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Environomic Design of Vehicle Integrated Energy System – Application on a Hybrid Electric Vehicle Energy System

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With the increasing trend of mobility of the human population, vehicles have to face the problem of primary energy resources scarcity. The vehicles need higher efficiency and better adaptation to the alternative energy sources.
The need to improve the efficiency of the vehicle energy system motivates to search for innovative solutions during the design process.
The main design criteria for modern sustainable development of vehicle powertrain are the high energy efficiency of the conversion system, the competitive cost and the lowest possible environmental impacts. These objectives are most of the time antagonistic. To cope with this challenge the automotive engineers need a structured optimization methodology. A multi-objective optimization methodology is being applied as search for the best powertrain design solutions.
This kind of approach named “multi-objectives optimization” is based on genetic algorithms, which are based on the process of natural selection.
An innovative decision- making methodology, using this optimization technic is currently under development at PSA Peugeot Citroën.
The idea is to obtain simultaneously a population of possible design solutions corresponding to the most efficient energy system definition for a vehicle. These solutions are optimal from a technical, economic and environmental point of view.
In this article the methodology is applied on a hybrid electric vehicle study in order to define the powertrain configuration of the vehicle, estimate the cost of the powertrain equipment and show the environmental impact of the technical choices on the lifecycle perspective of the vehicle.
For that a physical model of a hybrid electric vehicle is made. This model is coupled with a cost model for the vehicle and life cycle assessment (LCA) technics are used for the environmental assessment. After multi-objective optimization, the outcoming solutions from the Pareto frontiers curve are analysed.

1. Introduction

Energy strategies have been developed to reduce the usage of fossil fuels and reduce the CO_2 emissions (Gerber, 2012a). The NegaWatt scenario (ANW, 2011) can be given as an example. However, the mobility is almost 100 % insured by fossils.
In the traditional energy scenario by 2040, 90 % of the global transportation will run on liquid petroleum based fuels (ExxonMobil, 2012). The proliferation of hybrid and other advanced vehicles – along with improvement of the conventional vehicle efficiency will result in flattening the demand for petrol for personal transportation, even as the number of personal vehicles in the world doubles.
The global competition for affordable energy and resources will lead to an increase of the diversification of energy sources, fuel types, and vehicles (ERTRAC, 2011).
Alternative biofuels should be prospected for the reducing the CO2 impact of transport (Ensinas et al. 2013), but also other environmental impacts have to be taken into account trough an integrated approach based on the Well-to-Wheels analysis and LCA tools.

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The largest applied convertors in passenger cars are the internal combustion engines – gasoline, diesel, adapted also for operating on biofuels. The number of components that are necessary to realize modern future propulsion system is inexorably increasing. The best possible results are not obtained by an isolated optimization of each single component. Optimizing the entire system however is not possible with heuristic methods (Picollo et al., 2001). According to Guzzella (2013b), the only viable approach to cope with this dilemma is to develop mathematical models of the components and to use model-based numerical methods to optimize the entire system structure.

2. Optimization methodology

The vehicle simulation tool is SIMULINK®. The vehicle model is based on mechanical and electric flows. The level of the model is quasi-static. The vehicle is able to follow dynamic profiles coming from a library of normalized vehicle drive cycles.

For system problems optimization, numerical approaches are used. In this study, multi-objective optimization is performed with the OSMOSE tool. The general computational framework of OSMOSE has already been described in Gerber (2011) and used in (Mian et al. 2013). The methodology is adapted here for a vehicle application. The optimizer in OSMOSE is based on a genetic algorithm. This optimization technique is multi- modal and gives local optimums. Others algorithms and mathematical programming based methodologies (Hul, 1996), are used for unitary heuristic compounds design – for example vehicle battery or control systems (Earl and D'Andrea, 2002);

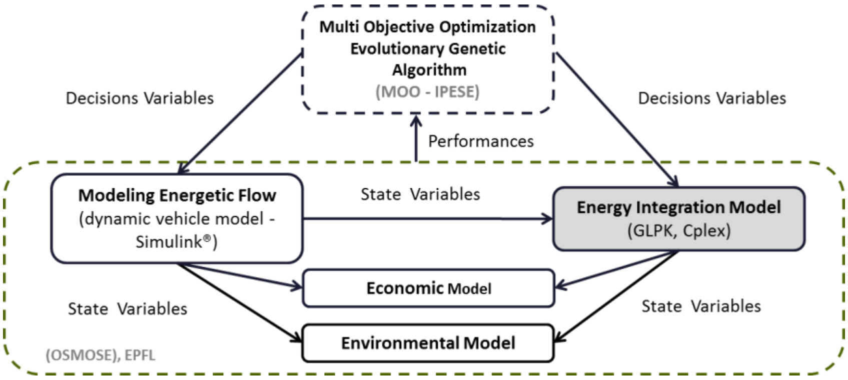

Figure 1 : Architecture of the environomic vehicle design model

2.1 Economic model:

The cost of the vehicle is computed for each run, as a function of the energy convertors and energy storage devices size and efficiency.

