Planning of feeding station installment for electric urban public mass-transportation system

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Abstract

During the last few decades, environmental impact of the fossil fuel-based transportation infrastructure has led to renewed interest in electric transportation infrastructure, especially in urban public mass-transportation sector. Generally, electric buses have several beneficial features compared with their petroleum-based counterparts, e.g., higher energy efficiency, no release of air pollutants, and less noise pollution. However, in the traditional implementation of electric bus transportation system, catenary wires are usually the undesired byproduct which is the one of the primary causes of visual pollution in urban cities. In this paper, we will introduce a revolutionary "catenary-free" and high-capacity electric bus transportation system proposed by the demonstrator TOSA (TPG-OPI-SIG-ABB) that will run between Palexo and Geneva Airport in Switzerland.

One of the main challenges in the project is to bring up a cost optimal feeding stations installation plan for the citywide bus transportation network. The complexity of the problem comes from the simultaneous consideration of the decisions such as the power capacity for the batteries in the buses, the locations and types of feeding stations, the feasible power of chargers, and whether to include additional electric storage devices for feeding stations or not, etc. To solve the problem, we develop a mixed integer linear programming mathematical model (called myTOSA) and test it through a preliminary study where only a depot and a bus line are included. Important insights from the test case will be drawn and we will also describe how to extend the model for future studies.

Keywords

Tacitial design, Facility location, Eletrical bus, Feeding station, Mathematical model

1 Introduction

In the last few decades, there has been growing concern about pollution in major cities, and in particular about the large contribution made by road transportation. Additionally, there have been parallel concerns about the emissions of carbon dioxide and their influence on climate change via the well-known green house effect (McNicol *et al.,* 2001). According to the World Resource Institute (2006), it is estimated that 65% of global carbon dioxide emissions come from energy use, with 21% from transportation due to its dependence on fossil fuels. To curb emissions of carbon dioxide especially in the transportation sector, a key and viable approach is to use renewable energy such as wind, solar, and geothermal etc., to generate electricity and to replace the current petroleum based vehicles by electric cars, in light of following two pertinent advantages: 1) electric cars don't produce the pollution associated with internal combustion engines; 2) even electric cars recharged from coal-powered electric generators cut carbon emission roughly in half (Electric Vehicle Society of Canada, 2013).

