Multi-Modal Intelligent Traffic Signal System

Assessment of Relevant Prior and Ongoing Research

FINAL

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Version 1.0

RECORD OF CHANGES

A – Added, M- Modified, D - Deleted

Version Number	Date	Identification of Figure, Table, or Paragraph	Title or Brief Description	Change Request Number
1.0	5/28/12	N/A	Initial Draft submitted for review and feedback.	CDRL 77
2.0	6/15/12	M	Response to Panel Comments	CDRL 80

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ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ATDM	Active Traffic and Demand Management
CoE	College of Engineering
ConOps	Concept of Operations
CTS	Center for Transportation Studies (University of Virginia)
DMA	Dynamic Mobility Applications
CTS PFS	Cooperative Transportation Systems – Pooled Fund Study
DOT	Department of Transportation
DSRC	Dedicated Short Range Communication
FDW	Flashing Don't Walk
FHWA	Federal Highway Administration
FSP	Freight Signal Priority
GHz	Gigahertz (1 x 10^9 Hz)
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronic Engineers
GRA	Graduate Research Assistant/Associate
ISIG	Intelligent Traffic Signal System
ISO	International Organization for Standardization
ITS	Intelligent Transportation Systems
MMITSS	Multi-Modal Intelligent Traffic Signal System
NCHRP	National Cooperative Highway Research Program
NTCIP	National Transportation Communications for ITS
PATH	Partners for Advanced Transportation Technology (PATH) *is administered by the Institute of Transportation Studies (ITS) at the University of California, Berkeley*
PFP	Pooled Fund Project
PFS	Pooled Fund Study
PPT	PowerPoint
SAE	Society of Automotive Engineers
SDD	System Description Document
SIE	Systems and Industrial Engineering
SPA	Standard Process Assets
SPaT	Signal Phase and Timing
SRD	System Requirements Document
TRB	Transportation Research Board
TSP	Transit Signal Priority
UA	University of Arizona
US	United States
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
UVa	University of Virginia
VDOT	Virginia Department of Transportation

1. Scope of the Assessment of Relevant Prior and Ongoing Research

1.1. Perspective and Goal of the Review

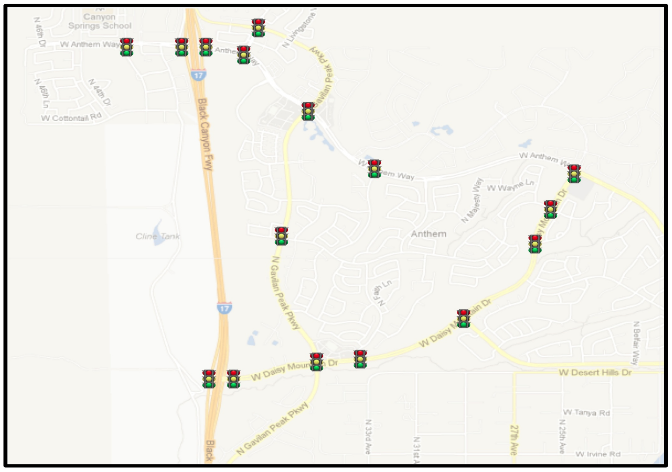
The purpose of this report is to review and assess research related to multi-modal intelligent traffic signal systems (MMITSS). The goals of the review are to understand research that has been completed or underway that could impact the design and operation of MMITSS as well as to identify key stakeholders and related concepts of operations that have been developed, as well as system designs, including architectures, algorithms, and performance measures identified related to MMITSS.

An important observation from this review is that while all traffic control systems serve multiple modes of travel, the review found no comprehensive study or demonstration project that addressed simultaneous optimization of all models of travel. There are many studies of adaptive traffic control, transit priority, emergency vehicle preemption, and some work related to traffic signal priority for trucks, and there are some combinations – such as adaptive signal control and transit priority. There is clearly a need for a comprehensive design that considers optimization all of the travel modes simultaneously.

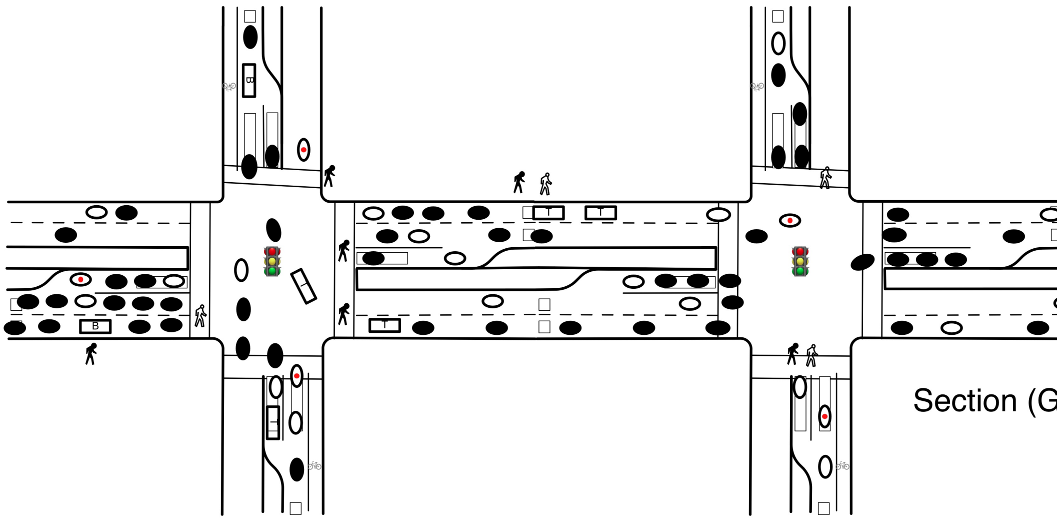
1.2. Review of Existing Practice

The state of the practice in traffic control today is actuated traffic signal control where different conflicting movements of vehicles are controlled by phases that are called by detectors when vehicles are present at the intersection. Typically, intersections are operated in a time-based coordinated operation with a signal timing plan that has been designed to accommodate different volumes of flow based on time of day traffic flow patterns.

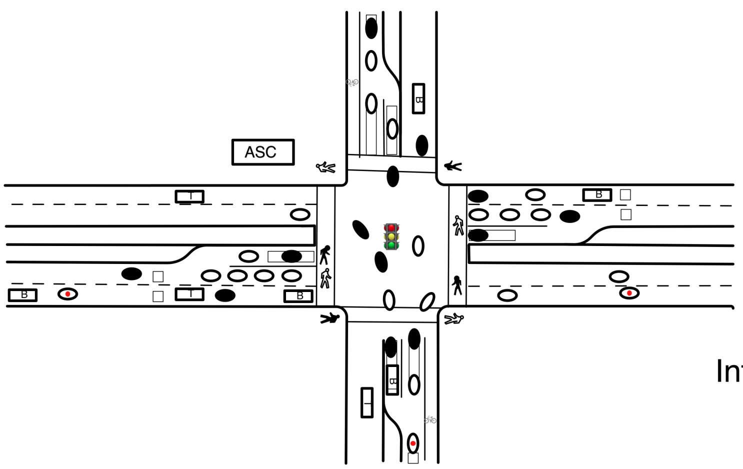
Traffic signal control can be considered as a hierarchical control problem starting at the lowest level with a single intersection, then a higher level that consists of collections or groups of intersections called sections, and finally, at the highest level, the entire system. Figure 1 illustrates the different hierarchical levels of a traffic control systems. At the intersection level, traffic control decisions are made based on vehicle detections that call and extend phases, or from pedestrian calls for the pedestrian phase intervals (Walk, Pedestrian Clearance, and Don't Walk). Phases are the signal control constructs that provide outputs to the signal heads for the different movements of traffic. At the section (or group) level, collections of traffic signals may be operated in a synchronized or coordinated fashion based on different conditions such as traffic flow, proximity of the intersections, or for special reasons such as a school zone or in the area around a shopping center. Figure 1 shows two intersections representing a section, however sections typically contain a larger number of intersections. At the highest level the entire system can be controlled for considerations such as time-of-day traffic patterns. The system view of traffic control is often more of a management and monitoring function than an active traffic control functions.



System



Section (Group)



Intersection

Figure 1. Hierarchical Levels of a Traffic Control System.

Figure 2 depicts an arterial with two typical intersections equipped with presence detectors at each of the minor traffic movements - which include the main street left turns and side street movements. These presence detectors will call (e.g. request service) from the associated phase when a vehicle activates the associated detector. In addition, passage detectors are frequently used to call a phase as well as to extend the green time as a vehicle approaches the intersection. Extension intervals are typically timed to provide sufficient time for a vehicle to clear the intersection stop bar after they cross the fixed detector position. Generally the main street may not have detectors, as the signal will rest in the main street phase when there are no calls on the minor phases and returns to this main street phase after serving another call. Frequently, system detectors are installed near mid-block locations on the main street to collect volume and occupancy data for traffic responsive operations.

In addition to vehicle detectors calling and extending a phase, other sources, including pedestrians and bicycles, can call a phase. Pedestrian service is called by pedestrian push buttons or by recalling the pedestrian interval, and service is provided by phase intervals that include a Walk, Pedestrian Clear (Flashing Don't Walk - FDW), and Don't Walk intervals that can significantly affect the duration of a phase. Head, Gettman, Bullock, and Urbanik (Head et al. 2007) developed a model that describes the interactions of the phases and intervals involved in traffic signal control.

