

# Bus-to-Route and Route-to-Bus Approaches in Hybrid Electric Buses Fleet for Li-ion Battery Lifetime Extension

## Enfoque Autobús-a-ruta y Ruta-a-autobús en flotas de autobuses híbridos-eléctricos para extensión de la vida útil de baterías de litio-ion

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**Abstract**— This paper aims to propose a methodology for managing Li-ion battery life for a whole fleet, focusing on improving the total operating costs for hybrid electric buses. This problem is approached in two different ways: bus-to-route and route-to-bus. Bus-to-route optimization focuses on developing an energy management strategy for each bus in the fleet. A techno-economic, energy and battery aging analysis of the fleet was carried out. As per the outcomes of this analysis, buses were grouped according to the state of health of the battery of each bus. Based on this analysis and classification, the route-to-bus approach was applied. This technique involves a re-evaluation of the energy management system and a re-organization of the buses according to the state of health of the battery of each bus. Increases in battery (BT) life of up to 10.7% were obtained using the proposed approach.

**Keywords**— Fleet energy management, battery state of health, dynamic programming, hybrid electric bus, Li-ion battery.

**Resumen**— El objetivo de este artículo es proponer una metodología para la gestión de la vida útil de las baterías de Litio-ion de una flota completa de autobuses eléctrico-híbridos orientado a mejorar el costo total de operación. Esta propuesta se ha abordado desde dos puntos de vista: autobús-a-ruta y ruta-a-autobús. La optimización autobús-a-ruta se enfoca en la generación de la gestión energética de cada autobús perteneciente a la ruta. Para este efecto, se ha llevado a cabo un análisis tecno-económico, energético y de esperanza de vida de las baterías de la flota de vehículos. Partiendo del resultado de este análisis, los

vehículos han sido agrupados de acuerdo al parámetro del estado de salud de la batería de cada autobús. Basándose en dicho análisis y clasificación, se ha realizado la aplicación del enfoque ruta-a-autobús. Esta técnica considera tanto una re-evaluación de la gestión energética y/o una re-organización de los autobuses de acuerdo al estado de salud de sus baterías. Se ha conseguido un incremento de hasta 10.7 % de la vida útil de las baterías haciendo uso de los enfoques propuestos.

**Palabras Clave**— Gestión energética de flota, estado de salud de batería, programación dinámica, autobús híbrido-eléctrico, batería de Litio-ion.

### I. INTRODUCTION

All sectors in Europe have recorded a reduction in greenhouse gas (GHG) emissions since 1990, except for the transport sector [1]. In 2015 transport was responsible for 25.8% of total emissions in Europe, with road transport being the most pollutant sub-sector, accounting for 72.8% in 2015 [1]. The most polluted areas are those with high population density. In these areas, public transport is a significant contributor to GHG emissions. Buses typically run in urban areas for approximately 16 hours per day. Furthermore, buses are the most used mean of public transport [2]. Thus, buses are a critical candidate for mass electrification.

Hybrid and electric bus integration is a challenging process. Several studies have pointed out the high initial

investment cost in comparison to conventional buses [3], [4]. To overcome this problem and to create a more attractive option for investors, total cost of ownership (TCO) is a critical point to focus on. Breaking down and analyzing TCO factors, it can be seen that despite the recent decrease in lithium-based battery (BT) prices (79% since 2010 [5]), BTs still have a significant influence on TCO, as their cost accounts for approximately a quarter of the total bus price [5], [6]. Moreover, BTs have a shorter life than electronic power systems, needing to be replaced and thus further increasing the TCO. Therefore, new techniques are needed to maximize BT life and minimize TCO. A proposed technique is continuous monitoring of the state of health (SOH) of the BTs, employing new opportunities for digitalization. Such monitoring would enable processing, analysis, and decision making which would extend BT life.

