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An agent-based model to study market penetration of plug-in hybrid electric vehicles

Margaret J. Eppstein [a,*], David K. Grover [b], Jeffrey S. Marshall [b], Donna M. Rizzo [b]

[a] Department of Computer Science, University of Vermont, Burlington, VT 05405, USA
[b] School of Engineering, University of Vermont, Burlington, VT 05405, USA

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ABSTRACT

A spatially explicit agent-based vehicle consumer choice model is developed to explore sensitivities and nonlinear interactions between various potential influences on plug-in hybrid vehicle (PHEV) market penetration. The model accounts for spatial and social effects (including threshold effects, homophily, and conformity) and media influences. Preliminary simulations demonstrate how such a model could be used to identify nonlinear interactions among potential leverage points, inform policies affecting PHEV market penetration, and help identify future data collection necessary to more accurately model the system. We examine sensitivity of the model to gasoline prices, to accuracy in estimation of fuel costs, to agent willingness to adopt the PHEV technology, to PHEV purchase price and rebates, to PHEV battery range, and to heuristic values related to gasoline usage. Our simulations indicate that PHEV market penetration could be enhanced significantly by providing consumers with ready estimates of expected lifetime fuel costs associated with different vehicles (e.g., on vehicle stickers), and that increases in gasoline prices could nonlinearly magnify the impact on fleet efficiency. We also infer that a potential synergy from a gasoline tax with proceeds is used to fund research into longer-range lower-cost PHEV batteries.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) have many potential advantages over conventional vehicles, but it is not clear what combinations of policies will be most cost-effective in promoting successful market penetration of this new vehicle technology. The intent of this article is to (a) present a framework for a novel agent-based vehicle consumer choice model, (b) illustrate how such a model could be used by policy-makers and vehicle manufacturers to help prioritize investments influencing PHEV adoption, and (c) identify additional empirical evidence that will be necessary to improve the predictive power of such a model. To motivate this work, we first review potential PHEV advantages, hurdles to PHEV market penetration, and related agent-based models.

A recent joint report by the Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC) (Duvall et al., 2007) found that PHEVs have the potential to substantially reduce greenhouse gas emissions. From a consumer perspective, PHEVs offer the higher fuel efficiency of electric vehicles (EVs) within the all-electric range, but also the convenience and flexibility of traditional fuels and existing refueling infrastructure for longer trips. Since vehicles travel on average at around 23 miles per day (37 km/day) in the U.S. (Bose et al., 2003), the majority of daily travel should be within the all-electric battery range of the most first-generation PHEV vehicles, anticipated to be about 30–60 miles (50–100 km), assuming recharging is available on a daily basis. Lifecycle analyses reported by Jaramillo et al. (2009) indicate PHEV greenhouse gas emissions to be about half of that of current gasoline and diesel motor fuels, even when using coal-fired electricity generation, assuming CO_2 capture and storage. Similar conclusions are reached in a study by Smith (2010) on the potential use of PHEVs in the automotive fleet in Ireland.

As primary power sources for the electric grid become greener and gasoline prices increase, emission reductions and fuel savings with PHEVs will even be greater. A projected lifecycle analysis for the year 2030 by Offer et al. (2010) compares PHEVs with battery–electric vehicles, hydrogen fuel-cell vehicles, and internal combustion vehicles. The study finds that the PHEV and battery–electric options offer much lower lifecycle costs than either the fuel-cell or internal combustion vehicle options. Widespread PHEV adoption would have the added benefit of substantially increasing the potential net electrical energy storage capacity in a community, which could increase the stability of the power system. For instance, Anderson et al. (2009) and Andersson et al. (2010) propose development of a vehicle-to-grid system, whereby electric vehicles would be used to store and release energy for the electrical power grid that

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[*] Corresponding author. Tel.: +1 802 656 3330; fax: +1 802 656 5838.
E-mail address: Maggie.Eppstein@uvm.edu (M.J. Eppstein).

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would serve to even out the peaks and valleys inherent in electrical energy usage and the fluctuating supply typical of renewable energy sources (such as wind).

Despite these potential advantages, there remain significant barriers to widespread adoption of new PHEV technology. In a 2008 survey of U.S. consumers, 69% of respondents reported little or no familiarity with PHEV technology (Axsen and Kurani, 2008), although in a 2010 survey over half of the respondents reported some awareness of the Chevrolet Volt (Zypryme Research and Consulting, 2010). Many consumers are hesitant to adopt unfamiliar technologies, and there may be significant consumer uncertainty about issues such as battery life, replacement costs, and recharging time (Sovacool and Hirsh, 2009; Zypryme Research and Consulting, 2010). Uncertainties in future petroleum prices and challenges in estimating fuel usage for different trip lengths make it difficult for consumers to accurately estimate the financial and/or environmental PHEV trade-offs relative to other vehicles. Studies based on data for consumer purchases of hybrid electric vehicles (HEVs) (Heffner et al., 2007; Turrentine and Kurani, 2007; Griskevicius et al., 2010) support the conclusion that most consumers elect to purchase HEVs for non-financial reasons, (e.g., to symbolize their commitment to reducing gasoline consumption, to reduce greenhouse gas emissions, to reduce dependence on foreign oil), rather than on detailed rational financial analyses of lifetime costs. In any case, HEVs are not currently a cost-efficient choice; a recent study by the British Columbia Automobile Association (BCAA, 2010) found that 15 of the 16 HEVs studied did not yield even a 5-year payback at 2010 Canadian gasoline prices (higher than U.S. gasoline prices), when compared to their similar gasoline vehicle (GV) counterparts (the one exception was an expensive luxury HEV).

