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A Benders decomposition approach for the charging station location problem with plug-in hybrid electric vehicles

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ABSTRACT

The flow refueling location problem (FRLP) locates p stations in order to maximize the flow volume that can be accommodated in a road network respecting the range limitations of the vehicles. This paper introduces the charging station location problem with plug-in hybrid electric vehicles (CSLP-PHEV) as a generalization of the FRLP. We consider not only the electric vehicles but also the plug-in hybrid electric vehicles when locating the stations. Furthermore, we accommodate multiple types of these vehicles with different ranges. Our objective is to maximize the vehicle-miles-traveled using electricity and thereby minimize the total cost of transportation under the existing cost structure between electricity and gasoline. This is also indirectly equivalent to maximizing the environmental benefits. We present an arc-cover formulation and a Benders decomposition algorithm as exact solution methodologies to solve the CSLP-PHEV. The decomposition algorithm is accelerated using Pareto-optimal cut generation schemes. The structure of the formulation allows us to construct the subproblem solutions, dual solutions and nondominated Pareto-optimal cuts as closed form expressions without having to solve any linear programs. This increases the efficiency of the decomposition algorithm by orders of magnitude and the results of the computational studies show that the proposed algorithm both accelerates the solution process and effectively handles instances of realistic size for both CSLP-PHEV and FRLP.

1. Introduction

Due to the economic and environmental concerns associated with gasoline, alternative fuel vehicles (AFVs) appeal to customers worldwide. In recent years, a proliferation of AFVs has been observed on the roads (U.S. Department of Energy, 2014). Liquefied petroleum gas (LPG), natural gas, hydrogen, electric and plug-in hybrid electric vehicles are some of the technologies that depend on some form of fuel, different than petroleum, to run. Several parties benefit from their introduction into the transportation sector. From the individual drivers' perspective, they are an efficient way of reducing the transportation costs and environmental impacts such as greenhouse gases (Arslan et al., 2014; U.S. Department of Energy, 2015a; 2015b; Windecker and Ruder, 2013). From the entrepreneurs' perspective, the vehicles themselves as well as the infrastructure they require are possible investment areas. For the oil-importing governments, the AFVs mean less dependence on export oil and governments (e.g., United States) are encouraging fuel provider fleets to implement petroleum-reduction measures (Congress, 2005).

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As the AFVs are known for their rather limited range, their increasing numbers naturally raise the problem of insufficient alternative refueling stations. Lack of enough refueling infrastructure has been identified as one of the barriers for the adoption of AFVs (Bapna et al., 2002; Kuby and Lim, 2005; Melaina and Bremson, 2008; Melaina, 2003; Romm, 2006). In this respect, the refueling station location problem has been touted in the recent literature. There are two mainstream approaches in AFV refueling station location: maximum-coverage and set-covering. The cover-maximization approach for refueling station problem has been considered by Kuby and Lim (2005) with the flow refueling location problem (FRLP). The objective of the FRLP is to locate *p* stations in order to maximize the flow volume that can be refueled respecting the range limitations of the vehicles. A demand is assumed to be the vehicle flow driving on the shortest path between an origin and destination (OD) pair on a roundtrip. Satisfying a demand, or in other words, refueling a flow requires locating stations at a subset of the nodes on the path such that the vehicles never run out of fuel. Kuby and Lim (2005) pregenerate minimal feasible combinations of facilities to be able to refuel a path, and then build a mixed integer linear programming (MILP) problem to solve the FRLP. There are applications of the problem in the literature (Kuby et al., 2009), analyses are carried out to better understand the driver behavior (Kuby et al., 2013) and different extensions to the original problem are considered such as capacitated stations (Upchurch et al., 2009), driver deviations from the shortest paths (Kim and Kuby, 2012; Yıldız et al., 2015) and locating stations on arcs (Kuby and Lim, 2007). Different than other studies on FRLM, Kuby et al. (2009) consider maximizing the vehicle-miles-traveled (VMT) on alternative fuel rather than maximizing the flow volume. The authors use FRLM for the location decisions of hydrogen stations in Florida and build a decision support system to investigate strategies for setting up an initial refueling infrastructure in the metropolitan Orlando and statewide. Since the pregeneration phase of the method by Kuby and Lim (2005) requires extensive memory and time, several solution enhancements have been proposed (Capar and Kuby, 2012; Capar et al., 2013; Kim and Kuby, 2013; Lim and Kuby, 2010; MirHassani and Ebrazi, 2013). In particular, MirHassani and Ebrazi (2013) present an innovative graph transformation and Capar et al. (2013) propose a novel modeling logic for the FRLP both of which increase the solution efficiency of the FRLP drastically. In the set-covering approach to the refueling station location problem, the objective is to minimize the number of stations while covering every possible demand in the network (Li and Huang, 2014; MirHassani and Ebrazi, 2013; Wang and Lin, 2009; Wang and Wang, 2010).

