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

Concept of Operations

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16. Abstract

The purpose of this project is to develop for the Intelligent Network Flow Optimization (INFLO), which is one collection (or bundle) of high-priority transformative applications identified by the United States Department of Transportation (USDOT) Mobility Program for development in 2011, the following:

- Concept of Operations (ConOps)
- Functional requirements and corresponding performance requirements
- High-level data and communication needs
- Test readiness Assessment Document

This particular document is the Concept of Operations or "ConOps". It is developed using the guidance in IEEE Standard 1362-1998, IEEE Guide for Information Technology – System Definition – Concept of Operations (ConOps) Document. The follow on functional and performance requirements will be developed following the guidance in IEEE Standard 1233-1998, IEEE Guide for Developing System Requirements Specifications. In addition, the project scope of work will identify and assess key technical and non-technical issues related to field-testing the INFLO bundle or its individual component applications.

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1 Introduction

1.1 Purpose of the Document

The purpose of this Concept of Operations (ConOps) document is to provide a thorough conceptual overview of the Intelligent Network Flow Optimization (INFLO) bundle of applications that fully considers the impact of wireless connectivity on the surface transportation system. This document is intended to convey the INFLO concept to stakeholders who may develop or refine the applications or implement operational systems based on the concept.

1.2 Scope of the INFLO Project

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.

Other considerations that will promote this widespread implementation include carefully considering user needs and requirements, ensuring the availability of required data sources, identifying potential barriers to implementation, and (wherever possible) using non-proprietary and/or open source approaches that can readily be adopted by a wide variety of potential end users in both the public and private sector.

The first task of this project was to conduct an assessment of the current state of practice and relevant prior and ongoing research for INFLO (see *Report on Assessment of Relevant Prior and Ongoing Research for INFLO*). The purpose of this assessment was to provide a clear understanding of relevant research in the area of network flow optimization that might impact the development and eventual deployment of an INFLO system. Relevant research and practices identified in the assessment formed the basis for the current state definition of this ConOps document.

The next task of this project was to conduct a face-to-face stakeholder workshop to solicit input on goals, performance measures, transformative performance targets, and high-level user needs for the INFLO bundle of applications (see *Report on Stakeholder Input on Goals, Performance Measures, Transformative Performance Targets, and High-Level User Needs for INFLO*). This workshop was conducted on February 8, 2012 at the Hall of States in Washington D.C. In total, 56 stakeholders participated in the workshop, representing a wide variety of backgrounds and expertise relevant to the analysis of the INFLO applications. Stakeholder input was crucial in defining the key goals, performance measures, and user needs described in this ConOps and in identifying key operational scenarios for each application.

This document, the INFLO Concept of Operations, defines the concepts for the three INFLO applications, offers relevant operational scenarios that demonstrate the capabilities of the applications, identifies the transformative goals (with respect to mobility, environment, and safety impacts) that the applications can realize, and suggests corresponding qualitative and quantitative measures for estimating the performance of the applications in achieving these transformative goals.

Following the finalization of the ConOps, 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.

The final phase of this project is to conduct a test-readiness assessment for the INFLO applications, which entails identifying the technical and non-technical issues related to field testing the applications.

1.3 Document Overview

This document is organized and will be presented following the guidelines of IEEE 1362-1998 - IEEE *Guide for Information Technology - System Definition - Concept of Operations (ConOps) Document*.

The sections are as follows:

- Chapter 1 – Scope
- Chapter 2 – Referenced Documents

- Chapter 3 – Current System or Situation
- Chapter 4 – Justification for and Nature of Changes
- Chapter 5 – Concept for Proposed System
- Chapter 6 – Operational Scenarios
- Chapter 7 – Summary of Impacts
- Chapter 8 – Analysis of Proposed System
- Chapter 9 – Appendices

Chapter 2. Referenced Documents

This section lists all supporting documentation referenced in this document.

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Chapter 3. Current State of Network Flow Optimization

This section provides a discussion of the current state of practice for dynamic speed harmonization, queue warning, and adaptive cruise control.

3.1 Speed Harmonization Current State

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 system 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.

3.1.1 Background

Speed harmonization techniques have been deployed to achieve a variety of different objectives, depending on the end goal of the deployment agency or authority. Main objectives include:

- Speed management and safety
- Delay breakdown and throughput improvement
- Speed control under inclement weather
- Incident management
- Tunnel and bridge safety
- Flow and safety control along work zones

Speed harmonization research (FHWA *ATM Scan*, 2007) has noted that speed variances tend to increase before the onset of flow breakdown on freeways and that by implementing speed harmonization systems (and thus reducing the range of variation of individual vehicle speeds), the onset of breakdown may be delayed or even avoided altogether. It has also been noted that the effectiveness of speed harmonization is improved when combined with other congestion management strategies, including temporary shoulder use (FHWA *Efficient Use of Highway Capacity*, 2010) (Nygårdhs, 2011) and ramp metering (Shladover et al., 2010). Utilization of vehicle-to-vehicle and vehicle-to-infrastructure communications technology is expected to enhance the effectiveness of speed harmonization applications.

The following are some of the significant findings from speed harmonization research and deployments:

Crash reduction: The most common objective for U.S. and international speed harmonization implementations has been to reduce crashes, whether due to speeding, poor visibility, inclement weather, or construction activities. Improved safety results, in terms of reduced crash rates and less severe crashes, have shown to be the most significant and consistent achievements across the deployments examined. The following are some summary findings from studies that examined VSL implementation impacts on safety:

- Analysis of Germany's A3, A4, A5, A8, and A9 showed a 20-30% reduction in crashes (FHWA *ATM Scan*, 2007) (Austroads, 2009) (FHWA *Efficient Use of Highway Capacity*, 2010).
- Analysis of the UK's M25 showed a 15% reduction in injury rates (FHWA *Speed Harmonization and Shoulder Use*, 2009) (United Kingdom Highway Agency, 2007).
- Analysis of Finland's E18 inclement weather VSL showed a 13% reduction in wintertime crashes and a 2% reduction in summertime crashes (FHWA *Speed Harmonization and Shoulder Use*, 2009).
- Analysis of Greece's Attiki Odos tunnel-warning VSL showed significant reduction in injury accidents and significant improvement in accident recovery rates (FHWA *ATM Scan*, 2007) (Harito, 2011).
- Analysis of Colorado's Eisenhower Tunnel downhill truck speed warning VSL showed a 5% reduction in truck-related crashes, even as truck traffic increased during the time (CDOT, 1999).
- Analysis of Missouri's I-270 showed significant reduction in number and severity or crashes (MoDOT, 2008) (King, 2010).

Speed reduction: The ability of speed harmonization systems to reduce crashes and improve safety is directly related to the ability of the system to promote reduced vehicle speeds and speed variance, especially in unsafe driving conditions. The speed harmonization systems examined have been generally very effective at effecting such speed and speed variance reduction. The following are some summary findings from studies that examined VSL implementation impacts on speed reductions:

- Analysis of Sweden's speed harmonization pilot program showed a 5-15 km/h reduction in average speeds (Nygårdhs, 2011).
- Analysis of Colorado's I-70 pilot rolling speed harmonization program showed a significant reduction in average speeds as well as a significant reduction in speed differentials among vehicles in the traffic stream (Heavy Duty Trucking, 2011).

- Analysis of Minnesota's I-494 Work Zone VSL showed a 25-35% reduction in the average maximum speed difference (for one-minute intervals) (Kwon et al., 2006).

Speed limit compliance: In order for a speed harmonization system to manage traffic flow effectively, it must be able to achieve sufficiently high rates of speed limit or advisory speed compliance within the target zones. Review of the literature has revealed many different approaches (including mandatory limits, advisory limits, strong enforcement, weak enforcement, and caps on the magnitude of speed limit changes) and decidedly mixed results. The following are some summary findings from studies that examined VSL implementation speed compliance:

High compliance

- Analysis of the Netherlands' A2 <u>mandatory and automated enforced</u> VSL showed high compliance, which was attributed to high public awareness of the automated enforcement FHWA *Speed Harmonization and Shoulder Use*, 2009).
- Analysis of the UK's M25 <u>mandatory and photo radar enforced</u> VSL showed high compliance, as well as high satisfaction rates among drivers and police (FHWA *Speed Harmonization and Shoulder Use*, 2009) (United Kingdom Highway Agency, 2007).
- Analysis of Finland's E18 <u>advisory</u> weather-related VSL showed a 76% compliance rate, as well as a 95% satisfaction rating from drivers (FHWA *Speed Harmonization and Shoulder Use*, 2009).
- Analysis of Sweden's speed harmonization pilot program, which utilized both <u>advisory and mandatory</u> signage, showed high compliance, especially during severe weather conditions (Nygårdhs, 2011).
- Analysis of Colorado's I-70 pilot rolling speed harmonization program (<u>mandatory and enforced</u>) showed high compliance, attributed to the fact that a police vehicle with flashing lights managed the speed harmonization directly within the traffic stream (Heavy Duty Trucking, 2011).

Mixed success

- Analysis of Maine's I-95 and I-295 <u>advisory</u> weather-related VSL showed low compliance in dry and wet weather conditions and high compliance in snowy and icy conditions. As a result of the uneven compliance, system managers are considering making the speed limits fully mandatory and enforced (Beltz et al., 2009).

Low compliance

- Analysis of Colorado's Eisenhower Tunnel downhill truck speed warning <u>advisory</u> VSL showed that speed limit compliance decreased dramatically when speed recommendations were much lower than current traffic speeds (CDOT, 1999).
- Analysis of Missouri's I-270 <u>mandatory</u> VSL showed low compliance, attributed partly to sign visibility issues. As a result of the low compliance, system managers later made the variable speed limits advisory (MoDOT, 2008) (King, 2010).

Throughput: Although not the primary goal for most U.S. and international speed harmonization deployments, improvements in throughput, though modest, have sometimes been achieved. A key point to keep in mind in this regard is that of appropriate reference point for the comparison, because speed harmonization does not increase throughput per se relative to flowing conditions, but rather enables the retention of those conditions over a longer period of time by delaying the onset of flow breakdown.

Successes

- Analysis of the UK's M25 showed "significant" increases in throughput, including a 1.5% increase in its first year of operation (FHWA *Speed Harmonization and Shoulder Use*, 2009) (United Kingdom Highway Agency, 2007).
- Analysis of Minnesota's I-494 Work Zone VSL showed a 7% increase in early morning (6-7am) throughput, but no change during the 7-8am time (Kwon et al., 2006).
- Analysis of Michigan's I-96 Work Zone VSL showed an increase in average speed and throughput (FHWA *Work Zone VSL Evaluation*, 2004).

Limited or no effect

- Analysis of Netherland's A2 showed no clear increase in throughput or capacity (FHWA *Speed Harmonization and Shoulder Use*, 2009) (Robinson, 2000).
- Analysis of Missouri's I-270 showed no increase in throughput (MoDOT, 2010) (King, 2010).

Travel time reliability: Speed harmonization implementations have been shown to have a moderately positive impact on travel time reliability, likely due to the resulting more uniform traffic flow (FHWA *Speed Harmonization and Shoulder Use*, 2009). The following are some summary findings from studies that examined VSL implementation impacts on travel time reliability:

- Analysis of the UK's M25 showed a "significant" increase in journey time reliability (FHWA *Speed Harmonization and Shoulder Use*, 2009) (United Kingdom Highway Agency, 2007).

3.1.2 Operational Policies and Constraints

The goal of a speed harmonization system is to determine appropriate speeds for the traffic stream to satisfy certain objectives (e.g. increase throughput and increase safety). This section discusses the key operational policies and constraints that impact the ability of current speed harmonization systems to meet this goal.

Time lag between event detection and response communication

An important operational consideration is that of the time lag between detecting such situations and communicating the reduced speeds to drivers. While improved predictive logic can speed the process, it cannot completely eliminate delay. It is essential to reduce to a minimum internal review and procedural times within the implementing agency—so that such interventions could be triggered and deployed automatically, with limited TMC operator intervention—so long as it falls within certain pre-approved operational parameters.

Minimum interval for posted speed recommendation adjustments
The minimum interval before changing displayed or disseminated speed recommendations is an important parameter of speed harmonization logic, and reflects a trade-off between driver expectation and operational effectiveness.

ITS staffing constraints
While the deployment of modern speed harmonization systems does not necessarily require the recruitment of new staff, it does require an increased investment in time and effort for training and monitoring, especially as the speed harmonization algorithms increase in sophistication. Workload for TMC operators can be expected to increase.

Data provision and ownership policies
Inter-agency, inter-jurisdictional, and public-private data sharing agreements are not currently well defined or consistently implemented in the current practice due in large part to issues related to privacy protection, liability concerns, and various institutional barriers. Such issues necessarily limit the ability of public and other agencies to meet essential operational goals. In the case of speed harmonization deployments, different implementation architectures have different implications for data availability, use, and ownership. Strategies that utilize sensor-derived data present the fewest data provision and ownership issues for the operating agency and therefore are the most common data approaches. Strategies that utilize vehicle probe data or individual-provided data may require further elaboration.

Algorithm effectiveness
Algorithms required for speed harmonization applications vary in terms of sophistication and effectiveness; research remains incomplete in this regard. ITS vendors offer proprietary speed harmonization algorithms, but effective strategies require local calibration, testing, and adaptation over time. This suggests the need for an open development framework.

System performance management
Effective speed harmonization, like most online dynamic control strategies, requires continual monitoring of and adaptation to changes in the external environment as well as behavioral adjustments displayed by system users.

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.

Compliance
The success and effectiveness of a speed harmonization system is directly influenced by the degree of compliance of the drivers by the selected and posted speed recommendation. Therefore, choosing an appropriate method to increase this compliance is essential before implementing a speed harmonization system. The current practice for increasing the compliance mainly focuses on automated speed enforcement, which presents many challenges relating to data privacy concerns, data ownership, legal authority questions, and user acceptance. The current practice can be improved by introducing incentive based strategies. However, extensive research on drivers' behavior is required to make the new system available. Note that better compliance can be achieved through educating drivers and reinforcing positive experiences with the system.

3.1.3 User Classes and Other Involved Personnel

The user classes associated with the operation, maintenance, and use of current active traffic management (ATM) speed harmonization systems are described in this section. There are seven major groups of users, as defined by their responsibilities, skill levels, work activities, and interaction modes, who interact with the system:

Guests: This user class has read-only access to the control center information. Guests need only to use the information and do not need any access to the control devices.

Field personnel: These personnel are maintenance staff or other staff working in the field. These personnel have the access to view data and input information on the status of the system (e.g., workzone locations or maintenance locations) but are not allowed to modify the functionality of the system.

Operators: Operators are personnel who operate and monitor the entire speed harmonization system. As the primary users of the system, operators are very familiar with system operations, interacting with it daily, and are able to troubleshoot various operational issues that may arise.

Supervisors: Supervisory personnel have comparable experience and capability to that of operators, but are provided additional access to the system. They have the ability to override operator actions and edit stored data.

Administrators: The system administrator sets up, configures, and maintains the system. The administrator has the highest access to the system and can reconfigure it to meet operational goals. The system administrator is responsible for maintaining the computer system, including network connections, workstations, and system software.

ITS engineers: ITS engineer personnel develop and deploy the speed harmonization system.

Software engineers: Software engineers are responsible for developing new features for the central software.

3.1.4 Support Environment

This section discusses the major components of the support environment that supports the core system.

Service monitor subsystem: The 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. In order to provide required maintenance, the core system maintainers need access to the core system software and hardware configuration.

Note that choosing a system based on commercially available hardware and software (rather than unique hardware and software packages) would significantly reduce the amount of system maintenance required.

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. In the latter case, a carefully structured agreement is essential to ensure the highest quality support and maintenance.

Maintenance and support processes: Established processes are required to ensure that there will always be enough personnel to support the system and keep it up to date. This includes but is not limited to a checklist for the operators to be able to identify, isolate, and solve potential issues, as well as managing the processes for parts replacement and software support.

3.2 Queue Warning Current State

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. It should be noted that queue warning is considered distinct from collision warning, which pertains to events or conditions that require immediate or emergency actions. Queue warnings are provided in order to reduce the likelihood of the formation of such emergency events.

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 system 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.

3.2.1 Background

Queue warning applications have been in place for some time both nationally and internationally using a variety of vehicle detection sensors and sign types. However, all forms of queue warning deployments to date have relied exclusively upon infrastructure-based detection and alerting. No known existing or planned deployments utilize vehicle-to-vehicle or vehicle-to-infrastructure communication for queue identification, response planning, or alert dissemination. For this reason, current queue warning approaches are fundamentally limited in their potential range, scope, and precision of queue detection.

Detection of queue conditions is typically performed by:

- Traffic Detectors,
- Visibility Sensors, and
- Pavement Condition Sensors

Controllers are used to collect and analyze the data and to create messages to be displayed.

Communications systems used include cellular modems to transmit messages to variable message signs.

Information dissemination occurs via:

- Fixed messages signs with flashers,
- Portable variable message signs, and
- Variable speed signs.

3.2.2 Operational Policies and Constraints

The goal of a queue warning system 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. This section highlights the key operational policies and constraints that impact the ability of current queue warning systems to meet this goal.

Queue warning sign location and distribution
Locating queue warning signs at positions sufficiently upstream of the queue condition is critical to allow drivers enough time to react safely. However, because the queue warning signs are fixed infrastructure and because queue conditions can shift along the facility, the effectiveness of any queue warning program is constrained by how well queue conditions align with the positioning and distribution of queue warning signs.

Queue warning sign visibility and legibility
A queue warning sign installed at an appropriate location must still be able to convey intended queue warning message to traffic in order for it to be effective. Low-visibility weather conditions and poorly designed displays or warning messages limit the effectiveness of queue warning installations at conveying queue alerts to upstream traffic.

Operational design and warning logic
The effectiveness of queue warning programs are constrained by the design of operational policies and warning logic. Key operational policies include queuing thresholds, persistence thresholds, message content, detection device failure strategies, and hours or operation. Ongoing reviews of effectiveness are crucial to ensuring that given policies are relevant and being followed.

