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# Optimization of incentive polices for plug-in electric vehicles

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ABSTRACT

High purchase prices and the lack of supporting infrastructure are major hurdles to the adoption of plug-in electric vehicles (PEVs). It is widely recognized that the government could help break these barriers through incentive policies, such as offering rebates to PEV buyers or funding charging stations. The objective of this paper is to propose a modeling framework that can optimize the design of such incentive policies. The proposed model characterizes the impact of the incentives on the dynamic evolution of PEV market penetration over a discrete set of time intervals, by integrating a simplified consumer vehicle choice model and a macroscopic travel and charging model. The optimization problem is formulated as a nonlinear and non-convex mathematical program and solved by a specialized steepest descent direction algorithm. We show that, under mild regularity conditions, the KKT conditions of the proposed model are necessary for local optimum. Results of numerical experiments indicate that the proposed algorithm is able to obtain satisfactory local optimal policies quickly. These optimal policies consistently outperform the alternative policies that mimic the state-of-the-practice by a large margin, in terms of both the total savings in social costs and the market share of PEVs. Importantly, the optimal policy always sets the investment priority on building charging stations. In contrast, providing purchase rebates, which is widely used in current practice, is found to be less effective.

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## 1. Introduction

The growing concerns about energy security and global climate change have stimulated the transition to alternative fuel vehicles (AFV), widely considered an important ingredient in sustainable transportation (NRS, 2010). Of the many competing technologies, plug-in electric vehicles (PEV) have received much attention thanks to their high energy efficiency (Eberhard and Tarpenning, 2006), the ability to substitute electricity for petroleum and the potential to reduce carbon footprint (Crist, 2012). However, the adoption of PEVs is hurdled by several barriers: high retail prices, the limited range of batteries, and the lack of supporting infrastructure, especially charging stations (Hidrue et al., 2011). In the US, policy makers have created various incentive programs aiming to overcome these barriers. The American Recovery and Reinvestment Act of 2009 (ARRA) signed into law a provision that will offer up to $7500 of tax credit for each new PEV purchase starting from 2010. The state governments in the US have also implemented various policies to encourage the ownership of PEVs and installation of

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charging stations. In Illinois, for example, Electric Vehicle Initiatives provide a rebate up to $49,000 toward the installation of Level II charging stations and a rebate up to $4000 for the purchase of a new alternative fuel vehicle.[1] It is clear that the public investment on these incentive programs is a scarce resource that should be carefully allocated to maximize its impact. The objective of this paper is to propose an optimization model that supports these macroscopic decisions about resource allocation. When fully implemented, the proposed model may help the policy makers decide when and how much money should be invested on what incentive programs in order to achieve a desired goal, e.g. reduced greenhouse gas emissions or reduced dependence on petroleum.

