STUDY OF HYBRID POWERTRAIN FEASIBILITY BY MEANS OF 1D SIMULATION

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ABSTRACT

In the last years more and more propulsion systems are developed in order to respond to the ever-increasing demands on fuel economy and environment protection. Developing hybrid drive vehicles is currently a major focus of automotive industry. This is seen as the right solution on the customer's demands for improved fuel economy, increased dynamic performances and good comfort.
This paper aims to demonstrate the effectiveness of employment of 1D modeling and simulation in feasibility study. The application adopted for the exemplification is a passenger car and the software used is LMS Imagine.Lab AMESim.

Keywords: hybrid drive, 1D simulation, AMESim, feasibility study

1. INTRODUCTION

A variety of hybrid drive concepts are now in series production or in an advance developing phase. Hybrid drive are use successfully to obtain a fuel economy improvement of 10-25 % but this came with a cost increase. To choose an appropriate configuration in respect with the desired application and to correctly dimensioning it is a difficult task. Usually this decision is the result of a feasibility study. During this process the number of architectures alternatives under consideration is usually quickly reduced. The research and information uncovered in the feasibility study will support the detailed planning and reduce the research time.

The employment of modern research instruments such as modeling and numerical simulation can reduce the time needed for feasibility studies. This paper aims to show the advantages of 1D simulation use in hybrid powertrain feasibility studies.

The simulation platform chosen for this study is LMS Imagine.Lab AMESim. This is an integrated platform for 1D multi-domain system simulation that offers a complete 1D simulation suite to model and analyze multi-domain, intelligent systems and predict their multi-disciplinary performance. Model components are described using validated analytical models that represent the system's actual mechanical, electric, hydraulic or pneumatic behavior.

The characteristics of the motor vehicle chosen for this study are:

- Type: passenger car;
- Engine type: spark ignition;
- Maximum ICE power: 50 kW;
- Kerb weight: 1400 kg;

- Drag coefficient: 0.3;
- Maximum vehicle cross-section: 2.15 m^2.

2. MODELS DEVELOPEMENT

Models of hybrid powertrains suitable for fuel consumption studies are necessary in order to have a rapid evaluation of envisaged solutions.

In AMESim the set of equations defining the dynamic behavior of the engineering system and its implementation as code is referred to as the model of the system. The model is built up from equations (and the corresponding code) for each component within the system. These are referred to as submodels. AMESim contains large libraries of icons and submodels of components. User submodels can also be developed and employed using a dedicated facility (AMESet).

2.1 Reference vehicle model

A model of the standard vehicle was developed in order to have a reference, figure 1. The parameters used for the simulation are those of the standard passenger car model.

