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Optimal deployment of autonomous vehicle lanes with endogenous market penetration

Zhibin Chen[a], Fang He[b], Lihui Zhang[c,*], Yafeng Yin[a]

[a] Department of Civil and Coastal Engineering, University of Florida, 365 Weil Hall, Gainesville, FL 32611-6580, United States
[b] Department of Industrial Engineering, Tsinghua University, N502 Shunde Building, Beijing 100084, PR China
[c] College of Civil Engineering and Architecture, Zhejiang University, B815 Anzhong Building, Hangzhou 310058, PR China

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ABSTRACT

This paper develops a mathematical approach to optimize a time-dependent deployment plan of autonomous vehicle (AV) lanes on a transportation network with heterogeneous traffic stream consisting of both conventional vehicles (CVs) and AVs, so as to minimize the social cost and promote the adoption of AVs. Specifically, AV lanes are exclusive lanes that can only be utilized by AVs, and the deployment plan specifies when, where, and how many AV lanes to be deployed. We first present a multi-class network equilibrium model to describe the flow distributions of both CVs and AVs, given the presence of AV lanes in the network. Considering that the net benefit (e.g., reduced travel cost) derived from the deployment of AV lanes will further promote the AV adoption, we proceed to apply a diffusion model to forecast the evolution of AV market penetration. With the equilibrium model and diffusion model, a time-dependent deployment model is then formulated, which can be solved by an efficient solution algorithm. Lastly, numerical examples based on the south Florida network are presented to demonstrate the proposed models.

1. Introduction

Due to potential benefits on traffic safety, driver productivity, road capacity, travel speed, energy consumption, and vehicular emission (Shladover et al., 2012; Greenblatt and Saxena, 2015; Levin and Boyles, 2016a,b; Mersky and Samaras, 2016), autonomous vehicles (AVs) have attracted tremendous attentions. Recent progress suggests AVs are on the horizon. Since 2009 when Google started testing self-driving technology in California, Google's AVs have already achieved a total mileage over 1.5 million miles (Google Self-Driving Car Project, 2016). The National Highway Traffic Safety Administration (NHTSA) of the United States has agreed to consider the Google self-driving computer system as the "driver" of the vehicle (NHTSA, 2016). Besides Google, many car manufactures, such as Volvo, BMW and Audi, are testing their prototype AVs. More recently, Japanese government announced that AVs could be used to ferry people around Tokyo during the 2020 Olympics and Paralympics (2025AD, 2016).

Despite all these exciting developments, it will still be many years for AVs to be widely adopted, and the heterogeneous traffic stream consisting of both conventional vehicles (CVs) and AVs will inevitably exist for a long time. To promote the adoption of AVs, efforts on both technical level and policy level are of critical importance. The former mainly refers to the development of AV technology primarily driven by private sectors (e.g., Google), and the latter refers to policies proposed

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* Corresponding author.
E-mail address: lihuizhang@zju.edu.cn (L. Zhang).

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by government agencies to adapt to the deployment of AV technology. From the policy aspect, apart from legalizing on-road AV test driving, the government agencies may need to identify proper locations to implement AV mobility applications, and enhance dedicated lanes, segments and areas for AVs. For example, some regular lanes can be converted into dedicated AV lanes, which can only be used by AVs. As demonstrated by Tientrakool et al. (2011), the capacity of those lanes will approximately become tripled due to the benefits (e.g., reduced inter-vehicle safe distance) resulted from vehicle-to-vehicle communication. Accordingly, deploying AV lanes can be expected to help AVs save trip times, which can further boost the market penetration of AVs and reduce the system delay. On the other hand, conversion of regular lanes to AV lanes may result in increased trip times of CVs due to their loss of accessibility to those AV lanes, and thus may damage the social welfare.

This paper attempts to propose a general mathematical model to help government agencies optimally deploy AV lanes in a way to minimize the social cost. The decision-making process in such a planning practice is a Stackelberg leader-follower game, in which government agencies act as the leader and travelers are the follower. In order for government agencies to optimize those planning decisions, travelers' spontaneous responses need to be proactively considered in the optimization framework. This type of Stackelberg games have been formulated as mathematical programs with equilibrium constraints for many transportation applications (see, e.g., Wu et al., 2011, 2012; Yin et al., 2008; He et al., 2013, 2015; Zhang et al., 2014; Chen et al., 2016). More specifically, given AV lanes deployed, we assume that CVs and AVs follow the Wardrop equilibrium principle to choose their routes that minimize their individual travel costs (Wardrop, 1952), and the resulting flow distribution is in a multi-class network equilibrium (e.g., Yang and Meng, 2001; Wu et al., 2006). Furthermore, since the net benefit (e.g., reduced travel cost for AVs) derived from deploying AV lanes plays an important role in promoting the AV adoption, we apply a diffusion model to forecast the evolution of AV market penetration. Based on the network equilibrium model and diffusion model, we proposed a time-dependent deployment model to optimize the location design of AV lanes on a general transportation network. The AV market penetration follows a progressive process instead of a radical one, thus the AV lanes should also be deployed in a progressive fashion. More specifically, the optimized deployment plan will not only specify where and how many AV lanes to be deployed, but also when to deploy them.

For the remainder, Section 2 applies the multi-class network equilibrium model to describe the flow distributions of both CVs and AVs. Section 3 proposes the AV diffusion model to forecast the market penetration of AVs. Section 4 presents the mathematical program to optimize the AV-lane deployment plan, followed by numerical examples in Section 5. Concluding remarks are provided in the last section.

Below are some notations used throughout the paper.

Sets

K	set of paired links
N	set of nodes
A	set of links
$\hat{A}$	set of AV links
M	set of travel modes: mode 1 denotes CVs, and mode 2 denotes AVs
W	set of origin-destination (OD) pairs
$P_\tau^{w,m}$	set of paths for travel mode $m \in M$ between OD pair $w \in W$ at year $\tau \in T$
$\hat{P}_\tau^{w,m}$	set of utilized paths for travel mode $m \in M$ between OD pair $w \in W$ at year $\tau \in T$
T	set of years

Parameters

m	index of travel mode, $m \in M$
w	index of OD pair, $w \in W$
p	index of path, $p \in P_\tau^{w,m}$
d^{w*}	potential AV market size for OD pair $w \in W$
γ_m	value of time (VOT) for drivers of travel mode $m \in M$
σ	interest rate
n	a factor converting social cost from an hourly basis to a yearly basis
τ	index of year $\tau \in T$
ς	unsafety factor for using CV
θ_a^k	if link a belongs to the k th link pair, and it is an AV link, then $\theta_a^k = 1$; If link a belongs to the k th link pair, and it is not an AV link, then $\theta_a^k = -1$; otherwise, $\theta_a^k = 0$

Variables

$d_\tau^{w,m}$	demand of travel mode $m \in M$ between OD pair $w \in W$ at year $\tau \in T$
$x_{a,\tau}^{w,m}$	flow of travel mode $m \in M$ on link $a \in A$ between OD pair $w \in W$ at year $\tau \in T$
$v_{a,\tau}$	aggregate flow on link $a \in A$ at year $\tau \in T$
y_τ^k	the number of lanes on the k th link pair that are converted into AV lanes at year $\tau \in T$
$C_\tau^{w,m}$	equilibrium travel time for mode $m \in M$ between OD pair $w \in W$ at year $\tau \in T$