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Multi-period planning for electric car charging station locations: A case of Korean Expressways

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ABSTRACT

One of the most critical barriers to widespread adoption of electric cars is the lack of charging station infrastructure. Although it is expected that a sufficient number of charging stations will be constructed eventually, due to various practical reasons they may have to be introduced gradually over time. In this paper, we formulate a multi-period optimization model based on a flow-refueling location model for strategic charging station location planning. We also propose two myopic methods and develop a case study based on the real traffic flow data of the Korean Expressway network in 2011. We discuss the performance of the three proposed methods.

1. Introduction

The use of electric passenger cars has gained considerable attention over the last decade as an environmentally friendly alternative to conventional cars that consume fossil fuels and emit greenhouse gases. There are, however, several barriers for electric cars to become more popular. The first and foremost barrier is the limited range that electric cars can be driven without recharging (Capar & Kuby, 2012; Lim & Kuby, 2010; Romm, 2006; Wang & Wang, 2010). Most electric cars available in 2014 have ranges, from a fully charged battery, of about 60 kilometers to 160 kilometers depending on various factors such as weather conditions, traffic congestion, and road types. Such driving ranges may be insufficient for electric cars to be used as a primary transportation mode. Another critical barrier is the lack of charging station infrastructure (Kuby & Lim, 2007; Melaina & Bremson, 2008; Ogden, 1999; Shukla, Pekny, & Venkatasubramanian, 2011; Wang, 2011). Since it would be difficult to increase the driving range of electric cars dramatically within the next few years, it is particularly important to have a well-planned charging station infrastructure. The goal of this paper is to help establish a multi-period strategic plan to build charging stations to maximize the total traffic flows covered.

There are a sizable number of papers in the literature that study and address the limited infrastructure issue and optimal locations for refueling or charging stations. Kuby and Lim (2005) suggest a flow-refueling location model (FRLM) to help find optimal refueling station locations for alternative-fuel vehicles (AFVs) that are powered by hydrogen, biofuels, or natural gas. The FRLM is based on the flow-intercepting model, proposed by Hodgson (1990) and Berman, Larson, and Fouska (1992), that maximizes the total traffic flow passing a given number of facilities such as service stations. The FRLM extends the flow-intercepting model and incorporates the requirement that AFVs need multiple refueling stations, rather than a single refueling station, for long trips. Lim and Kuby (2010) propose several heuristic methods to solve the FRLM. Wang and Lin (2009), Capar and Kuby (2012), and Capar, Kuby, Leon, and Tsai (2013) provide alternative formulations that are numerically more efficient. MirHassani and Ebrazi (2013) propose a network expansion method to improve the computability of the FRLM, which is the base of our proposed model.

While the FRLM is suggested for refueling station location problems for AFVs that usually require short refueling time, it can also be applied to electric vehicle charging station location problems under mild assumptions (Capar et al., 2013). Since the FRLM assumes drivers will stop at charging stations on the way to the final destination to gain additional driving range, it is apparent that Level 1 or 2 charging technologies, for which drivers need to wait 2–8 hours to fully charge their vehicles, are inappropriate. Therefore, we assume in our model that Level 3 fast charging or battery swapping technologies are used with about 20-minute long waiting time and that charging stations are uncapacitated, under which the FRLM and its variants would provide meaningful results.

Unlike other studies, our paper focuses on a multi-period optimal construction plan, since it may not be practical to build a sufficient number of stations within a short period of time due to, for example,

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the limited budget. Indeed, the authority responsible for building such infrastructure will not invest until there are enough electric cars to use the infrastructure. On the other hand, the potential consumers will be less inclined to buy electric cars unless there is sufficient charging station infrastructure (Bento, 2008); a so-called chicken-and-egg problem arises (Kuby & Lim, 2005; Leiby & Rubin, 2004; Melaina, 2007; Wang & Wang, 2010). We note that a market-driven approach may not resolve such an issue; thus, a strategic infrastructure plan controlled by a central authority is needed. In that vein, strategic multi-period planning is required to find a first stage construction plan, followed by next stage construction plans, and thereby to provide an overall plan over the planning horizon. In this paper, we propose three methods: a multi-period optimization method, a forward-myopic method, and a backward-myopic method. In our case study employing the real data of the Korean Expressway network, we show and discuss the results of the three proposed methods.

In traditional facility location problems that consider optimal initial, intertemporal, or terminal (re)locations of facilities, a multi-period scheme has been studied extensively since the seminal work of Wesolowsky (1973). Among others, it is worth mentioning Drezner (1995) for a dynamic p-median problem, Contreras, Cordeau, and Laporte (2011) for a multi-period uncapacitated hub problem, and Albareda-Sambola, Fernández, Hinojosa, and Puerto (2009) for a multi-period service facility location problem. However, to the best of our knowledge, our paper is the first to consider a multi-period refueling/recharging station location problem for alternative-fuel vehicles including electric vehicles. Miralinaghi (2012) considers multi-period travel demands, but not multi-period locational decisions.

In our case study, we apply the proposed methods to the Korean Expressway, which is mainly operated by Korea Expressway Corporation (KEC). KEC is a government-owned company, which determines locations of rest areas, facility types and sizes. When KEC would plan for charging stations, it would cooperate with Korea Electric Power Corporation (KEPCO) that is also government-owned. This makes a market-based approach for the Korean Expressway network much more unrealistic in addition to the fact that it is unsuitable for a charging station infrastructure problem in general due to the chicken-and-egg problem mentioned above. This paper considers methods for central planning.

