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Real Drive Well-to-Wheel Energy Analysis of Conventional and Electrified Car Powertrains †

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Abstract: Reducing fuel consumption and global emissions in the automotive sector has been a main focus of vehicle technology development for long time. The most effective goal to achieve the overall sustainability objectives is to reduce the need for non-renewable and fossil resources. Five vehicles, two conventional ICE, two hybrid-electric, and one pure electric powertrain, are considered. Non-renewable primary energy consumption and CO_2 emissions are calculated for each powertrain considered. All data—including calculated values—are based on the experimental measure of fuel consumption taken in real driving conditions. The data were recorded in an experimental campaign in Rome, Italy on urban, extra-urban streets, and highway on a total of 5400 km and 197 h of road acquisitions. The analysis shows significant reductions in non-renewable fossil fuel consumption and CO_2 emissions of hybrid-electric powertrains compared to conventional ones (petrol and diesel engines). Furthermore, a supplementary and very interesting comparison analysis was made between the values of energy consumptions measured during the tests in real driving conditions and the values deriving from the NEDC and WLTP homologation cycles.

Keywords: battery electric vehicle; full hybrid-electric vehicle; WTW analysis; non-renewable primary energy balance; real drive; NEDC; WLTP

1. Introduction

The EU commitment to greenhouse gas emissions reduction accounts for 80–95% by 2050 compared to 1990, with a mid-term target of 40% at 2030, and a reduction in the non-emission trading sectors (including transport) of 30% in line with the Paris Climate Agreement.

To achieve the stated objectives, very strong innovations are needed in mobility, as:

- Higher efficiency of vehicles;
- Optimized use of road space;
- Diffusion of alternative fuels;
- Low emission fuel production;
- Low, ultra-low, and zero emission powertrain technologies;
- Mobility and transportation intelligent management systems [1].

Road traffic, representing the main form of transport, is a major source of pollution in Europe: According to the latest data, it produces about 71% of total greenhouse gas emissions (GHG)—out of which two thirds are generated by cars [2].

Solutions to reduce fuel consumption and emissions include both fuel and traction systems: The use of cleaner traditional fuels has been a reality in the European refinery and distribution system for several years now, with biofuels mixed to fossil fuels, proportionally reducing climate emissions of conventional vehicles [3]. Bio-methane, in particular, has a high potential to achieve a significant decrease in consumption of fossil resources and overall environmental impact [3,4].

Consequently, hybrid traction systems are expected to become more and more electrically based, passing from micro, mild, and full hybrid, to plug-in hybrid (PHEV) [5,6]. The electric traction can in this way enter the habits of car customers without introducing in the short term the absolute need for a dedicated charging or fueling infrastructure, as for full electric powertrains like BEV (charging points) and FCEV (hydrogen stations).

So far, very few research data are available on the real time acquisition of values indicating the fuel consumption and the energy flows of hybrid systems.

This work, an update of a previous work [7], exclusively bases its analysis and calculation on experimental real time driving data and uses a well-defined procedural guideline called "Truth Test Protocol" [8]. The truth test protocol (TTP) is based on a statistical analysis of the energy behavioral data recorded in real drive conditions. The TTP was firstly applied to the energy analysis of full hybrid vehicles with the particular and adjunctive aim to fully evaluate the mileage and time driven in ZEV conditions. It has been designed for a much wider applicability and can be successfully used to assess the energy performance of all types of car powertrain.

In this paper the TTP shows to be effective to analyze conventional ICE vehicle (petrol and diesel), BEV, as well as the HEV. The consumption of non-renewable primary energy and GHG emissions are calculated and compared considering experimental real time driving data of the following cars:

- Conventional ICE powertrain

  ○　Toyota Yaris (petrol)
  ○　Toyota Auris (diesel)

- Hybrid-electric powertrain

  ○　Toyota Yaris Hybrid
  ○　Toyota Prius

- Electric powertrain

  ○　Nissan Leaf (BEV)

2. Well-to-Wheel (WTW) Analysis

The WTW analysis is based on the scheme of Figure 1. The vehicle consumption is measured in real drive conditions [8,9]. According to the consumption of the energy vector used, the consumption of non-renewable primary energy consumption (TTW NRPEC) and GHG emission (TTW GHG) are calculated.

The WTT analysis is referenced to EU-JRC (European Union Joint Research Center) published information [10].
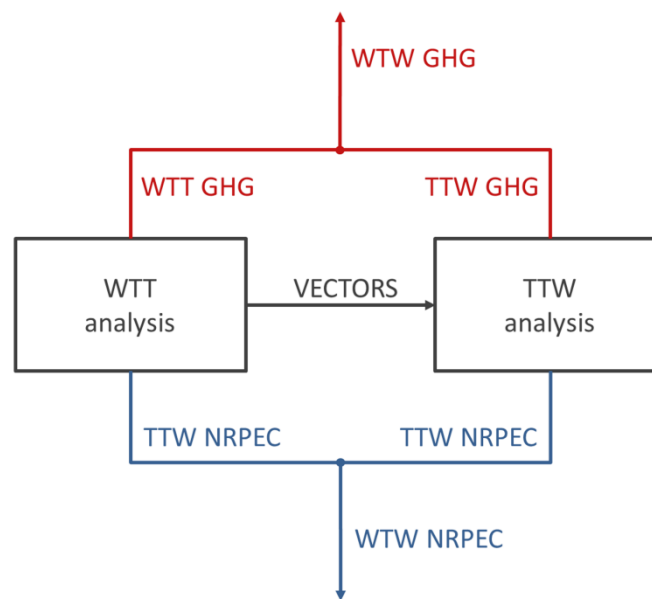
Figure 1. Well-to-wheel (WTW) analysis scheme.

2.1. Tank-to-Wheel (TTW) Analysis

The procedure used to test the energy performance of different powertrains has shown full applicability and solid reliability [5,6].

The test path, planned in metropolitan area of Rome, Italy, is designed to be in line with average per capita daily driving profile in Italy (length, time, road type distribution), as reported by the ISFORT mobility reports 2017 [11], 2018 [12], and 2019 [13], generally considered as a reference in Italy for this kind of data.

The test drives were made on five cars available on the market, equipped with a different electrification level of powertrain and characterized as shown in Table 1.

Table 1. Main specifications of vehicle tested.

Characteristic	Yaris Petrol	Auris Diesel	Yaris Hybrid	Prius	Leaf
Powertrain	ICE Petrol	ICE Diesel	Full Hybrid	Full Hybrid	BEV
Maximum power (kW)	82	82	74	90	80
Mass (kg)	1545	1320	1565	1790	1600

As can be seen in Table 1 the vehicles have been selected with quite similar specifications in terms of power and mass.

The powertrains have a range of electrification level, from 0 to 1. Level 0 is assigned to the two vehicles with conventional ICE and no electric aid to the traction, level 1 is given to the BEV, and the two hybrids have an electrification level between 0 and 1.

Considering hybrid vehicles, the hybridization ratio is considered as an electrification level. The hybridization ratio is the ratio between the power of the electric motor and the sum of the power of the electric motor and the engine, and is widely used in literature, [14–17]. The Toyota Yaris hybrid has a level of electrification higher than the Toyota Prius. Nevertheless, the experimental analysis on the behavior of vehicles in real drive conditions, with particular regard to the ZEV mode operation of the two vehicles [9], has shown the Prius operates in ZEV much more frequently than the Yaris.

Two test paths have been designed and used for the experimental activity: Urban and extra-urban/highway. The urban test path has high (Figure 2) and low (Figure 3) traffic density sections. The two urban sections are located in the so-called "green traffic area" and "railway ring area" (green and purple areas, respectively, in Figure 4) of Rome, regularly used as a reference for road traffic restrictions.
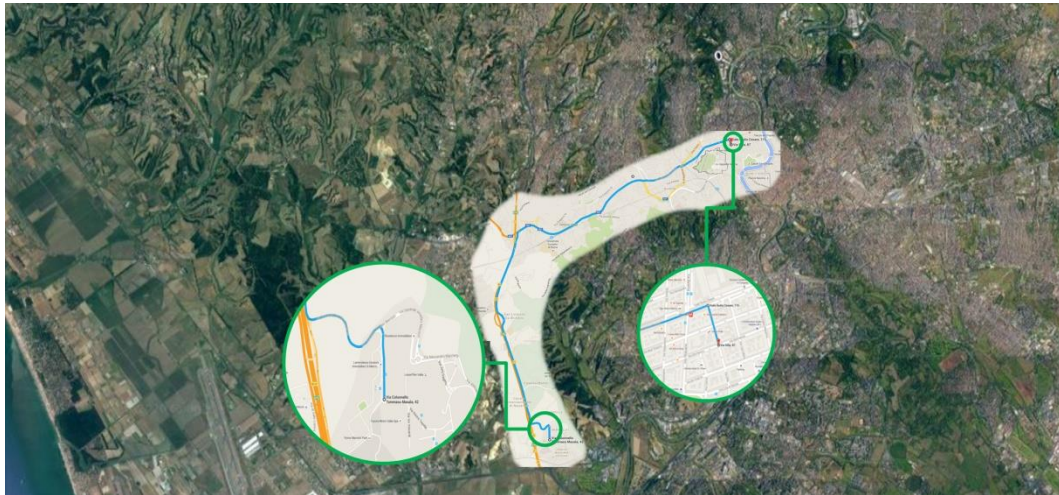

