Transportation Research Part C 95 (2018) 363–380

Contents lists available at ScienceDirect

Transportation Research Part C

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

Predicting the adoption of connected autonomous vehicles: A new approach based on the theory of diffusion of innovations

Ahmadreza Talebian[a,*], Sabyasachee Mishra[b]

[a] Department of Transportation Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Civil Engineering, University of Memphis, 112D Engineering Science Building, Memphis, TN 38152, United States

ARTICLE INFO

Keywords:
Connected autonomous vehicles
Social network
Diffusion of innovations
Agent-based modeling
Simulation
Adoption

ABSTRACT

On the grounds that individuals heavily rely on the information that they receive from their peers when evaluating adoption of a radical innovation, this paper proposes a new approach to forecast long-term adoption of connected autonomous vehicles (CAVs). The concept of resistance is employed to explain why individuals typically tend to defer the adoption of an innovation. We assume that there exists a social network among individuals through which they communicate based on certain frequencies. In addition, individuals can be subject to media advertisement based on certain frequencies. An individual's perceptions are dynamic and change over time as the individual is exposed to advertisement and communicates with satisfied and dissatisfied adopters. We also explicitly allow willingness-to-pay (WTP) to change as a result of peer-to-peer communication. An individual decides to adopt when (i) there is a need for a new vehicles; (ii) his/her WTP is greater than CAV price; and (iii) his/her overall impression about CAVs reaches a cutoff value. Applicability of the proposed approach is shown using a survey of employees of the University of Memphis. Our results show that the automobile fleet will be near homogenous in about 2050 only if CAV prices decrease at an annual rate of 15% or 20%. We find that a 6-month pre-introduction marketing campaign may have no significant impact on adoption trend. Marketing is shown to ignite CAV diffusion but its effect is capped. CAV market share will be close to 100% only if all adopters are satisfied with their purchases; therefore, the probability that an individual becomes a satisfied adopter plays an important role in the trend of adoption. The effect of the latter probability is more pronounced as time goes by and is also more prominent when CAV price reduces at greater rates. Some caveats may be inserted when considering the study results as the findings are subject to sample bias and data limitations.

1. Introduction

Connected autonomous vehicles (CAVs) are about to become a reality, and they are arriving much earlier than many would think. By incorporating features such as parking assist, adaptive cruise control, and collision avoidance systems, most automobile manufacturers have already incorporated some degrees of automation into the existing cars. Mercedes-Benz, Google, Tesla, and others have already developed and tested prototypes of the first fully autonomous vehicles. By aggressive testing of autonomous peer-to-peer ridesharing services, transportation network companies (TNCs), such as Uber and Lyft, are also pushing the introduction of automation. Overall, such policies promise a transition to a more spread use of ride sharing services. Thanks to these advancements,

* Corresponding author.
E-mail address: talebian@cc.iut.ac.ir (A. Talebian).

https://doi.org/10.1016/j.trc.2018.06.005
Received 4 June 2018; Received in revised form 11 June 2018; Accepted 14 June 2018

research on various aspects of CAVs has gained increasing attention over the past decade. While automobile manufacturers have made huge investments to make the technology more viable, affordable, and safer, academic efforts have been directed to areas such as safety (Alonso et al., 2011; Fagnant and Kockelman, 2015; Gurney, 2013; Kalra and Paddock, 2016; Liu and Khattak, 2016), congestion and traffic operations (Le Vine and Polak, 2016; Le Vine et al., 2017; Mirheli et al., 2018; van den Berg et al., 2016), travel behavior (Harper et al., 2016; Hohenberger et al., 2016; Truong et al., 2017), environmental impacts (Brown et al., 2014; Tsugawa et al., 2011; Wadud et al., 2016; Yi et al., 2018), freight operations (Kunze et al., 2009; Kunze et al., 2011; Muratori et al., 2017), and infrastructure design (Chen et al., 2017).

One key question that has been of interest to policymakers, academic researchers, and industry professionals is *how much will be the demand for ownership of CAVs and how will be the timing of adoption in long-term*? Most of the recent studies with focus on the demand for CAVs address respondents' willingness-to-pay (WTP) as well as their opinions, concerns, and determinants of adoptions (Bansal and Kockelman 2018; Choi and Ji, 2015; Daziano et al., 2017; Haboucha et al., 2017; Hulse et al., 2018; Kyriakidis et al., 2015; Lavieri et al., 2017; Leicht et al., 2018; Menon et al., 2016; Pettersson and Karlsson, 2015; Schoettle and Sivak, 2014). On the other hand, a limited number of studies attempt to forecast evolution of connected autonomous fleet.

