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Comparison of different Hybrid Electric Vehicles Concepts in terms of Consumption and Efficiency

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Abstract

The objective of this paper is to compare the most common HEV power train structures. As a first step, forward and backward models of these vehicle concepts are implemented using Modelica/Dymola in order to evaluate and compare the energy consumption. Taking into account fuel/electrical consumption and the losses in the powertrain components, a comparison of two different alternatives of Hybrid Electric Vehicle models (parallel structure and Range Extender) are presented in this publication. To simulate these models using different driving cycles, a rule-based operating strategy is implemented. As a second step, a Dynamic Programming (DP) based algorithm is applied to these models. This algorithm is used to determine the optimal fuel consumption for given driving cycles. A comparison of the DP results and rule-based results is carried out to evaluate the potential improvement that is possible to achieve optimizing the energy management strategy and the size of the powertrain components.

Keywords: energy consumption, efficiency, modelling, powertrain, series HEV, parallel HEV, simulation, optimization

1 Introduction

This paper presents a comparison of different powertrain HEV configurations [1] from the point of view of fuel/electrical consumption using Dynamic Programming. Applying the DP optimization method is possible to obtain the global optimum fuel consumption for a given driving cycle [2]. Forward and backward vehicle models have been parameterized and simulated to obtain the fuel consumption over different driving cycles using Modelica/Dymola [3, 4]. This tool is very useful for modeling and simulating complex integrated systems, for the automotive, aerospace, robotics and other applications. Simulating these configurations using similar parameters and under same conditions it is possible to calculate the possible improvement in order to get the optimal fuel consumption. Certain vehicle architecture is more efficient for drive in some routes than others. For this reason it is possible to classify these vehicle concepts according to adequate driving cycles. These different vehicle architectures are compared with three driving patterns: NEDC (New European Driving Cycle), FTP-72 (Federal Test Procedure) and a Real Life Driving Cycle (see section 4). Finally the main objective is to evaluate the structures to find out which is the most efficient for each driving profiles (urban, interurban roads, or high way driving). With this classification it will be possible to identify the suitable vehicle architecture for a certain driving profile. This paper contains a brief explanation of the studied vehicles concepts, a description of a rule-based operating strategy, an explanation of the considerations that had been assumed when DP is applied, also the results of different simulations, and finally the conclusions of this study.

2 Vehicle models

The vehicle models done are based on a systematic approach using energetic models for different subsystems. In order to compare the structures has been modelled a forward models, with a rule-based operating strategy, and a backward models, in which have been applied a DP algorithm. Also is modelled a conventional vehicle in order to have a reference model.

The results of this conventional vehicle model have been validated with roller test bench measurements. This is relevant in order to validate basic subsystems such as driver, chassis, clutch, gearbox, forces calculation and the Internal Combustion Engine (ICE).

For these vehicles models aspects such as the efficiency and inertia of the electric motor (EM), ICE and of the inverter are taken into account in the overall simulations [5, 6]. A control of each HEV models has been modelled using a Look-Up-Table for the consumption map of the internal combustion engine, and for the efficiency/losses of the electric motor. Models of the battery, battery management system, inverter, and control units are also implemented.

To simulate these vehicle models under different driving cycles a basic operating strategy was implemented in the hybrid control unit model. This strategy selects the driving mode depending on the driver requests giving inputs to the electric motor, ICE, the gearbox and to the clutch..

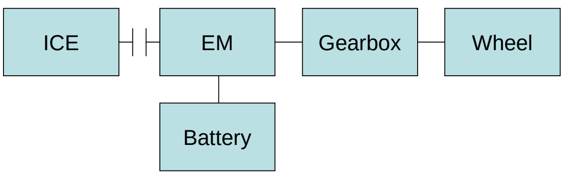

Figure 1: Powertrain of parallel HEV model

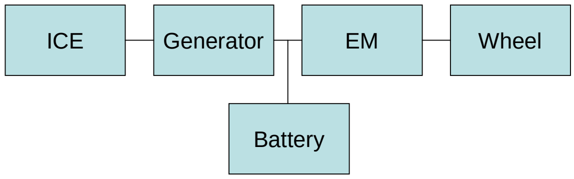

Figure 2: Powertrain of Range Extender model

In terms of strict comparison between different kinds of vehicles, the backward approach is especially well adapted since it inhibits driver's model. The principle of the backward approach is based on the knowing of the driving cycle and the vehicle characteristics [7]. Backward models are very useful from simulation time point of view, due to their simplicity and are enough fast to study the fuel consumption applying DP algorithm.

