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An integrated framework for electric vehicle rebalancing and staff relocation in one-way carsharing systems: Model formulation and Lagrangian relaxation-based solution approach

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ABSTRACT

In one-way electric vehicle (EV) carsharing systems, a practical issue that needs to be addressed is the imbalance of EVs with respect to the spatial time-dependent user reservations at different carsharing stations. In practice, appropriate EV rebalancing operations can satisfy user reservations with limited resources and effectively save system investments. This paper proposes an integrated framework that can determine the optimal allocation plan of EVs and staff on the strategic level while considering the operational EV relocation and staff relocation decisions, in order to minimize the total cost, including the EV and staff investment, EV rebalancing and staff relocation costs. In this framework, the dispatching routes of EVs and staff are represented by two sets of space-time paths in the planning time horizon by using a space-time network representation, and the considered problem is then formulated into a mixed-integer linear programming model (MILP). This model explicitly considers (1) the satisfaction of time-dependent user reservations through dynamically rebalancing EVs and relocating staff to keep the service quality of carsharing system, and (2) the EV battery capacity with limited traveling distance and the charging process of EVs at parking stations. A Lagrangian relaxation-based solution approach is developed to decompose the primal problem into several sets of computationally efficient subproblems. In order to generate good-quality solutions, we also propose a three-phase implementing algorithm based on dynamic programming according to the values of Lagrangian multipliers. An illustrative numerical example and a real-world case study (based on the operation data of Seattle, WA) are conducted to verify the applicability of the formulated model and effectiveness of the proposed approach.

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1. Introduction

The expansion of residents and private vehicles in large cities, such as Beijing, Tokyo and San Francisco, has imposed great pressures on the urban transportation systems. For example, in Beijing, the number of vehicles has increased by about 154 thousand (or 2.8 percent) from 2014 to 2015, and over 65% of these new vehicles are private cars. The number of annual average daily trips (AADT) in downtown area grows to over 28 million and the trips on private vehicles take over 31%. This may well explain the greatly worsened traffic and environmental conditions of Beijing in recent years. To overcome this urgent problem of big cities, one of the promising approaches is the application of carsharing systems, in which a group of people collectively own or use a number of spatially distributed vehicles. There has been abundant evidence that carsharing systems can effectively release the pressure to other public transportation modes, save urban parking space, and reduce air pollution e.g., Jian et al. (2016); Li et al. (2016) and Boyacı et al. (2017).

In general, the current carsharing systems are classified into three patterns according to their different rental modes, which are round-trip, free-floating and one-way carsharing systems, respectively (Becker et al., 2017). For round-trip systems, the origin and destination of each user are restricted to the same parking station. In other words, the users are required to return vehicles to their original stations. Due to this operational constraint, round trip systems are inflexible to many users (e.g., those with one-way trips or relatively long activity durations). In contrast, free-floating systems allow the users to drop the vehicles at any parking port in a predetermined area, which improves user convenience yet causes relatively high fleet management cost (e.g., the costs of collecting and returning the vehicles to relevant facilities)(Firnkorn, 2012; Weikl and Bogenberger, 2015). As a compromise, in one-way carsharing systems, each user can return a vehicle to a different station other than the pickup station, which has better flexibility than round-trip systems yet does not incur as high cost as free-floating systems. In other words, one-way carsharing systems strike a good balance between operation costs and flexibility. Many carsharing organizations such as Zipcar and Car2Go tend to increase the proportion of one-way service pattern in recent years[1][2](Jorge et al., 2015).

An outstanding challenge to one-way carsharing operations is the imbalance of available vehicles at different stations caused by the gravitational effect (Weikl and Bogenberger, 2015) among different areas and the tide phenomena of daily trips (Waserhole et al., 2013), which often lead to vehicle shortage in some stations yet too high vehicle inventories in others. This challenge apparently reduces the service quality of carsharing systems such that some users have to wait for available vehicles. Further, it causes waste of vehicle resources long sitting in particular stations without being used. In practice, an effective strategy to overcome this problem is to properly allocate the vehicles to parking stations at the beginning of operation cycle and timely rebalance the vehicles by a crew of drivers (namely fleet managing staff) (Kek et al., 2009; Smith et al., 2013; Nourinejad et al., 2015). Such staff-based vehicle operations, if not properly managed, may have imbalanced distribution of staff among the parking stations, or even disruptions of carsharing network operations. Hence, it is important to carefully determine the allocations of EVs and staff to parking stations while considering the vehicle rebalancing and staff relocation operations in one-way carsharing systems. In recent years, to further enhance the environmental and social benefits of carsharing systems, electric vehicles (EV) are gradually favored by most carsharing organizations, because EV sharing services are not only efficient but also sustainable (Li et al., 2016; Xu et al., 2017).

Nevertheless, the current studies that simultaneously consider the EVs and staff allocations, EV rebalancing and staff relocation through a systematic view are very few, which is partially due to the following two reasons. (1) On one hand, applying EVs actually brings new challenges to rebalancing of shared vehicles in one-way carsharing systems. Restricted by the limited battery capacity and the existing charging technology, most EVs need a considerable charging time after a limited travel distance or time. Therefore, in EV one-way carsharing systems, the rebalancing of EVs is actually a complicated problem that not only involves the space-time distribution of EVs but also is constrained by the limited battery capacity, which makes it extremely difficult to obtain a global-optimum or near-optimum solution. (2) On the other hand, the EV rebalancing design in one-way carsharing system is essentially a very complicated problem due to the complex coupling relationships among user activities, staff members and EVs. For bicycle sharing systems, the rebalancing of bikes is usually handled by dispatching a fleet of capacitated trucks to maintain the number of bicycles in each station (Dell'Amico et al., 2014; Forma et al., 2015; Zhang et al., 2016). Correspondingly, the relocation problem in EV carsharing systems faces a different kind of challenge since it is practically not suitable to use trucks for the relocation of multiple vehicles due to the complexity and inefficiency of EV loading/unloading process (Bruglieri et al., 2014). Hence, each vehicle rebalancing task in one-way carsharing system is generally achieved by one staff member, which means that we need to precisely capture the spatial-time user activities and then dynamically dispatch the staff members to balance the distribution of EVs (Boyacı et al., 2017). To achieve a global optimum for one-way carsharing systems, more coupling constraints among user activities, EVs and staff members should be rigorously considered, which however enhances the computational intensity for the problem of interest.

To address these above issues, this study first adopts a space-time network to represent the EV rebalancing and staff relocation operations in a one-way carsharing system, and then proposes an integrated framework to determine the optimal numbers of EVs and staff members allocated to each parking station at the beginning of the operation cycle while con-

[1] https://www.bostonglobe.com/business/2014/05/01/zipcar-test-one-way-car-sharing/5WkDIkVEwtK4B2m2CF6NhK/story.html.
[2] https://transportation.arlingtonva.us/carsharing/car2go/.

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