Hybrid Powertrain Simulation

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INTRODUCTION

The requirements of the EURO 5 (in the 1st decade of 2009) and EURO 6 norms (maybe in 2012 or later) in Europe and the requirements in US and Japan to reduce the harmful gases and CO_2 emissions from vehicles increased the interest of the car manufacturers in developing new technologies for automotive propulsion systems, among which the hybrid propulsion systems have a major importance.
The purpose of this paper is to create models and simulate the operation of several hybrid architectures, trying to find out the advantages and disadvantages of each other.
The next types of hybrid powertrain solutions has been analyzed: Serial hybrid with clutch between two electric motors, Combined hybrid with clutch between two electric motors, Parallel \`through the road\` hybrid (TTR), Parallel hybrid with motor-generator \`Between two clutches\` and also a mixt hybrid powertrain with \`power splitting device\`.
Some standard components and common parameters which remain the same for all hybrid solutions have been considered.

SPECIFICATIONS OF THE VEHICLE, ENGINE, ELECTRIC MOTOR AND BATTERIES USED IN THE ANALISED HYBRID POWERTRAINS

The main specifications of the vehicle for which the simulations were developed are:
1. Weight: m_a = 1400 kg;
2. Drag coefficient: c_d = 0.32;
3. Frontal area: A = 2.1 m^2;
4. Tires: 185/60R15 (or corresponding rolling radius: r_r = 0.3 m);

Internal combustion engine (ICE) integrated in the hybrid powertrain is a \`spark ignition petrol engine\` with the next specifications:
1. Displacement: V_s = 1800 cm^3;
2. Maximum torque: M_{max} =174 Nm at n_M=4500 rev/min;
3. Maximum power: P_{max}=89 kW at n_P=5000 rev/min;
4. Flywheel's moment of inertia: 0.1 kg·m^2;
5. Fuel consumption for hot engine at idle speed: 500 g/h;
6. CO emissions for hot engine at idle speed: 70 g/h;
7. HC emissions for hot engine at idle speed: 20 g/h;
8. NO_x emissions for hot engine at idle speed: 0.7 g/h;
9. Soot emissions for hot engine at idle speed: 0.0 g/h;
10. Fuel consumption for cold engine at idle speed: 500 g/h;
11. CO emissions for cold engine at idle speed: 70 g/h;
12. HC emissions for cold engine at idle speed: 20 g/h;
13. NO_x emissions for cold engine at idle speed: 0.7 g/h;
14. Soot emissions for cold engine at idle speed: 0.0 g/h;
15. Low threshold for engine temperature: 20 °C;
16. High threshold for engine temperature: 80 °C;
17. Fuel specific heating value: 42 700 kJ/kg;
18. Stoechiometric air fuel ratio: 14.4 [-];
19. Exhaust gas temperature at idle: 250 °C;
20. Engine torque and mechanical power curves:

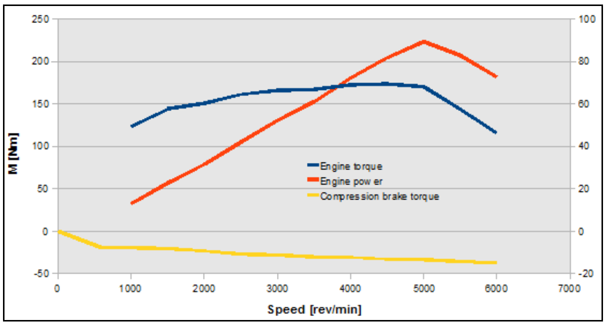

Figure 1: Torque and mechanical power for the engine used in simulations

Specifications of the battery for traction in electric mode and for storage of energy from recuperative braking are:
1. Battery terminal voltage (+): 144 V;
2. Number of cells in series per battery bank: 6;
3. Number of battery banks in parallel: 1;
4. Number of battery banks in series: 20;
5. Rated capacity of the battery: 6.5 Ah;
6. Depth of discharge at the beginning of driving: 10%.

The electric motor-generators working characteristics used in modeling are shown in Figure 2.
The moments of inertia used in simulations are 0.015 kg·m^2 for the electric motor-generator and 0.15 kg·m^2 for the engine.

