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Hybrid buses: defining the power flow management strategy and energy storage system needs

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Abstract

The following article will analyze the benefits of retrofitting a diesel-electric bus by hybridizing its drive train with a supercapacitor based energy storage system (ESS). Several power flow management strategies will be proposed and compared; and their respective ESSs will be sized and designed accordingly. The energy savings achieved range between 32 % and 40%, due to braking energy recovery and an improved ICE efficiency, and show the importance of the power flow strategy. Results are obtained by means of a quasi-static 'backwards/forward looking' simulation program, developed for this purpose, which includes a dynamic model of the ICE. Performance of the conventional bus and the hybrid bus is also compared.

Keywords: HEV, Public transport, Supercapacitor, Simulation, Energy Storage, Efficiency.

1 Introduction

To address energy issues in the transportation sector, hybrid vehicles have proved their validity when it comes to improve the vehicle efficiency and reduce their consumption and exhaust emissions [1].
From the nineties on, several hybrid topologies, parallel, series and combined, have been proposed and developed in order to improve the vehicles efficiency and performances. Since there is no clear topology superior to the others in all scenarios [2], the vehicle architecture has to be chosen according to the type of vehicle and its final use. Series-hybrid topology offers good performance for heavy duty vehicles doing city driving cycles [2]. One of the critical issues in hybrid vehicles is the selection of the appropriated energy storage system. Most of the systems proposed up to now consist of a main energy source such as Internal Combustion Engine (ICE) (or a fuel cell) and an energy storage system (ESS) that will assist the main energy source and will store the recovered braking energy. Batteries, supercapacitors and flywheels offer solutions to this issue [3,4]. Supercapacitors offer a good performance in terms of power density, efficiency and cycle life but their energy density does not compare to that of batteries and flywheels [5,6]. However, these characteristics are very convenient for Hybrid Electric Vehicle (HEV), especially to store the high braking power peaks, and they have already been used in certain applications for heavy hybrid vehicles [7,8,9]. The size of the energy storage system in terms of energy will differ according to the cycle driven and the strategy used [10,11] and it will be the limiting factor when designing a supercapacitor based ESS [12].
Section 3 will present an enhanced 'backwards/forward' vehicle simulator, which accounts for the ICE transients by means of a

dynamic model. In section 4, several power flow strategies are presented and the reasoning behind proper ESS sizing is given at section 5. Section 6 will compare the results of the different strategies and the most appropriate options for this case study will be chosen.

2 Case-Study

Within the framework of a larger scale project that assesses different applications of supercapacitors to increase the energy efficiency of the public transport fleet in Brussels [13,14], the particular case of the MERCEDES BENZ O520 Cito shown by Figure 1 is evaluated.

Weight:	*8550 kg (empty)*
Length:	*9.5 m*
Capacity:	*53 passengers*
Engine power:	*125 kW*
Generator power:	*85 kW*
Motor power:	*85 kW*

Figure 1. Mercedes Cito

The vehicle's diesel-electric topology is represented by Figure 2. The efficiency of this vehicle could be significantly improved by retrofitting its drive train with the inclusion of an ESS connected to the DC bus, as represented by Figure 3.

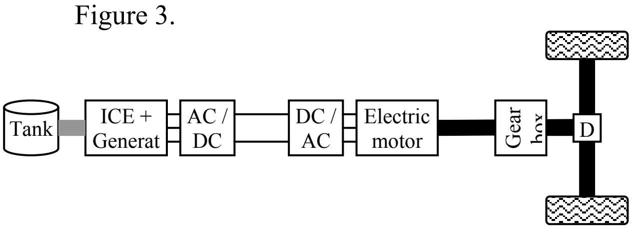

Figure 2. Diesel-Electric Bus.

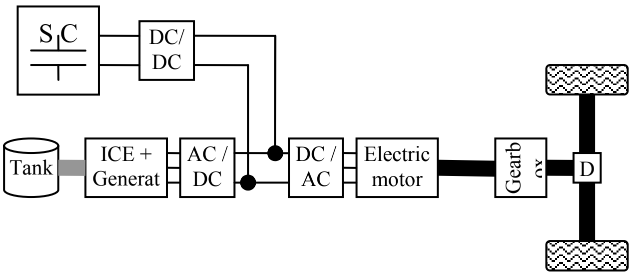

Figure 3. Series hybrid electric bus

Since the ICE efficiency of this bus is only known for the maximum torque region of the engine, for this study, data belonging to another engine with a similar power, torque and speed range is used.

3 Bus Model

A dedicated bus model has been developed based on [15]. The model is of 'quasi-static' nature for all the components to allow for high simulation speed, but a dynamic model is introduced to account for the vehicle ICE inertia.

The model is mainly based in the 'backwards-looking' or 'effect-cause' method [16], that calculates the energy consumed by a vehicle following a predefined driving cycle by going upstream the vehicle components and accounting for their losses depending on the working point. By doing this, it is assumed that the vehicle is able to follow the driving cycle and, therefore, a performance analysis could not be realized.

In some circumstances, the power (or another quantity such as current, torque, etc.) requested to a vehicle component, such as the motor or the ICE, is higher than the component rating. Thus it would be assumed that the vehicle is giving more than what it can actually give, and it would lead to wrong results.

To overcome this problem, a 'forward-looking' module is introduced. This module will calculate forwards when any of the vehicle components is requested a power (or other magnitude) level out of its working region and will eventually calculate the actual speed of the vehicle. For this, a simple controller sets the vehicle power in case any of the components is not able to follow the driving cycle.

This is done in a similar manner to that of other commercial available packages, like Advisor [17,18], with some improvements:

- Backwards and forward model are two different subsystems and the forward block is only executed when a component is out of its working boundaries. Thus, simulation time is shortened.
- The efficiency in the backwards and forward path are not necessarily the same, they are re-calculated on the forward path following the real delivered power.
- Within the general 'quasi-static' approach, the model of the ICE subsystem is dynamic. Therefore it considers the ICE transients, torque limitations and calculates the ICE actual speed, which may be different from the desired one.

