Transportation Research Part C 46 (2014) 65–82

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Multi-modal traffic signal control with priority, signal actuation and coordination

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ARTICLE INFO

Article history:
Received 19 February 2014
Received in revised form 2 May 2014
Accepted 2 May 2014

Keywords:
Traffic signal control
Signal optimization
Multi-modal traffic control
Connected vehicles
v2i
Transit priority
Pedestrian control

ABSTRACT

Both coordinated-actuated signal control systems and signal priority control systems have been widely deployed for the last few decades. However, these two control systems are often conflicting with each due to different control objectives. This paper aims to address the conflicting issues between actuated-coordination and multi-modal priority control. Enabled by vehicle-to-infrastructure (v2i) communication in Connected Vehicle Systems, priority eligible vehicles, such as emergency vehicles, transit buses, commercial trucks, and pedestrians are able to send request for priority messages to a traffic signal controller when approaching a signalized intersection. It is likely that multiple vehicles and pedestrians will send requests such that there may be multiple active requests at the same time. A request-based mixed-integer linear program (MILP) is formulated that explicitly accommodate multiple priority requests from different modes of vehicles and pedestrians while simultaneously considering coordination and vehicle actuation. Signal coordination is achieved by integrating virtual coordination requests for priority in the formulation. A penalty is added to the objective function when the signal coordination is not fulfilled. This "soft" signal coordination allows the signal plan to adjust itself to serve multiple priority requests that may be from different modes. The priority-optimal signal timing is responsive to real-time actuations of non-priority demand by allowing phases to extend and gap out using traditional vehicle actuation logic. The proposed control method is compared with state-of-practice transit signal priority (TSP) both under the optimized signal timing plans using microscopic traffic simulation. The simulation experiments show that the proposed control model is able to reduce average bus delay, average pedestrian delay, and average passenger car delay, especially for highly congested condition with a high frequency of transit vehicle priority requests.

1. Introduction

Modern urban transportation networks involve complex traffic dynamics composed of multiple travel modes, including passenger cars, transit buses, pedestrians, bicycles, trucks, light rail, emergency vehicles, and commercial and private modes of transportation. Traffic signal control systems traditionally treat either the aggregated flow of traffic or each mode

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http://dx.doi.org/10.1016/j.trc.2014.05.001

Table 1
Traffic signal control treatments for different traffic modes in current state-of-practice systems in the US.

Traffic mode	Traffic characteristics	State-of-practice treatment
Passenger cars	Mass volume and very low priority	Signal coordination and phase actuation
Buses	Low volume and medium priority	Transit signal priority
Pedestrians	Varying volume and no priority consideration; low speed and high vulnerable	Pedestrian dedicated intervals
Bicycles	Varying volume and no priority; medium speed and high vulnerable	Bicycle dedicated phases
Trucks	Medium to high volume and low priority	Freight signal priority
Light rail	Low volume and high priority	Signal preemption and Transit signal priority
Emergency vehicles	Very low volume and extremely high priority	Signal preemption

separately, as summarized in Table 1. For example, signal coordination aims to generate a "green wave" for passenger cars to progress along a route through several signalized intersections; signal preemption ensures the high priority requests from emergency vehicles are served in a timely fashion; and, transit signal priority (TSP) is widely used to favor bus and light rail movements. Aggregation of the modes into a single flow does not support the desire to provide priority for different modes to meet system operating objectives. Treating each mode separately is likely to result in sub-optimal system performance (He et al., 2012). Different travel modes have their own specific characteristics including travel speed, volume, priority level, and vulnerability, yet very little is understood about the interactions among signal control strategies for the different modes.

Multi-modal signal control systems can be considered as a natural extension of traditional signal priority control systems, which include emergency vehicle preemption and transit signal priority (TSP). An emergency vehicle requests signal preemption treatment by using either optical, acoustic, special inductive loop technology, or based on wireless communications using Global Positioning System (GPS) positions (Nelson and Bullock, 2000). Preemption generally involves a control strategy that immediately switches from the current phase to a pre-selected phase for the first request received. Transit signal priority has been adopted using similar technology, but can be served by minor modifications to traffic signal plan parameters (offset adjustment, green split reallocation, phase insertion or phase rotation) to favor the movements of transit vehicles (Evans and Skiles, 1970; Yagar and Han, 1994; Balke et al., 2000; Furth and Muller, 2000; Skabardonis, 2000; Baker et al., 2002; Head, 2002; Liu et al., 2003; Smith et al., 2005; Skabardonis and Geroliminis, 2008; Ma et al., 2010).

In current emergency vehicle preemption systems, only one request is served at a time. Therefore, if multiple vehicles are simultaneously approaching an intersection and they request conflicting traffic signal phases the first request received would be served even if a safer and more efficient solution could be achieved by considering all active request simultaneously. While emergency vehicle operators are trained to be observant and vigilant, there have been cases where two emergency vehicles have collided in an intersection (ABC13, 2009). Roadway safety has been noted as a significant emergency responder issue (The Transportation Safety Advancement Group, 2010).

TSP is a popular tool for improving transit performance and reliability (Smith et al. 2005). However, state-of-practice TSP is designed for one priority request at a time. Existing priority control systems are not capable of handling conflicting or multiple priority requests. For example, if two buses arrive on conflicting approaches at an intersection during a cycle, it is possible to serve both buses such that the total delay is minimized, but this may not be achieved if a first-come-first-serve policy is used. If the signal is already green for the second vehicle that arrives, the request from the first vehicle, which currently has a red signal, is likely to be served by an early green, which would result in an "early red" for the second vehicle. This would cause more delay than remaining in green to serve the second vehicle, then serving the first vehicle. Not only could this result in increased delay, it can result in increasing the delay variability (e.g. travel time reliability).

Most priority control systems do not address the multi-modal control need (University of Arizona, 2012). Agencies that operate traffic signal systems desire to establish a priority control policy that can favor one mode over another in a specific corridor during a specific time of day. For example, a traffic signal control system may be divided into several control sections based on the traffic flow pattern. One section might be in a region where there are many commercial trucks moving goods from warehouses to the interstate freeway system. Another section might be in a residential area where pedestrians and buses are a popular mode of transportation. The operating agency may want to provide priority for trucks in the first section and priority for pedestrians and transit in the second section. The ability to favor one mode over another is a desirable traffic control system characteristics.

With the advent of Connected Vehicles in United States (Research and Innovative Technology Administration, 2011), it may soon be possible to obtain additional information about the network state and vehicle operations. Connected Vehicles adopt a suite of communication technologies and applications to provide connectivity that includes vehicle-to-vehicle (v2v) communication and vehicle-to-infrastructure (v2i) communication, called v2x in general. Using v2i communication systems, the traffic signal control system can receive requests from equipped vehicles and pedestrians, and can generate an optimal signal timing plan that accommodates all of the active requests and the operating agencies priority policy.

In the past, communication technologies have been applied on transit signal priority (TSP) control projects (Chang et al., 1996; Liao and Davis, 2007; Ekeila et al., 2009). However, very few references can be found that address the multi-priority request issue. Head et al. (2006) proposed a mixed integer program which could accommodate multiple priority requests and minimize the total priority delay. However, deterministic priority vehicle arrival times are assumed in their work, which is reasonable for emergency vehicles but not realistic for transit buses. Recently, several algorithms have developed to resolve multiple transit priority requests (He et al., 2011; Zlatkovic et al., 2012; Ma et al., 2013). However, these studies