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Charge scheduling for electric freight vehicles

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ABSTRACT

We consider a fleet of electric freight vehicles (EFVs) that must deliver goods to a set of customers over the course of multiple days. In an urban environment, EFVs are typically charged at a central depot and rarely use public charging stations during delivery routes. Therefore, the charging schedule at the depot must be planned ahead of time so as to allow the vehicles to complete their routes at minimal cost. Vehicle fleet operators are subject to commercial electricity rate plans, which should be accounted for in order to provide an accurate estimation of the energy-related costs and restrictions. In addition, high vehicle utilization rates can accelerate battery aging, thereby requiring degradation mitigation considerations. We develop and solve a comprehensive mathematical model that incorporates a large variety of features associated with the use of EFVs. These include a realistic charging process, time-dependent energy costs, battery degradation, grid restrictions, and facility-related demand charges. Extensive numerical experiments are conducted in order to draw managerial insights regarding the impact of such features on the charging schedules of EFVs.

1. Introduction

Electric freight vehicles (EFVs) are fast becoming a viable alternative for short- and mid-haul goods distribution (Davis and Figliozzi, 2013; Lee et al., 2013; Pelletier et al., 2016; Quak et al., 2016; Franceschetti et al., 2017). Because they help reduce air and noise pollution they are often regarded as an attractive option in the context of city logistics. Most recent studies have dealt with the routing issues associated with EFVs, especially those that stem from their limited range, and have proposed models and algorithms for the optimization of routes that incorporate en route recharging (e.g., Felipe et al., 2014; Schneider et al., 2014; Bruglieri et al., 2015; Goeke and Schneider, 2015; Hiermann et al., 2016; Montoya et al., 2017). Some authors have also approached such optimization problems from a more strategic planning perspective by incorporating both routing and charging infrastructure location decisions in their models (e.g., Yang and Sun, 2015; Schiffer and Walther, 2017a; 2017b; 2018; Schiffer et al., 2018).

The issue of depot charge scheduling for electric vehicles has received less attention than the routing component, but it nevertheless raises interesting challenges whose solution could facilitate the integration of EFVs in goods distribution schemes. Indeed, many companies using EFVs prefer charging the vehicles at their own facilities (Morganti and Browne, 2018). This is due to a combination of factors, such as limited fast charging infrastructures in most regions, as well as long charging times associated with slow charging stations that lead to cargo security concerns and inefficient use of

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drivers' time when charging along delivery routes (Naberezhnykh et al., 2012; Nesterova et al., 2013; E-Mobility NSR, 2013). In addition, lower energy costs may be attained through commercial off-peak electricity rates when charging at the depot during specific periods of the day. Moreover, EFVs are more likely to be used in urban areas because of low driving speeds and frequent stop-and-starts, where their superior energy efficiency becomes relatively advantageous compared with that of diesel vehicles, and where financial incentives are more likely to be available. Since typical urban delivery routes are shorter than the range of currently available EFVs (Feng and Figliozzi, 2013), there is often no need to consider charging outside the depot. While some studies have focused on charge scheduling for EFVs (e.g., Sassi and Oulamara, 2014a; 2014b), several important issues have not yet been addressed.

