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Socially optimal electric driving range of plug-in hybrid electric vehicles

Eleftheria Kontou [a], Yafeng Yin [a,*], Zhenhong Lin [b]

[a] Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611, United States
[b] Oak Ridge National Laboratory, Knoxville, TN 37932, United States

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ABSTRACT

This study determines the optimal electric driving range of plug-in hybrid electric vehicles (PHEVs) that minimizes the daily cost borne by the society when using this technology. An optimization framework is developed and applied to datasets representing the US market. Results indicate that the optimal range is 16 miles with an average social cost of $3.19 per day when exclusively charging at home, compared to $3.27 per day of driving a conventional vehicle. The optimal range is found to be sensitive to the cost of battery packs and the price of gasoline. When workplace charging is available, the optimal electric driving range surprisingly increases from 16 to 22 miles, as larger batteries would allow drivers to better take advantage of the charging opportunities to achieve longer electrified travel distances, yielding social cost savings. If workplace charging is available, the optimal density is to deploy a workplace charger for every 3.66 vehicles. Moreover, the diversification of the battery size, i.e., introducing a pair and triple of electric driving ranges to the market, could further decrease the average societal cost per PHEV by 7.45% and 11.5% respectively.

Introduction

Plug-in hybrid electric vehicles (PHEVs) offer promise to reduce the dependency on oil and mitigate traffic emissions. The most attractive characteristic of PHEVs is that they can be deployed immediately in the marketplace without building infrastructure to support their operations (National Research Council, 2010). Moreover, the PHEV market is not constrained by the range-anxiety barrier of battery electric vehicles (e.g. Lin, 2014).

PHEVs in a series configuration typically operate in either of two modes: the charge-depleting mode using electrical power and consuming no gasoline and the charge-sustaining mode consuming only gasoline (blended-mode PHEVs, which consume electricity and gasoline simultaneously, will not be examined in this study). The vehicle starts up operating in the charge-depleting mode, until its battery reaches a threshold state of charge where the electric range is exhausted. Then, it switches to the charge-sustaining mode (Markel et al., 2009). The electric driving range is a critical parameter for designing a PHEV. In the U.S. market, the majority of PHEVs that operate in a series configuration cover an electric driving range of approximately 30–38 miles, depending on driving in an urban or a highway environment (Department of Energy, 2014a). The U.S. Advanced Battery Consortium has proposed two sizes of battery: a 10-mile range and a 40-mile range (Pesaran et al., 2007). The criteria for determining the ranges include (a) battery pack cost, volume, weight, life and efficiency, (b) charge power and cycles, (c) energy for charge-sustaining operations and (d) battery concerns such as operating temperature

* Corresponding author. Tel.: +1 352 3929537.
E-mail address: yafeng@ufl.edu (Y. Yin).

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and voltage (Pesaran et al., 2007). The Energy Policy Act of 1992 and the National Highway Traffic Safety Administration have set the minimum driving range; the final rule effective in 1999 allowed a minimum driving range of 7.5 miles on the EPA urban cycles and 10.2 miles on the EPA highway cycle for dual fueled electric vehicles (Department of Energy, 2014b). It is crucial to define the optimal electric driving range considering the developments of technologies, infrastructure and policies. Non-optimal driving ranges, if adopted, might hinder the success of the PHEV deployment and mislead relevant policy makings, resulting in greater societal costs (Lin, 2014).

This study focuses on determining optimal electric driving ranges of PHEVs in a series configuration to minimize the societal cost, which includes the cost internal and external to the users. More specifically, the former consists of the battery and daily operating costs while the latter is primarily environmental/emissions cost. Moreover, the paper aims at answering the research questions whether the government should deploy workplace chargers to further minimize the social cost, and if so, what is the optimal density of chargers to deploy.

Quite a few studies in the literature have investigated optimal driving ranges of electric vehicles. For example, from the users' perspective, Lin (2012, 2014) minimized the internal costs of battery and vehicle operations to define the optimal electric driving range for PHEVs and battery electric vehicles (BEVs) respectively. Shiau et al. (2010) optimized the PHEV design while allocating PHEVs, hybrid electric vehicles and conventional vehicles to the driving population for minimum petroleum consumption, greenhouse gas (GHG) emissions and life cycle cost. Traut et al. (2011) optimized the design of the previously mentioned mix of vehicles in order to minimize only GHG emissions by investigating workplace charging scenarios as well. Another contribution by Smith et al. (2011) finds the minimum battery capacity for a PHEV that meets the needs of urban commuters and their daily duty cycle. Another stream of studies have investigated the role of charging PHEVs within day on reducing gasoline consumption, e.g., Dong and Lin (2012), Zhang et al. (2011) and Dong and Lin (2014). More recently, Peterson and Michalek (2013) assessed the cost effectiveness of increased battery size and deploying nondomestic charging infrastructure for PHEVs to reduce gasoline consumption.

Compared to previous studies such as Lin (2012, 2014), this paper investigates the optimal electric driving range of PHEVs from a societal perspective, taking into account the environmental impacts of PHEVs, including the external cost of emissions during the manufacturing of batteries and the operations of the vehicles. The paper differs from other relevant studies such as Shiau et al. (2010) and Traut et al. (2011) by, e.g., examining how the deployment of workplace charging infrastructure affects the optimal electric driving range. Our framework allows for direct comparison of the effects of different policies, such as deployment of workplace charging or the diversification of battery sizes on the cost borne by society in order to access their effectiveness, under the scenario of universal adoption of PHEVs.

Our base modeling results confirm previous research findings (e.g., Michalek et al., 2011) where smaller batteries were found to offer larger social benefits per dollar. The diversification case yields results that are in general accordance with the USABC recommendations for PHEVs electric ranges of 10 and 40 miles (Pesaran et al., 2007). However, the recharging case results differ from the existing literature where a small PHEV battery (approximately 7-mile driving range) was suggested to be optimal for minimizing social costs (Shiau et al., 2009).

The remainder of this paper is organized in six sections. Section 'Electric driving range optimization framework' presents a basic modeling framework for optimizing electric driving range of PHEVs. Section 'Data' describes the data used in this study. Section 'Results' presents the results in the context of the U.S. market, followed by a sensitivity analysis in the following section. Section 'Model extensions' further extends the base model to consider the deployment of workplace chargers and the diversification of the battery size. The last section summarizes and concludes the paper.

Electric driving range optimization framework

This section presents a modeling framework to optimize the electric driving range of PHEVs. The framework aims at minimizing the relevant social cost of using the technology, which consists of three distinctive components: the first one is an internal user cost, accounting for the capital cost of battery packs and the energy cost of operating a PHEV; the second is an external environmental cost, incorporating the cost of greenhouse gases (GHG) emissions from the manufacturing process of battery packs and the operation process of the vehicle; and the third component represents the expenditure of installing workplace chargers. Note that we only consider cost items that are dependent on the electric driving range. Although some cost items may be perceived differently by different users (Stephens, 2013), we do not account for such heterogeneity in the paper.

The optimization model is written as follows:

$$\min C(r) = \sum_j (C_{u_j}(r) + C_{e_j}(r)) + C_g \tag{1}$$

$$\text{s.t.} \quad 0 \le r \le r_u \tag{2}$$

where the decision variable r is the electric driving range in miles; $C(r)$ is the daily social cost related to the electric driving range; $C_{u_j}(r)$ is the daily cost internal to user j, $C_{e_j}(r)$ is the daily cost external to user j, i.e., the environmental cost and C_g is the expenditure associated with the installation of workplace chargers. Constraint (2) dictates the lower and upper bound of the electric driving range, which is 0 and r_u respectively.