Transportation Research Part C 58 (2015) 1–12

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Optimal location of wireless charging facilities for electric vehicles: Flow-capturing location model with stochastic user equilibrium

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ARTICLE INFO

Article history:
Received 19 November 2014
Received in revised form 13 May 2015
Accepted 22 June 2015

Keywords:
Location
Optimization
Stochastic user equilibrium
Electric vehicle
Wireless power transfer
Charging facility

ABSTRACT

In this study, the optimal locations of a specific type of charging facilities for electric vehicles (EVs), wireless power transfer facilities, are investigated. A mathematical model has been developed to address this problem. The objective of the model is to locate a given number of wireless charging facilities for EVs out of a set of candidate facility locations for capturing the maximum traffic flow on a network. The interaction between traffic flow patterns and the location of the charging facilities is incorporated explicitly by applying the stochastic user equilibrium principle to describe electric vehicle drivers' routing choice behavior. Firstly, the problem is formulated into a mixed-integer nonlinear program, secondly a solution method is developed to obtain the global optimal solution of the linearized program. Numerical experiments are presented to demonstrate the model validity.

1. Introduction

Electric vehicles (EVs) have been developed as a promising solution for reducing vehicle emissions and petroleum dependence. However, without sufficient and convenient charging infrastructure, EVs will not be used by the broader public because of the range limitation and the resulting anxiety over the available range (Egbue and Long, 2012). Several types of charging infrastructure are available, for instance, plug-in charging (conductive) and wireless charging (inductive). In this study, the optimal locations of charging facilities with wireless power transfer are investigated. EVs, which are equipped with a pick-up coil, can use electromagnetic induction for wireless charging when they are driven over charging patches on the road. Wireless power transfer offers a number of advantages over plug-in charging: first, it is a more convenient way of charging for EV drivers because a physical charging cable is not needed; second, less urban space is required for EV charging on dedicated EV parking spots, which is ideal for cities with limited land resources, such as Singapore and Hong Kong. In Korea, a practical demonstration of a possible vehicle-infrastructure set-up featuring wireless charging was shown in 2010 (The Independent, 2010).

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http://dx.doi.org/10.1016/j.trc.2015.06.022
0968-090X/

1.1. Literature review

Owing to the high investment in building wireless charging facilities for electrification roadways, it is imperative for planners to understand the optimal location of these facilities. Mathematical frameworks describing the optimal power transmitter placement and battery capacity for wirelessly charged EVs operating on fixed routes are presented by Ko et al. (2012) and Jang et al. (2012). He et al. (2013a) presented an approach to determine the optimal prices of electricity and roads for wireless power transfer by maximizing social welfare and by considering scenarios of full and partial electrification of roads.

In literature, problems related to the optimal location of plug-in charging facilities have received much attention. A portion of the research can be classified as the maximal covering location problem (MCLP), which seeks to maximize demand coverage by locating a fixed number of facilities. This follows the seminal work of Church and ReVelle (1974). For comprehensive reviews on location science, one can refer to Farahani et al. (2012), Daskin (2008), and Hale and Moberg (2003). However, the MCLP deals with static point demands at nodes only. Hodgson (1990) considered network demands in the form of origin–destination flows and developed the flow-capturing location model (FCLM) to determine the optimal location of charging facilities. The FCLM aims to maximize the captured flow and thereby considers the quantity of flow between the origin and destination and the path of flow (Hodgson, 1990). Over the past decades, several researchers have extended the FLCM. For instance, Kuby and Lim (2005) complemented the FCLM by formulating the flow refueling location model (FRLM) which includes a flow refueling logic for alternative-fuel vehicles. Later, Kuby and Lim (2007) extended the FRLM by developing methods to determine possible candidate sites on links. Lim and Kuby (2010) proposed heuristic algorithms to solve the FRLM model more efficiently. Another extension, the capacitated flow-refueling location model, was introduced by Upchurch et al. (2009), who proposed to consider the limited capacity of charging facilities. Furthermore, the deviation-flow refueling model proposed by Kim and Kuby (2012) allows for the incorporation of deviations from the shortest paths. Additional publications dealing with the incorporation of deviation paths were presented by Huang et al. (2015) and Kim and Kuby (2013). In addition, Capar et al. (2013) presented a more efficient formulation of the FRLM, the arc cover path-cover FRLM (AC-PC FRLM). Furthermore, Wang and Lin (2013) developed a model for a capacitated multiple-recharging-station-location model including a vehicle-refueling logic.

An equilibrium-based modeling framework for locating plug-in charging facilities, which considers transportation and power networks and maximizes social welfare, was developed by He et al. (2013b). He et al. (2013c) presented a study which considers electricity prices and road pricing as instruments to improve the management of transportation and power networks. Dong et al. (2014) developed an activity-based approach for charging station planning. Additionally, He et al. (2014) presented three different network equilibrium models for battery electric vehicles (BEVs); these models integrated different flow dependencies and energy consumptions.

1.2. Contribution

In this study, we seek to address the optimal location problem of wireless charging facilities with a given number of wireless charging facilities to be deployed. The optimal location of wireless charging facilities for roadway electrification should ensure that the captured traffic flow on these roads is maximized, in other words a maximum number of vehicles can use these roads and access the wireless charging facilities. Consequently, the principle of the AC-PC FRLM can be applied to address this location problem. However, previous FCLMs and FRLMs found in the literature determine traffic flow assignment on the network by assigning the origin–destination (OD) demand to the shortest path on the basis of the assumption that travelers' routing choice behavior is governed only by the travel distance. Other factors such as availability of charging facilities and traffic congestion are not considered. Nevertheless, in the FCLMs and FRLMs, the traffic flow assignment on the network is the primary factor that determines the plan for optimal charging facilities' location. It is imperative for the location model to completely capture drivers' routing choice behavior. In reality, charging facility availability might affect the routing choice in a way that EV drivers are more likely to choose routes with charging facilities to mitigate range anxiety. Indeed, the location of charging facilities and traffic flow assignment are interactive, and this interaction can be incorporated into the AC-PC FRLM. In addition, the effects of traffic congestion on travel time should also be captured in the travelers' routing choice behavior. Previous studies pertaining to the development of the FCLMs and FRLMs did not completely consider these factors in electric vehicles' routing choice behavior. In this paper, both traffic congestion and the availability of wireless charging facilities are considered in the modeling framework. For illustration purposes, the multinomial logit (MNL) model stochastic user equilibrium (SUE) principle is employed to capture drivers' routing choice behavior. Previous FCLM and FRLM treat the network flow pattern as exogenously given, which is determined by the shortest-path principle and thus dictates the optimal location of charging facilities. In this study, the network traffic flow is determined endogenously using the SUE principle. On one hand, the optimal location of wireless charging facilities is decided by the equilibrium traffic flow; on the other hand, the location also affects drivers' routing choice and thus the equilibrium traffic flow.

Subsequently, the mutual interaction between the location of charging facilities and the resultant network traffic flow is considered explicitly in the model formulation for optimizing charging facility location. This is achieved by extending the AC-PC FRLM to take stochastic network loading into account. Furthermore, two influencing factors are considered: travel time and the availability of charging stations. The model is formulated into a mixed-integer nonlinear programming problem, which is intrinsically non-convex. A global optimization method is developed to solve the formulated model. Noting that the nonlinear terms of this problem stems from a bilinear function, MNL model, and nonlinear travel time function;