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The battery charging station location problem: Impact of users' range anxiety and distance convenience☆

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ABSTRACT

Key to the mass adoption of electric vehicles (EV) is establishing a sufficient recharging infrastructure network, based on customer behavior and psychology. This study examines the battery charging station location problem, considering users' range anxiety and distance deviations, two major barriers to the mass adoption of EV. The problem is formulated as a bi-level integer programming model based on a range anxiety function. Then, the problem is solved using an adaptive large-neighborhood search, combined with a k-shortest path algorithm and an iterative greedy heuristic. Finally, the effects of parameters are analyzed in the context of a real-world road network.

1. Introduction

Environmental climate change and diminishing oil reserves have encouraged policymakers across the world to implement more sustainable practices with respect to energy consumption and greenhouse gas emissions. Because transportation accounts for a large share of the demand for fossil-based fuels and is a major contributor to climate change, the use of electric vehicles (EV) is essential to reducing our reliance on fossil fuels and, thus, furthering smart growth.

Although several attempts have been made to introduce EV, there are many fundamental barriers to its mass adoption. One of the major barriers is the driving range, which is limited to the number of miles provided by the battery pack of the vehicle. This limitation affects EV users' behavior in terms of two factors: range anxiety and distance inconvenience. Car users have become accustomed to the ubiquitous network of gasoline fueling stations, established over the last 100 years. The lack of a similar EV charging infrastructure and the inability to "fuel up" almost anywhere means consumers are hesitant when driving an EV, or even when acquiring an EV. This hesitancy is referred to by some as "range anxiety." Range anxiety is the concern that the driving range of EV may not be sufficient to reach its destination, and is a major psychological obstacle to customers' purchasing intentions (Eberle and Von Helmolt, 2010). Even with the industry's recent proposals on enhanced battery capacity and charging technologies, this psychological fear on limited driving range still impedes consumers from adopting EVs. Pearre et al. (2011) investigated the range required for a day's driving and, thus, inferred the potential market share for limited-range EVs. Franke et al. (2012) introduced the idea of a "comfortable range." Their study is one of the first aimed at systematically understanding the psychology of the range experience, including stress-related personality traits, coping skills, and the ability to deal with an ambiguous range. The main strategies used to alleviate range anxiety among EV users include developing high-capacity batteries at a cost-effective price, improving the accuracy of

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navigation and range-prediction technology, and deploying an extensive charging infrastructure.

The high construction cost of a charging station implies that there will be few such stations in the early stages. As a result, EV users may need to deviate from their path to recharge a battery pack. The distance inconvenience caused by such deviations, which impact users' decisions on routes, have been studied in the context of the facility location problem (Berman et al., 1995; Kim and Kuby, 2012). Therefore, the successful mass adoption of EVs depends not only on battery capacity and charging technology, but also on the optimal design of a charging infrastructure that takes into account range anxiety and distance inconvenience. In addition to the functional aspect of the charging infrastructure, it offers consumers psychological support. Furthermore, both battery charging mode and swapping mode are generally experiencing rapid growth all over China. For example, On November 3, 2017, new energy automaker BAIC BJEV, a subsidiary of Beijing Automotive Group (BAIC Group), a company that ranks 160th among the Fortune 500, established the "Weilan Environmental Alliance" and put into place their "Optimus Prime Plan". A total of 10 billion RMB is to be invested in the Optimus Prime Plan. The plan seeks to make use of battery swapping and second-life battery technologies, integrating new energy vehicles, EV batteries, battery swapping stations, and PV technology, creating an intensive, intelligent, and convenient environmentally friendly system (CNESA, 2017; CISION, 2016). This new energy automaker plans to expand its battery swapping business in the car-sharing, online car-hailing and even the private vehicle markets (China Money Network, 2016). NIO is a premium auto maker in China for new-energy vehicles that, in Dec. 2017, proposed the worldwide first electric service system "NIO Power" and plans to construct more than 1100 battery swapping stations by 2020. Receives "supplement of electric energy is faster than that of gasoline" the belief in service, NIO Power is able to provide battery swapping service for an EV in 3 min (NIO, 2017).

