Development and Testing of Priority Control System in Connected Vehicle Environment

Jun Ding  
Department of Systems and Industrial Engineering  
University of Arizona  
Tucson, AZ 85721  
dingjun@email.arizona.edu

Qing He  
Departments of Civil, Structural, and Environmental (CSEE) and Industrial and Systems Engineering (ISE)  
University of Buffalo, The State University of New York  
Buffalo, NY 14260  
qinghe@buffalo.edu

K. Larry Head  
Department of Systems and Industrial Engineering  
University of Arizona  
Tucson, AZ 85721  
larry@sie.arizona.edu

Faisal Saleem  
Maricopa County Department of Transportation  
2901 W. Durango St.  
Phoenix AZ 85009  
faisalsaleem@mail.maricopa.gov

Wei Wu  
School of Transportation Engineering  
Tongji University  
Shanghai, P.R. China 201804  
wuwei@tongji.edu.cn

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ABSTRACT

Traffic signals provide service for multiple modes of travelers including vehicles, trucks, transit, pedestrians, bicycles, and emergency vehicles. Past research and experience have demonstrated the benefits of providing traffic signal priority for individual modes such as transit, emergency vehicles, and trucks. However, the priority treatment for each travel mode was addressed independently within the normal traffic signal operation. With the advancement of the wireless communication technologies, the global positioning system, and the development of the vehicle to vehicle (v2v) and vehicle to infrastructure (v2i) systems, called Connected Vehicles (CV), there is an opportunity to simultaneously identify, prioritize, and sever requests from multiple vehicles. This paper demonstrates the implementation of a decision framework for prioritizing requests for service from multiple modes within an integrated traffic signal control framework. The framework has been developed and tested using a microscopic hardware-in-the-loop simulation (HILS) environment based on VISSIM and field tested and demonstrated in a live network of six intersections in Anthem, Arizona. The successful demonstration shows that the potential for safer and more efficient multi-modal traffic signal operations is highly possible.

KEYWORDS

Priority Traffic Signal Control, Connected Vehicles, hardware-in-the-loop simulation
1. Introduction

Traffic signal control has experienced very few fundamental improvements in the past 50 years. The principles of movements controlled by intervals of phases and the use of point detection have formed the basis for traffic signal control. Coordination, preemption, and priority were higher level strategic behaviors that control the basic phase intervals by holding and forcing off phases and rings to achieve the desired behavior. Advances in signal control logic have primarily focused on enhancing priority control for transit vehicles and adaptively adjusting timing parameters. Tools and methods have been developed to enable traffic engineers’ better use of traffic signal control, but the fundamental logic and operations of the controller has not changed.

Traffic signal control in most urban areas today is dynamic (actuated) in nature and coordinated with other intersections to enable smooth flow, or progression, of traffic. However, these systems depend on loop detectors or video based systems that are located at fixed locations in space to call and extend signal control phases. These detection systems provide basic information such as vehicle count, occupancy, and/or presence/passage information. This limits the use of advanced logic that could potentially be built into modern day traffic signal controller (1).

The advancements in technology for traffic data collection have made it possible to collect a new form of traffic or vehicle data (i.e., disaggregated/individual traffic or vehicle data). These data sources fall under the umbrella of probe vehicle technologies (e.g., GPS vehicle probes (2), cell phone vehicle probes (3), Connected Vehicle probes (4), etc.). The recent advances in vehicle positioning, probe vehicle technologies and wireless communications provide a significantly improved opportunity for priority control. In the United States, the concept of Connected Vehicles aims to provide wireless communications between vehicles and the infrastructure to support applications to improve safety and mobility (5). The connected vehicle technology has identified 5.9 GHz Digital Short Range Communication (DSRC) as the primary communications mode for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) safety based applications, denoted as V2X.

