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Deploying public charging stations for electric vehicles on urban road networks

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ABSTRACT

This paper explores how to optimally locate public charging stations for electric vehicles on a road network, considering drivers' spontaneous adjustments and interactions of travel and recharging decisions. The proposed approach captures the interdependency of different trips conducted by the same driver by examining the complete tour of the driver. Given the limited driving range and recharging needs of battery electric vehicles, drivers of electric vehicles are assumed to simultaneously determine tour paths and recharging plans to minimize their travel and recharging time while guaranteeing not running out of charge before completing their tours. Moreover, different initial states of charge of batteries and risk-taking attitudes of drivers toward the uncertainty of energy consumption are considered. The resulting multi-class network equilibrium flow pattern is described by a mathematical program, which is solved by an iterative procedure. Based on the proposed equilibrium framework, the charging station location problem is then formulated as a bi-level mathematical program and solved by a genetic-algorithm-based procedure. Numerical examples are presented to demonstrate the models and provide insights on public charging infrastructure deployment and behaviors of electric vehicles.

1. Introduction

Battery electric vehicles (BEVs) have enjoyed fast-growing adoption in recent years, partly thanks to the concern of climate change, advancement of battery technologies and expeditiously rising prices of crude oil (e.g., Larminie and Lowry, 2003; Tamor et al., 2013; Feng and Figliozzi, 2013; He et al., 2013a,b,c). However, early adopters of BEVs do endure the inconvenience and cost incurred by limited driving ranges of BEVs, insufficient charging infrastructure and long battery charging times (e.g., He et al., 2013a; Nie and Ghamami, 2013). To further nurture the market for BEVs, many governments have incentive policies in place, such as offering purchase subsides and deploying charging infrastructure at convenient locations of urban areas. For example, the Ministry of Finance of China announced a pilot program to provide incentives up to 60,000 Chinese yuans for private purchases of new BEVs and 50,000 yuans for plug-in hybrid electric vehicles in five cities (Motavalli, 2010). British Columbia, Canada, plans to build 570 charging stations across the province (GLOBLE-Net, 2012).

To assist decision making on the deployment of public charging infrastructure in metropolitan areas, various approaches proposed in the literature can be applied. One typical approach is to apply clustering techniques to point recharging

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demands and then deploy stations to the cluster centers (e.g., Ip et al., 2010; Momtazpour et al., 2014). The flow-capturing approach aims at locating charging stations to maximize the amount of traffic flow that travels along a path with at least one station (Hodgson, 1990; Berman et al., 1992, 1995; Hodgson and Berman, 1997; Shukla et al., 2011). Variants of this approach also consider vehicle recharging or refueling behaviors to optimize the station locations to serve as many vehicles as possible (Kuby and Lim, 2005, 2007; Upchurch et al., 2009; Wang and Lin, 2013). Another popular approach is to simulate drivers' recharging needs based on their real-world driving profiles and then determine station locations to minimize the number of missed trips (Dong et al., 2013; Andrews et al., 2012). For a more detailed review of the literature, see He (2014).

The above studies ignore BEV drivers' potential responses to the deployment of charging infrastructure and assume travelers' activity engagement and travel choices remain the same regardless of charging station location plans. An activity-based approach has been proposed to overcome the above limitation. For instance, Kang and Recker (2009, 2012) and Schneider et al. (2012) investigated individuals' activity scheduling and routing with refueling, and then determined optimal locations of refueling stations. However, it imposes a tremendous computational challenge for the approach to capture the interaction among different drivers' travel and charging behaviors, and congestion effects, which may be profound.

Still lacking is a mathematically-tractable framework that optimizes the locations of public charging stations while considering drivers' spontaneous adjustments and interactions of travel and recharging decisions. As one of the first attempts of this quest, this paper proposes a tour-based BEV network equilibrium model to capture drivers' reaction to the deployment of charging stations in their route and recharging decisions, given the locations and types of public charging stations. Tour-based network equilibrium models assign traffic demand based on the analysis of a complete tour, which may consist of several trips in a pre-determined order (e.g., Lam and Yin, 2001; Lam and Huang, 2002; Maruyama and Harata, 2006; Maruyama and Sumalee, 2007). The advantage of the tour-based analysis lies in its ability to capture the connection of different trips conducted by the same traveler, which becomes significant for BEVs. This paper is among the first to develop a tour-based network equilibrium model with the consideration of BEV recharging behaviors. In the proposed model, each BEV traveler has a pre-defined tour plan, including the destinations to visit, the order of the visits and the dwelling time at each destination. To avoid running out of energy before completing their tours, BEV drivers can either drop by a public charging station en route to recharge batteries or leave their vehicles plugged-in while conducting other activities at destinations where the access to charging is available. For the latter, if it takes longer than the pre-determined dwelling time to recharge, drivers may choose to stay for some extra time. In essence, drivers are assumed to do what it takes to minimize the time spent on driving and recharging, while ensuring to complete their tours without running out of energy.

Compared to trip-based network equilibrium models with BEVs (e.g., He et al., 2014), the proposed tour-based model has two advantages. First, it accurately tracks the state of charge of battery, as the initial state of charge for a particular trip is always related to its previous trips. Second, it considers the duration times BEV drivers spend at various destinations, i.e., intermediate stops, in a tour, which may be utilized for recharging. Moreover, our model incorporates multi-class travelers with different initial states of charge of batteries and risk-taking attitudes toward the uncertainty of fuel economy. With the proposed tour-based BEV network equilibrium model, we then examine how to determine the locations and types of public charging stations to maximize social welfare within a given budget.

For the remainder, Section 2 describes a tour-based network equilibrium model with BEVs. Section 3 formulates the problem of finding an optimal charging station deployment plan, including the locations of stations and their types, as a bi-level mathematical program and proposes its solution algorithm. Section 4 presents a numerical example to derive insights on charging station deployment and BEV travel behaviors. Lastly, Section 5 summarizes the paper and discusses future research directions.

2. Tour-based network equilibrium models with BEVs

2.1. Illustrative example

We first use an illustrative example to highlight the need or importance of considering trip chaining in describing travel and recharging behaviors of BEVs.

In Fig. 1, nodes 1, 2 and 3 represent home, work place and shopping mall respectively. Public charging stations are located at both nodes 4 and 5 with the efficiency of refueling a range of 2.5 miles to batteries per minute of charging, and there are no other charging opportunities in the network except home charging. The travel time and distance of each link are also shown in the figure. Assume a BEV driver has a pre-defined tour plan, i.e., {home, work place, shopping mall, home}, and thus there are three trips in the tour, i.e., (1, 2), (2, 3) and (3, 1). It is assumed that the vehicle battery has a 30-mile initial range when the tour starts. If a trip-based approach is applied to describe the route-choice behavior, three trips will be considered separately. The approach will predict that the driver chooses path 1-2 to travel between nodes 1 and 2, path 2-3 between nodes 2 and 3. For the latter, although there is an alternative path 2-4-3, it is not desirable due to its longer travel time and the fact that the battery range is sufficient for the trip between the origin–destination (O–D) pair. When traveling home from the shopping mall, i.e., node 3 to 1, the driver will be predicted to make a detour to node 5 to spend 2 min on refueling a five-mile range to the battery in order to avoid running out of energy before reaching home. However, the above prediction may not be realistic because in practice the traveler will likely choose to drop by node 4 instead of 5 to recharge even when