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Network equilibrium models with battery electric vehicles

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ABSTRACT

The limited driving ranges, the scarcity of recharging stations and potentially long battery recharging or swapping time inevitably affect route choices of drivers of battery electric vehicles (BEVs). When traveling between their origins and destinations, this paper assumes that BEV drivers select routes and decide battery recharging plans to minimize their trip times or costs while making sure to complete their trips without running out of charge. With different considerations of flow dependency of energy consumption of BEVs and recharging time, three mathematical models are formulated to describe the resulting network equilibrium flow distributions on regional or metropolitan road networks. Solution algorithms are proposed to solve these models efficiently. Numerical examples are presented to demonstrate the models and solution algorithms.

1. Introduction

Battery electric vehicles (BEVs) have enjoyed fast-growing adoption in recent years, thanks to the concern about climate change, the 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., 2013b; Gardner et al., 2013). However, those early adopters of BEVs do endure the inconvenience and cost incurred by the limited driving range of BEVs, insufficient charging infrastructure and long battery charging or swapping time (e.g., He et al., 2013a; Nie and Ghamami, 2013). The fear of batteries running out of power en route, normally referred to as range anxiety in the literature (see, e.g., Pearre et al., 2011), will inevitably affect BEV drivers' travel choices. Although many governments are planning to deploy public charging stations in their regions, and a number of other strategies tackling range anxiety have emerged (e.g., He et al., 2013c), it seems unrealistic to expect that range anxiety can be eliminated in the near future.

Range anxiety is not just limited to BEV drivers. Indeed, drivers of other types of alternative-fuel vehicles often experience it. The literature of alternative-fuel vehicles has considered the potential need of recharging those vehicles to reach their destinations. For example, Kuby and Lim (2005) recognized their limited driving ranges and investigated locating refueling stations to ensure alternative-fuel vehicles to refuel more than once to successfully complete their entire trips. For the same purpose, Wang and Lin (2009) formulated the refueling logic of vehicles to be a system of linear equations. Both studies assume that travelers between an origin–destination (O–D) pair choose the shortest path, which is given and fixed. For electric vehicles, activity-based approaches have been proposed to investigate individual vehicle routing and scheduling problem with recharging in the literature (e.g., Kang and Recker, 2009, 2012; Schneider et al., 2012). Adler et al. (2013) defined a BEV shortest walk problem that finds the route between an O–D pair with minimum detouring, and proved the problem to be polynomially solvable. Note that the obtained shortest walk may include cycles for detouring to recharge

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batteries. In contrast to these previous studies, this paper investigates how the limited driving range and recharging requirement of BEVs affect their drivers' route choices and subsequently the equilibrium flow distribution on regional or large metropolitan road networks where charging stations are few and far between. Among others, the most relevant studies in the literature include Jiang et al. (2012), and Jiang and Xie (2013). In the former, a network equilibrium model is formulated upon paths whose lengths are within the driving ranges of BEVs. The so-called path-constrained traffic assignment model can be solved efficiently by a solution algorithm proposed in the latter. Jiang et al. (2013) further extended the model to consider mixed gasoline and electric vehicular flows, and their combined choices of destination, route and parking subject to the driving range limit. All three studies do not consider recharging behaviors of BEV drivers and assume the energy consumption of BEVs is independent of traffic congestion.

In this paper, assuming that the energy consumption of a BEV is not affected by traffic congestion, i.e., the consumption is flow-independent, we first formulate a network equilibrium model that abides by the driving ranges of BEVs and accommodates their recharging decisions. An iterative solution procedure is proposed to solve the model efficiently. We further extend the model to consider the time required for recharging, which can be substantial, depending on the amount of recharged energy and the type of charging stations. Lastly, considering the potential impact of traffic congestion on the fuel economy of BEVs, we investigate a novel network equilibrium model with flow-dependent energy consumption.

For the remainder, Section 2 formulates a base model that describes network equilibrium with flow-independent energy consumption of BEVs, and then proposes a solution procedure. Section 3 extends the base model to consider the recharging time while Section 4 investigates another network equilibrium model with flow-dependent energy consumption. Section 5 presents numerical examples to demonstrate the proposed models and solution algorithms. Lastly, Section 6 concludes the paper.

2. Base model

2.1. Notation

We consider a regional or metropolitan road network. Let $G(N, A)$ denote the network where N and A are the sets of nodes and links in the network respectively. We denote a link as $a \in A$ or its starting and ending nodes i.e., $a = (i, j) \in A$. Travel demands are between a set of O–D pairs, i.e., W. Let g^w and P^w be the travel demand and the set of paths between O–D pair $w \in W$ respectively. In addition, f_p^w represents the traffic flow on path $p \in P^w$ of O–D pair $w \in W$. We further denote $o(w)$ as the origin node of O–D pair $w \in W$, and $\delta_{a,p}$ is the path-link incidence, which equals 1 if path p traverses link $a \in A$ and 0 otherwise. Let v_a and d_a be the traffic flow and distance of link a. The travel time of link a is a strictly increasing function of the flow on the link, i.e., $t_a(v_a)$. For example, the following Bureau of Public Roads (BPR) function can be used:

$$t_a = t_a^0\left[1 + 0.15\left(\frac{v_a}{c_a}\right)^4\right]$$

where t_a^0 is the free-flow travel time of link a, and c_a represents the capacity of link a.

2.2. Definition and formulation of network equilibrium

It is assumed in this paper that all vehicles in the network are BEVs. This assumption is not necessarily restrictive as the models proposed below can be easily extended to accommodate both electric and regular vehicles. It is further assumed that a limited number of charging stations are located at certain nodes of the network, and thus vehicles traveling along a path may not pass by a charging station. We thus have the following definition:

Definition 1. A path is usable if a BEV is able to complete the path without or with recharging.

The distance of a usable path must be within the driving range of a BEV, if none charging station exists along the path. Otherwise, it is usable as long as the vehicle can recharge its battery at charging stations along the path to avoid running out of charge before reaching its destination. Fig. 1 is a simple example to further illustrate the definition.

The O–D pair 1–2 is connected by three paths, i.e., 1–2, 1–3–2 and 1–4–2. A charging station is located at both nodes 3 and 4. It is assumed that the battery size of the BEV is 24 kWh; its initial state of charge is 4 kWh and the energy consumption rate is 0.3 kWh/mi. It is easy to see that path 1–2 is not a usable path. Along the other two, the BEV can reach node 3 or 4

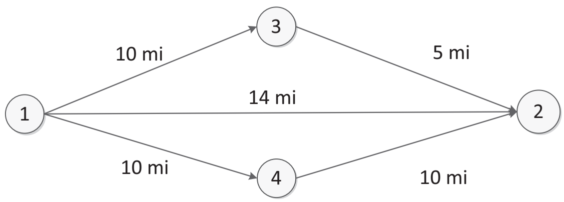

Fig. 1. A toy network with four nodes.