Adjacent intersections, or collections of intersections on an arterial or a grid, can be *coordinated* to allow vehicles to progress along the arterial or desired direction of vehicle travel. Each intersection operates using the same actuated control principles as single, isolated intersections, but is constrained by a *timing plan (or pattern)* that can provide coordination through a fixed *cycle length*, *offset*, and a set of *phase splits*.

The cycle length is typically chosen to provide sufficient time to serve all vehicles and pedestrians on all movements. Phases that are not called (skipped) return their allocated green split to the following phase or to the main-street coordinated phase. Shelby, et al. (Shelby, Bullock, and Gettman, 2005) showed that there are resonant cycle lengths that depend on network topology and traffic patterns that provide better performance than cycle lengths selected based on factors such as degree of saturation. The offset is selected to provide progression in at least one direction (generally the direction with the largest volume of traffic) and possibly both directions. Generally the offset value is programmed to be the travel time between intersections plus some time for a standing queue to clear before a vehicle from the upstream signal would arrive. The splits are selected to provide sufficient time for each phase to serve the traffic demand. Minor phases are allowed to gap out before the entire split is timed if there are no vehicles to generate an extension from the detectors.

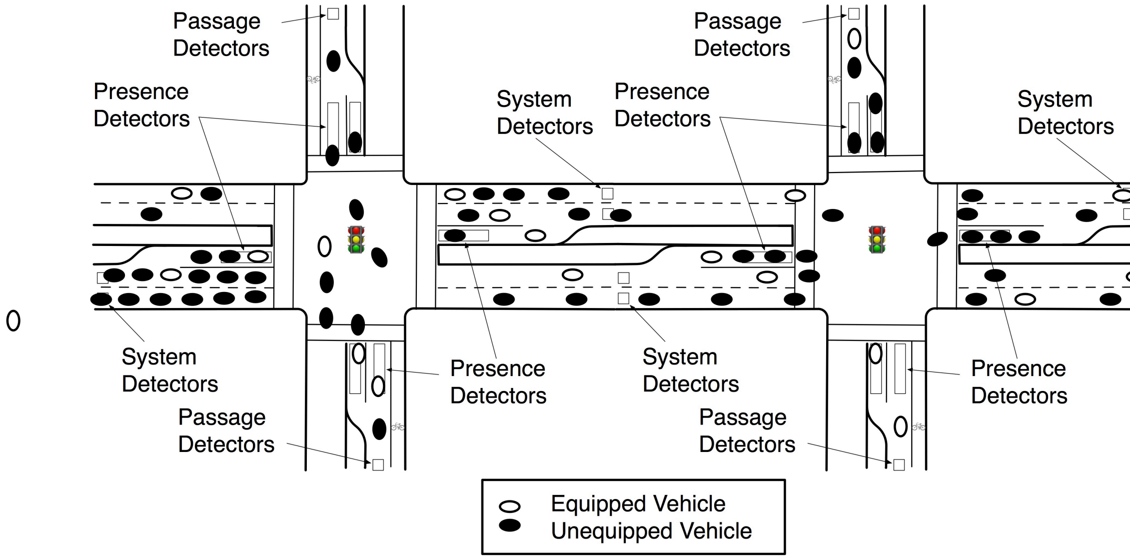


Figure 2. Simple Two-Intersection Arterial

A signal timing plan (or pattern) that contains a cycle length, offset, and phase splits may be defined for each characteristic traffic pattern that might result from time-of-day demand - such as morning and evening commutes, or special events such as sporting events, school, shopping center activities, etc. Signal timing plans are sometimes defined for special weather conditions such as snow, ice, and rain. Generally, signal timing plans are selected on a time-of-day basis, but plans can be selected manually from a traffic control center or a closed-loop master, or using a traffic responsive method that considers volume and occupancy data from system detectors and selects a plan that has been defined as a good match.

Special circumstances, such as railroad or emergency vehicle preemption or transit priority, can modify the coordinated as well as the actuated control to provide a high degree of priority at signals for certain classes of vehicles. These vehicles communicate with the traffic signal controller by sending a message that will call a special preemption timing feature on the traffic controller. Generally this message is a simple contact closure from the traffic signal controller point of view, but may be generated by an infrared signal or a railroad circuit. The time, or distance, upstream is generally fixed for a given application.

The architecture of traffic signal control logic can be characterized as shown in Figure 3 (NCHRP 3-66). This diagram is a UML package diagram that is used to show how logical functions can be grouped (Note: This is not a data flow diagram and the arrows represent relationships between packages and not flow of specific data elements). Each package in the architecture diagram represents a collaboration of activities that interact to accomplish the responsibilities of traffic signal control. At the center of the controller logic is the Core Logic package. In the modern North American controller, this is the familiar ring-barrier-phase structure. This structure is responsible for the basic behavior of phases and phase intervals. The Tactical Control package is responsible for calling, extending, and gapping out phases based on information derived from the Sensor package. Currently, the Sensor package represents vehicle detector information that may be provided by inductive loop detectors, video detectors, or other technologies such as radar or infrared. The specialization of the sensor package is shown to contain Vehicle Information that is derived from the vehicle generated Basic Safety Message and interpreted in the context of the SPAT and GID (MAP) data.

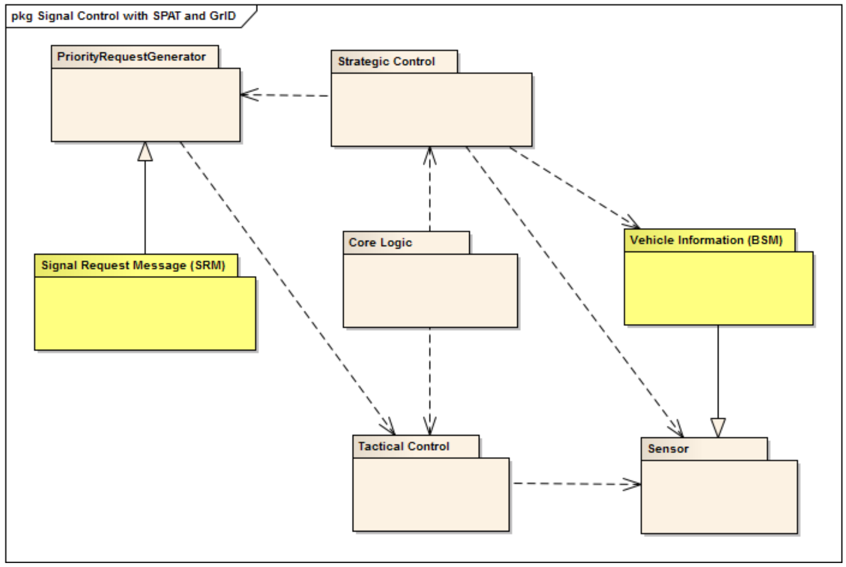


Figure 3. NCHRP 3-66 Controller Architecture with SPAT and GID (MAP) Information.

At the higher levels of the architecture, the Strategic Control package is responsible for coordination, preemption, and priority behaviors. Strategic control depends on information from sensors as well as requests for preemption and priority. In a connected vehicle deployment, the SPAT and GID/MAP information can be used to enhance the capabilities of the Strategic Control. This architecture provides a taxonomy for addressing the integration of new information into the traffic control logic environment.

1.3. Connected Vehicle Systems for Traffic Control

The purpose of this section is to provide a high level overview of connected vehicle systems within which multi-modal intelligent traffic signal systems would be developed and operate. This section is intended to introduce the basic concepts and to provide context for the following discussion.

The basic relevant elements of a connected vehicle system include vehicle and infrastructure computing and communications equipment:

- Roadside Equipment (RSE) – computing and communication device that is installed in the infrastructure. Has interfaces to a backhaul network (Ethernet) and support 5.9GHz wireless communications.

- On Board Equipment (OBE) - computing and communication device that is installed in the vehicle. Has interfaces to a backhaul network (Ethernet), vehicle systems, and support 5.9GHz wireless communications.

In addition to the computing and communications equipment there are critical artifacts that are key in the operation of connected vehicle systems for traffic control. These include:

- MAP – a digital representation of the geometry of the roadway that is serviced by an RSE (Battelle and Texas Transportation Institute 2011)

- SPaT – signal phase and timing data from the traffic signal controller representing the state of the controller (Battelle and Texas Transportation Institute 2011)
- Communication Messages between RSE and OBE – these messages include request for priority, signal status, and others that could be relevant to traffic signal control. The messages have been defined in a Society of Automotive Engineers standard SAE J2735. These messages include a version of the MAP and SPaT discussed above.
- BSM – Basic Safety Message – a SIE J2735 message that is broadcast at a frequency of 10 Hz by an OBE. This message contains the vehicle position, heading, velocity, acceleration and many other vehicle characteristics (SAE 2009).

