Transportation Research Part C 86 (2018) 300–327

Contents lists available at ScienceDirect

Transportation Research Part C

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

Towards a quantitative method to analyze the long-term innovation diffusion of automated vehicles technology using system dynamics

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ARTICLE INFO

Keywords:
Automatic vehicles
Innovation diffusion
System dynamics
Learning effects
Demand forecasting

ABSTRACT

This paper presents a novel simulation model that shows the dynamic and complex nature of the innovation system of vehicle automation in a quantitative way. The model simulates the innovation diffusion of automated vehicles (AVs) on the long-term. It looks at the system of AVs from a functional perspective and therefore categorizes this technology into six different levels. Each level is represented by its own fleet size, its own technology maturity and its own average purchase price and utility. These components form the core of the model. The feedback loops between the components form a dynamic behavior that influences the diffusion of AVs. The model was applied to the Netherlands both for a base and an optimistic scenario (strong political support and technology development) named "AV in-bloom". In these experiments, we found that the system is highly uncertain with market penetration varying greatly with the scenarios and policies adopted. Having an 'AV in bloom' eco-system for AVs is connected with a great acceleration of the market take-up of high levels of automation. As a policy instrument, a focus on more knowledge transfer and the creation of an external fund (e.g. private investment funds or European research funds) has shown to be most effective to realize a positive innovation diffusion for AVs. Providing subsidies may be less effective as these give a short-term impulse to a higher market penetration, but will not be able to create a higher market surplus for vehicle automation.

1. Introduction

Automated vehicles (AVs) may have a strong impact on the future of the transport sector, but also a much wider societal impact in the long-term, on safety, social equity and public health as discussed by Milakis et al. (2017b). A study by Hoogendoorn et al. (2014) shows the potential impact that AVs can have on traffic efficiency, highway capacity and congestion reduction. From a mobility point of view, Correia and van Arem (2016) look at the degrees of freedom that AVs bring in satisfying more trips of a household in the future, showing that AVs can satisfy more trips with some added traffic congestion resulting from the extra empty kilometers. Yap et al. (2016), Scheltes and Correia (2017) and Liang et al. (2016) studied the supply and demand of AVs as a last-mile/first-mile connection to train trips and observed changes in the value of travel time which disrupt the current mobility system as well as changes in the costs of operating these systems. But AVs are classified in different levels in terms of support and automation that they

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https://doi.org/10.1016/j.trc.2017.11.016
Received 13 May 2017; Received in revised form 12 November 2017; Accepted 13 November 2017
0968-090X/

offer. Currently, there are driver support systems and partially automated vehicles on the market (intermediate levels of automation) that already have an impact on traffic. A study by Kyriakidis et al. (2015) shows that there could be a significant impact of automation on decreasing the number of traffic accidents, which are estimated by Anderson et al. (2014) at 5.3 million automobile crashes per year in the USA alone.

The value that is being created by vehicle automation is often looked at in a third-person perspective, meaning that mainly the overall societal benefits are highlighted such as a decrease of travel time, improved traffic safety, and environmental benefits. However, Howard and Dai (2013) claim that: "the ability of automated vehicles to affect transformative change depends largely on how successful the vehicles are in attracting drivers from [conventional] automobiles. Once a critical mass of automated vehicles has been established, network benefits and other economies of scale enable environmental, safety, and travel time improvements". In order to attract a large number of consumers towards vehicle automation, there must be a clear value proposition for this technology. The magnitude of the societal changes that will result from this technology will be determined by how consumers adopt AVs as part of their lives. Therefore in this paper, the adoption of vehicle automation is analyzed from the perspective of the end user.

Due to the potential beneficial effects of vehicle automation, there is a high incentive by policy makers to stimulate the development and diffusion of this technology. Governments from various European countries like UK, Finland and the Netherlands (Dutch Ministry of Infrastructure and Environment, 2014) are putting a strong focus on stimulating the development of vehicle automation. However, in order to make beneficial decisions, policymakers should have insights into the interaction between technology development, personal preferences of the end-consumer and entrepreneurial activities around vehicle automation. This is important either to be able to adapt to changes in society due to vehicle automation as well as to guide the direction and speed of this innovation system if they want to be leaders in this technology production.

For the above-mentioned reason, it seems relevant to have a modeling framework that allows gaining more insights into possible adoption scenarios of AVs in the long-term as a function of some future scenarios of mobility evolution and policy decisions that countries can control. As Rosenberg (1983) stated: "One of the most important unresolved issues is the rate at which new and improved technologies are adopted". The difficulty of forecasting the adoption of new technologies in the particular case of vehicles is also underlined by (Shladover et al., 2001) the authors state that: "one of the most vexing problems has always been that of determining how to advance from the present-day manually-controlled vehicles to the future fully automated vehicles".

The present study is not the first one to aim at obtaining more insights on the diffusion of AVs into society. Some studies have explored the diffusion of AVs using both quantitative and qualitative methods. The methodologies that have been applied in those studies can be divided into historical analogies, expert interviews, panel consensus, trend projections and scenario development. Kyriakidis et al. (2015) studied the diffusion of Advanced Driving Assistance Systems (ADAS) in the period of 2012 to 2015 and compared the market penetration among different European countries. Milakis et al. (2017a) estimated through scenario development a market introduction of level 5 in a twenty-year time window between 2025 and 2045, depending on the speed of technology and the supportive nature of policies. Underwood (2014) conducted a survey among 217 experts in the field of AV systems, active safety systems, travel behavior and human factors. Kyriakidis et al. (2014) and De Winter et al. (2014) conducted a survey among, respectively, 4886 and 1517 respondents, which showed that most people expect vehicles to be driving fully automated on public roads around 2030.

The studies use different terminology, like market penetration, market introduction or deployment, nevertheless, their objective has been to understand innovation diffusion of AVs. Table 1 shows an overview of the estimates on the market penetration that have been found in those references. As it can be seen there is no consensus on market penetration for fully-automated vehicles (level 5).

Despite their value as a measure of what travellers are expecting from the transportation systems it is important to state that an estimation of the future car fleet has to be done independently of stated preferences and forecasting done by the consumers, because these can be highly biased. Expert opinion helps but it may be biased as well.

None of these studies have captured the complexity of different interacting factors on market penetration using quantitative

Table 1
Overview of market penetration estimations in literature.

Variable[a]	Range	Source
Market penetration level 1	0–10% in 2000 10–20% in 2015	Shladover (1995), Kyriakidis et al. (2015)
Market penetration level 2	0–5% in 2015	Kyriakidis et al. (2015)
Market penetration level 3	Introduction in 2017–2020 70% in 2020	Underwood (2014), Rangarajan and Dunoyer (2014), Juliussen and Carlson (2014)
Market penetration level 4	Introduction in 2018–2024 Highway and some urban streets before 2030	Underwood (2014), Shladover (2015)
Market penetration level 5	Market introduction between 2025 and 2045 25% in 2035 50% in 2035–2050 75% in 2045 – 2060 90% in 2055	Milakis et al. (2017a), Underwood (2014), Rangarajan and Dunoyer (2014), Bierstedt et al. (2014), Litman (2015), Juliussen and Carlson (2014),

[a] Levels explained in Fig. 1.