Transportation Research Part B 99 (2017) 44–61

Contents lists available at ScienceDirect

Transportation Research Part B

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

Optimal design of autonomous vehicle zones in transportation networks

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ARTICLE INFO

Article history:
Received 27 August 2016
Revised 5 November 2016
Accepted 1 December 2016
Available online 24 January 2017

Keywords:
Autonomous vehicle
Autonomous-vehicle zone
Mixed routing equilibrium
Optimal deployment

ABSTRACT

This paper advocates the need for infrastructure planning to adapt to and further promote the deployment of autonomous vehicle (AV) technology. It is envisioned that in the future government agencies will dedicate certain areas of road networks to AVs only to facilitate the formulation of vehicle platoons to improve throughput and hopefully improve the performance of the whole network. This paper aims to present a mathematical framework for the optimal design of AV zones in a general network. With the presence of AV zones, AVs may apply different routing principles outside of and within the AV zones. A novel network equilibrium model (we refer to it as the "mixed routing equilibrium model") is thus firstly proposed to capture such mixed-routing behaviors. We then proceed to formulate a mixed-integer bi-level programming model to optimize the deployment plan of AV zones. Numerical examples are presented to demonstrate the performance of the proposed models.

1. Introduction

Autonomous vehicles (AVs) are expected to offer extraordinary improvements to both the safety and efficiency of existing roadways and mobility systems. Although it will be many years before a widespread adoption of AV technology, recent developments suggest that they are fast-approaching. Google's AVs had driven more than 2000,000 miles on public roads by October 2016 (Google Self-Driving Car Project, 2016). More recently, nuTonomy, a software company, has launched the world's first self-driving taxi in Singapore (nuTonomy, 2016). Many car manufactures, such as Volvo and Audi, are currently designing and testing their prototype AVs. In the United States, states such as Nevada, Florida, California, Michigan, and Washington D.C. have legalized AVs for testing on public roads. While thus far the development of AV technology appears to be primarily driven by the private sector, it is critical for government agencies to change various policies and practices to adapt to and further promote the deployment of the technology.

In this paper, we advocate the need for infrastructure adaptation planning for AVs. Before manual driving can be completely phased out (or criminalized, as some have predicted), the traffic stream on a road network will still be heterogeneous, with both conventional vehicles (CVs) and AVs. We envision that government agencies can initially identify critical locations to implement various AV mobility applications. For example, a "bottleneck manager" can be implemented at a recurrent freeway bottleneck. When approaching, AVs send requests via vehicle-to-infrastructure wireless commutations to

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http://dx.doi.org/10.1016/j.trb.2016.12.021
0191-2615/

the “bottleneck manager,” which will prioritize the requests and optimize their trajectories to ensure timely passage while preventing the bottleneck from being activated. To leverage the growing adoption of AVs, government agencies may later dedicate certain traffic lanes, highway segments or even areas of networks exclusively to AVs to facilitate the formulation of vehicle platoons to further improve throughput. Subsequently implemented are innovative control strategies that aim to achieve system optimum in those areas. The dedicated AV areas will expand gradually as the level of the market penetration of AVs increases and eventually support a fully connected and automated mobility in the whole system. Similar ideas have been suggested in the literature. For example, as current managed lanes are equipped with advanced communication and data transfer systems, researchers have suggested converting some of them into dedicated lanes for AVs to reduce congestion and improve the safety of passengers (Davis, 2014; Levin and Boyles, 2016a, 2016b). To help boost the market penetration of AVs, Chen et al. (2016) proposed a time-dependent model to optimally deploy AV lanes on a general network consisting of both CVs and AVs. Godsmark and Kakkar (2014) pointed out that the presence of AV areas can maximize benefits brought by AVs as rapidly as possible, as well as promote the AV adoption.

