
Hybridisation effect on operating costs and optimal sizing of components for hybrid electric vehicles

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Abstract: Reductions of fuel consumption and gas emissions count among the main advantages of hybrid electric vehicles (HEV). It is well known that the level of hybridisation has a large influence on the fuel consumption, the manufacturing cost and the battery lifetime. Therefore, a proper selection of the size of components could be the result of a trade-off between them. This paper provides models and a methodology to address the sizing of components of a HEV. Specifically the work is focused on the series architecture with internal combustion engine and battery. The sizing criteria are oriented to reduce the operating costs, in which are included the fuel consumption and the battery-life consumption. Finally, the methodology proposed is applied in a case study. It corresponds to a real hybrid electric bus operating under urban driving conditions. Simulation results show that the best solutions are obtained by oversizing the battery with respect to power requirements.

Keywords: hybrid electric vehicle; hybridisation factor; optimisation; optimal sizing of components; lifetime of components.

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1 Introduction

Hybrid electric vehicles (HEV) have had a great impact on saving fuel and reducing emission compared to conventional internal combustion engine vehicles owing their capability of recovering braking energy and the higher efficiency operation of the internal combustion engine (ICE). The hybridisation factor (HF) is an important feature of the HEV, which points out the ratio between the installed power coming from the electric source and the total installed power. Commercial HEVs have shown improved fuel consumption as HF is increased. Improvements of up to 45% efficiency can be achieved with full-HEV (Tie and Tan, 2013). Contrasting to the advantages mentioned above, HEVs have higher costs than conventional vehicles because extra components such as electric machines and energy storage systems are required. Depending on the kind of HEV, the battery cost can reach one-third of the total vehicle cost (Tie and Tan, 2013). Other issues like security, space, and lifetime are associated with some components of HEV. Therefore, proper selection of the HF for a HEV has no trivial answer, but rather it will result from a complex

tradeoff taking into account the fuel consumption, lifetime and manufacturing costs, among others.

The research works oriented to the optimisation of the transport systems cover a wide range of simulations and process modelling such as the determination of the fleet scheduling (Pekel and Kara, 2016), speed profile optimisation (Cao and Liu, 2016; Cao et al., 2016) and powertrain optimisation, among others. Previous works from other authors addressed by simulations the sizing issue focusing on the fuel consumption. Lukic and Emadi (2004) and Holder and James (2006) analysed parallel- HEVs via simulation using ADVISOR™ (Wipke et al., 1999). Capata and Coccia (2010) tested series- HEV with a gas turbine as thermal engine. Cuddy and Wipke (1997) evaluated series and parallel-HEVs consumption through ADVISOR simulation. In a previous work (Carignano et al., 2015) we analysed the hybridisation effect on fuel consumption for series and parallel architectures under urban and highway driving conditions. While the literature regarding the election of HF focused on improving vehicle fuel consumption is extensive, the works done to address its impact on the lifetime of components are scarce. Serrao

et al. (2011) presents a methodology to account for battery aging in the supervisory control strategy for a hybrid electric vehicle, but the sizing of component is not addressed. This work, unlike previous one, shows how sizing of components affects the fuel consumption, the battery deterioration and the lifetime of the ICE. In addition, the concept of oversizing is formally introduced and its effect is analysed. To perform the simulations, a quasistatic model of the propulsion system was used. The battery deterioration is quantified offline using a dedicated aging model. The case study adopted is a series hybrid electric bus powered by a battery and an ICE. Regarding the power split, in most of the works reported in the literature, it was carried out through suboptimal online energy management strategies (EMSs). The online strategies, heuristics or based on optimisation, include some parameters that must be tuned (Sciarretta et al., 2014; Guzzella and Sciarretta, 2013). The optimal choice of them, i.e., those that archive the lower fuel consumption, change according size of components and the driving cycle selected, which leads to an iterative adjustment process. Besides, the usage of online strategies also required some iteration to fulfill final battery state constraints. In this work, in order to achieve a fair comparison between the different HF proposed, an optimal offline - instead of suboptimal online- EMS is applied. Specifically, the dynamic programming method is implemented, which allows to reach the minimal fuel consumption for each configuration avoiding the iterative process.

The paper is organised as follows. In Section 2, the series topology is described, the variables and the constraints of sizing are established, and the concept of oversizing factor is formally introduced. Also in this section, a brief description of the backward approach and the EMS are presented. Then, in Section 3, the models to quantify the lifetime of the battery and the ICE are presented; the concept of total operation cost is addressed; and the iterative sizing process is described. The case study and the results obtained are presented in Section 4. Finally, some conclusions, comments and future work are suggested in Section 5.

2 Hybrid electric vehicle model

2.1 Architecture, power flows and degrees of freedom

HEVs are frequently classified regarding their powertrain architecture. In HEVs powered by ICE and battery, series, parallel and combined are used. However, for urban driving conditions, series HEVs are preferred. Figure 1 shows a schematic representation of the architecture adopted. The electrical balance is represented by the following equation:

$$P_{ele} = P_{bb} + P_{gen} \quad (1)$$

where P_{ele} , P_{bb} are P_{gen} the electric power flows in motor, buck/boost converter and generator, respectively. Then, P_{ele}

is related to the power demanded at wheels (P_{dem}) as follows:

$$P_{ele} = \frac{P_{dem}}{(\eta_{DF}\eta_{mot})^{sign(P_{dem})}} \quad (2)$$

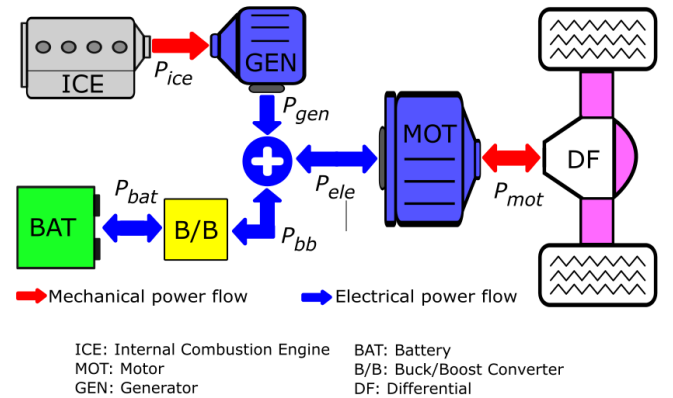
where η_{DF} and η_{mot} are the efficiencies of the differential and the motor respectively. The first one is considered fixed, while the second depends on its rotation speed and torque delivered (see Subsection 2.3). P_{dem} is assumed positive for positive accelerations and negative for the braking. The function *sign* shifts the efficiencies in cases where the Motor works as generator when braking. P_{bb} and P_{gen} are related to the power from battery and ICE as follows:

$$P_{bat} = \frac{P_{bb}}{(\eta_{bb})^{sign(P_{bb})}} \quad (3)$$

$$P_{ice} = \frac{P_{gen}}{(\eta_{gen})^{sign(P_{gen})}} \quad (4)$$

where η_{bb} and η_{gen} are the efficiencies of the buck/boost converter and generator respectively. The first one is considered fixed, while the second while the second depends on its rotation speed and torque delivered. Assuming that P_{dem} is known at each time, then there are five powers unknown (P_{ice} , P_{mot} , P_{bb} , P_{bat} , P_{gen}). Using the four equations (1) to (4) given above, the propulsion system has one free variable, which is decided by the supervisory controller through the EMS.