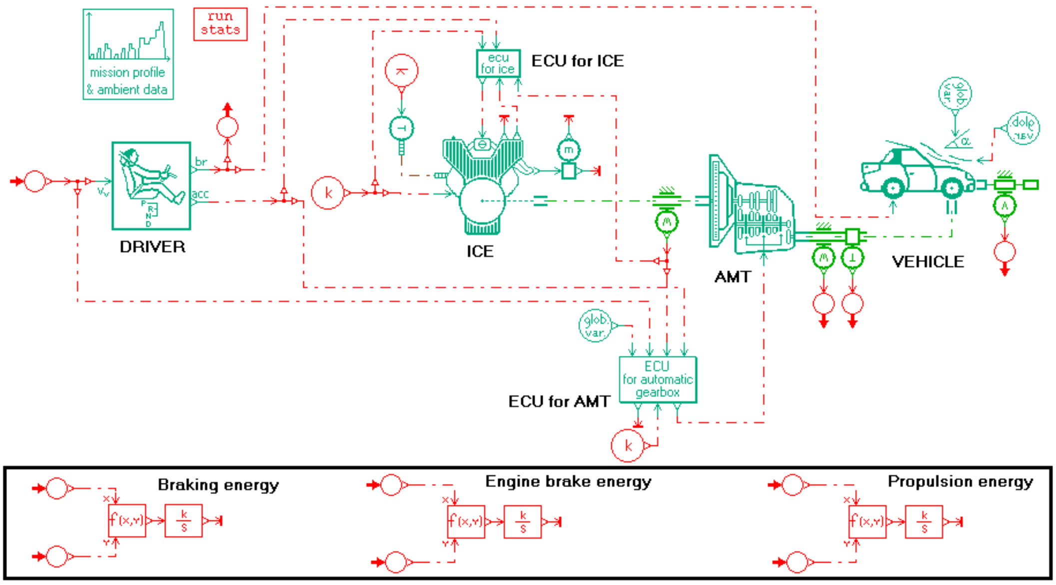

Figure 1: Reference vehicle model

Except the vehicle submodel, all submodels used to construct the vehicle model are from the AMESim standard libraries (IFP Drive, Mechanical, Signal, Control and Observers). A short description of these submodels is given.

The submodel of internal combustion engine (ICE) for cold or hot start computes the torque, the emissions (CO, HC, NO_x), the fuel consumption as well as the exhaust gas flow rate and the combustion thermal losses by means of user data files (1-D and multi-1D tables). A lag is applied on the torque. Therefore, there is a delay between the ECU torque request and the delivered engine torque. This delay depends on the engine configuration (atmospheric or turbo-charged) and the torque request variation-increase or decrease.

An ECU is used to control the engine. Different regulations are calculated by this ECU: idle speed, maximum speed, fuel resume speed.

For the transmission is used a simple dynamic modeling of a n-ratio manual gearbox. The primary shaft inertia, the clutch, the gears ratios, the powered axle ratio and the efficiency are taken into account.

An ECU is used to control the AMT. This is a submodel that determines the gear ratio from the engine rotary velocity and the acceleration pedal command.

The vehicle submodel introduce the vehicle mass, wheels inertia, rolling resistance, drag resistance and climbing resistance.

A driver submodel is also employed in order to be able to follow an imposed driving cycle.

The model also includes special integration function necessary to perform an energy analysis. Figure 2 show the time variation and the final balance of: the total used energy, the propulsion energy (computed at the transmission output) and the energy dissipated by engine braking (computed at the transmission output) and normal braking.

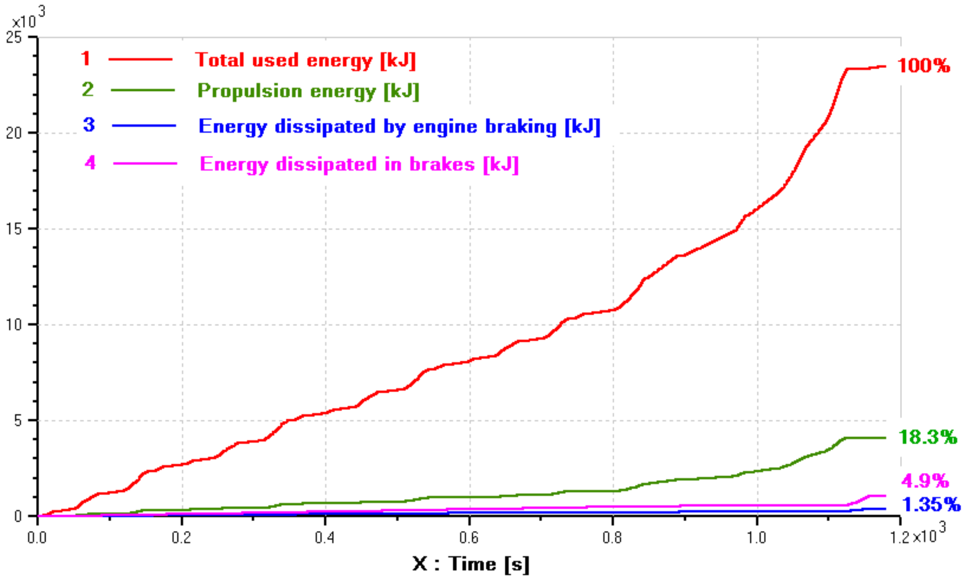

Figure 2: The energy balance of the reference vehicle model

The total energy E_T used is computed from the total fuel consumption C_T and the fuel specific calorific value H_u:

