The electric vehicle routing problem with nonlinear charging functions and capacitated charging stations

A. Froger\textsuperscript{1}, Jorge E. Mendoza\textsuperscript{1}, Ola Jabali\textsuperscript{2}, Gilbert Laporte\textsuperscript{3}

\textsuperscript{1} Université François-Rabelais de Tours, LI (EA 6300), ROOT (ERL CNRS 6305), Tours, France
\texttt{aurelien.froger@univ-tours.fr}
\textsuperscript{2} Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milano, Italy
\textsuperscript{3} Canada Research Chair in Distribution Management, HEC Montréal, Montréal, Canada

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1 Introduction

Electric vehicle routing problems (E-VRPs) started to be studied by the Operational Research community only recently. They consist in designing routes to serve a set of customers using a fleet of electric vehicles (EVs). Due to their relatively short driving range the EVs may need to detour to charging stations (CSs) to recharge their battery (specially true in the context of mid-haul or long-haul routing). Modeling the charging functions is a focal point of E-VRPs. Most of the research has focused on constant or linear charging functions. In order to model a more realistic charging process, the E-VRP with nonlinear charging function (E-VRP-NL) was recently introduced by Montoya et al. \cite{2}.

To the best of our knowledge, one of the key assumptions in the E-VRPs defined in the literature is that the CSs are uncapacitated, that is, they are able to simultaneously handle an unlimited number of EVs. In practice, however, each CS has a limited number of chargers. Needless to say, neglecting the CS capacity constraints may lead to poor decisions in practice.

In this research we focus on the E-VRP-NL and we extend it to consider capacitated CSs. We call the resulting problem the E-VRP-NL with capacitated CSs (E-VRP-NL-C).

2 Problem statement

The E-VRP-NL-C is defined as follows. A set of customers need to be served by an unlimited and homogeneous fleet of electric vehicles (EVs). At the beginning of the planning horizon, all EVs are located at a single depot that they leave fully charged. Traveling from a location to another location incurs a driving time and an energy consumption. Each CS has a charging technology (e.g., slow, moderate, fast) associated with a a piecewise linear charging function. Each CS has also a capacity, given by the number of available chargers. Feasible solutions to the E-VRP-NL-C satisfy the following conditions: 1) each customer is served exactly once by a single EV, 2) each route starts and ends at the depot, 3) each route satisfies a given maximum-duration limit, 4) each route is energy feasible (i.e., the SoC of an EV upon arriving at a location or departing from it lies between 0 and the battery capacity), and 5) the number of EVs simultaneously charging at each CS does not exceed the number of available chargers. The objective of the E-VRP-NL-C is to minimize the total time needed to serve all customers. This takes into account driving, service, charging, and waiting times.
3 Solution methods and results

The E-VRP-NL-C is a combined routing and scheduling problem. To extend previous formulations of the E-VRP-NL to include the CS capacity constraints, we draw some inspiration from scheduling models described in the literature. We propose two formulations: a flow-based and an event-based. In addition to a classical CS replication-based formulation (see [1],[3]), we also present a model that avoids replicating the charging stations nodes. We study the efficiency of these MILP models when running on a commercial solver. Results show that optimally solving small-sized instances is already challenging.

To tackle the E-VRP-NL-C we propose a route-first assemble-second matheuristic. In the first stage of this method, we build a pool Ω of high-quality routes while relaxing the capacity constraints. To generate the pool of routes, we use a local search-based metaheuristic that uses components from the routing literature and components designed for the charging decisions. Evaluating a move is also not straightforward for E-VRPs and raises challenges. Indeed, since the visits to CSs are optional and only increase the value of the objective function, removing or inserting one or multiple customers can make the current charging decisions useless or inadequate. Decoupling the revision of the charging decisions from the evaluation of classical VRP moves can have undesired effects. We investigate the trade-off between accurate evaluation of each move and efficiency of the method.

In the second stage of this method, we assemble routes from the pool Ω to build a solution to the problem using a Benders’ like decomposition method. Specifically, we decompose this assembling problem into a route selection master problem and a CS capacity management sub-problem. The master problem consists in selecting a set of routes such that every customer is covered exactly by one route. Every selection of routes yields a set of charging operations; each operation being defined by a CS, a starting time, and a recharge amount. Given these operations, the sub-problem checks if the CS capacity constraints can be met. We investigate three different versions of the CS capacity management problem ranging from a simple check of the capacity constraints to the introduction of waiting times in the selected routes. To efficiently solve the problem while exploiting this decomposition, we solve the route selection problem using a branch-and-bound algorithm. At each integer node of the tree, the corresponding solution is sent to the CS capacity management problem which discards by means of cuts infeasible solutions or solutions for which the objective is underestimated.

We report computational results on a set of instances we adapted from the literature by fixing a capacity at each CS. Our matheuristic finds optimal solutions for some instances and achieves good solutions for the other ones.

References

