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Moving from assumption to observation: Implications for energy and emissions impacts of plug-in hybrid electric vehicles

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HIGHLIGHTS

- The specific benefits or impacts of PHEVs ultimately relies on consumers purchase and vehicle use patterns.
- Simplifying, untested, assumptions have been made by prior studies about PHEV consumer driving, charging and vehicle purchase behaviors.
- Some simplifying assumptions do not match observed data from a PHEV demonstration project.
- Changing the assumptions about PHEV consumer driving, charging, and vehicle purchase behaviors affects estimates of PHEV impacts.
- Premature simplification may have lasting consequences for standard setting and performance based incentive programs which rely on these estimates.

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) are currently for sale in most parts of the United States, Canada, Europe and Japan. These vehicles are promoted as providing distinct consumer and public benefits at the expense of grid electricity. However, the specific benefits or impacts of PHEVs ultimately relies on consumers purchase and vehicle use patterns. While considerable effort has been dedicated to understanding PHEV impacts on a per mile basis few studies have assessed the impacts of PHEV given actual consumer use patterns or operating conditions. Instead, simplifying assumptions have been made about the types of cars individual consumers will choose to purchase and how they will drive and charge them. Here, we highlight some of these consumer purchase and use assumptions, studies which have employed these assumptions and compare these assumptions to actual consumer data recorded in a PHEV demonstration project. Using simulation and hypothetical scenarios we discuss the implication for PHEV impact analyses and policy if assumptions about key PHEV consumer use variables such as vehicle choice, home charging frequency, distribution of driving distances, and access to workplace charging were to change.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) can run on gasoline and grid electricity. Thus unlike battery electric vehicles (BEVs), PHEVs allow consumers to use gasoline and its fueling infrastructure to power their vehicles whenever charging with electricity is not possible or convenient. With this flexibility comes uncertainty. While PHEVs may reduce petroleum use, improve local air quality (Kalhammer et al., 2009; Gonder et al., 2009), and decrease greenhouse gas (GHG) emissions (Axsen et al., 2010; McCarthy and Yang, 2009; Sovacool and Hirsh, 2009), estimates about the extent of these reductions still depend on assumptions about PHEVs and the electricity used to charge them. It is difficult to characterize the aggregate effects of PHEVs on electric grid operations and energy and environmental goals, since the variety of potential PHEV designs (Gonder et al., 2009; Smart et al., 2010; Simpson, 2006), uncertainty about the potential market for such designs (Axsen and Kurani, 2008; Kurani et al., 2010; Axsen et al., 2011), and differences in consumer driving and charging behavior (Kurani et al., 2010; Davies and Kurani, 2010) all influence PHEV performance and impact. Prior studies of potential PHEV energy and emissions impacts use various sources of vehicle travel data and make differing assumptions about vehicle designs, charging behaviors and market penetration. We compare the data and assumptions of prior analyses to observed PHEV driving, charging and vehicle design predilections from households who participated in a PHEV demonstration project. Then, we simulate the

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implications of changing PHEV assumptions about user behaviors and market conditions. The simulation includes the possible effects of additional PHEV charging at the workplace on the utility factor (UF) and how the types of PHEV designs offered for sale to consumers could influence the PHEV market size, and electricity and gasoline consumption.

The present analysis differs from prior studies through the incorporation of a consumer informed PHEV market scenario and the use of a continuous seven days of travel and charging data for each household. This approach enables an exploration of the effects of day-to-day interdependencies of travel and charging behavior on the variation in the time of day (TOD) grid demand for PHEV charging. Given the small sample size from the demonstration, the specific numerical results may differ from results that will be obtained with different vehicles and a larger sample of multi-day data. However, the demonstration and subsequent analysis test prior assumptions and give direction to hypotheses about consumer PHEV design preferences and use that add insight to the discussion of PHEV impacts and consumer behavior.

1.1. *Relevant PHEV design and performance attributes*

Perhaps the most important PHEV design and performance attribute is charge-depleting (CD) range, i.e., the distance the vehicle can be driven while consuming energy from the grid by depleting the state of charge of its storage battery. PHEVs with different CD ranges will be denoted here by “PHEVXX” where XX is the distance in miles the vehicle can operate in CD mode on a single full battery charge. In the case of PHEVs in which CD operation is all-electric, electricity is the sole power source during CD mode. In contrast, blended PHEVs use both grid electricity and gasoline during CD mode. Because blended PHEVs of equal CD range to an all-electric PHEV require less powerful batteries, motors, and electronics, the incremental production cost of a blended PHEV drive train is expected to be less than that of an all-electric PHEV (Axsen et al., 2010). When the CD range is surpassed, all PHEVs revert to charge sustaining (CS) mode, in which liquid fuel (gasoline, ethanol, diesel, etc.) is consumed in an internal combustion engine (ICE) to power the vehicle and sustain the charge of the battery. The transition from CD to CS mode is automatic, and the vehicle can operate in CS mode as long as the liquid fuel is supplied to the ICE. The utility factor (UF) is defined as the ratio of miles driven in CD mode to all miles driven.

