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Incorporating demand dynamics in multi-period capacitated fast-charging location planning for electric vehicles

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ABSTRACT

We develop a multi-period capacitated flow refueling location problem for electric vehicles (EVs) as the EV market responds to the charging infrastructure. The optimization model will help us determine the optimal location of level 3 chargers as well as the number of charging modules at each station over multiple time periods. Our model can also be applied to fast-filling gaseous alternative fuel vehicles under similar assumptions. We define a number of demand dynamics, including flow demand growth as a function of charging opportunities on path as well as natural demand growth independent of charging infrastructure. We also present an alternative objective function of maximizing electric vehicle demand in addition to maximizing flow coverage. A case study based on a road network around Washington, D.C., New York City, and Boston is presented to provide numerical experiments related to demand dynamics, showing the potential problems in multi-period planning.

1. Introduction

Recently, alternative fuel vehicles (AFV) are gaining attention worldwide due to growing concerns of environmental problems. Different types of fuel including electricity, natural gas and hydrogen try to take place of petroleum to reduce the greenhouse and other emissions. However, the refueling facility network for AFVs is not as mature as that of conventional gas stations and is not widely distributed. The deficiency of charging stations has been mentioned as one of the barriers that prevent AFVs from becoming more popular in several studies (Melaina, 2003; Kuby and Lim, 2005; 2007; Melaina and Bremson, 2008; Shukla et al., 2011; Chung and Kwon, 2015). A better network of charging service would improve the use of electric vehicles (EV), and more EV users would promote the construction of infrastructure. Another barrier for promoting AFVs is the limited vehicle range (Shukla et al., 2011; Wang and Lin, 2009; Wang and Wang, 2010; Lim and Kuby, 2010; Capar and Kuby, 2012; Romm, 2006; Chung and Kwon, 2015). While the coming generation of luxury EVs should have ranges much higher than 160 km, most of the EVs currently have a range of 60 km to 160 km with full battery. Thus, the current EV range may not be sufficient for long distance intercity trips. Due to these limits, building a charging network and choosing the right locations for chargers is helpful to popularize the use of EVs and solve the environmental problems caused by conventional vehicles.

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These facts motivate the need of the study on optimal locations for refueling or charging stations in networks with different sizes. Thus, several models for optimal location of alternative-fuel stations are developed to solve this problem. Two popular models are the *p*-median and flow-refueling models. The *p*-median model locates a set of facilities to cover all the demands at the nodes of the network while minimizing the total traveled distance from each demand node to the facilities. Nicholas and Ogden (2006) worked on the applications in AFVs with *p*-median models. Similarly, the *p*-center location model is a minimax problem that locates *p* facilities to minimize the maximum distance from any demand node to its closest facility (Hakimi, 1964; 1965; Minieka, 1970; Suzuki and Drezner, 1996; Drezner, 1984). Also, the set cover model minimizes the number or cost of facilities needed to cover all demand nodes within a specific distance (Toregas et al., 1971). In addition, there are diverse models with different assumptions that the travel demands occur at facilities on paths, including convenient stores, gasoline stations and fast-food restaurants. The flow-capturing location model (FCLM) locates *p* facilities to capture the origin-destination flow, and travel demands are served by facilities located at nodes on the paths (Hodgson, 1990; Berman et al., 1992). Later, flow-refueling location problem (FRLM) enhance the model by cover the flow on a path with a combination of facilities, instead of one facility in FCLM, based on the assumption of the limited range of AFVs.

In this paper, we focus on modeling for EVs and charging stations. Our model aims to find optimal solution for the construction planning of level 3 or fast charging stations along highways, and we assume home charging has little effect on the planning decisions. For level 1 or level 2 charging stations, the full-charging time greatly depends on the remaining battery level of the vehicle and the station location is affected by the starting battery level. In addition, vehicles rarely recharge at level 1 or level 2 charging stations mid-route since the charging time is too long. Thus our model fits less well for slow charging facilities due to our current assumptions. (See Section 3.1) We, however, note that this model is general and applicable for other types of AFV refueling network planning. The capacity constraint in our model is based on the fact that limited EVs can be served in unit time. Capacity constraint can also be extended to refueling facilities for single-fuel vehicles that use liquid or gaseous fuels, such as H2 and CNG, since the amount of fuel available at each facility is limited. Our model applies well to those AFVs that refueled quickly in about the same amount of time regardless of tank level, given people rarely refuel those AFVs at home. Our extension is based on FRLM while considering facility capacity and infrastructure planning time. First, facility capacity, or charging times of EVs, should be included in the model. Different from conventional vehicles or other AFVs, EVs could take 2–8 h to be fully charged on Level 1 or 2 charging stations. Even on Level 3 charging stations, drivers may have to wait for 20 to 30 min to charge their vehicles. Thus, the number of vehicles that can be served at one charging facility in unit time is limited, which could be considered as the capacity of the facilities. Also, the “uncapacitated” assumption in FRLM is based on the limited number of early users of AFVs, and one facility might satisfy all of the demand. With the increasing market share of EVs, it’s less realistic to serve all of travel demands with one facility in the near future. Second, we consider the multi-period model since it usually takes a long time to plan and build a charging network with sufficient facilities. The facility location decision involves many factors, including investment and policy, and these factors might vary from time to time. In addition, the infrastructure should be compatible to the number of AFV users so the planner is more likely to finish the whole charging network in several time stages. Thus, a strategic multi-period infrastructure plan is more helpful to the decision maker.

We incorporate EV demand dynamics to multi-period capacitated flow refueling station planning, realizing the importance of charging availability in EV demand. Charging network (or charging availability) affects EV demand and the growth of the demand affects planning decisions. By incorporating demand dynamics in multi-period planning, we capture the effects of station siting decisions on future demand and this allows us to observe this interaction between demand and supply. In addition, we would also like to see how planning decisions will be reacting to different demand dynamics, as well as different objectives of station siting.

We introduce different travel demands (total vehicle flow and EV flow). The number of all vehicles, including conventional vehicle and AFVs, going from a location (origin) to another location (destination) in the network is referred to as the *total vehicle flow* of the OD pair, while the corresponding number of electric vehicles are referred as the *EV flow*. The proportion of electric vehicles in total vehicles is denoted as the *EV market share*. The amount of EV flow is naturally the *EV demand*, and market share is directly observed from these two demands. The concept of *demand dynamics* is to provide different scenarios on how vehicle demand changes with time and user’s decisions.

The remainder of this paper is organized as follows. In Section 2, we review the arc-cover-path cover formulation of FRLM, as well as the related research. In Section 3, we describe our problem and provide the formulation of our multi-period capacity model as well as the demand dynamics of EV. In Section 4, we present our heuristic method to solve the model, and utilize line search method to improve our computational efficiency. In Section 5, we present extensive computational results for the highway network for the region between Washington DC and Boston. Diverse scenarios with different demand dynamics and objectives are tested to evaluate model performance, and to provide help for policy makers. Numerical results of the influence of time periods in multi-period planning are also provided. Section 6 concludes the paper by listing the suggestions to policy makers and by providing directions for future research.

2. Literature review

Hodgson (1990) and Berman et al. (1992) developed the flow-capturing location model (FCLM), a flow-intercepting model to help locate retail facilities such as convenient stores, banking machines and billboards. Different from traditional node-