The cost of the equipment comes from the literature and is related to the size of the components (electric motor - 30 [€/kW]*p_em [kW], 15 [€/kW]*p_th_engine [kW] (Guzella, 2005), battery cost in table 1).

The nominal cost represents the vehicle body cost without the powertrain compounds. This linear correlation (Table 1) takes into account the prices of the parts and the manufacturing cost of the vehicle shell and includes the sales margin of the carmaker. For each calculation, a new vehicle weight is calculated, updated with the weight of the defined powertrain.

A simplified vehicle objective cost function is constructed, taking into account the vehicle powertrain cost (production) and vehicle operating cost.

The cost is presented from customer perspective and defines the total cost of mobility (Eq(3)).

$$\text{cost\_(customer investment)} = \text{cost\_powertrain} + \text{cost\_body} + \text{cost\_(CO2 emissions)}, [€] \quad (1)$$

$$\text{cost\_operating} = \text{cost\_(fuel consumption)} = \text{cost\_(fuel type)} * \text{fuel\_consumption} * \frac{150{,}000}{100} [€]$$

$$+ \text{cost\_(electric consumption)} * \text{electric\_consumption} * \frac{150{,}000}{100} [€] \quad (2)$$

$$\text{totalcost\_mobility} = \text{cost\_(customer investment)} + \text{cost\_operating} \; [€] \quad (3)$$

Table 1: Equations for the economic model

Components	Costs [€]
Storage system -Battery (Guzella, 2005)	600*[€/kW]* $q_{bat}^{0.2477*\log(bat_{specifmass}(bat\_type)+0.5126)}$, qbat- battery capacity
Body	
Nominal cost	17.3*mass[kg]-3905.4 [€]
Vehicle use in France 2013 (French government, 2013)	
Electricity household	0.14269 [€TTC/kWh]
Gasoline	1.645 [€/L]
Diesel	1.451 [€/L]

The vehicle cost of hybridization is the sum of the vehicle body and powertrain costs, depending on power-train architecture configuration and size. The vehicle cost during the use phase is only the cost of energy consumption for the LCA functional unit – 150,000 km. In this study the maintenance cost is neglected.

2.2 Environmental model

This study refers to the GWP 100 y impact. The functional unit for the LCA vehicle study is to transport passengers across on 150,000 km for 10 y (Richet, 2012). The inventory in the production phase is composed from a hybrid electric Peugeot 3008® vehicle combined with unitary processes from the Eco Invent® database. The use phase corresponds to the energy consumption of the vehicle. The inventory for the corresponding "energy carrier" production, comes from the Eco Invent® database. The maintenance and the end of life phases are represented by average technology car values from the Eco Invent® database.

3. Results: Application on a hybrid electric vehicle

3.1 Problem definition

A hybrid vehicle with multiple propulsion systems can be operated independently or together. The model contents are the electric machine, battery, thermal engine and fuel tank, with two possible fuels – diesel and gasoline. The objective is to size the components of the hybrid powertrain – the convertors and the storage tanks, regarding the fuel consumption and the cost objectives. A two objective optimization is considered, with minimization of the fuel consumption and minimization of the powertrain cost. At the same time, the environmental impact, GWP 100 y, from the Well-to-Wheel perspective is assessed. The optimization problem is defined in Table 2.

3.2 Multi objective optimization results for a hybrid electric vehicle with different fuels

The solutions of a two objective optimization converged on a Pareto Frontier optimal curve (Figure 2), representing the trade-off between the fuel consumption and the cost. With a vehicle body mass of 750 kg and as a function of the powertrain components design, one obtains solutions between 2.2 L/100 km and 0.6 L/100 km of fuel consumption. The cost, composed from of powertrain cost and the CO_2 taxes (bonus), varies between 7,500 € and 12,000 €.
The fuel consumption is influenced by the hybridization ratio, expressed through the battery size and the thermal engine efficiency (gasoline or diesel engine).

