Transportation Research Part E 110 (2018) 189–213

Contents lists available at ScienceDirect

Transportation Research Part E

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

A user-choice model for locating congested fast charging stations

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ARTICLE INFO

Keywords:
Electric vehicle
Fast charging
Location problem
User-choice behaviour
User-choice model
Congestion

ABSTRACT

We consider a maximal coverage problem for locating congested fast charging stations and deploying chargers in a stochastic environment. A user-choice behaviour considering various factors is modelled. A user-choice model fully reflecting it and system-choice models partially reflecting it are derived. A case study shows the decisions by the system-choice models may result in huge congestion from the user-choice behaviour, and it gives the following main managerial implications for the user-choice model. The model seems to make robust location decisions for different settings of budget and utility function parameters, and it may give less coverage when allowing a long detour.

1. Introduction

Electric Vehicles (EVs) such as hybrid EVs, plugin hybrid EVs, and battery-powered EVs use little fossil energy or none at all. Thus, as more EVs are used in place of combustion engine vehicles, the use of fossil fuel can be reduced more. For this reason, EVs have been receiving attention as eco-friendly vehicles. Many countries are therefore encouraging people to adopt EVs with various incentives, including consumption tax reduction, subsidy provision, and reduced parking prices. Nevertheless, the penetration rate of EVs was lower than expected (International Energy Agency, 2013, 2016). One of the biggest reasons is that people feel that the charging takes too long compared to refuelling combustion engine vehicles.

However, this inconvenience has been improved by (level 3) fast charging technologies, including the CHArge de Move standard (CHAdeMO) and the Combined Coupler Standard (CCS). Fast charging technologies enable an EV battery to be charged to up to 80% of its rated capacity within 0.2–1 h, whereas earlier level 1 and level 2 charging standards require 11–36 h and 2–3 h (Yilmaz and Krein, 2013). To increase the penetration rate of EVs, the large-scale deployment of fast charging stations (FCSs) may be crucial. For example, the Korean government has plans to deploy more FCSs for public charging service and even replace the deployed level 1 and level 2 charging stations with FCSs. As of 2015, 337 public FCSs have been deployed in Korea and 300 FCSs are planned for deployment by 2017 (Ministry of Environment of South Korea, 2015). In such a situation, the design problem for the service network with FCSs is an urgent issue for FCS service providers to solve.

1.1. Literature review

Let us review the related studies. First, we review network design problems for charging or refuelling service facilities. Second, although refuelling or charging facilities are given, a recent problem, where decisions for EVs as well as conventional vehicles should be determined at the same time, is reviewed. Then, problems for locating congested facilities in stochastic environments are reviewed, even for applications other than refuelling or charging facilities.

Researchers have been studying various network design problems for charging or refuelling service facilities. The problems can be

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https://doi.org/10.1016/j.tre.2017.11.009
Received 11 May 2017; Received in revised form 19 October 2017; Accepted 18 November 2017
1366-5545/

divided into inter-city and intra-city problems according to whether the charging facilities support long-distance or short-distance trips (Wang and Wang, 2010; Ghamami et al., 2016a). The word "city" in this case represents a region that is small enough for general trips to be completed via single-stop refuelling. The inter-city problems are associated with a network representing a large region with many cities represented by nodes. Such problems focus on multi-stop refuelling to enable drivers to complete long-distance origin-destination (O-D) trips over a general network.

Kuby and Lim (2005) dealt with a problem to maximize the total coverage for flow-based demands with a fixed number of facilities, which is a maximal coverage problem. In the problem, a flow-based demand is represented as the related path and the number of vehicles on it. This type of demand is used to model vehicle mobility explicitly and reflect the typical refuelling behaviour at charging facilities on a driving path. Wang and Lin (2009, 2013) considered a set-covering problem to minimize the number of stations while satisfying all flow-based demand. All these inter-city problems assume that each demand can travel via the associated shortest path only. Kim and Kuby (2012) and Li and Huang (2014) relaxed the assumption and allowed one of the paths within a small deviation from the shortest one to satisfy each demand. They proposed a maximal coverage problem and a set-covering problem, respectively. However, all the mentioned inter-city problems are deterministic problems. Hosseini and MirHassani (2015) considered the stochastic nature in the actual number of service requests via a scenario approach, but did not consider the stochastic nature in the actual timing of service requests and the service time at facilities. The scenario approach seeks to maximize the expected coverage in the situation where there are two types of stations (permanent and portable) and the actual number of service requests for each flow-based demand varies with scenarios each having its occurring probability. Note that all of these inter-city problems assume flow-based demand to consider vehicle mobility.

