PREDICTION OF DRIVING PERFORMANCE OF A HYBRID VEHICLE WITH CVT TRANSMISSION

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1. INTRODUCTION

The automobile industry has made significant contributions to the growth of modern society, by satisfying many of its needs for daily mobility. The rapid development of the automotive industry, unlike others, has prompted the progress of human society from primitive industrial society to a highly developed. The automotive industry and the others industries that serve it constitute the backbone of the world's economy and employ the greatest share of the working population.

However, the high number of vehicles in use around the world has caused and continues to cause serious damages for environment and human beings: air pollution, global warming, and the rapid depletion of the Earth's petroleum resources are now problems of vital interest.

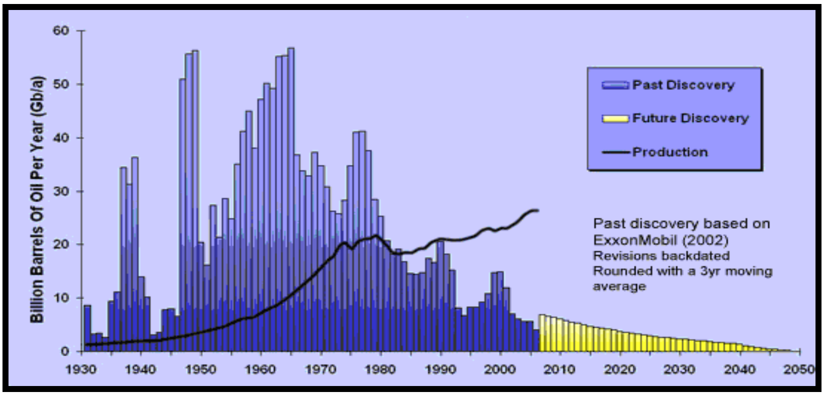

Figure 1: *Trends of discoveries of new reserves of oil versus consumption required*

In recent years, the research and development activities related to transportation have emphasized the development of less pollutant and safe vehicles with high efficiency.

Electric vehicles, hybrid electric vehicles, and fuel cell vehicles have been proposed for the future to replace traditional vehicles.

This paper focuses the study on a car which is the first production model with hybrid technology in history.

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2. HYBRID ELECTRIC VEHICLES

Any vehicle which integrates two or more sources of power, either directly or indirectly to the propulsion of that is a hybrid.

Most hybrid applications in the automotive field arises from the compromise between a traditional architecture powered by fuel and a purely electric one, so as to achieve the objective of both reducing emissions, a weak point of internal combustion engine vehicles (ICEVs), and increase autonomy, sore point of the electric vehicles (EVs).

As a result, the components that characterize a hybrid electric vehicle (HEV) are the sum of those found in a ICE vehicle and in an electric one:

- internal combustion engine
- fuel tank
- electric motor
- generator
- batteries
- driveline.

Depending on the different approach adopted in order to make the power units generate driving power that will be sent to the wheels, hybrid vehicles can be divided into different types:

- series hybrid
- parallel hybrid
- series/parallel hybrid.

Series hybrid system owes its name to "cascade" power flows, according to the sequence: engine, generator, electric motor, drive wheels. Great strength of hybrid series is the remarkable flexibility of the electric motor that also allows, thanks to its torque characteristic, to nicely face up to starting stages like standing start, without particular problems with a easier transmission than classical schemes. ICE is also sized to work in a range of low-speed, because of the lack of direct connection to the wheels, which allows an optimal adjustment with a high efficiency throughout the operating range. The disadvantages are primarily related to the excessive size of the electrical part.

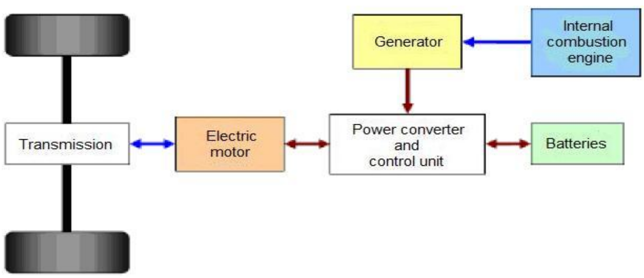


Figure 2: *Hybrid series system, block diagram*

In parallel architectures, both power units are mechanically connected to the wheels and can directly transfer power. Unlike the series systems, the generator lacks since the electric motor performs the job of recharging the battery. Therein is te reason for its limit: when the battery is recharged, the electric motor can not supply power to the wheels.

