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Development of an agent-based model for regional market penetration projections of electric vehicles in the United States

Mehdi Noori*, Omer Tatari

Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL 32816, United States

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ABSTRACT

One of the most promising strategies recommended for increasing energy security and for mitigating transportation sector emissions is to support alternative fuel technologies, including electric vehicles. However, there is a considerable amount of uncertainty regarding the market penetration of electric vehicles that must be accounted for in order to achieve the current market share goals. This paper aims to address these inherent uncertainties and to identify the possible market share of electric vehicles in the United States for the year 2030, using the developed Electric Vehicle Regional Market Penetration tool. First, considering their respective inherent uncertainties, the vehicle attributes are evaluated for different vehicle types, including internal combustion engine, gasoline hybrid, and three different electric vehicle types. In addition, an agent-based model is developed to identify the market shares of each of the studied vehicles. Finally, market share uncertainties are modeled using the Exploratory Modeling and Analysis approach. The government subsidies play a vital role in the market adoption of electric vehicle and, when combined with the word-of-mouth effect, may achieve electric vehicle market share of up to 30% of new sales in 2030 on average, with all-electric vehicles having the highest market share among the electric vehicle options.

1. Introduction

1.1. Introduction and scope of the study

By diversifying the fuel mix of the U.S. transportation sector, the electric vehicle industry helps to increase energy security and reduce dependence on petroleum [1], if the electricity is generated by other primary energy sources. Moreover, the transportation sector has an enormous effect on GHG (greenhouse gas) emissions, and is responsible for 27% of all GHG emissions in the U.S. as of 2013 [2]. EV (Electric Vehicle) market shares have greatly increased in recent years due to energy insecurity concerns [3], the increasing trends in oil prices, improvements in electrical power storage [4], and electricity's current status as the cheapest and most efficient energy source for the transportation sector in the foreseeable future [5]. Governments are now embracing the development of EVs on the road by setting goals to improve the EV industry. For instance, European Parliament and the council of the European Union (EU) has reached to an agreement of setting mandatory 2020 targets for EVs, including installing at least one charging station per 10 EVs in all EU member states [6]. China has set goal of 5 million EVs on the road by 2020 [7]. In the United States, although the Obama administration has backed off of its goal of one million electric vehicles on the road by 2015 [8], others have set a goal of an EV share of 20% in the U.S. transportation new sales fleet by 2030 [9]. There are also some goals in the state level such as California's ZEV (Zero Emissions Vehicle) mandate [10]. Additionally, significant cost reductions for EV components such as batteries have further stimulated this market share growth. However, despite all of these efforts and the current collective movement to facilitate the electrification of the U.S. transportation fleet, there are still barriers hindering the widespread adoption of EVs as a viable transportation option, including various technological, financial, market, and policy challenges to the full deployment of EVs.

The United States currently has the largest number of electric vehicles on the road, with almost 43 percent of all EVs sold in the U.S. However, EVs only comprised less than 1% of new car sales in the U.S. as of 2014 [11]. Therefore, greater adoption rates must be met in order to achieve the mid-term and long-term market share goals for EVs as described previously [12]. In light of these

* Corresponding author.
E-mail address: noori@ucf.edu (M. Noori).

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challenges, it is increasingly necessary to study EV market shares in more detail. Market forecasting is currently a well-developed and well-studied field with implications in various other fields (economics, business, finance, systems engineering, etc.), but often fails to consider uncertainties in the different factors affecting market shares. For this reason, market evaluations of new EV technologies is facing increasing degrees of complexity due to difficulty in modeling the relevant system factors [13].

Therefore, this paper aims to study the market penetration of EVs considering the inherent uncertainties involved. To this end, the purchase prices, M&R (maintenance and refueling) costs, EDC (environmental damage costs), and WFP (water footprints) of the studied vehicle types are estimated, considering their respective uncertainty ranges. Next, an ABM (agent-based model) is developed to simulate the market penetration of EVs in the U.S. Finally, different scenarios are applied via the EMA (Exploratory Modeling and Analysis) approach, and the most plausible outcome of this method is analyzed as needed. In this study, five different vehicle types are compared and analyzed: ICEVs (Internal Combustion Engine Vehicles), Gasoline HEVs (Hybrid Electric Vehicles), Gasoline PHEVs (Plug-in Hybrid Electric Vehicles), Gasoline EREVs (Extended-Range Electric Vehicles), and All-Electric Vehicles a.k.a. BEVs (Battery Electric Vehicles). For the purposes of this study, it is assumed that PHEVs and EREVs have all-electric range of 10 miles and 40 miles, respectively.

