Transportation Research Part C 85 (2017) 528–547

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Conflict-point formulation of intersection control for autonomous vehicles

Michael W. Levin[a,*], David Rey[b]

[a] 140 Civil Engineering Building, Department of Civil, Environmental, and Geo-Engineering, University of Minnesota, 500 Pillsbury Drive SE, Minneapolis, MN 55455, United States
[b] School of Civil and Environmental Engineering, UNSW Sydney, NSW 2052, Australia

ARTICLE INFO

Keywords:
Reservation-based
Intersection control
Autonomous vehicles
Conflict point
Collision avoidance

ABSTRACT

Reservation-based intersection controls, in which vehicles reserve space-time paths through the intersection, have the potential to make greater use of intersection capacity than traffic signals. However, the efficiency of previous microsimulations of reservations has been severely limited by a protocol that requires vehicles to request reservations and the intersection manager to accept or reject them. We propose a new protocol, AIM*, in which the intersection manager assigns reservations to vehicles, to greatly increase the optimization possibilities. Then, we present a mixed integer linear program for optimally choosing vehicle reservations under AIM*. The formulation is similar to conflict resolution models for aviation, and ensures separation at all points that vehicles might intersect. We therefore present a rolling-horizon algorithm to extend the method to larger numbers of vehicles. Results show that the optimal reservation assignments from AIM* significantly reduce delays over previous protocols. Furthermore, the rolling horizon solutions have similar delays to a fixed horizon, thereby providing an efficient method of implementing AIM*.

1. Introduction

Several new technologies have been proposed for connected autonomous vehicles (AVs) to improve traffic flow (Chen and Englund, 2016). This paper focuses on optimizing reservation-based intersection control (Dresner and Stone, 2004, 2005), which has been well-studied in the literature. In previous work on reservations, vehicles *reserve* a space-time path through the intersection by communicating wirelessly with an *intersection manager* (IM) computer. The IM accepts or rejects reservations based on forward simulation of vehicle requests.

Most previous studies have focused on the first-come-first-serve (FCFS) policy, in which vehicle requests are prioritized by the order they are received. FCFS was shown to reduce delays beyond optimized signals for certain scenarios (Fajardo et al., 2011; Li et al., 2013). Indeed, since reservations can implement traffic signals, the optimal reservation policy performs at least as well as signals (Dresner and Stone, 2007). However, Levin et al. (2016) found several situations in which FCFS would have higher delays than traffic signals. Therefore, more optimal policies are necessary before reservations can be deployed effectively.

The purpose of this paper is to optimize reservations in real-time using a conflict point separation model. The conflict point model is similar to work on aircraft separation (Rey et al., 2012, 2015a,b), although aircraft require different separation constraints than road vehicles. This differs from previous work on optimizing reservations in that the conflict point formulation includes all collision

* Corresponding author.
E-mail addresses: mlevin@umn.edu (M.W. Levin), d.rey@unsw.edu.au (D. Rey).

http://dx.doi.org/10.1016/j.trc.2017.09.025
Received 1 January 2017; Received in revised form 31 May 2017; Accepted 30 September 2017

avoidance constraints and directly specifies vehicle departure times and speeds for reservations. Therefore, the solutions from this formulation may be directly used for safe vehicle movement. Unfortunately, the current reservation protocol, called *autonomous intersection management* (AIM), is quite limited in the reservation solutions it can use. AIM checks the feasibility of vehicle requests, but is dependent on vehicles to propose a reservation timing solution. To use the solutions from our formulation, this paper also presents a more general reservation protocol, AIM*.

The contributions of this paper are as follows: we develop a new communications protocol for reservations, AIM*, to facilitate optimal reservation policies. Using a conflict point approach to vehicle separation, we formulate a mixed integer linear program (MILP) to optimize vehicle intersection trajectories. Since MILPs scale poorly with the number of variables, we develop a rolling horizon approach and evaluate empirically problem sizes that may be efficiently solved. We perform several experiments that reach the following conclusions. First, AIM* performs much better than AIM (with FCFS policy) even on a single, symmetric intersection due to the potential to optimize vehicle trajectories. Second, the rolling horizon approach loses little optimality over the single-horizon solution, and can therefore be used as an efficient algorithm for implementation.

