Concept Development and Needs Identification for INFLO:

Report on Stakeholder Input on Transformative Goals, Performance Measures and High Level User Needs for INFLO

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Mr. Mohammed Yousuf (COTM)

16. Abstract

The purpose of this report is to document the stakeholder input received at the February 8, 2012, stakeholder workshop at the Hall of States in Washington, D.C. on goals, performance measures, transformative performance targets, and high-level user needs for the Intelligent Network Flow Optimization (INFLO) bundle of mobility applications. This input will be used in the development of the Concept of Operations (ConOps) and high-level functional requirements for the INFLO applications. The INFLO project is part of the USDOT Dynamic Mobility Applications (DMA) program, which concerns assessing high-priority mobility applications capable of connecting vehicles, travelers, and infrastructure in order to increase roadway efficiency and improve individual mobility while reducing negative environmental impacts and safety risks. INFLO is one such DMA bundle and the queue warning (Q-WARN), dynamic speed harmonization (SPD-HARM), and cooperative adaptive cruise control (CACC) applications.

This report includes a discussion of the composition and formation of stakeholder group, the format of the workshop, key general findings from the workshop, and a presentation of the output from the discussions on goals, performance measures, transformative performance targets, and high-level user needs. The report concludes with a discussion of the next steps of the INFLO project.

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Chapter 1. Introduction

The purpose of this report is to document the stakeholder input received at the February 8, 2012 stakeholder workshop at the Hall of States in Washington D.C. on goals, performance measures, transformative performance targets, and high-level user needs for the Intelligent Network Flow Optimization (INFLO) bundle of mobility applications. This input will be used in the development of the Concept of Operations (ConOps) and high-level functional requirements for the INFLO applications.

The INFLO project is part of the USDOT Dynamic Mobility Applications (DMA) program, which concerns assessing high-priority mobility applications capable of connecting vehicles, travelers, and infrastructure in order to increase roadway efficiency and improve individual mobility while reducing negative environmental impacts and safety risks. INFLO is one such DMA bundle and encompasses three applications:

- Queue warning (Q-WARN),
- Dynamic speed harmonization (SPD-HARM), and
- Cooperative adaptive cruise control (CACC).

In selecting these applications, the USDOT sought applications that had the potential to be transformative (i.e., that they result in significant improvements in mobility and safety), that are achievable in the near-term, and that leverage the opportunities provided through connected entities. Since portions of each application currently exist or have been significantly researched, garnering input from stakeholders with relevant operational and research experiences is especially critical to develop a clear understanding of the appropriate goals, performance measures, and user needs for these applications.

This report includes a discussion of the composition and formation of stakeholder group, the format of the workshop, key general findings from the workshop, and a presentation of the output from the discussions on goals, performance measures, transformative performance targets, and high-level user needs. The report concludes with a discussion of the next steps of the INFLO project.

1.1 INFLO Applications Overview

1.1.1 SPD-HARM

The objective of speed harmonization is to dynamically adjust and coordinate maximum appropriate vehicle speeds in response to downstream congestion, incidents, and weather or road conditions in order to maximize traffic throughput and reduce crashes. Research and experimental evidence have consistently demonstrated that by that reducing speed variability among vehicles, especially in near-onset flow breakdown conditions, traffic throughput is improved, flow breakdown formation is delayed or even eliminated, and collisions and severity of collisions are reduced.

A dynamic speed harmonization (or SPD-HARM) application will be successful at managing upstream traffic flow by being able to:

1. reliably detect the location, type, and intensity of downstream congestion (or other relevant) conditions,
2. formulate an appropriate response plan (i.e., vehicle speed and/or lane recommendations) for approaching vehicles, and
3. disseminate such information to upstream vehicles readily and in a manner which achieves an effective rate of compliance.

The INFLO SPD-HARM application aims to accomplish these tasks by utilizing 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. Figure 1-1 below provides a stylized depiction of how the SPD-HARM concept could work.