3.2.3 User Classes and Other Involved Personnel

The user classes associated with the operation, maintenance, and use of current active traffic management (ATM) queue warning systems are described in this section. There are seven major groups of users, as defined by their responsibilities, skill levels, work activities, and interaction modes, who interact with the system:

Guests: This user class has read-only access to the control center information. Guests need only to use the information and do not need any access to the control devices.

Field personnel: These personnel are maintenance staff or other staff working in the field. These personnel have the access to view data and input information on the status of the system (e.g., workzone locations or maintenance locations) but are not allowed to modify the functionality of the system.

Operators: Operators are personnel who operate and monitor the entire speed harmonization system. As the primary users of the system, operators are very familiar with system operations, interacting with it daily, and are able to troubleshoot various operational issues that may arise.

Supervisors: Supervisory personnel have comparable experience and capability to that of operators, but are provided additional access to the system. They have the ability to override operator actions and edit stored data.

Administrators: The system administrator sets up, configures, and maintains the system. The administrator has the highest access to the system and can reconfigure it to meet operational goals. The system administrator is responsible for maintaining the computer system, including network connections, workstations, and system software.

ITS engineers: ITS engineer personnel develop and deploy the speed harmonization system.

Software engineers: Software engineers are responsible for developing new features for the central software.

3.2.4 Support Environment

This section discusses the major components of the support environment that supports the core queue warning system.

Service monitor subsystem: The 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. In order to provide required maintenance, the core system maintainers need access to the core system software and hardware configuration.

Note that choosing a system based on commercially available hardware and software (rather than unique hardware and software packages) would significantly reduce the amount of system maintenance required.

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. In the latter case, a carefully structured agreement is essential to ensure the highest quality support and maintenance.

Maintenance and support processes: Established processes are required to ensure that there will always be enough personnel to support the system and keep it up to date. This includes but is not limited to a checklist for the operators to be able to identify, isolate, and solve potential issues, as well as managing the processes for parts replacement and software support.

3.3 Cooperative Adaptive Cruise Control Current State

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.

3.3.1 Background

CACC systems, by utilizing vehicle-to-vehicle communication, represent the most advanced application of adaptive cruise control systems. Research in CACC has indicated its potential to improve the stability and efficiency of traffic flow by enabling vehicles to respond more quickly to shockwaves and thus mitigate their effects. CACC systems also result in more stable traffic flow compared to adaptive cruise control (ACC) systems due to the ability to estimate more precisely speed differences, distances, and accelerations through the use of surveillance equipment (VanderWerf et al., 2002) (Shladover et al., 2009) (Nowakowski et al., 2011).

Because a functioning CACC is reliant upon yet-to-be-implemented connected vehicle technologies, there are no existing operational deployments of the system today. However, a good deal of research and experimental design has been done on CACC and related technologies. Mobility-related findings from this research are summarized below:

Crash reduction: 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.

Throughput: 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 (Shladover et al., 2009) (Nowakowski et al., 2011). Further research is needed, however, to more precisely demonstrate the conditions under which such significant throughput and capacity gains can be achieved. While CACC research has indicated the potential for greatly increased throughput and capacity results, the degree of improvement is tightly connected to how well the CACC system can accommodate vehicle merging (van Arem et al., 2006). Research being conducted by the University of Virginia indicates that cooperative merging can significantly increase traffic flow. However, these algorithms have not been tested for the potentially higher flows associated with CACC system implementations.

Travel time reliability: As with speed harmonization systems, CACC has the potential to improve travel time reliability by enhancing the transportation system safety and reducing the number of collisions within the system. And unlike with speed harmonization, CACC can be expected to have a positive effect on travel time, due to its theoretical ability to increase roadway capacity and hence reduce traffic-slowing congestion.

Shockwave propagation: Although some research has indicated that shockwave speeds in CACC environments are faster and thus may pose a safety risk to drivers of non-CACC enabled vehicles in the traffic stream (Pueboobpaphan et al., 2010), it is expected that in a CACC environment the magnitude, frequency, and overall incidence of shockwaves would be lower due to the system's ability to automatically and rapidly make speed and headway adjustments to counter speed or acceleration perturbations (Shladover et al., 2009).

Delaying breakdown formation: By eliminating lag times in driver responses, reducing the speed differential among adjacent lanes, and creating more uniform flow, CACC is capable of delaying the onset of breakdown formation (Pueboobpaphan et al., 2010) (van Arem et al., 2006). Furthermore, after the occurrence of breakdown, CACC has the potential to minimize the capacity drop by increasing and harmonizing subsequent vehicle acceleration levels.

Environment: CACC can have a significant impact on reducing the 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; however this may reduce system throughput. Consequently, there is a need to find a good compromise in system aggressiveness to minimize capacity drops after the onset of congestion but at the same time reduce vehicle fuel consumption and emission levels.

User acceptance of the technology: Human factors research into CACC and similar adaptive cruise control systems have revealed that drivers are generally very accepting of autonomous and semiautonomous vehicle control and readily enable it to perform following maneuvers that would otherwise not be undertaken. Key supporting research includes the following:

- A University of California PATH CACC human factors experiment Nowakowski et al., 2011) found that subjects operating CACC-equipped vehicles most frequently elected to utilize the shortest time-gap setting available (0.6 s), representing a 50% decrease in the time-gaps opted for when operating non-cooperative adaptive cruise control vehicles.
- A University of Michigan study (Van Aerde et al., 1999) found that ACC *"….greatly reduces the driver's work, the ACC system leads to safer as well as more pleasant driving*."
- Fancher et al. (1998) found that *"…. ACC is remarkably attractive to most drivers. The research indicates that, because ACC is so pleasing, people tend to utilize it over a broad range of conditions and to adopt tactics that prolong the time span of each continuous engagement."*

These findings suggest that in a deployed CACC environment, driver participation and compliance would be high enough that the theoretical capacity and efficiency gains of CACC could in fact be realized.

3.3.2 Operational Policies and Constraints

Not applicable as there are no current operational deployments of cooperative adaptive cruise control systems.

3.3.3 User Classes and Other Involved Personnel

Not applicable as there are no current operational deployments of cooperative adaptive cruise control systems.

3.3.4 Support Environment

Not applicable as there are no current operational deployments of cooperative adaptive cruise control systems.

Chapter 4. Justification for and Nature of Changes

This section discusses the drawbacks and limitations of the current practice of speed harmonization, queue warning, and adaptive cruise control and considers the justification for developing the INFLO bundle of applications to address these limitations. In addition, this section will provide a discussion of the nature of the planned changes.

4.1 Speed Harmonization

4.1.1 Justification for Changes

The objective of speed harmonization is to 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. However, as discussed in Section 3.1, 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 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

A connected vehicle-enabled *dynamic* speed harmonization system has the potential to address each of these limitations. See Section 5.1 for a full discussion of the SPD-HARM concept.

4.1.2 Description of Desired Changes

In order to address the shortcomings of the current practice of speed harmonization as described above, the following are the key changes that a next-generation dynamic speed harmonization system should accomplish:

Develop a SPD-HARM application

A dynamic speed harmonization application (SPD-HARM) should be developed that makes use of the frequently collected and rapidly disseminated multi-source data drawn from connected travelers, vehicles, and infrastructure. The application should be a vehicle-integrated device (e.g., a vehicle manufacturer-installed or aftermarket integrated device), a personal wireless application (e.g., a smartphone or other handheld device), or another application capable of collecting, receiving, and disseminating movement and locational information. The goal of SPD-HARM should be to improve the nature, accuracy, precision, and speed of dynamic decision making by both system managers and system users.

Develop enhanced speed recommendation algorithms
Speed selection algorithms must be enhanced in order to achieve the mobility, safety, and environmental goals of dynamic speed harmonization. A connected vehicle environment will enable systems and algorithms that can generate traffic condition predictions, alternative scenarios, and solution evaluations in real time. Microscopic and macroscopic traffic simulations, incorporating both real-time and historical data, must be used, and traffic optimization models must be constantly evaluated, adjusted, and improved. Note that this requires an increase in computational capability as well as long-term storage for storing the historical data. Performance measurement will play an important role in evaluating and improving dynamic speed harmonization algorithms and methods.

Improve dissemination capabilities for communicating speed recommendations and related information
Conventional variable message signs can be an effective means of information dissemination to the drivers. However, to achieve the theoretical safety, mobility, and environmental benefits of a dynamic speed harmonization system, drivers must have highly accurate and detailed information on the characteristics of the traffic flow, potential safety issues, and speed recommendation details. Examples of some of this fine-grained information include alerts and location of upcoming incidents, road and weather conditions, and even estimates of fuel cost savings and emissions reductions that could be achieved by complying with the speed change recommendations. Connected vehicle-enabled communication is well suited to provide and disseminate this type of information and is capable of targeting recommendations to specific portions of the traffic flow.

In the longer term or in conjunction with semi-autonomous longitudinal control (i.e., CACC), speed recommendations may be implemented immediately and automatically, without the need for drivers to acknowledge or manually implement the recommendations. Such semi-autonomous control would enable faster, more precise, and more frequent speed adjustments, which in turn would improve the effectiveness of the dynamic speed harmonization program.

Improve compliance of speed recommendations
Current practice speed harmonization has shown uneven levels of speed compliance, attributable to differing methods of deployment, speed selection, and enforcement. A connected vehicle-enabled dynamic speed harmonization system would be able to positively affect compliance by communicating speed recommendations to drivers more intelligently and by expanding tracking and enforcement capabilities to system operators (note that although this is not a stated objective of connected vehicle systems, it is a potential capability for this technology). However, it is important to keep in mind that automated enforcement presents many challenges, particularly in the U.S., relating to data privacy concerns, data ownership, legal authority questions, and user acceptance. Such issues must be well addressed prior to instituting any form of automated enforcement.

Introducing incentives to drivers to comply with the speed limit is also another approach that has been taken in some countries (not specifically for speed harmonization systems). For instance, in Victoria, Australia, drivers are offered 30% rebate on license renewal if they have no citations in the last three years (Global Road Safety Partnership, 2008). The approach is expected to engender higher user acceptance; but selection of appropriate incentives could be very complicated and face several legal and social issues. Additional investigation of the effect of incentives on speed limit compliance would be desirable before implementing this approach. Note that better compliance can be accomplished through educating drivers about the rationale and logic of the interventions, and most importantly reinforcing positive experiences with the system. Furthermore, experience shows that only limited compliance could accomplish the desired system flow objectives. (See Section 5.1.2 for additional discussion of automated enforcement in the context of the SPD-HARM concept.)

Include more data sources and more accurate data

Data critical to dynamic speed harmonization will come from a variety of sources and should include:

- ***Real-time traffic data:*** Vehicle speed and location data collected and disseminated by the vehicles themselves as a part of connected vehicle system as well as traditional detection sources (inductive loop detectors, overhead radar, and CCTV cameras) provide traffic data for the speed harmonization system.
- ***Weather condition data:*** Localized weather condition form the vehicles (e.g. traction information, outside temperature readings, and windshield wiper activation) as well as Infrastructure-based road weather information systems (RWIS) and third-party weather data feeds can serve to supplement vehicle-acquired weather data. Note that the RWIS and third-party weather information data are likely to play a larger role for weather information sourcing, at least in the near term of connected vehicle deployments.
- ***Visibility data:*** Visibility detectors are used to help mitigate fog and other visibility-related weather impacts on roadways. Typical detection technology includes backscatter and forward scatter radar (as discussed in the discussions of the Alabama and Tennessee variable speed limit projects in the *Report on Assessment of Relevant Prior and Ongoing Research for INFLO*).
- ***Pavement condition data:*** Information on the real-time pavement surface conditions (e.g., dry, wet, snowy, iced, salted) can be provided by in-pavement sensors.
- ***Vehicle data:*** Vehicle characteristics data, including status, location, and movement, can be acquired from the vehicles themselves and disseminated to other vehicles, applications, and systems using V2V and V2I communications technologies. Specialized vehicle data, such as truck and cargo weight data, can be acquired and disseminated in the same manner, though in the near term of the connected vehicle environment, weigh-in-motion and other infrastructure-based devices will likely continue to be used.
- ***Historical data:*** In addition to real-time data, historical data will be a critical input into a dynamic speed harmonization application in order to perform effective analysis and prediction of traffic conditions.
- ***Crowd sourced data:*** Crowd sourced data platforms (e.g., Google's smartphone-based probe traffic data) enable data collection from large installed user bases, which can help supplement data gathered from other sources.

Develop a data collection system

Develop a data collection system that will obtain all of the necessary dynamic speed harmonization-related data, in real-time, from the various vehicles, on-board sensors, wireless devices, roadway traffic sensors, weather systems, message boards, and other related systems. This data should be placed in and/or accessible from a common data environment.

Develop a performance measurement system

A performance measurement system shall be created (or an existing one enhanced) that will measure the associated dynamic speed harmonization performance measures to identify whether the system goals and performance targets for the application are being achieved.

4.1.3 Priorities among Changes

For the changes described in the previous section, the following ordering reflects the priority of the implementation of the changes. It should be noted, however, that there will likely be a degree of parallel development for these changes, as they are each highly dependent upon one another.

1. ***Develop a SPD-HARM application.*** This task obviously is of prime importance as it is the basis purpose of this application within the bundle.
2. ***Develop enhanced speed recommendation algorithms.*** This task is identified as the second highest priority because it can be pursued even without utilizing connected vehicle communications or data. Even in a conventional environment, improved analytics are required to take advantage of three key elements: (1) improved prediction systems, (2) recent developments in traffic science and traffic dynamics, and (3) broadened objectives for system management.
3. ***Develop a data collection system.***
4. ***Develop performance measurement system.***
5. ***Improve dissemination capabilities for communicating recommended speed and related information.*** This task, though dependent upon an integrated connected vehicle system, is crucial to functioning of a dynamic speed harmonization application and must be achieved even in a test environment or a limited deployment scenario. This task includes methods of communicating speed information to drivers, so as to maximize compliance and eventual effectiveness of the measures. This calls for behavioral research into the best combination of information to provide users of the system, and more generally into models of user response to information. Interaction of these behaviors with the driving task, its cognitive demands and related attention/distraction issues are part of this priority area.
6. ***Include more data sources and more accurate data.*** Once a speed selection algorithm and an effective means for communicating speed recommendations are established, it is important to improve the quality of the data environment so that algorithms can be improved and more useful information can be communicated to users.
7. ***Improve compliance of speed recommendations.*** Finally, it is important to ensure that certain levels of compliance are achieved in order for the dynamic speed harmonization system to be maximally effective.

4.1.4 Changes Considered but not Included

Not applicable.

4.2 Queue Warning

4.2.1 Justification for Changes

The goal of queue warning is to provide drivers sufficient warning of impending queue backup in order to react safely. However, as discussed in Section 3.2, current queue warning 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:

- 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

A connected vehicle-enabled queue warning system has the potential to address each of these limitations. See Section 5.2 for a full discussion of the Q-WARN concept.

4.2.2 Description of Desired Changes

In order to address the shortcomings of the current practice of queue warning as described above, the following are the key changes that a next-generation system should accomplish:

Develop a Q-WARN application
A next-generation queue warning application (Q-WARN) should be developed that makes use of the frequently collected and rapidly disseminated multi-source data drawn from connected travelers, vehicles, and infrastructure. The application should be a vehicle-integrated device (e.g., a vehicle manufacturer-installed or aftermarket integrated device), a personal wireless application (e.g., a smartphone or other handheld device), or another application capable of collecting, receiving, and disseminating movement and locational information. The goal of Q-WARN should be to improve the nature, accuracy, precision, and speed of dynamic decision making by both system managers and system users.

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. A connected vehicle environment will enable systems and algorithms that can generate traffic condition predictions, alternative scenarios, and solution evaluations in real time. Microscopic and macroscopic traffic simulations, incorporating both real-time and historical data, must be used, and traffic optimization models must be constantly evaluated, adjusted, and improved. Note that this requires an increase in computational capability as well as long-term storage for storing the historical data. Performance measurement will play an important role in evaluating and improving queue warning algorithms and methods.

Improve dissemination capabilities for communicating queue warnings and relevant queue information

Conventional variable message signs and queue warning signs can be an effective means of information dissemination to the drivers. However, to achieve the theoretical safety and mobility benefits of a next-generation queue warning system, drivers must have highly accurate and detailed information on the characteristics of the upstream queue, potential safety issues, and response scenario options. Connected vehicle-enabled communication is well suited to provide and disseminate this type of information and is capable of targeting recommendations to specific portions of the traffic flow.

Include more data sources and more accurate data

Data critical to next-generation queue warning will come from a variety of sources and should include:

- ***Real-time traffic data:*** Vehicle speed and location data collected and disseminated by the vehicles themselves as a part of connected vehicle system as well as traditional detection sources (inductive loop detectors, overhead radar, and CCTV cameras) provide traffic data for the speed harmonization system.
- ***Weather condition data:*** Localized weather condition form the vehicles (e.g. traction information, outside temperature readings, and windshield wiper activation) as well as Infrastructure-based road weather information systems (RWIS) and third-party weather data feeds can serve to supplement vehicle-acquired weather data. Note that the RWIS and third-party weather information data are likely play a larger role for weather information sourcing, at least in the near term of connected vehicle deployments.
- ***Visibility data:*** Visibility detectors are used to help mitigate fog and other visibility-related weather impacts on roadways. Typical detection technology includes backscatter and forward scatter radar (as discussed in the discussions of the Alabama and Tennessee variable speed limit projects in the *Report on Assessment of Relevant Prior and Ongoing Research for INFLO*).
- ***Pavement condition data:*** Information on the real-time pavement surface conditions (e.g., dry, wet, snowy, iced, salted) can be provided by in-pavement sensors.
- ***Vehicle data:*** Vehicle characteristics data, including status, location, and movement, can be acquired from the vehicles themselves and disseminated to other vehicles, applications, and systems using V2V and V2I communications technologies. Specialized vehicle data, such as truck and cargo weight data, can be acquired and disseminated in the same manner, though in the near term of the connected vehicle environment, weigh-in-motion and other infrastructure-based devices will likely to continue to be used.
- ***Historical data:*** In addition to real-time data, historical data will be a critical input into a next-generation queue warning application in order to perform effective analysis and prediction of queue conditions.

Develop a data collection system

Develop a data collection system that will obtain all of the necessary queue warning and prediction related data, in real-time, from the various vehicles, on-board sensors, wireless devices, roadway traffic sensors, weather systems, message boards, and other related systems. This data should be placed in and/or accessible from a common data environment.