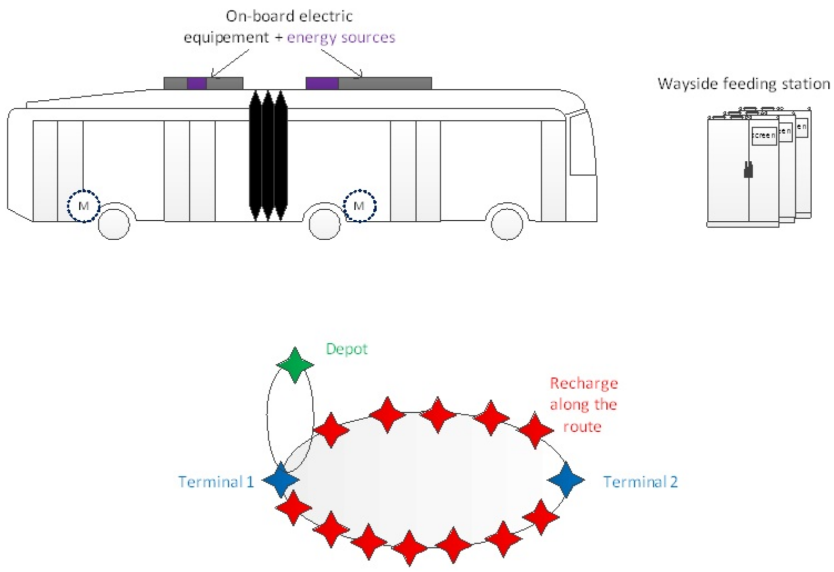

Figure 1: myTOSA system

The history of electric buses can be dated back to 1882 in Germany. For hundred years of development, the electric public mass-transportation system has been undertaken significant and remarkable evolution. In the early stage, electric buses, also known as trolleybuses, need to draw electricity from overhead wires using spring-loaded trolley poles. Such a design pattern is the source of several drawbacks for the system. To name a few, trolleybus systems have been criticized for aesthetic reasons mainly due to the unsightly jumble of overhead catenary wires (i.e., the so called visual pollution). Additionally, the catenary wires pose limitation on the accessibility and flexibility of the trolleybus systems. For example, if some roads of the trolleybus system are closed for maintenance, trolleybuses could be forced to detour several kilometers off their route in order to stay on the wires. Recently, along with the developments on the energy storage technology, battery electric urban public mass-transportation systems have been tested and adopted in several cities around the world. The myTOSA project initialized by ABB (Asea Brown Boveri, a global leader in power and automation technologies) is a pioneer testing of ABB's "biberonnage" concept which is a solution to fully use the efficiency of an electric traction chain while avoiding the inconvenience of a too heavy energy storage system or of the maintenance constraints of catenaries infrastructures, and finally the inherent "visual pollution" of such systems. As proposed, the revolutionary electric bus system will be tested in Geneva city (between Airport and Palexpo) during the World Congress and Mobility & City Transport Exhibition in May 2013.

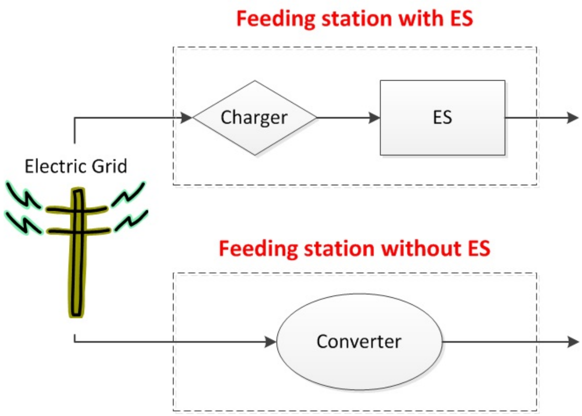

Figure 2: Two types of feeding stations

Figure (1) shows the myTOSA system. There are two key elements: buses and wayside feeding stations. All buses used in this project are homogeneous and have one battery and one on-board charger (OBC) inside (to our interests, we don't need to consider other electric devices such as motors etc.). Although equipped with a battery, any myTOSA bus will definitely run out of energy at certain point in her daily service route. Therefore, in order to guarantee all the buses can complete their tours and return back to a terminal, several numbers of wayside feeding stations should be installed along the bus route. In myTOSA, two types of feeding stations could be considered: the one with energy storage (ES) that is usually used for quick recharge and has low impact on the electric grid and the other without ES. As Figure (2) illustrates, a feeding station with ES consists of two components: an ES charger (ESC) and an ES. By contrast, a feeding station without ES has one converter. Based on Figure (2), it is also informed that if a bus arrives at a stop installed with a feeding station with ES, then the energy will flow following **ES** → **OBC** → **Battery** and after the bus leaves the stop, the energy from grid will recharge the ES by ESC hence it is a kind of indirect recharging. For the case of feeding station without ES, the energy flow would simultaneously follow the path **Converter** → **OBC** → **Battery** once the bus is connected to the converter. In other words, the energy drawn by the bus is directly supplied from the grid.