The basic operating concept includes an RSE that is broadcasting a MAP and SPaT message at a location in the network, such as at a signal controlled intersection. An equipped vehicle (e.g. OBE equipped) that enters the radio range of the RSE will receive the MAP and SPaT data and will be actively broadcasting basic safety messages (BSM). Based on the vehicle role in the system, the vehicle may send a request for priority message (J2735) and receive status from the signal. The actual traffic signal system role of different classes of vehicles is the subject of this study.

The RSE can communicate with the traffic signal controller (TSC) using the National Transportation Communications for ITS Protocol (NTCIP, 2012). NTCIP contains standards for Actuated Signal Control objects (NTCIP 1202) and for Signal Control and Prioritization (NTCIP 1211). These standards provide a mechanism for the RSE to request service (call) from the traffic signal controller and to request priority based on the active OBE's in the system. The dialog between the RSE and the controller is the subject of this study.

1.3.1. Safety

Another critical consideration of connected vehicle systems is the active role in improving safety. Under the Vehicle-Infrastructure Integration programs of cooperative system development, the ITS-JPO sponsored the development of two different types of collision warning systems for signalized intersections. The CICAS-V project developed a signal violation warning system to provide an in-vehicle warning to a driver approaching an intersection if the combination of approach speed and time indicated a high likelihood of an impending violation. The CICAS-SLTA project developed a situation awareness alert system to enhance the awareness by drivers making permissive left turns of the threats represented by vehicles approaching from the opposite direction, so that they would be prompted to reconsider whether to turn before or after the arrival of the approaching vehicles. This type of conflict is referred to as "Left Turn Across Path – Opposite Direction" (LTAP-OD), and accounts for about 27% of the intersection-related crashes in the U.S.

Virginia Tech, Virginia DOT and the CAMP consortium of automotive companies developed the CICAS-V system to alert red-light runners about their impending violations. For this application, the intersection infrastructure broadcast the signal phase information to all approaching vehicles using DSRC. The approaching vehicles used that information, combined with their own position and speed data and a digital map of the intersection to determine if they were in danger of violating a red signal. When a violation was predicted, the driver would receive an audible warning to encourage stopping. This project included extensive field data collection to quantify the behavior of drivers who violated red signals, and then went through several phases of design for signal violation countermeasures.

Early experiments with infrastructure-based violation alerts demonstrated that these were ineffective because they were no more noticeable to the violating drivers than the red signal. This led to an emphasis on the in-vehicle alerts, which were tested in experiments at an instrumented intersection on Virginia Tech's Smart Road. Audible alerts were found to be preferable to video alerts in those experiments, leading to a pilot field operational test of audible signal violation alerts on test vehicles driven in Blacksburg, VA. The specifications for the signal violation warning system were developed, but this has not yet been evaluated in a full-scale FOT.

Caltrans and PATH worked together on developing ITS technologies for reducing LTAP/OD conflicts, with U.S. DOT support, since early 2002, beginning as Intersection Decision Support (IDS) and continuing as CICAS. A Concept of Operations for an SLTA system based on V2I cooperation was developed as part of this work in 2008. Experiments were done to reveal drivers' turning behavior and the gaps that they would accept and reject when making permissive left turns. A prototype implementation was tested at an experimental intersection, showing the technical feasibility of detecting the vehicle trajectories, predicting the future trajectories, communicating the hazard level to the approaching vehicles using DSRC and using that information to produce in-vehicle alerts that were useful as decision support for the drivers.

2. Traffic Control in a Connected Vehicle Environment

2.1. Intelligent Traffic Signal Control

Intersection operation in North America is based on the dual-ring, 8-phase concept. Phases are called and extended by detectors, or recalled to minimum or maximum times. Pedestrians are served using intervals of a phase that provide the Walk, pedestrian clearance (Flashing Don't Walk), and Don't Walk indications. Groups of traffic signals are coordinated to provide progression along an arterial or route by selecting a common cycle length, phase splits, and an offset. Coordination plans can be changed based on time-of-day or in a traffic responsive manner. Railroad preemption is provided as an override to coordination or normal actuated operation to ensure that the railroad track can be cleared and the gates lowered in a safe manner. Preemption is often used for emergency vehicles and sometimes transit. Transit priority has been developed to provide early green and green extensions within the coordinated operation to avoid the disruptive transition behavior that can occur after a preemption is served. Generally, other classes of vehicles are not directly considered, but may be indirectly addressed by selecting operating parameters (e.g. minimum green times, etc.) to meet the needs of mixed traffic flows. These existing operating principles are generally very effective and when programmed intelligently can address many of the needs of modern traffic systems.

One notable effort in the integration of traditional traffic signal system and Connected Vehicle technologies is the SBIR Project 11.1-FH2 Augmenting Inductive Loop Vehicle Sensor Data with SPAT and GrID (MAP) via Data Fusion led by Savari (Savari, et.al. 2011). This project has completed the SBIR Phase I effort which resulted in the development of a Concept of Operations and successful development and demonstration of a prototype system. The Concept of Operations focused on the normal traffic operational scenarios where either an equipped or an unequipped vehicle interacts with the traffic control system through the broadcast of basic safety messages (BSM) or through existing vehicle detection. Connected vehicles could call and extend a traffic signal phase based on their position on the MAP, speed, and arrival time at the stop bar. The MAP application tracks all active BSMs and reports a set of moving objects to the traffic control logic that decides when to call and extend (hold) a phase. The existing traffic signal controller is allowed to actuate phases normally in the absence of connected vehicles.

Research over the past several decades has focused on methodologies for timing signals, transit priority algorithms, transition algorithms, time-of-day or traffic condition partitioning methods, and other special system considerations such as control in a light rail corridor. Developments in vehicle detection technologies have included vision based systems, radar, infrared, microwave and micro-loops. These detection technologies primarily provide point presence and passage information that is used by the local intersection actuation logic. Significant research has been conducted to develop adaptive traffic signal systems that dynamically adjust the signal timing or signal timing parameters to adapt to dynamic and changing traffic flow conditions.

Adaptive Signal Control Systems

Adaptive signal control can be considered the state of the art in traffic control. The characteristics of the existing adaptive signal control systems that have been implemented in the field are summarized in Table 1 below.

Table 1 Existing Adaptive Traffic Signal Control Systems

System	**Installa-tions**	**Architecture**	**Detection**	**Controller**	**Communications**
SCOOT	Over 200 worldwide	Centralized	Exit loops	NEMA (EPAC) or special	Once per second for hold, force-off omit and detector
SCATS	Over 50 worldwide	Hierarchical (plan based)	Stop bar loops	2070 or special	Strategic control from central and local tactical
OPAC	2	Decentralized	Exit loops	NEMA (with VS-PLUS firmware) and VME co- processor)	Once per cycle
RHODES	4	Decentralized	Fully actuated design	2070 (with NextPhase firmware and VME co- processor)	Peer-to-peer over IP, event based on upstream detections
BALANCE /MOTION* (Germany)	5	Central	Near Stop Bar	European	Once per second
INSYNC		Decentralized	Near Stop Bar	Existing (Insync Software)	Ethernet
ACS Lite	4	Decentralized	Stop bar loops Upstream	NEMA 2070	Serial or Ethernet
ATCS (Los Angeles)	1	Centralized	Fully actuated with system detectors	2070 with LADOT firmware	Once per second
TUC *(Chania, Greece)*	5	Central	System loops for VOS	European	Once per cycle
UTOPIA *(Torino, Italy)*	1	Distributed	Fully actuated design	European	

** BALANCE and MOTION are different systems with many similarities*

Adaptive systems continually optimize the signal settings over a short time interval ranging from 15 to 30 seconds (rolling horizon), without necessarily maintaining a common cycle length in the network. Most of these approaches evolved from experimental control of isolated intersections (MOVA, OPAC, RHODES and PRODYN). The Federal Highway Administration (FHWA) sponsored the development of three adaptive control system (ACS) prototypes - OPAC, RHODES, and RTACL that were field tested in Reston, Virginia; Seattle, Washington, and Chicago, Ill, respectively.

2.1.1. Connected Vehicle Data and Traffic Control

The use of connected vehicle probe data in the development of signal control strategies has been limited. Most of the work has been i) on the potential and limitations of probe data to describe operating conditions in a road network and its relationship to signal control (Head, 2008), and ii) the potential of using probe data for providing real-time information to drivers, e.g., pilot implementation of speed advisories on head-up displays in Germany (TRAVOLUTION, 2010). Ongoing work at the University of Virginia as part of the FHWA Pooled Fund study has proposed the use of probe data for better queue management and clustering of vehicle platoons (Venkatanarayana, et.al., 2011). Also, in a California PATH study aiming to develop a dynamic all-red extension strategy to reduce red-light-running (RLR) collisions, it was found that using vehicle trajectory data approaching the intersection with car-following status can improve the prediction of RLR occurrences by up to 40%, compared with conventional point detection from loops (Zhang, et al., 2012). Another ongoing work at the California PATH, UC Berkeley, funded by the FHWA Exploratory Advanced Research (EAR) program, aims at exploring control concepts enabled by connected vehicle data and impacts on performance of control algorithms thereof (FHWA–HRT–11–044, 2011). University of Virginia recently reported their CVIC (Cooperative Vehicle Intersection Control) system that enables cooperation between vehicles and infrastructure for effective intersection operations and management when all vehicles are fully automated and no traffic signal control is needed (Lee and Park, 2012). Similar ideas also include the Automated Intersection Management (AIM) system proposed by the University of Texas at Austin (Fajardo, et.al., 2012).