The model is depicted by Figure 4 where the direction of the simulation calculations is shown. Under normal conditions, the simulation tool behaves as a 'backwards' model calculating the power needed to follow the speed cycle. When the limit of the ICE is exceeded, the speed cycle is taken as a speed reference so that the engine

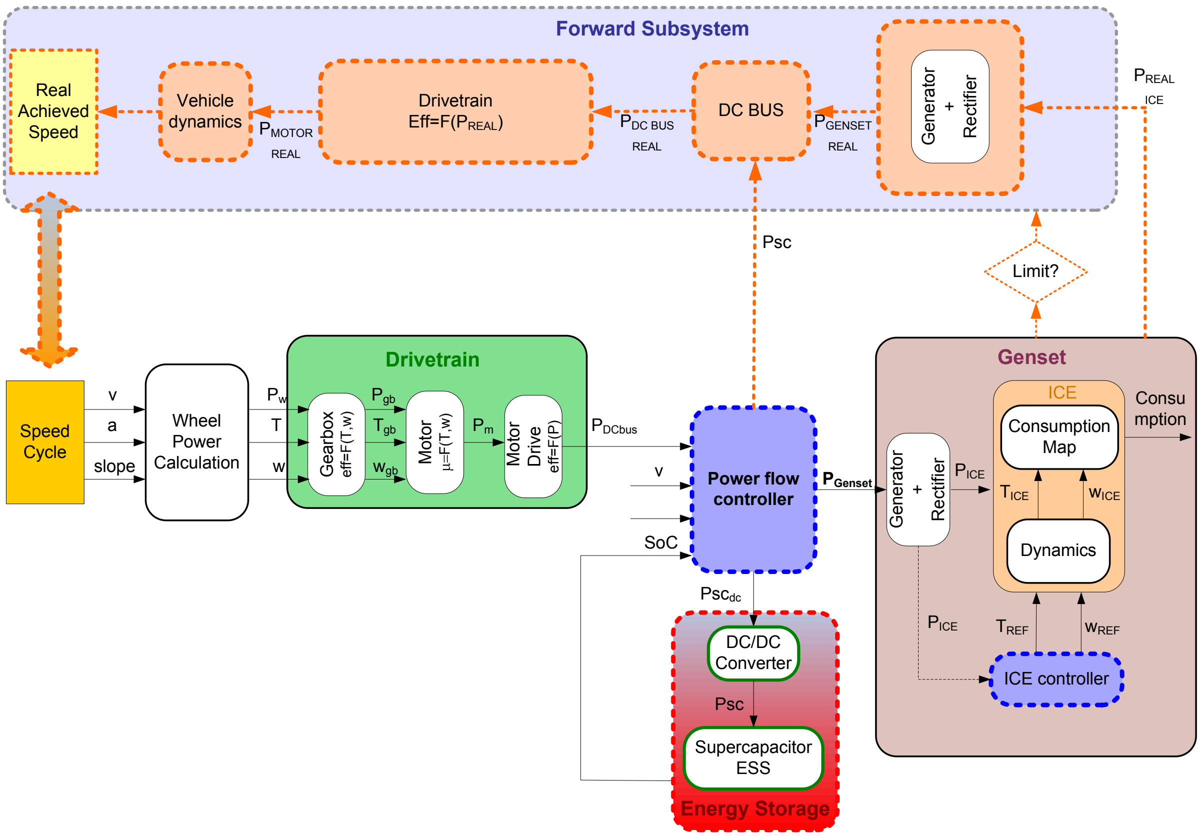

Figure 4. Vehicle model diagram

provides maximum power until the real speed reaches the reference. When this condition is met, and if the requested power to the ICE is within its working limits, at this moment, the program continues the 'backwards' simulation and the 'forward' subsystem is not executed.

The model is valid for both conventional diesel-electric bus and its upgraded series-hybrid counterpart. In the conventional vehicle, all the requested power at the DC bus level is to be given by the genset group. In the hybrid model of Figure 4, the DC bus requested power has to be split between the genset and the ESS.

This power distribution can be done in different ways depending on the strategy used, energy capacity of the ESS, etc. Different strategies will be further discussed in the next section.

Figure 5 below shows the performance of the CITO bus fully loaded (12500 kg) following the SORT cycle. In the first and second graph the speed and needed power at wheel level can be observed, required in blue and real in green.

It can be noticed how at the end of the acceleration (t = 485s) the vehicle can not yield the requested power. At that moment the 'forward subsystem' of the program starts its execution, as indicated in the 3rd graph, and the power delivered is limited by the genset maximum power which is kept until the real speed equals the requested speed.

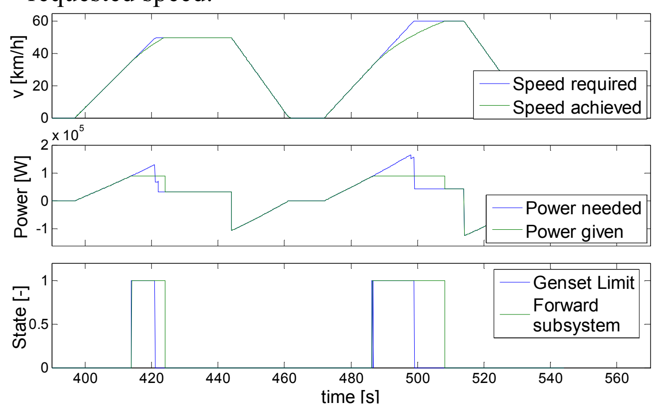

Figure 5. Simulation of bus following SORT cycle

During the execution of the forward subsystem a simple controller is needed so that the maximum genset power is provided until the desired speed is reached, This is shown on the 2nd and 3rd graph of Figure 5.

With the inclusion of an ESS, the driving cycle could be met with a proper energy management strategy. Figure 6 shows how the hybrid version of the same bus has a better performance and can follow the driving cycle, provided the motor can cope with the higher power peaks for a few seconds.

