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Locating multiple types of charging facilities for battery electric vehicles

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ABSTRACT

To reduce greenhouse gas emissions in transportation sector, battery electric vehicle (BEV) is a better choice towards the ultimate goal of zero-emission. However, the shortened range, extended recharging time and insufficient charging facilities hinder the wide adoption of BEV. Recently, a wireless power transfer technology, which can provide dynamic recharging when vehicles are moving on roadway, has the potential to solve these problems. The dynamic recharging facilities, if widely applied on road network, can allow travelers to drive in unlimited range without stopping to recharge. This paper aims to study the complex charging facilities location problem, assuming the wireless charging is technologically mature and a new type of wireless recharging BEV is available to be selected by consumers in the future other than the traditional BEV requiring fixed and static charging stations. The objective is to assist the government planners on optimally locating multiple types of BEV recharging facilities to satisfy the need of different BEV types within a given budget to minimize the public social cost. Road users' ownership choice among multiple types BEV and BEV drivers' routing choice behavior are both explicitly considered. A tri-level programming is then developed to model the presented problem. The formulated model is first treated as a black-box optimization, and then solved by an efficient surface response approximation model based solution algorithm.

1. Introduction

The global climate change due to air pollution stimulates the revolution of the transportation sector. A transition from fossil fuel to cleaner and more energy efficient alternative fuel vehicles is a vital step in reducing the road transportation greenhouse gas emission. Among all the available technologies, electricity has received much attention to substitute the fossil fuel due to its high energy efficiency, as well as the existing widespread electricity grid. The adoption of electric vehicle (EV) grows very fast ever since the introduction of models by global manufacturers, including all-electric or Battery Electric Vehicle (BEV), Plug-in Hybrid Electric Vehicle (PHEV) and other low-emitting electric vehicles. Although the latter two types of EVs have lower emissions as compared to the conventional internal combustion engine vehicle (ICEV), the BEV is a better choice towards the goal of zero-emission to protect the environment. However, the BEV is currently facing several barriers, which include the high purchasing price, extended recharging time and reduced driving range compared to ICEV or even PHEV, as well as lacking of charging facilities.

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The most common charging method for BEV is static conductive charging via a cable and a vehicle connector when a BEV is parking. Those chargers can be divided into different classifications according to the power rate used and nationally available power level (Haghbin et al., 2010). Yilmaz and Krein (2013) defined three levels with power rate ranging from 1.4 kW to 100 kW and the recharging time ranging from more than ten hours to less than half an hour. Apparently, even the expensive level 3 charger, also referred to as fast charging, can hardly compete with the conventional ICEV that could usually be refilled in several minutes. Another type of charging method is battery swapping, which can replace the depleted battery with a fully charged one in less than five minutes. Battery swapping requires huge space for heavy swapping machines, swapping chargers and a few extra EV batteries (Adler and Mirchandani, 2014). More importantly, it requires battery of EV to be easily swapped, which means it should be removable and standardized. However, since the core technologies of BEV lie in its battery packs, it seems very unrealistic for EV companies to do so. In addition to the extended recharging time, the limited range also restricts the public from purchasing BEV. Reports show that the expectations of consumers on alternative fuel vehicle range is at least 300 miles (Deloitte, 2011), while the current BEV battery capacities can generally provide about 100 miles, which cannot satisfy the needs of general consumers (Fuller, 2016).

The existing limitations lead to the studies of other possible charging technologies for BEV, wherein one option is inductive charging or wireless charging. BEVs adopting this technology do not need a cable for recharging and thus are viable for not only static charging (i.e., charging when parking) but also dynamic charging (i.e., charging when moving). Dynamic wireless charging extends driving range and reduces BEVs' charging time. If the dynamic charging system is widely applied on network, the potential of unlimited driving range may be achieved; other than this, the risk of electric shock will be completely removed (Chawla and Tosunoglu, 2012). Besides, the battery packs capacity may be reduced because the EV can directly get energy from roadway (Wu et al., 2011), and also the speed of EV can be increased due to reduced weight of heavy battery packs. What's more, dynamic wireless recharging do not require extra urban space, which is extremely desirable for cities with limited land resources, such as Singapore and Hong Kong (Riemann et al., 2015). Because of the advantages of wireless charging, it has attracted much attention from researchers recently but mainly on technical aspects (Budhia et al., 2013; Chen et al., 2015a; Chen et al., 2015b; Onar et al., 2013; Pelletier et al., 2014; Wu et al., 2011; Yilmaz and Krein, 2013).