A number of studies are concerned with the estimation of performance measures at traffic signals from probe data. It was found that probe data could provide satisfactory estimates of arterial travel times and midblock flow rates even at low market penetration, but queue length estimation errors, however, were high even at 100% market penetration (Vasudevan, 2007). As part of the PATH EARP project and the former VII California project, the use of probe vehicle data to represent arterial traffic was investigated based on a VISSIM micro-simulation of the El Camino Real corridor with 20 signalized intersections in the San Francisco Bay Area (Shladover and Kuhn, 2008). The simulated vehicle trajectories at 1 second resolution were treated as the ground truth for this corridor and were then sampled by a post-processor program that implements the probe vehicle sampling rules prescribed in the SAE J2735 standard. This research showed that the current probe vehicle sampling rules impose serious constraints on the usefulness of the data for real-time adaptive signal control. As part of the ongoing EARP project PATH is studying the benefits of fusing probe data with fixed point detector data to improve MOE observers' performance under relatively low market penetration rate of connected vehicle technology.

2.2. Transit Vehicle Priority

Delay at signalized intersections is a considerable part of the journey time for public transport in urban areas. Providing transit priority at traffic signals can be an effective Intelligent Transportation Systems (ITS) technology to reduce this delay thereby reducing travel time and improving service quality for buses at a relatively low cost.

Transit Signal Priority (TSP) is an operational strategy that facilitates the movement of in-service transit vehicles, either buses or streetcars, through traffic signal controlled intersections (ITS

America, 2004). To date, various deployment cases of TSP systems have demonstrated that TSP is effective in improving transit service quality. The benefits of TSP include reduced intersection delay and travel time, improved schedule adherence and travel time reliability, which lead to increased transit quality of service and improved customers' satisfaction (ITS America, 2005).

TSP can be implemented in a variety of ways. Figure 4 depicts a simplified TSP system (ITS America, 2005), where

a) A bus approaches a prioritized intersection and is detected at some point P_d upstream of the intersection (check-in, various detection technologies);
b) A transit priority request is communicated to the traffic controller C (various communication means) and the controller then initiates action to provide priority based on defined TSP control strategies (various); and
c) The controller resumes the normal signal timing when notified that the bus has cleared the intersection, which is detected at some point P_c downstream of the intersection (check-out) and is communicated to the controller.

Figure 4 Simplified TSP System (Source: ITS America, 2005)

TSP control strategies can be classified into three categories: passive, active and adaptive priority treatments. ***Passive*** priority strategies are static signal -timing plans (cycle length, splits and offsets) to favor transit vehicles along the arterials (Garrow & Machemehl, 1999, Skabardonis, 2000). With passive priority, signal-timing plans are not affected by the presence or absence of transit vehicles. Passive strategies are typically applied to fixed-time signal systems and do not require transit vehicle detection. Such strategies only work well when transit operations are highly predictable and frequent, and overall traffic conditions are light to moderate. With increase in uncertainty of arrival time at the intersection due to dwell time at transit stops, the benefits of passive priority decrease substantially.

Active strategies address some of the limitations of passive strategies by altering signal settings dynamically and only when necessary, i.e., upon the detection of the transit vehicle and subsequent priority request activation. As a result, active strategies are usually more effective than passive strategies. Essentially, active TSP senses oncoming transit vehicles and either advances the start of green for the movement where the transit vehicle has been detected (early green/red truncation) or holds the green until the transit vehicle clears the intersection (green extension). Other options include dynamically inserting a priority phase within the normal phase sequence only when a transit vehicle is detected and requests priority for this phase (phase insertion) or rotating the phases such that the transit vehicle is served as soon as possible (phase rotation). In general, green extension and early green (red truncation) are the most commonly applied strategies in current TSP implementation.

Active strategies aim to minimize delay to transit vehicles. Transit vehicle detection means and a communication link between the transit vehicle and the local signal controller are needed to support active priority. Impacts on non-transit traffic (mainly the cross-street traffic) are not explicitly considered but rather are introduced as operational constraints (for instance with a pre-determined maximum allowed priority duration in percentage of a signal cycle). No common methods are available for the determination of these constraints, which are usually conducted on the basis of traffic engineers' experience and fine-tuned afterwards. Active strategies often have unbalanced impacts on the non-transit traffic, and in many cases are responsible for loss of signal coordination and interruption in the progression of the vehicle platoons which can result to excessive delays (Christofa & Skabardonis, 2010).

Adaptive strategies take into consideration the trade-offs between transit delay saving and the impact on non-transit traffic, and use optimization-based control schemes to determine if and how to grant priority, thereby offering the promise to maximize benefits for both transit vehicles and the general traffic. The optimal signal timing for priority is usually determined by giving more weight to transit vehicles in the optimization routine. Transit vehicle detection means and a communication link between the transit vehicle and the signal controller are also required to support adaptive priority.

It is natural to incorporate adaptive strategies into adaptive signal control systems. Such systems use detection of vehicular traffic at some point upstream and/or downstream of an intersection to predict the traffic conditions and already possess the capability of optimizing signal timing in real time. In the literature, most adaptive strategies have been coupled with adaptive signal control systems, for example, SCOOT (Bretherton, Bowen, & Wood, 2002), SCATS (Cornwell, 1986), RHODES (Mirchandani, Knyazyan, Head, & Wu, 2001), UTOPIA (Mauro & Di Taranto, 1989), PRODYN (Henry, Farges, & Tuffal, 1983), and SPPORT (Conrad, Dion, & Yagar, 1998).

Although building dynamic priority strategies on top of adaptive signal control systems may offer more benefits, adaptive priority strategies can be built on top of closed-loop signal control systems (Luyanda, Gettman, Head, Shelby, Bullock, & Mirchandani, 2003), which account for over 90% of signal systems in use in the United States (Gettman, Shelby, Head, Bullock, & Soyke, 2007). While adaptive signal control systems are possibly the wave of the future, applying adaptive transit priority technology to closed-loop signal systems allows solving the transportation problems we are facing today. The Adaptive Transit Signal Priority (ATSP) System developed by the California PATH program at UC Berkeley, in collaboration with the California Department of Transportation (Caltrans) and San Mateo County Transit District (SamTrans) (Li, et al., 2010) is the only such system that was reported in the literature and has conducted large-scale field operational tests.

Currently, TSP systems operate using various types of commercial technologies for transit vehicle detection and communication between the transit vehicle and signal control infrastructure. Dedicated devices need to be installed at each intersection and individual buses to support TSP control, requiring an initial capital investment and regular maintenance costs. Recent advances in transit ITS technologies and connected vehicle technologies create the opportunity to implement and operate TSP control in ways that have not been possible before. The Computer Aided Dispatch, Automatic Vehicle Location and Advanced Communication Systems (CAD/AVL/ACS) have becoming popular among transit agencies to facilitate the management of transit fleet operations (FTA, 2006). By the late 1990s, agencies were generally adopting AVL systems using Global Positioning System (GPS), which became fully operational in 1995. By 2010, over 95% of transit buses and light rail vehicles in U.S. have been instrumented with CAD/CAS, and 60% with GPS-based AVL (USDOT, 2011). Under the connected vehicle environment, a transit vehicle communicates directly with the signal controller via V2I communication using on-board equipment (OBE) and roadside equipment (RSE) to update its operational status (e.g., latitude, longitude, heading, speed, service type (bus rapid transit, express route), schedule/headway adherence, passenger load, etc.) and the controller makes the decision if and how to grant the priority. Every bus fleet that has already instrumented its buses with CAD/AVL/ACS automatically becomes

TSP-capable along arterials with RSEs in place. This allows transit agencies, state, and local jurisdictions to leverage the TSP implementation costs with connected vehicle infrastructure.

2.2.1. State-of-Art of TSP Technologies

Transit Vehicle Detection and Communication Technology

Transit vehicle detection methods fall into three categories: point detection, zone detection, and movement detection (Fox, Montgomery, Smith, & Jones, 1998). Generally, most of the transit vehicle detection technologies were originally developed for Emergency Vehicle Preemption and adapted for TSP applications.

Point detection senses the vehicle at fixed locations. A transmitter equipped on the bus sends a message including the vehicle identification (ID) to a roadside receiver at some point upstream of the intersection when the bus crosses it. The detection information is transmitted to the controller via wired connection between the receiver and the controller. Point detection technology is commonly used for early TSP implementations. Implementation examples include King County Metro first generation of TSP that uses Radio Frequency Identification (RFID) technology for bus detection (King County Department of Transportation and City of Seattle Transportation, 2000), and LADOT Smart-Loop TSP (Hu, Skehan, & R.Gephart, 2001), among others.

Zone detection senses the presence of a vehicle on the approach to the intersection. An infrared (IR), radar or radio frequency emitter is mounted on the vehicle, and the messages are received by a beacon installed at the intersection when the vehicle occupies the area covered by this beacon. Messages can include complementary information such as vehicle ID, vehicle classification, and vehicle priority level.

