

A DISCUSSION OVER THE ENERGY STORAGE CAPACITY FOR HYBRID ELECTRIC VEHICLES

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***Abstract.** This paper focus on the study of energy storage and management for hybrid electric vehicles. The development of higher efficiency vehicles depends on the analysis of vehicle performance characteristics and driving conditions. Sizing the energy capacity of the storage system, using batteries or other kinds of electric components, can be considered a big challenge once oversizing means inefficiency due to the increase of weight and undersizing results in partial use of hybrid advantages. The forces involved in a vehicle movement such as aerodynamic drag, rolling resistance and grading resistance, are fully dependent on the conditions of every possible course the driver might run, most situations should be represented on the driving pattern cycle, used for emissions and consumption tests, which will be presented and discussed. Modeling vehicle dynamic to analyze power and energy demand of each vehicle during different test cycles provides an indication of the benefits on hybrid system for performance and fuel consumption.*

Keywords: Hybrid electric vehicle; Energy storage; Optimization of capacity; Vehicle Dynamics

1. INTRODUCTION

The need for personal mobility and transport in general has made the automobile become very important for the modern society development. Their wide diffusion made the automotive industry one of the main sectors on our economy. However, the current environmental issues and the depletion of natural resources suggest that some changes to the actual scenario might be inevitable.

The emissions of internal combustion engines are responsible for a great part of the air pollution, and researches indicate that the release of CO₂ in the atmosphere is related to the global warming. On the other hand, the extensive use of oil creates a difficult situation due to its limited availability, which generates recurring increases in price and even international conflicts. This encourages the search for new sources of energy, like the biofuels and the hydrogen technology, but most important the development of vehicles with greater efficiency.

In this scenario the development of hybrid vehicles has reached a level of technical and strategic importance never imagined. Many associations of conventional and alternative energy sources can be used to maximize performance, to minimize consumption and the environmental impact.

Previous experience in electric vehicles showed the potential of the sector and at the same time exposed some critical factors of the present technology. The energy storage in batteries or similar usually offer little autonomy and long reloading times. The hybrids can potentially reduce these problems. An internal combustion engine connected to a generator eliminates the problem of autonomy and recharge of the pure electric vehicles. A correct sizing of the energy storage system can increase the benefits and reduce the negative impacts.

2. Hybrid Vehicles

The searches for alternative propulsion systems have found many solutions based on hybrid systems, with more than one type of energy source, in order to explore the benefits of each traditional setting. The Hybrid Electric propulsion systems have been developed with the objective to use the advantages of pure electric vehicles, mainly their higher energy efficiency, along with the advantages of internal combustion engines, which are the low refueling time and the high amount of energy contained on chemical fuels.

Hybrid Electric Vehicles (HEV) combines the operation of Internal Combustion Engines (ICE) and electric motors. The large number of settings allows the division into two main groups: series hybrids and parallel hybrids. In a series hybrid a combustion engine turns a generator that powers the batteries and/or directly the electric motor. There is no mechanical coupling between the two types of motors. In a parallel hybrid the vehicle is propelled by the combustion engine, the electric motor or both together, generally the electric motor also work as a generator when not used for traction, to charge the batteries.

2.1 Performance and Strategies

The HEV's performance depends on the characteristics of these different motors. It's said that an ideal engine is one that produces a constant power regardless of speed, Jazar (2008). Internal combustion engines are far from the ideal conditions, so a transmission is set to keep the engine running in a working range around the maximum power. Most

vehicles use manual gear transmission, automatic transmission or CVT to obtain a traction force curve near to the ideal. Electric motors are approximated to constant power performance they can be used with single gear transmissions or even directly connected to the wheels.