This study distinguishes itself from previous efforts in several ways. Firstly, the previously developed EVRO (Electric Vehicle Regional Optimizer) is used to estimate the M&R cost, the EDC, and the WFP of the studied drive-train, and also considers all of the possible uncertainties of the LCC (life cycle cost), EDC, and WFP analyses to account for all applicable EV characteristics. Secondly, although some efforts have been made to develop a market share model to simulate the market penetration of EVs in the U.S., most of these efforts have considered an average U.S. electricity grid mix in their respective analyses, while this study considers 22 different electric grid regions and analyses the adoption rate of EVs in each region separately. Finally, an agent-based model (ABM) is developed in conjunction with the Exploratory Modeling and Analysis (EMA) method to integrate the relevant uncertainties into the market share of EVs in the year 2030.

The rest of the paper is structured as follows: First, the existing literature on the market share models of the EVs is discussed. Second, the methodology and general assumptions are described, the uncertainty ranges are explained, and the mathematical content of the EVReMP (Electric Vehicle Regional Market Penetration) tool is discussed. Finally, the results and implications of the EVReMP model are illustrated, and the study is concluded based on these results and implications.

1.2. Life cycle analysis, agent-based modeling, and market penetration of electric vehicles

Life Cycle Assessments of EVs have been extensively studied in today's literature. For instance, in one recent publication from the University of Central Florida, a state-based carbon and energy footprint analysis was performed for conventional, hybrid, plug-in hybrid, and electric vehicles [14]. In addition, Noori et al. compared the water footprint of different EV types and concluded that moving towards an electrified fleet would increase the water footprint, considering the current electricity mixes in the U.S. Moreover, The Union of Concerned Scientists published an informative report that investigated emissions from charging electric vehicles on a regional scale, including upstream emissions from building power plants, extracting and transporting fuel, converting fuel into electricity, and delivering electricity to the point of use [15]. In addition to the light-duty vehicles, LCA (Life Cycle Analysis) of battery electric transit buses are studied in Ercan and Tatari's research by using regional electricity generation mixes [16]. In addition, Viñoles-Cebolla et al. developed an integrated model to estimate the life cycle emissions of different vehicles using primary vehicle data such as weight, engine technology, and fuel type [17]. Moreover, Zhang et al. proposed a simulation model to analyze the economic and environmental performance of Evs, testing different conditions such as the electricity generation mix, smart charging control strategies, and real-time pricing mechanisms [18].

Agent-based modeling (ABM) is a simulation method that creates a virtual environment to model the interactions between different agents. ABM is previously used to model vehicle technology adoption, with different agents (consumers, automakers, policy makers, fuel suppliers, etc.) interacting in a virtual environment. For instance, Cui et al. developed a multi agent-based framework for the spatial distribution of PHEV ownerships at local residential household level [19]. In addition, Eppstein et al. developed a spatial explicit ABM to study market penetration of PHEVs and concluded temporary rebates have only short-term impacts on market share and gas prices must rise for a higher penetration rate [20]. Consumers are the primary agents in some aspect of the vehicle technology adoption portrayed with the ABM method, whereas more current models have expanded this environment by considering automakers, policy makers, and fuel suppliers as agents as well. One of the more advanced ABMs for evaluating the market share of Evs is the Virtual Automotive Market Place Model (acronym VAMPM) developed by the University of Michigan Transportation Research Institute (UMTRI) [21]. This model characterizes the market share of new technologies in a hypothetical "neighborhood" under different consumer, economic, and policy conditions, and considers four different agent types: consumers, governments, fuel producers, and vehicle producers/dealers. The unit cycle of the analysis is one month, and the agents communicate in each cycle based on their needs and benefits. The results indicate that, by 2015, sales of PHEVs could reach up to 3%. By 2020, sales could potentially reach up to 5% and up to 20% in 30 years, with a final market penetration of 16% by 2040. One of the advantages of the ABM method is its ability to use both hypothetical and data-driven consumer behavior during the modeling process [13].

Most of the ABM models in current literature were developed based on utility theory, in which the agent purchases a vehicle that maximizes his/her utility. For instance, Ting Zhang et al. proposed a novel ABM methodology to investigate factors that can facilitate the penetration of the alternative fuel technologies into the market [22], considering four different agents in their analysis: manufacturers, vehicles, consumers, and governments. The mathematical content of abovementioned study is now used as a basis for the formulation of the developed ABM in this research. Moreover, a consumer choice probability model is developed for evaluating the market share of Evs in Iceland by Shafiei et al. [23], with consumers weighing different vehicle attributes based on their own specific preferences. The mathematical content of the consumer choice model is also used to form the developed ABM in this analysis. The mathematical content of the developed Electric Vehicle Regional Market Penetration (EVReMP) Model is described in the next section.

2. Methods

This section will serve to explain the methodology framework in greater detail, and the following subsections will describe the conceptual basis and mathematical content of the methodology. First, the developed Electric Vehicle Regional Market Penetration