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Optimization models for placement of an energy-aware electric vehicle charging infrastructure

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ABSTRACT

This paper addresses the problem of optimally placing charging stations in urban areas. Two optimization criteria are used: maximizing the number of reachable households and minimizing overall e-transportation energy cost. The decision making models used for both cases are mixed integer programming with linear and nonlinear energy-aware constraints. A multi-objective optimization model that handles both criteria (number of reachable households and transportation energy) simultaneously is also presented. A number of simulation results are provided for two different cities in order to illustrate the proposed methods. Among other insights, these results show that the multi-objective optimization provides improved placement results.

1. Introduction

In order to achieve emission reduction targets and reduce dependency on (foreign) oil and fossil fuels in general, electric vehicles have drawn more and more attentions from governments and the general public. Developing electric vehicles and creating an electrified transportation system is an effective way to promote urban sustainable development as pointed out by Eberle and von Helmolt (2010), Bouscayrol et al. (2011), Khaligh and Krishnamurthy (2012) and Bilgin et al. (2015). Therefore policies to facilitate the growth and market penetration of electric vehicles (EVs) have been developed in almost every nation of the industrialized world. While over the last decade several car producers made EV models commercially available in the US, the market share trajectory of EVs in the US has been below predicted levels.

The acceptance of EVs by the public depends on a large variety of factors. An efficient, convenient and economic charging infrastructure system can enhance the willingness of consumers to purchase and promote industry development (Hatton et al., 2009; Guo and Zhao, 2015). The availability and convenient locations of charging stations in metropolitan environments is a key factor that globally affects not only the adoption process of EVs but also the sustainability of transportation. The energy-efficiency criterion is one of the principle considerations for enhancing sustainability (Kates et al., 2005). Therefore, it is necessary to employ proper methods to determine the optimal energy-aware charging station locations. Aiming to construct an energy-efficient charging infrastructure system for sustainable urban transportation systems, multiple objective energy-aware decision-making models are introduced in this paper. Two different criteria are proposed in the optimization models, which consider several energy-aware constraints.

First, we address the problem of optimal charging station placement from the viewpoint of reaching the most customers or households by providing an energy cost constraint, i.e. something a private charging station owner would typically

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consider. On the other hand, this problem is also of interest for municipalities, power companies, and federal agencies such as the Environmental Protection Agency (EPA) and the Department of Transportation (DOT). Given an energy bound, the corresponding reachable contours in Google Maps for different possible charging station centers are determined by using the energy model in Yi and Bauer (2014a). Maximizing the number of households, i.e. EV users, in this range is discussed subsequently.

Second, another criterion, namely minimizing overall transportation energy consumption to perform charging actions, is addressed. This is an important aspect to construct future sustainable transportation systems, which is of utmost interest for agencies such as EPA and DOT. Suppose all EVs charge once a day at the charging station away from home. Each EV has a corresponding energy consumption when it travels to a public charging station from home. The objective is to find a subset of locations from potential positions to achieve minimum overall transportation energy cost considering all charging actions. This objective is crucial for establishing future sustainable cities. Some other constraints, e.g. service capability of charging station, etc. also are included in the optimization model.

Third, we combine both criteria to get a more realistic decision making framework. The corresponding multiple objective optimization model will be proposed to obtain more balanced planning strategies under energy cost constraints. This multi-objective model will balance both introduced energy related requirements.

This paper is organized as follows. Section 2 provides a literature review, the main contributions of this paper, and a brief description of how this paper addresses open research problem in relative to other studies. In Section 3, the energy-aware charging station placement framework will be formulated. The optimization model for the maximum number of reachable households will be introduced in Section 4. In Section 5, the charging station placement problem considering minimum overall transportation energy cost will be proposed and discussed. In Section 6, the multiple objective optimization model will be constructed by considering both of the introduced requirements simultaneously. Conclusions are provided in Section 7.

2. Literature review

The problem of charging infrastructure placement has been investigated by many researchers. The most powerful and popular techniques are decision-making methods such as linear/nonlinear programming, multilayer programming and mixed-integer programming. Many very different criteria and constraints have been applied in these models.

A maximal coverage model to optimize the demand covered within an acceptable level of service has been investigated in Frade et al. (2011). The work in Worley et al. (2012) formulates the problem of locating charging stations as a discrete integer programming optimization problem based on the classic vehicle routing problem. In Liu (2012), an assignment model for different charging infrastructure assignment strategies was proposed by estimating the charging demand of the early electric vehicle market in Beijing. In Xi et al. (2013) an optimization model was developed to maximize total fleet-wide charging levels for the location of a public EV charging infrastructure. In Lam et al. (2013) and Lam et al. (2014), the electric vehicle charging station placement problem was formulated to minimize the total construction cost subject to the constraints for the charging station coverage and the driver convenience for EV charging. Environmental factors and service radius are considered in Liu et al. (2013) to determine the optimal charging station locations. In Wang et al. (2013b), an optimal location model of charging stations is established based on electricity consumption along city roads. A mixed-integer programming model was developed in Chen et al. (2013) to determine optimal location assignments of charging stations in Seattle, which minimized the station access cost of EV users and took the parking demand, local job, population density and trip attributes as constrains. In Pashajavid and Golkar (2013) the charging stations were allocated by minimizing energy loss and voltage deviation in the distribution system. In Wang et al. (2013a), the optimal location and size of charging stations were determined by maximizing the EV traffic flow under the constraint of battery capacity. The work in Xu et al. (2013) proposed a mathematical model with minimum total transportation distance to determine the optimal charging station locations. The work in Ghamami et al. (2014) formulated this problem as a fixed charge facility location model with charging capacity constraints, allowing unserved demands and considering driver preference for parking lots. A mixed-integer nonlinear optimization approach was proposed for determining the optimal place and size of fast charging stations in Sadeghi-Barzani et al. (2014), which took the station development cost, EV energy loss, electric loss and the location of electric substations as well as urban roads as constraints. In Yao et al. (2014), an equilibrium-based traffic assignment model was proposed to maximize the annual traffic flow captured by fast charging stations. The work in Cavadas et al. (2014) tried to plan the location of charging stations for EVs in a city by maximizing the number of vehicles served under a fixed budget for building charging stations. In Khalkhali et al. (2015), the optimal location of plug-in hybrid electric vehicle charging stations were determined by maximizing the benefit of the distribution system manager.

Several data-based methods for analyses of driving activities and travel behaviors were employed in order to improve the placement strategies. In the work of Sweda and Klabjan (2011) and Sweda and Klabjan (2015), a decision support system was presented for identifying patterns in residential EV ownership and driving activities to enable strategic deployment of a new charging infrastructure. A similar decision support system was also developed in Wagner et al. (2013), Wagner et al. (2014) and Cai et al. (2014). It was achieved by analyzing large-scale trajectory data to obtain travel patterns. The work in Andrews et al. (2013) proposed an optimization model based on a user charging model to find locations for charging stations by analyzing the needs of vehicle owners. In Dong et al. (2014), an activity-based assessment method was proposed to evaluate electric vehicle feasibility for the heterogeneous traveling population in the context of real world driving, and then