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Cost analysis of plug-in hybrid electric vehicles using GPS-based longitudinal travel data

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HIGHLIGHTS

- A spatial and longitudinal travel dataset was used to study PHEVs′ operating costs.
- Whether PHEVs have lower energy costs than CGVs/HEVs depends on charger coverage.
- Under small charging coverage PHEV40 is more costly than HEV if one′s DVMT is large.
- If the gas price is $3, PHEV10 is the least costly even if the battery cost is $200/kW.
- Impact of fast charging is trivial on energy cost, but significant on charging time.

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ABSTRACT

Using spatial, longitudinal travel data of 415 vehicles over 3–18 months in the Seattle metropolitan area, this paper estimates the operating costs of plug-in hybrid electric vehicles (PHEVs) of various electric ranges (10, 20, 30, and 40 miles) for 3, 5, and 10 years of payback period, considering different charging infrastructure deployment levels and gasoline prices. Some key findings were made. (1) PHEVs could help save around 60% or 40% in energy costs, compared with conventional gasoline vehicles (CGVs) or hybrid electric vehicles (HEVs), respectively. However, for motorists whose daily vehicle miles traveled (DVMT) is significant, HEVs may be even a better choice than PHEV40s, particularly in areas that lack a public charging infrastructure. (2) The incremental battery cost of large-battery PHEVs is difficult to justify based on the incremental savings of PHEVs′ operating costs unless a subsidy is offered for large-battery PHEVs. (3) When the price of gasoline increases from $4/gallon to $5/gallon, the number of drivers who benefit from a larger battery increases significantly. (4) Although quick chargers can reduce charging time, they contribute little to energy cost savings for PHEVs, as opposed to Level-II chargers.

1. Introduction

Electrification of transportation is widely regarded as an effective solution to energy security, climate change, and air quality (Ohnishi, 2008; National Research Council (NRC), 2010, 2013). The EV Everywhere Grand Challenge, announced by President Obama in March 2012, aims "to produce plug-in electric vehicles (PEVs) as affordable and convenient for the American family as gasoline-powered vehicles by 2022" (USDOE, 2013). However, fast growth of the PEV market faces two barriers. One is the high cost of battery packs. For example, according to a US Department of Energy (DOE) report (2013), the battery cost was $500/kWh in 2012. Another barrier is the lack of public charging facilities (Lin, 2012). Though plug-in hybrid electric vehicles (PHEVs) also have issues such as battery safety, durability, bulkiness, etc., they are less dependent on charger availability, compared to battery electric vehicles (BEVs). PHEVs can operate on gasoline when the battery is depleted. An adequate charging infrastructure, however, can increase a PHEV′s share of driving on electricity, thus increasing energy savings and promoting consumer acceptance. This paper aims to study the impacts of battery cost and charging infrastructure coverage on market acceptance of PHEVs.

PHEVs combine an internal combustion engine (ICE) with a battery which can be charged with grid electricity. PHEVs can operate in the charge-depleting (CD) mode, in which little or no fuel is consumed and little or no tailpipe pollutants are emitted.

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After the CD range is exhausted, PHEVs can continue to operate in the charge-sustaining (CS) mode, using the ICE as the major power source, in virtually the same fashion as that of a hybrid electric vehicle (HEV). Having the ability to partially substitute electricity for gasoline, PHEVs can reduce lifecycle greenhouse gas (GHG) emissions compared with conventional vehicles, unless the grid electricity comes from coal (Hawkins and Singh, 2012). A less controversial merit of PHEVs is enhancing the energy security of the nation (Vyas et al., 2009; Lin and Greene, 2011). These benefits come from operating PHEVs in the CD mode. Therefore, it is important to make a full use of the CD mode in PHEVs′ operations. The maximum distance that a fully charged PHEV can operate in the CD mode, known as the CD range, is determined by the effective battery capacity.[1] To take full advantage of a PHEV, motorists would hope to operate the vehicle mostly in the CD mode and return home with an empty battery. A long CD range is usually associated with a large and more expensive battery pack. Depending on their travel needs, different motorists might prefer batteries of different sizes. Lin (2012) estimated the optimal electric range for each individual in a national driver sample by tradeoffs of battery cost and energy cost, forming a national distribution of optimal ranges due to variation of driving patterns.

