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Signal control optimization for automated vehicles at isolated signalized intersections

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ABSTRACT

Traffic signals at intersections are an integral component of the existing transportation system and can significantly contribute to vehicular delay along urban streets. The current emphasis on the development of automated (i.e., driverless and with the ability to communicate with the infrastructure) vehicles brings at the forefront several questions related to the functionality and optimization of signal control in order to take advantage of automated vehicle capabilities. The objective of this research is to develop a signal control algorithm that allows for vehicle paths and signal control to be jointly optimized based on advanced communication technology between approaching vehicles and signal controller. The algorithm assumes that vehicle trajectories can be fully optimized, i.e., vehicles will follow the optimized paths specified by the signal controller. An optimization algorithm was developed assuming a simple intersection with two single-lane through approaches. A rolling horizon scheme was developed to implement the algorithm and to continually process newly arriving vehicles. The algorithm was coded in MATLAB and results were compared against traditional actuated signal control for a variety of demand scenarios. It was concluded that the proposed signal control optimization algorithm could reduce the ATTD by 16.2–36.9% and increase throughput by 2.7–20.2%, depending on the demand scenario.

1. Introduction

Automated vehicles are those that use mechatronics and connectivity to gather information and autonomously perform driving functions. The National Highway Traffic Safety Administration (NHTSA) defined vehicle automation into five levels, ranging from vehicles that do not have any automated control functions (level 0) through fully automated vehicles (level 4). Fully automated vehicles are able to perform all driving functions and monitor roadway conditions for an entire trip (NHTSA, 2013). They are different from autonomous vehicles which sense the environment, navigate and perform driving functions all by the vehicle themselves, or connected vehicles which are connected with the surrounding vehicles and roadside infrastructure but still need the drivers to control the steering, acceleration, and braking. The combination of the autonomous and communication functions allows the automated vehicle to operate more efficiently and safely. Automated vehicle

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technology has advanced significantly in the past few years. The availability and potential wider use of automated vehicles poses the question: How can we use this technology to improve traffic operations in our transportation systems?

Traffic signal control is an integral component of the existing transportation system and it has a significant impact on transportation system efficiency. According to the (National Transportation Operations Coalition (NTOC), 2012), delays at traffic signals are estimated to be 5–10% of all traffic delay on major roadways and contribute an estimated 25% to the increase in total highway traffic delays during the past 20 years. Therefore, improvement in traffic signal timing has the potential to significantly benefit the transportation system.

One source of delay at signals is inefficient green time utilization in response to fluctuating demand. Another source of delay is due to driver reaction-related delays. The use of automated vehicle technology has the potential to reduce the impact of these two factors, through the use of their communication capability as well as the potential to fully control vehicle trajectories. If accurate vehicle arrival information is obtained by the signal controller in advance then the controller will be able to produce a more efficient timing plan. Delay will be further reduced if the signal timing information and guidance including optimal vehicle trajectories is transmitted to approaching vehicles such that the green would be better utilized. For example, these optimal trajectories may direct vehicles to accelerate (up to a point) to ensure the intersection capacity is fully utilized.

The objective of this paper is to develop a signal control algorithm that allows for vehicle paths and signal control to be jointly optimized under an automated vehicle environment. The algorithm is compared to traditional actuated control to assess its effectiveness. It is assumed that this automated vehicle environment enables bidirectional communication between vehicles and signal controller. Also, all the vehicles are fully automated. Thus, signal timing schemes are optimized based on more detailed and accurate information (such as speed, location, etc.) obtained from all automated vehicles entering the intersection's communication range. At the same time, vehicle trajectories are optimized based on the signal timing, and are followed by the automated vehicles to minimize delay. The algorithm was implemented for a simple two-approach intersection in MATLAB and was compared against traditional actuated signal control for a variety of scenarios.

The next section of the paper summarizes related work in signal control optimization in an automated and/or connected environment, while the third section provides an overview of the methodology framework for a simple intersection. The fourth section details the trajectory optimization algorithm, and the fifth explains the rolling horizon algorithm implementation. The sixth section outlines the simulation effort along with a comparison of its performance against conventional actuated control. The last section provides conclusions and recommendations for future work.

2. Literature review

Most of the existing literature related to employing communication technology to improve intersection signal control can be summarized into two categories. The first category uses data obtained from approaching vehicles to improve the intersection control algorithm, while the second provides signal control information to the drivers so that they can optimize their trip.

In the first category, Gradinescu et al. (2007) proposed a method to improve adaptive signal control based on short-range wireless communication between vehicles. Yan et al. (2009) proposed a scheduling model for deciding the passing sequence of vehicles at an isolated intersection under an automated vehicle environment. Berg (2010) proposed improvements to the conventional red light preemption and green light extension algorithm based on instantaneous traffic data obtained through short-range wireless transmitters in cars and elements of the road infrastructure. Smith et al. (2011) developed three signal control algorithms based on the conventional control strategies to address spill back during oversaturated conditions, prevent the breakup of vehicle platoons on the major street, and reduce the predicted future vehicle delays using the real-time DSRC data. He et al. (2011) developed a signal optimization algorithm using a unified platoon-based mathematical formulation (PAMSCOD) under a vehicle-to-infrastructure communications environment.

In the second category, Sunkari and Balke (2011) developed an Advance Warning of End of Green Systems under the Connected Vehicle environment to improve intersection safety and reduce lost time. Cai et al. (2012) proposed a speed adjustment algorithm for leading vehicles in an adaptive signal control system to avoid unnecessary stops. Rakha et al. (2012) developed a fuel-optimal vehicle trajectory adjustment algorithm at signalized intersections using vehicle-to-infrastructure communication. Automobile companies have developed vehicle-to-traffic signal communication systems to assist vehicles to take advantage of the green wave (for example, the Audi Travolution project and BMW Green Wave project).

There are a few papers that have studied vehicle speed adjustment and vehicle passing time optimization for unsignalized intersections. Dresner and Stone, 2004 developed an automated intersection management (AIM) system utilizing a cell-based intersection reservation system. The system identifies clear paths that can direct the vehicles through the intersection by processing the time–space reservation requests sent from vehicles. Follow-on research was conducted to accommodate high-priority vehicles (Dresner and Stone, 2006) and traditional human-driven vehicles (Dresner and Stone, 2007) and to maximize the vehicle arrival speed in order to minimize the time spend inside the intersection (Au et al., 2010). The proposed system provides feasible paths for vehicles to go through the intersection without conflict and the calculated trajectory for a particular vehicle is the optimum for itself. However, the proposed system cannot optimize the system performance with the consideration of all the vehicles. For example, if the reservation request sent by a vehicle is denied because of an existing conflicting request, the vehicle has to slow down and make another reservation later. The front vehicle cannot speed up to create a gap for the vehicle to fill in.