SIMULATION OF AN HEV EQUIPPED WITH A VARIABLE DISPLACEMENT ICE

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ABSTRACT

The automotive manufacturers intend to improve average fuel economy and low harmful emissions from cars. As the automotive industry is progressing faster than ever it needs systems development which can ensure the new regulations demand to reduce climate change by improving fuel economy. Pollution control devices used on cars cannot reduce the car`s CO_2 emissions down to zero, they only can reduce them partially. Less CO_2 emissions and better fuel consumption will be obtained by combining more control devices. Hybrid-electric vehicles (HEVs) combine the benefits of gasoline engines and electric motors and can be configured to obtain different objectives, such as improved fuel economy, increased power, or additional auxiliary power for electronic devices and power tools. The electric motor provides additional power to assist the engine in accelerating, passing, or hill climbing. This allows for a smaller, more efficient engine to be used. In some vehicles, the motor alone provides power for low-speed driving conditions where internal combustion engines are least efficient. The variable displacement of the internal combustion engines by cylinder deactivation combined with an electric motor can build a hi tech HEV that better complies with the demands.

This paper aims to create models and simulate the operation of a parallel hybrid propulsion system equipped with an internal combustion engine, with 6 cylinders when three of the engine cylinders are deactivated trying to study the behavior of the propulsion system and the engine.

INTRODUCTION

New European standards will require auto manufacturers to reduce CO_2 tailpipe emissions down to 130 g/km by 2015. Hybrid vehicles are not the only answer to reduce harmful emissions and fuel consumption. The automotive manufacturers are developing an array of other promising technologies. To meet the requirement of decreasing emissions and fuel consumption they will have to enhance current internal combustion engine (ICE) technologies and develop some new ones. The variable displacement of the internal combustion engines by cylinder deactivation is one of them. Cylinder deactivation is part of a tool kit that the auto industry is using to improve fuel economy and reduce to CO_2 emissions. This technology helps the engine to seamlessly operate on a reduced number of cylinders under light conditions. Using cylinder deactivation is a way to reduce the number of active cylinders under light load conditions, or when the electric motor ensures most of the work.

Cylinder deactivation saves fuel by deactivating cylinders when they are not needed.

Disconnecting cylinders, in other words deactivating some of them at partial load, leads to savings of fuel consumption by 10 to 15%. This technology was introduced a few years ago in large engines (V12 and V8) and has been applied more recently in a V6 engine having a displacement of 3.5 liters. In the future, its application could be extended to 4-cylinder in-line engines, representative of the great majority of European applications, provided that a way can be found to relieve the problems of vibration and roughness resulting from the deactivation.

MODEL AND SIMULATION PARAMETERS

The HEV equipped with a variable displacement ICE will be simulated using the AMESim software tool. Developing the model for simulation consists in linking submodels from various software`s libraries. The submodels are shown as icons. After linking the icons (which represent each component of the vehicle) in sketch mode and choosing the proper submodel in submodel mode, the parameters will be set. Each icon covers a fragment of C code, written using the specific equations for the system.

The submodel for the driver used in this model controls/calculates braking, acceleration and gear shifting. When the vehicle velocity is below a certain threshold, the neutral is engaged to avoid the engine stalling. Acceleration and brake control take into account the anticipation of the speed control.

The submodel for the ICE, which is a V6 engine, computes the torque, the emissions, the fuel consumption, the exhaust gas flow rate and the consumption thermal losses. The ICE is controlled by a special ECU which manages the different regulation modes and controls the torque request and computes the four following variables: load requested by the driver, combustion mode, thermal coefficient combustion release, controlled idle speed. The ECU performs regulations for idle speed and maximum speed. Also the ECU controls the electric motor (the rotary velocity) and the battery (the state of charge), analyzing them in order to minimize the consumption of the battery. The electric motor and the engine are connected to the

