Locating electric vehicle fast-charging stations under uncertain driving range : a chance-constrained programming approach

Mouna Kchaou-Boujelben[1], Céline Gicquel[2]

[1] United Arab Emirates University, Al Ain, United Arab Emirates
[2] Université Paris Saclay, LRI, F-91405, France
celine.gicquel@lri.fr

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1 Problem description

Electric vehicles (EVs) are one of the promising solutions to face environmental and energy concerns in transportation. One of the major barriers towards the large scale adoption of EVs by private drivers is the lack of charging stations to recharge vehicles during long-distance trips, i.e. during trips whose length exceeds the vehicle range. Thus, in order to make EVs an attractive option for long-distance trips, an adequate infrastructure based on stations capable of charging a vehicle within a few minutes needs to be deployed. However, these fast charging stations require high installation and operating costs. It is thus important to carefully select their location so as to simultaneously enable as many EV drivers as possible to carry out their trip and comply with the restrictions on the investment budget.

We consider the problem of optimizing the deployment of an infrastructure based on fast charging stations in order to enable EV drivers to carry out long-distance trips. This leads to the formulation of a facility location problem in which the demand to be served is not located at nodes of the underlying network but rather is represented by a set of trips or flows to be refueled. This combinatorial optimization problem is known as the flow refueling location problem (FRLP) : see e.g. [2]. In the FRLP, a trip is said to be 'covered' or 'refueled' if the charging stations located on the shortest path between the origin and the destination of the trip allow an EV driver to travel from his point of departure to his destination and back without running out of fuel. The objective is to select the best locations for EV charging stations so a to maximize the number of drivers which will be able to carry out their trip while complying with the available limited investment budget.

The coverage of a trip depends mainly on two parameters : the battery energy status when the EV leaves a charging station and its power consumption. A trip will be covered if, for each pair of consecutive stations visited when traveling along the corresponding path, the energy available in the battery when leaving the first station is high enough to provide the power needed by the vehicle to reach the second station. Most previously published papers assume that these two parameters are deterministically known. However, in practice, they are subject to many uncertainties due e.g. to the age of the battery, the weather and the traffic conditions. We thus propose an extension of the FRLP in which the uncertainties related to the energy available in the battery after recharging at a station as well as the power consumption on each portion of the road network are explicitly taken into account.

2 Mathematical modeling

When the energy status of the EV battery after recharging and/or the power consumption on each road segment are subject to uncertainties, trip coverage becomes a matter of chance rather than of binary observation. Namely, it might not be possible anymore to ensure that a trip will be covered with a 100% probability, even if a large number of stations is opened on the corresponding path. We thus use the notion of coverage probability of a trip defined as the joint probability that the power consumption between any pair of consecutive stations visited by the EV driver in the outward and return directions of the trip be smaller than the amount of energy available in the battery after recharging. Furthermore, as suggested by de Vries and Duijzer in [4], an EV driver might not be willing to take a trip if the probability of running out of charge during the trip is above a maximum acceptable risk level α. De Vries and Duijzer thus propose the chance constrained flow refueling location model in which a trip is considered covered if its coverage probability is higher than $1 - \alpha$, and not covered otherwise.

This leads to the formulation of a chance-constraint program in which we seek to maximize the number of drivers for which the probability of running out of fuel when carrying out their trip is below a certain threshold. Note that this stochastic program involves a set of joint chance constraints, namely one for each trip considered in the problem modeling.

3 Solution approach and numerical results

We propose to use a solution approach based on a partial sample approximation (PSA) of the stochastic parameters. This technique is a recent extension proposed in [1] of the sample approximation (SA) approach. Similarly to the SA approach introduced by Lüdtke and Ahmed [3], it relies on a Monte Carlo sampling of the continuous distribution of the random variables but this sampling is carried out on all random variables except one (the stochastic battery energy status after recharging in our case). The main advantage of the PSA approach is that, unlike the SA approach, it does not require the introduction of additional binary variables in the formulation. It thus leads to the formulation of a mixed-integer linear program (MILP) which has more continuous variables and constraints than the deterministic problem but the same number of binary variables as the deterministic problem.

In order to compare the performance of the PSA approach with the one of a previously published approach based on Bonferroni's inequality, we carry out numerical experiments on a set of medium-size randomly generated and real life instances. Our results show that the proposed partial sample approximation approach outperforms the Bonferroni approach in terms of solution quality and gives station locations which provide a significantly improved demand coverage in practice. The PSA approach is more computationally intensive and leads to longer computation times than the Bonferroni approach. However, as determining the location of EV charging stations is a strategic long-term problem, increasing the computation time by a reasonable amount to obtain better quality solutions seems a relevant trade-off.

Références

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