Clearly, the impacts of the battery capacity and public charging facility coverage are highly correlated. With an extensive coverage of charging facilities that allow frequent charges, small batteries may meet motorists′ needs; on the other hand, if the government subsidy to PEVs increases, customers may prefer buying PEVs with large batteries, and thus reduce the need for investment in public charging facilities. Therefore, it is necessary to incorporate such correlations in the study of the long-term benefits and costs of PHEVs. For example, Peterson and Michalek, 2012 employed the 2009′s National Household Travel Survey (NHTS) data to investigate the cost of adopting PHEVs with different CD ranges, considering increasing battery capacity and infrastructure coverage. Zhang et al. (2011) used the 2009′s NHTS data taken in the South California to study energy consumption of PHEVs with different CD ranges under three charger coverage scenarios. These NHTS data were converted to a typical one-day travel pattern data. The results were compared with that of conventional gasoline vehicles (CGVs) and hybrid electric vehicles (HEVs), showing that a HEV could reduce 45% fuel consumption (in gallons) compared to a CGV and PHEV40 can help reduce additional 70% fuel consumption (in gallons), compared to a HEV. Furthermore, using the same dataset, Zhang et al. (2013) studied the operating costs of PHEVs and BEVs, assuming optimal charging strategies based on a time-of-use (TOU) electricity rate (which varies by season of a year) within a day. However, the NHTS data are aggregate data based on a cross-sectional survey, which cannot reflect the longitudinal variation in travel patterns of motorists. Furthermore, the NHTS data were collected through phone interview. The accuracy of the travel temporal and spatial information is low. Based on one school-day travel data collected in Austin, Texas, in 2005 or 2006, Dong and Lin (2012) studied the fuel savings and total energy cost of PHEVs under several hypothetical coverage levels of public chargers. These data were recorded by global-positioning-system (GPS) devices installed in vehicles. Therefore, they promise a high accuracy of the temporal and spatial information. However, studies in travel demand modeling and analysis have suggested great variations in motorists′ trip-making behavior, including daily variations in the trip frequency, trip length, trip chaining, departure time choice and its connections with demographic variables (Pas and Sundar, 1995; Elango et al., 2007; Lin et al., 2012). Specifically, daily vehicle miles traveled (DVMT) varies from one day to another for a particular motorist and also varies among motorists. Both the day-to-day variation in the DVMT and motorist heterogeneity could significantly impact the energy consumption of PHEVs (Lin and Greene, 2011).

In this paper, we focus on the impacts of two factors – battery capacity and charger coverage – on the energy costs from the perspective of motorists (i.e., we do not consider the cost of building public charger facilities) based longitudinal travel data of multiple motorists. By assuming different scenarios of charger coverage, we want to answer two questions: (1) How much energy cost savings over the long term could PHEVs bring compared with CGVs or HEVs? (2) Is a large-capacity battery worth buying for motorists, considering the trade-off between incremental battery costs and operating cost savings?

2. Data and methods

2.1. Longitudinal travel data

Recently, the Puget Sound Regional Council (2008) conducted a household travel choice study to determine how motorists change their travel behavior in response to tolling that varies by location and time of day. The study area was the Seattle metropolitan area, as shown in Fig. 1. A total of 451 vehicles from 331 households (randomly selected) participated in the study, and their detailed travel behavior over up to 18 months (from October 2004 to April 2006) was recorded through GPS devices installed in their vehicles. Khan and Kockelman (2012) studied potential market acceptance of PHEVs and BEVs based on these households′ DVMT revealed from these data.[2] However, they assumed that all PHEVs were to be charged only at home. On the other hand, their dataset does not have spatial information associated with each trip, so that it would be difficult to consider the public charging opportunities for these trips. To promote the PHEV market, the public charging opportunities should also be considered.

The Seattle dataset used in this paper includes detailed temporal and spatial information of each trip: start time, end time, start location, and end location. After data cleaning, a total of 758,612 trips from 449 vehicles were available. Of those, 415 motorists had active travel data for more than 90 days, and they made 749,828 trips in total. Note that even though the study spanned 18 months, some participants discontinued their participation at some point during this period for a variety of reasons. All 415 motorists′ travel data were used, and it was assumed that each vehicle represents one motorist. Therefore, a motorist′s travel behavior was recorded as the vehicle′s locations during the study period. It is found that most participants′ households were located in suburbs, as shown in Fig. 1. The vehicles participating in the study were all CGVs, so by using the data, we ignore the possible change of driving behavior between PHEVs and CGVs. This is appropriate because the focus is on the upfront battery cost and energy cost. Consideration of behavior change will distract the focus, although it could be an interesting extension of the study.

2.2. Battery schemes

2.2.1. Battery capacities and energy consumption rate

Four types of batteries are considered: PHEV10, PHEV20, PHEV30, and PHEV40, where 10, 20, 30, and 40 refer to the CD

[1] The battery′s capacity is also affected by operational discharge strategies. The total battery capacity is larger than the effective capacity, mainly for protecting the battery life.

[2] The data used in Khan and Kockelman (2012) were processed and provided by the National Renewable Energy Laboratory′s Security Transportation Data Project. The dataset is smaller than the one we used here. For example, it has 269,357 trips from 264 households while our dataset has 758,612 trips from 331 households.