Digitalization is the process of equipping vehicles with sensors to collect data, storing this information in cloud data to be later analyzed [7]. This new trend enables the energetic operation of each vehicle to be monitored. Indeed, monitoring the operation of each vehicle in a fleet makes it possible to widen the scope of the current EMS (Energy Management Strategy) from a localized EMS to a fleet level EMS. This new level will extend flexibility for energy management and improve energy efficiency across the entire fleet. However, the main challenge for fleet level EMS and digitalization is the large volume of data to be managed by fleet managers. Consequently, new automated and advanced tools are needed for data analysis and decision making, a growing area of research [8], [9].

In this regard, a methodology for analyzing, processing, and making decisions based on this processed data was proposed in [10], to improve the techno-economic performance of the whole fleet. Focusing on the decision making element of the methodology as mentioned above, the contribution of this paper lies in an approach for managing a BT life system for an entire fleet. This approach has been addressed in two ways: *bus-to-route* and *route-to-bus*. In the technical literature, a methodology for managing BT aging at the fleet level has yet to be presented.

*Bus-to-route* optimization is focused on the energy management strategy (EMS) of each bus in the fleet. The acquired data from the fleet is analyzed in terms of route energy, operation and BT aging for each urban route. Based on these analyses, each bus has been classified to facilitate decision-making. Based on this classification, the *route-to-bus* approach was implemented. This technique is focused on extending the fleet's BT life. This

Table I: Scenario approach [11].

Parameters	Ser	Par
Driving Cycle Profiles/Bus Configuration	10	10
Electric Motor Power [kW]	196.5	196.5
Internal Combustion Engine Power [kW]	-	160
Genset Power [kW]	160	-
Battery Packs C-rate/Energy [-/kWh]	7/24	7/24
Opportunity Charging Point [kW]	150	150

stage consists of a re-evaluation of the EMS and the re-organization of buses with the best SOH buses being allocated to the most energy demanding routes and vice versa. For ensuring the optimal operation of the re-organized HEBs (Hybrid Electric Bus) in the fleet, a *bus-to-route* re-optimization was carried out, with the updated BT capacity and urban route. Increases in BT life of up to 10.7% were obtained with the proposed approach

## II. SCENARIO OVERVIEW

The analysis in this paper was based on the fleet described in Table I. The fleet is composed of the following two power-trains, with the respective models presented in detail in [10], [11].

- Parallel HEB with Battery: a power train pulled with an internal combustion engine (ICE) and an electric motor, operated by a BT pack.
- Series HEB with Battery: a power train pulled by an electric motor powered by a BT pack and a genset (GS).

The urban routes have been generated from a database of standardized driving cycles. Each generated cycle has been applied to an HEB, as explained in Table I, creating a simulation of the fleet.

## III. FLEET MANAGEMENT BASED ON FLEET LEARNING METHODOLOGY

The proposed fleet learning methodology is shown in Figure 1, aiming to improve the techno-economic performance of the whole fleet, reducing the operation and maintenance costs [10]. This methodology is split into four stages:

1. *Design Stage*: In this first stage, the bus EMS is developed, based on off-line dynamic programming (DP) optimization of the corresponding route for each line [12]. The optimization problem is based on the following cost function (J):

$$J = \sum_{i=0}^{N-1} \Delta m_f(U(i)) \cdot T_s \quad (1)$$

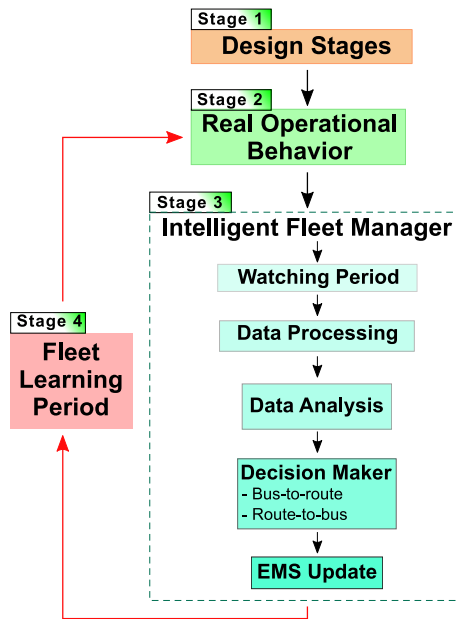


Figure 1: Proposed Fleet Learning methodology [10].

where  $\Delta m_f \cdot T_s$  is the fuel mass consumption at each time step ( $T_s=1$  s), determined by the torque (parallel configuration) or power (series configuration) split factor  $U$ , within the urban route length ( $N$ ).