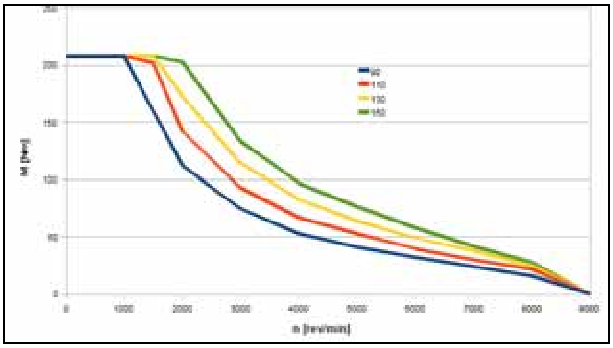

Figure 2: Motor-generator curves function of rotary speed, for different electric voltage

AMESim Libraries used for simulation sketches

The main categories of components used in modeling the hybrid systems were taken from the `Signal, Control and Observers`, `Mechanical`, `Powertrain`, `IFP-Drive` and `IFP-Drive Extra` libraries. The most important components are shown in figure 3.

Figure 3: AMESim libraries used for making the models

SIMULATION OF HYBRID POWERTRAIN SOLUTIONS

Serial hybrid with clutch between two electric motors

In the serial hybrid (Figure 4) the powertrain can be completely separated in mechanical terms and the power can be transmitted by purely electric means.

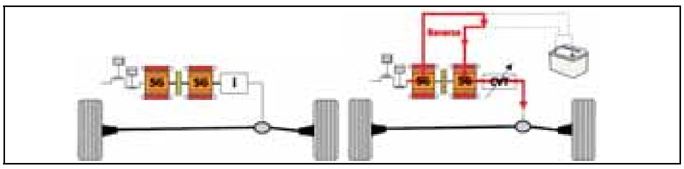

Figure 4: Serial Hybrid with clutch between two electric motors

The electric motors are arranged in series. They act as a generator giving power and also as a converter.

An automatic transmission or a continuously variable transmission (CVT) could equally be used. The continuously variable transmission has the advantage of only using the electrical motors at appropriate dimensions for the reverse gear (Figure 4).

The clutch placed between the two electrical motors was controlled using a function. It was engaged and disengaged when the car velocity reached a previously defined value; this value was introduced in the expression of the function. To avoid the slip of the clutch, it was necessary to slow the command of the function using an order lag in which the time constant and the gain had to be introduced.

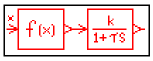

Figure 5: The function and the lag

In the simulated model there were used a continuously variable transmission and a special controller as shown in the picture below (Figure 6). The CVT-H controller is using the load of the engine and the velocity of the vehicle for a good control of the transmission.

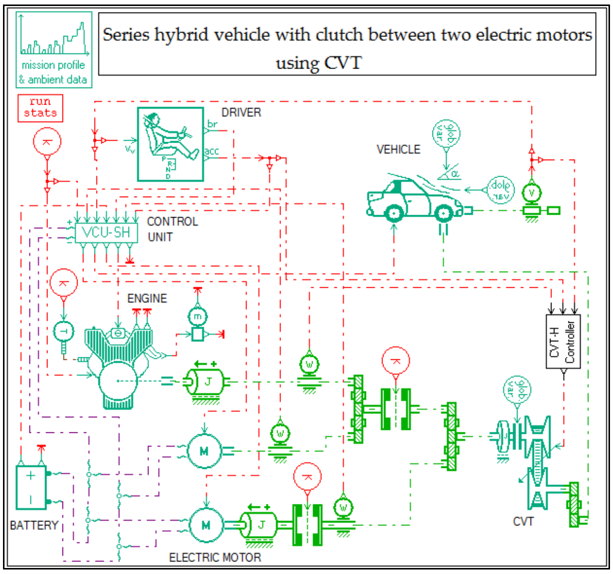

Figure 6: Series Hybrid vehicle with clutch between two electric motors using CVT

The continuously variable transmission used in this model was controlled by a `smart controller` depending of the engine load and the velocity of the vehicle.