Before the publication of the recent paper by Montoya et al. (2017), charging of EFVs in a routing context was either treated as a fixed time penalty (e.g., Conrad and Figliozzi, 2011; Afroditi et al., 2014; Preis et al., 2014), or was assumed to be linear with respect to time (e.g., Felipe et al., 2014; Schneider et al., 2014; Bruglieri et al., 2015; Lebeau et al., 2015; Goeke and Schneider, 2015; Hiermann et al., 2016), which does not always correspond to reality. Indeed, in order to prevent overcharging the battery (i.e., operating the battery at voltage values beyond a value specified by the manufacturer), the charging function usually comprises both a linear and a non-linear component with respect to time when large charging currents are employed. Moreover, certain charging practices of electric vehicles have been shown to adversely influence the lifespan of their batteries (Bashash et al., 2011; Lunz et al., 2012). Since the battery still remains a major cost component of EFVs (Pelletier et al., 2016), it is relevant to take this consideration into account when making charge scheduling decisions. This is particularly important since high use rates have frequently been identified as a means of increasing the cost competitiveness of EFVs because of their high purchase costs and low operational costs (Davis and Figliozzi, 2013; Lee et al., 2013). However, recent studies (e.g., Taefi, 2016; Taefi et al., 2016) have concluded that this may not be the case if costly battery replacements result from intensive usage in high utilization scenarios. In addition, such scenarios often involve using the vehicles in multi-shift contexts, whereby vehicles may need to perform multiple routes throughout day and night (EFVs are sometimes allowed to perform night-time deliveries in cities because they are silent, Taefi, 2016). As a result, fleet operators may have to install expensive chargers at the depot in order to charge the vehicles between consecutive delivery routes during specific periods of the day, and to benefit from off-peak electricity rates. A company would probably own a limited number of chargers, typically fewer than the fleet size, thus leading to tight charging schedules. Moreover, commercial electricity rate plans are often subject to both time-dependent energy costs and facilities-related demand (FRD) charges, the latter depending on the maximum power demand registered over the course of the billing period (see, e.g., Southern California Edison (2017)). Therefore, regardless of whether the operational context requires fast chargers or not, optimizing the charging schedule can help in determining the best alternative between paying a higher FRD charge and incurring lower energy costs (e.g., by charging many vehicles when electricity is cheap), or rather keeping such FRD fees low at the expense of spreading out the charging activites throughout the day, notably when electricity is more costly.

Two relevant studies in the context of depot charge scheduling for EFVs are those of Sassi and Oulamara (2014a,b). In the first of these papers, a fleet of electric and conventional vehicles must be assigned to a set of predetermined routes so as to maximize the usage of the electric vehicles and minimize the cost of the charging schedule. Charging can only take place at the depot when the vehicles are not performing routes. The planning horizon is discretized into periods during which the charging power remains fixed and must stay within a certain interval indicating the minimum and maximum charging power of the homogeneous chargers at the depot. Charging costs and grid capacities are time-dependent. Sassi and Oulamara (2014b) have extended this problem by considering different types of chargers at the depot and a limited number of each type. They also proposed different objective functions depending on whether certain considerations are taken into account or not. These include being allowed to exceed the grid capacity by paying fixed hourly penalties, treating the number of chargers of each type at the depot as decision variables with deployment costs, and the presence of time-dependent greenhouse gas emissions costs depending on the electricity generation mix at that time.

As in Sassi and Oulamara (2014b), we focus on the depot charging schedule rather than on en route charging at public stations, but we model a more realistic charging process which avoids overcharging, and hence battery deterioration (Lam, 2011). Moreover, we work with a planning horizon of several days rather than with a single day, since the assumption that the vehicles will always be fully charged overnight does not hold in certain multi-shift operational contexts. In addition, we incorporate battery degradation considerations when determining an optimal charging schedule, as well as FRD charges. Finally, we draw several managerial insights through our numerical experiments. These relate to the impact of time-dependent energy costs, battery degradation, grid restrictions, FRD charges and battery size on the charging schedules of EFVs. Such insights are relatively absent from the aforementioned related studies.

The scientific aim of this paper is to model, construct and analyze charging schedules of EFVs that must operate fixed delivery routes over the course of a multiple day planning horizon in a multi-shift operational context, thereby performing several routes per day, and using vehicles that can only be charged at a central depot. With this goal in mind, Section 2 describes the problem at hand and presents a first mathematical formulation without battery degradation considerations. Section 3 explains how certain battery health considerations can be incorporated into the model. Section 4 provides extensive computational results and derives managerial insights. The paper closes with conclusions in Section 5. Appendix A contains a glossary of the abbreviations used in the paper, including those related to energy and electricity units.