Movement detection refers to GPS-based AVL systems that can track the movement of a transit vehicle when approaching the intersection. This type of detection technology considerably improves the capability in predicting the arrival of the transit vehicle at the intersection, which leads to more effective TSP control. As a result, movement detection has been emerging as the most favorable detection technology for TSP.

The rapid development of wireless communications systems and digital broadcasting has been one of the most exciting developments in electronics in recent years. The use of Wi-Fi (WLAN) technology as a communication link for TSP is growing rapidly today (FTA, 2008). The Wi-Fi based system promises low maintenance, high reliability, high communication bandwidth allowing greater data flows, and less geometric constraints. Many agencies are now implementing or transitioning to Wi-Fi based systems, and several commercial off-the-shelf (COTS) products are available. According to Kittleson & Associates Inc. (Braud & Urbanik, 2011), Opticom IR, Opticom GPS, EMTRAC, Iteris and Novax are the five leading vehicle detection and communication technologies in U.S.

Table 2 presents the key features and deployment samples for each of these technologies. As shown in

Table 2, GPS-based vehicle positioning and wireless communication have become the cutting-edge technology for vehicle detection and TSP communication.

Table 2 Vehicle Detection and Communication Technologies and Deployment Samples (Source: Braud & Urbanik, 2011)

Technology	Vehicle Positioning Location Medium	Vehicle to Intersection Communication Medium	Deployment Examples
Opticom IR	Infrared signal	Infrared signal	Portland, OR Alameda & Contra Costa Counties, CA

			Tacoma, WA
Opticom GPS	GPS	Radio (2.4 GHz)	Jacksonville, FL Broward County, FL Orlando, FL
EMTRAC	GPS	Radio (900 MHz)	Minneapolis, MN Houston, TX San Jose, CA
Iteris	GPS	Wi‐Fi (2.4 or 4.9 GHz) Network	Los Angeles County, CA Seattle, WA
Novax	GPS	Wi‐Fi (2.4 or 4.9 GHz) Network	Chicago, IL

There are very limited studies on using DSRC (Dedicated Short Range Communication) for TSP in the literature, mainly because the availability of DSRC is currently limited. Liao et al. (Liao, Davis, & Iyer, A Bus Signal Priority System Using Automatic Vehicle Location / Global Position Systems and Wireless Communication Systems - Final Report, 2008) developed a prototype wireless TSP system including DSRC and Wi-Fi (802.11x protocol), and conducted experimental field testing to compare these two types of communication technology for TSP. The authors reported that, while the data flow, priority request generation and priority execution were successful for both DSRC and Wi-Fi, DSRC provided wider communication range, shorter latency and faster data rate. The difference in communication latency (4 to 6 milliseconds with DSRC vs. 10 to 30 milliseconds with Wi-Fi) might be critical in situations for safety applications but is not likely to make much difference for TSP control. The factors of communication range, available communication bandwidth, network reliability and data security need to be considered when selecting DSRC or Wi-Fi technology for vehicle-to-roadside communication.

While most of the existing TSP implementation requires vehicle-to-infrastructure communication, Zhang et al. (Zhang, et al., 2011) developed and field tested an integrated ATSP and Dynamic Passenger Information (DPI) system that does not pose this requirement. The system utilizes the existing transit CAD/AVL/ACS system for vehicle detection and communication. Priority service requests are generated at the dispatch center and routed to the local controller through the super master PC located at the traffic management center. Available communication bandwidth in the ACS system is used for dynamically polling bus GPS location on a need-basis.

2.3. Pedestrian Mobility

The Mobile Accessible Pedestrian Signal (MAPS) system concept involves use of a portable device such as a smart phone to provide an audible and/or tactile indication of the current traffic signal phase, to help visually impaired persons cross streets safely. It represents a narrow example of how connected vehicle technologies could help improve pedestrian crossing safety and efficiency.

There only appears to be one published study on this subject (Liao, 2011), by the University of Minnesota, which studied the crossing behavior of visually impaired people to support the development of design specifications and guidelines for implementation of a MAPS. There was also a TRB paper and ITS World Congress paper (Liao, 2011) presented by the authors of this study, but their project report is cited here because it likely to be more complete. Their report includes a literature review of relevant background information, with 72 reference citations. The TRID database of research in progress (the superset of TRIS and the ITRD International Transportation Research Documentation database) notes a new project (March 2012 to March 2014) at Virginia Tech called “Connected Vehicle Beacon for At-Risk Pedestrians”, which appears to be related. In this case the portable device carried by the pedestrian would broadcast a “Here I

Am" message to indicate its location, heading direction and speed of motion so that it could alert connected vehicle drivers.

There are commercially available GPS navigation systems designed for blind people, such as the Kapsten Plus voice-activated GPS with maps. Devices such as these could become elements of a MAPS system if provided with a wireless communication function to receive real-time traffic signal data.

Savari (2012) has completed an SBIR Phase I project to develop Smartphone applications for assisting pedestrians. This effort has focused on the use of wireless communications (Wifi in the demonstration) to allow a Smartphone application to send a pedestrian call to the local traffic signal controller when the pedestrian is located at the start of the crosswalk and oriented in the proper direction. The Smartphone application uses the internal GPS and inertial sensors to position a pedestrian on a MAP that is broadcast by an RSE using the wireless network. The Smartphone application provides visual and auditory feedback to a pedestrian about the active pedestrian interval and the time remaining when the Don't Walk interval is timing. The application was demonstrated to a group of visually impaired travelers at the April 26, 2012 Maricopa County Department of Transportation SMARTDive demonstration in Anthem, AZ. The participants reported interest in the concept and provided feedback for the team's Phase II SBIR proposal.

Japan has pioneered the development of systems to assist blind pedestrians. The Pedestrian Information and Communication System (PICS), developed with support from the National Police Agency, was demonstrated at the ITS World Congress in Nagoya in 2004 and described in (Ohkubo, et.al., 2005). Users could receive signal status information via an infrared communication link or a portable phone.

For the Safety Pilot Model Deployment in Ann Arbor, MI, Battelle is using the MS-Sedco SmartWalk XM, a pedestrian detection system based on a 24.125 GHz (k-band) Microwave transmitter/receiver system that uses a microprocessor-analyzed Doppler detection method. As with all such sensor systems, there is a continuing challenge in adjusting sensitivity of detection to minimize both missed detections and false detections, since these tend to be in conflict with each other. The information about pedestrians in crosswalks detected by this sensor will be combined with pedestrian push button information and the intersection's SPaT data to be communicated to approaching buses using DSRC wireless communication so that this can be displayed to the bus driver, representing an infrastructure-vehicle connected vehicle

If the broader improvement of pedestrian crossing safety and efficiency is to be considered, there is a much wider range of information available, particularly with regard to detection of pedestrians at crosswalks. For example, if information about pedestrian presence in crosswalks can be broadcast to vehicles approaching an intersection the drivers will be more aware and better able to avoid colliding with them. PATH did a review of pedestrian detection technology for a report in 2006 (Chan, et.al., 2006), considering both infrastructure-based and vehicle-based sensors, with 71 reference citations. More recently, the University of Manitoba did a state of the art review of pedestrian detection technology for the Institute of Transportation Engineers (Markowitz and Montufar, 2010), with 83 reference citations.

Japan has also worked on identification of pedestrian locations by using triangulation of transmissions from wireless devices carried by the pedestrians, as explained in (Tokuhiro, et.al., 2007; Kato, et.al., 2007; Nakasu, et.al., 2008; Tokuhiro, et.al., 2008). This concept has also received preliminary attention in Germany (Hinsberger, et.al., 2008).

Nissan and NTT DocoMo developed and field tested a system for pedestrian detection based on comparison of positioning information from GPS-equipped cell phones carried by the pedestrians and from navigation systems in the cars (Fukushima and Yasuhara, 2009). This was designed and tested for residential areas with relatively light traffic and many blind intersections.

Belgian researchers have also considered how low-power wireless technologies such as Zigbee or Bluetooth could be used on devices carried by pedestrians to broadcast their locations so that vehicles and their drivers could be informed of their presence (Carels, et.al., 2011).

The City of San Francisco has experimented with video detection to identify the presence of late-crossing pedestrians in a crosswalk, to dynamically extend the protected crossing time by up to three seconds, but found that this produced only a modest performance improvement (Lovejoy, et.al., 2012).

One of the most elaborate pedestrian (and bicyclist) detection systems was developed by Amparo Solutions in collaboration with the Swedish road administration (Rydstrom, et.al., 2009). With this system, the pedestrians or bicyclists would carry a small battery-powered active badge, which transmits a wireless beacon to notify the system about its presence. A roadside passive infrared detection unit detects location, direction and velocity of movement of the person carrying the beacon based on body heat, and a roadside Doppler radar discriminates between vehicles and humanoid targets, based on the fact that different parts of the body move at different speeds for pedestrians or bicyclists. The detection information is used to illuminate a warning sign to alert approaching drivers to watch out for the peds or bikes.