For this project, at the current stage, we only focus on one bus line consisting of one depot, two terminals, and multiple stations in between of the two terminals (see Figure (1)). At the beginning of a day, after an overnight charging, all the buses leave the depot and start to serve the bus line starting at terminal 1. After a few minutes of recharging at the terminal, each bus commences from the terminal with battery fully charged and follows her fixed service schedule. When she arrives at a stop installed with a feeding station, she draws energy from the wayside device. The amount of energy that can be transferred from wayside to the on-board battery is limited by several physical constraints such as the remaining capacity of the battery, the power size of the OBC, and energy capacity of the wayside ES (in the case that the feeding station has an ES) etc. We call a bus completes a service **cycle** if she completes the tour from terminal 1 to terminal 2 and then from terminal 2 back to terminal 1. In the daily operation, after finishing a constant number of cycles, all the buses return back to the depot and stay there for another overnight charging. In the sequel, Section 2 will provide a more detail description on the problem and a concise literature review. In Section 3, a mathematical model will be presented. In Section 4, we will solve the developed mathematical model in Section 3 by using real data provided by ABB. Finally, Section 5 will conclude the paper and summarize several remarks for future researches.

2 Problem description and literature review

First of all, it should be highlighted that the optimization problem proposed for myTOSA project is only suitable for strategic planning. That is, given the life cycle (around 30 years) of the project, it is inappropriate to develop an optimization model to depict the energy consumption & replenishment pattern for individual bus for each single time step (say, one hour) in the project lifetime. To simplify the problem, ABB suggests the following 3 hard constraints:

1. It should be guaranteed that at depot, after overnight charging, all the buses should become fully recharged;
2. It should be guaranteed that after recharging at one of the two terminals, all the buses should become fully recharged;
3. In the time period equal to the headway between any two consecutive buses, each ES (if any) should be able to be fully recharged.

In light of the first hard constraint, it suggests that all the buses deployed to the bus line will behave exactly the same in each single day since after they return back to the depot and finish the overnight charging, the bus system restores to the same state as the previous day's. The second constraint implies that for each bus, the energy consumption & replenishment pattern that she behaves in one cycle is enough to capture the daily pattern. In other words, the daily energy consumption & replenishment pattern for a bus is the combination of multiple energy consumption & replenishment pattern in every cycle. Finally, the last hard constraint tells that it is not necessary to distinguish the energy consumption & replenishment pattern for individual bus since all of them are homogeneous and will have the same behavior in every cycle. In summary, all the buses have the same energy consumption & replenishment pattern in every cycle. The only difference between any two of them is the service start time. Moreover, it is sufficient to calculate the overall project (operation) cost based on the energy consumption cost of one bus occurred in one cycle.

The proposed optimization problem for the myTOSA project can be described as follows. Given a set of stops (depot, terminals, stations) of a bus line, we need to determine:

1. The battery capacity and power value of the OBC for a bus;
2. To install a feeding station at stop i or not. If yes, to include an ES or not;
3. If a feeding station with ES need to be installed at stop i, what would be the ES energy capacity and the power of the ESC;
4. If a feeding station without ES need to be installed at stop i, what would be the power value of the converter.

in order to make sure that the bus can complete a cycle without running out of energy at any point in the bus route and several technical considerations (e.g., the battery lifetime requirement).

Generally speaking, the optimization problem that we are going to introduce for myTOSA project is a facility location problem (namely, determine which bus stop should have a feeding station). For a comprehensive review on such a problem, the interested readers can refer to Owen and Daskin (1998). However, the proposed problem is more complicated than the traditional facility location problem in the sense that the decision is hierarchic (to determine to install a feeding station first, then to select which kind of feeding station) and much more comprehensive (need to synthesize the decisions from both the bus system and the wayside system). In the literature, scarce studies can be found dealing with the similar problem. The main reason for such a phenomenon is that our problem has more degrees of freedom for the decision and our model aims to depict more accurate energy consumption & replenishment pattern. For example, Wang (2007) studied the optimal location choice for the electric scooter recharge stations. However, in his model, the battery capacity of a scooter is predetermined and in order to ensure that a scooter can accomplish a journey, the author only forced that the total time of recharging should be greater than a minimum time required for a given journey, which to certain extent, is too weak to guarantee that the scooter can successfully complete its journey. For other researches on the location problem for refueling station (not battery recharging), the readers can refer to Wang and Lin (2009),Wang and Wang (2010), and Capar *et al.* (2012) etc.

