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Experimental analysis of the auxiliaries consumption in the energy balance of a pre-series plug-in hybrid-electric vehicle

Santiangeli Adriano[a], Fiori Chiara.[b], Zuccari Fabrizio.[a], Dell'Era Alessandro.[a], Orecchini Fabio.[b], D'Orazio Annalisa.[b]

[a]*University of Guglielmo Marconi, DME - Mechanical and Energy engineering Department, 00193 Rome, Italy.*

[b]*Univerisity of Rome Sapienza, SEM - Energy and Mobility Systems of CIRPS - Interuniversity Research Centre for Sustainable Development, Piazza San Pietro in Vincoli, 10 - 00184 Rome, Italy*

Abstract

The purpose of this study is to evaluate on a real urban driving cycle the performance of a plug-in hybrid-electric vehicle, which is part of a series of pre-marketing vehicles, taking into account the real driving conditions. For this purpose have been considered the driving style influence, the traffic level, the path slope and the comfort level requested inside the vehicle by the driver. In particular the influence of auxiliary systems consumption on the total consumption of the vehicle has been evaluated. Attention has been paid to assess the effect of auxiliary systems consumption on the autonomy of the vehicle on electric mode. The data were collected under real driving cycles in the city of Rome. The importance and innovation of this work consist of two principal concepts: (i) the auxiliary systems consumption and its influences on total consumption and (ii) the acquisition analysis under real driving cycle. Different drivers were involved during the acquisition campaign along several itineraries characterized by the features of a real urban cycle (length, slope, traffic light posts, etc.). The data acquisition was carried out on-board in real time using a measurement chain which included: OBDII (On - Board Diagnostic systems - second version), hardware, laptops and software. Acquired parameters were: traveled distance, speed, air flow, equivalence ratio, RPM, voltage, SOC (State Of Charge) of the batteries. The calculated variables from acquired data were: fuel consumption, consumption and incidence of auxiliaries on the autonomy in electric drive.

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Keywords: Plug-in hybrid-electric vehicle; state of charge; consumption; auxiliaries; real driving cycle; Energy System.

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1. Introduction:

As is known, in order to prevent the dangerous anthropogenic impacts on the climate system, the concentrations limits of greenhouse gases in the atmosphere have been indicated by the Kyoto Protocol . In between the greenhouse gases, many efforts have been spent to evaluate the environmental and economical impact of the CO2 emission, including different studies about the costs and CO_2 emissions of electric cars ([1-5]). The rising interest of the automotive field for the electric cars can be understood in the light of the fact that the transport sector is responsible of 32% of the total CO2 emissions ([6-8]).

The vehicles with a high degree of electrification (hybrid, plug-in hybrid-electric) can be a solution to reduce the emissions of the transport sector [2-6] (especially considering the increase of energy plants for the electricity production based on renewable energy sources) because they are characterized by a higher energy efficiency in respect to the conventional vehicles. In fact, the vehicles with a high degree of electrification consume less energy and emit less carbon dioxide ([2-6]) if compared with Internal Combustion Engine (ICE) vehicles being more efficient and sustainable than other conventional solutions. Among the advantages of these vehicles [10] it is worth to remember the greater energy efficiency achievable by the energy recovery during the braking [11]. Moreover, as already mentioned, another advantage is the possibility to obtain the electricity input from renewable sources.

Nomenclature

AUX	Auxiliary systems
A/C	Air conditioning System
BMS	Battery Management System
D_e	Electric Average autonomy
ECU	Electronic Control Unit
EV	Electric Vehicle
HV	Hybrid Vehicle
ICE	Internal Combustion Engine
OBDII	On - Board Diagnostic systems - second version
PWR	Power
RMP	Revolutions Per Minute
SOC	State Of Charge
TBC	Total Battery Capacity

1.1. The importance of auxiliary systems consumption in the energy balance of pre-series plug-in hybrid-electric vehicle

In order to reduce the high level of CO_2 emissions of the vehicles, the evaluation of the effect of auxiliary systems on energy consumption is also necessary. According to different studies of the NREL (National Renewable Energy Laboratory), every year in America each gasoline vehicle consumes an average of 2300 liters of fuel. 235 liters of such an amount are consumed only to supply the air-conditioning system. A decrease 400 m/l would correspond with a savings of about $ 6 BILLION/year [12]. The analysis performed in the present work highlights that the consumptions during the real cycles are greater than in the homologation ones [13,14]. The U.S. legislation has indeed provided additional cycles (SFTP - Supplementary Federal Test Procedure) with the aim to evaluate the fuel consumption and the emissions under specific driving conditions. In particular, the SFTP SC03 cycle has been introduced to calculate the consumptions and the emissions associated with the air conditioning unit in vehicles. Simulation studies carried out by NREL (National Renewable Energy Laboratory) through the simulator ADVISOR (Advanced Vehicle Simulator) using SFTP SC03 cycle showed that the impact on the autonomy of electric vehicles is around 16% and the impact on the consumption of hybrid vehicles is around 26% [15].

