A Technical, Environmental and Financial Analysis of Hybrid Buses Used for Public Transport

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Abstract

This paper presents a technical, financial and environmental analysis of four different hybrid buses operated under Buenos Aires driving conditions. A conventional diesel bus is used as reference and three electric hybrids equipped with different energy storage technologies, Li-Ion, NiMH batteries and double layer capacitors (ultracapacitors), are evaluated, along with a hydraulic hybrid platform which uses high-pressure accumulators as its energy buffer. The operating conditions of the buses are set using real driving GPS data collected from various bus routes within the city. The different vehicle platforms are modeled on AUTONOMIE SA and validated by comparing the obtained fuel consumption results to those reported by local transport authorities and values found in the literature. The embedded energy and CO_2 emissions of each platform are estimated using GREET and the total cost of ownership of each vehicle is calculated and compared to that of the conventional bus. Furthermore, aging models are proposed to evaluate the life duration of the batteries and ultracapacitors. Results show that, independent of the energy storage technology, the fuel economy performance of all hybrids is highly dependent on the size and configuration of the powertrain and energy storage components. When optimized, all hybrids achieve significant fuel consumption reductions compared to a conventional diesel bus, however, the ultracapacitor based system seems to outperform the other technologies. The battery based electric buses achieve similar fuel consumption reductions, but the NiMH based batteries shows a considerably shorter life expectancy. This has a significant impact on both the economic and environmental performance of this vehicle. The life cycle emission analysis shows that, given the high fuel consumption of a conventional bus, the additional embedded CO_2 emissions of the hybrid vehicles are offseted by the achieved reduction of in-service CO_2 emissions due to fuel consumption reductions. Regarding the economic performance of the different platforms, results show that the fuel savings achieved by all hybrids displace the higher capital costs required. Overall, all hybrid buses show a strong potential to reduce both CO_2 emissions and costs, resulting in negative costs of CO_2 abatement.

1. Introduction

The ongoing global energy demand and the increasing need to reduce anthropogenic greenhouse emissions, to avoid the worst-case scenarios of global warming, requires the introduction of cleaner and more sustainable technologies and practices into all sectors of the economy [1]. In particular, the transport sector accounts for almost 1/4 of all global greenhouse gas emissions [2]. Furthermore, 50% of these correspond to road passenger mobility, underlining the substantial effect that reducing emissions in this area would have on overall global emissions [3].

Hybrid vehicles aim to combine the robustness and versatility of internal combustion engines and the high energy density of fuels, with the efficiency and performance benefits of electric/hydraulic transmissions, which amongst other things, enable regenerative breaking. As shown on the work published by [4, 5], the benefits obtained by the use of these technologies are maximized when applied to urban heavy-duty vehicles. The highly transient driving conditions to which these are subject to, make conventional vehicles highly inefficient, resulting in high fuel consumption.

Many alternatives for hybrid configurations are currently being considered. Regarding light-duty passenger cars, the commercial introduction of the Toyota Prius and the Honda Insight, among others, have uphold hybrid electric platforms over other hybrid alternatives. However, several studies suggest that due to the high cost and bounded battery life, hydraulic based technologies could provide an interesting solution for heavy-duty applications such as trucks and buses [6, 7].

John Kargul et al., at the United States Energy Environmental Protection Agency's (EPA), developed and tested an integrated drive module for a commercial series hybrid hydraulic truck and bus. The system was tested under different urban stop-go driving cycles showing that such platform could achieve considerable reductions in fuel consumption [8]. Further work done by the EPA showed that the payback period of different hybrid vehicles could vary from 1.2 to 9.6 years depending on the vehicle and its application [9]. Moreover, it also showed that heavy vehicles tend to obtain better results in terms of payback, as fuel cost represents a larger portion of their total cost of ownership. Namwook Kim et al. at Argonne National Laboratory performed a comparative study of a hydraulic hybrid systems for class 6 trucks [7]. Throughout this work, the AUTONOMIE simulation platform was used to compare different powertrain configurations under different driving cycle conditions. It was found that series hydraulic vehicles outperform (less fuel consumption) series electric vehicles in aggressive driving conditions. Furthermore, Boretti and Steck [10] undertook a complete overview of hydraulic hybrid technologies and a case study was presented: a series hybrid hydraulic system for a military truck. Simulations and real tests were performed yielding fuel consumption reductions of up to 27% in aggressive start-stop driving conditions. In all, several papers uphold the potential of hydraulic hybrid powertrains to achieve greater fuel consumption reductions than those obtained by electric hybrids [11, 12, 13].

There are a few publications in the literature concerning general hybrid electric vehicle configurations [7, 14] and vehicle energy management strategies [15, 16, 17]. Regarding the implementation and performance of a hybrid electric powertrain on a heavy-duty vehicle, Williamson et al. performed a comparative investigation of series and parallel hybrid electric drive-trains for heavy-duty transit bus applications to establish the potential fuel consumption reductions that such systems could achieve [18]. The vehicle platforms were simulated using ADVISOR and tested under different driving conditions. Results showed that both configurations achieved considerable fuel savings when compared to a conventional vehicle. Moreover, it was observed that the parallel configuration analyzed slightly outperformed the series configuration in terms of fuel consumption. However, no parametric analysis was performed regarding the energy storage capacity of each configuration.

One of the main concerns regarding the implementation of hybrid electric systems is establishing the type and size of the energy storage unit. Different types of batteries are used in hybrid and electric platforms: Li-ion, Nickel Metal Hydride and Lead Acid. Li-ion, in all its forms, has shown to be the most trending technology, due to their high energy density, relatively high cycle life and on growing power density [20, 21, 22].

The other energy storage technology analyzed throughout this paper are ultracapacitors (UC). These are well known to have high power density and high cycle life but very low energy density [23]. However, due to their high power density, ultracapacitors are being used in hybrid electric vehicles, where high electrical power is needed rather than electrical energy [20]. Ultracapacitors are also being used combined with high energy storage capacity systems such as batteries. Vulturescu et al. implemented a hybrid energy storage system composed by NiCd batteries and high power ultracapacitors on a 3.5 ton urban bus. Although the bus was equipped with an internal combustion engine and a generator, tests were performed in fully electric mode. It was observed that the introduction of high power capacitors yielded a reduction of energy losses within the battery, increasing its lifetime expectancy and improving the vehicle performance [24].

As mentioned before, hybrid platforms can result in considerable fuel savings, however, their implementation also carries significant challenges. To start with, their purchase cost is higher than that of a conventional vehicle. In addition, to fully understand their total cost of ownership and real environmental benefits battery degradation must be considered. This is not trivial given that predicting the battery life-time not only depends on its size and specific cell degradation profile but also requires knowledge regarding the vehicle configuration, overall control system strategy and specific driving conditions [6].

Extensive work has been done regarding the life-cycle assessments of vehicles, where embedded energy and emissions, cost of abatement and in-service energy consumption and emissions are assessed [25, 26, 27, 28, 29, 30]. However, not much has been done in addressing the impact of battery replacements, due to degradation, on the techno-economic performance of the vehicle.

Battery degradation is a big burden that needs to be taken into account when performing a life cycle analysis of a given technology as it greatly contributes to embedded greenhouse gases, embedded energy and total cost of ownership. In order to predict battery life, different models are being developed and used: electrochemical models using Arrehnius equation to predict the effects of temperature and other parameters on battery performance [31] and the so called weighted Ah-throughput model. These relate the end of life of the battery to easily measured parameters such as depth of discharge, temperature, C-rate and number of cycles [32, 33, 34, 35].

Therefore, although extensive work is available regarding the technical, financial and environmental performance of different hybrid platforms, there is a lack of published work that assesses all of the above-mentioned parameters under the same evaluation methodology. To accurately compare different powertrain configurations and technologies, the paper at hand focuses in comparing the technical, environmental and economic performance of four different hybrid class 8 passenger buses operating under real Buenos Aires driving conditions. To do this, first, the bus driving operating conditions are established. After this, the different hybrid platform parameters are discussed, and the different simulation models presented. Subsequently results are discussed, and conclusions drawn.

2. Bus Operating Conditions

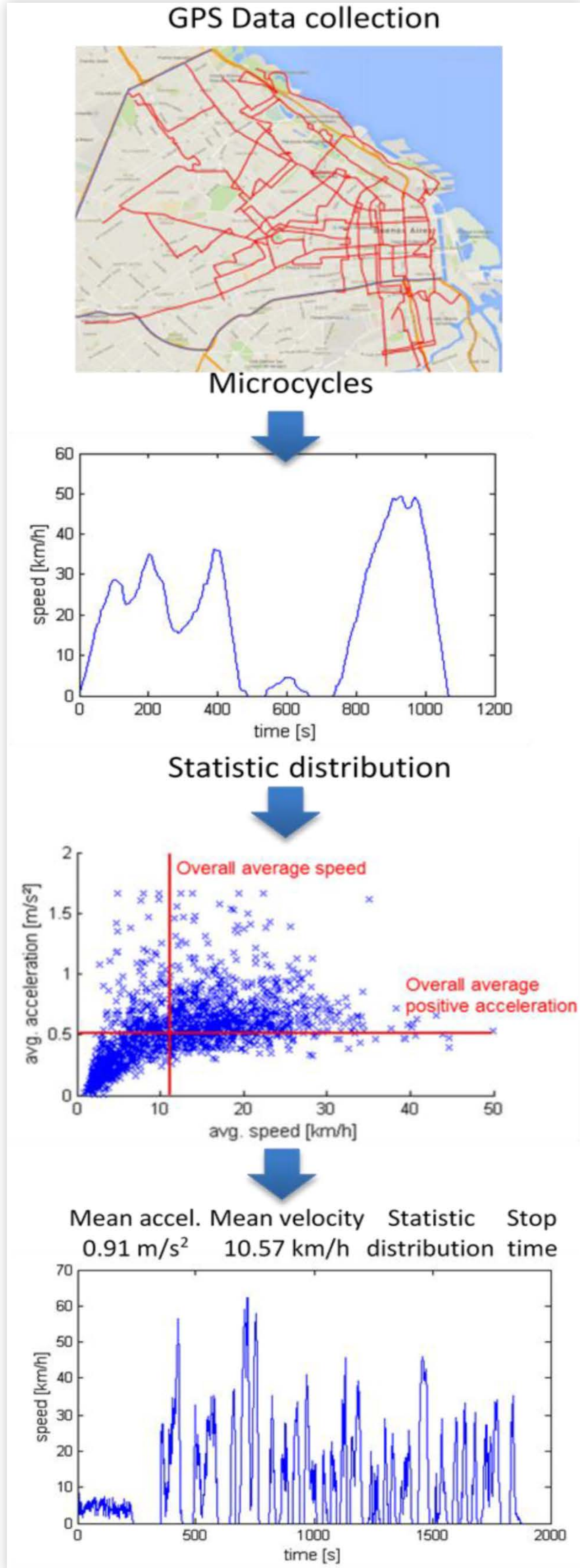
To accurately predict how the different proposed platforms, comply with real driving operating conditions, such conditions must be established. In the case of a public transport city bus, driving conditions vary significantly whether the bus is circulating on a street, on an avenue or on a bus rapid transit lane.