3 Mathematical model

Let the depot be indexed as 0 and the two terminals be indexed as 1 and k^*, respectively. Note that terminal 1 has direct connection with depot 0. Index the rest of the stations from 2 to K (except for k^*). As mentioned in Section 2, only the energy consumption & replenishment pattern in one cycle needs to be studied. Therefore, for modeling convenience, we can create a dummy terminal denoted as $K + 1$, which is a copy of terminal 1. Let sets $\mathcal{I}$ and $\mathcal{I}^\Omega$ be defined as following:

- $\mathcal{I}$: the set of stations and terminals, i.e., $\{1, 2, \cdots, K\}$
- $\mathcal{I}^\Omega$: $\mathcal{I}^\Omega = \{0\} \cup \mathcal{I} \cup \{K + 1\}$.

3.1 Parameters

All the parameters needed for the model are listed below. Note that we choose capital characters to represent parameters. CHF is the unit for Swiss franc; kW and kWh are the units for the power and energy, respectively.

- A^{ES}: the price of ES (CHF/kWh)
- $A^{Battery}$: the price of battery (CHF/kWh)
- $A^{Electricity}$: the price of electricity (CHF/kWh)
- A^{Tax}: Electricity peak tax (CHF/kWh); Depending on the agreement between the electric bus operator and the electricity provider, it is possible that if the daily total electricity consumption amount exceeds certain amount (the parameter B below), then an electricity peak tax will be levied
- A^{ESC}: the price of ES charger (CHF/kW)
- $A^{Converter}$: the price of converter (CHF/kW)
- A^{OBC}: the price of on-board charger (CHF)
- B: Electricity peak threshold (kW)
- C_i: Power connection cost at stop i (CHF/kW)

- D_{ij}: the distance between stops i and j (km)
- E: the energy consumption (normal route) per kilometer (kWh/km); the normal route is the route in which the bus is in service
- E^d: the energy consumption (depot route) per kilometer (kWh/km); the energy consumption rates for normal route and depot route are different because for the depot route all the passengers have been alighted
- F_i: the fixed cost to install a feeding station at i (CHF)
- G: the number of daily service cycles for the bus line
- H: the time interval between two consecutive buses of this line (Hour)
- N: the number of buses
- $\overline{N}$: the number of feeding stations at depot
- M: a sufficient large positive number
- O: salary of one driver per month (CHF)
- P: the number of years for the project
- Q_b: the lifetime of the battery in the bus; the lifetime of the ES (year)
- Q_v: the lifetime of a bus (year)
- R: the yearly discount rate for the project
- S_t: the state of charge (SOC) when the bus stops at terminal; the SOC is an important parameter to guarantee the lifetime of a battery. For example, in order to maintain a 10-year lifetime for certain battery, usually the SOC for normal route is 60%
- S_d: the SOC when the bus stops at depot
- T_i: the dwelling time at i (Hour)
- V: the cost of a bus, e.g., traction chain, motors, energy transfer system (CHF)
- $L^{Battery}$,$U^{Battery}$: Lower bound and upper bound of energy range for battery (kWh)
- L^{ESC},U^{ESC}: Lower bound and upper bound of power range for ES charger (kW)
- L^{ES},U^{ES}: Lower bound and upper bound of energy range for ES (kWh)
- $L_{TF}^{Converter}$,$U_{TF}^{Converter}$: Lower bound and upper bound of power range for converter at terminals and stations (kW)
- $L_{D}^{Converter}$,$U_{D}^{Converter}$: Lower bound and upper bound of power range for converter at depot (kW)
- U^{OBC}: Upper bound of power for on-board charger based on the module selected (kW)

3.2 Decision variables

Note that we choose lower case characters to represent decision variables.

