Transportation Research Part E 89 (2016) 32–52

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

The Electric Traveling Salesman Problem with Time Windows

R. Roberti [a,*], M. Wen [b]

[a] *Technical University of Denmark, 2800 Kgs. Lyngby, Denmark*
[b] *Xi'an Jiaotong-Liverpool Univeristy, 111 Ren Ai Road, Suzhou, Jiangsu 215123, China*

ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form 14 December 2015
Accepted 18 January 2016
Available online 4 March 2016

Keywords:
Electric vehicles
Green logistics
Traveling Salesman
General Variable Neighborhood Search
Dynamic Programming
Time windows

ABSTRACT

To minimize greenhouse gas emissions, the logistic field has seen an increasing usage of electric vehicles. The resulting distribution planning problems present new computational challenges.

We address a problem, called *Electric Traveling Salesman Problem with Time Windows*. We propose a mixed integer linear formulation that can solve 20-customer instances in short computing times and a Three-Phase Heuristic algorithm based on General Variable Neighborhood Search and Dynamic Programming.

Computational results show that the heuristic algorithm can find the optimal solution in most small-size instances within a tenth of a second and achieves goods solutions in instances with up to 200 customers.

1. Introduction

According to US Environmental Protection Agency (2015), the total US greenhouse gas emissions amounted for 6673 million metric tons CO_2 equivalent mass units in 2013, showing an increase of 5.9% from 1990. Approximately 82.5% of total greenhouse gas emissions by human activities was CO_2. Along with passenger cars, which generated 42.7% of CO_2 emissions, the second largest source of CO_2 emissions in transportation was freight trucks (22.8%). To tackle this environmental problem, in the logistic field, *Electric Commercial Vehicles* (ECVs) are considered as a valid alternative to *Internal Combustion Commercial Vehicles* (ICCVs) because they are environmentally friendly and produce minimal noise.

Due to these practical considerations along with political factors (e.g., in 2009, the US Government granted 2.4 billion dollars to "accelerate the manufacturing and deployment of the next generation of US batteries and electric vehicles", see US Department of Energy (2009)), ECVs are more and more common in last-mile delivery distribution, for example in small-package shipping or in the distribution of food and beverages, and several companies have started deploying ECVs for their daily operations (see FedEx, 2010; Motavalli, 2010). This gives birth to a whole new field of research concerning the conditions under which ECVs are more convenient than ICCVs.

A recent study by Davis and Figliozzi (2013) compared the overall costs of three different vehicles, one diesel truck and two electric trucks, over a long planning horizon and showed that electric vehicles are competitive especially when the traveling distance is long, congestion is prevalent, and customer stops are frequent. Davis and Figliozzi (2013) also pointed out the importance of efficient and tailored distribution plans when utilizing electric vehicles. The *Vehicle Routing Problems* (VRPs) arising when dealing with ECVs present new challenges for researchers and practitioners who want to provide such optimized distribution plans.

* Corresponding author.
E-mail addresses: rorob@transport.dtu.dk (R. Roberti), Min.Wen@xjtlu.edu.cn (M. Wen).

http://dx.doi.org/10.1016/j.tre.2016.01.010
1366-5545/

The literature about optimization methods for traditional ICCVs is rich (see Vigo and Toth (2014) for a comprehensive survey on the topic), while only few recent papers provide optimization algorithms for electric VRPs. One of the seminal papers on the subject can be considered Schneider et al. (2014), where a hybrid heuristic combining *Variable Neighborhood Search* (VNS) and tabu search is proposed to solve the *Electric Vehicle Routing Problem with Time Windows and Recharging Stations* (E-VRPTW). The E-VRPTW is the problem of defining a least-cost distribution plan for capacitated electric vehicles, located at a central depot, that are used to satisfy the demands of a set of customers within given time windows; because of the limited capacity of the batteries of such vehicles, stops at recharging stations may be needed along the routes.

In this paper, we address the single-vehicle version of the E-VRPTW under two recharging policies: *full* (the battery is fully recharged at each stop) and *partial* (any amount can be recharged at each stop). To the best of our knowledge, this problem, which we call *Electric Traveling Salesman Problem with Time Windows* (E-TSPTW), has not been addressed in the literature yet. The E-TSPTW can be easily stated as the problem of finding a shortest Hamiltonian tour for visiting a set of customers within given time windows in such a way that the battery level is always non-negative – this can be achieved by stopping at intermediate recharging stations to recharge the battery. The E-TSPTW is a generalization of the well-known and well-studied *Traveling Salesman Problem with Time Windows* (TSPTW), so it is also NP-hard.

