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

Assessment of Relevant Prior and Ongoing Research

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16. Abstract

Through the USDOT Dynamic Mobility Applications (DMA) program, a number of high-priority mobility applications have been assessed and identified that can connect vehicles, travelers, and infrastructure in order to provide better information to travelers and increase individual mobility. This document concerns one such bundle of DMA applications, called Intelligent Network Flow Optimization (INFLO). This bundle encompasses three applications: 1) Queue Warning (Q-WARN), 2) Speed Harmonization (SPD-HARM), and 3) Cooperative Adaptive Cruise Control (CACC). This document is an initial deliverable that will assist with the concept development and needs identification for INFLO. It is called the *Assessment of Relevant Prior and Ongoing Research for INFLO* and its purpose is to provide a clear understanding of relevant research in the area of Intelligent Network Flow Optimization (INFLO) that might impact the development and eventual deployment of an INFLO system.

Relevant research identified in this Assessment will form the basis for the current state definition within the Concept of Operations (ConOps).

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1 Purpose of the Document

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1.2 Document Overview

This document is organized as follows:

- The background against which the study is being performed;
- A definition and vision for the INFLO applications;
- A scan of the existing practice;
- A scan of relevant prior and ongoing research; and
- The proposed concept and associated impacts and challenges.

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Chapter 2. Background

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. See Figure 2-1 below. 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 had 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.

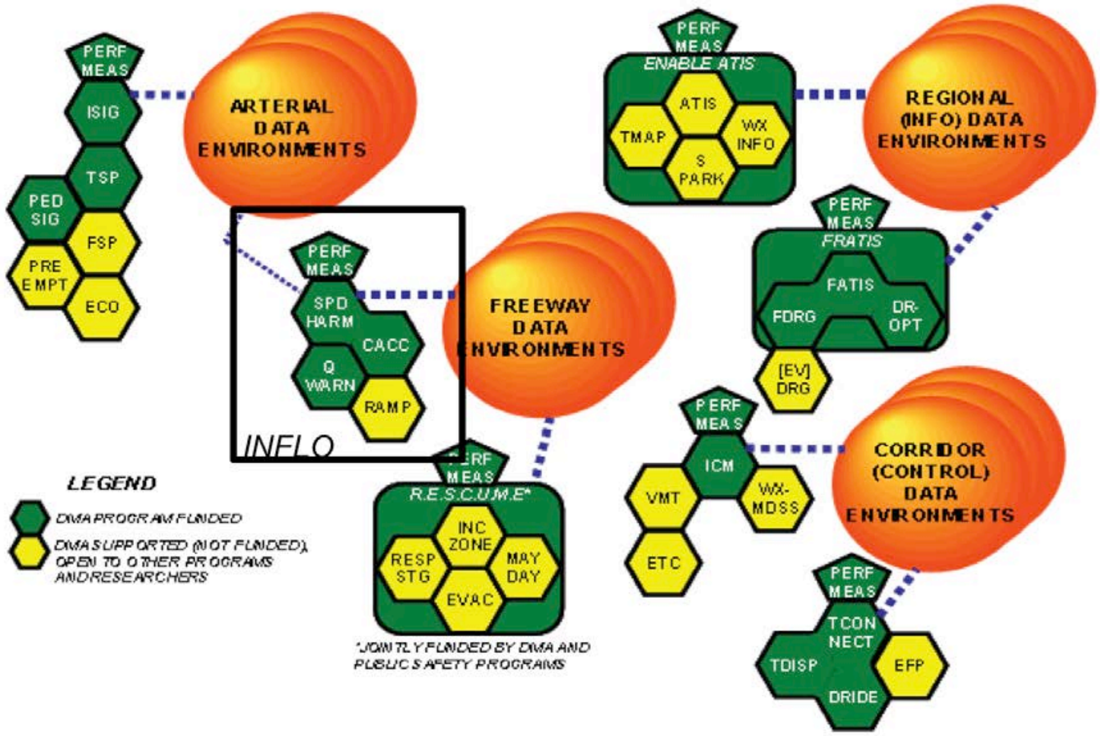

Figure 2-1. USDOT Dynamic Mobility Application Bundles. (RITA, ITS Joint Program Office, March 2012)

The purpose of the INFLO project is to facilitate concept development and needs refinement for the INFLO applications and assess readiness for development and testing. The research identified in this Assessment will form the basis for the current state definition of the concept development.

The sections below reflect the results of the literature review that was initiated of current and historical studies, programs, and field tests that have a direct or indirect link to the three INFLO applications.

2.1 INFLO Applications Overview

2.1.1 Q-WARN Definition and Overview

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

- Daily recurring congestion caused by bottlenecks
- Work zones, which typically cause bottlenecks
- Incidents, which, depending on traffic flow, lead to bottlenecks
- Weather conditions, including icing, low visibility, sun angles, and high wind

- Exit ramp spillovers onto freeways due to surface street traffic conditions

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

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

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

The INFLO Q-WARN application aims to accomplish these tasks by utilizing Connected Vehicle technologies, including vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications, whereby the vehicles within the queue event broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to nearby upstream vehicles in order to minimize or prevent rear-end or other secondary collisions. Figure 2-2 below provides a stylized depiction of how the Q-WARN concept could work.

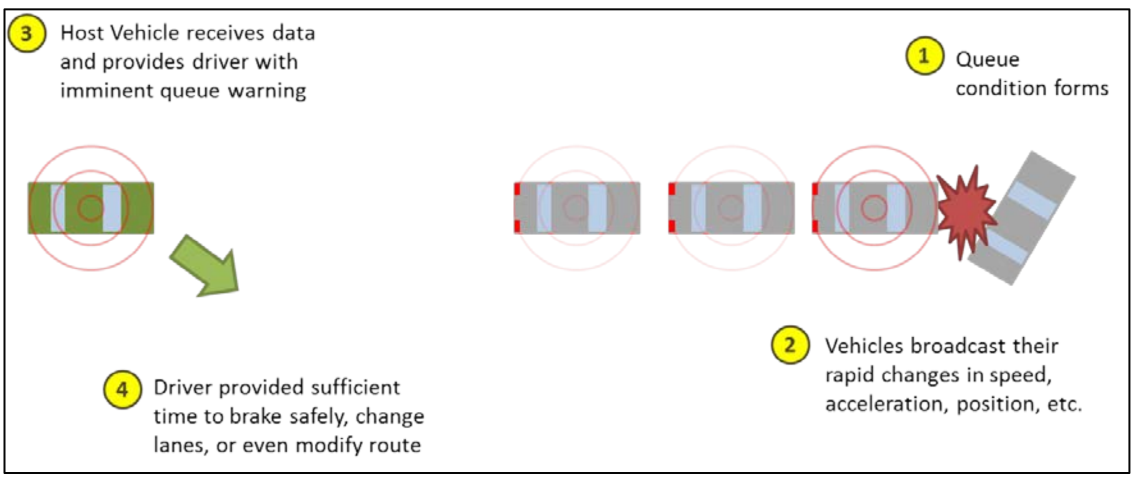

Figure 2-2: Stylized Depiction of a Connected Vehicle-Enabled Q-WARN Application (RITA, ITS Joint Program Office, March 2012)

It is important to note that in the near term, in which Connected Vehicle fleet penetration rates will be limited, it is anticipated that traditional infrastructure-based detection and alerts (including loop detectors and dynamic message signs) will continue to play a major role in providing queue warning to motorists.

2.1.2 SPD-HARM Definition and Overview

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

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

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

The INFLO SPD-HARM application aims to accomplish these tasks by utilizing Connected Vehicle V2V and V2I communication to detect the precipitating roadway or congestion conditions that might necessitate speed harmonization, to generate the appropriate response plans and speed recommendation strategies for upstream traffic, and to broadcast such recommendations to the affected vehicles. Figure 2-3 below provides a stylized depiction of how the SPD-HARM concept could work.

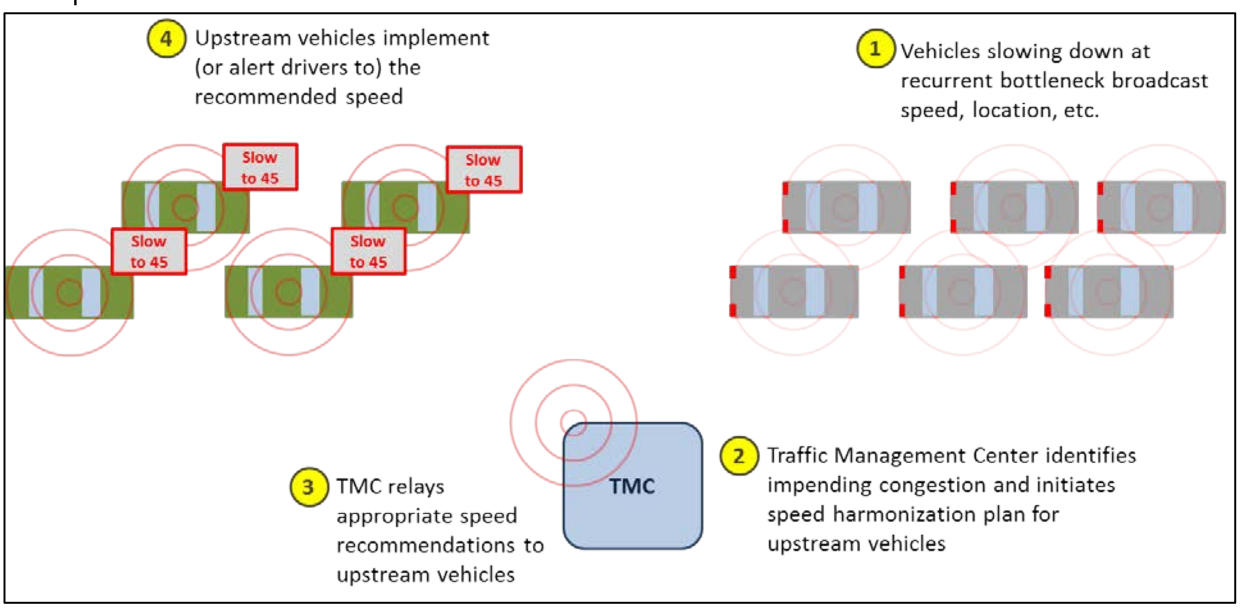

Figure 2-3. Stylized Depiction of a Connected Vehicle-Enabled SPD-HARM Application. (RITA ITS Joint Program Office, March 2012)

As it is currently implemented, speed harmonization is considered a component of Active Traffic Management (ATM), which is defined as a process of managing and controlling traffic flow to maximize safety and throughput on transportation infrastructures based on the prevailing traffic conditions. Speed harmonization (sometimes referred to as variable speed limit control) has been used in Germany and Netherlands starting in the 1970's, and more widely starting in the

2000's in the United States, Europe, and Australia (FHWA *ATM Synthesis*, 2010). Typical deployments utilize prevailing traffic detection, road surface conditions, and weather condition information together with forecast information to determine the maximum appropriate speed at which drivers should be travelling (Austroads, 2009).

Review of current and past deployments indicates that a successful and efficient implementation of speed harmonization depends highly on the intensity of ITS sensor coverage, selection of efficient enforcement strategies, and implementation of appropriate and effective control strategies for speed limit selection (FHWA *Speed Harmonization and Shoulder Use*, 2009). Real-world examples have demonstrated that the manner in which dynamic speed limits are introduced also affects the outcome of the control strategy. In general, there are two approaches for introducing the selected speed limit to the drivers:

1) **Mandatory (regulatory) speed limit**. By setting the selected speed from the control strategy as the speed limit, the drivers have to follow this speed limit change and they are controlled by the enforcement strategy, which is mostly automated speed enforcement.
2) **Advisory speed limit.** The implementation of mandatory speed limit places considerable liability on the responsible agency for potential rear end crashes, though the evidence remains inconclusive with regard to the impact of speed harmonization (Metz et al., 1997). The liability issue led the agencies to the idea of implementing the speed limit as advisory rather than mandatory. In this case, if an accident occurs due to violating the advisory speed limit, the liability would be on the driver himself.

While the main goal of speed harmonization is to decrease the speed differential among drivers and adjacent lanes to achieve a smooth and safe driving condition, variable speed limits have also be used to create a safer work situation in the presence of active work zones by encouraging lowered speed for approaching traffic. The following SPD-HARM sections will discuss past and current speed harmonization deployments and relevant research into the potential for Connected Vehicle-enabled dynamic speed harmonization implementations.

2.1.3 CACC Definition and Overview

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

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

ACC by utilizing V2V communication to automatically synchronize the movements of *many* vehicles within a platoon.

Figure 2-4 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.

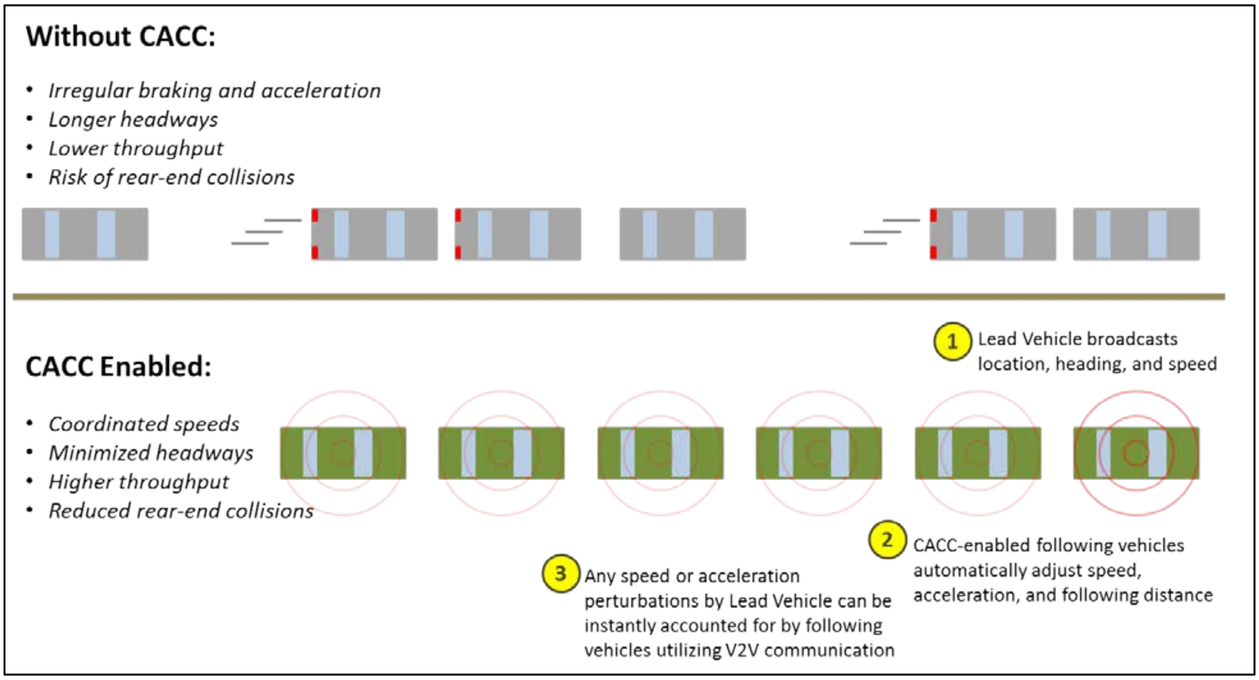

Figure 2-4. Stylized Depiction of Connected Vehicle-Enabled CACC. (RITA, ITS Joint Program Office, March 2012)

Chapter 3. Scan of Current Practice

This section details the state of the current practice for queue warning, speed harmonization, and cooperative adaptive cruise control, noting prominent systems throughout the world and some emerging trends and developments.

3.1 Q-WARN Initiatives and Deployed Systems

The 2003 (updated 2007) Texas Transportation Institute report by Wiles et al. includes a detailed review of current United States and International initiatives being used for queue warning systems. These initiatives are summarized below. *Note that the term Variable Message Sign (VMS) is used throughout this deployed systems overview and for the purposes of this overview should be considered synonymous with Dynamic Message Sign (DMS).*

3.1.1 International

Country	Queuing Condition	Technology
Australia	Exit ramp spillback	Loops, Variable speed signs (VSS) and variable message signs (VMS)
Belgium	Construction zone queues	Video detection, VMS panels, Trailer-mounted VMS
Canada	US border crossing near Niagara Border queues	Static signs with flashers
Finland	Fog – visibility and recurrent congestion	Loops, VSS, VMS
Japan	Recurrent congestion and Incident congestion	Ultrasonic detectors, VMS
New Zealand	Recurrent congestion	Static Signs
Norway	Special queue warning	VMS with flashers
Turkey	Recurrent congestion, Incident congestion and, Construction zone queues	Doppler radar, VSS, VMS
United Kingdom	Secondary collisions	Loops, VSS, VMS

3.1.2 United States

State	Queuing Condition	Technology
Alabama	Fog – visibility	Forward-scatter visibility sensors, CCTV, VSS, VMS
California	Temecula -Exit ramp spillback	Static sign with pre-timed

State	Queuing Condition	Technology
		flashers for PM peak period
California	Highway 17 - Secondary collisions (near mountain pass)	Loops, Fog detectors, VMS
Florida	Construction zone queues	Video detection, Radar, Trailer-mounted VMS
Georgia	South Georgia Fog	VMS with preprogrammed messages
Illinois	Construction zone queues	Radar, Trailer-mounted VMS
Illinois	Tollway - Exit ramp spillback	Loops, Microwave detectors, Static signs with flashers
Indiana	Exit ramp spillback	Loops, Static signs with flashers
Minnesota	Recurrent congestion (at freeway lane drop), Rear-end collisions	Optical detectors, Static sign with flashers and a VMS
Missouri	Recurrent congestion, Rear-end collisions, Unfamiliar drivers	Static sign with flashers activated by time of day
New Jersey	Turnpike – Weather	VSS manually operated
North Carolina	Construction queues, Recurrent congestion, Rear-end collisions	Static signs with flashers
Pennsylvania	Construction zone queues, Sight distance limitations, Rear-end collisions	Infrared beams, Series of VMSs
South Carolina	Low Visibility warning	Forward-scatter visibility sensors, CCTV, VMS
Texas	San Antonio - Recurrent congestion, Rear-end collisions	Loops, VMSs
Texas	Fort Worth - Exit ramp spillback, Recurrent congestion, rear end collisions	Video detection by TMC staff using cameras, Static Signs with flashers
Texas	Irving - Recurrent congestion, Sight distance limitations, Rear-end collisions	Series of Static signs
Utah	Fog – visibility	Visibility sensors, portable VMS
Virginia	Spillback at truck weigh stations	Loops, Electronic signs that tell truckers if the station is open
Washington	Exit ramp spillback signed to tell truckers to use another ramp to approach the Port	Video detection, Static sign with flashers
West Virginia	Fog – visibility	Loops, Sign that warns motorists to slow down and use caution

3.1.3 Recent Systems

Recently, the Illinois State Toll Highway Authority implemented two new sub-systems: an adaptive queue warning system and a smart work zone system. The queue warning system uses sensors to detect both spillbacks from exit ramps and from downstream mainline locations.

Based on a queue detection algorithm, flashers mounted on static signs are turned or off depending on conditions. The basic architecture is shown below in Figure 3-1. The system verifies operation of all detection equipment and adjusts strategies in real time. All actions are controlled by a set of tunable thresholds shown below in Table 3-1.