The remainder of this paper is organized as follows. Section 2 describes previous work on optimizing reservations. Section 3 presents AIM*, which admits the conflict point MILP developed in Section 4. Section 5 develops a rolling horizon formulation, which is used for numerical results in Section 6. We discuss conclusions in Section 7.

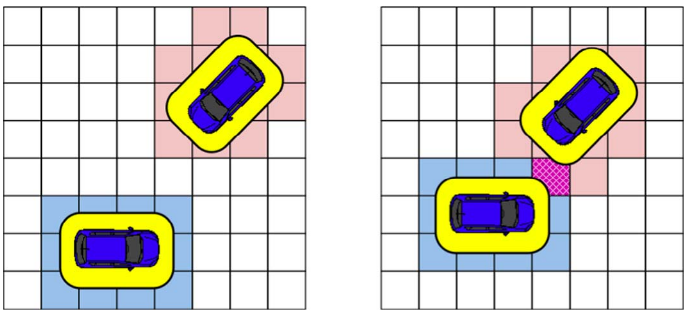
2. Literature review

Connected and automated vehicle technologies can be used to improve intersection delays and throughput (Chen and Englund, 2016). These technologies range from incorporating vehicle-to-infrastructure communications into adaptive signal timing to protocols that entirely obviate traffic signals. We focus on the AIM protocol proposed by Dresner and Stone (2004, 2005) as an alternative to traffic signals for AVs. In AIM, vehicles communicate wirelessly to request a reservation from the intersection manager (IM). A reservation specifies the turning movement as well as the time at which the vehicle can enter the intersection. The IM simulates reservation requests on a space-time grid of tiles (illustrated by Fajardo et al. (2011) in Fig. 1) and accepts requests if they do not conflict with other reservations. If two vehicles will occupy the same tile at the same time, a potential conflict exists and the request must be rejected.

2.1. Vehicle prioritization

The design of AIM lends itself to the FCFS policy: vehicles are prioritized by order of vehicle request. This is a simple policy to implement within the framework of AIM because it involves simulating vehicle requests in the order that they are received, and accepting or rejecting them based on tile occupancies of previous reservations. Consequently, FCFS has been studied in much of the literature on reservations. Fajardo et al. (2011) and Li et al. (2013) compared FCFS with optimized traffic signals, and found that FCFS reduced delays in certain scenarios. However, FCFS is only one of many potential policies for reservations. For instance, Dresner and Stone (2006) proposed a policy that prioritizes emergency vehicles. Schepperle and Böhm (2007, 2008) proposed to use intersection auctions to decide on vehicle priority. In addition to the reservation request, vehicles would also communicate a willingness to pay. The vehicle willing to pay the most would receive the highest priority (and pay a corresponding amount). Schepperle and Böhm (2007, 2008) found that auctions reduced delay weighted by vehicle value-of-time, and Vasirani and Ossowski (2012) found similar results for a network of intersections. Carlino et al. (2013) used system bids to further improve the efficiency of auctions. However, Levin and Boyles (2015) found that high value-of-time vehicles could become trapped behind low value-of-time vehicles, making it difficult to realize higher travel time savings for high-bidding vehicles.

AIM can easily implement traffic signals as a policy by rejecting requests to enter the intersection during red lights. Therefore, the optimal policy for AIM can perform at least as well as traffic signals. However, the widely-used FCFS policy is far from optimal. In fact, although FCFS can reduce delays beyond traffic signals for certain intersections (Fajardo et al., 2011; Li et al., 2013), Levin et al. (2016) found several instances for which FCFS reservations had *higher* delay than traffic signals. These occurred because FCFS does not account for capacity differences in roads or coordinate between intersections. Therefore, more work is needed on optimizing



(a) Accepted (b) Rejected

Fig. 1. Tile-based reservation protocol (Fajardo et al., 2011).