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Equitable distribution of recharging stations for electric vehicles

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ABSTRACT

Given the limited driving range of battery electric vehicles and lack of sufficient charging infrastructure, locating charging stations is an important decision problem to enable long-distance travels by battery electric vehicles. This paper considers an important political factor in such location problems: the equitable access to charging stations among geographical regions. We propose three types of equity constraints to the flow refueling location model: two constraints based on travel demand and the other based on traffic flow. For solving the problem with flow equity constraints, we propose a multi-phase heuristic method. We test the proposed models and computational method in a real expressway network in Korea.

1. Introduction

In the United States, the transportation sector comprises 28% of total greenhouse gas emissions. Light-duty vehicles, such as passenger cars and light trucks are responsible for 62% of total greenhouse gas emissions [32]. As a way to solve the greenhouse gas problem of the transportation sector, electric vehicles (EVs) have attracted public attention. The CO2 emission per mile of EVs, including emission during electricity production, is approximately 50% of the CO2 emission per mile of fossil fuel vehicles [25]. Also, the travel cost of EVs (2–3 cents per mile) is cheaper than the travel cost of fossil fuel vehicles (13 cents per mile) [18]. Due to the environmental and economic advantages of EVs, the demand for EVs is predicted to gradually increase. However, there are two barriers to the widespread adoption of EVs. One is the limited driving range of EVs per refueling, and the other is an insufficient refueling station infrastructure [2,15,28]. The driving range of EVs is typically much shorter than the driving range of fossil fuel vehicles. The driving range of most EVs on the market since 2014 is about 60 km–160 km [5]. The only way for a mass number of drivers to utilize EVs as a primary vehicle, despite the limited driving range of EVs, is the construction of a sufficient refueling station infrastructure. However, no investors are interested in supporting an EV refueling station infrastructure under the circumstances that there are only a few EVs. On the other hand, consumers will not buy EVs if the refueling station infrastructure remains insufficient [22,29]. To facilitate the widespread adoption of EVs while solving this early-stage problem, government support for constructing infrastructure is needed [6]. Moreover, the number of refueling stations that can be constructed with initial government support is not sufficient to cover all EV demand. Accordingly, strategic planning to construct refueling stations at optimal locations is necessary.

In this paper, we consider a *public* EV recharging station location problem, especially when the government is involved in the location decision and the operations of those stations. As illustrated in Section 4, we consider the Korean Expressway network as a case study subject, which is managed and operated by the government and public companies; therefore charging stations become public properties. There have been a lot of research works on how to optimize an EV refueling station network [13,14,31,34]. The majority of previous studies have focused on identifying the best locations for refueling stations to maximize traffic flow. Based on this objective, most studies designate optimal locations for refueling stations in metropolitan or downtown areas, where traffic flow is high. Taking into account the *public* nature and the *equitable* distribution of facilities, however, it is inappropriate to densely locate refueling stations in only certain regions. In particular, when it comes to designating locations for public service facilities—the objective of which is not profit maximization—it is important to equitably distribute the benefits of facilities to all stakeholders.

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Equity is more greatly influenced by location changes and facility capacity than efficiency [21]. Accordingly, equity should be prioritized in addressing issues of facility location, particularly in the context of public service facilities. In terms of designating locations for EV refueling stations, however, there is no research considering the issue of equity.

While there have been equity considerations in the literature of other transportation and public facility areas, it remains rather unclear what type of equity constraints is the most appropriate form to be considered in the context of EV recharging station location problems. To fill this gap in the literature, this paper suggests and compares three kinds of equity constraints for a refueling station location model, and applies them to an arc-cover path-cover flow refueling location model (AC-PC FRLM) proposed by Capar et al. [3]. We compare three equity constraints in terms of both computational efficiency and locational differences.

The remainder of this paper is organized as follows. In Section 2, we review related research. The formulation of AC-PC FRLM and equity constraints are introduced in Section 3. In Section 4, numerical experiments are conducted using data from the Korean Expressway network. We discuss a way to generate equitable distribution networks and propose a multi-phase method to efficiently find solutions. Section 5 concludes the paper with suggestions for future research.

2. Literature review

We provide a review of the current literature. We first introduce related research results in refueling/recharging station location problems for alternative-fuel or electric vehicles. Then we discuss equity issues considered in general other transportation problems.