Meanwhile, two studies to be reviewed dealt with somewhat different intra-city problems from the above problems which focused multi-stop refuelling for flow-based demands over a general network. Ghamami et al. (2016b) developed a model to locate charging stations at evenly distant candidate nodes along a corridor and deploy chargers to the charging stations. O-D trips, each associated with the O-D pair and the O-D trip rate, are given, and each trip take places in the identical interval associated with the rate over a corridor, not a general network. The model minimizes the total system cost composed of infrastructure construction cost, inconvenience cost (represented as the sum of travel and waiting time for the trips), and battery cost while completing all trips. He et al. (2013) provided an algorithm to obtain the optimal number of charging stations to be constructed in each city in order to maximize the total utility in equilibrium, under the following assumptions. The authors considered charging in destination cities to travel, not multi-stop refuelling in the middle of O-D trips. The travel time on the road is assumed to be affected by the number of EVs passing through it. Given deterministic travel demand from EV users in each city (represented as a node), they focused on the user-choice behaviour that EV users choose cities and the routes that maximizes their own utility function composed of travel time, the number of charging stations at the destination, locational attraction, and charging price when choosing cities to travel. This study is distinct from the above studies in that the user-choice behaviour is considered. The charging price is assumed to vary across cities, with the price being affected by EVs traveling to the city and the electricity power network to supply electricity to charging stations in the city.

In contrast, intra-city problems are associated with a network representing a small region that includes a metropolitan city or a few small cities, and the nodes in the network represent administrative districts or specific locations within the region. Due to the relatively small region, single-stop refuelling is assumed for short-distance O-D trips or refuelling demands originating from nodes, during the analysed time period.

Under the assumption that short-distance O-D trips can be completed via single-stop refuelling, Hodgson (1990), Berman et al. (1992, 1995) have dealt with problems for locating uncapacitated refuelling facilities in a deterministic environment. The main application area of these studies was gas stations, but they can be used as base problems to develop extended problems, which other major considerations are additionally taken into account, for EV charging facilities. It is noteworthy that the above inter-city problems focusing multi-stop refuelling are extended problems, inspired by these studies. More specifically, Hodgson (1990) and Berman et al. (1992) dealt with maximal coverage problems for flow-based demands, each of which is associated with the predetermined path and the flow amount. As extended problems from these studies, Berman et al. (1995) have developed three models by allowing one of the paths within a small deviation from the shortest one to satisfy each demand. Among the models, two ones are maximal coverage problems and the other one is a set covering problem. Meanwhile, Zockaie et al. (2016) studied a problem of locating fuel stations to minimize the extra cost spent in refuelling while satisfying all flow-based demands via single-stop refuelling. In the problem, each flow-based demand is associated with the O-D pair and the flow amount. The authors proposed a base model for uncapaciated facilities as a mixed integer program along with an extended model for capacitated facilities, and they also developed a simulated annealing heuristic for the models.

On the other hand, under the assumption that refuelling demands originate from nodes and the demands can be satisfied via single-stop refuelling during the analysed time period, most of recent studies have focused on the accessibility to charging stations from long stay spots, such as residences or workplaces. Thus, node-based demand is assumed, which implies that demand originates from nodes in the network. Compared with flow-based demand, this type of demand does not explicitly represent the mobility of EVs.

Dashora et al. (2010) proposed a model that includes the capacities at charging stations to minimize the total construction cost of charging stations and the traveling cost to them for node-based demand, which is a capacitated fixed-charge location problem. Frade et al. (2011) dealt with a problem subject to capacities at charging stations to maximize the coverage weighted with the associated traveling cost for node-based demand, which is a capacitated maximal coverage problem. Cavadas et al. (2015) assumed that the parking times at candidate station nodes representing parking locations are known for each EV. The demand contribution for each node was computed from the parking times. They allowed each EV to charge in at most one of such nodes and proposed a capacitated maximal coverage problem with node-based demand. Ghamami et al. (2016a) and Zhu et al. (2016) dealt with capacitated fixed-charge location problems similar to Dashora et al. (2010). Ghamami et al. (2016a) proposed an extended model where node-based