2.1 Vehicle Concepts

The HEV concepts studied in this paper are the parallel and the Range Extender structure.

2.1.1 Parallel HEV model

The parallel hybrid vehicle (Fig.1) has an ICE and an EM with a sufficient size to allow the vehicle traction electric mode. The EM gets its power from a battery-pack of high voltage. Both engines are connected in a way that allows the joint operation of both or only one of them. In electric mode, the ICE is stopped. The hybrid mode introduces flexibility in the propulsion system to optimize ICE operation. Also it is important to notice that this structure has a simple and efficient energy conversion path compared to Range Extender because the electrical energy flows from the battery to the wheel.

2.1.2 Range Extender model

The Range Extender (Fig.2) always operates with electric traction, which requires sizing the EM in order to get a defined driving performance. The electric drive eliminates the transmission and thereby reduces the mechanical complexity of the vehicle. The generator coupled to the ICE is able to supply electric power to the battery for charging or directly to the electric traction motor, or a combination of both. When the traction power is generated by the ICE there are greater losses than parallel concept due to the additional inverter and the electric machine (generator).

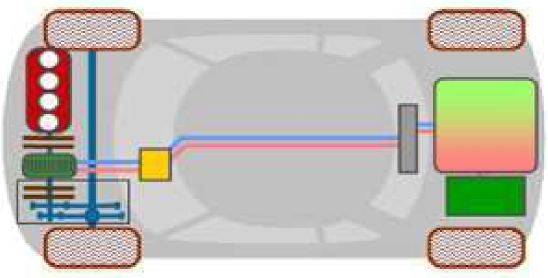

Figure 3: Parallel HEV concept

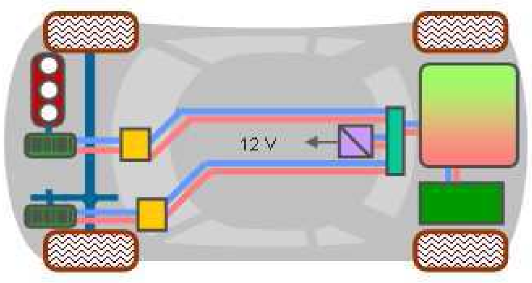

Figure 4: Range Extender concept

2.2 Rule-based operating strategy

In this section are explained the basic operating strategies implemented for parallel HEV and Range Extender vehicle models.

2.2.1 Parallel HEV strategy

In a parallel hybrid electric vehicle (Fig.3) the ICE and the electric motor work on the same axis to add their torque. The maximum torque is the sum of the curves of maximum torque electric and combustion engine. Not always the vehicle uses the two traction motors.

When power demand is low, it may be sufficient to use only the electric motor. In regenerative braking also the electric motor is used as a generator. In hybrid mode has been implemented "Recharge" and "Boost", in both traction motors are used. In "Recharge" mode, combustion engine generates more torque demanded by the driver to recharge the battery.

If the driver demands more power than the electric motor can generate, is entered in "Boost", in which the two electric machines accelerate the vehicle. "Regenerative Braking" mode always comes when the driver brakes and the SOC does not exceed its maximum value, that means that the battery can store this energy.

The strategy of parallel HEV has to choose the mode of operation, the gear and torque set point of the engines. The strategy is based in "charge depleting (CD)" that consists to use the energy stored in the battery until to reach a minimum SOC (State Of Charge) of 20 %. Then the strategy attempts to maintain this minimum level SOC mode using "charge sustaining (CS)".

This operating strategy usually is called AER (All Electric Range). At the time that the battery SOC reaches his minimum, the strategy enters the CS mode, in which the combustion engine is also used. Depending on the speed, in this case at 80 km/h, the vehicle enters the hybrid mode (Boost or Charge) or remains in electric mode.

The changing way between the modes depends on the SOC of the battery. To avoid continuous changes between the modes, if the vehicle drives just this edge has including a hysteresis of 5 km/h. At speeds above those is turned on the engine and enters to the hybrid mode. If the speed exceeds the limit of maximum speed in electric mode, the car changes into the hybrid mode. This means that the combustion engine is on and the two engines contribute to the acceleration of the car.