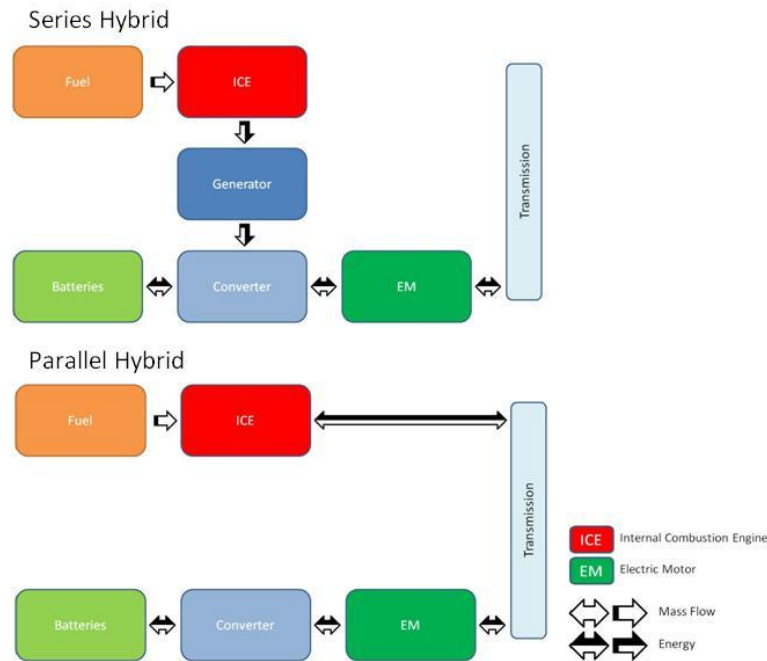


Figure 1. Series and Parallel settings.

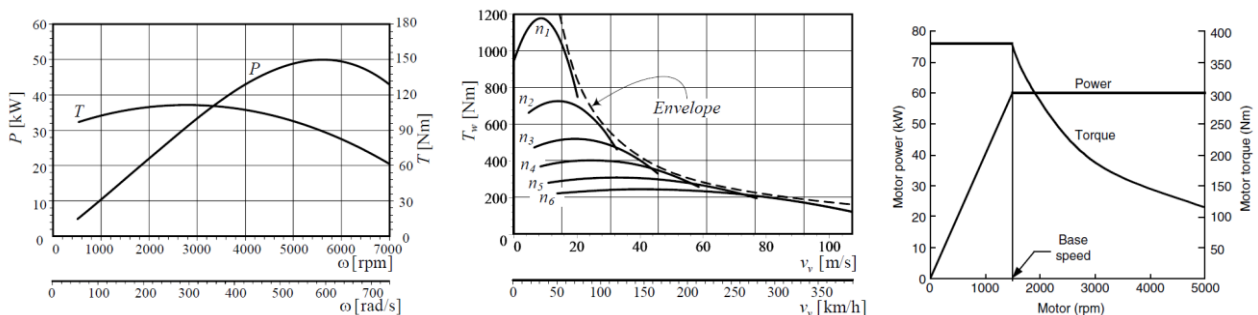


Figure 2. On the left internal combustion engine characteristic performance, Jazar (2008), on the middle tractive effort for a conventional vehicle, Jazar (2008), on the right electric motor characteristic performance, Ehsani *et al.* (2005).

The required power for the vehicle movement has large variations during a real path due to acceleration, braking, climbs and descents. This power can be decomposed into two parts, one of constant value with the average power and the other a dynamic component, with mean equal to zero. A strategy to obtain better operation efficiency, should concern the electric motor efficiency and the engine efficiency. Usually the electric motor efficiency is less sensitive to load variation. One possible strategy is to set the combustion engine to work optimized to maximum efficiency, providing the average power, and let the electric motor be responsible for the dynamic variation of the load.

2.2 Energy Storage

Batteries used for vehicle traction must meet certain characteristics: high specific energy to obtain good range, high power density to provide the necessary performance, long cycle life and low maintenance requirements. The most used technologies for batteries are the Lead, Nickel and Lithium based batteries.

For over a hundred years, the lead-acid batteries have been the standard electrical energy storage for power applications, including traction, backup and standby power systems. Some significant advances in research, over the last decades, the development of the sealed lead-acid has provided an alternative to the flooded lead-acid designs, still more

energy density is being demanded. The advances produce specific energy over 40Wh/kg and specific power over 280W/kg, Kiehne (2003).

The Nickel based batteries have been in existence since for almost a century. The Ni-Cd systems started with a modest beginning, advances since 1950 have brought enormous improvements in specific energy (85Wh/kg), specific energy (over 220W/kg), long cycle life (up to 2000 cycles) and wide operating temperature (-40 to 85°C). A strong growth of the rechargeable battery consumer appliance made the Ni-Cd to be a market dominator for quite a while. However, the carcinogenicity and environmental hazard of cadmium has accelerated the development of the alternate Ni-MH system. The use of hydrogen absorbed in a metal hydride has eliminated the toxicity and improved the specific energy compared to the Ni-Cd.

The Ni-MH is still under development. Its characteristics are very similar to the Ni-Cd. For high energy applications the present technology delivers up to 95Wh/kg of specific energy and up to 200W/kg of specific power. For high power applications offers specific energy of about 40Wh/kg and specific power of about 1kW/kg. It's been used in hybrid vehicles like Toyota Prius and Honda Insight.