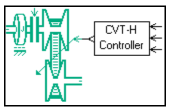

Figure 7: The continuously variable transmission and the special controller

There were taken into account the flywheel and the pulleys moments of inertia. The clutch was included in the CVT.

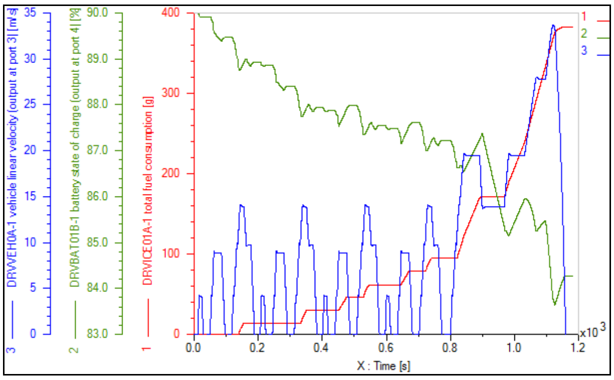

Figure 8: Total fuel consumption [g] / Battery state of charge [%] / Vehicle linear velocity [m/s] during the New European Driving Cycle (NEDC) – serial hybrid

The engine started 138 seconds after the beginning of the test and stopped after the second 157, then started again after the second 333 and ran 20 seconds, and so on until the cycle finished. In Figure 8 the fuel consumption curve is constant while the engine was stopped and increased when the engine was working. It can be seen that the total fuel consumption at the end of the cycle was 383 g while the battery state of charge was 84%.

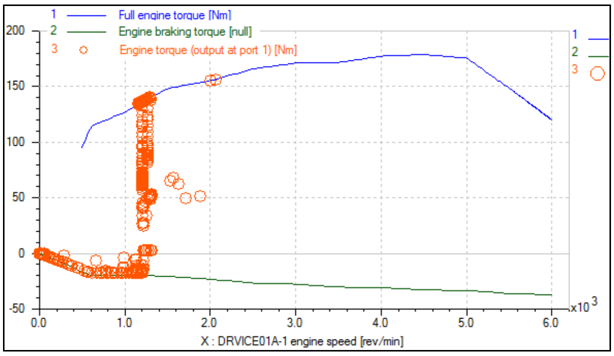

Figure 9: The position of the working points during the test - Serial hybrid with clutch between two electric motors

Figure 9 shows the position of the working points during the test in the engine torque characteristic. It can be seen that the engine was working mainly at 1200 rev/min, at different loads from idle to maximum due to the functional characteristic of the CVT.

Combined hybrid with clutch between two electric motors

Next will be described the model of a combined hybrid equipped with a special ECU (Figure 10), including a parallel ECU and a series ECU, working separately depending on the velocity of the car. The command of the new ECU was made by a switch. The method was the same with the one used before at the series hybrid with clutch between electric motors, but instead of the CVT an automatic gearbox equipped the system.
At the end of the cycle the fuel consumption was under 380g and the battery state of charge was near 65% (Figure 11).

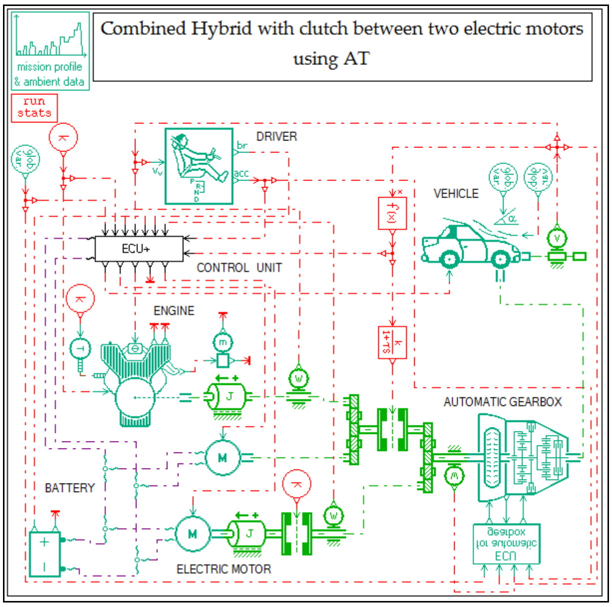

Figure 10: Combined Hybrid vehicle with clutch between two electric motors using AT