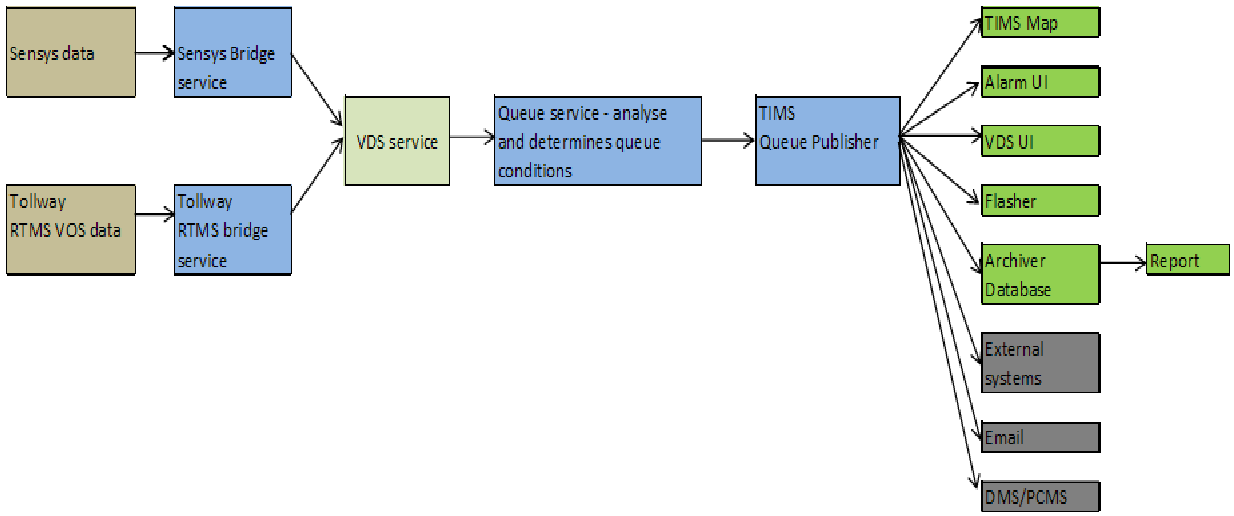

Figure 3-1. Illinois State Toll Highway Queue Warning Basic Architecture (Illinois State Toll Highway Authority *Traffic and Incident Management System Queue Modernization Design Report*, April 2011.)

Table 3-1. Illinois State Toll Highway Queue Warning Tunable Thresholds.

Variable	Description
SpeedOnThresh	When the current speed is less than or equal to this value a possible queue is present
SpeedOffThresh	When the current speed is greater than or equal to this value a possible queue has dissipated (must be > SpeedOnThresh)
OccOnThresh	When the current occupancy is greater than or equal to this value a possible queue is present
OccOffThresh	When the current occupancy is less than or equal to this value a possible queue has dissipated (Must be < OccOnThresh)
OnPersist	When there is no Queue present this represents the number of seconds of possible queue detection required to declare a queue (must be in multiples of ScanRate)
OffPersist	When a Queue is present this represents the number of polls of possible non-queue detection required to declare the queue has cleared (must be in multiples of ScanRate)
QueueDisable	This is a user control to disable the queue detector
FlasherDisable	This is a user control to disable the flasher

Variable	Description
Manual Mode	When the user puts the flasher on manually this flag is set
ManualTimer	When the user puts the flasher on manually this represent s the number of minutes before automatically turning the flasher off

The Smart Work Zone (SWZ) system is intended to automatically manage information to motorists heading into a long-term construction site that experience queuing. The system uses traffic detectors within and upstream of the work zone and portable and fixed VMSs to provide information including backups from the work zone.

The Oregon Department of Transportation is planning a queue warning system to improve safety at targeted highway locations. The central software system infrastructure will host independent “instance modules” for each project, such as the Advanced Traffic Management (ATM) Variable Speed System for the I-405/I-5 merge. The instance module will implement customized business rules, which typically involve reading loop detector values, traffic sensor values, performing business rule calculations, and possibly setting dynamic sign messages which include variable speed limit signs.

3.2 SPD-HARM Initiatives and Deployed Systems

Early forms of speed harmonization as practiced today were first started in the 1970’s in Germany and the Netherlands (FHWA *ATM Synthesis*, 2010). In recent years, more traffic agencies in different countries have initiated congestion management programs and implemented variable speed limits as a strategy to achieve this goal. However, the underlying reason for implementing this technology varies among agencies. Although they mostly focus on congestion relief and safety, the following objectives can be identified in different implementations (Austroads, 2009):

Speed management and safety. There is evidence that excessive speed is a major factor affecting the frequency and severity of road crashes. Based on the National Highway Traffic Safety Administration (NHTSA), speeding was the main result of 30 percent of all fatal injuries in 2003 (NHTSA, 2005). Among the several speed management strategies, speed harmonization is of particular interest. Adjusting speed limit to match the prevailing traffic conditions to environmental conditions followed by effective automated speed enforcement techniques would diminish the excessive speed for the prevailing condition as well as speed discrepancy among drivers and enhance the safety.

Delaying breakdown formation and increasing throughput. In situations of high traffic volume and demand, small perturbations in traffic stream can be propagated and affect many motorists on the highway, especially when the speed difference between the adjacent lanes is conspicuous. In this situation, lane changing from the fast or slow lane to the other would cause a shockwave which propagates backward in the traffic stream and reduces the throughput of the system, increase the risk of accident and create a stressful driving condition.

As the density along the highway increases, the effect of these small perturbations magnifies and at some point, results in flow breakdown. As can be seen in Figure 3-2, once critical density is reached, resulting flow begins to decrease due to breakdown formation occurring. Speed harmonization results in more uniform distribution of speed along the highway, which leads to better utilization of the available capacity on the highway. By keeping density below a certain critical value and reducing the number of shockwave occurrences, speed harmonization is capable of delaying breakdown formation and keeping the throughput at its maximum sustainable level. This method is even capable of increasing the maximum flow by shifting the critical density to a higher value (Papageorgiou et al., 2008).

Speed control under inclement weather conditions. Under adverse weather conditions where the posted speed limits may be unsafe for the drivers, a variable speed limit system is capable of reducing the speed limit to its safe value.

Incident management. A variable speed limit system is utilized for incident management by reducing traffic speeds upstream of the incident in order to minimize sudden and unexpected decelerations which often result in secondary collisions. Such speed harmonization programs are made even more effective when used in combination with lane control management strategies.

Tunnel and bridge safety. The variable speed limit is used to manage the safe speed limit in long tunnels as well as on long bridges. In this case, the lane control signal systems are also combined with variable speed limit to ensure the higher safety standards.

Flow and safety control along work zones. The purpose of installing variable speed limit in work zones is to manage and enforce the speed as well as increase the throughput. The increase in compliance with posted speed limit is also considered as a goal in these implementations. Note that the use of supporting strategies and technologies is essential to improve the effectiveness of speed harmonization on congestion management and safety (e.g., lane control signals and temporary shoulder use).

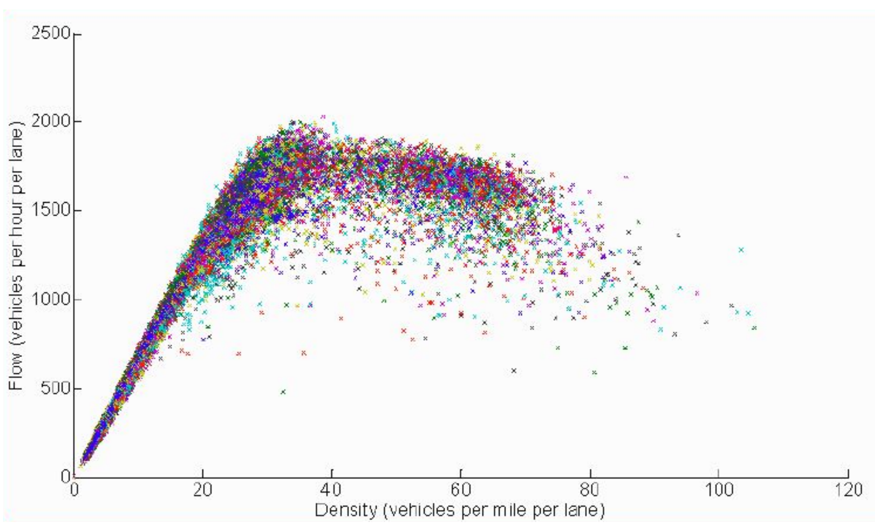

Figure 3-2. Fundamental diagram and Breakdown formation at critical density. Data is accumulated for 92 days and belongs to I-880 southbound (Dervisoglu et al., 2009)

The following sections discuss significant international and national speed harmonization implementations, with a focus on technologies, system performance, and key benefits and issues that arose.

3.2.1 Greece

After joining the European Union (EU), Greece experienced significant economic growth, which led to increased levels of congestion on all major roadways. Exasperating the increased road demand was the fact that most of the road infrastructure comprised two-lane undivided highways, which were unable to accommodate the increased levels of traffic. In response, in the mid 2000's, Greece identified the major corridors critical for passenger and commodity movement that would most benefit from enhanced mobility improvements. The Attiki Odos Toll Motorway (see Figure 3-3), a key link to the city of Athens, was one such corridor where variable speed limits for tunnel entrances were introduced (FHWA *ATM Scan*, 2007). The purpose of these variable speed signs is to notify drivers when the advisory speed limit inside the tunnel is different from the other parts of the motorway. Signing would also alert drivers if one lane in the tunnel was closed (due to an incident or maintenance). Figure 3-4 depicts the variable speed limit signings along this motorway.

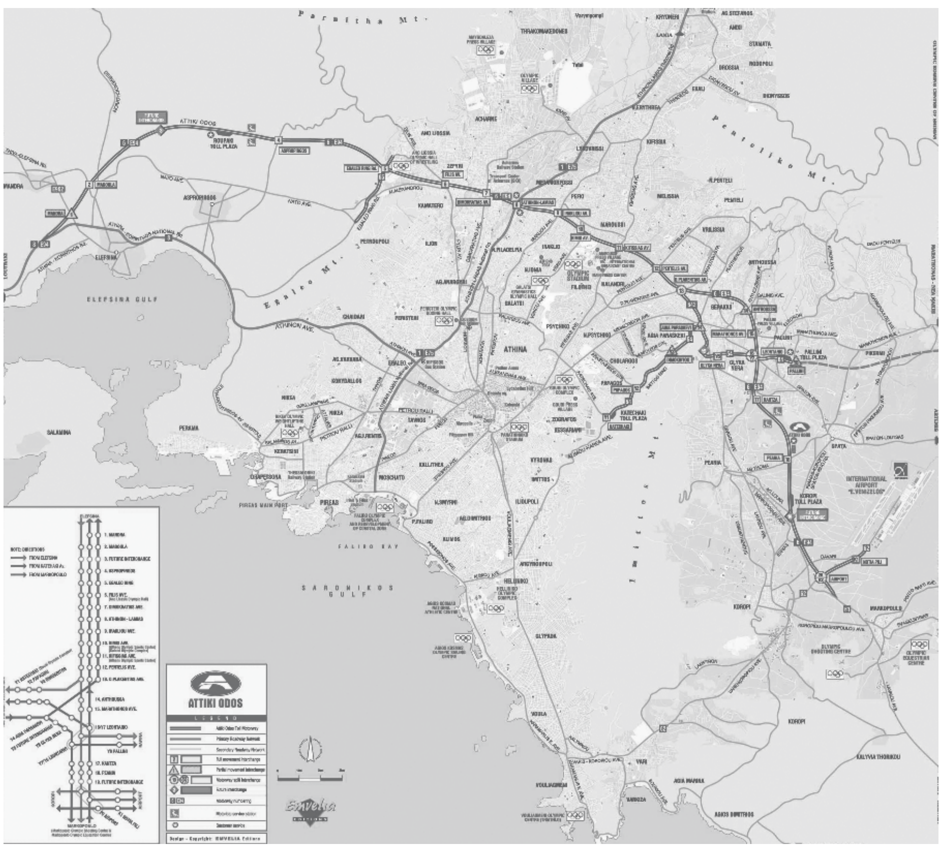

Figure 3-3. Attiki Odos Toll Motorway in Athens, Greece (FHWA ATM Scan, 2007).

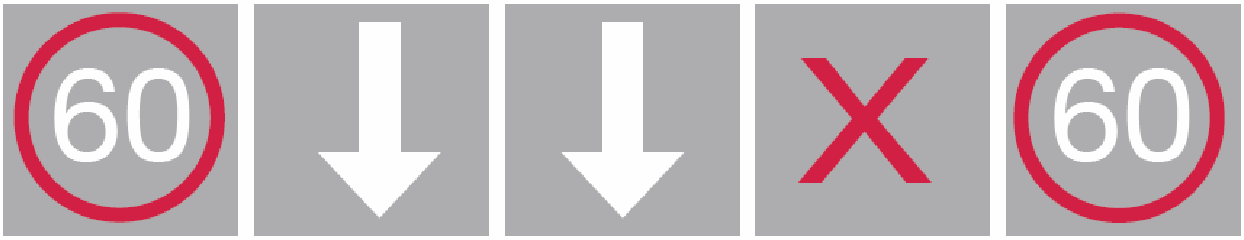

Figure 3-4. Attiki Odos Toll Motorway Variable Speed Limit Signs in the Tunnel Entrance (FHWA *ATM Scan*, 2007).

To operate the tollway as well as perform incident management functions, a traffic management center (TMC) is operated 24 hours a day, seven days a week, to monitor the traffic operation along the motorway. The traffic data are collected by means of inductive loop detectors. The collected data are then transmitted to the TMC to inform them of the prevailing traffic conditions. The authorities also operate closed-circuit television (CCTV) surveillance, emergency roadside phones, and patrol units to quickly respond to incidents.

The primary purpose of the Attiki Odos variable speed limit implementation is to provide advice to motorists approaching the tunnel regarding the safe speed limit inside the tunnel. Though the speed limits are advisory and not enforced, an analysis of accidents in the corridor revealed a significant reduction in injury accidents and significant improvement in the accident detection and recovery rate.

Caltrans' PeMS performance measurement system was deployed for this motorway in order to help determine advisory speed limits. It relies on information from loop detectors, incident reports, and toll data to analyze different performance measures and set appropriate speed limits (Harito, 2011).

3.2.2 Germany

Currently, the Federal Motorway Network in Germany comprises 12,000 km of roadway, extends across 10 states, and carries an average about 49,000 vehicles per day (averaged across the entire network). Vehicle volume is expected to increase by 16% for passenger vehicles and by 58% for freight traffic by 2015 (FHWA *ATM Scan*, 2007). Such travel demand growth has motivated German authorities to implement intense ITS-based congestion management programs, which have a long history in the country. In 1972, Germany introduced one of the very first speed harmonization programs, which utilized automatic traffic and weather detection as inputs to the congestion management system (Austroads, 2009). This program had the twin goals of improving traffic safety and improving traffic flow. Today, about 200 km of congested roadways are currently managed through speed harmonization combined with temporary shoulder use and to address the capacity bottlenecks on the German Autobahns (FHWA *Efficient Use of Highway Capacity*, 2010). Traffic Control Centers monitor disturbances in traffic flow and weather conditions in order to modify speed limits to respond to the prevailing or upcoming situation appropriately. Figure 3-5 shows Traffic Center Hessen, which is responsible for speed harmonization and other congestion management strategies on Rhine-Main area. Figure 3-6 shows a three-lane Autobahn control gantry combined with temporary shoulder use.

Figure 3-5. Speed Harmonization at Traffic Center Hessen, Germany (FHWA *ATM Scan*, 2007)

Figure 3-6. Speed Harmonization Combined with Right Shoulder Use, Germany (Pilz, 2006)

In the early 1990s on the 50 km of the A4 Autobahn from Cologne to Aachen, 32 sets of variable speed limit signs were installed (16 in each direction) and on 45 km section of Autobahn from Ulm to Stuttgart, 43 sets of variable speed limit signs were installed (Austroads, 2009). Other speed harmonization deployment locations include A8 between Salzburg and Munich, A3 between Sieburg and Cologne, A5 near Karlsruhe, and A9/A92/A99 between Munich and Nord (Robinson, 2000).

In the typical installation, traffic flow condition information (including speed, density, and flow) is gathered from loop detectors on each lane and weather information is collected from fog detectors installed along the routes (FHWA *ATM Scan*, 2007). The microscopic traffic simulation model, VISSIM, is used to model the impact of operational decisions on the network. VISSIM interfaces with the speed harmonization system to provide different speed limit threshold recommendations for the target facility. Currently, only three speed limit options are available: 100, 80, or 60 km/hr. In addition to speed limit indications, signing also provides information about hazardous conditions ahead.

Although nearly all variable speed limits are advisory and not enforced (as parts of the Autobahns have unlimited speed limits), analysis of before and after crash data has shown a 20-30% reduction in crash rates (Robinson, 2000). A benefits-cost analysis concluded that the cost savings realized from the reduction of accidents in just the first three years of the system covered the entire cost of implementing the system Note that in corridors where speed limits were enforced, enforcement was typically done utilizing video detection.

Boice, et al. (2006) analyzed the effects of variable speed limit and hard shoulder usage on key highway capacity parameters on A9 German Autobahn between Munich and Nürnberg. More precisely, they analyzed the effect of VSL and hard shoulder usage on dynamic features of bottleneck such as capacity, mechanism of activation and mechanics of queue formation and propagation. They analyzed the one-minute average speed, flow, and density from the loop detector data before and after the implementation of the system. Their results showed that the pre-queue and queue discharge flows of three-lane segment is 21% and 25% higher than two-lane segment, respectively. They also provided a comparison between measured maximum flow and the estimated capacity by the U.S. Highway Capacity Manual (HCM) and the German Handbuch für die Bemessung von Strassenverkehrsanlagen (HBS).

In terms of congestion management, Germany's speed harmonization systems were generally found to be very adaptive to the prevailing traffic conditions and sensitive to downstream speed. However, despite a high degree of coordination among message signs, significant shockwaves along corridors are still prevalent.

3.2.3 Netherlands

Congestion management in the Netherlands is operated by National Traffic Control Center (NTCC) with the support of five regional control centers (FHWA *ATM Scan*, 2007). As one of the early European pioneers of implementing speed harmonization, the Netherlands has since developed an extensive deployment of speed harmonization systems around the country. Not all systems were developed for the same objectives, however. Some speed harmonization implementations seek to promote safer driving condition in adverse weather conditions (e.g., Urban A16 near Breda), while others seek to promote the dual objectives of improved (i.e., more uniform) traffic flow and increased safety (e.g., Rural A2 between Amsterdam and Utrecht). Figure 3-7 below shows a typical Netherlands variable speed limit sign.

When the system goal is to provide safe driving condition in adverse weather (as in Urban A16 near Breda), visibility sensors are deployed. In the case of A16, 20 visibility sensors over a 12km segment (approximately every 700-800m) as well as automatic incident detection were installed. In normal weather conditions the posted speed limit is 100 km/h, but as visibility drops the posted speed limit is reduced, based on analysis of visibility information. If visibility distance drops below 140m the speed limit is reduced 80 km/h and if visibility drops below 70m the speed limit drops to

60 km/h. If an incident is detected, the speed limit for upstream traffic is reduced to 50 km/h (Robinson, 2000).

Figure 3-7. Speed Harmonization Signs, Netherlands (FHWA ATM Scan, 2007).

However, for systems in which the goal is to increase traffic flow uniformity and reduce shockwave potential (as is the case for Rural A2 between Amsterdam and Utrecht), a denser implementation of sensors and congestion management strategies are employed. Early speed harmonization efforts to achieve this goal took place in the 1980s and involved a relatively simple algorithm: if there was any active maintenance on the road, the advisory speed limit was set to 70 km/h. If the one-min speed average dropped to 35 km/h, the advisory speed limit was set to 50 km/h (Austroads, 2009). Note that the displayed speed limits were not mandatory.