Figure 1 Series HEV (see online version for colours)



2.2 Sizing constraints, hybridisation factor and oversizing factor

In this subsection the power requirements and the sizing constraints are defined. The sizing is focused on the ICE, motor, generator and battery. The size of these components can be expressed by the maximum power they are able to deliver or receive. In general, the battery size could be defined by either the maximum power flow allowed or its storage capacity (Carignano et al., 2014). However, in HEV, the battery operates far from its charge limits. According to

that, in this case, the battery size is conditioned by the maximum power flow allowed.

A main requirement to take into account for sizing is the maximum total power of the HEV, i.e., the maximum power available at wheels ($P_{wh,max}$). This value is used to define the size of the motor:

$$P_{mot,max} = \frac{P_{wh,max}}{\eta_{DF}} \quad (5)$$

On the other hand, the size of the ICE is defined by the size of the generator:

$$P_{ICE,max} = P_{gen,max} \quad (6)$$

Then, due to the fact that the motor is powered by the battery and the generator, the following inequality constraint must be fulfilled:

$$\frac{P_{mot,max}}{\eta_{mot,max}} \leq (P_{gen,max} \eta_{gen,max} + P_{bat,max} \eta_{bb}) \quad (7)$$

where $\eta_{mot,max}$ and $\eta_{gen,max}$ are the efficiencies of the motor and generator at the maximum power. Notice that there are two degrees of freedom for the designer, $P_{bat,max}$ and $P_{gen,max}$, and the election of them is only constrained by the inequality (7).

An extra constraint associated with the sustained-cruising-speed is considered. It establishes that the HEV must be able to maintain a certain speed without using power from battery. Knowing the electric power required by the motor at the sustained-cruising-speed ($P_{mot,cruising}$), the inequality constraint is:

$$P_{gen,max} \geq \frac{P_{mot,cruising}}{\eta_{gen,max}} \quad (8)$$

or its equivalent, using (6):

$$P_{ICE,max} \geq \frac{P_{mot,cruising}}{\eta_{gen,max}} \quad (9)$$

This constraint defines a lower limit to the size of the ICE. Returning to (7), the concept of oversizing is formally defined through the oversizing factor (OF). In this case, it is explicitly defined as:

$$OF \triangleq \frac{P_{gen} \eta_{gen,max} + P_{bat,max} \eta_{bb}}{\left(\frac{P_{mot,max}}{\eta_{mot,max}} \right)} \quad (10)$$

Notice that when $OF = 1$, there are not oversizing, while if OF is greater than 1, the propulsion system is oversized respect to the power required. As it was mentioned in the introduction, oversizing the component of propulsion system increases manufacturing cost. However, it also

produces lighter operation conditions in the components, which extend their lifetime.

Another important concept in this kind of vehicle strong reported in the literature is the hybridisation factor (HF). In this kind of architecture, the hybridisation factor gives an idea of the size of the battery compared to the size of the set ICE-generator. The HF tends to zero 0 when maximum available power from battery tends to zero (converging to the cases of conventional vehicles or vehicles with electric drive-train without electric storage). On the opposite, HF should tend to one when the maximum available power from ICE-generator tends to zero (the limit case of pure electric vehicles). The HF capturing this concept for the series architecture was defined explicitly in a previous work (Carignano et al., 2015):

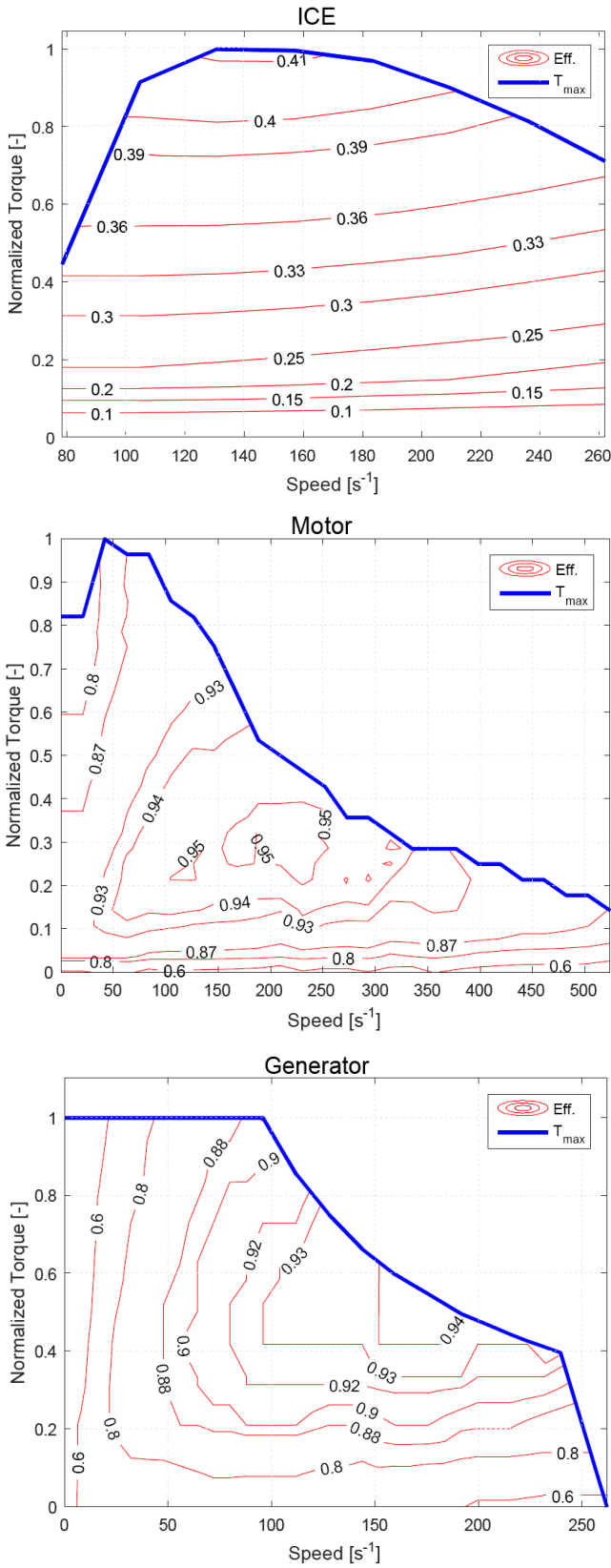
$$HF \triangleq \frac{P_{bat,max} \cdot \eta_{bb}}{P_{bat,max} \cdot \eta_{bb} + P_{gen,max} \cdot \eta_{gen,max}} \quad (11)$$

The term ‘design’ will be used in this work to refer to the adoption of the component size. According to these definitions, each design proposed can be classified according to the HF and OF.

