



Spatiotemporal intersection control in a connected and automated vehicle environment

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ABSTRACT

Current research on traffic control has focused on the optimization of either traffic signals or vehicle trajectories. With the rapid development of connected and automated vehicle (CAV) technologies, vehicles equipped with dedicated short-range communications (DSRC) can communicate not only with other CAVs but also with infrastructure. Joint control of vehicle trajectories and traffic signals becomes feasible and may achieve greater benefits regarding system efficiency and environmental sustainability. Traffic control framework is expected to be extended from one dimension (either spatial or temporal) to two dimensions (spatiotemporal). This paper investigates a joint control framework for isolated intersections. The control framework is modeled as a two-stage optimization problem with signal optimization at the first stage and vehicle trajectory control at the second stage. The signal optimization is modeled as a dynamic programming (DP) problem with the objective to minimize vehicle delay. Optimal control theory is applied to the vehicle trajectory control problem with the objective to minimize fuel consumption and emissions. A simplified objective function is adopted to get analytical solutions to the optimal control problem so that the two-stage model is solved efficiently. Simulation results show that the proposed joint control framework is able to reduce both vehicle delay and emissions under a variety of demand levels compared to fixed-time and adaptive signal control when vehicle trajectories are not optimized. The reduced vehicle delay and CO₂ emissions can be as much as 24.0% and 13.8%, respectively for a simple two-phase intersection. Sensitivity analysis suggests that maximum acceleration and deceleration rates have a significant impact on the performance regarding both vehicle delay and emission reduction. Further extension to a full eight-phase intersection shows a similar pattern of delay and emission reduction by the joint control framework.

1. Introduction

Current traffic signal control strategies, including fixed-time, vehicle-actuated and adaptive control, allocate green times to different vehicle movements to avoid conflicts at intersections. Infrastructure-based vehicle detection systems are widely used to collect real-time traffic data as the input to control algorithms. With the rapid development of connected and automated vehicle (CAV) technologies, vehicles can communicate with roadside equipment (RSE) through dedicated short range communications (DSRC). Data collected at RSE provide much richer information on vehicle states than conventional detector data. At the same time,

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data from RSE (e.g. signal status and intersection map) can be broadcast to vehicles within the communication range. The two-way real-time communication between CAVs and infrastructure makes vehicles “controllable” through either speed advisory systems in human-driven connected vehicles or control systems in CAVs.

Therefore, in a CAV environment, not only traffic signals but also vehicle trajectories can be controlled to improve traffic efficiency and gain environmental benefits. Control framework is expected to be extended from one dimension (either spatial or temporal) to two dimensions (spatiotemporal). However, current research efforts mainly address only one side of the joint control problem.

Eco-driving and speed advisory mainly focus on vehicle trajectory control, which is spatial control of vehicle movements. These applications assume that signal timing is fixed and known to vehicles. Optimal control or feedback control (Yang and Jin, 2014) models are built. It is often difficult to solve an optimal control model efficiently in case of complex objective or constraint formulations. Therefore, different simplification methods are proposed to address this issue. A typical method is to divide a vehicle trajectory into several segments with constant acceleration/deceleration for each segment (He et al., 2015; Wu et al., 2015). The optimal control problem is transformed into a nonlinear optimization problem with much fewer decision variables. In addition to trajectory segmentation, numerical solution algorithms are often applied. Meta-heuristics such as genetic algorithm, or gradient-based method, for example, offered by General Pseudospectral Optimal Control Software (GPOPS), can be used to solve various optimal control problems (Benson et al., 2006; Garg et al., 2010; Rao et al., 2010). However, this method may be computationally intensive, especially with a large problem size and the solutions may be worse than the approximation model (He et al., 2015). While most of the studies try to address the trajectory control of an individual vehicle or a few vehicles, a parsimonious shooting heuristic (SH) algorithm was proposed to construct all vehicle trajectories considering vehicle kinematic limits, traffic arrival patterns, car-following safety and signal operations (Ma et al., 2016; Zhou et al., 2017).

CAV based signal control applications consider vehicle trajectories as the input to signal control algorithms, which perform temporal control of traffic signals, and vehicle trajectories are not optimized. Real-time trajectory data (e.g., location, speed, and acceleration) of CAVs are used for signal optimization, based on which phase sequences and green durations are optimized. Link parameters such as traffic demand and queue length are calculated for phase skipping, extension or interruption (Gradinescu et al., 2007). Standard North American NEMA dual-ring, eight-phase controller is usually adopted to generate the optimal signal phase sequence and duration (Feng et al., 2015; He et al., 2012). Minimization of vehicle delay is considered as the optimization objective, and the problem is solved using different optimization techniques such as dynamic programming (DP) or mixed integer linear programming (MILP). In addition to using delay in the objective function, other performance metrics are explored such as weighted cumulative waiting time (WCWT) (Datesh et al., 2011) and cumulative travel time (CTT) (Lee et al., 2013). Instead of mathematical optimization models, microscopic simulations are also applied with vehicle trajectory data for optimal signal plans (Goodall et al., 2013).

One notable solution to the joint control problem of vehicle trajectories and traffic signals is so-called “signal free” intersections where traffic signals are removed, and all vehicles pass the intersection in a self-organized way (Lee and Park, 2012; Zohdy and Rakha, 2014). However, this approach requires 100% penetration rate of fully automated vehicles, which is not realistic in the near future. It can be predicted that in the next ten to twenty years, traffic signals will still play an important role in urban transportation operations.

Another related study which investigated the joint control problem (Li et al., 2014) intuitively divided a vehicle trajectory into four segments with constant acceleration and deceleration rates to reduce the number of decision variables. However, no mathematical proofs were given regarding the optimal number of trajectory segments in terms of fuel consumption or emissions under different situations, which are specifically addressed in this paper. The signal control algorithm enumerated all possible timing plans, which cannot be extended to complex phase structures.

This paper proposes an integrated framework for joint control of traffic signals and vehicle trajectories. A two-stage optimization model is built where traffic signals and vehicle trajectories are optimized sequentially. DP is applied to the signal control problem with the objective to minimize vehicle travel time delay. Optimal control theory is applied to control the trajectories of platoon leading vehicles with the objective to minimize fuel consumption and emission. The trajectories of following vehicles are captured by a car-following model. Currently, a fully CAV environment is assumed, where all vehicle are controllable, although only a few vehicles are controlled. To identify the leading vehicle of each platoon, a platoon identification algorithm is designed. A simplified objective function is proposed for the vehicle trajectory control model, and analytical solutions are derived.

The rest of the paper is organized as follows. Section 2 introduces the methodologies of the joint control framework. Section 3 provides the rolling horizon scheme to perform the two-stage optimization. Section 4 presents numerical examples through simulation and sensitivity analysis on critical parameters. Section 5 concludes the paper and lays out the direction of further research.

2. Model formulations

2.1. Notations

Before the model presentation, notations are summarized in Table 1. The notations in brackets represent the same variable with some of the subscripts omitted for simplicity.

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