Transportation Research Part C 90 (2018) 307–333

Contents lists available at ScienceDirect

Transportation Research Part C

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

Roads in transition: Integrated modeling of a manufacturer-traveler-infrastructure system in a mixed autonomous/human driving environment

Mohamadhossein Noruzoliaee[a], Bo Zou[a,*], Yang Liu[b]

[a] Department of Civil and Materials Engineering, University of Illinois at Chicago, USA
[b] Department of Industrial and Systems Engineering, National University of Singapore, Singapore

ARTICLE INFO

Keywords:
Autonomous vehicles
Endogenous market penetration
Pricing
Travel time saving
Road capacity
Linearization

ABSTRACT

This paper develops an integrated model to characterize the market penetration of autonomous vehicles (AVs) in urban transportation networks. The model explicitly accounts for the interplay among the AV manufacturer, travelers with heterogeneous values of travel time (VOTT), and road infrastructure capacity. By making in-vehicle time use more leisurely or productive, AVs reduce travelers' VOTT. In addition, AVs can move closer together than human-driven vehicles because of shorter safe reaction time, which leads to increased road capacity. On the other hand, the use of AV technologies means added manufacturing cost and higher price. Thus, traveler adoption of AVs will trade VOTT savings with additional out-of-pocket cost. The model is structured as a leader (AV manufacturer)-follower (traveler) game. Given the cost of producing AVs, the AV manufacturer sets AV price to maximize profit while anticipating AV market penetration. Given an AV price, the vehicle and routing choice of heterogeneous travelers are modeled by combining a multinomial logit model with multi-modal multi-class user equilibrium (UE). The overall problem is formulated as a mathematical program with complementarity constraints (MPCC), which is challenging to solve. We propose a solution approach based on piecewise linearization of the MPCC as a mixed-integer linear program (MILP) and solving the MILP to global optimality. Non-uniform distribution of breakpoints that delimit piecewise intervals and feasibility-based domain reduction are further employed to reduce the approximation error brought by linearization. The model is implemented in a simplified Singapore network with extensive sensitivity analyses and the Sioux Falls network. Computational results demonstrate the effectiveness and efficiency of the solution approach and yield valuable insights about transportation system performance in a mixed autonomous/human driving environment.

1. Introduction

Recent advances in autonomous vehicle (AV) technologies and legislations show significant prospect of AV use in the future (Fagnant and Kockelman, 2015; Litman, 2017). Among the benefits that AVs can bring to urban transportation, this paper focuses on two of them. First, by making in-vehicle time use more leisurely or productive, AVs reduce travelers' value of travel time (VOTT) (Le Vine et al., 2015; van den Berg and Verhoef, 2016). Second, AVs can move with reduced headways compared to human-driven vehicles (HVs) because of shorter reaction time of in-vehicle computers than human brains. This will lead to higher road network

* Corresponding author.
E-mail addresses: mnoruz2@uic.edu (M. Noruzoliaee), bzou@uic.edu (B. Zou), iseliuy@nus.edu.sg (Y. Liu).

https://doi.org/10.1016/j.trc.2018.03.014
Received 11 October 2017; Received in revised form 19 March 2018; Accepted 20 March 2018

capacity (Le Vine et al., 2015; Wang et al., 2015b). On the other hand, due to the new technologies used in AVs such as sensors, navigation and communication systems, software, and Light Detection and Ranging systems (LIDAR), AVs will be more expensive (Fagnant and Kockelman, 2015). The price of AVs is further affected by the market supply-demand interactions, in which the willingness of travelers to use AVs will depend on the changes in the travelers' VOTTs using AVs vs. HVs. To understand the impacts of the above-mentioned factors brought by AVs on urban transportation, this paper contributes to the literature by developing an integrated model that encompasses AV manufacturing cost and pricing, combined vehicle and route choice of travelers who have heterogeneous VOTTs, endogenous road capacity with mixed AV and HV traffic, and transportation network performance.

The integrated model is developed under a leader-follower game structure, in which an AV manufacturer acts as the leader. Given the cost of producing AVs, the profit-maximizing AV manufacturer determines AV price anticipating the consequent AV market penetration. With the AV price, the vehicle and routing choice of travelers are modeled by combining a multinomial logit model with multi-modal multi-class user equilibrium (UE). The overall problem is formulated as a mathematical program with complementarity constraints (MPCC), which is challenging to solve due to: the non-convex feasible region caused by the UE complementarity constraints; the nonlinear multivariate travel time and multinomial logit functions in the constraints; and the non-concave objective function. To overcome this challenge, we propose a new solution approach based on linearizing the MPCC as a mixed-integer linear program (MILP) and solving the MILP to global optimality.

