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Advantages of retrofitting old electric buses and minibuses

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Abstract

Old electric buses and minibuses equipped with obsolete energy storage systems are today circulating on the roads all over the world. A minibus prototype equipped with Ion-Lithium batteries developed in the ENEA Casaccia Research Centre demonstrated that an old minibus can be retrofitted by replacing the old lead acid batteries pack with a new pack assembled with LiFePO4 electrochemistry. The new batteries provide sufficient power to the electric motor, an amount of energy to cover nearly 30 kilometers with a full charge, with a new battery load of 50% of the previous battery pack. The new technology allows fast charging, thus solving the problem linked due to the long periods requested to charge of the conventional batteries. For example during public transport service, the minibus can be charged with only twenty minutes, allowing such operation at the terminus while waiting for the passengers. A "depleting" strategy can be applied in order to allow the minibus to be operating all the day with several charges at the stops.

Keywords: retrofit, lithium battery, electric bus, fast charge.

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1. Introduction

The use of electric bus for passengers transport in small and medium downtown is common. For many years, Battery Electric Vehicle (BEV) use lead acid batteries, many issues limit usability and diffusion of electric mobility characterized this battery technology.

Nowadays, the Lithium technology for batteries bring to electric bus market an important step forward, it improves the efficiency and usability of the electric mobility and it also raise the range of the vehicle. The lithium technology provides higher energy and power densities, together with a longer lifetime. Indeed, this technology needs a narrow range for temperature and voltage of each single cell of the battery.

The ENEA research center project made in collaboration with University of Pisa and Rome aims to describing the implementation and test of an electric minibus based on a lithium battery and the fast charging.

This paper represents a step forward from the previous work [1], which described the main characteristics and functionalities of architecture deployed and provided a detailed description of each component and some initial measurements. Meanwhile, this work aims to explain the reasons why to retrofit an old electric minibus instead of scrap it and buy a new one:

1. Every bus actually fed by lead-acid batteries can be retrofitted easily and rapidly, by installing a few components and a new battery pack without particular legislative duties.
2. Usually the lifetime of a BEV vehicle (independent from battery chemical) is more than 10 years, the battery pack has to be replaced several times because it deteriorates in 2 or 3 years (dependent from battery chemical). The new battery pack has a Battery Management System (BMS) that allows to minimize unexpected failures and to maximize the battery lifetime.
3. Due to limited daily mile-range (with a single charge) of an electric bus fed by lead acid batteries, the average mileage when it reaches the end of lifetime is lower than a conventional bus. In-fact both mechanical and electric components of an electric bus are designed for much more mileage.
4. Due to availability of fast charging technology, now it could be possible to develop several electric configurations in order to extend the market.
5. Maybe with these new batteries the old retrofitted bus can be suitable for more and long missions of transport.
6. As the relative chapter describes a bus retrofitted is cheaper than new bus in a short-term period.

For all these reasons, it could be profitable to invest in an old electric bus by: changing its battery pack, adding the necessary electronics, and making a general revision. Usually, the revision concerns these four issues: mechanical systems, electronic systems, external body and interior equipment.

This paper is divided into four chapters, the first chapter describes the constructive aspects; the second describes the performance analysis. The third is the financial analysis. The last chapter concerns conclusions and further developments.

2. Constructive aspects

The electric minibus is an old Gulliver U520 provided by Tecnobus and shown in Figure 1. Table 1 compares the main electrical characteristics of the old battery and the new one.

Figure 1 shows the powertrain layout, before and after the retrofit, it describes the modifications that concern only the electric components, as the battery and the additional features (BMS, safety contactors and charging station interface).

Figure 2 and Figure 3 show the prototype, the paper [1] and [2] describe it thorough, the project had the objective to install the new battery pack by making less possible modifications.

In particular, the retrofit focuses on the following four aspects:

1. *Electrical revision*. Traction motor, chopper, all electronic systems and wiring up to the final connector with batteries are the same; they need only a general test for safety reason, it also does not need any wiring adaptation.
2. *Mechanical revision*. New batteries substitute the old ones in the same volume and the same boxes, only with a little adaptation work for the fastening system.

