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Energy consumption of a last generation full hybrid vehicle compared with a conventional vehicle in real drive conditions

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Abstract

Hybrid vehicles are one of the most important choices to improve efficiency and reduce CO2 production of vehicles.

Benefits in using hybrid powertrains are generally found in urban environment where lower average speeds, higher accelerations make the internal combustion engine run at lower efficiency points.

The originality of the present paper consists in the data elaboration and analysis collected in a measurement campaign on road in real driving conditions, on an ad hoc path planned according to the average national daily mileage in metropolitan urban context, which thus acquires a significance generalizable in that specific context, which led to the consumption quantification and an analysis of the main factors that determine the reduction in consumption of full-hybrid vs conventional vehicles. Another important and original aspect of this paper is the analysis of the operating times in ZEV mode of hybrid vehicles, which shows how this solution leads to a significant reduction of pollutant emissions in urban contest.

An on-road experimental campaign has been done by comparing two different versions of the same model (Toyota Yaris Hybrid and a conventional one, Toyota Yaris 1.5 gasoline) and a hybrid vehicle with different characteristics (the hybrid born - Toyota Prius), like size, traction battery capacity, generator/motor electric power. Thirty drivers on a fixed path have done this experimental campaign and in this paper, the results are reported.

The results show that a strong influence on consumption is due not only to the type of vehicle, but also to driving style and speed.

The comparison between the two versions of Yaris, shows a strong reduction in consumption using hybrid vehicle for low and medium speeds (for 20 km/h about 50%), such benefit decreases with the increasing speed and for values higher than 90 km/h both the vehicles have the same consumption. The reduced consumption of the hybrid vehicle at low speeds is due, on the one

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hand, to the greater efficiency of the hybrid vehicle engine compared to the conventional one and on the other hand to the high functioning in ZEV mode, with the engine off, (63% of time) thanks to the use of the electric motor.

The comparison between the two hybrid vehicles with different characteristics (YarisHy and Prius) shows that the consumption trend vs. speeds is similar but the Prius has lower consumption due above all to the high efficiency of the braking energy recovery system, despite the greatest mass.

This lead then to significant consumption reduction, but also lower emissions in places where such parameters have an important role: the urban environment.

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Keywords: Hybrid vehicle, real drive conditions, energy analysis

Nomenclature

BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicles
HEV	Hybrid Electric Vehicles
PHEV	Plug-in Hybrid Electric Vehicles
OBD	On Board Diagnostic
ZEV	Zero Emission Vehicle
MG1	Motor Generator 1 of Toyota Hybrid System
MG2	Motor Generator 2 of Toyota Hybrid System
ICE	Internal Combustion Engine

1. Introduction

As stated in the report issued by the European Commission, Directorate-General for Communication, Citizens' Information on Transport Policies [1], in order to achieve the EU's climate change goals it is necessary to drastically reduce transport emissions, whose carbon dioxide production accounts for at least 20% of EU greenhouse gas emissions.

To reduce global greenhouse gas emissions by 80% and thus reduce climate change within safety limits, the transport sector has to cut emissions by 60% by 2050. Road traffic, representing the main form of transport, is the major source of pollution: according to the latest data, it produces about 71% of total CO_2 emissions (two thirds of which are generated by cars).

A quarter of EU transport emissions are produced in urban areas; small and large cities play therefore a key role in mitigating climate change. Many of them also have to struggle with congestion problems and improve air quality, which is currently unsatisfactory.

Solutions to reduce fuel consumption and emissions include fuel and traction systems: the use of cleaner fossil fuels is a reality in the Italian working park for several years now, biofuels can be mixed with traditional fuels, reducing climate emissions of internal combustion vehicles [2]. In particular, biomethane has a particular potential for reducing fuel consumption and environmental impact [2], [3].

As far as traction systems are concerned, short, medium and long-term solutions go towards a progressive electrification vehicles into fully electric vehicles (BEV), which today mark a significant growth in Europe and worldwide (in Europe, +101% between 2014 and 2015 and +7.2% in the first half of 2016), with a market penetration exceeding the percentage unit in many European Countries, and FCEV, this solution to date is technologically available and can be a medium-term opportunity. HEV represent an evolution of conventional motorization that is becoming increasingly widespread on the market, with a growth rate of 50% per annum and a steady increase in the standard models offered by car manufacturers [2].

Hybrid traction systems are set to become more and more electrical, passing from Micro, Mild, and Full Hybrid to Plug-in Hybrid (PHEV) [4] [5], without the constraint of the charging infrastructures needed for fully electric technologies such as BEV (charging columns) and FCEV (hydrogen distributors).

