OPTIMAL DEPLOYMENT OF PUBLIC CHARGING STATIONS FOR PLUG-IN HYBRID ELECTRIC VEHICLES

Fang He[a], Di Wu[a], Yafeng Yin[a, 1] and Yongpei Guan[b]

[a] *Department of Civil and Coastal Engineering, University of Florida,*
365 Weil Hall, Gainesville, FL 32611-6580

[b] *Department of Industrial and Systems Engineering, University of Florida,*
303 Weil Hall, Gainesville, FL 32611-6595

Extended Abstract

Electric vehicles have been long recognized as a promising way to reduce traffic emissions locally and petroleum dependence. Early models of electric vehicles all came with limitations and costs that prevented them from competing with gas-fueled cars. However, recent advances in battery technologies and expeditiously rising prices of crude oil have helped re-launch electric vehicles. Among the emerging models, plug-in hybrid electric vehicles (PHEVs) enjoy special attention, thanks to the cost savings, flexibility and extended driving range they offer to the customers (e.g., Kalhammer et al., 2009; Markel, 2010). PHEVs are vehicles with a battery storage system of 4kWh or more, a means of recharging the battery from an external source and the ability to drive at least 10 miles in all-electric mode (IEEE, 2007). The powertrain of a PHEV consists of an electric motor, an internal combustion engine and a plug to connect to the power grid. In a range-extended deign, a PHEV operates in an all-electric mode and draws propulsion energy entirely from the battery until it reaches the target state of charge. The vehicle then switches to a charge-sustaining mode and the gasoline engine provides energy to propel the vehicle and maintains battery charge near the target state of charge (e.g., Bradley and Frank, 2009). Loosely speaking, if the battery's charge is sufficient, the vehicle operates as an all-electric vehicle like Nissan Leaf, while in a charge-sustaining mode it is effectively a hybrid electric vehicle like Toyota Prius. Compared to the latter, PHEVs offer more fuel savings due to their much larger battery, which can be recharged at home from typical 110V or 220V outlets. PHEVs provide extended driving range and eliminate the "range anxiety" that kept customers away from all-electric vehicles (Markel, 2010). Recognizing the potentials of PHEVs, many governments have plans to promote the deployment of PHEVs. For example, the Obama Administration in the U.S. has proposed to put a total of one million PHEVs on road by 2015 (Obama, 2008).

[1]Corresponding author. Tel: 352-392-9537 Ext. 1455; Email: yafeng@ce.ufl.edu

Although currently most PHEVs in the U.S. are conversions of conventional hybrid electric vehicles, major vehicle manufactures, including Toyota, General Motors and Ford, have their PHEVs available in the market starting 2011 (Rotering and Ilic, 2011). A fast-growing adoption of PHEVs can be expected.

With the existing charging technologies, PHEVs are generally plugged into 110V or 220V outlets for a few hours to fully recharge their batteries. Although these charging activities mostly take place at home and work places (e.g., Davies and Kurani, 2010), providing public charging infrastructures is critical for the growth of the PHEV market (Morrow et al., 2008). Many governments are planning to deploy public charging stations in their regions. For example, California announced to build 200 public fast-charging stations and wire for 10,000 plug-in units at 1,000 locations across the state. British Columbia, Canada, has a plan of building 570 charging stations across the province (GLOBLE-Net, 2012). Important decisions in deploying those charging stations will include, among others, allocating a number of charging stations to metropolitan areas, and determining locations of the allocated charging stations and their corresponding capacities.

A few studies have investigated locating public charging stations in metropolitan areas. Frade et al. (2010) formulated a maximum covering model to locate a certain number of charging stations to maximize the demand covered within a given distance. Ip et al. (2010) first applied a hierarchical clustering analysis to identify the demand clusters of PHEVs and then formulated simple assignment models to locate charging stations to those demand clusters. Pan et al. (2010) developed a two-stage stochastic program to optimally locate PHEV battery swapping stations prior to the realization of battery demands, loads and generation capacity of renewable power sources. Finally, Sweda and Klabjan (2011) developed an agent-based decision support system for electric vehicle charging infrastructure deployment.

The above studies ignore the interactions between transportation and power systems, which are coupled by PHEVs (e.g., Galus and Andersson, 2008; Kezunovic et al., 2010). Generally speaking, the policies and measures implemented in the transportation system will change the spatial and temporal distribution of PHEVs and thus the pattern of their energy requirement, thereby affecting the operations of the power system. On the other hand, the provision of the charging infrastructure and the associated charging strategies and expenses will affect the travel patterns of PHEVs and consequently the operations of the transportation system. Using Pennsylvania-New Jersey-Maryland Interconnection as a case study, Wang et al. (2010) demonstrated that, under existing charging infrastructures, even a small magnitude of load increase caused by PHEV charging activities can have a significant undesirable impact on the electricity price. The impact could be mitigated to a varying extent by advanced controls based on future charging infrastructures. Wehinger et al. (2010) pointed out that the timing of PHEV charging has a major impact on market prices of electricity. If PHEVs are mainly charged during off-peak hours, the daily load curve would be flattened and the volatility of hourly price of electricity can be reduced. These studies in the power engineering field have demonstrated the influence of PHEV charging loads on the spatial and temporal difference of market prices of electricity. More recently, Sioshansi (2012) examined the impacts of electricity price on PHEV drivers' charging decisions, and compared the costs and emissions under different price structures and the ideal case of charging controlled by the system operator.

For the deployment planning of public charging infrastructure, it is thus of importance to consider the interplay between transportation and power systems, which is expected to be multifaceted and thus difficult to model. We envision a hierarchical modeling structure where a strategic planning model captures the interactions between regional transportation network and transmission power grid to determine the optimal allocation plan of charging stations while a tactic planning model focuses on the interconnectivity between urban transportation network and power distribution network to optimize the locations and capacities of charging stations in a metropolitan area. This paper reports our effort to construct a strategic planning model. More specifically, we adopt a static game theoretical approach to investigate the interactions among availability of public charging stations, destination choices of PHEVs, and prices of electricity. The interactions lead to an equilibrium in the coupled transportation and power networks where prices of electricity, and traffic and power flow distributions can be determined. We formulate the equilibrium conditions into a convex mathematical program. We then examine how to allocate public charging stations to maximize the social welfare associated with the coupled networks.

The paper will consist of five sections. Following the introduction in Section 1, Section 2 describes the transportation and power networks and examines the equilibrium state in the coupled networks. A mathematical program is developed to estimate the equilibrium prices of electricity and flow distributions on both networks. Incorporating the equilibrium conditions as constraints, Section 3 formulates finding an optimal allocation of public charging stations as a mathematical program with complementarity constraints, and then proposes its solution algorithm. Section 4 presents a numerical example to demonstrate the allocation model. Lastly, Section 5 concludes the paper.