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The electric location routing problem with time windows and partial recharging

Maximilian Schiffer*, Grit Walther

RWTH Aachen University, School of Business and Economics, Chair of Operations Management, Kackertstraße 7, Aachen 52072, Germany

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ABSTRACT

Electric commercial vehicles are expected to contribute significantly to the mobility of the future. Furthermore, there are first pilot projects of logistics companies operating electric commercial vehicles. So far, planning approaches for electric fleets either address routing decisions with emphasis on the limited driving range and long charging times of the vehicles, or focus on the siting of charging stations in order to implement the necessary charging infrastructure. In this paper, we present a location routing approach to consider routing of electric vehicles and siting decisions for charging stations simultaneously in order to support strategic decisions of logistics fleet operators. Thereby, we regard different recharging options due to real world constraints. Furthermore, we also take alternative objective functions into account minimizing not only the traveled distance, but also the number of vehicles needed and the number of charging stations sited as well as total costs. Results are presented for the total traveled distance of the location routing model, and potential improvements compared to a vehicle routing model are shown. Shorter overall distances can be achieved if simultaneous siting as well as extended recharging options are allowed. Besides, results for the other objective functions are shown with respect to the impact of the objectives and conflicting targets.

1. Introduction

High effort is necessary in the transportation sector to tackle challenges of climate change and limited availability of fossil energy sources as well as air quality concerns caused by increasing urbanization. The European Union (EU) is aiming at a reduction of greenhouse gas (GHG)-emissions by 20% until 2020 and by 40% until 2030 relative to 1990 (European Comission, 2014). This is a challenge for the transportation sector, which contributes with 20% to total GHG-emissions (European Environment Agency, 2014b). Additionally, quality of air within urban areas (NO_x, fine dust) is becoming an important topic with increasing urbanization (European Environment Agency, 2014a), and there is even a discussion on a ban of internal combustion engine vehicles (ICEVs) in urban areas of Europe (European Comission, 2011). Electric vehicles help to tackle these challenges. Accordingly, planning approaches for electro-mobility have recently become popular for researchers as well as practitioners. First pilot projects on electric logistic fleets have been started by UPS and DHL (DPDHL, 2014; UPS, 2013).

Electric commercial vehicles (ECVs) have several advantages over ICEVs. First, ECVs are one of the cleanest means of transportation in urban areas and mega cities, since they have zero tank-to-wheel (i.e. local) emissions. Even a zero well-to-wheel emission balance can be obtained if electricity is generated by renewable energy sources. A significant noise reduction results as well. Furthermore, ECVs are able to contribute to increase the share of renewable energy sources that can be handled by the electrical grid, since ECVs could serve as small decentralized energy storages and thus balance the fluctuating renewable energy supply. Additionally, ECVs contribute to intentions to become independent of fluctuating oil prices and politically unstable countries. Concluding, ECVs are a great opportunity that will play a major role within a sustainable mobility of the future.

However, two major challenges have to be solved to realize electric mobility concepts in real world applications. On the one hand, routing decisions for ECVs have to take the limited driving range of ECVs as well as necessary charging times into consideration. On the other hand, necessary charging infrastructure is still lacking. This means that there is a chicken and egg dilemma as ECVs cannot be used without infrastructure, while infrastructure is only built if a certain number of ECVs is already on the roads. Furthermore, these two aspects are interdependent, because routing decisions for vehicles with limited driving range might depend on

* Corresponding author.
E-mail addresses: maximilian.schiffer@om.rwth-aachen.de (M. Schiffer), walther@om.rwth-aachen.de (G. Walther).
URL: http://www.om.rwth-aachen.de (M. Schiffer)

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available charging infrastructure, while siting decisions for charging infrastructure will be based on the charging demand that is estimated based on driving patterns and driving range.

With regard to costs, ECVs could become an important mean of transportation, since they have lower operational costs compared to conventionally fueled trucks. This holds especially for ECVs in vehicle fleets, since advantages in operational costs are the higher the more the vehicle is utilized. However, higher acquisition costs for vehicles and infrastructure occur. Thus, competitiveness of ECVs depends heavily on the relation between operational costs and acquisition costs as Davis and Figliozzi (2013) point out. While ECVs are currently not yet competitive, this ratio might shift in the near future if penalty charges for emissions have to be paid (e.g., an excess emission premium of 95€ per subsequent gCO_2/km that exceeds a treshold of 95 gCO_2/km (valid from 2021 on) is levied, cf. EC, 2012), or if emission certificates are released for the transportation sector (cf. Kieckhäfer et al., 2015).