In this paper, an on-road experimental campaign has been done with a full hybrid vehicle, the Toyota Yaris Hybrid and a conventional one, the Toyota Yaris 1.5 gasoline on two fixed paths (Urban and Extra-Urban area, and the second in Extra-Urban and Motorway area) and the results are analyzed.

Tests were conducted in roads of Rome with both vehicles on urban, mixed, extra-urban and highway test path designed to evaluate them in a wide operating range. During the tests, the instantaneous data were acquired by the thermal engine control unit of both vehicles through the OBD diagnostic socket using the instrumentation supplied by Toyota Motor Italia. The acquired data were processed and analyzed for the comparative evaluation of consumption in function of the speed of the vehicle [6]. The speed range analyzed is 0÷130 km/h in accordance with the limits imposed by the highway code in the various sections of test paths.

2. Tests

The tests were conducted on two versions of the same model of the Toyota (the Yaris, in the Hybrid version and in the 1.5 Petrol version) and a different size hybrid model (Prius). The following are their main technical characteristics.

2.1. Technical characteristics of vehicles

The technical characteristics of the three vehicles are shown in the Table 1.

Table 1. Data sheet of the two Yaris models and the Prius one.

Characteristic	Yaris Hybrid	Yaris 1.5 Petrol	Prius
Empty mass (kg)	1,090	1,065	1,375
Total mass (kg)	1,565	1,545	1,790
Tires	175/65 R15	175/65 R15	215/45 R17
Engine displacement (cm^3)	1,497	1,496	1,798
Engine compression ratio	13,4:1	13,5:1	13,0:1
Engine maximum power (kW)	54 at 4,800 rpm	82 at 6,000 rpm	72 (5,200 rpm)
Engine maximum torque (Nm)	111 at 3,600 – 4,400 rpm	136 at 4,400 rpm	142 (3,600 rpm)
Emission class	EURO 6	EURO 6	EURO 6
Electric motor	permanent magnet synchronous	n.a.	permanent magnet synchronous
Electric motor maximum power (kW)	45	n.a.	53
Electric motor maximum torque (Nm)	169	n.a.	163
Traction battery	Nickel-Metal Hydride	n.a.	Nickel-Metal Hydride
Traction battery nominal voltage (V)	144	n.a.	201.6
Traction battery capacity (Ah)	6.5	n.a.	6.5
Energy traction battery capacity (Wh)	936.0	n.a.	1,310.4
Powertrain maximum power (kW)	74	82	90

As can be seen from Table 1, the differences between the two Yaris (hybrid and conventional) concern those that are the capacity of the tank, which is justifiably greater for the model with petrol only, and what is the total mass that, in the hybrid, a mainly due to the batteries, it is a few kilograms greater. From Table 1 you can see how the real power developed by the Hybrid Synergy Drive is very close to the one made available by the Yaris thermal engine powered exclusively by petrol (respectively 82 and 74 kW) thus ensuring a realistic comparison of performance.

Instead the differences between the two Hybrid vehicles (YarisHy and Prius) concern those that are vehicle mass, engine maximum power, Electric motor maximum power and energy traction battery capacity.

2.2. The test paths

The test paths are two: the first one is Urban (with low and high traffic density) and Extra-Urban area, and the second is Extra-Urban and Motorway area.

In the Urban/Extra-Urban path, the test run (Fig. 1, a), planned in line with average per capita daily travel, as reported by the "ISFORT mobility report" [7] has a total length of 37 km, and was divided into three sections:

- 1st section: Urban with low traffic density and extra-urban. This section is about 17.4 km long; it starts at the city outskirts and ends at the city center with speed limits up to 130 km/h;
- 2nd section: Urban with high traffic density. This section is approximately 6 km long, entirely at the city center (inside the ring railway), with maximum speed limits of 50 km/h;
- 3rd section: Urban with low traffic density and extra-urban. This section is about 16.3 km long; it starts at the city center and ends at the city outskirts with speed limits up to 130 km/h.

In the Extra-Urban and Motorway path, the test run (Fig. 1, b), has a total length of 44.9 km, and was divided into five sections:

- 1st section: Extra-Urban. This section is about 4 km long;
- 2nd section: Highway. This section is approximately 10,5 km long;
- 3rd section: Extra-Urban. This section is about 16.3 km long;
- 4th section: Highway. This section is approximately 11.4 km long;
- 5th section: Extra-Urban. This section is about 2.7 km long.

Overall the Extra-Urban stretch is about 23 km while the Motorway stretch is about 21.9 km.

