Operational Concepts

6.1 SPD-HARM

The INFLO SPD-HARM application concept utilizes connected vehicle V2V and V2I 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 SPD-HARM concept reflects an operational environment in which speed recommendation decisions are made at a TMC or other traffic management entity and then communicated to the affected traffic. In such an environment, the SPD-HARM application is considered to reside within the traffic management entity and be external to the vehicle. This approach was taken because it was agreed that effective speed harmonization requires the coordination of traffic across large portions of the road network, a task not well suited to ad-hoc vehicle-to-vehicle communication.

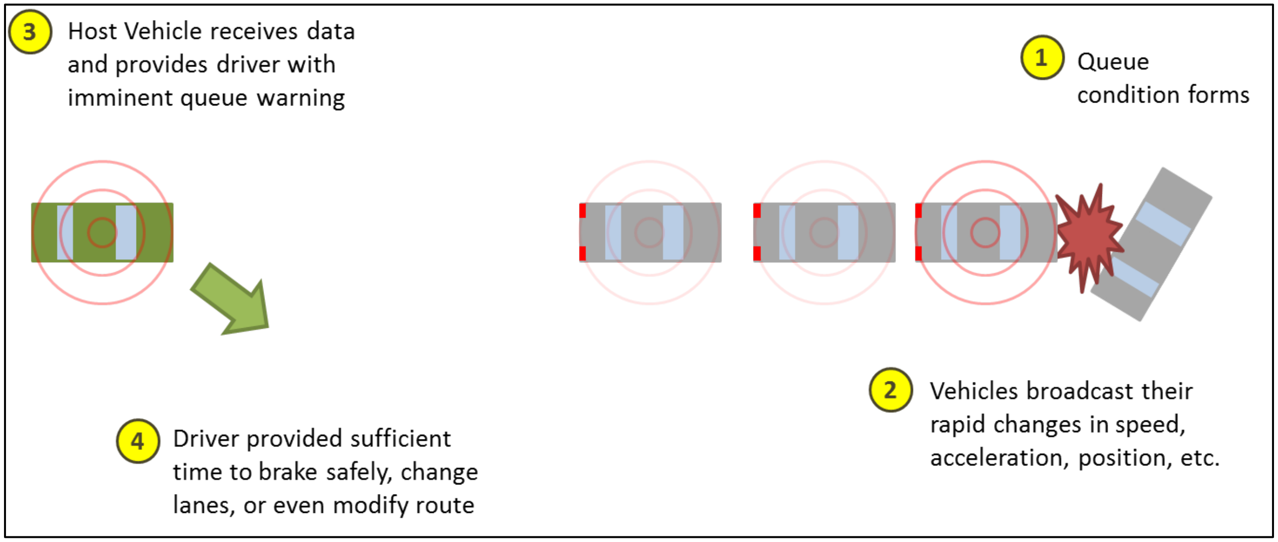
SPD-HARM Operational Policy/Constraint	Accept/Reject/Modify	Comments
Minimum interval for posted speed limit adjustments Absent CACC (or a similar autonomous car following environment), connected vehicle drivers can be expected to acknowledge and adjust to only so many varying speed target recommendations before they stop attending to SPD-HARM recommendations completely		
ITS staffing constraints Some investment in time and effort is required for initial training, and monitoring and tracking. This may increase the workload to some degree on TMC operators after initial implementation		
Data provision and ownership policies Issues related to privacy protection and liability concerns as well as the institutional barriers that have frequently impeded the ability of transportation agencies to share operational data must be overcome		
System performance management Effectiveness of sped harmonization requires continual monitoring and adaptation to reflect changes in the external environment, as well as the behavioral adjustment displayed by system users		
Algorithm effectiveness The success of a connected vehicle based SPD-HARM application will depend on how effective the underlying speed harmonization algorithm is at interpreting traffic and weather conditions data and generating speed recommendation plans in response. Effective strategies are likely to require local calibration, testing and adaptation over time, which are best undertaken within an open framework		

SPD-HARM Operational Policy/Constraint	Accept/Reject/Modify	Comments
System architecture design flexibility The degree of flexibility in system architecture design and operational deployment affects the ability of the system to respond to changing conditions, improved technology, and other developments in this rapidly evolving field (e.g., the heightened role of connected social networks)		

SPD-HARM Support Environment	Accept/Reject/Modify	Comments
Service Monitor Subsystem Provides support to the main system by sending alerts to operators in case of any issues with the system and provides operators with information on fixing or isolating the issues.		
System Support Personnel Developers, administrators, and maintainers are the key personnel in core system support. The support group may be the same as the system administrator and maintenance personnel or it may comprise external agency personnel.		
Maintenance and Support Processes Checklists for the operators to be able to identify, isolate, and solve potential issues, as well as manage the processes for parts replacement and software support.		
Diagnostics Subsystem Provides ability to perform detailed diagnostics on issues with the application.		

6.2 Q-WARN

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, whereby the vehicles within the queue event 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 conceptual Q-WARN application performs two essential tasks: queue determination (detection and/or prediction) and queue information dissemination. In order to perform these tasks, Q-WARN solutions can be vehicle-based or infrastructure-based or utilize a combination of each. See the following table for a summary of the capabilities and advantages of these approaches for essential Q-WARN tasks.

Task	Vehicle-based Q-WARN	Infrastructure-based Q-WARN
Queue determination – *detection*	Yes (less precise, wider range)	Yes (more precise, limited range)
Queue determination – *prediction*	No (insufficient visibility into traffic state)	Yes (able to monitor traffic state for given locations)
Queue information dissemination	Yes (V2V)	Yes (I2V)

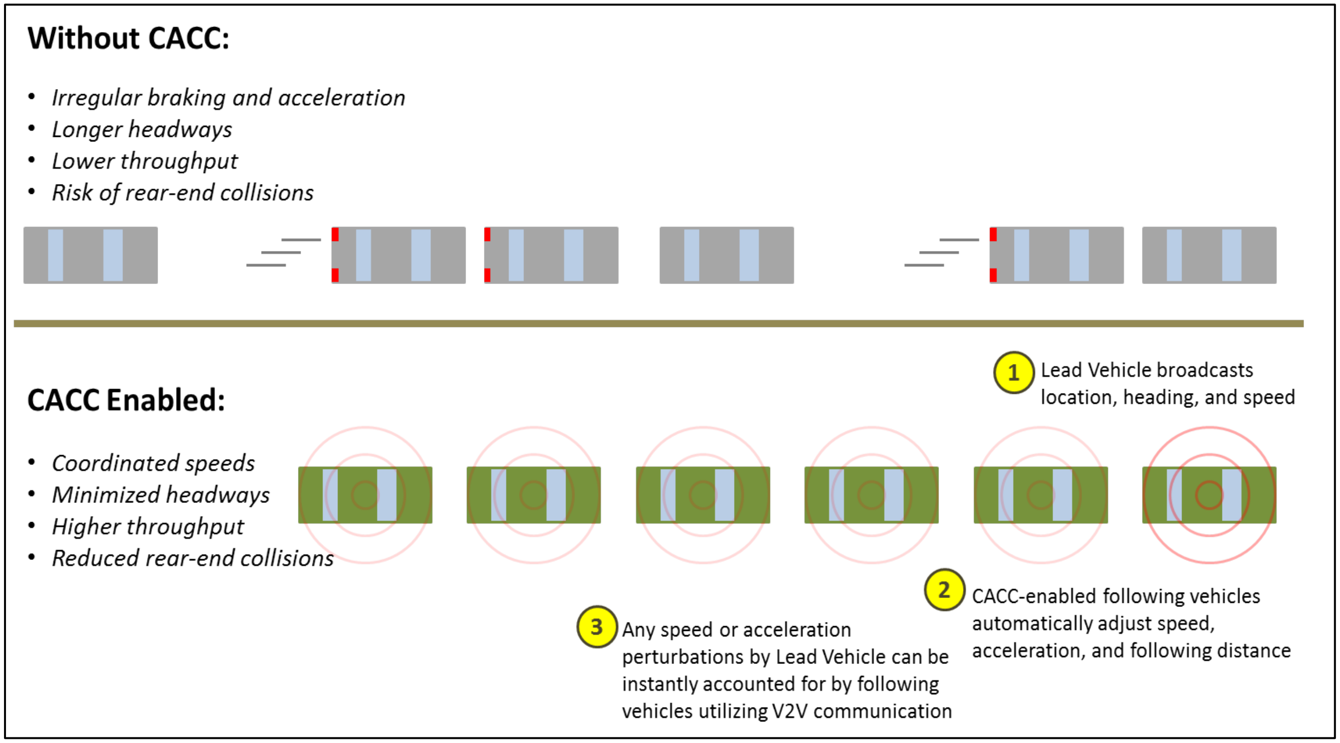
Q-WARN Operational Policy/Constraint	Accept/Reject/Modify	Comments
ITS staffing constraints Limited ability (from both time and budget points of view) for hiring and training the new staff. As a result, the current staff might have more duties compare to their current duties after implementing the new Q-WARN system		
Data provision and ownership policies Issues related to privacy protection and liability concerns as well as the institutional barriers that have frequently impeded the ability of transportation agencies to share operational data must be overcome		
System performance management Effectiveness of queue warning requires continual monitoring and adaptation to reflect changes in the external environment, as well as the behavioral adjustment displayed by system users		
Algorithm effectiveness The success of a connected vehicle based Q-WARN application will depend on how effective the underlying queue detection algorithm is at interpreting streaming connected vehicle data and reliably identifying formed or impending queues. Producing too many false positive queue warnings may result in drivers taking the warnings less seriously or even ignoring them completely		
System architecture design flexibility The degree of flexibility in system architecture design and operational deployment affects the ability of the system to respond to changing conditions, improved technology, and other developments in this rapidly evolving field (e.g., the heightened role of connected social networks)		

Q-WARN Operational Policy/Constraint	Accept/Reject/Modify	Comments

Q-WARN Support Environment	Accept/Reject/Modify	Comments
Service Monitor Subsystem Provides support to the main system by sending alerts to operators in case of any issues with the system and provides operators with information on fixing or isolating the issues.		
System Support Personnel Developers, administrators, and maintainers are the key personnel in core system support. The support group may be the same as the system administrator and maintenance personnel or it may comprise external agency personnel.		
Maintenance and Support Processes Checklists for the operators to be able to identify, isolate, and solve potential issues, as well as manage the processes for parts replacement and software support.		
Diagnostics Subsystem Provides ability to perform detailed diagnostics on issues with the application.		

6.3 CACC

The CACC operational concept represents an evolutionary advancement of conventional cruise control (CCC) systems and adaptive cruise control (ACC) systems by utilizing V2V communication to automatically synchronize the movements of many vehicles within a platoon.



The CACC concept reflects an operational environment in which CACC-related decisions are made within the vehicles themselves and supplemented by external information (for example, from a TMC providing reduced speed recommendations due to downstream congestion). This approach was taken because it was agreed that vehicle-based decision-making would be sufficient to organize and coordinate vehicles effectively within a local platoon, but that platoon-level speed recommendations should come from an external entity (such as a TMC) that has visibility into the conditions of the entire road network.

CACC Operational Policy/Constraint	Accept/Reject/Modify	Comments
Availability of an on-board diagnostic (OBD) reader to access the subject vehicle data These data may include the vehicle speed, fuel consumption, engine speed, brake pedal level, throttle level, turn signal indicator, anti-lock braking system (ABS) status, etc.		
High resolution digital map availability		
WAAS GPS availability A Wide Area Augmented System (WAAS) Global Positioning Systems (GPS) is required in order to identify precisely the location of the vehicle on a digital map		
On-vehicle radar system availability A radar system to measure the spacing and headway between the subject and surrounding vehicles		
DSRC (or similar) communication system availability DSRC is necessary to enable communication between other vehicles and infrastructure (e.g., traffic signal controller) in the vicinity of the subject vehicle. Cellular communication hardware is also necessary to communicate with the TMC to send and receive platoon-level speed recommendations		

CACC Operational Policy/Constraint	Accept/Reject/Modify	Comments
Road surface conditions sensor availability Sensors or vision-based technology is necessary to measure the roadway coefficient of friction and rolling resistance coefficient or identify the condition and type of roadway surface		
On-board data fusion and algorithm processing An on-board central processing unit (CPU) is necessary to fuse the various data sources and compute the optimal longitudinal motion decisions.		
Data accuracy The system will need to incorporate safety measures to deal with errors in vehicle speed measurements, vehicle spacing and headway measurement errors, and vehicle location errors		
Communication latency and lags in the provision of data		
Communication losses or communication system breakdown The system should be able to revert safely to manual driving in the event that the communication link fails		
Market penetration rates What level of market penetration is needed for the system to operate successfully? Will the initial deployment be successful for low levels of market penetration?		