2. *Real Operational Behavior*: Once the EMSs are implemented for each bus, at this stage the data is simulated or extracted from a real fleet. For this study, the HEBs mentioned above have been modeled and simulated in MATLAB.

A daily trip consists of approximately 16 hours, with a yearly operation of 300 days. To simulate real driving behavior, some disruptions were randomly introduced to these routes. For this scenario, road, auxiliary power, and passenger disruptions were all considered [10].

3. *Intelligent Fleet Manager*: The third stage is aimed at managing data. The acquired data is collected, processed and analyzed in order to make decisions based on this analysis and thus update the EMSs or re-organize the fleet.

4. *Fleet Learning Period*: In this last stage, the decisions taken are evaluated in terms of overall fleet efficiency.

#### IV. BUS-TO-ROUTE AND ROUTE-TO-BUS

Based on the proposed methodology, the contribution of this paper lies in an approach for extending the BT life system for a whole fleet. This approach, as shown in Figure 2, has been addressed from two points of views, the *bus-to-route* and the *route-to-bus* approaches. In the following lines, the applied methodology is explained.

#### Stage 1: Design Stages

In the first stage the fleet bus-to-route optimization was implemented. This optimization is focused on the EMS of each bus in the fleet (as shown in Table I). The EMS is based on that proposed in [10].

From the aforementioned paper [10], it was concluded that global optimization based on DP does not harness BT utilization. The reason for this lies in the cost function (Eq. 1). This function is designed to minimize global fuel consumption, with the constraint of starting and finishing at the same state of charge (SOC) [13]. Consequently, the optimization tends to under-utilize the BT, to avoid extra-fuel consumption of the GS or ICE recharging the BT.

The maximum and minimum SOCs are extracted based on the optimal operation of each line. These limits are used in the EMS to maintain the SOC within limits. To harness BT consumption, these limits are set according to the following equations:

$$\begin{cases} SOC_{max} = SOC_{DPmax} \\ SOC_{min} = SOC_{DPmin} \cdot \gamma \end{cases} \quad (2)$$

where  $\gamma$  is a constant defined for the depth of discharge (DOD) management, which will enable BT utilization to increase.

#### Stage 2: Real Operational Behavior

Based on the optimized routes, at this stage, a MATLAB simulation of the fleet was carried out, as noted in Section III Stage 2. Figure 3-A shows an example of a simulated 7 day observation period. A full day operation profile (24 hours) has been simulated, with a depot charge at the end of the day. The available time to charge the bus at the depot varies according to the daily operation time, and the power value has been set as the minimum to recharge until the SOC is 85%.

Daily operation is shown in 3-B, in which an opportunity fast charging point of 150 kW is placed at the terminal station for each round trip line, charging the bus for 2.5 minutes. These charging points allow buses to start and finish the day at the same SOC.

#### Stage 3: Intelligent Fleet Manager

This stage is where the novelty of the paper lies. The obtained data is processed for subsequent fleet data analysis. Based on this analysis, EMS updating and/or the *route-to-bus* approach is implemented. A more detailed description is given below.