The Lithium-Ion battery is considered to be the most promising rechargeable battery. Lithium is the metal with highest negative potential and lowest atomic weight. Batteries using lithium have the greatest potential for attaining the technology to provide the electric vehicles the best performance characteristics in terms of range and acceleration. Also under development the present technology for high energy applications provides specific energy up to 150Wh/kg and specific power up to 300W/kg. Li-ion batteries for high power applications offer specific energy of about 60Wh/kg and specific power up to 1.5kW/kg. There is still another kind of lithium batteries using a solid state electrolyte called the Lithium-Polymer (Li-P or PLi-ion) some of the advantages are the very low self-discharge rate (0.5% per month) and the possibility of different shapes and sizes in a safe design, Ehsani *et al.* (2005).

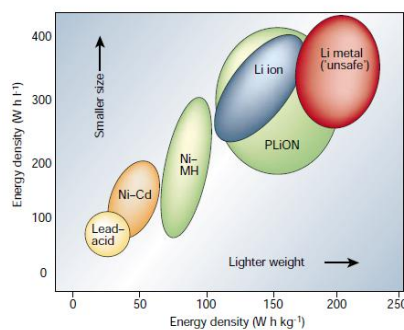


Figure 3. Relation between volumetric energy density and mass energy density, for the main types of batteries, Tarascon and Armand (2001).

The battery life cycle is directly affected by the degree of discharge (DoD), which is defined as the difference between the initial and the final SOC. The State of Charge (SOC) is defined as the amount of charge still present in the battery, so a fully charged battery has SOC equal to 100%, and a fully discharged has SOC equal to 0%. This means that to increase the number of cycles, the DoD must be reduced. An amount of charge will be carried but not used. The operation in a conventional HEV, when all the energy comes from the engine, is called Charge-sustaining mode, in this mode the state of charge increase and decrease during one cycle, but in the end the SOC return to the initial value. The operation for a Plug-in HEV (PHEV), this kind of vehicle has bigger energy storage to provide all electric operation range. They work on the Charge-depleting mode in which the stored energy has a deep reduction during one cycle. When the SOC decreases to a minimum level the vehicle starts working as a conventional HEV on the Charge sustaining mode.

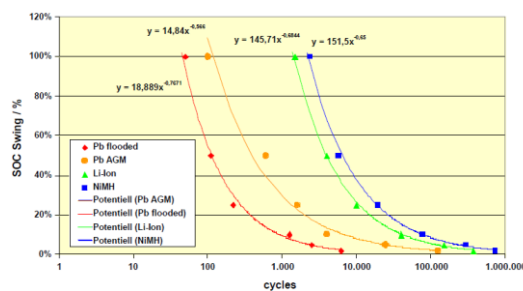


Figure 4. On the left estimated cycle life for different degrees of discharge, Pesaran (2007), and on the right cycle life for 80% of discharge, McDowall (2001).

Because of the frequent acceleration/deceleration operation the charging profile of the storage system is highly varied. Design for storage system try to obtain maximum specific energy and specific power on the same batteries. The difficulty in achieving this situation ends up increasing costs. This has led to suggest the use of two kinds of storage one with high energy and another with high power characteristic. Another possible kind of electric storage is the supercapacitor or ultracapacitor.

Supercapacitors have much greater advantage over batteries when storing and supplying short bursts of power due to their higher specific power limits, and ability to charge and discharge very quickly. The specific power can reach over 10kW/kg, and the specific energy, on present technology, about 3Wh/kg. Applying supercapacitors also allows for a smaller battery pack. Direct connection of the supercapacitors and the batteries does reduce transient currents and prevent battery abuse, but to achieve optimal performance the best way is to control its energy content through a power converter, Pay and Baghzouz (2003). Control strategies are presented on Fig. 5.