Develop a performance measurement system
A performance measurement system shall be created (or an existing one enhanced) that will measure the associated queue warning performance measures to identify whether the system goals and performance targets for the application are being achieved.

4.2.3 Priorities among Changes

For the changes described in the previous section, the following ordering reflects the priority of the implementation of the changes. It should be noted, however, that there will likely be a degree of parallel development for these changes, as they are each highly dependent upon one another.

1. ***Develop a Q-WARN application.*** This task obviously is of prime importance as it is the basis purpose of this application within the bundle.
2. ***Develop enhanced queue warning algorithms.*** This task is identified as the highest priority because it can be pursued even without utilizing connected vehicle communications or data.
3. ***Develop a data collection system***
4. ***Develop performance measurement system***
5. ***Improve dissemination capabilities for communicating queue warnings and relevant queue information.*** This task, though dependent upon an integrated connected vehicle system, is crucial to functioning of a next-generation queue warning application and must be achieved even in a test environment or a limited deployment scenario.
6. ***Include more data sources and more accurate data.*** Once a queue warning algorithm and an effective means for communicating relevant warnings and response strategies is established, it is important to improve the quality of the data environment so that algorithms can be improved and more useful information can be communicated to users.

4.2.4 Changes Considered but not Included

Not applicable.

4.3 Cooperative Adaptive Cruise Control

4.3.1 Justification for Changes

The objective of cooperative adaptive cruise control (CACC) is to dynamically and automatically coordinate cruise control speeds among platooning vehicles in order to significantly increase traffic throughput, reduce crashes, and lower energy consumption. As discussed in Section 3.3, no operational CACC implementations currently exist since CACC is reliant upon yet-to-be-deployed connected vehicle technologies. However, recent research and experiments on CACC and related technologies have indicated that 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

See Section 5.3 for a full discussion of the goals and benefits of the CACC application concept.

4.3.2 Description of Desired Changes

In order to achieve dynamic and automatic coordination of platooning vehicles, two key developments in cruise control technologies must occur:

Develop a CACC application
A cooperative adaptive cruise control application (CACC) should be developed that makes use of the frequently collected and rapidly disseminated multi-source data drawn from connected travelers, vehicles, and infrastructure. The application should be a vehicle-integrated device (e.g., a vehicle manufacturer-installed or aftermarket integrated device) that is capable of collecting, receiving, disseminating movement and locational information, and communicating with other vehicles in addition to controlling the longitudinal motion of the vehicle. The goal of CACC should be to improve the nature, accuracy, precision, and speed of dynamic decision making by both system managers and system users.

Develop enhanced vehicle following algorithms
Vehicle following algorithms must be further developed in order to achieve the mobility, safety, and environmental goals of CACC. A connected vehicle environment will enable systems and algorithms that can generate general traffic condition predictions, platoon movement predictions, and response scenarios in real time. Microscopic and macroscopic traffic simulations, incorporating both real-time and historical data, must be used, and traffic optimization models must be constantly evaluated, adjusted, and improved. Note that this requires an increase in computational capability as well as long-term storage for storing the historical data. Performance measurement will play an important role in evaluating and improving CACC vehicle following algorithms and methods.
Human factors testing will be required to ensure that the system provides an acceptable level of comfort to the drivers while at the same time achieving the desired goals. This could require significant tuning of the systems to match driver population needs and expectations of the system. The system might also require tuning depending on the location the driver is driving. For example, the system might need to maintain closer headways in highly congested urban areas but maintain longer headways when the system operates in rural areas where drivers are less aggressive in their driving behavior.

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 (V2V) communication in order to function. V2V and multi-hop communication enables micro

level decisions within and between individual vehicles to be made based on vehicle location and class (including platoon).

Develop a data collection system
Develop a data collection system that will obtain all of the necessary cooperative adaptive cruise control related data, in real-time, from the various vehicles, on-board sensors, wireless devices, roadway traffic sensors, weather systems, message boards, and other related systems. This data should be placed in and/or accessible from a common data environment.

Develop a performance measurement system
A performance measurement system shall be created (or an existing one enhanced) that will measure the associated CACC performance measures to identify whether the system goals and performance targets for the application are being achieved.

4.3.3 Priorities among Changes

For the changes described in the previous section, the following ordering reflects the priority of the implementation of the changes. It should be noted, however, that there will likely be a degree of parallel development for these changes, as they are each highly dependent upon one another.

1. ***Develop a CACC application***
2. ***Develop enhanced vehicle following algorithms***
3. ***Develop a data collection system***
4. ***Develop a performance measurement system***
5. ***Improve real-time speed and gap communication capabilities***

4.3.4 Changes Considered but not Included

Not applicable.

Chapter 5. Concepts for the Proposed INFLO Applications

This section describes the operational concepts for the three INFLO applications and provides justification for their selection. The operational concepts are not intended to be detailed designs of the applications, but high-level, conceptual descriptions of how the applications are expected to operate. The concepts provide only as much detail as is needed to be able to develop meaningful operational scenarios.

5.1 SPD-HARM

5.1.1 Operational Concept

As discussed in Section 3.1.1, speed harmonization of traffic flows in response to downstream congestion, incidents, and weather or road conditions can greatly help to maximize traffic throughput and reduce crashes. 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.

The INFLO SPD-HARM application concept aims to realize these benefits 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 5-1 below provides a stylized depiction of how the SPD-HARM concept could work.

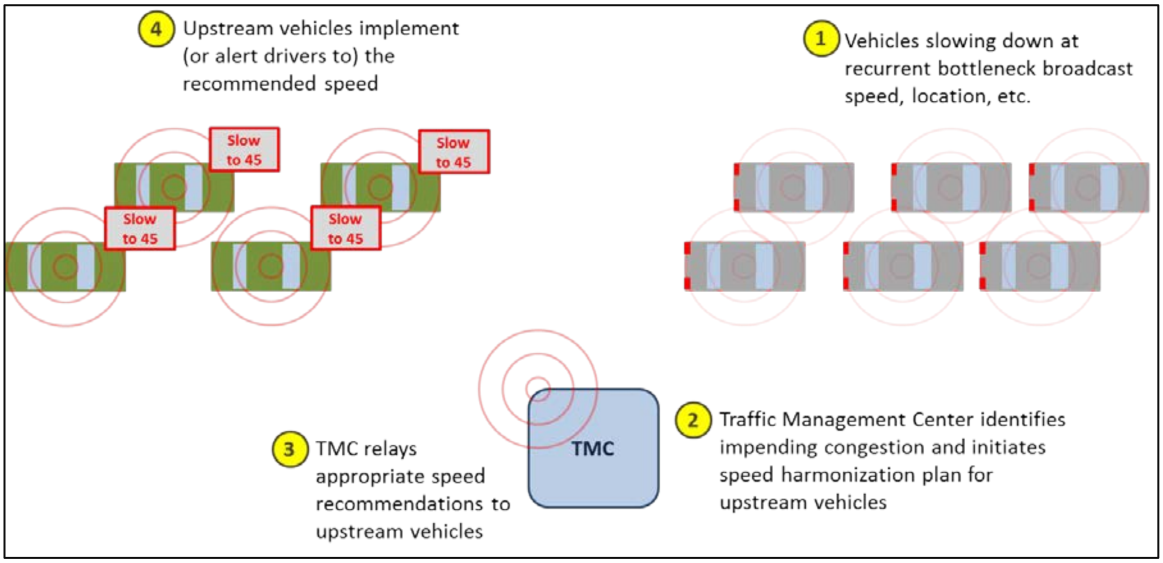

Figure 5-1. Stylized Depiction of a Connected Vehicle-Enabled SPD-HARM Application

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 driver communication will always give priority to crash avoidance/mitigation safety applications when such applications determine that a safety alert is necessary.

5.1.2 Subsystems

To implement the SPD-HARM concept, several subsystems should be considered. These subsystems can be categorized into two groups:

1. ***Essential subsystems:*** Subsystems required by SPD-HARM in order to operate.
2. ***Desirable subsystems:*** Subsystems that can help improve the performance of speed harmonization strategies, in terms of magnitude of impact as well as breadth of objectives.

This section describes these subsystems in more detail.

5.1.2.1 Essential Subsystems

Traffic Information Collection Subsystem (Data Acquisition)
The purpose of this subsystem is to collect and transmit information about the current traffic condition and vehicle classifications to the control center. Two primary sources of data are available to collect traffic information:

1. Fixed-location sensor stations, providing an operator's perspective on facility condition and operational state
2. Mobile sources, namely the Connected Vehicles, providing individual-specific information on vehicle state and user-experienced traffic.

The traffic information subsystem compiles, fuses and interprets data gathered from both sensors and vehicles, and provides information about the traffic condition along the facility. The information is then used for the purpose of congestion alerts and speed selection, including personalized information when considered in conjunction with vehicle-specific conditions. This can be done on a reactive or predictive basis (depending on the underlying algorithms).

The information from these two sources is different in nature as well as in format, though similar indicators could be computed from both sources for basic versions speed harmonization strategies.

- For traffic sensors, the aggregated speed, flow, and occupancy data collected are specific to both line and link. Effective use of speed harmonization to improve traffic fluidity and avoid flow breakdown requires accurate measurement of vehicle speeds over a stretch of highway, and computation of the variance of these measurements over short intervals of no more than 1~2 minutes, and possibly 30 seconds if sufficient number of connected vehicles are sending information (and thus enabling calculation of a meaningful sample variance). Connected Vehicle architectures enable greater flexibility and possibilities in terms of local vs. central processing than fixed-location sensors, but in all cases the main monitoring and algorithmic functions are best executed centrally so as to consider facility-wide and system-wide perspectives rather than a purely local segment-level one.
- Unlike fixed-location traffic sensors, the Connected Vehicle subsystem provides information on individual vehicles and their unique experience. The Connected Vehicle Subsystem is capable of providing all the required information for decision-making for speed selection, incident detection, and breakdown formation identification. Depending on the degree of technological sophistication and user permissions, information could include vehicle mechanical status and driver preferences, as well as recent experience with the facility. In addition to providing the control center and/or the speed harmonization application with complementary information to that provided by fixed sensors, especially when aggregated over several vehicles in a given local neighborhood, information through the Connected Vehicle subsystem can also form the basis for customizing and personalizing user instructions, as well as monitoring the performance, effectiveness and gaps of the supplied control, and therefore provide essential information for improving and adapting the control logic over time.. In the case where connected vehicle penetration is low or the Connected Vehicle Subsystem is not fully functional, traffic sensors can be supplemental or backup source of data.

The SPD-HARM traffic information collection subsystem also requires a user interface where the users can change the configurations of the data collection (e.g., the aggregation interval for the traffic data). This interface will likely be a map-based interactive interface, in which link traffic conditions are easily distinguishable and information on data sources, average speeds, flow, and density (occupancy) is readily available. In addition, information about the speed variance is needed for speed harmonization applications.

Environmental Information Collection Subsystem
The purpose of this subsystem is to collect and transmit the current environmental condition to the control center. Four sources of data collection are available to collect environmental information:

1. Environmental sensor stations
2. Third-party data providers
3. Probe vehicles
4. Connected vehicles

Information from these sources is transmitted to the control center and used to generate weather responsive alerts and appropriate speed selections. The kinds of environmental information collected by connected vehicles are relatively limited and include traction status, outside temperature readings, and windshield wiper activation information. Environmental sensor stations (also known as Road Weather Information Systems (RWIS)), however, collect a great deal more environmental data from the field, including visibility, air temperature, road temperature, humidity, wind speed, pressure, and precipitation.

The SPD-HARM environmental information subsystem requires a user interface that allows for configuration of the environmental data collection, including modifying the schedule for data collection intervals. An interactive map is also useful for providing key information to the user, such as visibility, air temperature, road temperature, humidity, wind speed, and precipitation for specific locations and links.

Note that certain applications of speed harmonization may not be intended to address weather-related problems, or may be limited in application to "normal" weather conditions. In this case, the environmental data subsystem would not be essential. However, the ability to provide speed information for all applicable weather conditions would enhance the system's effectiveness and the public's confidence in the information provided. Accordingly, we include this subsystem in the essential category.

Speed Harmonization Response Generation Subsystem
The purpose of the speed harmonization subsystem is to use the data collected from the traffic and environmental information collection subsystems to select appropriate speed recommendations and generate other recommended actions for specific segments and road users of the facility. A speed selection algorithm should be used to determine the timing, locations, and values of speed adjustments. Note that the algorithm must be capable of predicting traffic conditions, identifying potential solutions, and evaluating these solutions in real-time. Traffic simulation capabilities, incorporating both real-time and historical data, form the basis of the estimation and prediction capability. These, as well as the traffic optimization models must be constantly evaluated, adjusted, and improved.

An interface should provide the speed harmonization subsystem user the ability to access SPD-HARM connected vehicle driver alerts and infrastructure-based VSLs for a given segment and modify configuration settings if necessary. Any action taken by the operator or system should be recorded in the Data Storage Subsystem (see Data Storage discussion below).

Information Dissemination Subsystem

The purpose of this subsystem is to send speed harmonization related information generated by the response generation subsystem to road users on specific segments of the road facility via in-vehicle alerts and/or traditional DMS and lane control signal (LCS) systems. The subsystem should allow for simultaneous control of message transmission to connected vehicles and infrastructure-based signs for a given road segment. It should also allow for the configuration of in-vehicle messages or lane control signals for portions of the traffic flow on a lane-by-lane basis.

Certain pre-defined thresholds are used for the determination of high risk situations for fog events, road freezing events, and high winds. When the measured values cross certain thresholds, specific responses, including speed reduction and weather advisory alerts, activate for the facility. Environmental information can also be collected from third-party data providers and portable environmental sensor stations.

Data Storage (Warehouse)

Major changes in facility management decisions and changes in system device status should be stored for a reasonable amount of time (e.g., the system could store data for 13 months so that to make one year of data always available). The system also should store the traffic and environmental data for the purpose of using as historical data in the speed selection algorithm as well as automatic incident detection. This will support the dual functionality of performance monitoring and assessment, as well as algorithm and knowledge-based enhancement.

Service Monitoring Subsystem

The role of this subsystem is to alert operators to system issues and to provide operators with information on how to address or isolate the issues. In addition, the service monitor subsystem notifies the maintenance and support team. When a part of a subsystem is malfunctioning or requires maintenance, the information may come to the operator in the control center to send a work order to the maintenance and support team. Note that this subsystem does not integrate all the functionality of the maintenance system, but rather provides alerts to operators to help facilitate the required maintenance.

5.1.2.2 Desirable Subsystems

CCTV Camera Subsystem

The purpose of this subsystem is to allow CCTV camera subsystem users to control CCTV cameras and watch video images. The objective of this subsystem is to provide operators the ability to monitor the target segment and help them to make appropriate decisions under emergency situations and incidents. The subsystem should be able to perform several functions for several cameras simultaneously considering the point that each camera should be under the control of one user at each time. Each user should be able to watch the video and create a tour using a camera by selecting it on a map or from a list. Note that an alert should be displayed when another user is trying to access a busy camera.

Automated Incident Detection Subsystem

This capability falls under the general system management category—not directly essential to speed harmonization, but beneficial as part of the overall package of interventions that include speed harmonization. The purpose of this subsystem is to automatically alert users of potential incidents or events (e.g., congestion occurrence) by controlling and analyzing connected vehicle system, sensors, and video data. The subsystem monitors traffic data and video and compares them with historical data to determine any anomalies in the traffic flow pattern.

Note that the use of connected vehicle technology makes the incident detection algorithms much simpler as the output of the conventional algorithm can be directly transmitted to the control center through the V2I protocols. Furthermore, experience over the past 10 years has shown that the widespread availability of cell phones all but guarantees that authorities are alerted of any incident long before it can be detected by any algorithm.

Compliance Monitoring Subsystem
The purpose of this system is to automatically identify speed recommendation violations and to alert the control entity of such events. Violator identification can occur either by conventional automated speed detection methods (e.g., overhead radar) or by connected vehicle-based detection and identification (e.g., Electronic Vehicle Identification and Intelligent Speed Assistance).

Automated enforcement is not considered a part of the compliance monitoring system due to its associated challenges, particularly in the U.S., relating to data privacy concerns, data ownership, legal authority questions, OEM participation, and user acceptance. While international experience in speed harmonization indicates that automated enforcement generally promotes increased speed compliance (see *Report on Assessment of Relevant Prior and Ongoing Research for INFLO*), it is unlikely that any SPD-HARM deployment in the U.S. will utilize mandatory speed limits or automated enforcement of speed recommendations.

However, as discussed previously, there is evidence that speed harmonization can be largely self-enforcing, as limited compliance in the kind of high-volume, high-density situations where speed harmonization is generally called for would be sufficient to bring the entire traffic stream into compliance as passing opportunities become virtually non-existent. Greater user acceptance and compliance could also be encouraged through incentive-based systems, discussed previously.

Map Display
The purpose of this subsystem is to provide a detailed map display with configurable layers. The map helps the system user to interpret traffic data, environmental data, video, lane speeds and operation, incidents, and planned events (e.g. workzones) on individual layers.

5.1.3 Operational Policies and Constraints

This section discusses the key operational policies and constraints that are expected to impact the operations of the proposed SPD-HARM concept.

Minimum interval for posted speed adjustments
The minimum interval before changing displayed or disseminated speed recommendations is an important parameter of speed harmonization logic, and reflects a trade-off between driver expectation and operational effectiveness. 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
It is not necessary to recruit new staff to deploy SPD-HARM applications, especially as the algorithms become more intelligent and more adaptive. However 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
Inter-agency, inter-jurisdictional, and public-private data sharing agreements—in particular with respect to connected vehicle data—must be well defined in order for the SPD-HARM concept to operate. This means that the current day 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. Specifically with regard to speed harmonization applications, different implementation architectures will have different implications for data availability, use and ownership. Strategies based on sensor-derived data are least controversial from an agency standpoint; strategies using information provided by individual vehicles may require further elaboration.