- x_i: $x_i \in \{0, 1\}$, $x_i = 1$, if a feeding station will be installed at i, $i \in \mathcal{I}^{\Omega}$; 0, otherwise

- y_i: the amount of energy of a bus when it leaves $i \in \mathcal{I}^\Omega$ (kWh)
- z_i: $z_i \in \{0, 1\}$, $z_i = 1$, if a feeding station with ES will be installed at $i \in \mathcal{I}^\Omega$; 0, otherwise
- p_i^{ESC}: the ES charger power selected for station $i \in \mathcal{I}^\Omega$ (kW)
- $p_i^{Converter}$: the converter power selected for station $i \in \mathcal{I}^\Omega$ (kW)
- r_i: the ES energy capacity selected for station $i \in \mathcal{I}^\Omega$ (kWh)
- p^{OBC}: the on-board charger power selected for buses (kW)
- $r^{Battery}$: the battery energy capacity selected for buses (kWh)
- q_i: the energy amount that will be drawn by bus at stop $i \in \mathcal{I}^\Omega$ (kWh)
- w: the total energy amount that is drawn from the grid (kWh)
- u: the energy amount drawn from the grid that exceeds the energy peak threshold (kWh)

3.3 Mathematical formulation

The main objective of this model is to minimize the total project cost in the lifetime. Note that since the project length of myTOSA can be more than 30 years, to respect the value of time, it is reasonable to introduce a discount rate R to convert the future cost to the current cost. Therefore, the task to identify the one-time costs and recurrent costs is very crucial.

$$
\begin{aligned}
\min: \quad & N \cdot (A^{OBC} + V) \sum_{i=0}^{\lfloor P/Q_v \rfloor} (1+R)^{-iQ_v} + N \cdot A^{Battery} r^{Battery} \sum_{i=0}^{\lfloor P/Q_b \rfloor} (1+R)^{-iQ_b} + \\
& \overline{N}(A^{Converter} p_0^{Converter} + F_0) + \\
& \sum_{i \in \mathcal{I}} [(A^{ESC} + C_i) p_i^{ESC} + (A^{Converter} + C_i) p_i^{Converter} + A^{ES} r_i \sum_{i=0}^{\lfloor P/Q_b \rfloor} (1+R)^{-iQ_b} + F_i x_i] + \\
& N \cdot O \sum_{i=0}^{12P} (1 + R/12)^{-i} + \\
& (A^{Electricity} w + A^{Tax} u) \sum_{i=0}^{365P} (1 + R/365)^{-i} && (1) \\
s.t. \quad & x_0 = 1, x_1 = 1, x_{k^*} = 1, x_{K+1} = 1 && (2) \\
& z_0 = 0, z_1 = 0, z_{k^*} = 0, z_{K+1} = 0 && (3) \\
& x_i \geq z_i, \forall i \in \mathcal{I}^\Omega && (4) \\
& p^{OBC} \geq p_i^{Converter}, \forall i \in \mathcal{I}^\Omega && (5) \\
& M x_i \geq q_i, \forall i \in \mathcal{I}^\Omega && (6) \\
& q_0 \leq r^{Battery} && (7)
\end{aligned}
$$

$$q_i \leq r^{Battery} - [y_{i-1} - E \cdot D_{i-1,i}, \forall i \in \mathcal{I}^{\Omega} - \{0\} \tag{8}$$

$$q_i \leq p^{OBC} T_i, \forall i \in \mathcal{I}^{\Omega} \tag{9}$$

$$q_i \leq r_i + M(2 - x_i - z_i), \forall i \in \mathcal{I}^{\Omega} \tag{10}$$

$$q_i \leq p_i^{Converter} T_i + M z_i, \forall i \in \mathcal{I}^{\Omega} \tag{11}$$

$$q_0 = y_0 \tag{12}$$

$$y_i \leq r^{Battery}, \forall i \in \mathcal{I}^{\Omega} \tag{13}$$

$$y_i = y_{i-1} + q_i - E \cdot D_{i-1,i}, \forall i \in \mathcal{I}^{\Omega} - \{0\} \tag{14}$$

$$y_i \geq E \cdot D_{i,i+1}, \forall i \in \mathcal{I}^{\Omega} - \{K+1\} \tag{15}$$

