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Isolated intersection control for various levels of vehicle technology: Conventional, connected, and automated vehicles

Kaidi Yang [a,*], S. Ilgin Guler [b], Monica Menendez [a]

[a] Traffic Engineering Group, Institute for Transport Planning and Systems, ETH Zurich, Switzerland
[b] Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, United States

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ABSTRACT

Connected vehicle technology can be beneficial for traffic operations at intersections. The information provided by cars equipped with this technology can be used to design a more efficient signal control strategy. Moreover, it can be possible to control the trajectory of automated vehicles with a centralized controller. This paper builds on a previous signal control algorithm developed for connected vehicles in a simple, single intersection. It improves the previous work by (1) integrating three different stages of technology development; (2) developing a heuristics to switch the signal controls depending on the stage of technology; (3) increasing the computational efficiency with a branch and bound solution method; (4) incorporating trajectory design for automated vehicles; (5) using a Kalman filter to reduce the impact of measurement errors on the final solution. Three categories of vehicles are considered in this paper to represent different stages of this technology: conventional vehicles, connected but non-automated vehicles (connected vehicles), and automated vehicles. The proposed algorithm finds the optimal departure sequence to minimize the total delay based on position information. Within each departure sequence, the algorithm finds the optimal trajectory of automated vehicles that reduces total delay. The optimal departure sequence and trajectories are obtained by a branch and bound method, which shows the potential of generalizing this algorithm to a complex intersection.

Simulations are conducted for different total flows, demand ratios and penetration rates of each technology stage (i.e. proportion of each category of vehicles). This algorithm is compared to an actuated signal control algorithm to evaluate its performance. The simulation results show an evident decrease in the total number of stops and delay when using the connected vehicle algorithm for the tested scenarios with information level of as low as 50%. Robustness of this algorithm to different input parameters and measurement noises are also evaluated. Results show that the algorithm is more sensitive to the arrival pattern in high flow scenarios. Results also show that the algorithm works well with the measurement noises. Finally, the results are used to develop a heuristic to switch between the different control algorithms, according to the total demand and penetration rate of each technology.

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* Corresponding author.
E-mail addresses: kaidi.yang@ivt.baug.ethz.ch (K. Yang), iguler@engr.psu.edu (S.I. Guler), monica.menendez@ivt.baug.ethz.ch (M. Menendez).

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1. Introduction

Traffic signals are essential components for urban traffic management. Traffic signals interrupt the progression of vehicles, increasing travel time, gas emissions and fuel consumption (Unal et al., 2003; Coelho et al., 2005; Li et al., 2009). It is estimated that delays at traffic signals contribute to as much as 5–10% of all traffic delay or 295 million vehicle-hours of delay on major roadways in the U.S. (National Transportation Operations Coalition (NTOC), 2012). Moreover, field tests have shown that stop-and-go vehicles cause 14% extra exhaust gas emissions compared to vehicles that drive at a constant speed (Xia et al., 2012).

Traditional signal control strategies use either historical data (fixed-time) or real-time information provided by loop detectors (actuated or adaptive) to determine departure priority. Those devices are usually installed at a fixed location and cannot provide detailed information about the movement of individual vehicles. Therefore, even if those signal control strategies can adapt to the variations in demand, there is still room for improvement.

The recent development in connected vehicle technology (i.e. vehicles that can communicate with each other and infrastructure to provide information on speed, location, etc.) makes it possible to track and control the movement of vehicles and thus has attracted increasing attention in traffic control. With real-time information obtained from connected vehicles, better signal control strategies can be developed. Moreover, wireless communication systems and automated driving can help advise drivers or control vehicles, providing a more flexible design of signal control strategies.

A recent research (Guler et al., 2014) proposed a signal control algorithm for an isolated intersection. It used information provided by different penetration rates of connected vehicles present in a traffic stream, and evaluated the benefits of this technology. This paper further exploits the value of connected vehicle technology by extending the above research. In this work, additionally, a certain percentage of connected vehicles are assumed to be automated. This allows the central controller to optimally design the trajectories of these automated vehicles to further improve the operations. Compared to Guler et al. (2014), the contributions of this paper are threefold. First, this work proposes a scheme to show how the algorithm should evolve with different development stages of connected vehicle technology, considering three different types of vehicles. Second, it enables bidirectional vehicle-to-infrastructure communication and successfully integrates trajectory design for automated vehicles into the signal control scheme. Third, it further improves the performance indices by reducing both the delay and the number of stops.

This paper is organized as follows. Section 2 presents a short review on signal control strategies utilizing connected vehicle technology. Section 3 introduces the algorithm developed. Section 4 evaluates the performance of this algorithm by comparing it to an actuated signal control algorithm, and analyzes its robustness. Section 5 proposes a demand responsive control strategy based on the application bounds of the new algorithm. Section 6 concludes the paper.

2. Literature review

This section presents a short literature review on signal control strategies based on connected vehicle technology. The interested readers can refer to Florin and Olariu (2015) for a comprehensive survey of traffic signal optimization methods using connected vehicles from a technology perspective, and L. Li et al. (2014) which, from the control side, summarized the general traffic control strategies and highlighted the transition from feedback control to feed-forward control thanks to the connected vehicle technology.

The existing research on intersection control using connected vehicles can be classified into two categories. In the first category, it is assumed that vehicles report position and speed information to a central controller. The central controller then optimizes the intersection control based on such information. Some studies focus on the optimization of the signal phases (Priemer and Friedrich, 2009; Hu et al., 2015), whereas other studies provide priority to individual cars to optimize departure sequences (Wu et al., 2007; Pandit et al., 2013). Most of the early works assume all or a majority of the vehicles are connected. Only a few recent works relaxed this assumption by taking into consideration incomplete information. The arrival information of unequipped vehicles is estimated using either traffic models (He et al., 2012, 2014; Guler et al., 2014; Feng et al., 2015), statistical methods (Lee et al., 2013), or simulations (Goodall et al., 2013). It is shown that the algorithms in the aforementioned works perform well with lower penetration rates. However, the benefit of this technology is not fully exploited in this category, as these works assume only uni-directional communications.

The second category takes advantage of automated driving and integrates trajectory design into the signal control scheme. Vehicle trajectories can be designed to minimize evacuation time (Li and Wang, 2006), or to provide cooperative control (Lee and Park, 2012). A reservation based algorithm that reserves space at the intersection for each car in advance was proposed for automated vehicles only (Dresner and Stone, 2004) and for connected vehicles with human drivers mixed with automated vehicles (Dresner and Stone, 2006). Au and Stone (2010) presented a trajectory planning algorithm for automated vehicles to reduce the number of stops. Z. Li et al. (2014) presented an on-line algorithm to optimize vehicle trajectory and traffic signal simultaneously for an intersection of two one-way streets. A rolling horizon scheme is adopted to identify each control stage. In each stage, trajectory is designed and signal timing plans are enumerated to minimize total delay. Kamal et al. (2015) used model predictive control to coordinate automated vehicles at an unsignalized intersection to maximize the intersection capacity and avoid collision. One limitation in the previous works in this category is that they assume all vehicles to be automated or connected.