3. *Installation of extra components*. New and dedicated components (i.e. the BMS) and some electric devices allow managing safety the new battery (two white boxes shown in the top of Figure 3). A light metallic frame support them.
4. *Adaptation of battery's boxes*. The new battery has a different packaging and it needs only some mechanical adaptation, in order to anchor batteries inside the boxes.

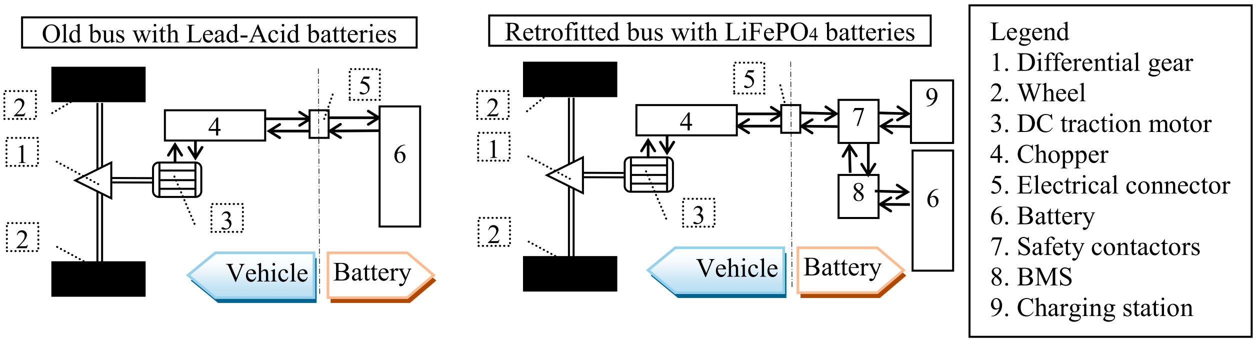

Figure 1 Powertrain layout of Tecnobus Gulliver U520 before and after the retrofit

In order to allow the fast charge technology, one of those boxes include a specific addition connector and wiring for link the battery with the charging station.

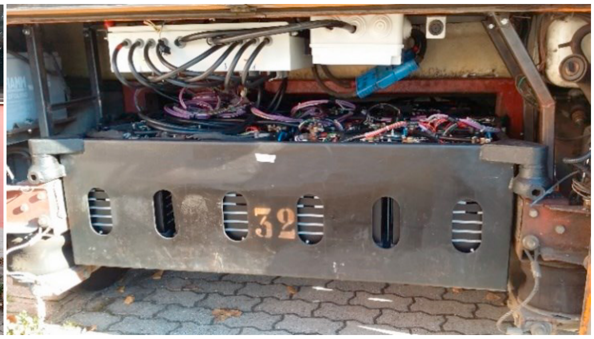

Figure 2 The electric minibus used

Figure 3 New battery pack installed

Table 1 Comparison between battery pack of bus before and after the retrofit

	Old bus Lead-Acid Batteries	New bus Li-Ion Batteries
Nominal Voltage	72	76.8
Maximum Current (Discharge)	600 A (continuously) 1000 A (instantaneously)	720 A (continuously)
Maximum Current (Charge)	60 A	720 A

During this project, a fast charging technology was used in order to demonstrate the feasibility of satisfying a daily mission as broadly described in [3] and [4], in this paper the fast charge technology was used without any particular analysis that will be done in future works.

3. Performance analysis

This chapter aims to explain a performance comparison between the two battery technologies installed in Tecnobus Gulliver.

There was not available a Lead-Acid battery to equip the bus and test it with same method. The data for comparison derive from [5], [6] and [7].

Prototype is equipped with an embedded computer provided by Advantech, it reads and store signals measured by bus sensors thorough the ECU. Meanwhile, the same computer acquires data from BMS via CAN connection.