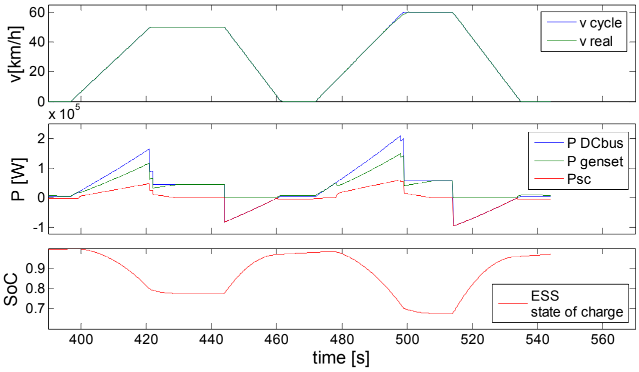

Figure 6. Hybrid bus following SORT cycle

As it is observed in the second graph, the ESS provides some power (red curve) during the acceleration. Thus the power to be provided by the engine (in green) is within its operational region.

3.1 Engine-generator group

To understand the ICE model behaviour, the full subsystem of the engine-generator-tank is represented by Figure 7.

The power to be delivered by the generator comes from de DC bus, following the backwards simulation approach. This power is processed in the generator block where the losses are estimated and the total power requested to the ICE is given.

At this point, the ICE can deliver this power in a different range of torque and speed values, i.e., there is a degree of freedom to control the ICE. Therefore, a controller is introduced to set the reference speed, *Wref* in Figure 7, at which the ICE efficiency would be the highest. This reference will be the input block of the ICE subsystem, where the needed torque will be estimated.

To calculate the engine efficiency, an efficiency map of an ICE is used. However, the values on these maps are based on steady-state conditions and will differ during transients [11]. To account for this, a penalization block will drop the engine efficiency linearly up to 75% of its tabulated value during fast power changes.

The engine power is then transformed into fuel consumption by the *tank* block according to the fuel properties, energy contents and density.

When the engine is not providing any torque at its idling speed, an idling consumption is set in this block too.

Finally, if either the generator or the ICE subsystems are not able to deliver the requested power, a signal will trigger the 'forward subsystem' in order to determine the new speed following the real given power.

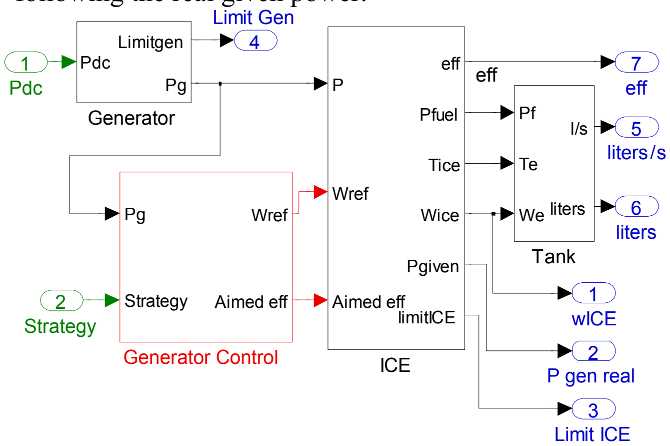

Figure 7. Genset block in Simulink

3.1.1 ICE subsystem

The ICE model has the purpose of accounting for the inertial torque needed to change the ICE speed in addition to the torque delivered to the generator, as shown by Eq 1:

$$T_{ICE} - T_{GENERATOR} = J\frac{dw}{dt} + Bw, \qquad \text{Eq 1}$$

with *J* the inertia and *B* the friction coefficient.

While in a 'forward looking' or 'cause-effect' vehicle dynamic model $T_{GENERATOR}$, in Eq 1, is function of the generator current, in this model, due to the 'backwards' method utilized, the generator torque is calculated dividing the power requested by the generator by the actual ICE speed as per Eq2.

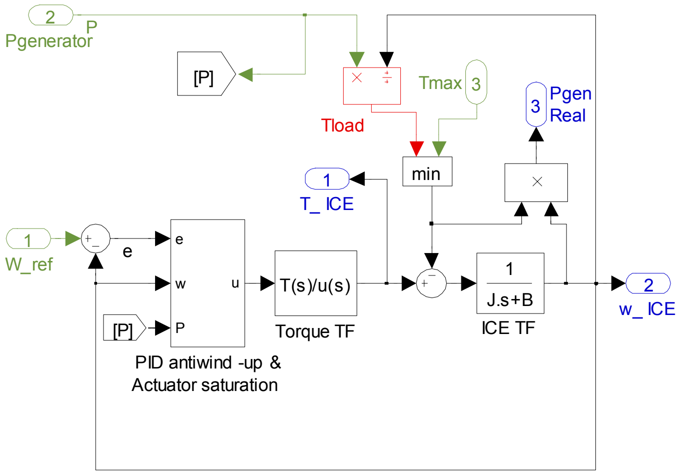

Figure 8. ICE model in Simulink

$$T_{GENERATOR} = P_{GENERATOR} / w \qquad \text{Eq 2}$$

Thus, nonlinearity is introduced in the model due to the combination of the backwards approach and the dynamic model. It is highlighted in red in Figure 8, where the Simulink ICE model is depicted.
To control the ICE speed, a PI controller is utilized. The output of the controller [*u(s)*] is translated into torque [*T(s)*] by means of the transfer function *T(s)/u(s)*. For simplicity reasons, the relation between ICE torque and control input is assumed to be of static nature, without time dependency.
The generator torque is limited to the maximum torque of the ICE, which is dependant on the speed. If at any moment, the torque requested by the generator is higher than the ICE maximum torque; the requested torque will be reduced to the ICE maximum torque. This means that the power requested by the generator will not be provided by the ICE. From this point on, the ICE will provide an amount of power (*Pgen Real,* output 3, in blue, in Figure 8) lower than that requested. This will trigger the 'forward subsystem' (see Figure 4) which will calculate the real speed of the vehicle.