2.4. Freight Signal Priority

Commercial vehicles have received little attention related to the operation and timing of traffic signals. The I-95 Coalition and State of New York C-VII (2012) program is an advanced research and development aimed at using advanced technologies to improve commercial vehicle safety and performance. C-VII is primarily focused on highway facilities and hasn't addressed signalized intersections directly. Applications include enhanced vehicle situational awareness, driver credential verification, roadside inspection, and vehicle-to-vehicle communications using on-board equipment (OBE) of hazards and warnings.

Liu (Liu et al. 2007) developed a prototype system using wireless communications (as part of the Trusted Truck infrastructure) that focused on minimizing truck stops and waiting time. The scheduling algorithm develop produced reduced stops and waiting time for trucks with some impact on regular vehicles, but overall delay was improved over traditional actuated control logic. The system was implemented using hardware controllers based on the NTCIP (2004) standard.

Sunkari (Sunkari, Charara, and Urbanik 2000) developed a truck priority system using TCC 540 classifiers and industrial PCs to implement this logic. The goal was to reduce truck stops in corridors near the international border with the objective of reducing truck stops and extending pavement life. The project reports success in reducing stops, but the impact to other traffic was not reported.

A Norwegian research project, PRINT, has equipped commercial trucks with positioning and communications devices to request priority at traffic signals with the goal of reducing emissions and fuel consumption (Tveit and Bang 2009). The PRINT system uses a combination between the use of priority lanes and requests for priority, that are subordinated to emergency vehicle and transit vehicles. The system has shown a benefit in reducing emissions and fuel consumption, but the impact on other classes of vehicles was not reported.

Clearly there is an opportunity to provide priority at traffic signals for commercial vehicles/trucks that could improve safety and efficiency. The ability to reduce the number of stops can improve emissions and fuel consumption as well as reduce the impact on the pavement. The use of priority lanes and a hierarchical priority request and control system is consistent with priority applications for transit vehicles.

The European Commission's Freilot Project is developing and field testing approaches for improving the energy efficiency of truck operations in Europe using connected vehicle technology (called Cooperative Systems in Europe). Freilot has developed the concept of "energy efficient intersections", involving two-way communications between trucks and the traffic signal controller. This provides speed advice to the truck driver to assist in passing through the intersection without stopping, but also provides for adjustments to the traffic signal cycle so that the equipped trucks can gain priority for green time relative to other road users. This is expected to save travel time and improve travel time reliability for the trucks, as well as encouraging truck traffic in urban areas to concentrate in the equipped corridor(s), thereby avoiding other areas where it is considered desirable to discourage through truck traffic. The specific truck priority algorithm, developed and implemented by Peek Traffic, does not appear to have been published yet.

2.1. Emergency Vehicle Preemption

Preemption of traffic signals is a technique that is used to give a very high level of priority to a preemption request (call)(Shibuya, et.al., 2000). Generally, preemption is used for highway-rail road crossings where a traffic signal is near (200 feet) a railroad crossing, or for emergency vehicles (fire, ambulance)(USDOT, 2006), and sometimes for transit priority. The NEMA definition of preemption is “The transfer of the normal control of signals to a special signal control mode for the purpose of servicing railroad crossings, emergency vehicle passage, mass transit vehicle passage, and other special tasks, the control of which require terminating normal traffic control to provide the priority needs of the special task.” (NEMA 2003). NTCIP (NTCIP 2005) defines the parameters of a standard preemptor, but each controller manufacturer tends to implement slightly different logic depending on their customers desires and preferences. The US DOT prepared an over view report on traffic signal preemption systems for emergency vehicles (US DOT 2006).

There are several technologies that have been used to implement Emergency Vehicle preemption. These same technologies have been used in Transit Priority Systems (see Section 2.2.2). Historically, 3M produced the most popular preemption system, Opticom, which uses an infrared emitter mounted on the vehicle to transmit presence information from the vehicle to a receiver at the intersection. The receiver is connected to the traffic signal controller through a simple relay that signals the controller that a vehicle is present on one of the approaches. Global Traffic Technologies (GTT 2012) is the current supplier of Opticom. GTT has expanded their line of products to include GPS based products that are based on distance and travel time rather than depending on line of sight and distance alone. They use secure (unspecified) wireless communications to send the request for priority from the vehicle to the intersection. There are several other companies that provide similar technologies including EMTRAC (EMTRAC 2012), TOMAR (TOMAR 2012), and several manufacturers that provide emitters that claim compatibility with existing systems.

The preemption logic (algorithms) are generally an integral part of the traffic signal controller, but can be implemented externally on devices or processors that have either hardware or software interfaces to the controller. Generally, when a preemption call is received, the controller drops from coordination to free operation. Railroad preemption uses track clearance phases to ensure no vehicles are stopped on the railroad track. Generally, track clearance isn’t required for emergency vehicles. The controller will terminate any current phases, unless the current phase is the desired service phase, and enter the service phase (dwell) until either the preemption call is cleared or a maximum dwell timer is reached. The controller will then exit to predetermined exit phases then eventually transition back into coordination (assuming the controller was operating in a coordinated pattern before the preemption request was received).

Adoption of a system for emergency vehicle preemption generally receives mixed reviews (Gifford, et.al., 2001). First responders are in favor of these systems since they are intended to improve response time and safety. Traffic engineers are often less accepting given potential for disruption of network coordination and increased delay to traffic. Nelson and Bullock (2000) studied the impacts of emergency vehicle preemption on a small network of closely spaced signals. They concluded that a single preemption event can have a minimal impact, but multiple preemption events in a short period of time can have a significant impact. The severity of the impact depends on how well the preemption system is programmed (Yun, et.al., 2008) and on the current state of traffic and the availability of slack time that can be leveraged to let the signals recover (transition back to coordination).

3. National Test Beds and Other Deployments

There are several national and regional test beds that are in development that are primarily focused on testing and providing concepts from Connected Vehicle systems and technologies.

3.1.1. Michagan National Connected Vehicle Test Bed

The Michigan National Connected Vehicle Test Bed has been developed in cooperation between US DOT, Michigan Department of Transportation, and several state partners. It has been developed to provide a large scale test bed for mobility, safety, and environmental applications. The test be is located in Oakland County, Michigan. The RSE installation covers 45 square miles, comprising 75 center-line miles made up of 32 Interstate and Divided Highway and 43 arterial miles. The ongoing Michigan expansion will cover an additional 6 Arterial Center-Lane miles. The system includes communications to back office facilities for data processing and application support. The network is shown in Figure 5 below.

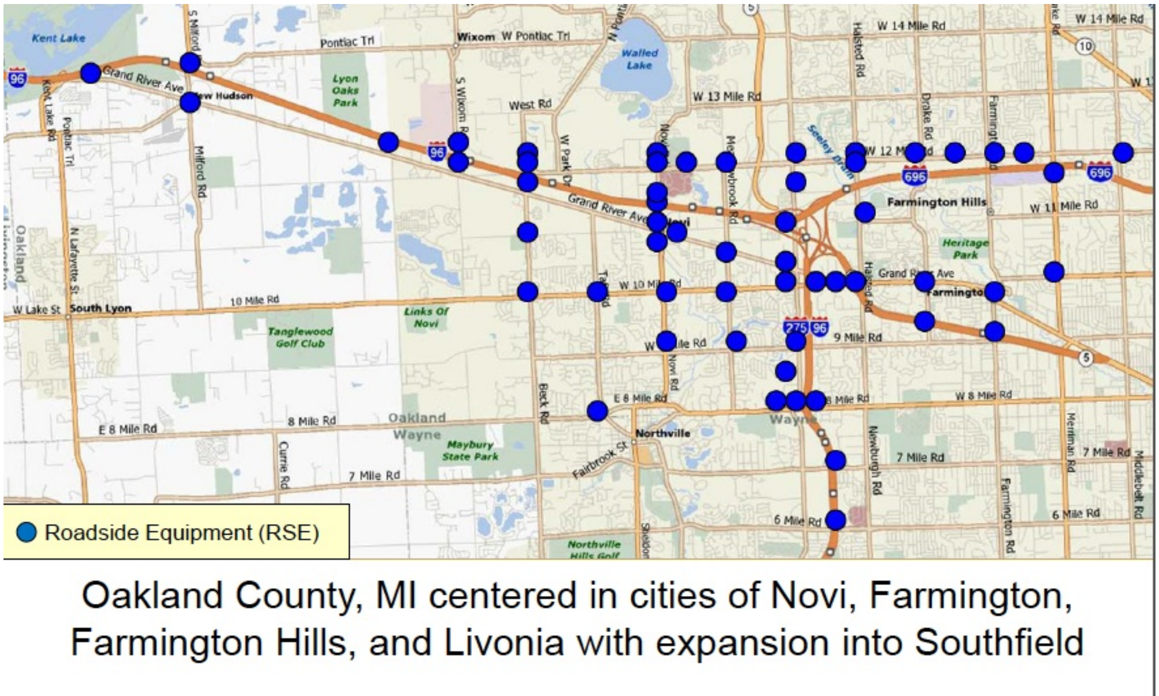


Figure 5. Michigan Test Bed (source: mdot_working_group_meeting_CVPC_5.2.2011_352499_7)

3.1.2. Maricopa County Department of Transportation SMARTDrive Field Test Network

The Maricopa County Department of Transportation's SMARTDrive Field Test Network consists of six (6) intersection in Anthem, Az (northern Maricopa County). This Connected Vehicle field test site was developed to support research, development, and demonstration of Connected Vehicle applications to improve safety and efficiency - specifically priority traffic signal control for first responders and transit.