System performance management
Effectiveness of sped harmonization, like most online dynamic control strategies, requires continual monitoring and adaptation to reflect changes in the external environment, as well as the behavioral adjustment displayed by system users. Policies should be set for renewing the devices and algorithms that fall outside of the predefined standards in the policy. Note that the policies related to SPD-HARM should be consistent with the policies for the other INFLO applications and systems, as they will likely use the same devices and facilities.

Algorithm effectiveness
Algorithms currently utilized for speed harmonization applications vary in terms of sophistication and effectiveness and research remains incomplete in this regard. 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.

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. The new design should also consider backward compatibility and be able to read and receive data based on older standards including data formats and communication protocols.

Software and hardware development process
Development and validation of the SPD-HARM application and communication system must follow a structured product development process for hardware and software.

Software distribution
Based on analysis of the performance of the speed harmonization system, software and algorithm updates must be transmitted wirelessly to the connected vehicles/devices in the field. This will reduce the amount of required coordination between the operators and OEMs and provides a less vehicle-dependent environment in which to operate the system.

Accident liability
Policies must be developed that cover liability and litigation issues that may arise due to accidents and malfunctions with SPD-HARM systems. Vehicle manufacturers in particular are concerned about the risks and liability potential associated with vehicle systems that rely on externally generated information.

Compliance
As explained previously, speed harmonization systems would only require a small percentage of complying drivers to achieve much of their intended benefit. However, attaining this level of compliance would still require a combination of driver education and incentive-based approaches, including devising opt-in participatory programs. (See Section 5.3.1 for a fuller discussion of the benefits of an opt-in program for INFLO-enabled vehicles on managed lanes.)

5.1.4 Modes of Operation

This section discusses the various modes of operation for the proposed SPD-HARM concept. The speed harmonization system should mostly activate during recurrent congestion periods (e.g., morning and evening peaks) and non-recurrent events (e.g., incidents and weather conditions).

The typical modes of operation for the SPD-HARM concept are:

Normal Mode: SPD-HARM in the normal operation mode should have all the designed functionality available. All systems and subsystems should work properly.

Degraded Mode: In this mode, some function(s) are not working properly and might go offline. Many different scenarios could result in operation in this mode, such as failed communication.

Training Mode: The control center should have the capability of operating in the training mode for the purpose of training the new operators. The mode allows new operators to train on simulations without interfering with the actual daily operations.

Maintenance Mode: During the maintenance of the system, some subsystems and their functionalities may go offline. This mode is very similar to the Degraded Mode but the system usually can go online if needed. This means that this mode would not affect the normal operation.

Failsafe Mode: The system should have the ability to perform normal operation (or at least some levels of normal operation) when there is no connection between the system and the control center.

5.1.5 System Users and Needs

The following table identifies the key users of the SPD-HARM concept application, including human end users as well system entities that interact with the application. The table also includes a discussion of the high-level needs associated of the users.

Table 5-1. SPD-HARM System 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. Such information must be provided succinctly and in such a way that it is not overly distracting to the driver.
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. Such information must be provided succinctly and in such a way that it is not overly distracting to the driver.
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.
Vehicle operator	4. Needs personal data to remain private and secure	The privacy of individuals in the traffic stream must be maintained as data about their behavior is anonymized and shared across multiple jurisdictions.

User	High-Level User Need	Discussion
Connected Vehicle/Device	5. Needs to collect relevant vehicle data	The connected vehicle, aftermarket device, or other interacting application must be able to obtain relevant 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	6. Needs to disseminate relevant vehicle data to other vehicles or systems	The connected vehicle/device must have a dissemination capability so that the vehicle data it has obtained can be accessed by other vehicles and systems.
Connected Vehicle/Device	7. Needs to receive relevant information from other vehicles or systems	In order to be able to provide useful information to the driver, the connected vehicle/device must be able to receive such information from other vehicles and systems.
Connected Vehicle/Device	8. 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	9. 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	10. 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	11. 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.

User	High-Level User Need	Discussion
Traffic Management Entity	12. 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	13. Needs to analyze performance of SPD-HARM system	Based on data received from the field, the traffic management entity must be able to validate the reliability of data, analyze the performance of the SPD-HARM system overall, and make changes to the algorithm or software to improve performance.
Data Capture and Management Environment	14. 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.

5.1.6 Support Environment

This section discusses the major components of the support environment that supports the core SPD-HARM system.

Service Monitor Subsystem: The 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. In order to provide required maintenance, the core system maintainers need access to the core system software and hardware configuration.

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. In the latter case, a carefully structured agreement is essential to ensure the highest quality support and maintenance.

Maintenance and Support Processes: Established processes are required to ensure that there will always be enough personnel to support the system and keep it up to date. This includes but is not limited to a checklist for the operators to be able to identify, isolate, and solve potential issues, as well as managing the processes for parts replacement and software support.

Software Support and Update: Established processes are required to ensure that the all the required software are available and up-to-date both in the main system and vehicles. The system should be able to transmit the required updates to the vehicles wirelessly to keep the system running consistently.

5.2 Q-WARN

5.2.1 Operational Concept

As discussed in Section 3.2.1, queuing conditions present significant safety concerns, particularly with the increased potential for rear-end collisions. They also present disruptions to traffic throughput by introducing shockwaves into the upstream traffic flow. The INFLO Q-WARN application concept aims to minimize the occurrence and impact of traffic queues by utilizing connected vehicle technologies, including vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications, to enable vehicles within the queue event to automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to nearby upstream vehicles and to infrastructure-based central entities (such as the TMC) in order to minimize or prevent rear-end or other secondary collisions.

It is important to note that the Q-WARN application concept is not intended to operate as a crash avoidance system (e.g., like the forward collision warning [FCW] safety application). In contrast to such systems, Q-WARN will engage well in advance of any potential crash situation, providing messages and information to the driver in order to minimize the likelihood of his needing to take crash avoidance or mitigation actions later. As such, Q-WARN-related driver communication will always give priority to crash avoidance/mitigation safety applications when such applications determine that a safety-related alert is necessary.

Figure 5-2 below provides a stylized depiction of how the Q-WARN concept could work.

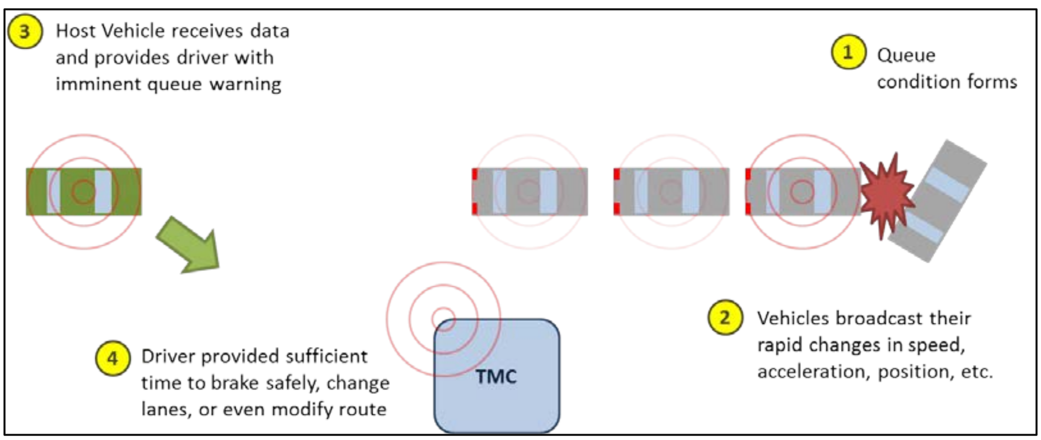

Figure 5-2. Stylized Depiction of a Connected Vehicle-Enabled Q-WARN Application

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 Table 5-2 for a summary of the capabilities and advantages of these approaches for essential Q-WARN tasks.

Table 5-2. 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. 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-equipped 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.

5.2.2 Operational Policies and Constraints

This section discusses the key operational policies and constraints that are expected to impact the operations of the proposed Q-WARN concept.

ITS staffing constraints
There is also 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
Inter-agency, inter-jurisdictional, and public-private data sharing agreements—in particular with respect to connected vehicle data—must be well defined in order for the Q-WARN concept to operate. This means that the current day 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
Policies should be set for renewing the devices and algorithms that fall outside of the predefined standards in the policy. Note that the policies related to Q-WARN should be consistent with the policies for the other INFLO applications and systems, as they will likely use the same devices and facilities.

Algorithm effectiveness
Algorithms currently utilized for queue warning and queue detection vary in terms of sophistication and effectiveness and research remains incomplete in this regard. 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.

Accident liability
Policies must be developed that cover liability and litigation issues that may arise due to accidents and malfunctions with Q-WARN systems. Vehicle manufacturers in particular are concerned about the risks and liability potential associated with vehicle systems that rely on externally generated information.

Software and hardware development process
Development and validation of the Q-WARN application and communication system must follow a structured product development process for hardware and software.

Software distribution

Based on analysis of the performance of the Q-WARN system, software and algorithm updates must be transmitted wirelessly to the connected vehicles/devices in the field. This will reduce the amount of required coordination between the operators and OEMs and provides a less vehicle-dependent environment in which to operate the system.

5.2.3 Modes of Operation

This section discusses the various modes of operation for the proposed Q-WARN concept. The queue warning system should mostly activate at fixed queue generation points and during recurrent congestion periods (e.g., morning and evening peaks) and non-recurrent events (e.g., incidents and weather conditions).

The typical modes of operation for the Q-WARN concept are:

Normal Mode: Q-WARN in the normal operation mode should have all the designed functionality available. All systems and subsystems should work properly.

Degraded Mode: In this mode, some function(s) are not working properly and might go offline. Many different scenarios could result in operation in this mode, such as failed communication.

Training Mode: The control center should have the capability of operating in the training mode for the purpose of training the new operators. The mode allows new operators to train on simulations without interfering with the actual daily operations.

Maintenance Mode: During the maintenance of the system, some subsystems and their functionalities may go offline. This mode is very similar to the Degraded Mode but the system usually can go online if needed. This means that this mode would not affect the normal operation.

Backup Mode: The system should have the ability to perform normal operation (or at least some levels of normal operation) when there is no connection between the system and the control center.

5.2.4 System Users and Needs

The following table identifies the key users of the Q-WARN concept application, including human end users as well system entities that interact with the application. The table also includes a discussion of the high-level needs associated of the users.

Table 5-3. Q-WARN System 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. Additionally, such information must be provided succinctly and in such a way that it is not overly distracting to the driver.
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. Additionally, such information must be provided succinctly and in such a way that it is not overly distracting to the driver.
Vehicle operator	3. Needs personal data to remain private and secure	The privacy of individuals in the traffic stream must be maintained as data about their behavior is anonymized and shared across multiple jurisdictions.
Connected Vehicle/Device (queued vehicle)	4. Needs to detect a queued state	The vehicle, aftermarket device, or other interacting application must be able to detect that the vehicle is in a queue state so that other vehicles and systems can be alerted to the lane and facility location of the queue.
Connected Vehicle/Device (queued vehicle)	5. Needs to disseminate queued status alert to upstream vehicles and other systems	The connected vehicle/device must have a dissemination capability so that the vehicle queued alert status can be received and interpreted by other vehicles and systems.
Connected Vehicle/Device (upstream of queue)	6. Needs to receive relevant queue information from other vehicles or systems	In order to be able to provide useful information to the driver, the 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)	7. 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)	8. 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	9. 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	10. 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	11. 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	12. 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	13. 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	14. 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	15. Needs to analyze performance of Q-WARN system	Based on data received from the field, the traffic management entity must be able to validate the reliability of data, analyze the performance of the Q-WARN system overall, and make changes to the algorithm or software to improve performance.

User	High-Level User Need	Discussion
Traffic Management Entity	16. 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	17. 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	18. 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	19. 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.

5.2.5 Support Environment

This section discusses the major components of the support environment that supports the core Q-WARN system.

Service Monitor Subsystem: The 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. In order to provide required maintenance, the core system maintainers need access to the core system software and hardware configuration.

Note that choosing a system based on commercially available hardware and software (rather than unique hardware and software packages) would significantly reduce the amount of system maintenance required.

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. In the latter case, a carefully structured agreement is essential to ensure the highest quality support and maintenance.

Maintenance and Support Processes: Established processes are required to ensure that there will always be enough personnel to support the system and keep it up to date. This includes but is not limited to a checklist for the operators to be able to identify, isolate, and solve potential issues, as well as managing the processes for parts replacement and software support.

5.3 CACC

5.3.1 Operational Concept

As discussed in Section 3.3.1, cooperative adaptive cruise control can significantly increase traffic throughput by tightly coordinating in-platoon vehicle movements to reduce headways between vehicles, 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.

The CACC operational concept represents an evolutionary advancement of conventional cruise control (CCC) systems and adaptive cruise control (ACC) systems by utilizing V2V and V2I communication to automatically synchronize the movements of many vehicles within a platoon.

As with SPD-HARM and Q-WARN, CACC-related driver communication will always give priority to crash avoidance/mitigation safety applications when such applications determine that a safety-related alert is necessary.

Figure 5-3 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.

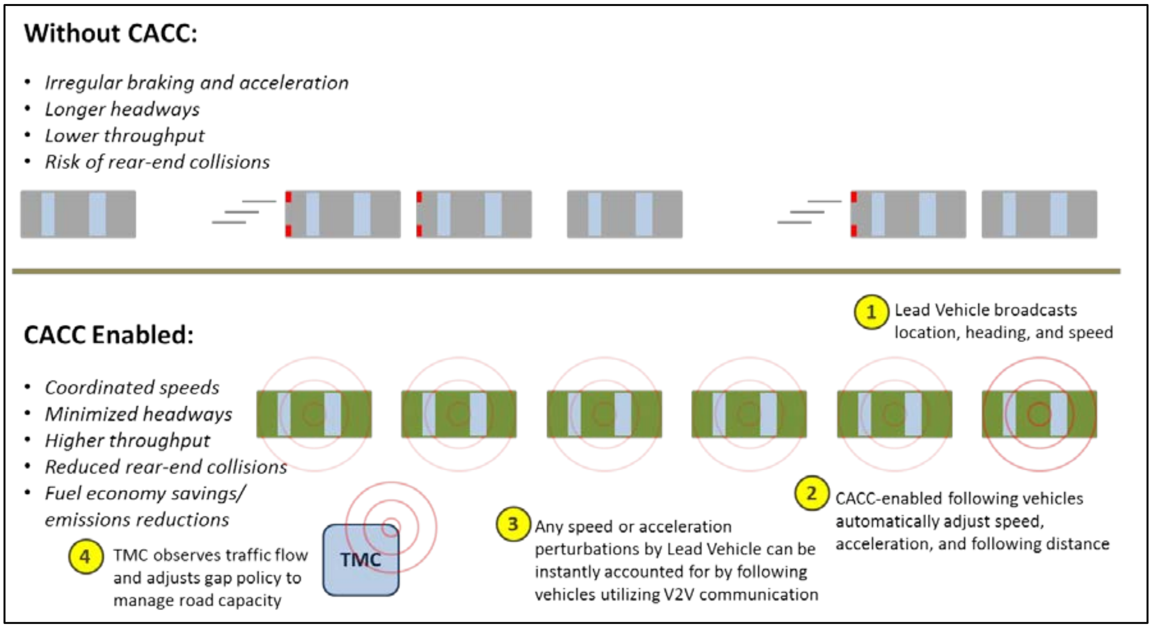

Figure 5-3. Stylized Depiction of Connected Vehicle-Enabled CACC

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. Micro-level decisions based on vehicle location and class within and between individual vehicles, however, can be made utilizing strictly V2V and multi-hop communication.

Platoons are not strictly required, however, for the CACC system to provide benefit. For instance, the CACC platform can be utilized to implement automated speed harmonization for vehicles traveling in mixed technology environments.

The CACC concept as described in this section will most likely be realized as an opt-in program, in which dedicated lanes or even entire facilities are made available to connected vehicle drivers who have signed up for the program and agree to abide by CACC speed, gap, and other recommendations and policies in order to receive the benefits (in terms of improved travel times, safety, and comfort) of the CACC facilities. Frequent violators could be banned from the facility much in the same way that frequent toll road violators today are identified and then excluded from the toll facilities.

An opt-in approach, as opposed to a mandatory program, would mitigate the inherent regulatory, enforcement, privacy, and liability related burdens on system implementers, transportation agencies, and industry partners. Such issues are discussed in more detail in the sections below on operational and institutional policies.

5.3.2 Operational Policies and Constraints

The critical operational policies and constraints related to the CACC concept relate to hardware, technical, institutional, and data-related issues. These policies and constraints are discussed below.

5.3.2.1 Hardware-related policies and constraints

Availability of vehicle bus data for subject vehicle
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.

Brake and throttle actuation
CACC requires that the vehicle systems be automatically actuated to achieve the longitudinal performance needed. This hardware (or software in the case of drive-by-wire) is typically not included in today's vehicles and as such must be integrated with CACC systems.

High resolution digital map availability
A high resolution map is needed in order to ensure that the vehicle can adjust its speed to reflect changes in the roadway horizontal and vertical profile. Furthermore, high resolution maps can also provide the system with information on location of various traffic control devices including stop and traffic signalized intersections.

Vehicle location hardware
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. The system may also use dead reckoning or other forms of vehicle tracking in the event that the GPS signal is lost. For example, Google identifies a "landing strip" at locations where vehicles can stop. The landing strip could simply be a mark on the ground, a sign on a wall, or lines or arrows showing where the vehicle should be parked. This then triggers the second set which receives data informing the machine where it is positioned and where it should go. Using the "landing strip" the vehicle can monitor its path and knowing where it started from, track the distance it traveled from the "landing strip" and thus adjust its direction at the appropriate places. Google has submitted a patent for the landing strip concept and is currently using it in its autonomous vehicles (http://www.bbc.co.uk/news/technology-16197664).

On-vehicle radar system availability
A radar system is required to measure the spacing and headway between the subject and surrounding vehicles. This is important especially in the event that V2V communication is lost by allowing the vehicle to track surrounding vehicles without the need for V2V communication.

Collision avoidance systems
CACC vehicles should also be equipped with forward collision avoidance systems to ensure that the vehicle is able to avoid collisions with surrounding vehicles in the event that communication between the subject vehicle and surrounding vehicles is lost. The system should also have some in-vehicle warning system to communicate to the driver in the event that the system loses communication with surrounding vehicles and manual intervention is required.