This is mainly due to the mean and maximum speeds, positive and negative acceleration rates and frequency and length between stops in each type of road infrastructure. Therefore, to create a driving cycle that correctly represents the overall driving patterns of a city bus, data was collected from different bus lines, which operate within the city of Buenos Aires using a GPS tracking device. Sixty journeys were made, collecting 30 hours of data, containing information of more than 380 km.

The gathered information is then used to calculate the characteristic values of the overall data pool. These are: mean speed, mean acceleration and idle/driving time ratio. Using these parameters and a construction algorithm, random microcycles[1] are picked ensuring that the 30 minutes representative driving cycle created respects the characteristic parameters of the overall data pool.

Figure 1 shows the bus lanes traveled over the map of the City of Buenos Aires, the statistical distribution of the microcycles recorded, mean speed and mean acceleration of the overall data pool and the representative driving cycle created. This cycle will be used to evaluate the performance of the different vehicles pertinent to the work at hand.

FIGURE 1 GPS data collection, data postprocessing, statistical distribution and Buenos Aires Driving Cycle (BADC).



3. Bus Model Description, Validation and Optimization

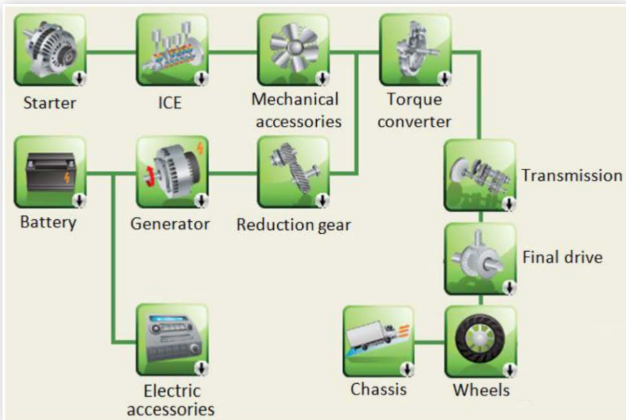
Having established the operating conditions to which the buses will be subjected to, a conventional bus (CB), a series hybrid hydraulic bus (SHHB) and three series hybrid electric buses (SHEB) are developed and uploaded to the AUTONOMIE simulation platform. The three hybrid electric platforms use different energy storage technologies: Li-ion based batteries, NiMH based batteries and ultracapacitors. Throughout this section the different models will be presented, described, validated and optimized. Furthermore, in the case of the hybrid electric platforms, aging models are presented and used to evaluate the premature degradation of the different battery packs and ultracapacitors.

3.1. Conventional Bus Model

3.1.1. Conventional Bus Model Description The CB is the reference platform against which the technical, environmental and economic performance of the different hybrid vehicles will be compared. Simulations are based on an OH 1618 L-SB Mercedes Benz bus. It is a conventional class 8, 2-wheel drive bus, with an automatic transmission. This is a common vehicle used for urban buses in Argentina and Latin

[1] Microcycle: driving event were the vehicle starts and ends at zero speed whilst remaining above zero for all instances in between.

FIGURE 2 CB powertrain configuration.



America. Figure 2 shows a schematic representation of the CB architecture.

Subsequently, parameters such as the internal combustion engine (ICE) power, torque and fuel consumption maps, gearbox reductions, frontal area and drag coefficient are modified to match that of the Mercedes Benz bus. Key vehicle parameters are shown on Table 1.

3.1.2. Conventional Bus Model Validation To validate the developed model, results are compared to those obtained on chassis dynamometer tests done by VTT technical research center of Finland, over the Braunschweig driving cycle [42]. The Braunschweig City Driving Cycle (BCDC) is a well-known transient driving schedule representative of urban bus driving in start- stops conditions. Given that tests were done at bus maximum passenger capacity, equivalent to 6000 kilograms of cargo, the AUTONOMIE conventional bus platform is also simulated under these conditions. Results are shown on Figure 3.

The first thing that can be noted is that the proposed platform can cover both driving cycles. Further, when comparing the results obtained by the bus simulation platform

TABLE 1 CB key technical parameters (load weight is set to 2400 kg which is the equivalent of 32 passengers with an average weight of 75 kg).

Mass	Curb [kg]	10,590
	Cargo [kg]	2,400
Body work	Frontal area [m^2]	8.06
	Drag coefficient	0.65
Wheels	Radius [m]	0.51
	Number of wheels	6
Accessories	Average power [W]	5000
Engine	Maximum power [kW]	130 @ 2200 rpm
	mm lift	
	Maximum torque [Nm]	675 @ 1200 rpm
Gearbox	Reductions	9.2, 5.2, 3.1, 2.0, 1.4, 1
Differential	Final drive	4.3

FIGURE 3 CB simulation results for both the BADC and the BCDC.

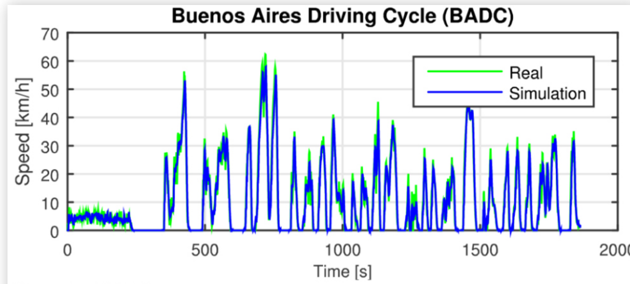


Figure 3a. BADC

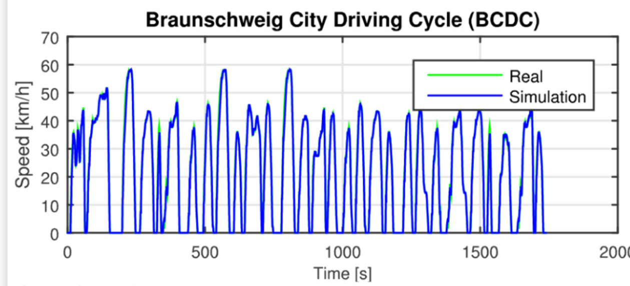


Figure 3b. BCDC

	BADC	BCDC	Discrepancy
CNRT (2.4T cargo)	51.4 L/100km	-	-
Sim CB (2.4T cargo)	54.0 L/100km	37.4 L/100km	44%
Discrepancy	5%	-	-
Sim CB (6T cargo)	65.5 L/100km	45.0 L/100km	45%
Dyno Test (6T cargo)	-	46.0 L/100km	-
Discrepancy	-	2%	-

Figure 3c. Bus fuel consumption over the different driving cycles and under varying loads.

and the dyno tests performed over the BCDC, under the same load conditions, these show a discrepancy of approximately 2%, thus validating the proposed platform. On the other hand, it is also clear that the BCDC is not compatible with Buenos Aires urban city bus operation, given that running the simulation platform over the different driving cycles, at two different cargo loads, results in fuel consumption differences of around 45%.

Another important result is the fact that when running the model over the BADC, under the average cargo conditions (2.4 tons), fuel consumption results are comparable to those reported by the National Commission of Transport Regulation (CNRT), with discrepancies being less than 5%. This is evidence that the created Buenos Aires Driving Cycle is an accurate representation of the operating conditions under which buses operate within the city and is therefore considered an appropriate input to undertake a performance comparison of the hybrid platforms.

The difference between the reference fuel consumption and the simulation results could be due to the fact that the reference value established by the CNRT is an average based on all buses operating close to the metropolitan region, some of which operate on highways or in less traffic intensive areas. This, of course, results in lower fuel consumption.

3.2. Series Hybrid Hydraulic Bus

3.2.1. Series Hybrid Hydraulic Bus Model Description It could be argued that when designing a specific hybrid vehicle, most of the vehicle components could be optimized based on the operating conditions to which the vehicle will be subject to. However, in order to have a parametric comparison of the different platforms, most of the components used for both the SHEB and the SHHB, such as the ICE; chassis; bodywork and differential will be the same as those used for the CB.

The SHHB model is developed using the architecture of the 2-wheel drive series hydraulic hybrid class 6 vehicle, included in the AUTONOMIE library. Subsequently, parameters are modified to match the characteristics of a class 8 bus. Figure 4 shows the main layout of the vehicle.

Both the pump and the hydraulic motor used are bent axis type systems. These are selected due to their ability to deliver a wide range of power requirements at constant speed with high efficiencies, even at high loads and high displacement conditions.

On the other hand, the efficiency of such systems is low at low loads and low speed. This is mainly because frictional (mechanical) loses and fluid leakage remain constant over the operating range of the system and therefore, at low power outputs, become proportionally greater [8]. This must be considered when optimizing the size and operating conditions of the overall platform.

The energy storage system used for this configuration is a steel bladder type, high pressure accumulator and reservoir. The maximum working pressure of the high-pressure circuit is set to 350 bar, while the minimum operating pressure is set to 100 bar. This is done to achieve an optimum utilization of the accumulator bladder and long service life [36]. The low-pressure circuit is set to operate at 5 bar to avoid cavitation in the inlets of the motor and pump.

3.2.2. Series Hybrid Hydraulic Model Optimization The component sizing is done by performing a parametric sweep to establish optimal fuel consumption, whilst considering the availability of components in the market.

FIGURE 4 SHHB powertrain configuration.

In the particular case of the hydraulic hybrid, the systems that need optimizing are the hydraulic motor, the hydraulic pump and the hydraulic accumulators. To do this, three configurations of pumps and motors are modeled for different hydraulic accumulator size and power capacity. Furthermore, for each configuration, the coupling between the ICE and the hydraulic pump is optimized for both components to work at their optimal regime most of the time. The AUTONOMIE inbuilt energy management control strategy is used throughout these simulations [7].

Figure 5 shows the fuel consumption for the three evaluated pump-motor configurations as a function of both hydraulic accumulator power capacity (5a) and energy storage capacity (5b), variation in capacity is achieved by increasing the number of accumulators and, hence, the total available volume. Each accumulator has an energy storage capacity of 0.15kWh.