CACC Operational Policy/Constraint	Accept/Reject/Modify	Comments
Combining strategic TMC and local tactical car-following speed recommendations to compute a final vehicle speed decision The system will need to deal with contradicting speed recommendations. For example the TMC might recommend a speed reduction based on downstream conditions, however local conditions dictate a speed increase		
Ensuring platoon car-following asymptotic stability The system will need to include multiple-leader car-following models in order to ensure platoon car-following asymptotic stability		
Accommodating entry of non-equipped vehicles into a platoon The system will have to deal with the potential non-equipped vehicles entering a platoon even if the system entails dedicated lanes for equipped vehicles. These situations could potentially arise from driver error entering the dedicated lane		
Accommodating a non-equipped vehicle platoon leader The system should be able to deal with the situation in which a platoon of equipped vehicles encounters a lead non-equipped vehicle		
Accommodating merging and weaving The system should be able to deal with merging and weaving sections when vehicles join and leave the platoon		

CACC Operational Policy/Constraint	Accept/Reject/Modify	Comments
CACC-dedicated lane transitions The system will need to deal with transitions from dedicated to non-dedicated lanes and transitions from automated to semi-automated or manual control		
Effects of automated vehicle control on driver behavior The system will have to deal with long-term effects on driver behavior as a result of fully-automated vehicle control		
Accommodating varying vehicle-specific limitations The system will have to deal with different vehicle-specific limitations (e.g., differences in acceleration capability, especially with respect to heavy-duty trucks and buses in the traffic stream)		
System introduction and full-scale implementation policies From an institutional standpoint, should transportation agencies dedicate lanes for fully automated CACC systems and if so should automobile manufacturers first develop these systems? Should the system be introduced gradually by first introducing driver assist and collision avoidance systems before going into fully automated CACC systems?		
Capability of institutions to co-deploy with SPD-HARM or other applications Is it feasible for transportation agencies and partners to introduce CACC systems in conjunction with SPD-HARM and other mobility systems or should they be introduced independently?		

CACC Operational Policy/Constraint	Accept/Reject/Modify	Comments
Accident liability What are the litigation issues that have to be dealt with in the event of an accident involving CACC systems?		
Data storage capability constraints What are the data storage issues that have to be dealt with when these systems are widely implemented in the field?		
Data cleansing capability constraints How should the system deal with inconsistencies discrepancies across different data sources?		
Error handling capability constraints How should the system deal with and identify errors in the various data sources?		

CACC Support Environment	Accept/Reject/Modify	Comments
Service Monitor Subsystem Provides support to the main system by sending alerts to operators in case of any issues with the system and provides operators with information on fixing or isolating the issues.		
System Support Personnel Developers, administrators, and maintainers are the key personnel in core system support. The support group may be the same as the system administrator and maintenance personnel or it may comprise external agency personnel.		
Maintenance and Support Processes Checklists for the operators to be able to identify, isolate, and solve potential issues, as well as manage the processes for parts replacement and software support.		
Diagnostics Subsystem Provides ability to perform detailed diagnostics on issues with the application.		

7 INFLO System Users and Needs

The following system users and associated user needs were defined based on stakeholder feedback received during the February 8, 2012 face-to-face workshop on INFLO goals, performance measures, and user needs.

7.1 SPD-HARM

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Vehicle operator	1. Needs to know the recommended speed to travel	In the case where the vehicle operator is making the decision to comply with speed recommendations (i.e., not in a semi-autonomous vehicle environment, as with CACC), the driver must be made aware of the appropriate speed to travel so that he or she can adjust the throttle accordingly.		
Vehicle operator	2. Needs to know which lane to be in	A robust dynamic speed harmonization system will be able to optimize not only vehicle speeds but also lane utilization to achieve efficient flow of traffic. This includes recommendations based on vehicle weight or class. Therefore, in addition to knowing the recommended speed, the vehicle operator must also know the appropriate lane to be in.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Vehicle operator	3. Needs to know why the given speed change is being recommended	To be effective, a SPD-HARM system must be proactive in providing speed change recommendations, which often means slowing down traffic far upstream to the source of the traffic disturbance. For drivers to feel compelled to comply with the recommended speed changes when the immediate traffic conditions appear to be free flowing (for example), it is psychologically important for them to know why they are being asked to change their behavior. Examples of information that may be beneficial to drivers include alerts and location of upcoming incidents, weather, or other road conditions, or even estimates of fuel cost savings and emissions reductions that could be achieved by complying with the speed change recommendations. Such information must be provided succinctly and in such a way that it is not overly distracting to the driver.		
Connected Vehicle/Device	4. Needs to collect relevant subject vehicle data	The connected vehicle, aftermarket device, or other interacting application must be able to obtain relevant subject vehicle data (including position, movement, actions, and road conditions/weather) so that it can be communicated to and processed by other vehicles and systems.		
Connected Vehicle/Device	5. Needs to disseminate relevant subject vehicle data to other vehicles or systems	The connected vehicle/device must have a dissemination capability so that the subject vehicle data it has obtained can be accessed by other vehicles and systems.		
Connected Vehicle/Device	6. Needs to receive relevant information from other vehicles or systems	In order to be able to provide useful information to the driver, the subject connected vehicle/device must be able to receive such information from other vehicles and systems.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Connected Vehicle/Device	7. Needs to communicate relevant information to vehicle operator	Speed recommendations and other instructions and information must ultimately be conveyed to the driver. Therefore, the connected vehicle/device, which receives such information externally, must be able to communicate it to the driver in such a way that it is accepted and can be acted upon. Examples of this communication to the driver include auditory, visual, or haptic alerts and on-screen messages.		
Traffic Management Entity	8. Needs to receive multi-source data	The traffic management entity, which includes TMCs or other entity responsible for traffic management functions, must be able to receive relevant data from connected vehicles/devices, roadway traffic detection systems, weather systems, and third party systems in order to process it and make speed recommendations.		
Traffic Management Entity	9. Needs to process multi-source data	The traffic management entity must be able to aggregate, organize, and clean the received transportation and weather data in order to develop speed recommendations from it.		
Traffic Management Entity	10. Needs to generate speed harmonization strategies	The critical function of the SPD-HARM system is to use algorithms and modeling to generate optimal speed recommendations based on the information received on the conditions (traffic, incidents, weather, etc.) of the transportation network.		
Traffic Management Entity	11. Needs to disseminate speed harmonization recommendations and information to connected vehicles/devices	Once speed harmonization strategies and recommendations have been developed, the traffic management entity must be able to communicate this information to the appropriate affected connected vehicles/devices.		
Traffic Management Entity	12. Needs to analyze performance of SPD-HARM system	Based on data received from the field, the traffic management entity must be able to analyze the performance of the SPD-HARM system overall and to make changes to the algorithm or software to improve performance.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Data Capture and Management Environment	13. Needs to collect SPD-HARM data and disseminate relevant information to other dynamic mobility applications	In order to maximize the benefit of the co-deployment of different DMAs, relevant SPD-HARM data should be shared with the other DMAs. The interface for such sharing is the Data Capture and Management environment.		

7.2 Q-WARN

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Vehicle operator	1. Needs to know of a downstream traffic queue in sufficient time to react safely	In the case where the driver must engage the brakes or throttle in order to change the vehicle speed (i.e., not as in a semi-autonomous vehicle environment, as with CACC), the driver must be made aware of the downstream queue with sufficient notice to take into account typical human reaction times.		
Vehicle operator	2. Needs to know what actions to take to respond to the impending queue	In order to react appropriately, the driver must be provided sufficient information about the queue to make a decision. This information includes distance to end of queue, estimated duration of the queue (including alerting when the queue has cleared), and other descriptions of the queue condition.		
Connected Vehicle/Device (queued vehicle)	3. Needs to detect a queued state	The vehicle, aftermarket device, or other interacting application must be able to detect that the subject vehicle is in a queue state so that other vehicles and systems can be alerted to the queue.		
Connected Vehicle/Device (queued vehicle)	4. Needs to disseminate queued status alert to upstream vehicles and other systems	The connected vehicle/device must have a dissemination capability so that the subject vehicle queued alert status can be received and interpreted by other vehicles and systems.		
Connected Vehicle/Device (upstream of queue)	5. Needs to receive relevant queue information from other vehicles or systems	In order to be able to provide useful information to the driver, the subject connected vehicle/device must be able to receive relevant information from other vehicles and systems.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Connected Vehicle/Device (upstream of queue)	6. Needs to generate queue warning response strategies	The critical function of the vehicle-based Q-WARN system is to generate optimal recommendations based on the detection of a downstream queue. (Strategies may include speed reduction, lane change, or diversion.) In addition, pertinent queue-related information, including distance to end of queue, estimated duration of the queue, and other descriptions of the queue condition, should be generated.		
Connected Vehicle/Device (upstream of queue)	7. Needs to communicate recommendations to vehicle operator	Braking, lane change, and other recommendations must ultimately be conveyed to the driver. Therefore, the connected vehicle/device must be able to communicate this information to the driver in such a way that it is accepted and can be acted upon. Examples of this communication to the driver include auditory, visual, or haptic alerts and on-screen messages. In the semi-autonomous vehicle environment (e.g., a Q-WARN/CACC co-deployment), braking or other throttle adjustment actions will occur automatically.		
Traffic Management Entity	8. Needs to collect relevant traffic, road condition, and weather data	To supplement vehicle-generated traffic data, traffic management entities will utilize infrastructure-based detection systems to gather traffic, road condition, and weather data. Infrastructure-based detection plays an important role both in the near-term (where connected vehicle/device penetration rates are lower) and at known fixed queue generation points.		
Traffic Management Entity	9. Needs to disseminate relevant traffic, road condition, and weather data to vehicles	To supplement gaps in vehicle-generated traffic data, infrastructure-based detection systems will disseminate traffic, road condition, and weather data to connected vehicles/devices. Infrastructure-based detection and information dissemination plays an important role both in the near-term (where connected vehicle/device penetration rates are lower) and at known fixed queue generation points.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Traffic Management Entity	10. Needs to detect formed queues	One of the critical functions of the infrastructure-based Q-WARN system is to be able to quickly and reliably detect a formed queue, in particular at fixed queue generation points where vehicle-based communication and detection may not be feasible (for example, at a tunnel entrance where line-of-sight obstructions may prevent direct communication between vehicles).		
Traffic Management Entity	11. Needs to predict impending queues	In addition to detecting formed queues, the infrastructure-based Q-WARN system should be able to predict impending queue formation based on the relevant traffic, road condition, and weather data collected for a given road segment or fixed queue generation point.		
Traffic Management Entity	12. Needs to generate queue warning response strategies for upstream vehicles	The other critical function of the infrastructure-based Q-WARN system is to generate optimal recommendations for upstream vehicles based on the detection of a formed or impending queue, including speed reduction, lane change, or diversion recommendations. In addition, pertinent queue-related information, including distance to end of queue, estimated duration of the queue, and other descriptions of the queue condition, should be generated.		
Traffic Management Entities	13. Need to disseminate recommended queue warning strategies to upstream vehicles	Queue response strategies and pertinent queue-related information generate traffic management entities must be disseminated to vehicles upstream of the queue. The information will be communicated to the vehicles via in-vehicle alerts and roadside signage. (Traditional roadside infrastructure will continue to play an important part in information dissemination in the near-term, where Connected Vehicle penetration is expected to be relatively low).		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Traffic Management Entity	14. Needs to analyze performance of Q-WARN system	Based on data received from the field, the traffic management entity must be able to analyze the performance of the Q-WARN system overall and to make changes to the algorithm or software to improve performance.		
Traffic Management Entity	15. Needs to push Q-WARN application updates and modifications to connected vehicles/devices	Based on analysis of the performance of the Q-WARN system, algorithm or software updates must be able to be pushed (wirelessly) to connected vehicles/devices in the field.		
Arterial Signal Systems	16. Need to disseminate signal phasing information to approaching vehicles	In the arterial environment, queues generate around traffic signals. By providing approaching connected vehicles/devices information about impending signal changes, sudden vehicle stops and rear-end collisions and shockwave propagation can be limited.		
Data Capture and Management Environment	17. Needs to collect Q-WARN data and disseminate relevant information to other dynamic mobility applications	In order to maximize the benefit of the co-deployment of different DMAs, relevant Q-WARN data should be shared with the other DMAs. The interface for such sharing is the Data Capture and Management environment.		
Data Capture and Management Environment	18. Needs to collect and aggregate Q-WARN related data and disseminate to freeway and arterial traffic management entities	In order for aggregate Q-WARN performance to be evaluated by traffic management entities, the data must first be collected and disseminated.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment

