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# Endogenous market penetration dynamics of automated and connected vehicles: Transport-oriented model and its paradox

Toru Seo[1], Yasuo Asakura

*Tokyo Institute of Technology, 2-12-1-M1-20, O-okayama, Meguro, Tokyo 152-8552, Japan*

**Abstract**

Automated and connected vehicles (ACVs) have received a great deal of attention. Indeed, their full market penetration will be desirable in terms of traffic efficiency, as ACVs can efficiently drive by precisely and instantaneously communicating, recognizing, and reacting to other ACVs. However, it is not yet certain whether traffic efficiency is improved in mixed traffic where ratio of manual vehicles is substantially high. This is because, for example, ACVs in mixed traffic may require excessive safety clearance, as they have to rely on relatively imperfect vision/radar-based vehicle recognition. Meanwhile, relative benefit of ACVs compared to manual vehicles would be proportional to travel time (because the most significant merit of ACVs for their driver is comfortable in-vehicle experience) and therefore severity of congestion. Consequently, equilibrium states of a myopic car market may suffer severer congestion and higher social cost than the current state—this is congestion paradox. This kind of phenomena can be considered as a consequence of market penetration of a good with network externality or social interaction, where market penetration of ACVs is endogenously determined based on their cost/benefit which depend on current number of ACVs users. This study analyzes this problem under idealized conditions. Specifically, a theoretical model of endogenous market penetration of ACVs considering changes in value of time, travel time, and transportation fare, which are the most direct impacts of ACVs to the society, is formulated. Then, its market dynamics is analyzed. Finally, strategic policies to avoid congestion paradox and achieve social optimum are proposed.


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*Keywords:* autonomous vehicle; traffic flow theory; endogenous market penetration; multiple equilibria; network externality; social interaction

[1] Corresponding author. Tel.: +81 3 5734 2575
*E-mail address:* t.seo@plan.cv.titech.ac.jp

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## 1. Introduction

*Automated and connected vehicles (ACVs)* have received a great deal of attention (Hörl et al., 2016; Milakis et al., 2017). Indeed, their full market penetration will be desirable in terms of traffic efficiency thanks to the *connected vehicle technology (CVT)*, by which ACVs can efficiently drive by precisely and instantaneously communicating, recognizing, and reacting to other ACVs. It is called *cooperative driving*. However, it is still an open question whether traffic efficiency is improved in mixed traffic where ratio of *manual vehicles (MVs)* is substantially high. This is mainly due to that ACVs in mixed traffic may require excessive safety clearance (headway). Specifically, ACVs in mixed traffic have to rely on relatively imperfect vision/radar-based vehicle recognition instead of CVT, and relation between efficiency and safety of ACVs involves various technological and ethical issues (Le Vine et al., 2015, 2016; Bonnefon et al., 2016). If long headway is required to ensure safety, then it results in low traffic capacity and traffic efficiency is degraded.

New technology penetrates a market gradually when it is beneficial than the conventional counterpart for the consumers. Relative benefit of ACVs compared to MVs would be almost proportional to the in-vehicle travel time; because the most significant merit of ACVs for their driver is comfortable in-vehicle experience (i.e., reduced value of time (VoT) and safety) (Milakis et al., 2017). In other words, the worse congestion gets, the worthier ACVs are. Therefore, if ACVs are inefficient in mixed traffic and cause congestion, equilibrium states of a myopic car market may suffer severer congestion and even higher social cost than the current state. This can be considered as a *congestion paradox* where ACVs which naively intend eliminating congestion induce congestion due to market mechanism. It is important to know under what conditions such paradox occurs.

The aforementioned features of ACVs can be considered as *network externality* or *social interaction* (Rohlfs, 1974; Durlauf, 2001), which means that *cost/benefit of ACVs depend on current number of ACVs users*. In general, market penetration of goods with such network externality is difficult to be estimated by naive questionnaire surveys that simply ask the willingness-to-pay. Therefore, to predict market penetration of ACVs, it would be necessarily to develop an ACVs' *endogenous market penetration* model which explicitly considers the network externality based on its mechanism and determine penetration rate of ACVs endogenously.[2] Such model often has multiple market equilibria with different social cost; and policy implication on how to achieve socially desirable equilibrium can be obtained by analyzing the model (Yang, 1998; Fukuda and Morichi, 2007). The congestion paradox of ACVs corresponds to socially undesirable equilibria which may be achieved if there are no strategic policy intervention.

The aim of this study is to develop a model of market penetration dynamics of ACVs considering their impact to traffic flow via the network effects, to show when the congestion paradox occurs, and to propose appropriate strategic policy to avoid the paradox. Specifically, a theoretical model of endogenous market penetration of ACVs considering changes in VoT, travel time, and transportation fare, which are the most fundamental and direct impacts of ACVs to the society (Milakis et al., 2017), is formulated in Section 2. The proposed model is analyzed and some notable solutions of the market penetration problem are presented in Section 3. Conditions when the congestion paradox occurs and measures to avoid the paradox are discussed based on the results.

## 2. Model of Market Penetration Dynamics of ACVs

This study proposes a model that represents endogenous market penetration of ACVs considering their effects to transportation system. In this model, each traveler has to use either an MV or ACV for his/her commuting trip; and this decision is myopically[3] made considering cost and benefit of using these vehicles for the trip at that moment.

The framework of the proposed model is illustrated in Fig. 1. The model consists of three sub-models, namely, traffic flow model (Section 2.1), congestion model (Section 2.2), and market penetration model (Section 2.3). In this

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[2] Few studies investigated ACVs' endogenous market penetration based on similar ideas. van den Berg and Verhoef (2016) investigated a departure time choice problem combined with ACV market. Chen et al. (2016) investigated an optimal deployment problem of dedicated lanes for ACVs. Miyoshi (2016) proposed a model of market penetration of collision avoidance system.

[3] "Myopic" in this context means that users do not know/predict the future; and long-term vehicle ownership decision making process is not considered. One of the interpretations of this situation is carsharing service where user can use either an MV or ACV at each moment.