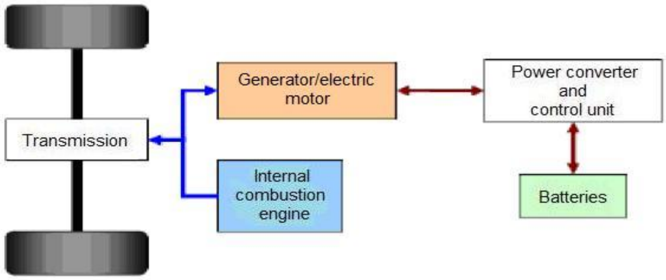


Figure 3: *Parallel hybrid system, block diagram*

Intermediate solution between the two outlined above is the series/parallel hybrid.

Equally to parallel structures, both motors are connected mechanically to the wheels and, equally to series ones, the heat engine feeds, by using the generator and battery, the electric motor. The strategy of division of power is managed by a control unit (Electric Control Unit - ECU) in order to achieve maximum efficiency and then obtain the required power in the cheapest way.

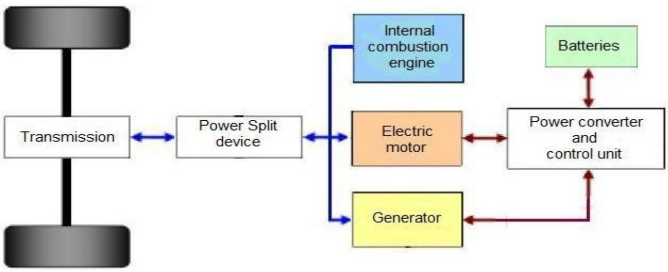


Figure 4: *Series/parallel hybrid system, block diagram*

The mechanical coupling that makes the combined use of two power units consists of an epicyclic gearing, which is also linked to the generator.

Regardless of the configuration, the extent of hybridization of a vehicle can be quantified by means of the parameter *Degree Of Hybridization* (DOH) defined as:

$$DOH = \frac{P_{el}}{P_{el} + P_{term}} = \frac{P_{el}}{P_{tot}} \qquad (1)$$

where the symbols have the following meanings:

P_{el} total power of electrical equipment installed on board

P_{term} power of the internal combustion engine.

The DOH assumes zero value for a conventional vehicle, the unit for a pure electric vehicle. Intermediate values cover all possible hybrid systems.

3. FEATURES ADOPTED

One of the features of hybrid vehicles is to be equipped with an engine smaller than conventional vehicles, to the benefit of efficiency.

The reasons why an underpowered engine is more efficient than a larger one are:

- lower mass
- lighter pistons and other components
- displacement volume lower
- fewer cylinders.

In addition, hybrid vehicles make use of the following devices to further increase the autonomy:

- regenerative breaking
- off the engine if the vehicle is motionless
- advanced aerodynamics
- low rolling resistance tires
- lightweight materials.

4. CRITERIA FOR OPTIMAL CHOOSING

A given configuration is preferable depending on use and performance that the vehicle is called to fulfil. Choosing the type of architecture is influenced by several factors:

- vehicle weight
- the mission profile, that is the ratio between average power and maximum power needed for the motion

It is preferable to install a series configuration type for trucks which have to travel for urban cycles whereas the parallel configuration is chosen for light vehicles or trucks carrying goods, since often they have to travel extra urban cycles.

Elements necessary to size the propulsion system are:

- power of the heat engine
- power of the motor / generator
- energy storage system
- relation between power and energy storage system

	Fuel consumption improvements				Driving performance	
	Idling stop	Energy recovery	High-efficiency operation control	Total efficiency	Acceleration	Continuous high output
Series	●	◎	●	●	○	○
Parallel	●	●	○	●	●	○
Series/parallel	◎	◎	◎	◎	●	●

◎ Excellent ● Superior ○ Somewhat unfavourable

Table 1: *Degree of excellence of the performance of hybrid systems in relation to some methods of increasing autonomy*

5. COMPONENTS OF THE VEHICLE

The model under study in this paper is equipped with a thermal gasoline propulsion unit with 1.5 litres and 57 kW, combined with a 50 kW electric permanent V-structure buried magnets.

In order to optimize fuel consumption and emissions, the thermodynamic cycle used is a reduced-compression Atkinson cycle, instead of the classic Otto cycle, so as to have less pumping losses, the higher thermal efficiency and a more efficient coupling to the electric motor. Indeed, denoted by ρ the compression ratio of the cycle (the ratio between the volume of the cylinder when the piston is at bottom dead centre and the volume of the cylinder when the piston is at top dead centre), the ideal efficiency η is defined as:

$$\eta = 1 - \frac{1}{\rho^{k-1}} \tag{2}$$

which implies that whether ρ increases, efficiency rises too.