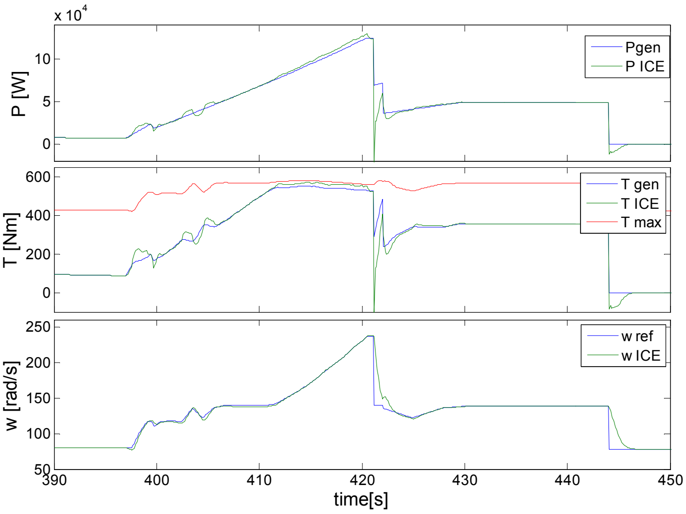

Figure 9. Detail of ICE torque and speed under a variable generator load

Figure 9 shows an example of the ICE subsystem behaviour. The power requested by the generator has to be supplied by the ICE. The genset controller decides which is the most efficient point for every power level within the operating region and sets the reference speed, *w_ref*, for the ICE. Then the PI controller adjusts the ICE torque so that the speed reference is followed. It can be observed how the ICE power and torque are higher than those of the generator when the reference speed is increasing. This is due to the ICE inertia. In addition, one can see that the requested torque never exceeds the ICE maximum torque (red curve).

3.1.2 ICE on-off transients

In hybrid vehicles that allow the ICE to shut down at certain moments, the simulation of the engine start-up from stand-still to idling speed can also be carried out. In this scenario, the generator would act as a motor that would take the ICE to idling speed by using the ESS energy.

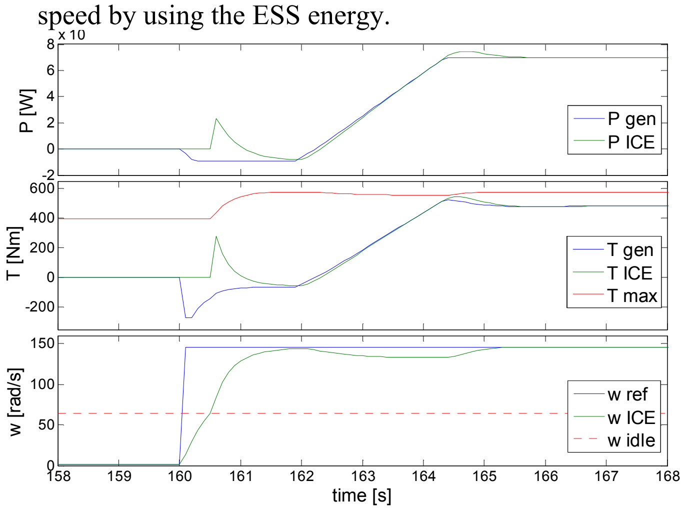

Figure 10. Detail of ICE start-up

This concept is shown by Figure 10 where a transient from *w* = 0 rad/s to the idling speed occurs. In the beginning of the transition, at time t=160s, the generator is acting as a motor, i.e., it produces a torque in the same direction of the engine motion until the ICE reaches the idling speed of 64 rad/s, represented by a red dotted line on the third graph of Figure 11. Until that moment the ICE is not producing any torque. After the start up is done at t=160.5s, the engine starts providing torque to follow the reference speed.
At t=162s, the generator starts to load the ICE with a gradual power from 0 to 70 kW, that is reached at t=165s.
This capability allows the program to estimate the fuel consumption reduction by avoiding idling times and the penalties of the engine transients during the start up.

4 Power flow control strategies

Hybridizing a vehicle has the utmost goal of reducing the energy consumption but it can produce some side benefits like emissions and noise reduction, etc.

Concerning the energy consumption reduction, there are mainly 2 mechanisms: recovery of braking energy and more efficient operation of the ICE.
Braking energy recovery is quite straight forward; it can be recovered as long as the ESS has enough capacity to store it. To improve the efficiency of the ICE, the ICE is operated in areas where its efficiency is higher.

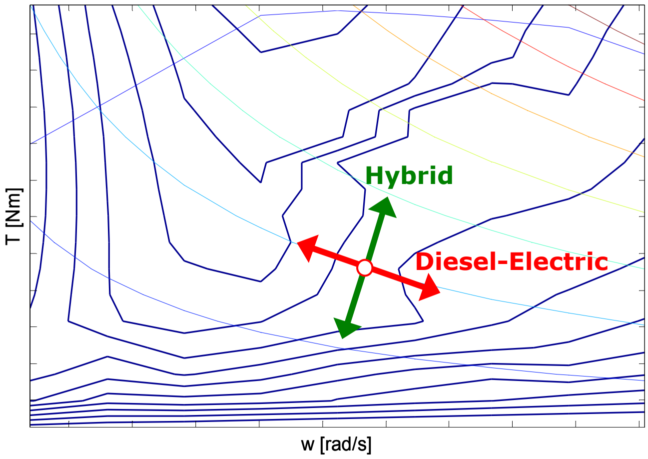

Figure 12. ICE efficiency map

In section 3.1 it has been mentioned that unlike for conventional vehicles, where the ICE speed is proportional to the vehicle speed, the diesel electric topology has an extra degree of freedom: it is possible to change the operating point of the ICE along its iso-power curves. This is represented by the red arrows in Figure 12. When this vehicle is hybridized in a series hybrid topology (see Figure 3), a second degree of freedom is introduced by controlling the amount of power that the engine has to provide, represented by the green arrows that allow the controller move the ICE working point in every dimension of the speed-torque map.
For this purpose several strategies can be proposed. Each strategy will entail different benefits and constraints. Next we will describe the different strategies subjects of the study of this article.

