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A multiclass cell transmission model for shared human and autonomous vehicle roads

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A R T I C L E I N F O

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A B S T R A C T

Autonomous vehicles have the potential to improve link and intersection traffic behavior. Computer reaction times may admit reduced following headways and increase capacity and backwards wave speed. The degree of these improvements will depend on the proportion of autonomous vehicles in the network. To model arbitrary shared road scenarios, we develop a multiclass cell transmission model that admits variations in capacity and backwards wave speed in response to class proportions within each cell. The multiclass cell transmission model is shown to be consistent with the hydrodynamic theory. This paper then develops a car following model incorporating driver reaction time to predict capacity and backwards wave speed for multiclass scenarios. For intersection modeling, we adapt the legacy early method for intelligent traffic management (Bento et al., 2013) to general simulation-based dynamic traffic assignment models. Empirical results on a city network show that intersection controls are a major bottleneck in the model, and that the legacy early method improves over traffic signals when the autonomous vehicle proportion is sufficiently high.

1. Introduction

Autonomous vehicle (AV) technology is rapidly maturing with testing permitted on public roads in several states. When AVs become available to the public, computer precision and communications may allow new behaviors to increase network capacity. For instance, Dresner and Stone (2004) proposed the tile-based reservation (TBR) intersection policy which reduces delay beyond optimized traffic signals (Fajardo et al., 2011). Besides offering new intersection behaviors, AVs may also increase link capacity because reduced reaction times requires smaller following distances, and AVs may be less affected than human-driven vehicles (HVs) by certain adverse road conditions. However, capacity improvements are complicated by sharing roads with HVs, which will likely be the case for many years before AVs are sufficiently available and affordable to be driven by all travelers.

TBR is compatible with shared roads (Dresner and Stone, 2007), and link behaviors may be performed safely with a mixed fleet of vehicles. However, modeling link and intersection capacity improvements from shared road policies is still an open problem. Most current models of AVs are micro-simulations, which are not computationally tractable for the traffic assignment typically used to determine route choice. Levin and Boyles (2015a) modified static link performance functions model to predict capacity improvements as a function of the proportion of AVs on each link based on Greenshields et al.,

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1935Greenshields' (1935) capacity model. However, in reality the proportion of AVs on each link will vary over time. Dynamic traffic assignment (DTA) models flow more accurately than static models and can include the varying-time effects of capacity. Kesting et al. (2010) predicted theoretical capacity for adaptive cruise control and used linear regression to extrapolate for various proportions of connected vehicles (CVs) and non-CVs. For consistency with DTA, we use a constant acceleration model to analytically predict capacity and wave speed as a function of the proportion of each vehicle class on the road, and generalize to multiple classes with different reaction times. Whereas many previous papers on CVs use micro-simulation experiments, we use DTA on a city network to study the impacts of AVs under dynamic user equilibrium (DUE) route choice.

This paper makes several contributions with the aim of developing a shared road DTA model: First, a multiclass cell transmission model (CTM) is proposed that admits space-time variations of capacity and wave speed. Second, a link capacity model based on a collision avoidance car following model with different reaction times is presented. The link capacity assumptions lead to the triangular fundamental diagram assumed by Newell (1993) and Yperman et al. (2005). To facilitate shared intersections, the conflict region (CR) algorithm from Levin and Boyles (2015b) for general SBDTA models is modified using Bento et al. (2013)'s control policy. Intersection efficiency scales dynamically with the proportion of AVs using the intersection. Results from studies on a single intersection and the downtown Austin city network suggest that travel time reductions when using reservation-based controls scale linearly with the proportion of AVs, but do not improve over signals until 80% AV penetration or greater.

The remainder of this paper is organized as follows. Section 2 discusses literature relevant to multiclass DTA and AV flow. Section 3 presents the multiclass DTA model and shows consistency with the hydrodynamic theory of traffic flow. Section 4 develops a dynamic capacity and wave speed model based on driver reaction times. A shared intersection model for general SBDTA is developed in Section 5. In Section 6, we present a case study on a city network involving varying levels of human-driven and autonomous vehicles, and Section 7 discusses conclusions.

2. Literature review

This literature review starts by discussing multiclass DTA in Section 2.1 to provide a context for the AV models discussed in Section 2.2.

2.1. Dynamic traffic assignment

DTA includes a number of different flow models, some of which are solved analytically and others which are simulation-based (SBDTA). For an overview of DTA, we refer to Chiu et al. (2011). This paper focuses on the cell transmission (CTM) SBDTA model (Daganzo, 1994, 1995a), which is a discrete approximation of the Lighthill–Whitham–Richards (LWR) model (Lighthill and Whitham, 1955; Richards, 1956). The partial differential equations of the LWR model are generally more difficult to solve when multiple vehicle classes result in varying capacities. However, the discretized space and time in CTM simplifies the multiclass solution method. The multiclass CTM presented in Section 3 is shown to be compatible with the conservation equations of LWR.

Multiclass DTA has previously been studied in the literature although primarily with a focus on heterogeneous vehicles of length and speed. Wong and Wong (2002) allowed vehicles to have a class-specific speed and demonstrate that their model adheres to flow conservation. However, they use a new discrete space-time approximation to solve their model, and it is not clear whether it is compatible with the most common simulation-based approximations, which is desirable for integration with existing DTA models. Tuerprasert and Aswakul (2010) formulated a multiclass CTM with different speeds per class, including how different speeds affect cell propagation. It is not clear, though, whether their model solves a multiclass form of LWR, or is a modification of CTM with useful properties.

2.2. Autonomous vehicle flow

The model presented in this paper is concerned with varying capacities and wave speeds due to the multiple classes of human-driven and autonomous vehicles. We assume that speed does not depend on vehicle class, which is reasonable because some AVs are programmed to exceed the speed limit to maintain the same speed as surrounding traffic (Miller, 2014) for improved safety (Aarts and Van Schagen, 2006).

Potential improvements in traffic flow from CVs and AVs have begun to receive attention in the literature. Adaptive cruise control (ACC) (Marsden et al., 2001) has been developed to improve link capacity and, if it is not incorporated into AVs, will likely influence AV car-following behavior. Van Arem et al. (2006) used a micro-simulation to show that cooperative ACC can improve efficiency. Kesting et al. (2010) developed a continuous acceleration behavior model of CVs to predict theoretical capacity. They use a linear regression to extrapolate for different proportions of CVs and non-CVs. We generalize by including multiple vehicle classes with different reaction times in our constant acceleration model and predict both capacity and wave speed as a function of the proportion of each vehicle class. Schakel et al. (2010) used simulation to study traffic flow stability, finding that ACC increases stability and also increases shockwave speed. This is consistent with the theoretical wave speed