The strategy intends to use the ICE at every moment at the highest efficiency point of the current angular velocity. If the driver request more torque, the strategy sends the maximum possible torque, getting out of this efficient curve. In figure 5 is shown the CS and CD modes of the AER strategy. Also it can see the SOC and vehicle speed for several NEDC cycles.

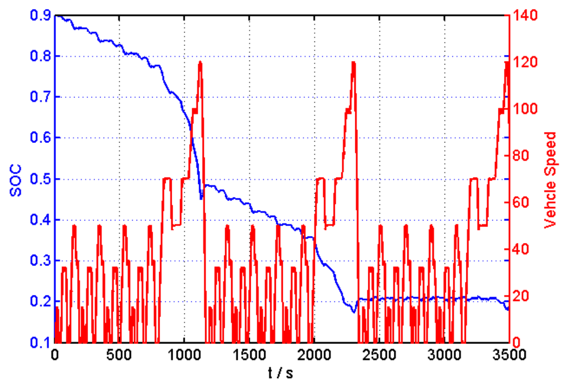

Figure 5: AER strategy for parallel HEV in a three NEDC driving cycles

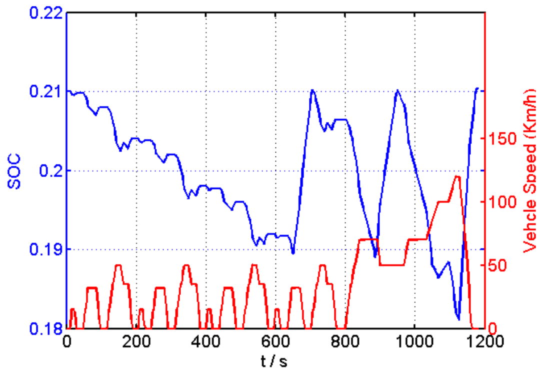

Figure 6: Charge sustaining strategy for a Range Extender in a NEDC driving cycle

The gear is chosen by the vehicle through the HCU unit and the driver has no chance of selection, as in many conventional vehicles with automatic transmission, and is determined according to the speed. Moreover, the decision of the gear follows the same strategy in hybrid mode as in electric mode. The shift points are adapted while driving at low speed to the electric motor and at high speed to the internal combustion engine, as this engine has to always work in his optimum zone.

2.2.2 Range Extender strategy

The Range Extender (Fig.4) is driven as an electric vehicle until to reach a minimum SOC of 20 % driving at a charge sustaining mode. At this moment the ICE is started and through the generator charges the battery consuming gasoline, similar as occurs in parallel HEV. In figure 6 is shown the CS mode, and the SOC for a NEDC driving cycle. In the next simulations has been set that the ICE is turned on at SOC level of 19 % and turned off at 21 %. This means for all-electric driving, that the engine's combustion is completely stopped and only turns on and off when entering or leaving these SOC limits.

In this concept it is very relevant to choose the optimal work point of the ICE and generator set because it is important that they work at their most efficient point and they are not directly coupled to the wheels. For this reason has been calculated their efficiency maps, and analyzed which is the point with less losses of the two efficiency maps together.

3 DP optimization strategy

Dynamic programming is defined as a computer based method to solve an optimization problem where the objective function is a sum of non negative terms. This is the case for fuel consumption during a driving cycle for a HEV. The function to be minimized during a cycle of N sample time is then the following:

$$J = \sum_{i=1}^{N} D(I_{bat}(i), k(i)) T_e \tag{1}$$

Where $D(I_{bat}(i), k(i))$ are the instantaneous fuel rate for a given battery current and a given ratio, and T_e is the sample time. In the optimization problem we must consider the final SOC as a constraint. In order to control the SOC deviation, the battery SOC is taken as the state variable of the problem and its evolution as a trajectory from the initial SOC to the imposed final SOC. The minimum of J is then obtained for the optimal trajectory of SOC. The minimum consumption leads to the best strategy (SOC trajectory = instantaneous battery current) for a set of fixed initial and final SOC values (usually equal) [7]. These models have been used for rapid analysis of the performance and fuel economy of hybrid electric vehicles providing a backbone for the detailed simulation and analysis from which take full advantage of the modeling, and flexibility to their integration to Matlbat/Simulink applying the DP optimization method.