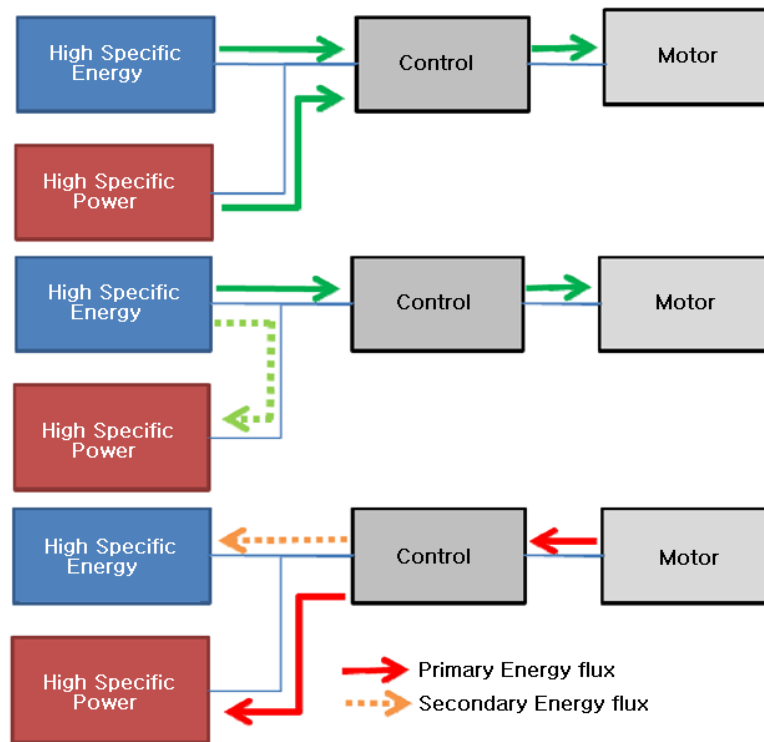


Figure 5. Energy flux under three different situations, maximum performance, low demand state and regenerative braking.

2.2 Longitudinal Vehicle Model

Vehicle Longitudinal Movement is composed by the Traction Force (front, rear or both), and the Resistance Forces (rolling resistance, aerodynamic drag and grading resistance).

$$M_v \frac{dv}{dt} = F_{traction} - F_{resistance} \quad (1)$$

$$M_v \frac{dv}{dt} = (F_{t\ front} + F_{t\ rear}) - (F_{rolling} + D_{aerodynamic} + F_{grading}) \quad (2)$$

$$F_{traction} = M_v \frac{dv}{dt} + F_{resistance} \quad (3)$$

The rolling resistance is one of the most important resistance forces, on speeds under 80-90km/h it is the bigger component. During the tire turning on a road, the material that goes over the pavement undergoes a deflection. The material hysteresis dissipate part of this deformation energy and change the contact pressure distribution moving the resultant contact force to the front of the tire, fig. 8, creating a moment opposing to the turning of the wheel.

The rolling resistance force equation is expressed on Eq. 4, where P is the vehicle weight over the tire, f_r is the rolling resistance coefficient and α is the ground inclination.

$$F_r = P * f_r * \cos(\alpha) \quad (4)$$

The rolling resistance coefficient is depends on several aspects, empiric relations for speed can be used for certain conditions. Eq. 5 can be used to speeds lower than 130km/h.

$$f_r = 0,01 * (1 + \frac{V}{100}) \quad (5)$$

The aerodynamic drag is usually expressed by the Eq.6, derivate from the Bernoulli equation, where A is the projected frontal area, C_d is defined as the Drag coefficient, ρ is the air density and V is the relative speed between the vehicle and the wind.

$$D_A = \frac{1}{2} * A * C_d * \rho * V^2 \quad (6)$$

The grading resistance is related to the horizontal weight component created by an inclined road, Eq. 7.

$$F_i = M_v * g * \text{sen}(\alpha) \quad (7)$$

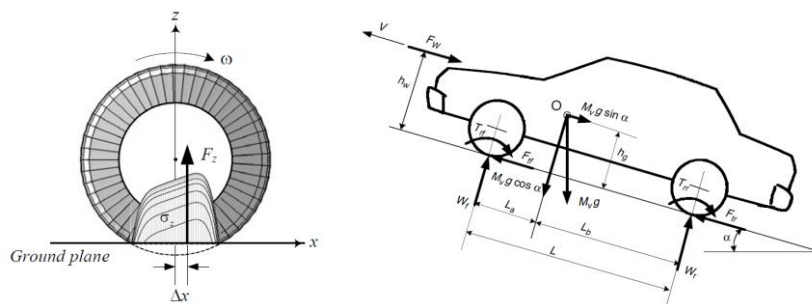


Figure 8. On the left, tire contact force distribution, Jazar (2008) and on the right, forces acting on the vehicle, Ehsani *et al.* (2005).