2.3 ICE, motor and generator

Fuel consumption and global efficiency of a HEV depend on the efficiency of each powertrain component. ICE, motor and generator are the main components that contribute to overall efficiency. Owing to the highly complex phenomena present in each of these components, detailed analytical models should be employed to obtain their efficiency. A common practice is testing each of them and obtaining an efficiency table as a function of their power port variables (torque and speed). Figure 2 shows the characteristic of the components used in this work, which were extracted from the AutonomieTM database (Autonomie, 2016). The figure includes the torque limits, within which the components must be operated. The y-axis is expressed in terms of the normalised torque. Once the size of the components defined, their final efficiency is obtained by scaling linearly these curves along the torque-axis.

Notice that in this vehicle the motor can work both as motor and generator while the generator only works as generator. The efficiency of the motor working as generator is the same that as motor. Efficiency of power electronics converters as rectifiers or inverters is included in these curves. In case of the set ICE-generator, for a given electric power load (P_{gen}), it is possible to find the values of speed and torques that provides the maximum efficiency of this set. These values are precomputed and used during the simulations to define how to operate the ICE and the generator for a certain P_{gen} .

Figure 2 Characteristics of components (see online version for colours)


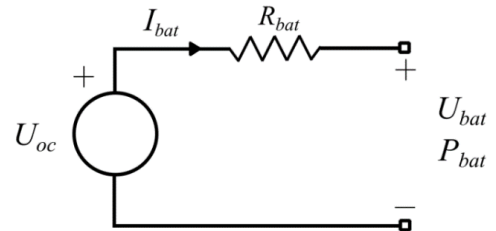
2.4 Battery model

In this subsection, in contrast with previous ones where numerical maps were used, an analytic expression of battery efficiency and energy storage will be deduced. A battery is composed by a number of cells in series (N_{ser}) and a number of branches in parallel (N_{par}). The dynamics, efficiency and constraints are deduced from an equivalent circuit composed of an ideal voltage source in series with an internal resistance (see Figure 3). Variations of the latter due to the varying state of charge of the battery are neglected. A simple model of the battery pack can be expressed in terms of the power demanded (P_{bat}) and its state of charge (SOC) (Guzzella and Sciarretta, 2007):

$$\left\{ \begin{array}{l} U_{OC}(SOC) = (k_1 + k_2 SOC) N_{ser} \\ U_{bat}(SOC) + \frac{U_{OC}}{2} + \left(\frac{U_{OC}^2}{4} - P_{bat} R_{cell} \frac{N_{ser}}{N_{par}} \right) \\ I_{bat} = \frac{P_{bat}}{U_{bat}} \\ \dot{SOC} = - \frac{I_{bat}}{Q_{cell} N_{par}} \end{array} \right. \quad (12)$$

where k_1 , k_2 , R_{cell} and Q_{cell} are parameters of a single cell. U_{OC} and U_{bat} are the open circuit voltage and terminal voltage of battery respectively. In addition to battery dynamics, the following constraints must be considered:

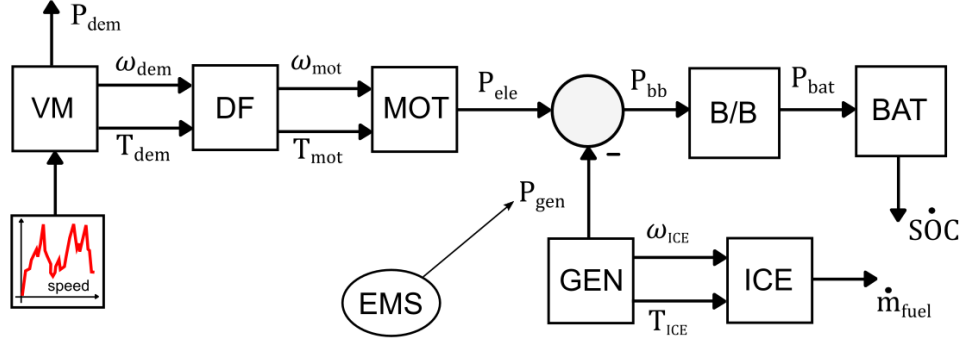
$$\left\{ \begin{array}{l} SOC_{min} \leq SOC \leq SOC_{max} \\ I_{cell,min} \leq \frac{I_{bat}}{N_{par}} \leq I_{cell,max} \\ U_{bb,min} \leq U_{bat} \leq U_{bb,max} \end{array} \right. \quad (13)$$

Figure 3 Battery equivalent circuit


where $I_{cell,max}$, $I_{cell,min}$, SoC_{max} and SoC_{min} are parameters recommended by the manufacturer; and $U_{bb,max}$ and $U_{bb,min}$ are the upper and lower voltage limit of the buck/boost converter. Finally, the maximum power of the battery can be computed as:

$$P_{bat,max} = \frac{U_{nom} U_{bb,min} - U_{bb,min}^2}{R_{batt} \cdot N_{ser}} N_{par} \quad (14)$$

where U_{nom} is the nominal voltage of the battery.

Figure 4 Quasistatic causal model (see online version for colours)

2.5 Backward approach and energy management strategy

As mentioned in the introduction, a backward approach (Chan et al., 2010) is used in this work. This means that dynamics and control from power components are not modelled as they were assumed fast enough to be neglected. Figure 4 shows the quasistatic causal model of the series-HEV. VM is the first order nonlinear vehicle model that considers inertial forces, rolling and aerodynamic resistances (Carignano et al., 2014). EMS stands for energy management strategy, which performs the power flow management, i.e., the power split between the electrical and the thermomechanical sources. As mentioned in the introduction, in order to find the minimum fuel consumption attainable with each design proposed, the optimal EMS was applied.

