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A cell transmission model for dynamic lane reversal with autonomous vehicles

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ABSTRACT

Autonomous vehicles admit consideration of novel traffic behaviors such as reservation-based intersection controls and dynamic lane reversal. We present a cell transmission model formulation for dynamic lane reversal. For deterministic demand, we formulate the dynamic lane reversal control problem for a single link as an integer program and derive theoretical results. In reality, demand is not known perfectly at arbitrary times in the future. To address stochastic demand, we present a Markov decision process formulation. Due to the large state size, the Markov decision process is intractable. However, based on theoretical results from the integer program, we derive an effective heuristic. We demonstrate significant improvements over a fixed lane configuration both on a single bottleneck link with varying demands, and on the downtown Austin network.

1. Introduction

The computer precision of autonomous vehicles (AVs) admits consideration of novel traffic behaviors such as reservation-based intersection control (Dresner and Stone, 2004, 2006), which uses wireless communications and highly specified vehicle trajectories to increase intersection utilization and reduce delays (Fajardo et al., 2011; Li et al., 2013). Similar communication and behavior protocols may be used to implement lane reversal, in which lane direction changes in response to traffic conditions. Use of lane reversal and other capacity improvements may be particularly important for AVs because induced demand and empty repositioning trips may increase traffic congestion (Levin and Boyles, 2015).

Lane reversal has already been explored through contraflow lanes. Most literature pertains to evacuation (see, for instance, Zhang et al., 2012; Wang et al., 2013; Dixit and Wolshon, 2014), because of the costs associated with reversing lanes for human drivers, but several papers study contraflow for daily operations. Zhou et al. (1993) use machine learning on queue length and total delay for scheduling the lane reversal. Xue and Dong (2000) similarly applied neural networks on fuzzy pattern clustering to contraflow for a bottleneck tunnel. Meng et al. (2008) use a bi-level optimization to address the driver response to contraflow lanes through user equilibrium (UE) behavior. As demonstrated by the Braess (1968) and Daganzo (1998) paradoxes, consideration of UE routing behavior is important as it can adversely affect potential network improvements. Therefore, our results include solving dynamic traffic assignment (DTA) on a city network.

The primary constraint on existing work on contraflow lanes for daily operations is communication with and ensuring safety of human drivers. Reversing a lane with human drivers therefore often requires significant time and cannot be performed frequently. Furthermore, it is impractical to perform on every road segment (link), and, where it is used, the lane

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is reversed on the entire link. Partial lane reversal could increase flow by adding temporary turning bays. Consequently, a more frequent dynamic lane reversal (DLR) for AVs, controlled by a lane manager agent per link in communication with AVs on the link, could result in significant improvements over contraflow lanes.

Our work is primarily motivated by the greater communications available for AVs due to the frequency of lane reversals we propose for DLR. We assume that lane direction can be changed at very small intervals of space–time, such as a few hundred feet of space and 6 s time steps. Such frequent reversals of lane direction can be used to optimize lane direction for small variations in demand over time. Contraflow lanes are typically reversed for the duration of a peak period, whereas DLR could change lane direction many times within a peak period to reduce queueing and spillback. However, such small space–time intervals for DLR cannot be safely implemented with human vehicles. The more precise and greater bandwidth AV communications are necessary.

In this paper, we assume that lane manager agents exist that can communicate the direction of each lane at space and time intervals to all vehicles on the link. Hausknecht et al. (2011) suggest using AV intersection controllers as a lane manager to specify the direction of lanes for the entire link at different times. With some changes the intersection controllers could communicate lane direction at space intervals as well, and we also assume that AVs could be forced to obey these policies. Therefore, rather than study an enabling protocol, we focus on the potential benefits.

Hausknecht et al. (2011) found that DLR improved capacity on a micro-simulation of a small network and used optimization techniques on the lane reversal problem for static traffic assignment (STA). A natural extension is how to model DLR and construct optimal lane direction policies for city networks with dynamic demand and more realistic flow models. Computational tractability becomes a major concern. As noted by Hausknecht et al. (2011), even for a static flow model, STA becomes a subproblem to finding the DLR policy, forming a bi-level optimization problem. As the number of lanes is integer, the top level involves integer programming (IP), a potentially NP-hard problem. Dynamic demand also introduces stochasticity from the perspective of the lane manager because future conditions may not be known perfectly. Therefore, finding the optimal DLR policy could require impractical computational resources. However, a heuristic that yields consistent improvements over current fixed lane configurations would be valuable.

This paper incorporates DLR into the cell transmission model (CTM) and studies optimal policies for DLR. We consider two types of information availability for finding the optimal DLR policy. First, when future demand is known, we study DLR in the context of IPs and present theoretical results and motivating examples. When future demand is stochastic, we formulate DLR as a Markov decision process (MDP) and present a saturation-based heuristic for computational tractability that appears to perform well on a variety of demands for a single bottleneck link. We then solve DTA on a city network using this heuristic, and demonstrate significant improvements in system efficiency.

The remainder of this paper is organized as follows: Section 2 discusses previous work on autonomous vehicles. Section 3 presents a CTM for DLR. Section 4 studies DLR under the perfect information scenario, and Section 5 considers stochastic demand. Section 6 discusses results on a city network, and we present our conclusions in Section 7.

2. Literature review

Because lane reversal at small time intervals cannot be safely implemented with human drivers, DLR has only been previously studied by Hausknecht et al. (2011) in the context of AVs. Furthermore, reversing lanes at multiple spatial intervals within links has never been studied. Therefore, we begin by reviewing proposed intersection technologies for AVs that could be used to enable DLR. Then, we discuss flow models for AVs to justify the use of CTM.

2.1. Technology for dynamic lane reversal

The precision and communications potential of AVs have been used to propose several new traffic behaviors such as DLR. A primary topic of study is improving intersection efficiency, and the communications required for the proposed intersection controller can be adapted to the requirements of DLR.

Dresner and Stone (2004, 2006) introduced reservation-based intersection control, in which AVs communicate with an *intersection manager* to request intersection passage. The intersection manager simulates requests on a grid of space–time tiles, which are accepted only if they do not conflict with other requests. Fajardo et al. (2011) and Li et al. (2013) demonstrated that reservations can reduce delays beyond optimized signals. Therefore, when AVs are a sufficiently high proportion of vehicular demand, reservations are likely to be used in place of signals (Dresner and Stone, 2007).

The seminal DLR paper of Hausknecht et al. (2011) observed that the intersection manager could be used to control lane usage by restricting AVs from entering certain lanes. This could enforce DLR by ensuring that AVs do not enter a lane in the wrong direction. Therefore, the reservation protocol is sufficient for implementing lane reversal where lanes have the same direction for each link.

In this paper, we consider lane reversal at multiple spatial intervals within a link. This can also be handled by a modification to the intersection manager. In the reservation protocol, AVs communicate with the intersection manager well before reaching the intersection to request a reservation. These longer-range communications can be used to establish lane direction at small space–time intervals and require AVs to switch lanes to comply with lane reversals.