The network is located north of Phoenix, Arizona in Anthem,Az and includes six (6) intersection. The anchor intersection is at W Daisy Mountain Drive and N Gavilan Peak Pkwy. The GPS coordinates for the intersection are: Latitude: 33.843008°, Longitude: -112.134994°. All of the intersections are equipped with Savari Streetwave RSE units, modern Econolite ASC/3 controllers and fiber optic – Ethernet backbone. Each intersection has both advanced and stop bar detection on all movements. There is no operating transit service in the network at this time, but a Valley Metro bus was used in the April 26, 2012 demonstration and there are bus pullouts built into the infrastructure. The Anthem Fire Department strongly supports the project and has participated in testing and demonstrations.

Traffic patterns in the neighborhood are heavy in the AM and PM peak periods, but very low in the mid-day periods. This allows ample time for testing, demonstrations, and data collection. A public demonstration was conducted on April 26, 2012 where transit priority and emergency vehicle priority as well as the Savari SmartCross (SBIR) prototype system. The demonstration successfully demonstrated advanced traffic signal control using Connected Vehicle technology.

A satellite image of the network is shown in Figure 6.

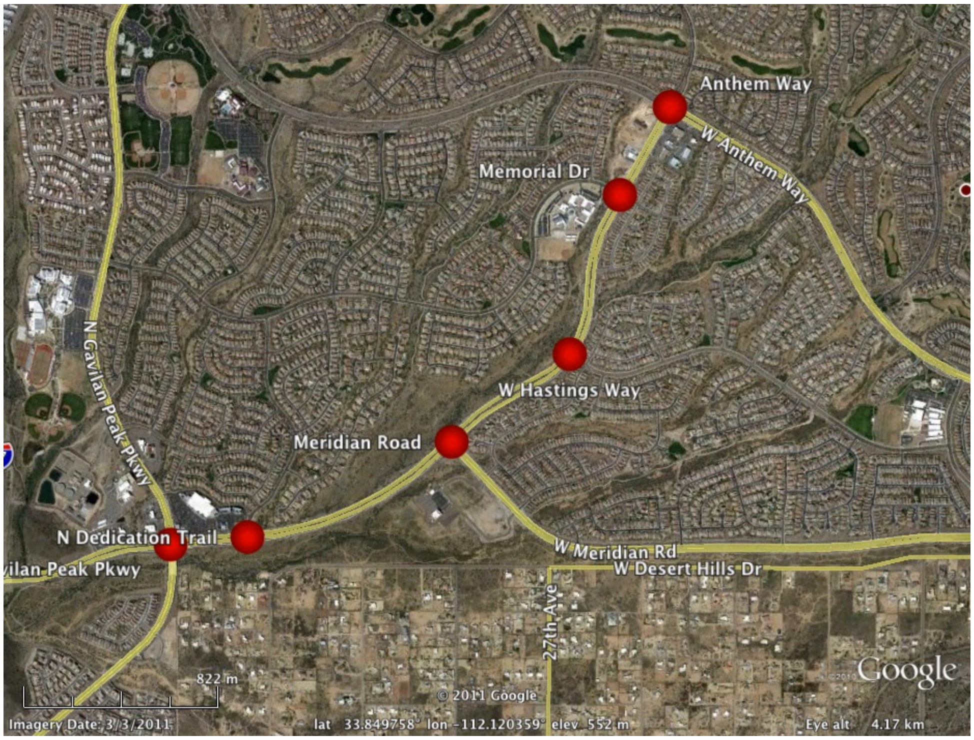


Figure 6. Maricopa County Department of Transportation SMARTDrive Test Network.

This network has been used for demonstration of the SBIR Phase I Projects (Savari, Inc. - InFusion and SmartCross applications). Future plans for the network in Summer of 2012 include upgrades to the DSRC to comply with the national WAVE standards and use of proper J2735 messages for all applications.

3.1.3. El Camino Real DSRC Testbed Environment

During 2005-6, Caltrans and MTC funded the development and operation of a testbed environment for DSRC communications, so that this technology could be tested for use in supporting a variety of traffic management applications. That testbed relied on an early generation of DSRC radios that are now obsolete, but the remainder of its infrastructure is being largely re-used, with replacement of the radios by the latest generation of DSRC radios, consistent with those being used for the Safety Pilot Model Deployment in Michigan. The radio upgrade is being scheduled based on when DOT can provide the new generation DSRC radios (anticipated autumn 2012).

The pre-existing testbed environment includes 12 locations that were equipped with DSRC radios, antennas, and interfaces to the local power supplies, signal controllers and backhaul communication networks. Of those locations, five that are located sequentially within a 1.9 mile stretch of El Camino Real in Palo Alto are being upgraded later this year (at the intersections of Stanford, California, Page Mill, Curtner and Charleston)(See Figure 7). In order to provide continuous coverage at all the signalized intersections within that stretch of El Camino Real, new DSRC installations will be added at the remaining six signalized intersections along that stretch (Cambridge, Portage/Hansen, Los Robles, Maybell and Matadero). In addition, new DSRC installations will be implemented at two intersections along North First Street in San Jose, where these can be used to test applications to help avoid collisions between left turning motor vehicles and Valley Transportation Authority (VTA) light rail trains that run along the median of North First Street.

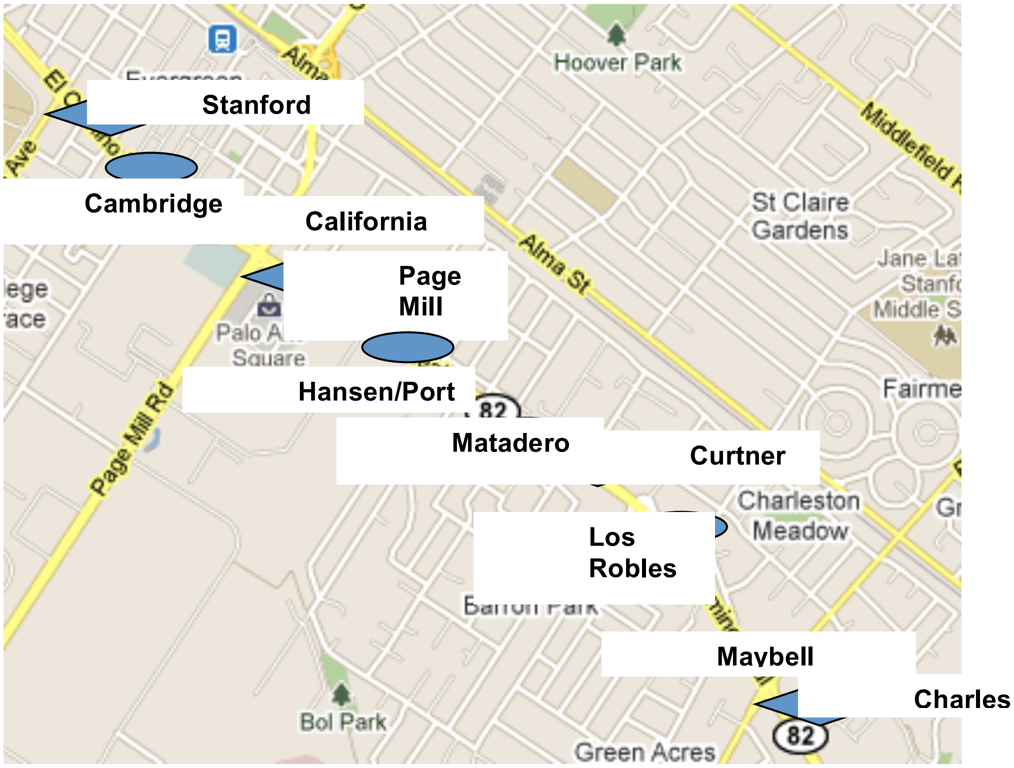


Figure 7. El Camino Real Connected Vehicle Test Network.

3.1.4. New York/I-95 Coalition Test Network

The New York/I-95 Coalition C-VII program has established a test network (Figure 8) for testing and demonstrating the various applications developed as part of their research program. The network consists of a section of I-495 in the INFORMS system. The balloons show the locations of RSE that has been installed in the network.