In a discretised time domain, where the total cycle time T is divided in N equal intervals, the objective function to be minimised is the accumulated fuel consumption, which can be expressed as follows:

$$J_{fuel} = \sum_{i=1}^N \dot{m}_{fuel}(i)t_s \quad (15)$$

where \dot{m}_{fuel} represents instantaneous fuel rate consumption and $t_s = T/N$ is the time step. This is considered to be constant during one interval of time. \dot{m}_{fuel} depends on instantaneous torque and speed on the ICE. Using the optimal pre-computed table mentioned in Section 2.3 for the set ICE-generator, for a certain P_{gen} required, the torque and speed are established, and then \dot{m}_{fuel} can be expressed as function of the power delivered by the generator (P_{gen}). Based on this, (15) can be written as:

$$J_{fuel} = t_s \sum_{i=1}^N \dot{m}_{fuel}(P_{gen}^*(i)) \quad (16)$$

P_{gen} is the free variable used as control variable in the optimisation problem. The state variable is the SOC , and its dynamics is described by equation (12). The optimal solution of this problem consists of the sequence control variable $\{P_{gen}^*(1), P_{gen}^*(2), \dots, P_{gen}^*(N)\}$ that minimises (16) subject to the component constraints. The latter includes

SOC , power, torque and speed constraints, which were described in the previous sections. In addition, to perform fair comparisons, the charge-sustaining operation, i.e., $SOC(1) = SOC(N)$, must be fulfilled. When the driving cycle is known in advance, dynamic programming (DP) is a widely used procedure relying on Bellman's Optimality Principle (Kirk, 2012), that allows to find the optimal solution. In the literature different ways to implement DP in an optimisation problem associated with a HEV are reported (Vinot et al., 2014; Pérez et al., 2006). Summarising, DP in this case provides the optimal control variable P_{gen} that generates the minimum fuel consumptions for a given cycle (known in advance). The information from DP is used as EMS in the quasistatic model shown in Figure 4 to perform simulations, obtaining the minimum fuel consumptions associated to each design. This procedure has to be repeated for each design proposed. In the following sections the models to quantify the battery aging and lifetime of the ICE are presented.

3 Components' lifetime and operating cost

3.1 Aging of battery

Typical data offered by battery manufacturers provides information about how many repetitive cycles can withstand at a given depth of discharge (DOD), under controlled current and temperature conditions. However, these conditions are very different from those suffered by a battery in a HEV under real driving conditions. The literature reports different methods to quantify lifetime of the batteries under dynamic conditions. In this case the method proposed by the Ohio State University for electric vehicles will be used (Serrao et al., 2005, 2009; Marano et al., 2009; Di Filippi et al., 2010). This is based on the concept of *Ah-throughput*, which assumes that there is an amount of charge that can circulate through the battery (on charge or discharge situations) before than it reaches its end of life (EOL). The model takes also into account the effect of the operating temperature, the DOD and C-rate. In the sequel a brief description of the model is presented.

For a given current expressed in amps, the C-rate index is defined as:

$$C_{rate} = \frac{I_{bat}}{Q_{bat}} \quad (17)$$

where Q_{bat} is the nominal capacity of the battery expressed in Ah and I_{bat} is the current through the battery in amps. The information provided by manufacturers is normally expressed in terms of C_{rate} , and the tests to evaluate durability are usually performed at $C_{rate} = 1$ or lower. The DOD is the complement of the SOC , i.e.:

$$DOD = 1 - SOC \quad (18)$$

High values of C_{rate} and high values of DOD contribute to accelerate the battery deterioration. Another factor that contributes to accelerate the battery deterioration is the high operation temperature. For simplicity, it will be considered that the temperature is controlled and kept at a desired value.

For a given battery, the nominal Ah -throughput is defined as:

$$Ah_{thr,nom} = \int_0^{EOL} |I_{nom}(\tau)| d\tau \quad (19)$$

Typically, the nominal condition refers to $C_{rate} = 1$, $DOD = 100\%$ and temperature $25^\circ C$. Then, for a certain current profile, the effective Ah -throughput is computed as:

$$Ah_{thr,eff}(t) = \int_0^t |I_{bat}(\tau)| \cdot \sigma(C_{rate}(\tau), DOD(\tau)) d\tau \quad (20)$$

where σ is the severity factor. Then, according to the aging model, the fraction of battery life consumed is estimated as:

$$Bat_{life/cycle}(t) = \frac{Ah_{thr,eff}(t)}{Ah_{thr,nom}} \quad (21)$$

The aging is cumulative, and when it equals 1, the battery has reached its EOL and must be replaced. The effect of the C_{rate} and DOD in the lifetime of the battery is not given by battery manufactures, and in fact, the behaviour of severity factors is difficult to estimate. It is proposed in this work to compute the severity factor as follows:

$$\sigma(C_{rate}, DOD) = \sigma_{C_{rate}}(C_{rate}) \cdot \sigma_{DOD}(DOD) \quad (22)$$

where $\sigma_{C_{rate}}$ quantifies the severity produced by high currents and σ_{DOD} the severity produced by high DOD . The first one is expressed by a quadratic function adjusted with values taken from (Serrao and Sciarretta, 2011):

$$\sigma_{C_{rate}}(C_{rate}) = 1 + 0.0025 C_{rate}^2 \quad (23)$$

Then, σ_{DOD} can be associated to reported results that provide the cycle to failure ($C2F$) of a battery as function of DOD (Serrao et al., 2005; Markel and Simpson, 2006). An approximation of that for Li-ion battery can be expressed as follows:

$$C2F(DOD) = N_{bat,nom} DOD^{-2.35} \quad (24)$$

where $N_{bat,nom}$ is the cycle to failure for $DOD = 1$. Then, the Ah -throughput until the EOL can be expressed as function of the DOD , i.e.:

$$Ah_{EOL}(DOD) = (N_{bat,nom} DOD^{-2.35}) \cdot (2 Q_{bat} DOD) \quad (25)$$

Notice that when $DOD = 1$ the value of (25) is equal to $Ah_{thr,nom}$ given by (19). With these equations, σ_{DOD} results:

$$\sigma_{DOD}(DOD) = \frac{Ah_{EOL}(DOD=1)}{Ah_{EOL}(DOD)} = DOD^{1.35} \quad (26)$$

With (23) and (26), the severity factor as function of C_{rate} and DOD is:

$$\sigma(C_{rate}, DOD) = (1 + 0.0025 C_{rate}^2) \cdot DOD^{1.35} \quad (27)$$

Figure 5 shows the behaviour of severity factor. Finally, using (27) in (21), the fraction of battery life consumed during a cycle is estimated as:

$$Bat_{life/cycle} = \frac{\int_0^t |I_{bat}(\tau)| \cdot (1 + 0.0025 \cdot C_{rate}(\tau)^2) \cdot DOD(\tau)^{1.35} d\tau}{Ah_{thr,nom}} \quad (28)$$

This expression will be used in Subsection 3.3 to estimate the cost associated with the battery-life consumption.