The second wave of implementing the speed harmonization in Netherlands started in 1992, with more than 150km of highways equipped with such systems. Algorithms became more complex and speed limits were now mandatory and enforced (FHWA *Speed Harmonization and Shoulder Use*, 2009). One major example was A2 where a control strategy was developed with the goal of inducing more homogenous speed and flow as well as more uniform lane usage (Robinson, 2000). Speed and flow data were collected by means of dual loop detectors every 500m over a 20km segment and an automatic incident detection system was implemented. The control strategy for traffic flow homogenization involved reducing the posted speed limit from 120 km/h during normal conditions to a range between 70-90 km/h depending on the specific congestion conditions. In the case of incidents, the posted speed limit could be reduced to as low as 50 km/h. The decision on the posted speed limit is made every minute based on the recent one-minute speed and volume averages and is based on the goal of keeping the posted and actual average speeds within a an acceptable range of each other. Automated enforcement of the posted speed limits is conducted via photo radar.

A before and after analysis as well as a survey of 1300 drivers were conducted to measure the effectiveness of the A2 speed harmonization program. Highlights from the findings include:

- Speed harmonization combined with automated speed enforcement was very successful at creating homogenous traffic flow. As a result, fewer speed variations and less severe shockwaves developed and headway distances were shortened.

- Despite producing more homogenous traffic flow, no clear increase of system capacity was observed (six months after deployment).
- Driver awareness of automated enforcement devices was strongly correlated with increased compliance.

3.2.4 United Kingdom

Over the past several decades, the United Kingdom has experienced significant increases in vehicle miles traveled and congestion levels. In 2004, the Department of Transport established a long term strategy to modernize and increase the efficiency of the transport system in order to meet the anticipated continued travel demand growth while also meeting emissions-related environmental objectives (FHWA *ATM Scan*, 2007). Since 2000, the strategic focus has been on improving the safety and serviceability of the transportation system. Speed harmonization has been embraced as one of the main tools to help meet the national strategic objectives. This section discusses two key U.K. speed harmonization implementations, on highways M25 and M42.

The speed harmonization project on western quadrant of the M25 was started on 1995 with the goal of managing congestion by smoothing traffic flow, reducing stop-and-go waves, controlling traffic speed, improving the road user's driving experience, and managing fuel consumption (Austroads, 2009). More than 22km of M25 highway was equipped with lane-by-lane variable speed display signs and variable message panels, spaced 1km apart from each other. Figure 3-8 shows the variable speed display signs on M25.

Figure 3-8. Variable Speed Limit Signs and Variable Message Sign, M25, the United Kingdom (United Kingdom Highway Agency, 2007).

Speed and occupancy data are collected by means of dual loop detectors spaced 500m apart and traffic flow is also monitored via a CCTV system housed at a traffic control center. When first implemented in 1995, the speed limit selection logic was very simple: when traffic volume exceeded 1650 veh/hr/ln the variable speed limit was adjusted to 60 mph (the speed limit in normal condition is 70 mph). When traffic volume exceeded 2050 veh/hr/ln the speed limit was reduced to 50 mph. In the case of an incident or queue formation, the posted speed limit was set to between 20 and 40 mph. In February 1997, the highway agency changed the speed limit selection method after receiving complains about the speed limit reduction when there was no sign of congestion on the road (Austroads, 2009). As a result, the displayed speed selection algorithm was modified to consider both volume and speed variables in calculating appropriate speed limits. The same year, the speed harmonization system was advanced further to include high occupancy incident detection and queue warning. The system automatically lowered the speed limit to 40 mph in the event of a detected incident and would provide queue formation warnings to upstream traffic via variable message signs. This advanced system was called Motorway Incident Detection and Automatic Signaling (or MIDAS). Speed limits under this system were mandatory and enforcement occurred via automated photo radar technology.

Analysis of the performance of the MIDAS system on M25 has been conducted since the opening of the segment in 1995 (FHWA *Speed Harmonization and Shoulder Use*, 2009) (United Kingdom Highway Agency, 2007). Highlights from the findings include:

- Since implementation of speed harmonization and other related congestion management systems, throughput was shown to have improved significantly: in the first year of implementation throughput increased by 1.5% and the more uniform flow and headway was recognized.
- While average journey times over the whole day remained relatively unchanged, they actually increased slightly during off-peak hours (presumably due to lower vehicle speeds during free flow conditions).
- While journey times showed little overall change, journey time reliability increased significantly.
- Driver compliance of the posted speed limits was consistently high and surveys of both police and road users revealed high satisfaction rates for the system.
- Injury rates were reduced by about 15% (between 1990 and 2002), attributable to the speed harmonization system.
- Environmental benefits, including reduced fuel consumption and noise levels, were realized.

Another successful implementation of speed harmonization was as part of an Active Traffic Management (ATM) pilot launched in 2001 on highway M42. The goals of the program were to provide enhanced information to drivers, improve journey time reliability, and effectively manage recurrent and non-recurrent congestion (FHWA *ATM Scan*, 2007). Figure 3-9 includes a map of the boundaries of the speed harmonization project and some snapshots of different speed harmonization and hard shoulder signing. The system, completed in 2003, includes lightweight gantries, lane control signals, variable speed limit signs, variable message signs, CCTV, automated enforcement, roadway sensors, enhanced lightening, and hard shoulder running capability.

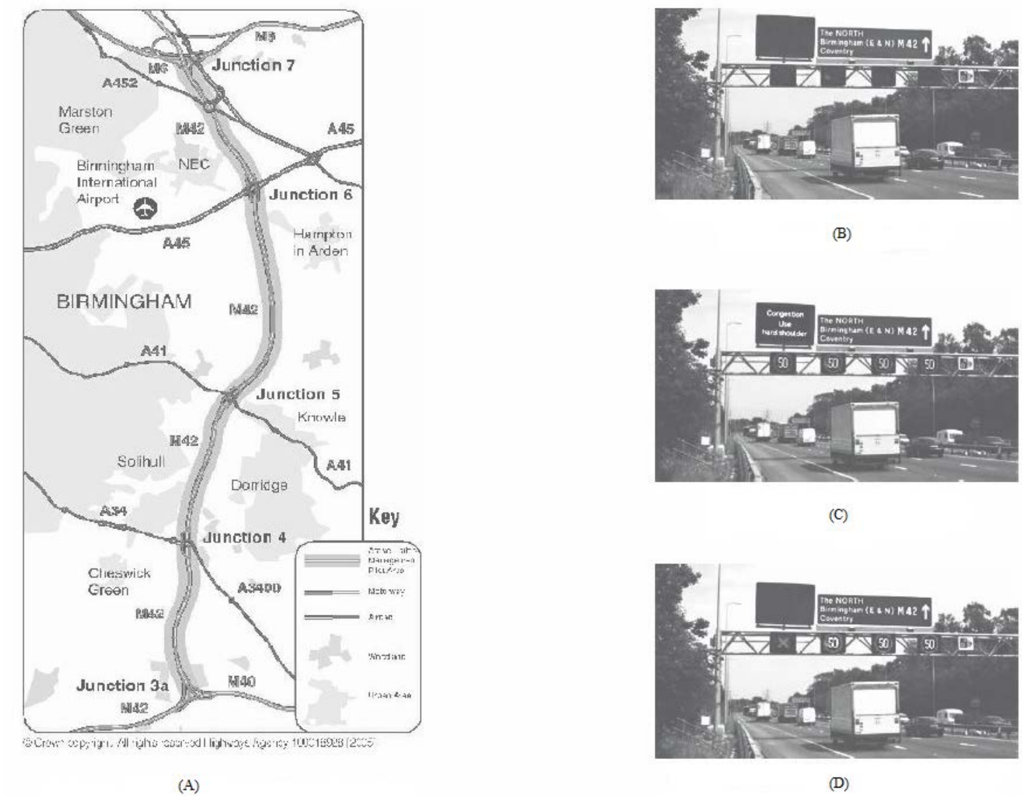

Figure 3-9. Speed Harmonization on M42, the United Kingdom (A) The Project Limits, (B) Normal Usage of the Facility, (c) ATM with Hard Shoulder Usage, and (d) ATM without Hard Shoulder (FHWA ATM Scan, 2007).

As with the M25 implementation, the M42 speed harmonization corridor utilizes the Motorway Incident Detection and Automatic Signaling (MIDAS) active traffic management system to generate posted speed limits by using speed, flow, and occupancy data obtained from road sensors (FHWA *ATM Scan*, 2007). The objective of MIDAS is to use speed limits and shoulder lane access to minimize speed differentials not just within lanes but among lanes in order to reduce actual speeds prior to the onset of breakdown formation.

3.2.5 Finland

In 1990, the Finnish Road Administration began implementing weather control variable message signs and variable speed limits (Rama, 2001). The first test occurred along E18 in southern Finland between Kotka and Hamina where 67 variable speed limit signs and 13 variable message signs were used over a 25 km stretch of roadway (Robinson, 2000). Metrological data, including weather readings and road surface conditions, were collected every five minutes by means of six road weather sensors stationed along the roadway. Speed and headway data were also collected using loop-based detection (FHWA *Speed Harmonization and Shoulder Use*, 2009). A central control unit analyzed the data and selected one of three speed limits (120 km/h, 100 km,h, or 80 km/h) to display, based on driving conditions. Variable message signs were used to display slippery road condition warnings.

Surveys of road users revealed very high satisfaction levels of the system, with 95% of drivers reporting positive ratings of its effectiveness. Compliance rates were high, with 76% of drivers obeying the posted speed advisory limits. A before and after analysis was conducted, which revealed significant safety improvements attributable to the weather speed harmonization implementation: accidents during the winter dropped by 13% and during the summer by 2%. Currently, more than 300 km of the Finnish highways are equipped with weather advisory variable speed limits (Austroads, 2009).

3.2.6 Sweden

The Swedish Road Administration ran a speed harmonization trial from 2003 to 2008 (Nygårdhs, 2011) for the purpose of evaluating speed limit compliance and accessibility improvement. Variable speed limit signs were installed in 19 selected study sites and both advisory and mandatory speed limit strategies were utilized (Austroads, 2009). Figure 3-10 shows the difference between the advisory and mandatory speed limit signs in this study. Speed selection varied between 30 km/h and 120 km/h.

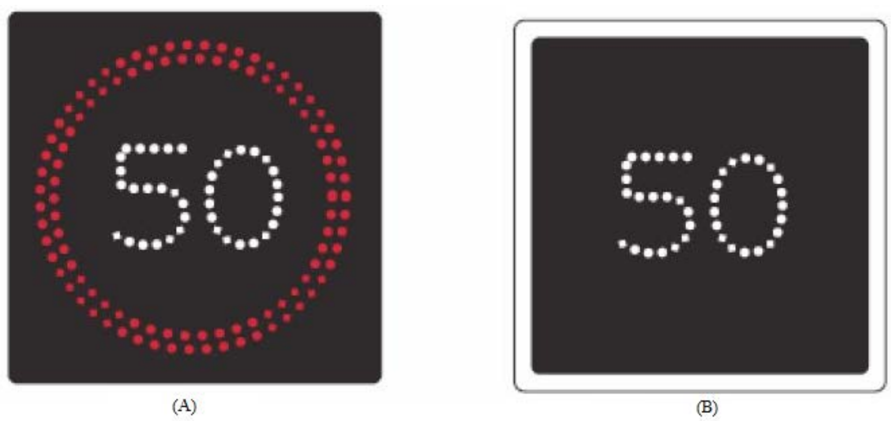

Figure 3-10. Variable Speed Limit Signs in Sweden. (A) Mandatory, (B) Advisory (Austroads, 2009).

A before and after analysis of the trial revealed a 5 to 15 km/h reduction in speeds across the study sites, high rates of speed compliance (in particular in severe weather conditions), fewer disturbances in traffic flow, and less severe shockwaves (Nygårdhs, 2011). The analysis also indicated that speed harmonization implementations were most effective when they combined with additional speed enforcement and better information.

3.2.7 United States

3.2.7.1 Alabama

In response to the tragic fog-related pile-up in 1995 involving 193 vehicles in a seven-mile segment of Bay Bridge on I-10, the Alabama Department of Transportation launched a low visibility warning system along the segment (FHWA *Road Weather Management,* 2003). Six visibility sensors placed every mile and 25 CCTV cameras were installed along the bridge to monitor weather conditions and traffic flow. 24 variable speed limit signs and five variable message signs were also installed in order to display either mandatory or advisory speed limits and weather warning messages. Two system operators manned the control center 24 hours a day, 7 days a week to monitor fog conditions and adjust the posted speed limit as needed. If fog was observed, the operators consulted the central computer for road weather sensor measurements. Speed limit selection was done according to the criteria outlined in in Table 3-2. If conditions warranted a speed limit reduction, the operators could determine to notify local enforcement officials and highway patrol for traffic guidance and assistance.

Table 3-2. Low Visibility Warning System Strategies in Alabama ().

Visibility Distance	Advisories on DMS	Other Strategies
Less than 900 feet (274.3 meters)	"FOG WARNING"	Speed limit at 65 mph (104.5 kph)
Less than 660 feet (201.2 meters)	"FOG" alternating with "SLOW, USE LOW BEAMS"	"55 MPH" (88.4 kph) on VSL signs "TRUCKS KEEP RIGHT" on DMS
Less than 450 feet (137.2 meters)	"FOG" alternating with "SLOW, USE LOW BEAMS"	"45 MPH" (72.4 kph) on VSL signs "TRUCKS KEEP RIGHT" on DMS
Less than 280 feet (85.3 meters)	"DENSE FOG" alternating with "SLOW, USE LOW BEAMS"	"35 MPH" (56.3 kph) on VSL signs "TRUCKS KEEP RIGHT" on DMS Street lighting extinguished
Less than 175 feet (53.3 meters)	1-10 CLOSED, KEEP RIGHT, EXIT ½ MILE	Road Closure by Highway Patrol

Source: FHWA Road Weather Management, 2003

The original design of the system called for backscatter visibility sensors for vehicle detection; however, due to bridge vibration-related sensor interference, forward scatter detection was utilized instead. Despite relying on a somewhat less effective detection method, safety improvement results have been significant.

3.2.7.2 Arizona

Arizona State University (ASU) and Arizona Department of Transportation (ADOT) partnered in the late 1990s to develop a weather-related speed harmonization program (Austroads, 2009). The major goal of this study was to develop a fuzzy logic control system for speed limit selection based on prevailing traffic conditions, weather, and the road surface condition (ADOT, 2001). The control system took as input the road surface condition, average wind speed, wind gust speed, visibility, degree of crosswind, precipitation intensity, prevailing traffic conditions, and any emergency-related information. Using an active set of rules for the given input variables, the control system outputted a recommended maximum speed limit. In the event of emergencies, the speed limit could be adjusted manually. Test runs were conducted along a stretch of I-40, where atmospheric, road surface, and traffic conditions detection were installed. However, no evaluation results have yet been reported.

3.2.7.3 Colorado

In 1995, a Dynamic Downhill Truck Speed Warning System was installed at the Eisenhower Tunnel on I-70 west of Denver with the goal of reducing runaway truck incidents (CDOT, 1999). The system utilized weigh-in-motion (WIM) sensors and inductive loops to calculate the weight, axle configuration, and speed of approaching trucks. A rules-based system used this information to calculate an appropriate speed, which was then displayed on a variable message sign. Each

passing truck generated an individualized recommended safe speed alert, based on the unique configuration and characteristics of that truck. A before and after analysis showed a five percent reduction in the number of truck-related incidents due to the implementation, even as the roadway witnessed increased truck traffic in the years since the speed warning system was installed. The analysis also found that speed limit compliance rates decreased dramatically when the speed recommendations were much lower than the actual traffic speed.
Another notable Colorado implementation is still-in-development rolling speed harmonization system along a 27-mile segment of I-70 (Heavy Duty Trucking, 2011). The most recent test of the system was conducted on September 25, 2011 on the eastbound portion of the I-70 between Silverthorne and the Eisenhower/Johnson Memorial Tunnel (EJMT), in coordination with the Colorado State Patrol and the Silverthorne Police Department. As part of this test, a police vehicle with lights on was positioned in front of the traffic as a way to enforce a more uniform traffic flow. Preliminary analysis of this test showed high driver compliance and significant reduction in speed differentials among vehicles. As of this writing, the system has not yet gone live, but it is expected to utilize 15 side-mounted LED variable speed limit signs in both directions and detection of traffic flow and weather (FHWA *Elk Mtn Corridor VSL*, 2010). It is anticipated that the rolling speed harmonization will be fully implemented by early 2012.

3.2.7.4 Delaware

The Delaware Department of Transportation (DelDOT) has implemented a speed harmonization system on I-495, a six-lane highway near the city of Wilmington (Werner, 2003). This segment is one part of a long-term congestion management program to install speed harmonization along 150 miles of Delaware highway. There are currently 23 variable speed limit signs on this highway segment and the posted speed limit is adjusted base on prevailing traffic conditions, incidents, weather, and road pavement conditions. The Chief Traffic Engineer uses these data to determine when and if to change the posted speed limit. Approval for a speed limit change request is given by the Delaware State Police. Because this is a very recent system, there is no formal evaluation yet available.

3.2.7.5 Florida

The Florida Department of Transportation (FDOT) has implemented a speed harmonization system on a 10-mile segment of I-64 between Maitland Boulevard and Orange Blossom Trail (FDOT, 2008). Figure 3-11 shows the location of this corridor. The system consists of 20 side-mounted variable speed limit signs, with traffic condition information collected through a network of loop detectors. Posted speed limits are adjusted based on prevailing traffic conditions and considering certain thresholds for occupancy and speed, corresponding to free flow traffic, light occupancy, or heavy occupancy. The system also incorporates an adjustment and recovery threshold in order to avoid rapid back-and-forth changes in posted speed limits when roadway occupancies are at or around thresholds. Recommended speed limits are posted in 5 mph increments, with a minimum posted limit of 30 mph.

While a formal evaluation of the system has not yet been completed, a lessons-learned report concluded the following (USDOT RITA, 2009):

- Identifying appropriate advisory and mandatory speed limits is essential before launching a speed harmonization program.

- Developing a concept of operation is essential before designing the speed harmonization system.
- The algorithms for speed limit selection should account for the presence of low-speed vehicles during uncongested flow.
- Operator approval of recommended speed limit changes should be gained.

Figure 3-11. Speed Harmonization Location, Orlando Florida (FDOT, 2008).

3.2.7.6 Maine

There are two variable speed limit implementations in Maine, one along an 82-mile stretch of I-95 and the other along a 41-mile stretch of I-295 (Beltz et al., 2009). Advisory speed limit selection for both implementations is based on the prevailing traffic conditions, the road surface condition, and various weather variables (including precipitation levels and type). Speed values are set within 5 mph of the average actual speed on the segment. Table 3-3 below shows the criteria for speed limit selection for different weather and road surface conditions. Average speed is collected at 10-minute intervals. If the current average speed drops more than 20 mph from the last reading, on-site DOT crew and state police are alerted in order to determine whether to adjust the posted speed limit. Radio room personnel monitor the target site with CCTV cameras to help advise state police about when to activate a new speed limit.

Table 3-3. Criteria for Speed Limit Selection in Different Weather and Road Surface Conditions (Beltz et al., 2009).

	Clear	Partly Cloudy	Cloudy	Raining	Freezing Rain	Sleet	Light Snow	Heavy Snow	Heavy Rain (T-Storm)
Bare and Dry	Off	Off	Off		--		--	--	--
Bare and Wet	Off	Off	Off	Off	--		45-55	--	45
Snow Covered	25-45	25-45	25-45	25-45	25-45	25-45	25-45	25-45	--
Icy	25-35	25-35	25-35	25-35	25-35	25-35	25-35	25-35	--
Slush	--	--	--	--	--	45	45	45	--

A survey of road users showed high levels of awareness of and support for the variable speed limit system; however an analysis of speed and crash outcomes showed mixed results. Based on speed measurement and accident data collected between 2006 and 2008, motorists showed low levels of advisory speed limit compliance in dry and wet weather conditions but high levels of compliance in snowy and icy weather conditions. As a result, system managers are considering making the variable speed limits fully mandatory and enforced.