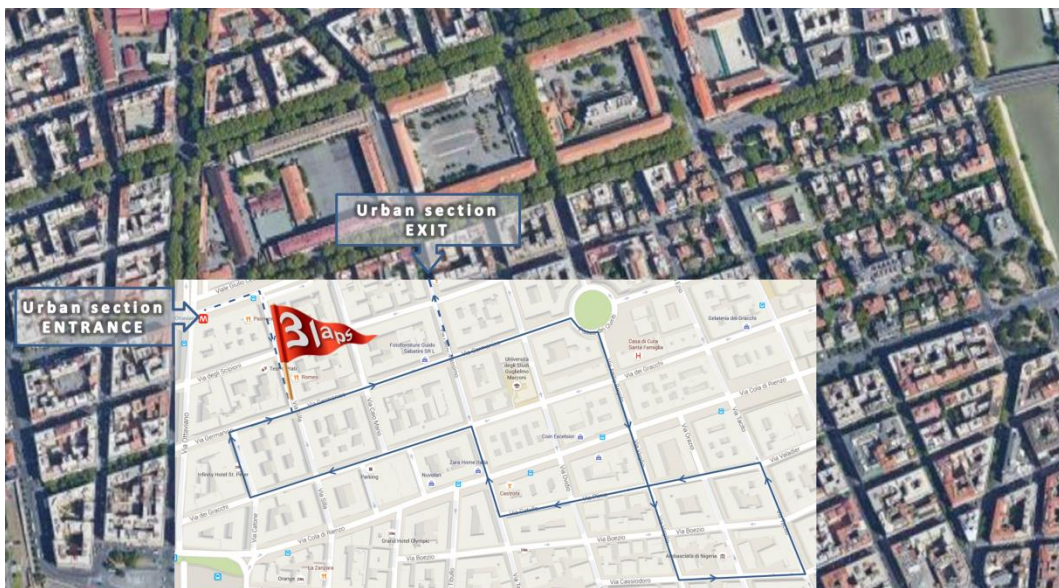
Figure 2. Urban with high traffic density section.

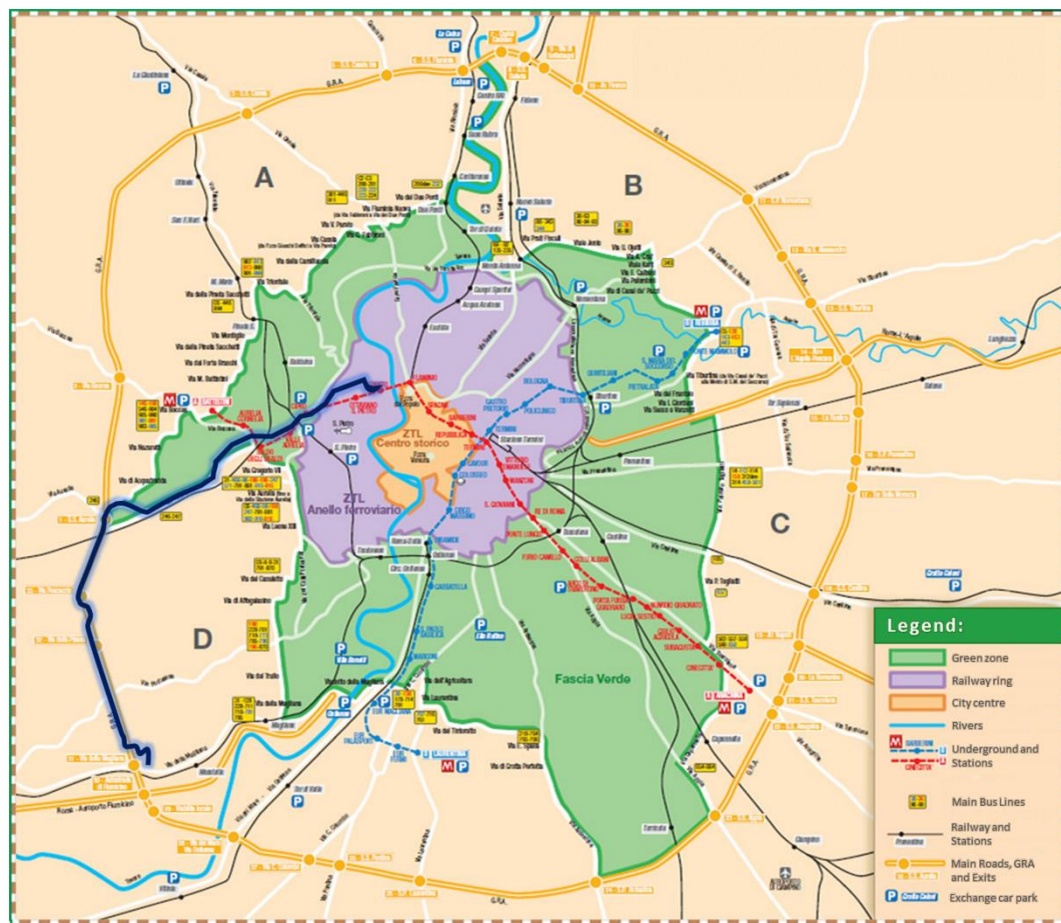**Figure 3.** Urban with low traffic density section.

Figure 4. Map of Rome (highlighted in green: LEZ—low emission zone; blue line: Test drive path).

The extra-urban/highway test path is shown in Figure 5 [9]. The test paths have been assembled considering the average per capita daily travel in Italy, as reported by the ISFORT mobility report [14]. In the test paths four sections have been identified:

- Urban with high traffic density;
- Urban with low traffic density;
- Extra-urban;
- Highway.

The test conditions were designed considering all the main variables affecting the energy performance, like driving attitude, circulation intensity, and auxiliaries energy request [18–22].

The tests were conducted on the routes described above according to our test protocol [8] which includes:

- Compliance with speed limits;
- Drivers clustered by gender and age (to take into account different driving styles);
- Three tests in three different time slots for each driver (10:00–13:30–15:00);
- Tests carried out on standard traffic days, i.e., not on holidays, or holiday periods (Christmas, Easter, July–August);
- Auxiliaries (for example air conditioning) turned off;
- Eco-mode (when selectable).

Figure 5. Extra-urban—highway sections.

As the objective of the study was not to analyze the energy result on a specific driving cycle, but in generally meaningful conditions, a large number of tests has been made on the same path with comparable traffic conditions (considering time, day of the week) and the tests were analyzed mainly considering the average speed.

The energy performance is assessed exclusively referring to real time measured values, and related calculations; consumption and/or efficiency models of the vehicles analyzed have not been used.

Figure 6 illustrates the energy consumption (MJ/km) of the tested vehicles found in the experimental acquisition campaign in the test run in the different sections it is divided into. The Leaf BEV had the lowest energy consumption thanks to the greater efficiency of the traction system: −114% compared to Full HEV Prius, −193% compared to Full HEV Yaris, −376% compared to Yaris ICE petrol, and −330% compared to Auris ICE Diesel. Lower consumption occurred in urban with high traffic density sections (0.47 MJ/km) and remained substantially unchanged for urban with low traffic intensity sections (0.52 MJ/km, +8.5%) and extra-urban sections (0.46 MJ/km, −2.1%), and increased significantly in the highway sections (0.71 MJ/km, +50%). Consumption of the two Full HEV vehicles (Prius and Yaris) showed completely similar trends; the lower consumption of the Prius was due to the greater efficiency thanks to the higher braking energy recovery capacity of the Prius [9].
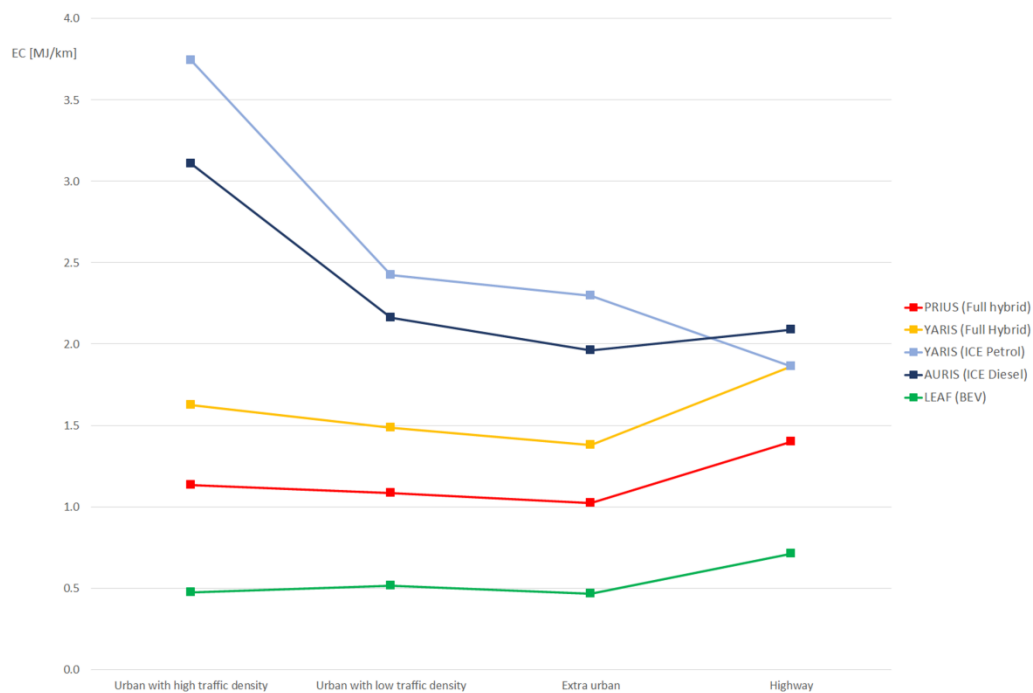
Figure 6. Energy consumption of vehicle tested in the test path (MJ/km).