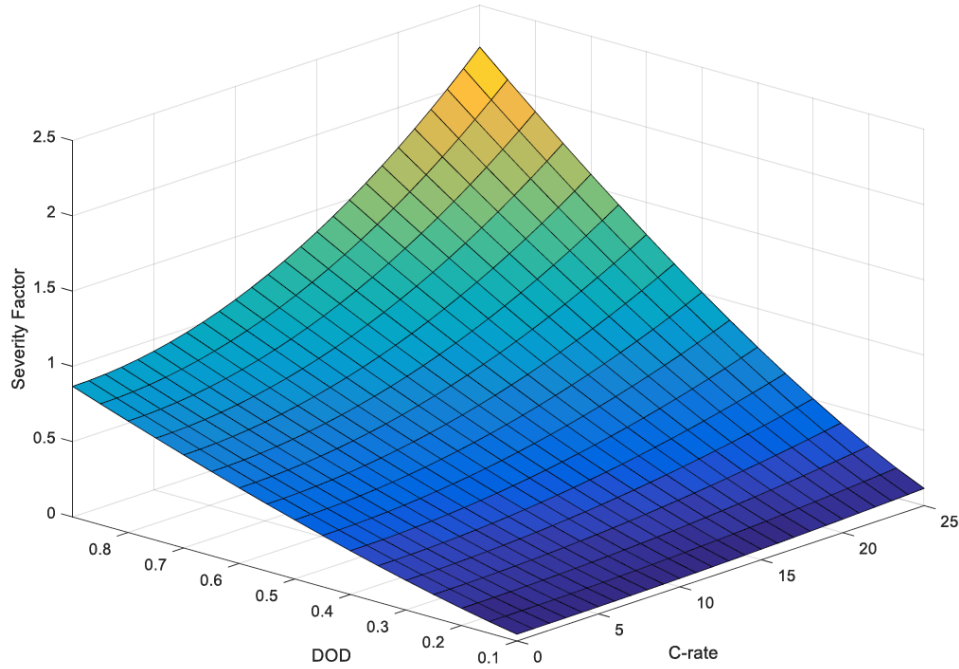
3.2 ICE life estimation

The method to estimate the lifetime of the ICE was derived from a report from the United State Environmental Protection Agency (EPA, 2010). It is based on the concepts of median life (ML_{ICE}) and load factor (LF). It establishes that the lifetime in years can be estimated as:

$$ICE_{lifetime} = \frac{ML_{ICE}}{Activity \cdot LF} \quad (29)$$

where $Activity$ is expressed in number of hours per year, and ML_{ICE} is the estimated life of the ICE in hours when it works at rated power (maximum power). These values are listed by horsepower class and engine type in the mentioned report. Then, for a given cycle of N -seconds length, the LF is computed as the relation between the rated power and the average power deliver by ICE, it is:

$$LF = \frac{\sum_{i=1}^{N_{on}} P_{ICE}(i)}{N_{on} \cdot P_{ICE,max}} \quad (30)$$

Figure 5 Severity factor as function of C-rate and DOD (see online version for colours)

Notice that N_{on} is used instead of N to compute only the point where the ICE is running. According to (29), the fraction of life consumed during a cycle can be expressed as:

$$ICE_{life/cycle} = \frac{N_{on} \cdot LF}{3,600 \cdot ML_{ICE}} \quad (31)$$

and using (30) results:

$$ICE_{life/cycle} = \frac{\sum_{i=1}^{N_{on}} P_{ICE}(i)}{3,600 \cdot ML_{ICE} \cdot P_{ICE,max}} \quad (32)$$

Finally, the estimated lifetime of the ICE results:

$$ICE_{lifetime} = \left(\frac{t_{cycle}}{t_{year}} \right) \frac{1}{ICE_{life/cycle}} \quad (33)$$

where

- $ICE_{lifetime}$ is the estimated lifetime of the ICE, in years
- t_{cycle} is the length of cycle, in seconds
- t_{year} is the time that HEV works per year, in seconds.

3.3 Total operating cost

Operating cost in conventional vehicles refers mainly to the cost associated to the fuel consumption. However, in HEVs the battery has shorter lifetime than the rest of the components, and it is likely to be replaced sometimes before the end of life of the vehicle. According to the model presented in the previous subsection, the battery-life is consumed as it is used. Therefore, the cost of the battery

will be considered as an operating cost. For this purpose, in this work the concept of total operating cost is adopted. It includes both the cost associated to the fuel consumption and the cost associated to the fraction of the consumed battery-life. Notice that this cost does not have incidence the maintenance costs associated to the electric machines, power converters and ICE. It is assumed that lifetime of these components is longer than the lifetime of the HEV.

The operating cost will be computed from the simulations results obtained with HEV model under dynamic conditions given by a certain driving cycle. Then, the cost per year associated to fuel consumption is:

$$C_{fuel/year} = Lts_{cycle} \cdot \frac{t_{year}}{t_{cycle}} \cdot C_{fuel/ltr} \quad (34)$$

where

- $C_{fuel/year}$ is the cost of the fuel consumed during a year;
- Lts_{cycle} is the fuel consumed during a cycle, in litres;
- t_{cycle} is the length of cycle, in seconds;
- t_{year} is the time that the bus works per year, in seconds;
- $C_{fuel/ltr}$ is the fuel cost per litre.

Then, the cost associated to the battery is:

$$C_{bat/year} = \left(Bat_{life/cycle} \cdot \frac{t_{year}}{t_{cycle}} + \frac{1}{Cal_{bat,life}} \right) \cdot C_{bat/kWh} \cdot E_{bat} \quad (35)$$

where

- $C_{bat/year}$ is the cost of battery-life consumed during a year
- $Bat_{life/cycle}$ is the fraction of battery life consumed in a cycle
- $C_{bat/kWh}$ is the cost of the battery per kWh
- E_{bat} is the nominal energy of the battery, in kWh
- $Cal_{bat,life}$ is the estimated calendar life of the battery, in years.

The last one establishes the lifetime when the battery is stored without been used. Notice that the first term in (35) counts the cost associated to the usage of battery while the second counts the cost associated to the calendar life. Finally, the total operating cost in US\$ per year of the HEV results:

$$C_{year} = C_{fuel/year} + C_{bat/year} \quad (36)$$

3.4 Iterative sizing procedure

In the previous sections, some methods and models to quantify the fuel consumption and the lifetime of components were presented, and finally an expression to estimate the total operating cost associated to the HEV was proposed. On this basis, the optimal size of the components of the propulsion system is one that minimises the total operating cost. In order to find the optimal size, an iterative procedure was implemented.