manual gearbox; the ECU manages the power requested to the engine and the electric motor; if the battery needs to be regenerated, the engine is used to drive the vehicle, and if the power requested is lower than its optimum power (according to its rotary velocity), the difference is sent to the electric motor to charge the battery. This ECU can be used only with a parallel hybrid vehicle.
The model for the electric motor can be used as an electric motor and a generator, being independent from the technology of the engine.
The battery is an internal resistance model, which characterizes the battery with a voltage source and an internal resistance. The battery output voltage is calculated as follows V=V0-I*R, where V [V] is the output voltage, V0 [V] is the open circuit voltage, R [Ohm] is the equivalent internal resistance, I [A] is the input current. The battery consists of banks in serial and parallel arrangements; each battery bank consists of cells.
The submodel for the 6 ratio gearbox includes the clutch and is controlled by the driver. The gearbox ratio is read in a data table. The primary shaft inertia and the powered axle are taken into account.
The submodel for the vehicle models a simple vehicle load when considering no longitudinal slip between the tire and the ground.

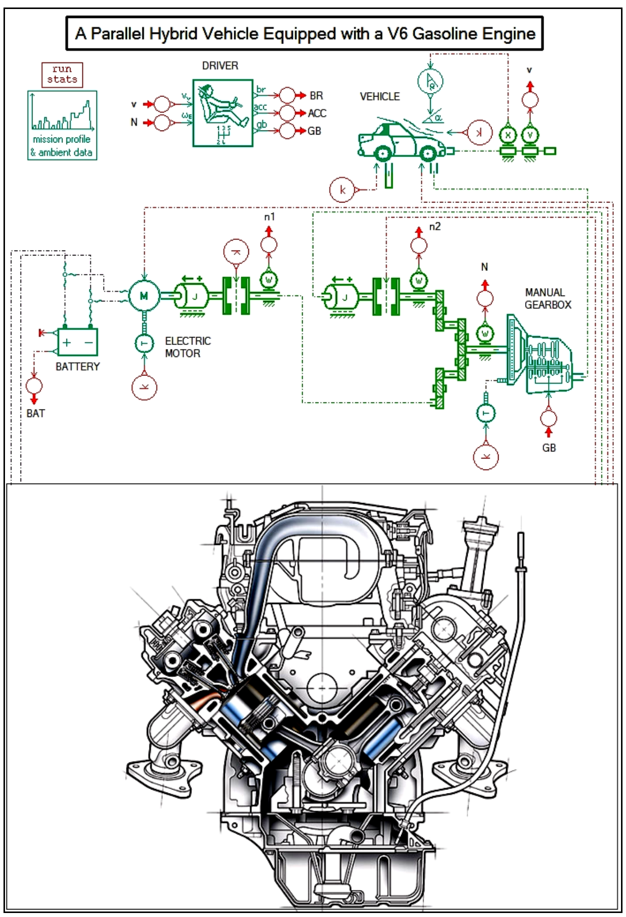


Figure 1: Model of the HEV equipped with a variable displacement ICE

The parameters used in the simulation are borrowed from an existing vehicle and are shown in Table 1.

Table 1: The most important parameters used in simulation

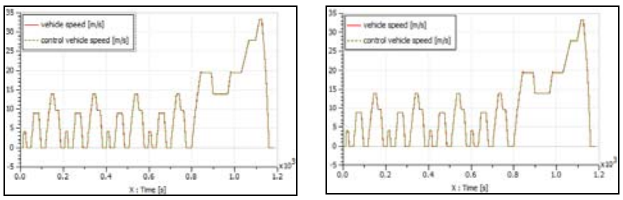
Submodel	Parameter	Value / Unit
Engine	Type	ICE-Spark Ignition
	Displacement	2997 cm^3, 499,5cm^3/cylinder
	Maximum power	180 kW / 5500 rev/min
	Maximum torque	298 Nm / 3750 rev/min
	Low threshold for engine temperature	20 degC
	High threshold for engine temperature	80 degC
	Hot engine idle speed	700 rev/min
	Cold engine idle speed	1100 rev/min
	Hot idle consumption	500 g/h
Electric motor	Type	M&G
	Maximum power	18,5 kW
	Maximum torque	208 Nm
	Efficiency	0.85
	Maximum rotary velocity	9000 rev/min
Battery	Voltage	288 V
	SOC	0.9
	Cells in series per battery bank	8
	Battery banks in series	30
Gearbox	Final drive gear ratio	4,25
	Final drive efficiency	0,97
	1st / 2nd/ 3rd/ 4th/ 5th/ 6th gear ratio	3,5 / 2/ 1,4 / 1 / 0,85 / 0,7
	Gearbox efficiency	0,9
Vehicle	Kerb weight	1310 kg
	Wheel Inertia (4 wheels)	2,5 kgm^2
	Wheels	235/45R18 99V
	Maximum brake torque	1000 Nm
	Drag coefficient	0,3
	Frontal area	2,14 m^2

