Applied Energy 211 (2018) 282–295

Contents lists available at ScienceDirect

Applied Energy

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

# Electric bus fleet size and mix problem with optimization of charging infrastructure

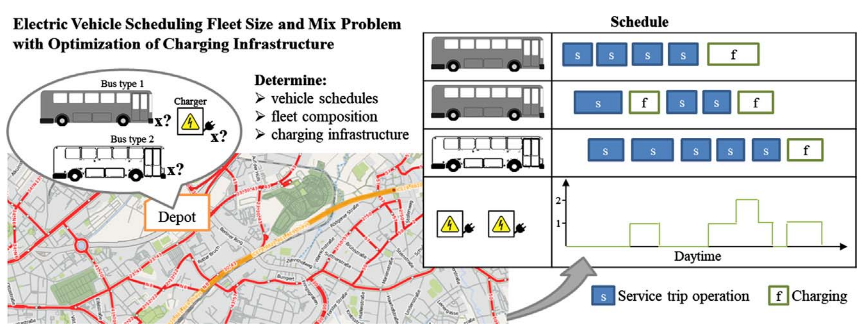
Matthias Rogge[a,b,*], Evelien van der Hurk[c], Allan Larsen[c], Dirk Uwe Sauer[a,b,d]

[a] Chair for Electrochemical Energy Conversion and Storage Systems, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Jaegerstrasse 17-19, 52066 Aachen, Germany
[b] Juelich Aachen Research Alliance, JARA-Energy, Germany
[c] DTU Management Engineering, Technical University of Denmark, Denmark
[d] Institute for Power Generation and Storage Systems (PGS), E.ON Energy Research Center, RWTH Aachen University, Germany

## HIGHLIGHTS

- A framework for the cost-efficient planning of battery bus fleets is proposed.
- The approach combines a genetic algorithm and mixed-integer-linear-programming.
- Two electrification scenarios of European cities are analyzed in a case study.
- Energy efficiency is discussed for two competing battery bus concepts.
- Operation of lightweight buses enables energy savings of about 30%.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Keywords:*
Electric bus scheduling
Charger scheduling
Transportation system modeling
Infrastructure planning
TCO optimization
Genetic algorithm

## ABSTRACT

Battery electric buses are seen as a well-suited technology for the electrification of road-based public transport. However, the transition process from conventional diesel to electric buses faces major hurdles caused by range limitations and required charging times of battery buses. This work addresses these constraints and provides a methodology for the cost-optimized planning of depot charging battery bus fleets and their corresponding charging infrastructure. The defined problem covers the scheduling of battery buses, the fleet composition, and the optimization of charging infrastructure in a joint process. Vehicle schedule adjustments are monetized and evaluated together with the investment and operational costs of the bus system. The resulting total cost of ownership enables a comparison of technical alternatives on a system level, which makes this approach especially promising for feasibility studies comprising a wide range of technical concepts. Two scenarios of European cities are analyzed and discussed in a case study, revealing that the cost structure is influenced significantly by the considered bus type and its technical specifications. For example, the total energy consumption of the considered lightweight bus is up to 32% lower than the total consumption of the high range bus, although the deadheading mileage increases. However, the total costs of ownership for operating both bus types are relatively close, due to the increased fleet size and driver expenses required for the lightweight bus system. The case study furthermore reveals that a mixed fleet of different bus types could be advantageous depending on the operational characteristics of the bus route.

* Corresponding author at: Chair for Electrochemical Energy Conversion and Storage Systems, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Jaegerstrasse 17-19, 52066 Aachen, Germany.
*E-mail address:* batteries@isea.rwth-aachen.de (M. Rogge).

https://doi.org/10.1016/j.apenergy.2017.11.051
Received 20 February 2017; Received in revised form 5 November 2017; Accepted 6 November 2017

**Nomenclature**

| | |
|---|---|
| $A$ | set of arcs, union of $A^s$ and $A^f$ |
| $A^f$ | set of arcs connecting charging events by charger |
| $A^s$ | set of arcs representing feasible deadhead trips |
| $a_i$ | starting time of event $i \in S \cup F$ |
| $c_e^k$ | energy costs per unit for bus type $k \in V$ |
| $c_t$ | time related operational costs for a bus in € per hour |
| $d_f$ | duration of charging event $f \in F$ in seconds |
| $E^k$ | usable battery capacity of bus type $k \in V$ |
| $e_i^k$ | current energy level of a bus of type $k \in V$ after servicing trip $i \in S_{n+1}$ |
| $F$ | set of nodes representing possible charging events $f \in F$ |
| $F_0$ | union nodes representing all charging events $F$ and the bus depot source node $0_f$ |
| $F_{n+1}$ | union nodes representing all charging events $F$ and the bus depot sink node $q_f$ |
| $G$ | multi-graph defined by node set $N$ and arc set $A$ |
| $h_{ij}^k$ | energy consumption for servicing trip $j \in N_{n+1}$ after trip $i \in N_0$ using vehicle type $k \in V$ in kWh |
| $M$ | Constant, $M \gg a_i$ |
| $m^k$ | Purchasing costs of bus type $k \in V$ in € |
| $N$ | Set of nodes, union of $F$, $0_f$, $q_f$, S, $0_s$ and $q_s$ |
| $p$ | purchasing costs per charger in € |
| $r^k$ | recharging capability of bus type $k \in V$ |
| $S$ | set of nodes representing $n$ service trips |
| $S_0$ | set of nodes, union of $S$ and $0_s$ |
| $S_{n+1}$ | set of nodes, union of $S$ and $q_s$ |
| $t_i$ | duration of service trip $i \in S$ in seconds |
| $t_{ij}$ | time required for servicing trip $j \in S_{n+1}$ after trip $i \in S_0$ in seconds |
| $u_f$ | supplement for postponing charging event $f \in F$ in seconds |
| $V$ | set of bus types, type $k \in V$ |
| $w$ | weighting factor for shift penalties between 0 and 1 |
| $x_{ij}^k$ | binary indicator whether bus type $k$ services event $j$ after event $i$, $k \in V$,$(i,j) \in A^s$ |
| $z_{lm}$ | binary indicator of charging event $m$ takes place after charging event $l$, $(l,m) \in A^f$ |
| $0_f$,$q_f$ | source and sink node representing bus depot for charging events |
| $0_s$,$q_s$ | source and sink node representing bus depot for service trips |
| $\beta_i$ | start time of service trip $i \in S$ |
| $\gamma$ | earliest start time of charging events |
| $\delta$ | latest feasible start time of charging events |