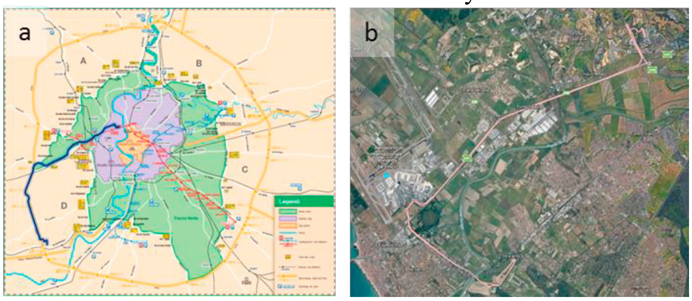

Fig. 1. Urban and extra urban (a) and extra urban Motorway (b) test path.

In the definition of the test conditions, all the variables that may affect the energy performance of the vehicle were taken into account, such as driving style, traffic conditions and energy consumption of auxiliaries [6, 8, 9, 10, 11].

The test drives were carried out by using the two Yaris models described above with hybrid version set on the ECO MODE, and both models with no air conditioning, and traveling speed complying with the road traffic speed limits for each type of road.

3. Result analysis

In order to show the benefit of hybrid vehicles in comparison with conventional ones, an aggregation of the collected data with the average speed has been made. Such parameter can be a good one to characterize the environment in which the vehicle moves, so for lower average speeds the vehicle in urban environment, for very low ones the vehicle is in congested traffic environment, while at increasing values in rural and motorway. Curves for consumption are then been built from values of average speed of 10 km/h to 120 km/h.

In Fig. 2 the consumption is plotted with the average speed of the vehicle for the Toyota Yaris Hybrid, the Yaris conventional and Prius.

There is a big consumption reduction for the major part of the average speed values of the hybrid technology compared to the conventional one: at the lowest values (10 km/h) is about 65%, decreasing increasing the speed. The reasons are mainly three: the thermal engine efficiency (Atkinson cycle that works at operating points with higher efficiency), the hybrid subsystem that allows to run ZEV mode for a big part of the time and the regenerative braking of the Hybrid Synergy Drive.

This is confirmed by the fact that the Prius and YarisHy consumptions trend vs. average speeds are similar but the Prius has lower consumption values due above all to the high efficiency of the braking energy recovery system, despite the greatest mass. This high efficiency of the Prius braking energy recovery system is due to the increased power of the electric motor/generator and to the greater capacity of the traction batteries (see paragraph 3.1).

At these low speed values, where there are many accelerations and decelerations, the ability of the drivers is not negligible and when conventional vehicles are driven [11], additional negative results can be obtained; clearly, this fact is not present in hybrid vehicles or it is smoothed thanks to its powertrain.

Increasing the speed, the role of the electric subsystem decreases and for high values, representative of motorway, the consumption of hybrid and conventional is similar.

However, the great advantage of hybrid powertrains is in urban environments and together with a lower consumption, there is the advantage of "electric like" behavior for a big part of the time.

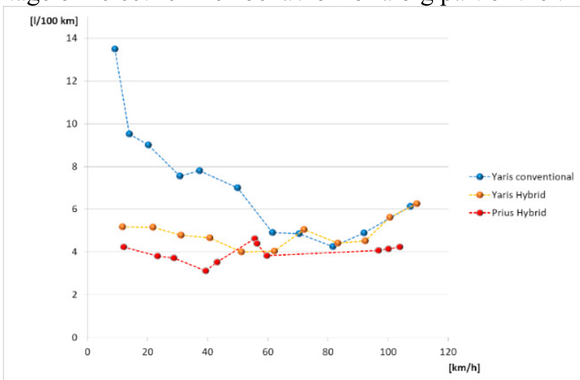

Fig. 2. Consumption values vs average speed for the two Toyota Yaris (Hybrid and conventional) and Toyota Prius.

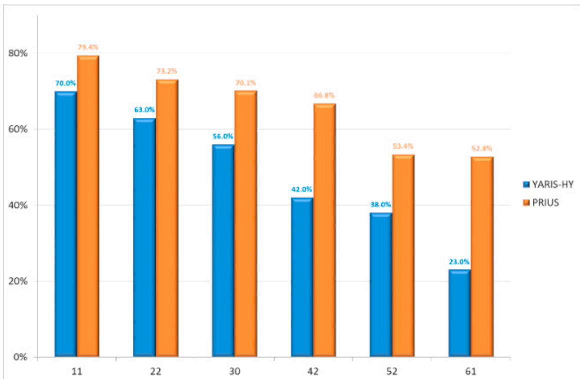

Fig. 3. Percentage in ZEV mode for the Toyota Yaris Hybrid and Prius in function of the average speed.