The variables measured are: speed, pedal position, motor load, current, voltage and temperature (for each cell of the battery and for whole electronics installed).

Future analysis will elaborate data to build a schematic model of the bus for simulation purpose.

3.1. Performance measured for retrofitted bus

The dynamic performance of the bus remain steady after the retrofit, so it has the same maximum acceleration, and maximum speed. One of the things that change with the retrofit is the weight: the empty bus without battery weights 2700 kg, and battery passes from 1500 kg (lead-acid) to 800 kg (lithium). The reduction of weight cut average consumption.

Mainly, it is due to two reasons:

- The maximum power of the motor (20 kW nominal, 25 kW peak) that can be satisfied by both types of battery;
- The weight of a bus is distributed in the body for 70% and 30% in the energy storage;

The Figure 4 shows the trend of current in comparison with the speed of the bus during an acceleration phase, the same result is available with lead acid batteries; the speed profile is not equal due to two reasons:

- The acquisition system is not the same;
- Test route is not the same.

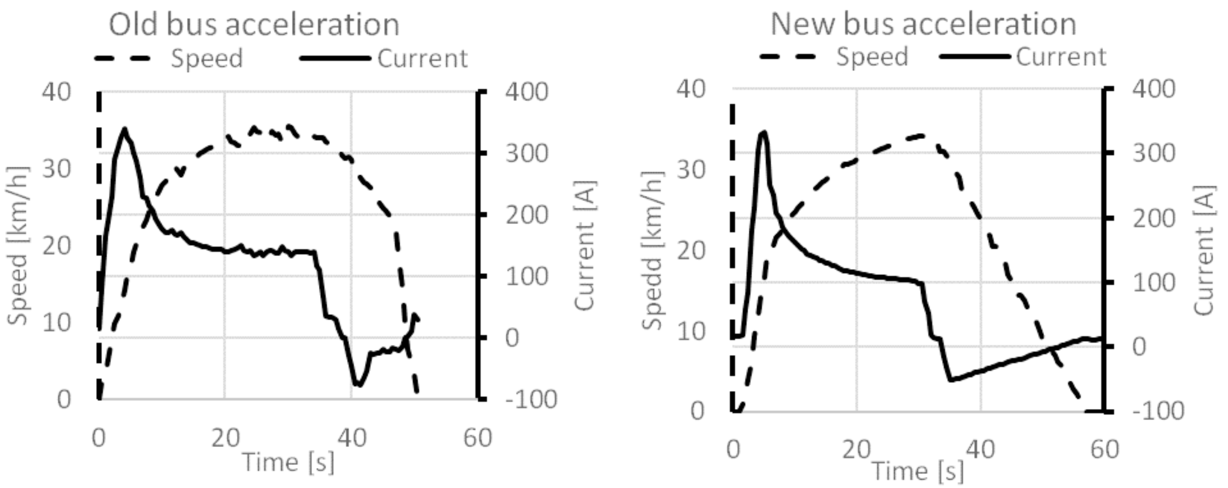

Figure 4 Comparison of maximum acceleration, current and speed measurement

Moreover, some tests concerns the regenerative braking function. A specific controller manages this feature, in this study this power was only measured in order to built a model for calculation.

In general, the braking of an electric bus in a good opportunity to recover a good part of energy through the regenerative braking functions. In this case, the motor controller manages the motor/generator and offers a negative torque to driven axle when the bus goes at speed greater than 5 km h^{-1}. The energy recover happens in corrispondence to one of these events:

- cut off (accelerator pedal is in initial position, load is equal to 0%);
- brake pedal is pressed.

When only the cut off occours, the controller produces a negative torque (and also a electrical genereration) and it is much high the greater is the speed (usually with a current limit due to the maximum allowable recharging current of battery) , when also the brake pedal is pressed an addictional negative torque is produced (simultaniously at the negative torque generated by motor generator, mechanical brake act as conventional).

Figure 5 shows the power of regenerative braking during the cut off driving phase, the measurement of power is outside of battery, read by hall sensors of BMS, it evals the current ingoing (or outgoing from battery).