The guidelines of the present work are the evaluation and optimization criteria of the Energy Systems (ES) [16-19]. as the vehicle is a subsystem (Tank To Wheels – TTW) of a wider global system (Well To Wheels – WTW). This work has been conceived in the framework of the experience gained in ES modeling and optimization [20,21].

In this work the data acquisition has been performed under real driving cycle to evaluate the incidence of auxiliary systems on the consumption and the autonomy. Real driving cycle analysis is very important because the homologation cycle is not representative of the real consumption and emissions. In the homologation cycle, consumption and emissions are indeed lower than in the real one because the path features and the driving style are not considered. An aggressive drive produces an higher consumption than a low-demanding drive. To date, only simulations or test-bench studies have been lead on this field and there are no studies on real driving cycle to evaluate the incidence of auxiliaries consumption on the vehicle autonomy and on its overall consumptions ([22-27]). Taking into account that modern vehicle present on board a number of auxiliaries day by day more consistent, it becomes fundamental evaluating the energy balance of the whole system in real conditions. To perform the respective tasks, the auxiliary systems absorb a portion of the power delivered by the engine. This causes a subtraction of energy to be delivered for the traction and therefore affecting the total vehicle consumption in a real driving cycle. As the power required by the traction, even the power absorbed by the auxiliary is a function of operating conditions and driving style, in addition it is also depending on the comfort needs of the driver and its passengers. The evaluation of the consumption of these devices is very important to increase the overall efficiency of the energy system of the vehicles. The knowledge of the percentage incidence of the auxiliary systems on the total consumption of the vehicle would allow to use the auxiliaries in a "more rational" way, to use auxiliary systems able to consume less energy and to manage the energy flows on board the vehicle to optimize the performances of the auxiliary themselves. The conditioning system of the vehicle analyzed is a heat pump system. Today a lot of papers have been written on energetic analysis of hybrid vehicles ([28-31]) but only few of these are focused on real driving cycle, in particular considering the auxiliary loads. This study aims to estimate the incidence rate of consumption of the auxiliary systems on the total consumption of the vehicle energy on a real driving cycle, because, up to the present, the estimated rates are due to simulation ([31,32]) or dynamometer test bench. For this purpose, different drivers have been involved in order to take into account different driving styles of several individuals of different gender and age (however the related statistical information about the obtained driving cycle profiles are out of the scope of this work and will be included in a different work).

2. Description

This research has analyzed the energy request of the auxiliaries of a series-parallel plug-in hybrid-electric vehicle during a real driving cycle in order to evaluate the impact on both consumption and autonomy in electric mode. The declared autonomy in electric mode only is 20 km. In Table 1 are reported the characteristics of the vehicle power train, where the Maximum Vehicle Power is the maximum power of the hybrid synergy drive.

Battery	**Lithium-ion batteries; 345 V; 5,2 kWh, 15 Ah**
Maximun vehicle speed	180 km/h
Maximun vehicle power	100 kW
Electric Motor	60 kW; 650 V; 207 Nm
ICE	Four-cylinder gasoline engine 1800 cm^3; 73 kW; 142 Nm
Vehicle weight	1500 kg

Table 1: Power train datasheet.