7.3 CACC

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Vehicle operator	1. Needs to join a CACC platoon	The driver must be made aware of how, when, and where to safely join a CACC platoon.		
Vehicle operator	2. Needs to establish or accept a speed and gap policy	Once a driver has joined a platoon, he must be able to establish or accept a recommended speed and gap policy for his connected vehicle to implement.		
Vehicle operator	3. Needs to exit a CACC platoon	When a driver decides to leave the platoon (for example, because she is exiting the freeway), she must be able to regain manual throttle control and change lanes safely.		
Connected Vehicle	4. Needs to collect relevant subject vehicle data	The connected vehicle must be able to obtain relevant subject vehicle data (including position, movement, actions, and road conditions/weather) so that it can be communicated to and processed by other vehicles and systems.		
Connected Vehicle	5. Needs to disseminate relevant subject vehicle data to other vehicles or systems	The connected vehicle must have a dissemination capability so that the subject vehicle data it has obtained can be accessed by other vehicles and systems.		
Connected Vehicle	6. Needs to receive relevant information from other vehicles or systems	In order to be able to provide useful information to the driver, the subject connected vehicle must be able to receive such information from other vehicles and systems.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Connected Vehicle	7. Needs to communicate actions and other relevant information to vehicle operator	Speed and gap recommendations, platoon entry and exit points, and other information must ultimately be conveyed to the driver. Therefore, the connected vehicle must be able to communicate it to the driver in such a way that it can be acted upon. Examples of this communication to the driver include auditory, visual, or haptic alerts and on-screen messages.		
Connected Vehicle	8. Needs to generate cruise control strategies	The critical function of the on-board CACC system is to quickly and reliably generate speed and gap decisions by interpreting the streams of internally collected and externally received data.		
Connected Vehicle	9. Needs to automatically engage vehicle throttle and other equipment to enact cruise control strategies	The on-board CACC system must be able to translate strategies into actions by autonomously controlling vehicle throttle and other equipment.		
Connected Vehicle	10. Needs to integrate external commands from traffic management entities with self- or platoon-generated cruise control strategies	The on-board CACC system must be able to receive and accept speed and other recommendations from external traffic management entities.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Traffic Management Entity	11. Needs to receive multi-source data	The traffic management entity, which includes TMCs or other entity responsible for traffic management functions, must be able to receive relevant data from connected vehicles/devices, roadway traffic detection systems, weather systems, and third party systems in order to process it and make gap and speed recommendations.		
Traffic Management Entity	12. Needs to process multi-source data	The traffic management entity must be able to aggregate, organize, and clean the received traffic data in order to develop gap and speed recommendations from it.		
Traffic Management Entity	13. Needs to generate speed or gap strategies	The traffic management entity must be able to use algorithms and modeling to generate optimal speed and gap recommendations for platoons based on the information received on the conditions (traffic, incidents, weather, etc.) of the transportation network.		
Traffic Management Entity	14. Needs to disseminate speed and gap recommendations and other information to connected vehicles	Once speed and gap recommendations have been developed, the traffic management entity must be able to communicate this information to the connected vehicles in the platoon.		
Traffic Management Entity	15. Needs to analyze performance of CACC system	Based on data received from the field, the traffic management entity must be able to analyze the performance of the CACC system overall and to make changes to the algorithm or software to improve performance.		

User	User Need	Discussion	Accept/ Reject/ Modify	Comment
Data Capture and Management Environment	16. Needs to collect CACC data and disseminate relevant information to other dynamic mobility applications	In order to maximize the benefit of the co-deployment of different DMAs, relevant CACC data should be shared with the other DMAs. The interface for such sharing is the Data Capture and Management environment.		

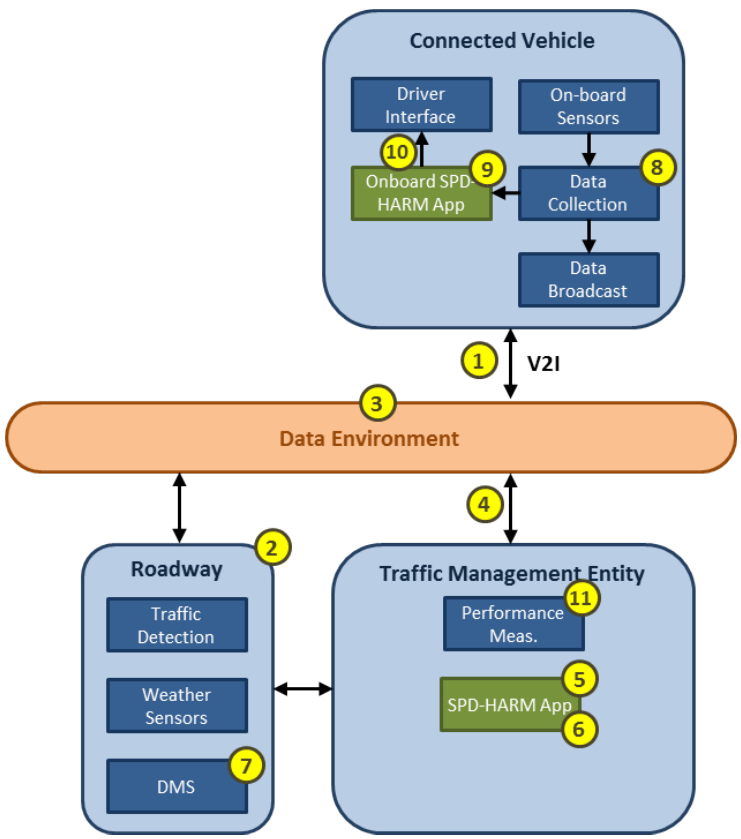
8 Operational Scenarios

The scenarios detailed in this section are not intended to prescribe specific technologies or design, but only to address the key functional elements of the applications at a high level. In addition, the scenarios are intended to convey the evolution of each application's capabilities from the near-term to the long-term.

8.1 SPD-HARM

Scenario 1: Fixed Point Breakdown Formation (External-to-Vehicle Processing; V2I-Dissemination)

In this scenario, a flow breakdown starts to form at a known flow breakdown point. Applicable situations include known bottlenecks on the facility (e.g., bridges, tunnels, on- and off-ramps, and positive grades). Because the boundaries of the breakdown formation point are known, roadside equipment (RSE) and infrastructure-based systems have been installed to monitor traffic flow conditions and generate speed recommendations for approaching vehicles. Appropriate speed and lane usage recommendations are disseminated to upstream vehicles via infrastructure-to-vehicle (V2I) communication as well as dynamic message signs (DMS).



Preconditions
Flow and density increase toward the critical point at a known breakdown formation location. The variance of the speed distribution also increases.

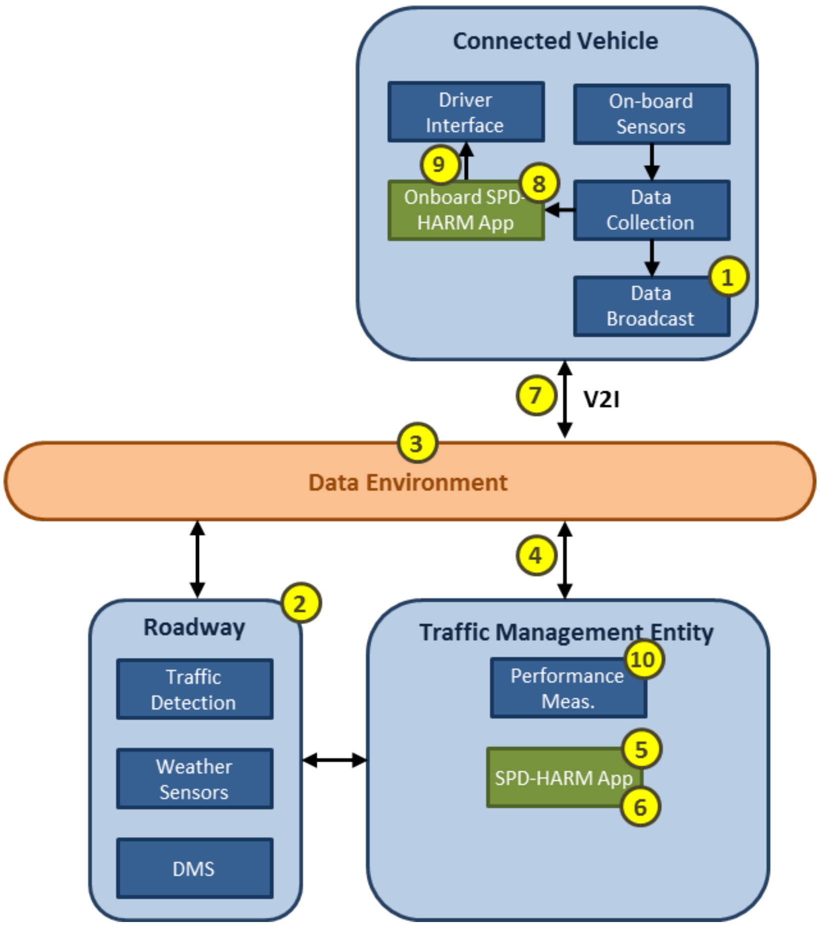
Steps
1. Connected Vehicles near known fixed point breakdown location transmit self-generated position, movement, actions, and road and weather conditions data to data environment.
2. RSE installed to monitor conditions at the fixed point breakdown location collect traffic flow, density, and speed data and transmit to data environment.
3. Data Environment aggregates, organizes, and summarizes streaming data received from connected vehicles and RSE.
4. Traffic Management Entity receives aggregated connected vehicle traffic and weather data from data environment.
5. Traffic Management Entity-operated SPD-HARM application detects flow breakdown event based on real-time data received.
6. Traffic Management Entity-operated SPD-HARM application utilizes real-time data and historical performance analysis to generate anticipatory speed harmonization strategies for the facility, including lane-based speed recommendations for traffic upstream of the bottleneck point.
7. Traffic Management Entity displays appropriate lane-based speed recommendations and related information on DMS signs at locations along the facility.
8. Traffic Management Entity transmits generic speed recommendations and relevant speed harmonization information to affected connected vehicles.
9. Onboard SPD-HARM application individualizes message based on vehicle location with respect to the bottleneck location.
10. Onboard SPD-HARM application communicates individualized speed recommendation to driver.
11. Traffic Management Entity-operated SPD-HARM application records information about the breakdown event, generated response strategies, actions taken, and results for offline performance evaluation.

Discussion
By managing the flow of upstream traffic, the expected outcome of the SPD-HARM application in this scenario is a significant delay or even total elimination of breakdown formation for the given location prone to flow breakdown. However, the computational effort required in the scenario is significant. The Traffic Management Entity's SPD-HARM application must perform extensive modeling and prediction of the formation and propagation of the flow breakdown in real time, incorporating large volumes of streaming data as well as historical analysis of the given location. Results of speed harmonization actions must also be incorporated into the predictive models in order to continually improve and fine-tune the SPD-HARM algorithms.

Because this scenario does not depend exclusively upon connected vehicle technology (for example, detection and information dissemination can occur via roadway infrastructure), this approach to speed harmonization for known common breakdown locations could be deployed in the near-term and operate in a mixed technology environment.

Scenario 2: Non-Location Specific Breakdown Formation (External-to-Vehicle Processing; V2I-Dissemination)

In this scenario, flow breakdown occurs at a location that is not closely monitored as a known fixed flow breakdown point. As a result, high detail infrastructure-based detection and segment-specific predictive models of flow breakdown are not available. The primary means of traffic conditions detection and speed recommendation dissemination is via connected vehicle-based communication. Traffic flow analysis and speed recommendation determination occurs external to the vehicle (i.e., by the Traffic Management Entity's SPD-HARM application).



Preconditions

An incident, sudden lane change, or other non-recurring event occurs, which results in an increase in the flow and density toward the critical point at the location of the disturbance. Upstream speed variances increase suddenly.