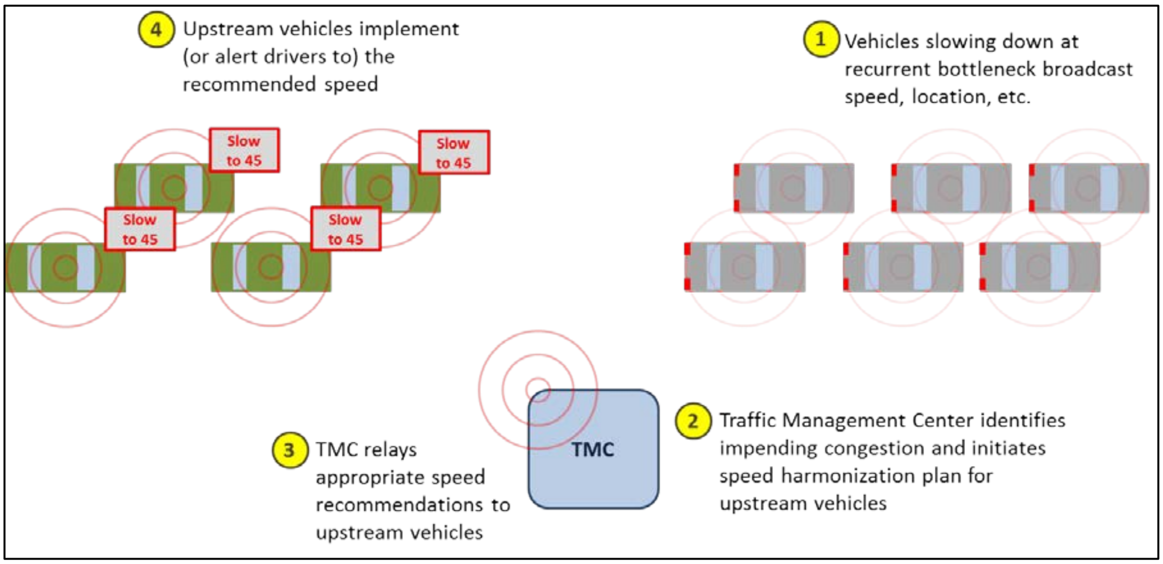

Figure 1-1. Stylized Depiction of a Connected Vehicle-Enabled SPD-HARM Application

1.1.2 Q-WARN

The objective of queue warning is to provide a vehicle operator sufficient warning of impending queue backup in order to brake safely, change lanes, or modify route such that secondary collisions can be minimized or even eliminated. A queue backup can occur due to a number of conditions, including:

- Daily recurring congestion caused by bottlenecks
- Work zones, which typically cause bottlenecks
- Incidents, which, depending on traffic flow, lead to bottlenecks
- Weather conditions, including icing, low visibility, sun angles, and high wind
- Exit ramp spillovers onto freeways due to surface street traffic conditions

In all cases, queuing is a result of significant downstream speed reductions or stopped traffic and can occur with freeways, arterials, and rural roads. Queuing conditions present significant safety concerns; in particular, the increased potential for rear-end collisions. They also present disruptions to traffic throughput by introducing shockwaves into the upstream traffic flow.

A queue warning (or Q-WARN) application will be successful at minimizing secondary collisions and the resulting traffic flow shockwaves by being able to:

1. rapidly detect the location, duration, and length of a queue propagation,
2. formulate an appropriate response plan for approaching vehicles, and
3. disseminate such information to the approaching vehicles readily and in an actionable manner.

The INFLO Q-WARN application aims to accomplish these tasks 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. Figure 1-2 below provides a stylized depiction of how the Q-WARN concept could work