$$E_T = C_T \cdot H_u \qquad (1)$$

The energy dissipated in brakes E_b is determined by integration of the brake power P_b:

$$P_b = c_b \cdot \frac{T_{b\_max}}{r_r} \cdot v \qquad (2)$$

$$E_b = \int P_b dt \qquad (3)$$

Were:

- v – vehicle linear velocity;
- T_{b_max} – maximum braking torque;

- c_b – brake command;
- r_r – rolling radius.

The energy dissipated by engine braking E_{eb} is determined by integration of the engine braking power P_{eb} computed:

$$P_{eb} = \min(T_w \cdot \omega_w, 0) \qquad (4)$$

$$E_{eb} = \int P_{eb} dt \qquad (5)$$

Were:

- ω_W – wheel angular velocity;
- T_W – wheel torque.

The propulsion energy E_{pr} is determined by integration of the propulsion power P_{pr}:

$$P_{pr} = \max(T_w \cdot \omega_2, 0) \qquad (6)$$

$$E_{pr} = \int P_{pr} dt \qquad (7)$$

2.2 Hybrid architecture selection

In general, hybrid vehicles can be separated into four different categories, regarding the electrical power, the additional functions, the electrical storage capacity and the resulting fuel savings (Table 1), [1], [2], [4]. According to this classification different hybrid systems can be grouped into the “Micro“, the “Mild“, the “Full” and the “Plug-in” hybrid system.

Table 1: Types of hybrid drivetrains

		Type			
		micro	mild	full	plug-in
Additional functions	Electric auxiliaries	X	X	X	X
	Start/stop	X	X	X	X
	Boosting		X	X	X
	Recuperation		X	X	X
	Electric driving			X	X
	High autonomy in pure electric mode				X
Fuel consumption improvement*		5÷7%	12÷18%	20÷25%	n.a.
Hybridization factor *H***		cca. 5%	cca. 10%	cca. 25%	
Electrical installed power (for passenger cars)		4÷6 kW	10÷15 kW	30÷50 kW	
Complexity/supplementary costs*		+	+ +	+ + + +	

* compared with a classical propulsion system
**as defined in relation (8)

The hybridization factor H is defined in function ICE power P_{ICE} and electric motor power P_{El}, [3]:

$$H = \frac{P_{El}}{P_{El} + P_{ICE}} \cdot 100 \qquad (8)$$

A dedicated model was developed using AMESim in order to evaluate the driving and braking (regenerative) power needed to drive the vehicle in an imposed cycle, figure 3.

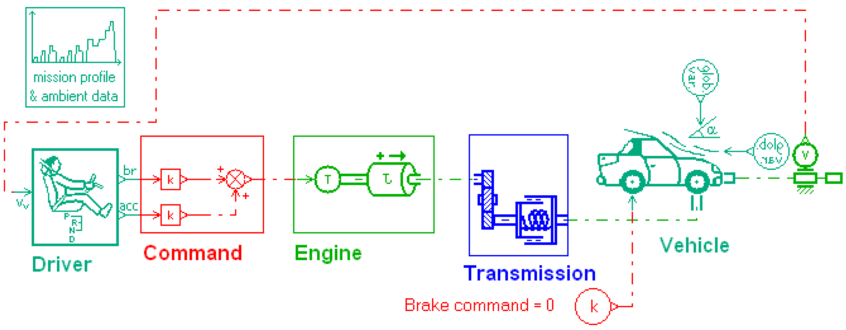

Figure 3: Dedicated model for power distribution studies

Figure 4 shows the vehicle velocity and propulsion power evolution for the NDEC, FTP75 and 10-15 mode driving cycles.

