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A statistical approach to estimating acceptance of electric vehicles and electrification of personal transportation

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A B S T R A C T

The environmental and economic impact of electric vehicles (EVs) will depend on the fraction of users that can accept an EV of a given capability, and then in turn on how those EVs are actually used. Historically, estimates of the fraction of total travel that could be electrified as a function of EV range are based on vehicle usage data for large populations of vehicles, most often the National Household Travel Survey (NHTS). Two assumptions implicit in such estimates are subject to question: (1) that any user could accept an EV as a primary vehicle and would use it for all trips within its range, and (2) that the usage patterns of any individual EV user are the same as that exhibited by entire population. The first assumption is clearly unrealistic; willingness to accept an EV is dependent on the transportation needs and alternatives readily available to each individual user. As a surrogate for *a priori* knowledge of individual preferences, we use a crude metric of acceptance defined as a threshold frequency of need for alternative transportation above which all users would not accept the inconvenience. To test the validity of the second assumption and better estimate market and electrification potential, we analyze roughly 1 year of usage data for each of 133 instrumented vehicles in Minneapolis–St. Paul. We find a characteristic individual usage pattern that does not resemble the average over a large number of vehicles. Using the surrogate metric of EV acceptance and a simple payback model, we show that although the market acceptance and electrification potential of EVs are severely limited by battery cost, it is possible to determine an optimal EV range. Using the same usage data and payback model, we show that plug-in hybrid electric vehicles (PHEVs) can be much more effective than all-electric vehicles in electrifying personal transportation.

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1. Introduction

Near the dawn of the automobile era, electric vehicles commanded roughly 30% of the nascent market. At that time, some major cities promoted EVs as a means to reduce the urban environmental impact of horse-drawn transportation. Preferred over chemically-fueled vehicles for their dependability, silence, simplicity of operation and ease of 'refueling', there was little to suggest that the EV would virtually disappear only 20 years later. Limited travel range is one major factor contributing to this early demise. Advertisements sought to mitigate concern for range by asking how frequently motorists actually travelled beyond some limited distance from home (Schiffer, 1994). Even then, it was apparent that the choice of vehicle, almost always the first automobile in the household, was heavily influenced by travel needs that occur infrequently, but for which the owner would prefer to use their own vehicle rather than find an alternative mode of transportation (Kirsch, 2000). Today, with the return to the market of electric vehicles the range problem has returned as well. While the impetus has moved from

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equine emissions to greenhouse gas emissions and independence from fossil petroleum, the driving range of the modern electric vehicle is only modestly greater than that of its predecessor a century ago! What has changed is the context of a mature automobile market. Experience enables greatly improved ability to describe how vehicles are actually used, and the large fraction of multi-vehicle households can make choices unsuitable to single-vehicle households. Golob et al. (1996) and Kurani et al. (1992, 1996) strongly indicate that households with multiple vehicles will seek to optimize a combination of vehicle types that best meets their unique set of needs. More recently, Ahn et al. (2008) showed that while an EV is an unlikely choice for a primary vehicle, there are sufficient multivehicle households with sufficient flexibility to create a viable EV market. Given the widely held belief that electric vehicles will achieve a large market penetration and thereby electrify a significant fraction of personal travel, studies of their potential to do so based on real-world customer usage are clearly warranted.

Two factors determine the fuel-saving impact of an electric vehicle: (1) it must be accepted by the prospective customer and (2) it must be used. Absent any knowledge of individual needs, an upper limit to the electrification potential of an EV with a given range can be estimated simply by assuming that all customers in a given region are the same: i.e. (1) that all will accept that EV as their primary vehicle and (2) all will use that EV for all trips within its range with the frequency and distance of those trips being characteristic of the population as a whole. By such an estimate, 100 miles of electric range would electrify roughly 70% of all personal travel in the US (Vyas, 2009). Both assumptions are suspect simply because they do not reflect individual transportation needs and alternatives. [Note that this approach may be applicable to plug-in hybrid electric vehicles, PHEV where limited electric range does not determine whether the vehicle is capable of a given trip (Bradley and Quinn, 2010; Gonder et al., 2007).] The impact of day to day variations in travel distance on the ability to use vehicles of limited range was emphasized by Greene (1985) who did demonstrate the ability to infer individual daily travel distance distributions from vehicle refueling data. In this work, we eplore both these assumptions to make a more realistic estimate of the electrification potential of plug-in electric and hybrid-electric vehicles. As a surrogate for *a priori* knowledge of individual preferences and options, we use a crude metric of acceptance defined as a threshold frequency of need for alternative transportation above which users would not accept the inconvenience. To test the validity of the second assumption and better estimate market and electrification potential, we analyze roughly 1 year of usage data for each of 133 instrumented vehicles in the Minneapolis–St. Paul region (Minnesota, 2006). While Minneapolis–St. Paul is typical of mid-size cities in the US, and annual usage of vehicles usage in this study (11,500 miles/year) is roughly the national average (12,300 miles/year), we do not claim that the details of usage are necessarily representative of other regions. Comparisons based on analysis of similar data from other regions are the subject of ongoing work.

The structure of our analysis is as follows: (1) we first introduce the concept of a trip-chain, defined as the distance traveled between long rests that constitute charging opportunities, and characterize vehicle usage by the frequency distribution of trip chain distances. Every individual trip chain frequency distribution (ITCD) is then fit with a four-parameter distribution representing a combination of recurring 'habitual' trips empirically associated with regular activities such as commuting to school or work, and a broad 'random' distribution associated with non-recurring short errands and longer journeys such as day trips and vacations. (2) Because we cannot know who makes the purchase decision, who owns the vehicle and who is driving it on a given trip, we are forced to conflate these entities as the vehicle 'user' who decides to accept an EV (or not) as a replacement for the conventional vehicle from which the usage data was collected. We then define a metric of individual acceptance of an EV of a given range initially only in terms of the number of days per year that the EV cannot be used in lieu of that conventional vehicle. By varying the acceptance threshold over a wide range from 1 to 24 days/year, we estimate the fraction of Minnesota vehicles that might be replaced with EVs and the fraction of travel that would be electrified by those EVs. (3) Finally, we make the definition of acceptance more realistic by including cost of ownership as a criterion, and explore the impact of incremental battery cost on electrification. This analysis does suggest an optimal battery range that maximizes electrification, as well as a target cost for incremental battery energy that would enable high acceptance of EVs. We also use the simple payback model to compare the electrification potential of battery electric vehicles to that of plug-in hybrid electric vehicles in the same population.

2. Trip chains and vehicle usage data

For the purpose of this study, the relevant measure of travel distance is the trip chain, defined as the total distance traveled between rest periods of a predetermined duration. A chain can consist of multiple trips, or legs, between key-on and key-off events, and each rest period is considered to be a prospective charging opportunity for an EV or PHEV. A single trip chain should not be equated to a single day of travel; it is possible to complete more than one trip chain in a single calendar day, while a single trip chain could span 2 or more days.

The vehicle usage data set most often cited in estimates of the fuel-saving potential of electric vehicles is the National Household Travel Survey which has been conducted since 1983 (NHTS, 2009). The NHTS generates representative national and regional population samples via a list-assisted random digit dialing telephone survey. The ensemble of roughly one-hundred and fifty thousand fully completed surveys, each of which includes a single-day travel diary, comprises the NHTS daily travel data set used in this work. For the purpose of estimating electrification potential, these NHTS 1-day travel diaries can be used to generate a frequency distribution of trip chains as a function of the total distance of each chain. Our definition of a trip chain is not perfectly compatible with travel surveys that record only a 24 h period usually beginning early in the

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