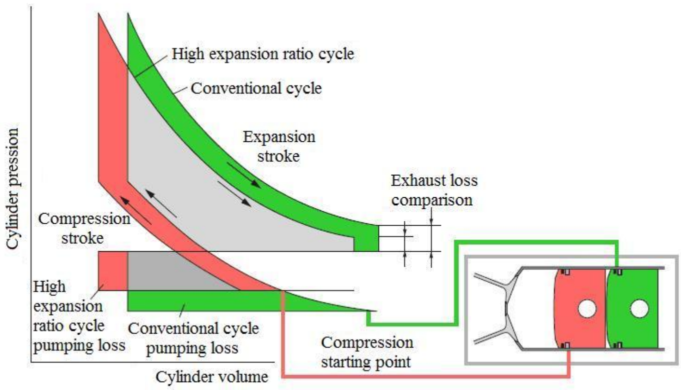
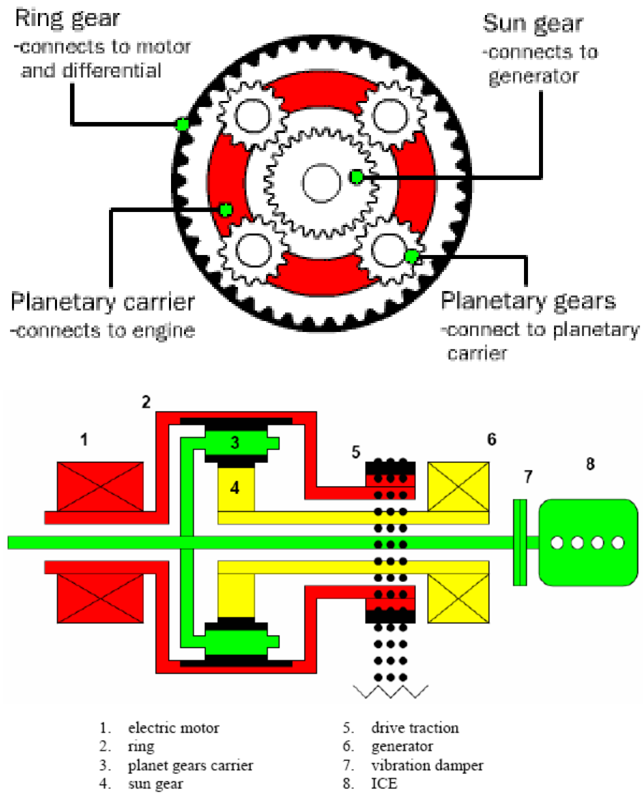


Figure 5: *Atkinson cycle with high growth and low compression compared to Otto cycle*

Because it is a series/parallel architecture, a generator is used: an AC synchronous electric machine with V-structure buried permanent magnets, with ability to turn over 10,000 rpm, which makes possible the production of more electricity during the march of the car at medium speed.

The ECU is responsible for maintaining the level of constant load by monitoring the amount of discharge during acceleration, and recharging by regenerative braking or when there is surplus energy.

A differential mechanism comprehending a planetary gearing is used for the division of power from the engine. It is identified by the acronym PSD (Power Split Device) and can be implemented by a ring gear internally toothed and five gears, one central (sun gear), and four satellites. The ring gear is connected to the electric motor, a planetary carrier, united to the four satellites, is connected to the internal combustion engine, whereas the sun gear is linked to the generator.



Fiure. 6: *Gear components of the Power Split Device (PSD)*

The gears have the following numbers of teeth:

- solar wheel $z_s = 30$
- satellites wheels $z_p = 23$
- ring wheel $z_r = 78$

By denoting the solar wheel with the subscript "s", the ring gear with the subscript "r", the carrier with the subscript "c", and selecting the carrier as a frame, the construction ratio of the gearing in question is equal to:

$$\frac{\omega_s - \omega_c}{\omega_r - \omega_c} = -\frac{z_r z_p}{z_p z_s} = -\frac{z_r}{z_s} = -k \qquad (3)$$

and *k=2,6*; the angular velocities are related by the following relation:

$$\omega_s + k\omega_r - (1+k)\omega_c = 0 \qquad (4)$$

Hypothesized that the mechanical power is fully transferred to the two electric machines (no losses), one can write:

$$P_c = \alpha P_c + \beta P_c \tag{5}$$

where $\alpha P_c = P_s$ and $\beta P_c = P_r$, with α and β real numbers such that the sum is 1. Knowing that power is equal to the product of torque and angular velocity and referring to (4) yields:

$$T_s = \frac{T_r \omega_r (1-\beta)}{\beta\left[(k+1)\omega_c - k\omega_r\right]} \tag{6}$$

The control strategy that allows to verify what the actual distribution of power is, is not known. In this regard, as it proceeds will be referring to the distribution of the total power consumption in the field of vehicle speed, obtained experimentally through test on the rollers.

It is useful to focus on the relation between the angular velocity of the electric motor and the angular velocity of driving wheels connected by a set of toothed gears, whose characteristics are shown in Figure 7.