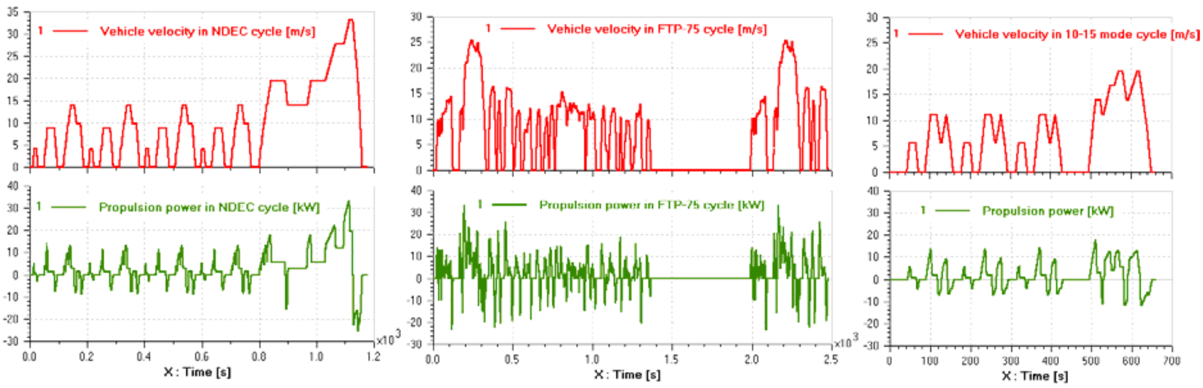

Figure 4: Vehicle velocity and engine power evolution for the NDEC, FTP-75, 10-15 mode driving cycles

A special developed Matlab script is used to read the simulation results from the AMESim results file and to compute the power distribution. The power distribution obtain (figure 5) can be used to correctly adopt the electric motor.

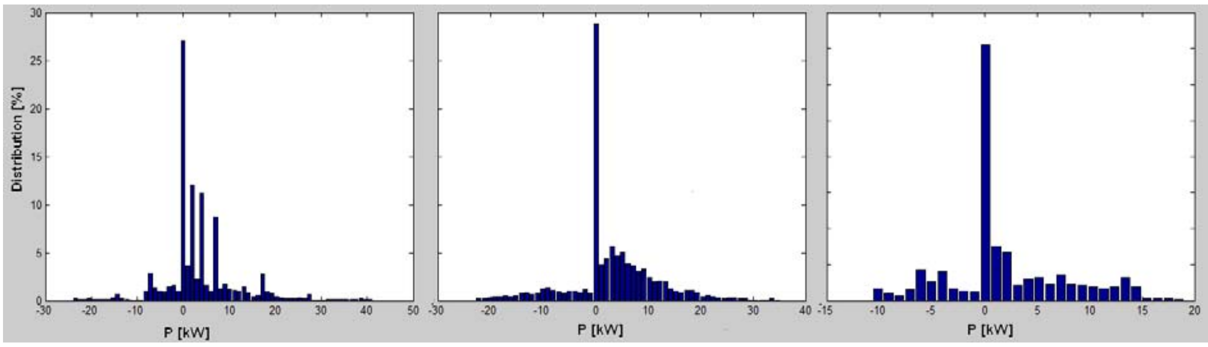

Figure 5: Power distribution in NEDC, FTP-75, 10-15 mode driving cycles

As can be seen a driving or braking power of 10 kW is enough to drive:

- 85% of NDEC cycle (29% idling and free rolling, 42% in traction mode and 14% in braking mode);
- 78% of FTP75 cycle (30% idling and free rolling, 37% in traction mode and 11% in braking mode);

- 85% of 10-15 mode cycle (35% idling and free rolling, 28% in traction mode and 17% in braking mode).