$$y_i \geq E^d \cdot D_{i,0}, i \in \mathcal{I}^{\Omega} - \{0\} \tag{16}$$

$$y_1 = r^{Battery}, y_{k^*} = r^{Battery}, y_{K+1} = r^{Battery} \tag{17}$$

$$r^{Battery} - E \cdot D_{0,1} \geq S_t \cdot r^{Battery} \tag{18}$$

$$y_{k^*-1} - E \cdot D_{k^*-1,k^*} \geq S_t \cdot r^{Battery} \tag{19}$$

$$y_K - E \cdot D_{K,K+1} \geq S_t \cdot r^{Battery} \tag{20}$$

$$r^{Battery} - E^d \cdot D_{1,0} \geq S_d \cdot r^{Battery} \tag{21}$$

$$H p_i^{ESC} \geq r_i, \forall i \in \mathcal{I}^{\Omega} \tag{22}$$

$$p_1^{Converter} = p_{K+1}^{Converter} \tag{23}$$

$$w = N \cdot q_0 + G \cdot N(\sum_{i=1}^{K+1} q_i) + \sum_{i \in \mathcal{I}} r_i \tag{24}$$

$$u \geq w - B \tag{25}$$

$$L^{ESC} z_i \leq p_i^{ESC} \leq U^{ESC} z_i, \forall i \in \mathcal{I}^{\Omega} \tag{26}$$

$$L_{TF}^{Converter}(x_i - z_i) \leq p_i^{Converter} \leq U_{TF}^{Converter}(x_i - z_i), \forall i \in \mathcal{I}^{\Omega} - \{0\} \tag{27}$$

$$L_D^{Converter} \leq p_0^{Converter} \leq U_D^{Converter} \tag{28}$$

$$L^{ES} z_i \leq r_i \leq U^{ES} z_i, \forall i \in \mathcal{I}^{\Omega} \tag{29}$$

$$L^{Battery} \leq r^{Battery} \leq U^{Battery} \tag{30}$$

$$p^{OBC} \leq U^{OBC} \tag{31}$$

$$x_i, z_i \in \{0,1\}, q_i, y_i \geq 0, \forall i \in \mathcal{I}^{\Omega}, w, u \geq 0 \tag{32}$$

The objective function is to minimize the project life cycle cost. In (1), $N \times (A^{OBC} + V) \sum_{i=0}^{\lfloor P/Q_v \rfloor} (1 + R)^{-iQ_v}$ is the cost of buses (excluding battery). Here the term $\sum_{i=0}^{\lfloor P/Q_v \rfloor}(1+R)^{-iQ_v}$ is the future value to present value conversion formula; $N \cdot A^{Battery} r^{Battery} \sum_{i=0}^{\lfloor P/Q_b \rfloor}(1+R)^{-iQ_b}$ is the present value of the cost related to battery in the bus which will be replaced every Q years; $\overline{N}(A^{Converter} p_0^{Converter} + F_0)$ is the cost related to depot feeding stations; $\sum_{i \in \mathcal{I}}[(A^{ESC} + C_i)p_i^{ESC} + (A^{Converter} + C_i)p_i^{Converter} +$

