Optimal planning of swapping/charging station network with customer satisfaction

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Abstract

Key to the mass adoption of electric vehicles is the establishment of a sufficient battery service infrastructure network on the basis of customer behavior and psychology. Motivated by EV service infrastructure network design under the battery leasing/electric car sharing service business models, we present an electric vehicle battery service network design problem considering a customers satisfaction related to “range anxiety” and “loss anxiety”. The problem is formulated as a linear integer programming model under deterministic and fuzzy scenarios. A Tabu Search heuristic combined with GRASP is proposed to efficiently solve the problem. Finally, we conduct parametric analysis on real-world road networks.

1. Introduction

Given the economic and environmental concerns associated with fossil fuel usage, electric vehicles (EVs) have recently become an attractive alternative transportation tool across the world. An increasing number of people are starting to look at EVs as a viable driving option. Potential buyers still have concerns about EVs regarding battery cost, charging time, and driving range.

According to a consumer survey by Green Car Report (2011), the price of a battery pack is a major barrier for the wide-scale adoption of EVs because the battery pack represents up to 45 percent of the cost of these vehicles. Reducing that cost will be crucial to the widespread consumer acceptance of EVs. To assuage consumer concerns over the initial purchase price of an EV and the high cost of replacing battery packs, some EV manufacturers have designed a new business model: battery leasing and service contracts. Instead of buying the battery packs, customers only need to pay a small monthly rental fee. For example, Smart established a battery business model in the U.S. market through which nearly 90% of ForTwo Electric Drive buyers opted to lease a battery (Clean Technica, 2013). In Europe, Renault and French OEM Mia Electric also deployed this strategy, which is attractive to more mainstream buyers. This business model allows for a more affordable initial EV purchase price and reduces the financial risk to EV owners (Navigant Research, 2012; Autoblog, 2016). In China, the Beijing New Energy Automobile Co., LTD and Sinopec have established a strategic cooperative partnership to set up a battery operating joint company. The former sells EVs to customers without battery packs and the latter is gradually constructing battery swapping stations. The new battery operating company is fully responsible for battery lease, maintenance, charging, transportation and swapping service (China Sinopec, 2015).
In addition, the electric car-sharing service has become a major global industry. Hundreds of cities in more than 30 countries are at the forefront of this new model of multi-modal on-demand mobility. Autolib (Smart Cities Council, 2013), Car2go (CAR2GO, 2017a,b), and others are known as the pioneers of the electric car-sharing service. In China, new point-to-point car sharing services are starting up across cities. BAIC BJEV plans to expand its battery swapping business in the car-sharing, online car-hailing, and private vehicle markets (China Money Network, 2016). Pand Auto is a car-hailing platform in China for new-energy vehicles that, in 2016, expanded its car-sharing service to three provinces. (China Daily USA, 2016).

From the customer’s perspective, these new business models will alleviate some of the worry over battery life spans and warranties if customers are leasing batteries or EVs. Nevertheless, even with the rapid industry development of enhanced battery capacity and charging technologies, limited driving range still obstructs a consumer’s adoption of EVs. The lack of EV service infrastructures makes it almost impossible to fuel up these vehicles anytime or anywhere, which makes most consumers hesitant to venture out with, or even acquire, an EV. This hesitancy can be interpreted as range anxiety and loss anxiety. Range anxiety is drivers’ concern that a vehicle’s driving range may be insufficient to arrive at their destinations (Eberle and von Helmolt, 2010). Franke et al. (2012) introduced the definition of a comfortable range. Their paper spearheaded the systematic knowledge of the psychology of the range experience. Loss anxiety is associated with the willingness to not swap or charge a battery because the remaining energy is still fairly high. Given an insufficient infrastructure, EV drivers may have to swap or charge battery packs even though significant power remains. Otherwise, the battery will run out of energy before arriving at the destination or the next BSS.

Fig. 1 illustrates a simple example with a single path \( O \to A \to B \to C \to D \). Let the driving range \( Q = 200 \). The EV is able to arrive at the destination \( D \) after swapping the battery pack at node \( A \). Note that, in Fig. 1(a), the EV has almost no remaining energy when reaching \( D \) and the driver may suffer serious range anxiety. To alleviate the influence of range anxiety, it is better to swap the battery once more to maintain its proper state during the trip. In Fig. 1(b), the EV has its battery pack swapped at node \( A \), and a subsequent exchange at node \( B \) may cause loss anxiety because 80% of the energy remains before the batteries are swapped. By swapping a battery at nodes \( A \) and \( C \), a driver may be satisfied through less loss anxiety and range anxiety, as seen in Fig. 1(c). Through this analysis, the proper deployment of EV service infrastructures is one of the main solutions to alleviating the influence of anxiety among EV customers. In addition, drivers’ anxiety over range and loss may be different because of their heterogeneous perception and time concerns, according to empirical studies. In the remainder of this paper, drivers are divided into different types according to their range anxiety and loss threshold.

Locating the swapping/charging station on a popular long distance travel route appeals to the time and anxiety sensitivity of these potential drivers. Proper deployment of EV service infrastructures and new business models are designed to lower the barriers surrounding EVs that center on battery costs, charging time, and customer anxiety associated with their adoption of such vehicles (Dong et al., 2014). Our study is motivated by the EV service infrastructure network design under the battery leasing/electric car-sharing service business models. To maximize profit and attract an adequate number of potential customers, we present an electric vehicle battery swapping station network design problem (EV-BSNDP) to determine the location and service strategy of battery swapping/charging stations (BSSs) by considering customer satisfaction and heterogeneous perception. The BSSs location decision has direct influence on customers recharging swapping decision, which is a key factor of their satisfaction. More customers will be attracted to join this business model only on the condition that station locations can match customer range anxiety and loss anxiety to ensure customer satisfaction is higher than a certain level.

The remainder of this paper is organized as follows. In Section 2, a related literature review is presented. Section 3 proposes the customer satisfaction function and establishes a deterministic model for the problem. Then, the fuzzy model is formulated in Section 4. In Section 5, a hybrid algorithm combined with Tabu Search and the Greedy Randomized Adaptive Search Procedure (GRASP) is developed. In Section 6, computational results are reported to assess heuristic performance on different size instances. Then, certain related parameters are analyzed. Finally, in Section 7, some conclusions and future research are discussed.

![Fig. 1. Range anxiety and loss anxiety.](image-url)
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