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Infrastructure planning for fast charging stations in a competitive market

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ABSTRACT

Most existing studies on EV charging infrastructure planning take a central planner's perspective, by assuming that investment decision on charging facilities can be controlled by a single decision entity. In this paper, we establish modeling and computational methods to support business-driven EV charging infrastructure investment planning problem, where the infrastructure system is shaped by collective actions of multiple decision entities who do not necessarily coordinate with each other. A network-based multi-agent optimization modeling framework is developed to simultaneously capture the selfish behaviors of individual investors and travelers and their interactions over a network structure. To overcome computational difficulty imposed by non-convexity of the problem, we rely on recent theoretical development on variational convergence of bivariate functions to design a solution algorithm with analysis on its convergence properties. Numerical experiments are implemented to study the performance of proposed method and draw practical insights.

1. Introduction

The emergence of electric vehicles (EVs) has brought great opportunities to both transportation and energy sectors. For the transportation sector, EVs are considered as a promising alternative vehicle technology for GHG emission reduction. For the power sector, EVs provide potential in accommodating high levels of intermittent renewable generation via vehicle-to-grid (V2G) technologies. However, several obstacles impede immediate large EV adoption, one of which is scarcity of charging infrastructure and long charging duration. This paper focuses on the development of modeling and computing methods that can be used to support business-driven fast charging facility deployment strategy.

The topic of EV charging has attracted attention from both transportation and power sectors. Different charging types (i.e., home, workplace, or public charging) have called for different research emphases. For home and workplace charging, since charging locations are fixed and allowable charging duration is long, most existing studies focus on the control of electricity resource allocation on charging. For example, Huang and Zhou (2015) developed an optimization framework for workplace charging strategies considering different charging technologies and employees' demographic distributions; Lopes et al. (2009) studied smart charging strategies to enhance grid performance and maximize renewable energy resource integration. There are also studies assessing the impacts of EV charging on existing power grid operation (Putrus et al., 2009), emissions (Jansen et al., 2010), and both (Sohnen et al., in press). For public charging, since the infrastructure is yet to be developed,

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most studies focus on identifying the best facility deployment strategies. There are two main schools of thought: from either transportation/location science or power system viewpoint. For example, with a focus on power side, Sadeghi-Barzani et al. (2014) considered the impact of EV charging on grid reliability and proposed a method to minimize the facility development cost as well as charging cost. EV charging infrastructure planning studies in the transportation literature focus more on capturing the interaction between charging and travel (destination and route choice) behaviors. These studies can be further categorized into node-based (Hakimi, 1964) and flow-based (Hodgson, 1990) approaches. Node-based approaches, with a strong root in classic facility location models (e.g. *p*-median, center, and max-coverage), consider charging demands (typically assumed exogenous) happening at given nodes (Goodchild and Noronha, 1987; Frade et al., 2011). Dong and Lin (2012) and Dong et al. (2014) combined node-based infrastructure deployment approaches with activity-based travel demand modeling to identify charging location, quantity, and duration based on real travel activities. He et al. (2013) developed an integrated model to capture the interaction between power grid and traffic network. In contrast, flow-based infrastructure deployment approaches, such as Flow Intercepting Location Model (FILM) (Hodgson, 1990; Berman et al., 1992), allocate charging resources to support travelers' preferred routes (such as shortest paths). Different objectives, such as budget-constrained maximum flow coverage (Kuby and Lim, 2005; Kuby et al., 2009) and set-covering minimum cost problem (Wang and Lin, 2013), have been investigated. Building upon (Berman et al., 1995), deviated paths were considered in (Kim and Kuby, 2012; Li and Huang, 2014). All of the above studies take a central planner's point of view.

Our vision is that as EV demand grows, more investors from the private sector are likely to enter EV charging business. In this context, the future charging infrastructure system will be shaped by collective investment actions of many individual decision entities, who are selfish and competitive by nature. How would such business-driven investment decisions influence the layout of future public charging infrastructure? A good understanding of this question is critical to support effective energy planning at a system level. However, as listed above, most existing studies on EV charging take a central planner's perspective, assuming that investment decision can be fully controlled by a single decision entity. Business-driven investment behaviors of EV charging facilities have been recognized in Schroeder and Traber (2012), but models capturing selfish and competitive investment behaviors are lacking. To our knowledge, only two studies (Bernardo et al., 2015; Yu et al., 2015) have addressed the market side of charging station allocation. Bernardo et al. (2015) studied fast charging stations planning with free entry. Discrete-choice structural models were developed for the travelers as well as the investors' decision processes. Yu et al. (2015) considered the market dynamics of electric vehicle diffusion using a sequential game model. However, both studies ignored the network effect of the underlying transportation and charging infrastructure, which is a critical component that directly influences travel and charging behaviors. For example, Bernardo et al. (2015) is built based on a simple transportation model where origins and destinations are directly connected with known link costs. This treatment simplifies the problem, but is inadequate to capture the congestion effect of the underlying traffic network.

In the broader community of location science, there is a rich body of literature on competitive location problems (Smith et al., 2009; Kress and Pesch, 2012; Hakimi, 1983). However, consideration of congestion is typically at the facility level. For example, (Brandeau and Chiu, 1994; Drezner and Weolowsky, 1996; Lee and Cohen, 1985) characterized the equilibrium in disaggregate facility choice systems subject to congestion-elastic demand at each facility. Congestion on the transportation network, which is important for our study because it directly influences drivers' accessibility to potential charging facilities, has not attracted much attention. Yang and Wong (2000) proposed a mathematical model for assessing market share among given facilities, considering network congestion and elastic demand of the customers. Even though that paper does not address facility location decision, it sheds light on integrating network analysis with facility location problems.

The goal of this paper is to establish a mathematical model to support EV charging facility planning in a competitive market environment. To this end, several modeling challenges need to be addressed. First of all, the system involves multiple decision entities with different objectives: investors make infrastructure deployment decisions to maximize their individual profits, while travelers decide where and how to fulfill their travel and charging needs to maximize their own utilities. These decisions are interconnected and must be modeled simultaneously as a whole. Secondly, the physical infrastructure of charging facilities, power grid and urban traffic network are interdependent in terms of physical, spatial, and functional relations, which naturally brings a complex network structure into the problem. To address these modeling challenges, we develop a network-based multi-agent optimization model, which reflects the selfish nature of each decision entity while simultaneously capture the interactions among all over a complex network structure. To overcome the computational difficulty imposed by non-convexity of the problem, we exploit recent theoretical development on variational convergence of bivariate functions to design a solution algorithm with analysis on its convergence properties. To our knowledge, this study is the first in the EV charging literature that provides a theoretical foundation, from both modeling and computing perspectives, for analyzing business-driven EV charging infrastructure investment planning while considering the traveler-infrastructure interactions in a transportation network.

The remainder of this paper is organized as follows. In Section 2, we present the general modeling framework with specific problem formulation for each decision entity involved in the fast charging infrastructure system. In Section 3, we demonstrate how the original multi-agent problem may be reformulated to a problem of finding a maxinf-point of certain bifurcation, followed by convergence analysis and algorithm design. In Section 4, we present numerical results of a widely used benchmark case study in the transportation literature and draw planning and policy implications. The last section concludes the paper with insights, discussions, and future extensions.