Steps

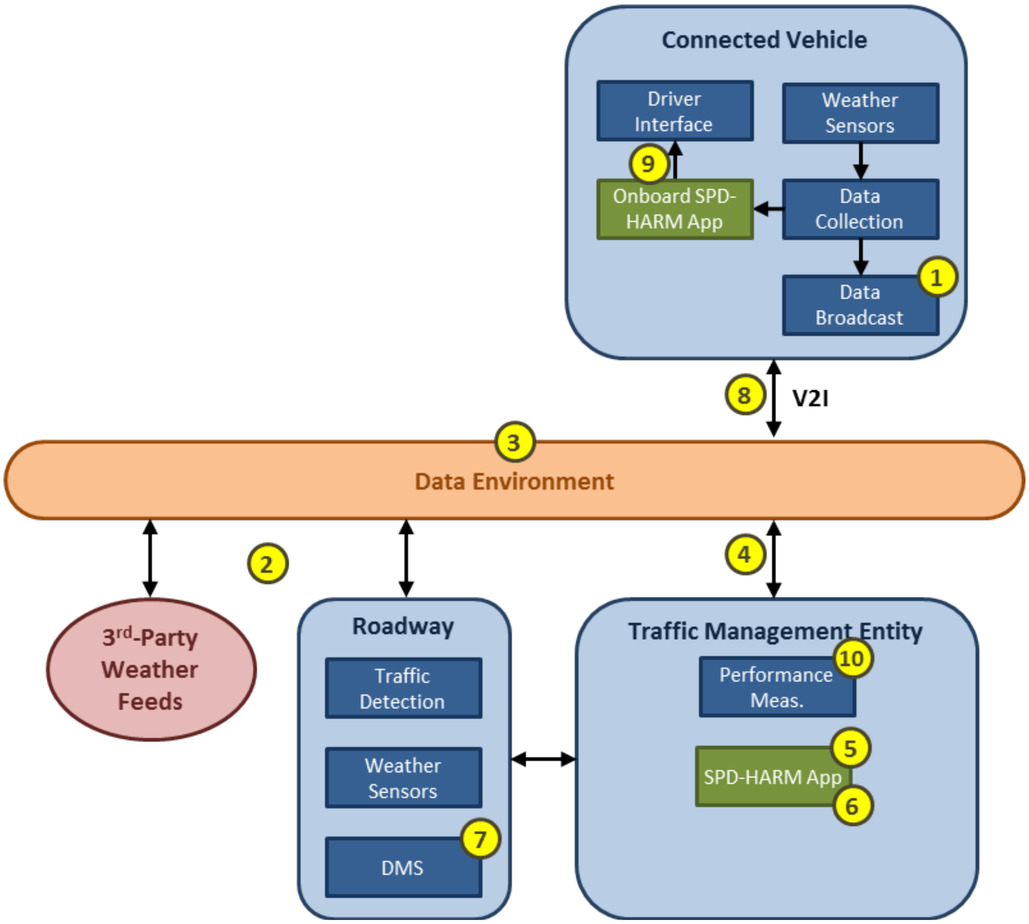
1. Connected Vehicles near the breakdown location transmit self-generated position, movement, actions, and road and weather conditions data to data environment.
2. Available RSE detection provides supplementary traffic flow, density, and speed data to the data environment.

3. Data Environment aggregates, organizes, and summarizes streaming data received from connected vehicles and RSE.
4. Traffic Management Entity receives aggregated connected vehicle traffic and weather data from data environment.
5. Traffic Management Entity-operated SPD-HARM application detects flow breakdown event based on real-time data received.
6. Traffic Management Entity-operated SPD-HARM application utilizes conditions-appropriate generic speed harmonization models and available relevant historical performance analyses to generate anticipatory speed harmonization strategies for the facility, including lane-based speed recommendations for traffic upstream of the bottleneck point.
7. Traffic Management Entity transmits generic speed recommendations and relevant speed harmonization information to affected connected vehicles.
8. Onboard SPD-HARM application individualizes message based on vehicle location with respect to the bottleneck location.
9. Onboard SPD-HARM application communicates individualized speed recommendation to driver.
10. Traffic Management Entity-operated SPD-HARM application records information about the breakdown event, generated response strategies, actions taken, and results for offline performance evaluation.

Discussion

As with Scenario 1, the Traffic Management Entity-based SPD-HARM application detects and locates flow breakdown events and produces speed recommendation strategies. However, because the flow breakdown event is not location-constrained, speed harmonization response strategies will necessarily rely more heavily upon connected vehicle-originated data sources and will not have access to as applicable of historical analogues to model against. Therefore, this scenario should be seen as reflective of the long-term state of the connected vehicle environment.

Scenario 3: Weather-Related Speed Harmonization (External-to-Vehicle Processing; V2I-Dissemination)
This scenario requires fairly extensive real-time modeling of weather impacts on traffic to choose the safe speed for the prevailing weather condition. The Traffic Management Entity's SPD-HARM application uses traffic and weather data collected from connected vehicles throughout the transportation network, environmental sensors, and other third party agencies to provide appropriate speed guidance to maximize traffic flow and reduce safety risks.



Steps

1. Connected vehicles broadcast self-generated position, movement, actions, and road and weather conditions data to data environment.
2. Roadside weather devices and third-party weather feeds provide localized road and weather conditions data to data environment.
3. Data environment aggregates, organizes, and summarizes streaming data.
4. Traffic Management Entity receives aggregated connected vehicle traffic and weather data from data environment.
5. Traffic Management Entity-operated SPD-HARM application identifies road locations adversely affected by weather conditions.

6. Traffic Management Entity-operated SPD-HARM application utilizes predictive models to determine appropriate speed recommendations for given locations.
7. Traffic Management Entity displays speed recommendations and other relevant information to applicable DMS.
8. Traffic Management Entity broadcasts speed recommendations and other relevant information to affected connected vehicles.
9. Connected Vehicle onboard SPD-HARM application communicates individualized speed recommendation and other pertinent information to driver.
10. Traffic Management Entity-operated SPD-HARM application records information about the speed recommendations provided, other actions taken, and results for offline performance evaluation.

Discussion

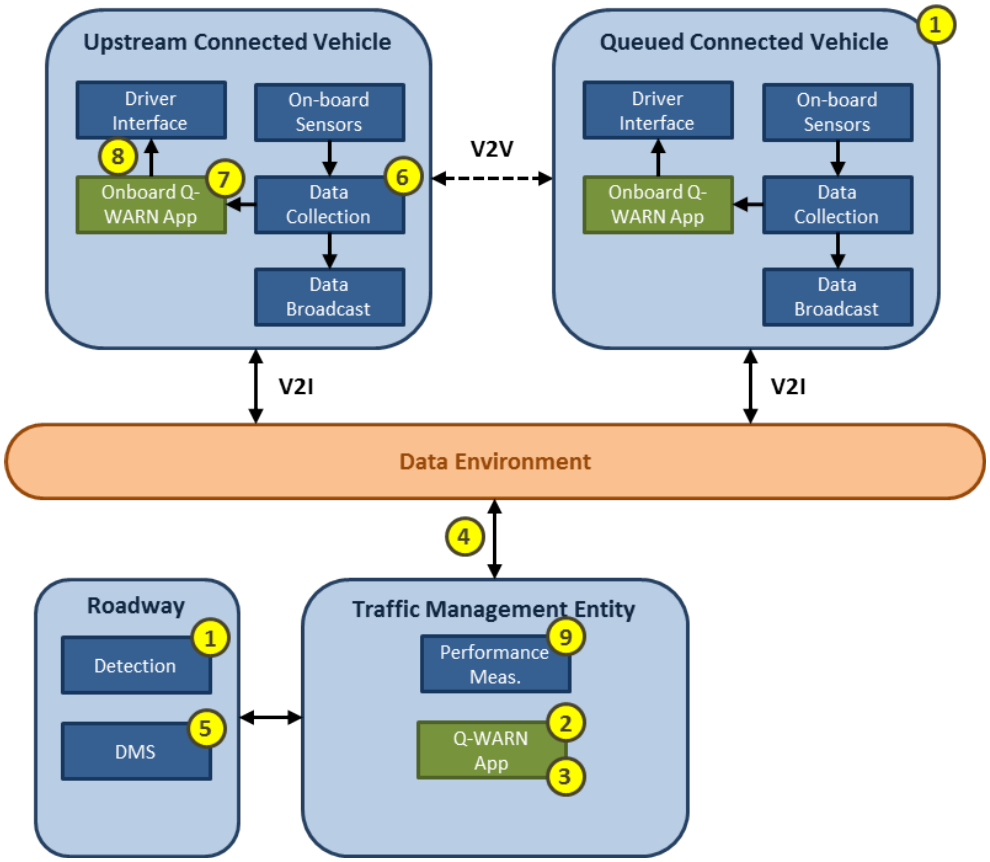
The Traffic Management Entity in this scenario conducts an extensive amount of data processing related to weather and traffic conditions modeling and prediction and speed limit optimization for safety and mobility.

Adverse weather related speed harmonization as described in this scenario will be most effective with a high penetration rate of connected vehicles, enabling a highly detailed picture of the road weather conditions for the regional transportation network. However, elements of this scenario can also be applied in the near-term as well, by depending more on fixed sensor-based detection and speed recommendation dissemination via DMS.

8.2 Q-WARN

Scenario 1: Fixed Queue Generation Point Queue Warning (External-to-Vehicle Processing; I2V-Dissemination)

In this scenario, a queue forms at a known queue generation point. Applicable situations include spillover at exit ramps, border crossings, bridges, and tunnels. Because the queue generation point is known, roadside equipment (RSE) and infrastructure-based systems have been installed to monitor queue conditions and generate warnings and response strategies for approaching vehicles. Externally-originated queue warnings and response strategies are disseminated to upstream vehicles via infrastructure-to-vehicle (I2V) communication as well as dynamic message signs (DMS).



Pre-conditions

Queued vehicles exiting the freeway spill over past the exit ramp and onto the freeway.

Steps

1. RSE installed to monitor conditions on the ramp collect traffic data and transmit to Traffic Management entity in real-time.
2. Traffic Management Entity-operated Q-WARN application detects the queue and the characteristics of the queue based on data received from RSE and connected vehicles.

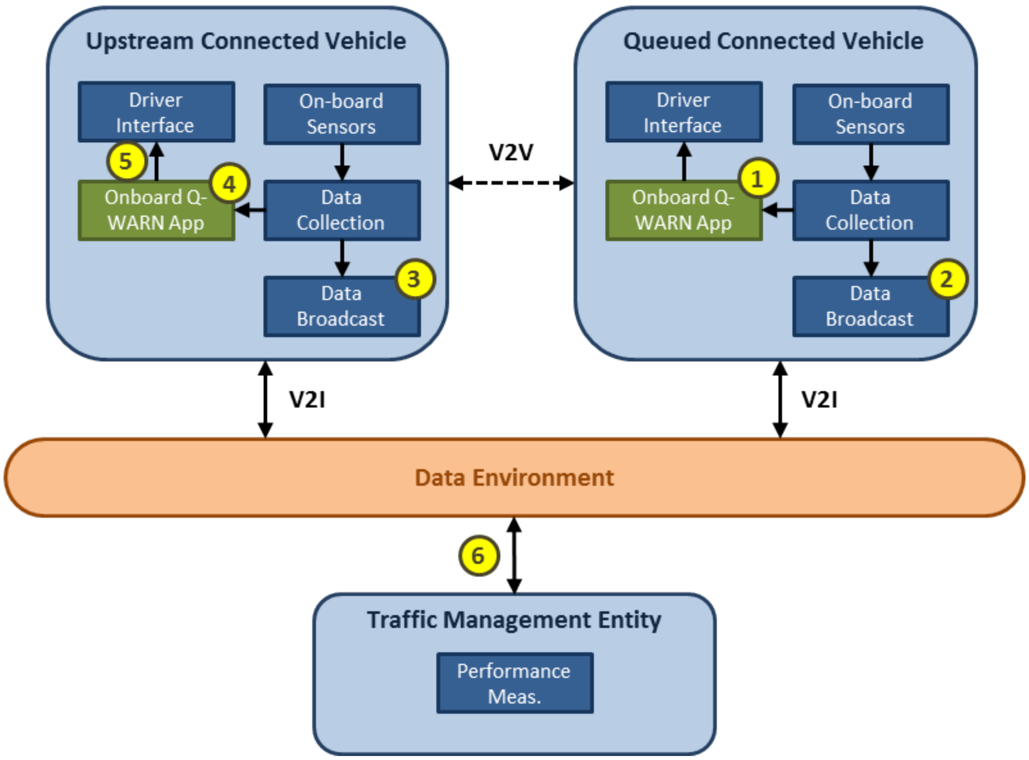
3. Traffic Management Entity-operated Q-WARN application generates generic queue warning, queue description, and response strategies based on data collected by the RSE.
4. Traffic Management Entity broadcasts generic queue warning messages and response strategies to upstream vehicles.
5. Traffic Management Entity displays appropriate queue warning message on DMS signs.
6. Upstream Connected Vehicle receives generic queue warning message and queue description.
7. Onboard Q-WARN application individualizes message based on vehicle location with respect to the end of the queue.
8. Onboard Q-WARN application communicates individualized queue warning and response strategy recommendation to driver.
9. Traffic Management Entity-operated Q-WARN application records information about the queue, generated response strategies, actions taken, and results for offline performance evaluation.