4 Simulation Results

Three driving cycles are tested, NEDC, FTP-72 and a Real Life Driving Cycle based on 33 km with slope road done in Spain (Fig.7).

Table 1: Powertrain Components

	Parallel	Range Extender	Conventional
EM *(kW)*	40	85	-
ICE *(kW)*	51	51	51
Generator *(kW)*	-	40	-
Battery *(kWh)*	4	4	-
Weight *(kg)*	1450	1600	1450

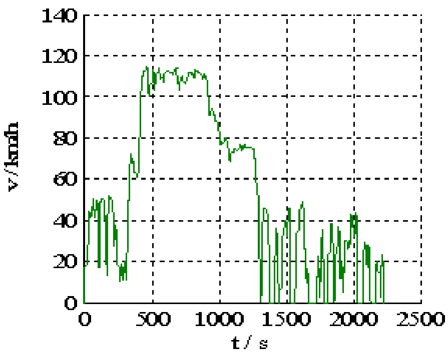

Figure 7: Real life driving cycle

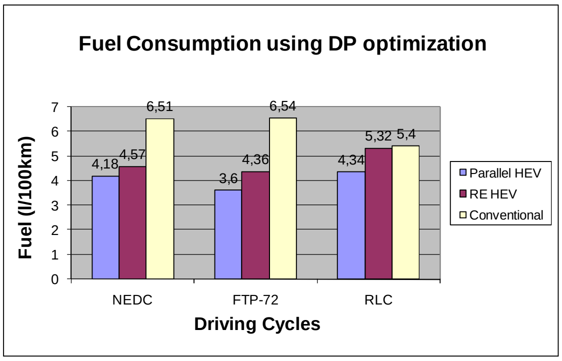

Figure 9: Fuel consumption for DP Optimization

In order to compare these concepts, similar components are used in all simulations. The main difference is that the Range Extender is heavier due to the weight of the extra electric machine. These vehicle parameters used for the simulations are listed in table 1. Main results are listed in figures 8, 9, 10 and 11. It is important to mention that fuel consumption is calculated using the average of a simulated cycle during charge sustaining mode. It is not applied the norm ECE R101 commonly used for NEDC, due to the needed comparison to other driving cycles.

For a better understanding of the results it is needed to examine the NEDC and FTP-72 properties. In these cycles there a lot of stops and idle times and on it ICE is consuming fuel. A lot of stops increase the fuel consumption as the ICE is inefficient at low speeds. The ICE in the parallel and Range Extender concept is stopped in these waiting times and also at low speeds, so in these cases the fuel consumption is zero. On the contrary in the Real Life Driving Cycle the fuel consumption of the conventional vehicle is lower than FTP-72 and NEDC because it has a longer part of highway driving at higher speed

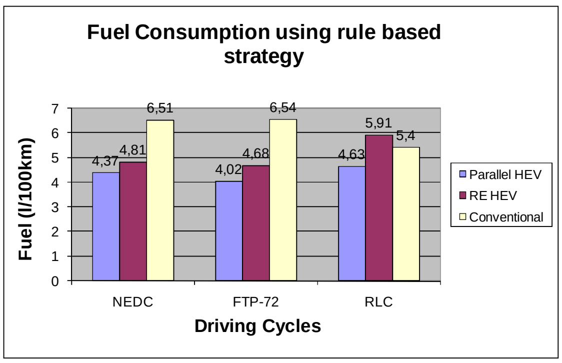

Figure 8: Fuel consumption for rule based strategy

(nearly 120 km/h), which lies better efficiency zone from the point of view of the ICE. In this driving profile also it is noticeable that the fuel consumption for the Range Extender is the highest one mainly due to the worst electric energy conversion path from the ICE to the battery and from the battery to the traction motor.

In the figures 8 and 9 it is remarkable to see that in general, the parallel concept compared to Range Extender and conventional vehicle has the best fuel consumption, basically due to have a gearbox that allows the ICE to work in better efficiency region and also because it is lighter than Range Extender. In addition to this reason that Range Extender concept it is heavier caused by the mass of the generator, also it is important to observe that has a low efficiency in the energy conversion path (attributable to more electric components in the powertrain).