#### Stage 3.1: Fleet Data Analysis

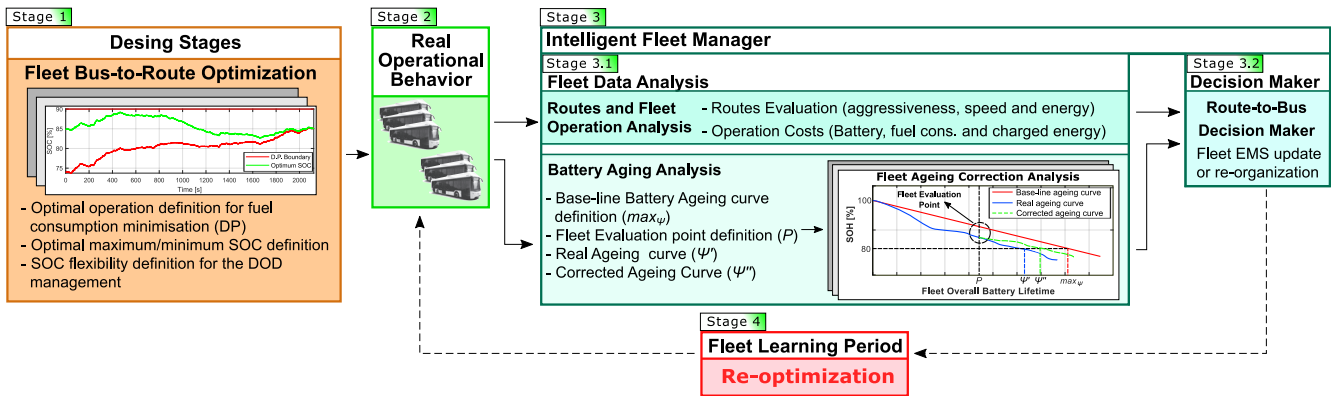


Figure 2: Bus-to-Route and Route-to-Bus battery lifetime methodology.

At this stage, an analysis of the whole fleet is carried out, to facilitate the resulting decisions. The different bus lines are analyzed based on the routes and fleet operation analysis. Consequently, the BT aging evaluation plan is designed, based on the BT aging analysis.

*Routes and Fleet Operation Analysis*

First, to extract information from the bus lines, an energy evaluation is performed. The evaluated terms are related to bus dynamics, intending to evaluate the routes objectively, without taking into account vehicle configuration. Consequently, the analyzed parameters are mean speed, energy consumption per kilometer, and aggressiveness (A), which is calculated as follows [14]:

$$A = \frac{\int (a \cdot v) dt}{\int (v)} \quad a > 0 \quad (3)$$

where  $a$  is acceleration [ $m/s^2$ ] and  $v$  is speed [ $m/s$ ].

In order to evaluate the operation of the fleet and the

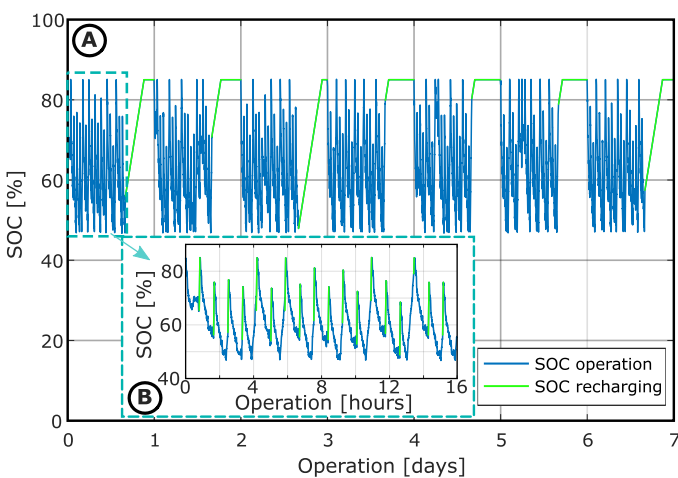


Figure 3: A- Evaluated weekly driving SOC operation. B- Daily SOC operation.

EMS behavior on each line, daily operation costs are calculated. The evaluated operation parameters are mean fuel consumption, BT aging, and mean recharging costs.

*Battery Aging Analysis*

For the fleet BT aging analysis, first, the optimized operation based on DP is evaluated in terms of BT aging. From this evaluation, the fleet BT aging prediction ( $max_{\Psi}$ ) and the fleet evaluation point ( $P$ ) are determined, calculated as follows:

$$P = \frac{\min(\Psi_1, \Psi_2, \dots, \Psi_n)}{2} \quad (4)$$

$$max_{\Psi} = \frac{\sum_{k=1}^n (\Psi_1, \Psi_2, \dots, \Psi_n)}{n} \quad (5)$$

where  $\Psi$  represents the BT aging lifetime and  $n$  the number of lines.

