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A real-time adaptive signal control in a connected vehicle environment

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ABSTRACT

The state of the practice traffic signal control strategies mainly rely on infrastructure based vehicle detector data as the input for the control logic. The infrastructure based detectors are generally point detectors which cannot directly provide measurement of vehicle location and speed. With the advances in wireless communication technology, vehicles are able to communicate with each other and with the infrastructure in the emerging connected vehicle system. Data collected from connected vehicles provides a much more complete picture of the traffic states near an intersection and can be utilized for signal control. This paper presents a real-time adaptive signal phase allocation algorithm using connected vehicle data. The proposed algorithm optimizes the phase sequence and duration by solving a two-level optimization problem. Two objective functions are considered: minimization of total vehicle delay and minimization of queue length. Due to the low penetration rate of the connected vehicles, an algorithm that estimates the states of unequipped vehicle based on connected vehicle data is developed to construct a complete arrival table for the phase allocation algorithm. A real-world intersection is modeled in VISSIM to validate the algorithms. Results with a variety of connected vehicle market penetration rates and demand levels are compared to well-tuned fully actuated control. In general, the proposed control algorithm outperforms actuated control by reducing total delay by as much as 16.33% in a high penetration rate case and similar delay in a low penetration rate case. Different objective functions result in different behaviors of signal timing. The minimization of total vehicle delay usually generates lower total vehicle delay, while minimization of queue length serves all phases in a more balanced way.

1. Introduction

It has been almost 150 years since the first prototype colored traffic signal light was installed in Westminster, England in 1868 (Webster and Cobbe, 1966). Signal control systems have experienced tremendous development both in hardware and in control strategies. Currently, there are three major traffic control strategies: fixed-time, actuated and adaptive.

Fixed-time control systems utilize historical traffic data to create timing plans for different times of the day (TOD) to address the demand fluctuation. It is assumed that within the entire time period of a particular plan, the traffic demand remains similar. However in reality, the traffic demands may fluctuate quickly. Both actuated and adaptive control strategies

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have been developed to address the problem in real-time. Actuated control collects real-time data from infrastructure-based sensors, e.g. loop-detectors, video detectors, or radar, and applies a simply logic that includes phase calls, green extension, gap out, and max out to make control decisions. Current adaptive control strategies utilize similar real time sensor traffic data to predict near future traffic conditions and seek an optimal timing based on a defined objective function to make control decisions. Several current adaptive signal control systems include ACS-Lite (Luyanda et al., 2003), SCATS (Sims and Dobinson, 1980), SCOOT (Bing and Carter, 1995), OPAC (Gartner, 1983), MOTION (Brilon and Wietholt, 2013), UTOPIA (Mauro and Taranto, 1989) and RHODES (Mirchandani and Head, 2001).

Current adaptive signal control systems rely mostly on data from infrastructure-based sensors, including in-pavement or video based loop detectors. There are two limitations to using the loop based detection. First, loop-detectors are point detectors that only provide instantaneous vehicle location when a vehicle is passing over the detector. There is no direct measurement of vehicle states (location, speed, acceleration) when a vehicle passes the detector. Second, the installation and maintenance cost of the detection system is considered high. If one or more loop detectors are malfunctioning, the performance of the adaptive signal control system can be degraded significantly.

With the advances in wireless communication technology, vehicles are able to communicate with each other (V2V) and with the infrastructure (V2I) through dedicated short range communications (DSRC) and are referred to as connected vehicles. The USDOT suggested that connected vehicle technologies can be applied to areas of safety, mobility and the environment (US DOT Intelligent Transportation Systems Joint Program Office, 2014). Mobility applications utilizing V2I communication enable the intersection to acquire a much more complete picture of the nearby vehicle states. Data from connected vehicles provide real-time vehicle location, speed, acceleration and other vehicle data. Based on this new source of data, traffic controllers should be able to make “smarter” decisions. Collecting connected vehicle data depends on a single infrastructure device (radio) and is significantly less expensive to install and maintain a suite of detectors (e.g. video or loop). If one or more connected vehicles cannot communicate to the intersection due to communication failure, it will only decrease the penetration rate slightly and will have a small impact to the system performance. If the infrastructure based device fails, the intersection returns to the current state of the practice actuated or fixed time control.

The objective of this paper is to present a real-time adaptive traffic control algorithm by utilizing data from connected vehicles. The algorithm is based on improvements of the controlled optimization of phases algorithm (COP) (Sen and Head, 1997) which is used in the RHODES adaptive traffic control system (Mirchandani and Head, 2001). The original COP algorithm was based on a sequence of stages, e.g. A, B, C, D, where a stage could represent phases 1 and 5 (denoted A), or phases 2 and 6 (denoted B), but it did not support flexible, or dual ring, phase sequences. The phase allocation algorithm presented in this paper applies a two-level optimization scheme based on the dual ring controller in which phase sequence and duration are optimized simultaneously.

One of the major problems with the reliance of connected vehicle data for signal control is that the penetration rate of connected vehicles is low, at least for the next few years. Previous research showed that even after federal mandatory installation of DSRC ratio on new light vehicles manufactured in U.S, it may take 25–30 years for connected vehicles to reach a 95% penetration rate (Volpe National Transportation Systems Center, 2008). As a result, in order to provide more accurate arrival data for traffic control, the location and speed of unequipped vehicles needs to be estimated from data from connected vehicles.

The remainder of the paper is organized as follows. Section 2 provides a brief literature review on signal control with connected vehicle data. Section 3 introduces the system framework developed to test signal control applications in a connected vehicles environment in both a real road network and a simulation environment. Sections 4 and 5 describe the phase allocation algorithm and estimating location and speed of unequipped vehicles algorithm, respectively. Section 6 provides test results of the two algorithms based on a VISSIM model. Section 7 closes the paper with conclusions and further research.

2. Literature review

There have been several studies utilizing connected vehicle data for signal control. Different from loop detector data, trajectory data from connected vehicles provide more information of the vehicle states. Utilizing data from connected vehicles, traffic control decisions can be made to be more dynamically responsive to real-time traffic conditions.

Priemer and Friedrich (2009) developed a decentralized adaptive traffic signal control algorithm with V2I communication data. The algorithm was phase based and discretize time into 5 s intervals. The forecast horizon was 20 s. The objective was to minimize total queue length and the problem was solved by dynamic programming and complete enumeration. Goodall et al. (2013) proposed a predictive microscopic simulation algorithm (PMSA) for signal control. The algorithm took data from connected vehicles including position, heading and speed, and then utilized a microscopic simulation model to predict future traffic conditions. A rolling horizon strategy of 15 s was chosen to optimize either delay only or a combination of delay, stops and decelerations. The algorithm considered several market penetration rates and the states of unequipped vehicle were estimated based on equipped vehicle states (Goodall, 2013). However, the algorithm cannot be applied in real-time due to the computational requirements of the parallel simulation to predict the future traffic conditions.

He et al. (2012) proposed a traffic signal control framework for multi modes in a network of traffic signals under V2I environment named PAMSCOD. A headway-based platoon recognition algorithm was developed to identify pseudo-platoons in the network. A mixed-integer linear programming (MILP) problem was solved to find the optimal signal plan based on

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