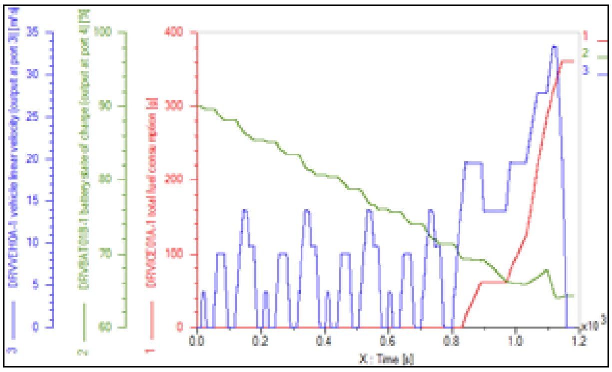

Figure 11: Total fuel consumption [g] / Battery state of charge [%] / Vehicle linear velocity [m/s] during the NEDC (1180s) – combined hybrid

Parallel `through the road` hybrid (TTR)

In this solution, the internal combustion engine and the electric motor are placed on different axles. For the front wheel drive the transverse powertrain arrangement remains unchanged. In addition, the rear axle is driven by an electric motor, as shown in Figure 12.

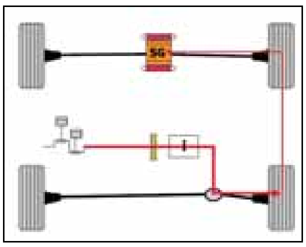

Figure 12: `Through the road` hybrid solution (TTR)

The model used for simulation in this case was shown in Figure 13. The continuously variable transmission was controlled by a smart controller depending of the engine speed and the velocity of the vehicle. This controller could change the CVT transmission ratio between the limits 0.4 … 2.5. The results of simulation for the NEDC are shown in the next charts.

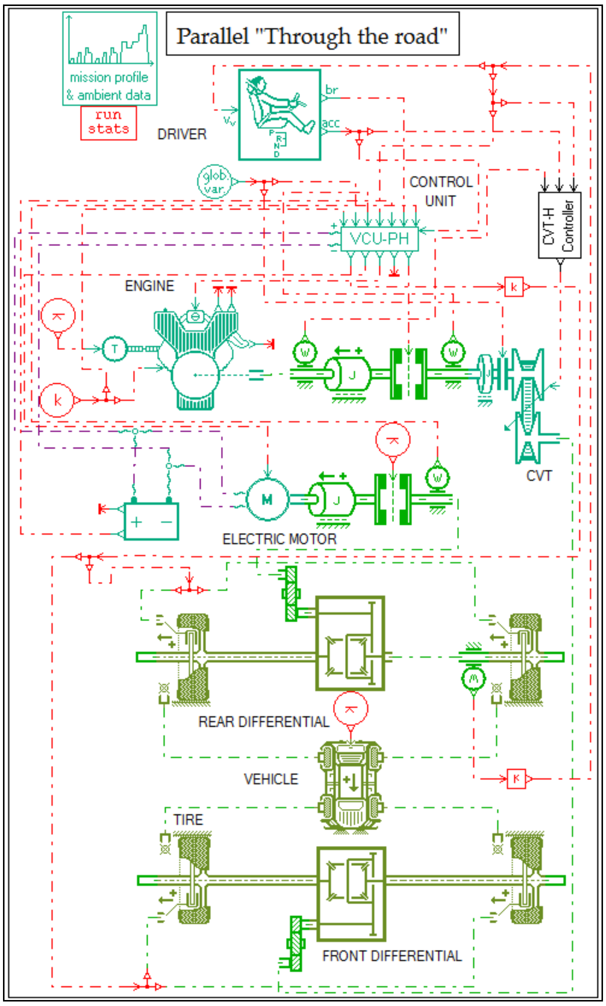

Figure 13: `Through the road` hybrid solution

As in the models shown before, the CVT was controlled by the same controller made especially to use this kind of transmission without any architectural or mechanical problems. Using the CVT helped the internal combustion engine to function close to the economic pole. The velocity of the car is taken directly from the wheel with a velocity sensor.