Discussion

Because this scenario does not depend upon connected vehicle technology (for example, detection and information dissemination can occur via roadway infrastructure), this approach to queue warning could be deployed in the near-term and operate in a mixed technology environment. In the long-term, connected vehicle-based data collection and information dissemination would largely replace infrastructure-based approaches for these tasks.

Scenario 2: Non-Location Specific Queue Warning (Vehicle-Based Processing; V2V-Dissemination)

In this scenario, a queue forms on a roadway with sparse roadside equipment (RSE) coverage. Queue detection will be done in-vehicle, alerts will be propagated upstream solely via V2V communication, and response strategies will be devised in-vehicle on the fly. Because this scenario relies wholly on connected vehicle-based detection, communication, and response development, non-connected vehicles will be unable to participate. Therefore, this scenario should be considered representative of the long-term state of the connected vehicle environment.



Pre-conditions

A stalled car in the number three lane results in a queue quickly forming behind it.

Steps

1. Onboard Q-WARN applications of the queued vehicles quickly and accurately detect their queued state based on collected position, speed, and braking data.
2. Queued vehicles broadcast queue warning and pertinent queue information rapidly to upstream traffic.
3. Upstream vehicles receive queue warning and continue to propagate the message further upstream.
4. Onboard Q-WARN applications of upstream vehicles generate appropriate warning messages and response strategies based on vehicle's distance to the end of the queue, characteristics of the queue, and roadway conditions. (Response strategies may include slowing down, changing lanes, or modifying route.)

5. Onboard Q-WARN applications communicate queue warning and response strategy recommendations to drivers. (Alerts and recommendations may be communicated via visual or graphical display, audible words or sounds, flashing lights, or haptic [i.e., vibrational] feedback.)
6. Onboard Q-WARN applications cache information about the queue, generated response strategies, actions taken, and results for transmission to the data environment for performance evaluation.

Discussion

A wholly vehicle-based queue detection and response system has significant benefits in terms of scalability, geographic coverage, and implementation and operational costs. With a sufficiently high penetration rate of connected vehicles and sufficiently developed Q-WARN algorithms and communications standards, queue warning can be achieved under this scenario on any roadway, anywhere, with essentially no infrastructure-based detection, communications, or signage needed to be constructed, operated, or maintained.

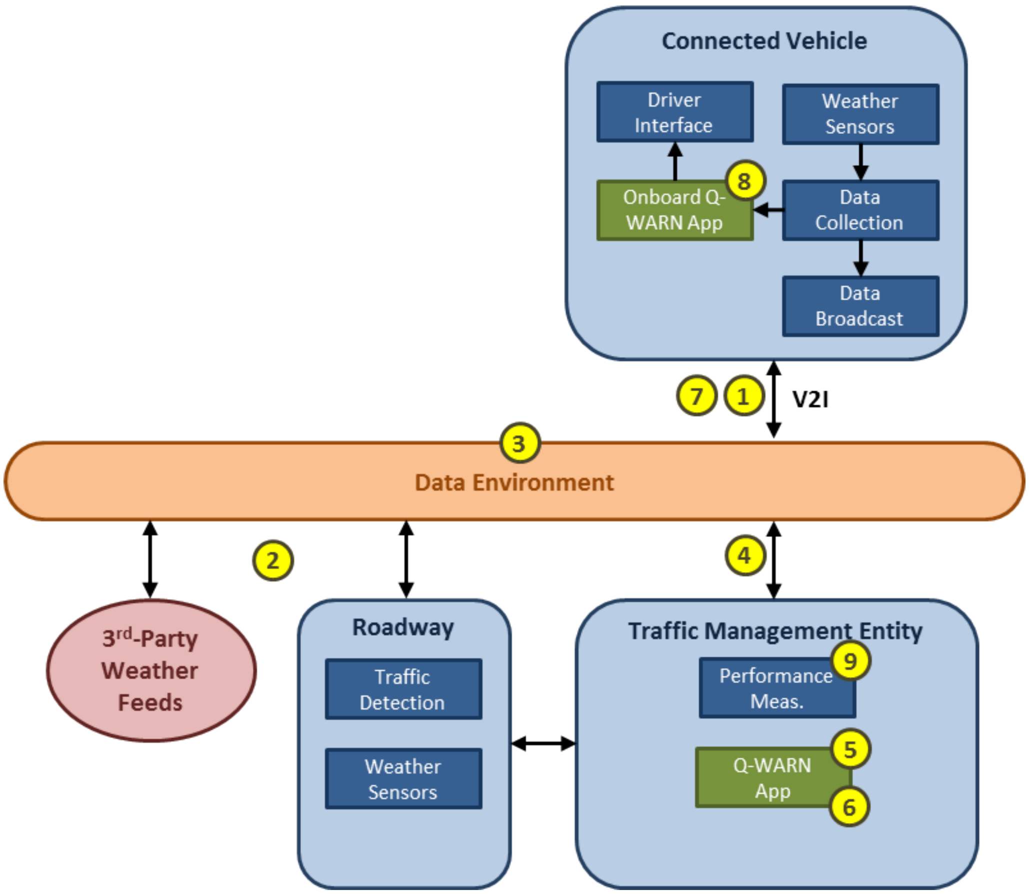
However, there are some drawbacks to this approach: while it is reasonable to expect that vehicle-originated queue detection and alerting would be sufficiently accurate and timely, the response strategies devised by individual vehicles would likely be less effective than strategies devised by an infrastructure-based system that has visibility into the wider traffic conditions.

Additionally, there are some situations in which V2V communication is not feasible or sufficiently reliable (for example, at a tunnel where line-of-sight obstructions may prevent or limit direct communication between vehicles). In such situations, a V2I and infrastructure-based solution would be required in order to provide queue warning coverage.

Finally, this approach requires near-universal adoption of connected vehicle technology in order to be effective, since the propagation of the queue warning message flows vehicle-by-vehicle back through the traffic stream. A non-equipped vehicle in the middle of the traffic stream has the potential of blocking the warning message from being fully dispersed.

Scenario 3: Weather-Related Queue Prediction and Warning (External-to-Vehicle Processing; I2V-Dissemination)

In this scenario, the Traffic Management Entity conducts extensive real-time modeling of weather impacts on traffic to predict impending queue formation. The Traffic Management Entity's Q-WARN application draws extensively from traffic and weather data from the data environment collected from connected vehicles throughout the transportation network. By anticipating imminent queue formation, the Traffic Management Entity will provide proactive warnings and recommendations to affected vehicles in order to minimize the impact of or even eliminate completely the predicted queue.



Preconditions

None.

Steps

1. Connected vehicles broadcast self-generated position, movement, actions, and road and weather conditions data to data environment.
2. Roadside weather devices and third-party weather feeds provide localized road and weather conditions data to data environment.
3. Data environment aggregates, organizes, and summarizes streaming data.
4. Traffic Management Entity receives aggregated connected vehicle traffic and weather data from data environment.

5. Traffic Management Entity-operated Q-WARN application feeds the received data into predictive models to predict the location and characteristics of potential imminent queues.
6. Traffic Management Entity-operated Q-WARN application generates anticipatory queue mitigation strategies for select locations.
7. Traffic Management Entity broadcasts potential queue warning messages and response strategies to affected vehicles.
8. Onboard Q-WARN application communicates individualized potential queue warning and response strategy recommendation to driver.
9. Traffic Management Entity-operated Q-WARN application records information about the queue, generated response strategies, actions taken, and results for offline performance evaluation.

Discussion

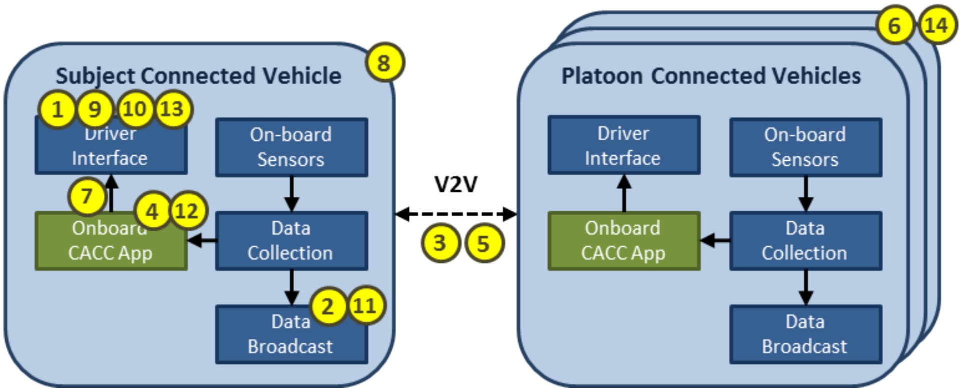
Adverse weather related queue warning as described in this scenario will be most effective with a high penetration rate of connected vehicles, enabling a highly detailed picture of the road weather conditions for the regional transportation network. However, elements of this scenario can also be applied in the near-term as well, by depending more on fixed sensor-based detection and queue warning display via DMS (if available).

8.3 CACC

Scenario 1: Joining and Exiting a CACC Platoon (Vehicle-Based Processing; V2V-Dissemination)
In this scenario, the subject vehicle joins a platoon of CACC-equipped vehicles, travels with the platoon for some distance, and then finally exits the platoon. The joining of the platoon involves V2V communication with the vehicles in the platoon for the identification of how, when, and where to join the platoon in order to ensure that platoon stability is maintained (asymptotic stability).

Merging into the platoon entails a transition from manual vehicle control to cooperative adaptive cruise control: the driver authorizes autonomous vehicle speed and gap control and relinquishes manual brake and throttle control (although these can be manually reengaged at any time).

Finally, when the driver elects to leave the platoon, the CACC application must identify the best location and time to depart the platoon, revert from automatic to manual or semi-automated control, and merge with regular traffic lanes.



Preconditions
A driver of a CACC-enabled vehicle wishes to enter a CACC platoon in the adjacent lane. This adjacent lane may be a dedicated CACC managed lane (as may be the case in the near-term) or any mixed flow lane (long-term).

Steps

1. Subject vehicle driver indicates desire to enter a CACC platoon.
2. Subject connected vehicle broadcasts self-generated position, speed, vehicle characteristics, and intention to join platoon.
3. CACC platoon acknowledges and confirms entry request.
4. Subject vehicle computes the optimum entry point into the platoon based on the speed and gap policy of the platoon and the speed and position of the subject vehicle relative to the platoon.
5. Subject vehicle communicates to the CACC platoon the position in the platoon that it will enter (e.g., between vehicles 7 and 8).

6. Upstream platoon vehicles adjust speeds and gaps to allow the subject vehicle to merge into the CACC lane.
7. Subject vehicle informs driver to merge into the CACC platoon at the appropriate speed and position.
8. Subject vehicle driver merges into the CACC platoon and maintains longitudinal movement control until the vehicle has fully entered the CACC lane.
9. Subject vehicle driver authorizes vehicle to engage autonomous throttle and brake control (which can be manually overridden at any time).
10. Subject vehicle driver indicates desire to exit the CACC platoon (e.g., via turn signal activation).
11. Subject vehicle communicates impending platoon exit to surrounding vehicles.
12. Subject vehicle computes optimum platoon exit strategy and provides recommendation to driver.
13. Subject vehicle driver reengages manual throttle control and exits platoon.
14. Remaining upstream and downstream platoon vehicles reconstruct the CACC platoon.