Once these points are defined, the data obtained from the real driving simulation is processed until point  $P$ . From this evaluation, the SOH of each bus is calculated.

Based on the analysis outlined above, three groups are classified. This classification groups the routes with the best SOH, the worst SOH and the routes with a similar SOH.

**Stage 3.2: Decision Maker**

*Route-to-bus*

At this stage, the route-to-bus decision maker approach is implemented. This stage aims to extend BT life for the whole fleet. Therefore, at this point a decision is made, whether this is a re-evaluation of the EMS (for those buses with a similar SOH) or a re-organization of the buses (for those buses with the best and worst SOHs), based on the classification of the SOH of buses. Firstly,

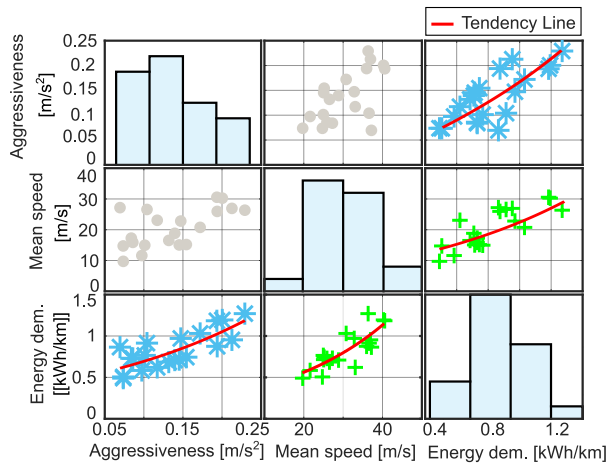


Figure 4: Bus routes evaluation results.

buses with the best SOH are swapped with the ones with the worst SOH. Secondly, routes with similar SOH are re-optimized.

#### Stage 4: Fleet Learning Period

##### Re-optimization

According to the decision taken for each bus, in this stage, the EMS is updated. The EMS update for buses with a similar SOH is based on the re-adjustment. For the buses that are swapped to other lines, the EMS is re-optimized with the updated BT capacity and urban route. Finally, the obtained BT end-of-life points, and the operation are analyzed to evaluate the proposed approach.

## V. RESULTS AND ANALYSIS

In order to validate the proposed bus-to-route and route-to-bus approaches, the fleet presented in Table I has been simulated as described in IV Stage 1.

The obtained results have been presented in four subsections, following the battery extension approach explained in Fig. 2.

##### A. Routes and fleet operation analysis

In this subsection, the energetic evaluation of the routes and the fleet operation results are presented.

The bus routes energetic evaluation results are shown in Fig. 4. The energetic evaluation has been performed analyzing the correlation between the variables as mentioned earlier (explained in Section IV Stage 3.1). It is noteworthy that the energy demand versus aggressiveness and versus mean speed has a positive correlation. Therefore, these two correlations are worth mentioning as indicators for the energetic classification of the routes.

Evaluating all the different lines energetically provides an overview of the scenario, helping to define the EMS for each line.

Fig. 5 depicts the operation costs of each line with the EMS developed from the fleet *bus-to-route* optimization. This analysis helps to evaluate each line economically, providing a clear picture of the case scenario. The most significant factor impacting on HEB operation costs is fuel consumption, with lines 2 and 12 reflecting the highest operating costs. However, the goal is to improve TCO for the whole fleet, so all factors have to be considered in order to improve the variables to be managed. The information from the battery and recharged energy indicators are noteworthy in this study. These indicators help to identify the lines that are most demanding in terms of battery. Lines 11, 15, and 20 have the highest BT costs.

##### B. Battery Aging Analysis

The BT aging analysis was performed from different points of view. The observation period for data collection lasted for seven days (Fig. 3) and evaluated up until the fleet evaluation point with this operation.