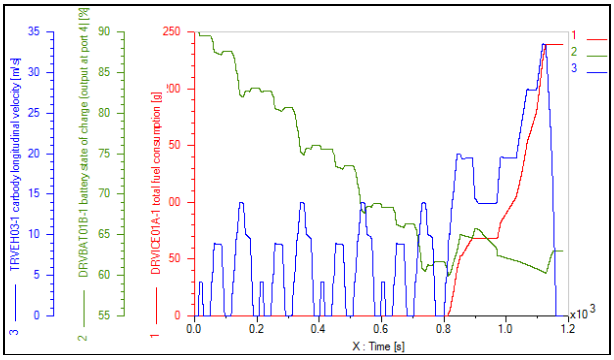

Figure 14: Total fuel consumption [g] / Battery state of charge [%] / Vehicle linear velocity [m/s] during the NEDC (1180s) – TTR

It can be seen that during 813 seconds the vehicle`s internal combustion engine didn`t work; after that moment the battery`s state of charge reached the value under 60%. After this, the engine started and the battery was charging until the time reached the second 970. After that the engine started again and continued to function till the second 1126, close to the end of the cycle.

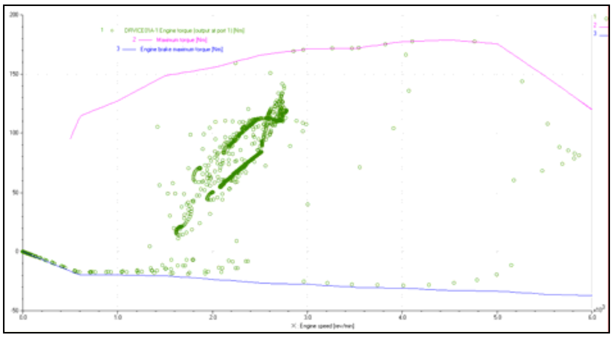

Figure 15: The position of the working points during the test – Parallel `through the road` hybrid

It can be seen that engine function points respected the usual order and orientation, being close to the economic pole.

`Between two clutches` hybrid architecture

This architecture is based on the idea that the internal combustion engine can be shut down and decoupled from the transmission, resulting less friction losses during its cycle. The clutch (usually a dry clutch) is not used as a starting clutch.

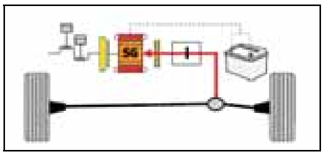

Figure 16: Powertrain with a starter between two clutches

This kind of architecture includes an automatic transmission or a continuously variable transmission, as shown in the pictures below.