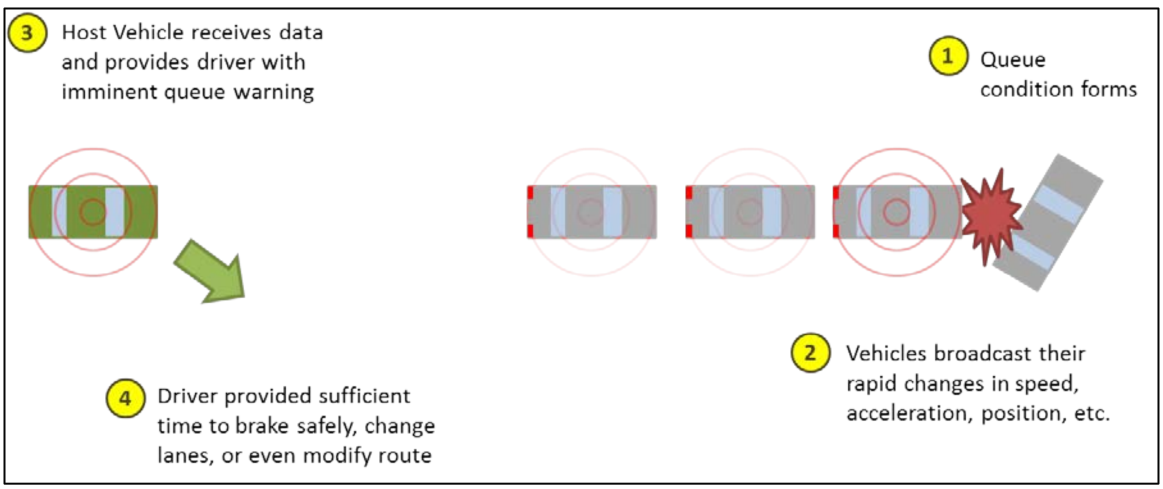

Figure 1-2. Stylized Depiction of a Connected Vehicle-Enabled Q-WARN Application

1.1.3 CACC

The objective of cooperative adaptive cruise control (or CACC) is to dynamically and automatically coordinate cruise control speeds among platooning vehicles in order to significantly increase traffic throughput. By tightly coordinating in-platoon vehicle movements, headways among vehicles can be significantly reduced, resulting in a smoothing of traffic flow and an improvement in traffic flow stability. Additionally, by reducing drag, shorter headways can result in improved fuel economy and provides the environmental benefits of lowered energy consumption and reduced greenhouse gas emissions.

CACC represents an evolutionary advancement of conventional cruise control (CCC) systems and adaptive cruise control (ACC) systems. ACC systems, which are commonly available in modern vehicle fleets, advanced upon traditional CCC systems by providing drivers the ability to specify a particular headway between the subject vehicle and the vehicle in front of it. This headway would be automatically maintained by the vehicle by utilizing on-board radar (or similar technologies) to detect following distances and electronically-controlled downshifting and/or braking in order to maintain the desired following headway. The CACC concept advances upon ACC by utilizing V2V communication to automatically synchronize the movements of *many* vehicles within a platoon.

Figure 1-3 below provides a stylized depiction of how the flow of a traffic lane could be improved by the utilization of Connected Vehicle CACC-enabled V2V communications and strategies.