Compared to conventional ICE vehicles, the two full HEVs had low energy consumption in urban with high traffic density sections (1.13 MJ/km Prius and 1.63 MJ/km Yaris); these consumptions decreased passing to urban with low traffic density sections (1.08 MJ/km, −4%, Prius and 1.49 MJ/km, −9%, Yaris) and presented a minimum in the extra-urban stretches (1.02 MJ/km, −10%, Prius and 1.38 MJ/km, −15%, Yaris) thanks to the greater contribution of regenerative braking which increased the efficiency of the hybrid traction system. The energy consumption of full HEVs vehicles increased in the highway sections (1.40 MJ/km, +23%, Prius, and 1.86 MJ/km, +14%, Yaris) where they were similar to those of conventional ICE vehicles.

The two conventional ICE vehicles had high energy consumption in urban areas with high traffic density (3.47 MJ/km Yaris petrol and 3.11 MJ/km Auris Diesel) due to the low efficiency of the thermal engine at low engine speeds; these consumptions decreased significantly passing to urban sections with low traffic density (2.42 MJ/km, −35% Yaris petrol, and 2.16 MJ/km, −31%, Auris Diesel) and extra-urban sections (2.30 MJ/km, −39% Yaris petrol, and 1.96 MJ/km, −37%, Auris Diesel). Turning to the motorway sections, the consumption of the Yaris decreased compared to the extra-urban sections (1.86 MJ/km, −19%), while those of Auris Diesel remained almost constant but slightly increasing (2.09 MJ/km, +6%).

For the car models fueled by fossil fuels, the mileage (ML (g/km)) was obtained from data acquisition, while for the electric vehicle the value measured was the need of electricity (EC (MJ/km)).

Consumption was calculated from data acquired by the vehicle control unit via the OBD interface with a PC with suitable software for reading and storing the selected data. In vehicles powered by fossil fuel, the data stored was the flow rate (g/s) of fuel, while for the electric vehicle it was the electrical power (voltage and current) supplied by the traction battery pack.

From the mileage the energy consumption was calculated considering the low heating value (LHV) (MJ/kg):

$$EC = ML \cdot HLV \tag{1}$$

Starting from energy consumption, TTW NRPEC and the TTW GHG (Figure 1) were obtained considering a non-renewable primary energy consumption factor f_{NR} and GHG emission factor f_{GHG} (g/MJ) identified considering national standard parameters [23].

$$TTW_{NRPEC} = EC \cdot f_{NR} \quad (2)$$

$$TTW_{GHG} = EC \cdot f_{GHG} \quad (3)$$

Table 2 shows the values of the low heating value, non-renewable primary energy consumption factor, and GHG emission factor for the energy vectors used [23].

Table 2. Low heating value (LHV), non-renewable primary energy consumption factor (fNR), and greenhouse gas (GHG) emission factor (fGHG) of the energy vectors used.

Energy Vectors	LHV [MJ/kg]	f_{NR}	f_{GHG} [g/MJ]
Petrol	42.817	1	73.335
Gasoline	42.877	1	73.583
Electricity	n.a.	0	0

2.2. Well-to-Tank (WTT) Analysis

As already mentioned, the WTT analysis reference is based on EU-JRC published values [10]. For the electric vehicle, several charging systems have been taken into account [24]:

- 50 kW (maximum power output of mostly diffused quick charge stations);
- 43 kW ("fast AC" power output on European standard);
- 22 kW (three-phase power for AC on-board charger);
- 16 kW (contractual power for the main electric distributor in Italy);
- 3 kW (standard residential power in Italy).

Figure 7 shows the charger efficiency, battery efficiency, and overall charging efficiency of the different charging systems.
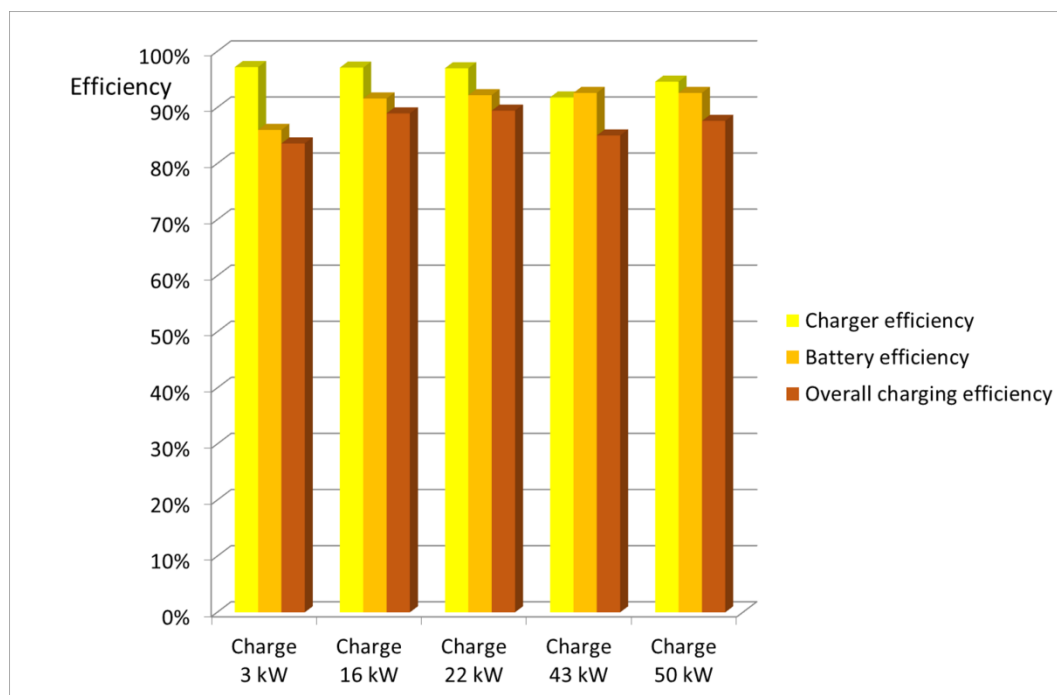

Figure 7. Charger efficiency, battery efficiency, and overall charging efficiency.

Figure 8 shows the well-to-tank analysis of electricity [10], considering the listed charging systems. The electricity production box considers the average efficiency of a power plant in EU

countries, including fuel extraction, transportation, and pumping losses. The transport, transformation, and distribution box consider transport and distribution losses and transformation efficiency at the low voltage. The vehicle battery charge box considers the overall efficiency of the charging systems analyzed (Figure 7).
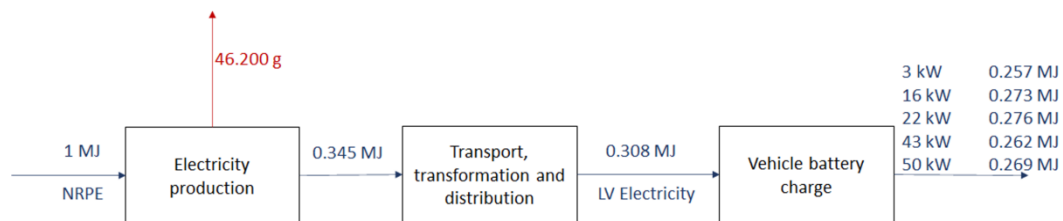

Figure 8. Well-to-tank analysis of electricity considering several charging devices.