Results show that the minimum fuel consumption is obtained using 355 cc (378 kW) motor and a 250 cc (321 kW) pump. The fact that the minimum fuel consumption is obtained with a pump that has a higher power than that of the ICE (see Figure 5) is related to the efficiency of the pump.

FIGURE 5 SHHB fuel consumption for different component configurations.

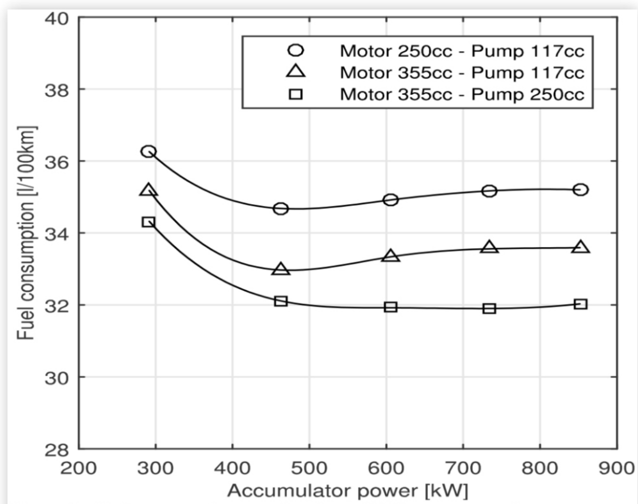


Figure 5a. Fuel consumption as a function of ESS power capacity.

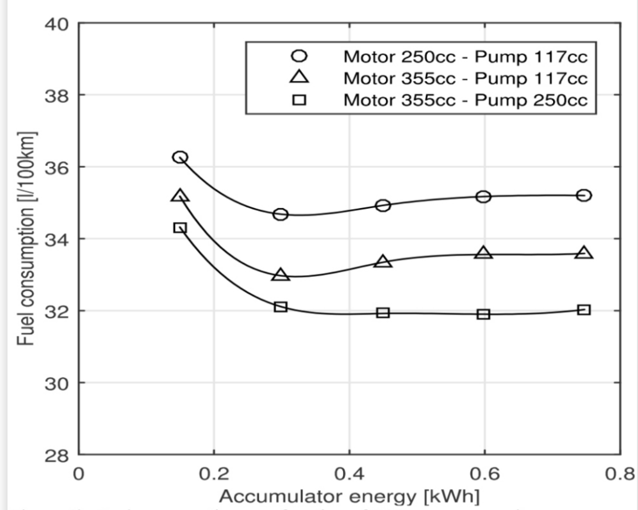


Figure 5b. Fuel consumption as a function of ESS energy capacity.

TABLE 2 SHHB optimal configuration.

Total weight	11,300 kg
ICE	130 kW
Motor	355 cc (378 kW)
Pump	250 cc (321 kW)
Accumulator	150 cc (0.5 kWh)
Fuel consumption	31.92 L/100 km

Given that the smaller pump (177 cc-130 kW) operates at a lower efficiency, increasing the pump size yields higher efficiencies along the driving cycle resulting in an overall lower fuel consumption.

Figure 5 also shows that increasing both the power and energy storage capacity of the hydraulic accumulator initially results in a drop of fuel consumption reaching a minimum after which further increases tend to reduce the vehicle's fuel economy. This is due to the fact that, beyond a given capacity, no more efficiency gains are obtained from brake regeneration or engine optimal operation, therefore, adding further storage capacity only results in a greater vehicle mass which of course results in a lower vehicle efficiency.

Table 2 shows the optimal configuration for the hydraulic hybrid bus for which three accumulators of 50 liters are used to reach the power capacity showed.

3.2.3. Series Hybrid Hydraulic Model Validation

To validate the proposed model, results are compared to those obtained by Rousseau et al. [7]. The latter involve the operation of a class 6 truck, series hydraulic hybrid, operating over the Manhattan Driving Cycle (MDC). The comparison is therefore, not straight forward. As shown on Table 3, the Argonne National Labs (ANL) platform is considerably lighter than the SHHB platform here presented and has an ICE with 23% more power. In particular, the reduced vehicle weight, results in a considerably lower fuel consumption. On the other hand, the hydraulic pumps, motors and accumulators are of comparable size and capacity to those here presented. Therefore, to validate the proposed platform, both systems are simulated over the MDC and the ANL platform is subsequently modified to have the same weight as the SHHB. Results are shown on Table 3.

Results show that the hydraulic vehicle presented by Rousseau et al., when modified to have the same weight as the SHHB, obtains a fuel consumption of 30.9 L/100 km. This represents a discrepancy of less than 3% when compared to the results obtained by the SHHB over the same operating conditions. This is considered sufficient validation of the proposed model and its optimization.

TABLE 3 Comparative values for SHHB.

	ITBA	ANL [7]	ANL (bus size)
Total weight [kg]	11,300	8,654	11,300
ICE [kW]	130	159	159
Motor [cc]	250	256	256
Pump [cc]	250	245	245
Accumulator [L]	150	136	136
Fuel Consumption [L/100 km]	31.09	23.8	30.09

3.3. Series Hybrid Electric Bus

3.3.1. Series Hybrid Electric Bus Model Description

The AUTONOMIE library does not have a standard heavy-duty hybrid electric vehicle platform, therefore, a light duty; 2-wheel drive; hybrid vehicle with no gearbox is used to establish the basic architecture of the vehicle. The latter is shown on Figure 6.

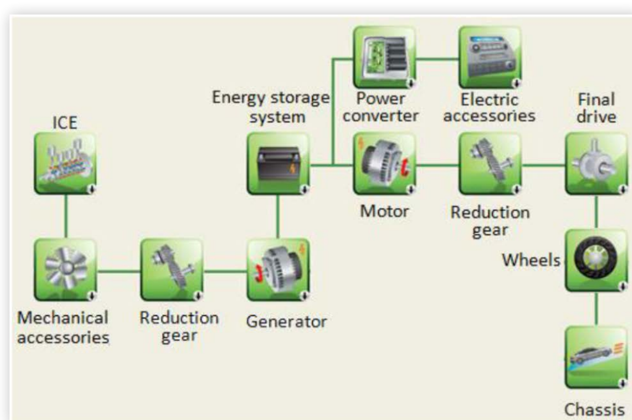
To achieve a representative model of the vehicle in question, the following system components are modified:

- The ICE parameters are changed for those used in the CB model.
- The reduction gear and final drive (as in Figure 6) are set to the relation that maximizes fuel economy and vehicle performance.
- The generator and motor are changed for ones with higher power and subsequently scaled accordingly.
- The battery and ultracapacitor packs are modified (series and parallel stack) to match the required voltage, amperage, energy capacity and power.
- The electric accessory electrical consumption is increased accordingly.
- The total weight, frontal area, drag coefficient, weight distribution and number of wheels among other parameters are also modified.

As shown on Figure 6, the main difference between the SHEB platform and that of the CB, is that the ICE is now coupled to a generator that supplies electric power to an energy storage system, which subsequently supplies electric power to the motor/generator coupled to the vehicle's wheels. The main advantages of such a system are:

- Decoupling the engine from the wheels enables the former to operate close to its maximum efficiency condition independently of traffic conditions.
- Engine and battery power can be combined to cover high power demand conditions. This allows engine downsizing.

FIGURE 6 SHEB powertrain configuration.



- The electrical powertrain and availability of an energy storage system (ESS) enables regenerative braking.

All of the above allow for improvements in the overall vehicle efficiency resulting in potential fuel savings.

As mentioned before, different types of energy storage technologies are used throughout this analysis: Li-Ion and NiMH based batteries are evaluated as well as ultracapacitors. Table 4 shows the specific characteristics of each technology based on what is available in the market.

The sizing of the energy storage system is crucial when optimizing the overall performance of each hybrid bus. Conventionally, the system is only optimized to minimize fuel consumption. However, given the high cost of the energy storage unit, its degradation should also be considered when evaluating the economic performance of the system. To estimate the lifetime of the energy storage system, aging models are used and discussed in Section 3.3.3. Additionally, when sizing the batteries and ultracapacitors of the hybrid platform, the configuration of the required energy storage cells is of great concern (number of cells in series and parallel). The open circuit voltage (OCV) of the ESS must be greater than the minimum voltage required by the motor power electronics controller, for the latter to be able to operate at all times. Moreover, if the OCV drops throughout the vehicle's operation, to match the power required by the wheels the current supplied by the system will rise, exposing the electric drive components to higher thermal stress.

Another important factor when optimizing a hybrid configuration is the Energy Management Strategy (EMS). As shown on [16], the latter can have a significant impact on the life cycle of the vehicle. Throughout this study, all electric hybrid platforms will be controlled using a Load Following EMS. This is a ruled based control strategy, which sets the conditions of the different subsystems based on the power demand at the wheels.

FIGURE 7 SHEB fuel consumption for different component configurations as a function of both ESS energy capacity and power capacity (the different motor to generator power ratios are denoted kW/kW).

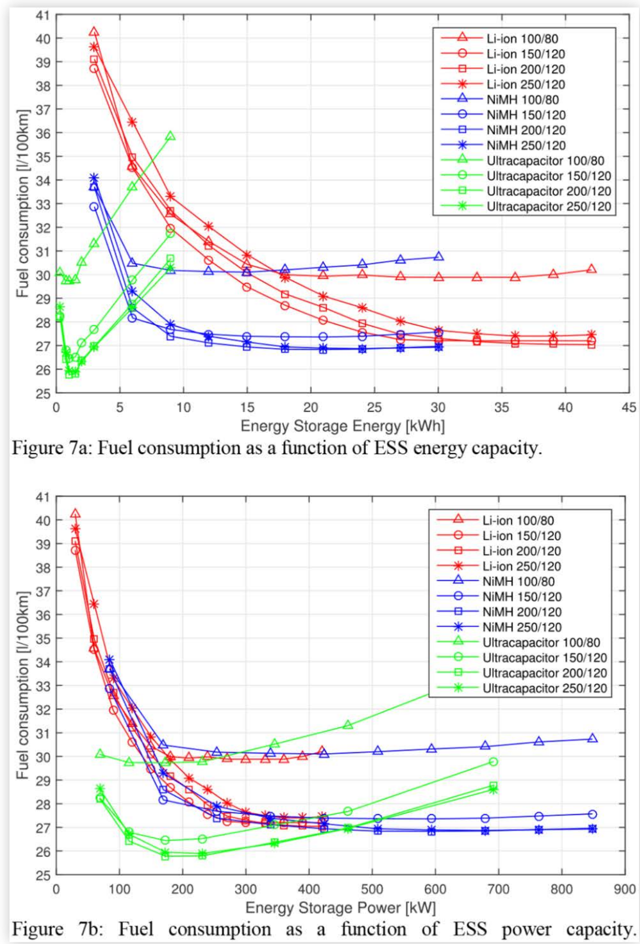


Figure 7a: Fuel consumption as a function of ESS energy capacity.

