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A general corridor model for designing plug-in electric vehicle charging infrastructure to support intercity travel ☆

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ABSTRACT

This paper proposes to optimally configure plug-in electric vehicle (PEV) charging infrastructure for supporting long-distance intercity travel using a general corridor model that aims to minimize a total system cost inclusive of infrastructure investment, battery cost and user cost. Compared to the previous work, the proposed model not only allows realistic patterns of origin–destination demands, but also considers flow-dependent charging delay induced by congestion at charging stations. With these extensions, the model is better suited to performing a sketchy design of charging infrastructure along highway corridors. The proposed model is formulated as a mixed integer program with nonlinear constraints and solved by a specialized metaheuristic algorithm based on Simulated Annealing. Our numerical experiments show that the metaheuristic produces satisfactory solutions in comparison with benchmark solutions obtained by a mainstream commercial solver, but is more computationally tractable for larger problems. Noteworthy findings from numerical results are: (1) ignoring queuing delay inducted by charging congestion could lead to suboptimal configuration of charging infrastructure, and its effect is expected to be more significant when the market share of PEVs rises; (2) in the absence of the battery cost, it is important to consider the trade-off between the costs of charging delay and the infrastructure; and (3) building long-range PEVs with the current generation of battery technology may not be cost effective from the societal point of view.

1. Introduction

Successful transition to alternative fuel vehicles (AFV) demands well planned supporting infrastructure, especially a network of refueling stations. The problem of optimally designing the refueling network has been studied separately for different AFVs, see e.g. Stephens-Romero et al. (2010) and Nicholas et al. (2004) for hydrogen vehicles, Frick et al. (2007) for compressed natural gas vehicles, and Frade et al. (2011), Dashora et al. (2010) and Sweda and Klabjan (2011) for PEVs, including plug-in hybrid electric vehicles (PHEV) such as Chevrolet Volt and battery electric vehicles (BEV) such as Nissan Leaf. We shall focus on PEVs in this paper because of their high energy efficiency (Romm, 2006; Eberhard and Tarpenning, 2006), the ability to substitute electricity for petroleum and the potential to reduce the carbon footprint (Samaras and Meisterling, 2008; Crist, 2012).

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The design of charging infrastructure is a facility location problem, which may be classified as "covering point demand" (e.g., Toregas et al., 1971; Daskin, 1995), "capturing origin–destination (O–D) demand" (Ghosh and McLafferty, 1987; Hodgson, 1990; Ghosh, 1991) and considering both types of demand (so-called hybrid models) (Goodchild and Noronha, 1987; Hodgson and Rosing, 1992). The point demand approach has been a popular choice in the context of locating charging stations for PEVs. The idea is to place these stations near the urban activity centers (e.g. home, shopping malls and work-places) so as to minimize the access cost of PEV owners. With this approach the charging design problem is typically formulated as a set covering or P-median facility location problem (e.g. Dashora et al., 2010; Pan et al., 2010; Frade et al., 2011; Chen et al., 2013; Sweda and Klabjan, 2011; He et al., 2013; Huang et al., 2015; Ghamami et al., 2016). The point demand approach does not typically address intercity trips traditionally made using passenger vehicles. The premise of our study is that making charging facilities available along the corridors where these long-distance trips concentrate is important to resolving the range anxiety issue that has been considered a critical obstacle to PEV adoption (Hidrue et al., 2011; Shiau et al., 2009).

Flow capturing facility location models (FCLM) (e.g. Hodgson, 1990) are better suited to tackle intercity trips. Kuby and Lim (2005) and Kuby and Lim (2007) are among the early efforts to apply the FCLM in the context of the refueling problem for range-limited vehicles. The objective of these refueling location models is to locate refueling facilities to maximize the total vehicle flows refueled. Lim and Kuby (2010) propose a few efficient heuristic algorithms for solving this type of problems. The refueling station location problem studied in Wang and Lin (2009) and Wang and Wang (2010) also considers O–D demands. Yet, instead of trying to maximize flow being captured, their model minimizes the total facility cost while ensuring all flows are properly served according to a "refueling logic". Nie and Ghamami (2013) propose a conceptual model to analyze travel by PEVs along a long corridor. The objective of their model is to select the battery size and charging capacity to meet a given level of service in such a way that the total social cost is minimized. In a similar spirit, Sathaye and Kelley (2013) develop a continuous facility location model (Daganzo, 2005) for the optimization of PEV charing facility deployment for highway corridors. Unlike Nie and Ghamami (2013), their model does not consider the battery cost. Rather, the focus is to complement private charging infrastructure by publicly funded charging stations, while considering demand uncertainty. Mak et al. (2013) propose a robust location model of battery swapping stations, which also considers demand uncertainty explicitly.

The analysis of Nie and Ghamami (2013) reveals the interesting tradeoff between charging capacity, battery size and the level of service experienced by PEV drivers (measured by the extra time spent on charging). Yet, a couple of simplifying assumptions make their model unsuitable even for sketchy design in a practical setting. These include: (1) trips take place between a single origin–destination pair with a fixed refueling logic; (2) each station is equipped with as many charging capacities as required to accommodate all PEVs as if they would use the facility simultaneously. The first assumption restricts the analysis to trips connecting two ends of a single corridor, and the second leads to potential overbuilding of charging capacities. This study aims to operationalize Nie and Ghamami (2013)'s corridor model by relaxing the above assumptions. Notably, the proposed general model will consider congestion at the charging stations (i.e., the fact that PEV drivers may wait in the line during peak periods), and how the *flow-dependent queuing delay* affects the optimal configuration of infrastructure and optimal refueling decisions. To the best of our knowledge, few have endogenized the waiting cost at charging stations in the context of modeling PEVs. A notable exception, De Weerdt et al. (2013), considers queuing delay at charging stations but their focus was on optimal routing instead of infrastructure planning. While the proposed model is labeled as "general", our focus is still on tandem linear corridors, which implies that the general route choice is not explicitly considered. The reason for this simplification is twofold. First, for the intercity travel that motivates this study, it is not uncommon that only one viable route is available for a given O–D pair. Second, the model proposed herein can be readily extended to cases involving multiple routes between O–D pairs, which could elevate computational challenges (because of the need to partially enumerate routes) but only add modest analytical complexities.

Because the general corridor model is formulated as a mixed integer nonlinear program, solving it poses a significant challenge. While off-the-shelf solvers for such problems do exist, we note that these general purpose tools often scale poorly. To address this limitation, a specialized metaheuristic solution method based on Simulated Annealing (SA) is developed and compared against a popular commercial solver in several numerical experiments. Note that the SA algorithm has been successfully employed to solve challenging optimization problems in general (e.g. Boston and Bettinger, 1999; Baskent and Jordan, 2002; McKendall et al., 2006; Dong et al., 2009), and facility location problems in particular (e.g. Murray and Church, 1996; Arostegui et al., 2006; Paik and Soni, 2007; Davari et al., 2011; Zockaie et al., 2016).

For the remainder, Section 2 presents the model formulation, followed by the development of a specialized solution algorithm in Section 3. Section 4 presents the setting and results of numerical experiments. Section 5 concludes the study with remarks on directions for future research.

2. Model formulation

Consider a set of tandem linear highway corridors that are divided into N segments with uniform length h (see Fig. 1). The corridors consist of a set of nodes denoted as $\Omega = \{0, 1, \ldots, N\}$, with 0 and N being the first and last nodes, respectively. Each highway segment is identified by its end node – that is, the index of the segment from node $n-1$ to n is n. Without loss of generality, we assume that the length of each corridor is the multiple of h. Thus, the starting and ending nodes of any