If an electric machine with a maximum power of 10 kW is used this corresponds for the considered application to a hybridization factor of 16.67%. As seen in table 1 this match to a mild hybrid.

The classification of the hybridization depending on the installed electrical power offers relevant information on the available functions but is not relevant for the structure and the design of the driveline. A classification depending on the systems architectures is presented in table 2, [1] and [4].

Table 2: Classification according to drivetrain topology

Hybrid drivetrains (HD)		
1. Serial HD		
2. Parallel HD	2.1. Torque addition	2.1.1. Single-shaft HD
		2.1.2. Double-shaft HD
	2.2. Traction force addition	
	2.3. Speed addition	
3. Mixed HD	3.1. Combined HD	
	3.2. Power-split HD	

Two configuration of a parallel mild hybrid drive with torque addition are investigated:

1. Double-shaft with torque addition before the gearbox, (figure 6);
2. Double-shaft with torque addition after the gearbox, (figure 7).

2.2 Hybrid vehicles models

In both configurations the electric machine is use for vehicle start-up, engine boosting, regenerative braking and the shifting of the engine operating points to the efficient ranges.

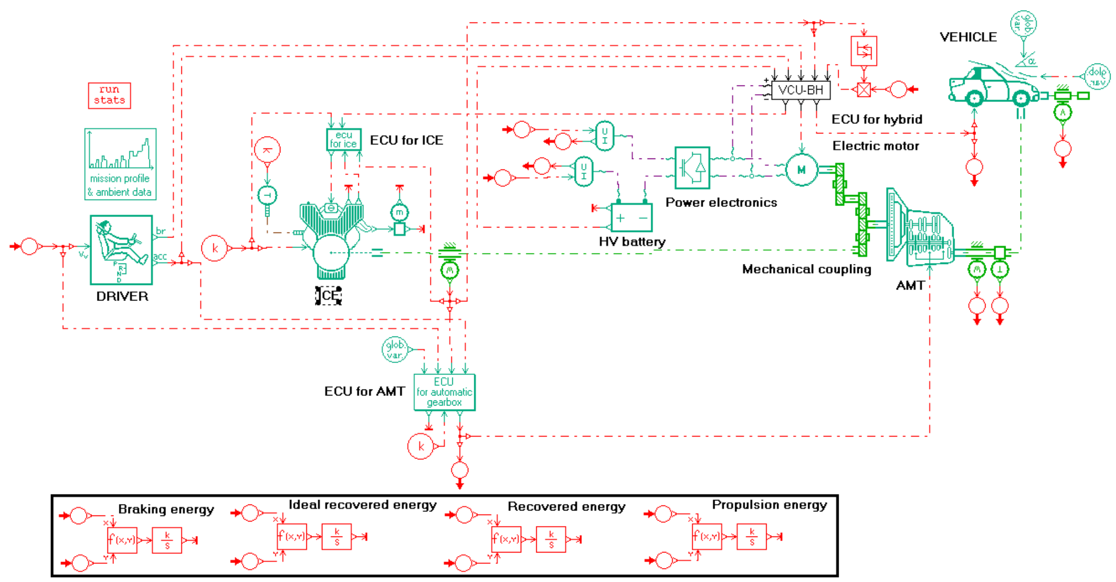

Figure 6: First hybrid configuration vehicle model

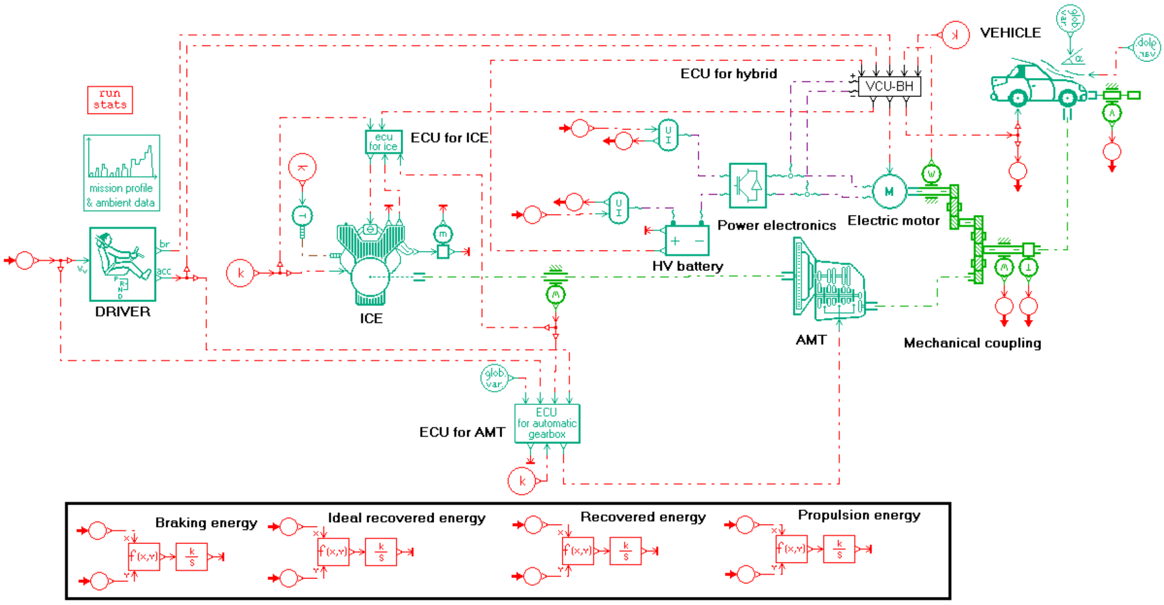

Figure 7: Second hybrid configuration vehicle model

In addition to the submodels used in the conventional vehicle, the new models employ standard submodels for the electric machine, power electronics, HV battery and a special developed command unit for the hybrid system.

The electric machine submodel is a static energetic model of an electric motor/generator using data files to determine the limited torque and power lost. The static energetic model is bidirectional (motor/generator), and independent from the technology of the motor.

The power electronics submodel is used to introduce the losses due to the power electronic converter. The losses are characterized by an efficiency to correct the power supplied by the voltage source.

The battery submodel is an internal resistance model, which characterizes the battery with a voltage source and an internal resistance.

The command unit for the hybrid system was developed and encapsulated in a supercomponent. It is implemented using submodels from signal, control and observers library as shown in figure 8.

This unit is adapted to the specific application and is simple enough in order to have a good understanding of its functions. A more complex unit can be easily developed by adding supplementary functions after the results analyze.

The control strategy is a simple one:

- At braking the generator is used to brake the vehicle and recuperate the energy as much as possible. Only if the recuperation is not possible (the storage device is full or the engine speed drops below an acceptable limit) or if the desired deceleration cannot be realized, the wheel brakes are applied;
- In traction the needed power is delivered using the engine and the motor. The splitting of the driver acceleration control is done using a variable ratio.