3.2.7.7 Michigan

Michigan's first variable speed limit system, installed in 1962 and maintained for five years, covered a 3.2-mile segment of the M-10 (John C. Lodge Freeway) in Detroit between the Edsel Ford Freeway (I-94) and the Davison Freeway (Robinson, 2000). It utilized 21 manually controlled variable speed limit signs, which were changed in 5 mph increments, to provide motorists information about approaching congestion. Operators used CCTV cameras to observe traffic flow and pen plots to calculate freeway speeds in order to make posted speed limit recommendations. Speed limits were advisory, however, and driver compliance rates were relatively low.

Source: FHWA

In 2002, another variable speed limit project was initiated as a part of a larger work zone safety program on I-96 south and west of Lansing (Kwon et al., 2006). The program was a joint effort of the Michigan Department of Transportation, Michigan State Police, and Michigan State University. In preparation for the I-96 implementation, a trial run of the system was tested on a local road. Figure 3-12 shows the variable speed limits signs that were used in the project. Speed limit selection was based on the prevailing speed statistics (e.g., average speed) using pre-established logic called “Settings Files.” The settings files were developed specifically for each site based on individual site characteristics. Operational difficulties were encountered throughout the implementation, including the frequent ripping out of the pneumatic tubes used for speed and occupancy detection due to traffic-induced wear and tear.

A before and after analysis of the system showed a number of positive results, including a reduction in travel time, an increase in average speed, fewer speed limit violations, and a reduction in number and severity of crashes. Additionally, a survey of motorists showed high levels of awareness of and support for the system (FHWA *Work Zone VSL Evaluation*, 2004). However, the analysis also concluded that due to the durability and reliability issues frequently encountered with the detection equipment, any wider implementation of the safety program would require the use of updated technologies.

3.2.7.8 Minnesota

In 2006, the state of Minnesota implemented a work zone variable speed limit system for the I-494 southbound work zone near the Wakota Bridge in Twin Cities for the three weeks of the construction (Kwon et al., 2006). The segment was 2.5 miles long with a work zone speed limit of 55 mph. The goal of the system was to reduce the speed of the vehicles approaching the work zone. Three advisory speed limit signs were installed along the segment and five sets of radar and Doppler sensors were installed for measuring speed and volume. Collected data were transmitted using web-based wireless communication technology. Figure 3-13 below shows the site layout. Speed limit selection was based on speed and flow measurements using an algorithm which calculated the advisory speed limit every minute in 5 mph increments.

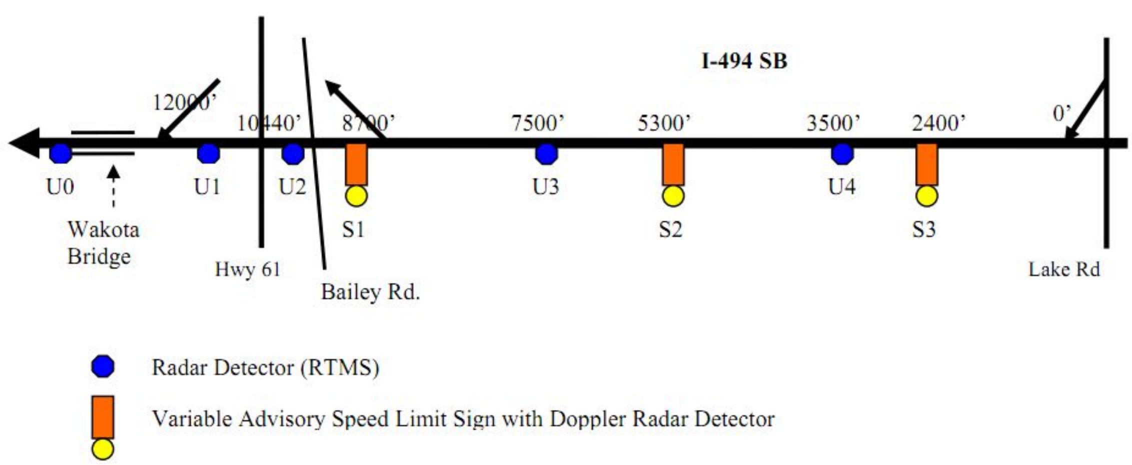

Figure 3-13. Layout of the I-494 Work Zone Variable Speed Limit, Minnesota (Kwon et al., 2006).

The results of a before and after analysis showed a 25-35% reduction in maximum one-minute average speed and a 7% increase in throughput between 6 and 7 a.m., though no throughput increase between 7 and 8 a.m. Although the speed limit was advisory, motorist compliance was significant.

In July 2010, Minnesota implemented another speed harmonization and variable message sign program on I-35W near the Twin Cities, with the goal of preventing the rapid propagation of the shockwaves by reducing the speed of the traffic gradually (Kwon et al., 2010). Figure 3-14 shows the speed harmonization and variable message signs on I-35W.

Figure 3-14. Speed Harmonization and Variable Message Signs on I-35 West, Minnesota (Kary, 2011).

Speed data are collected every 30 seconds by means of loop detectors. The advisory speed limit selection follows the flow chart in Figure 3-15 based on the prevailing traffic conditions. Performance analysis and data collection are currently ongoing and results are not yet available.

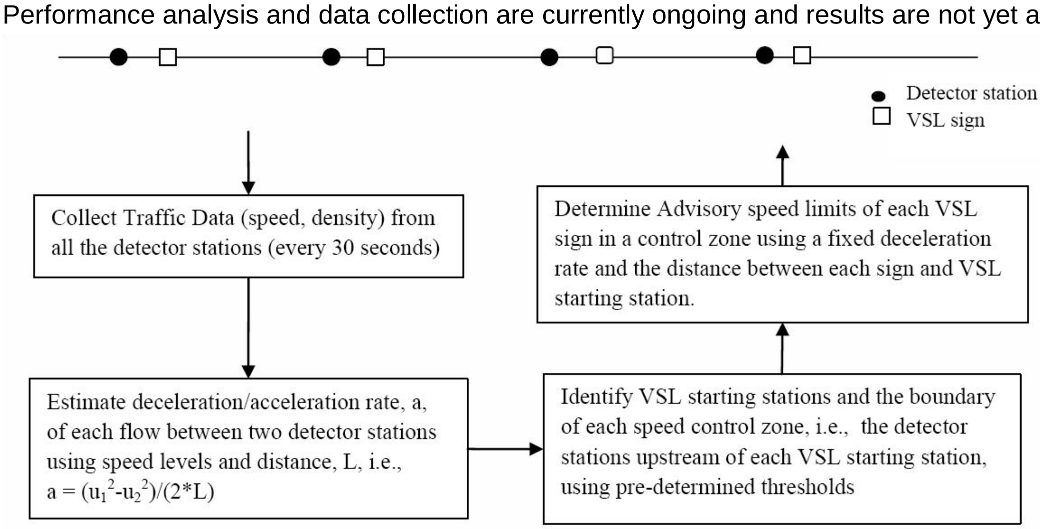

Figure 3-15. Speed Limit Selection Process on I-35 West, Minnesota (Kwon et al., 2010).

3.2.7.9 Missouri

On May 2008, the Missouri Department of Transportation (MoDOT) began a two-year speed harmonization pilot project for a section of I-270 near St. Louis (King, 2010). 70 solar-powered variable speed limit signs were installed. Figure 3-16 shows the locations of the 70 signs.

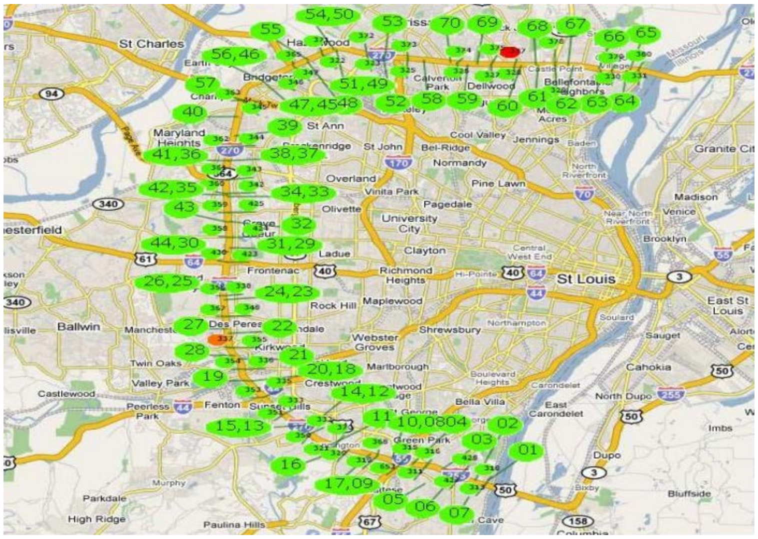

Figure 3-16. Speed Harmonization Location, Missouri. (King, 2010)

The maximum and minimum speed limits on the corridor are 60 mph and 40 mph, respectively, and the mandatory and enforced variable speeds are adjusted in 5 mph increments. The segment is divided into subsections in which the speed limits are the same. Adjustments to the posted speed limit may be made every five minutes or sooner if an incident has been observed. Significant changes in loop detector occupancy data are monitored by the system, which provides operators an alert to use the CCTV cameras to investigate slowdown spots. If conditions warrant a change in posted speed, the operators adjust the signs accordingly.

An evaluation of the pilot project was conducted that focused on three different categories: mobility, safety and public opinion (MoDOT, 2010). While no mobility gains (in terms of throughput improvement or congestion reduction) were observed, the evaluation did show a significant reduction in number and severity of crashes. However, motorists and law enforcement officials alike reported dissatisfaction with the program's effect on congestion reduction. Speed limit compliance remained surprisingly low, even though the signs were mandatory. A contributing factor to the low observed compliance, according to the evaluation, may have been visibility-related issues with the signs themselves. In response to the findings from the evaluation, MoDOT decided to change the posted speed limits from mandatory to advisory (Leiser, 2011).

3.2.7.10 Nevada

The Nevada DOT (NDOT) has implemented a mandatory and enforced variable speed limit system and a Roadway Weather Information System (RWIS) on I-80 in Coalfire Valley east of the city of Reno (Austroads, 2009). Speed limit selection is based on the combination of the 85th percentile speed from loop detector data, visibility data, and pavement condition. A logic tree is used to calculate the speed limit for each factor and pick the maximum allowable speed in order to generate the appropriate speed limit for the prevailing condition (Robinson, 2000). The selection is posted on four VSL signs, two in each direction. Signs are only active during inclement weather conditions and remain blank on clear days. Reliability issues with visibility sensors have been found to negatively impact the operation of the system.

3.2.7.11 New Hampshire

The New Hampshire DOT is currently working on installation of dynamic message signs, CCTV cameras, and variable speed limit signs along I-93 between the Massachusetts state line and Manchester (NHDOT, 2011). Operations are expected to begin in 2012.

3.2.7.12 New Jersey

The New Jersey Turnpike Authority (NJTA) has operated an Advanced Traffic Management System (ATMS) on the Turnpike since the 1960s and has made several improvements to it since the 1980s (FHWA *Road Weather Management,* 2003). Along the 148-mile Turnpike, one of the most congested corridors in the nation, are 120 variable speed limit signs and 113 dynamic message signs, which have been installed with the goal of providing drivers early warning of slow traffic or hazardous road conditions. Mandatory and enforced speed limit selection is based on weather conditions and average travel speed as detected by inductive loops. CCTV cameras are also installed at certain points to provide a closer view the traffic flow. Weather related information is collected by the turnpike's Road Weather Information System (RWIS), which includes 30 environmental sensor stations. All the data from the sensors are sent to the Traffic Operations Center (TOC), where operators decide when to reduce the speed limit and what to reduce it. Posted speed limits range from 30 mph to 55 mph and adjust in 5 mph increments.

Operators may also activate dynamic message warning signs, which display a speed reduction message consisting of "reduce speed ahead", the reason for the speed reduction, and the distance to the congestion. There are currently six reasons given for speed limit reduction warnings: crashes, congestion, construction, ice, snow, and fog. The criteria for weather and accident related speed limit selection is presented in Table 3-4. The posted speed limit is enforced by law enforcement officials on the corridor and the authority believes that the project is effective is providing safer driving conditions by reducing the frequency and severity of the accidents, particularly in adverse weather (Robinson, 2000).

Table 3-4. Criteria for Speed Limit Selection in Different Weather and Road Surface Conditions (FHWA *Road Weather Management,* 2003).

Condition	Speed Limit
Accident within 2 miles of a sign	45 mph
Congestion within 2 miles of a sign	45 mph
Visibility within 2 miles of a sign 500-800 yards	55 mph
Visibility within 2 miles of a sign 300-500 yards	50 mph
Visibility within 2 miles of a sign 200-300 yards	45 mph
Visibility within 2 miles of a sign 150-200 yards	40 mph
Visibility within 2 miles of a sign 100- 150 yards	35 mph
Visibility within 2 miles of a sign less than 100 yards	30 mph

Condition	Speed Limit
Snow within 2 miles of a sign	Maintenance Crew Advises
Spot salting of an affected area	50 mph
Full salting of an affected area	45 mph
Plowing of an affected area	35 mph

3.2.7.13 New Mexico

In 1989, a speed harmonization system was implemented on I-40 eastbound in Albuquerque as part of a U.S. test bed for speed harmonization research to minimize crashes and provide motorist informing on downstream hazards (Austroads, 2009). Maximum as well as minimum speeds were displayed on variable speed sings. Figure 3-17 shows the variable message signs used in the project.

Figure 3-17. Variable Speed Limit Signs, New Mexico (Austroads, 2009).

Dual loop detectors were used to collect speed data and light and precipitation sensors were used to detect environmental conditions. Speed limit selection was based on three factors: the smoothed prevailing traffic speed, the time of the day, and precipitation and light conditions.

A before and after analysis showed a slight reduction in crash rates. However, high average speeds and sign visibility problems (related to sun glare) affected the effectiveness of the project (Robinson, 2000). In 1997, I-40 was widened and the system was not redeployed.

3.2.7.14 Oregon

In 2002, the Oregon Department of Transportation implemented a system to advise truck drivers of the safe downhill speed along Emigrant Hill, a six-mile section of I-84 between Pendleton and La Grande with a 6% downgrade (Robinson, 2000). The system uses weigh-in-motion sensors and automatic vehicle identification readers to calculate the safe speed for each truck and post it on the variable message sign. No official evaluation of the system is available.

3.2.7.15 Pennsylvania

The Pennsylvania Turnpike Commission operates a variable speed limit system along a 10-mile stretch of the Turnpike, from MP 162 to MP 172, to improve safety during low visibility conditions. The system consists of 28 variable speed signs and speed limit selection is based on visibility information from Road Weather Information Systems (RWIS) combined with stopping site distance calculations using ASHTO Policy of Geometric Design of Highway and Streets. Dispatcher approval must be granted for any displayed speed limits. No official evaluation of the system is available.

3.2.7.16 Tennessee

In response to the 1990 fog-related chain collision on I-75, Tennessee officials implemented a low visibility warning system, covering 19 miles of the highway (FHWA *Road Weather Management*, 2003). Completed in 1994, the system collects data from two environmental sensor stations, eight forward scatter visibility sensors, and 44 vehicle detectors. If the system detects both fog conditions and a significant reduction in average speed (i.e., speed below 45 mph), an alarm is provided to the Highway Patrol office for further verification using a visible delineator post count to verify a low visibility condition. Once low visibility is verified, the control center manager activates the appropriate speed limit adjustment based on the recommendation of the system. The criteria for speed limit selection are presented in Table 3-5.

Table 3-5. Criteria for Speed Limit Selection in Different Visibility Conditions.

Visibility Distance (ft)	Speed Posted on VSL Signs
> 1320	70 mph
1320 > Visibility > 480	55 mph
480 > Visibility > 240	35 mph
< 240	Corridor closed and traffic detoured

An analysis of the implementation showed a significant reduction in crashes. Since it was implemented, this section of I-75 has seen only one fog-related crash, compared to over 200 fog-related crashes from 1973 to 1994.

3.2.7.17 Utah

The Utah Department of Transportation has designed a test project to evaluate the effectiveness of variable speed limits and speed harmonization on work zone speed before implementing it widely throughout the state highways (McMurtry et al., 2009). A six-mile segment on I-80 north of Wanship was chosen for this purpose and 12 weeks of data were collected. Two variable message signs were used on the segment and the vehicle speed were collected using Jamar tube counters in 5 locations along the segment. Figure 3-18 shows the location of VSLs and sensors along the segment. Three different scenarios were tested against each other:

- Standard 65 mph speed limit sign
- VSL sign set to 65 mph
- VSL sing set to 55 mph during the day and 65 mph during the night

Analysis of speed data showed that the driver response to the VSL was positive and variation in speed was generally reduced. However, the analysis emphasized that a longer period of study is required to better ascertain the long-term effects of VSL on work zones.

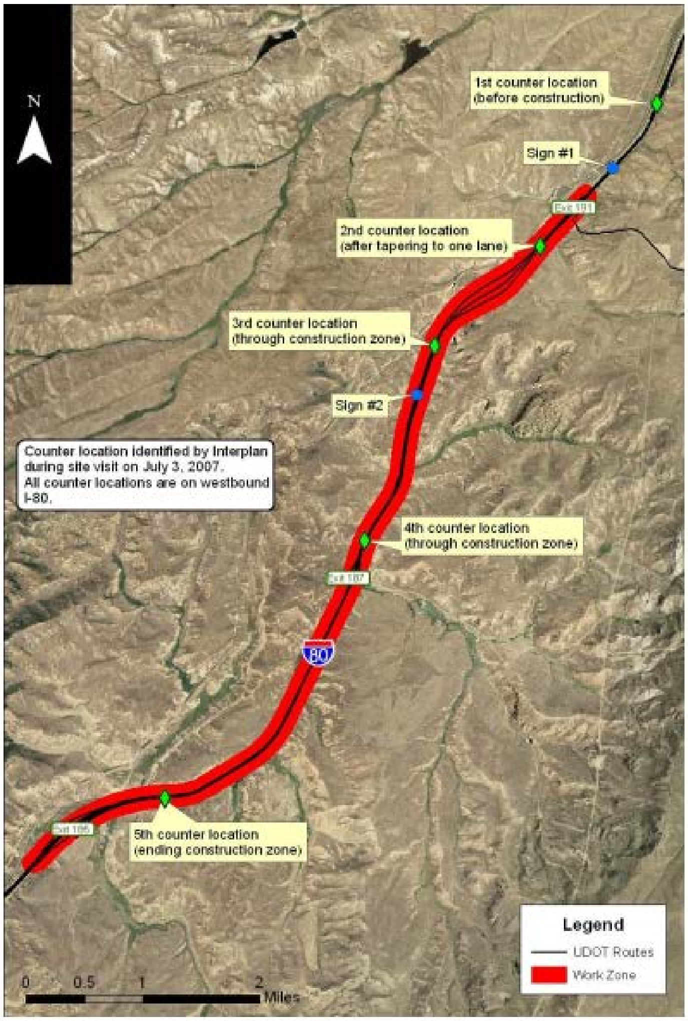

Figure 3-18. Location of VSL Signs and Sensor Locations (McMurtry et al., 2009).