The movement equation for the vehicle is expressed on Eq. 8.

$$M_v \frac{dV}{dt} = F_{traction} - (0,01 * (1 + \frac{V}{100}) + \frac{1}{2} * A * C_d * \rho * V^2 + M_v * g * \text{sen}(\alpha)) \quad (8)$$

$$F_{traction} = M_v \frac{dV}{dt} + 0,01 * (1 + \frac{V}{100}) + \frac{1}{2} * A * C_d * \rho * V^2 \quad (9)$$

$$P_{required} = [M_v \frac{dV}{dt} * V + 0,01 * (V + \frac{V^2}{100}) + \frac{1}{2} * A * C_d * \rho * V^3] \quad (10)$$

2.3 Simulations

To know the direct influence of this technology on existing vehicles, it's important to perform some simulations and further tests to obtain results. The urban driving cycle (NBR6601), is 12km long, has average speed of 32km/h and maximum speed of 91.2km/h. The vehicle stand still on 17.2% of the time, on real traffic of big cities this time may be a lot longer. This cycle also doesn't include uphill or downhill operation. Although the urban cycle doesn't fully represent real driving conditions, it is a good way for comparing energy consumption. Assuming the average distance driven per day is 37.87km, Kiehne (2003), each simulation will run 3 urban cycles, resulting 36km.

Three situations are going to be availed, first a conventional vehicle, than an HEV and finally a Plug-in HEV which can have external electric charge.

A normal HEV works on an operation mode called Charge-sustaining mode in which the final state of charge is equal to the initial. For those vehicles the real energy source is the fuel used on the ICE as the balance between the initial and the final electric energy on the storage system is zero. The advantages here are the regenerative braking, and the possibility to keep the ICE working on a better efficiency level.

The Plug-in HEVs have the same architecture of the normal HEVs. These vehicles have two energy sources due to the charging of the energy storage system on the electrical grid. They work in Charge-depleting mode which means that the final SOC is different from the initial. In these cases the vehicle uses the electric propulsion more often increasing the influence on fuel consumption. During the depleting of the storage system, once the SOC reaches one programmed minimum level the vehicle starts working in Charge-sustaining mode just like a normal HEV.

The following simulations will be used to analyze the potentialities of these solutions compared the conventional vehicle. One relevant factor on these solutions is the increase of weight produced by the storage system, and the electric motor itself. Giving importance to analyze the effect of the vehicle added weight on the total energy consumption. The input data for the simulations are, Mass = 900kg; $A = 1.8m^2$; $C_d = 0.32$; $\eta_{eng.(opt)} = 0.35$; $\eta_{eng.(average)} = 0.21$; $\eta_{transm.} = 0.84$; $\eta_{elect.motor/generator} = 0.8$; Gasoline (E22) Heat Value = 9600kcal/kg (11.43kWh/kg).

2.4 Results

2.4.1 Simulation 1 – Conventional vehicle

The results for the first simulation can be seen on Fig. 9, which for better viewing show the results for the first third of the simulation. These results are calculated as the speed, traction force and required power at the wheels. After considering the efficiencies involved, the energy and power are given for the first case. The maximum power was 34.2kW, the energy provided on the wheels 4.72kWh, equivalent to 2.25kg of fuel giving an average consumption of 12.1km/l.