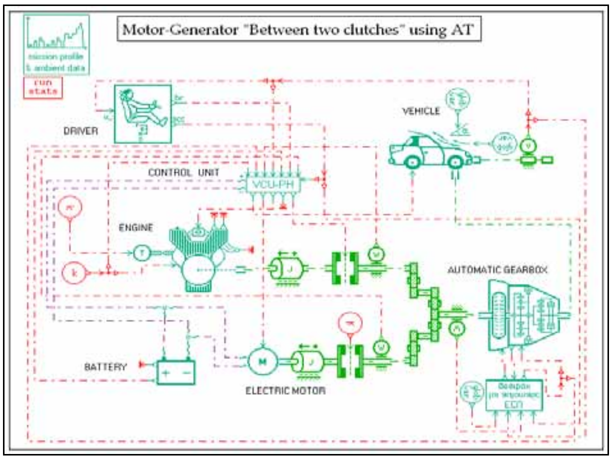

Figure 17: The model using automatic gearbox

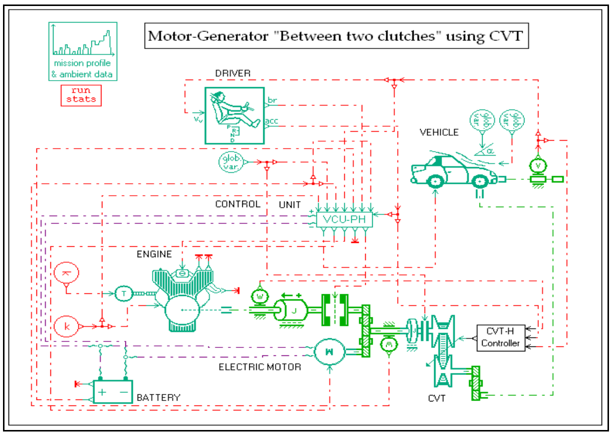

Figure 18: The model using continuously variable transmission

The automatic gearbox is controlled by a special ECU, designed for automatic gearboxes, achieving a simple dynamic modeling of an `n-ratio` (Figure 19).
The continuously variable transmission is controlled by a smart controller depending of the load of the engine and the velocity of the vehicle (Figure 20).

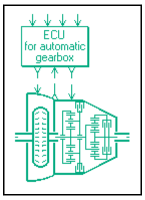

Figure 19: A `n-ratio` automatic gearbox with integrated torque converter and the `ECU`

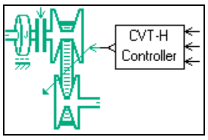

Figure 20: The continuously variable transmission and the special controller

For the automatic gearbox, the torque converter, its moments of inertia (impeller and turbine) and the powered axle were taken into account. Parallel with the torque converter there a lockup clutch was added, bypassing the torque converter when the rotary velocities of the turbine and impeller were close to each other.
For the continuously variable transmission, the flywheel and the pulleys moments of inertia were taken into account. In the CVT a clutch was included.

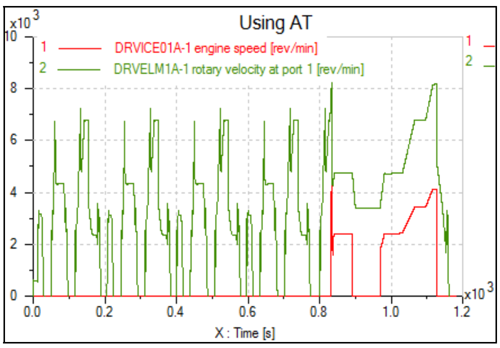

Figure 21: Variation of engine speed and rotary velocity of the electrical motors during NEDC (1180s) – AT

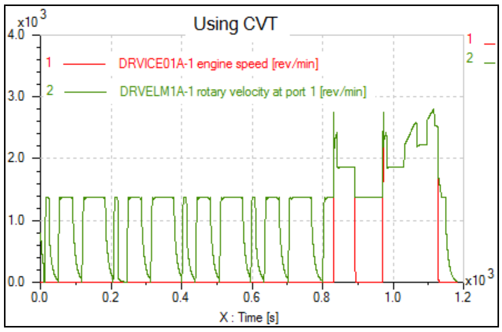

Figure 22: Variation of engine speed and rotary velocity of the electrical motors during NEDC (1180s) – CVT

It can be observed that in both cases the vehicle had used only its electrical motor during 831 seconds, and only after that the engine had started. The engine speed was higher in the case of the automatic gearbox (~ 4200 rev/min) compared to the CVT (~2700 rev/min).

Power Splitter hybrid architecture

This device, usually referred as the `PSD`, was the core of the full hybrid system in Prius. Using it the gasoline engine and two electric motors were connected. Because all of the components are permanently engaged, the power is transferred like in the case of a common differential rather than a traditional automatic transmission providing remarkably smooth operation and rapid responsiveness.
When the `PSD` operates, it splits and/or combines power to achieve the greatest efficiency. The large electric motor sometimes provides power, sometimes captures power, and sometimes just spins without any electricity flowing in either direction.