$A^{ES} r_i \sum_{i=0}^{\lfloor P/Q_b \rfloor}(1 + R)^{-iQ_b} + F_i x_i]$ is the cost related to feeding stations at terminals and stations; $N \cdot O \sum_{i=0}^{12P}(1 + R/12)^{-i}$ is the present value of drivers' salary (discounted monthly); $(A^{Electricity} w + A^{Tax} u) \sum_{i=0}^{365P}(1 + R/365)^{-i}$ is the present value of cost related to electricity consumption (discounted daily). Constraints (2) and (3) state that at depot and terminals, feeding stations (without ES) should be installed. Constraints (4) depict the relationship between x_i and z_s. Constraints (5) make sure that the power for on-board charger is greater than the power for all the wayside converters. Constraints (6) enforce that if no feeding station is installed at stop i, no energy can be transferred to the battery on board. Constraints (7) to (9) set the upper bound for q_i considering the restriction from bus. By contrary, constraints (10) and (11) define another upper bound for q_i if the stop is an feeding station with ES or an feeding station without ES, respectively. Constraint (12) states that the energy drawn from depot feeding station should equal to the energy amount in the battery when the buses leave the depot. Constraints (13) to (16) state the properties for y_s. Especially, constraints (14) are the energy conservation equations, constraints (15) and (16) are to guaranteed that the energy in battery is enough to cover the consumption to travel to next station and back to depot. Constraint (17) makes sure that all the buses are fully recharged at the terminals. Constraints (18) to (21) are the battery SOC requirement in order to make sure the lifetime of the battery to be Q. Constraints (22) enforce the third hard constraint mentioned in Section 2 that during the time interval between two-bus arrivals, the ES charger should be able to fully recharged the E. Since the stop $K + 1$ is a copy of terminal 1, constraint (23) guarantees that the decision on the selected power for converter should be the same. Constraints (24) define the daily electricity usage amount w. Due to minimization nature of the problem, constraints (25) define the decision variable u. Constraints (26) to (31) are the lower/upper bound constraints. Finally, constraints (32) define the domain for the rest of decision variables.

4 Case study

To test the developed mathematical model, we use the data provided by ABB and the bus line we selected is shown in Figure (3). There are 38 bus stops in the bus line. The two terminals are Airport and Hospital. The depot is closed to Airport terminal with the distances of around 10km. The project length is set to 30 years and no discount rate (i.e., $R = 0\%$) is considered in the current test. The proposed mixed integer programming (MIP) model is solved by IBM ILOG CPLEX 12.4 in a DELL computer with CPU 2.60GHz and RAM 7.88GB. For the selected bus line, the MIP can be solved within 2 seconds and the feeding station installation plan generated by CPLEX is shown in Figure (4).