3.2.7.18 Virginia

In 2008, Virginia Department of Transportation (VDOT) began a speed harmonization program on I-495 and the Woodrow Wilson Memorial Bridge between the Springfield Interchange and the Maryland state line (FHWA *Work Zone VSL*, 2010). The purpose of the project was to evaluate the effectiveness of variable speed limits on traffic flow and safety improvements for urban congested work zones. The study location was divided into certain zones where all the posted speed limits were the same. Volume and occupancy data were collected from microwave sensors located adjacent to the VSL signs and cumulative volume and occupancy was calculated for each zone. Based on the calculated values and threshold values defined by VSL vendors, the appropriate speed limit was selected for each zone. The system ensured that the downstream speed limit never exceeded the upstream speed limit.

While the speed limits were considered mandatory, because VDOT had limited speed enforcement authority, relatively few violators were ticketed. Analysis of the system showed a slight reduction in average speed along the corridor. Compliance with the posted speed limit was high, with only 21 speeding citations issued in the first four months of operation.

3.2.7.19 Washington

Washington State Department of Transportation (WSDOT) operates two adverse weather variable speed limit systems, one on a 15-mile stretch of I-90 and the other on a seven-mile stretch of US 2. Inputs to the speed limit selection algorithm include traction conditions, road surface conditions, visibility, weather conditions, and incident detection.

In the last few years, WSDOT has developed an active management system on I-90 and SR 520 with the goal of smoothing traffic and improving safety (WSDOT, 2011). Variable speed limit signs and lane status signs have been installed at 19 locations on SR 520 and 25 locations on I-90. Figure 3-19 shows one of these locations on SR 520 where different speed limits have been posted for each lane.

Annie Johnson, WSDOT

Figure 3-19. Different speed limits for each lane on SR 520 in Bellevue, WA.

Preliminary results have indicated that driver compliance of the posted signs has been high; however WSDOT is still in the process of evaluating these systems in terms of congestion benefits and safety.

3.2.7.20 Wyoming

The Wyoming Department of Transportation recently implemented a variable speed limit program on 52 miles of I-80 Elk Mountain corridor between Laramie and Rawlins in southeastern Wyoming with the goal of reducing traffic speeds during inclement weather conditions (FHWA *Elk Mountain VSL*, 2010) (Krishna, 2010). The system comprises 10 variable speed limit signs (five in each direction) and speed selection is done manually by state highway patrol.

Evaluation results indicate that speed compliance is much lower during severe weather conditions compared with normal driving conditions. Speed variance has also shown to be very high. A review of the system recommended that to improve compliance rates, speed limit selection should be made using an automated control strategy system.

3.3 CACC Initiatives and Deployed Systems

A number of initiatives have been conducted to implement CACC systems as documented in the literature. Several key initiatives are described in this section.

3.3.1 Sweden

The Swedish Road and Transport Research Institute (SRTRI) conducted a study of an adaptive cruise control (ACC) system using a simulator. The study involved 10 male and 10 female drivers between the ages of 26 and 46. One half of the group (equal female and male participants) performed the test with the ACC system activated while the other half performed the test based on manual driving. The ACC system prototype that was tested used controlled speed and distance headways with the use of throttle and brake control. The maximum braking capabilities of the ACC system were 20 to 30 percent the force of gravity. The ACC system could be active in the speed range of 30 to 130 km/h. At higher speeds the system operated as a conventional cruise control (CCC) system while at lower speeds the system shut off. The ACC system that was tested could not detect stationary vehicles (Nilsson, 1995).

A number of simulated scenarios were tested on a two-lane roadway that had a designated speed limit of 110 km/h and a length of 100 kilometers (Nilsson, 1995). The first scenario involved following a hard braking lead vehicle (braking at a rate of 8 m/s^2). In this scenario, an acoustic tone was activated to nine out of the ten ACC drivers to indicate to the driver that he/she was required to take control over the system or else a collision was inevitable. The comparisons indicated that there was no statistical difference in the reaction times between manual and ACC driving at a 95 percent level of confidence (driver reaction time of 1.33 seconds for manual driving and 1.49 seconds for ACC driving).

The second scenario involved the subject vehicle passing a vehicle and having a car pull out in front of the subject vehicle. Once again the maximum ACC system deceleration capability was insufficient to avoid a collision; however, in this case no acoustic warning was activated. The time between the left direction indicator activation and the braking action was on average 1.11 seconds for the ACC drivers and 1.17 seconds for manual drivers. This difference in reaction times was not found to be statistically different at a 95 percent level of significance.

The third and final scenario that was tested had the subject vehicle approach a stationary queue. The queue covered both lanes of the road and since the ACC system did not detect stationary vehicles as lead vehicles all response to the queue was manual. A total of 5 collisions were observed in this test situation. Four resulted from ACC supported drivers and one from the group of drivers without ACC support.

In summary, the study indicated that the different driving scenarios produced varied driver behavior depending on the type of vehicle control. The study did draw some doubts on the safety impacts of the ACC system especially when approaching a stationary queue. However, it should be emphasized that the study was conducted on a vehicle simulator and these findings could be a result of the lack of realism of the simulator.

In a later study Strand et al. (2011) explored end-user experiences of ACC systems. A qualitative approach was applied and data were collected by means of focus group interviews. A qualitative content analysis was carried out to analyze and interpret collected data. The study consisted of three focus group sessions with five to seven participants in each. Themes explored included interaction between user and system, functional limitations and trust, and system effects on driving behavior. Key findings included reported driving behavior changes as, for instance, an increasing tendency to stay in the right lane as well as users' conception of system functionality from which it can be concluded that end-users of ACC carry rough mental models of the system. A potentially hazardous situation for other road-users following the use of ACC was highlighted and discussed. In addition, some features desired by the end-users were discussed, for example, the call for conventional cruise control functionality when weather conditions warranted that.

3.3.2 Netherlands

A number of publications have focused on CACC system initiatives in the Netherlands. These publications have described the algorithmic developments, testing of systems within a simulation environment, and some limited field testing. The efforts are a collaboration between the Dutch Ministry of Economic Affairs, TomTom, TNO, NAVTEQ, the Technical University of Delft, the Technical University of Eindhoven, and the University of Twente.

Van Arem and his colleagues at the Technical University of Delft wrote a paper quantifying the impact of CACC on traffic-flow characteristics (van Arem et al., 2006). The research used the MIXIC traffic simulation software for evaluation purposes. The authors studied the impact of a CACC initiative on a highway-merging scenario from four to three lanes. The study concluded the following from the literature review:

Vehicle-to-vehicle communication can provide an ACC system with more and better information about the vehicle it is following. Not only following distance and speed difference with respect to its direct predecessor, but also information about other surrounding vehicles in the traffic stream. The information could include precise speed information, acceleration, fault warnings, warnings of forward hazards, maximum vehicle braking capability, and current braking capability. With information of this type, the ACC controller can better anticipate problems, enabling the vehicle to be safer, smoother, and faster in response and, as a result, enable closer vehicle following with time gaps reduced to 0.5 s. In addition, a CACC system has the potential to increase capacity by minimizing time gaps between consecutive vehicles and traffic flow stability by improving string stability. While the effectiveness of a CACC system depends on the penetration levels of its deployment, when fully deployed a CACC system has the potential to double the capacity of a highway.

Van Arem’s original research findings showed an improvement of traffic-flow stability and a slight increase in traffic-flow efficiency could be achieved through the implementation of CACC technology compared with the merging scenario without CACC equipped vehicles. Consequently, the study could not generate the capacity gains that the authors had initially anticipated. In fact the authors challenged what they called the myth that CACC systems can increase the roadway capacity significantly. The authors did acknowledge that current simulation software are unable to model congestion properly and further enhancements would be required to validate these results and conclusions. It should also be noted that a valid deployment of CACC systems would also have to consider merge control and assistance systems, which was not considered in the van Arem study. The FHWA is currently funding research on advanced freeway merging systems that have the potential of increasing the roadway capacity in merge, diverge and weaving sections.

In a later study (Pueboobpaphan et al., 2010), van Arem and his colleagues extended their previous analysis to focus on traffic stream stability by making some modifications to the Intelligent Driver Model (IDM) and integrating it with CACC algorithms. They also evaluated data from a field operational test (FOT). The FOT was conducted on the A270 public highway in the Netherlands, in order to demonstrate the potential of CACC systems to improve traffic efficiency and shockwave behavior in particular. A string of 50 Acceleration Advice Controller (AAC) equipped vehicles was put through a series of experiments in which shockwaves were induced with varying speeds and decelerations. AAC was an advisory version of a CACC system. The CACC generated an acceleration advice to the driver instead of controlling the throttle and brakes directly. Various decelerations were performed up to -5 m/s^2. A control group of 50 unequipped vehicles was put through the same experiments in the adjacent lane. The time headway of the AAC system was set at the average of the unequipped vehicles at 1.2 s. In addition to the field experiments, a simulation study was conducted. In the simulation study, human drivers and CACC equipped vehicles were simulated on a 4 km stretch of road with a single lane. The first vehicle was pre-programmed to drive at 90 km/h for the first 80 seconds covering the first 2 km. Then the vehicle decelerated at a rate of -5 m/s^2 (as in the A270 field test) to a speed of 36 km/h. This speed was maintained for 5 seconds after which the vehicle accelerated at a rate of 1 m/s^2 back to 90 km/h. As this initial perturbation resulted in a deceleration to a speed of 36 km/h, there was room left for shockwave growth due to unstable behavior.

The study concluded that car-following models to date appear unable to capture human driving behavior with realistic traffic flow stability, capacity and reaction times. The study made modifications to the IDM model to develop the IDM+, which showed realistic traffic flow stability but had no reaction time. Given that CACC systems are particularly better than humans at estimation and reaction time, a sensitivity analysis of used reaction times and estimation errors would have been valuable. As a result, the conclusions of this study should be considered explorative. In a qualitative sense the modeling results appeared to be similar to the A270 field experiment. The study demonstrated 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. However, in a CACC environment it is expected that 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.

The study also demonstrated an interesting aspect of human drivers and that is the interdependency of reaction time and time headway. At merging and diverging sections drivers were faced with short headways and thus adjusted their reaction times (level of attention) accordingly. This is opposite to the often-used notion that drivers will keep a safe distance, depending on their reaction time. Consequently, the study concluded that a dynamic reaction time might be the key to having collision-free traffic operations with realistic parameter values in car-following models that include a finite reaction time, estimation errors and anticipation while having a realistic macroscopic capacity. These results demonstrate that a successful CACC system would require some form of cooperative merging logic in order to enhance traffic operations at merge, diverge, and weaving sections.

3.3.3 Grand Cooperative Driving Challenge (GCDC)

This section describes some research efforts related to CACC systems and describes some of the deployment issues. The discussion focuses on the Grand Cooperative Driving Challenge (GCDC), which is a challenge that involves international teams competing to deliver the most effective cooperative vehicle-infrastructure system in pre-determined traffic scenarios. This challenge is a unique opportunity to conduct research in the CACC arena, while at the same time provides a unique challenge for competing teams. The GCDC aims to accelerate the implementation of these systems and contribute significantly to alleviate traffic problems worldwide. The challenge entails a team negotiating its vehicles as efficiently as possible through a range of predetermined traffic scenarios. The extent to which the traffic flow is improved by developed system and the speed at which this improvement can be implemented is used as a criterion by judges to determine the challenge winner. The challenge is thus a unique tool for the rapid transfer of research findings to real-life driving conditions. The first GCDC was conducted in May 2011.

The 2011 GCDC enacted a predefined scenario that entailed a shock wave damping test with CACC vehicles provided by the participating teams negotiating these scenarios. The primary focus was on driving in close proximity to the vehicle in front (fuel reduction) and on maintaining smooth traffic flow (throughput). A total of 11 teams from various countries (Germany, the Netherlands, Spain, Canada, the USA, Latvia, Turkey, Sweden, and the UK) participated in the 2011 GCDC (Das et al., 2011) (Agusto et al., 2011) (Bonsen et al., 2011) (Geiger et al., 2011) (Milanés et al., 2011) (Lidström et al, 2011) (Strazdins et al., 2011) (Uygan et al., 2011) (Alam et al., 2011).

It should be noted that 10 of the 11 teams developed and tested the CACC systems only considering communication with the lead vehicle and did not entail communication with a stream of vehicles. The joint Fontys Hogenscholen, University of Twente and Waterloo University team—calling themselves FUTURUM—did consider four types of control: manual, conventional cruise control, ACC, and CACC (Das et al., 2011). The CACC system that was developed considered information from the entire platoon of vehicles, however the specifics on how algorithm was developed in not described in detail. The FUTURUM CACC+ system collected information faster and more accurate information from a platoon of three vehicles. This approach overcomes major drawbacks in driving comfort and traffic stability and flexibility. With more information, vehicles can make more precise decisions for speed to achieve smoother and safer driving. In addition, the road capacity can be increased. The FUTURUM algorithm also receives information from the vehicle behind the subject. This allows the subject vehicle to operate in a manner that does not pose a safety hazard to the vehicle following it. The FUTURUM control box can handle the following control modes: Cruise Control (CC), ACC, CACC, and CACC+. Vehicles switch from one mode to another directly as needed. However, studies have shown that a sudden change in mode might lead to abrupt changes in speed and produce a safety hazard. The FUTURUM team attempted to overcome this limitation by designing a special gliding algorithm to optimize safety and comfort.

Based on a review of these systems, there is a need to expand the current research as was identified earlier to fuse data from a platoon of vehicles and thus make the system more responsive. Furthermore, there is a need to integrate CACC systems with cooperative merging systems to minimize traffic flow instability at merge, diverge and weaving sections.

Chapter 4. Scan of Relevant Prior and Ongoing Research

This section reviews the key queue warning, speed harmonization, and adaptive cruise control research that have been conducted recently.

4.1 INFLO Research

4.1.1 Q-WARN Research

Several reports have been made regarding at least in part on queue warning. This section highlights the major research topics and findings.

4.1.1.1 Advance warning of stopped traffic on freeways

A major safety concern on freeways is traffic flowing at normal speed encountering unexpected slow or stopped traffic. Traffic can be queued due to recurrent congestion, work zones, or collisions and/or other incidents. Drivers encountering queues are often faced with rapidly changing conditions in terms of queue length, sight distance to the end-of-queue, terrain, and available warning devices for traffic control. The rear-end collision is the most common type of multi-vehicle freeway collision, often due to slow/stopped traffic on the main lanes.

In the observational field studies (Wiles, P.B., 2003), researchers found instances of sustained, repetitive, and excessive queue propagation speeds. In many instances, multiple lanes were impacted. Queue warning systems, in order to be effective, should be installed in consideration of rapidly fluctuating queues. Warning signs placed too close to queue tails might be overrun, and signs placed too far from the queue can become inaccurate. Conditions change too quickly for human operators to handle appropriate warning sign adjustments, necessitating an automated system. Many factors remain to be addressed in future research; however, observations conducted in this project can provide guidance to those testing and implementing and operating systems for advance warning of slow/stopped traffic on freeways.

4.1.1.2 Work zone safety

A Work-Zone Safety ITS System for a distributed, queue-warning system that adapts in real time to upstream of the work zone was developed (Sullivan, J.M., 2005). The system consists of a *smart barrel* that contains a speed sensor with an adjustable signaling system and communication equipment to a central controller. (See Figure 4-1.) The study focused on an inexpensive, but sufficiently capable speed sensor and an effective signaling system.

Three prototype speed sensors were developed and evaluated which used active infrared, passive infrared and magnetic sensor technologies, respectively. The active infrared system was found to be the most accurate but consumed the most power: an important factor for a device that will be battery-power in the field. The passive infrared system was nearly as accurate and required the least power of the three approaches. Simple signaling schemes were also prototyped and presented to drivers in a pilot experiment using a driving simulator. Both subjective opinions about the utility of the system and objective measures of driving performance were collected. Results suggest that drivers find the adaptive systems more helpful than static road signs and there is evidence for systematic change in their driving performance indicative of enhanced safety.

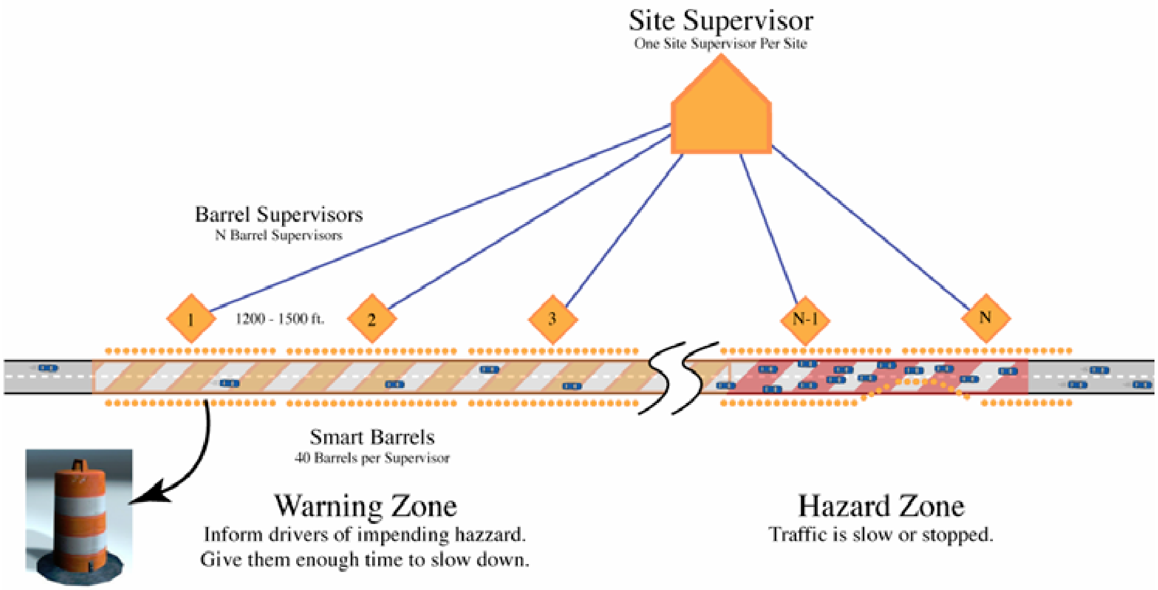

Figure 4-1. *Smart Barrel* Implementation Design. (Sullivan, 2005)

4.1.1.3 Traffic control strategies for congested freeways and work zones

Geza Pesti et al. (2007) conducted a study of traffic control strategies for congested freeways and work zones, with a focus on identifying and evaluating effective ways of improving traffic operations and safety. There was particular interest in finding condition-responsive traffic control solutions for the following problem areas: (1) end-of-queue warning, (2) work zones with lane closure, and (3) queue spillover at exit ramps. Available techniques considered by this research include combination of static and dynamic queue warning systems, dynamic merge control in advance of freeway lane closures, and various traffic control strategies, such as traffic diversion and ramp metering, to mitigate queue spillover at exit ramps. Three studies were conducted: first, two queue warning systems deployed based on field observations. Second, strategies to resolve a ramp spillover problem El Paso, Texas, were analyzed using traffic simulations. Third, the Dynamic Merge work zone traffic control concept was evaluated using traffic simulations, and recommendations were developed for its potential use for various work zone types with different lane closure configurations.

4.1.1.4 Robust Queue Detection

Research has been done at the Beijing University of Technology (Yang et al., 2011) on the methods for detecting real-time queuing and dissipation of a vehicle queue by utilizing video image technology with fixed cameras. One camera was positioned at the front of the stop line and the other behind the stop line. The cameras jointly monitored the interested region with opposite and long-range views. Firstly, the position changes of the tail and head of a vehicle queue, which accurately describe the formation and dissipation of the queue, can be efficiently tracked in each camera at intersection during morning and evening rush hours. Secondly, the data of these two cameras in this large-area outdoor traffic application are fused at decision level to improve the accuracy of the tracking, according to the tracking result in each camera. Then, the queue length and stop delay of vehicles can be calculated readily.