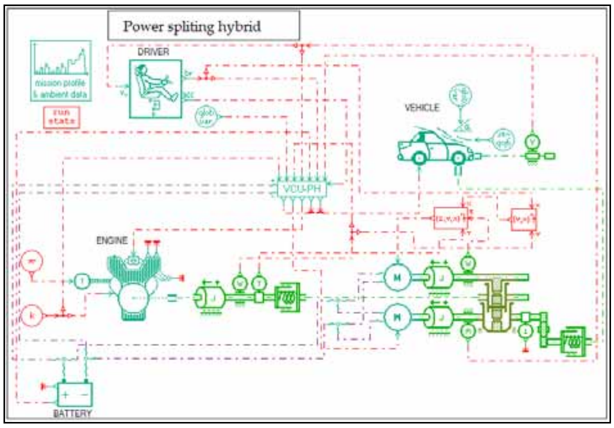

Figure 23: Model simulations of `Power Splitter` Hybrid architecture

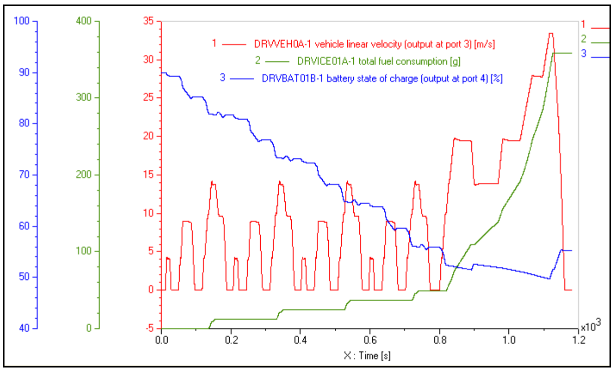

Figure 24: Total fuel consumption [g] / Battery state of charge [%] / Vehicle linear velocity [m/s] during the NEDC (1180s) – PSD

It could be seen that the engine started near the second 150, the consumption at the end of the cycle reached 358.7g and the battery state of charge got under 60% (55.25%).

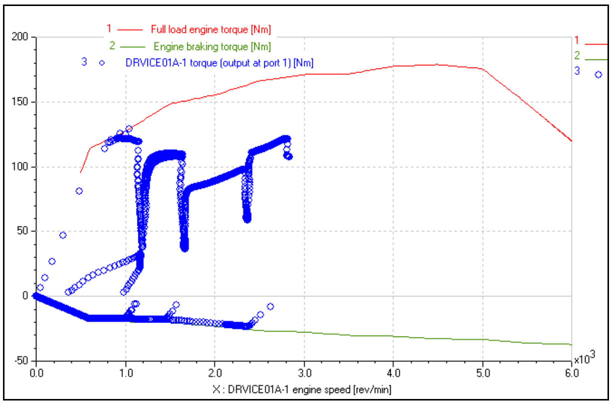

Figure 25: Engine function points, near to the economic pole consumption

CONCLUSIONS

Using AMESim it is possible to simulate different hybrid powertrain solutions to obtain data about fuel consumption and other parameters, and compare this solutions even if they were not yet physically achieved.
In the next table it can be seen the fuel consumption in NEDC cycle, for every hybrid architecture simulated.
Although the instantaneous velocities were kept inside the tolerances of NEDC, the total displacement was different from one model to another due to functional characteristics of each model.
The lowest fuel consumption model was the `Parallel through the road, using CVT`, while, in this case, the battery state of charge was kept above the lowest accepted limit of 60%. Therefore this model seems to be the most economic in the NEDC conditions, but its dynamic performances outside the NEDC have to be studied in the future.
Another interesting architecture is ` Between two clutches, using CVT`, but the fuel consumption was 7.5% higher than in the previous case; the eventual higher dynamic performances that may result from this higher consumption will be verified.

In the case of the architecture `Clutch between two electric motors` the battery state of charge at the end of the cycle was the highest, but the fuel consumption was also the highest.
The hybrid architecture `PSD` did not respect the lowest acceptable limit of 60% for the battery state of charge that assures a long life for the batteries.

Table 1: The most important parameters resulted after the simulation

Hybrid architecture	N.E.D.C.			
	Total displacement [km]	Total fuel consumption [g]	Battery state of charge [%]	Mixt fuel consumption [l/100 km]
Between two clutches, using CVT	11037.2	272.02	61.46	3.34
Between two clutches, using AT	11106.6	344.9	78,11	4.21
Combined hybrid	11086.6	380	65	4.68
Clutch between two electric motors	11009.9	383	84.27	4.72
Through the road, using CVT	11047.9	239.07	63.01	2.94
Power splitter device	11061.1	358.7	55.25	4.4

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