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Optimal recharging strategies for electric vehicle fleets with duration constraints ☆

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ABSTRACT

Electrical vehicles (EVs) have become a popular green transportation means recently because they have lower energy consumption costs and produce less pollution. The success of EVs relies on technologies to extend their driving range, which can be achieved by the good deployment of EV recharging stations. This paper considers a special EV network composed of fixed routes for an EV fleet, where each EV moves along its own cyclic tour of depots. By setting up a recharging station on a depot, an EV can recharge its battery for no longer than a pre-specified duration constraint. We seek an optimal deployment of recharging stations and an optimal recharging schedule for each EV such that all EVs can continue their tours in the planning horizon with minimum total costs. To solve this difficult location problem, we first propose a mixed integer program (MIP) formulation and then derive four new valid inequalities to shorten the solution time. Eight MIP models, which were created by adding different combinations of the four valid inequalities to the basic model, have been implemented to test their individual effectiveness and synergy over twelve randomly generated EV networks. Valuable managerial insights into the usage of valid inequalities and the relations between the battery capacity and the total costs, number of recharging facilities to be installed, and running time are analyzed.

1. Introduction

According to greenhouse gas emission statistics by the European Environment Agency (EEA), transportation has contributed 22% of the total EU-28 greenhouse gas emissions (or 1030 million tons of CO_2-equivalents) in 2012. It is believed that the global warming caused by conventional fueled-based vehicles may be remedied by the adoption and popularity of electrical vehicles (EVs) or other alternative-fuel vehicles (AFVs) because these vehicles consume less energy and produce less pollution. More counties have set new environmental regulations or begun to provide incentives to push the greater use of EVs to replace fuel-based vehicles. Some companies such as FedEx (FedEx, 2010, 2014), Frito Lay (Morris, 2012), and Staples (Ramsey, 2010) have also introduced EV fleets for freight shipments.

There are two major obstacles that hinder the popularity of EVs: (1) the lack of recharging infrastructures due to high installation costs, which in turn reduces the interest for customers to purchase EVs (MirHassani and Ebrazi, 2012; Kuby and Lim, 2005), and (2) the limited driving range of EVs due to their lower energy efficiency and weight limitations

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(Lim and Kuby, 2010; Wang and Lin, 2009). These difficulties may be resolved, to some extent, by an effective deployment of recharging stations and good recharging schedules for EVs. In particular, by setting up the right number of recharging facilities in the right places, all EVs can be recharged whenever and wherever necessary, with the minimum total costs, including facility setup and recharging operational costs. The cost savings would be even more significant for a transportation network composed of fixed routes, as commonly seen in some logistics or bus companies, where each EV periodically moves along a pre-specified sequence of depots or stops to collect or drop off cargo or people.

The optimization problem considered in this paper covers two difficult subproblems at the same time: (1) a special facility location problem that seeks optimal locations to install recharging stations and (2) an optimal recharging schedule for an EV fleet. The transportation network is composed of a set of EV routes, where each route is run by an EV periodically. When an EV visits a depot on its route for conducting a transport operation or rest, it must obey a duration constraint (e.g., no longer than 1 h for a daytime transport task or no longer than 6 h for an overnight rest). This duration constraint is necessary in our problem. Without considering the duration constraint, an EV can be recharged for as long as necessary to minimize the total costs, which is not realistic. For example, an electric bus that picks up and drops off passengers should not stop by an intermediate station for too long, or the on-board passengers will have a long waiting time to their destinations. In addition, the length of the duration would also affect the location decisions for setting up recharging facilities.

If the depot is equipped with a recharging facility, the EV can be recharged to gain more battery power. A battery can, at most, be recharged to its capacity, and an EV must maintain a sufficient battery level to reach its next depot at all times. As a result, the optimal recharging schedule must be considered in conjunction with the locations to install recharging stations. To this end, this paper first provides a mixed integer linear program to address both subproblems and then investigates how the solution time can be further shortened by our proposed valid inequalities.

The paper is organized as follows: Section 2 reviews the related literature. In Section 3, we present a basic mixed integer programming formulation for the problem, propose new valid inequalities, and demonstrate our formulation by a small illustrative example. Extensive computational tests and analyses are reported in Section 4, where the performance of the basic MIP model in conjunction with different combinations of added valid inequalities is compared. Section 5 summarizes our findings and suggests several possible topics for future research.

2. Review of related literature

Our paper investigates a special facility location that has been extensively studied for decades. Here, we only review the literature related to EV or AFV fleets and the literature regarding refueling scheduling problems.

Based on given potential locations, there are many studies examining the AFV refueling facility-location problem. Kuby and Lim (2005) extended the flow capturing location model (FCLM) of Hodgson (1990) to give a flow refueling location model (FRLM) that considers range-limited vehicles. In particular, FRLM calculates the optimal deployment for a given number of refueling stations to maximize the total refueled flow volume for given round-trip paths. Based on FRLM, Lim and Kuby (2010) developed three heuristic algorithms to eliminate the pre-generation of all combinations of candidate locations required in FRLM such that the model could be used for larger realistic networks. Capar and Kuby (2012) also proposed a new mixed binary integer programming model to solve larger FRLM problems, which resolves the difficulty of having too many generated candidate sites in the previous model. To the best of our knowledge, Capar and Kuby (2012) has tested the largest network (1000 nodes, 80 O–D pairs) considered to date in the related literature for solving a relaxed FRLM formulation called MBIP. Their model requires many new types of variables and constraints to ensure the same covering rules for round trips. Capar et al. (2013) presented a generalized FRLM formulation based on covering the arcs that comprise each path. Their new formulation is more efficient, compact, and flexible and can thus account for different fuel types and geographic scales.

Lam et al. (2014) studied an EV charging station placement problem (EVCSPP) for seeking the best locations to construct charging stations in smart city planning. In order to guarantee the charging station network spans the entire city, they gave a mathematical programming model with quadratic constraints. They also proposed four solution methods (iterative MILP, greedy approach, effective MILP, and Chemical Reaction Optimization heuristics).

Wang (2007) proposed a set covering model with nonlinear constraints to address the e-scooter recharging facility location problem. Their model considers candidate sites located on a given route/path of a single origin and destination (O–D) and is validated on an island to recharge the recreation-oriented e-scooters for tourists. Based on Wang (2007), Wang (2008) formulated a battery exchange station location model on a single path by a mixed integer program that can address multiple O–D routing demands on that path. Then, Wang and Lin (2009) further extended the works of Wang (2008) to calculate a minimum cost recharging facility location problem that considers intercity O–D round-trips based on a given 2-dimensional distance matrix between all candidate locations. A hybrid model with dual objectives of minimum cost and maximum coverage was formulated by Wang and Wang (2010). Their hybrid model could account for the travel of both long (inter-city) and short (intra-city) distances. However, both models (i.e., Wang and Lin, 2009 and Wang and Wang, 2010) still require the recharging capacity constraints at recharging sites to be eliminated such that an exact algorithm, such as branch-and-bound, can work properly.

MirHassani and Ebrazi (2012) formulated a flexible MIP model based on the same assumptions of FRLM (Kuby and Lim, 2005) and similar assumptions of Wang and Lin (2009). Their model was more efficient than previous set covering models