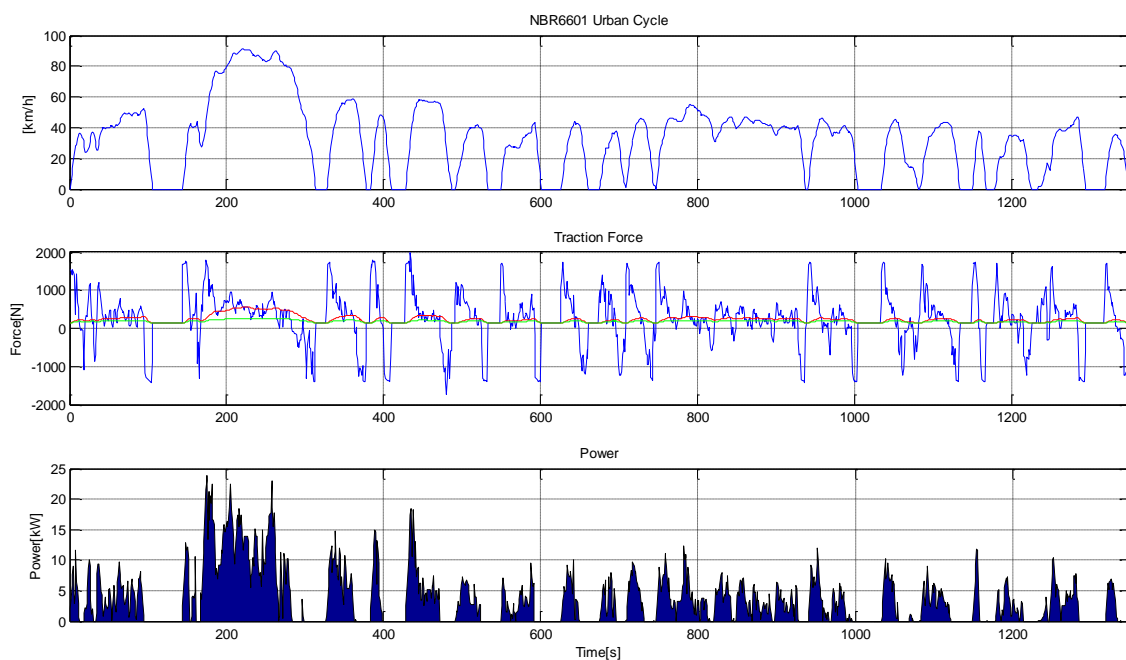


Figure 9. Speed (km/h), Traction Force (N) and Power (kW) for the first 12km urban cycle on a conventional vehicle.

2.4.2 Simulation 2 - Hybrid Electric Vehicle, Charge-sustaining mode

For the second case there are now two power sources and as explained before for better overall fuel economy the ICE keeps providing the average power required on the cycle and the electric source provides the transient power, Fig. 11. On this strategy the Charge-sustaining mode is respected as the initial SOC is the same as the final SOC, Fig. 12. Now the electric energy storage has to provide a maximum power of 31,6kW and must have at least 396Wh of capacity for the SOC variation during the cycle. The ICE provides 4.72kW and 4.46kWh at the wheels. This doesn't take into account the extra weight of the electrical components which will be added later.

Table 1. Power and energy requirements on urban cycle for the HEV.

Power and energy requirements			
Electric		ICE	
Maximum Power	31.6kW	Average Power	4.72kW
Energy Window	396Wh	Total energy	4.46kWh

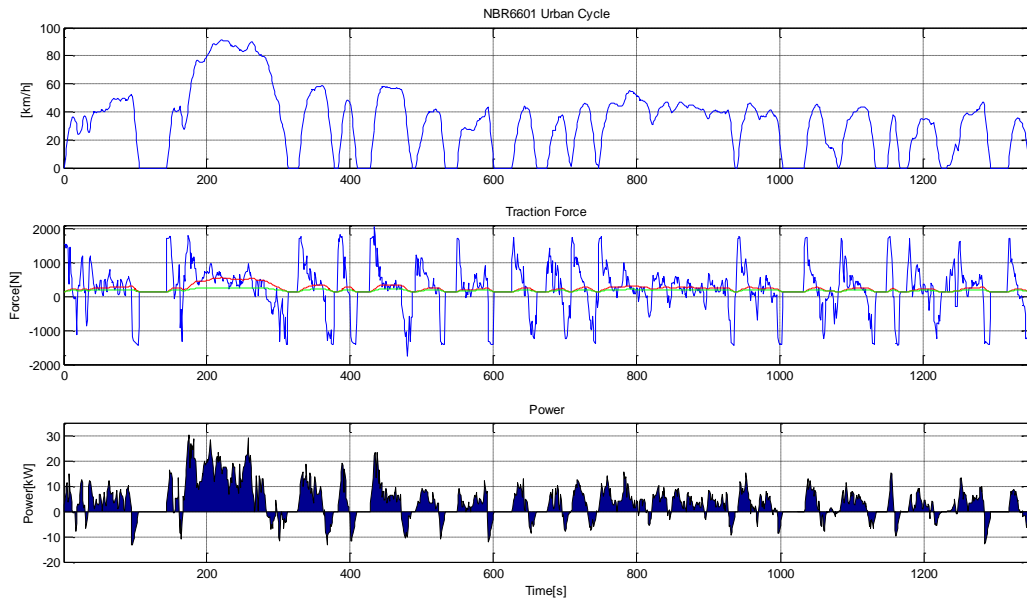


Figure 10. Speed (km/h), Traction Force (N) and Power demand (kW) for the first 12km urban cycle on a HEV.