Figure 6 shows the obtained BT aging results from the DP optimization and the "real" driving (RD) behavior. From the obtained DP optimal operation of each line, point  $P$  and  $max_{\psi}$  have been determined based on Eqs. 4 and 5 respectively. Point  $P$  has been used as the baseline for the BT lifetime estimation reference.  $max_{\psi}$  has been determined a 131% greater than  $P$  reference point.

It is noteworthy that the DP results predict shorter BT lifetimes in the case of the parallel configuration

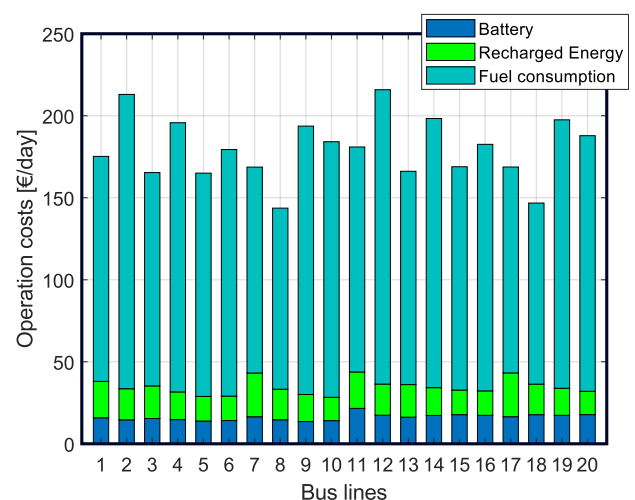


Figure 5: Bus lines operation costs.

(decrease of 20.3%) and similar lifetimes for the series configuration (an increase of 1.4%). Analyzing the obtained results, it has been concluded that the parallel configuration has higher BT use in the optimal operation than in the real driving behavior. These lifetime estimations have been calculated with the obtained results from the one week simulation, replicating this operation until the BT end-of-life.

A correlation of variables analysis was carried out. From this analysis, the correlation of the BT consumption, daily driven distance and BT aging has been found, as shown in Fig. 7. This analysis demonstrates the correlation of the three mentioned factors, BT aging decreasing with BT consumption increase and daily distance increase. This correlation is a useful indicator for the BT aging pre-analysis, evaluating BT degradability for the different routes.

The SOH evaluation was the final evaluation. The obtained results are depicted in Fig. 8, with the driven daily distance and BT consumption of each route. Analyzing the obtained results, three groups are proposed: the routes with the best SOH (lines 5, 8 and 10), the routes with the worst SOH (11, 15 and 20) and the routes with similar SOH (remaining routes). It can be seen that the SOH is higher for all series configuration as compared to parallel configurations.

Further analysis of the obtained SOH results and comparison of these results with the routes previously identified as most BT demanding routes in Subsection V-A, demonstrate that the buses with the worst SOH match with these.

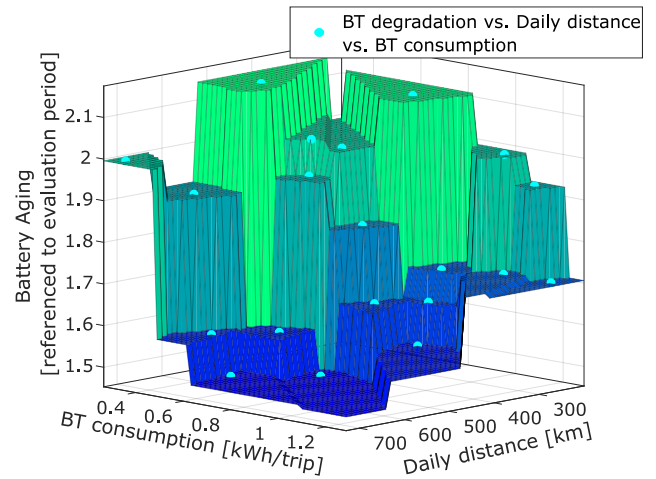


Figure 7: BT aging correlations.

### C. Route-to-bus decision maker

Based on the BT classification from the SOH results, the route-to-bus decision maker is implemented. Firstly, buses in the group with the best SOH are swapped to higher BT degrading routes and vice-versa. Table II shows the new fleet outline. EMSs for HEBs are re-optimized for the corresponding new lines.