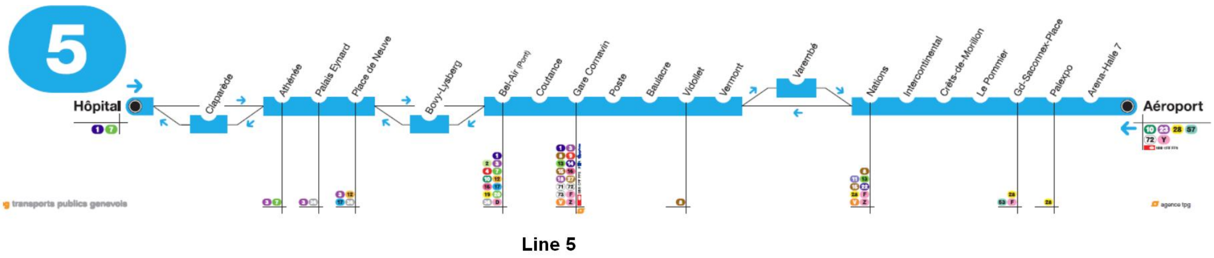

Figure 3: The tested bus line in Geneva

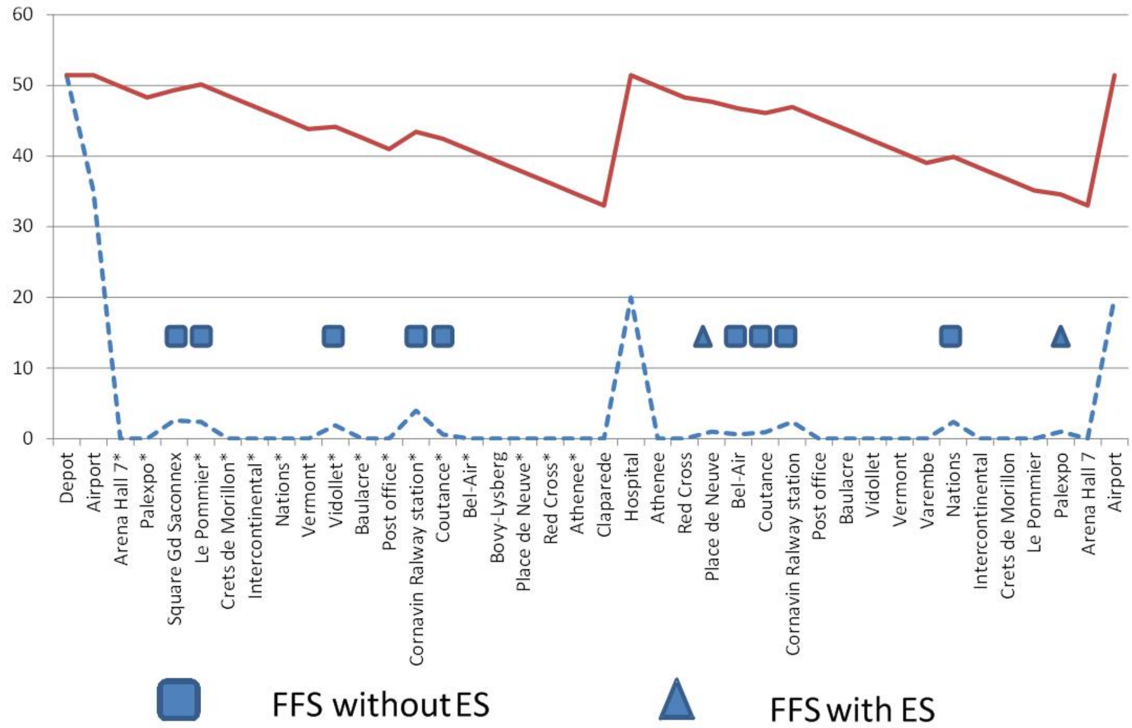

Figure 4: The feeding station installation plan and the energy profile

In Figure (4), the solid line represents the remaining energy amount in the battery when a bus leaves a certain stop. The dotted line shows the energy amount that a bus will draw from a particular wayside feeding station. Additionally, it is shown that two feeding stations with ES and 9 feeding stations without ES will be installed along the bus route. The optimal cost for the project in 30 years is 127.11 million CHF (i.e., roughly 4.24 million CHF per year).

5 Conclusions and future works

In this paper, we propose a mixed integer programming model to determine the cost effective feeding station installation plan for myTOSA project. Based on the three practical hard constraints (see Section 2), we are able to simplify the problem and argue that in order to figure out the total operation cost for one bus line, it is sufficient to study the energy consumption and replenishment pattern of one bus in one cycle. To test our proposed mathematical model, real data provided by ABB are used and the computational results clearly reveal that the proposed model is capable to obtain a good feeding station installation plan (compared to ABB's manual planning) in a swift way while respecting all the practical considerations such as the battery state of charge requirement etc. To extend the study in the future, we have three remarks to make:

1. In the current version, we don't consider the battery temperature constraint. For example, it is possible that the combination of a quite small battery and an OBC with high power value can appear in the optimal solution. However, in reality, especially at terminals, if the battery is relatively small while the OBC is quite high, the temperature of the battery would exceed an ideal one, which will do harm to the battery and shorten its life time and finally leads to higher project cost.
2. The current model is restricted to only one bus line. However, it is expected that myTOSA project will be extended to a network level. In the network scale, the complexity of the feeding station installation planning problem will exponentially increase. For example, at a station which is shared by two distinct bus lines, if a feeding station with ES will be installed there, the capacity of the ES should be carefully chosen such that even two buses from two different bus lines arrive at the stop at the same time, the total energy amount in the ES is enough to recharge the two buses to their required amounts.
3. All the data used in this study are deterministic. However, in real life application, a lot of data can be easily subjected to change such as the traveling time and dwell time of the buses (especially in rush hours). Hence, to develop a robust and risk-proof investment plan is of paramount importance for ABB. In the next step, a comprehensive sensitivity analysis will be carried out to understand the impact of each parameter and the trade-offs.

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