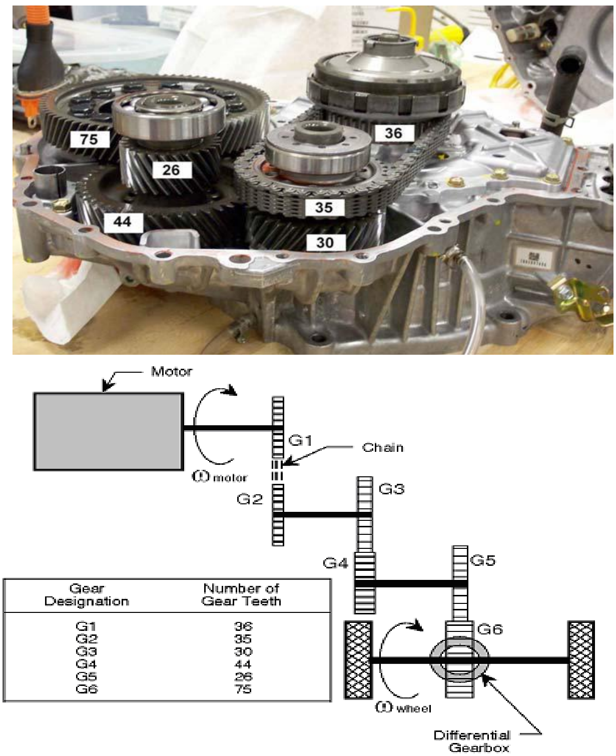


Figure 7: *Mechanism of connection between the electric motor and drive wheels*

Working on the transmission ratios between the gears yields :

$$\frac{\omega_{motor}}{\omega_{wheel}} = 4{,}113 \qquad (7)$$

and, considering that the car is supplied with tires measuring 195/55 R16, with rolling radius R_0 approximately equal to 0.2921 m, one can obtain the translational speed of the car, depending on the angular velocity of the wheel.

5.1 TOYOTA HYBRID SYSTEM (THS)

Toyota Hybrid System is the set of processes attributed to the optimal management of combined operation of the two sources of power, which is installed on Toyota cars characterized by a series-parallel design concept, propelled by the electric motor either in conjunction with or alternative to the gasoline one. Conceptually, the THS is the "mind" whereas the "arm" is the epicyclic gearing, just studied, through which one can act on the various components (engine, and the two electrical machines, motors and generators) in order to subdivide the power appropriately

$$v = \omega_{wheel} \cdot R_0 \cdot 3{,}6 = \omega_{wheel} \cdot 1{,}05156 \qquad (8)$$

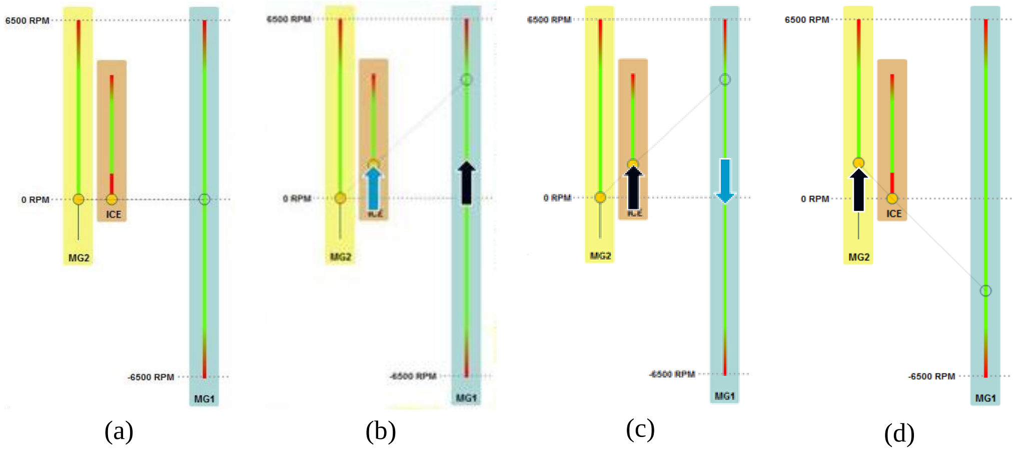
which is expressed in kilometres per hour.