DSRC (or similar) communication system availability
DSRC or a similar hardware technology 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 (also known as strategic CACC decisions).

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. This algorithm will develop tactical CACC recommendations that will be use the strategic recommendations made by the TMC together with the data gathered from the subject vehicle and the other equipped vehicles in its vicinity.

5.3.2.2 Technical policies and constraints

This section identifies a number of important issues and design challenges that must be addressed before CACC can be introduced.

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. The system will also need to consider fail-safe or defaults to revert to normal driving. Research is required to identify the optimum transition from automated to manual control and how the driver should be informed of the switch in mode of operation.

Communication latency and lags in the provision of data
The system must be able to deal with latency and lags in the provision of data. Specifically, the system might consider longer headways to ensure that the system can respond to these latencies without resulting in vehicle collisions. The system should also include collision avoidance systems that use radar sensors to ensure that for longer than normal latencies the vehicle is able to avoid collisions.

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. This transition to manual driving must consider the situation that the driver/vehicle is in relative to other vehicles. It is also anticipated that the system would include some form of collision avoidance systems to ensure the safety of the driver/vehicle during such transitions. Figure 5-4 illustrates a theoretical timeline for how the collision mitigation techniques might be applied along the continuum of time leading up to a crash when communication breaks down. The driver warning system is best applied when the driver has adequate time to interpret the warning, make a decision about the best corrective action, and implement the decision. With greater time to collision, there are usually more potential options for avoiding the crash and drivers are fairly well equipped to assess the available options and make a decision that conforms to their expectations and those of other drivers on the road. At the opposite end of the spectrum when time to collision is very low, the options for avoiding a collision are significantly reduced. In these cases, it might be that an effective system might perform better than the driver by selecting the most appropriate action and performing it to the limits of the vehicle's dynamic capability. This, however, can result in the following vehicle crashing with the subject vehicle if the following vehicle is not fully equipped and does not have sufficient time to respond to the abrupt behavior of the subject vehicle. Further research will be required to develop safe transitions

between automated and manual control and identify when manual control is best and when automated control is best.

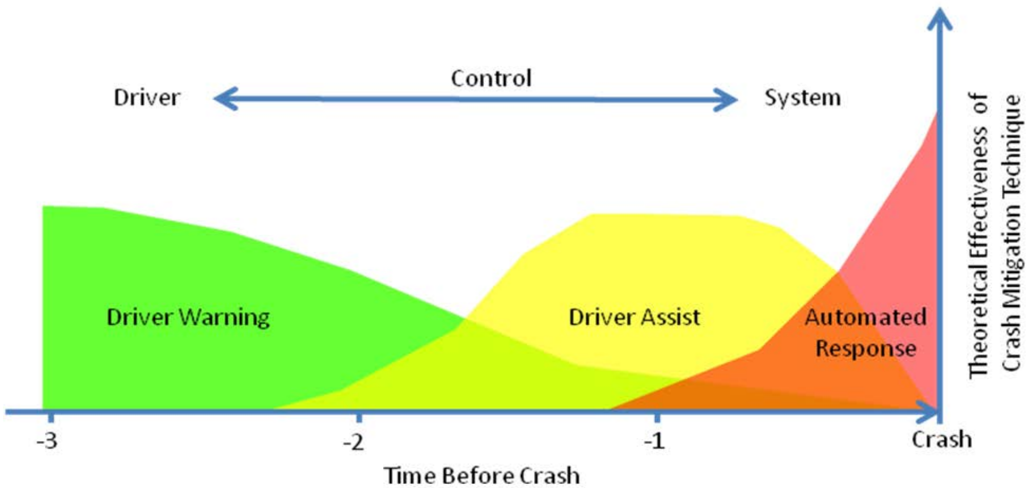

Figure 5-4. Pre-crash Driver Control Continuum.

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. The system will need to derive a final decision that is some compromise between the two recommendations.

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. The system will also 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. The system should be able to deal with the situation in which a platoon of equipped vehicles encounters a lead non-equipped vehicle. Finally, the system should be able to deal with merging and weaving sections when vehicles join and leave the platoon. In order to minimize the opportunities for disruptions to the platoon, it may be necessary, especially in near-term deployment, to limit the potential length of any single CACC platoon (e.g., a cap at eight vehicles per platoon).

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 semi-autonomous longitudinal vehicle control. Although the driver will have control of the steering wheel the driver may become less attentive once he/she proceeds into the CACC lane. These issues will require further investigation and study.

Accommodating varying vehicle-specific limitations
CACC requires that engine and other components of the vehicles respond efficiently. For example, there will be a difference in response times of electric vehicles and internal combustion engine vehicles. The age and the characteristics of vehicles with CACC are also critical. Thus, vehicle fleet will be as important as the algorithms in each vehicle.

Software and hardware development process
Development and validation of the CACC application and communication system must follow a structured product development process for hardware and software.

Software distribution
Based on analysis of the performance of the CACC system, software and algorithm updates must be transmitted wirelessly to the connected vehicles/devices in the field. This will reduce the amount of required coordination between the operators and OEMs and provides a less vehicle-dependent environment in which to operate the system.

5.3.2.3 Institutional policies and constraints

System introduction and full-scale implementation policies
It is important to consider how the system should be introduced and transitioned into full implementation. 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?

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? What applications should be introduced first that would not necessarily require high levels of market penetration to be successful?

Heterogeneous vehicle fleet
How will the system deal with heterogeneous vehicle fleets (e.g. the interaction of trucks and vehicles)? Should trucks be banned from use of CACC lanes initially until the system has been tested sufficiently on light duty vehicles? Once trucks are equipped with CACC systems should they have their dedicated lanes to account for their longer deceleration distances and longer headways?

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?

Liability issues
What are the litigation issues that have to be dealt with in the event of an accident involving CACC systems? Vehicle manufacturers in particular are concerned about the risks and liability potential associated with vehicle systems that rely on externally generated information.

5.3.2.4 Data-related policies and constraints

Data storage capability constraints
With regards to data storage constraints, it is important that the system can manage the data storage issues that have to be dealt with when these systems are widely implemented in the field.

Data cleansing capability constraints
The system should be able to deal with inconsistencies discrepancies across different data sources. Some form of fallback system should be developed when data sources demonstrate inconsistencies. The system should also be able to deal with noise in the data using filtering techniques.

Failure management constraints
The system should be able to deal with and identify errors in the various data sources. This can be achieved through some form of data redundancy within the system. The system should also be able to identify potential sources of error in one data source and assign weights to the data depending on the level of trust in the data source. The system design might use some particle filtering techniques to update the weights using a Bayesian filtering framework.

5.3.3 Modes of Operation

This section discusses the various modes of operation for the proposed CACC concept. The CACC system should mostly activate during recurrent congestion periods (e.g., activated upstream of congestion points and bottlenecks during morning and evening peaks) and non-recurrent events (e.g., activated upstream of incidents).

The typical modes of operation for CACC concept are:

Normal Mode: CACC in the normal operation mode should have all the designed functionality available. All systems and subsystems should work properly.

Degraded Mode: In this mode, some function(s) are not working properly and might go offline. Many different scenarios could result in operation in this mode, such as failed communication. In such cases, vehicles in CACC-specific and other lanes would revert to manual control.

Training Mode: The control center should have the capability of operating in the training mode for the purpose of training the new operators. The mode allows new operators to train on simulations without interfering with the actual daily operations.

Maintenance Mode: During the maintenance of the system, some subsystems and their functionalities may go offline. This mode is very similar to the Degraded Mode but the system usually can go online if needed. This means that this mode would not affect the normal operation.

Backup Mode: The system should have the ability to perform normal operation (or at least some levels of normal operation) when there is no connection between the system and the control center.

5.3.4 System Users and Needs

The following table identifies the key users of the CACC concept application, including human end users as well system entities that interact with the application. The table also includes a discussion of the high-level needs associated of the users.

Table 5-4. CACC System 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. Such information must be provided succinctly and in such a way that it is not overly distracting to the driver.
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. Such interaction must occur in such a way that it is not overly distracting to the driver.
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.
Vehicle operator	4. Needs personal data to remain private and secure	The privacy of individuals in the traffic stream must be maintained as data about their behavior is anonymized and shared across multiple jurisdictions.
Connected Vehicle	5. Needs to collect relevant vehicle data	The connected vehicle must be able to obtain relevant 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	6. Needs to disseminate relevant vehicle data to other vehicles or systems	The connected vehicle must have a dissemination capability so that the vehicle data it has obtained can be accessed by other vehicles and systems.
Connected Vehicle	7. Needs to receive relevant information from other vehicles or systems	In order to be able to provide useful information to the driver, the connected vehicle must be able to receive such information from other vehicles and systems.

User	High-Level User Need	Discussion
Connected Vehicle	8. 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	9. 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	10. 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	11. 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.
Traffic Management Entity	12. 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	13. 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	14. 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.

User	High-Level User Need	Discussion
Traffic Management Entity	15. 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	16. Needs to analyze performance of CACC system	Based on data received from the field, the traffic management entity must be able to validate the reliability of data, analyze the performance of the CACC system overall, and make changes to the algorithm or software to improve performance.
Data Capture and Management Environment	17. 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.

5.3.5 Support Environment

This section discusses the major components of the support environment that supports the core CACC system.

Service Monitor Subsystem: The 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. In order to provide required maintenance, the core system maintainers need access to the core system software and hardware configuration.

Note that choosing a system based on commercially available hardware and software (rather than unique hardware and software packages) would significantly reduce the amount of system maintenance required.

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. In the latter case, a carefully structured agreement is essential to ensure the highest quality support and maintenance.

Maintenance and Support Processes: Established processes are required to ensure that there will always be enough personnel to support the system and keep it up to date. This includes but is not limited to a checklist for the operators to be able to identify, isolate, and solve potential issues, as well as managing the processes for parts replacement and software support.

Chapter 6. Operational Scenarios

This section presents the key operational scenarios for each INFLO application. The scenarios are intended to reflect the operations of each application at a high level, indicating how the flow of information should occur between and among systems, users, and institutions. Scenarios enable stakeholders and readers of the ConOps document to grasp the operational significance of the proposed system and to clearly see what expected roles are to be. Scenario discussions consider the impacts and operational differences of deployments in the near-term (1-10 years), mid-term (10-20 years) and long-term (20+ years).

6.1 SPD-HARM Operational Scenarios

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

Description
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).

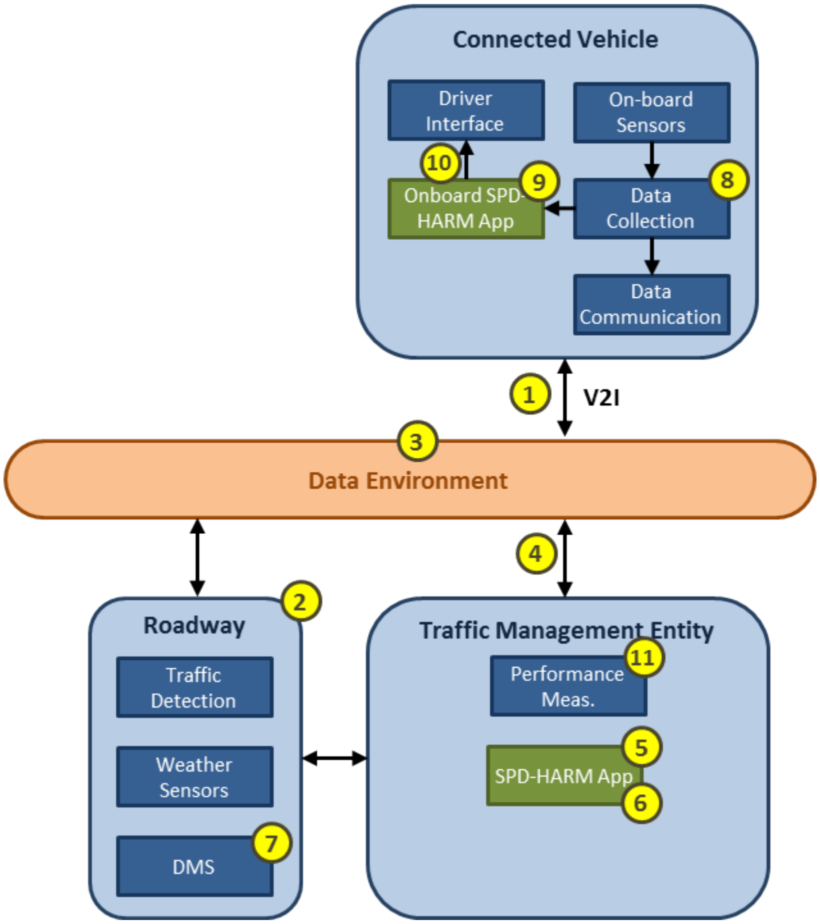

Figure 6-1. SPD-HARM Scenario 1 System Information Flow Diagram.

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 infrastructure-based systems.
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.

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

Description

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).

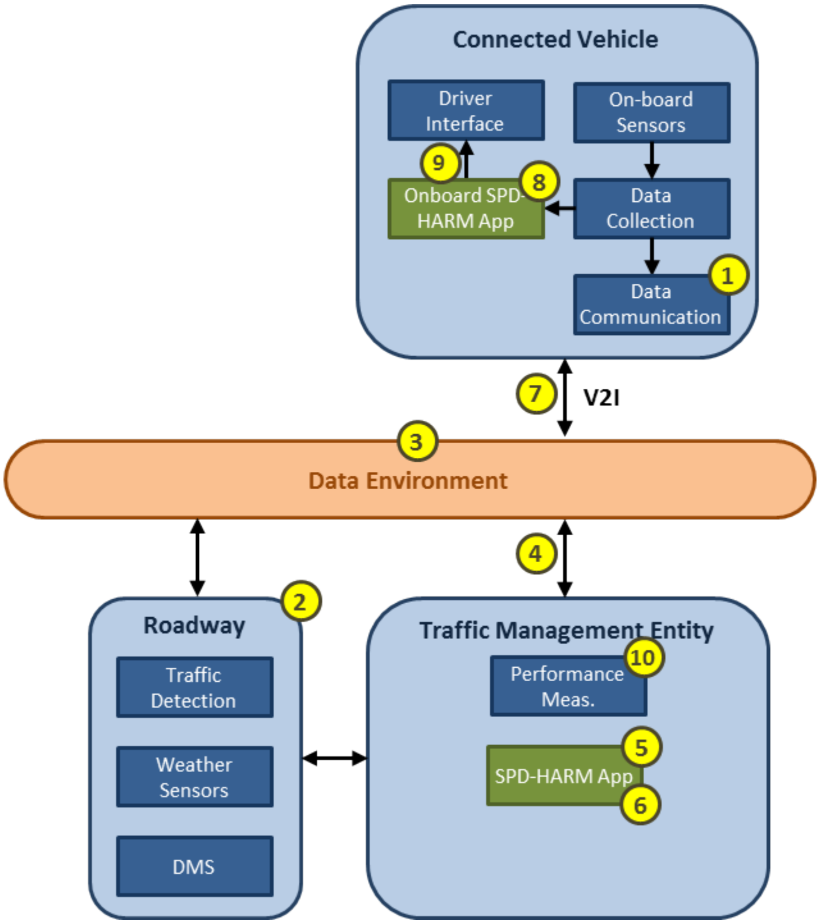

Figure 6-2. SPD-HARM Scenario 2 System Information Flow Diagram.

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 infrastructure-based systems.
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, while aspects of this scenario can be implemented in the near-term using a few enabled vehicles supplemented with infrastructure-based data, this scenario is more reflective of the medium- and long-term state of the connected vehicle environment.

6.1.3 Scenario 3: Weather-Related Speed Harmonization (External-to-Vehicle Processing; V2I-Dissemination)

Description

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.

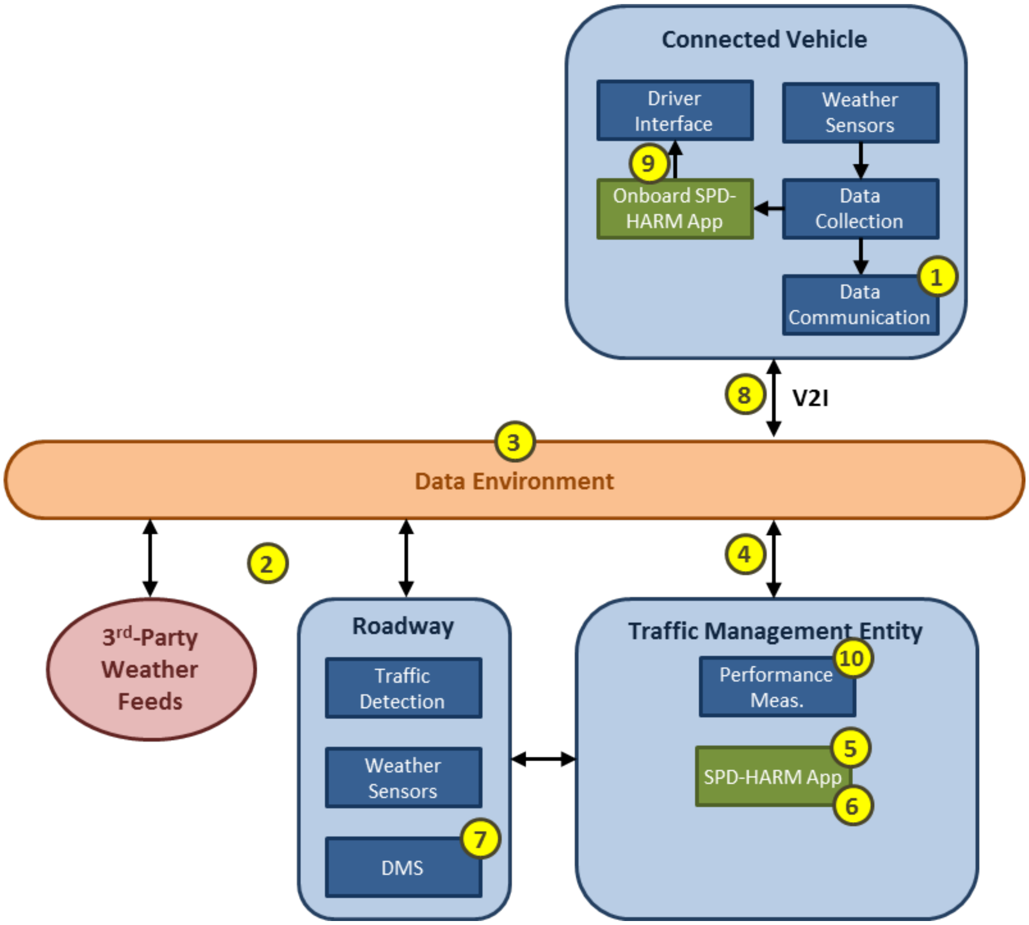

Figure 6-3. SPD-HARM Scenario 3 System Information Flow Diagram.