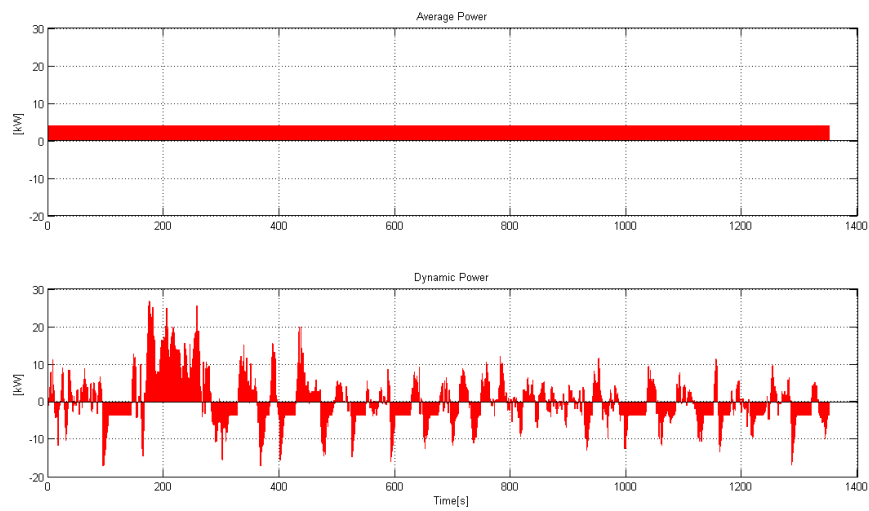


Figure 11. Average and dynamics Power components for the first 12km.

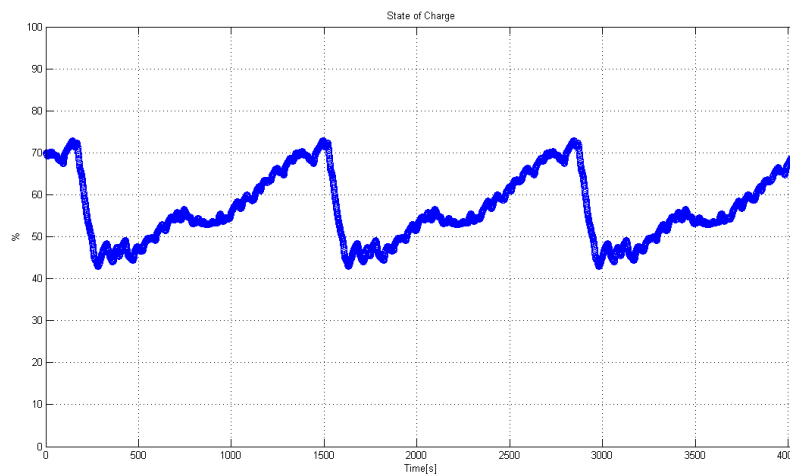


Figure 12. State of charge during the 36km simulation cycle.

2.4.3 Simulation 3 - Plug-In Hybrid, Charge-depleting mode

On the last simulation the ICE is kept turned off for the first 24km where the vehicle is on full electric traction, Figure 12. At this point the engine starts up to stabilize the SOC like in a normal HEV on the Charge-sustaining mode, Figure 13. On this situation the ICE consumption reduces even more but it's necessary to take into account the energy supplied by the electric grid. The peak power for the electric storage is 35.9kW and the energy capacity must be at least 3.16kWh where 2.88kWh were depleted during the Charge-depleting mode. The ICE had to provide a maximum power of 4.9kW and 1.49Wh to the wheels.

Table 2. Power and energy requirements on the 36km urban cycle for the PHEV.

Power and energy requirements			
Electric		ICE	
Maximum Power	35.9kW	Average Power	4.9kW
Depleted Energy	2880Wh	Total energy	1490Wh
Energy Window	3160Wh		

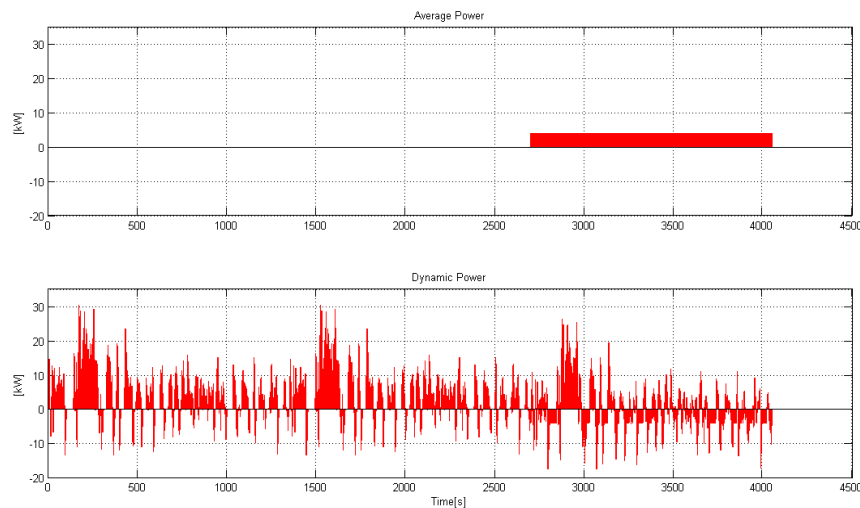


Figure 13. Average and dynamic Power components for the complete 36km cycle.