Two contributions are made in developing the solution approach. The first contribution lies in linearization techniques. In the MPCC formulation, the UE complementarity constraints are linearized using disjunctive constraints and additional binary variables. Other nonlinear functions in the constraints and the objective function are approximated by piecewise linear functions. We construct the piecewise linear functions in a way that requires the number of additional binary variables and constraints to be only *logarithmic* – rather than linear as in existing methods (Farvaresh and Sepehri, 2011; Liu and Wang, 2015; Wang et al., 2015a) – in the number of the piecewise intervals, based on a recent development in the disjunctive programming literature (Vielma and Nemhauser, 2011). To our knowledge, this logarithmic-sized linearization has never been considered in the transportation network modeling literature. Compared to the existing methods, the logarithmic-sized linearization considerably reduces the size of the MILP obtained from linearization, yet without compromising the approximation error.

Besides linearization techniques, we make a second contribution by devising two strategies to reduce approximation error brought by the linearization. The first strategy is to *non-uniformly* locate breakpoints that delimit the piecewise intervals in linearizing a constraint. The basic idea is to locate the breakpoints such that the total approximation error across the piecewise intervals is minimized, given a set of candidate breakpoints and the desired number of breakpoints to select from the candidate breakpoints. The idea is materialized by formulating a constrained shortest path problem using dynamic programming, built on the work of Dahl and Realfsen (2000) who cast the general problem of constrained shortest path into a dynamic programming formulation. The second strategy is to employ a *feasibility-based domain reduction* technique (Caprara and Locatelli, 2010) that shrinks the domains of the linearized functions by discarding infeasible solutions to the MILP. Same as the logarithmic-sized linearization, we are not aware of its use in transportation network modeling. This strategy allows all breakpoints to be placed in the feasible domains, which also contributes to reducing approximation error.

The model and the solution approach are implemented in simplified Singapore and Sioux Falls networks. The computational experience demonstrates the effectiveness and efficiency of the solution approach. In addition, several important insights are obtained. Specifically, in the scenario that producing an AV costs $10,000 more than an HV and AV travelers save 20% VOTT, the AV market share will be 2.4% (Singapore) and 6.1% (Sioux Falls). The change in aggregate system performance such as total travel time and generalized travel cost will be marginal. The smaller AV market share in Singapore is due to the significantly high overhead cost of buying a car and smaller VOTTs assumed in Singapore than in the US (Sioux Falls). Extensive sensitivity analyses are performed on the Singapore network to investigate the impacts on system performance of VOTT savings, AV manufacturing cost, cost perception variation of travelers, and market size, with the following major findings:

- As AV travelers enjoy a greater extent of VOTT savings, AV price will increase (up to 90% higher than HV). Most AV users will be with high VOTT and their choice between AVs and HVs is more sensitive to VOTT savings than low-VOTT travelers. The AV market share among high-VOTT travelers will increase to over 90%. Because of the AV use, network capacity will increase by up to 40%. Total travel time and generalized travel cost will decrease by up to 11% and 9%.
- As the AV technology cost falls, AV manufacturer profit will increase. So will AV market share (up to 55%), total travel time saving (up to 5%), total generalized travel cost saving (up to 4%), and network capacity (up to 19%). High-VOTT travelers are more sensitive to AV technology cost than low-VOTT travelers.
- As the cost perception variation of travelers decreases (travelers perceive more "accurately" the benefit and cost of using AVs), AV price will decrease. Travelers become more rational in using AVs: low-VOTT travelers will use AVs less, whereas high-VOTT travelers will first decrease then increase AV use. System travel time and network capacity follow the trend of AV market share. System generalized travel cost will decrease.
- As the market size increases, the AV manufacturer will earn more profit with fluctuating price. AV market share will first increase and then decrease, the latter due to more severe congestion which offsets travel time savings after switching to AVs. Change in network capacity follows a similar trend as AV market share.

These results are expected to help researchers and policy makers to gain further understanding about the impact of AVs on urban transportation and inform infrastructure investment decisions in the advent of vehicle automation.

The rest of the paper is organized as follows. Section 2 reviews the literature on AVs and transportation network optimization,