Cost efficient network of electric buses with battery degradation

Yousef Maknoon[a,], Jeroen Vester[b], Shadi Sharif Azadeh[b]

[a]*Faculty of Technology, Policy and Management, Delft University of Technology, Netherlands*
[b]*Econometric Institute, Erasmus University Rotterdam, Netherlands*

Abstract

This paper presents an integrated optimization approach to incorporate battery degradation to design Battery Electric Bus (BEB) network. With the introduction of fast charging technology, it is possible to reduce the ownership cost of BEBs by using smaller batteries. However, this comes with more frequent charging which could increase the cost of ownership for two main reasons. First, the operator needs to invest more in establishing charging facilities. Second, frequent charging can lead to faster battery degradation and can dramatically reduce the life expectancy of batteries. In this paper, we present three types of battery degradation models and incorporate them into bi-objective mixed-integer linear optimization framework. The optimization model can be used to determine the trade-offs between the size of batteries, their life expectancy as well as infrastructure investment. We test our model on a bus line in Geneva. The results depict significant improvement in battery lifetime without increasing ownership cost.

Introduction

With the advancement of charging technology, Battery Electric Bus (BEB) become a viable option to replace conventional vehicles in public transport systems. They offer zero-emission solution and have higher operational flexibility compare to catenary vehicles. Despite their attractiveness, BEBs require large investment which is mostly resulted from batteries. For routes with high energy consumption and long travel time, larger battery is required which dramatically increases the ownership cost.

BEBs are generally equipped with Li-ion batteries which are capable of fast-charging. This way buses can be recharged while passengers are boarding and disembarking. In addition, it enables operators to use smaller batteries and hence decrease ownership cost. On the other hand, re-sizing batteries reduces vehicle autonomy and extensive charging infrastructure are required to guarantee network-wide coverage. Moreover, frequent charging directly affects the lifetime of batteries. Here the central question is how to incorporate battery degradation with infrastructure design and battery sizing to provide a cost-effective solution of using BEBs in public transport system.

The purpose of this paper is to present an integrated optimization model that minimizes ownership cost taking into account battery sizing, charging infrastructure as well as battery degradation.

Problem description and solution methodology

We define the design problem on an existing bus network with known stations and lines. Stations are either terminus or regular stop. Lines are defined as an ordered-set of stations. For each line, the frequency of the service is known (the frequency can vary during the day). We model the bus operation as a series of trips. Every day, the bus first is pulled-out from the central depot to the terminus. The trip starts when the bus arrives at terminus and ends when it pulled-in to the central depot. During this period, the bus can operate in different lines and visiting different stations and terminus. Here, we have to mention that the location of the central depot is known in advance and it is not a part of the design problem. Moreover, we assume that all the buses are fully charged when they pulled-out from the central depot.

We present the problem on a graph $G(V, A)$ in which V is the set of nodes and A is the arc set. For each line, we add a series of nodes to represent the visiting station. In this problem, we use two types of arcs: service and waiting. Service arcs are used to model the bus movement from one station to another. Waiting arcs are used to represent stopping time at the terminus. With each arc two values are associated: travel time and consumed energy.

To design the infrastructure, we consider two types of charging facilities each of which offers specific benefits and challenges. (1) Regular charging stations where no energy storage is used. These facilities require medium-high voltage electricity which will retrieve from the grid. For these stations, the received energy is relatively proportional to the charging time (here we use piecewise function to model the vehicle charge). (2) Fast charging station which uses ultracapacitors to store the energy. Fast charging units can charge the battery with high-voltage and uses low-medium voltage electricity. For these stations, we assume that battery reaches its maximum value after charging. For the design problem, several types of regular and fast charging facilities exist which are differs based on their storage size and output energy. The decision of installing a charging facility is modeled by using a binary variable on each node of the above mentioned graph.

To track the charge of the vehicle, we define a dwell time at each station (i) which can be varied between Δ_i^{min} and Δ_i^{max}. These values are estimated based on the average loading and unloading time at station i. If a charging facility installs at a given station, we use this dwell time to determine the state of the charge of the battery.