Since the market penetration of ECVs is still low and only sparse charging infrastructure exists, there are currently high potentials if charging station siting and vehicle routing are considered simultaneously. While the entire potential of these advantages cannot be utilized if siting and routing decisions are taken by different players (e.g. governments decide on siting infrastructure and private persons decide on routes), operators of electric logistics fleets currently decide on both aspects simultaneously. Thus, the present situation holds unique options for fleet operators. However, it will not be sufficient to focus on the minimization of the total distance. Instead, fleet operators also have to take the minimization of the number of charging stations sited as well as the minimization of the total number of ECVs used or the complete life cycle costs into account. Thus, simultaneous siting and routing decisions are necessary, since the number of vehicles needed is directly influenced by the number and position of charging stations sited and vice versa.

Besides the simultaneous routing and siting decision, realistic recharging options as well as additional restrictions for logistic fleets have to be taken into consideration. State of the art vehicle routing problems (VRPs) consider customer demands, vehicle freight capacities, customer time windows and service times. In realistic applications of ECVs, it might not only be possible to recharge at special charging stations on the route, but also at customer sites as this offers several advantages. For instance, overall time needed for service and recharging of vehicles is minimized if vehicles that serve the customer can use service time for recharging. Moreover, charging stations at customer sites benefit from the existing electrical grid infrastructure and are less likely to be destroyed by vandalism. By even allowing vehicles that do not serve a certain customer to use a charging station at the customer's site, the number of charging stations can be decreased while the utilization of this costly infrastructure can be increased. Additionally, partial recharges have to be considered in realistic applications, since this enables vehicles to recharge only as much energy as the vehicle needs to finish its next trip. Thus, additional time windows of customers might become feasible, since waiting time due to unnecessary recharging at previous nodes is reduced. From a practical point of view, it might be profitable to recharge the vehicle's battery only as much as necessary if the missing energy can be recharged at lower electricity prices overnight at the depot (cf. Felipe, Ortuño, Righini, & Tirado, 2014).

Recent literature has so far been focusing on selected aspects of the described planning problem. Research has been done on siting charging station infrastructure for different fields of application. Furthermore, additional constraints have been added to existing VRPs to extend these models for electric vehicles. A first approach on modeling simultaneous routing and siting decisions has been presented by Yang and Sun (2015) focusing on battery swapping stations (BSSs). However, three important aspects are still missing. First, time window constraints are not considered. Second, the model is not applicable for charging stations, because recharging time is not considered. Third, the range of recharging options is not covered.

Table 1
Overview of related research streams for the ELRP-TWPR.

Aspect	ESPPs	EVRPs	Location-models	Location routing models
Routing decisions	✓	✓		✓
Siting decisions			✓	✓
Logistic fleet constraints		✓		✓
Electric vehicle constraints	✓	✓	✓	

Links between related research streams and single aspects of our objective.

Thus, the aim of our paper is to develop a model that takes simultaneous routing and siting decisions as well as the whole range of recharging options into consideration. In addition, state of the art constraints for logistics fleets (time windows, capacity constraints, customer demand) are taken into account. Besides the frequently used objective of minimizing the overall traveled distance, we also present other objectives: we minimize the number of vehicles used for a given number of charging stations as well as the number of charging stations sited for a given number of vehicles. In addition, we obtain a weighted sum of vehicles used and charging stations sited as a third objective, and total costs as a fourth objective. Results for all objectives are presented and compared using existing test instances. Furthermore, the benefit of an integrated routing and siting decision model is pointed out.

Our paper is structured as follows: in Section 2 an overview of related research streams and literature is given. In Section 3 the electric location routing problem with time windows and partial recharging (ELRP-TWPR) is introduced and explained in detail. Section 4, describes the experimental design. Results for the proposed model regarding the different objective functions are presented in Section 5. A comparison with vehicle routing problem (VRP) approaches highlights the benefit of simultaneous siting and routing decisions. Section 6 concludes this paper with a short summary and an outlook on future research.

2. Literature review

The problem formulation shown in this paper is related to various kinds of research streams. This section gives a detailed overview of related research streams focusing on electric commercial vehicle (ECV) specific optimization models, whereas only short overviews including useful references for further studies are given as far as broader research is concerned.

Single aspects of our planning problem can be found in four different research streams (see Table 1). The first stream focuses on energy shortest path problems (ESPPs) and provides new routing algorithms for ECVs by taking the overall consumed energy on a route into consideration. The second stream focuses on electric vehicle routing problems (EVRPs) and extends existing VRPs by additional constraints for ECVs. The third stream focuses on location models for siting charging infrastructure. An overview on these streams is presented by Touati-Moungla and Jost (2010), who give an ESPP formulation, a formulation of a capacitated vehicle routing problem (CVRP) including a range limitation by battery capacity and energy consumption as well as an overview on facility location approaches for charging infrastructure. The fourth stream our planning problem is related to is research on location routing problems (LRPs), which have been extensively discussed in recent literature. Prodhon and Prins (2014) give a profound overview on recent research on LRPs from 2007 until today. In addition, an overview of recent research on standard LRPs can be found in Drexl and Schneider (2014a). Another literature review is given by