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Electric vehicles in car sharing networks – Challenges and simulation model analysis

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ABSTRACT

In this paper, we examine the operation of electric vehicles in urban car sharing networks. After surveying strategic and operational differences and comparing them to gasoline-fueled cars, a simulation study was carried out. The proposed discrete event simulation tool covered important operational characteristics of electric vehicles, including realistic charging routines. Different vehicle types were compared under various conditions and on multiple markets to determine their performance. The data obtained indicated the competitiveness of electric vehicles in car sharing networks. Key success factors included advantageous relations between the market environment (e.g. electricity and fuel prices) and important characteristics of electric cars (e.g. price and range).

1. Introduction

The role of electric vehicles (EVs) in prospective and sustainable mobility is relevant for all modes of transportation, including car sharing (CS). In particular, urban centers with high population densities are currently aiming to reduce the number of conventionally powered vehicles (Engel-Yan and Passmore, 2013). Along with other alternative modes of transportation with the potential to reduce emissions and/or overall traffic volumes, emission-free vehicles have become the focus of considerable attention (Moradi and Vagnoni, 2018). After the introduction of the first CS system in Switzerland in 1948, several commercial projects where established in larger cities around the world. Surprisingly, even one of the first CS networks in the world (WITKAR, Netherlands, established 1974) operated EVs. Due to technical limitations including a maximum vehicle speed of only 30 km/h, it could not satisfy customer demands to a sufficient degree. However, CS proved its utility in complementing or even replacing individual car ownership as an alternative mobility concept during this period fostered by the oil crises of the 1970s (Millard-Ball, 2005; Cepolina and Farina, 2012). Vehicle sharing experienced steady growth during the 1990s, and was revolutionized by the advent of mobile internet services and devices (Shaheen and Cohen, 2013). The flexibility and spontaneity that distinguishes CS in general from conventional car rental could now be utilized directly by customers through smartphone devices.

Today, CS companies face ever-greater demands and constantly extend their areas of operation (Lindloff et al., 2014). It is evident that the combination of CS and e-mobility offers a promising mode of individual inner-city transportation. Additionally, the overlap of key characteristics of CS and e-mobility provides a perfect application for both (Abdelkafi et al., 2013). Both are preferably used for urban mobility and offer the potential to decrease emissions in transportation. They also benefit from higher utilization decreasing fixed cost of a vehicle for its users. However, according to the recent study of some 101 CS providers in Germany by Parzinger et al. (2016), 66 do not offer EVs in their current fleet. This number mostly refers to smaller enterprises with fleet sizes of less than 20 vehicles. However, high growth rates in the number of utilized EVs by CS providers have been identified and confirmed by 70% of the

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larger CS enterprises that already provide electric vehicles (Parzinger et al., 2016).

Our work in this area is directed toward increasing the proportion of EVs in CS fleets in order to fully utilize the ecological potential of electric vehicle car sharing (EVCS) with regard to inner-city emission reduction. In contrast to the research in this field conducted to date (see Sections 2 and 3), we employ a simulation approach built around a realistic vehicle state-of-charge (SOC) simulation in Section 4. This methodological approach offers the flexibility to model typical characteristics of EVs operation under stochastically distributed demand and trip times. It allows us to overcome the common but unrealistic simplification of fully recharging a vehicle before it reenters the pool of available vehicles in a CS network. We analyze the results from this simulation tool in Section 5 and aim to answer the following research question: Might the operation of EVs in any CS network compete with gasoline-fueled cars? The influence of different market conditions and different vehicle types are a major part of the study. Accordingly, if applied as part of a decision support system, our work represents a preliminary phase to the common approaches based on mixed integer programming and profit optimization for entire networks that can be found in many recent articles.