Figure 7b: Fuel consumption as a function of ESS power capacity.

3.3.2. Series Hybrid Electric Bus Model Optimization

The sizing of the vehicle components for all electric storage technologies is done by performing a parametric sweep of the power of the vehicles electric motor and generator, whilst varying the energy storage capacities. Results are shown on Figure 7, each curve represents fuel consumption variation for a certain motor/generator power ratio.

As for the SHHB, Figure 7 shows that, indifferently of the energy storage technology, all vehicles initially show a drop in fuel consumption as the ESS capacity is increased. At a given point, all systems reach an optimum, after which, the fuel consumption starts to rise. This is considerably more evident for the ultracapacitor based system, given the energy specific weight of this technology is much higher than that of the battery based systems.

Furthermore, results also show that the initial increase of the electric motor and generator power capacities has a dramatic impact on fuel consumption. However, as with storage capacity, beyond a given point, further gains by increasing the power capacity of such systems are negligible and the extra weight of the components results in an increase of fuel consumption. Most electric hybrid configurations in the literature show a 5/4 power ratio configuration between the electric motor and the electric generator, therefore, although the Li-Ion and ultracapacitor platforms obtain further fuel reductions with a 200/120 configuration, the 150/120 configuration will be used for all electric platforms.

Regarding the energy storage technologies, both battery and ultracapacitor yield approximately the same fuel consumption but with considerably different energy storage capacities. In hybrid vehicles, the energy storage is sized based on the peak power output required by the wheels, as the fuel and the ICE provide the energy density required for long-term operations. Therefore, when using batteries, the ESS is normally oversized in terms of energy storage capacity,

TABLE 4 Characteristics of batteries cells and ultracapacitors.

	Li-Ion	NiMH	Ultracapacitor
Nominal voltage [V]	3.6	1.2	2.7
Nominal capacity [Ah]	17.5	6.5	2,600 [F]
Specific Energy [Wh/kg]	106.1	45.9	5.6
Specific Power [W/kg]	1,060	1,300	4,100

resulting in a narrow State of Charge (SOC) variation when compared to that of fully Electric Vehicles (EV) [35]. As it will be shown below, this helps also preserve the battery and therefore, before establishing the optimal size of the ESS for the different electric hybrid buses, the endurance of the storage units is assessed.

3.3.3. Battery and Ultracapacitor Aging Model

Battery manufacturing, in particular, is highly energy intensive and costly, therefore, having to replace the battery pack over the lifetime of the vehicle, could have a considerable impact on both the economic and environmental performance of a given bus. Consequently, before continuing with the life cycle assessment of the different hybrid vehicles, it is important to establish the lifetime of the different energy storage technologies.

Premature aging of a battery pack is induced when the latter is charged and discharged during the vehicle's operation. The system's degradation is reflected in a lower charging capacity and an increase of the batteries internal resistance. This results in lower system efficiency and higher operation temperatures. This could generate safety concerns as the system becomes more susceptible to short circuits and fire hazards. When one of the mentioned parameters exceeds a predetermined value, the battery is considered to have reached its "end of life" (EOL).

The most relevant parameters that affect battery aging are: depth of discharge (DOD), discharge rate (C_{rate}) and operating temperature. The main problem when trying to predict battery degradation and its EOL is that all aging tests are performed with well-defined charge and discharge cycles, while in a hybrid electric vehicle (HEV) batteries work under varying conditions that are different to those used throughout the charge/discharge tests.

Ultracapacitors EOL is also affected by depth of discharge and charge and discharge currents but as there are no chemical reactions involved, longer life expectancy can be achieved, typically more than 1,000,000 cycles compared to the 2,000-10,000 cycles of batteries [21, 37].

Hydraulic systems used in the SHHB, on the other hand, are well established and report considerably high life duration. Therefore, it will be assumed that the hydraulic components of the SHHB outlast the life of the vehicle.

Throughout this section, the life expectation of both batteries technologies and ultracapacitors is to be analyzed.

Li-Ion & NiMH battery aging model: Many models designed to predict battery aging can be found in literature. Throughout the present work, battery aging, for both Li-Ion & NiMH based systems, will be established using the model developed by the Ohio State University [32, 33, 34, 35]. This model is based on the "Ah throughput" concept, which states that a battery can deliver a finite amount of energy over its life cycle.

The model relies on battery DOD, C_{rate} and operating temperature.

Increasing the operating temperature of a battery pack increases rapidly its premature degradation. However, given that setting the batteries operating temperature should not be a problem if the heat evacuation system is well designed and managed, temperature variations will be neglected throughout this evaluation and the operating temperature of the system will be therefore assumed constant and set at 25 °C. On the other hand, the depth of discharge of a storage system is defined as *DOD = 1 - SOC*, and relates to the minimum state of charge to which the system is subject to.

The discharge rate of the energy storage unit reflects the relative aggressiveness of the operation. The information provided by manufacturers is generally expressed as:

$$C_{rate} = \frac{I_{nom}}{Q_{nom}} \quad (1)$$

where I_{nom} is the nominal current of the battery pack in *Amperes* and Q_{nom} is its nominal capacity in *Ah*.

The nominal *Ah* throughput of a battery is then defined as:

$$E_{nom} = \int_0^{EOL} \left| I_{nom}(\mathcal{T}) \right| d\mathcal{T} \quad (2)$$

where nominal conditions are generally *DOD = 1*, $C_{rate} = 1$ and temperature 25 °C. For nominal conditions, E_{nom} can be also defined as [38]:

$$E_{nom} = 2 Q_{nom} N_{C2F} \quad (3)$$

where N_{C2F} (Cycles to Failure) is the number of cycles with nominal conditions needed for the battery to reach its EOL condition (typically when capacity fades by 20%). This parameter is provided by battery manufacturers. Throughout the present work, the N_{C2F} used for the different battery technologies are 2500 and 1000 for Li-Ion and NiMH, respectively [21, 39].

Based on the above, the battery degradation of the system when operated under non-nominal conditions can be modeled as:

$$E_{cycle}(t) = \int_0^t \left| I_{bat}(\mathcal{T}) \right| * \sigma(DOD, C_{rate}) * d\mathcal{T} \quad (4)$$

where I_{bat} is the battery current taken from the simulation and $\sigma(DOD, C_{rate})$ is the severity factor of every charge and discharge [33]. The severity factor used is that proposed by Carignano et al. [38]:

$$\sigma(DOD, C_{rate}) = \left(1 + 0.0025 * C_{rate}^2\right) * DOD^{1.35} \quad (5)$$

According to the aging model, the fraction that the battery degrades with one driving cycle is given by:

$$Batt_{life}^{cycle} = \frac{E_{cycle}}{E_{nom}} = \frac{\int_0^t \left| I_{bat(\mathcal{T})} \right| * \left(1 + 0.0025 * C_{rate}^2\right) * DOD^{1.35} * dt}{2 * Q_{nom} * N_{C2F}} \quad (6)$$

Aging is cumulative and therefore when $Batt_{life}^{cycle}$ reaches 1, the battery has reached its *EOL*.

It is worth mentioning that the severity factor map used in this paper is an estimation and can be considered a generic map [33]. To obtain a more accurate and realistic severity factor map, aging experiments should be carried out using the discharge profiles induced by the real operating conditions of the vehicle.

Ultracapacitor aging model: In the case of ultracapacitors, an aging model is proposed. Using the same concept as the one proposed for the "Ah throughput" model, ultracapacitors can deliver a certain amount of energy until their *EOL*. This can be calculated as:

$$E = \int_{q1}^{q2} V * dq = \int_{0}^{t} V(\mathcal{T}) * |i(\mathcal{T})| * d\mathcal{T} \quad (7)$$

where $dq = i * d\mathcal{T}$, q is the electric charge, V the open circuit voltage and i the current.

Therefore the *EOL* of an ultracapacitor can be defined as:

$$EOL = \frac{\int_{0}^{t} V(\mathcal{T}) * |i(\mathcal{T})| * d\mathcal{T}}{E_{EOL}} \quad (8)$$

where C is the capacitance and $E_{EOL} = N_{C2F} * V^2 * C$ is the total energy a capacitor can deliver until its *EOL* and N_{C2F} is the number of cycles an ultracapacitor can withstand until it's *EOL*, with nominal cycle conditions[2]. The *EOL* of an ultracapacitor is typically defined based on the equivalent resistance of the system or its capacitance reduction. That is, when the electric equivalent resistance is doubled, or the capacitance is reduced by 20%, respectively [40].

In this aging model, as no severity factor is used, the correction of aging due to high currents is done by setting N_{C2F} to 25000 [41]. As for batteries, the systems temperature is supposed constant at 25 °C. It is important to note that the objective of this model is to obtain an estimation of the *EOL* of ultracapacitors to compare different electric storage technologies. In order to validate this model, real tests should be performed.

Energy storage system EOL estimation: If a city bus operates 20 hours per day, 350 days a year, applying the aging models above described the end of life of each electric energy storage system can be estimated. Results are shown on Figure 8.

Figure 8a shows the percentage of battery deterioration, for every BADC completed, as a function of the systems energy storage capacity. All systems are susceptible to premature aging under the imposed operating conditions. Furthermore, in all cases, the deterioration is reduced as the capacity of the system is increased. As expected, the deterioration of the ultracapacitors seems to be considerably lower than that of the battery based systems. For the latter, the NiMH batteries show to be more sensible to cycling than the Li-Ion based technologies.

However, in order to assess the impact of the energy storage system degradation on the vehicle's life cycle assessment it is important to know if the storage unit can endure the life of the bus or if it has to be replaced and if so, how many times. Figure 8b shows the life estimation of the different evaluated systems as a function of their storage capacity.

NiMH based batteries seem to only endure up to 2 years in the imposed operating conditions. As shown on Figure 7, minimum fuel consumption of the SHEB with NiMH batteries

FIGURE 8 ESS degradation evaluation.