SIMULATION AND RESULTS

The simulation mode must follow the mission profile defined using tables and it will use the New European Driving Cycle (NEDC). The NEDC consists in the fact that the engine starts at 0 (zero) seconds and the emission sampling begins at the same time. The duration of the cycle is 1180 seconds.
The ECU analyses the driver command (acceleration and braking) in order to minimize the battery consumption and also the fuel consumption and CO_2 emissions. During the braking the electric motor behaves as a generator to charge the battery. Depending on vehicle speed, the electric motor or/and the ICE

is used to realize the displacement of the vehicle. Depending on the load given by the driver and the battery state of charge the ICE can sustain the electric motor with partial or full torque and power with or without cylinder deactivation. If the optimum power of the ICE is higher than the requested one, when it is working, the difference could be used to charge the battery. Three of the cylinders were deactivated when the load value was 30% of the maximum engine load.

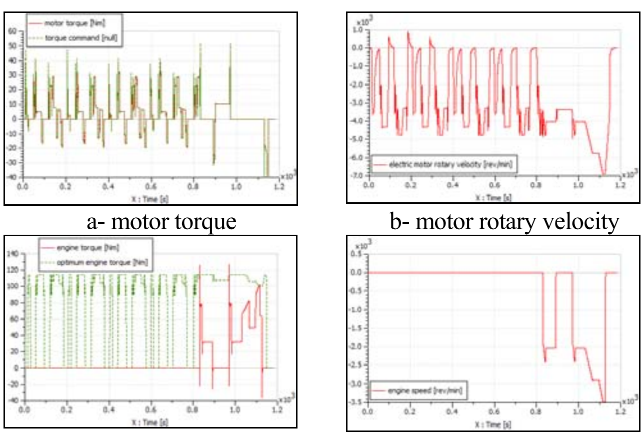
Comparing the curve of vehicle speed with the control speed in both cases (with and without cylinders deactivated) it can be observed that the vehicle speed follows the control speed, showing that the model is functioning correctly, with cylinders deactivated (figure 2). The settings of the driver allow a good agreement between the curves.



a-NCD b-CD

Figure 2: The evolution of the vehicle speed and the control speed during NEDC (1180s): a-NCD (without cylinders deactivated),
b-CD (with cylinders deactivated)

Figure 3 describes the behavior both of the electric motor and of the engine; it can be seen that the engine works at the final of the cycle for the last acceleration, when the battery is being charged. The behavior of the electric motor and of the engine is quite similar to the case of NCD, as shown in figure 4. Deactivating three of the cylinders won`t harm the behavior of the HEV. The electric motor will provide more torque when three of the cylinders are being deactivated, at the final of the cycle, when the ICE starts.