Figure 9 shows the well-to-tank analysis for the fossil fuels; petrol (a) and diesel (b).
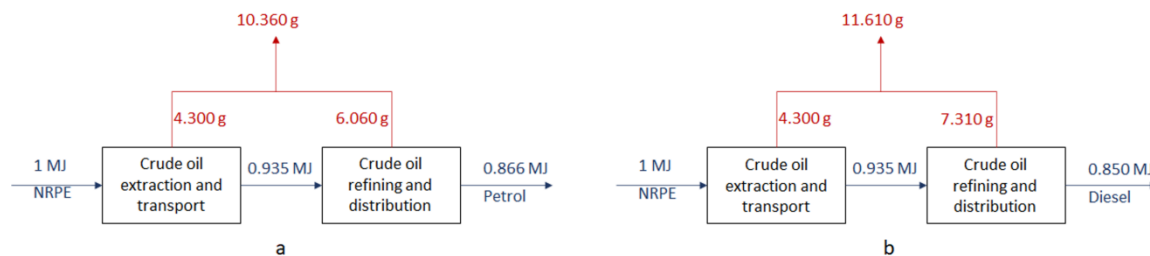

Figure 9. Well-to-tank analysis of fossil fuels, petrol (**a**) and diesel (**b**).

3. Result Analysis

The main results of the WTW analysis, obtained on the basis of what is set out in the previous Sections 2.1 and 2.2, are shown below.

Figure 10 shows the primary non-renewable energy consumption of the vehicle analyzed in urban roads with high traffic density (a), urban low traffic intensity (b), extra-urban (c), and highway. Referring to the Nissan Leaf, different charging systems are specifically assessed: 3 (CH_3), 16 (CH_16), 22 (CH_22), 43 (CH_43), and 50 kW (CH_50).

Figure 10 clearly shows that through the powertrain electrification it is possible to reach an important consumption decrease of non-renewable primary energy in real drive conditions.

The reduction was higher in urban traffic conditions, with better results with stronger circulation (the lower the average speed, the higher the fuel save). The two cars equipped with conventional powertrain, compared with the two hybrids, had in urban traffic-intensive sections a non-renewable primary energy consumption 2.5 times larger. The difference in consumption of primary energy decreased as the average speed increases. The conventional cars, compared with the two hybrids, showed a non-renewable primary energy consumption 1.8 times higher in low traffic density and extra-urban sections, and 1.2 times higher on the highway section.

The hybrid model Toyota Prius recorded the lowest consumption of non-renewable primary energy of the whole test campaign. The overall efficiency of the powertrain showed the highest value, mainly due to the excellent performance of the energy recovery system during deceleration phases [9].
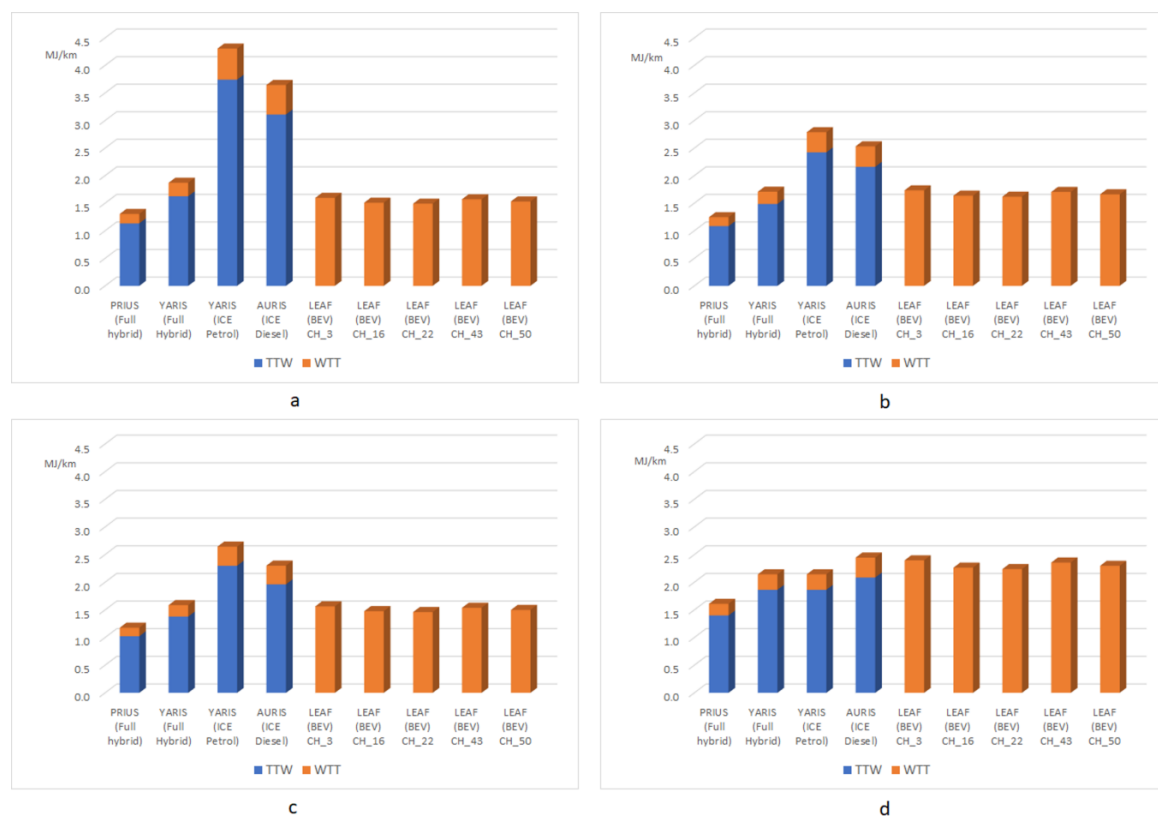
Figure 10. Non-renewable energy consumption of the vehicle analyzed in urban roads with high traffic density (**a**), urban low traffic intensity (**b**), extra-urban (**c**), and motorway (**d**).

The electric Nissan Leaf recorded a lower overall consumption value than conventional cars (except on the highway), but still slightly higher in most conditions than hybrid cars.

In detail, the WTW non-renewable primary energy need of the Nissan Leaf is the following:

- Urban with high traffic density: −61% compared to conventional vehicles and −3% compared to full hybrid vehicles;
- Urban with low traffic density: −37% compared to conventional cars and +12% compared to full hybrid cars;
- Extra-urban: −39% compared to conventional cars and +8% compared to full hybrid cars;
- Highway: +1% compared to conventional cars and +19% compared to full hybrid cars.

GHG emissions are directly proportional to fossil fuel consumption. The electric vehicle, considering the European production system for electricity, showed in all conditions lower GHG emissions than both conventional and hybrid cars.

In detail, the GHG emission analysis of the Nissan Leaf is the following (Figure 11):

- Urban with high traffic density: −76% compared to conventional cars and −65% compared to full hybrid cars;
- Urban with low traffic density: −61% compared to conventional cars and −42% compared to full hybrid cars;
- Extra-urban: −62% compared to conventional cars and −47% compared to full hybrid cars;
- Highway: −37% compared to conventional cars and −30% compared to full hybrid cars.
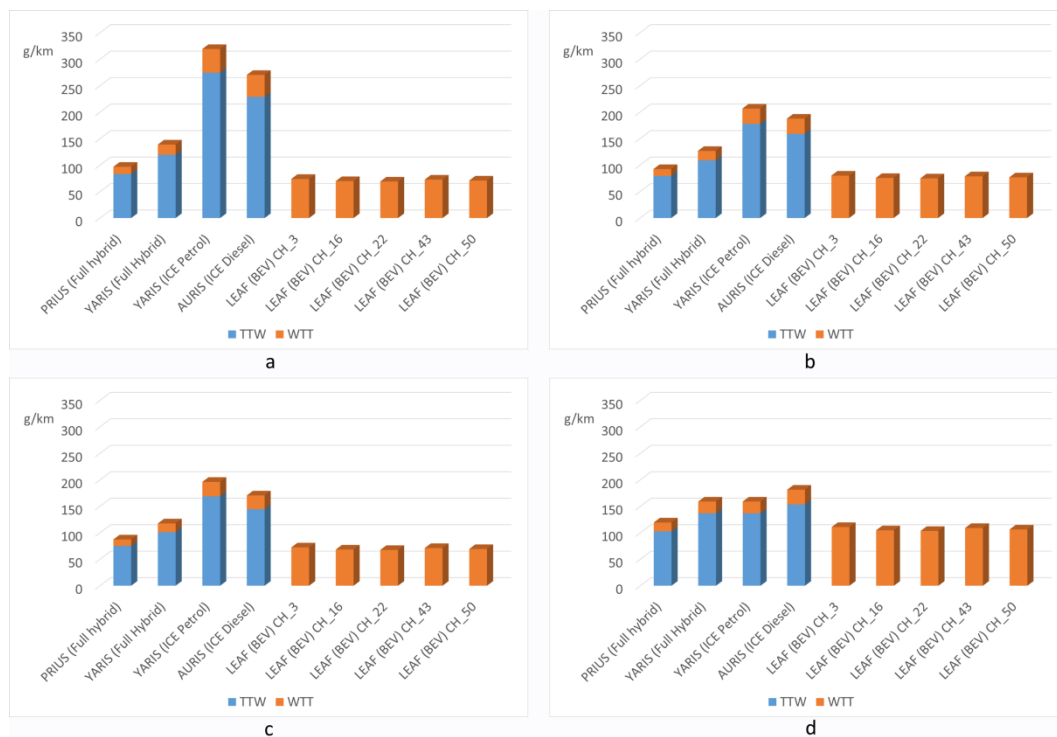
Figure 11. GHG emission of the vehicle analyzed in urban roads with high traffic density (**a**), urban low traffic intensity (**b**), extra-urban (**c**), and motorway (**d**).