FRLM and flow covering problems in general have recently been used in the literature to locate charging stations (Chung and Kwon, 2015; Hosseini and MirHassani, 2015; Jochem et al., 2015; Wang, 2011; Wang and Lin, 2009; 2013). Along with the ideas behind all these applications of flow based models to the charging station location problem, Nie and Ghamami (2013) identified Level 3 fast charging as necessary to achieve a reasonable level of service in intercity charging station location. A similar result is also attained in Lin and Greene (2011) using the National Household Travel Survey. Therefore, similar to aforementioned studies, we assume that the charging stations to be located provide Level 3 service.

In this study, our objective is to embed the plug-in hybrid electric vehicles (PHEVs) into the charging station location problem. All of the aforementioned studies related to refueling or charging station location consider single-type-fueled vehicles. However, using dual sources of energy, PHEVs utilize electricity as well as gasoline for transportation.

Even though PHEVs penetrated the market after HEVs and EVs, they have comparable sales numbers. The sales of PHEVs increased faster than EVs globally in 2015 (Irle et al., 2016) and experts estimate that PHEV sales will surpass EVs in the short term (Shelton, 2016). In 2015, total PHEV sales in Europe and US were 194.615 and 193.757, respectively (Pontes, 2016; U.S. Department of Energy, 2016b). Among top selling PHEVs in US are Chevrolet Volt, Toyota Prius, Ford Fusion and Ford C-Max forming approximately 95% of the US PHEV market. Mitsubishi Outlander, BYD Qin, BMW i3 are the top three selling brands in Europe sharing more than half of the European PHEV market. Shelton (2016) reports that the sales of EVs and PHEVs are expected to reach to 1 million and 1.35 million in 2020, respectively. Furthermore, PHEV global sales are expected to double by 2025, reaching to 2.7 million PHEVs on the roads.

Similar to the approach by Kuby et al. (2009), we maximize the VMT on electricity which minimizes the total cost of transportation under the existing cost structure between electricity and gasoline. Even though maximizing the AFV numbers in long-distance trips brings environmental benefits, maximizing VMT brings along additional value from an environmental point of view; and in essence, it is also equivalent to minimizing the effects of greenhouse gases. In this context, green transportation is an emerging research topic that has made its debut in the literature in recent years. There are different studies taking into account the green perspective in transportation problems and considering the mileage driven on electricity such as green vehicle routing problem (Erdoğan and Miller-Hooks, 2012; Schneider et al., 2014) and optimal routing problems (Arslan et al., 2015). With our approach to the charging station location problem, the environmental benefits of charging station location are fully exploited by considering VMT and additionally taking the PHEVs into account.

1.1. Contributions

We introduce the charging station location problem with plug-in hybrid electric vehicles as a generalization of the flow refueling location problem by Kuby and Lim (2005). To our knowledge, this is the first study to consider the PHEVs in intercity charging station location decisions. We minimize the total cost of transportation by maximizing the total distance traveled using electricity. We also address the topic of multi-class vehicles with different ranges in our formulations, which has been discussed as a future research topic in several studies starting with Kuby and Lim (2005). For the exact solution of this practically important and theoretically challenging problem, we present an arc-cover model. To enhance the solution process, we propose a Benders decomposition (BD) algorithm. We construct subproblem solutions in closed form expres-