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Siting and sizing of fast charging stations in highway network with budget constraint

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HIGHLIGHTS

- The equilibrium distribution of vehicle flows is estimated by an iterative approach.
- A mixed integer programming model is developed.
- A new heuristic, genetic algorithm and their combination are designed and compared.
- A practical case from Hebei, China, is studied.
- Both random and practical networks are utilized in the experiment.

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ABSTRACT

An appropriate infrastructure of fast charging stations is critical to customers for adopting plug-in electric vehicles. In this paper, we investigated the siting and sizing problem of fast charging stations in a highway network, where the budget constraint and the service capacities of charging spots are considered. The utility theory is employed to analyze drivers' charging strategies, and an iterative approach is developed to calculate the equilibrium distribution of vehicle flows in the network when the charging infrastructure is insufficient. Based on the assignment rules of the drivers for each charging station, a mixed integer programming model is developed to formulate the problem. Three algorithms, including the genetic algorithm, a problem specified heuristic and an algorithm by combining the heuristic and genetic algorithm, are employed to maximize the overall valid plug-in electric vehicles flows in the network. A practical case based on the highway network in Hebei, China, is investigated, through which the proposed approach is illustrated and the critical factors impacting the deployment of charging infrastructures are analyzed. The analysis results indicate that improving the endurance range may be one of the most efficient ways to expend the adaption of plug-in electric vehicles in a highway network. Random networks and practical networks with different sizes are used to test the robustness and efficiency of the proposed algorithms.

1. Introduction

In recent years, the increasing consumption of fossil fuels has brought serious environmental and social problems [1]. Air pollution, fog and haze arise frequently in many areas, e.g., in central and northern China, which has brought increasing pressure to the government and policy makers. Plug-in Electric vehicles (PEVs) are regarded as a promising solution to reduce air pollution as they can reduce emission as well as increase the efficiency of energy usage [2]. Meanwhile, renewable energy can be taken advantage of through the PEVs [3].

There are two major barriers obstructing the widespread adoption of PEVs. The first one is "range anxiety". The endurance range of PEVs is shorter than that of internal combustion engine (ICE) vehicles of the same price [4]. Although the coming generation of Tesla PEVs claims to have a theoretical range of approximately 400 km with a full battery [5], the actual range of civilian PEVs recently can only reach approximately 200 km [6], which is insufficient for long-term intercity trips. The other barrier is the insufficiency of charging infrastructures. Due to the high cost of construction and maintenance [7], the charging

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facilities are not easy to find in either urban area or highway networks. Meanwhile, the quantity of charging facilities cannot bolster the raising demand of PEVs due to the limited capacity, especially for intercity transportation. A PEV usually needs approximately 30 min to obtain a full charge, which means that a charging spot can only serve at most 50 vehicles per day. The high investment needs to be collected from a large demand, and the adoption of PEVs needs a sufficient infrastructure, which creates a chicken-and-egg problem [3].

From the view of the policy maker, a well-distributed network of charging stations is necessary for expanding the market share of PEVs. Although the numbers of PEVs and charging facilities in China are growing rapidly, most of the PEVs are used in urban areas. It can be seen from the statistics of the China EV100 (one of the most authoritative communities concerning the development of PEVs) that the number of civilian PEVs reached 1 million in 2017 [8], among which 98% are used for trips of less than 150 km [9]. Meanwhile, the number of charging facilities has reached 450,000, which is also distributed mainly in urban area [10]. The construction of charging stations in highway network is still at the beginning stage, which limits the PEV market for intercity trips. However, the investment required for building charging infrastructures is high. There is usually no sufficient budget for building the required stations and spots to satisfy all the potential demands. Another observation in China shows that the average usage efficiency of these charging facilities is only 15% [11] because the location and capacity of charging facilities cannot match the charging flows well. Thus, when considering the construction of charging stations in highway network, a critical problem faced by planners is how to optimize the siting and sizing decisions to capture as much potential PEV flows as possible, subjected to a limited budget. The optimal deployment of charging stations to better match with the PEV charging requirement is also an important way to improve the utilizing efficiency of the electricity charging infrastructure.

From a review of the current literatures, we can see that the network design and configuration problem for fast charging stations has become an important research topic in areas related to the construction and management of electric power infrastructure. Most of the current studies aim to minimize the investment of the charging infrastructure while satisfy the charging demand of PEV flows, such as in [12,13]. There is still a lack of studies for the charging network designs with the budget constraint. When the investment in the charging infrastructure is considered to be limited, new challenges in both modeling and solution methodology are raised, such as equilibrium analysis of PEV flows, modeling with more variables and design of new heuristics.