The energetic analysis of the vehicle has been led in real conditions. The itinerary performed during the tests, shown in Figure 1, has been chosen in reason of its length, slope, insertions number, traffic lights, etc., in order to be representatives of a typical real urban driving. The total distance traveled by each driver, chosen with different characteristics in terms of gender and age (23-46 years), for each test is approximately 27.6 km obtained by 6 laps of the circuit shown in Figure 1, of 4.6 km length. The elevation profile of the reference path is shown in Figure 2. In Figure 3 an example of the real driving cycle achieved is represented. As can be seen, the speed profile is irregular and it is characterized by sudden accelerations and decelerations. This profile is very different from the NEDC (New European Driving Cycle) characterized by many segments at a constant speed. For what concerning the auxiliary set-up, the vehicle is equipped with a heat pump having an electric compressor. The heat transfer fluid of the heating and cooling system is the “HFC134a” fluid. The average power of the heat pump is about 600W and the thermal power provided turns out to be roughly 1680 W considering an average COP (Coefficient Of Performance) equal to 2.8 [33]. The vehicle is also equipped with 3 electric heaters, of 280W power, that in the case of a high thermal demand start taking energy from the batteries. Even the ICE water pump is electrically controlled. Characteristic of this vehicle is the possibility to pre-heat the passenger compartment directly by the grid, before the vehicle starts. This option allows to reach the desired temperature without affecting the autonomy of the electric drive and the energy provided by the vehicle battery pack, in this case, is only the amount needed to maintain the temperature. It is important to highlight that only the absorption of the compressor has been taken into account because it is the component absorbing the highest energy amount among the auxiliaries considered. All the others have a global energy absorption negligible in comparison to the compressor.

Figure 1: Reference path, Rome

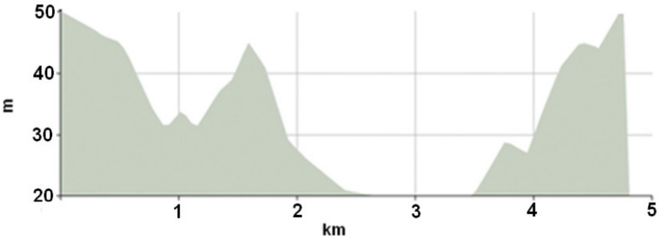

Figure 2- Elevation profile of the reference path

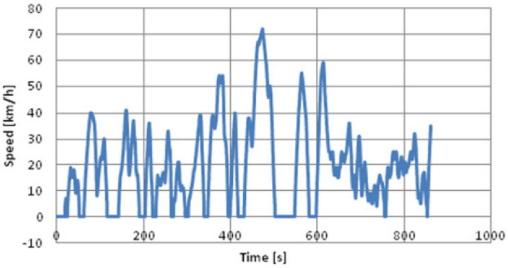

Figure 3: example of real driving cycle performed

3. Methodology

The data acquisition system for monitoring the vehicle performance has been chosen on the basis of the operational characteristics of the electronic board system. The instrumentation for data acquisition consists of: a laptop, a PCAN-USB interface and a homemade program in LabVIEW allowing to query, simultaneously, the different control units. The LabVIEW program for data acquisition from the CAN bus of the vehicle has been designed specifically for this vehicle. In this way, it has been possible to monitor the various variables needed. The software allows to read and store in a text file the monitoring parameters for suitable intervals of time. The On-Board Diagnostics (OBD) also allows, through the use of appropriate equipment, to read and acquire certain parameters processed by the various units in the vehicle. In this vehicle there are three control units, that, if properly interrogated, can give information about significant parameters of several components of the power train, as ICE, electric motor and battery system. The sampling time was set at 500 ms. In this way all the parameters have been detected and after processing data the energetic analysis has been realized. [15].

3.1. Acquisition tests

The acquisition tests were carried out during the winter and during the summer to take into account different weather conditions affecting the auxiliaries use by the drivers. Two daily drives (six laps for each mission) have been done at 10:30 AM and at 15:00 PM. Before the mission, the vehicle was fully recharged to guarantee the maximum value of SOC. The vehicle provides two driving modes, that is the Eco mode (optimized power management) and the Power mode (frequent ignition Internal Combustion Engine). For this reason each driver has been requested to drive two times in the two different modes Power and Eco. However, this study is focused in particular on the Eco mode because it is the one characterized by less consumption and emission. The drives involved in the acquisition have been 8 in winter and 6 in summer. To cover all the 27.6 km, each acquisition took about 1 hour and 45 minutes and during this period it was possible to monitor the EV (Electric Vehicle) and HV (Hybrid Vehicle) drive. In order to analyze the influence of the auxiliaries, each test has been performed by setting the air-conditioning system in the Auto mode, with a temperature suitable to the level of comfort required by each driver. It is worth to stress that in the pre-series vehicle tested, the function EV is preeminent in respect the HV and it is set automatically; this means that the vehicle automatically starts using the autonomy of 20 km in pure electric (up to a speed of 100 km/h). On board there are three lithium ion battery packs with three separate BMS (SUB1, SUB2 and MAIN); two of them are used for the electric mode (SUB1 and SUB2) and one (MAIN) for the hybrid mode. After the 20 km of autonomy in EV, the vehicle automatically switches to hybrid mode. In the pre-marketed series of vehicle, this feature (EV) can be set, as suggested by studies as in this paper. After the experimental campaigns on the pre-marketed series, in the marketed series the EV autonomy range has been changed from 20 km to 25km (pure electric) up to a speed equal to 85 km/h (this means that the vehicle automatically starts using the autonomy of 25 km in pure electric and in this range the ICE keeps being inactive up to the speed of 85 km/h). It is worth to take into account that, as reported by [34], 25 km is the mean distance value of the daily travels for 80% of the European citizens (as shown by 5 years research of a vehicle producer involving many hundred users and taking into account SOC, charge frequency, travel extension, percentage of EV mode exploitation, driving efficiency, for total 800.000 km).