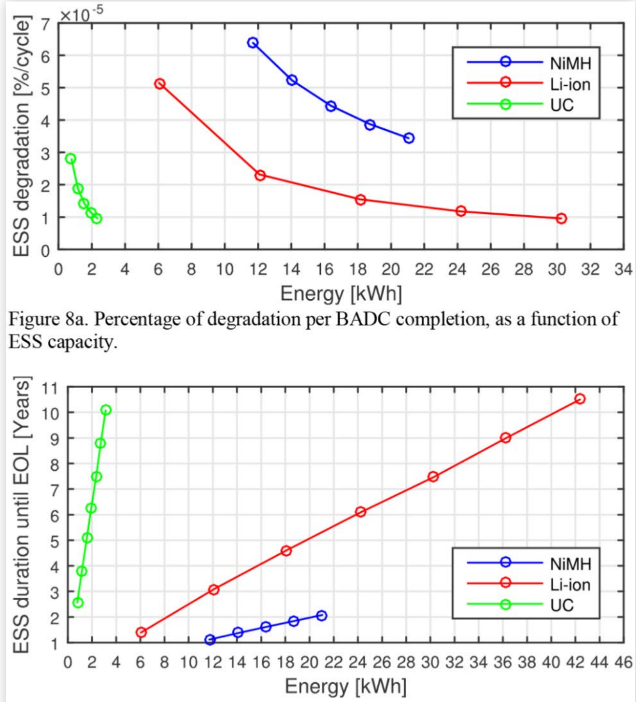


Figure 8a. Percentage of degradation per BADC completion, as a function of ESS capacity.

Figure 8b. ESS life estimation as a function of capacity.

is achieved for an energy storage unit of 21 kWh, this yields 4 battery pack replacements over the lifetime of the bus. As it will be shown later, this has a high impact over the life cycle performance of the vehicle.

Li-Ion based batteries, on the other hand, seem to achieve the life expectancy of the bus when using a ESS with a 40kWh capacity. Based on the results presented on Figure 7, this is the same capacity required to achieve minimum fuel consumption. Therefore, the optimum vehicle configuration is easy to establish.

In the case of ultracapacitors, these seem to be able to achieve the life expectancy of the bus (10 years) but with a slightly larger ESS than that required to achieve the optimal fuel consumption. Therefore, the overall bus design will most probably be a trade-off between optimal fuel consumption and ESS preservation. In order to assess this trade-off, two ultracapacitors configurations are evaluated. The first replicates the condition of minimum fuel consumption, which will require 3 ultracapacitor pack replacements over the life of the bus and the second is the configuration that can achieve the life expectancy of the bus without the need of replacing the ESS. The latter requires a 3kWh ultracapacitor pack.

3.3.4. Series Hybrid Electric Bus Model Validation

As for the CB, to validate the above presented models, the optimum configuration of the NiMH SHEB is simulated over the Braunschweig driving cycle, to compare results to those obtained on chassis dynamometer tests done by VTT technical research center of Finland [42].

Again, tests were done at bus maximum passenger capacity, equivalent to 6000 kilograms of cargo. Table 5 shows the obtained results.

[2] Nominal cycle conditions for the ultracapacitor used is defined as charging and discharging cycles from V_{nom} to 0.5 V_{nom} and vice-versa.

TABLE 5 Fuel consumption of a CB and a NIMH hybrid bus over the Braunschweig driving cycle at maximum vehicle passenger capacity.

	ITBA	VTT	Discrepancy
CB Fuel Consumption [L/100 km]	45.0	46.0	2.3%
SHEB Fuel consumption [L/100 km]	31.0	32.1	3.4%
Fuel consumption reduction	31%	30%	1%

The fact that results obtained by the modeled platforms and those obtained by the tested vehicles differ by less than 3.5% validates the presented models. Furthermore, the 1% difference between the projected fuel consumption reduction obtained by the hybrid vehicles, when compared to the CB, ensures that the economic and environmental benefits of the different evaluated platforms, under the BADC operating conditions, are accurate.

3.4. Optimum Hybrid Bus Configurations

To sum up the current section, Figure 9 shows the fuel consumption of all hybrid platforms as a function of their ESS power capacity (9a) and energy capacity (9b), when operating under the BADC conditions.

Results show that all evaluated technologies yield considerable fuel consumption benefits when compared to a conventional bus, which as shown in Section 3.1 has a fuel consumption of 54 L/100 km. While the hydraulic vehicle obtains a maximum fuel consumption reduction of around 40%, all electric platforms yield benefits of around 50%. It is worth pointing out that this is larger reduction to that achieved over the Braunschweig driving cycle which is around 30%. This shows that fuel savings achieved by hybrid buses in real traffic conditions are greater than those found in literature.

Figure 9a shows that for both battery electric technologies, the drop in the bus fuel consumption, as a function of the ESS power capacity, is almost the same, with minimum fuel consumption attained with an installed ESS power capacity of around 500 kW. The hydraulic hybrid bus shows a similar tendency, but achieves a more moderate minimum fuel consumption. On the other hand, the UC hybrid shows a faster drop in fuel consumption as the power capacity of the EES is increased and achieves its minimum fuel consumption at a power capacity of around 200 kW. The main reason for UC based systems to require a considerably smaller ESS, in terms of power capacity, is the systems high efficiency, response rate and capability to absorb its nominal power capacity, which in a start-stop operating condition is more important than the systems energy storage capacity, since when using regenerative braking this enables the absorption of higher electric currents, thus, a higher portion of the braking power requirements.

Figure 9b shows further insight into the above mentioned behavior. The latter shows the different buses fuel consumption, as a function of their ESS energy capacity. While the optimized hydraulic system requires a storage capacity of 0.5kWh, battery based electric vehicles require capacities of around 20kWh and 40kWh for the NiMH and Li-Ion batteries respectively. However as mentioned above, at the minimum fuel consumption condition, all three ESS have a similar power capacity. This prompts the fact that EES power capacity is the dominating factor when establishing the optimum configuration of a hybrid bus operating under start-stop conditions. The difference between ESS energy capacity for minimum fuel consumption for the two battery based technologies is mainly due to the higher power density to energy density ratio of the NI-MH batteries. Table 4 shows that the power to energy ratio of a NiMH battery is 3 times that of the Li-Ion systems. Therefore, as the ESS energy capacity is increased, the power capacity increases at a higher rate, hence, the higher reduction in fuel consumption. Beyond the optimum condition, as the power capacity of the ESS is further increased other systems in the power train become the limiting factors in the regen capacity of the bus and thus further increases of the ESS capacity result in moderate improvements, which are displaced by the added weight of the system. In the case of UC this is very evident, given the high energy specific weight of these systems.

FIGURE 9 Bus fuel consumption of optimal configurations of motor/generator and motor/pump.

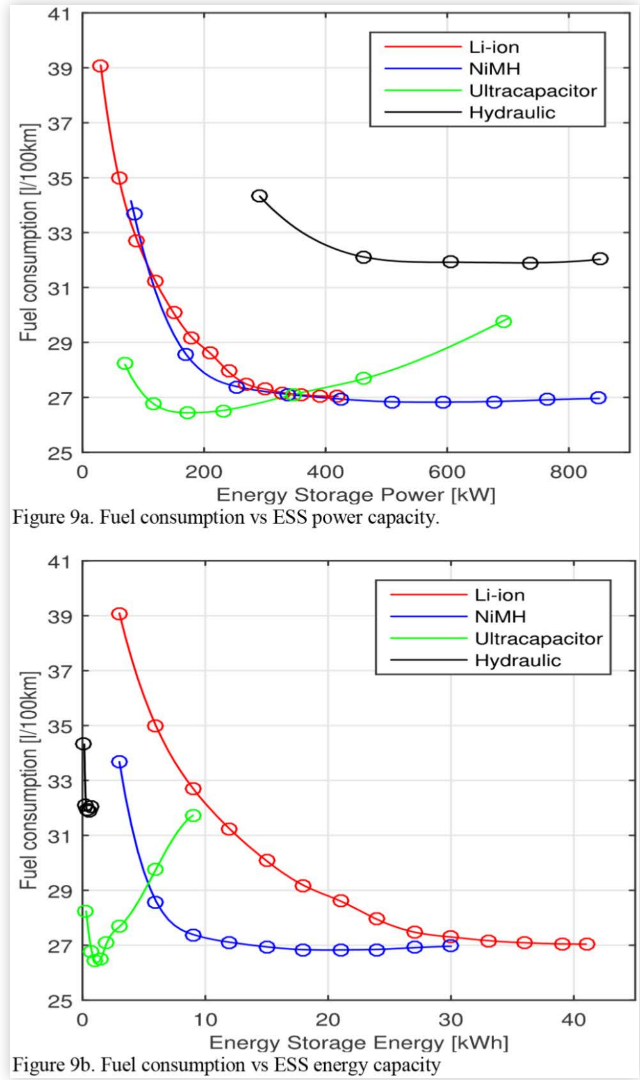


Figure 9a. Fuel consumption vs ESS power capacity.

Figure 9b. Fuel consumption vs ESS energy capacity

TABLE 6 Energy and power of different ESS for optimal configuration.

ESS Technology	Energy [kWh]	Power [kW]	Fuel Consumption [L/100 km]	Reduction
Hydraulic Accumulator	0.5	550	31.8	40%
Li-Ion	40	400	27.0	50%
NiMH	21	600	26.8	50%
UC (min FC)	1	200	26.5	51%
UC (max EOL)	3	450	27.0	50%

The ultracapacitor based vehicle is optimized with a 1kWh energy storage unit, achieving the largest fuel consumption reduction of all ESS (51%). However, when ESS premature aging is considered, both the NiMH and ultracapacitor based electric systems require an increase in storage capacity to reduce the effect of cycling on the ESS life duration. This results in an increase of the bus fuel consumption due to the increased weight of the system.

Based on the above analysis, Table 6 shows the optimal set configuration for the evaluated hybrid platforms. As mentioned before, in the case of the ultracapacitor based bus, two configurations will be evaluated: one that minimizes fuel consumption (UC minFC) and another that ensures that the ESS will endure the life operation of the bus (UC maxEOL).

These configurations will be used to compare the environmental and economic performance of the different technologies.

4. Life Cycle Emission Analysis

Having set the operating conditions of a bus in the city of Buenos Aires (Figure 1) and having optimized and validated the different vehicle models it is possible to establish a parametric analysis of the latter to compare their operational performance.

Throughout this section the environmental performance of each system is evaluated. To do this, the greenhouse life cycle emissions of all hybrid buses are calculated, analyzed and compared to those of a CB.

It is worth mentioning that to establish the true environmental performance of a given bus, particular matter and nitric oxide emissions should be taken into account, as these are largely responsible for the air quality deterioration registered in different cities of the world. However, as mentioned above the analysis at hand will only focus on greenhouse gas emissions.