In Fig. 3, it can be observed that when the traffic is congested, or for lowest average speeds, the hybrid vehicle run in ZEV mode most of the time (70% Yaris and 79.4% Prius); for values of 30 km/h these values are reduced to 56% for Yaris and 70.1% for Prius. It is interesting to note that for higher average speeds (around 60 km/h) the operation in ZEV mode is drastically reduced for Yaris (23%) while for Prius it is higher than 50%, thanks to the greater "electrification" of powertrain (greater power of the electric motor and greater capacity of the traction batteries). This will lead to significant reduction also of the local emissions, much important for air pollution of cities.

3.1. Analysis of the reduction in fuel consumption of the hybrid vehicle compared to the conventional one at low average speeds (Yaris hybrid vs Yaris conventional)

The lower consumption of the hybrid vehicle at low average speeds (Urban and Extra-Urban tests) illustrated in the Fig. 2, are due to three factors:

- Energy recovery braking system
- Powertrain management of the Hybrid Synergy Drive System
  - improvement of the engine operating conditions: management of the transients with the aid of the electric motor and reduction of operation at low power (the engine in the hybrid system never works at idle) [12].
  - engine shutdown in the absence of power supply to the wheels
- Higher efficiency of the Atkinson cycle compared to the Otto cycle [12].

In Fig. 4, average energy flows are shown for the Urban and Extra-Urban tests carried out versus the distance covered (kJ/km).

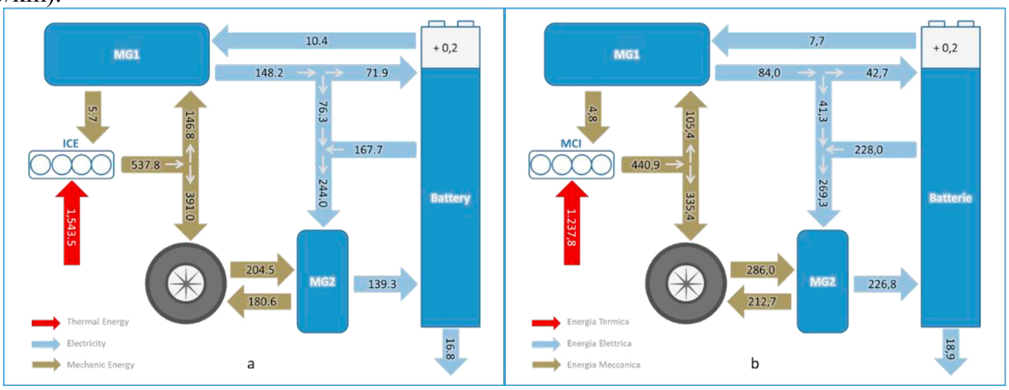

Fig. 4. Chart of energy flows (average values in Urban and Extra-Urban tests) of the traction system of the Yaris Hybrid (a) and Prius (b).

The analysis of the energy flows of Yaris Hybrid shown in Fig. 4 a highlights that out of 571.6 kJ/km to the wheels, 180.6 kJ/km (31.6%) are supplied by the MG2 electric motor against a power consumption of 244.0 kJ/km. The braking energy recovery system is particularly efficient as it can produce about 139.3 kJ/km of electricity (about 48% of total energy produced by the system during the test). It should be pointed out that in the test conditions analyzed, 14.3% (81.9 kJ/km) of the power used in the wheels derives from "inertial braking regeneration" (renewable energy), additional 17.3% (98.7 kJ/km) from electricity produced by MG1 and 68.4% (391.0 kJ/km) directly from ICE as shown in Fig. 5 a.

Thanks to the energy recovery braking system, in the Yaris hybrid system the engine delivers less energy than that supplied to the wheels which (94.1%), in the conventional vehicle, must be supplied entirely by the engine. Furthermore, the conventional vehicle engine operates with substantially lower efficiency than the hybrid vehicle for the following reasons:

- the engine of full hybrid vehicle operates with Atkinson cycle with higher efficiency; the use of this cycle is possible thanks to the presence of an electric motor which "compensates" the power loss due to the Atkinson cycle (see Table 1)
- as already mentioned, in the hybrid vehicle the engine works in better conditions thanks to the contribution of the electric motor in the transients and in the operation at low power regimes