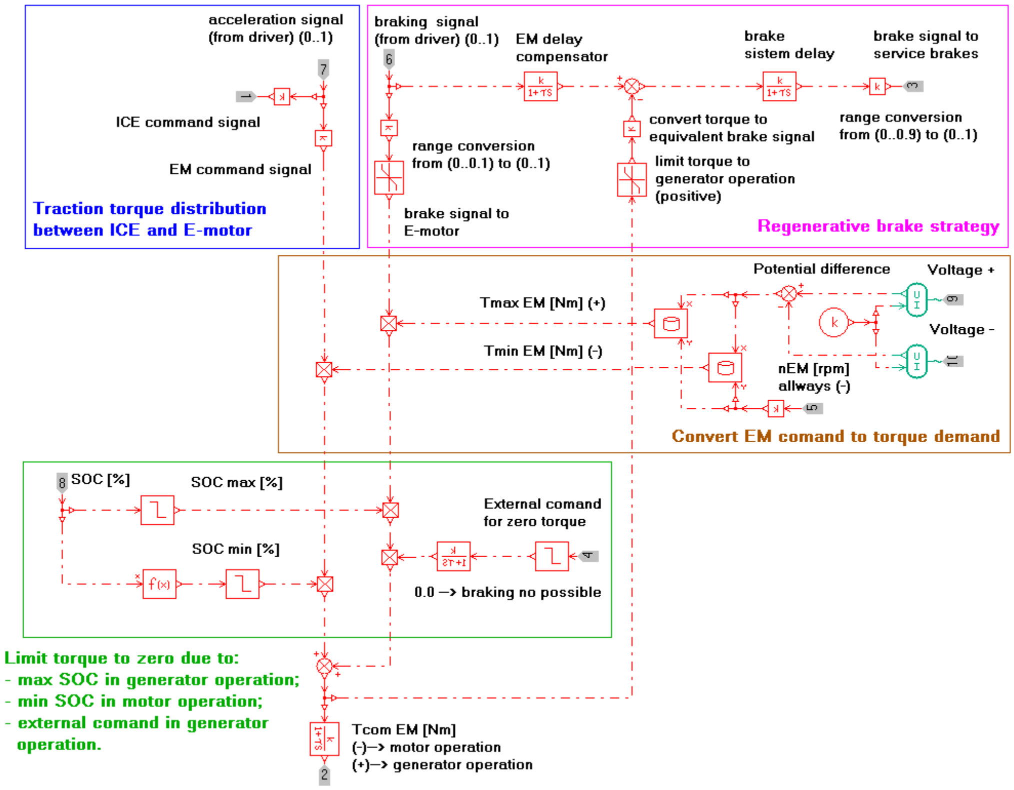

Figure 8: Hybrid command unit implemented using submodels from signal, control and observers library

The models also include special integration function necessary to perform an energy analysis. Two new energies are defined: the energy recovered by an ideal system and the recovered energy.

The energy recovered by an ideal system represents the maximum energy that can be recovered at the wheel. It is computed in the same way as the engine brake energy, see relations (4) and (5).

The recovered energy E_{rec} is computed at the battery terminals without taking into account the battery charging efficiency. This is done by integration of the recovered power P_{rec}:

$$P_{rec} = \min(I_{bat} \cdot U_{bat}, 0) \qquad (9)$$

$$E_{rec} = \int P_{rec} dt \qquad (10)$$

Were:

- I_{bat} – battery current intensity;
- U_{bat} – battery electric potential difference (voltage).

3. RESULTS

Changing the parameters of the presented models it is easy to simulate different constructive measures such as: Stop&Go and VVT mechanism for engine drag elimination.

Figure 9 shows the comparative simulation results in terms of fuel consumption improvement for the two hybrid solutions in basic configuration and also, for the first solution, in advance configurations (with and without Stop&Go, with and without engine drag). A batch run is used for to optimize the control of the first hybrid solution in order to maximize the fuel economy. The results of the optimization process are also shown in figure 9.

