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Optimal deployment of charging lanes for electric vehicles in transportation networks

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A B S T R A C T

Given the rapid development of charging-while-driving technology, we envision that charging lanes for electric vehicles can be deployed in regional or even urban road networks in the future and thus attempt to optimize their deployment in this paper. We first develop a new user equilibrium model to describe the equilibrium flow distribution across a road network where charging lanes are deployed. Drivers of electric vehicles, when traveling between their origins and destinations, are assumed to select routes and decide battery recharging plans to minimize their trip times while ensuring to complete their trips without running out of charge. The battery recharging plan will dictate which charging lane to use, how long to charge and at what speed to operate an electric vehicle. The speed will affect the amount of energy recharged as well as travel time. With the established user equilibrium conditions, we further formulate the deployment of charging lanes as a mathematical program with complementarity constraints. Both the network equilibrium and design models are solved by effective solution algorithms and demonstrated with numerical examples.

1. Introduction

Owing to the rapid development of battery technology and growing concern about greenhouse effect, the adoption of electric vehicles (EVs) has grown significantly in the past few years. For example, EV sales in the U.S. have increased to approximately 120,000 in 2014, about six times of the sales in 2011 (Geier, 2015). Although they only made up about 0.73% of total vehicle sales, some have predicted that their market share would reach 50% by 2030 (EPRI, 2007). It is well recognized that the deployment of public charging infrastructure plays a critical role in nurturing the EV market and promoting the adoption of EVs (e.g., Morrow et al., 2008; He et al., 2013a; Nie and Ghamami, 2013). Among various types of charging technologies, charging-while-driving (CWD) holds great promise. It can be achieved by either conductive or inductive charging. The former is similar to the technology used for trams and trains, charging EVs via lines overhead or metal bars in the pavement, while the latter, often referred to as dynamic wireless charging, transmits power without using any physical connector; the enabling mechanism includes, among others, inductive coupling, magnetic resonance coupling and microwaves (Vilathgamuwa and Sampath, 2015). CWD can electrify roads to be a charging infrastructure (He et al., 2013b). With charging lanes deployed, EV drivers may not fear any more running out of battery en route. Such a pervasive wireless charging platform can mitigate or even eliminate the “range anxiety” of EV drivers and further boost the adoption of EVs.

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Recent progress shows CWD and charging lanes are on the horizon (e.g., Cirimele et al., 2014; Lukic and Pantic, 2013; Ning et al., 2013; Yu et al., 2011; Choi et al., 2013; Shinohara et al., 2013; Vilathgamuwa and Sampath, 2015; Fuller, 2016). The Energy Dynamics Laboratory at Utah State University has proved that enough power can be transferred wirelessly to safely and effectively charge electric vehicles (Morris, 2015). Future versions of their system are expected to wirelessly charge vehicles at a speed of 75 mph. Companies such as Scania and Qualcomm are also developing their own inductive charging technologies. 15 miles of charging lanes have been constructed in Gumi, South Korea, which recharge a dozen of buses while in motion (Bansal, 2015). Scania and Siemens are investigating an overhead charging technology and have a 2 km test track outside Berlin (Scania Newsroom, 2014; Herron, 2014). Volvo is field testing two conductive charging technologies at a 4 m track near Gothenburg, Sweden (Schiller, 2013). The British government is working with BMW, Renault and Scania to test dynamic wireless charging technology in 2015 (TRL, 2015). Siemens, in conjunction with Volvo, is to trial an eHighway system on a two-mile stretch of highway in California in the vicinity of the ports of Los Angeles and Long Beach (Siemens, 2014). Recently, after completing a feasibility study, Highways England has announced to trial charging lanes in 2015 (Highways England, 2015a,b).

We thus envision in this paper that charging lanes are deployed in general road networks via either conductive or inductive charging. With charging lanes deployed, drivers of EVs, when traveling between their origins and destinations, can select routes and decide battery recharging plans to minimize their trip times while preventing the batteries of their vehicles from running out of charge. A battery recharging plan will dictate which charging lane to use, how long to charge, and at what speed to operate an EV. The operating speed will decide how long the EV will stay on a charging lane, thereby affecting the amount of electricity that can be recharged. More specifically, a lower operating speed will allow more time to recharge but yield higher travel time. Therefore, EV drivers need to make a tradeoff between their energy need and travel time. Although previous studies have formulated network equilibrium models with EVs (e.g., Jiang et al., 2012, 2014; He et al., 2014, 2015, 2016), all focus on accommodating the limited driving range of EVs, and none is able to capture such a tradeoff, which arises uniquely in the context of charging lanes. With the tradeoff, the relationship between traffic volume and actual travel time is no longer described by a single link performance function. Drivers' choice of operating speeds on charging links need to be explicitly modeled. In this paper, we will first consider EV drivers' route choice and recharging decision over a network where charging lanes are deployed and formulate a new user equilibrium model to describe the consequent equilibrium conditions.

We then proceed to optimize the deployment plan of charging lanes over a general network. A large body of literature has been devoted to optimal locations of refueling, recharging or battery swapping stations for EVs in a metropolitan area (see, e.g., Dong et al., 2014; Jung et al., 2014; Riemann et al., 2015). However, most of them do not consider the impacts of charging infrastructure on EV drivers' travel choices. Among a few exceptions, He et al. (2013a) assumed that the availability of charging opportunities may affect drivers' destination choices and subsequently allocate charging stations to maximize social welfare associated with transportation and power networks. Kang and Recker (2014) investigated individuals' activity scheduling and routing with refueling, and then determined optimal locations of refueling stations for alternative fuel vehicles. Jung et al. (2014) proposed a bi-level programing model for locating electric taxi charging stations where a dispatch algorithm at the lower level determines where a taxi should be replenished and which station the taxi should visit. Recently, He et al. (2015) optimized the location of charging stations by considering EV drivers' adjustments of travel and recharging decisions. In this paper, as charging lanes will inevitably affect drivers' route choice and recharging decision, such spontaneous reactions need to be proactively accommodated when optimizing the locations of charging lanes.

For the remainder, Section 2 presents the operational concept of charging lanes considered in this paper and basic assumptions for the proposed models. Section 3 formulates a network equilibrium model and discusses its solution algorithm. The deployment of charging lanes is optimized in Section 4. Lastly, Section 5 concludes the paper.

2. Basic considerations

It is envisioned that a government agency strategically locates charging lanes along certain road segments. When traveling between their origins and destinations, drivers of EVs make route choices and decide whether to use the lanes. They can decide where to enter and leave the lanes, how long to charge, and at what speeds they operate their vehicles. It is plausible that the amount of energy transferred from a charging lane to an EV will depend on the time that the vehicle stays on the lane. Therefore, driving speed is one of the critical decisions for charging an EV. Drivers can also decide whether to charge their vehicles while driving on charging lanes. In other words, EVs are not necessarily charged on charging lanes.

Since the overarching goal of this paper is to optimize the deployment plan of charging lanes, a static game-theoretic modeling framework is adopted, which does not allow us to fully capture the operational characteristics of charging lanes. Below we summarize our basic considerations or assumptions for the modeling and analysis of charging lanes in this paper:

I. A link in the network is either a regular or charging link. All lanes on a charging link are charging lanes. This consideration is not overly restrictive as we can always represent charging lanes as separate links.
II. All vehicles in the network are EVs with the same battery size and initial state of charge (SOC). This assumption can be easily relaxed by introducing multiple classes of EVs.