The experiments showed that the proposed method can detect the formation and dissipation of the queue under varying illumination in real time, and that the accuracy rate is about 90.24%. Therefore, this method can be further applied to traffic congestion monitoring and traffic signal controlling.

4.1.1.5 Wireless long haul applications for queue warning systems at border crossings

Ever since 9/11, heightened degrees of security at Ontario's Sarnia/Port Huron border crossing have led to typical truck queues on the order of 5 to 10 km. The overall process to clear vehicles at the border has led to an unusual mix of fast moving passenger traffic and slow moving truck queues on the Hwy 402 approach to the border. Line-of-sight problems on Hwy 402 due to horizontal or vertical highway curves compound this problem such that motorists travelling at high speeds under free flow conditions unexpectedly meet slow or stopped border crossing traffic. This issue had led to a number of fatalities from queue end collisions.

The Ministry of Transportation Advanced Traffic Management Section led an initiative to implement a Queue Warning System on Hwy 402 to automatically detect queues and then warn motorists in advance of the queue via Variable Message Signs (Browne, R., 2008).

4.1.2 SPD-HARM Research

This section discusses key literature related to advanced speed harmonization research, with specific focus on strategies and algorithms and their implications for future speed harmonization implementations.

4.1.2.1 2010 University of California PATH Analysis of Combined VSL and Ramp Metering

The University of California PATH program assessed the ability to defer or avoid traffic flow breakdowns for recurrent congestion at bottleneck locations by coordinating variable speed limits and ramp metering (Shladover et al., 2010). Simulations achieved a significant reduction of travel delays and improvement in traffic flow. How to implement the VSL feedback to the driver (e.g., via VSL signs or in-vehicle communication) to achieve the best driver response is a further study recommendation.

4.1.2.2 2011 V2I-Enabled Signal-Vehicle Cooperative Controlling System Study

In their 2011 IEEE conference paper, Tung Le, et al. (2011) examined the potential of producing an optimal schedule for traffic lights and an optimal speed for incoming cars to minimize stops by utilizing V2I communication with the downstream intersection controller. The overall goal of devising such a schedule is to minimize idling, reduce stop-then-start cycles, and improve throughput. Under this system, the downstream controller communicates recommend speeds for approaching “smart” (i.e., V2I-enabled) vehicles.

The simulation showed that under “moderate” levels of traffic demand for a 100-second period, the V2I-enabled smart car scenario was able to produce a 5% reduction in average delay and a 33% reduction in average number of stops when compared to the no-smart-car scenario.

4.1.2.3 VDOT Study of Hard Shoulder Use, VSL, and Ramp Metering for Congestion Management

Mazzenga and Demetsky (VDOT, 2009) were investigating the solutions to congestion on freeways for the Virginia Department of Transportation (VDOT). They targeted I-66 and I-95 in Northern Virginia and tested the effects of hard shoulder usage, speed harmonization and ramp metering on the congestion management. Figure 4-2 shows the selected segments on both highways. They used ramp queue length, average flow, average lane occupancy, average speed, vehicle miles traveled (VMT), travel delay and fuel consumption to evaluate the performance of the test targets under different congestion management strategies. They used PTV Vision’s VISSIM as their microsimulation software for simulating different scenarios. For the purpose of simulating the speed harmonization, determining the appropriate speed limits and the location of implementing them is playing the main role. They implemented the following publicly available speed harmonization algorithm:

1) Identify the bottlenecks.
2) Collect the speed, flow and density data from the detectors in the congested segments.
3) Generate the speed-flow and speed-density curves.
4) Compare the corresponding flow and density with the optimal values.
5) Develop coding from the step 4 results.
6) Implement the speed decision points.

The simulation results showed the capability of speed harmonization in smoothing the flow over the facility and congestion reduction through delaying its occurrence. However, speed harmonization did not perform well after breakdown formation. It is also pointed that combination of hard shoulder usage and speed harmonization is very effective in congestion reduction.

4.1.2.4 2009 TxDOT Study of Speed Harmonization and Hard Shoulder Use for Congestion Management

Another study in this category is the study by Waller et al (FHWA *Speed Harmonization and Shoulder Use*, 2009) for the Texas Department of Transportation (TxDOT) on the effectiveness of speed harmonization and hard shoulder usage on congestion management. Their target location was Loop 1 (also called Mopac Expressway) in Austin, TX. Figure 4-3 shows this test corridor.

They considered average speed, average density, throughput, trip travel time and total travel time over the network as their performance measures. They incorporated a multi-resolution simulation framework using VISSIM/VISTA. They performed the traffic simulation for the entire network of Austin and fed the vehicular flow at the boundaries of the Loop 1 to VISSIM to perform microscopic simulation.

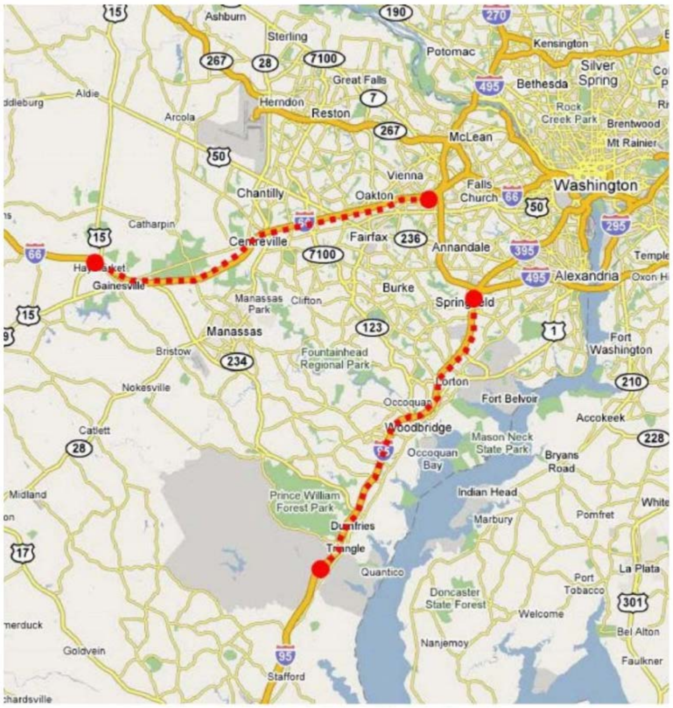

Figure 4-2. Selected Segments on I-64 and I-95 near Washington, D.C. (VDOT, 2009).

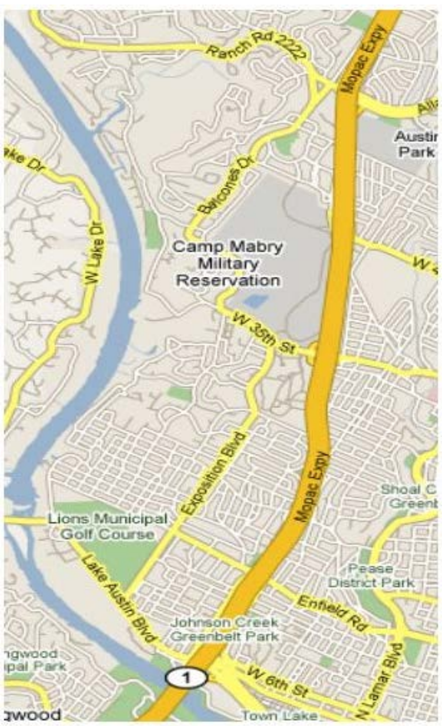

Figure 4-3. Test Segment for Speed Harmonization and Hard Shoulder Use in Austin, Texas (Google Maps, 2009).

They had two approaches for the speed limit selection, off-line algorithm and on-line algorithm. In the off-line case, the speed limit selection is based on the historical traffic data (i.e. flow at certain time of the day at certain point of the highway). In the on-line case, based on the prevailing traffic and weather condition, the appropriate speed limit is selected. Their simulation results showed that speed harmonization and shoulder usage did not affect the throughput significantly.

However, they were very effective in harmonizing the traffic flow. They also pointed that if these two strategies implemented before the breakdown formation the result would be significant and they can delay the breakdown formation. These two strategies also contributed to the slightly increase in travel time due to the speed limit reduction.

4.1.2.5 Research on Algorithms and Strategies for Speed Limit Selection

The traffic agencies that are in charge of operating the speed harmonization on their facilities, rarely revealed the details of their speed limit selection algorithms (VDOT, 2009). Therefore the literature in this group mostly belongs to academia and focuses on developing on-line algorithms for the speed limit selection.

Lee et al. (2004) developed a real-time crash prediction model that is capable of evaluating the speed selection choices from the safety stand point based on the prevailing traffic parameters (i.e., coefficient of variation of speed, average density and speed difference upstream and downstream of the target location), road geometry and peak/off-peak period. They used microscopic simulation models to evaluate the drivers' response to each strategy. Their simulation results showed that their speed limit selection method is capable of reducing the crash counts despite of slightly increasing the travel time.

In another study, Placer (ADOT, 2001) developed a fuzzy logic control algorithm that incorporates the road surface data and weather condition data to find the appropriate speed limit for the condition. They test the system in I-40 in Arizona and the results were promising.

4.1.3 CACC Research

This section highlights some of the key CACC and ACC research that has been conducted in the United States and internationally.

4.1.3.1 UMTRI studies on the effectiveness of ACC

The University of Michigan Transportation Research Institute (UMTRI) conducted two studies of the effectiveness of ACC. The first of these studies involved 36 drivers who drove an 88-kilometer route during off-peak hours (Van Aerde et al., 1999). Both velocity and braking of all participants were analyzed for velocities above 88 km/h (55 mph). No statistical difference was observed between ACC, CCC, and manual driving. The mean number of brake applications was found to be statistically different with 5.8 applications for manual driving, 11.3 for CCC, and 7.4 for ACC driving. The study also demonstrated that the 1.4-second available for driver response supported by the ACC system was larger than average driver response times thus providing more time for drivers to decelerate and potentially reduce the rear-end crash risk. The ACC system was more responsive to relative vehicle velocities thus potentially providing a more orderly and consistent approach. The study also demonstrated that "*drivers tend to be moving the accelerator pedal continuously with a ratio of standard deviation to the mean of approximately 0.43 at highway* *speeds. To the extent that the benefits of removing this effort (and all of the associated neurological decisions to increase or decrease speed), greatly reduces the driver's work, the ACC system leads to safer as well as more pleasant driving*."

In the second study, a field operational test was conducted in which a group of 108 randomly selected volunteers drove, as their personal car, a passenger vehicle equipped with an adaptive cruise control (ACC) system (Haney et al., 2000). The ACC system was incorporated into a fleet of ten passenger cars, each employing a sensor that detected vehicles ahead and controlled both the speed and headway of the test vehicle through gear down shifting without vehicle braking capabilities.

Fancher et al. (1998) indicate that "the field test placed the ACC-equipped vehicles in the hands of 108 randomly-invited citizens for use as their personal car for two weeks for 84 of the driver/participants and, during the later stages of the project, 24 drivers were given the vehicle for a total of five weeks. In this manner, the vehicles were put into naturalistic use, without constraining where the person drives, or when, or how. Each driver was also free to choose between operating manually or with conventional cruise control during the first week and between manual or ACC driving during the second (or subsequent) weeks…. Approximately 35,033 of the mileage was covered with ACC control actually engaged out of a total of 114,044 miles representing 11,092 individual driving trips. (ACC was used in 2,364 of the 11,092 trips.) No crashes occurred during ACC driving. Persons drove primarily in Michigan but some also undertook long trips within the United States."

Fancher et al. (1998) report that "the central finding presented here is 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. Notwithstanding having some concerns, field test participants were completely successful at operating ACC over some 35,000 miles of system engagement. In examining the results, the researchers observe that the role played by the driver as the supervisor of ACC entails subtle issues whose long-term safety and traffic impacts are unknown. These issues pertain to the shared-control nature of ACC driving requiring a fine match to the perceptual and cognitive behavior of drivers in a safety-central task that affects others driving nearby. Thus, while offering great promise for improving the quality of the driving experience, ACC implies an inherent necessity for human-centered design."

4.1.3.2 Before and after impacts simulation for ACC

In a paper by Van Aerde and Rakha (1999) discussed the requirements and logic that are needed in order to be able to simulate the before and after impacts of an adaptive cruise control system. These requirements relate to an ability to capture and calibrate steady-state car-following behavior, vehicle acceleration and deceleration behavior, and consequent lane changing, fuel consumption, and emission models. The model would need to be able to capture the absence of adaptive cruise control and then capture the impacts of adaptive cruise control when it is present. It is noted that some of the attributes that are needed to model the after condition can be derived directly from the design specifications of the adaptive cruise control system. However, many other attributes are associated with the way that drivers use the system and can only be measured through direct field measurements. The paper provides some sample data that illustrates how the calibration steps for the before condition can be conducted. A complementary paper describes the statistical analysis of the differences in the after condition.

4.1.3.3 Field Operation Test of ACC vs. CCC

In a publication in 2001 Rakha et al. evaluated the safety impacts of an ACC system relative to a Conventional Cruise Control (CCC) utilizing data that were gathered as part of a Field Operational Test (FOT) in Ann Arbor, Michigan. The safety of the ACC system was quantified considering three surrogate safety measures. The first safety measure considered the car-following behavior of an ACC system relative to manual driving in order to identify potential differences in driver/vehicle aggressiveness. The second safety measure considered changes in demands on driver resources associated with ACC technology. The third, and final safety measure, considered differences in number of braking maneuvers and near encounters associated with ACC and CCC driving. These three surrogate safety measures were utilized to identify any potential hazards that could be associated with an ACC system. The three surrogate safety measures demonstrated consistency between ACC and manual car-following behavior, an increased usage of cruise control with adaptive features, reductions in driver manual resources and potential reductions in visual resources, and no differences in braking interventions and "near encounters." These findings collectively suggested that the use of ACC did not appear to impose a safety hazard on the transportation system.

4.1.3.4 Monte Carlo simulation of system-wide CACC impacts

In a study in 2002, VanderWerf et al. conducted a Monte Carlo simulation study to quantify the system-wide impacts of a CACC system. The vehicle capabilities chosen for the evaluation were:

- Vehicles driven by "normal" human drivers using a state-of-the-art car-following model;
- Vehicles whose speed is controlled by a relatively simple, but high-performance, Autonomous Adaptive Cruise Control (AACC) system, with a driver-selected time-gap setting of 1.4 s between consecutive vehicles; and
- Vehicles whose speed is controlled by a more advanced CACC system, using vehicle–vehicle communications to enable operations with a time-gap setting of only 0.5 s between consecutive vehicles.

The AACC system was intended to represent a typical first generation product such as those now entering the market. The time-gap setting of 1.4 s is typical of the middle range setting on such vehicles, which are generally adjustable for time gaps from 1.0 to 2.0 s.

The CACC system was intended to represent a significantly more advanced product in which the equipped vehicle's speed control system could receive wireless communication of the speed, acceleration, and fault conditions of a similarly equipped preceding vehicle. It was assumed that when the similarly equipped vehicle was immediately ahead, it became possible to reduce the operating time gap to 0.5 s. This shorter time gap was chosen to take advantage of the improved ability of the vehicle to match speed changes of its predecessor, which reduces the fluctuations in the clearance between vehicles and makes it possible for the vehicle to respond more quickly and safely to fault conditions. These reduced fluctuations should also help make the smaller time-gap operations acceptable to drivers. At this short time gap, the ACC system also needs to have a high enough level of reliability and fault tolerance that it does not need to depend on the driver's manual intervention to avoid hazardous conditions (because the driver would not necessarily be capable of intervening quickly enough). When the CACC vehicle drives behind a vehicle that is not similarly equipped, it cannot operate at the reduced time gap but must fall back to the larger time gap of the AACC system.

The analyses were initially conducted for the distinct cases of 100% manually driven vehicles, 100% AACC, and 100% CACC to validate the modeling approach under these simplest cases. Once the cases were completed, mixed vehicle populations were then analyzed in all feasible multiples of 20% of each vehicle type. The study found that for time-gap settings of 1.55 s and 1.4 s, the AACC curves peaked at approximately 20% and 40% market penetration, respectively. For these two time-gap settings, a mixture of AACC vehicles with manually driven vehicles improved flow because the authors indicated that these vehicles tended to smooth out disturbances. In the case of the CACC system deployment the capacity increased by 100% given that the CACC vehicles followed at a headway of 0.5s compared to the manual driving of 1.1s. It should be noted that these results are inconsistent with the results of other studies that showed only minor increases in capacity (Van Arem, 2006). The study demonstrated that the capacity effect is very sensitive to the CACC vehicle market penetration, demonstrating the importance to gather the highest proportion possible of CACC vehicles into the same lane. This provides a strong justification for giving priority access to a special lane for CACC vehicles. For example, a four-lane freeway occupied entirely by manually driven vehicles could accommodate 8,200 vehicles/h based on the study simulations. However, if one of those lanes were devoted entirely to CACC vehicles, it could accommodate more than 4,200 vehicles/h by itself, and, if it were combined with the other three conventional lanes, the overall capacity of the freeway could be increased to 10,500 veh/h.

4.1.3.5 University of California PATH CACC Human Factors Experiment

In a recent study, a CACC system was developed by adding a wireless vehicle-to-vehicle communication system and new control logic to an existing commercially available ACC system (Shladover et al., 2009). The CACC was intended to enhance the vehicle-following capabilities of ACC so that drivers would be comfortable using it at shorter vehicle-following gaps. CACC was shown to produce a significant opportunity to increase traffic flow density and efficiency without compromising safety or expanding roadway infrastructure. The reports described the design and implementation of the CACC system on two Infiniti FX-45 test vehicles, as well as the data acquisition system that was installed to measure how drivers use the system, so that the impacts of such a system on highway traffic flow capacity and stability could be estimated. The results of the quantitative performance testing of the CACC on a test track were presented, followed by the experimental protocol followed for on-road testing with human subjects.

The overall purpose of this experiment was to determine whether or not the driving public would be comfortable with the very short (less than a second) time-gap settings that could be offered by a CACC system (Nowakowski et al., 2011). However, since the level of public awareness and market penetration of ACC systems was very low at the time of the experiment, the experimental test plan included about a week-and-a-half of testing with a conventional ACC system to allow the participants to become familiar with ACC systems. In terms of the results of the study, the study found that for the ACC system, the shortest time-gap setting, 1.1 s, was used most frequently, nearly 50 percent of the time when aggregated over all of the participants' commuting trips, but there were some fairly significant gender differences. On the whole, most of the males preferred the shortest time-gap setting, while most of the females preferred the middle, or 1.6 s, time-gap setting, but at least one male and two females spent the majority of the ACC testing period using only the longest, 2.2 second, time-gap setting.

Similarly, in the case of the CACC system, the shortest time-gap setting of 0.6 s was used most frequently (over 55 percent of the time when aggregated over all of the participants' commuting trips) but again, there were some fairly significant gender differences. On the whole, most of the males preferred the shortest time-gap setting, while most of the females preferred the 0.7 second time gap setting, but at least two of the females preferred the 0.6 second setting. Only one participant in the study (a female) showed a pattern of always using the longest time-gap setting on both the ACC and CACC systems.

The results of these field tests seem to indicate that drivers would be willing to accept such short time-gap settings. These results are very promising given that they demonstrate a 50% decrease in the time-gap setting for CACC versus ACC systems. These results would suggest a 60% increase in the roadway capacity if CACC systems could be implemented in the field (this assumes that the headway includes an additional 0.2 s to account for the vehicle length).

4.1.3.6 VTTI Eco-CACC

Most recently, the Center for Sustainable Mobility (CSM) at the Virginia Tech Transportation Institute (VTTI) developed an Eco-CACC system. The proposed system combines a predictive eco-cruise control system (ECC) with a car-following model to develop an eco-CACC system. The proposed model uses the Virginia Tech Comprehensive Power-based Fuel Model (VT-CPFM) to compute the optimum fuel-efficient vehicle control strategies (Rakha, 2011).