Emissions are divided into fuel based in-service CO_{2eq} emissions and embedded energy CO_{2eq} emissions. The latter include the replacement of ESS components of the SHEB or fluids in the case of the SHHB. It is acknowledged that these could be included or analyzed as in-service maintenance CO_{2eq} emissions, however, given that all other maintenance in-service CO_{2eq} emissions of the hybrid vehicles are considered to be equal to those of a conventional bus (tyre replacement, engine oil, brake fluid, engine coolant, etc), these will be excluded from the analysis, as they will cancel each other out. Therefore, including the CO_{2eq} emissions related to ESS replacement as embedded emissions, does not change the overall results and helps simplify the analysis.

4.1. Fuel Based in-Service CO_{2eq} Emissions

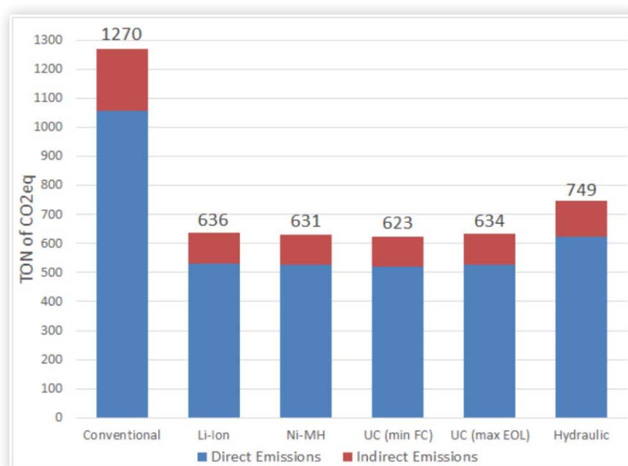
In-service fuel based emissions can be divided into indirect and direct emissions. The first are known as “well to tank” emissions and are related to the CO_{2eq} emissions emitted when producing and transporting the fuel. Direct emissions, on the other hand, are referred to as “tank to wheel” emissions as they are generated during vehicle operation.

Diesel has an average direct CO_{2eq} emission intensity of 2.64 kgCO_2/L [43]. On the other hand, indirect emissions vary from one country to another as they depend on many regional factors, in the case of Argentina they are around 0.53 kgCO_2/L [44].

The lifetime of a city bus is around 10 years, through which it covers, on average, 740,000 kilometers. Subsequently, the overall fuel based in-service CO_{2eq} emissions of each vehicle can be calculated as their fuel consumption over their life use, times the sum of the direct and indirect diesel CO_{2eq} emission intensities. Based on the fuel consumption values presented above, Figure 10 shows the in-service emissions CO_{2eq} of the optimal configuration of each bus.

As expected, all hybrid vehicles show considerable reductions of in-service CO_{2eq} emissions when compared to the conventional bus and are proportional to the fuel consumption reductions shown on Figure 9.

FIGURE 10 Fuel based in-service CO_{2eq} emissions for the different evaluated vehicles.



4.2. Embedded Energy and CO_{2eq} Emissions of the Different Hybrid Buses

Now that the optimal vehicle configuration has been set, as well as the number of storage units required for each technology over the lifetime of the bus, it is possible to determine the embedded energy and CO_{2eq} emissions of each vehicle. To do this, a Life Cycle Inventory (LCI) analysis of the different platforms is undertaken. The Greenhouse Gases Regulated Emissions and Energy use in Transportation (GREET) program compiles data for all the different stages of a vehicle's life cycle and allows access to the used data to perform a competent LCI of the evaluated mobile platform. In order to make a proper assessment of the burdens it is pertinent to divide the LCI into several stages [27], these being:

- Materials Production. This includes raw material acquisition and processing to make the constituent materials of the vehicle.
- Vehicle manufacture and assembly (VMA). This includes all processes involved in the transformation of materials to produce parts and components as well as the assembly of these into a product and finishing operations.
- End of Life (EOL). This includes shredding and disposal, as well as material recycling.

At the same time, GREET classifies vehicle's embedded energy and emissions (EEE) into four major categories: 1) vehicle materials (components), 2) batteries, 3) fluids and 4) assembly, disposal and recycling (ADR). The latter includes the EOL.

The material burdens depend on the amount of each material used and their energy and emissions intensity. When calculating the amount of each material in the vehicle, its unladen mass must be computed, as well as the weight of all major components (body, chassis, batteries, fluids, powertrain, and transmission or gearbox). This, together with the material composition of each component, which is estimated by GREET, outputs the amount of each material used to build the vehicle.

4.2.1. Bus Models of Embedded Energy and CO_{2eq} Emissions

As it was done for the fuel consumption calculations, first the conventional bus is modeled to establish the reference scenario. Subsequently, each hybrid powertrain is modeled based on the optimal configurations detailed on Table 6. The control system hardware of the different hybrid platforms is not included in the analysis, as its contribution is considered negligible in comparison to the overall EEE of the bus. Also, when calculating EEE related to vehicle assembly, GREET only takes into consideration general stages such as painting, HVAC & lighting, heating, welding and material handling. Therefore, the EEE generated during the assembly of electric or hydraulic components of the different hybrid platforms are also neglected.

Conventional Bus: A conventional pick-up truck (PUT) platform is selected from the GREET library. Subsequently, the weight of the powertrain, transmission, chassis and body part components are adapted to those reported for the Mercedes Benz bus as shown on Table 7 [45].

TABLE 7 Components weight of the CB platform.

Component	Weight [kg]
Powertrain	1,220
Transmission	253
Chassis	4,500
Body	4,500
Battery (Lead-Acid)	55
Fluids	56
Total	10,590

Series Hybrid Hydraulic Bus: Since GREET does not have a hybrid hydraulic platform, the conventional PUT platform is selected and modified.

Regarding the powertrain, a hydraulic pump, a motor, an accumulator, a reservoir and hoses are added using information provided by different manufactures [36, 46, 47]. Since the majority of the fluid in a hydraulic system is in the accumulators, the number of liters needed is calculated based on the working pressure range of the accumulator (100 to 350 bar) [36]. A further 8 liters are added as result of hoses and connections between the different hydraulic components. The density of the oil is 0.84 kg/L [9]. Overall, modifications result in a total hydraulic bus weight of 11450 kg. Component weights are detailed on Table 8.

As mentioned previously, all hydraulic components can withstand the life service duration of a regular city bus. However, the service life of both the hydraulic pump and motor are highly dependent on the cleanliness level of hydraulic fluid. The contamination of the hydraulic fluid with solid particles during the operation of the bus is inevitable. Therefore, to preserve the hydraulic components, replacement of the fluid needs to be done several times over the lifetime of the bus, this implies a direct increment in both EEE and total cost of ownership of the SHHB. Typically, hydraulic fluid needs to be changed every year or every 2000 hours of service, whichever occurs first [48]. A Buenos Aires city bus operates 20 hours a day, 350 days per year with a lifetime of 10 years. This implies a total of 34 fluid replacements over the life time of the bus.

As it will be shown below, this has a considerable impact on the EEE of the vehicle.

Series Hybrid Electric Bus: For the SHEB a hybrid electric PUT platform is selected from GREET library. First, the vehicle layout is modified as follows:

- Powertrain: the alternator and starter are removed, as they are no longer required.

TABLE 8 Components weight for the SHHB.

Component	Weight [kg]
Powertrain	1,203
Hydraulic Powertrain	843
Transmission	226
Chassis	4,500
Body	4,500
Battery (Lead-Acid)	55
Fluids	123
Total	11,450

TABLE 9 Components weight for the SHEB.

Component	Weight [kg]
Powertrain	1193
Transmission	20
Chassis	4500
Body	4500
Motor/Generator	270/90
Electric Controller	30
Fluids	42
Total w/o ESS	10645

- Transmission: the gearbox is removed, this implies a reduction in the amount of transmission fluid required and hence, a reduction on the overall amount of fluid used
- Electric components: the motor, the generator and the ESS are scaled to fit the characteristics of the SHEB modeled in Section 3.3.

Overall, the hybrid electric bus, without its energy storage unit, has a total weight of 10645 kg. The weight of the different electric hybrid bus components is detailed on Table 9.

In the case of the energy storage system, the GREET library contains models for both the Li-Ion and NiMH batteries, but not ultracapacitors, Therefore, an ultracapacitor model is created based on the reported information provided by a supplier [35]. Table 10 details the energy capacity, the specific energy capacity and the weight of the different electric energy storage technologies.

It is important to point out that all electric components of the hybrid platforms, except for the NiMH based battery one, are assumed to last the lifetime of the bus. This, as shown in section 3.3.3, will have to be replaced at least 4 times. Also, the disposal and recycle of the batteries and ultracapacitor is not taken into consideration.

4.2.2. Embedded Energy and CO_{2eq} Emissions As mentioned before, GREET classifies EEE into four categories (vehicle materials, batteries, fluids and ADR). Since vehicle materials vary for the different powertrains, this category is divided into two sub-categories, Chassis and Bodywork (where ADR is incorporated) and Powertrain. Results for the embedded energy and CO2eq emissions of the different evaluated buses are presented on Figure 11a and Figure 11b respectively. The calculations contemplate the replacement of both the Ni-MH battery pack on the SHEB and the hydraulic fluid of the SHHB.

Figure 11 shows that, as expected, the CB has lower EEE than all hybrid platforms, in particular, that of the NiMH based SHEB and the SHHB. This is due to their respective required changes of battery packs and hydraulic oil. As it will be shown below, this does not have a significant effect on the environmental performance of the respective buses, but affects considerably their economic outlook.

In the case of both ultracapacitor configuration, embedded emissions are equal, given that over the life cycle of the bus the number of KWh of ultracapacitors required is the same for both platforms.

TABLE 10 Weight of the different electric energy storage units.

Energy Storage	Li-Ion	Ni-MH	Ultracapacitor
Capacity [kWh]	40	21	3
Specific capacity [kWh/kg]	0.106	0.046	0.0056
Weight[3] [kg]	472	652	670

[3] Values include a packaging factor of 1.25.

FIGURE 11 EEE of the different evaluated buses.

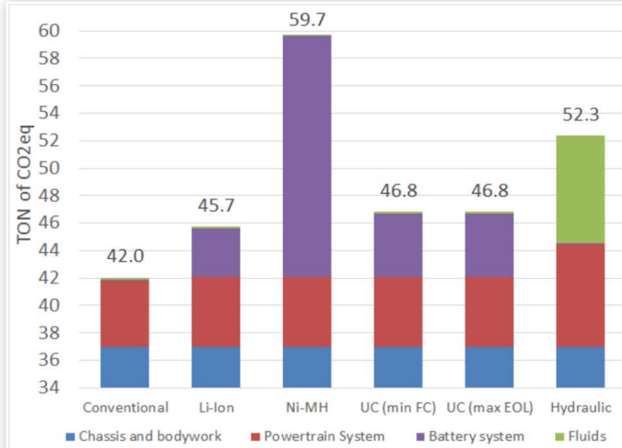


Figure 11a. Embedded CO2eq emissions of the different evaluated buses.