The advances in Connected Vehicle (CV) technologies provide the first real opportunity for transforming traffic signal control in terms of the traffic signal controller logic, operation, and performance. Connected Vehicle technology combines leading edge technologies--advanced wireless communications, on-board computer processing, GPS navigation, equipped infrastructure, and others--to provide the capability for vehicles to identify threats and hazards on the roadway and communicate this information over wireless networks to give drivers alerts and warnings. The advent of DSRC, and other wireless communications technologies, in vehicular communication provides a critical component that, when coupled with meaningful messages (SAE J2735), has the potential to provide detailed information required for intelligent traffic signal control. DSRC can be leveraged to provide real-time knowledge of vehicle class (passenger, transit, emergency, etc.), position, speed, and acceleration on each approach to an equipped signalized intersection as well as to provide real-time Signal Phase and Timing (SPaT) information to authorized vehicles approaching signalized intersections.

The objective of this study is to develop a multi-modal priority signal control system in which several priority requests from different modes (e.g. fire engines, public transits) can be
accommodated simultaneously. This system has been first studied and tested in a microscopic Hardware-In-a-Loop Simulation (HILS) environment with VISSIM. Then the system has been demonstrated in a live network of six intersections in Anthem, Arizona.

2. Literature Review of Priority Signal System

Signal priority is the technique of changing or maintaining traffic signal timing in order to reduce the stopped delay for targeted vehicles, like buses or emergency vehicles. Traditional traffic signal control logic has provided priority for different classes of users (vehicles, pedestrians, emergency vehicles, transit, etc.) and control strategies (actuated phases and coordination) through essentially independent mechanisms when the special or desired service is requested. Preemption and Transit Signal Priority (TSP) are considered as two common types of priority. Behaviors such as emergency vehicle preemption generally require higher priority consideration than transit priority might.

Considering preemption requests within an integrated priority control framework allows multiple simultaneous preemption requests to be addressed. Traditionally, preemption requests are served in a first-come-first-served manner with a possible override for one approach over another and complete override of coordination. Although emergency vehicle operators are trained to be observant and vigilant, there have been cases in which two emergency vehicles have collided in an intersection (6). Statistics reveal that nearly 13% of the firefighters and police officers who lost their lives in the line of duty are killed in vehicle-related incidents (7); roadway safety has been noted as a significant emergency responder issue recently.

Coordination is not usually considered a form of priority but the underlying goal is the same: be sure the traffic signal is in a specific interval (state) at a specific point, or interval, in time. Including coordination as a form of priority opens the opportunity for multi-modal integration of many requesting entities within one integrated decision framework. The relative importance of emergency vehicles, transit, pedestrians, coordination, or other modes can be determined based on an agencies operating policy.

TSP is a popular and promising tool for improving transit performance and reliability (8). Much attention has been paid on developing TSP strategies and documenting the benefits of implementation (9-13). Basically, TSP can be classified into three categories: passive priority, active priority, and adaptive or real-time priority (14). Passive priority operates continuously regardless of whether the transit is present or not (15). Active priority strategies provide priority service when a transit vehicle sends a priority request (16). Adaptive or real-time TSP strategies provide priority while trying to optimize given performance criteria including person delay, transit delay, vehicle delay, and/or a combination of these criteria (17).

Typically, a priority strategy includes extending a phase to allow a transit vehicle to pass or terminate conflicting phases allowing early service to reduce delay (18-20). However, it is possible, and maybe likely, that more than one bus may arrive on conflicting approaches at an intersection during a cycle. In that case there is a need to simultaneously consider the multiple requests for priority in a way that is not disruptive, or inefficient, to other traffic. Other factors, such as occupancy and schedule adherence, are important considerations that can be used to...
manage which priority requests should be served, but it is still likely that multiple transit vehicles
will desire priority service. Although the signal priority control strategies are applied worldwide,
little effort has been spent on the multiple priority requests scenarios (21-24). Integration of the
multiple requests for priority and the desire to operate the signal as part of a coordinated system
indicates there is a need for new signal control logic. Motivated by recent advances in vehicle
positioning, V2X communications, and DSRC technology, this paper addresses the simulation
and field implementation of an integrated priority control framework for multi-modal traffic
signal control.

