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Transition to eBuses with Minimal Timetable Disruptions

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Abstract

The implementation of a sustainable and efficient electric transportation network requires addressing multiple concerns such as: limited driving range, battery charging/discharging times and avoiding battery damages. Therefore, the transition to a fully electric bus transportation system involves multiple challenges including timetable design and the charging location problem. In this paper, we address these problems that arise by transitioning from regular diesel buses to electric buses (eBuses).

Introduction

Currently the average driving distance of eBuses ranges between 70KM and 200KM on a full charge. Therefore, the charging infrastructure must be implemented in a way that charging time and limited driving range will not impact the quality of the service. Charging time varies depending on the technology from a couple minutes (with fast-charging stations) to hours (with slow-charging stations). In this paper, we assume that the buses start operations with full energy capacity (e.g., with slow overnight charging).

We recall that buses in urban cities operate under fixed routes and strict timetables that are designed to satisfy the demand of the city. Therefore, we prioritise the minimisation in the disruptions of the original bus timetables to facilitate the eBuses transition. The eBuses transition is subject to additional constraints in relation to the optimal placement of the charging infrastructure. In this context, we investigate three critical components for transitioning to eBuses, i.e., placement of charging units, timetable disruptions, and battery longevity.

(**?**) describes four problems that must be addressed during the transition, i.e., network design, timetable development, vehicle scheduling, and crew scheduling. (**?**) investigates the charging location problem with an empirical evaluation for Berlin in Germany. In this paper, we formalise a model for transitioning to eBuses with the three above mentioned objective functions. Additionally, we present a successful evaluation of our model with real data from three Irish cities.

Mathematical Model

Let $b \in \mathcal{B}$ be a set of identical buses, $\mathcal{S}_b$ be a sequence of ordered stations $s_j \in \mathcal{S}_b$ indicating the traveling path of b in a workday (i.e. $\mathcal{S}_b = \{s_0, s_1, ..., s_n\}$). Each scheduled stop s_j has an associated constant timetabled arrival time (given by the original schedule) τ_{bj}; actual arrival time t_{bj}; deviation time Δt_{bj} between the actual arrival time and the planned one; battery capacity c_{bj} indicating the remaining energy level of the battery of the bus b at station j; energy added e_{bj} by recharging the bus for a certain amount of time ct_{bj}; and a Boolean variable x_{bj} indicating whether we recharge bus b at the j-th stop of the bus.

For each trip between stations i and j let us define D_{ij} as the amount of energy required to complete the trip between the two stations; T_{ij} denotes the time needed to complete this trip. Additionally, let x_i be a Boolean variable denoting whether we install a charging unit at station i. Hereafter, we describe our linear constraint model and objective functions.

$$\forall_{b \in \mathcal{B}} \forall_{s_i \in \mathcal{S}_b \setminus \{s_0\}}, j = i - 1 :$$

$$C_{min} \leq c_{bi} \leq C_{max} \tag{1}$$

$$c_{bi} \leq c_{bj} + e_{bj} - D_{ij} \tag{2}$$

$$t_{bi} \geq t_{bj} + ct_{bj} + T_{ij} \tag{3}$$

$$\Delta t_{bi} \geq t_{bi} - \tau_{bi} \tag{4}$$

$$\Delta t_{bi} \geq \tau_{bi} - t_{bi} \tag{5}$$

$$\beta x_{bi} \geq ct_{bi} \tag{6}$$

$$x_i \geq x_{bi} \tag{7}$$

Constraint 1 sets the min. and max. energy level at all times and ensures that the buses will have enough power to complete the predefined trip. Constraints 2 and 3 calculate the energy level and arrival time for a given bus b in the scheduled trip. Constraints 4 and 5 calculate the deviation time from the original bus timetable.

Manufactures recommend to avoid fast charging the batteries for more than a given threshold (e.g., 80% of the capacity) to reduce overheating and potential damages in the lifetime of the batteries. Taking this into consideration, Constraints 6 regulates the maximum charging time per charging cycle to up β minutes. Constraint 7 indicates whether a charger unit will be required at a given station s_i in the bus network.