The GHG emissions of an electric vehicles are the emissions caused by the production of the electricity by the European power generation system. Figure 12 shows the GHG emission accounting, referring to electricity production from different energy resources (EU average values) [25].
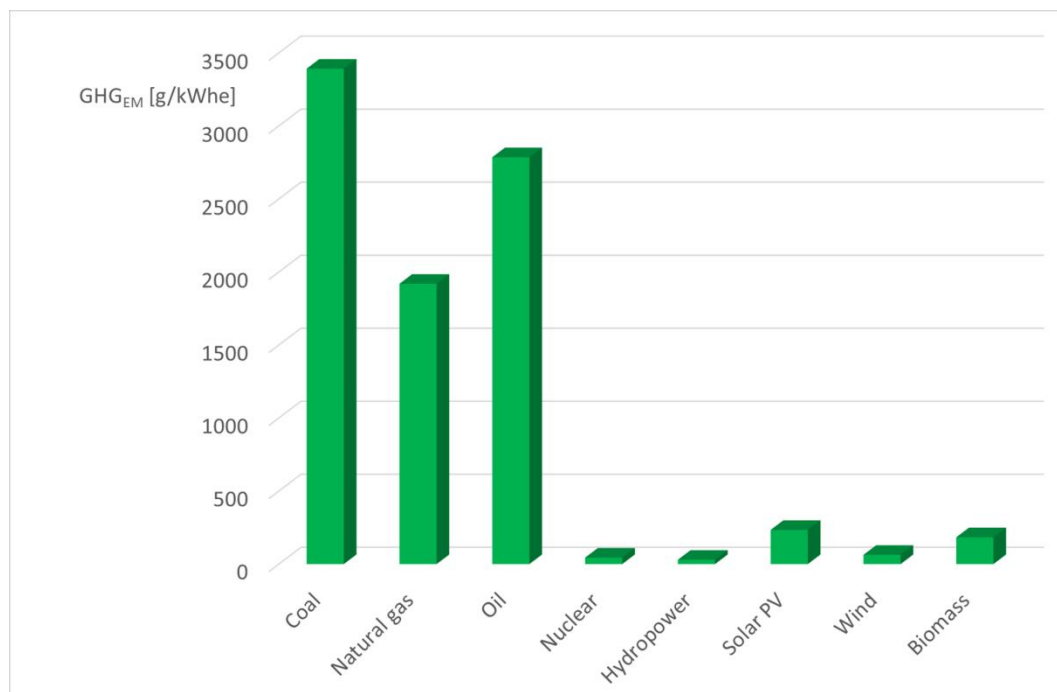

Figure 12. GHG emissions for the electricity production for different sources.

Referring to GHG emission accounting reported in Figures 12 and 13 shows the GHG emission of the Nissan Leaf referred to the different primary sources.
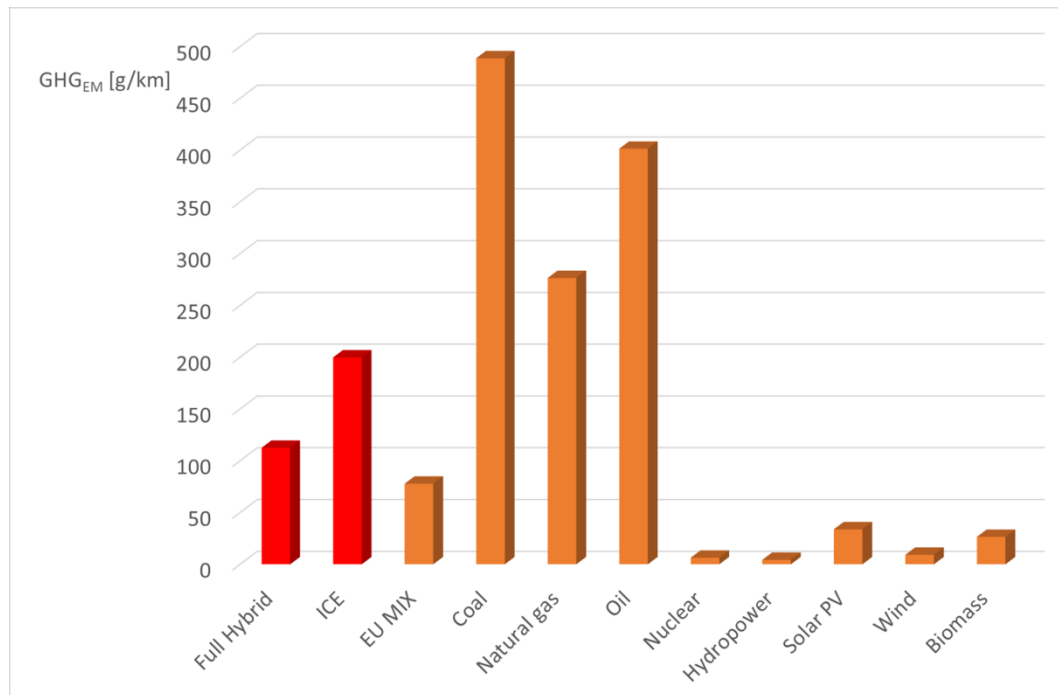

Figure 13. GHG emission of BEV for electricity produced by several energy sources.

3.1. Energy Vectors Cost

Table 3 shows the comparison between the energy vector cost of the five vehicles considering the four sections of the path considered we have, calculated considering average prices (including taxes) of petrol, gasoline [26], and electricity [27] in Italy in 2019:

- Petrol: 1.574 €/L;
- Diesel: 1.479 €/L;
- Electricity: 20.67 c€/kWh.

Table 3. Energy vectors cost (c€/km).

Characteristic	Yaris Petrol	Auris Diesel	Yaris Hybrid	Prius	Leaf
Urban with high traffic density	18.46	12.85	8.03	5.60	3.52
Urban with low traffic density	11.96	8.92	7.33	5.35	3.82
Extra-urban	11.34	8.11	6.80	5.05	3.45
Highway	9.20	8.62	9.19	6.91	5.28

Despite the higher energy cost of electricity (about 74 €/GJ) compared to petrol (about 49 €/GJ) and gasoline (about 41 €/GJ), the unit cost (€/km) of the energy vector per BEV was the lowest thanks to the high efficiency of these vehicles [28]. For BEV, the unit costs of the energy vector increased passing from urban with high traffic density sections (3.52 €/km) to highway sections (5.28 €/km); for conventional ICE vehicles (Otto cycle and Diesel cycle) the trend was opposite and the unit costs of the energy vector decreased passing from urban with high traffic density sections (18.96 €/km Yaris petrol and 12.85 €/km Auris Diesel) to the highway sections (9.20 €/km Yaris petrol and 8.62 €/km Auris Diesel). The difference in unit costs between petrol and diesel was due in part to the lower costs of diesel compared to petrol and in part to the greater efficiency of the diesel vehicle. Hybrid vehicles, on the other hand, had a minimum of unit costs in extra-urban stretches.

Compared to the unit costs of the BEV energy vector, in the urban areas with high traffic densities the unit cost of the traditional petrol vehicle was more than 5 times higher and that of the diesel vehicle almost 4 times, due to the low efficiency of the traditional ICE vehicles and the high efficiency of the BEV in these sections. Hybrid vehicles have high efficiency in urban high traffic density sections and the difference in unit costs compared to BEV is limited (about 2 times).

3.2. Comparison between Tests Result and Homologation Energy Consumption

This paragraph will compare the WWT energy consumption found in the tests in real conditions of use with those declared by the car manufacturers on the basis of the NEDC and WLTP homologation cycles.

Table 4 illustrates the consumption values declared by the car manufacturers based on the NEDC and WLTP procedure of the 5 vehicles tested: For the Leaf (BEV) and Auris Diesel, being registered before the entry into force of the approval procedure based on WLTP, the consumption data on this cycle are not available.

Table 4. Energy consumption in NEDC and WLTP homologation tests (MJ/km).

	NEDC	WLTP
Leaf	0.54	n.a.
Prius	1.13	1.47
Yaris Hybrid	1.21	1.53
Yaris Petrol	1.62	1.94
Auris Diesel	1.43	n.a.