According to Subsection 2.2, the battery size and the ICE size are design variables. The iterative process consists in evaluating the feasibility and the operating cost for each design proposed. Feasibility is reached when the design proposed meets the *power constraint* and the *ICE-lifetime constraint*. The first one is verified using inequality (7) and it can be evaluated before the simulation in the driving cycle. The second establishes that the lifetime of the ICE must be longer than the lifetime of the HEV, and therefore this constraint is verified after the simulation in the driving cycle.

Finally, the iterative methodology proposed to address the sizing can be summarised in the following steps:

- 1 choosing a battery size and ICE size
- 2 updating the model and efficiency of the components according to the new design
- 3 checking *power constraint* according to equation (7)
- 4 running the driving cycle using DP as EMS
- 5 computing the estimated lifetime of the ICE with (32) and checking *ICE-lifetime constraint*

6 computing the battery life consumed per cycle with (28)

7 computing the total operating cost with (36).

The number of iterations depends on the amount of designs evaluated. In the next section the proposed methodology is applied to a real case study.

4 Case study and results

4.1 Case study: hybrid electric bus

The case study described below was used to obtain the sizing results presented in the next subsection. It corresponds to a hybrid electric bus (HEB) used for urban transport. The characteristics of the bus and the components of the propulsion system are listed in Table 1.

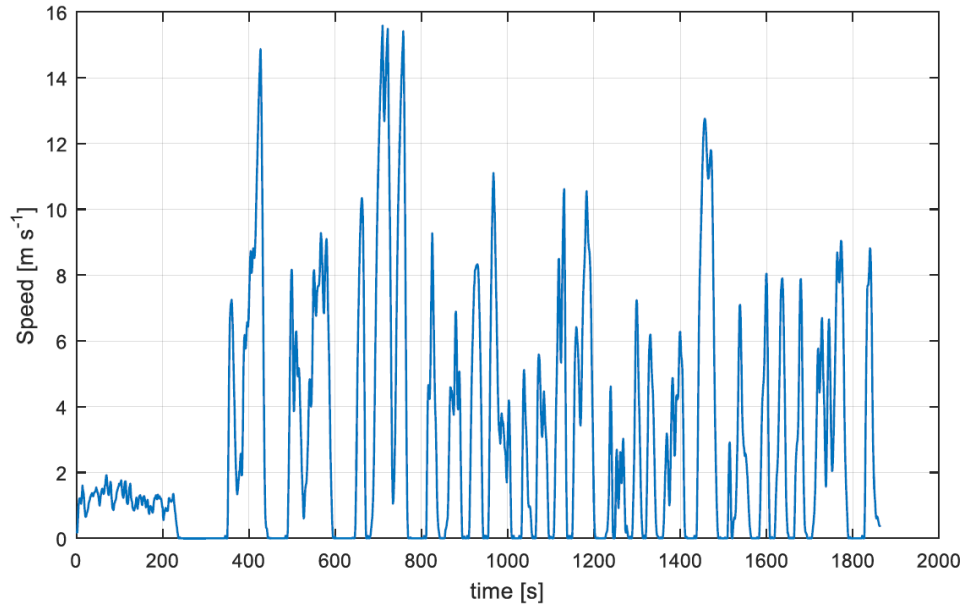
Table 1 Parameters of HEB

Chassis	Max. power, $P_{wh,max}$	125 kW
	Body mass	11,700 kg
	Frontal area	8.06 m ²
	Drag coefficient	0.65
	Rolling resistance	0.008; $1.2e-4 \text{ m}^2\text{s}^{-2}$
	Differential, η_{DF}	0.95
	Cargo mass	2,400 kg
Li-ion battery	Wheel radius	0.51 m
	Nominal voltage	305 V
	Cell capacity, Q_{cell}	2,5 Ah
	Cells in series, N_{ser}	95
	Max. cell current, $I_{cell,max}$	120A
Calendar life, $Cal_{bat,life}$	10 years	
Buck/boost	η_{bb}	0.95
	$U_{bb,min}; U_{bb,max}$	260 V; 360 V

The driving conditions and activity are based on a real bus in service in the city of Buenos Aires. The driving conditions are given by the speed profile shown in Figure 6.

The bus operates six day a week and 16 hours a day. On the other hand, the costs considered are 1 US\$/Ltr for the fuel and 500 US\$/kWh for the li-ion battery (Nykqvist and Nilsson, 2015). Finally, the lifetime expected for the bus is seven years.

The battery sizes proposed are obtained by varying the number of branches in parallel (N_{par}). In this way, the sizes tested varies from $N_{par} = 1$ (21 kW), with step 1, to $N_{par} = 16$ (332 kW). Regarding the ICE, the sizes proposed vary from 40 kW, with step 15 kW, to 145 kW. The lower limit was defined by considering a sustained-cruising-speed condition of 16 ms^{-1} (see Subsection 2.2).

Figure 6 Buenos Aires driving cycle (see online version for colours)**Table 2** ICE-lifetime estimations (years)

		ICE power (kW)							
		40	55	70	85	100	115	130	145
Battery size (branches in parallel)	1	NaN	NaN	NaN	NaN	NaN	NaN	9,0	10,9
	2	NaN	NaN	NaN	NaN	8,2	9,5	9,9	12,0
	3	NaN	NaN	NaN	7,4	8,7	10,0	10,4	12,6
	4	NaN	NaN	6,2	7,6	8,9	10,3	10,7	13,0
	5	3,4	4,8	6,2	7,6	9,0	10,4	10,9	13,1
	6	3,4	4,9	6,3	7,7	9,1	10,5	10,9	13,2
	7	3,4	4,9	6,3	7,8	9,2	10,5	11,0	13,3
	8	3,5	4,9	6,4	7,8	9,2	10,6	11,0	13,3
	9	3,5	4,9	6,4	7,8	9,2	10,6	11,1	13,4
	10	3,5	5,0	6,4	7,8	9,2	10,7	11,1	13,4
	11	3,5	5,0	6,4	7,9	9,3	10,7	12,1	13,5
	12	3,5	5,0	6,4	7,9	9,3	10,7	12,1	13,5
	13	3,5	5,0	6,5	7,9	9,3	10,7	12,1	13,5
	14	3,5	5,0	6,5	7,9	9,3	10,7	12,1	13,5
	15	3,6	5,0	6,5	7,9	9,3	10,8	12,1	13,5
	16	3,6	5,0	6,5	7,9	9,3	10,8	12,2	13,5

4.2 Sizing results

According to the procedure described in Subsection 3.4, before to evaluate the operating cost, the feasibility of the proposed designs must be checked. Unfeasibility is caused by not meeting the *power constraint* or by not meeting the *ICE-lifetime constraint*. Table 2 shows the ICE estimated lifetime for the set of the proposed designs. Cells with *NaN* means that the design proposed does not meets the *power constraint*.