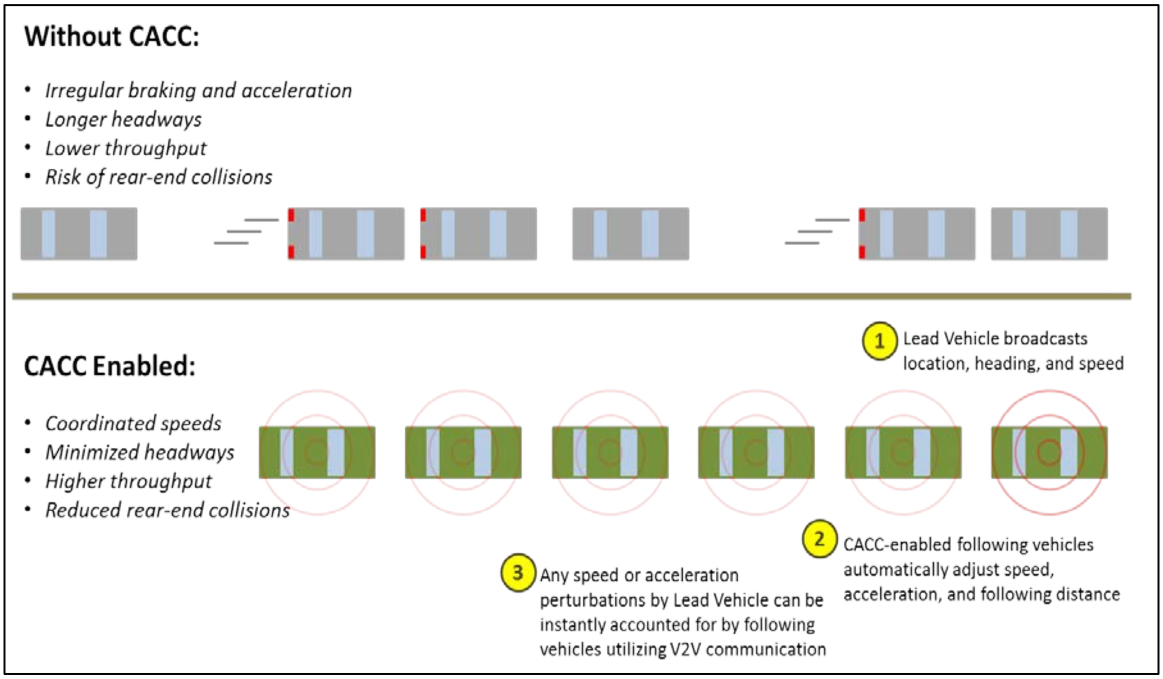

Figure 1-3. Stylized Depiction of Connected Vehicle-Enabled CACC

Chapter 2. INFLO Stakeholders

As part of the effort to complete the Concept of Operations (ConOps) for the INFLO bundle of applications, stakeholder input was solicited to identify goals, performance measures and corresponding transformative performance targets, and high-level user needs for the three applications. This input will be used in the development of the ConOps and high-level functional requirements for the INFLO applications.

The stakeholders identified for this project and who participated in the February 8 workshop comprise a wide variety of backgrounds and expertise relevant to the analysis of the INFLO applications. In total, 45 participants attended the in-person workshop and 11 attended the webinar. The table below indicates the individuals who attended in-person.

Note: asterisks (*) indicate individuals who are part of the INFLO Performing Organization Team.

Name	Organization
Khaled Abdelghany	Southern Methodist University
Sheila Andrews	American Motorcyclist Association
Morgan Balogh	WSDOT
Joe Bared	FHWA
John Benda	Illinois Tollway
Brian Cronin	USDOT
Daniel Dailey	University of Washington/USDOT
Jeffery Dale	Kimley-Horn
Richard Dye	Maryland DOT
Paul Eichbrecht	VII Consortium
Bob Ferlis	FHWA
Edward Fok	FHWA
Gary Golembowski*	SAIC
John Halkias	FHWA
Larry Head	University of Arizona
Christopher Hill	Mixon Hill
Elliot Hubbard*	Delcan
Jim Hunt	FHWA
Tom Jacobs	University of Maryland CATT

Name	Organization
Tom Kearney	FHWA-HOFM
Bob Koeberlein	Idaho DOT
Walter Kosiak	Delphi Corporation
Eil Kwon	University of Minnesota, Duluth
Dan Lukasik*	Delcan
Hani Mahmassani*	Northwestern University
Alvin Marquess	Maryland State Highway Administration
Nick Mazzenga	Kimley-Horn
Gene McHale	FHWA
Ben McKeever	FHWA R&D
Laura Meitz	Battelle
Kris Milster	FHWA
Dan Murray	ATRI
Bryan Myers	Skyline
Diane Newton*	SAIC
Steve Novosad	Atkins Global
Hilary Owen	Michigan DOT
Joseph Peters	FHWA R&D
Kala Quintana	Nova Transportation
Hesham Rakha*	Virginia Tech
Bob Rausch	TransCore
Robert Sheehan	FHWA
Steven Shladover	UC Berkeley PATH
Candice Sutton	VDOT
Dale Thompson	USDOT ITS JPO
Meenakshy Vasudevan	Noblis
Ardalan Vahidi	Clemson University
Nhan Vu	VDOT
Thomas West	UC Berkeley PATH
Karl Wunderlich	Noblis
Balaji Yelchuru	Booz Allen Hamilton
Mohammed Yousuf	FHWA (Project COTM)

The following table lists the stakeholders who participated via the webinar:

Name	Organization
Juan Aparicio	Siemens
Roger Berg	DENSO
James Colyar	FHWA
Darryl Dawson	Illinois State Toll Highway Authority
Gabe Guevara	FHWA
Mohammed Hadi	Florida International University
Kate Hartman	RITA ITS-JPO
Bernard Istasse	ESIS
Albert Piñol Sole	Colegio San Gabriel
Peter Thompson	SANDAG
Vann Wilber	VII Consortium

Chapter 3. Stakeholder Feedback on Goals, Performance Measures, Targets, and User Needs

This section presents the stakeholder feedback on INFLO goals, performance measures, transformative performance targets, and high-level user needs gathered at the February 8th face-to-face workshop. Stakeholder input on goals, performance measures, and associated performance targets was solicited through open group discussion with facilitation by the INFLO project team. Stakeholder input on high-level user needs was obtained in three concurrent facilitator-led breakout sessions, one each focused on Q-WARN, SPD-HARM, or CACC. Stakeholders were selected for one of the three user need sessions based on their interest in the respective applications. Findings from the user need breakouts were then shared and discussed with the full group.