For example the bus has a electrical absorption due to auxiliary load of about 0.8-1.3 kW.

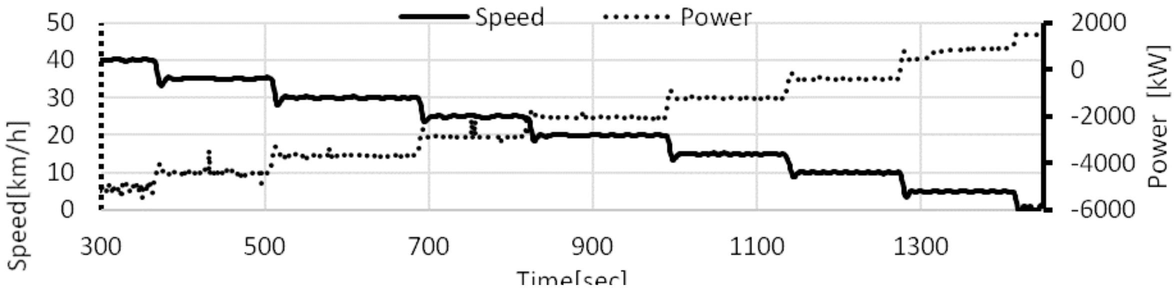

Figure 5 Power of regenerative braking

3.2. Energy consumption

Figure 6 shows the consumption trend by varying speed. Hall current sensors measured the current flows, and a numerical integration of current gave the consumption.

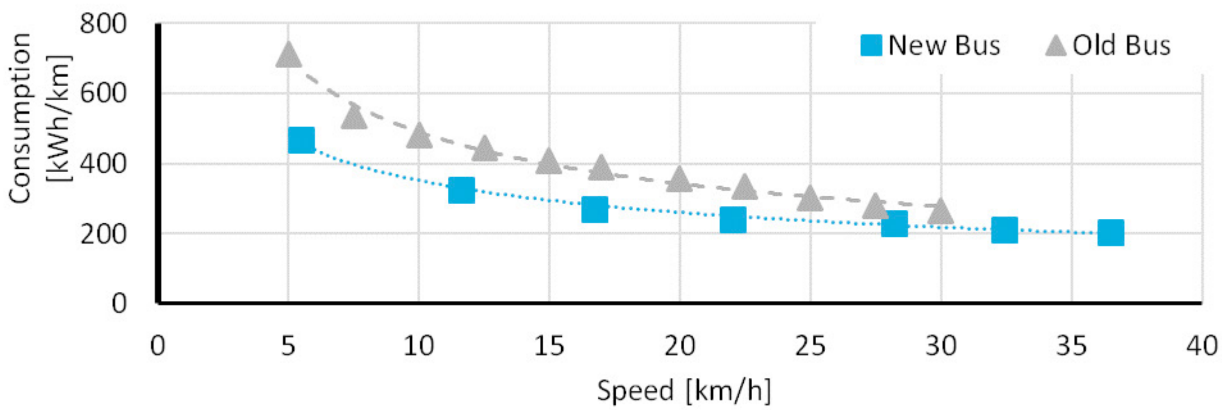

Figure 6 Consumption comparison for the bus run empty

When the speed goes up, the motor efficiency rise up to its maximum in correspondence of maximum rotational speed, thanks to the differential gear the maximum rotational speed correspond to 40 kmh^{-1}.

The rolling and aerodynamic forces (resistances) increase slightly up to the maximum speed for the bus, with almost linear law and low angular coefficient. The gravitational force is non-influential in the road used for tests.

As described in [6] and in [7], an old bus fed by lead acid batteries (same bus model) had a total average consumption of 1230 $Whkm^{-1}$ (123 kWh per 100 km in Figure 7). As the same studies said, the average specific consumption was 700 $Whkm^{-1}$.

During the tests, there were 10 passengers inside and 27 is the maximum capacity (driver not included), it means a load of 40% (650 kg of total 1760 kg, from vehicle registration certificate).