Non-overlapping constraints. The following set of constraints ensure admisible schedules with non-overlapping charging times, i.e., the charging time for any pair of buses cannot overlap. Let Z_{bdij} be a Boolean variable denoting whether buses b and d are using the same charging station or not (i.e., Constraints 8, 9, and 10). If so, Constraints 11, 12, and 13 ensure that the two buses are not using the same charging station at the same time. We assume that M is an arbitrary large constant.

$$\forall_{b,d\in B|b\neq d}\forall_{s_i\in\mathcal{S}_b},\forall_{s_j\in\mathcal{S}_d}|s_i = s_j :$$

$$Z_{bdij} \leq x_{bi} \tag{8}$$

$$Z_{bdij} \leq x_{dj} \tag{9}$$

$$x_{bi} + x_{dj} \leq Z_{bdij} + 1 \tag{10}$$

$$t_{bi} \geq t_{dj} + ct_{dj} - Mz_{bdi} \tag{11}$$

$$t_{dj} \geq t_{bi} + ct_{bi} - Mz_{dbi} \tag{12}$$

$$z_{bdi} + z_{dbi} - (1 - Z_{bdij}) \leq 1 \tag{13}$$

Multi-objective Function. The multi-objective function in Equation 14 aims at (in this order) minimizing the number of charging stations (primary objective), reduce the cumulative deviation time from the expected times and minimize the total charges done in the whole schedule. The last objective aims at optimising battery longevity by avoiding excessive tiny recharges during a workday.

$$\text{Min: } \lambda_1 \sum_{i}^{n} x_i + \lambda_2 \sum_{b}^{|B|} \sum_{s_i}^{|\mathcal{S}_b|} \Delta t_{bi} + \lambda_3 \sum_{b}^{|B|} \sum_{s_i}^{|\mathcal{S}_b|} x_{di} \tag{14}$$

Experiments

In this paper, we simulate a transition to eBuses for three cities in Ireland, i.e., Cork, Galway and Limerick. The bus network in Cork includes 8 lines operated with 90 buses and 32847 scheduled stops; the network in Galway includes 6 lines operated with 50 buses and 15417 scheduled stops; and the network in Limerick includes 6 lines operated with 41 buses and 11139 scheduled stops.[1]

We solve our multi-objective optimization problem in two phases. The first phase aims at optimising the first objective, i.e., minimizing the number of fast charging stations. For the second phase, we fix the charging stations with the output of the first phase and use a linear combination of the two remaining objectives with $\lambda_2 = 10^7$ and $\lambda_3 = 1$, so that, the timetabling objective has a higher priority than the battery longevity one.

We conducted our experiments with CPLEX 12.9 on a MacBook Pro featuring a 1.4 GHz Intel Core i5 processor and 16GB of memory. We assume an average speed of the buses of 30 km/h, a kilowatt-hour (kWh) power consumption per kilometre, a charging rate of the 10 kWh per minute, a security margin time between charges of 1 minute, β=12 minutes, and C_{min} = 15 kWh.

City	Objective	60 kWh	120 kWh	180 kWh
Cork	T. Chargers	6	4	3
	Dev. Time	15747	12614	12233
	T.C. Events	361	111	49
Galway	T. Chargers	7	3	2
	Dev. Time	6478	6760	6313
	T.C. Events	165	44	15
Limerick	T. Chargers	3	1	1
	Dev. Time	2029	1331	1183
	T.C. Events	97	21	4

Table 1: Experiments with Cork, Galway, and Limerick.

Table 1 reports the experimental results for our three reference cities with three different batteries, i.e., 60 kWh, 120 kWh, and 180 kWh. *T. Chargers* denotes the required number of charging units, *Dev. Time* (in minutes) denotes the total cumulative deviation time from the original timetables, and *T. C. Events* denotes total cumulative number of charging events required for the daily operation of the buses. As expected the required number of charging stations decreases as we increase the capacity of the batteries, for Cork (resp. Galway and Limerick) we need at least 3 (resp. 2, and 1) charging stations for the scenario with the largest batteries (i.e., 180 kWh). The deviation time in the original timetable varies on average from 2 to 5 minutes per scheduled stop in the worst-case scenario for our reference cities.

Conclusions and Future Work

This paper has presented a MIP model to simulate a transition to eBuses with minimal timetable disruptions and good practices for battery longevity. Our experiments indicate that our reference cities will need ranging from three to six fast charging stations and minor modifications in the original timetables, i.e., on average from two to five minutes per scheduled stop for the scenario with the largest battery capacity. In the future, we plan to evaluate more elaborated multi-objective optimisation techniques to calculate the pareto frontier of our multi-objective problem. Furthermore, we plan to consider bigger cities such as Dublin.

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[1] The GPS location of the bus stations and timetables are available at https://www.buseireann.ie.