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Evaluation of charging infrastructure requirements and operating costs for plug-in electric vehicles

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HIGHLIGHTS

- PHEVs: all charging infrastructure options show operating cost reduction
- PHEVs: meager operating cost reduction with more non-home charging locations
- Unlike PHEVs, sufficient non-home EVSE must be installed to satisfy BEVs
- BEV60: 88% of drivers need only LEV2 home charging; EVSE everywhere satisfies 96%
- BEVs: optimal distribution is 80%, 9% and 11% EVSE at home, work and other places

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ABSTRACT

Plug-in electric vehicles (PEVs), including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), have the potential to improve the energy and environmental landscape of personal transportation, but face a hurdle of access to charging infrastructure. Additionally, the types, locations, and quantities of electric vehicle supply equipment (EVSE) that will be required are not well established. This study investigates the charging infrastructure requirements from the perspective of PEV operating cost and BEV feasibility. California was selected as the research region and PEV parameters were selected based on the early deployed vehicles available in the emerging commercial market. To minimize operating cost, an optimal charging strategy based on 24 h travel patterns is proposed. Results indicate that charging time strategy is the most important factor in reducing PEV operating cost while greater numbers of charging locations provide diminishing benefits for PHEVs. Higher charging power capability, combined with an acceptable charging time strategy offer only slight benefits for PHEVs, but charging power is an important factor in increasing BEV functionality and decreasing public charging requirements. The approximation of the electric vehicle supply equipment (EVSE) needed at different types of locations (e.g., home, work place, shopping) is proposed based on an optimal charging strategy.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) having onboard electricity and gasoline storage, and battery electric vehicles (BEVs) powered solely by electricity, collectively referred to as plug-in electric vehicles (PEVs) herein, offer substantial environmental and energy improvements over petroleum powered vehicles [1]. The benefits provided by PEVs include reduction in fuel consumption, improvement in well-to-wheel efficiency, and decrease in greenhouse gas and pollutant emissions [2,3]. Due to these attributes, many federal, state, and local governments have advocated for PEV deployment, such as the Clean Car Rule and Governor's Executive Order in California [4,5]; concurrently, major automakers are either manufacturing, or planning, PEV models.

Charging infrastructure will play a pivotal role on PEV deployment, and, in the absence of a proactive plan and schedule, is a major impediment to mass market adoption. Infrastructure limitations are particularly pertinent to BEVs due to their sole dependency on electricity, range limits, and long recharging time. However, little research has emphasized the differences in charging infrastructure requirements between PHEVs and BEVs. The charging infrastructure includes all of the hardware and software that ensures energy is transferred from the electric grid to the vehicle. It can be specified by location, power level, and charging time strategy.

Several studies evaluated the energy, emissions, and economic impacts of PEV adoption [6–13], while other studies [14–19]

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focused on detailed vehicle and grid operation to determine smart and optimal charging time strategies Specifically, a group of studies [6,7,10,11,13] used either nationwide or statewide household travel surveys to investigate PHEV energy consumption, but the infrastructure scenarios were not fully illustrated and the charging time strategies were unsophisticated. Other research [8,9] utilized detailed electricity dispatch models and focused on the overall emission impacts of plug-in vehicles, but advanced charging time strategies were neither implemented nor explicitly explained. Two studies [12,16] include detailed PHEV dynamic models to assess and optimize energy, economic, and environmental impacts, but include neither representative travel behavior nor detailed electricity cost considerations. A few studies [14,15,18] implemented optimal charging strategies and verified performance by minimizing the impact or the cost on the grid. However, these strategies were based on single daily charging events (overnight dwelling) due to the lack of realistic driving pattern data. Two final studies [17,19] conducted optimal charging strategies over a 24 h period to minimize vehicle operating costs with the real time price of electricity, and included real travel pattern data. Neither, however, considered ranges of charging power and charging location options.

As a next step, this paper attempts to systematically and comprehensively address (1) the relationship between charging infrastructure characteristics, PEV operating cost, and BEV feasibility, and (2) the infrastructure characteristics required to support PHEVs or BEVs, especially with regard to EVSE allocation. The goal is to evaluate the impact of realistic charging infrastructure options on real travel behavior in order to delineate PEV operating cost, BEV feasibility, and optimal charging strategy designed to identify the quantity and location of chargers and charger types in a given area. California was used as the focus of this study due to progressive PEV legislation and a relatively avid PEV marketplace (57% of U.S. PEVs were sold in California in 2011 [20]).