In this table can be seen that the battery size has low effect on the ICE-lifetime while the ICE size affects linearly its lifetime. According to this table and taken into account that the expected lifetime for the bus was established in seven years, the feasible designs require $P_{ICE,max} \geq 85$ kW.

For the feasible designs, Tables 3 and 4 show the costs associated to the fuel consumption and battery-life consumption respectively. In contrast to the previous result, in this case the battery size has a great effect on both consumptions, while the ICE-size has low influence.

Table 3 Fuel consumption cost (1,000 US\$/years)

	ICE power (kW)				
	85	100	115	130	145
	Battery size (branches in parallel)				
1	NaN	NaN	NaN	18,13	18,27
2	NaN	15,95	15,95	16,00	16,10
3	15,08	14,99	14,98	15,00	15,07
4	14,63	14,55	14,52	14,54	14,59
5	14,45	14,39	14,36	14,37	14,43
6	14,33	14,28	14,25	14,25	14,31
7	14,25	14,19	14,16	14,17	14,22
8	14,18	14,13	14,10	14,11	14,16
9	14,12	14,08	14,06	14,06	14,09
10	14,09	14,04	14,01	14,01	14,06
11	14,05	14,01	13,97	13,98	14,03
12	14,02	13,98	13,94	13,95	13,99
13	13,99	13,95	13,92	13,93	13,96
14	13,98	13,92	13,89	13,93	13,95
15	13,95	13,91	13,88	13,90	13,93
16	13,93	13,89	13,86	13,88	13,91

Table 4 Battery-life cost (1,000 US\$/years)

	ICE power (kW)				
	85	100	115	130	145
	Battery size (branches in parallel)				
1	NaN	NaN	NaN	3,95	3,86
2	NaN	5,36	5,09	5,18	4,55
3	4,70	4,48	4,45	4,30	3,96
4	2,86	2,65	2,60	2,63	2,56
5	2,48	2,35	2,30	2,29	2,21
6	2,27	2,17	2,14	2,12	2,11
7	2,16	2,07	2,06	2,01	2,00
8	2,10	2,05	2,01	1,94	1,96
9	2,06	2,03	1,98	1,93	1,95
10	2,06	2,04	1,97	1,93	1,94
11	2,06	2,04	1,97	1,94	1,94
12	2,07	2,05	1,99	1,96	1,95
13	2,08	2,07	2,00	1,97	1,96
14	2,12	2,08	2,01	2,00	1,98
15	2,14	2,09	2,03	2,03	2,01
16	2,17	2,12	2,07	2,06	2,04

Then, Table 5 and Figure 7 show the total operating cost. The minimum cost is reached at $P_{ICE,max} = 115$ kW and $N_{par} = 14$. However, the minimum is placed on a region of the graph with a reduced slope, which means the designs close to the optimal do not increase too much the total operating cost.

Table 6 shows the variation of the total operation cost respect to the optimal design. This information can be used together with other factors to make the final decision about the best design. These factor can include the cost of the ICE,

the volume occupied by components, the cost and volume of the generator, the cost of power converters, among other. It is worth noticing that adopting designs closed to the optimal, the expected life time of the battery is 2.5 years, which implies that nearly three batteries are consumed during the lifetime of the bus.

Table 5 Total operating cost (1,000 US\$/years)

	ICE power (kW)				
	85	100	115	130	145
	Battery size (branches in parallel)				
1	NaN	NaN	NaN	22,08	22,13
2	NaN	21,31	21,03	21,19	20,65
3	19,78	19,46	19,43	19,30	19,03
4	17,48	17,20	17,12	17,17	17,15
5	16,93	16,74	16,65	16,66	16,64
6	16,60	16,44	16,39	16,37	16,42
7	16,41	16,26	16,22	16,18	16,22
8	16,27	16,18	16,10	16,05	16,12
9	16,18	16,11	16,04	15,99	16,05
10	16,14	16,07	15,98	15,95	16,00
11	16,10	16,05	15,94	15,92	15,97
12	16,08	16,03	15,92	15,91	15,94
13	16,08	16,02	15,92	15,91	15,93
14	16,09	16,00	15,90	15,92	15,93
15	16,09	16,00	15,92	15,93	15,94
16	16,11	16,01	15,92	15,94	15,95

Table 6 Variations of total operation cost respect to optimal design (%)

	ICE power (kW)				
	85	100	115	130	145
	Battery size (branches in parallel)				
1	NaN	NaN	NaN	38,9	39,2
2	NaN	34,0	32,3	33,2	29,9
3	24,4	22,4	22,2	21,4	19,7
4	10,0	8,2	7,6	8,0	7,9
5	6,5	5,3	4,7	4,8	4,6
6	4,4	3,4	3,1	3,0	3,3
7	3,2	2,3	2,0	1,7	2,0
8	2,4	1,8	1,3	0,9	1,4
9	1,8	1,3	0,9	0,5	0,9
10	1,5	1,1	0,5	0,3	0,6
11	1,3	1,0	0,3	0,1	0,4
12	1,2	0,8	0,1	0,1	0,3
13	1,1	0,7	0,1	0,1	0,2
14	1,2	0,6	0,0	0,1	0,2
15	1,2	0,6	0,1	0,2	0,3
16	1,3	0,7	0,2	0,2	0,3

Figure 7 Total operating cost (see online version for colours)