4.1.3.7 Coordination of Ad-Hoc Groups

In a study conducted by Ohio State University (Biddstone, Redmill & Özgüner, 2011), researchers investigated multi-vehicle formation ad-hoc group creation using autonomous vehicles. The goal was to determine the best possible path to desired destinations in an urban road network and use the framework to form groups of convoys with the same immediate goals. The groups/platoons were used to provide a more efficient traffic flow through traffic lights and in the presence of non-networked vehicles. The research described a distributed framework creating ad-hoc groups of autonomous vehicles using a distributed approach which allow for vehicles to create groups even when a central coordinator is out of range or doesn't exist. This process allows groups to be formed without predetermined formation points and facilitates a more natural vehicle grouping. This research provided a framework for autonomous vehicles to travel in an urban environment individually as well as working in groups to provide more efficient traffic.

4.1.3.8 Vehicle Automation with V2I and Nomadic Devices

In research conducted by the German Aerospace Center (DLR), Institute of Transportation Systems (Löper, Catalá-Prat, Gacnik, and Köster, 2011), a prototype evaluation was conducted to test wireless vehicular communication between vehicles and infrastructure, thus enabling a variety of new ITS use cases. The test scenario included automated driving, environment perception, communication with the infrastructure (Vehicle to Infrastructure, V2I) and with nomadic devices. The presented solution was demonstrated in February 2011 at the DLR research facility in Braunschweig. During the demonstration, the FASCar was able to automatically drive up to the traveler upon calling, drive fully automated on the route, interact with a traffic light and properly stop in front of an obstacle (crossing vehicle).

4.1.3.9 CACC and ACC Controller Architecture

Researchers at Laval University, Canada (Tsai et al., 2010) have been conducting research designing controllers to manage CACC systems. The design of these controllers is not an easy task when the problem is considered in its entirety, since the interactions taking place in the environment (from vehicle physics and dynamics to multi-vehicle interaction) are extremely complex and hard to model formally. That is why many ITS approaches consider many levels of functionalities. In their research, the team designed a multiple-level architecture using reinforcement learning techniques. They designed a longitudinal ACC controller, which is the first step toward a fully functional CACC low-level controller. The CACC approach combines a low-level controller to carry out low-level actions such as following vehicles and a high-level controller that coordinates vehicles and chooses the right low-level controller according to the state of other vehicles. These controllers were designed using reinforcement learning techniques and game theory for multi-agent coordination. The study showed that reinforcement learning can provide very interesting results for the efficiency of the low-level ACC controller as well as for coordination control. The study showed promising results for complete CACC design using reinforcement learning. However, much work has to be done to implement CACC functionalities with reinforcement learning techniques. Even though the paper described vehicle-following control and lane-changing coordination, many other control policies could be added. The researchers indicate that they plan to improve their system and integrate them into a general architecture to test it in a realistic vehicle simulator.

4.1.3.10 Proposed Further Research

Based on the earlier discussion of CACC systems, there is a need to conduct research in a number of areas. These research areas relate to the evaluation of the safety, throughput, and environmental impacts of such systems in order to ensure that the systems operate adequately. The following are proposed research topics in the area of CACC system development:

1. Enhance the agent-like capabilities of existing microscopic traffic simulation tools by separating and explicitly modeling the human and vehicle agents. This allows for capturing of the goals and limitations of individual drivers and vehicles & provides a unique framework for modeling emerging in-vehicle and connected vehicle applications.
2. Current microscopic traffic simulation software assume that cooperation between vehicles is limited to cooperation between a lead and following vehicle in the case of car-following behavior and that gap acceptance behavior involves a binary decision made solely by the lane-changing driver/vehicle. The design and development of agent-based cooperative vehicle-to-vehicle (V2V) systems will enhance current tools in order to capture the current limited cooperation between drivers and furthermore model cooperative systems.
3. Incorporate V2V and V2I communication models within traffic simulation software. When vehicles decide to transmit information to others, they pass the message through their communication systems. With this architecture, it will be possible to develop longitudinal and lateral controllers.
4. Develop a hierarchical controller architecture. The low level of this architecture is devoted to actuators whereas the high level to positioning and communication systems. The middle level is devoted to a CACC system that has two separate layers: the coordination layer and the action layer. The first is responsible for the selection of ``high level actions'' such as lane-changing or secure vehicle-following. Once this layer has chosen the

appropriate action to take, it transmits it to the action layer which must achieve this action by selecting the appropriate ``low-level actions'' that correspond to the vehicle's steering, brake and throttle. At the high level, the positioning system collects all data from all sensors and determines the position of the vehicle. The steering is used to enhance vehicle lane-changing behavior for use in cooperative merging systems.

5. Conduct traffic simulations to evaluate the potential safety, capacity, efficiency, energy, and environmental impacts of CACC systems for different network types (e.g. freeways, arterials, etc.), different levels of congestion, different levels of market penetration of CACC systems, and different CACC architectural configurations.
6. Conduct Field Operational Tests (FOTs) to characterize driver behavior and test promising CACC system configurations.

4.2 INFLO Theory of Operation

This section provides the operational definitions for the three INFLO applications in order to give the reader a fundamental understanding of how the applications and associated systems should work and what factors, in terms of technology and operations, are required for the system to function.

4.2.1 Q-WARN and Theory of Operation

The objective of a Q-WARN application 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 must be able to:

- Detect queues, through traffic detection systems or V2I or V2V deployments
- Be responsive to the dynamic nature of queue formation and propagation by being able to properly analyze the data in real time including location and propagation rates
- Provide an effective and timely deployment of the information through signing, I2V and possibly V2V deployments
- In a connected vehicle deployments, interface with a dynamic navigation system to provide rerouting alternatives

4.2.1.1 Technology Factors

Active

- Detection: Depending on the application
  - Traffic Detectors
  - Visibility Sensors
  - Pavement Condition Sensors
- Controllers
  - Used to collect, analyze the data and possibly create messages to be displayed
- Communications
  - Possibility via cellular modems to Variable Message Signs
- Information Dissemination:
  - Fixed messages signs with flashers
  - Portable Variable Message Signs
  - Variable Speed signs

Adaptive - Interactive

- Detection: Depending on the application
    - V2V, V2I, I2V technologies, including vehicle-based radar/laser sensors and communication devices
    - Shared vehicle data such as velocity, throttle position, brake activation
    - Traffic Detectors
    - Visibility Sensors
    - Pavement Condition Sensors
- Controllers
    - Used to collect, analyze the data and possibly create messages to be displayed
- Communications
    - Cellular modems to Variable Message Signs
    - Communication systems to central locations
    - Infrastructure to vehicle communications
    - Vehicle-to-vehicle communications
- Information Dissemination:
    - Fixed messages signs with flashers
    - Portable and fixed Variable Message Signs
    - Radio
    - Web Pages
    - Direct to vehicles
- Central
    - Software to manage a variety of queuing situations from simple to complex
    - Provide interaction with other subsystems like Variable Speed Limit signing

4.2.1.2 Operational Factors

Active

- Signing locations sufficiently upstream of condition and clearly visible
- Locations sufficiently upstream of condition and clearly visible
- Clear operational policies including queuing thresholds, persistence thresholds, content of messages, strategies when detection devices fail, and hours or operation
- Ongoing reviews of effectiveness

Adaptive - Interactive

- Signing locations sufficiently upstream of condition and clearly visible
- Other information dissemination technologies sufficiently upstream of condition
- Clear operational policies including queuing thresholds, persistence thresholds, content of messages, strategies when detection devices or communications fail, methodology of interaction with other subsystems, and hours or operation
- Ongoing reviews of effectiveness

4.2.1.3 Implementation Sequencing Considerations

Active

- Possible regarding the use of Variable Message Signing

Adaptive - Interactive

- Review of state of the practice

- Definition of a concept of operations
- Possible test environment
- Procurement
- Software development
- Deployment
- Operations

4.2.2 SPD-HARM Theory of Operations

The objective of dynamic speed harmonization (SPD-HARM) is to dynamically adjust and coordinate vehicle speeds in response to congestion, incidents, and road conditions to maximize throughput and reduce crashes. Current speed harmonization implementations have been shown to be an effective part of active traffic management, especially when combined with other strategies such as queue warning and temporary shoulder use.

There are three key factors that contribute to the operation of an effective speed harmonization system. The first factor is the availability of information on the prevailing condition on the field. The second factor is the existence of a reliable strategy for the speed limit selection. The last factor is the flow of information from the field to decision making center and vice versa. Basic operation process is as follows,

- The data on vehicles locations and movements, prevailing traffic condition (i.e., speed, density and flow), weather condition, and road surface condition is collected by sensors and transmitted to a decision making center.
- The decision making center can be an on-site computer, off-site computer, traffic control center, or even law enforcement personnel. This center is in charge of making decisions on the appropriate speed limit, which can be based on an on-line algorithm, off-line algorithm, or professional judgment and experience.
- The selected speed limit is transmitted directly to the vehicles to be displayed to the driver in-vehicle. Automated speed adjustments can be made by the vehicle control system, which would consider adjacent traffic conditions in determining appropriate vehicle speeds.

A variety of methods and technologies are at hand to support each process. Note that speed limit selection is in the core of this operation and operational efficiency and safety highly rely on it. The availability of information also plays an imperative role in the success of this process. However, following the approach discussed above is not sufficient for the success of a speed harmonization system. The following factors are essential in achieving the goal of implementing a reliable system.

4.2.2.1 Technology Factors

Timely, accurate and reliable transmission of information between and among vehicles, road sensors, infrastructure-based signs, and control centers is crucial to an effective dynamic speed harmonization system. In addition, since data relevant to speed harmonization are also critical to other safety and mobility applications and Advance Traffic Management Systems (ATMS), any speed harmonization-related data and communication decisions made will necessarily impact these other systems, and vice versa.

Data Sources

Data critical to dynamic speed harmonization will come from a variety of sources, including:

- **Real Time Traffic Data:** Vehicle speed and location data collected and disseminated by the vehicles themselves will comprise a critical input to a Connected Vehicle-enabled real time traffic data store. However, traditional detection sources will continue to provide traffic data as well, especially in the near term of Connected Vehicle technology deployments. Such detection includes inductive loop detectors (single or dual loops), overhead radar, and CCTV cameras.
- **Weather Condition Data:** In the Connected Vehicle environment, a great deal of localized weather condition data can be acquired from the vehicles themselves, including traction information, outside temperature readings, and windshield wiper activation information. Infrastructure-based road weather information systems (RWIS) and third-party weather data feeds can serve to supplement vehicle-acquired weather data and will likely play a larger role for weather information 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 Alabama and Tennessee variable speed limit projects).
- **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 SPD-HARM application in order to perform effective analysis and prediction of traffic conditions.

Data Processing and Speed Limit Selection

Speed limit selection is the critical function of the SPD-HARM application. No matter how high Connected Vehicle penetration rates are or how effectively and reliably information is communicated to drivers, the effectiveness of a dynamic speed harmonization program is ultimately constrained by the accuracy and intelligence of its target speed limits calculations. Thus, how data are processed and modeled and what algorithms are used on these data is as important as the quality of data received.

The following is a discussion of the major approaches to speed limit selection for speed harmonization applications:

- **Personal Experience:** In this method, an operator decides to choose speed limit based on the prevailing condition (e.g., variable speed limit in Wyoming). Note that the operator sometimes gets advice on the appropriate speed limit from a computer program.
- **Off-line:** In this method, pre-determined speed limits, based on historical data and time of day, are used for the speed limit selection.
- **On-line:** In this method, an appropriate speed limit is selected based on a computer-based algorithm or look-up matrix using the real-time prevailing conditions of the roadway as input.

However, a speed limit selection algorithm robust enough for effective dynamic speed harmonization in the future Connected Vehicle environment must go beyond these traditional methods. It must be capable of predicting traffic conditions, identifying potential solutions, and evaluating these solutions 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.

Dynamic Speed Limit Display:

The display of the selected speed limit is the ultimate and main user-facing output of the SPD-HARM application. In the Connected Vehicle environment, speed limit display and/or alert will occur in-vehicle, to be provided to the user via the interface developed by the vehicle or device manufacturer. Traditional infrastructure-based speed limit signage, which typically utilizes fiber optic communication technology and LED displays, will likely continue to be used in the near term of Connected Vehicle deployment. However, due to the sparseness of typical sign deployment and frequent poor visibility conditions, infrastructure-based dynamic speed harmonization solutions must be considered only a supplemental part of any future Connected Vehicle dynamic speed harmonization program.

4.2.2.2 Operational Factors

Speed harmonization implementations today typically operate within the purview of the local traffic management center (TMC), with input from associated transportation and law enforcement agencies. The TMC, in cooperation with these other groups, is ultimately responsible for the selection and display of speed limits. In a future Connected Vehicle environment, it is anticipated that the key responsibilities for speed selection and display will remain with the TMC. In this environment, however, data feeding to the TMC's speed selection algorithm will come mostly from live vehicles via V2I communication and the resulting speed limit recommendations will be communicated directly back to the vehicles to be displayed in-vehicle. The critical task of determining appropriate speed limits for a given corridor will occur within that corridor's affiliated TMC.

Advisory vs. Mandatory Speed Limits

A SPD-HARM application should be able to operate in environments in which broadcast/posted speed limits are mandatory or advisory. While compliance is expected to be higher in a mandatory speed limit environment, experience has shown that an advisory environment can achieve high levels of compliance as well (through providing broad public outreach and education, minimizing large or rapid changes in speed limits, and providing justification or explanation for requested speed changes—see Section 3.2 for further discussion). An additional tool to use to encourage compliance in an advisory environment could be to extend the usage-based car insurance model[1], which utilizes in-vehicle sensors to measure driving performance (tracking distance traveled, acceleration levels, and other characteristics), to tie speed limit adherence to insurance premiums.

In today's mandatory speed limit environment, which is most commonly found in European speed harmonization deployments, enforcement occurs using automated speed enforcement technologies, in particular automated overhead speed detectors. However, expanded deployment of V2I-based communication raises the prospect of utilizing novel and more effective methods of speed limit enforcement. For example, Electronic Vehicle Identification (EVI), a system that identifies individual vehicles electronically, can be used to more accurately identify violators. Intelligent Speed Assistance (ISA) technologies, which enable the communication of localized speed limits to in-vehicle devices, can keep drivers better informed of current speed limits and also provide law enforcement information as to where speed violations are occurring and which vehicles are speeding. Another novel approach, which simultaneously provides a disincentive to speeding and an incentive to obeying the speed limit, is the Speed Camera Lottery System, a 2010 demonstration project implemented in Stockholm, Sweden. Under the lottery system, money collected from identified speed violators is regularly gifted to randomly selected individuals who have been identified as speed compliers. Results from the lottery system have shown a 22% average reduction in speeding.

4.2.3 CACC Theory of Operation

The objective of cooperative adaptive cruise control (CACC) is to dynamically adjust and coordinate cruise control speeds among platooning vehicles to improve traffic flow stability and increase throughput.

4.2.3.1 Technology Factors

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

[1] Usage-based car insurance products are steadily gaining in popularity in the U.S. auto insurance market. Progressive®, an industry leader in the area, currently offers a product called Snapshot℠ (http://www.progressive.com/auto/snapshot-how-it-works.aspx). Customers who sign up for the program install a device that measures and sends to Progressive driving behavior, including time of operation, vehicle speed, and rates of acceleration and braking. These data are used to provide a more accurate assessment of a user's driving behavior and accident risk and thus can help produce a more precise and potentially lower insurance quote or premium. More importantly, from a safety and mobility improvement perspective, it provides the motorist a direct incentive to drive smarter and safer.

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.

4.2.3.2 Operational Factors

The communication is the means used by drivers to cooperate on the road and it will be important to know how vehicular communication can be used. Within this context, wireless inter-vehicular communication supplies CACC systems with data in order to achieve secure longitudinal following with a front vehicle. To this end, a solution that mixes approaches coming from optimal control and machine learning techniques may be required, specifically reinforcement learning using function approximation techniques. More specifically, function approximation techniques with gradient-descent learning algorithms can be used as means to directly modify a policy in order to optimize the CACC performance. Once longitudinal control is obtained, the system may also (while out of the scope of the INFLO project) incorporate a lateral control system. This could be done using reinforcement learning where the reward function is viewed under the form of a potential function over the width of a lane, similar to current force feedback given by existing lane-keeping assistance systems. Thus, this reward function can direct the driving agent towards learning an adequate lane change policy.

In addition to longitudinal and lateral controls, vehicular communication is also used to supply drivers with information regarding (and related to) the conditions of the traffic on the road. Of course as the driver is in the loop of lateral and longitudinal controls, the final decision is on the driver regarding the current situation and the information that is received via vehicular communication.

Other operational factors include identifying and addressing the fundamental micro and macro cyber-physical issues associated with the development, implementation, and deployment of CACC systems. In addressing these operational factors there is a need to attempt to answer the following questions:

1. What is the optimum level of information and automated response that should be provided to a driver for various potential crash avoidance scenarios?
    a. What types of crash scenarios is a driver good at resolving and what types are better addressed through automation?

   i. Can a taxonomy of imminent crash characteristics be identified that will allow for the creation of rules or guidelines for when the driver should be advised/warned, assisted, or taken out of the response loop?
   ii. What are the limits of perception, decision, response that can feed into the model? For example when should the system take action in order to allow the driver sufficient response time?
   iii. What is the driver good at resolving? What is the automation good at resolving? When should the system transition between assumed levels of human response and automated response?

b. What types of issues must be addressed to assure an effective transition between human response and automated response?
   i. What are the drivers' expectations about the automated response of the system?
   ii. What role do individual differences in driving style, risk acceptance, technology acceptance, etc. play in the driver's desires for how the system should operate?
   iii. What types of feedback are appropriate for letting the driver know what level of automation is being applied by the system?
   iv. What is the role of driver intent on developing an effective zero crash cyber-physical system? For example, a driver making a left turn followed by a right turn might know based on experience which lane to be in. How can the system benefit from the driver's experience?
   v. What are the user interface design issues?
   vi. Can the system adapt to driver characteristics, driving styles, preferences, etc.?

2. What is the potential for the emergence of unintended consequences caused by using such systems?
   a. Can the system affect driver behavior in the long run?
      i. Will drivers begin to fully trust the system, become less vigilant, and therefore take themselves further out of the control loop?
      ii. Will drivers fail to develop basic hazard perception and collision avoidance skills as they become less necessary?
      iii. What is the effect of having drivers go from an equipped to a non-equipped vehicle? Will they be able to adapt to the different driving control algorithms?
      iv. What happens when the system fails or sensors don't provide quality information and how does the system convey this failure to the driver?
      v. How will the driver react to false alarms? Will the driver start to ignore the system input?
      vi. How will surrounding vehicles that do not have such systems react to these fully-equipped vehicles?
   b. Can automated vehicle responses that avoid an initial collision raise the risk of other or higher severity crashes? For example, the automation steers away from a 10 mph rear-end collision into a 60 mph head on collision.

3. What are the potential negative impacts on the overall traffic safety?
   a. Can equipped vehicles raise the safety hazard of non-equipped vehicles by causing asymptotic instability within the traffic stream?
   b. How will non-equipped vehicles respond to the behavior of equipped vehicles?

4. Are there high-level concepts that can be applied to the development of a system operating philosophy?
    a. Should automation apply to braking only vs. steering and braking?
    b. What are key opportunities for standardization of user interface elements?
5. What are the expected benefits of such systems?
    a. Does the system produce crash reductions?
    b. What are the impacts on system-wide network efficiency, energy, and the environment?