3. Architecture of Multiple Priority Requests (MPR) Signal Control System

Among many wireless communication technologies including WiFi, 3G/4G, DSRC, and
Bluetooth, DSRC was chosen as the communication platform for information exchange because
of its low latency which is typically less than one second. The National Transportation
Communications for ITS Protocol (NTCIP) provides both communication protocols and the
vocabulary (called objects) necessary to allow electronic traffic control equipment from different
manufacturers to operate with each other as a system. The NTCIP 1211 Signal Control and
Priority (SCP) Concept of Operations is comprised of two primary components, the Priority
Request Generator (PRG) and a Priority Request Server (PRS). A vehicle acting as the PRG,
which could be an emergency vehicle, transit bus, light rail train, or other type of transit or
priority eligible vehicle, submits a request for priority to the PRS. These two elements can be
thought of as a logical process that could be physically implemented in more than one way. The
standardization occurs at the interface of these processes and represents the objects developed by
NTCIP 1211.

The two primary interfaces are (1) between PRG and PRS and (2) between PRS and the traffic
signal controller. Based on where the PRG and PRS are located and what inputs are being
transmitted and received, five SCP scenarios are proposed in (25) to provide a logical architecture
for implementation of priority in different traffic operating environments. At a systematic level,
these five scenarios can be categorized according to whether they are implementing priority in a
centralized or distributed architecture. These architectures are based upon the traffic signal
system, on-board vehicle equipment, and communication infrastructure. The major concepts of
the distributed architecture are adopted in the multiple request priority control system discussed
in this paper. The system architecture of implementation is illustrated in Figure 1.
According to the Intelligent Transportation Society of America (ITSA) (26), a physical TSP system is composed of three major components: the vehicle detection system that detects transit vehicles and generates priority requests, the traffic signal control system that receives and processes the request for priority at the intersections, and the communications system that links the vehicle detection system with the traffic signal control system. This architecture is not limited to TSP and is appropriate for all forms of priority control.

In the multiple request based priority signal control system, the three major components are the On-Board Equipment (OBE), Road Side Equipment (RSE), and the Actuated Signal Controller (ASC). The vehicle detection system and priority request generator (PRG) are realized by the OBE, while the communication system is realized by the wireless (DSRC) system, and the request processing system (PRS) is realized by the RSE. There is also communication between the RSE and traffic signal controller to implement the priority timing strategy from the PRS. All these systems and communications are achieved by the applications (software) residing in the OBE, RSE, and traffic signal controller.

The OBE is a vehicle-resident device that is comprised of an embedded computer with DSRC, WiFi, and positioning system (GPS) accurate to within two meters in normal operation. Two major and one visualization software applications are running on the OBE:

- ** obe_listener:** “listens” and receives messages, including a MAP (a map with geometric information about the intersection), from nearby RSEs.
• **obe_PRG**: generates the request(s) based on the GPS data and MAPs that are received.

• **obe_webserver**: provides a user interface for visualizing the signal status, request table and priority control status.

The flow of events in the OBE includes:

1. A connected vehicle, OBE, continuously receives messages from nearby RSEs including a digital MAP of the intersection, current signal status, and a table of priority requests that are currently being served by the RSE. The **obe_listener** is responsible for this process.

2. The connected vehicle (OBE) reads vehicle information including the speed, position, and heading from the GPS receiver and vehicle systems. This occurs frequently, such as at 5 Hz.

3. The connected vehicle (OBE) parses the MAP and locates its position using the GPS data. It determines the estimated time of arrival (ETA) at the intersection stop bar. It also determines the desired service phase (traffic signal phase) using data included in the MAP (Note: the current SAE J2735 MAP message does not include the movement based service phase and recommends using an in-lane and out-lane pair instead of service phase. This requires that the RSE translate the in-lane and out-lane to signal phase).

4. The connected vehicle (OBE) formats and transmits a signal request message (SRM) based on the service phase, ETA and vehicle type to the RSE. This processing is done by the **obe_PRG** process.

The RSE is an intersection-resident device comprised of an embedded computer with DSRC, WiFi, and Ethernet connections. Each RSE is connected to the intersection’s traffic-signal controller using the Ethernet connection. The RSE receives prioritized requests from approaching Priority Request Generators (PRG) - connected (OBE equipped) vehicles.