In addition, a webinar was conducted concurrently with the face-to-face workshop, providing remote stakeholders the opportunity to not only view the presentation slides and listen in to the discussion, but also to participate in the conversation by submitting typed comments, which were shared with the full group in real-time.

The following subsections, organized by application, summarize the output of the day's stakeholder discussions.

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 *Section 5 Glossary*.

3.1 General Findings

Several overarching themes emerged during the stakeholder discussion of goals, performance measures, and transformative performance targets, which helped to guide and refine their development across all three applications:

- Stated INFLO goals and associated performance targets should reflect "stretch goals", i.e., that they are representative of an end state or condition that is vastly superior to the current condition.
- Since it is anticipated that penetration rates of Connected Vehicle-enabled vehicles will increase gradually, stated goals, performance measures, and targets should include a timeframe reference indicating whether the goal is achievable in the near, medium, or long term. The following are the current working definitions for near, medium, and long term:

  - ***Near-term (today-2020):*** 0 to 10% connected vehicle penetration; limited mostly to subsets of freight and transit fleets
  - ***Mid-term (2020-2030):*** High penetration rates among freight and transit fleets; building adoption among private passenger vehicles growing from 10% to 60%
  - ***Long-term (beyond 2030):*** Growing from 60% to greater than 90%; majority of vehicle types and classes are equipped

- As user acceptance is critical to the success of the INFLO applications, there is value in promoting "user-centric" goals (i.e., goals that clearly reflect value to the typical individual road user) in addition to "system-wide performance" goals, where the direct value of the goal to an individual user may be less transparent.
- Performance targets will likely vary based on roadway setting (metropolitan vs. suburban vs. rural), roadway type (mixed flow freeway, designated truck or transit lanes, arterials, etc.), and vehicle type (passenger vehicles, freight vehicles, motorcycles, etc.).
- Performance target values will also be affected by the degree to which the INFLO applications are deployed together. For example, a jointly deployed SPD-HARM and CACC system will be much more effective at dissipating traffic shockwaves than a SPD-HARM system by itself.
- Education of the driving public on variable speed limits (i.e., the theory behind how they combat congestion and why they are important) should be considered a high priority in order to ensure the levels of compliance necessary to make the INFLO applications successful.

3.2 SPD-HARM Discussion Output

SPD-HARM stakeholders described 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.

3.2.1 SPD-HARM Goals, Performance Measures, and Transformative Performance Targets

During stakeholder discussion of dynamic speed harmonization (SPD-HARM), it was agreed that a deployed SPD-HARM system would provide significant benefit in three key areas:

1. Roadway throughput (which is considered synonymous with flow and capacity),
2. Safety of road users, and
3. Energy consumption.

These benefits align closely with the stated purpose of the USDOT Dynamic Mobility Applications program, which is to develop systems and applications that increase roadway efficiency and improve individual mobility while reducing negative environmental impacts and safety risks. The goals, performance measures, and targets described in Table 3-1 on the following pages support these benefits and reflect the specific ways in which a SPD-HARM enabled environment can help achieve them. Goals, performance measures, and targets are combined into a single table to better illustrate how they relate to each other. The table is organized as follows:

- The goal
- Associated performance measure(s)
- Near-, medium-, and long-term performance targets
- Predominant benefit of the goal (whether mobility, safety, or energy related)
- Whether the goal is oriented toward the individual user or the whole transportation system generally

Table 3-1. SPD-HARM Goals, Performance Measures, and Targets.

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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)	Safety/mobility	System-oriented
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)	Safety/mobility	System-oriented
	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)	Safety/mobility	System-oriented
3. Improve speed limit compliance	Compliance rate of posted or recommended speed limit	• 75% compliance (near) • 95% compliance (mid) • 100% compliance (long)	Mobility	System-oriented

* See Section 5 - Glossary of Terms for a discussion of key traffic shockwave and queue terminology.

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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	Mobility	System-oriented
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)	Mobility	User-oriented
	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)	Mobility	User-oriented
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)	All	User-oriented
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)	Safety	System- / user-oriented

† See Section 5 - Glossary of Terms for a fuller discussion of crash and safety terminology.