Table II: Bus lines re-organization.

Group	Bus number	Current line	Swap to line	SOH [%]
Best SOH	5	5	11	90.65
	8	8	20	90.51
	10	10	15	90.04
Worst SOH	11	11	5	86.51
	20	20	8	86.61
	15	15	10	87.08

Secondly, lines within the similar SOH group are re-optimized, re-determining the  $\gamma$  (see Section IV Stage 1) constant.

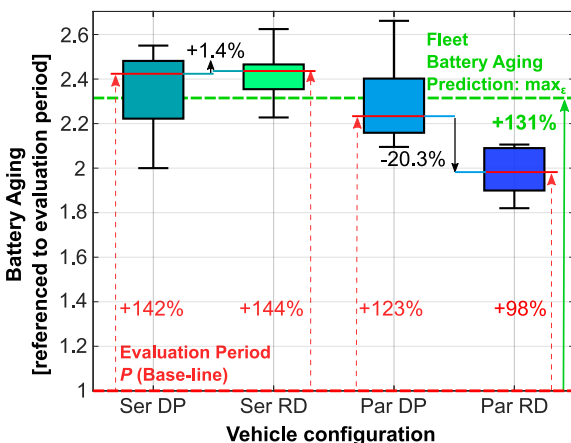


Figure 6: Battery aging variation.

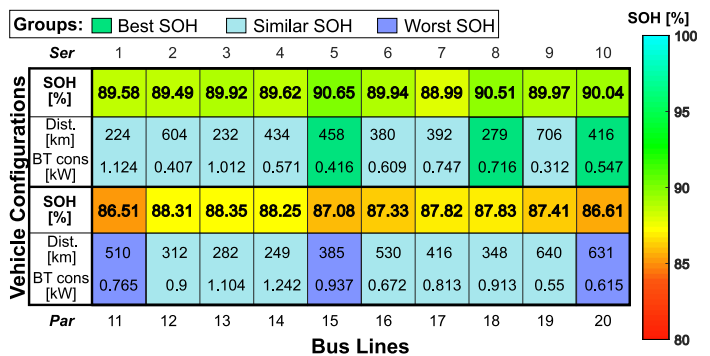


Figure 8: HEBs battery SOH at the evaluation point.

#### D. Re-optimized buses results and analysis

Finally, the re-organized scenario is evaluated, in terms of BT aging and fuel consumption.

Fig. 9 depicts the obtained new BT aging results from swapping the bus lines, as described in Table II. The series configuration buses have shown a decrease in BT life of up to 8.51%, as they were swapped to the most demanding lines. On the contrary, the tendency for parallel configuration buses has been to increase BT life by up to 6.13%.

The new fleet BT aging layout is presented in Table III. For most of the lines, after applying the proposed approach, BT life has tended to increase. Buses without a remarkable aging increase have not been updated. The only buses with a BT life decrease have been the aforementioned series configuration buses (buses 5, 8 and 10), as they were swapped to more demanding routes. From the overall results, it is noteworthy the highest increase for BT life for the series configuration was an increase of 10.7%. The reason for this is that there is greater flexibility for charging the BT than in the parallel configuration (where the highest increase reached is up to 6.13%).

Finally, to evaluate the change in fuel consumption after the route-to-bus approach, the obtained variations are presented in Fig. 10. There is a slight 1.1% increase in fuel utilization from the pre-update scenario (before the *route-to-bus* approach application) to the post-update scenario (after the *route-to-bus* approach was applied). This is considered normal behavior, since to manage BT aging, fuel utilization increases. However, it is possible reach a trade-off between fuel and BT utilization.