4.1 Kinetic strategy

The aim of this strategy is mainly to recover the braking energy of the vehicle to improve its energy consumption. The ESS energy is handled in function of the speed. The main guidelines are:

- Keep the state of charge (SoC) of the ESS high at low speeds
- Keep the ESS SoC low at high speeds

The braking energy stored in the ESS can be used to 'shave' the ICE power peaks during the acceleration. However the ICE will still follow the vehicle load.
The advantage of this strategy is the small size of the ESS needed and the reduced losses on the ESS, since the energy that passes through it is limited to the braking energy. However the ICE efficiency is not significantly improved.

4.2 ICE on-off

This strategy attempts to obtain the maximum efficiency of the ICE. For this purpose, the engine works at the most efficient point of the efficiency map providing a constant power. The difference between this set point and the power needed is absorbed by the ESS.
In this case, the optimal working point is located between 70 and 80 kW, which is higher than the average power needed to run the city driving cycle. This means that after a while the ESS will be fully charged and the ICE will be shut down. At that moment the ESS will be providing all the driving power until its SoC is low again, moment at which the ICE will take over.
The benefits of this strategy are an optimal ICE efficiency and almost no inertial losses. The drawbacks are that a larger ESS is needed so that the engine's on-and-off cycles are not too short. In addition high losses are produced on the ESS since the power flow is very high.
Supercapacitors are very efficient and convenient for this purpose, but still, an important part of the losses are produced on the DC/DC converter.

4.3 Average power

The idea is to operate the ICE in an almost constant operating set point corresponding to the average power of the driving cycle.
The ESS will absorb the remaining energy and power and therefore it should be sized accordingly
The advantages of this system are the lack of inertial movements and a relatively high efficiency of the ICE due to the constant operation.
However, for this case study, the efficiency at the average power set point (between 20 and 30 kW, depending on the driving cycle), is not the highest since the ICE was sized to drive the vehicle by itself and its most efficient point is given at higher powers. This strategy would be more interesting when designing a hybrid vehicle from scratch. A smaller ICE could be used with its peak efficiency at the average driving power.