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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)	Safety	System- / user-oriented
9. Reduce number of secondary crashes†	Number of secondary crashes	• Reduce number by 50% (near) • Reduce number by 75% (mid) • Zero secondary crashes (long)	Safety	System- / user-oriented
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)	Energy	System-oriented
	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)	Energy	System-oriented
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)	Costs	System-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
	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)	Costs	System-oriented

3.2.2 SPD-HARM High-Level User Needs

High-level user needs agreed to in the SPD-HARM user needs breakout session are identified and discussed in Table 3-2, below.

Table 3-2. SPD-HARM High-Level User Needs.

User	High-Level User Need	Discussion
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	High-Level User Need	Discussion
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	High-Level User Need	Discussion
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	High-Level User Need	Discussion
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.

3.3 Q-WARN Discussion Output

During stakeholder discussions of Q-WARN, it was agreed that the 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 Table 3-3 for a summary of the capabilities and advantages of these approaches for essential Q-WARN tasks.

Table 3-3. Comparison of Vehicle- and Infrastruture-based Q-WARN Capabilities

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)

Queue determination (detection and/or prediction):

A strictly vehicle-based Q-WARN application is necessarily *reactive*, in that it can only detect and respond to an already-formed queue because it has visibility only into the immediate local traffic condition. Vehicle-based Q-WARN is not capable of predicting potential queue formation because it does not have a comprehensive picture of the traffic state, in terms of historical patterns and the wider traffic conditions. Additionally, limited visibility into the traffic state is likely to reduce the precision and reliability of vehicle-based queue detection. Despite these limitations and given high enough levels of connected vehicle penetration (likely only in the long term), vehicle-based Q-WARN has the advantage of being immediately deployable on nearly any roadway without the need for the construction, operation, or maintenance of queue warning related infrastructure.

An infrastructure-based Q-WARN application, on the other hand, can be *proactive*—utilizing its broader visibility into the traffic state to predict likely queue formations. A central entity (such as a Traffic Management Center) can predict, using data collected over a period of time and over a geographical area, the location, length, duration, and likelihood of a queue forming. This allows for preemptive actions to be taken to either minimize the impact or prevent the formation of a vehicle queue. Thus, an infrastructure-based component for the Q-WARN application is necessary for queue prediction even in the long-term.

Queue information dissemination:

A strictly vehicle-based queue information dissemination approach (i.e., without external intervention from infrastructure systems or traffic management entities) would provide adequate upstream traffic queue warning, given sufficient levels of connected vehicle market penetration. Vehicle-based queue information dissemination would also be viable for queue warnings and related information generated by infrastructure-based entities. However, due to the need for high connected vehicle penetration levels, the vehicle-based information dissemination approach is likely to be more applicable in the mid-to-long term.

An infrastructure-based queue information dissemination approach, on the other hand, will be more effective in the near-term at providing sufficient queue warning when there are fewer equipped vehicles on the road. Additionally, in cases where vehicle-based communication may not be feasible (for example, at a tunnel entrance where line-of-sight obstructions may prevent direct communication between vehicles), infrastructure-based information dissemination will be required in order to provide a queue warning capability.

3.3.1 Q-WARN Goals, Performance Measures, and Transformative Performance Targets

The key benefit of queue warning (Q-WARN) that emerged from stakeholder discussions was improvement in safety (via reduction or elimination of secondary crashes). Although it was agreed that Q-WARN could have a positive effect on throughput (by reducing the number of traffic-impeding crashes), this benefit was seen as secondary to the primary benefit of improving safety.

The safety and associated mobility benefits Q-WARN still closely align with the stated purpose of the USDOT Dynamic Mobility Applications program, which is to develop systems and applications that increase roadway efficiency and improve individual mobility while reducing negative environmental impacts and safety risks.

Goals, Performance Measures, and Transformative Performance Targets for Q-WARN are captured in Table 3-3, on the following pages.

Table 3-4. Q-WARN Goals, Performance Measures, and Targets.