Discussion

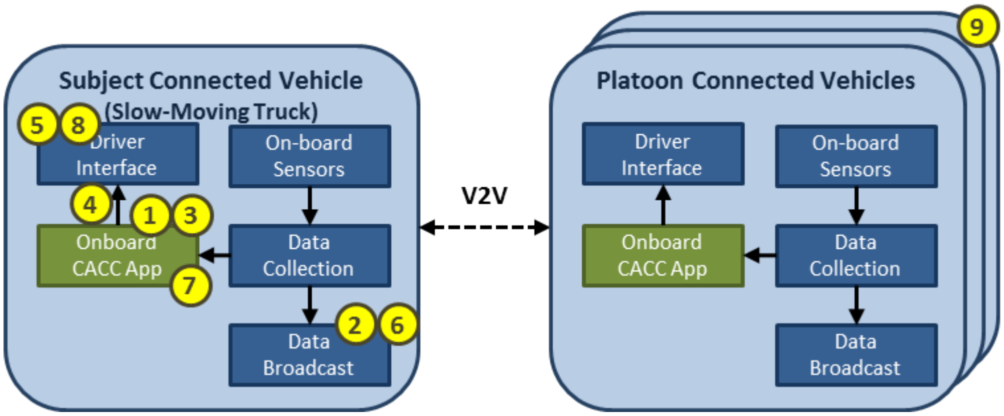
This approach assumes that the transition from manual to automated and automated to manual control is smooth. Some form of in-vehicle driver warning system will be required to alert the driver of such transitions in vehicle control. It is also likely that the vehicle will have to create a larger gap with the vehicle ahead of it before it reverts to manual control to allow the driver to take control of the vehicle in a non-hazardous manner.

The computation of the optimum location for entering a platoon might require extensive enumeration of potential scenarios and may require data on the positions of non-equipped vehicles in the platoon. This may be achieved if the subject vehicle has some form of radar technology to measure the spacing and speed differential between the subject and surrounding vehicles.

Finally, this scenario will be a very common scenario given that the vehicles will be continuously entering and exiting CACC lanes in a future CACC environment. Consequently, extensive research is required to develop algorithms to ensure that these maneuvers are executed safely with minimal reductions in system throughput and minimal environmental and energy impacts.

Scenario 2: Traveling in a CACC Platoon with Non-Homogenous Vehicles (Vehicle-Based Processing; V2V-Dissemination)

In this scenario, a platoon of CACC-equipped vehicles includes a heavy-duty truck or a low powered light duty vehicle traveling along a mountainous terrain. As a result of the steep terrain, the truck is unable to maintain the platoon speed, resulting in a large gap ahead of the truck and the formation of a moving bottleneck.



Preconditions

Subject vehicle within a CACC platoon is not capable of maintaining platoon speed (due to steep terrain or vehicle performance issues).

Steps

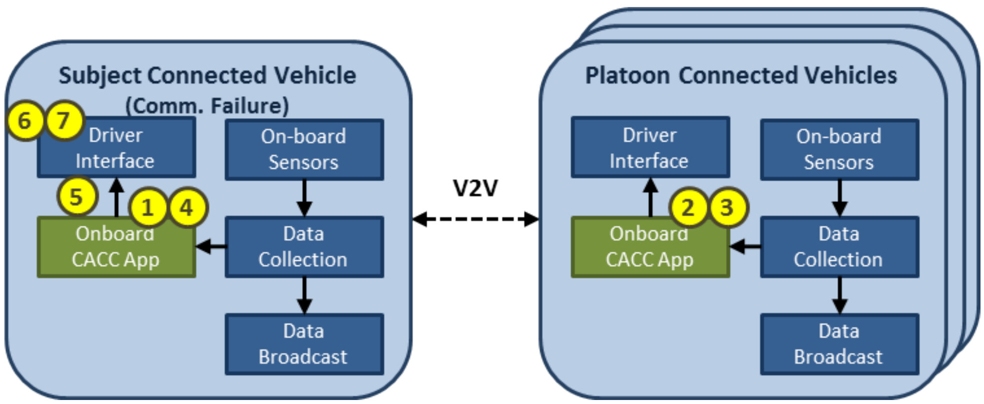
1. Subject vehicle detects that it cannot maintain platoon speed and gap requirements.
2. Subject vehicle broadcasts performance discrepancy to CACC platoon.
3. Subject vehicle determines that it should exit the CACC platoon.
4. Subject vehicle provides recommendation to driver to exit the CACC platoon due to noncompliance with platoon speed and gap policy.
5. Subject vehicle driver acknowledges recommendation and indicates intention to exit the platoon (e.g., by activating the turn signal).
6. Subject vehicle communicates impending platoon exit to surrounding vehicles.
7. Subject vehicle computes optimum platoon exit strategy and provides recommendation to driver.
8. Subject vehicle driver reengages manual throttle control and exits platoon.
9. Remaining upstream and downstream platoon vehicles reconstruct the CACC platoon.

Discussion

Heavy-duty trucks can significantly impact the flow of upstream traffic due to their vehicle dynamics constraints. It is therefore important to define individual platoons by vehicle class (i.e., requiring that all vehicles within a given platoon have comparable weight, size, and performance characteristics). This will enable platoons to maximize efficiency (by maintaining vehicle performance homogeneity) and allow all vehicles to participate in CACC.

Scenario 3: Traveling in a Platoon with V2V Communication Failure (Vehicle-Based Processing; V2V-Dissemination)

In this scenario, the subject vehicle traveling within a CACC platoon experiences a V2V communication failure. The subject vehicle and trailing CACC platoon vehicles must revert to manual or ACC control. The driver of the subject vehicle attempts to exit the platoon as safely as possible.



Preconditions

Subject vehicle within a CACC platoon loses V2V communication with surrounding vehicles.

Steps

1. Subject vehicle detects that it has lost communication with the CACC platoon.
2. CACC platoon vehicles detect communication failure with subject vehicle.
3. CACC platoon vehicles initiate communication loss response plan: e.g., trailing platoon vehicles reduce platoon speed and increase gap between platoon and subject vehicle; trailing platoon vehicle leader disengages CACC and engages ACC mode.
4. Subject vehicle automatically engages ACC mode.
5. Subject vehicle alerts driver of communication failure and provides recommendation to exit the CACC platoon.
6. Subject vehicle driver acknowledges recommendation and indicates intention to exit the platoon (e.g., by activating the turn signal).
7. Subject vehicle driver reengages manual throttle control and exits platoon.

Discussion

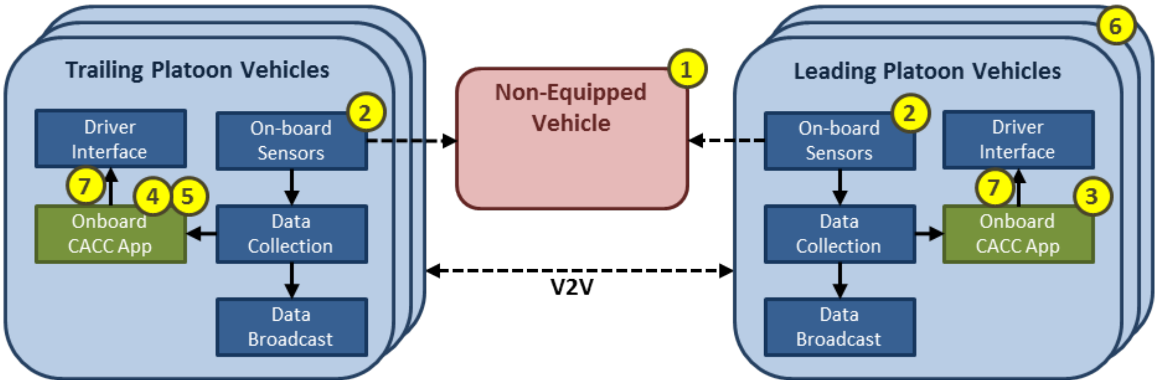
Failure of communication is a critical issue in the event a driver has to revert to manual control abruptly and the driver is distracted. The availability of ACC as an automatic fallback is critical to ensuring a safe transition to manual mode. The following research issues will need to be addressed to ensure an effective transition between automated and human responses:

- What are the drivers' expectations about the automated response of the system?
- What roles do individual differences in driving style, risk acceptance, technology acceptance, etc. play in the driver's desires for how the system should operate?

- What types of feedback are appropriate for informing the driver as to the degree of automation being applied by the system?
- What is the role of driver intent on developing an effective zero crash system?
- What are the user interface design issues?
- Can the system adapt to driver characteristics, driving styles, preferences, etc.?

Scenario 4: Non-Equipped Vehicle Enters CACC Platoon (Vehicle-Based Processing; V2V-Dissemination)

In this scenario, a non-CACC equipped vehicle merges into a CACC platoon. The connected vehicles within the CACC platoon detect the entry of the non-equipped vehicle and adapt gap and speed policies accordingly: in this case, by splitting the platoon into two and maintaining appropriate speed and gap between the trailing platoon and the non-equipped vehicle.



Preconditions

A CACC platoon is operating normally.

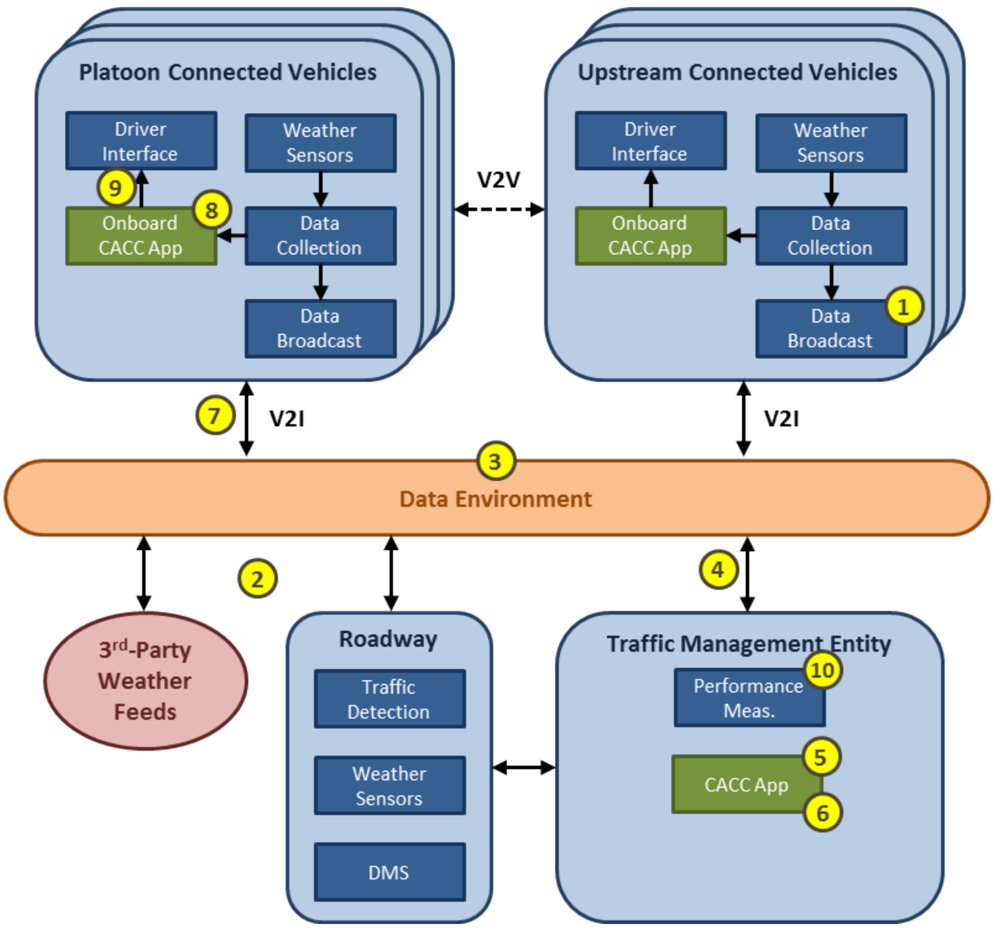
Steps

1. Non-equipped vehicle merges into the CACC platoon.
2. CACC platoon vehicles detect platoon intrusion and correctly identify it as a merging non-CACC equipped vehicle.
3. Leading CACC platoon vehicles maintain speed and gap policies.
4. Trailing platoon vehicles reduce platoon speed and increase gap between platoon and non-equipped vehicle.
5. Trailing platoon vehicle leader disengages CACC and engages ACC mode.
6. Trailing platoon vehicles establish themselves as a new and separate CACC platoon.
7. Leading and trailing platoon vehicles notify drivers of change in platoon status (e.g., by an updated screen graphic of the platoon).