Preconditions

Not applicable.

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 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. Clarus and other weather data systems will likely comprise key weather data sources in the near term. The Vehicle Data Translator, developed by NCAR for FHWA, uses road weather data and data from mobile sources and adds value to it. Also, the RWM Program has commissioned the development of weather responsive traffic management models that have proven to be useful and successful.

6.2 Q-WARN Operational Scenarios

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

Description
In this scenario, a queue forms at a known queue generation point. Applicable situations include spillover at exit ramps, border crossings, lane merges, 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. V2V communication is supplemented by externally-originated queue warnings and response strategies, which are disseminated to upstream vehicles via infrastructure-to-vehicle (I2V) communication as well as dynamic message signs (DMS).

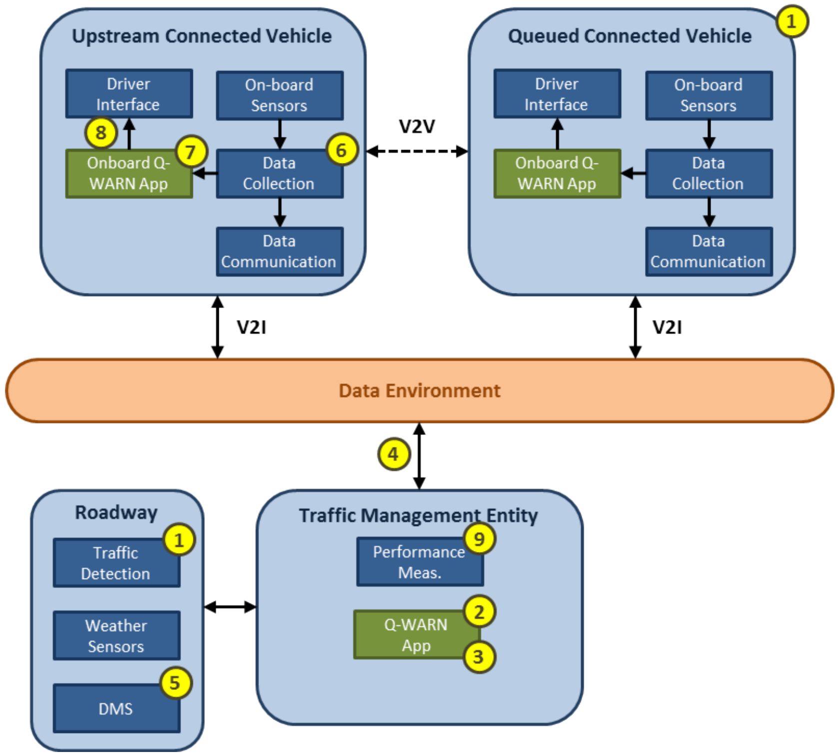

Figure 6-4. Q-WARN Scenario 1 System Information Flow Diagram

Pre-conditions

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

Steps

1. RSE and other infrastructure installed to monitor conditions on the ramp collect traffic data and weather conditions 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.

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

Description
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.

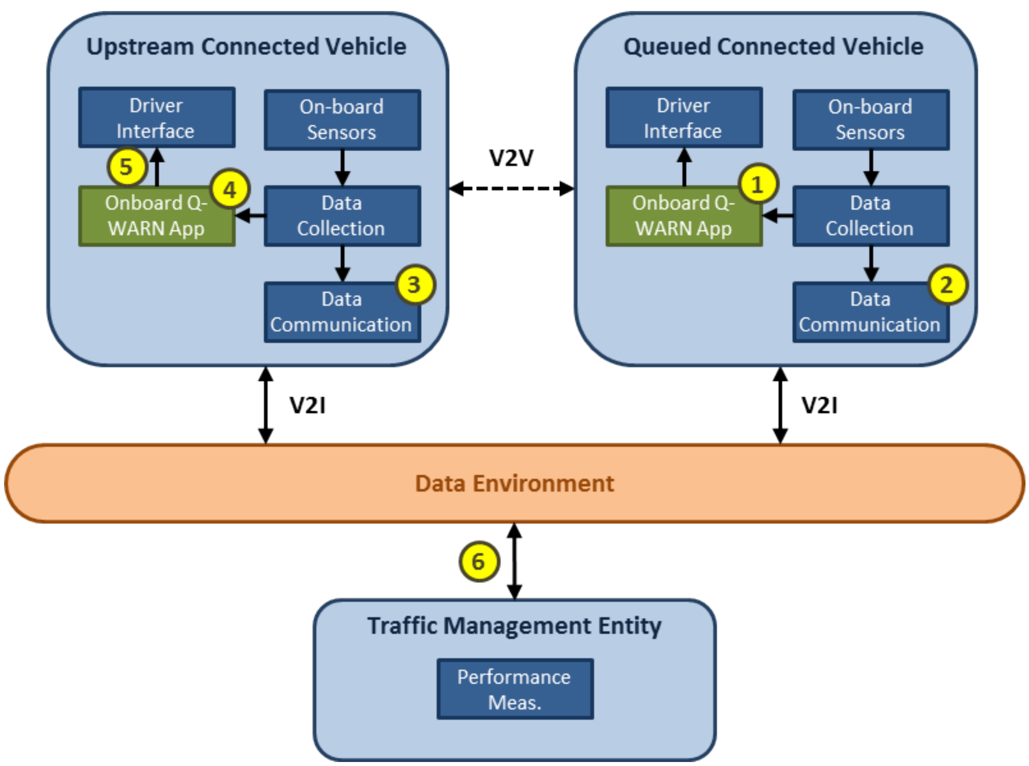

Figure 6-5. Q-WARN Scenario 2 System Information Flow Diagram.

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 potential for reducing 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 most roadways in most locations, with a limited need for infrastructure-based detection and information dissemination. However, there are a number of drawbacks and limitations 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.

Also, 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. Several non-equipped vehicles in the middle of the traffic stream have the potential to block a queue warning message from being fully dispersed.

In regards to the potential for cost savings, the elimination of infrastructure elements in a connected vehicle environment does not guarantee system level cost savings when individual vehicle-based equipment costs (communication, decision making, and driver-vehicle interface hardware and software) are considered. Additionally, in the near-to-mid term, mixed mode operation will require both infrastructure and in-vehicle elements in many cases.

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

Description

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.

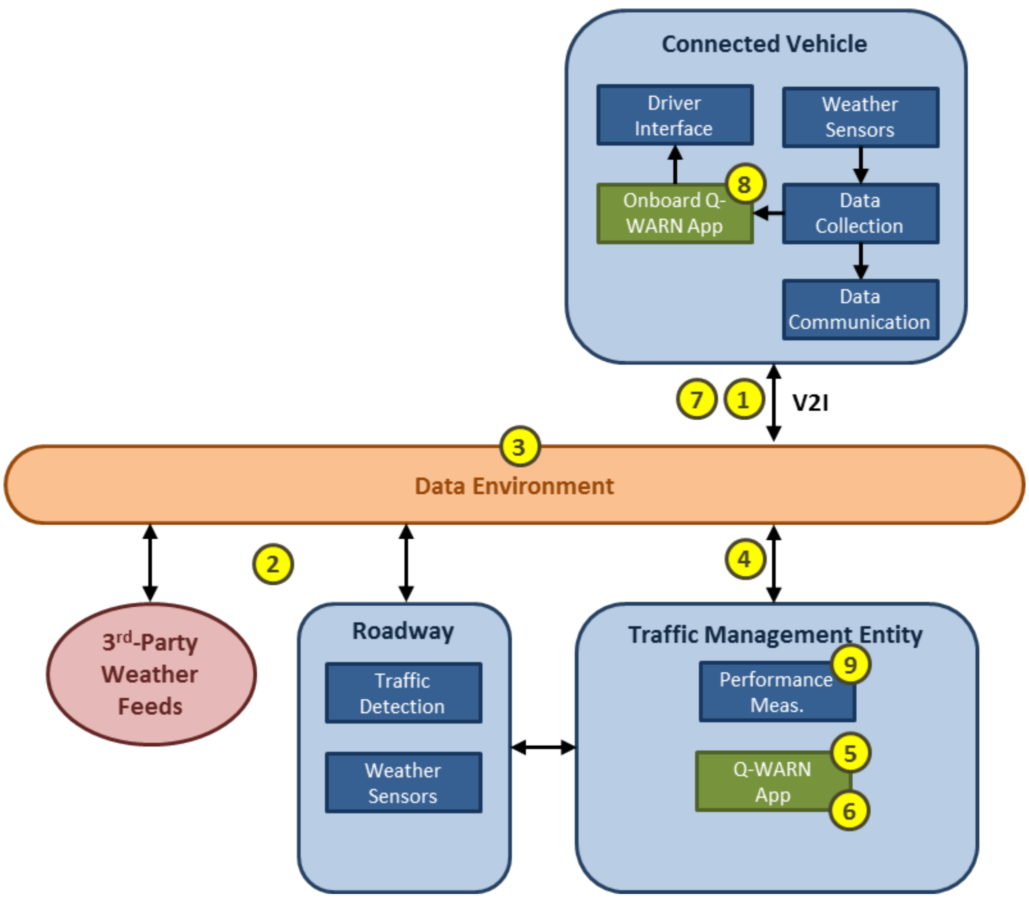

Figure 6-6. Q-WARN Scenario 3 System Information Flow Diagram.

Preconditions
Not applicable.

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).

6.3 CACC Operational Scenarios

6.3.1 Scenario 1: Joining and Exiting a CACC Platoon (Vehicle-Based Processing; V2V-Dissemination)

Description
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.

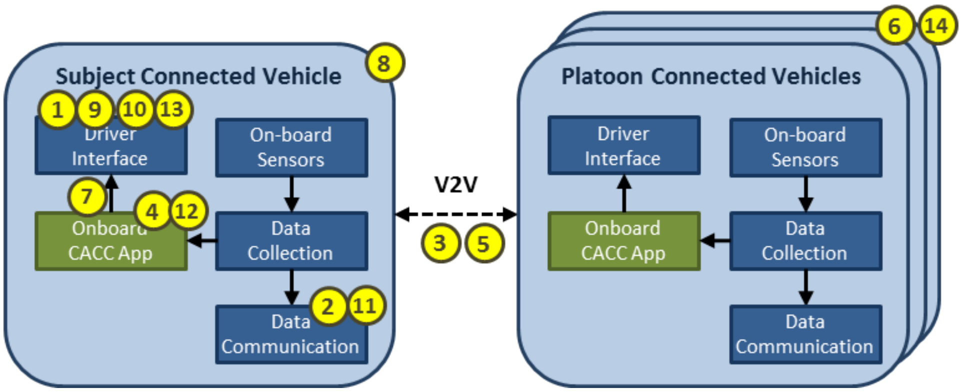

Figure 6-7. CACC Scenario 1 System Information Flow Diagram.

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.

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.

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

Description
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.

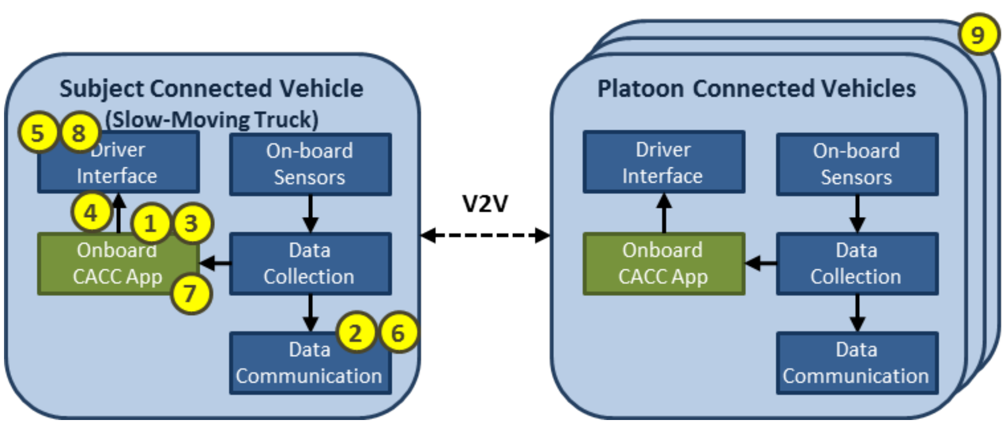

Figure 6-8. CACC Scenario 2 System Information Flow Diagram

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.

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

Description
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.

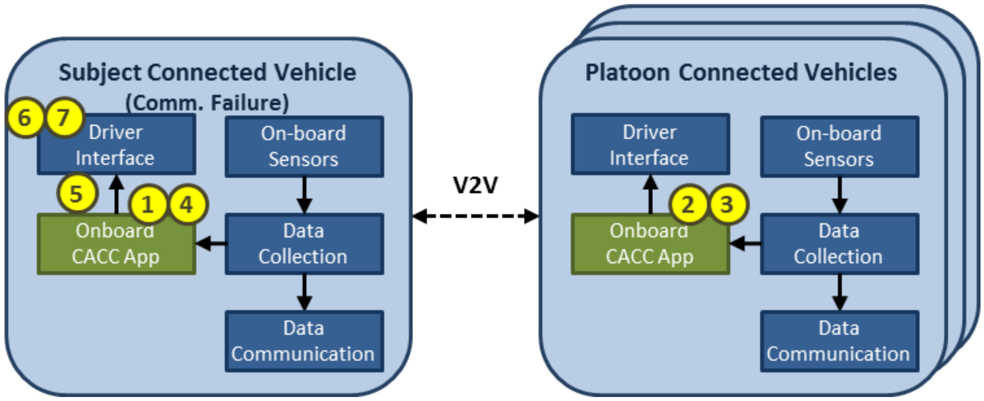

Figure 6-9. CACC Scenario 3 System Information Flow Diagram.

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.?
- How will the Human-Machine interface be designed and tested?

This scenario demonstrates the need for connected vehicles to be aware of the identity and location of the other connected vehicles with which it is communicating. Without being able to accurately differentiate and locate other platooning vehicles, detection and localization of an individual vehicle experiencing communications failure would not be possible.

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

Description
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.

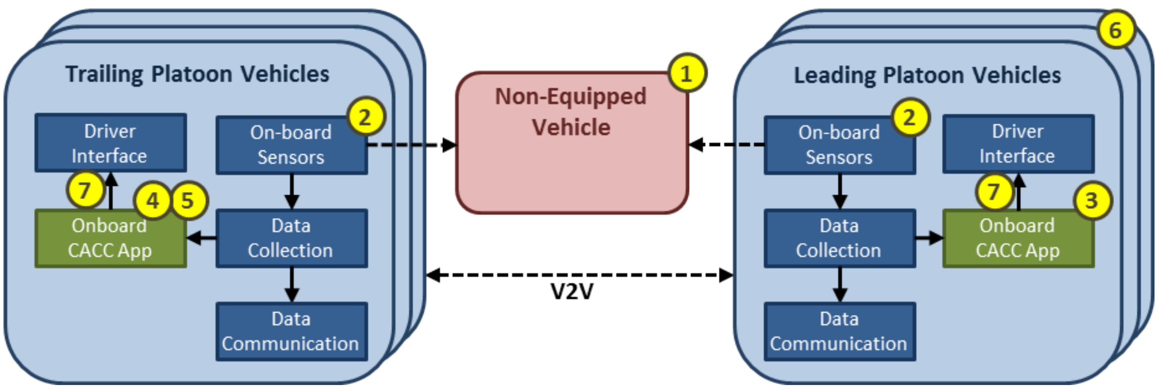

Figure 6-10. CACC Scenario 4 System Information Flow Diagram.

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.

6.3.5 Scenario 5: Traveling in a Platoon in Inclement Weather (V2V and TMC Communication)

Description
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.

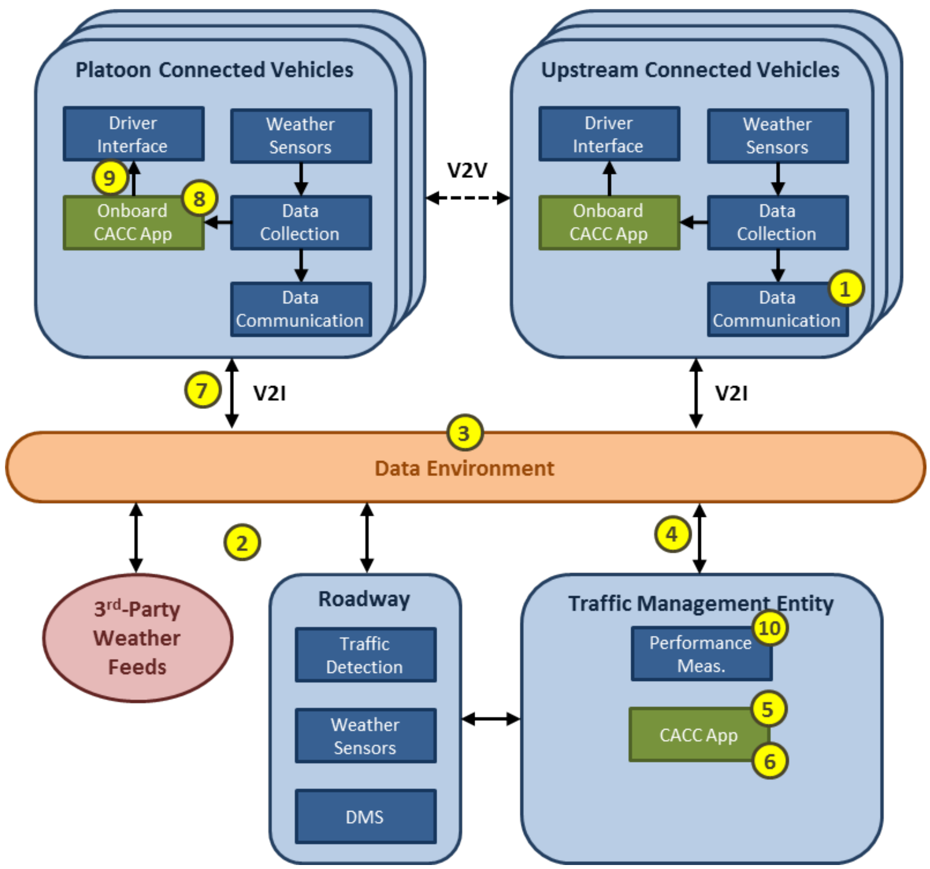

Figure 6-11. CACC Scenario 5 System Information Flow Diagram.

