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Operational performance of a congested corridor with lanes dedicated to autonomous vehicle traffic

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ABSTRACT

This paper considers the operational performance impact of autonomous vehicles (AV) on a multi-lane freeway corridor with separate lanes dedicated to AV and non-AV traffic. Autonomous vehicle behavior is modeled at the macroscopic level by modifying the fundamental diagram relating hourly traffic flow and vehicle density, a step that is justified by adjusting a parameter from Newell's car-following model at the microscopic level and transforming back to a macroscopic representation. The model is applied to the I-95 corridor between Washington, DC and Baltimore, MD during the PM peak period, where the impact of introducing a managed AV-only lane is assessed at varying penetration rates of autonomous vehicles. The results show that the overall corridor performance metrics improve with increasing penetration rates up to 30%, 40% or 50% (depending on the underlying assumptions that govern AV behavior), after which the performance deteriorates drastically. Implications of the results are discussed in light of the per-lane and aggregated metrics, and future directions for research are proposed.

1. Introduction

In order to assess the value of allocating autonomous vehicle traffic to a dedicated lane, this paper focuses on steady-state traffic dynamics, adopting Newell's linear car-following model and applying the corresponding triangular fundamental diagram to model standard and autonomous vehicles with different reaction time assumptions. Taking a macroscopic view of traffic flow, we calibrate a model based on real-world measurements from a congested corridor in order to capture baseline traffic conditions without AVs. Afterward, we introduce AVs with varying behavioral assumptions and market penetration to the calibrated macroscopic model, and carry out subsequent simulations to draw conclusions about when it may be useful to allocate a lane to AV traffic.

This research is motived by rapidly-maturing autonomous vehicle technology, which is increasingly entering the marketplace in the form of basic driver assist features (e.g., adaptive cruise control and lane departure assistance), and also being used to create advanced highly-automated prototypes (e.g., DARPA Urban Challenge, Buehler et al., 2009). In light of this imminent disruptive technology, it is important for planners and policy makers to understand the impact autonomous vehicles will have on traffic management and freeway operations, which requires developing traffic models that can capture salient aspects of AV behavior.

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Initial autonomous vehicle modeling efforts have mostly taken a microscopic perspective, seeking to describe vehicle-level interactions in light of AV technology. Kesting et al. (2010) uses an adapted Intelligent Driver Model (IDM) car-following model to model adaptive cruise control effects (ACC), which is an automated driving strategy. By focusing on connected rather than fully autonomous vehicles, Ge and Orosz (2014) assume vehicles have knowledge of the acceleration of nearby downstream vehicles through vehicle-to-vehicle communication (V2V), and develop a model for connected cruise control (CCC) that attempts to stabilize the flow of a group of vehicles. Similarly Li et al. (2016) propose a car-following model based on the full velocity difference (FVD) model by integrating V2V communications and a shared knowledge of throttle information with vehicles in close proximity. An alternative approach utilizes existing car-following models, but modifies parameter values to capture how AVs may behave differently than standard, human-driven vehicles (e.g., Levin and Boyles, 2016). Since lower vehicle response time may be a distinguishing AV characteristic, other non AV-oriented papers in this area provide relevant insight into how reaction time or delay impact traffic behavior (e.g., Bando et al., 1998).

In contrast to the individual vehicle-level focus of car-following models, the macroscopic modeling perspective describes aggregate traffic behavior in terms of vehicle flow, speed, and density. From an AV modeling perspective, the goal is to quantify how AVs will affect aggregate steady-state traffic dynamics, including capacity. This aggregate behavior can be discovered through simulation-based approaches (e.g., Kesting et al., 2010; Minelli et al., 2015; Talebpour et al., 2016) or analytical ones that start with microscopic car-following models, apply steady-state conditions (i.e., no acceleration or lane changing behavior) and transform average microscopic quantities such as time and space headway to their macroscopic counterparts: traffic flow and density. An example of the analytical approach is Levin and Boyles (2016), who modify a collision-avoidance car-following model (Kometani and Sasaki, 1959) to account for AV reaction times, transform to a triangular fundamental diagram under steady-state conditions, and develop a multi-class Cell Transmission Model (CTM) to quantify the impact of different proportions of AV and regular vehicles on the same road.

This paper takes an analytical macroscopic perspective, adopting Newell's linear car-following model and corresponding triangular fundamental diagram to model autonomous vehicles' equilibrium traffic behavior as a function of reaction time. Its major contribution is using the model to evaluate impacts of a dedicated lane for autonomous vehicles on an important real-world commuter corridor, focusing in particular on how AV reaction time and market penetration affect traffic operations during peak periods. To this end, we develop a macroscopic traffic model representing the I-95 corridor between Washington, DC and Baltimore, MD, and calibrate the model under existing conditions using real-world measurements and an advanced stochastic optimization algorithm. By introducing autonomous vehicle at different levels of market penetration with varying behavioral assumptions to the calibrated macroscopic simulation model, we draw conclusions about the conditions under which it is beneficial to allocate a lane to AV traffic.

The paper is organized as follows: we begin by providing a brief overview of the macroscopic first order traffic model, Newell's car-following model, and the connection between Newell's model and the triangular fundamental diagram. We then apply this model to autonomous vehicles, yielding triangular fundamental diagrams whose shapes depend on AV reaction time. Next, we propose a case study to assess the value of introducing an AV-only lane to a real world corridor, and describe the macroscopic modeling framework, simulation tools, model calibration/validation procedure, and scenarios to be evaluated. Finally, we summarize the case study results, draw conclusions and discuss future extensions to the work.

2. Material and methods

2.1. Macroscopic first order model

2.1.1. Overview

The first order continuum traffic flow model was first proposed by Lighthill and Whitham (1955) and Richards (1956), and is summarized in Eqs. (1) and (2), where q is the hourly vehicle flow, ρ is the vehicle density, V is the space mean speed, and x and t represent position and time respectively. Eq. (1) relates aggregate traffic flow to density, and is often referred to as the fundamental diagram. The shape of the curve is based on empirical observations, and several models that do a good job of replicating observed behavior have become popular in literature, including the triangular fundamental diagram used in this paper Daganzo (1993). Eq. (2) is a partial differential equation that characterizes how aggregate traffic density changes over time based on flow gradients and the assumption that vehicle flows are conserved.

$$q = \rho V \tag{1}$$

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \tag{2}$$

2.1.2. Network representation

Following a common network modeling perspective described by Papageorgiou et al. (2010), a freeway corridor can be modeled as a directed weighted graph structure, with nodes representing entrance/exit ramps and points of discontinuity, and links connecting the nodes in the direction of travel. This network structure of contiguous links can be used as the basis for macroscopic modeling, with each link having temporally varying traffic states specified by the density, flow and space mean speed.