Our contributions are summarized as follows: (1) we propose three methods to help construct a multi-period plan for charging station infrastructure; (2) we perform an extensive numerical case study with the real Korean Expressway data to compare the three proposed methods; (3) to further investigate the differences among the three proposed methods, we perform another numerical study using five different demand profiles; (4) we show that multi-period location decisions from the three methods can be significantly different; and (5) we show in our case study that excluding short-distance and low-demand paths makes the problem solvable with a standard optimization solver within a reasonable time without losing coverage.

The remainder of this paper is organized as follows. In Section 2, we discuss the formulation of the single-period FRLM. In Section 3, we introduce the three methods for multi-period planning. We describe the Korean Expressway network in Section 4, and explain how we collected, organized, summarized, and manipulated the network topology traffic volume raw data. We also provide descriptive statistics that are helpful to understand the Korean Expressway traffic pattern. In Section 5, we report extensive computational results under a variety of scenarios and describe insights gained. We conclude this paper in Section 6 with some remarks on future research directions.

2. An expanded network and the flow refueling location problem

In this section, we review the network expansion technique proposed by MirHassani and Ebrazi (2013) for formulating the FRLM, which is the base for the three methods proposed in Section 3 of this paper. First, we assume that there exists a unique shortest path for each origin–destination (O–D) pair, and also assume that drivers always use the shortest path. Associated with each shortest path are the travel demand, flow, and an O–D pair. A *path* is an ordered set of arcs from O to D; *demand* is the number of vehicles that want to travel from O to D; and *flow* is the movement of demand loaded on a path or an arc. When charging stations located on a path enable electric vehicles to travel on the path, we say that the *path is covered* by those charging stations; when the number of vehicles traveling on such a covered path is in discussion, we say that the *flow is covered*.

To introduce the network expansion technique proposed by MirHassani and Ebrazi (2013), we first consider a road network that consists of a *single path* q, denoted by $G(\mathcal{N}^q, \mathcal{A}^q)$ where $\mathcal{N}^q$ is the set of nodes on path q and $\mathcal{A}^q$ is the set of arcs on path q. The distance between any two nodes i and j on path q is denoted by $d_q(i, j)$ and the ordering index of node i on path q is denoted by $\text{ord}_q(i)$. For example, if i is the fourth node from the initial node on path q, then $\text{ord}_q(i) = 4$. We denote the driving range of an electric car by R.

We make two additional assumptions. If, for some two consecutive nodes i and j on path q, $d_q(i, j) > R$, then j is unreachable from i. Therefore, we assume that $d_q(i, j) \leq R$ for any two consecutive nodes i and j on any path q in the road network G. If there exists an arc with a length greater than the range R, then it is suggested to add node(s) on the arc—see Kuby and Lim (2007) for methods to generate candidate node locations. We also assume, following Kuby and Lim (2005), that cars are at least half charged at the origin and destination nodes. This implies that there must be at least one charging station within the distance of $R/2$ from the origin and the destination, respectively. If there is no charging station at the destination, a driver must have traveled some distance (up to $R/2$) from the last charging station to reach the destination at which the battery must remain at least half charged to visit the charging station for the next trip. The same logic applies to the origin node. Note that this assumption does not exclude the case where charging stations are located at the origin and/or the destination.

We construct an expanded network for each path q by adding the source and sink nodes and pseudo arcs to the existing network. We denote the expanded network for path q by $G(\widehat{\mathcal{N}}^q, \widehat{\mathcal{A}}^q)$ where $\widehat{\mathcal{N}}^q$ is the set of nodes and $\widehat{\mathcal{A}}^q$ is the set of arcs in the expanded network, respectively. The steps to construct the expanded network are illustrated as follows.

Step 1. Add a source node s before the origin node O and connect the two nodes by adding a pseudo arc (s, O). Also, add a sink node k after the destination node D and connect the two nodes by adding a pseudo arc (D, k). That is,

$$\widehat{\mathcal{N}}^q = \mathcal{N}^q \cup \{s, k\}, \quad \widehat{\mathcal{A}}^q = \mathcal{A}^q \cup \{(s, O), (D, k)\}$$

Step 2. Connect the source node s to any other node, say i, in path q by adding a pseudo arc (s, i) if node i can be reached from the origin node O with a half charged battery. That is,

$$(s, i) \in \widehat{\mathcal{A}}^q \quad \text{if} \quad d_q(O, i) \leq \frac{R}{2} \quad \forall i \in \mathcal{N}^q$$

Step 3. Connect the sink node k to any other node, say j, in path q by adding a pseudo arc (j, k) if the destination node D can be reached from node j with a half charged battery. That is,

$$(j, k) \in \widehat{\mathcal{A}}^q \quad \text{if} \quad d_q(j, D) \leq \frac{R}{2} \quad \forall j \in \mathcal{N}^q$$

Step 4. Connect any two nodes, say i and j, in path q if the ordering index of node i is less than that of node j, and node j can be reached from node i with a fully charged battery. That is,

$$(i, j) \in \widehat{\mathcal{A}}^q \quad \text{if} \quad \begin{cases} d_q(i, j) \leq R \\ \text{ord}_q(i) < \text{ord}_q(j) \end{cases} \quad \forall (i, j) \in \mathcal{N}^q$$