Table 2: Decision variables for the design

Hybrid electric propulsion system components:	Range	Unit
Electric Machine	37	kW
Battery Li-Ion capacity	[6.5 - 26]	kWh
Thermal Engine	43	kW
Fuel	[Gasoline-Diesel]	[-]

The powertrain cost is strongly influenced by the battery capacity, with a proportional coefficient of 600 €/kWh (Table 1). The solutions in Figure 2 can be organized in two zones, according to the hybridization ratio: Hybrid Electric Vehicles (HEV) and Range Extender (REX) - Plug-in Hybrid Electric Vehicles (PHEV).

The algorithm converges on battery size solutions regarding from 11 kWh to 26 kWh. For a Li-Ion battery, with an energy density of 90 Wh/kg, the battery mass varies between 120 kg and 288 kg. The integral vehicle mass is between 950 kg and 1,300 kg.
One point in each zone is selected and the design details are in Table 3.
In the HEV zone, for fuel consumption solutions around 2 L/100 km, the advantage of the diesel efficiency is visible. The minimal fuel consumption, for the body mass of 750 kg, is 0.6 L/100 km.
For an urban HEV vehicle of around 1,000 kg, with fuel consumption target of 2L/100km, a powertrain with a small engine (30 kW) could be interesting.
Figure 3 displays the cost structure for each point – 2 L/100 km HEV and REX vehicle. A commercial urban vehicle – Peugeot 107®, with a small gasoline engine, and a thermal powertrain is introduced for comparison.
The environmental bonus is applicable for all solutions. The vehicles are emitting less than 105 gCO_2/km. With an increase of the hybridization ratio, the powertrain cost increases strongly – from around 10 % of the cost of a conventional vehicle, to almost 50 % for the REX vehicle. This tendency is due to the increasing high tension (HT) battery cost (Table 4).

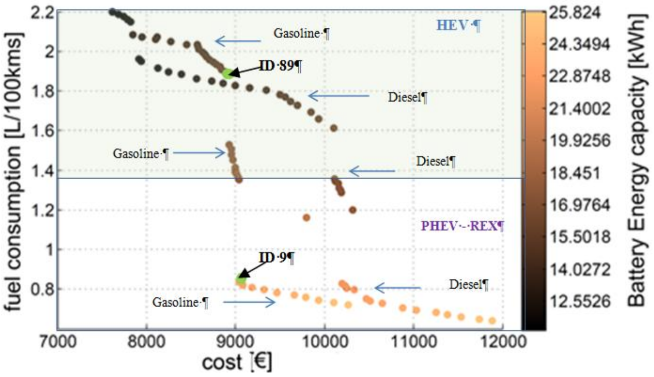

Figure 2: Multi-objective Pareto curve – hybrid vehicle: fuel consumption to powertrain cost

Table 3: Multi objective optimization results – details of the Pareto points

Characteristics	ID 89	ID 9
q_batt [kWh]	15.5	23.3
Battery type	Li-Ion	Li-Ion
Battery mass	172	259
Fuel type	Gasoline	Gasoline
Fuel consumption [L/100km]	1.88	0.83
Emissions CO_2 [gCO_2/km]	45.00	20.00
CO_2 emissions cost (bonus)	-5,000	-7,000
Battery cost [€]	9,300	13,980
Vehicle mass[kg]	970	1,060

Table 4: Orders of magnitude for powertrain configuration and fuel consumption for urban car

Cost structure	Peugeot 107® thermal	ID 89 HEV	ID 9 REX
Body cost [€]	8,700	9,070	9,069
High tension battery cost [€]	0	9,030	13,980
Electric machine cost [€]	0	1,110	1,110
Thermal engine cost [€]	750	645	300
Powertrain cost [€]	1,250	11,055	15,390
Vehicle mass [kg]	790	970	1,060
Thermal engine power [kW]	50	43	20

Table 5: Orders of magnitude for powertrain configuration and fuel consumption for urban car

Cost structure	Peugeot 107® thermal	ID 89 HEV	ID 9 REX
El machine power [kW]	-	37	37
Battery capacity [kWh]	0	15.5	23.3
Electric consumption [kWh]	0	0	5
Fuel type	gasoline	gasoline	gasoline
Fuel consumption [L/100km]	4.3	1.88	0.83
CO_2 emissions [g/km]	99	45	20