Instead, it was unknown the average slope of route selected (in the paper there is an elevation graph, but not the average value). The comparison between the two types of batteries comes from literature, because there is not a common route in order to compare both systems. Instead, the old bus has a 50 km range; this bus equip a 43 kWh lead acid battery with an average consumption of 700 $Whkm^{-1}$.

The retrofitted bus with an average consumption in the SORT cycle ([1]) of 500 $Whkm^{-1}$ in almost the same conditions of passengers transported has a range of 30 km but with a fast charge during the several stops, it reaches easily the range of a day.

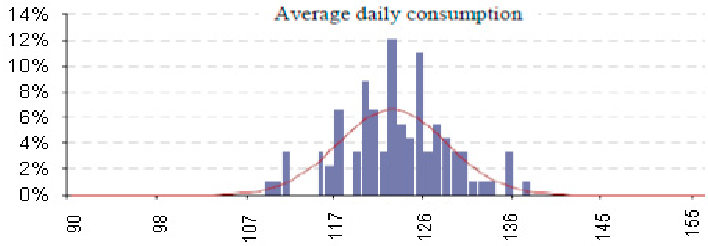

Figure 7 Average daily consumption of old bus (source [6])

4. Financial analysis and market dimension

An economic evaluation in 20 years with a cumulative costs trend and a net present value could demonstrate that this retrofit strategy could be a good alternative instead of buying new buses.

A financial analysis, which compares relative costs of new or retrofitted buses equipped by different types of batteries, calculating the present values of negative cash flows related to the various different options, demonstrates that the retrofit strategy could be the most cost-effective option. The three options considered are:

- A. retrofitted Bus equipped with Ion-Lithium batteries, comparable to the prototype developed by the ENEA research center project ;
- B. New Bus equipped with Lithium battery (provided by Bredamenarini);
- C. New Bus equipped with Lead Acid battery (provided by Tecnobus).

Table 2 shows the present values (PV) of negative cash flows related to the three different options considering a real rate of interest of 3% over 20 years operation and bus lifetime (for calculations see [8]).

Option	**PV in euro**
A	- 194 764
B	- 305 832
C	- 367 554

Table 2 The present value of three options.

The “A” option is the most cost effective because it has the lowest present values of costs.
The simplifications made for this analysis are the same for all options:

- All costs for the legislative duties (insurance, taxes and so on);
- Length of route travelled;
- Consumptions (each battery are dimensioned for cover the mission assigned and each bus has the same efficiency for the conversion on energy);
- The dynamic performance and the speed profile is the same for all, they consume the same amount of energy.

The assumptions made are:

- Battery costs estimated are fixed during all period, actually it has a great fluctuation from each year, and the trend expected is a significantly decrease for all chemistry for next years. This fact could be unlikely to forecast and in this project, it was preferred to keep steady them.

A cumulative cost analysis demonstrates the cost of each option year by year, and the Figure 8 compares the cumulative costs in euro (thousands) for three options considered.

This chart demonstrates that the "A" solution (with a retrofitted bus) has a lower impact to annual cost in the period considered. Especially it allows having a good solution of electric bus, which could be convenient for the public entities and some transport agencies with cash flow issues.

