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Deployment of stationary and dynamic charging infrastructure for electric vehicles along traffic corridors

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A B S T R A C T

As charging-while-driving (CWD) technology advances, charging lanes can be deployed in the near future to charge electric vehicles (EVs) while in motion. Since charging lanes will be costly to deploy, this paper investigates the deployment of two types of charging facilities, namely charging lanes and charging stations, along a long traffic corridor to explore the competitiveness of charging lanes. Given the charging infrastructure supply, i.e., the number of charging stations, the number of chargers installed at each station, the length of charging lanes, and the charging prices at charging stations and lanes, we analyze the charging-facility-choice equilibrium of EVs. We then discuss the optimal deployment of charging infrastructure considering either the public or private provision. In the former, a government agency builds and operates both charging lanes and stations to minimize social cost, while in the latter, charging lanes and stations are assumed to be built and operated by two competing private companies to maximize their own profits. Numerical experiments based on currently available empirical data suggest that charging lanes are competitive in both cases for attracting drivers and generating revenue.

1. Introduction

The market size of electric vehicles (EVs) has grown steadily in recent years due to the rapid development of battery technology, concern over climate change, and the growing deployment of public charging infrastructure (e.g., Statista, 2016a, 2016b). Generally, charging infrastructure can be classified into two types: stationary and dynamic. The former, i.e., charging stations and battery swapping stations, have been deployed in many places, where vehicles need to stop for services. The latter, i.e., charging lanes that can charge vehicles while they are in motion, is an emerging application of charging-while-driving (CWD) technology being developed and tested around the world. Charging lanes function by either conductive or inductive charging. The former charges EVs via lines overhead or metal bars in the pavement, while the latter transmits electric power via inductive coupling, magnetic resonance coupling or microwaves (Vilathgamuwa and Sampath, 2015). Recent conductive charging experiments include Scania's field test at a 2-kilometre Siemens eHighway in Gross Dolln, Germany (Herron, 2014; Scania Newsroom, 2014) and the construction of a 400-meter track by Volvo near Gothenburg, Sweden (Schiller, 2013). On the other hand, a 15-mile inductive charging lane has been constructed in Gumi, South Korea

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to serve a dozen buses (Bansal, 2015). Other companies and universities, such as Qualcomm and Utah State University, are also testing their own CWD technology.

Anticipating that charging lanes can be technically ready for deployment in the foreseeable future, this paper investigates the deployment of charging stations and lanes along a long traffic corridor, in which charging infrastructure is more critical for EVs to finish their trips than in dense residential areas (Nie and Ghamami, 2013). We are particularly interested in determining how charging lanes compare with charging stations. To do so, we model EV drivers' choice of charging facility and then optimize a deployment plan of charging stations and lanes along the corridor to serve the charging need of EVs. The deployment plan specifies the number of charging stations, the number of chargers installed at each station, the length of charging lanes, and charging prices at charging stations and lanes. Based on the deployment plan, we explore the competitiveness of charging lanes for attracting drivers and generating revenue.

We consider two scenarios of charging infrastructure provision: a government agency builds and operates both types of charging facilities or private companies are franchised to do so. For the former, the government agency is considered to minimize the social cost (we refer to this situation as the "public provision"). For the latter, different operators may compete with each other to maximize their own profits (we refer to this as the "private provision"). For simplicity, it is assumed in this paper that there are two private operators each specialized in providing either charging lanes or charging stations. Based on both the public and private provision scenarios, we investigate the optimal deployment of the charging infrastructure and examine the competitiveness of charging lanes.

In contrast to a large body of literature on charging station deployment (see, e.g., He et al., 2013, 2015, 2016; Ghamami et al., 2016, for recent reviews), there are a limited number of studies on the deployment of charging lanes. Riemann et al. (2015) formulated a flow-capturing model to optimize the location plan of charging lanes, and a linearized approach is proposed to solve the model. Fuller (2016) proposed an optimization approach to minimize the total capital cost of deploying charging lanes on the California freeway network. Chen et al. (2016) developed a novel user equilibrium model to describe EV drivers' travel and charging choices when charging lanes are deployed. Further, an optimal deployment of charging lanes is obtained by solving a mathematical program with complementarity constraints. In a series of efforts, Jang and his colleagues optimized the locations of charging lanes and the battery size to minimize the total social cost for an electrified bus line (e.g., Jang et al., 2015, 2016a, 2016b; Jeong et al., 2015; Ko and Jang, 2013; Ko et al., 2015). In particular, Jang et al. (2016a) qualitatively compared stationary, quasi-dynamic, and dynamic wireless charging and suggested that dynamic wireless charging may not be as competitive as the other two due to the high infrastructure cost.

This study contributes to the literature by offering, to our best knowledge, the first study that investigates the deployment of different types of charging infrastructure while taking into account drivers' choice of charging facilities; it explores the competition between charging facilities and examines the competitiveness of charging lanes in both public and private provision scenarios.

The remainder of the paper is organized as follows. In the next section, basic assumptions for the proposed models are presented. In Section 3, the charging-facility-choice equilibrium is formulated to delineate EV drivers' choice of facility for charging their vehicles. Section 4 then models the optimal deployment of charging stations and lanes under both the public and private provision, followed by a discussion and analysis of their solutions in Section 5. Section 6 provides empirical analysis to examine the competitiveness of charging lanes, and Section 7 concludes the paper.

2. Basic considerations

Since the intent of this paper is to answer a "big picture" question regarding the competitiveness of charging lanes against charging stations, we adopt a highly simplified setting, first used by Nie and Ghamami (2013), where there lies a traffic corridor and fully-charged EVs with identical battery size travel from one end to the other; the corridor is sufficiently long so that no EV can finish the trip without recharging. We will discuss the deployment of charging stations and lanes along the corridor. The models to be developed are macroscopic, and do not attempt to optimize specific locations of charging stations and lanes. Instead, they aim to provide a mathematically tractable means to characterize the deployment and operations of charging lanes and stations. Considerations and assumptions of the modeling framework are summarized as follows:

i. Both charging stations and charging lanes are deployed along the corridor.
ii. The number of charging stations is sufficient to support a trip, i.e., an EV can finish its trip by charging only at charging stations.
iii. Similarly, charging lanes are sufficiently long to support a trip, i.e., an EV can traverse the corridor by using charging lanes only.
iv. Charging stations are uniformly deployed along the corridor (see Fig. 1).
v. Charging lanes can be intermittent, and the length of each segment may be different (see Fig. 1).
vi. Travel speed of EVs across the corridor is constant.
vii. EVs do not need to slow down to recharge on charging lanes.
viii. There is no delay for accessing or egressing a charging station nor waiting for a charger at the station.
ix. While preventing their vehicles from running out of energy, drivers of EVs minimize their travel costs, which consist of driving time, a charging fee and the charging time at charging stations or the equipment cost for enabling CWD.