Let's consider that the customer is buying the entire car and the purchase price that he has to invest at the beginning varies from around 10,150 € for a conventional car, to 17,460 € for an REX vehicle, with a small gasoline engine (Figure 3).
If we consider the operating cost, for a thermal vehicle, for the functional unit of 150,000 km, it is equal to the investment cost, around 10,000 €. For the HEV, due to its low fuel consumption – (less than 2 L/100 km) its operating cost is reduced by more than 50 % to 4,640 €. For the REX vehicle, the operating cost is even lower – 3,100 € and represents 30 % of the conventional vehicle operating cost. The fuel consumption is responsible for 2/3 of the cost and the electricity consumption from the grid for 1/3 of the REX vehicle operating cost. The vehicle is considered being charged at home in France, with a cost of 0.14 kWh for the grid electricity. One has to notice, that in this study, the maintenance cost is neglected.
The total cost of mobility with a small urban vehicle, after 150,000 km, is almost the same for all discussed solutions, around 20,000 €. The thermal propulsion vehicle still represents the highest mobility cost. The hybrid electric vehicle presents an advantage of 1,000 €, in comparison to the conventional vehicle. The REX vehicle has the intermediate mobility cost – 20,558 €.
The REX vehicle solution presents the advantage of having extremely low CO_2 emissions- only 20 gCO_2/km, especially in its use phase. These powertrains are technological solutions for the European automotive industry to achieve the strict CO_2 emissions regulations.
The cost structure depends on the vehicle class, customer usage and place of use.
The environmental analysis takes into account this sensitivity. Figure 4 shows the Well-to-Wheel global CO2 impact, based on the category GWP 100 y, for the REX vehicle. The production phase of the vehicle and the use phase are contributing to the major GWP impact. The electricity consumption contributes to the GWP of 7,387 equivalent kg CO_2, in Germany and is 7 times higher than the one in France. This is due to the different electricity production mixes between France and Germany. The French electricity mix is 77 % based on nuclear, while for the German one, 45 % comes from coal. The environmental impact of the use phase of the REX vehicle strongly depends of the electricity mix of the country where the vehicle is driven.

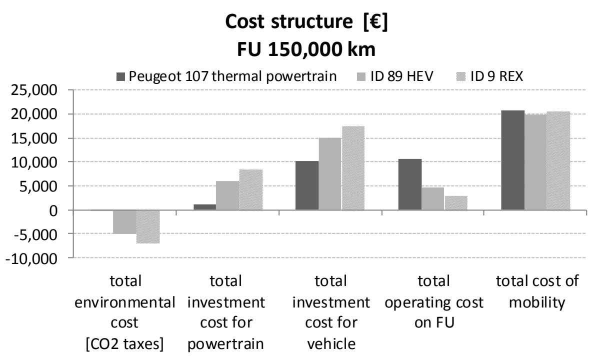

Figure 3: Cost analysis of the selected Pareto curve solution points and real urban car

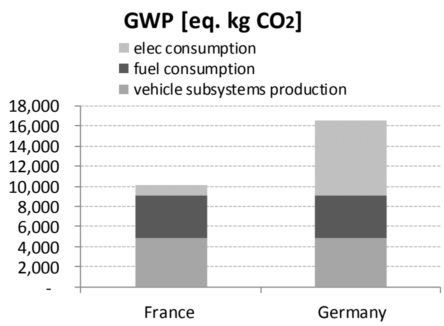

Figure 4: Environmental analysis for a functional unit 150,000 km and from the life cycle perspective, based on GWP 100 y indicator, point 9- REX vehicle

4. Conclusion

This paper presents the results of an optimization study of a hybrid electric vehicle, with around 1,000 kg of weight, for urban mobility. The demonstration of the simultaneous configuration of the powertrain, with sizing of the components, and the assessment of the economic and the environmental impacts is done. The obtained solutions for an urban car range between 2.2 L/100km and 0.6 L/100km of fuel consumption. All these solutions are, with low tank-to-wheel, CO_2 emissions – less than 50 gCO_2/km. In the case of purchase in France, these vehicles benefit from an economic bonus, given by the government.
The customer investment price for the powertrain is between 7,500 € and 12,000 €. The powertrain cost has the highest contribution to the vehicle cost – between 30 % and 50 %. This cost increases with the hybridization ratio, with a factor of 600 €/kWh of battery energy capacity.
HEV is a suitable solution for customer investment charge and sustainable mobility. For the HEV vehicle, with 1.8 L/100km of fuel consumption, the battery cost is around 9,000 €.
The major advantage for the PHEV and REX vehicles is the total operating cost. For the studied point ID 9, it represents around 3,000 €, which is 30 % of the operating cost of small urban vehicle with thermal powertrains. The total mobility cost for the discussed urban vehicles is almost equivalent, around 20,000 €, due to the differences in the investment purchase cost for the customer.
The use phase of the PHEV and REX is sensitive to the place of use. The environmental impact GWP 100 years, takes into account the well-to-wheel CO_2 emissions and shows the environmental impact of the different production electricity mixes.

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