Only a few existing research works deal with the operational problems related to the practical implementation of wireless charging facilities. Based on the introduction of a wireless charging electric transportation system that was developed at Korea Advanced Institute of Technology (KAIST), a series of researches (Jang et al., 2015; Jang et al., 2012; Jang et al., 2016; Ko and Jang, 2013; Ko et al., 2012; Ko et al., 2015) described the system design and system architecture issues, developed mathematical models to optimize key design parameters in the system, including allocating the power transmitters and evaluating the battery size; and also discussed on the recent advances, commercialization process and further development of wireless charging EV under the background of ITS. What's more, the benefit in the perspective of energy logistics was analyzed qualitatively and economic design optimization models were also developed separately for wireless charging electric transit bus system in closed and open systems. Assuming that high-power, high-efficiency wireless power transfer technologies are mature in the near future, He et al. (2013b) presented mathematical models to determine the optimal prices of electricity and roads to pursue the maximum social welfare. Riemann et al. (2015) investigated optimal locations of a given number of wireless power transfer facilities, aiming to capture the maximum traffic flow on network while considering the road users' routing behavior. Chen et al. (2016) formulated a deployment model with consideration of user equilibrium condition to optimize the locations of wireless charging lanes for a given budget. Fuller (2016) presented a flow-based set covering problem to determine how much dynamic charging facilities are needed in California.

As was in He et al. (2013b), we envision that the wireless recharging technology would be mature in the near future and a new type of wireless recharging BEV is available to be selected by customers. In this situation, when the government authorities plan for locations of the charging facilities for BEV, they should consider deploying different types of charging facilities to meet the need of different BEV types, with considerations of the behaviors of road users. In fact, there are two types of choice behaviors to be taken into consideration: first, as there are multiple types of BEVs in the market, the road users will first decide which type of BEV to purchase; second, road users usually tend to select routes incurring minimum cost for their trips (i.e., travelers' routing behavior). To our best knowledge, no previous research papers in the literature have addressed this charging station location problem considering vehicle ownership of multiple types of BEVs and heterogeneous types of charging facilities. This study aims to fill in this research gap by proposing a tri-level programming approach to explicitly model and solve the location plan of multi-type charging facilities for different BEVs.

Conventional methods in the literature modeled the charging facilities location problems as maximal covering location problem (MCLP) (Church and ReVelle, 1974; Daskin, 2008; Farahani et al., 2012; Hale and Moberg, 2003), flow-capturing location model (FCLM) (Hodgson, 1990), flow-refueling location model (FRLM) (Kuby and Lim, 2005, 2007; Lim and Kuby, 2010), capacitated flow-refueling location model (Upchurch et al., 2009), deviation-flow refueling model (Huang et al., 2015; Kim and Kuby, 2012, 2013), the arc cover path-cover FRLM (Capar et al., 2013), flow-based set covering model (Wang and Lin, 2009) and so on. These location problems do not include the travelers' routing choice behavior. Indeed, only several papers in the literature include transportation network equilibrium in the location problems. He et al. (2013a) allocated a given number of public charging stations for PHEV with consideration of interaction between transportation and power system. He et al. (2015) explored optimally locating public charging stations for BEV considering a tour-based network equilibrium. Lee et al. (2014) developed a model for locating rapid charging stations while considering batters' state of charge and traveling behavior. Besides, a few studies only explored the network equilibrium problem related to EV