Optimizing Regional Zero-Emission Bus Operations via Multi-Depot Electric Vehicle Scheduling

Elisabeth Gaar[1], Xenia Haslinger[2], and Sophie N. Parragh[2]

[1]University of Augsburg, Institute of Mathematics, Universitätsstraße 14, 86159 Augsburg, Germany, ✉ elisabeth.gaar@uni-a.de
[2]Johannes Kepler University Linz, Institute of Production and Logistics Management, JKU Business School, Altenberger Straße 69, 4040 Linz, Austria, ✉ xenia.haslinger@jku.at, ✉ sophie.parragh@jku.at

Policy initiatives such as the "avoid–shift–improve" paradigm and the European Clean Vehicles Directive have accelerated the transition toward low-carbon public transport systems. Although battery electric buses are increasingly deployed in urban networks, their use on regional routes introduces additional operational complexity, mainly due to longer trip distances and constrained charging opportunities. This work addresses these challenges by studying a multi-depot electric vehicle scheduling problem for regional bus operations under a fixed timetable with different zero-emission propulsion technologies. This problem was already studied for example by Wen et al. [1].

We propose a modeling framework that lexicographically optimizes three key performance criteria: fleet size, the number of charging events, and overall energy consumption. A time-expanded graph representation is introduced that captures partial charging decisions without the explicit use of time variables. Based on this representation, we derive both a three-index and a two-index mixed-integer linear programming formulation. While the three-index model can be handled directly by standard optimization solvers, the two-index formulation involves an exponential number of constraints, for which we developed a sophisticated solution framework, in which the cutting planes are dynamically generated.

The proposed models were developed and applied within the research project Zero Emission Mobility Salzburg (ZEMoS) and supported strategic planning decisions of a regional public transport authority during the procurement of zero-emission bus services in two pilot areas. Key outcomes included recommendations on vehicle technology selection and fleet sizing. Battery electric buses derived from this planning process are already in service. In addition, the optimization results informed total cost of ownership analyses and serve as a foundation for future extensions toward heterogeneous fleets and multi-line regional network planning.

References

[1] M. Wen, E. Linde, S. Ropke, P. Mirchandani, and A. Larsen. An adaptive large neighborhood search heuristic for the electric vehicle scheduling problem. *Computers & Operations Research*, 76:73–83, 2016.