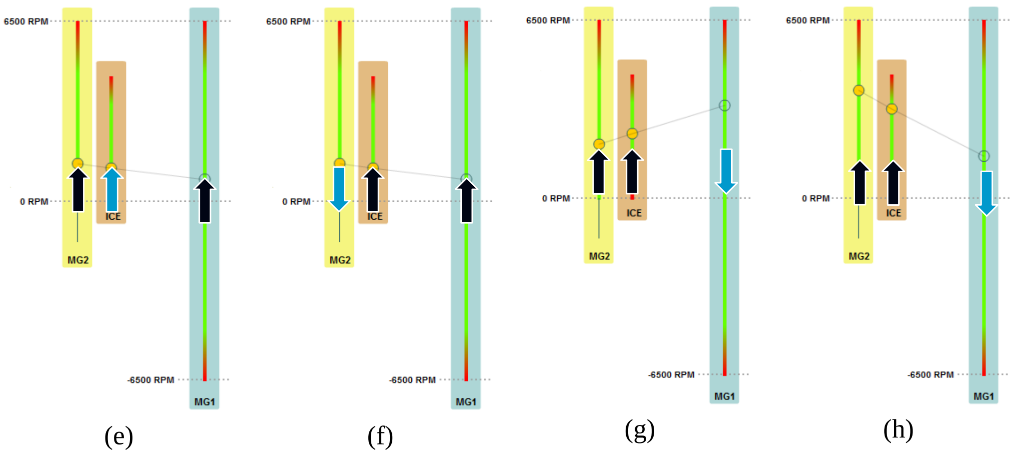
To qualitatively understand the management implemented by the system, consider the following possibilities of travel:

- ready system (READY ON State)
- starting off
- cruising
- full acceleration (maximum power)
- deceleration.

Since the relation between the angular speeds of the machines administrated by the THS is constantly and perfectly linear, the tools that are most appropriate for the performance analysis are known as "nomograms": they are many vertical lines as variables that are wanted to be monitored (in this case, the angular velocities for internal combustion engine ICE, the generator MG1 and the electric motor MG2). Above the horizontal line passing through the point of inactivity of ICE the direction of rotation is positive (counter clockwise), below negative (clockwise), and then in ordinates there is the number of revolutions per minute each machine can assume.

Furthermore, the black-filled arrow indicates that the machine associated with provides motor torque whereas the blue-filled arrow indicates the resistive torque. In the cases of deceleration, the green-filled arrow associated with the electric motor MG2, shows the couple issued in order to recharge the battery; in these cases, therefore, the electric motor performs the function of generator, since receiving the torque supplied by the wheels.





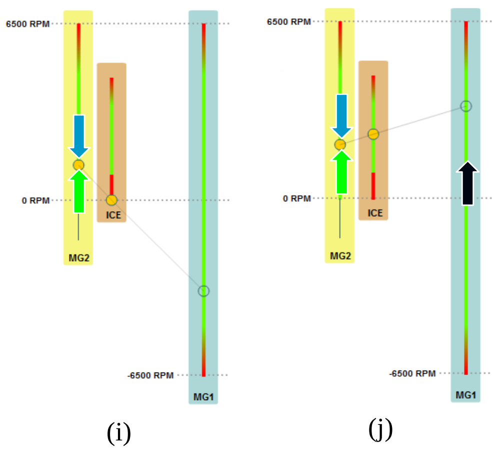


Figure 8: *Nomograms for:*

- *a) ready system with enough battery charge and proper coolant temperature;*
- *b) ready system in case one of the conditions in the preceding point is not verified (ICE turns on);*
- *c) stage after ICE turns on;*
- *d) starting off with battery sufficiently charged;*
- *e) starting off in case battery is not sufficiently charged;*
- *f) recharging after ICE turns on (after event (e));*
- *g) running constantly;*
- *h) acceleration (maximum power)*
- *i) deceleration with gear lever in "D";*
- *j) deceleration with gear lever in "B"*

6. CALCULATION OF CONSUMPTION PERFORMANCE

Electric hybrid architectures show a pollutant power well below that of traditional vehicles. This is extremely linked to the decrease in consumption. In the following paragraph, a theoretical study of consumption highlights the performance improvement of consumption of the car.

The characteristics of the internal combustion engine are briefly reported:

Displacement	1.5 l	
Maximum Power	57 kW	5000 rpm
Maximum Torque	115 Nm	4000 rpm

To obtain the diagrams of power and torque for the combustion engine depending on the number of rotations, it is acceptable to approximate the power curve with a cubic parabola of the type:

$$N = an^3 + bn^2 + c \qquad (9)$$

and to define that, it is necessary to have the values of the three coefficients *a*, *b*, *c*, which can be determined through the imposition of the following three conditions:

- maximum power condition, $N = N_{\max}$;
- maximum torque condition, $C = C_{\max}$;
- derivative of torque equal to zero for $C = C_{\max}$.

The reason why the linear coefficient is omitted is because the curve of characteristic power does not show a maximum with horizontal tangent, so that lacks a boundary condition.

Calculations are omitted but, once carried out, they allow obtaining the curves of power and torque for the heat engine, respectively shown in Fig. 9 (a) and (b).

