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## Long-term strategic planning of inter-city fast charging infrastructure for battery electric vehicles<sup>☆</sup>



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### ABSTRACT

This study introduces a multistage chance-constrained stochastic model for strategic planning of battery electric vehicle (BEV) inter-city fast charging infrastructure. A mixed integer programming model is developed to determine where and when charging stations are opened, and how many chargers are required for each station to meet the growing BEV inter-city demand. The model is applied to a case study in California and solved by genetic algorithm. This study showed that investment in inter-city charging infrastructure is vital to alleviate the range anxiety. Also, planning decisions depend on many factors, such as the design level of service and vehicle range.

### 1. Introduction

Promoting battery electric vehicles (BEV) is deemed an effective solution to help the United States reduce its dependency on imported oil and improve its competitive position in the emerging era of renewable energy market. Several agencies have enacted incentive policies to promote the mass adoption of BEVs. These policies include the Federal American Recovery and Reinvestment Act (ARRA) tax program, California's Zero Emission Vehicle (ZEV) Action Plan, and the Corporate Average Fuel Economy (CAFE) standards. Encouraged by these policies and standards, manufacturers are actively developing affordable BEVs with low manufacturing costs and plausible vehicle performance (e.g., vehicle range and power) (EPA et al., 2016). All these efforts by agencies and manufacturers contribute to success in the current BEV market. In particular, plug-in electric vehicles (PEVs, including both BEVs and plug-in hybrid electric vehicles (PHEVs)) garner about 1% of today's total sales (Davis et al., 2016). To be fully competitive with conventional vehicles (CVs, such as gasoline vehicles), "range anxiety" concerns have to be resolved.

Range anxiety, as the name suggests, is the fear of insufficient range to reach destinations (Eberle and von Helmlolt, 2010). Unlike PHEVs, which can have unlimited range by running on conventional fuels, BEVs can run only on electricity. To alleviate range anxiety during trips, consumers need adequate charging infrastructure; this applies to both intra-city (short distance) and inter-city (long distance) travels. The intra-city travel problem has been well studied. Examples of effective solutions include establishing home and workplace charging systems (Huang and Zhou, 2015), and supporting intra-city public charging networks (NREL, 2017) that include level-1 (L1, 1.4 kW) chargers, level-2 (L2, 6.2 kW) chargers, and direct current fast chargers (DCFC, > 50 kW).

However, the problem becomes more challenging for inter-city travels. First, inter-city travel distances can be longer than the

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vehicle range. Recharging is inevitable for long distance travel, and home or workplace charging cannot be relied upon. Second, unlike intra-city public charging during which travelers can tolerate relatively long recharging time by conducting other activities (e.g., shopping and dining), inter-city public charging may have stricter charging time limits as there are few activities available while charging along rural highway corridors. Therefore, a mature inter-city DCFC fast charging network with proper service capacity is necessary to satisfy the growing inter-city BEV trips. As building the DCFC charging network is costly (the facility can cost more than \$50,000 per charger (NRC, 2013)), we need solutions to identify where to locate charging stations, when to install them, and how many chargers to allocate at each station in response to the changing BEV market.

To serve this need, this study aims to develop a multistage optimization modeling framework. The framework will gradually establish and expand DCFC charging infrastructure in terms of both *network coverage* and *service capacity* to alleviate increased range anxiety issue with growing BEV inter-city travel demand.

Existing literature describes two major modeling directions for problems related to facility location of refueling and charging infrastructure. One direction is to develop *node-based* facility location models stemming from p-median facility location problems (Daskin, 1995; Hakimi, 1964). Representative works include the studies (Ip et al., 2010; Jung et al., 2014; Momtazpour et al., 2014). However, Li et al. (2016) suggest that the node-based facility location model may not be well suit for charging location problems as it cannot properly model flows of goods or passengers in a network. Wide recognition of this issue has led to richer literature on the second direction, to develop *flow-based* facility location models that stem from flow-capturing location-allocation models (FCLMs) (Hodgson, 1990). Representative works include the studies (Berman et al., 1992; He et al., 2013, 2015; Hodgson, 1990; Huang et al., 2015; Kuby and Lim, 2005; Li and Huang, 2014; Li et al., 2016; Wang and Lin, 2009).