The RSE then formulates the received requests of varying priority levels into an optimization problem that is solved to provide a signal timing schedule that will minimize the weighted priority delay. Details of the optimization problem can be found in (22-23). The solution of the optimization problem generates a signal timing schedule that provides the time for each phase to serve between the current time and the total time requested by all active priority requests. The schedule is implemented on the ASC controller by setting NTCIP phase control objects including phase HOLD, phase FORCE-OFFs, phase CALL, and phase OMIT commands.

Three applications are running in the RSE:

• **rse_PRS**: receives requests from approaching connected vehicles and selects which requests to serve.

• **rse_mprsolver**: solves the optimization problem formed by the selected requests and current signal status, and then implements the schedule on the ASC.

• **rse_msg_transmitter**: transmits (broadcasts) current signal status, the MAP of the intersection, and the table of active request.
The flow of events in the RSE includes:

1. The RSE reads the signal timing and phase status from the signal controller.
2. The RSE receives requests from approaching equipped vehicles (OBEs) and updates the table of active priority requests.
3. The RSE decides when to solve the optimization problem based on changes to the request table. The request table can be updated by the receipt of a new request, the updating of an existing request, or the canceling of an existing request. The RSE will implement the solution from the solver using NTCIP commands.
4. The RSE continuously (1Hz) broadcasts messages that include the MAP of the intersection, signal status and request table.

4. Microscopic Hardware-In-a-Loop Simulation (VISSIM) Testing Support

Successful deployment of the priority based traffic signal control algorithm requires thorough laboratory testing and evaluation using simulation before field implementation. Many traffic control algorithms have been studied using hardware-in-the-loop simulation (27-28). Hardware-in-the-loop simulation uses a combination of simulation software and real signal controller hardware to evaluate traffic conditions and priority control algorithms in a laboratory setting. Compared to the traditional HILS, that primarily includes traffic signal controllers, simulation of Connected Vehicle systems also requires RSEs and OBEs as well.

The implementation of hardware-in-the-loop simulation is based on the use of a microscopic simulation program, VISSIM in this study, with an Econolite ASC/3 controller, and two Savari MobileWave units, one that is used as the RSE and one, or more, that are used as OBEs. In addition, OBEs can be simulated in software so more vehicles can be considered in a simulation scenario. A controller interface device (CID) is used to provide a real-time link between the simulation program and the traffic controller (29). Figure 2 illustrates the setup used in the HILS. The HILS needs to be run in real-time to coordinate the VISSIM simulation and hardware traffic controller unit, hence the simulation speed in VISSIM was set to one simulation second per second and ten simulation steps per second.
The HILS schematic is shown in Figure 3. The simulation computer, RSE, OBE, and the ASC/3 controller are all in the same Local Area Network (LAN) domain. As shown in Figure 3, these devices all have the Ethernet IP address starting with “LAN IP.*”. The DSRC and WiFi in the OBEs and RSEs are also in the same domain, so the OBE and RSE can communicate to each other. Three types of network connections are considered. The first is the Ethernet connection between RSE and Econolite ASC/3 controller, hardware and software OBEs and the computer running VISSIM. The priority control applications (software) running on the RSE can retrieve controller status and implement a priority timing schedule on the controller by communicating to it through NTCIP. A Dynamic-link library (DriverModel.dll) is used to pass a message from VISSIM to the OBEs. The DriverModel.dll gets the x-y position of the specified (connected) vehicle modeled in VISSIM, converts the x-y position to real-world GPS coordinates and sends this position information to the OBE’s IP address. The second is the DSRC connection between hardware OBEs and RSE, which allows the RSE and hardware OBEs exchange information. The third is WiFi connection between a laptop running Putty Terminal and the RSE or OBE. After connecting the laptop to RSE or OBE through WiFi, one can log into the RSE or OBE using Putty Terminal to view status of the applications that are running. If the laptop is connected to an OBE, the signal status and request table etc. can be displayed in a web browser by calling a shell script in OBE.
The flow of the HILS is described as the following:

1. Run the isolated intersection, or network, in VISSIM with the specified GPS position origin and scale, see Figure 4.
2. In the DriverModel.dll, convert the x-y positions of the connected vehicles into real world positions (GPS coordinates) (30).
3. The connected vehicles send the converted “GPS” coordinates to the associated OBE.
4. The OBEs receive MAP, signal status and the active request table from RSE and “GPS” coordinates from VISSIM. The OBEs determine whether to send out request or not by parsing the received MAP and based on a defined DSRC range.