1.1. NHTS

The vehicle travel behavior data used in this paper are derived from the 2009 National Household Travel Survey (NHTS) [21]. Several processing steps were required in order to prepare the data for input to the model. In particular, data for California were selected, trips occurring without a personally owned vehicle were deleted, person-chain data were converted to vehicle-chain data, daily trips data with unlinked destinations or significant overspeed were deleted, and tours were organized into home based daily tours (first trip from home, last trip to home). 20,295 vehicles were selected covering 83,005 single trips with an average of 7.85 miles per trip and 32.13 miles per vehicle per day.

1.2. PEV charging rates

All the major investor owned utilities in California have released their specified PEV charging rates, including Pacific Gas & Electric (PE&E) [22], Southern California Edison (SCE) [23] and San Diego Gas & Electric [24]. In these service territories, customers can either combine their PEV charging with other consumption in the household, or independently with the installation of a separate meter. The latter option provides a time-of-use (TOU) rate which varies by season of the year, hour of the day, and by weekday and weekend. Fig. 1 is the E-9B rate schedule for PEV charging published by PG&E in the summer of 2011 [25], where the temporal trends reflect the general behavior of the system wide electricity demand. Similar TOU rates have been developed by the other utilities, but the PG&E rate shown is used in this work because it has three levels: peak, partial peak, and non-peak hour.

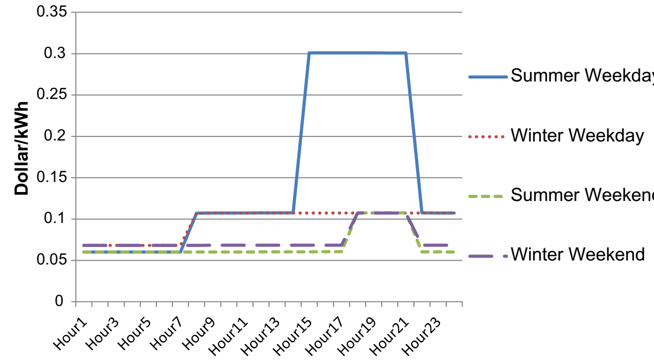

Fig. 1. PG&E residential PEV charging rates.

1.3. Vehicle information

Similar to other research [6,7,10,11,13], this study focuses on the macro scale of vehicle behavior where the detailed physical vehicle model was not considered; instead a parameterized vehicle operating and charging model was used. Table 1 shows vehicle parameters used in this study which were all derived from current production vehicles [26,27]. Gasoline price is assumed to be U.S. $4.00 per gallon throughout this work.

2. Model

2.1. Non-optimal charging

The non-optimal PHEV charging model is based on previous work [6], with the addition of two scenarios: 1) smart charging, and 2) smart charging with fuel price. "Non-smart" charging strategies of immediate charging, delayed charging, and average charging are carried over from the previous study for comparison. For the smart charging and smart charging with fuel price strategies, a cost signal, e.g. Fig. 1, is incorporated into the model such that the driver is able to minimize charging cost during a specific dwelling activity, such as an overnight stay at home. The smart charging with fuel price strategy is designed specifically for PHEVs and compares operating costs for gasoline and electricity such that charging is not undertaken if electricity is more expensive than gasoline during that dwelling period. Charging power scenarios are chosen based on current charger specifications, standards, regulations, and future projections [28,29]. All charging infrastructure options are listed in Table 2.

2.2. Optimal charging

The optimal charging strategy considers an entire day's travel pattern and determines the optimal charging behavior based on a specific charging rate schedule. This differs from the above "non-optimal" methodology because it assumes complete knowledge of an entire day's travel and electricity price. This is not unreasonable in most cases as daily commutes are generally repetitive and electricity rates are currently published in advance.

Table 1
Simulation parameters for all vehicles.

Vehicle type	MPG	Gasoline price ($/gallon)	kW h/mi (DC)	All-electric range (miles)	Efficiency from grid to battery
HEVs	40	4.00	N/A	N/A	N/A
PHEVs	40	4.00	0.34	4–40	0.85
BEVs	N/A	N/A	0.31	45–100	0.85