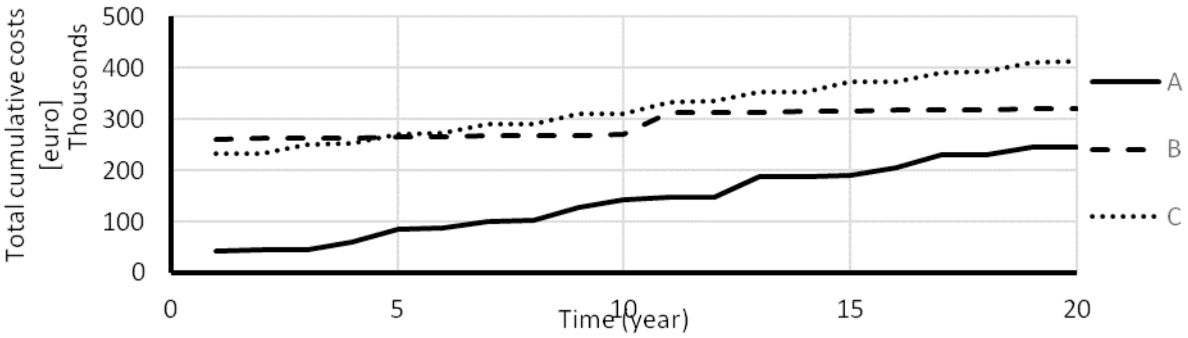

Figure 8 Costs trend for different technologies

Maybe in 30 years the cumulative costs could be equal between retrofitted bus and new bus with lithium battery provided from the bus factory, but this long term analysis is improbable due to the variability of this market and the always increasingly demand of electric bus, this is the trend registered in the two last years (see [9]).

A negative issue of the solution "A" is the availability of old buses in acceptable conditions, they need a low cost mechanical revision to maintain the convenience, moreover this action has to be repeated approximately every three years, and eventually in some cases, it could be difficult to find any replacement parts.

The solution "C" (new bus with lead acid batteries) has same shortcomings of solution A, but with greater costs for the bus. It is clear that between C and B the most cost effective solution is the B, in line with to the lowest PV value.

The market dimension within limits to the bus provided by Tecnobus seems to be of hundred, but considering all electric bus fed by lead acid it could be in thousands. The project has build a prototype of one retrofitted bus, but it could be made for other manufacturers easily with a little designing activities.

A separated market could be created by the retrofitting of bus originally with internal combustion engine, that it could be converted in electric motor with more important investment and registration costs. In fact, Italian Ministry of Infrastructure and Transport approved recently the D.M. n°. 219/2015 that allows this conversion and permits a new certification for all the retrofitted buses.

This important Decree allows converting all buses independently from the age and the power supply excluded from circulation because too pollutant. Maybe, it can use for convert instead of buy a new one. Same decreto could interest all light and heavy transport vehicles for goods. In this case the potential market expand at several hundreds of thousands vehicles.

5. Conclusions and further development

The goal of this paper is to demonstrate that a retrofit of old buses joined with a cautious managing of lithium battery could be economically feasible for re-use electric and conventional buses (with further efforts of designing). This retrofit solution is also applicable to other categories of vehicles like the heavy and light duty trucks for goods. Some advantages of retrofit are:

- Avoid bus disposal and production of waste (obsolete EURO standards), if it is re-used it will avoid the costs and the pollution linked with the disposal operation;
- Reduce pollution if the retrofit involve conventional vehicles;
- Low impact in the economic exposure of public transport agency, it could be easier if they also got old buses (and they are obliged to keep off the bus from fleet).

- Energy consumption reduction about of 15%, that in this paper has a secondary relevance but in order to do a feasibility analysis it could be more important. Furthermore, if the weight losses increase (as shown in [10]) the consumption reduction could raise.

Disadvantages could be:

- Difficulty to find old bus in acceptable condition (not entailing excessive repair and revision costs);
- Difficulty to find replacement parts.

Afterwards, this project is applicable directly to bus fed by electricity that can be retrofitted without any certification (only for the batteries that should be aware to respect the ISO standards). As the prototype, a new performable Lithium battery could replace an old lead acid one in almost all buses with 72 V nominal voltage or similar.

The dynamic performance and the electric specifications remain approximatively constant, except of energy stored on board that can be reduced, and thanks to fast charging method, each bus could reach a range compatible with the mission required.

Further development may arise by developing other retrofit – kit for other bus or vehicles. In particular, it is necessary to develop a parametric procedure helping designers in the choice of optimal battery size, to fit needs of specific vehicle applications.

Nomenclature

BMS	Battery Management System
ECU	Electronic Control Unit
BEV	Battery Electric Vehicle
PV	Present Value
ISO	International Standardization Organization

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