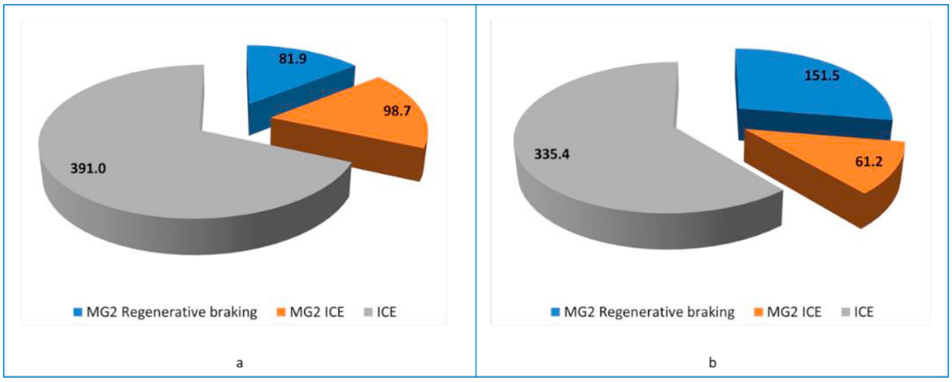

Fig. 5. Distribution of energy to the wheels (kJ/km) of the Yaris Hybrid (a) and Prius (b).

Another factor contributing to the reduction in consumption of the hybrid vehicle at low average speeds (Urban and Extra-Urban tests) is the shutdown of the engine in the absence of power delivery to the wheels. In the Urban and Extra-Urban tests, it was found that for 48.8% of the total duration of the test the engine is switched off due to the absence of power supplied to the wheels (15.4% with stationary vehicle and 33.4% with advancement without power delivery). Considering the data shown in Table 2, engine idling would result in an 11.8% increase in consumption compared to those actually measured.

Table 2. Parameters for calculating fuel consumption with the engine idling in urban context.

Parameter	Yaris Hybrid	Prius
Average travel time of 1 kilometer (s/km)	162.7	155.1
Time with power delivery to the wheels (s/km)	83.2	85.7
Time with stationary vehicle (s/km)	25.1	11.6
Time with vehicle advancement without power delivery (s/km)	54.4	57.8

3.2. Analysis of the reduction in fuel consumption between the two hybrid vehicles with different characteristics (YarisHy and Prius) at low average speeds

Energy flows of the two hybrid systems (YarisHy and Prius) comparison (Fig. 4 and Fig. 5) shows that the lower consumption of Prius is essentially due to the greater efficiency of the braking energy recovery system obtained thanks to the greater "Electrification" of the hybrid powertrain: increased power of the electric motor/generator and greater capacity of the traction batteries (Table 1). In fact, the avoided consumption (compared to the conventional vehicle) due to the engine shutdown in the absence of power to the wheels (Table 2) are essentially the same: 11.8% of the Yaris and 12.7% of the Prius (in fact this avoided consumption depends on the traffic conditions more than from the characteristics of the hybrid powertrain). Also the reduction of fuel consumption (compared to the conventional vehicle) due to the adoption of the Atkinson cycle and the best working conditions are similar. Therefore, the main factor for the Prius reduction of fuel consumption (compared to Yaris Hybrid) is the greater efficiency of the braking energy recovery system: as shown in Fig. 5, 27.6% of energy to wheels derives from energy recovery braking (against 14.3% of the Yaris). Thanks to this recovery, the Prius engine supplies only 80.4% of the total energy to the wheels, compared to 94.1% of the Yaris one (Fig. 4).

4. Conclusion

The results show that a strong influence on consumption is due not only to the type of vehicle, but also to driving style and speed. The comparison between the two versions of Yaris shows that there is a strong reduction in consumption using hybrid vehicles for lower and medium speeds (for 20 km/h about 50%), such benefit decreases with the increasing speed and for values higher than 90 km/h both the vehicles have the same consumption. the reduced consumption of the hybrid vehicle at low speeds is due, on the one hand, to the greater efficiency of the hybrid vehicle engine compared to the conventional and on the other hand to the high functioning with the engine off (63% of time) thanks to the use of the electric motor.

The comparison between the two hybrid vehicles with different characteristics (YarisHy and Prius) shows that the Prius has lower consumption (around 17% overall) due above all to the high efficiency of the braking energy recovery system, despite the greatest mass, which turns out to be the main factor for the greater efficiency of the hybrid powertrain compared to the conventional one. High efficiency of the braking energy recovery system is linked to the "electrification" of the hybrid powertrain, (greater power of the electric motor and greater capacity of the traction batteries). These characteristics are also decisive for the operating times in ZEV mode of the hybrid vehicles which is significantly higher for the Prius than the Yaris Hybrid (Fig. 3). This lead then to significant consumption reduction, but also lower pollutant emissions in places where such parameters have an important role: the urban environment.

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