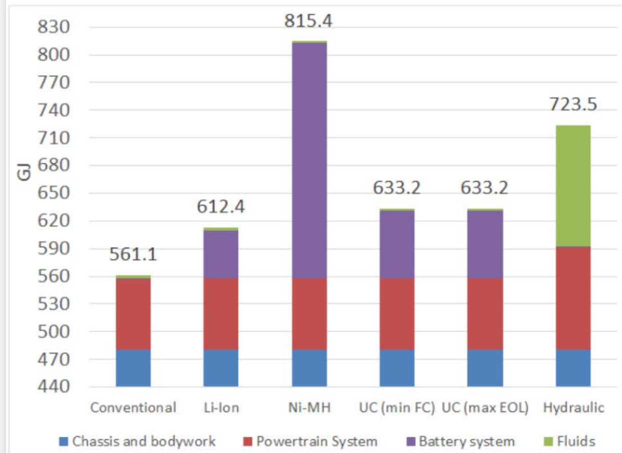


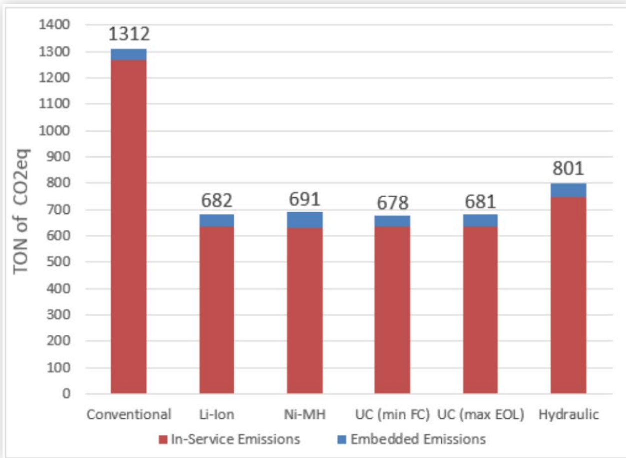
Figure 11b. Embedded Energy of the different evaluated buses.

4.3. Life-Cycle Emissions

Now that both the in-service and the embedded emissions of each bus have been estimated, it is possible to calculate the life cycle emissions of the different platforms and asses their environmental performance. Figure 12 shows the final results.

Different to what happens with light duty private cars, were EEE are normally around 30% of the life cycle emissions of a conventional vehicle, Figure 12 shows that, in the case of an urban bus, these account for less than 10% of the overall life cycle emissions. Therefore, the in-service emission reduction achieved by all hybrid platforms here evaluated, are in clear excess of the increases related to their EEE. In fact, in the case of the SHEB, overall life cycle emissions are halved when compared to that of a CB.

FIGURE 12 Life cycle emissions of the different platforms.



In conclusion, the implementation of any of the evaluated platforms shows great potential for reducing CO_2 emissions of urban bus fleets.

However, to understand the true feasibility of implementation their economic performance must be evaluated.

5. Financial Modeling

The performance and environmental analysis of the different buses is of course a major part of establishing the potential penetration of a given technology into the market, however, the selection of the preferred technology is most often based on its economic outlook. It is therefore of interest to compare the increase in fabrication costs, due to hybridization, and contrast these with the reduction of the in-service costs, achieved by the different evaluated platforms, due to fuel consumption reductions.

To do this, the total cost of ownership of the different buses is calculated and compared. This involves establishing the purchase price, fuel cost and maintenance cost of the different buses. As for the EEE analysis, except for the cost of battery pack and hydraulic fluid replacements, the in-service maintenance costs of all buses will be considered equal and will therefore not affect their relative economic outlook.

5.1. Purchase Price

5.1.1. Conventional Bus Price The market price of the CB provided by Mercedes Benz is of around USD 235,000 [45].

This price will be used to establish the cost of the glider and bodywork of the different hybrid buses. The overall purchase cost of the latter is set by adding the cost of additional systems and subtracting those included in the CB that the new platforms do not require.

5.1.2. Series Hybrid Hydraulic Price To establish the cost of the additional hydraulic system required for the SHHB, a mass base calculation taken from a technical report of EPA [9] is used.

TABLE 11 Weight specific price and final cost of the different hydraulic components.

Motor	14 USD/kg	2,380 USD
Pump	14 USD/kg	1,400 USD
Accumulator	15.4 USD/kg	8,090 USD
Hose	11.1 USD/kg	445 USD
Hydraulic Fluid	4.6 USD/kg	310 USD

Given that the referenced work dates from 2004, prices need to be adjusted to present values. A manufacturer's suggested retail price ratio of 1.54 is applied. Table 11 shows the weight specific price of the different hydraulic components and the overall cost of each system. These are calculated using the information detailed on Table 8.

5.1.3. Series Hybrid Electric Price Three main additional components are considered to establish the purchase price of the different SHEB: the electric motor, the generator and the ESS. Also, as mentioned before, this platform contains no gearbox. This implies a direct reduction in the base cost of the bus.

The motor and generator prices are estimated using the methodology described by Brooker et al. [49]. As for the ESS, given that battery prices found in the literature vary significantly, low and high cost scenarios are evaluated. These are detailed on Table 12.

The cost of the different additional components of the SHEB are detailed on Table 13.

5.1.4. Bus Purchase Price Using the above presented analysis, the purchase cost of the different hybrid buses, for both ESS prices, are presented on Figure 13.

Results show that, as expected, the purchase price of the hybrid buses is higher than that of a conventional bus. Additional costs vary between USD 15,000 and USD 55,000 depending on the technology applied and the specific cost of the ESS. Overall, the SHHB has the lowest purchase cost of all the hybrid platforms here presented. It is also clear that purchase cost of the ultracapacitor hybrid optimized to maximize the EOL of the ESS results in the most expensive bus.

TABLE 12 Battery and ultracapacitor best and worst-case scenario costs [50, 51, 52].

	Low [USD/kWh]	High [USD/kWh]
Li-Ion	500	1,000
NiMH	1,000	1,500
Ultracapacitor	9,900	14,800

TABLE 13 Costs of the additional components of the different SHEB for both high and low scenarios

	Low [USD]	High [USD]
Motor	3,900	
Generator	3,030	
Li-Ion	20,000	40,000
NiMH	21,000	31,500
Ultracapacitor	29,700	44,400

FIGURE 13 Costs of construction of the different evaluated buses.

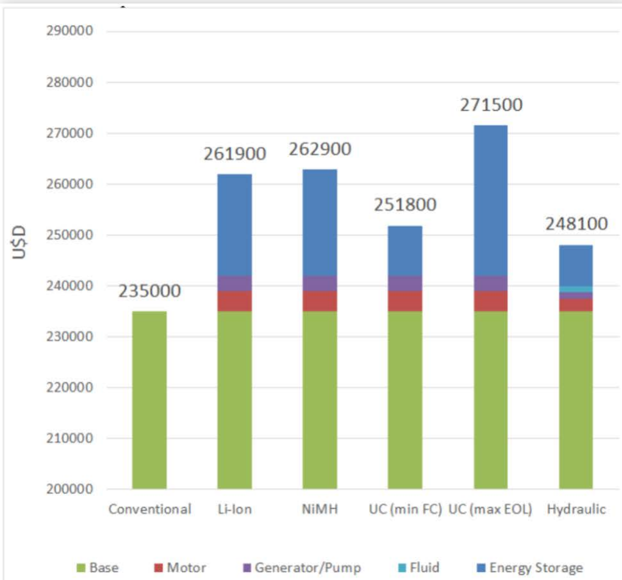


Figure 13a. Costs of construction for best case scenario.

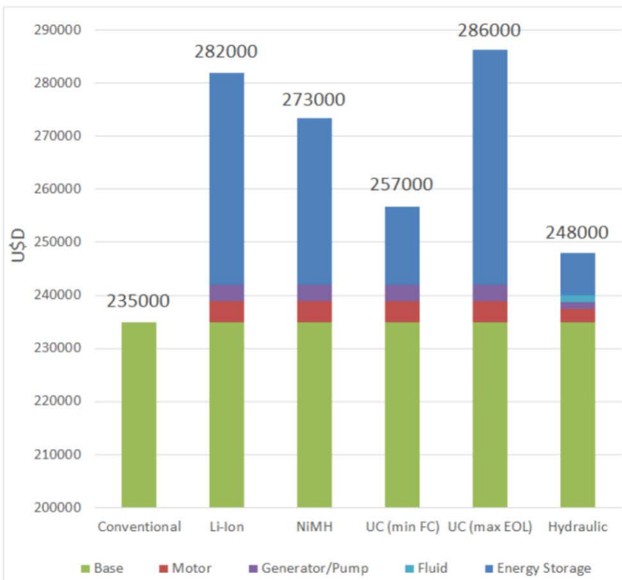


Figure 13b. Costs of construction for worst case scenario.

5.2. In-Service Maintenance Costs

As mentioned above, the only maintenance costs that will be analyzed throughout this study are those related to the replacement of the ESS systems and hydraulic fluid, as all other maintenance cost are considered equal for all buses and will therefore cancel themselves out.

Throughout Section 3.3.3 it was established that the NiMH SHEB would require at least 4 battery pack replacements over the life of the bus. The UC(minFC) optimization requires 3 ESS changes and although the hydraulic systems of the SHHB are considered to outlast the bus life, the hydraulic fluid would need to be replaced 34 times over the life of the system. The Li-Ion and UC(maxEOL) SHEB do not require any additional maintenance than the CB.

Now, given that the above-mentioned replacements will be spread out over the life of the bus, to properly asses their economic impact on the total cost of ownership of the respective technologies, the Net Present Value (NPV) of each erogation must be calculated based on an established discount rate and the time of each payment. An annual discount rate of 8% is used for these calculations.

Figure 14 shows the accumulative NPV of the in-service maintenance costs for the analyzed hybrid buses. Both best and worst cost scenarios.

of battery and ultracapacitor costs are used for the replacement calculation.

Figure 14a show that the cost of hydraulic fluid replacement over the life time of the bus is only around UDS 7,300, which is a small percentage of the SHHB purchase cost.

On the other hand, Figure 14b shows that in the case of the NiMH SHEB the costs of future battery replacements are significant and will therefore have a considerable impact on the financial performance of the vehicle, as these represent 20% to 30% of the original bus purchase cost. In the case of the UC(minFC) hybrid bus, the replacement of the ESS is

FIGURE 14 Accumulative NPV of the in-service maintenance costs for the different hybrid platforms.