If priority request table is updated in the RSE, the RSE_mprsolve application will form a priority control optimization problem and solve it, then implement the schedule (solution) through NTCIP on the Econolite ASC/3 controller connected to the CID. The CID will update the controller status in VISSIM.

5. Field Experiments in Anthem

The Maricopa County Department of Transportation SMARTDrive field test bed is a state-of-the-art laboratory for testing new transportation technologies systems under the connected vehicle environment, including vehicle prioritization at six signalized traffic intersections along a 2.3-mile stretch of Daisy Mountain Drive in the Anthem, Arizona. A live demonstration of the multiple request based priority control strategy was conducted on April 26, 2012. This demonstration included equipping the six intersections with RSEs and several vehicles (two REACT vehicles, one fire engine, and a Valley Metro Transit Bus) with OBEs to demonstrate the
capabilities of the system to manage public transit and emergency vehicles during mock incident responses.

Figure 4: An isolated intersection in VISSIM: Daisy Mountain Dr. and Gavilan Peak

Participants in the demonstration boarded a Valley Metro bus and traveled through the SMARTDrive network as shown in Figure 5. Along the route, three scenarios involving Emergency Vehicles (EVs) were demonstrated:

1. The bus starts at the west end of the network and proceeds along Daisy Mountain Drive.
2. While the bus was approaching Anthem Way from Memorial (phase 8), a REACT (Regional Emergency Action Coordinating Team) vehicle (EV) was approaching from the northwest (phase 2). The priority requests were visible to the participants on the bus, and the transit priority was overridden by the EV priority. The exact timing sequence depended on where in the cycle the signal was when it received the first and second requests, but the timing favored the higher priority EV;
3. As the bus returned back to the Gavilan Peak intersection (start) approaching from Dedication (phase 2), a REACT vehicle and a fire engine (both EVs) approached the intersection from the north and south (phases 4 and 8), but conflicting with the bus. Priority was granted to the two emergency vehicles and not the bus, but the three requests were shown in the request table to the bus passengers;
4. After the bus passed the Gavilan Peak intersection, two more emergency vehicles approached the intersection from conflicting phases (phases 6 and 8). This allowed the participants on the bus to see the two vehicle priority requests again and allowed the team to explain the events, logic, and timing.

Details for each of these scenarios are described below.

Figure 5 The route for the field demonstration (Courtesy Jeff Jenq, Oz Engineering)

5.1 Detailed descriptions of the three scenarios involved with EVs

Different assumptions for the multimodal signal control system are made for the case studies with and without Emergency Vehicle (EV), listed in Table 1.

<table>
<thead>
<tr>
<th>Without EV</th>
<th>With EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Green Time extension is MaxGreenTime*(1+a) for Transit Vehicle (typically 0&lt;a&lt;0.5, “a” is used to extend the maximum green time of the current plan)</td>
<td>Maximum Green Time extension equals 240s for EV requested phases</td>
</tr>
<tr>
<td>No phase skipping allowed</td>
<td>Phases skipping allowed</td>
</tr>
<tr>
<td>Actuated control on non-priority vehicle phases</td>
<td>Phases skipping allowed</td>
</tr>
</tbody>
</table>
Scenario 1: An EV from conflicting phase to the bus

When the bus (OBE22) approaches the intersection of Anthem Way and Daisy Mountain Dr. (phase 8), it is actively requesting phase 8 with priority of level 2 (class TRANSIT). A REACT vehicle (simulated EV, OBE25) approaches the same intersection on a conflicting movement from west (phase 2) with a request for phase 2 and 5 with priority of level 1 (class EV). The \textit{RSE\textsubscript{mprsolver}} in the RSE generates a solution to the optimization problem considering only the highest priority level 1 request. As can be seen in Figure 6, there is a green tick icon in the first column of each active request that is being served and a red cross icon in the first column of the request that is not being served. The bus had to stop before reaching the stop bar, so its queue clear time is not 0. This accounts for the needed green time to clear the queue that exists between the bus and the stop bar. It should be noticed that the REACT vehicle (EV) requests two phases which is the desired behavior when a single emergency vehicle approaches the intersection. This will allow both the left turn and through movements to serve clearing the approach so the vehicle can take either movement. The EV route information is not assumed to be known.