Motivated by the practical requirement and theoretical gap, this paper investigated the siting and sizing problem for charging stations under a budget constraint, which contributes to the current literature in the following aspects.

When the charging station and charging spots are insufficient, the strategies of drivers for selecting charging stations are important for estimating the distribution of PEV flows in the network. Based on the PEV range constraint and driver charging logic, the utility theory is utilized to analyze the drivers' strategies for selecting charging stations under a given siting and sizing scheme. An iterative approach is proposed to calculate the equilibrium state of PEV flows in the network.

Second, a mixed integer programming model is presented to formulate the siting and sizing problem by extending the flow refueling location model, where the location of charging stations and the configured number of charging spots are optimized. Three algorithms are proposed to solve the problem. The first is the genetic algorithm, where encoding and decoding strategies are newly designed. The second is a heuristic that we designed based on the characteristic of the problem. The third algorithm is a combination of the first two algorithms.

Finally, a case study from Hebei, China, is proposed, which is also the practical motivation for us to study this problem. The influence of budget, endurance range and charging capacity of spots are analyzed. The efficiency of the three algorithms is tested and compared through random and practical networks.

The rest of this study is structured as follows: Section 2 reviews existing studies. Section 3 analyzes the charging rules for drivers to select stations and develops the main model of the problem. Section 4 introduces the genetic algorithm, the designed heuristic algorithm and the combination algorithm for solving the problem. Section 5 presents a realistic case study based on the practical highway network in Hebei, China. Random networks and three practical networks are also designed to test the efficiency of the three algorithms in Section 5. Concluding remarks and future works are discussed in Section 6.

2. Literature review

The charging station siting and sizing problem is a special type of facility location problem based on flow demand. When drivers travel from one city to another through the highway network, they usually have to charge the vehicle several times during the trips. Thus, the charging demand in the road network is commonly described as traffic flow from origin to destination (O-D). In the refueling station location problem, Hodgson [14] presented a strategy to express this type of demand as a traffic flow from origin to destination (O-D), and developed a new type of model named the flow-capturing location model (FCLM). Kong et al. [15] proposed a comprehensive three-layered system model for the fast charging stations, where the decisions related with station location, grid resource allocation and operation of the stations are better cooperated. Also, the battery charging dynamics is considered the model, which makes the study in [15] closer to the practical situation. Wu and Sioshansi [16] investigated the location problem for public fast charging stations, where the number of opened stations is limited. A stochastic FCLM is utilized to formulate the problem and to compute the expected flows captured by the stations.

There is no passing limit in traditional FCLM, as the range of ICE vehicles is sufficient for most transportation demand and their refueling time is very short, which makes it inapplicable for the charging station location problem. Kuby and Lim [3] extended the FCLM. They added the driving range restriction into the FCLM, which fixes the traffic flows so that vehicles can proceed only if there are enough facilities at fixed distances along the road. This extended model is called the flow refueling location model (FRLM). A 0–1 integer linear programming formulation is developed to determine which combination should be chosen. Then, Kuby et al. [7] applied this approach to realistic cases in Florida at two different scales, metropolitan Orlando and statewide. They found that the most difficult part is that the number of combinations grows exponentially with the number of nodes in the network. To overcome this difficulty, Lim and Kuby [17] developed some heuristic algorithms (e.g., greedy-adding, greedy-adding with substitution) and compared them with the genetic algorithm, which demonstrates that the refueling station location problem can be solved well. Kuby et al. [18] also develop a method to solve the added-node dispersion problem, which allows adding potential locations of facility along the arcs in the network.

In the charging station location problem, the charging time is relatively long and cannot be ignored. The models developed in [3,7,17] are for ICE vehicle refueling station locations in which the capacity of the facility is assumed to be unlimited, because the refueling time of an ICE vehicle is relatively short. Upchurch et al. [19] found that this assumption is unrealistic for the charging station location problem, and thus, developed a capacitated flow refueling location model (CFRLM). In their model, the capacity of the charging stations is measured by the number of spots in the station. The problem becomes more complicated when considering capacity constraints, as the number of charging spots in a station could be any nonnegative integer. Meanwhile, the charging strategy of drivers also impacts the potential PEV flow of each station. Upchurch et al. [19] proposed a method to avoid this complexity by assuming that the flow of vehicles charged by each station is determined in a system-optimal manner. Upchurch and Kuby [20] further