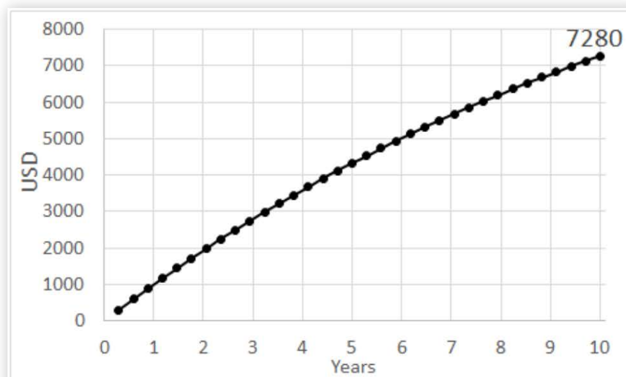


Figure 14a. Hydraulic fluid replacement.

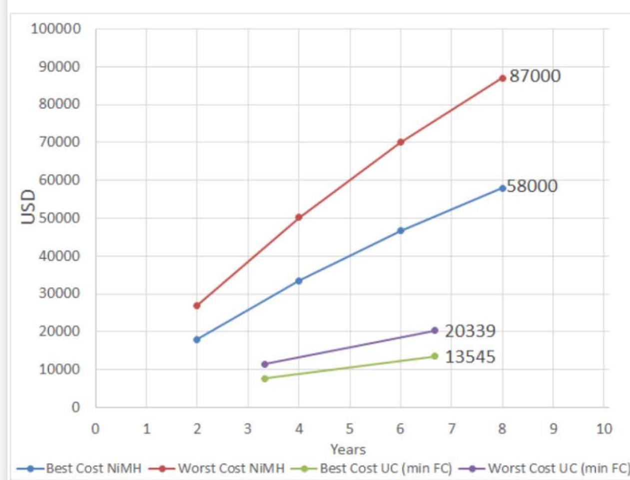


Figure 14b. NiMH and Ultracapacitor pack replacements.

higher than that of the hydraulic fluid but considerably lower than that of the NiMH batteries. The overall economic performance of the bus will depend on the achieved fuel savings.

5.3. In-Service Fuel Cost

As shown on Figure 9, bus hybridization leads to considerable fuel reductions. These imply a direct reduction of in-service fuel costs.

Given the uncertainty of future fuel prices, to evaluate the sensitivity of each technology to the latter, two scenarios are analyzed. When calculating the in-service fuel costs of each bus. In the first scenario the current price of diesel is used (according to the Ministry of Energy and Mining of Argentina, the local present diesel price is of 1USD/L [53]), with no consideration of possible variations over the lifespan of the bus. The second scenario sets a 50% increase in diesel prices over the lifetime of the bus.

As mentioned on Section 4.1 a bus operating within Buenos Aires covers, on average, 740000 km over its lifetime. Therefore, knowing the fuel consumption of each platform (Figure 9), the total fuel consumption cost can be calculated. As for the in-service maintenance costs, the NPV of the in-service fuel costs is calculated using an 8% discount rate. Results are shown on Figure 15.

As expected, hybrid platforms generate substantial in-service fuel cost reductions, with savings mounting up to USD 140,000 and USD 170,000 depending on the price of diesel. This represents more than half of the purchase price of a brand new conventional bus.

5.4. Total Cost of Ownership

Based on the above calculations, the NPV of the total cost of ownership of the different buses can be calculated by summing up the NPV costs of vehicle purchase, maintenance and fuel.

Furthermore, to understand the financial sensitivity of the presented technologies, optimistic and pessimistic hybridization scenarios are set. The pessimistic scenario contemplates high ESS costs and low diesel prices, while the optimistic contemplates low ESS costs and high diesel prices. Figure 16 shows the NPV of the total cost of ownership of each bus platform for both scenarios above described.

Results show that all hybrid platforms achieve considerable overall cost reductions when compared to a CB. These are of course maximized in the optimistic hybridization scenario. The Li-Ion and both ultracapacitor configurations seem to slightly outperform the SHHB, whilst the NiMH based systems shows the worst economic performance of all evaluated hybrid buses.

In the case of the two ultracapacitor bus configurations, the UC(minFC) shows a slightly better economic performance, induced by both the lower fuel consumption and the lower life cycle cost of the ESS system.

On the other hand, as shown on Table 14, the payback period of the investment related to the additional purchase cost of the different hybrid platforms varies significantly between the different technologies and scenarios. The SHHB seems to have the lowest payback period of all technologies, indifferently of the evaluated scenario. This is consistent with the vehicles lower purchase cost. Meaning that the overall investment is less profitable but safer. The ultracapacitor and Li-Ion buses have slightly lower payback periods in the optimistic scenario but are more susceptible to the cost of the ESS and fuel. In the case of the NiMH hybrid bus the payback period is at least half the life of the bus. This is not a promising result.

FIGURE 15 NPV of accumulated in-service fuel costs, for the different buses, in both diesel price scenarios.

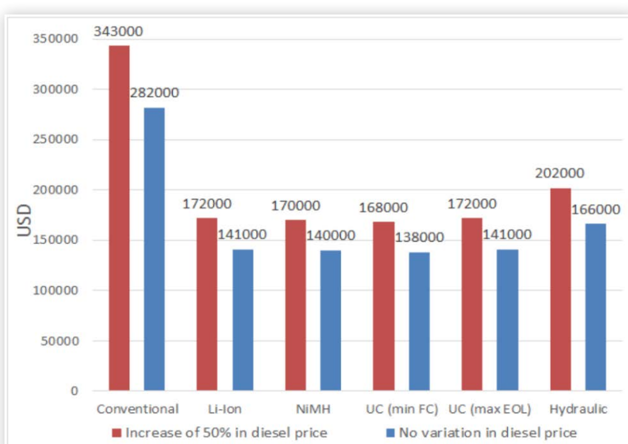


FIGURE 16 Total cost of ownership for the different buses and for an optimistic and pessimistic hybridization scenario.

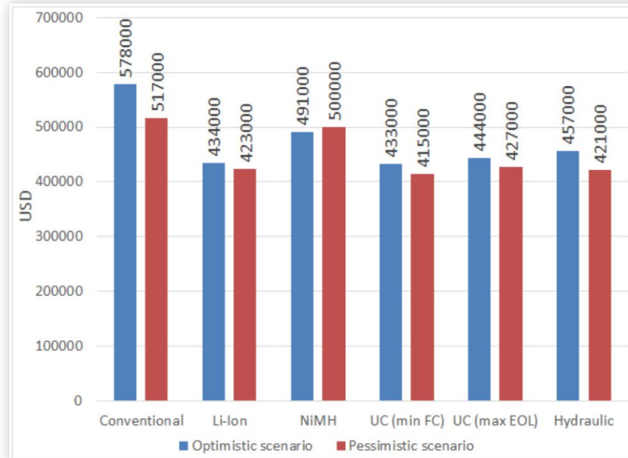


TABLE 14 Payback period of the additional purchase cost of different hybrid buses for both the optimistic and pessimistic hybridization scenarios.

	Optimistic Scenario	Pessimistic Scenario
Li-Ion	1.6 years	3.3 years
NiMH	5.0 years	7.2 years
Ultracapacitor	2.1 years	3.6 years
Hydraulic	1.4 years	1.8 years

6. Conclusions

This paper presented a technical, financial and environmental analysis of four different hybrid class 8 public buses operated under Buenos Aires city driving conditions. A conventional diesel bus was analyzed and used as a reference scenario to which the performance of the different series hybrid configurations was compared against. Three electric hybrids equipped with different energy storage technologies: Li-Ion and NiMH batteries and double layer capacitors (ultracapacitors) were simulated along with a hydraulic hybrid platform. The operating conditions of the bus were set using real driving GPS data collected from various bus routes within the city. The different vehicle platforms were modeled on AUTONOMIE SA and validated by comparing the obtained fuel consumption results to those reported by local transport authorities and values found in the literature. Furthermore, the bus fuel consumption was used as an optimization parameter to size the components of the different hybrids (motors, generators, energy storage unit, etc.) and establish, along with the in-service CO_{2eq} emissions, the minimum fuel consumption achieved by each vehicle. Subsequently, aging models were proposed to evaluate the life duration of the batteries and ultracapacitors used in the electric platforms, when operated under Buenos Aires driving conditions. This allowed to understand the impact that premature degradation of the energy storage unit has on the life cycle economic and environmental performance of the different technologies. Once the life cycle duration of the different components was set, the embedded energy and CO_{2eq} emissions of each platform was estimated using GREET. Finally, the total cost of ownership of each vehicle was calculated and compared to that of the conventional bus.

Results show that, independent of the energy storage technology, the fuel economy performance of all hybrid platforms is highly dependent on the size and configuration of the powertrain and energy storage components. However, when optimized all the evaluated hybrid platforms seem to achieve significant fuel consumption reductions when compared to a conventional diesel bus, 40% and 50% for the hydraulic and electric hybrids respectively.

Regarding the premature aging of the energy storage systems, the NiMH based batteries shows a considerably shorter life expectancy than the Li-ion based technology. This has a significant impact on the economic performance of the vehicle.

The life cycle emission analysis of the vehicles shows that, given the high fuel consumption of conventional diesel buses, the additional embedded emissions generated during the manufacturing of the hybrid vehicles are off-set by reductions of in-service emissions achieved over the life operation of the vehicles.

Regarding the economic performance of the different platforms, results show that the fuel savings achieved by all hybrids displace the higher capital costs required. Furthermore, even in a pessimistic scenario were battery prices are high and fuel prices are low all hybrid buses show savings over the life span of the bus.

Overall, all hybrid platforms show a strong potential to reduce both CO_{2eq} emissions and costs related to the operation of urban buses, with the Li-Ion and ultracapacitor based platforms seemingly outperforming the other technologies under start-stop urban operating conditions. These result in lower life cycle emissions and the cheapest total cost of owner ship. However, from a financial point of view the SHHB could be the best option as its investment payback period is the shortest of all evaluated vehicles and is almost insensitive to fuel price.

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Definitions, Acronyms, Abbreviations

BADC - Buenos Aires driving cycle

BCDC - Braunschweig city driving cycle

CB - Conventional bus

DOD - Depth of discharge

EOL - End of life

EPA - Environmental protection agency

ESS - Energy storage system

GREET - Greenhouse gases, regulated emissions and energy use in transportation model

ICE - Internal combustion engine

NEDC - New European driving cycle

NPV - Net present value

OCV - Open circuit voltage

SOC - State of charge

SHEB - Series hybrid electric bus

SHHB - Series hybrid hydraulic bus

UC - Ultracapacitor

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