2. Literature

According to the notable work of Abdelkafi et al. (2013), CS represents a business model that could benefit from the typical characteristics of e-mobility. This includes a feasible use case for limited vehicle range and preferably application in business fleets due to the higher vehicle cost. Additionally, a satisfying charger infrastructure is expected to grow faster in urban areas than in rural areas (Kihm and Trommer, 2014). A specific business model for an EVCS network can be found in Luè et al. (2012). The authors design a CS network including customers and operators as well as private and commercial providers and highlight its contribution to sustainable transportation (Luè et al., 2012). CS is also highlighted as a perfect application for EVs by Fairley (2013). The report relies on current success and advantages of EVs as well as practical usage patterns mostly from a customer's point of view (Fairley, 2013). In contrast, the operators perspective is covered in Xu et al. (2017). Also success factors for EVCS systems are evaluated. The results underline the high importance of customer satisfaction and the need for appropriate planning of EVCS (Xu et al., 2017). While the publications noted above focus on operational issues, the following provide insights into the technical aspects of EVs that make them suitable for CS. The high technical relevance of EVs (e.g. regarding smart energy storage) for future mobility is outlined by Farid (2017) and Fuentes et al. (2017). Moreover, Vervaeke and Calabrese (2015) understand EVCS as a service that is experiencing constant growth, thus underlining the significance of our own work for future urban mobility. Along with technical and operational aspects, also the readiness of users to embrace EVs plays an important role. A survey analyzing the reactions and experiences of EVCS users is presented by Kim et al. (2015). Yoon et al. (2017) found no added willingness to pay for EVCS in comparison with conventional powered cars. However, market penetration of EVCS also depends on external factors. Considerations such as government subsidies for vehicle purchase or the development of fuel and electricity prices comprise some of the factors that could promote or hinder the adoption of EVCS (Reining et al., 2014; Plötz et al., 2015). After giving a short review on the thematically framework behind electric vehicle sharing, the following quantitative studies offer noteworthy findings determining our own research.

The modeling of EVCS is quite advanced because some findings from studies of conventionally fueled CS vehicles could be transferred to EVCS. Recent research, however, has already been designed for EVCS. For review purposes and for a general introduction to the modeling and demand issues associated with one-way CS and the related vehicle relocation problem, the interested reader may be directed to Le Vine et al. (2014), Shaheen et al. (2015) and Gavalas et al. (2015). Furthermore, there are examples for modeling EVCS networks that deal with a wide range of research questions. The strategically oriented work conducted by Boyacı et al. (2015) addresses the location planning of network stations depending on shifts in demand. Operational aspects like SOC of EVs are neglected. Longer vehicle downtimes due to battery charging and specific recharge operations are investigated by Weikl and Bogenberger (2015), Li et al. (2016), Brandstätter et al. (2017) and He et al. (2017). However, all of these papers are based on profit optimization through mixed integer programming, thus exhibiting weaknesses that result in limited real-world applicability. In order to avoid unmanageable problem sizes or model complexities, it is assumed that cars always fully recharge after any operation. Practices such as idling in-between trips without recharging or partly recharging until the next customer arrives are not considered, nor is even freeing up a charger due to the arrival of a vehicle with a lower SOC. Consequently, battery capacities (which determine vehicle ranges) do not bear any influence on model outcomes unless they limit the distance of a single trip – which is irrelevant in short-term CS applications. Moreover, underlying costs and profits in the target functions are based on case study-specific conditions in only one market. Recent research conducted by Yoon and Cherry (2018) aims to compare conventional vehicles with EVs in a dedicated sharing network. Their fleet optimization model leads to the conclusion that longer operation times are required to offer the same profitability as EVs at least within their case study. A fixed vehicle range is assumed and recharging is not part of the model (Yoon and Cherry, 2018).

Avoiding any simplification in the vehicle recharging process – thus simulating the actual SOC for any car individually, as well as performing a market- and case study-independent cost analysis – represents a considerable research gap. This gap is addressed in our paper with respect to the role of conventionally and electrically powered vehicle types vis-à-vis the efficiency and profitability of CS networks.

3. Background

3.1. Scope and forms of CS

The two most important characteristics of a CS network are their trip type and station policy. Most CS systems offered today are