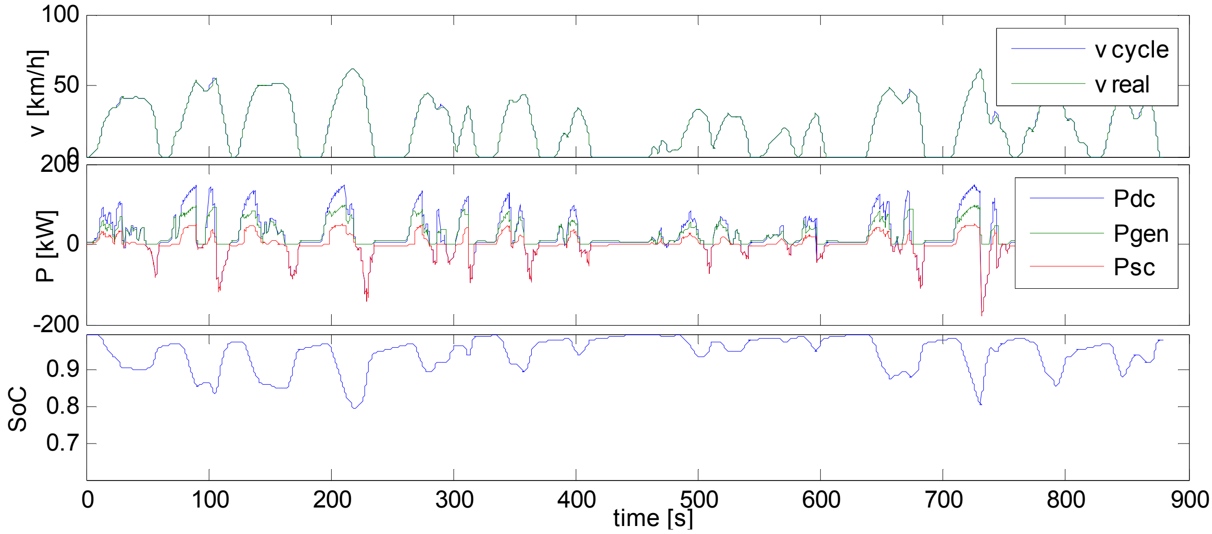

Figure 13. Detail of 'Kinetic Strategy' under the DUBC cycle

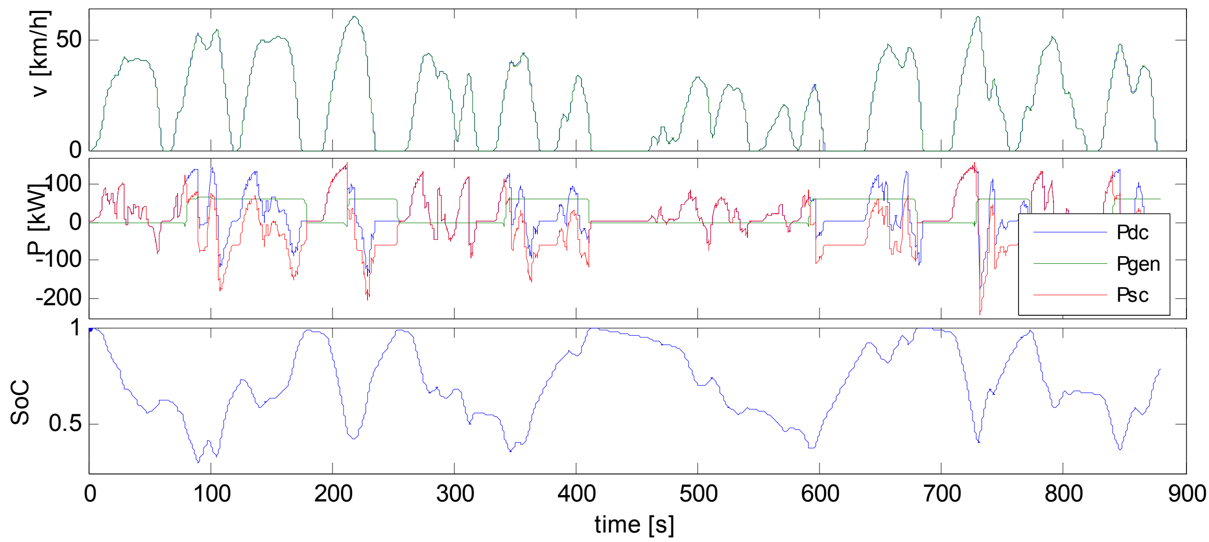

Figure 14. Detail of 'ICE on-off' strategy under DUBC cycle

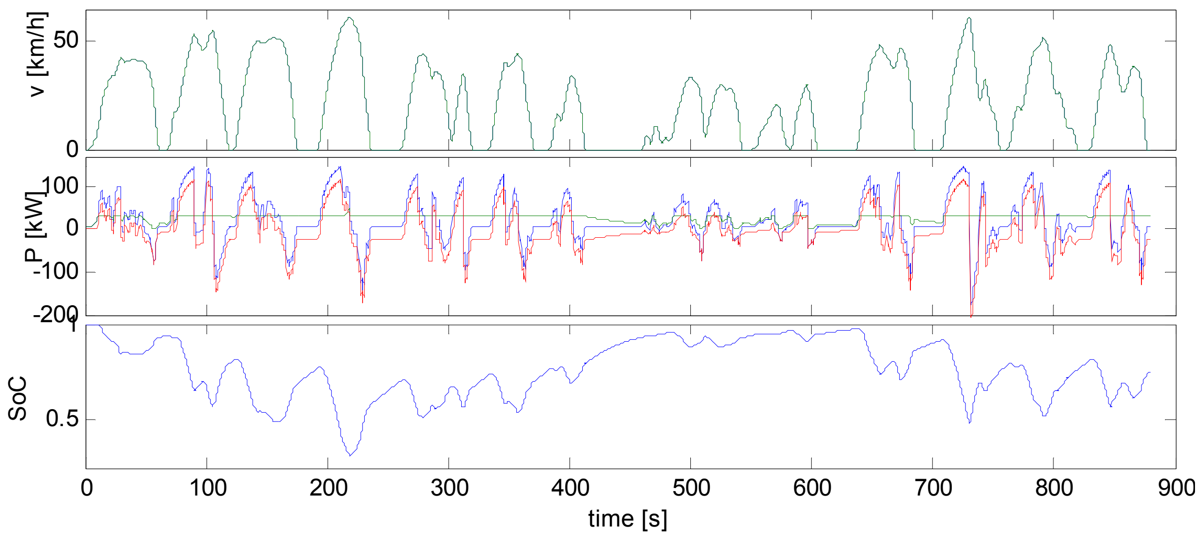

Figure 15. Detail of Average Power Strategy with corrections in function of ESS SoC

An example of the 'kinetic', 'on-off' and 'average power' strategies are shown in Figure 13, Figure 14 and Figure 15 respectively. For comparison purposes only, all three are using an ESS with a usable energy capacity of 0.94 kWh.
It can be observed in Figure 13, that with Kinetic strategy the SoC variation is only about 25% of the total capacity, thus, a smaller ESS would work perfectly.
With the 'on-off' strategy of Figure 14, the engine goes on-and off constantly in cycles of 1-2 minutes, depending on the driving conditions. The bigger the ESS, the longer these cycles will be and the more ICE steady conditions.
Figure 15 shows the 'average power' strategy where the ICE set point is 30 kW, the average power level. From the graph one could say that the ESS is not big enough to let the ICE operate at a constant power during the whole cycle. Theoretically the ESS should be bigger, but with some little modifications to the strategy, the ICE can modify its power when the ESS SoC is close to its lower or upper boundaries. This is why at t=400s, the ICE power is reduced.

5 Energy Storage System

As mentioned in the introduction, supercapacitors are chosen for this purpose due to their high efficiency, high power capability and long lifetime especially.

5.1 Supercapacitor model

Supercapacitors parameters are given by manufacturers as fixed values. Nevertheless, it has been proved by experiments that these values deviate from the manufacturer data at different working points [19,20]. Sophisticated models that describe supercapacitors behaviour have been proposed [20,21,22,23], but the complexity of the systems represented will slow down the simulation speed without a clear advantage for the aim of this article: the study of the bus energy consumption. For this purpose the model presented at [19] with a variable capacitance in function of the voltage, and depicted by Figure 16, is of particular interest to properly size the ESS, since the energy content of the super capacitor is affected by its voltage dependant capacitance. The relation between the rated capacitance and the measured is given by Eq 3.

$$C(V) = C_{rated} \cdot \left(1 - n \cdot \frac{V_{rated} - V}{V_{rated}}\right) \quad \text{Eq 3}$$

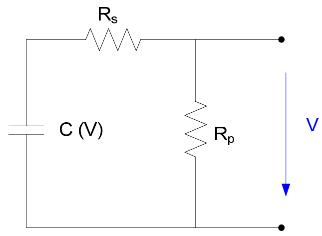

Figure 16. Supercapacitor model

5.2 Energy Storage System Sizing

To size the ESS several aspects should be considered.