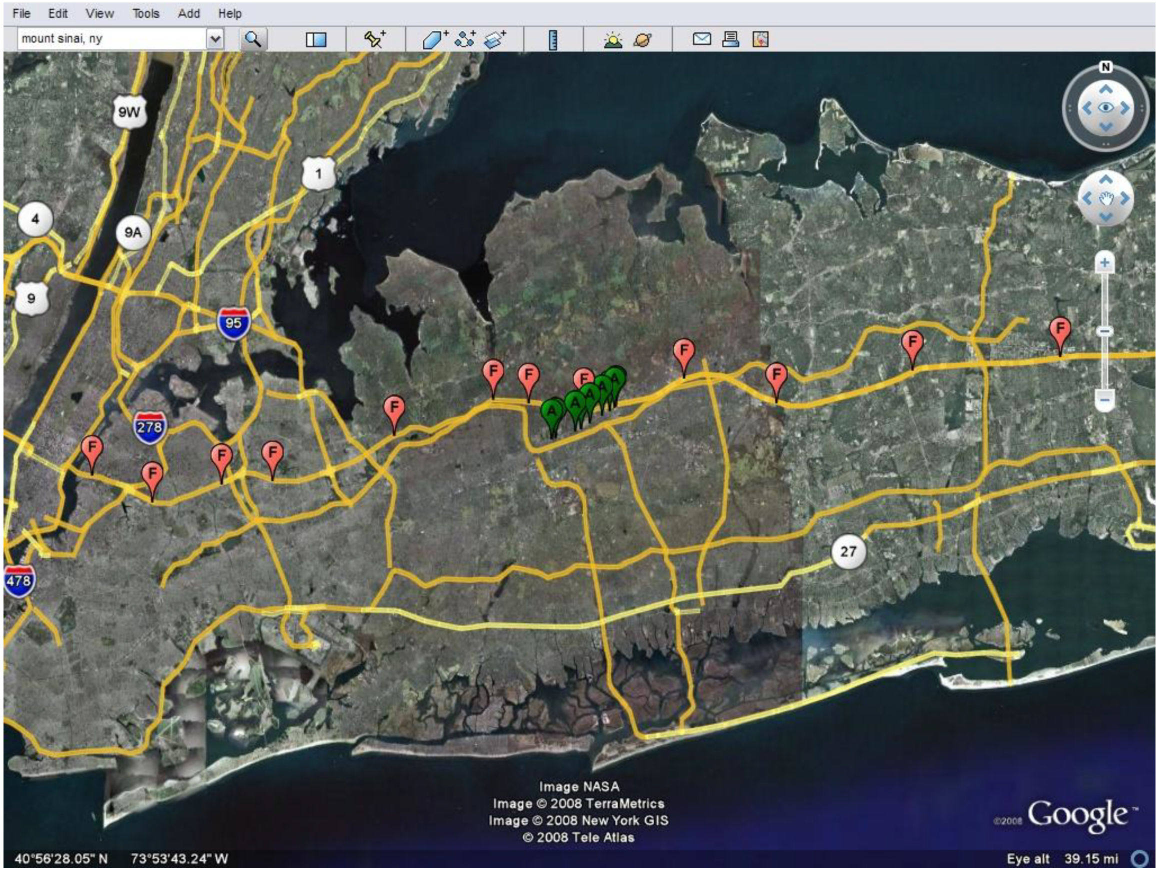


Figure 8. Map representation of the New York/I-95 Coalition Test Network (source: Rick McDonough, NYSDOT, 2011 ITS-NY 18th Annual Meeting and Technology Exhibition Saratoga Springs, NY.)

3.1.5. Orlando, Florida – ITS World Congress

(The following description was taken from http://www.dot.state.fl.us/trafficoperations/ITS/Projects_Deploy/CV/Connected_Vehicles-WC.shtm)

The Florida Department of Transportation (FDOT) is demonstrating Florida's connected vehicle test bed at the 18th World Congress (October 2011) on Intelligent Transport Systems in the Mobility Village of the Technology Showcase. As part of this showcase, FDOT has deployed 26 roadside equipment (RSE) units in an area around the Orange County Convention Center. These RSEs will interface with demonstrators' onboard equipment (OBE) and connect to the FDOT District Five SunGuide® advanced transportation management system production software through the District's fiber optic network.

Over the past year, FDOT enhanced the SunGuide® software, Florida's statewide advanced transportation management software, enabling it to communicate with the RSE units installed on 25 miles of Interstate 4, International Drive, and John Young Parkway. The United States Department of Transportation (USDOT) provided the RSE units to FDOT in an effort to start a Florida connected vehicle test bed, which is the only transportation management center-based operational test bed in the country.

FDOT will demonstrate how information is collected from 42 specially equipped vehicles provided by Lynx, I-Ride Trolley, and various FDOT and demonstrator vehicles. These vehicles will operate on the test be route to provide basic safety messages to the SunGuide® software via RSE units, and they will receive traveler advisory messages back from the SunGuide® software. The RSE units communicate with vehicles through a two-way radio with a global positioning system.

As a part of the Technology Showcase, there will be over 20 demonstrations by various vendors. Many of these demonstrations will also take advantage of the RSEs to communicate.

Signal phasing and time (SPaT) controllers are planned to be deployed at specific intersections along the World Congress demonstration route. These SPaT controllers will interface with RSEs which will broadcast the SPaT data to the demonstration OBEs. The information received by these units will provide the driver with feedback about the signal status for the specific lane that their vehicle is traveling in.

Following the World Congress, FDOT plans to leave the infrastructure in place to create a test bed for future testing as well as taking advantage of any vehicles that will continue to use Vehicle Awareness Device equipment to broadcast basic safety messages.

4. Additional Considerations

This Section discusses additional considerations that have not been identified as part of the applications discussed in Section 2. These considerations are important in traffic signal systems, but are not necessarily common in all systems.

4.1.1. Railroad Crossings

The highway-rail interface requires special consideration from a traffic signal system perspective. When a train, freight, commuter or light rail, approach a gate controller crossing of a roadway it is necessary to clear the tracks so that the gates can close without any vehicles trapped in the trains path. If there is a traffic signal nearby, this could require preempting the signal so that the queue of vehicles can clear the track clearance region. The timing and decisions on how long the track clearance service needs to be active currently depend on several assumptions including the time required for a queue of vehicles to clear the distance from the signalized intersection stop bar back to the railroad gate down position. If the traffic consists of truck, buses, and vehicles the time can be variable. If a driver is distracted or has mechanical problems the queue clearance can be delayed. The use of ITS to address these concerns (Wallach and Lapalus 2001) includes providing uniform advanced warning times, active signs, advanced detection systems, and special treatments when emergency vehicles are attempting to cross the tracks. None of these treatments is superior to the use of Connected Vehicle technology to determine if a vehicle can clear the tracks. This is a simple and valuable extension of existing signal control capabilities within the Connected Vehicle environment.

4.1.2. Freeway-Arterial Interchanges

The freeway-arterial interface can often be a critical network traffic control point. When the freeway is metered or congested the ramp queue can spillback into the arterial causing severe congestion and requires special considerations to keep arterial traffic flowing. There have been several studies on strategies for control of the freeway-arterial interface that address coordination and diversion(Kloos et al. 2005; Wu, Hallenbeck, and Wang 2009). Rindt studies the a real-time control system for the freeway-arterial interface (Rindt, Jayakrishnan, and McNally 1997) and Head (Head and Mirchandani 1997) developed a real-time ramp metering strategy that directly considered the queues on the ramps. There hasn’t been any significant literature on the us of connected vehicle technology for the freeway-arterial interface.

A similar issue exists on the off-ramp side of the freeway. Queues from the downstream traffic signal can cause spillback onto the freeway which can cause severe congestion (Chang and Li 2010; Hagen, Lin, and Fabregas 2006; Li, Chang, and Natarajan 2009). All of these systems require the measurement and estimation of queue length. Connected vehicle technology can significant improve this aspect of these control systems.

4.1.3. Active Traffic and Demand Management (ATDM)

Recently, the concepts of active traffic and demand management have become popular, especially on freeways (Levecq, Kuhn, and Jasek 2011; Dowling et al. 2011). Application of these concepts to signalized networks offers some interesting opportunities. Control mechanisms include speed advisories, lane preference/restrictions (e.g for transit vehicle or trucks), queue warning, . Speed advisories can be used to improve progression and avoid shockwaves and can have a significant impact on reducing rear-end collisions. Speed advisories can be made to all vehicles on the roadway, or could be made on a vehicle-by-vehicle basis to improve speed advisory performance and compliance. For example, trucks could be assigned a slower speed that would allow them to progress along an arterial and reduce the potential for sudden stops. Transit vehicles could have their speed adjusted to compensate for schedule consideration, progression, stop locations, etc.

Lane preferences and restrictions have been used in some special circumstances such as when turning volumes from a freeway exit exceed single lane capacities (Bullock, Harvey, and Messer 1999). It is envisioned that lane preference and restrictions could be used in a variety of ways to improve traffic flow on signalized networks. Lane preference could be given to transit (Eichler and Daganzo 2006) and emergency vehicles to improve performance. Commercial vehicles could be given short term lane blocking permission to make deliveries - if traffic conditions permit and restricted if they don’t.

When enhanced traffic control methods, such as lane preference and speed advisories, are used in cooperation with adaptive signal timing there are significant opportunities for improving performance and safety. There are challenges to using control mechanisms such as lane restrictions in signalized environments. For example, if commercial vehicles are restricted to using only right hand lanes and their routes require a left turn, then some control strategies such as early green, or queue jump, may be utilized to provide them an opportunity to cross to the desired lane. This may require lane-by-lane signalization (or in-vehicle signing).

Active traffic and demand management concepts present interesting, advanced concepts that could be realized in a connected vehicle environment. They may not be “near term” capabilities, but they definitely could be transformative.

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