3.2.1. Comparison between Tests Result and NEDC Homologation Energy Consumption

Figure 14 illustrates the NEDC homologation cycle. As is known, the NEDC cycle is composed of the ECE cycle (urban driving cycle—UDC) repeated four times and the EUDC cycle.
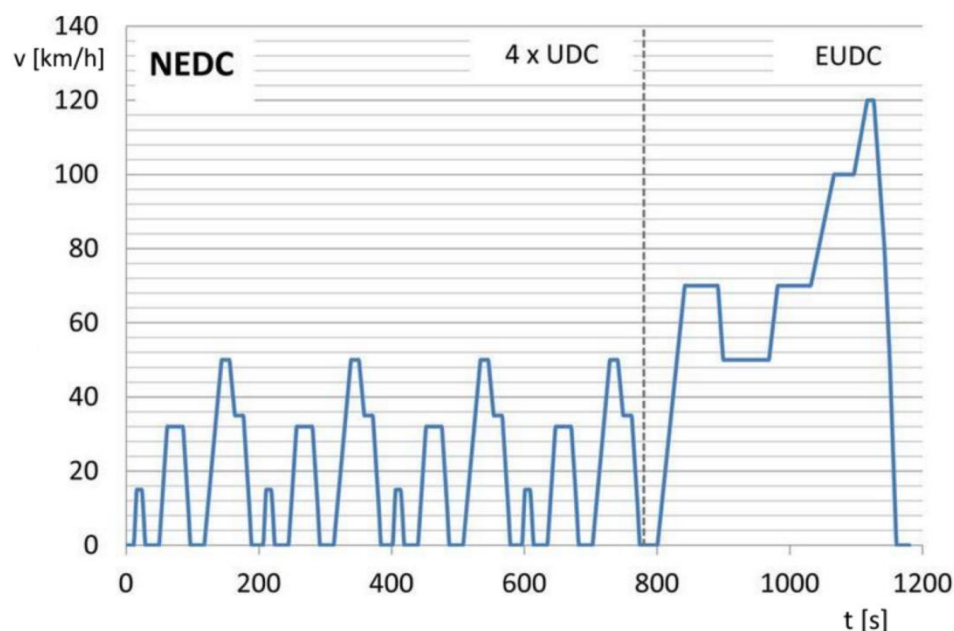

Figure 14. NEDC cycle.

Figure 9 shows the lengths of the urban and extra-urban section of the NEDC.

To compare the specific energy consumption (MJ/km) obtained in the tests in real conditions of use and those declared by the car manufacturer on the basis of the NEDC cycle, the tests' specific

energy consumption was calculated as the weighted average of the consumption detected in the four sections in which the test path was divided (Section 2.1). The weights were calculated by associating the urban with high traffic density and urban with low traffic intensity sections to the ECE cycle and the extra-urban and highway sections to the EUDC cycle according to the distances shown in Table 5, as illustrated in Figure 15.

Table 5. NEDC distance.

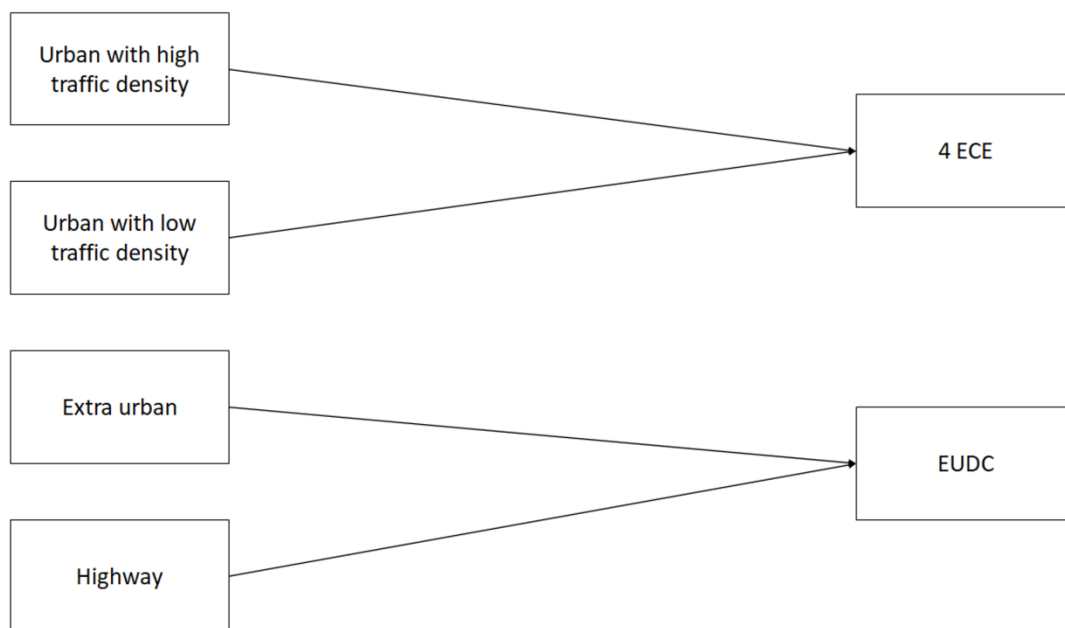|	Distance (m)	Distance (%)
4 ECE	3978	36.4
EUDC	6955	63.6
Total	10,933	100.0

Figure 15. Scheme of calculation of energy consumption in the tests to compare with energy consumption in NEDC (4 ECE, EUDC).

Based on the above, the specific consumption obtained in the tests under real conditions of use of the five vehicles analyzed is calculated as follows:

$$EC_{T,NEDC} = \frac{EC_{UHTD} + EC_{ULTD}}{2} \cdot 0.364 + \frac{EC_{EU} + EC_H}{2} \cdot 0.636 \tag{4}$$

Figure 16 shows the comparison between the specific energy consumption obtained in the tests and those declared by the car manufacturers based on the NEDC cycle.

From Figure 16 it can be seen that the higher specific energy consumption in the tests compared to the NEDC cycle varies significantly for the different powertrains: In fact, for the BEV vehicle, the energy consumption in the tests was lower (−12.3%) compared to the NEDC cycle (this could be due to very low speeds in the urban with high traffic density section); for the full HEV Prius the consumption in tests was slightly higher (+3.7%) than in the NEDC cycle; while for the full HEV Yaris the increase in consumption in tests was more relevant (+24.3%). For both conventional ICE vehicles the difference was very high, +33.7% for the Yaris petrol and +36.4% for the Auris Diesel.

It is interesting to make some considerations regarding the different values of the deviations between the energy consumptions in the tests and those in the NEDC cycle for the two full HEV vehicles; Figure 17 shows that the two hybrid cars are in ZEV mode a very large part of the driving

time (70% of the driving time for the Toyota Yaris Hybrid and 79.4% of the driving time for the Toyota Prius) in congested traffic conditions; when the average speed analyzed increased to 30 km/h, the ZEV driving time to 56% for Toyota Yaris Hybrid and 70.1% for Toyota Prius.
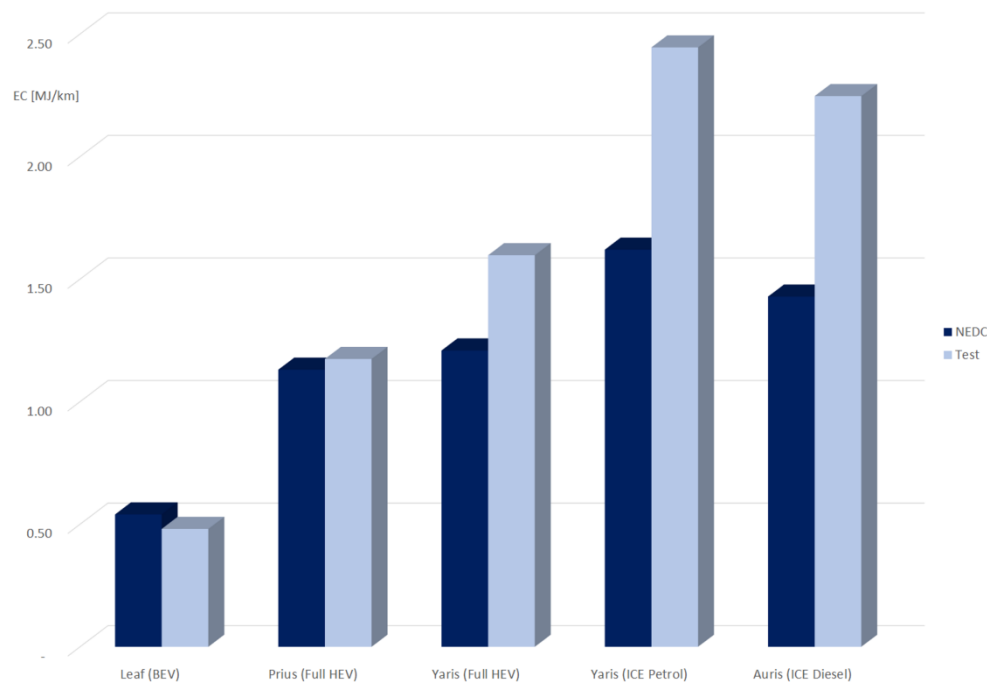