- Vehicle characteristics: Weight, ICE efficiency map.
- Driving cycle: max speed, acceleration.
- Strategy used to control the power flow
- ESS use conditions

For design purposes supercapacitors are normally used between their maximum rated voltage V_{MAX} and 50 percent of this value $V_{MAX}/2$, which gives a usable energy of 75% of the energy capacity with constant capacitance.

$$E_R = \int_{t0}^{t1} P dt = \int_{t0}^{t1} vi dt = \int_{t0}^{t1} v C_R \frac{dv}{dt} dt = \int_{V_{MAX}/2}^{V_{MAX}} v C_R dv =$$

$$E_R = \frac{3}{4} \cdot \frac{1}{2} C_R V_{MAX}^2$$

Considering the variable capacitance, the usable energy capacity from V_{MAX} to $V_{MAX}/2$, goes down to

$$E = \int_{t0}^{t1} P dt = \int_{t0}^{t1} vi dt = \int_{t0}^{t1} v C(v) \frac{dv}{dt} dt =$$

$$= \int_{V_{MAX}/2}^{V_{MAX}} v C_R \left(1 - n \frac{V_{MAX} - v}{V_{MAX}}\right) dv$$

$$E = C_R V_{MAX}^2 \left(\frac{3}{8} - \frac{1}{12} n\right) \quad \text{Eq 4}$$

$$\frac{E}{E_R} = 1 - \frac{2}{9} n$$

For the value of n=0.35 taken from [19], E/E_R=0.922. This fact should be accounted for when configuring the ESS so that it contains the necessary usable energy.

5.2.1 ESS for kinetic strategy

Considering the Dutch Urban Bus Cycle (DUBC) where the maximum speed is around 60 km/h, the

maximum kinetic energy that the bus will have when it is fully loaded (12000kg) is 0.46 kWh.
Out of this energy, only around 60 to 65% reaches the supercapacitors due to the losses on the vehicle components, and the energy used to overcome the rolling resistance and the aerodynamic drag. An ESS with a usable energy capacity of 0.3kWh would be sufficient in this worst case scenario.
Utilizing Eq 4 to estimate the needed configuration:

$$E_{TOTAL} = N_{CELL} C_{Rcell} V_{MAXcell}^2 \left(\frac{3}{8} - \frac{1}{12} n \right)$$

$$E_{TOTAL} = 0.3kWh$$

With

$n=0.35$ and $V_{MAXcell}=2.5V$;

Now there are two degrees of freedom to choose the configuration. Using 3000F cells:

Configuration: 1string x 167 cells
Usable energy: 0.3 kWh
Max Voltage: 417.5 V
Cells weight: 91.8 kg

5.2.2 ESS for On-Off strategy

Due to the fact that the operation of the ICE will be at a power level higher than the average driving power (see section 4.2), the ESS absorbing the remaining power will receive an average power during the ICE on time expressed by.

$$\overline{P}_{SC} \cong \left(P_{ICEon} \eta_{gen} - \overline{P}_{cycle} \right) \cdot \eta_{DC/DC} \qquad \text{Eq 5}$$

Where:
$\overline{P}_{SC}$ is the average SC stored power during ICE-on time: $\overline{P}_{cycle}$ the average cycle driving power at vehicle DC bus and P_{ICEon}, the ICE power during its on period.
To define the energy capacity of the ESS for this strategy, the minimum ICE on-period (t_{ICEon} *in* Eq 6) should be defined.

$$E_{SC} \cong \overline{P}_{SC} \cdot t_{ICEon} \qquad \text{Eq 6}$$

The usable energy capacity of the system is therefore defined by $\overline{P}_{SC}$ and the average 'on-time'. In the case of the DUBC cycle, the average driving power, P_{cycle} is 20 kW and the ICE on power is 70 kW (power at which the ICE efficiency is maximum).
From Eq 5, $\overline{P}_{SC} \cong 39$ kW.
Assuming we would like to ensure an average ICE operation of 1 min after the engine started, then, according to Eq 6 the ESC should have, at least, 0.65 kWh of energy capacity. This on-time period will depend on the cycle part. If the vehicle is accelerating and cruising, the ICE-on time will be longer. However, if there are several braking phases, the ICE on-time will be shorter.
A possible configuration using 3000F cells:

Configuration: 2 string x 180 cells
Usable energy: 0.65 kWh
Max Voltage: 450 V
Cells weight: 198 kg

Smaller size should be avoided for this strategy since the engine on-time would be very short

5.2.3 ESS for Average Power Strategy

The Average power needed for the cycle at the DC bus level is 20.7 kW. Accounting the losses on the DC/DC converter, the average power should be 24.4 kW.
The remaining power to be provided by the SC presents the profile given by Figure 17.

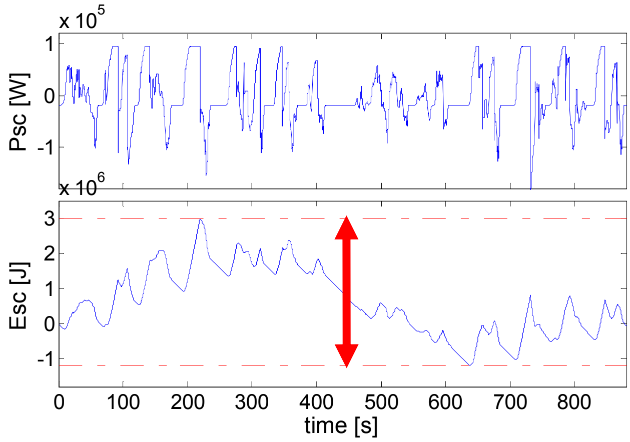

Figure 17. Needed ESS power & energy profile

The theoretical energy needed to cover this cycle is obtained from the energy chart of Figure 17 and it would be 1.17 kWh. Using again Eq 4 and 3000F cells

Configuration: 4 string x 165 cells
Usable energy: 1.19 kWh
Max Voltage: 412.5 V
Cells weight: 363 kg

The needed energy content of the ESS for this strategy is very high. However it could be reduced if the ICE could slowly vary its power in function of the load and the ESS state of charge.

6 Results

Simulations are based on the DUBC cycle. However, the conventional vehicle can not follow the whole cycle due to power limitations. Therefore the real speed achieved by the conventional vehicle (green line in Figure 18) is used to compare its consumption with that of the hybrid retrofitted version.