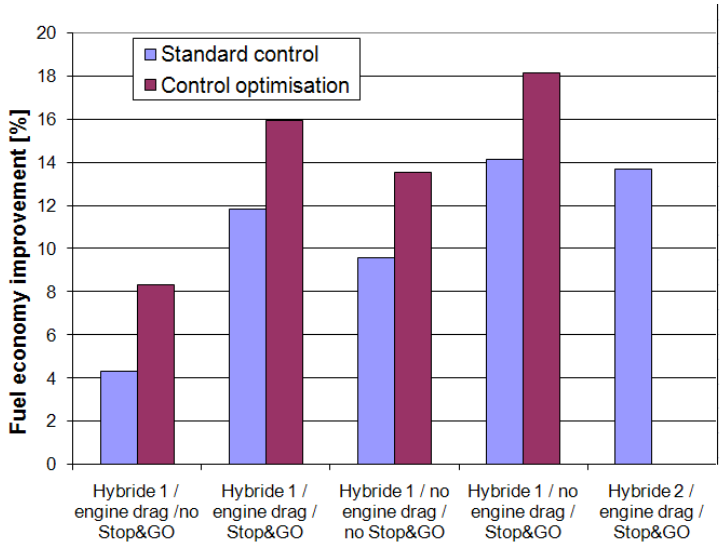

Figure 9: Comparative results of two different hybrid configurations

The perfection of the solutions in terms of energy recuperation was checked by comparing the percent of the recovered against the percent of the energy recovered by an ideal system as shown in figure 10 for the first hybrid configuration.

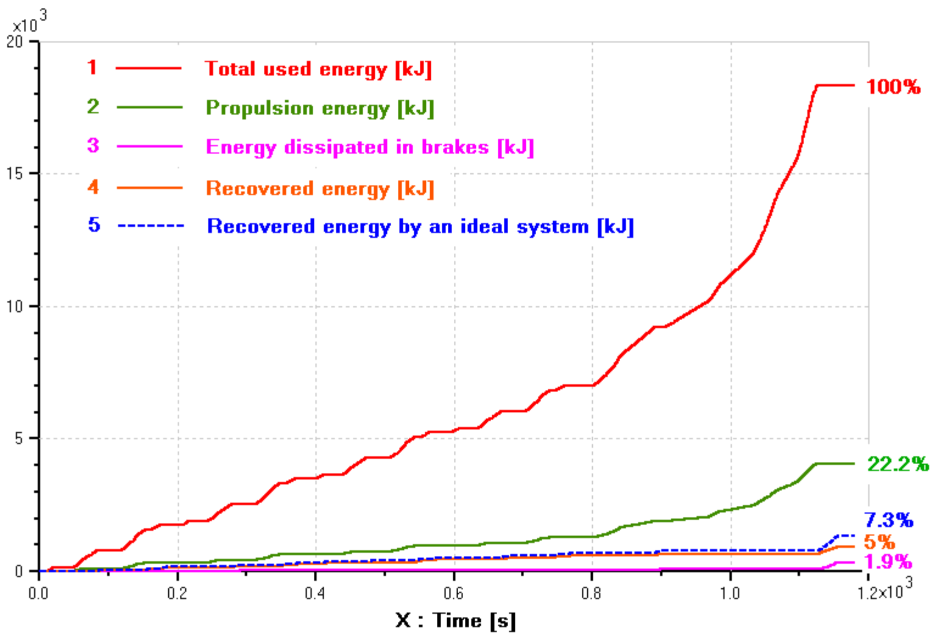

Figure 10: Energy analysis for the hybrid driveline

Base on these results, the future potential (give by the control optimization) and taking into account the technical difficulties for each solution a justified decision can be taken.

4. CONCLUSION

Models of hybrid powertrains suitable for fuel consumption studies were developed in order to have a rapid evaluation of envisaged solutions. The fuel consumption improvements obtain for a passenger car are consistent with the values presented in literature.

It is shown that various hybrid architectures can be quickly compared in terms of fuel economy by means of 1D simulation. Moreover the impact of different constructive measures is easy quantified.

The models integrate an energy analyze tool that can be used to determine the performance of the systems in terms of braking energy recuperation.

5. ACKNOWLEDGEMENT

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7. GLOSSARY

1D: One Dimensional
AMT: Automated Manual Transmission
ECU: Electronic Control Unit
EM: Electric Machine
HD: Hybrid Drive
HV: High Voltage
ICE: Internal Combustion Engine
FTP: Federal Test Procedure
NDEC: New European Driving Cycle
SOC: State of Charge