![Figure 6. When the bus (OBE22) approaches phase 8, a REACT vehicle (OBE25) requests phases 2, and 5.](image)

Scenario 2: Two EVs on concurrent phases but conflicting to the bus

When the bus (OBE22) returned back to the intersection of Gavilan Peak from Dedication, it requested phase 6 with priority of level 2 (class TRANSIT). A REACT vehicle (simulated EV, OBE25) approached this intersection from south (phase 8), requesting phase 8 with priority of level 1 (class EV), while another fire truck (OBE26) approached this intersection from south (phase 4) almost simultaneously with the REACT vehicle, requesting phase 4 with priority of level 1 (class EV). The request table is shown in Figure 7. As can be seen from the request table,
the queue clear time for the bus is not 0, which means the bus is stopped because of its lower level of priority.

Figure 7 When the bus (OBE22) approached phase 6, a REACT vehicle (OBE25) requested phase 8 and fire truck (OBE26) requested phase 4.

Scenario 3: Two EVs from conflicting phases

After the bus (OBE22) passed the intersection of Gavilan and stopped, a REACT vehicle (simulated EV, OBE25) approached this intersection from east (phase 6), requesting phase 6 with priority of level 1, while another fire engine (OBE26) approached this intersection on the conflicting movement from the south (phase 8) a little later than the REACT vehicle. The request table is shown in Figure 8. As can be seen from the request table, the queue clear time for OBE26 is not 0, which means the fire engine is stopped because the conflicting phase is served first and it has to wait in the queue.
After the bus (OBE22) passed the intersection, a REACT vehicle (OBE25) requested phase 6 and fire engine (OBE26) requested phase 8.

5.2 The Results of the Field Experiments

After parsing the log file recording GPS positions, the GPS positions were extracted and plotted in the GoogleEarth as white dots shown in Figure 9. It is seen that the trace of the bus conforms very well to the real road. The start position (yellow star) and stop position (yellow triangle) are used to calculate the travel time for the whole route. When scenario 2 was tested, the bus has to stop in front of the Gavilan Peak because the EVs approaching at conflicting phases to the bus, so the time at the stop position is picked to be the end time of the route.
The total route is about 6.23 miles (10 km). Average speed is about 17 m/s (38 mph) for the bus, and 20 m/s (45 mph) for EVs. After finding the starting time and the ending time for the route, the travel time was calculated.

In the demonstration, the travel time for first trip without priority was 0:22:02 hours (1320 s), for the next three trips with priority the travel times were 0:10:58 hour (658 s), 0:11:20 hour (680 s), and 0:13:20 hour (800 s), respectively. The average time for the three cases with priority is 713 s. Although more field tests need to be run in order to show improvement over the none-priority case or other priority control systems, the observers did experience the benefits brought by the priority signal control strategy. The multi-modal priority signal control system was also considered to make public transit more attractive and reliable (31).

6. Conclusions

Motivated by the rapid developments of the wireless communication methods especially the advent of DSRC, a decision framework for prioritizing requests for service from multiple modes and simultaneously accommodating several priority requests is addressed within an integrated framework in connected vehicle environment. The setup of HILS and various wireless communications among different components of HILS are detailed. The validation of the multiple requests based signal priority control system has been tested and evaluated using microscopic HILS with VISSIM. The multi-modal priority control system has been demonstrated in a live network with six-intersection in Anthem, Arizona. The results of the demonstration showed that the discussed priority control system has the potential to provide safer and more efficient multi-modal traffic signal operations.
In addition to the functions like EV priority and transit priority presented in the paper, the priority control system can be used to realize additional functions including coordination and pedestrians. More field experiments will be conducted to testify the functions of coordination and other features in the near future. The Maricopa County SMARTDrive test network is an important tool in the development and testing of Connected Vehicle applications for advanced transportation management.

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