Within the possibilities defined by the PHEV drivetrain (all-electric vs. blended) and CD range, driving and charging behaviors will determine electricity use and other impacts. Daily life provides varying degrees of structure and routine, and a household's use of any particular PHEV will be incorporated into some social framework and lifestyle, such as commuting to work, trips to chauffer children, shopping, etc. (Kurani et al., 2010). While there may be some degree of predictability in these routines, households will vary in the extent to which they prioritize charging the PHEV, are able to fit charging into the context of their established routines, or are willing to create new routines. Diligence in charging will vary given differences in lifestyles, understanding of PHEV operation and technology, access to charging infrastructure, and the perceived benefit and importance of plugging in for personal or societal benefits (Kurani et al., 2010). Information provided to vehicle users from human machine interfaces (HMI) and vehicle designs (such as built in time of day charging schedulers) may also shape PHEV use. While real world data from users of production PHEVs is still limited, the (Idaho National Laboratory, 2012) reports some PHEV drivers increase their CD driving through enhanced trip planning, vehicle substitution, and plugging in more than once on days the vehicle is driven.

1.2. *Previous assumptions about PHEV usage*

Given the relative dearth of actual PHEV user data, researchers have created scenarios to combine various sources of travel data with assumptions of user charging behavior and vehicle designs to estimate PHEV impacts. A sample of PHEV impact studies and their respective assumptions about consumer PHEV driving, charging, and (often implicitly) purchase behaviors is in Appendix A. This paper will compare the results from the PHEV demonstration drivers and vehicle designs (both the PHEV they drove and the vehicle designs they created) with the following three assumptions:

1.2.1. *Assume single driving day is sufficient to characterize travel*

Prior analyses commonly use single day travel diary data from conventional vehicles, e.g., the National Household Travel Survey (NHTS), as a source of travel behavior data for the US. While the NHTS is a readily available national travel database its use to evaluate PHEV impacts implies assumptions about future travel behavior. First, the use of past ICE vehicle data implies that travel demand and vehicle assignment within households will remain constant irrespective of time and the portfolio of vehicles each household operates (including EVs, PHEVs, hybrids and conventional vehicles). Interviews and travel diary data from BEV users in a demonstration and market research study showed changes over time in travel behavior and vehicle assignment within households after introducing a BEV to the household fleet (Turrentine et al., 2011). Second, one-day data cannot address dependencies within a household's travel over multiple travel days. Third, since the NHTS in particular omits 0-mile travel days it cannot be used to provide unbiased estimates of total travel (VMT) or the energy associated with that travel.

1.2.2. *Assume PHEV owners will plug-in their vehicle once a day*

It has commonly been assumed that PHEV owners will plug-in their vehicle once a day, regardless of their daily driving distance or access to charging infrastructure. However, given PHEVs operating characteristics and assuming a costs advantage of operating in charge depleting mode, it is plausible that some consumers will change their travel behavior—including the reassignment of multiple household vehicles or charging behavior to increase CD mode operation of their PHEV when possible. Additional charging has clear implications for the time of day (TOD) use of electricity since charging could take place over a different temporal or spatial pattern than assumed. Furthermore, additional charging under the right circumstance may lead to additional CD mode operation thus changing the gasoline and electricity consumption of PHEVs.

1.2.3. *Most analyses assume one or a small number of PHEV drivetrain designs and vehicle sizes for all consumers*

The type of PHEV consumers purchase (all electric or blended), size of the vehicle and CD range will directly shape PHEV energy use and gasoline displacement. Currently, automakers plan to offer, or are offering, PHEVs with battery sizes from 4 to 16 kW h of capacity and can charge at rates from 1.2 to 6.6 kW. In this respect, consumers' valuation of vehicle characteristics and charging behavior as well as the charging infrastructure they install at home play an important role in shaping PHEV impacts. Furthermore, the possible link between vehicle choice and travel behavior remains unexplored. Prior analysts