This paper deals with a particular issue in the above infrastructure adaptation planning process and aims to present a mathematical framework for the optimal design of AV zones in a general network. With only AVs being allowed to enter, an AV zone consists of a set of links that are tailored to AVs. Note that in order not to compromise CVs’ accessibility to various locations, the nodes within the zone in particular, the AV zone can be designed to consist of only urban expressways or arterial roads, excluding minor streets. It is assumed that within the zone, AVs cannot choose their routes. Instead, they report their exits and are then guided by a central controller to achieve the system optimum flow distribution in the zone. AV zones will enable full utilization of the AV technology within the zones to hopefully improve the performance of the whole network. These zones can help reduce travel times for AVs and further nurture the AV market. However, the existence of AV zones likely increases travel times for some CVs. Therefore, government agencies will need to make a tradeoff between these pros and cons in designing AV zones. The optimal design will depend on the market penetration of AVs, network topology and link characteristics, and more importantly, the route choices of both CVs and AVs in the network.

Optimal design of AV zones possesses a structure of the leader-follower or Stackelberg game, in which government agencies serve as the leader while CVs and AVs are the followers. Given a design of the AV zone, this paper firstly develops an innovative user equilibrium model we call the “mixed routing equilibrium model” to describe the flow distribution of AVs and CVs across the network. The novelty of the proposed model lies in the aspect that some paths consist of both links outside of and within the AV zones; AVs follow the user-optimum routing principle in the former and a different routing principle such as the system-optimum one in the latter. This new equilibrium model is most relevant to mixed equilibrium models in the literature, e.g., Haurie and Marcotte (1985), Harker (1988), Yang and Zhang (2008), Zhang et al. (2008), and He et al. (2013), where both the user-optimum and system-optimum route choice behaviors are considered. In all these previous models, all types of players share the same network, and each type of player applies a particular routing principle to traverse the whole network. In contrast, in our model, AVs and CVs may face different network topologies (recall that CVs are not allowed to enter AV zones) and, more importantly, AVs may apply different routing principles at different sub-networks. Mixed routing behaviors may become more relevant with the deployment of automated and connected vehicles. Capturing them in the network equilibrium framework is very challenging, which actually constitutes one of the major contributions of this paper.

Given the proposed mixed routing equilibrium model, we proceed to optimize the deployment plan of AV zones over a general network. The design problem is formulated as a mixed-integer bi-level programing model that is very difficult to solve. The problem appears to have a similar structure as the cordon design problem for cordon congestion pricing (see, e.g., Zhang and Yang, 2004 and Sumalee, 2004), which was solved previously using genetic-algorithm-based heuristics, such as the cutset-based approach (Zhang and Yang, 2004), the branch-tree approach (Sumalee, 2004), and the Delaunay triangulation approach (Hult, 2006). However, most of the above algorithms have low efficiency on generating new feasible design plans. In this study, we adopt a simulated annealing algorithm or SAA (Kirkpatrick et al., 1983; Cerny, 1985) to solve the AV zone design problem, since a simple but efficient plan-updating strategy can be tailored for SAA in order to generate new feasible design plans efficiently.

For the remainder, Section 2 illustrates the operational concept of AV zones considered in this paper and basic assumptions for the proposed models. Section 3 formulates the mixed routing equilibrium model and proposes its solution algorithm. Further, Section 4 optimizes the design of AV zones, and Section 5 concludes the paper.

2. Problem description

We consider a network where both AVs and CVs are present. The origin–destination (O–D) matrices of the vehicular trips of AVs and CVs are considered given. It is envisioned that a government agency strategically designs AV zones on a road network. An AV zone is cordoned off by a virtual loop. See Fig. 1 for an example of where the nodes and links within loop C comprise an AV zone. To facilitate the presentation of the model formulation, this study hereinafter considers the deployment or presence of a single AV zone over the network, but the proposed model can be easily extended to the case with multiple AV zones directly. Below we illustrate the operational concept for the AV zone:

i. Only AVs are allowed to use the links within the zone;