Although the market share of electric vehicles is still limited in many countries today, the deployment of electric freight vehicles is expected to grow because of upcoming restrictions on vehicle emissions and because more and more incentives have been provided for using environmentally-friendly vehicles. The application of the E-TSPTW is potentially wide, in particular in last-mile delivery of parcels in urban areas. In FREVUE's reports (Nesterova et al., 2013), a two-phase delivery is considered as an interesting logistics concept for electric freight vehicles. Goods are first sent to an urban consolidation center (UCC), a logistics facility that is close to the denser urban area, by conventional trucks and later are transferred to the electric vehicles for last mile deliveries. This concept has been successfully adopted in many cities, such as Leiden, Bristol, Malaga and La Rochelle, in all of which the electric vehicles are used for transport in the city center zone (van Duin et al., 2010). Some large logistic companies, e.g. FedEx, have also put electric vehicles into use for delivering parcels in urban areas (FedEx, 2010). It can be further expected that when charging infrastructure is deployed along routes connecting cities and when the driving range of electric vehicles is extended, the intercity parcel delivery will gain its momentum (Pelletier et al., in press).

Having efficient solution methods for the E-TSPTW is important not only for solving practical applications of the problem, but also for solving more involved Electric VRPs. It is well-known (see Desaulniers et al., 2005; Vigo and Toth, 2014) that the state-of-the-art exact algorithms for a wide range of VRPs are based on the column generation framework. The most relevant issue when developing these algorithms is arguably the resolution of the pricing problem, which is usually an NP-hard problem for which exact algorithms are time-consuming. Therefore, many column generation algorithms generate columns by means of heuristic algorithms and rely on exact methods only at the very last iterations. We believe that future exact algorithms for Electric VRPs will rely on column generation (a first example from the literature is the exact method of Desaulniers et al. (2014) for the E-VRPTW), and the resulting pricing problems will present most of the challenges tackled when solving the E-TSPTW considered in this paper.

The main contributions of this paper are the following. We define the E-TSPTW and model it as a compact *Mixed Integer Linear Problem* (MILP). We propose an alternative MILP model, both for the full and the partial recharge policies, that has an exponential number of variables (with respect to the number of recharging stations) and defined several rules to limit the number of variables necessary to achieve an optimal solution. Then, we describe a Three-Phase Heuristic algorithm based on *General VNS* (GVNS) and Dynamic Programming to find near-optimal solutions of the E-TSPTW, where simple adaptations are required to consider the full recharge policy instead of the partial recharge policy (and vice versa). Finally, we introduce two sets of benchmark instances derived from well-known TSPTW instances from the literature and show the computational performance of the proposed MILP model and of the Three-Phase Heuristic algorithm for both recharging policies.

The rest of the paper is organized as follows. Section 2 is the literature review. A formal definition of the E-TSPTW and a compact MILP formulation are reported in Section 3. The alternative formulation with exponentially many variables is illustrated in Section 4. The proposed Three-Phase Heuristic algorithm is developed in Section 5. Section 6 reports the computational results. Some conclusions are drawn in Section 7.

2. Literature review

The E-TSPTW is a generalization of the well-known TSPTW. The TSPTW has been extensively addressed in the literature both with exact and heuristic methods. Gendreau et al. (1998) proposed an insertion heuristic that gradually builds the solution by inserting a vertex in its neighborhood and performing a local re-optimization, and, once a feasible solution is achieved, tries to improve it through removal and reinsertion of all vertices. Ohlmann and Thomas (2007) described a variant of Simulated Annealing, called Compressed Annealing, that embeds a variable penalty method to consider time windows constraints that are relaxed and stochastic search. A hybrid method that combines Beam search with Ant Colony Optimization, called Beam-ACO, was proposed by López-Ibáñez and Blum (2010).

More recently, da Silva and Urrutia (2010) and Mladenović et al. (2012) showed the potential of solving the TSPTW by mean of GVNS and proposed two heuristic algorithms that can be considered the state-of-the-art for solving the TSPTW. The algorithm of da Silva and Urrutia (2010) is composed of a constructive stage followed by an optimization stage. In the constructive stage, the goal is to achieve a feasible TSPTW solution by using a VNS; in the optimization phase, the solu-