The majority of studies on adoption forecasting are based on expert knowledge, projection of adoption trends of other technologies, and sales estimates. Among the studies in the first category, a group of experts from the Institute of Electrical and Electronics Engineers (IEEE) suggest that about 75% of all vehicles will be CAVS by 2040 (IEEE, 2012). Bierstedt et al. (2014) forecast that the autonomous fleet will be in the range of 50%–75% between 2035 and 2045. Using future sale estimates, IHS Automotive (2014) determines that nearly all vehicles in use will be autonomous after 2050. Trommer et al. (2018) use a Gompertz function to predict the number of newly registered autonomous vehicles of Levels 4 and 5 in the US and Germany. They find that fleet share of autonomous vehicles can be up to 42% in Germany in 2035. This share, however, will be lower in the US mainly due to longer vehicle lifetimes. Based on the adoption patterns of previous vehicle technologies such as navigation systems, air bags, and hybrid vehicles, Litman (2014) forecasts that in the most optimistic and pessimistic scenarios, CAVs will be 95% and 70% of vehicles in 2070, respectively. By applying probit models to the data obtained from a survey in the Greater Toronto and Hamilton Area, Laidlaw et al. (2018) find that land use, age, price, and information about CAVs are the main predictors of adoption. They suggest that about half of new vehicle sales can be autonomous if the additional price of automation is $1000. This share would decrease to 5% if the price premium is greater than $15,000. Bansal and Kockelman (2017) develop a micro-simulation model to forecast long-term adoption of CAVs in the US. Multiple discrete choice models are used in a Monte Carlo simulation to emulate decisions such as buying or selling a car, purchasing a used or new car, adding connectivity and automation features. In three scenarios, the authors assume that individuals' WTP increase at the rates of 0%, 5%, and 10%, annually. The study suggests that the fleet of light-duty vehicles in the US will not be near homogenous by 2045.

In addition to the above efforts aiming at predicting the adoption trend of CAVs, there exists a growing body of literatures focusing on analytical modeling of CAV market penetration. Chen et al. (2016), for example, develop an optimization model that yields a time-dependent deployment plan of CAV-exclusive lanes (i.e., when, where, and the number of CAV lanes to be deployed). The objective is to minimize the social cost considering the market penetration of CAVs characterized by a diffusion model. Chen et al. suggest that CAV-exclusive lanes should be employed when adoption reaches a relatively high level (e.g., about 20%). In a more recent study, Noruzoliaee et al. (2018) establishes a leader–follower game to determine CAV market penetration. Anticipating CAV market penetration, the CAV manufacturer (leader) determines CAV price such that its profit is maximized. At the lower level, the vehicle and routing choice of travelers are considered using a multinomial logit model and multi-modal multi-class user equilibrium. By applying the model to a simplified Singapore and Sioux Falls networks, the authors find that CAV market share would be less than 10% when saving in value of travel time is 20% and CAV premium is $10,000.

Discrete choice modeling has been the prevailing approach in understanding various aspects of the demand for CAVs (Bansal and Kockelman, 2017; El Zarwi et al., 2017; Haboucha et al., 2017; Laidlaw et al., 2018; Lavieri et al., 2017; Liu et al., 2017; Menon et al., 2016, 2018). Choice models try to capture decision makers' preferences amongst a set of available alternatives. These models are based on the notion of stated preference which assumes that an individual's expectations are the same as market outcome; thus, stated preferences will remain valid. This assumption, known as rational expectations, could be problematic when a radical innovation, such as CAVs, is introduced to the market. In such a case, consumers have no previous experience on which they can base expectations (Snowdon et al., 1994). Empirical evidence suggests that individuals heavily rely on the information they receive from their peers when assessing adoption of a radical innovation (Henry, 2009; Wilson and Dowlatabadi, 2007). Traditional discrete choice models have limited capability to capture the effects that adoption of an individual may have on other individuals within his/her network (Dugundji and Walker, 2005). More advanced models, however, have incorporated peer effects into discrete choice analysis (Dugundji and Walker, 2005; Dugundji and Gulyás, 2008; Gaker et al., 2010; Kamargianni et al., 2014; Kim et al., 2014; Páez et al., 2008; Walker et al., 2011).

One promising avenue to forecast the demand for the next generation of transportation fleet is the theory of Diffusion of Innovations (DOI). DOI theory seeks to understand how an innovation will diffuse as a result of communication and consumer interactions in a social network. DOI theory considers innovation diffusion as a social phenomenon which has four aspects: (i) the demand to adopt the innovation; (ii) communication through certain channels; (iii) communication among individuals in a social network; and (iv) communication over time (Rogers, 1976, 2010). It should be noted that innovation is not limited to new technologies, but also includes new ideas and practices although in this paper we focus on the technological side (i.e., CAVs). Diffusion research has been of interest to the academic community for an extended period of time. The seminal diffusion study was published in 1943, when Ryan and Gross (1943) modeled the diffusion of hybrid seed corn among Iowa farmers. In 1969, the revolutionary paradigm of Bass (1969) was introduced in which adoption is forecasted based on the number of previous adopters. The basic idea