The general objective of this study is to develop a bi-level model for the battery charging station location problem (BCSLP) for an EV charging infrastructure. The BCSLP is formulated to minimize the construction cost of battery charging stations (BCS) and the costs of path deviations, considering users' range anxiety and service level. The remainder of the paper is organized as follows. Section 2 reviews related literature. Section 3 proposes the range anxiety functions, and develops a bi-level mathematical formulation of the problem (BCSLP). Then, in Section 4, a hybrid algorithm is combined with an adaptive large-neighborhood search, a k-shortest path algorithm, and an iterative greedy heuristic in order to solve the problem. In Section 5, the computational results are reported to assess the heuristic performance on the Sioux Falls network, and related parameters are analyzed. Finally, Section 6 concludes the paper, and includes a discussion on possible areas of future research.

2. Literature review

Two streams of research are directly related to our paper. The first stream investigates the facility location problem. The flow capturing location model (FCLM) was firstly proposed by Hodgson (1990). Kuby and Lim (2005) extended FCLM by considering the driving range and designed the flow-refueling location model (FRLM). The FRLM has been applied to real-world network including locating scooter recharge stations (Wang, 2007), battery exchange stations in the tourism transport (Wang, 2008). Then, the variants of the FRLM were further studied in literature such as capacity on the stations (Upchurch et al., 2009), dispersion of candidate sites on arcs (Kuby and Lim, 2007), multiple types of recharging stations (Wang and Lin, 2013). Specially, when the stations are sparsely deployed, FCLM/FRLM need to be formulated based on realistic assumptions about users' recharging behavior. To handle larger networks, MirHassani and Ebrazi (2012) reformulated the FRLM and presented a flexible mixed integer linear programming model, which was able to obtain an optimal solution much faster than the previous version. Yang and Sun (2015b) proposed a modified genetic algorithm(GA) to solve the EV-BSS location problem using stochastic traffic flow on the basis of FRLM. Arslan and Karasan (2016) proposed a Benders decomposition approach for the charging station location problem as a generalization of the FRLM. Vries and Duijzer (2017) proposed a novel mixed-integer programming formulations for the FRLM, and showed how these models can be extended to the case for which the driving range varies during a trip. Wu and Sioshansi (2017) studied a stochastic flow-capturing location model (SFCLM) to optimize the EV charging station location problem, which aimed at solving the uncertainty of charging demands. Furthermore, the EV infrastructure network are designed on the basis of the assumption customers may deviate from the preplanned or shortest paths to visit a service facility. For example, Berman et al. (1995) proposed two new FCLM models to maximize market size and minimize the total deviation distance, respectively. Kim and Kuby (2012) also relaxed the FRLM to consider the willingness of consumers to deviate from their shortest paths to visit a service station. Their results showed that the choice of deviation decay function and maximum allowed deviation have significant influence on solution quality and optimal facility location strategy. Li and Huang (2014) developed a multipath recharging station location problem with driving range. Then, heuristic approaches were proposed for the flow-based set covering problem.

Apart from the above extended FRLM, the EV infrastructure network and service design models are based on the location-routing problem. Escobar et al. (2014) proposed a granular variable tabu neighborhood search for the station location problem with capacity constrains. Martnez-Salazar et al. (2014) introduced a bi-objective LRP problem, which was an extension of the two stage LRP, and proposed a metaheuristic algorithms to solve this problem. Rivera et al. (2015) studied the multi-trip cumulative capacitated LRP and presented a multi-start iterated local search. Koc et al. (2016) dealt with the fleet size and mixed LRP with time windows. Their study extended the station location problem by considering a heterogeneous fleet. Li et al. (2016) developed a multi-period multi-path charging station location model. The model determined a cost-effective station scheme on both spatial and temporal dimensions. Hof et al. (2017) studied the BSS location-routing problem with capacitated EVs using an AVNS algorithm for this problems with intermediate stops. Jeong (2017) introduced an optimal approach for a set covering version of the refueling-station location problem in a traffic network. Miralinaghi et al. (2017a) studied a capacitated charging station location problem while accounting for multi-period travel demand and the deviations to recharge. Miralinaghi et al. (2017b) provided a framework for the refueling demand uncertainty and the effect of travelers' deviation to refuel considerations in the network. To guarantee the preplanned proportion of