Discussion

CACC platoon interruption will likely be a common occurrence in the CACC-enabled connected vehicle environment, especially in near-term deployment. Such interruptions must be planned for to ensure that CACC-optimized platoons remain intact and as robust as possible. This will require the development of standard response plans as described in the scenario steps above. As in Scenario 3, the availability of ACC as an automatic fallback is critical to ensuring that CACC operations remain effective in the face of non-equipped vehicle intrusions, communication failure, or other interruptions to the CACC platoon.

Scenario 5: Traveling in a Platoon in Inclement Weather (V2V and TMC Communication)
In this scenario, inclement weather begins to form that will affect the roadway on which a CACC platoon is traveling. The Traffic Management Entity generates new speed and gap recommendations for the platoon based on weather data received from downstream infrastructure-based detectors and connected vehicles.



Preconditions
A storm system develops and heavy rain begins to fall downstream of a CACC platoon that is operating normally.

Steps
1. Upstream connected vehicles broadcast self-generated position, movement, actions, and road and weather conditions data to data environment.
2. Roadside weather devices and third-party weather feeds provide localized road and weather conditions data to data environment.
3. Data environment aggregates, organizes, and summarizes streaming data.
4. Traffic Management Entity receives aggregated connected vehicle traffic and weather data from data environment.

5. Traffic Management Entity-operated CACC application identifies road locations and CACC platoons adversely affected by weather conditions.
6. Traffic Management Entity-operated CACC application utilizes predictive models to determine appropriate speed and gap recommendations for given locations.
7. Traffic Management Entity broadcasts speed and gap recommendations and other relevant information to affected CACC platoon vehicles.
8. CACC platoon vehicles implement new speed and gap policies
9. CACC platoon vehicles notify drivers of policy change and reasons for the change.
10. Traffic Management Entity-operated CACC application records information about the speed recommendations provided, other actions taken, and results for offline performance evaluation.

Discussion

An alternative to having the Traffic Management Entity determine and institute new speed and gap policies is to have the CACC platoon receive traction and weather conditions data directly from downstream connected vehicles via V2V communication and then independently determine appropriate speed and gap responses.

Research is needed to develop effective speed and gap recommendations for roadway traction and weather conditions. In addition, research is needed to develop algorithms that provide a smooth transition from one policy to another. Finally, the development of driver warning systems is required to inform drivers of such a transition.

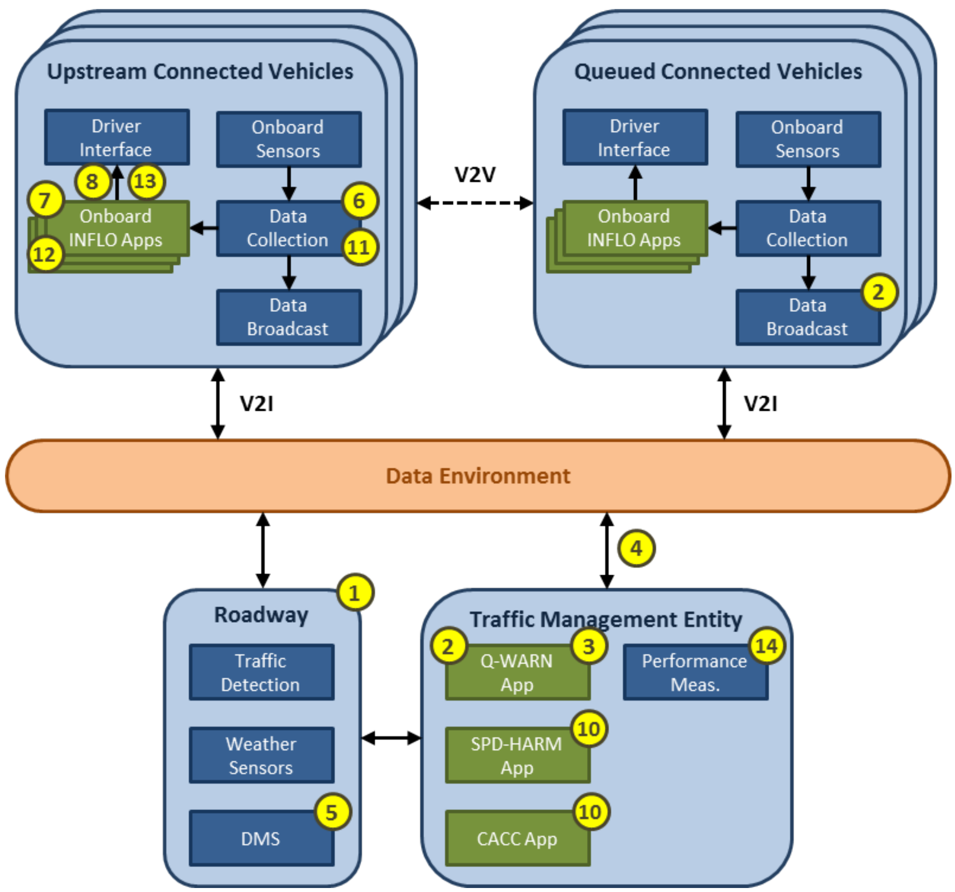
Combined INFLO Operational Scenario: Congestion on the INFLO Managed Lane

This scenario takes place in an integrated corridor that includes dedicated INFLO/CACC managed lanes. Drivers of connected vehicles who have opted into the INFLO program are granted exclusive use of the special managed lane.

In this scenario, a queue forms at a known queue generation point (in this case, where the INFLO managed lane ends and merges with the mixed traffic lane). Because the queue generation point is known, roadside equipment (RSE) and infrastructure-based systems have been installed to monitor queue conditions and generate warnings for approaching vehicles. Queue warnings are disseminated to upstream vehicles via infrastructure-to-vehicle (I2V) communication as well as dynamic message signs (DMS).

In response to the queue formation, the system generates and disseminates reduced speed recommendations to vehicles farther upstream via I2V communication as well as DMS in order to manage the traffic flow approaching the queue.

Approaching CACC platoons receive and implement the new speed and gap recommendations in order to maximize roadway capacity so that flow breakdown can be avoided.



Preconditions

Vehicles queue at the exit of the INFLO/CACC managed lane.

Steps

1. RSE installed to monitor conditions on the ramp collect traffic data and transmit to Traffic Management entity in real-time.
2. Traffic Management Entity-operated Q-WARN application detects the queue and the characteristics of the queue based on data received from RSE and connected vehicles.
3. Traffic Management Entity-operated Q-WARN application generates generic queue warning, queue description, and response strategies based on data collected by the RSE.
4. Traffic Management Entity broadcasts generic queue warning messages and response strategies to upstream vehicles.
5. Traffic Management Entity displays appropriate queue warning message on DMS signs.
6. Upstream connected vehicle receives generic queue warning message and queue description.
7. Onboard Q-WARN application individualizes message based on vehicle location with respect to the end of the queue.
8. Onboard Q-WARN application communicates individualized queue warning and response strategy recommendation to driver.
9. Traffic Management Entity-operated SPD-HARM and CACC applications utilize real-time data and historical performance analysis to generate anticipatory speed and gap strategies for the upstream CACC platoons.
10. Traffic Management Entity displays appropriate speed recommendations and related information on DMS signs at locations along the facility.
11. Traffic Management Entity transmits platoon-level speed and gap recommendations and relevant information to affected connected vehicles.
12. CACC platoon vehicles implement new speed and gap policies.
13. CACC platoon vehicles notify drivers of policy change and reasons for the change.
14. Traffic Management Entity-operated Q-WARN, SPD-HARM, and CACC applications record information about the breakdown event, generated response strategies, actions taken, and results for offline performance evaluation.

9 Impacts of INFLO

This section presents the potential key operational, organizational, and procurement/developmental impacts for the users, developers, support and maintenance organizations, and sponsoring institutions involved with the operation of the INFLO applications.

9.1 INFLO Operational Impacts

Operational Impacts	Accept/Reject/Modify	Comments
Shift to vehicle-based operations and systems Connected vehicles will enable a shift from infrastructure- and roadside-based operations to vehicle-based information collection, processing, and communications		
Increased demands on data collection and storage capabilities New data sources will be crucial to populating historical databases required for optimized speed limit selection and long-term planning		
Revised operational procedures and interfaces In order to accommodate connected vehicle data sources and communications methodologies		

Operational Impacts	Accept/Reject/Modify	Comments
New training requirements Maintenance personnel training to support the system and to keep the new system working		
Increased focus on information security Due to the reliance on private vehicle data and wireless communications, their will necessarily be an increased dedication of resources and technologies to ensure data and network security		
Increased public outreach Extensive public outreach and educational campaigns will become a more significant part of agency operations in order to achieve motorist acceptance and compliance		
Establishment of connected vehicle liability laws and regulations Due to increased role of autonomous control, automatic intervention, and system-generated driver recommendations, how liability is allocated among stakeholders when something goes wrong must be well established		

9.2 INFLO Organizational Impacts

Organizational Impacts	Accept/Reject/Modify	Comments
Tighter collaboration and interaction between public agencies and private industries Between automotive manufacturers, the cellular and phone industry, the hardware industry, the mapping industry, and state and federal transportation agencies		
Increased professional cross-over between transportation and electrical engineering INFLO systems will also bring the transportation profession into close interaction with the electrical engineering profession (e.g., via IEEE)		
Overhaul of standards and protocols development process Modifications may be required for the various messaging protocols, including the J2735 messages, to provide additional information for INFLO application usage		
Increased inter-agency and inter-jurisdictional data sharing Standardization of data formatting and sharing across different TMCs so that vehicles can travel across various jurisdictions seamlessly and receive similar data regardless of the jurisdiction		
Increased partnerships with weather data providing entities and industries Current weather data lack the reliability needed for INFLO applications; as such collaboration will be required with the weather gathering and providing industry		

Organizational Impacts	Accept/Reject/Modify	Comments
Redefined organizational structures Operating agencies may outsource the deployment process or use its own resources for this purpose. In either case, new organizational structures will arise		
Increased ITS budget allocations Budget considerations will become important and this extra cost should be included in the cost-benefit analysis of the system		

9.3 INFLO Procurement/Development Impacts

Procurement/Development Impacts	Accept/Reject/Modify	Comments
Increased focus on cyber-physical issues INFLO-related development and planning will be focused on the various cyber-physical issues that relate to the driver's interaction with partially and fully automated systems (especially relevant to CACC)		
Revised transportation planning process INFLO-optimized facilities (e.g., dedicated CACC or SPD-HARM lanes) will impact transportation planning, given their potential for greatly increasing the facility capacity. Consequently, such systems will require that they be integrated within planning decisions		
New requirements, training, and testing for road users Required testing of ability to operate in-vehicle systems, traveling in lanes at very short gap settings, transitioning from manual to automated driving and vice versa, etc.		
Third-party system certification procedures Third-party certification of the system will be required prior to full deployment. A comprehensive testing and certification process must therefore be developed		

10 Analysis of the Proposed System

10.1 SPD-HARM

10.1.1 Key Improvements

Key Improvement	Accept/Reject/Modify	Comments
Delayed or eliminated flow breakdown formation, which will improve mobility and reduce emissions		
Reduced shockwave occurrences (both number and duration), which will improve mobility and safety and will reduce emissions		
Improved traffic stream evenness, which will improve mobility and safety especially during lane changing maneuvers		
Improved travel times and travel time reliability, which improves mobility and increases user acceptance and support of the system		

Key Improvement	Accept/Reject/Modify	Comments
Improved speed limit compliance (essential for the success of SPD-HARM), which will improve mobility and safety along the facility		
Reduced number and severity of primary and secondary crashes, which directly translates to improved safety and has positive effects on user acceptance		

10.1.2 Disadvantages and Limitations

Disadvantage/Limitation	Accept/Reject/Modify	Comments
Data processing capabilities The incorporation of connected vehicle data, predictive algorithms, and simulation and optimization procedures in the conceptual SPD-HARM system will impose significant demands on data storage capabilities. It is likely that data storage, access, and processing technologies will require significant development in order to achieve the operational targets defined by the SPD-HARM concept.		
Training/retraining expenses Training is key to the success of any operational system and will be even more important because increased coordination is required. In some situations due to changes in existing operational procedures or systems, training expenses may be even higher due to the number of personnel that need to be trained or retrained		
Drivers' willingness to follow speed recommendations The effectiveness of SPD-HARM is limited by the degree to which drivers follow its recommendations. Recommendations that do not seem warranted based on traffic conditions or recommendations that come too frequently or that require severe speed adjustments risk causing drivers to stop attending to SPD-HARM recommendations completely.		

