Transportation Research Part A 90 (2016) 14–25

Contents lists available at ScienceDirect

Transportation Research Part A

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

Paradoxes of reservation-based intersection controls in traffic networks

Michael W. Levin *, Stephen D. Boyles, Rahul Patel

Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, United States

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 28 December 2015
Accepted 5 May 2016

Keywords:
Autonomous vehicles
Reservation-based intersection control
Dynamic traffic assignment
Paradoxes

ABSTRACT

Reservation-based intersection control is a revolutionary idea for using connected autonomous vehicle technologies to improve intersection controls. Vehicles individually request permission to follow precise paths through the intersection at specific times from an intersection manager agent. Previous studies have shown that reservations can reduce delays beyond optimized signals in many demand scenarios. The purpose of this paper is to demonstrate that signals can outperform reservations through theoretical and realistic examples. We present two examples that exploit the reservation protocol to prioritize vehicles on local roads over vehicles on arterials, increasing the total vehicle delay. A third theoretical example demonstrates that reservations can encourage selfish route choice leading to arbitrarily large queues. Next, we present two realistic networks taken from metropolitan planning organization data in which reservations perform worse than signals. We conclude with significantly positive results from comparing reservations and signals on the downtown Austin grid network using dynamic traffic assignment. Overall, these results indicate that network-based analyses are needed to detect adverse route choices before traffic signals can be replaced with reservation controls. In asymmetric intersections (e.g. local road-arterial intersections), reservation controls can cause several potential issues. However, in networks with more symmetric intersections such as a downtown grid, reservations have great potential to improve traffic.

1. Introduction

Connected autonomous vehicles (CAVs), which are currently in testing on public roads, offer several new technologies that could revolutionize traffic operations. Cooperative adaptive cruise control (Van Arem et al., 2006), using short range communications between CAVs, can reduce following headways to increase capacity (Kesting et al., 2010; Shladover et al., 2012) and stability (Schakel et al., 2010). On the other hand, empty repositioning trips could greatly increase vehicular traffic demand, resulting in a net increase in congestion despite these capacity increases (Levin and Boyles, 2016). However, further optimizations have been proposed. Dynamic lane reversal (Hausknecht et al., 2011) could optimize lane configurations for dynamic traffic demand to maximize road usage. Reservation-based intersection control (Dresner and Stone, 2004, 2006), which is the focus of this paper, is a radical intersection control mechanism that takes advantage of the reduced safety margins necessary for CAVs to increase use of the intersection capacity. Comparisons of reservations against signals on a

* Corresponding author.
E-mail address: michaellevin@utexas.edu (M.W. Levin).

http://dx.doi.org/10.1016/j.tra.2016.05.013
0965-8564/

single intersection using the first-come-first-serve (FCFS) policy have indicated that for some situations reservations may reduce delays for all vehicles beyond optimized signals (Fajardo et al., 2011; Li et al., 2013).

While these results are promising, they represent only a subset of potential scenarios. Braess (1968) and Daganzo (1998) paradoxes demonstrate that capacity improvements may increase travel times for all vehicles. Furthermore, policy goals such as the fairness of FCFS may be less efficient for the overall system. Thus far, no literature has presented negative comparisons of reservations with traffic signals. The primary purpose of this paper is to demonstrate that such situations exist to motivate the necessity for greater study before replacing signals with reservations. We present several paradoxical situations in which traffic signals outperform FCFS reservations. From a policy standpoint, it is important to recognize situations in which replacing signals with reservation-based controls may increase delays or congestion.

Although many previous studies have used FCFS for prioritizing vehicles, the reservation protocol is general enough to admit a large range of policies such as intersection auctions (Schepperle and Böhm, 2007). However, this range makes it impossible to generalize our studies to arbitrary policies. Indeed, as Dresner and Stone (2007) note, traffic signals may be viewed as a specific case of the general reservation protocol. Accordingly, there is always a reservation policy that performs identically to current signal technology. Therefore, the examples in this paper are based on the FCFS policy. It is the focus of most of the literature on reservation-based control (Dresner and Stone, 2004; Fajardo et al., 2011; Li et al., 2013), etc. Also, because of its inherent fairness, FCFS is a good candidate for a widely accepted control policy. We also discuss how the theoretical issues with FCFS reservations may extend to more general classes of reservation policies.

The contributions of this paper are to present and characterize several scenarios in which the use of FCFS-based reservations results in greater delays than signals. We present three theoretical examples, including a temporarily saturated arterial-local road intersection to a demonstration that replacing signals with reservations can result in infinite queuing. Finally, we solve dynamic traffic assignment (DTA) on a city network, and find that reservations significantly reduce travel time. Overall, these results demonstrate that while reservations perform better than traffic signals in certain situations, network-based analyses are necessary to detect adverse route choices before reservations can be used to replace signals entirely. In particular, asymmetric intersections (e.g. local road-arterial intersections) can cause several potential issues with reservation controls. However, based on the city network results, reservations have great potential for improving traffic.

The remainder of this paper is organized as follows. Section 2 describes previous work on reservation-based controls. Section 3 presents three theoretical examples in which signals outperform FCFS, and Section 4 contains results on realistic networks. We conclude in Section 5.

2. Reservation-based protocol

This section describes the tile-based reservation protocol introduced by Dresner and Stone (2004) and Dresner and Stone (2006) and the conflict region simplification proposed by Levin and Boyles (2016). The latter is tractable for large DTA networks and is also a more intuitive method of describing the behavior reservation protocol. Therefore, it is used in the theoretical examples and the DTA simulations. Finally, we discuss properties of the FCFS policy that is the focus of most literature on reservation-based control methods.

2.1. Tile-based reservations

The tile-based reservation protocol proposed by Dresner and Stone (2004, 2006) operates through an intersection manager agent communicating wirelessly with individual vehicles. The intersection manager divides the intersection into a grid

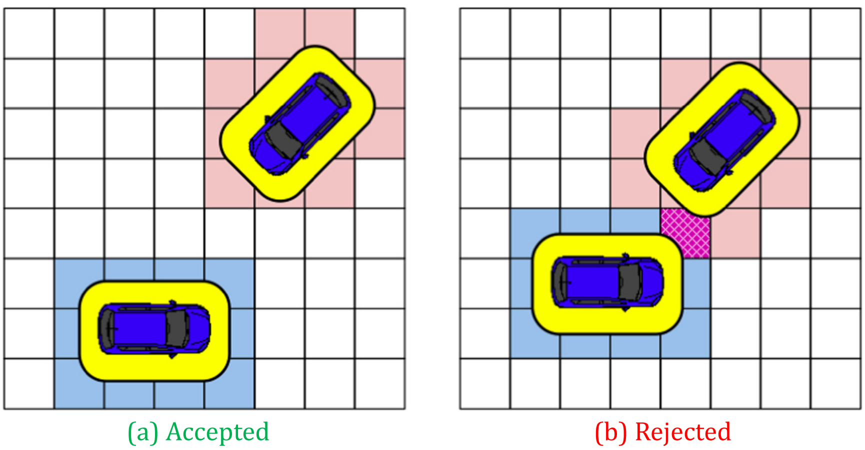

Fig. 1. Tile-based reservation protocol (Fajardo et al., 2011).