Figure 16. Comparison between test and NECD energy consumption.
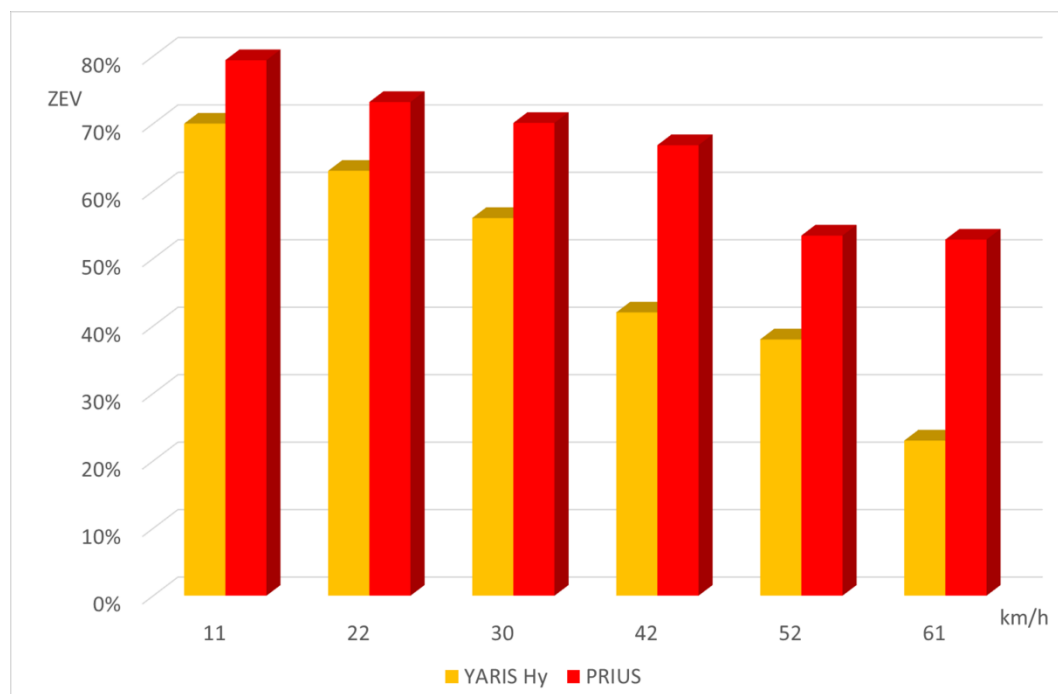

Figure 17. ZEV value of HEV vs. average speed.

At higher average speeds (around 60 km/h) the driving time in ZEV mode was dramatically decreased to 23% for the Toyota Yaris Hybrid.

The Toyota Prius in the ZEV mode kept over 50% of the driving time even at 60 km/h, showing again that its higher electrification of the powertrain allowed for a higher efficiency [9].

Hence, it can be said that the full HEV Prius had a substantially greater degree of "electrification" than the full HEV Yaris. From the above it is evident that the increase in energy consumption in tests in real conditions of use compared to those in the NEDC cycle decreased with increasing degrees of electricity in the powertrain.

3.2.2. Comparison between Test Result and WLTP Homologation Procedure Energy Consumption

The official indication of emission and fuel consumption levels of cars is provided by the worldwide harmonized light vehicles test cycles (WLTC) developed by the UN ECE GRPE (Working Party on Pollution and Energy) group in the more general framework of worldwide harmonized light vehicles test procedures (WLTP).

The acronyms WLTP and WLTC are not interchangeably: WLTP procedures define a larger number of procedures, are finalized to type approve a vehicle and are applied in addition to the WLTC test cycles.

The transition from the previous NEDC-based procedure for type approval testing of light-duty vehicles to WLTP has occurred over 2017–2019. Also in Japan, the WLTP has been introduced for vehicle certification.

The WLTP procedures include several WLTC test cycles for different vehicle categories based on power-to-mass (PMR) ratio defined as the ratio between rated power (W) and the curb mass (kg) (not including the driver) and on the maximum speed (vmax) of the vehicle as declared by the car manufacturer (Table 6).

Table 6. WLTC test cycles.

Category	PMR (W/kg)	Vmax (km/h)	Speed Phase Sequence
Class 3b	PMR > 34	Vmax ≤ 120	Low 3 + Medium 3-2 + High 3-2 + Extra-high 3
Class 3b	PMR > 34	Vmax > 120	Low 3 + Medium 3-1 + High 3-1 + Extra-high 3
Class 2	22 < PMR ≤ 34	-	Low 2 + Medium 2 + High 2 + Extra-high 2
Class 1	PMR ≤ 22	-	Low 1 + Medium 1 + Low 1

Table 7 illustrates the definition of the WLTP procedure class of the five vehicles analyzed based on their specifications. Table 7 shows that all vehicles are in the WLTP procedure 3b class.

Table 7. Class in WLTP classification of vehicle tested.

	Power (W)	Mass (kg)	PMR (W/kg)	Vmax (km/h)	WLTP Class
Leaf	80,000	1600	50.0	>120	3b
Prius	90,000	1790	50.3	>120	3b
Yaris Hybrid	74,000	1565	47.3	>120	3b
Yaris Petrol	82,000	1545	53.1	>120	3b
Auris Diesel	82,000	1320	62.1	>120	3b

Figure 18 illustrates the NEDC homologation cycle. As is known, the NEDC cycle is composed of the ECE cycle (urban driving cycle—UDC) repeated four times and the EUDC cycle. As is shown in Figure 18, the WLTP procedure class 3b cycle is composed of four sections: Low, medium, high, and extra-high.

Similarly to what is stated in Section 3.2.1, to compare the specific energy consumption (MJ/km) obtained in the tests in real conditions of use and those declared by the car manufacturer on the basis of the WLTP procedure, the tests' specific energy consumption was calculated as the weighted average of the consumption detected in the four sections in which the test path was divided (Section 2.1). The weights were calculated by associating the urban with the high traffic density to low section, the urban with the low traffic intensity sections to medium section, extra-urban to high section, and highway to extra-high section according to the distances shown in Table 8, as illustrated in Figure 19.
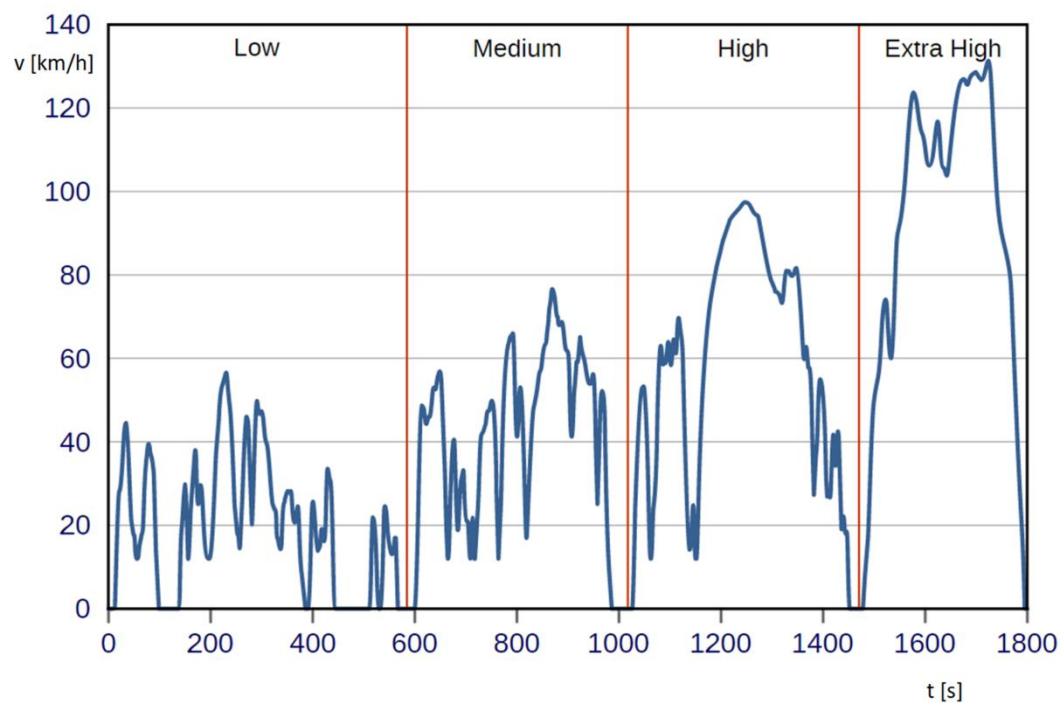
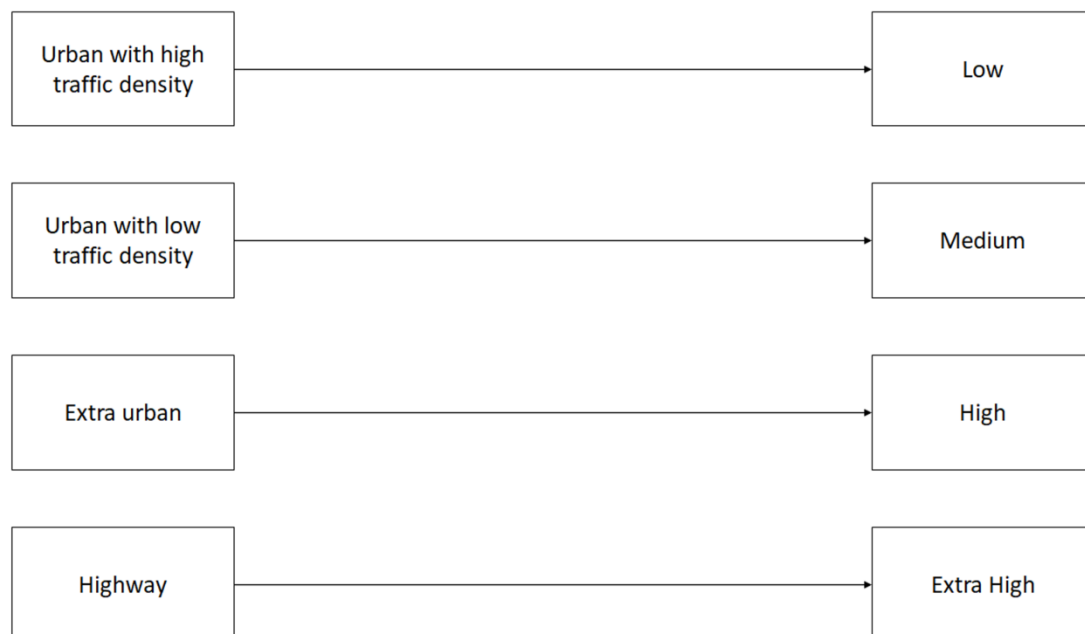**Figure 18.** WLTC cycle for class 3b vehicles.