2.1. Refueling station locations

Several attempts have been made to designate optimal locations for EV refueling stations. The existing work on the topic can be classified according to its perspective on demand, with node-based demand models and flow-based demand models. The *p*-median model is a well-known node-based demand model. The *p*-median model locates *p* facilities to potential nodes to minimize the total weighted distance between demand nodes and the nearest facilities [9]. Nicholas and Ogden [26] used the *p*-median model to determine the number of hydrogen refueling stations required to satisfy a certain level of service. Similarly, Lin et al. [17] determined optimal locations for hydrogen refueling stations using the *p*-median model. The authors used vehicle miles traveled to minimize the total fuel-travel-back travel time. However, node-based demand models are not suitable for the problem of determining locations for refueling stations, because people prefer to visit refueling stations on the way to a destination rather than to visit stations only for purposes of refueling [11]. Moreover, Moreover, Upchurch and Kuby [30] compared the *p*-median model and FRLM by applying the locations derived from each model to the objective function of the other. The results showed that the location scheme derived from the FRLM performs better than that of the *p*-median model.

Flow-based demand models can be classified into sets of covering location models and maximal covering location models. Wang and Lin [34] developed a flow-based set covering model that is applicable when traffic flow data is not available. They applied this set covering model to the Taiwan network, and observed changes in the number of refueling stations according to changes in driving ranges and refueling coefficients representing the amount of fuel required for a vehicle to completely refuel at each node. Wang and Wang [36] proposed a multi-objective model that minimizes costs and maximizes covered population based on vehicle refueling logics, and solved it with a weighted sum method. Wang and Lin [35] extended the model by Wang and Lin [34], taking into account multi-type refueling stations, capacity of nodes, and budget limitations.

The second type of flow-based demand model is a maximal covering location model. Hodgson [10] introduced a maximal covering location model that locates *p* facilities to maximize the total traffic flow covered. The model is called the flow capturing location model (FCLM), and is the basis of FRLM. In FCLM, demand is expressed as the traffic flow between pairs of origin and destination (OD), and traffic flow is captured when there is at least one service facility located on the OD route. It is not appropriate to apply FCLM to the EV refueling station location problem, because an EV may need to be refueled more than once to complete a long-distance trip due to the limited driving range of EVs.

Kuby and Lim [14] extended FCLM to FRLM in order to account for the need for multiple refueling stops on a path by using combinations of nodes that enable round trips without fuel shortages. This model requires combinations of nodes for all OD pairs, which are determined in a pre-generation stage. Thus it is time-consuming work for any large-scale network. To avoid pre-generation work and reduce computation time, Lim and Kuby [16] developed three heuristic algorithms (a greedy-adding algorithm, a greedy-adding with substitution algorithm, and a genetic algorithm) that do not require the generation of combinations to solve FRLM. Applying the heuristic algorithms to the state of Florida's network obtained solutions in a way that typical FRLM was unable to, because the extensive generation of combinations was impossible for such a large-sized network. Capar and Kuby [2] developed a new formulation for FRLM that does not require the pre-generation of combinations. They also experimented with the formulation in the context of the Florida state network, comparing the new formulation with the heuristic algorithms [16]. MirHassani and Ebrazi [24] proposed the reformulation of FRLM with the concept of an expanded network.

Capar et al. [3] introduced AC-PC FRLM to determine an optimal location scheme for refueling stations. In AC-PC FRLM, a traffic flow is successfully refueled when all the arcs in the route are passable without an out-of-fuel status. The results of this experiment showed that AC-PC FRLM provides faster solutions than the formulation by Capar and Kuby [2] in large-scale networks. Our formulation and computation method are developed based on AC-PC FRLM.

Some researchers have extended the basic FRLM model in various directions. Upchurch et al. [31] extended FRLM by considering the capacity of refueling stations. Kim and Kuby [13] relaxed one of the assumptions of FRLM, which states that drivers use a fixed route. The authors took into account that drivers change their routes to accommodate nearby refueling stations, which are not always on the shortest or most direct route to a destination. Chung and Kwon [5] proposed multi-period FRLM based on the formulation of MirHassani and Ebrazi [24]. They compared the multi-period model with a single-period model that solves for each period based on the Korean Expressway network.

In this paper, we use the AC-PC FRLM model of Capar et al. [3] as the base model.

2.2. Equity

In making decisions regarding public services, it is important to take equity into account. The equity issue has been considered in several areas of research, including facility location problems for public services, hazardous materials management, and road network design. Marsh and Schilling [20] reviewed equity