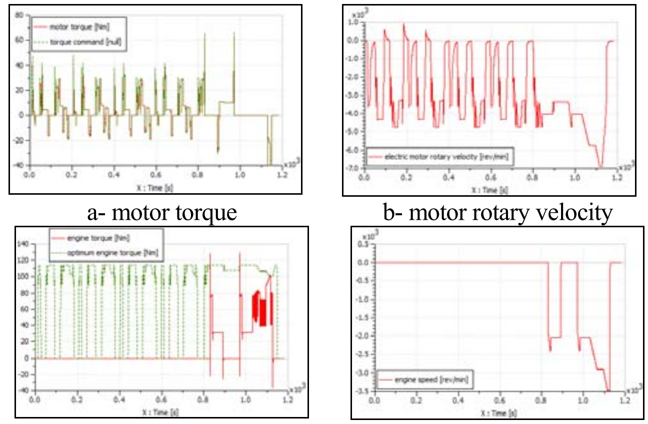


a- motor torque b- motor rotary velocity

c- engine torque d- engine speed

Figure 3: Behavior of the electric motor and ICE (NCD)

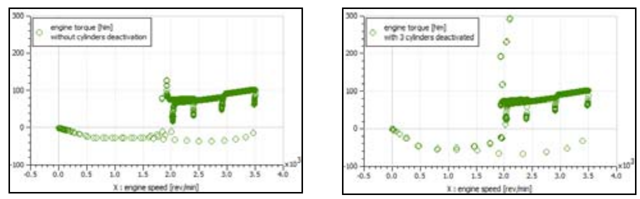
Evaluating the engine torque in both cases (figure 5), with three cylinders deactivated and, respectively, without deactivated cylinders, shows that the mission of the electric motor to achieve the propulsion meets the requirements of fuel economy and less harmful emissions. The electric motor ensures the displacement of the vehicle during all the NEDC assisted only by 3 from 6 of the ICE`s cylinders. ICE operates between 2000-3500 rev/min developing the demanded torque. The engine is generally used for a load higher than 50% to improve its efficiency. In this case, the electric generator limits the optimization of the system because the optimum engine torque cannot be reach.



a- motor torque b- motor rotary velocity

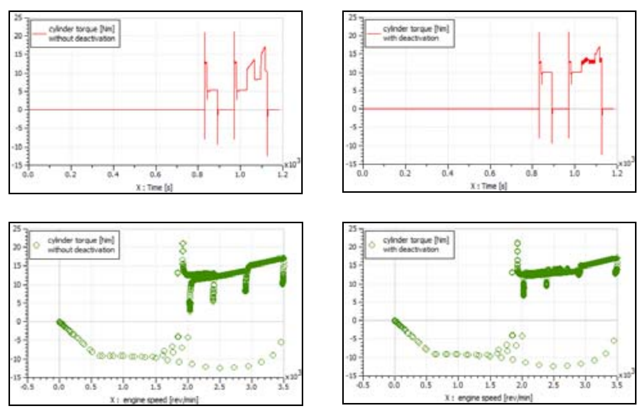
c- engine torque d- engine speed

Figure 4: Behavior of the electric motor and ICE (CD)



a-NCD b-CD

Figure 5: Evaluating the engine torque: a- without cylinders deactivation; b-with 3 cylinders deactivated



a-NCD b-CD

Figure 6: Evaluating torque from one cylinder
a- without deactivation; b-with deactivation

Deactivating some of the cylinders tries to realize fuel economy. The hybrid system does not suffer from these changes, keeping the required properties. Evaluating ECU behavior and considering the regenerating function of the batteries no changes occurred, as shown in figure 7.

During the NEDC the model without cylinders deactivation realized a fuel consumption of 349,07 g, while the battery state of charge reached 88,16 %, as shown in figure 8 and table 2 (NCD).

The model with three cylinders deactivated realized a fuel consumption of 305,55 g, while the battery state of charge reached 88,16 %, as shown in figure 9 and table 2 (CD).
In both cases, the ICE started at a vehicle speed of 15 m/s, at which the hybrid mode starts, after running 830 seconds of the cycle. While deactivating three of the cylinders the economy obtained reaches 12,47 %.