## 1. Introduction

Emission mitigation is one of the major topics of the 21st century. Negative consequences of the continuously increasing output can be observed on the global and local scales. Reducing the usage of fossil fuels is a commonly agreed upon measure to target this issue. The transport sector is requested to contribute by increasing the efficiency of conventional fuel-powered drivetrains and by introducing electric vehicle concepts powered by renewable energy sources [1–3]. Several national policies and subsidy schemes exist to promote this transition process [4,5].

Especially commercial fleets, such as public transport buses, are seen as a prime starting point for the introduction of electric vehicles. Their operation is planned in advance and dominated by high mileages per vehicle, so that higher investment costs of the electric drivetrain could be compensated by reduced operational costs. Indeed, battery electric buses have been successfully tested in several projects worldwide [6] and, with decreasing battery system costs, have become increasingly competitive with conventional buses [7]. However, the reduced operational performance of electric buses is still a major barrier for the transition process. The aim of the present work is to contribute to this process by providing a framework for the cost-optimized planning of electric public transport bus fleets.

The paper addresses strategic electric bus planning by focusing on the "Electric Vehicle Scheduling Fleet Size and Mix Problem with Optimization of Charging Infrastructure" (EVS-FMC), minimizing the total cost of ownership (TCO) of electric vehicle fleets. The TCO is the main decision criterion for investment alternatives. It consists of the initial investments in vehicles and charging infrastructure, as well as the operational costs within a defined time period. Provided a set of service trips and a candidate set of vehicle types, the EVS-FMC proposes a fleet-composition investment, in terms of number of vehicles to by per vehicle type, as well as a vehicle schedule that serves all service trips, and a set of chargers to buy per depot, that all together minimize TCO.

The EVS-FMC can be considered as an extension of the "Vehicle Scheduling - Fleet Size and Mix Problem", with the addition of range constraints per vehicle, the scheduling of charging time, and the scheduling of charging infrastructure. It relates directly to the general "Fleet Size and Mix Problem" analyzed in operations research, and is a subcategory of the "Vehicle Routing Problem", in which routing is performed jointly with a determination of the required number of vehicles [8]. Fleets can consist of single vehicle types (homogeneous fleet) or multiple vehicle types (heterogeneous fleet). Recent work has mainly referred to the area of goods distribution. A comprehensive review focusing on electric vehicles in this field is provided in [9]. The discussed approaches differ in terms of the considered vehicle types (homogeneous or heterogeneous electric vehicle fleet, with and without conventional combustion engine vehicles) and the methodology of handling charging events. Goeke et al. and Lebeau et al. extensively studied the routing of mixed fleets composed of conventional and electric vehicles [10,11]. They emphasized the need to consider vehicle types' specific energy consumptions, especially for vehicles with varying weights; this motivates the energy consumption simulation in this work. Van Duin et al. did not consider battery charging [12], whereas Gonçalves et al. defined that charging could take place at every customer's location [13]. In another study, Hiermann et al. included an insertion of charging events so that vehicles could explicitly drive to recharging stations when needed [14]. However, none of these authors considered investments in charging infrastructure or usage fees. Sassi et al. included usage fees as time-dependent charging costs for a "Mixed Fleet Routing Problem" [15]. However, the number of chargers in their model was still pre-defined and fixed.

By focusing on public transport buses, the routing problem becomes a scheduling problem, because service trips (regular operation in passenger service) are fixed in time and location. Routing alternatives are limited to deadhead trips, which are the connecting elements between service trips. The electric vehicle scheduling problem can be seen as a "Vehicle Scheduling Problem with Route and Fueling Time Constraints". The objective is to minimize fleet size and operational expenses. As for vehicle routing, previous studies differ in their way of considering battery charging. Li proposed a methodology for scheduling a fleet of battery buses with battery renewal or fast charging [16]. The implemented truncated column generation with variable fixing and local search is highly competitive, but the durations of charging events are not linked to the energy consumption, and charging costs are defined as a fixed value per event. Other approaches considering the charging in more detail are based, for example, on ant colony optimization [17,18]. However, these approaches do not provide the ability to handle heterogeneous fleets. In contrast, Paul and Yamada focused on the problem of fast-charging bus operation and scheduling charging