From the point of view of electrical consumption and autonomy (see figures 10 and 11), regenerative braking contributes to overall system efficiency. The electric motor works as a generator and charge the batteries during braking at the stops and downhill driving. The autonomy it is low because the battery it is small and has little energy capacity. Commonly parallel concept also has the best performance taking into account the electrical consumption due to is lighter.

It is interesting to notice that the costs of both powertrains are comparable, but the vehicle integration of the Range Extender allows more flexibility because the generator set can be put in a more convenient place. Finally the parallel topology requires all main components except the battery to be built into the engine compartment. Therefore vehicles with this type will resemble more the conventional vehicle.

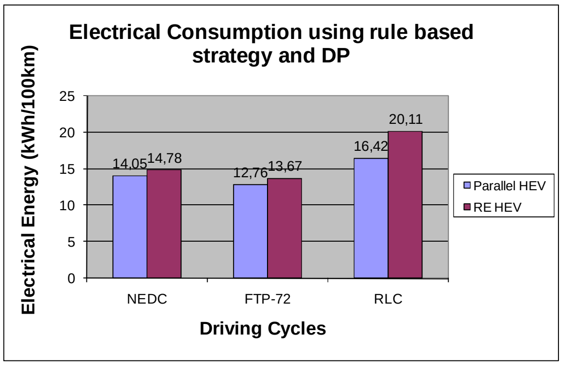

Figure 10: Electrical consumption for rule based strategy and DP optimization

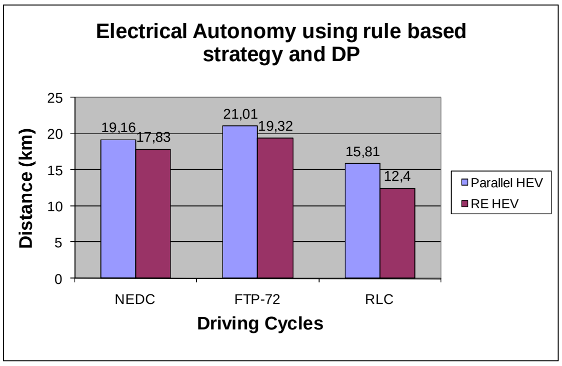

Figure 11: Electrical Autonomy for rule based strategy and DP Optimization

The potential improvement between the rule-based strategy and the DP optimized strategy is listed in table 2 and shows the possible improvement after optimizing the operating strategy, or the size of the components. The differences between these results are not greater due to seem that the rule-based strategy it is one well optimized strategy and the improvements margins are sight.

The next researches could be focused on the cases in which there has been calculated a major potential of improvement: on the parallel HEV for an urban roads (10,45 %), and also on the Range Extender under extraurban driving profiles (9,98 %).

In summary both configurations achieve similar characteristics when operating in electric mode. Range Extender configuration appears to be an appropriate choice for long All Electric Ranges due to its simple control and its ability to operate in EV mode at high vehicle speed. Meanwhile parallel configuration provides the best fuel economy as a result of its lower weight, also because of their efficient path of conversion energy from the engine to the wheel. And finally, despite of it has a lower efficiency of the gearbox, has higher electric machine efficiency due to the possibility to use different gears.

It is important to consider that has been used a bibliographic comparison of published test data from other models and researches observing a similar behavior of the concepts studied and concluding that the parallel reach a better fuel consumption than Range Extender [8], [9].

Table 2: Potential to improve the fuel consumption in each driving cycle (%)

Improvement (%)	NEDC	FTP-72	RLC
Parallel	4,35	10,45	6,25
Range Extender	4,99	6,84	9,98

5 Conclusions

Simulations show that the parallel HEV topology is more fuel efficient than a Range Extender. These results represent the maximum fuel economy that can be achieved by each configuration in the simulated driving cycles.

Thanks to this method it is possible to know the potential improvement for each HEV configuration, basically optimizing the operating strategy and the sizing of the powertrain components. In this paper it has been described a methodological approach to investigate the maximum fuel economy that could be achieved by a hybrid vehicle with a parallel and Range Extender configurations for a known drive cycle. Models are used for the computation of fuel consumptions. The Dynamic Programming optimization process was used to find out the global optimum fuel consumption over a known driving cycle.

In future these models will be implemented in a test-bench using rapid prototyping tools. Hardware in the Loop (HIL) test will be done in order to validate the results of the models using real components.

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