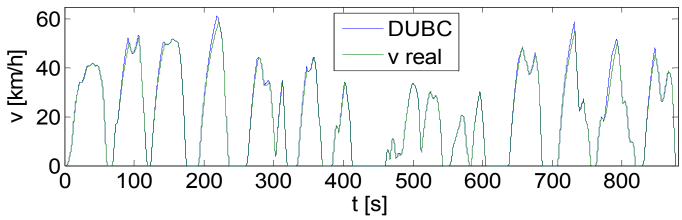

Figure 18. DUBC cycle vs. vehicle real speed

Results are displayed in Table 1. In the normal case scenario the savings go from 32.6 % when using the *kinetic strategy* and a small ESS (0.3 kWh) to 40 % when using the ICE on-off strategy and an ESS of 0.65 kWh.
The advantages of the kinetic strategy are the small size of the ESS and the reduced losses on the ESS due to the fact that it mainly stores the braking energy; there is almost no energy from the ICE stored on the ESS. On the other hand the ICE efficiency is not much improved (from 29.5% of a conventional vehicle to 33%).

The strong points of the *ICE on-off* strategy are the high ICE efficiency (40.9 %) and the avoidance of the ICE idling consumption. Their drawbacks are the high losses in the ESS (1.23 kWh against the 0.49 kWh of the kinetic strategy) due to the high energy flow on it (6 kWh stored against the 2.42 kWh in the kinetic strategy). All in all the performance is very good and reaches up to 40% fuel consumption reduction. Increasing the ESS size improves the performance due to the fewer on-off engine transients (see *ICE on-off 2* row of Table 1).

The 'average power' strategy does not seem to be a good solution for this case study since it requires a huge ESS and does not produce an outstanding performance (36% energy savings with 1.19 kWh ESS against the 32.6% of the kinetic strategy using an only 0.3 kWh ESS). Its strong points are the inexistent ICE inertial losses and the, in principle, good ICE efficiency (36.3 % in this case). On the negative side, it can be observed that the losses on the ESS are also very high (0.96 kWh).
This strategy can be slightly modified in a way that the ICE follows the load when the SoC of the ESS is going beyond the upper or lower boundaries. Thus, a smaller ESS could be used. Results are shown in Table 1 (under *Av power 2* row), where a 0.65 kWh ESS (against the 1.19 kWh of the original) is used. The savings fall to 34.3% (only 1.7% less than the original). ICE efficiency is slightly reduced and the energy flow on the ESS decreases, which entails lower losses on the ESS.
Since the losses on the ESS are important especially for the 'ICE on-off' and 'average power' strategies, another scenario is run when the efficiency of the DC/DC converter goes up to 95 % (originally it was set to 91%). This fact strongly improves the performance of these two strategies with fuel consumption reductions almost 5% higher. In the kinetic strategy, the fuel consumption reduction is improved by only 2 %.

	EES		Results								Savings
Strategy	Usable energy [kWh]	DC/DC eff [%]	Consump [l/100 km]	ICE eff [%]	ESS given energy [kWh]	ESS stored energy [kWh]	DeltaE [kWh]	Losses ESS [kWh]	Energy generator [kWh]	Eq. fuel consump [l/100km]	Energy savings [%]
Conventional	-		52,89	29,58	-				6,80	52,89	-
Hybrid											
Kinetic	0,30	91	35,85	33,11	1,89	2,42	0,03	0,49	5,20	35,66	**32,6%**
ICE on-off	0,65	91	33,22	40,90	4,53	6,07	0,32	1,23	6,04	31,72	**40,0%**
Av. power	1,19	91	35,26	36,30	4,09	5,31	0,27	0,96	5,81	33,83	**36,0%**
Modified											
ICE on-off 2	**0,97**	91	30,59	41,46	4,39	5,54	0,07	1,08	5,73	30,26	**42,8%**
Av. power 2	**0,65**	91	34,96	35,17	3,71	4,68	0,03	0,93	5,57	34,75	**34,3%**
DC/DC eff 95											
Kinetic	0,30	**95**	34,76	33,11	2,02	2,37	0,03	0,32	5,04	34,54	**34,7%**
ICE on-off	0,65	**95**	30,89	40,96	4,66	5,76	0,34	0,76	5,63	29,29	**44,6%**
Av. power	1,19	**95**	34,16	36,15	4,11	5,12	0,47	0,54	5,60	31,62	**40,2%**
Modified											
ICE on-off 2	**0,97**	**95**	30,17	41,29	5,03	6,07	0,31	0,73	5,62	28,71	**45,7%**
Av. power 2	**0,65**	**95**	33,40	34,99	3,82	4,51	0,13	0,58	5,27	32,70	**38,2%**

Table 1. Results of energy savings of the hybrid bus with different ESS and power flow management strategies

7 Conclusion

An enhanced backwards/forward model of a series hybrid vehicle has been presented with the aim of reducing the fuel consumption, evaluate different power flow management strategies and design the adequate ESS.

In addition, several strategies have been presented and compared. It has been proven that the influence of these strategies in both the energy savings and the sizing of the ESS, is very clear and that the appropriate power flow strategy should be chosen in function of the vehicle features and use.

The results obtained in the simulation lead to two possible options for this case-study. The small ESS (0.3 kWh) used for the *kinetic strategy* leads to very good results. Up to 32 % fuel consumption reduction is achieved by means of braking energy recovery and slight ICE efficiency improvement.

The other possibility for this case is the ESS of 0.65 kWh with the *ICE on-off* strategy. This option would be really interesting if a high efficient DC/DC converter was present, in which case, the energy savings would reach 44%.

The average power strategy is not an option for this case study since the ICE was designed to drive the vehicle by itself. However this strategy could be interesting when designing a hybrid vehicle from scratch. In that case, the ICE could be downsized and designed to perform at maximum efficiency at the average driving power (between 20 and 30 kW for the considered driving cycle).

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