4.2.3.3 Implementation Sequencing Considerations

The implementation of CACC systems requires that a number of sequencing considerations be considered. These considerations are discussed briefly in this section.

First, prior to implementing and developing such systems, a survey of the industry is required to assess the state-of-the-art in vehicle sensing systems. A taxonomy of required and desired sensor inputs for a CACC system needs to be defined that specify the categories of data that the sensing systems shall supply. Candidate sensing systems within each category will be researched for the specified accuracy, reliability, practical applicability to the CACC concept. The next step will entail identifying the best sensing system candidates for actual vehicle deployment over the next five years. Candidate sensing systems identified in the previous step will be assessed for their likelihood of being deployed in a large-scale vehicle environment (cost, form factor, etc.) and technical maturity over the next five years. The optimum sensing systems that could be used on a crash-resistant vehicle will be identified.

The following step will entail outfitting instrumented test vehicles with a suite of state-of-the-art sensing systems. The optimum sensing systems identified in the previous step should be acquired and installed on instrumented test vehicle. The outputs of each of the sensing systems will be captured in real-time along with the standard video and sensor data normally captured. For each sensing system measure, there will be a secondary data source that will allow for its validation. For example, if a forward radar system is tested, a secondary laser-based distance detection sensor or perhaps manual video data reduction would be used to validate the results being produced by the forward radar sensor.

Operate the instrumented test vehicle in a wide variety of traffic and vehicle operating conditions. During this step, the instrumented vehicle with all installed sensing systems will be operated in a wide variety of traffic and driving conditions. Continuous output from each sensing system will be captured and stored along with the video and sensor data.

Compare the captured sensing system data to results generated by manual or other secondary sensor analyses to evaluate data quality from each sensing system. Depending on the scope of the analyses either a continuous or sampling strategy could be employed to regions of the collected data set and could be analyzed for sensor data quality. Once the data regions of interest are identified, manual data reductionists will review the data in the video and compare to reported sensor values or the data will be compared between two exclusive sources to determine agreement. The data values will be evaluated for availability and accuracy.

Report the actual data quality for each sensor and identify how the data quality results will necessarily impact the cyber-physical interface concept development. The final step of this process will be to determine the data quality parameters for each likely sensing system. The results of the manual or semi-manual data analysis conducted in the previous step will be reported. In addition to raw results, we will seek to assess for each sensor variable whether issues of data quality could be improved through intelligent data management by using filtering, prediction, or other data handling techniques. The remainder of this task will address how the quality of data coming from the individual data sources might be addressed in the cyber-physical interface design. We will explore creative ways to both handle data quality degradation and how to inform the driver that crash-resistance functions may not be operating at 100 percent capability. One method of handling imperfect data in an algorithm is to report a continuous confidence level for the algorithm output that indicates how well the algorithm thinks it is performing. Once a confidence value is determined, it must be decided how to modify system response to account for system degradation. There are many questions to be answered from that point forward including the following; Should the driver be notified of the degradation? If so, how should drivers be notified to be sure they comprehend the deficiency and what it means to overall system performance? Should specific aspects of system be temporarily disabled when data is found to be less than acceptable? If poor data results in the failure of only one subsystem, should the entire system be disabled or perhaps just the one function?

The next step will entail running various simulation runs considering different forms of CACC systems and quantifying the system-wide impacts of these systems. Prior to conducting the simulation runs, behavioral models need to be developed using the field, controlled field, and driver simulator data that would be gathered. Various measures of effectiveness will be considered in the evaluation, including: system throughput, system delay, number of vehicle stops, vehicle fuel consumption, environmental impacts, and safety impacts.

This task will attempt to answer the following questions:

a. What are the potential negative impacts on the overall traffic safety?
b. What are the expected benefits of such systems on other measures of effectiveness (e.g. system throughput, efficiency, fuel consumption, and the environment)?

In addressing these two questions the analysis would need to use the developed behavioral model to evaluate the impact of equipped vehicles on the safety hazard of non-equipped vehicles and how the various vehicle fleets will interact with one another. This analysis would consider fully equipped vehicles, partially equipped vehicles, and non-equipped vehicles. Different levels of market penetration would be considered in the analysis. Field operational tests must also be conducted prior to the full deployment of the system. Partnering with automakers will be a critical requirement for advancing research into a deployment stage.

4.3 Benefits of Co-Deploying Q-WARN, SPD-HARM, and CACC

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. See Figure 4-4 for an illustrative example of how all three applications used in conjunction can help minimize the impact of a freeway incident on traffic flow.

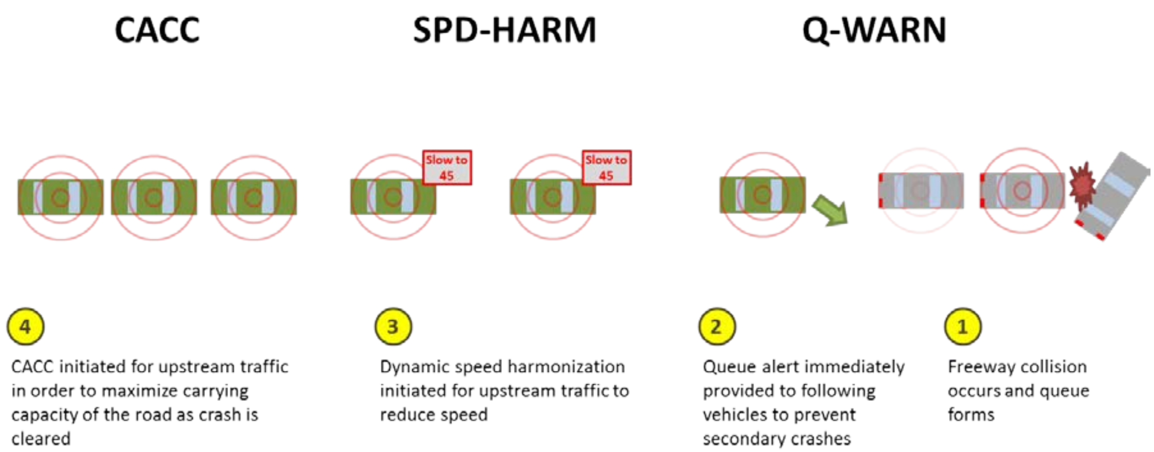

Figure 4-4. Combined Q-WARN/SPD-HARM/CACC Illustrative. (RITA, ITS Joint Program Office, March 2012)

In addition to the benefits of deploying the three bundled INFLO mobility applications in concert, the applications would also benefit from integrating with other applications, including safety systems like Electronic Stability Control (ESC) systems, Night Vision Systems, Curve Speed Warning systems, Lane Departure Warning systems, Alcohol Monitoring systems, Brake Assist Systems, Steering Assist Systems, Forward Collision Warning (FCW) systems, and Pre-crash sensing systems. Coordination with ramp metering systems, as Shladover et al. (2010) demonstrated in speed harmonization research, would also help provide the INFLO applications a better connection with the overall transportation network. Finally, integrating the INFLO applications with Advanced Traveler Information Systems (ATIS) would provide road users enhanced information about the state of the transportation system, pre-trip planning, route-making, and incident avoidance.

4.4 Role of Basic Safety Message for INFLO

Basic Safety Message (BSM) is one of the key message sets defined by the USDOT, under *SAE J2735 - Dedicated Short Range Communications (DSRC) Message Set Dictionary*, for the standardization of messages, data frames, and data elements to be used in vehicle-to-vehicle and vehicle-to-infrastructure communication that utilize 5.9 GHz DSRC (1000-meter transmission range). There are two types of BSM that can be transmitted:

- ***BSM Part 1*** – periodic transmission (at about 10 broadcasts per second) of core data elements, including vehicle position, heading, speed, acceleration, steering wheel angle, and vehicle size; and
- ***BSM Part 2*** – event-triggered broadcasts of data elements drawn from an extensive list of optional elements (e.g., ABS activated).

The Basic Safety Message, in particular BSM Part 1, will likely comprise key data sets for the INFLO applications, owing to the highly relevant data that BSM captures and the frequency with which the data are collected and transmitted. However, the intention of the INFLO concept development effort is not to specify a particular communications protocol (e.g., DSRC), but rather to determine the kinds of data and transmission frequencies that are required for the INFLO applications to function properly. Commercial cellular (including 3G, 4G, and 4G LTE), Bluetooth, and other wireless communication systems will be considered in addition to DSRC as potential communications technologies for the INFLO application to utilize to disseminate and receive BSM and other relevant data.

Chapter 5. Summary of Results/Synthesis of Findings

5.1 Q-WARN

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.

The queue warning applications that have been deployed have been done so for varied reasons, some of which include (Wiles et al., 2003):

- Construction zone queues
- Border crossings
- Fog warnings
- Weather warnings
- Exit ramp spillback
- Recurring congestion
- Incident congestion
- Secondary collisions

5.1.1 Benefits and Impacts

The following are some of the significant findings from queue warning research and deployments:

- Due to the fact that queue propagation fluctuates rapidly and occurs in multiple lanes, a queue warning application utilizing vehicle-to-vehicle or vehicle-to-infrastructure communication will be much more effective at dissipating shockwaves than traditional static queue warning applications (Wiles et al., 2003).
- The effectiveness of queue warning is greatly increased when combined with other traffic management strategies. In particular, as evidenced in the Washington State I-405 advanced traffic management study (WSDOT, 2011), coordinating queue warning with speed harmonization (via variable speed limit signing) produced a significant reduction of rear-end collisions in corridors where both applications were utilized in concert.

5.1.2 Lessons Learned

Some of the key lessons learned from queue warning deployments and research include:

- Warning signs placed too close to queue tails might be overrun, and signs placed too far from the queue can become inaccurate (Wiles et al., 2003).
- Conditions change too quickly for human operators to handle appropriate warning sign adjustments, necessitating an automated system (Wiles et al., 2003).

5.2 SPD-HARM

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 (Austroads, 2009):

- 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.

5.2.1 Benefits and Impacts

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, especially in unsafe driving conditions. The speed harmonization systems examined have been generally very effective at effecting such speed 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 maximum one-minute average speeds (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 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 advisory 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 advisory 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 mandatory 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:

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).

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).

5.2.2 Lessons Learned

Some of the key lessons learned from speed harmonization deployments and research are discussed below.

To achieve high speed limit compliance, it is important to consider driver perception of safe speeds when posting variable speed limits. As discussed in Section 5.2.1, higher rates of speed compliance were observed when there was a high correlation between the posted speed limit and the drivers' perception of safe speed limit (CDOT, 1999) (Beltz et al., 2009) (MoDOT, 2010) (Nygårdhs, 2011). While speed limit enforcement is positively correlated with high compliance, advisory speed limits have been shown to achieve high levels of compliance when accompanied by broad public outreach and education, minimized large or rapid changes in speed limits, and provided justification for requested speed changes (Kwon et al., 2006) (FHWA Work Zone VSL Evaluation, 2004) (FHWA Speed Harmonization and Shoulder Use, 2009) (CDOT, 1999) (Beltz et al., 2009) (MoDOT, 2010) (FHWA Elk Mountain VSL, 2010).

Speed harmonization when combined with queue warning can provide very effective incident management. Speed harmonization is capable of slowing down the upcoming traffic in the case of incidents and, if combined with lane control signals and queue warning, can produce and excellent platform for incident detection and management (FHWA *ATM Scan*, 2007) (Harito, 2011) (FHWA *Speed Harmonization and Shoulder Use*, 2009) (United Kingdom Highway Agency, 2007).

The Florida Department of Transportation's evaluation of the I-64 speed harmonization implementation (USDOT RITA, 2009) produced the following relevant lessons learned:

- Identifying the advisory and mandatory speed limits is essential before launching a speed harmonization program.
- Developing the concept of operation is essential before designing the speed harmonization system.
- The algorithms of speed limit selection should account for vehicles with low speeds during uncongested flow.
- Effectiveness of speed harmonization is improved when human operators can intervene and adjust algorithmically-generated speed limit change recommendations.

5.3 CACC

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 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).

5.3.1 Benefits and Impacts

The benefits and impacts discussed in this section reflect the theoretical potential of CACC systems, as they have only been deployed to date in experimental, tightly controlled settings and not in operational environments.

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).

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.

5.3.2 Lessons Learned

Some of the key lessons learned from CACC and related systems research include:

- Given the fact that, especially in the near term, the road network will comprise a mix of CACC and non-CACC enabled vehicles, it is important to investigate further the safety and mobility implications of a traffic flow environment comprising a mix of technology-enabled vehicles (Pueboobpaphan et al., 2010).
- Drivers have been shown to adjust their reaction times (level of attention) based on the situation they are faced with on the roadway: at merging and diverging sections where drivers were faced with short headways, they adjusted their reaction times positively. This is opposite of the conventional understanding that drivers' reaction times are constant and that drivers will maintain a safe following distance accordingly (Pueboobpaphan et al., 2010).
- Car-following models (as discussed in van Arem's research in the Netherlands) must be improved upon in order to sufficiently capture human driving behavior with realistic traffic flow stability, capacity and reaction times.
- CACC systems should utilize dynamic reaction times as part of their car-following models due to the fact that human drivers have been observed to adjust their level of attention (a stand-in for reaction time) in situations like merging and diverging where drivers are faced with short headways (Pueboobpaphan et al., 2010).

Chapter 6. Concept Development

By definition, concept development is a process driven by a set of customer needs and target requirements (and eventually, specifications), which are then converted into a conceptual design(s) and potential technological solution(s). User needs will be identified during Subtask 2.2 when we solicit stakeholder input on transformative goals, performance measures and user needs. The final concept of operations document, which will be developed in Subtask 2.3, will be a guideline for the implementation of the INFLO bundle.

However, given the current state-of-the-practice with Q-WARN, SPD-HARM, and CACC, and project team's experience with the implementation of current technologies that reflect these concepts, we can begin to define the proposed implementation of these technologies. Further, we can describe the potential impacts of INFLO implementation from an institutional, operational and technical perspective. The following subsections cover initial thoughts about the implementation of the INFLO bundle and the impacts resulting from the implementation.

6.1 Proposed INFLO Project Implementation

Given the research described in this report and the upcoming tasks, this subsection covers the process that is proposed to USDOT for the eventual implementation of the INFLO bundle. The first step in this process is gathering stakeholder input on the needs associated with the three mobility applications. The purpose of this step, according the Statement of Work, is "to solicit stakeholder input in identifying transformative benefits or goals for [each] application, corresponding performance measures, and user needs for [each] application, which shall be used in the development of the INFLO Concept of Operations and functional requirements." This step will include conducting a webinar and face-to-face meeting to obtain this stakeholder input. The input will consist of the stakeholders' view of the transformative benefits or goals for each application, performance measures, and user needs.

The second step leading to implementation is the development of the Concept of Operations. This step will incorporate the findings from assessment of relevant prior and ongoing research described in this report and the stakeholder input received in the previous step. The final Concept of Operations document will be a guideline for the implementation of the INFLO bundle. It will identify connections and attributes of the three applications, and the interfacing entities and systems. The Concept will include operational scenarios for the three applications. Stakeholders may use these scenarios as they consider those scenarios they would like to include in the final Concept of Operations.

The third step is the development of the functional requirements, qualitative and quantitative performance targets for each functional requirement that must be accomplished in achieving the transformative goals identified in the prior step, and high-level data and communication needs. System Requirements serve as the foundation for developing an effective solution. In order to ensure successful implementation, system requirements must be correct, compatible, complete, clear, feasible, verifiable, traceable, and modifiable. This assessment report will enable the project team to address the needs, interface and capability requirements identified during the research. The Team will convert these items into a set of requirements in a matrix format that ties each requirement back to the original driver. The team will address all required aspects of the development to support defining the functional and performance requirements including the software application, hardware components, network protocols, data needs, and interfaces that the applications will need to support. This will help ensure that the applications support the range of capabilities desired by USDOT including interfacing with the connected vehicle system and other identified systems.

The fourth step includes the identification of high-level data and communications needs based on the Concept of Operations, and Functional and Performance Requirements.

The final step prior to deciding whether or not INFLO applications should be demonstrated is determining how realistic it will be to begin further development. This requires an understanding of the criteria for testing the applications. The purpose of this task will be to assess the technical and non-technical issues related to the field-testing of the INFLO System.

6.2 INFLO Implementation Issues and Challenges

Because the user needs, Concept of Operations, and requirements will be developed after the submission of this report, the potential impacts of INFLO implementation are not completely known at this time. However, there are a number of potential issues and challenges that are likely to impact the eventual deployment of the INFLO applications that can be introduced here.

6.2.1 Institutional Challenges

The implementation of the INFLO bundle may present a number of critical institutional challenges. First, the existing institutional environment in the location or region where the implementations will take place will be a key factor in the success of the deployment. If the institutions involved have not worked together or coordinated before, there could be a significant effort needed to bring the stakeholders together. This institutional issue also extends to application vendors (e.g., auto manufacturers and aftermarket device makers), who traditionally provide proprietary solutions and do not share information with their competitors. And there may be changes necessary within the organizations participating in the implementation. For example, staff may need to be reassigned to focus on the INFLO implementation.

Other potential institutional issues include:

- Changes required to the existing institutional environment in the location(s)/region(s) being considered for deployment
- Coordination with other providers and agencies in order to jointly procure systems and/or exchange data and information

- Lacking ITS technical experience - this can relate to either human or computer resources
- Changes needed in the technology vendor community to successfully develop and implement new systems to accomplish the goals of the three INFLO technologies
- The USDOT does not have full responsibility over infrastructure deployments/operations:
  - Responsibilities divided among state, county, and municipal agencies, with each having different capabilities and priorities
  - Variations among regions and populations, with different preferences and propensities regarding adopting new technologies

6.2.2 Operational Challenges

In addition to institutional-level challenges, several operational challenges must be met in order to successfully deploy the INFLO bundle of applications:

- Funding necessary for technology procurement, implementation, and on-going operations and maintenance
- Concerns over data privacy—how will user data be used and protected and who owns the data
- Law enforcement's access to data that are generated and communicated
- Liability issues:
  - How is liability allocated among stakeholders?
  - Amplified when driver cedes control responsibility of the vehicle
- Public outreach and education will be critical to achieve motorist buy-in and compliance
- Methods for ensuring data and network security for V2V and V2I communication must be developed
- Third-party certification of the system will be required prior to full deployment; a comprehensive testing and certification process must be developed

6.2.3 Technological Challenges

Cooperative ITS literature review by Shladover et al. (2009) identified various technological challenges relevant to the implementation of the INFLO bundle of applications, including:

- Electronic actuation of driving functions (steering, engine, transmission, brake)
- Sensors to accurately and reliably detect range and closing rate to other vehicles and to lane boundaries
- Robust vehicle absolute positioning technologies and high accuracy digital maps
- Obstacle detection, warning and avoidance
- Robust information processing systems, including fault detection, identification and accommodation
- Safety critical software systems
- Systems to manage the transitions between automated and manual driving (check-in and check-out)

6.3 Potential Impact of the INFLO Bundle

A major outcome of the INFLO project is an assessment of what impact an operational INFLO system, incorporating Q-WARN, SPD-HARM, and CACC applications, will have on safety, individual mobility, system productivity, and the environment. Such potential benefits will be examined in more detail as part of the Concept of Operations portion of this task order; however current practice experiences and ongoing research results suggest that in the Connected Vehicle environment the INFLO applications will be able to achieve significant transformative outcomes in these areas, in particular on safety and throughput. Key INFLO impacts on safety and throughput, based on our understanding of the INFLO applications, are discussed below.

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 will achieve 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 will achieve 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

Lastly, 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.

A fuller discussion of how the three INFLO applications can be deployed together and how such a co-deployment can benefit each will be presented in the Concept of Operations portion of this task order.

Appendix A – List of Abbreviations/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

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