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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)	Safety	System- / user-oriented
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)	Safety	System- / user-oriented
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)	Safety	System- / user-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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)	Safety/mobility	System-oriented
	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)	Safety/mobility	System-oriented
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)	Safety/mobility	System-oriented
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)	Safety/mobility	System-oriented
	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)	Safety/mobility	System-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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)		User-oriented
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)	Safety	System- / user-oriented
	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)	Safety	System- / user-oriented
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)	Costs	System-oriented
	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)	Costs	System-oriented

3.3.2 Q-WARN High-Level User Needs

High-level user needs agreed to in the Q-WARN user needs breakout session are identified and discussed in Table 3-4, below.

Table 3-5. Q-WARN High-Level User Needs.

User	High-Level User Need	Discussion
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	High-Level User Need	Discussion
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	High-Level User Need	Discussion
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).
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.

User	High-Level User Need	Discussion
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.

3.4 CACC Discussion Output

CACC stakeholders described 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.

3.4.1 CACC Goals, Performance Measures, and Transformative Performance Targets

As with the SPD-HARM discussions, the cooperative adaptive cruise control stakeholder discussions led to agreement that a deployed CACC system would provide significant benefit in the areas of:

1. Roadway throughput,
2. Safety of road users, and
3. Energy consumption.

And like with SPD-HARM, these CACC benefits align with the stated purpose of the USDOT Dynamic Mobility Applications program, which is to develop systems and applications that increase roadway efficiency and improve individual mobility while reducing negative environmental impacts and safety risks.

The alignment of benefits between SPD-HARM and CACC is reflective of the potential value that a joint deployment of these two applications has to each. In discussions, stakeholders emphasized that the degree to which CACC goals and performance targets can be met depends largely on the degree to which dynamic speed harmonization (and to a lesser extent, queue warning) is integrated with a CACC deployment. Goals, Performance Measures, and Transformative Performance Targets for CACC are captured in Table 3-5, on the following pages.

Table 3-6. CACC Goals, Performance Measures, and Targets.

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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)	Mobility	System-oriented
	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)	Mobility	System-oriented
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)	Safety/mobility	System-oriented
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)	Safety/mobility	System-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
	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)	Safety/mobility	System-oriented
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	Mobility	System-oriented
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)	Mobility	User-oriented
	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)	Mobility	User-oriented
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)	[All]	User-oriented
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)	Safety	System- / user-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
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)	Safety	System- / user-oriented
9. Reduce number of secondary crashes	Number of secondary crashes	• Reduce number by 50% (near) • Reduce number by 75% (mid) • Zero secondary crashes (long)	Safety	System- / user-oriented
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)	Energy	System-oriented
	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)	Energy	System-oriented
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)	Costs	System-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
	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)	Costs	System-oriented

3.4.2 CACC High-Level User Needs

High-level user needs agreed to in the CACC user needs breakout session are identified and discussed in Table 3-6, below.

Table 3-7. CACC High-Level User Needs.

User	High-Level User Need	Discussion
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.

User	High-Level User Need	Discussion
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.
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	High-Level User Need	Discussion
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.
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.

Chapter 4. Next Steps

The next step in this project is to develop the INFLO Concept of Operations (ConOps), which will incorporate the stakeholder input received as captured in this document. A preliminary draft ConOps will first be submitted for USDOT review. A revised draft will then be shared with the INFLO stakeholder group for review and comment. The final INFLO ConOps will be reflective of the stakeholder feedback received.

The ConOps will include for each application: an overview of existing systems, justification for and nature of proposed changes, the concepts for the proposed systems, operational scenarios, a summary of anticipated impacts, and an analysis of the proposed system.

Following the approval of the final ConOps, the functional and performance requirements will be developed. The requirements will identify what the INFLO bundle of applications must accomplish in order to meet the goals and objectives identified in this report. The requirements will be organized into sub-systems in order to ensure that they can be traced back to the needs and issues identified in the ConOps. In addition to the requirements, the high-level communications needs for implementation will be determined.

Both the ConOps and the functional requirements will be packaged into draft reports for review by the USDOT team and the stakeholder group. These documents will be reviewed in a face-to-face walkthrough meeting with the USDOT team.

The final phase of this project includes an assessment of test-readiness for the INFLO applications. This step includes identifying the technical and non-technical issues related to field testing the applications. This information will be packaged in a brief summary report and submitted to the USDOT team.

Chapter 5. Glossary of Terms Relevant to Goals, Performance Measures, and Targets

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., $(Q_2-Q_1)/(K_2-K_1)$, 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."

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487
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