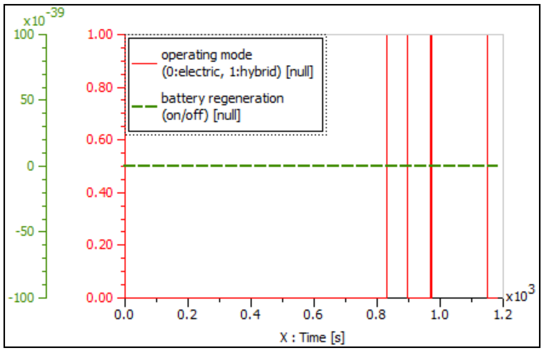


Figure 7: The vehicle mode (electric or hybrid mode) compared with the necessity to charge the battery

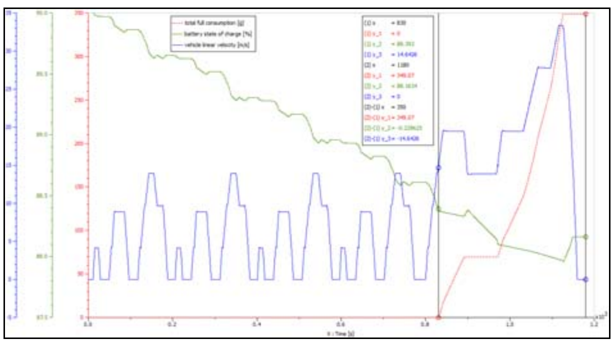


Figure 8: Total fuel consumption [g] / Battery state of charge [%] / Vehicle linear velocity [m/s] during the New European Driving Cycle (NEDC) without cylinders deactivated

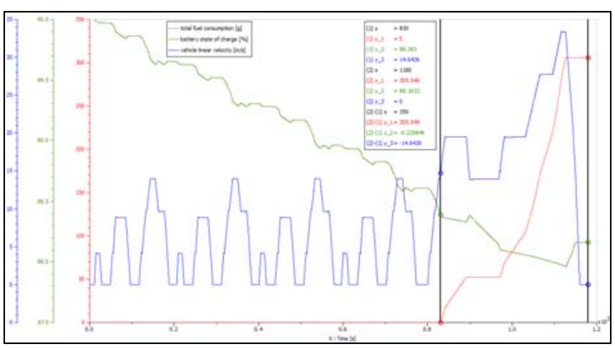


Figure 9: Total fuel consumption [g] / Battery state of charge [%] / Vehicle linear velocity [m/s] during the New European Driving Cycle (NEDC) with cylinders deactivated

Table 2: Results for fuel consumption, battery state of charge and vehicle linear velocity during NEDC

NCD		CD	
(1) x	= 830	(1) x	= 830
(1) y_1	= 0	(1) y_1	= 0
(1) y_2	= 88.393	(1) y_2	= 88.393
(1) y_3	= 14.6426	(1) y_3	= 14.6426
(2) x	= 1180	(2) x	= 1180
(2) y_1	= 349.07	(2) y_1	= 305.549
(2) y_2	= 88.1634	(2) y_2	= 88.1632
(2) y_3	= 0	(2) y_3	= 0
(2)-(1) x	= 350	(2)-(1) x	= 350
(2)-(1) y_1	= 349.07	(2)-(1) y_1	= 305.549
(2)-(1) y_2	= -0.229625	(2)-(1) y_2	= -0.229846
(2)-(1) y_3	= -14.6426	(2)-(1) y_3	= -14.6426

CONCLUSIONS

It is essential to know the evolution of the fuel consumption depending on the engine load when the cylinders are deactivated. Taking values from 10% to 90% of the maximum engine load (EL in figure 10) for the moment when the cylinders will be deactivated will result the dependence of the fuel consumption on this parameter. Following the example above there were studied the next cases: hybrid combined with cylinder deactivation (HEVCD), hybrid combined with usual ICE, without deactivation (HEVNCD), ICE with cylinder deactivation (NORCD), ICE without cylinder deactivation (NORNCD).