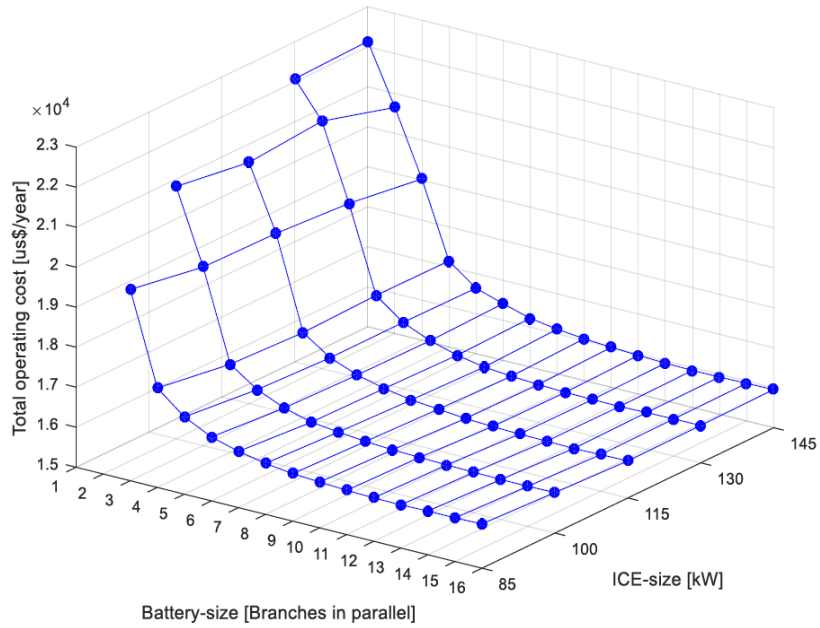
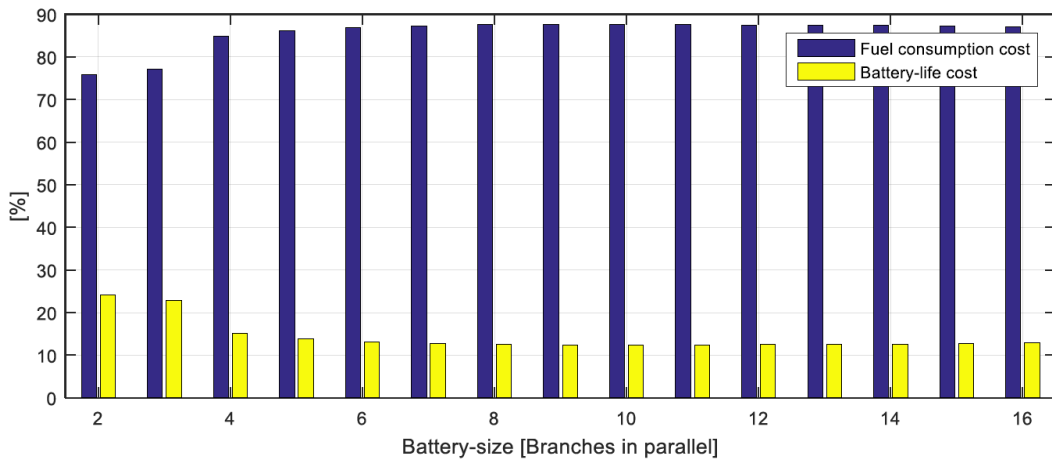


Figure 8 Contribution of fuel consumption and battery-life to the total operating cost (see online version for colours)



Note: ICE-size 115 kW.

Figure 9 OF effect on total operating cost (see online version for colours)

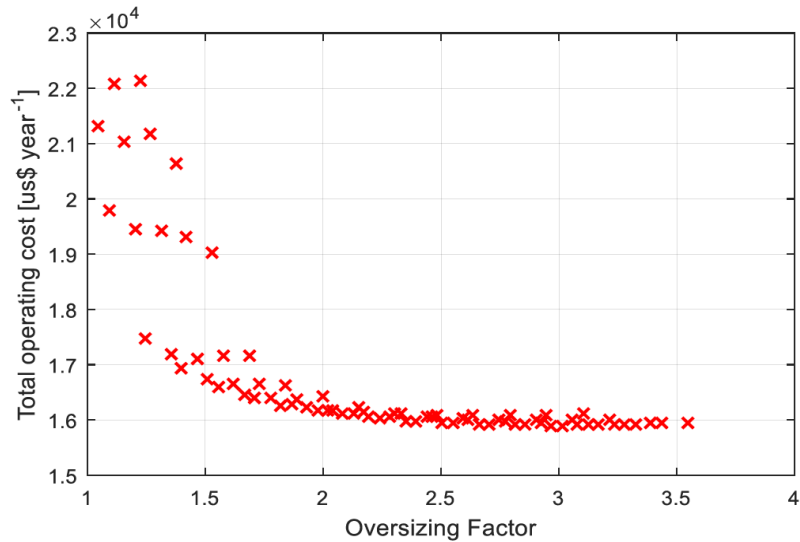


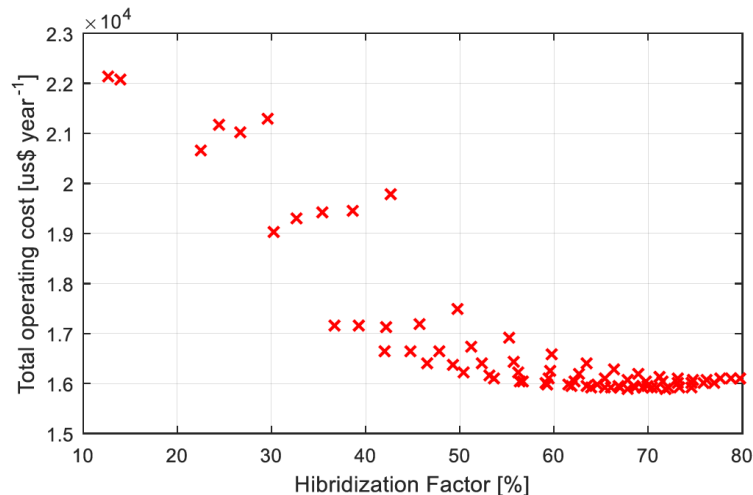
Figure 10 HF effect on total operating cost (see online version for colours)

Figure 8 shows the contribution of the battery-life cost in the total operating cost. It can be seen that in the range of the optimal designs, i.e., between 9 and 16 branches in parallel, the costs associated to the battery life consumption represent less than 15% of the total operating cost. Finally, Figures 9 and 10 show the effect of the oversizing and hybridisation factors OF and HF on the total operation cost. As can be seen, the best results are obtained with OF between 2.5 and 3.5, and HF between 0.6 and 0.8.

5 Conclusions and discussions

A methodology to address the optimal sizing of components for HEVs has been presented in this work. The optimisation was focused on reducing the total operating cost, in which the fuel consumption as well as the battery cost were included. For this purpose, a quasistatic model of the hybrid electric vehicle was developed and dedicated models to quantify the lifetime of the battery and the ICE were implemented. Finally, the methodology proposed was applied to address the sizing in a hybrid electric bus.

Regarding the simulation results obtained on the case study, the following conclusions can be drawn:

- the size of the ICE affects mainly its lifetime but it has little influence on the total operating cost
- the size of the battery has significant influence on the total operating cost, especially when the oversizing factor is close to 1
- small deviations of battery-size and ICE-size around the optimal design increment increases very slightly the global operating cost
- in those designs with lower costs, the cost associated to the battery-life consumption represents around 15% of the total operating cost
- the lower cost designs have hybridisation factor around 65% and oversizing factor around 3.

Besides these results, which are valid only for a particular case study, it is worth mentioning that the methodology presented in this paper is general enough to cover a wide range of problems concerning the optimisation of HEVs. Regarding the accuracy of the results obtained with the proposed methodology, the estimation of lifetime consumed from the battery is the largest source of uncertainty. This is because the lack of accurate models to estimate the complex aging phenomena in the batteries. Finally, the results obtained with the methodology proposed provide valuable information that must be complemented with other aspects, such as the costs or the volume occupied by components, before making the final decision about the more convenient design.

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