Figure 19. Scheme of calculation of energy consumption in the tests to compare with energy consumption in WLTP procedure (ECT, WLTP).

Table 8. WLTP procedure distance.

	Distance (m)	Distance (%)
Low	3095	13.3
Medium	4756	20.4
High	7162	30.8
Extra-high	8254	35.5
Total	23,267	100.0

Based on the above, the specific consumption obtained in the tests under real conditions of use of the five vehicles analyzed is calculated as follows:

$$EC_{T,WLTP} \ = \ EC_{UHTD} \cdot 0.133 + EC_{ULTD} \cdot 0.204 + EC_{EU} \cdot 0.308 + EC_H \cdot 0.355 \tag{5}$$

As already mentioned, for the Leaf (BEV) and Auris (ICE Diesel) vehicles, the energy consumption for WTLP procedure was not available as it was registered before the entry into force of the legislation that provided for approval with the WLTP procedure. Figure 20 shows the comparison between the specific energy consumption obtained in the tests and those declared by the car manufacturers based on the WLTP procedure.
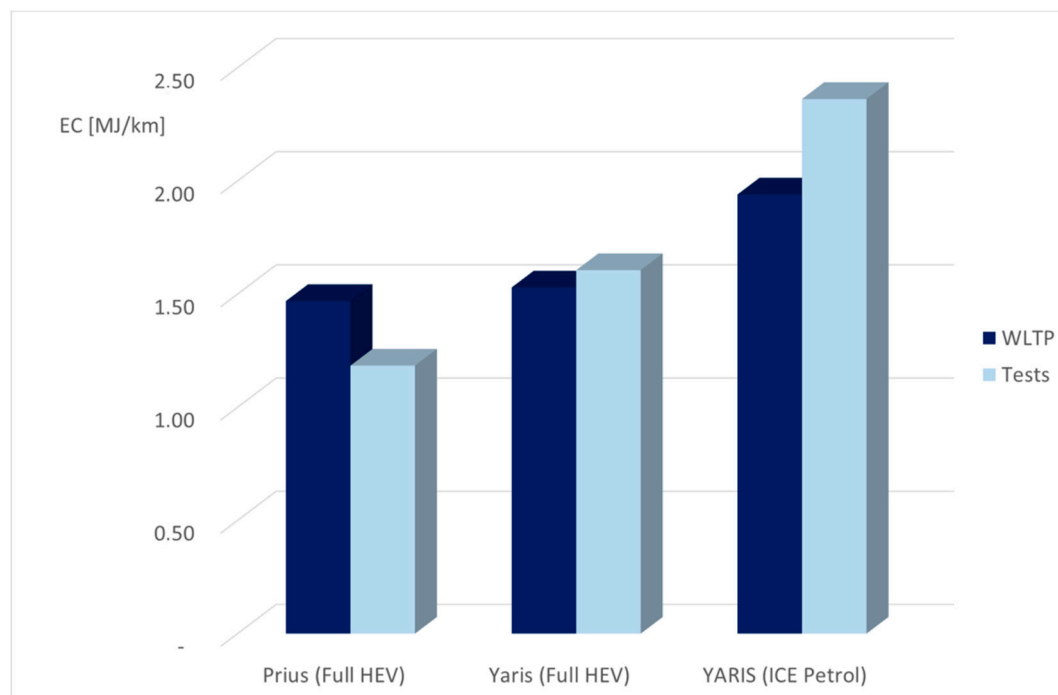

Figure 20. Comparison between test and WLTP procedure energy consumption.

In this case the difference between the energy consumption in the tests and in the homologation procedure was lower compared to the NEDC, but also in this case the increase in energy consumption in the tests compared to homologation consumption decreased with the increase in the electrification degree of the vehicle.

In fact, for the full HEV Prius the consumptions in the tests were lower than the homologation ones (−24.1%), those of the full HEV Yaris were substantially the same (+4.7%), and those of the ICE petrol Yaris were substantially higher (+17.8%).

4. Conclusions

The results of the experimental tests in real driving conditions of conventional (petrol and diesel), hybrid-electric, and full electric models clearly show the electrification of the powertrain is an effective way for primary non-renewable energy consumption and GHG emission reduction. The real drive achievable reductions, in comparison with conventional ICE-only cars, were significant in urban conditions (both low and high traffic density) and were less significant in extra-urban and highway driving conditions.

In the transition time towards pure electric vehicles, hybrid systems can be considered a good transitory solution for the reduction of primary non-renewable energy consumption and GHG emission without any need for supplementary charging/refueling infrastructure [29]. The most electrified of the

two hybrid cars analyzed, the Toyota Prius, showed a very high percentage of driving time in electric mode and a very high capacity for regenerative braking [9].

The efficiency of the Nissan Leaf (BEV) measured in real drive conditions was very high with an average energy need for 0.470 MJ/km (electricity) compared to the energy need for 2.456 MJ/km (fuel) for conventional ICE vehicles. The non-renewable primary energy consumption and GHG emissions of the BEV depended on the production, transport, transformation, and distribution method of electricity (the charging system does not have a very relevant weight on the total efficiency). A possible adjunctive advantage can be given by energy traceability that could allow us to know the actual production source of the renewable electricity made available at the charging point [30].

From the comparison of the consumptions detected in the tests in real conditions of use and those of homologation for the five vehicles analyzed, it emerged that with the WLTP procedure the differences were less than the NEDC and, in both cases, the differences varied significantly for the various powertrains analyzed (conventional ICE Diesel and petrol, HEV, and BEV) based on the degree of electrification of the vehicle.

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Nomenclature

BEV	Battery electric vehicle
EC	WTT energy consumption
ECT, NEDC	Energy consumption in the tests to compare with energy consumption in NEDC
ECT, WLTP	Energy consumption in the tests to compare with energy consumption in WLTP
ECE	Urban driving cycle (UDC)
EUDC	Extra-urban driving cycle
FCEV	Fuel cell electric vehicle
fGHG	GHG emission factor
fNR	Non-renewable primary energy consumption factor
GHG	Greenhouse gasses
GHGEM	Greenhouse gasses emission
HEV	Hybrid-electric vehicle
ICE	Internal combustion engine
LHV	Low heating low value
ML	Mileage
NEDC	New European driving cycle
NRPEC	Non-renewable primary energy consumption
PHEV	Plug-in hybrid-electric vehicle
PMR	Power-to-mass ratio
TTW	Tank-to-wheel
TTWGHG	Tank-to-wheel GHG emission
TTWNRPEC	Tank-to-wheel non-renewable primary energy consumption
WTT	Well-to-tank
WTW	Well-to-wheel
WLTC	Worldwide harmonized light vehicles test cycle
WLTP	Worldwide harmonized light vehicles test procedure
ZEV	Percentage of operating time in ZEV mode with respect to total time

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