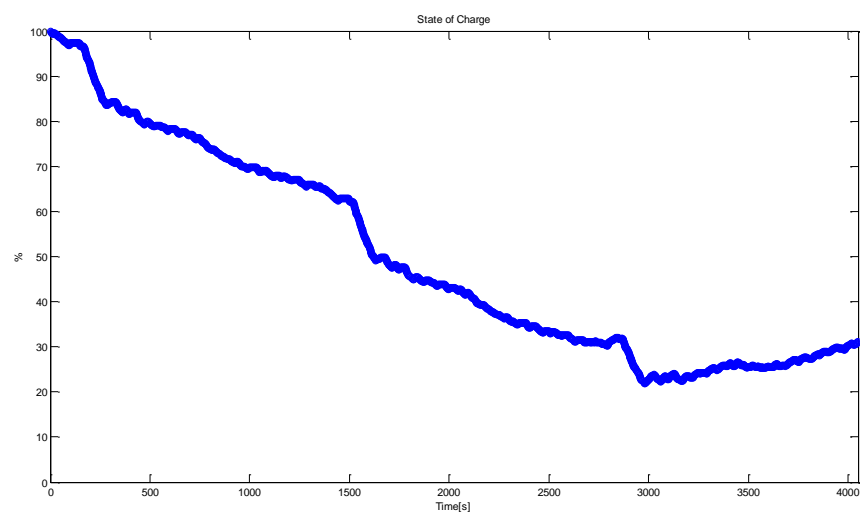


Figure 14. State of charge during the complete 36km cycle.

The life cycle expected for a battery package in a HEV is about 10 to 15 years. For the cycle simulated earlier the HEV has three deep discharges during one day, approx. 15000 cycles, and the Plug-in HEV has one deep discharge during a day, approx. 5000 cycles. Duvall (2005) present estimated relations between DOD and life cycle of different

batteries. For the HEV case using NiMH batteries the DOD is 29%, using Li-ion Batteries the DOD is 20%. For the Plug-in HEV, NiMH batteries use 59% of DOD and Li-ion Batteries use 42% of DOD.

Table 3. Energy requirements for the storage system.

	Energy Requirements (Wh)	NiMH Weight (kg)	Li-ion Weight (kg)	Supercapacitor Weight (kg)
HEV	396	34	30	99
Plug-in HEV	3160	76	83	785

Table 4. Power requirements for the storage system.

	Power Requirements (kW)	NiMH Weight (kg)	Li-ion Weight (kg)	Supercapacitor Weight (kg)
HEV	31.6	31.6	21	3.5
Plug-in HEV	35.9	199	163	4

The Li-ion Batteries take advantage over the NiMH when only using electrochemical batteries on both simulated situations. Proposing the use of two types of storage components, batteries and supercapacitors, different results are obtained, for the HEV the use of high power Li-ion batteries still results on the minimum weight, but for the Plug-in HEV the use of NiMH batteries in association with supercapacitors present the minimum weight, as seen on Tab. 5.

Table 5. Comparison between different solutions.

	Best Battery Solution	Best Associated Solution
HEV	Li-ion: 30kg	Li-ion+SC: 33.5kg
Plug-in hev	Li-ion: 163kg	NiMH+SC: 80 kg

Table 6. Final results of the simulations, influence of the increased weight and total fuel consumption.

	Energy Consumption (kWh)	Increase Energy Consumption		Fuel Consumption (kg);(km/l)
		Batteries	Bat.+SC.	
Conventional	4.72	0%	0%	2.25kg; 12.1km/l
HEV	4.46	2%	2%	1.35kg; 20.2km/l
Plug-in HEV	1.49	10.8%	5.3%	0.49kg; 55.4km/l

2.5 Conclusion

The present analysis shows some possible advantages of hybrid electric vehicles. The results showed significant reduction in fuel consumption for the described simulations. The effect of the weight due to the addition of electric components represents a significant part on energy consumption. So, the development of efficient energy management strategies and new electric storage technologies is very important to the design of higher efficiency vehicles, to decrease oil dependency, emissions of CO_2 and pollutant gases produced by internal combustion engines. The main obstacle on the process is recognizing the vehicle use for each driver, once the driving conditions are highly connected to the energy consumption, being necessary to analyze each case in particular.

3. ACKNOWLEDGEMENTS

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