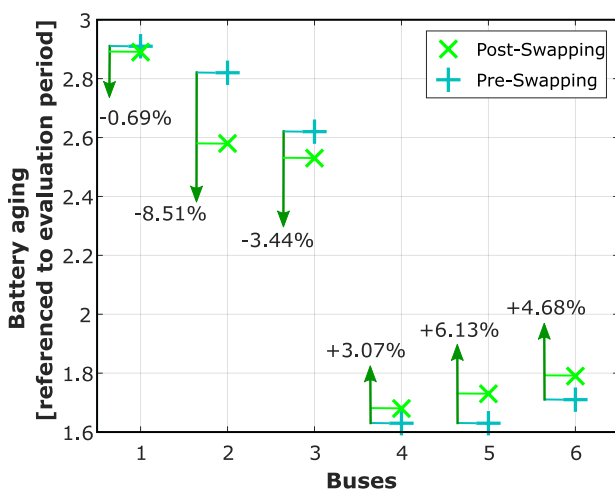


Figure 9: Bus lines re-organization lifetime estimations.

Table III: Bus lines new layout regarding BT aging.

Bus	Aging Prediction			Bus	Aging Prediction		
	Evaluations 1.	Evaluations 2.	Diff. [%]		Evaluations 1.	Evaluations 2.	Diff. [%]
1	2.43	2.69	+10.7	11	1.63	1.68	+3.07
2	2.39	2.5	+4.6	12	2.02	2.02	0
3	2.56	2.8	+9.38	13	2.02	2.03	+0.5
4	2.37	2.47	+4.22	14	1.98	1.98	0
5	2.91	2.89	-0.69	15	1.71	1.79	+4.68
6	2.53	2.58	+2	16	1.77	1.77	0
7	2.19	2.2	+0.46	17	1.87	1.88	+0.53
8	2.82	2.58	-8.51	18	1.87	1.87	0
9	2.54	2.54	0	19	1.77	1.77	0
10	2.62	2.53	-3.44	20	1.63	1.73	+6.13

## VI. CONCLUSIONS

In this paper, a *bus-to-route* and *route-to-bus* approach was presented, oriented to extending BT life. In order to validate the proposed approach, a simulation of the fleet was carried out, as presented in Table I.

The BT lifetime increase with the proposed methodology is up to 10.7%. It was possible to obtain higher BT lifetimes for the series configuration than for the parallel configuration. The main reason for this lies in the higher flexibility for recharging BT with the GS for the series HEBs than for the parallel HEBs.

The performed *route-to-bus* re-organization approach compensates for BT aging imbalances. Therefore, the buses with the best SOH have been swapped to the most demanding lines and the buses with the worst SOH have been swapped to the least demanding lines. As a result, the HEBs swapped to the most demanding lines show a decrease in BT life (up to an 8.51%), and those moved to the least demanding lines show an increase in BT life (up to 6.13%). For correct evaluation, the mean

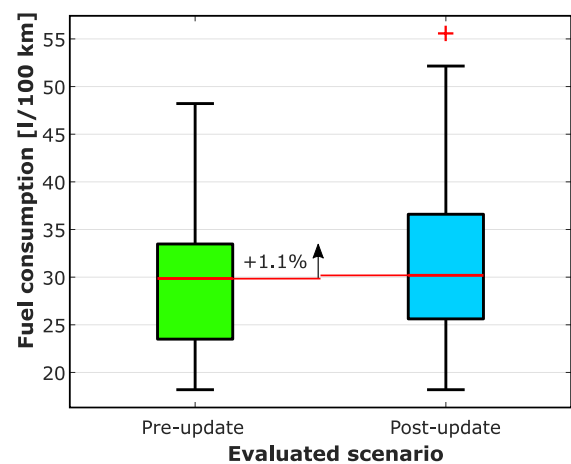


Figure 10: Fleet fuel consumption evolution.



fuel consumption increase for the fleet was evaluated, obtaining an increase of 1.1% after the route- to-bus application.

Furthermore, the correlations for the bus lines evaluation and the BT aging have been analyzed, to facilitate re-organization of the buses. Firstly, for route correlations, the energy demand versus aggressiveness and versus mean speed is noteworthy. Secondly, in terms of BT aging correlations, BT consumption and the driven daily distance was identified.

Future research will focus on developing a clustering classification for *route-to-bus* automation.

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