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Modeling Transportation Systems involving Autonomous Vehicles: A State of the Art

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Abstract

Autonomous Vehicles (AVs) promise many benefits for future mobility. Several modeling studies investigated their potential impacts with special focus on spatial and/or socio-economic features. Spatial modeling represents (i) in detail the technical specifications of the novel mode, and ii) the spatial features of the area in which the system is implemented. Most of these models are agent-based. Socio-economic modeling addresses the conditions of market penetration and diffusion using mathematical methods with commercial or social orientation. Furthermore, it investigates investment and operating costs.

This paper summarizes the main modeling works on transportation systems involving AVs that were published in the academic literature up to end 2016. In addition, we provide some examples of applications and address their respective outreach and limitations. We present recommendations for future developments.

This way, the paper takes part to a research project of which the ultimate goal is to build a predictive model that can be used by operators and policy-makers in order to test AVs scenarios.

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1. Introduction

Since the beginning of prosperity of the automotive era, the automation of car-driving has attracted specific studies: let us quote the car-to-car communication system using radio waves in Milwaukee during the 1920s (The Milwaukee Sentinel, 1926), the electromagnetic guidance of vehicles in the 1930s and 1940s, or the testing of smart highways by adding magnets to vehicles during the 1950s and 1960s (The Victoria Advocate, 1957). In 1980, Mercedes-Benz and Bundeswehr University Munich created the first autonomous car in the world, enabling to start thinking about legislation adaptation (Davidson, et al., 2015). Since then, many companies launched themselves in the quest for the perfect car or autonomous system, including Mercedes-Benz, General Motors, Google, Continental Automotive Systems, Inc. Autoliv, Bosch, Nissan, Toyota (Google Car), Audi, Oxford University, among others. Addition impetus was provided by the DARPA Grand Challenges I (2004), II (2005) and III (2007). In 2016, five US states (California, Florida, Michigan, Nevada, Tennessee and the District of Columbia) allowed to test autonomous vehicles, while 16 other states are considering taking legislative bills about automated driving (Weiner, et al., 2016). The experiments on autonomous vehicles show promising results. Such in-field experiments are mainly intended to test self-

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driving technology and possibly also the attitudes, use gestures and behaviours of potential users. Yet, up to now there has been no large scale implementation of AV fleet in a given territory. Prior to that, it is obviously important to deliver safe and reliable technology and to settle a suitable regulatory framework. Even more important, though less obvious, is the requirement to ensure commercial success, i.e. the purchase or hiring of AVs by individual customers or firms, which requires in turn convincing evidence of AV-based services attractiveness within the range of travel solutions that compete to serve mobility purposes. This is why a number of researchers have modelled AV-based services as mobility solutions under particular territorial conditions.

This paper reviews the models developed so far, with the aim to summarize their findings and to assess their outreach and limitations. As it turns out, the reviewed models fall into two broad categories depending on their main orientation that can be geographic or socio-economic. Geographic or spatial models focus on technical conditions concerning service performance, operations and availability in relation to users' needs and alternative solutions. The choice from among alternative solutions indeed leads to economic issues. Models belonging to the socio-economic category put the emphasis on the temporal conditions of AV development: this involves issues of technology readiness, legal framework, demand inclination and adoption, in relation to the production costs of self-driving cars.

The rest of the paper is organized in four parts. Section 2 reviews models that emphasize spatial conditions: they can be further divided according to whether they are rooted in travel demand needs and choices, or in the dynamic performance of a technical system that links the supply and demand sides. Then, Section 3 addresses socio-economic models, from market penetration to production costs passing by customership issues. Next, Section 4 reports on the evaluation of potential impacts that range from traffic volumes and parking demand to environmental impacts, passing by safety. Lastly, Section 5 discusses the outreach and limitations of the reviewed models and their applications, before proposing some directions for further research.

2. Spatial Models of AV-based Services

2.1. Models rooted in Travel Demand

Levin et al. (2015a) propose a four-step model dividing demand into classes by value of time and AV ownership. AVs are considered as private vehicles. Mode choice is between parking, repositioning, and transit based on a nested logit model. Static traffic assignment uses a generalized cost function of time, fuel, and tolls. Levin (2015b) incorporates dynamic traffic assignment (DTA) with endogenous departure time choices. Thus, the model considers more realistic flow propagation and intersection control options. In addition, it has only studied the case of full autonomous vehicles.

Results of static and dynamic assignment prove that using autonomous vehicles improves the capacity of the intersections, but does not reduce significantly the congestion.

Auld et al. (2017) used a simulation model (POLARIS) which includes an activity-based model (ADAPTS) and a traffic simulation model. Market penetration is controlled on a regional scale by adjusting road capacity. Results show that capacity and value of time affect significantly vehicle-kilometres travelled (VKT).

Klooststra et al. (2017) assumed that autonomous vehicles will change road capacity thanks to ACC technology. Then, they modified road links capacities to simulate theoretical increase in throughput enabled by AV driving behaviour. They distinguished two types of road links: freeways and arterial streets. A static assignment in Emme 4 is realised. In addition, they analysed the impacts on parking operations.

2.2. Agent-based models

Agent-based models are an effective tool for the study of innovative urban services, as agents act and react according to the information received in real time. On the other hand, activity models offer improved reproduction of the demand and allow a more realistic analysis of users' mobility. Thus, agent-based models are highly used in literature to describe and analyse operations of AV.

In 2013, Burns et al. estimate the utility of shared autonomous vehicles (SAV) for users (waiting time) and operators (cost of production). They consider as variables local specifications, trip length, speed, fleet size and vehicle's cost parameters (Burns, et al., 2013). The model assumes that the vehicle speed is constant and origin-destination trips are uniformly distributed over the study area. In addition, an application on three US cities of different sizes Ann Arbor, Babcock Ranch (Florida) and Manhattan (New-York) confirms the economic potential of AV.

The study realized by ITF (2015) simulates the shared mobility in the real network of Lisbon using agent-based models. Mode choice process is based on a rule-based approach. The demand is generated based on the Lisbon Travel Survey. The user groups, especially for new services, are not considered. A trip is generated when a user send a request. Route choice minimizes travel time by integrating the average speed per section per hour. Sixty stations are spread in the city and three types of vehicles' are considered in the model of two-, five- and eight-passenger cars.

One of the most relevant studies is that developed by Fagnant and Kockelman (2014). They simulate SAVs in Austin (Texas) using an agent-based model (MATSim). SAVs are used by 2% of the total demand. The city is composed into traffic zones. Each traffic zone is characterized by an factor of attractiveness. All the trips are generated every 5 minutes a day using Poisson distributions. The model is then structured by following four major steps: (1) *SAV location and trip assignment*, which determines which available SAVs are closest to waiting travellers (prioritizing those who have been waiting longest), and then assigning available SAVs to those trips. The assignment is done according to a First-Come First Served (FCFS) order. A vehicle

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