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 (platoon leader initiates policy and following vehicles follow suit).
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.

6.4 Combined INFLO Operational Scenario: Congestion on the INFLO Managed Lane

Description

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 infrastructure-to-vehicle (V2I) communication as well as dynamic message signs (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.

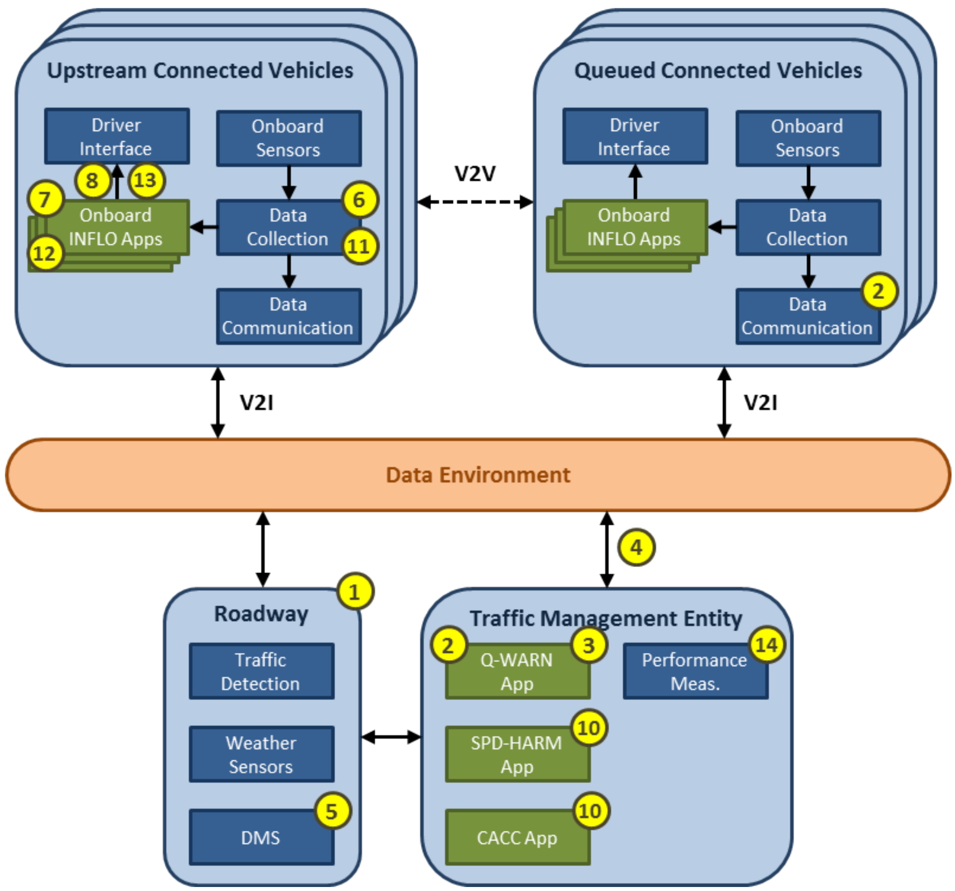

Figure 6-12. Combined Scenario System Information Flow Diagram.

Chapter 7. Summary of Impacts

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

7.1 Operational Impacts of INFLO

From an operational perspective, the introduction of any or all of the INFLO applications would have the following major impacts:

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 selection and long-term planning. This data will be mostly vehicle-based rather than link-based.

Increased reliability of traffic control systems

Revised operational procedures and interfaces
In order to accommodate connected vehicle data sources and communications methodologies, operational procedures and interfaces will have to be revised. Updated training of system operators will also be required.

New training requirements
Because of the changes in work descriptions and workload, it might be necessary to hire or retrain additional personnel for operating the system. Maintenance personnel also need extra 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
Since motorist acceptance and compliance is critical for the applications to operate effectively, extensive public outreach and educational campaigns will become a more significant part of agency operations.

Establishment of connected vehicle liability laws and regulations
Due to the greater dependence that the INFLO applications have on autonomous control, automatic intervention, and system-generated driver recommendations, how liability is allocated among stakeholders when something goes wrong must be understood. The development and implementation of the INFLO applications will require that laws and regulations related to such liability issues be well established.

Methods for achieving compliance
Compliance of speed, gap, and other INFLO-based targets and recommendations is critical to realizing the full benefit of the system. One approach to maximizing compliance is through automated enforcement, although this presents many challenges relating to data privacy concerns, data ownership, obtaining industry support, legal authority questions, and user acceptance.

Another approach would be to make INFLO (CACC and SPD-HARM in particular) an opt-in program, in which dedicated lanes or even entire facilities are made available to connected vehicle drivers who have signed up for the program and agree to abide by the speed, gap, and other recommendations and policies in order to receive the benefits (in terms of improved travel times, safety, and comfort) of the special facilities. Frequent violators could be banned from the facility much in the same way that frequent toll road violators today are identified and then excluded from the toll facilities.

An opt-in approach, as opposed to a mandatory program, would mitigate the inherent regulatory, enforcement, privacy, and liability related burdens on system implementers, transportation agencies, and industry partners.

7.2 Organizational Impacts of INFLO

From an organizational perspective, the introduction of any or all of the INFLO applications would have the following major impacts:

Tighter collaboration and interaction between public agencies and private industries
The successful implementation of an INFLO application will require close collaboration and interaction between automotive manufacturers, the cellular and phone industry, the hardware industry, the mapping industry (e.g. NAVTEQ and Google), 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. Key agencies that may be included in such applications include the Institute of Electrical and Electronics Engineers (IEEE) and American Association of State Highway and Transportation Officials (AASHTO).

Streamlined standards and protocols development process
Modifications may be required for the various messaging protocols, including the SAE J2735 messages, to provide additional information for INFLO application usage. Some additional information could include the instantaneous vehicle fuel consumption rate for use in “green” or efficiency-optimized applications. Functional safety standards (e.g., ISO 26262), which require the assessment of safety risks, may also be considered.

Increased inter-agency and inter-jurisdictional data sharing
The successful implementation of INFLO systems will require standardization of data formatting and sharing across different TMCs. Vehicles should be able to travel across various jurisdictions seamlessly and receive similar data regardless of the jurisdiction.

Redefined organizational and governance structures
The operating agency may decide to outsource the deployment process or use its own resources for this purpose. In either case, new organizational structures should be defined.

Professional capacity building of operations and maintenance personnel

Increased ITS budget allocations
Budget considerations will become important and this extra cost should be included in the cost-benefit analysis of the system.

7.3 Procurement/Development Impacts of INFLO

From a procurement and development perspective, the introduction of any or all of the INFLO applications would have the following major impacts:

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). Research will need to focus on a number of issues, including:

- What is the optimum level of information and automated response that should be provided to a driver for various potential crash avoidance scenarios?
- What types of issues must be addressed to assure an effective transition between human response and automated response?
- Can the system affect driver behavior in the long run (e.g., will drivers rely more on the vehicle)?
- Can automated vehicle responses that avoid an initial collision raise the risk of other or higher severity crashes?
- What are the potential negative impacts on the overall traffic safety, system throughput, and the environment?

Revised transportation planning process
The introduction of INFLO-optimized facilities (e.g., dedicated CACC or SPD-HARM lanes) would have a significant impact on transportation planning, given their potential for greatly increasing the facility capacity. Consequently, such systems will require that they be integrated within planning decisions. Furthermore, the introduction of alternative routing strategies (e.g., eco-routing) may alter the procedures used in the fourth step of the four-step planning process (i.e., traffic assignment step).

New requirements, training, and testing for road users

The introduction of connected vehicle-enabled mobility applications might also entail changes in the driving tests administered to drivers. For example, the test might also include tasks that entail the use of in-vehicle systems, traveling in lanes at very short gap settings, and transitioning from manual to automated driving and vice versa. The vehicles of the future will include significant in-vehicle technologies and systems and thus there is a potential for cyber-physical associated with such systems for older and to a less extent less educated drivers. Differences in driver expectations and comfort with technology will be an issue of utmost importance in deploying such systems.

Third-party system and interface certification procedures

Third-party certification of the system and relevant interfaces will be required prior to full deployment. A comprehensive testing and certification process must therefore be developed.

Chapter 8. Analysis of the Proposed INFLO Applications

This section presents an analysis of the benefits, limitations, advantages, disadvantages, alternatives, and trade-offs considered for the proposed INFLO bundle of applications.

In the connected vehicle environment the proposed INFLO applications will be able to achieve significant transformative outcomes in the areas of safety and throughput.

INFLO will significantly improve motorist safety. Improved safety, to road users, translates to fewer and less severe crashes as well as the perception of a safer environment. The INFLO bundle achieves this by:

- Reducing speed variability among vehicles, which minimizes the number and severity of collision opportunities
- Reducing or even eliminating secondary crashes
- Reducing the likelihood of initial crashes (due to advanced warnings of or even automatic intervention in dangerous situations)
- Reducing reliance upon human decision-making in dangerous situations in which drivers have been shown systematically to perform poorly (e.g., in high speed stop distance judgment, lane-merging, and fast reaction time dependent situations)

INFLO will significantly improve system throughput. Improved system throughput, to road users, translates to decreased travel times and better travel time reliability. The INFLO bundle achieves this by:

- Reducing speed variability among vehicles (which improves traffic flow)
- Minimizing or delaying flow breakdown formation
- Coordinating vehicle speeds and movements to maximize network efficiency
- Reducing or even eliminating secondary crashes
- Reducing headways between platooning vehicles

It should be emphasized the individual benefit that co-deployment of the whole INFLO bundle has for each application. Review of queue warning, speed harmonization, and adaptive cruise control literature has shown that the most successful active traffic management implementations have been those that combine multiple different freeway management control applications. In a connected vehicle environment, Q-WARN, SPD-HARM, and CACC applications would similarly benefit from co-deployment. Because the applications are so closely linked, the effectiveness of each can be improved by taking advantage of the benefits to traffic flow and safety that the others provide. For example, SPD-HARM benefits Q-WARN by slowing and managing upstream traffic, thus reducing the risk of secondary collisions. CACC benefits SPD-HARM by providing a mechanism for harmonizing traffic flow and reducing or mitigating acceleration variability. Q-WARN benefits CACC by providing the platoon sufficient notification of an impending queue to effectively manage a response.

The following sections summarize the benefits, limitations, and alternatives specific to each INFLO application concept.

8.1 SPD-HARM

8.1.1 Summary of Improvements

The SPD-HARM concept provides some enhanced capabilities which introduce several benefits over the current system. The use of connected vehicle technologies and predictive algorithms for speed selection will result in the following improvements:

- ***Delayed or eliminated flow breakdown formation, which will improve mobility and reduce emissions.*** Our simulation results show that even reactive speed harmonization is capable of delaying or eliminating breakdown formation in certain cases. Based on research on predictive traffic control, it is expected that predictive algorithms could prevent or delay breakdown formation under a wider range of situations than reactive approaches.

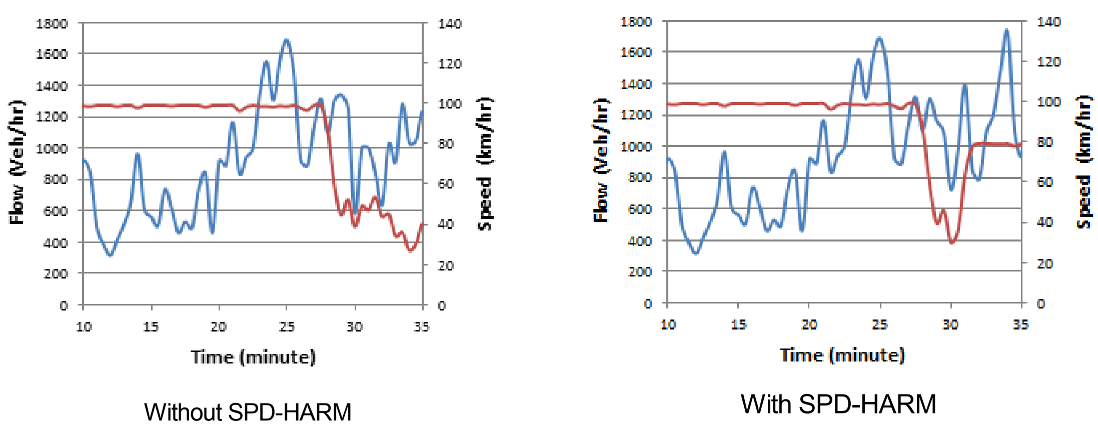

Figure 8-1. Effect of Speed Harmonization on Flow Breakdown Elimination.

- ***Reduced shockwave occurrences*** (both number and duration), which will improve mobility and safety and will reduce emissions. The simulation results obtained by Breton et al. (2002) showed that speed harmonization could eliminate shockwave formation under certain conditions. Additional research is required to better understand the effects of speed harmonization on shockwave occurrence, and the conditions under which such effects occur.
- ***Improved traffic stream evenness***, which will improve mobility and safety especially during lane changing maneuvers. Piao and McDonalds (2008) showed that SPD-HARM has significant potential to reduce the speed difference between

adjacent lanes and adjacent road sections (no specific quantitative evidence is presented).

- ***Improved travel times and travel time reliability***, which improves mobility and increases user acceptance and support of the system. The simulation results by Hegyi et al. (2005) showed about 20% improvement in Total Time Spent (TTS) in the network. The variable speed limit in St. Louis Missouri showed up to 19.1% reduction in travel time and up to10.1% reduction in Travel Time Index (TTI) in some segments. Note that they also observed some increase in travel time and TTI in some segments (Bham et al., 2010).
- ***Improved speed compliance*** (essential for the success of SPD-HARM), which will improve mobility and safety along the facility. Different compliance rates were observed in different locations and different studies. The compliance could be very high (e.g. 76% compliance was observed in Finland (FHWA *Speed Harmonization and Shoulder Use*, 2009)) or could be very low (e.g. King (2010) reported low compliance in Missouri's I-270 mandatory VSL). Additional research is needed to better understand the factors that affect compliance with speed harmonization measures.
- ***Reduced number and severity of primary and secondary crashes***, which directly translates to improved safety and has positive effects on user acceptance. Reductions ranging between 2% to 30% in crash rate were observed in different studies (FHWA *Efficient Use of Highway Capacity*, 2010 and FHWA *Speed Harmonization and Shoulder Use*, 2009).

8.1.2 Goals, Performance Measures, and Transformative Performance Targets

Through discussions with INFLO stakeholders on the potential benefits of the SPD-HARM concept (see *Report on Stakeholder Input on Goals, Performance Measures, Transformative Performance Targets, and High-Level User Needs for INFLO*), the following goals, performance measures, and performance targets specific to the SPD-HARM concept were developed (see Table 8-1 below).

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

Note: For a discussion of some of the key terms used in this section (including goals, performance measures, performance targets, crashes, and shockwaves), see *Appendix C: Glossary of Terms Relevant to Goals, Performance Measures, and Targets*.

It should be emphasized that the transformative performance targets described here are aspirational in nature. They are meant to reflect "stretch goals", in that they are representative of an end state or condition that is vastly superior to the current condition. Transformative Performance Targets were arrived at through discussions with and feedback from the INFLO stakeholder group and were informed by operational experience of the stakeholders and findings from relevant studies and literature in active traffic management, traffic flow theory, and other fields.

Performance targets will likely vary based on roadway setting (metropolitan vs. suburban vs. rural), roadway type (mixed flow freeway, HOV/HOT managed lanes, 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.

For these reasons, the identified performance targets should be understood to be flexible and subject to modification as more connected vehicle related research is conducted and operational approaches are better defined.

Table 8-1. 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 traffic shockwaves	Number of 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	Length of formed shockwaves	• Reduce average shockwave length by 25% (near) • Reduce average shockwave length by 50% (mid) • Reduce average shockwave length by 75% (long)	Safety/mobility	System-oriented
	Propagation speed of formed shockwaves	• Reduce average (backwards) shockwave propagation speed by 25% (near) • Reduce average (backwards) shockwave propagation speed by 50% (mid) • Eliminate (backwards) shockwave propagation (long)	Safety/mobility	System-oriented
3. Improve throughput	Vehicles per hour	• 10% increase in number of vehicles per hour (near) • 25% increase in number of vehicles per hour (mid) • 50% increase in number of vehicles per hour (long)	Mobility	System-oriented
4. Improve speed compliance	Compliance rate of posted or recommended speeds	• 75% compliance (near) • 95% compliance (mid) • 100% compliance (long)	Mobility	System-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
5. 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
6. 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
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)	[All]	User-oriented
	Voluntary compliance with recommended SPD-HARM operating strategies	• 75% compliance of enabled vehicles (near) • 85% compliance of enabled vehicles (near) • 95% compliance of enabled vehicles (near)	[All]	User-oriented
8. 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
9. 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
10. 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
111. 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 facility fuel consumption by 10% (near) • Reduce facility fuel consumption by 25% (mid) • Reduce facility fuel consumption by 50% (long)	Energy	System-oriented
12. 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

8.1.3 Disadvantages and Limitations

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. However, developments in other areas with high transaction volumes and active customer relation management in retail, financial services and electronic logistics marketplaces point to successful implementations and robust hardware and software solutions that may be readily adapted to this environment

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

In order for the SPD-HARM concept to be successful, driver compliance with the application's speed recommendations is crucial. Absent CACC (or a similar autonomous car following environment), connected vehicle drivers will have to acknowledge and make manual throttle adjustments in response to the varying speed target recommendations of the SPD-HARM application. 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.