To model the degradation of battery, we consider the most significant factors that influence capacity degradation during its daily cycle. That is Depth-Of-Discharge (DOD), State Of the Charge (SOC) and temperature. We express battery degradation as a relative lifetime loss. The lifetime loss of the battery is modeled by the set of constraints in the formulation. We assume that the battery reaches its end-of-life when it reaches 80% of its original capacity.

The problem is formulated as bi-objective integer programming model. The first objective is to minimize the ownership cost and the second objective maximizes the battery lifetime. The constraints of the model can be grouped into four blocks. The first block of constraints decides about the installation of charging facilities. The second block of constraints is used to track SOC of bus and estimate battery degradation. The third block of constraints is used to model the charging behavior of batteries at charging station. Here we should note that instead of using a linear function, we use a piecewise linear function to determine the SOC of battery after charging. Finally, the last block of constraints is used for fleet sizing and determining the size of batteries.

The above mentioned bi-objective model have conflicting objectives as improving one can have a negative impact on others. For instance, a solution with few fast-charging stations installed on the line would have low ownership cost, but can also diminish battery lifetime due to large depth-of-discharge. In order to solve the problem we use the ϵ-constraint method. With this approach, we can reduce the problem into single objective optimization (minimizing ownership cost) and translate battery degradation as a restriction of the problem.

Results

The described methodology is coded with C++ and we use CPLEX to solve the optimization problem. To test our algorithm, we choose a bus line in Geneva which travels between the airport and the main railway station.

The energy consumption is calculated on the basis of the mean of some data from a major supplier of bus charging stations. Three different distributions (Named A,B and C) are then scaled with this mean so that different passenger load can be simulated (i.e. varying passenger load can be translated into various energy consumption between stations). Each distribution is obtained by superposing two Gaussian functions which are added to a constant. For each distribution, this constant is calculated such that the peak is three times higher than the minimum value. The sum of the energy consumption, however, is the same across the three resulting energy profiles.

In order to estimate the cost of ownership, we use our model without battery degradation to solve the problem. For energy consumption profile "A", the total ownership cost is 6.41 million CHF. This value is slightly lower for energy consumption profile "B" and "C" which is due to the variation in the size of battery.

	Energy consumption profile		
	A	B	C
Without Battery degradation	1682	1613	1790
With battery degradation	1977	1943	2142
Improvement	315	330	352
Improvement (%)	18.7	20.4	19.6

Table 1: Battery lifetime (days) for various energy consumption scenario

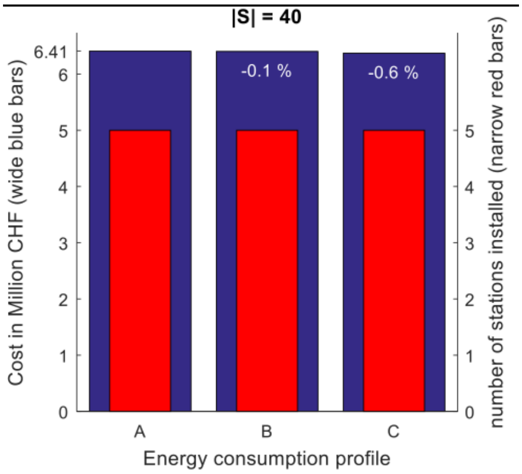

Figure 1: Cost and number of stations installed for the three energy consumption profiles

Thereafter, we use the full model to determine the value of incorporating battery degradation into the design problem. Table 1, denotes the average battery lifetime (expressed in days) resulting in the same design with and without battery degradation. As can be seen, taking into account battery degradation can improve the lifetime of batteries by approximately 20% for our studied case. As both solutions have the same number of charging facilities and the capacity of battery is the same, the improvement is achieved by controlling SOC of the battery. In other words, the model finds smarter locations to installed charging facilities.

Conclusion

In this study, our aim is to find a way to incorporate battery degradation in the design of BEBs network for public transport. We formulate the problem as a bi-objective mixed-integer linear optimization. We test our model on a case of bus line in Geneva. The results indicate that by incorporating battery degradation one can significantly improve the lifetime of batteries without increasing the cost.