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Development of a signal-head-free intersection control logic in a fully connected and autonomous vehicle environment

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ABSTRACT

Establishment of effective cooperation between vehicles and transportation infrastructure improves travel reliability in urban transportation networks. Lack of collaboration, however, exacerbates congestion due mainly to frequent stops at signalized intersections. It is beneficial to develop a control logic that collects basic safety message from approaching connected and autonomous vehicles and guarantees efficient intersection operations with safe and incident free vehicle maneuvers. In this paper, a signal-head-free intersection control logic is formulated into a dynamic programming model that aims to maximize the intersection throughput. A stochastic look-ahead technique is proposed based on Monte Carlo tree search algorithm to determine the near-optimal actions (i.e., acceleration rates) over time to prevent movement conflicts. Our numerical results confirm that the proposed technique can solve the problem efficiently and addresses the consequences of existing traffic signals. The proposed approach, while completely avoids incidents at intersections, significantly reduces travel time (ranging between 59.4% and 83.7% when compared to fixed-time and fully-actuated control strategies) at intersections under various demand patterns.

1. Introduction

Congestion cost is an immediate consequence of population growth causing 6.9 billion hours of travel delay and extra 3.1 billion gallons of fuel waste in 2014. It has contributed to $160 billion cost in the US in 2014 demonstrating 40% rise compared to 2000 (Schrank et al., 2015). Besides, the increasing trend in vehicle ownership has contributed to traffic safety and reliability concerns. National highway traffic safety administration reports annual rates of severe traffic accidents between 2012 and 2014 that have resulted in 33,117 life losses (NHTSA, 2014). Vehicular movements on busy intersections are mainly controlled by traffic signals, where possible maneuvers for passing through an intersection are regulated. The controllers aim to prioritize traffic movements and coordinate with neighboring controllers while avoiding conflicting flows, where controlling the stop-and-go conditions is not often considered as the highest priority. Signal timing of intersections can be optimized to reduce the congestion delay; yet, there is more opportunity to further minimize the control delay through innovative use of advanced technologies that help avoid unnecessary stops and provide safe vehicle trajectories.

Recent advancements in communication technologies and the internet of things provide promising solutions to future-oriented transportation problems, e.g., reducing delay of traffic movements without compromising traffic safety. Moving towards such capabilities, the emerging connected vehicle technology is offering vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I)

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communication that allow passing basic safety message (e.g., vehicle location, speed, and acceleration) between the entities. Besides, vehicle information can be transmitted to an intersection control unit over time that provides vehicles with their desired trajectory for next time intervals. Such technologies enable replacing the conventional traffic control systems by an effective communication scheme among vehicles and a local controller. This control strategy is much more effective in a connected and autonomous vehicle (CAV) environment, where (i) perception-reaction (P-R) times are reduced (i.e., less than 1.0–1.5 s measured for experienced drivers compared to 2–2.5 sec for typical human drivers (NAHSC, 1996)) and (ii) stochastic human-based errors are excluded from the system. Therefore, spacing between CAVs will be shorter and higher level of roadway capacity will be experienced (Wei et al., 2016). Finding optimal vehicle trajectories under safety constraints is often very challenging when the traffic volume is high. Adding vehicles to the optimization models increases the state space and enlarges the number of variables in each time period, which makes the problem even more complex such that existing commercial solvers will be unable to find their optimal solutions. Besides, introducing uncertainties to the problem (e.g., accidents, miscommunications among vehicles and controllers) will add more variables to handle the stochasticities. Literature has presented research efforts on the implementation of a rolling horizon approach in a deterministic environment with moderate traffic volumes. Most studies have used dynamic programming (DP) approaches by looking at stochastic look-ahead models that consider uncertainties over time (Bent and Van Hentenryck, 2004; Powell, Simao and Bouzaiene-Ayari, 2012). To facilitate decision making in each time interval, state and action spaces are discretized in these methods (Puterman, 2014). Similarly, on a different case study, Al-kanj et al. (2016) have formulated the vehicle routing problem in emergency storm response as a sequential stochastic optimization model and applied a Monte Carlo tree search (MCTS) algorithm in a stochastic look-ahead policy to handle unknown events in the next steps.

This paper first presents a formulation for signal-head-free intersection control logic (SICL) that obtains vehicular movement information, allocates the desired speed to CAVs approaching the intersection, and assigns acceleration/deceleration rates to vehicles with conflicting movements (see Fig. 1).

The problem includes both through and left-turn movements. The objective is to maximize the intersection throughput under a set of conflict avoidance constraints on the intersection approaches and inside the intersections. Previous studies minimize total length of overlapped trajectories only for crossing vehicles (e.g., Lee and Park (2012)). Expanding upon those studies, this paper applies the control logic to all approaching CAVs and adjusts each vehicle's trajectory before crossing the intersection. The problem is solved using a stochastic look-ahead technique based on the MCTS algorithm and applied to a set of case study scenarios to evaluate its performance. The proposed methodology is also compared to the conventional traffic control systems and a set of benchmark solutions at various demand rates. The proposed SICL methodology efficiently determines near-optimal CAV trajectories for high traffic volumes and various turning movements. The computation time of the proposed technique is sufficiently short that allows finding feasible solutions without the need to use a recovery mode. SICL can handle uncertainties (e.g., in traffic demand) and it can find the trajectories of all vehicles in the intersection neighborhood and re-optimize the trajectories if an unexpected event happens.

The remainder of this paper is organized as follows. Section 2 summarizes previous studies on different traffic control algorithms under deterministic and stochastic conditions. Section 3 presents the mathematical formulation for the proposed SICL and Section 4 details the solution technique. Section 5 presents the numerical experiments and evaluates the mobility impact of the proposed control logic under varying traffic demand. Finally, Section 6 concludes the paper and discusses future research directions.

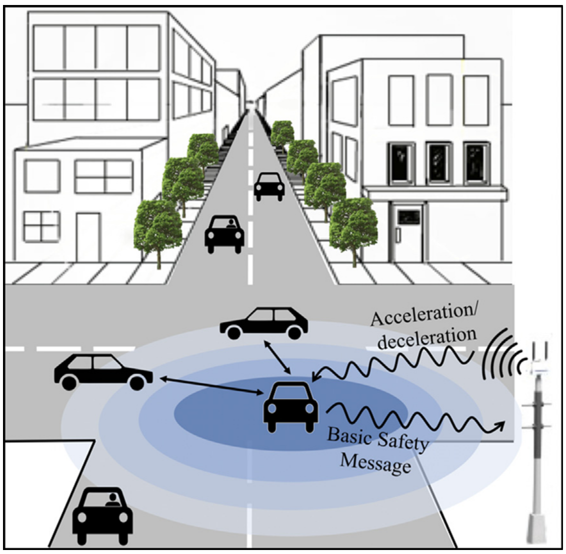

Fig. 1. Cooperative traffic control in the intersection neighborhood.