Few existing studies are available on BEV inter-city DCFC facility location models. Wang and Lin (2009) introduced a single-path set-covering model based on vehicle routing logic. Jochem et al. (2016) developed a single-path inter-city fast charging infrastructure planning model for a case study in Germany. To recognize the heterogeneity of BEV travelers in choosing paths, a multi-path (multi-deviated paths) flow based set covering model was proposed in the study by Li and Huang (2014). The model was later extended to a multistage formulation to capture topological changes in inter-city network over time (Li et al., 2016). Different from other node- or flow-based modeling efforts, Sathaye and Kelley (2013) developed a continuous facility location model that yields solutions on station densities instead of locations, and the model is less computationally intensive. Note that all these models do not consider charging station capacity.

However, long-term planning of inter-city DCFC charging infrastructure should consider both locations and charging capacity. Otherwise, charging congestion is inevitable and increases the frustration of using BEV for inter-city trips. There are several approaches to modeling charger capacity. One simple and direct method is to use deterministic capacitated facility location models (Sadeghi-Barzani et al., 2014; Upchurch et al., 2009). However, those models simplified the logic between charging activities and required charger capacity with assumed daily or annual capacity (e.g., vehicles per day). On the other hand, using the Global Positioning System (GPS)-based travel survey data, NREL (2017) determined the required number of chargers to avoid conflicts in charging activities by different vehicles at the same time and location. The method is straightforward to implement, but it may create the over-fitting bias as the decisions are only based on sampled trip data. Alternatively, Ge et al. (2011) and Jia et al. (2012) assumed charging demand is positively correlated with the traffic flow rate (vehicles/hour) and the share of BEVs in the flow. With this assumption, charging capacity can be determined if the average recharging frequency is known. All the prior studies neglect the stochasticity in charging activities at each station. To capture both randomness in charging demand arrivals and actual charging service time, an alternative approach is to model charger operations using stochastic queuing models (Fang and Hua, 2015; Gusrialdi et al., 2014; Said et al., 2013).

In this study, we propose a flow-based multistage (multi-period) chance-constrained stochastic modeling framework in planning long-term DCFC charging infrastructure expansion to serve growing BEV inter-city trips. The framework is built upon the multi-period multi-path refueling location model ( $M^2PRLM$ ) (Li et al., 2016), and allows multistage expansions of the charging infrastructure and multiple deviated paths. In addition, we model charging station capacities by using the stochastic queuing theory (Fang and Hua, 2015; Gusrialdi et al., 2014; Said et al., 2013). In order to better reflect stochasticity in charging activities, we introduced the level of service concept formulated using stochastic chance constraints to determine charger capacity. Note that the  $M^2PRLM$  is a set-covering problem. We also relax the set-covering formulation by providing penalty terms for infeasible trips, so that the model can further investigate the tradeoff between the high investment cost in DCFC charging infrastructure and the high range anxiety cost caused by trip infeasibility. As the model is a facility location problem and is NP-hard, we developed a genetic algorithm based heuristic method to efficiently solve the model.

The model will be applied to a large-scale case study in California to understand long-term infrastructure requirements to meet the growing inter-city travel demand. Compared to previous modeling efforts, we expect the proposed framework to yield additional managerial insights and policy implications on future inter-city DCFC charging network in many ways. First, a complete set of decisions on both charger location and capacity can help stakeholders better understand when, where, and how much capital investment should be made on the charging infrastructure. Also, integration of the stochastic queuing models as well as the level of service concept gives policy makers detailed analyses of infrastructure requirements, such as the suitability of opening large or small charging stations at various conditions.

In the rest of the paper, we will first demonstrate the modeling framework and the solution method in Sections 2 and 3, respectively. In the remaining sections, we will describe the California case study, discuss the modeling results, and summarize the study in the conclusion.

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