Table 3: Comparing studied cases

	HEV CD		HEV NCD		NOR CD	NOR NCD
EL	TFC [g]	SOC [%]	TFC [g]	SOC [%]	TFC [g]	TFC [g]
0,1	348,82	88,163			688,20	
0,2	331,53	88,163			651,41	
0,3	305,54	88,163			615,76	
0,4	291,32	88,159			576,36	
0,5	280,4	88,159	349,07	88,163	554,88	691,62
0,6	272,12	88,160			541,15	
0,7	267,28	88,161			535,87	
0,8	263,87	88,162			532,47	
0,9	263,87	88,162			532,61	

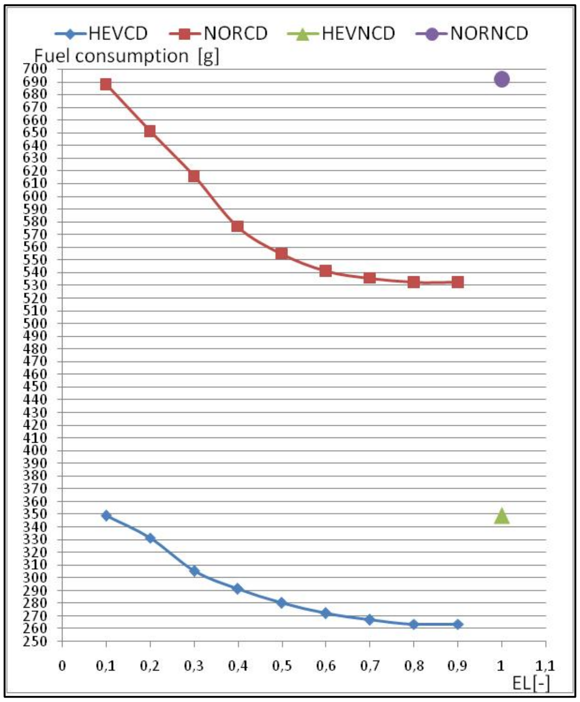


Figure 10: The fuel consumption during NEDC

Using both hybrid technology and cylinder deactivation, the fuel economy reaches high values. Comparing the HEVCD model with NORCD model the fuel economy using the hybrid technology was improved. The HEVNCD model fuel consumption is higher than the highest HEVCD fuel consumption. The HEV is able to operate approximately two times more efficiently than conventional vehicles.
The model presented in this paper provides an efficient tool for the simulation of a parallel hybrid vehicle associated with cylinder deactivation. It can be used for issues as the development, validation and optimization of the energy strategy, taking into account fuel consumption and pollutant emissions. This model can also be used as an initial application in order to build a more advanced model and to take into account more issues.
For a hybrid electric vehicle the electric motor and the battery are the core of economically functioning. Associating the cylinders deactivation less fuel consumption and CO_2 emissions will be obtained.
AMESim Software simulates different hybrid powertrain solutions and cylinders deactivation method in order to obtain data about fuel consumption and other parameters, and compares these solutions even if they were not yet physically achieved.
More efficient vehicles can bring important advantages to society in terms of environmental benefits. Hybrids will never be true zero-emission vehicles, however, because of their internal combustion engine. But improving cylinder deactivation method combined with hybrid technology the emissions and fuel consumption will go down.

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BIOGRAPHY

VALERIAN CROITORESCU was born in Ramnicu Valcea, Romania, and attended the courses of University `POLITEHNICA` of Bucharest, in 2002, where he studied Automotive Engineering and obtained his Automotive Engineer Degree in 2007, being also the valedictorian. He prepared his final degree dissertation paper (diploma project) in France, at `Ecole Nationale D`Ingenieurs De Tarbes`, and also presented it in Romania, at University `POLITEHNICA` of Bucharest. He also obtained two Master of Science Degrees, after attended two Master programs, namely `Economicity And Security In Automotive Engineering` and `Environmental Management`, at University `POLITEHNICA` of Bucharest. His academic records include numerous awards and certifications. In September 2007 Valerian joined the academic stuff of Automotive Engineering Department. In August 2008, he founded AUTOJOBS.RO, a specialized web portal in automotive industry having the goal to help and provide job seekers and employers the opportunity to be connected. He is currently attending a PhD Program, having the main interest Hybrid Electric Vehicles Development, at University `POLITEHNICA` of Bucharest.