The data on the electric motor are summarized below

Type	AC synchronous tri-phase	
Maximum Power	50 kW	1200-1540 rpm
Maximum Torque	400 Nm	0-1200 rpm

The electrical power is given by the product:

$$P_{el} = P_{batt} \cdot \eta_{batt} \qquad (10)$$

where the symbols have the following meanings:

P_{batt} power supplied by the battery

η_{batt} battery efficiency (assumed equal to 1).

Its power and torque curves are visible in Fig. 9 (c) and (d).

It is essential to specify that the power taken into account in order to calculate the power consumption is the only one coming from the engine.

The curves of power and torque just seen are for the two motor units of the vehicle, but, when viewed separately, do not characterize the full performance level of the car in question, because the two motors work in harmony during the regular drive. In this regard, it is necessary to have graphs that represent the curves of power and torque for the combination of these propulsion units.

It has already been mentioned that the strategy of combination of power and torque between the two units is not known, thus graphs obtained experimentally, for example by putting the car on rollers suitable for measuring the magnitude mentioned, are used. Here, it is done by approximating the curves of combined supply with sixth order polynomial equations, shown in Fig. 9 (e) and (f).

It has to be noted that, for both diagrams, the x-axis shows the travel speed of the vehicle rather than the traditional angular velocity, since the two engines work at different speeds, instant by instant.

The characteristics of consumption, analyzed below, refer to the use of the car with distance obtained with the gear lever in "D".

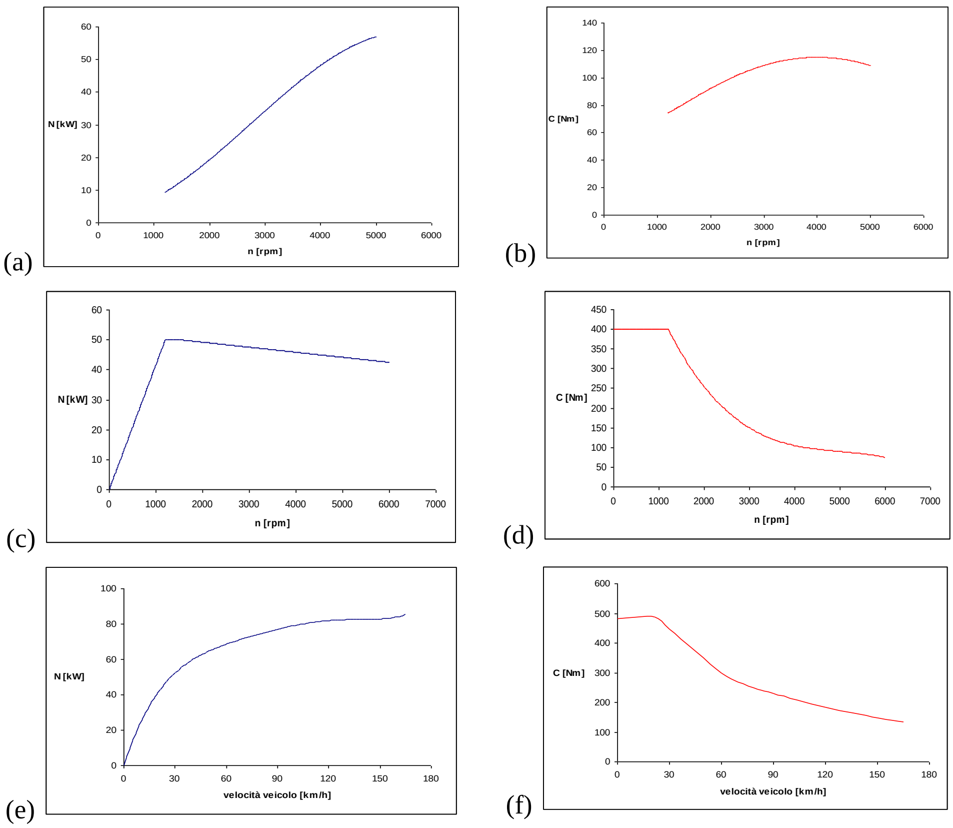


Figure 9: *Curves of (a) the internal combustion engine power, (b) the internal combustion engine torque, (c) the electric motor power, (d) the electric motor torque, (e) power from the combination of motor units, (f) torque from the combination of motor units*

In that circumstance it is assumed that the angular velocities of the three machines installed on board show the trends visible in Fig. 10, depending on time:

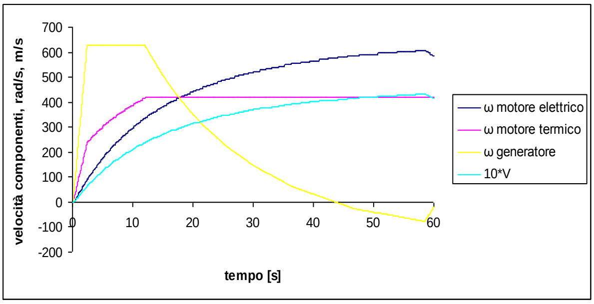


Figure 10: *Diagram of the angular velocities of the combustion engine (in pink), the electric motor (in blue), the generator (in yellow) and speed of the car (in blue) versus time.*

In that chart, it can be also seen the curve representing the speed of the car, expressed in meters per second and multiplied by a factor of 10, for reasons of scale.