10.1.3 Alternatives and Trade-Offs Considered

Alternatives and Trade-Offs Considered	Accept/Reject/Modify	Comments
Data processing and storage Data processing and storage represents a significant component of the SPD-HARM system and is computationally and resource intensive. The SPD-HARM operating agency can reduce this burden by outsourcing the processing and storage of data to third-parties that might be better able to accommodate the demands on the data. One concern with the outsourcing approach is the increased exposure of data it entails. Data security and privacy issues would have to be resolved before any large scale data outsourcing program is begun)		
Co-deployment with other mobility and safety applications Co-deploying SPD-HARM with other applications that utilize similar data sets and processing methods could potentially reduce implementation and operational costs and improve performance. However, application co-deployment also increases the complexity of system integration and the strain on data resources. Connected vehicle-based applications and systems are undeveloped and thus risky. Introducing applications simultaneously might multiply this risk.		

10.2 Q-WARN

10.2.1 Key Improvements

Key Improvement	Accept/Reject/Modify	Comments
Reduced number of secondary crashes at fixed queue points (at border crossings, ramp spillover locations, construction zones, etc.) and at variable locations (due to incidents, weather, traffic stops, etc.)		
Improved safety outcomes of queue-related crashes due to less severe crashes		
Reduced intensity of queues, in terms of length and speed differential between approaching traffic and the queue		
Reduced occurrence and severity of traffic shockwaves upstream of queue		
Reduced queue warning-related system costs, in terms of Q-WARN infrastructure and related systems construction, operation, and maintenance		

10.2.2 Disadvantages and Limitations

Disadvantage/Limitation	Accept/Reject/Modify	Comments
Data processing capabilities The incorporation of connected vehicle data, predictive algorithms, and simulation and optimization procedures in the conceptual Q-WARN system will impose significant demands on data storage capabilities. It is likely that data storage, access, and processing technologies will require significant development in order to achieve the operational targets defined by the Q-WARN concept.		
Training/retraining expenses Training is key to the success of any operational system and will be even more important because increased coordination is required. In some situations due to changes in existing operational procedures or systems, training expenses may be even higher due to the number of personnel that need to be trained or retrained		
Drivers' willingness to accept queue warnings and follow recommendations The effectiveness of Q-WARN to minimize severe decelerations in response to downstream queues is limited by the degree to which drivers accept the application-generated warnings and follow its recommendations. False alarms and recommendations that do not seem warranted based on traffic conditions risk causing drivers to stop attending to Q-WARN alerts and recommendations completely.		

10.2.3 Alternatives and Trade-Offs Considered

Alternatives and Trade-Offs Considered	Accept/Reject/Modify	Comments
Data processing and storage Data processing and storage represents a significant component of the Q-WARN system and is computationally and resource intensive. The Q-WARN operating agency can reduce this burden by outsourcing the processing and storage of data to third-parties that might be better able to accommodate the demands on the data. One concern with the outsourcing approach is the increased exposure of data it entails. Data security and privacy issues would have to be resolved before any large scale data outsourcing program is begun.		
Co-deployment with other mobility and safety applications Co-deploying Q-WARN with other applications that utilize similar data sets and processing methods could potentially reduce implementation and operational costs and improve performance. However, application co-deployment also increases the complexity of system integration and the strain on data resources. Connected vehicle-based applications and systems are undeveloped and thus risky. Introducing applications simultaneously might multiply this risk.		

10.3 CACC

10.3.1 Key Improvements

Key Improvement	Accept/Reject/Modify	Comments
Increased roadway capacity Research and experiments on CACC systems have shown them to be able to increase roadway capacities as much as by a factor of two by reducing vehicle headways within coordinated platoons		
Reduced shockwave occurrences (both number and duration), which will improve mobility and safety and will reduce emissions		
Improved traffic stream evenness, which will improve mobility and safety especially during lane changing maneuvers		
Improved travel times and travel time reliability, which improves mobility and increases user acceptance and support of the system		
Increased road user safety CACC has the potential to greatly reduce the number and severity of crashes due to its ability to create more uniform traffic flow, to harmonize vehicle responses to hazards, and to generate faster reactions to hazards		

Key Improvement	Accept/Reject/Modify	Comments
Reduced fuel consumption and emissions CACC can have a significant impact on reducing noise, drivers' stress, and fuel consumption by creating a more uniform flow pattern. The system could also reduce vehicle acceleration levels to minimize fuel consumption		

10.3.2 Disadvantages and Limitations

Disadvantage/Limitation	Accept/Reject/Modify	Comments
Data accuracy issues The system will need to incorporate safety measures to deal with errors in vehicle speed measurements, vehicle spacing and headway measurement errors, and vehicle location errors		
Communication latency issues and lags in the provision of data		
Communication losses or communication system breakdown The system should be able to revert safely to manual driving in the event that the communication link fails		
Combining strategic TMC and local tactical car-following speed recommendations The system will need to deal with contradicting speed recommendations. For example the TMC might recommend a speed reduction based on downstream conditions, however local conditions dictate a speed increase. The system will need to derive a final decision that is some compromise between the two recommendations.		
Non-equipped vehicles entering a platoon Even if the system entails dedicated lanes for equipped vehicles, such situations could potentially arise from driver error entering the dedicated lane.		

Disadvantage/Limitation	Accept/Reject/Modify	Comments
Long-term effects on driver behavior as a result of fully-automated vehicle control		
Vehicle-specific limitations The system will have to deal with different vehicle-specific limitations (e.g., differences in acceleration capability, especially with respect to heavy-duty trucks and buses in the traffic stream)		

10.3.3 Alternatives and Trade-Offs Considered

Alternatives and Trade-Offs Considered	Accept/Reject/Modify	Comments
Integration of steering and throttle control through the use of fully automated vehicles The introduction of steering or lateral vehicle control would entail the possibility of autonomous vehicle lane-changing, negotiating curves autonomously, and maintaining lane adherence		
Developing a predictive cruise control system The current CACC systems are reactive systems in the sense that they react to the movement of the vehicle ahead of them by maintaining a speed and gap policy. An alternative system would be the development and deployment of predictive cruise control systems that in addition to maintaining a gap policy maintain the vehicle speed within a user-defined speed window. These systems use high resolution digital maps to develop a control strategy that ensures the optimal performance of the vehicle (e.g. minimization of fuel consumption) using some form of look-ahead moving horizon optimization algorithm to work within the speed window.		
Integration with roadway infrastructure CACC systems can also be integrated with roadway infrastructure (e.g. traffic signal controllers) to report Signal Phasing and Timing (SPaT) information for adaptation of vehicle speeds to minimize sum objective function (e.g. fuel consumption		

Alternatives and Trade-Offs Considered	Accept/Reject/Modify	Comments
Co-deployment with other mobility and safety applications Co-deploying CACC with other applications that utilize similar data sets and processing methods could potentially reduce implementation and operational costs. Since there are complementary factors among the various mobility and safety applications, it is expected that CACC would benefit from its integration with other applications by taking advantage of the positive effects on traffic flow and safety that the other applications generate. However, application co-deployment also increases the complexity of system integration and the strain on data resources. Connected vehicle-based applications and systems are undeveloped and thus risky. Introducing applications simultaneously might multiply this risk.		

Appendix A – Glossary of Terms Relevant to Goals and Performance Measures

Goal. In the context of the INFLO concept development, the term *goal* refers to a high-level description of the desired end result or achievement. An appropriate goal will describe the desired result, but will not prescribe the means for achieving it.

Example: *Reduce secondary crashes*.

Performance Measure. A *performance measure* is directly associated with a particular goal and reflects measurable evidence that can be used to determine progress toward that goal. This evidence can be quantitative in nature (such as the measurement of customer travel times) or qualitative (such as the measurement of customer satisfaction and customer perceptions).

Example: *Number of secondary crashes.*

Transformative Performance Target. A *transformative performance target* prescribes an appropriate magnitude for the associated performance measure. As the term "transformative" in the phrase suggests, the target should reflect performance results that are highly impactful and provide a significant (transformative) benefit.

Example: *Zero secondary crashes.*

High-Level User Need. *High-level user needs* describe the most fundamental requirements of the system entities (or users) that must be satisfied in order to operate the system. A high-level user need identifies the specific need as well as the associated user.

Example (in the SPD-HARM environment): *Vehicle operator needs to be provided the recommended vehicle speed.*

Primary Crash. For the purposes of INFLO, a *primary crash* is considered to be an initial vehicle crash or incident that is generally unavoidable or unpredictable in nature. It may be due to driver error, vehicle failure, roadway conditions, or other hazards. The main focus of INFLO is not on primary crashes, but rather on how connected vehicles can best respond to primary crashes when they occur (see Secondary Crash discussion below). Although not the main focus, primary crashes can be expected to decrease in a connected vehicle environment because many of the common causes of crashes (within-traffic speed variations and human errors related to reaction times and distance judgments) will be positively affected by INFLO and other connected vehicle safety and mobility applications.

Secondary Crash. For the purposes of INFLO, *secondary crashes* are considered to be crashes that occur as a direct result of an initial primary crash or incident. Secondary crashes often occur as a result of driver distraction, poor driver reaction time, and poor driver decision making. Secondary crashes are a main focus of INFLO because connected vehicle technologies and applications have the potential to help supplement limited human responses and decision making.

Shockwave. *Shockwaves* can be defined as transition zones between two traffic states (e.g., from free-flow to congestion) that move through a traffic environment like a propagating wave. Shockwaves are one of the major safety concerns for transportation agencies because of the increased accident potential associated with the sudden changes of speed caused by shockwaves. Shockwaves are typically caused by a change in capacity on the roadways (a 4 lane road drops to 3), an incident, a traffic signal on an arterial, or a merge on freeway. Speeds of the vehicles moving through the bottleneck will of course be reduced, but the drop in speed will cascade upstream as following vehicles also have to decelerate.

Measuring and detecting shockwaves is difficult to do with current standard roadway detection systems because it requires data on individual vehicle movements and interactions over time and space. Such data are very limited and usually only available for short sections of roadways as part of traffic studies for specific road segments. Connected vehicle technologies, however, would enable the collection of the kinds of vehicle-level data necessary for fine-grain shockwave detection and analysis because each connected vehicle can act as a vehicle-level traffic conditions monitor.

Significant Shockwave. For the purposes of INFLO, *significant shockwaves* are defined as shockwaves that result in growing queues (back-ups) affecting 7 or more vehicles in a lane. The number 7 is chosen because car following research indicates that accidents are most likely to occur at the 7^{th} to 9^{th} vehicle in a queue. However, no standards regarding shockwave significance currently exist; further research is likely needed in order to characterize shockwaves adequately and to identify the most appropriate associated performance measures and targets.

Shockwave Propagation. Traffic shockwaves typically move upstream (or “backwards”) relative to a wave front that marks the transition between the two states, through the traffic stream. The direction and speed of propagation of a shockwave depends on the respective differences in flow and density associated with the two states (i.e., $(Q_2\text{-}Q_1)/(K_2\text{-}K_1)$, where Q_1 and Q_2 denote flows associated with states 1 and 2, and K_1 and K_2 the corresponding densities). When slower traffic approaches faster traffic, a so-called rarefaction wave that travels forward develops—these are not of concern from a safety standpoint. The main concern is with shockwaves that arise when faster traffic approaches slower traffic—shockwaves that propagate fast tend to travel further, resulting in rapidly accumulating queues, longer back-ups, and higher accident risk.

Queue. For the purposes of INFLO, the 2000 Highway Capacity Manual (HCM) definition of *queue* shall be used. According to HCM (Appendix A, page 16-90), a queue is "a line of vehicles [or bicycles or persons] waiting to be served by the system in which the flow rate from the front of the queue determines the average speed within the queue. Slowly moving vehicles…joining the rear of the queue are…considered part of the queue. The internal queue dynamics can involve starts and stops..." A vehicle is considered as queued “when it approaches within one car length of a stopped vehicle and is itself about to stop.”

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