Understanding how incentive programs might affect the adoption of PEVs calls for a behavioral model that can predict consumers' vehicle choice. There is a vast literature devoted to building such models with various discrete and discrete-continuous choice modeling approaches, see Bhat et al. (2009) for a review. Vehicle choice may be characterized using the number of vehicles owned by the household (Bhat and Pulugurta, 1998; Dargay and Vythoulkas, 1999; Golob and Burns, 1978), type of each vehicle owned (body type, fuel type, vintage and powertrain technology) (Ahn et al., 2008; Brownstone et al., 2000; Bunch et al., 1993; Dagsvik et al., 2002; Hensher and Greene, 2001; Lave and Train, 1979; Mabit et al., 2015; Mannering and Mahmassani, 1985; Mannering et al., 2002; Mohammadian and Miller, 2003; Yavuz et al., 2015), and the number of miles driven by each vehicle (Ahn et al., 2008; Bhat and Sen, 2006; Bhat et al., 2009; Fang, 2008; Train and Lohrer, 1982). Previous studies (Bhat et al., 2009; Lave and Train, 1979; Mohammadian and Miller, 2003) have also identified many factors that influence the choice of conventional vehicles, ranging from demographic characteristics (such as income, household size, number of children), vehicle attributes (price, operating cost, fuel efficiency), fuel price, driver personality and built environment characteristics. For alternative fuel vehicles, empirical evidence (Bunch et al., 1993; Dagsvik et al., 2002) identified the purchase price and the range between refueling as important attributes, in addition to those associated with conventional vehicles. A number of recent studies attempt to predict the evolution of market penetration of AFV by simulation. Many of these studies simulate the vehicle choice behavior of agents using classical multinomial logit (Shafiei et al., 2012) or nested logit model (Lin and Greene, 2010; NRC, 2013). A different decision process is proposed in Eppstein et al. (2011) to account for spatial and social effects, as well as media influences. Simulation studies are often employed to evaluate the impact of energy policy (Lin and Greene, 2010), fuel prices (Eppstein et al., 2011; Shafiei et al., 2012), and availability of infrastructure (Lin and Greene, 2011; Lin et al., 2014) on the future market share. While they are useful for the evaluation purpose, the simulation studies are not designed for optimizing interventions. The vehicle choice model employed in this paper is developed along the line of those used in the simulation studies by Lin and Greene (2010) and NRC (2013), with a few additional simplifying assumptions.

Numerous recent studies have examined the planning of charging infrastructure for PEVs (see e.g. Dashora et al., 2010; Frade et al., 2011; Chen et al., 2013; Sathaye and Kelley, 2013; Nie and Ghamami, 2013; He et al., 2013; Mak et al., 2013; Ghamami et al., 2014; Lim and Rong, 2014; Bhatti et al., 2015; Gnann and Plotz, 2015). These studies consider the optimal configuration of charging stations (e.g., location, charging power) either within city (intracity) or between cities (intercity), but typically assume the demand for such facilities as given. In other words, the interactions between planning decisions for charging stations and the long-term adoption of PEVs are not modeled. Another line of recent work in this field is concerned with more detailed routing and recharging decisions of potential PEV users (see e.g., Adler et al., 2014; De Weerdt et al., 2013; Fontana, 2013; He et al., 2014; Chen and Nie, 2015). Such problems address the range anxiety issue by balancing the need for minimizing travel cost and fulfilling relay requirements. Because the focus of this paper is on "sketchy decisions" at a highly aggregated level, we postulate that the outcomes are relatively insensitive to specific details of infrastructure planning and/or individual travel behaviors.[2] Consequently, the representation of charging infrastructure and travel behaviors is simplified in this study in order to highlight the tradeoff in the bigger picture. Specifically, the densities of public charging stations within and beyond a city limit are employed as the main surrogate for charging availability, which determines the probability of finding charging facilities.

The rest of this paper is organized as follows. The next section presents the problem and main assumptions. Section 3 first describes the travel and vehicle choice models, and then introduces the main optimization model that is formulated as a nonlinear program. Section 4 proposes a solution algorithm and Section 5 reports the results of numerical experiments. Conclusions and directions for future research are given in Section 6.

## 2. Problem statement and main assumptions

We consider the PEV adoption over a fixed analysis period. Each year, a certain number of consumers need to purchase a new vehicle from a discrete set of vehicles, of which a subset is PEVs. The choice of vehicles is affected by, among other things, the purchase price and charging availability, which affects the operating cost of PEVs. The government offers two incentives over the entire analysis period: purchase rebates and publicly funded charging stations, with the objective of promoting PEVs and/or minimizing social cost of travel (potentially including the environmental impacts). The question

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[1] https://www2.illinois.gov/gov/green/Pages/ElectricVehicleInitiatives.aspx.

[2] This is not to dispute the value of detailed planning of charging infrastructure. Rather, the point is that a sketchy model can help the decision makers better understand the fundamental tradeoff and hence come up with simple guiding principles. The detailed design can always be performed on the basis of the blueprints obtained from the sketchy model.

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