The evolution of specific fuel consumption, *q*, depending on the number of engine revolutions and at fully open throttle, approximated by a curve of the sixth order, is shown in Fig. 11 (a). Knowing the curve of the fuel specific consumption yields to calculate the hourly consumption of the engine, whose graph is shown in Fig. 11 (b) expressed in litres per hours using the formula:

$$C_t = \frac{qN}{\eta_t \rho} \quad (11)$$

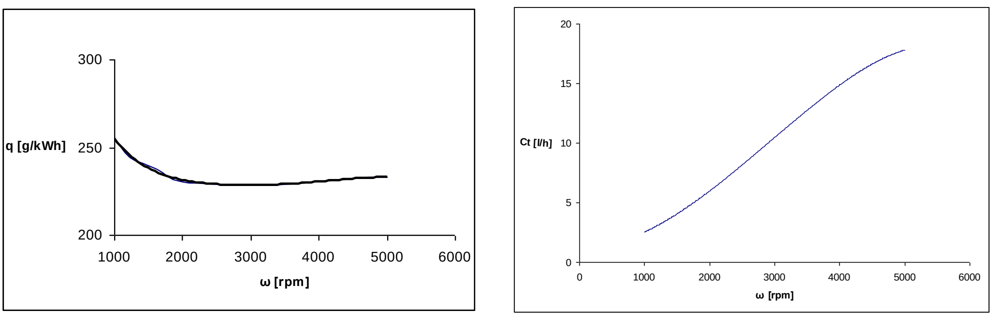


Figure 11: *Curves of (a) fuel specific consumption, q, and (b) hourly consumption,* C_t

where:

- N is the power, expressed in kW
- η_t is the transmission efficiency, assumed equal to 0,95
- ρ is the fuel density, in g/l (for gasoline $\rho = 785 g/l$).

It is now necessary to calculate resistance power. To do this, the following data must be considered:

Drag coefficient, C_x	0,26
Lift coefficient, C_z	0,19
Vehicle mass with driver, *m*	1420 kg
Front section vehicle, *S*	2,16 m^2
Air density, *ρ*	1,2257 kg/m^3

The overall resistance R_{tot}, acting on the car during motion, consists of three rates:

- aerodynamic drag
- rolling resistance
- grading resistance

summing those yields:

$$R_{tot} = \frac{1}{2} C_x \rho S \left(\frac{V}{3{,}6} \right)^2 + \left[a + b \left(\frac{V}{3{,}6} \right)^2 + 10i \right] P \qquad (12)$$

where:

- *a* and *b* are coefficients respectively assumed equal to 15 and 0,0065
- *i* is the grading expressed in percentage
- *P is car weight which* decreases with increasing speed because of the effects of lift that is taken into account through the following equation:

$$P = mg - \frac{1}{2} C_z \rho S \left(\frac{V}{3{,}6} \right)^2 \qquad (13)$$

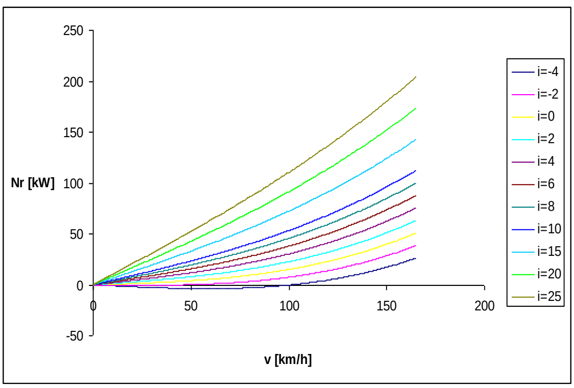


Figure 12: *Curve of resistance power depending on car speed for different inclinations*

The calculation of consumption is carried out considering the car driving in plan ($i = 0$).