8.1.4 Alternatives and Trade-Offs Considered

Alternatives and trade-offs have been considered for the proposed system in the following key areas:

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. Since there are complementary factors among the various mobility and safety applications, it is expected that SPD-HARM 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. In particular, CACC would benefit SPD-HARM by providing an automatic mechanism for harmonizing traffic flow and reducing or mitigating acceleration variability, thereby significantly increasing speed compliance and allowing for more precise management of the traffic flow.

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. Speed harmonization per se could be introduced with varying degrees of sophistication starting in the early stages of connected vehicle deployment (including reactive strategies at fixed locations pre-connectivity). The sophistication could evolve as connected vehicle deployments become more mature and more prevalent, and the science base advances through application and testing.

8.2 Q-WARN

8.2.1 Summary of Improvements

There are a number of improvements that the Q-WARN concept is anticipated to produce related to the effects of vehicle queue formation:

- ***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

8.2.2 Goals, Performance Measures, and Transformative Performance Targets

Through discussions with INFLO stakeholders on the potential benefits of the Q-WARN concept (see *Report on Stakeholder Input on Goals, Performance Measures, Transformative Performance Targets, and High-Level User Needs for INFLO*), the following goals, performance measures, and performance targets specific to the Q-WARN concept were developed (see Table 8-2 below).

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

Note: For a discussion of some of the key terms used in this section (including goals, performance measures, performance targets, crashes, and shockwaves), see *Appendix C: Glossary of Terms Relevant to Goals, Performance Measures, and Targets*.

Table 8-2. 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
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

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
	Duration of formed queues at variable locations	• Reduce average duration of formed queues by 50% (near) • Reduce average duration of formed queues by 75% (mid) • Queue formation at variable locations eliminated (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 traffic shockwaves	Length of formed shockwaves	• Reduce average shockwave length by 25% (near) • Reduce average shockwave length by 50% (mid) • Reduce average shockwave length by 75% (long)	Safety/mobility	System-oriented
	Propagation speed of formed shockwaves	• Reduce average (backwards) shockwave propagation speed by 25% (near) • Reduce average (backwards) shockwave propagation speed by 50% (mid) • Eliminate (backwards) shockwave propagation (long)	Safety/mobility	System-oriented
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)	[All]	User-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
	Voluntary compliance with recommended Q-WARN operating strategies	• 75% compliance of enabled vehicles (near) • 85% compliance of enabled vehicles (near) • 95% compliance of enabled vehicles (near)	[All]	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

8.2.3 Disadvantages and Limitations

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
In order for the Q-WARN concept to be successful, driver acknowledgement of queue warnings and compliance with the application's speed reduction recommendations in response to downstream queues are crucial. Absent CACC (or a similar autonomous car following environment), connected vehicle drivers will have to acknowledge and make manual throttle adjustments in response to the varying speed target reduction recommendations of the Q-WARN application. 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.

8.2.4 Alternatives and Trade-Offs Considered

Alternatives and trade-offs have been considered for the proposed Q-WARN system in the following key areas:

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. Since there are complementary factors among the various mobility and safety applications, it is expected that Q-WARN 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. In particular, SPD-HARM would benefit Q-WARN by effectively slowing and managing upstream traffic, thus reducing the risk of secondary collisions caused by sudden stopping.

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.

8.3 CACC

8.3.1 Summary of Improvements

User acceptance
Human factors research into CACC and similar adaptive cruise control systems have revealed that drivers are generally very accepting of autonomous and semiautonomous vehicle control and readily enable it to perform following maneuvers that would otherwise not be undertaken. Key supporting research includes the following:

- A University of California PATH CACC human factors experiment Nowakowski et al., 2011) found that subjects operating CACC-equipped vehicles most frequently elected to utilize the shortest time-gap setting available (0.6 s), representing a 50% decrease in the time-gaps opted for when operating non-cooperative adaptive cruise control vehicles.
- A Virginia Tech study (Van Aerde and Rakha, 1999) found that ACC "*….greatly reduces the driver's work, the ACC system leads to safer as well as more pleasant driving.*"
- Fancher et al. (1998) found that "*…. ACC is remarkably attractive to most drivers. The research indicates that, because ACC is so pleasing, people tend to utilize it over a broad range of conditions and to adopt tactics that prolong the time span of each continuous engagement.*"
- These findings suggest that in a deployed CACC environment, driver participation and compliance would be high enough that the theoretical capacity and efficiency gains of CACC could in fact be realized.

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 (Shladover et al., 2009; Nowakowski et al., 2011). Further research is needed, however, to more precisely demonstrate the conditions under which such significant throughput and capacity gains can be achieved. While CACC research has indicated the potential for greatly increased throughput and capacity results, the degree of improvement is tightly connected to how well the CACC system can accommodate vehicle merging (van Arem et al., 2006). Research is currently underway to develop cooperative lane-changing algorithms to reduce the negative impacts of lane-changing behavior.

Reduced shockwaves and enhanced traffic stream smoothness
Although some research has indicated that shockwave speeds in CACC environments are faster and thus may pose a safety risk to drivers of non-CACC enabled vehicles in the traffic stream (Pueboobpaphan et al., 2010), it is expected that in a CACC environment the magnitude, frequency, and overall incidence of shockwaves would be lower due to the system's ability to automatically and rapidly make speed and headway adjustments to counter speed or acceleration perturbations (Shladover et al., 2009).

Reduced travel time and enhanced travel time reliability
As with speed harmonization systems, CACC has the potential to improve travel time reliability by enhancing the transportation system safety and reducing the number of collisions within the system.

And unlike with speed harmonization, CACC can be expected to have a positive effect on travel time, due to its theoretical ability to increase roadway capacity and hence reduce traffic-slowing congestion.

By eliminating lag times in driver responses, reducing the speed differential among adjacent lanes, and creating more uniform flow, CACC is capable of delaying the onset of breakdown formation (Pueboobpaphan et al., 2010) (van Arem et al., 2006). Furthermore, after the occurrence of breakdown, CACC has the potential to minimize the capacity drop by increasing and harmonizing subsequent vehicle acceleration levels.

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.

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; however this may reduce system throughput. Consequently, there is a need to find a good compromise in system aggressiveness to minimize capacity drops after the onset of congestion but at the same time reduce vehicle fuel consumption and emission levels.

8.3.2 Goals, Performance Measures, and Transformative Performance Targets

Through discussions with INFLO stakeholders on the potential benefits of the CACC concept (see *Report on Stakeholder Input on Goals, Performance Measures, Transformative Performance Targets, and High-Level User Needs for INFLO*), the following goals, performance measures, and performance targets specific to the CACC concept were developed (see below).

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

Note: For a discussion of some of the key terms used in this section (including goals, performance measures, performance targets, crashes, and shockwaves), see *Appendix C: Glossary of Terms Relevant to Goals, Performance Measures, and Targets*.

Table 8-3. 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 traffic shockwaves	Number of 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	Length of formed shockwaves	• Reduce average shockwave length by 25% (near) • Reduce average shockwave length by 50% (mid) • Reduce average shockwave length by 75% (long)	Safety/mobility	System-oriented

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
	Propagation speed of formed shockwaves	• Reduce average (backwards) shockwave propagation speed by 25% (near) • Reduce average (backwards) shockwave propagation speed by 50% (mid) • Eliminate (backwards) shockwave propagation (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

Goal	Performance Measure	Transformative Performance Target (near-, mid-, or long-term)	Predominant Benefit	User- / System-Orientation
	Voluntary compliance with recommended CACC operating strategies	• 75% compliance of enabled vehicles (near) • 85% compliance of enabled vehicles (near) • 95% compliance of enabled vehicles (near)	[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
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 facility fuel consumption by 25% (near) • Reduce facility fuel consumption by 50% (mid) • Reduce facility fuel consumption by 75% (long)	Energy	System-oriented

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

8.3.3 Disadvantages and Limitations

Cooperative driving may be established through the introduction of in-vehicle communication technologies. Vehicular communications (VC) lay at the core of many research initiatives attempting to enhance the efficiency and safety of transportation systems. Vehicles and road-side infrastructure units (i.e., network nodes) will be equipped with on-board processing and wireless communication modules. V2V and V2I communication will enable intelligence gathering on incidents as well as road conditions (e.g., snow, ice, etc.). Thus, VC is important particularly in real-time decision making especially in the efficient coordination, re-routing of traffic in real-time, CACC, and merge assistance systems. This is vital for the reduction of the recovery time of an impaired network.

The current assumption is that DSRC (Dedicated Short Range Communications) protocol could be used; however the CACC concept is intended to be technology independent. DSRC, which utilizes a protocol of communication technology applied on several 10 MHz channels, would require application enhancements if used. These include: (i) grouping communication mechanisms for vehicles; (ii) enhancing DSRC communications, (iii) bringing out the inter-vehicle cooperation, and (iv) simulating and testing these communication systems.

The CACC system requires vehicular communications that are resilient: this step requires the design and building of vehicular communication protocols and systems that block any abuse or misbehavior while remaining resilient to on-going attacks or incidents. In addressing this issue there is a need to describe the problems that characterize security, robustness, and resilience of vehicular communications. Subsequently there is a need to study possible (preliminary) solutions, some of them leveraging existing techniques relative to communication networks. VC exhibits its own characteristics, in particular: (i) the high speed and intermittent connectivity of the vehicles (especially with infrastructure), (ii) the dilemma of liability vs. privacy, (iii) the high relevance of geographic location of vehicles, and (iv) the large scale of the road network.

As was discussed earlier, there are a number of technical constraints that will have to be addressed. These constraints include:

- Dealing with 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.
- Dealing with communication latency issues and lags in the provision of data.
- Dealing with 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 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. The system will need to derive a final decision that is some compromise between the two recommendations.
- The system will need to include multiple-leader car-following models in order to ensure platoon car-following asymptotic stability.

- 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.
- The system should be able to deal with merging and weaving sections when vehicles join and leave the platoon.
- The system should be able to deal with the situation in which a platoon of equipped vehicles encounters a lead non-equipped vehicle. This could happen if the communication system failed.
- The system will need to deal with transitions from dedicated to non-dedicated lanes and transitions from automated to semi-automated or manual control.
- The system will have to deal with long-term effects on driver behavior as a result of partially- or semi-automated vehicle control. Given that CACC systems would still require driver control of the steering wheel, it is anticipated that such systems will not have such serious negative driver behavior consequences.
- The system will have to deal with different vehicle-specific limitations. For example, suppose a low-powered vehicle is the third vehicle in a platoon of ten equipped vehicles. The vehicle behind it is a high powered vehicle and is capable of accelerating at a much higher rate than the low powered vehicle. How and what recommendation should the system recommend for the high powered vehicle? How can the system deal with different vehicle capabilities? How should the system consider the vehicle capabilities in making speed recommendations? Platoon management concepts might consider building on the capabilities of the vehicles in the platoon and adjusting the behavior to accommodate the lowest power vehicle in the platoon. Consumer acceptance is a major research question that needs to be addressed with regards to such issues. The successful deployment of these systems requires that the users recognize the benefits of these systems.
- The system should also deal with heavy-duty trucks and buses in the traffic stream.

The potential institutional constraints include:

- How can the system be introduced and transitioned into full system implementation. From an institutional stand-point should transportation agencies dedicate lanes for semi-autonomous CACC systems and if so should automobile manufacturers first develop these systems?
- What are the litigation issues that have to be dealt with in the event of an accident involving CACC systems?
- Should the system be introduced gradually by first introducing driver assist and collision avoidance systems before going into semi-autonomous CACC systems?
- Should CACC systems be introduced with SPD-HARM systems or should they be introduced independently initially?

The potential data-related constraints include:

- What are the data storage issues that have to be dealt with when these systems are widely implemented in the field?
- How should the system deal with inconsistencies discrepancies across different data sources?
- How should the system deal with and identify errors in the various data sources?

8.3.4 Alternatives and Trade-Offs Considered

The proposed CACC systems entail the use of longitudinal vehicle control to control the motion of the vehicle while it travels in a specific lane. A number of alternative systems could be considered, as follows:

Integration of steering and throttle control through the use of semi-autonomous 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. The bundling of lateral and longitudinal functions can result in a reduction in driver vigilance and attention, which may have significant safety implications.

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. This system has the advantage of the current configuration in that it ensures the platoon moves in an optimum fashion.

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). In addition, these systems may also include roadway sensors that are capable of supporting driver assistance systems by providing independent data to vehicles and roadside management systems. Although roadway sensors are expensive and not feasible for full deployment, the potential of these sensors for relatively limited applications such as managed lanes is promising.

Automated intersection movement control
Finally, CACC systems can be used to control vehicle movements at intersections without the use of traffic control devices. Instead, vehicles may submit a request to travel through the intersection, the traffic controller then computes the optimum vehicle movements to minimize some objective function (e.g., vehicle delay). Researchers at the Center for Sustainable Mobility (Zohdy and Rakha, 2012) are developing such systems and they have been demonstrated to produce significant benefits (fivefold reduction in delay) over traffic signal control for volume-to-capacity rations of up to 80%. These systems produce delays comparable to roundabout intersection control.

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. Current List of Project Stakeholders

Khaled Abdelghany (Southern Methodist University)

Sheila Andrews (American Motorcyclist Association)

Juan Aparicio (Siemens)

Morgan Balogh (Washington State DOT (WSDOT))

John Benda (Illinois Tollway)

Roger Berg (DENSO)

Glenn Blackwelder (Utah DOT)

Bob Burrows (G4 Apps Inc.)

Darryl Dawson (Illinois Tollway)

Rick Dye (Maryland DOT)

Paul Eichbrecht (VIIC)

Henry Guerriero (Illinois Tollway)

Mohammed Hadi (Florida International University)

Ali Haghani (University of Maryland)

Larry Head (University of Arizona)

Bernard Istasse (ESIS)

Tom Jacobs (University of Maryland)

Howard Jennings, Jr. (Arlington Transportation Partners)

Bob Koeberlein (Idaho Transportation Department)

Peter Koonce (City of Portland)

Walter Kosiak (Delphi Electronics and Safety Systems)

Thomas Kurihara (TKstds Management)

Eil Kwon (University of Minnesota, Duluth)

Ken Laberteaux (Toyota Research Institute-North America)

Melissa Lance (Virginia Department of Transportation)

Greg Larson (Caltrans)

Bill Legg (Washington State DOT (WSDOT))

Alvin Marquess (Maryland DOT)

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Jim Misener (Booz Allen Hamilton)

Dennis Mitchell (Oregon Department of Transportation (ODOT))

Dan Murray (ATRI)

Bryan Myers (Skyline)

Steve Novosad (Atkins Global)

Hilary Owen (Michigan Department of Transportation)

Michael Pack (University of Maryland)

Jennifer Portanova (NCDOT)

Kala Quintana (Northern Virginia Transportation Authority)

Frank Quon (LACMTA (Los Angeles Metro))

Bob Rausch (TransCore)

Steven Shladover (University of California PATH Program)

Brian Smith (University of Virginia)

Albert Sole (Colegio San Gabriel)

Candice Sutton (Virginia Department of Transportation)

Peter Thompson (SANDAG)

Stephan Travia (IDOT)

Ardalan Vahidi (Clemson University)

Harry Voccola (NAVTEQ)

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David Zavattero (Chicago Department of Transportation (CDOT))

Xuesong Zhou (University of Utah)

APPENDIX B. List of Acronyms

The following is a list of the acronyms described in this document:

AAC	Acceleration Advice Controller
AACC	Autonomous Adaptive Cruise Control
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
ADA	Advanced Driver Assistance
ADOT	Arizona Department of Transportation
ATIS	Advanced Traveler Information System
ATM	Active Traffic Management
ATMS	Advanced Traffic Management System
CACC	Cooperative Adaptive Cruise Control application
CCC	Conventional Cruise Control
CCTV	Closed-Circuit Television
ConOps	Concept of Operations
DMA	Dynamic Mobility Application
DMS	Dynamic Message Sign
DSRC	Dedicated Short-Range Communications
ESC	Electronic Stability Control
FDOT	Florida Department of Transportation
FOT	Field Operational Test
HCM	U.S. Highway Capacity Manual
IDM	Intelligent Driver Model
INFLO	Intelligent Network Flow Optimization
ITS	Intelligent Transportation System
LED	Light-Emitting Diode
MIDAS	Motorway Incident Detection and Automatic Signaling (United Kingdom)
MoDOT	Missouri Department of Transportation
NDOT	Nevada Department of Transportation
NHTSA	National Highway Traffic Safety Administration
NJTA	New Jersey Turnpike Authority
NTCC	National Traffic Control Center (Netherlands)

OFDM	Orthogonal Frequency-Division Multiplexing
Q-WARN	Queue Warning application
RWIS	Roadway Weather Information System
SPD-HARM	Speed Harmonization application
SRTRI	Swedish Road and Transport Research Institute
TMC	Traffic Management Center
TxDOT	Texas Department of Transportation
UMTRI	University of Michigan Transportation Research Institute
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure/Infrastructure-to-Vehicle
V2V	Vehicle-to-Vehicle
VC	Vehicular Communications
VDOT	Virginia Department of Transportation
VMS	Variable Message Sign
VMT	Vehicle Miles Traveled
VSL	Variable Speed Limit
VSS	Variable Speed Sign
VTTI	Virginia Tech Transportation Institute
WSDOT	Washington State Department of Transportation

APPENDIX C. 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, as their name states, a propagating wave. Shockwaves are one of the major safety concerns for transportation agencies because the sudden change of conditions drivers experience as they pass through a shockwave often can cause accidents.
Shockwaves can be seen by the cascading of brake lights upstream along a highway. They are often 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 passing the bottleneck will of course be reduced, but the drop in speed will cascade upstream as following vehicles also have to decelerate. (http://en.wikibooks.org/wiki/Fundamentals_of_Transportation/Shockwaves)

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.

Shockwave Propagation Speed: Measured as the traveling speed of local minima of consecutive vehicle speed trajectories. Most shockwaves have similar upstream propagation speeds, experimentally measured at about 12 mph (or 20 kph). These backwards propagation speeds tend to be independent of the traffic flow speed prior to congestion. (http://gateway.path.berkeley.edu/~xylu/paper/shockwave_TRB.pdf)

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