A wide variety of governmental regulations and incentives have been proposed or implemented to accelerate market penetration of PHEVs (www.afdc.energy.gov/afdc). Morrow et al. (2010) discuss the effects of fuel taxes, increases in fuel economy standards, and purchase tax credits for fuel-efficient vehicles. They examine the sensitivity of fuel-efficient vehicle purchases using these approaches and predictions of the U.S. Energy Information Administration's National Energy Modeling System. They find that, in general, purchase tax credits are expensive and ineffective at reducing emissions, whereas the most effective approach for increasing fuel efficiency is to increase gasoline costs. Skerlos and Winebrake (2010) examined the impact of tax credits for PHEV purchase, which were introduced in 2009 by the U.S. government and are available to all consumers equally in all parts of the country. The authors argue that these tax credits would be more effective if targeted in certain geographic locations where PHEV technology offers maximum benefit, and if they were dependent on consumer income. Diamond (2009) examined the relationship between hybrid adoption rates and governmental incentive policies in different U.S. states. His findings similarly indicate a strong relationship between hybrid adoption and gasoline price, but a much weaker relationship between hybrid adoption and government incentives.

While studies based on past data trends for HEVs and other fuel-efficient vehicles provide relevant insight, they are of limited applicability for estimating consumer response to the very different conditions associated with current-day adoption of PHEV technology. The plug-in technology offers new challenges to market penetration, and environmental attitudes and awareness are also very different than those in past decades. While awareness of the role of vehicle emissions in global climate change is high in many parts of the world, it is not clear how consumers will weigh a vehicle's heuristically perceived benefits against rational financial considerations when making a vehicle-purchasing decision. Consumer choices are not necessarily based on financially accurate assessments of alternatives (Turrentine and Kurani, 2007), and values that affect consumer choices are often influenced by media and social networks (Yin, 1999; Newig and Hesselmann, 2004; Pew Research Center for the People and the Press, 2009). Traditional discrete-choice models assume a static distribution of decision strategies and do not support consumer behavior changes in response to social or other external pressures. However, recent variations of discrete-choice models have been proposed that demonstrate the importance of social or psychological factors (Bolduc et al., 2008) and 'neighbor effects' on consumer attitudes as the market share of a given vehicle type grows (Mau et al., 2008).

Agent-based models (ABMs) stochastically simulate spatially explicit interactions and behaviors of autonomous and heterogeneous agents in order to observe and study the emergence of coherent (but dynamic) system behaviors at larger spatial and temporal scales. ABMs have become increasingly popular in studies of transportation logistics and traffic flow (Dia, 2002; Henesey et al., 2005). In a particularly relevant ABM, Mueller and de Haan (2009) studied the influence of incentives on car purchases and the effect of feebate approaches to encourage purchase of high energy efficiency vehicles (de Haan et al., 2009). In another relevant PHEV market penetration ABM (Sullivan et al., 2009), vehicle preferences depend on size, performance, and brand, with the proviso that they must stay within their monthly budgets. Consequently, PHEV penetration is shown to be strongly dependent on permanent PHEV tax rebates, subsidies, and sales tax exemptions.

In this article, we present an ABM of heterogeneous interacting vehicle consumer agents that accounts for correlated demographic agent variability as well as several unique spatial and social effects. We examine the effects of (i) gasoline prices, (ii) ability of agents to consider fuel costs, (iii) PHEV purchase price and rebates, (iv) PHEV all-electric battery range, (v) consumer values regarding financial vs. non-financial concerns in vehicle purchase, (vi) agent comfort thresholds with the PHEV technology, and (vii) social and media influences on PHEV market penetration and fuel efficiency of the resulting fleet after 25 years. Preliminary insights gained from our results and potential model uses for informing energy and transportation policy are discussed.

2. Agent-based model

In the model implementation presented herein we make several simplifying assumptions, due in large part to low model sensitivity to specific details or a lack of empirical data that could justify a more complex model. For example, we currently assume that each agent's age and social network are static; we model individual consumers rather than households; we assume uniform daily driving patterns and availability of daily recharging; and we model only a small subset of vehicle options. Despite these limiting assumptions, exploration of model sensitivities provides useful insights into qualitative system behavior and interactions between potential leverage points. As more data become available, the model framework can easily accommodate more realistic assumptions and vehicle options.

Vehicle consumers weigh the costs and benefits of many vehicle characteristics in addition to fuel type, such as seating capacity, cargo capacity, safety, reliability, and drive train, when determining which vehicle to purchase. We originally considered modeling a two-step decision process similar to that employed by Mueller and de Haan (2009). The first step would involve a screening process that identifies which different models fit some basic set of desired attributes (other than fuel type), followed by a cost-benefit analysis between the remaining models. However,