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Electric vehicle fleet size and trip pricing for one-way carsharing services considering vehicle relocation and personnel assignment

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ABSTRACT

This study proposes an interesting electric vehicle fleet size and trip pricing (EVFS&TP) problem for one-way carsharing services by taking into account the necessary practical requirements of vehicle relocation and personnel assignment. The EVFS&TP problem aims to maximize the profit of one-way carsharing operators by determining the electric vehicle fleet size, trip pricing, and strategies of vehicle relocation and personnel assignment subject to the elastic demand for the one-way carsharing services. A mixed-integer nonlinear and nonconvex programming model is first built for the EVFS&TP problem. By exploiting the unique structure of the original built model, a mixed-integer convex programming model is subsequently developed. An effective global optimization method with several outer-approximation schemes is put up to find the global optimal or ε-optimal solution to the EVFS&TP problem. A case study based on a one-way carsharing operator in Singapore is conducted to demonstrate the efficiency of the proposed model and solution method and further analyse the impact of demand, the degree of demand variation, the fixed operational cost of the vehicles as well as payment for personnel on the performance of the one-way carsharing services.

1. Introduction

As an attractive alternative to buying and owning a car, carsharing services have gained an increasing popularity worldwide over the past 20 years. In Germany and North America, for example, more than 14,000 carsharing vehicles are accessible for more than 750,000 registered users or members (Weikl and Bogenberger, 2015). The number of carsharing members in North America has exponentially grown from 905 in 1998 to 208,584 in 2012 (Shaheen and Cohen, 2012). Carsharing services can be viewed as a more flexible kind of car rental service because they provide users with accessibility to vehicles parked at many stations for a short period of time. Traditional carsharing systems are often referred to as the “two-way” carsharing services in the literature (Boyacı et al., 2015; Nourinejad and Roorda, 2014; Nourinejad et al., 2015). In two-way carsharing services, a fleet of vehicles operated by a carsharing operator is initially distributed throughout the designated stations. Registered members or users are required to reserve vehicles in advance and return their rented vehicles to those

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stations where they were picked up. The fee is generally time-dependent, i.e., the longer the rental, the higher the rental fee, and the hourly fee rate may vary across different periods of time such as peak hours and non-peak hours.

To make carsharing services more attractive and convenient to users, some carsharing operators, for example Car2Go in Germany (Car2Go, 2017) and Smove in Singapore (Smove, 2017), already provide the "one-way" carsharing services that allow users to pick up and return vehicles at different stations. The one-way carsharing services can be further classified into the free-floating and station-based carsharing services based on whether the vehicles are allowed to be picked up or returned at non-designated stations, e.g., along street (Balac et al., 2017; Li et al., 2018; Weikl and Bogenberger, 2013; 2015;). Compared to the two-way carsharing services, although the one-way carsharing services offer flexibility and convenience to users, they present a vehicle imbalance issue across designated stations: the number of vehicles/parking spots available at a specific station or an area over a particular period cannot well match users' demand. Waserhole and Jost (2012) pointed out that the gravitational effect due to dynamic vehicle stock at each station or area and the tide phenomenon caused by demand oscillation are the primary factors leading to this vehicle imbalance issue. Jorge and Correia (2013) made a comprehensive review of the existing methods for the better deployment of carsharing services, and they pointed out that the key issue for one-way carsharing services is the dynamically disproportionate distribution of vehicles across stations or areas. Elimination of the imbalance issue inevitably requires implementation of periodic vehicle relocation operations between a station or an area with surplus vehicles/parking spots and another station or area with deficient vehicles/parking spots, plus corresponding personnel assignment to perform these operations.

A number of strategies have been proposed to deal with several decision-making problems arising from the one-way carsharing services over the past decades. These strategies can be classified into three categories: strategic, tactical, and operational. The determination for the locations, amounts, and parking capacities of stations falls in the first category, while vehicle fleet deployment belongs to the second group. Apart from the strategic and tactical strategies, other critical operational decision-makings for one-way carsharing services involves vehicle relocation, personnel assignment and trip price setting (Boyacı et al., 2015). This study aims to determine the optimal fleet size and trip pricing for the one-way carsharing services with electric vehicles (EVs) while taking the vehicle relocation and personnel assignment into account.

1.1. Relevant studies and research gaps

Some researchers have focused on the strategic-level decision-making processes of one-way carsharing services, aiming to optimize the stations' location, number, and parking capacity, as well as vehicle fleet size and the initial distribution of vehicles. For example, given the demand for carsharing services between each pair of origin and destination stations (O-D station pair) at each time slice, Correia and Antunes (2012) proposed a mixed-integer linear programming model based on a time-space network to optimally determine the station location and trip selection. Correia et al. (2014) later made an extension by incorporating the flexibility of users in their choice of pick-up and drop-off stations when the information on vehicle stock at nearby stations was provided. They showed by a case study of Lisbon that the incorporation of this flexibility could significantly increase the profit of one-way carsharing operators. Li et al. (2016) recently addressed a joint station location and fleet size problem for large-scale one-way EV sharing systems by proposing a continuum approximation model under stochastic and dynamic trip demands. Hu and Liu (2016) formulated a mixed queuing network model for the joint design of parking capacity and fleet size for one-way carsharing systems subject to road congestion constraints.Boyaci et al. (2015) developed a multi-objective mixed-integer linear programming model for the determination of station location, parking capacity, and fleet size of such services with EVs. Brandstätter et al. (2017) developed a two-stage stochastic programming model to determine the optimal locations for charging stations of electric carsharing systems under stochastic demand.

Apart from the high-level decision-making problems, various optimization or simulation-based models have been proposed in the past few years for vehicle relocation or its combination with personnel assignment to eliminate the vehicle imbalance issue (Boyaci et al., 2017; Bruglieri et al., 2014; Jorge et al., 2014; Kek et al., 2009; Nourinejad and Roorda, 2014; Nourinejad et al., 2015). These studies all assumed that the travel demand of carsharing users and the trip price charged for them between each O-D station pair are known a priori. In contrast, a few researchers have proposed some interesting regulations or price incentives to improve the performance of one-way carsharing services by considering stochastic or elastic demand for vehicles between each O-D station pair. For example, under the assumption that the trip demand between each O-D station pair is a stochastic process, Kaspi et al. (2014) demonstrated the efficiency of a parking reservation policy in the vehicle sharing systems by a Markov chain model and a simulation study of a large real-vehicle sharing system in Tel Aviv. Among the existing studies, the explicit consideration of demand elasticity was pioneered by Jorge et al. (2015). They developed a mixed-integer nonlinear programming model to optimize trip pricing in one-way carsharing systems without considering vehicle relocation operations and personnel assignment. An iterative local search metaheuristic was proposed to solve the nonlinear and nonconvex optimization model. The efficiency of the proposed metaheuristic was demonstrated by a case study created from the carsharing services in Lisbon, Portugal. The existing studies on the one-way carsharing are summarized in Table 1.

According to Table 1, it can be seen that EVs have drawn growing attention over the past few years, and a few studies have focused on EV carsharing services. Compared with gasoline vehicles (GVs), however, EVs currently suffer from impediments due to their limited driving range and long charging time. Investigations into the one-way carsharing services using EVs, which takes their limited driving range and charging requirement into consideration, are thus highly anticipated. However, the existing studies conducted by Boyaci et al. (2015; 2017), Bruglieri et al. (2014), Correia and Santos