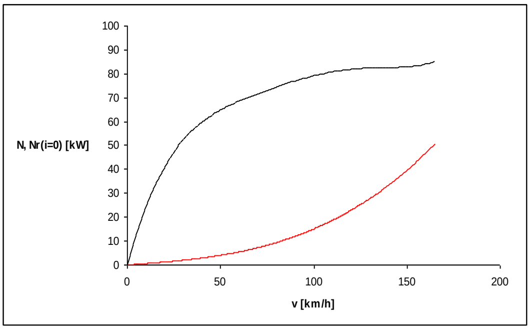
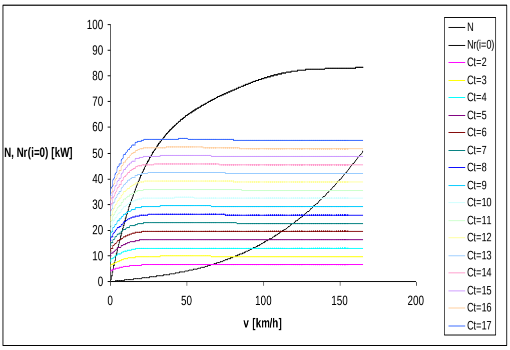


Figure 13: *Curve of power from the combination of propulsion units and curve of resistance power in plan*

With the data held and resorting to (11), it is possible to plot the hourly equal-consumption curves throughout the domain of operation of the car. In addition, the curves of constant consumption per kilometre, which is the fuel consumption in litres equivalent to a distance of 100 km, have been obtained from the following relation:

$$C_{100} = \frac{C_t}{v} 100 \qquad (14)$$



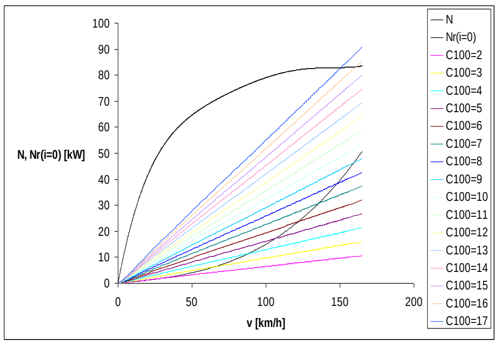


Figure14: *Curves of (a) hourly equal-consumption, (b) equal-consumption per kilometre*

7. COMPARISON WITH OTHER CARS AND DISCUSSION

The values of consumption obtained in the previous section assume further prestige when compared with those of common cars with simple gasoline engines, which present values of maximum power and torque comparable to the vehicle under study.

It has been chosen to perform the comparison with two models belonging to different Car Maker and currently on the market.

The data on consumption per kilometre at constant speed are listed in tab. 2:

Displacement cm^3	**Max power kW/rpm**	**Max torque Nm/rpm**	**Velocità Km/h**	**C_t l/h**	**C_{100} l/100km**
			90	3,7	4,10
			100	4,6	4,63
			130	8,6	6,53
1368	57/6000	115/3000	90	-	5,88
			100	-	6,49
			130	-	9,52
1360	54/5400	118/3300	90	-	5,13
			100	-	5,68
			130	-	7,87

Table 2: *Comparison between the values of C_{100} of the car under study and several conventional cars at constant speeds*

From the above table it is immediate to realize the decrease in consumption, in terms of C_{100}, which features a hybrid architecture including an electric motor. Although the values considered are reported at constant cruising speed, one understands that the efficiency lowers as distances are characterized by variable speeds.

Furthermore, although the calculations are purely theoretical, the results are comforting whether considered that phenomena such as regenerative braking or turning off the heat engine when at rest have not been taken in account, which should certainly be in favour of further reduction in consumption.

In addition, if one considers that the car includes a fully electric mode of operation, *EV-mode*, which can be chosen by the driver (the car must travel at less than 45 km/h, the battery must be sufficiently charged and the gasoline engine must be warm, usable only for a maximum of 2 km), use of the hybrid is even more advantageous.

The car also offers extremely low emissions compared to other either gasoline or diesel engines: during a year it emits up to one tonne of carbon dioxide less, because only 104 g/km of CO_2 are emitted in the combined cycle. As regards hydrocarbons and oxides of nitrogen (NO_x), the values are already in line with the Euro 5 legislation, as table 3 shows.

Emissions g/km	CO	NO_x	HC	HC +NO_x	PM
Vehicle in study	0,18	0,01	0,02	0,03	-
Euro IV gasoline	1	0,08	0,1	-	-
Euro IV diesel	0,5	0,25	-	0,3	0,025
Euro V gasoline	1	0,06	0,1	-	-
Euro V diesel	0,5	0,180	-	0,23	0,005

Table 3: *Comparison between emissions of the car in study and EURO IV and EURO V*

8. CONCLUSIONS

Theoretical analysis highlights the benefits in terms of efficiency of a hybrid car and makes possible the obtaining of results in harmony with that statement, demonstrating the goodness of the analytical procedure that is characterized by feedback on the plan real.

Overall, the entire work has led to knowledge of an area as current as still developing in the automotive field, allowing even the application of appropriate models and theoretical approaches consistent with the characterization not only qualitative but also quantitative of the object under study.

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