4. Results

4.1. Heating and Cooling systems incidence on consumptions

By the tests performed, it has been possible to carry out an evaluation of the incidence on the consumptions of the energy requested by the heating and cooling systems . In particular the consumptions in Eco and Power mode, measured with and without A/C for different drivers, are highlighted in the following figures 4, 5 and 6 . The consumptions are related only to petrol contribution and do not take into account the battery consumption. However a sign of the battery consumption is the autonomy decrease of the electric mode observed in the different cases, also if not included in the present discussion. The average consumption in Eco and in Power mode respectively is shown in Figures 4 and 5.In Figure 4 can be seen that in Eco mode with AUX there is an increase of consumption for 75% of the drivers (driver 1 to 6), , while for the remaining drivers 7 and 8 (25% of drivers) was observed a lower consumption driving with auxiliary system. This second case is related to such drivers having a driving style particularly aggressive: indeed in Eco mode, it influences predominantly on consumption. In figure 5, instead, is shown the average consumption in Power mode, with and without the auxiliaries., Differently than the Eco mode, the consumption without auxiliaries never overcomes the one with auxiliaries. Driving in Power mode, indeed, the high frequency of the ICE on-off (also during the EV driving) increased the global consumption as expected. This can be explained taking into account the ECU's control logic of the A/C system. In fact, in the case of the Power mode, the control unit activates the ICE in order to reach a useful temperature for heating by means of the heat transfer fluid. In Eco mode the ICE starts less frequently than in Power mode, indeed in Eco mode the batteries provide the majority of the power requested by the auxiliaries, while the ICE starts essentially to satisfy the traction needs. In Figure 6 the comparison of the average consumption in Eco and Power mode is shown. The average consumption in Eco mode is 2.6 l/100 km and 2.4 l/100 km with and without A/C respectively, while the average consumption in Power mode is 3.4 l/100 km and 2.6 l/100 km respectively. Therefore, in the tests performed, the influence on the global consumption of the energy request of heating system stands at around 8.3% and 30.7% respectively in Eco and Power mode. However when, in Eco mode, the energy request from auxiliaries system is higher, as in cooling case, the contribution of the ICE increases, determining a consumption even 20% higher than the heating case. In Figure 7 is shown the comparison among heating and cooling consumption in Eco mode. The Figure 7 highlights that in Eco mode the consumption measured when the cooling system is on results to be, on average, about 20% higher than the case when the heating system is on, as it is shown in table 2.

It is important to highlight, as reported in figures 4,5 and 6, that the consumptions recorded have been significantly lower or higher than the averages values reported, because of the influence of the driving styles and the testing on real conditions, where the same driver can consume less in a specific test and more in another one.

The data related to each mission are strongly affected by different parameters, and the variance can be significant. The main parameters affecting the data difference are:

- Different traffic conditions
- Different driving style (also in the case of the same driver)
- Different weather conditions (affecting the auxiliaries consumption)

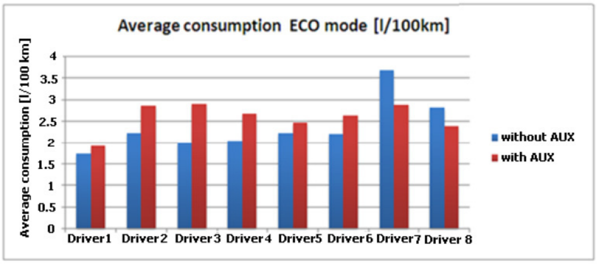

Figure 4: Comparison of individual consumption with and without auxiliary in Eco mode

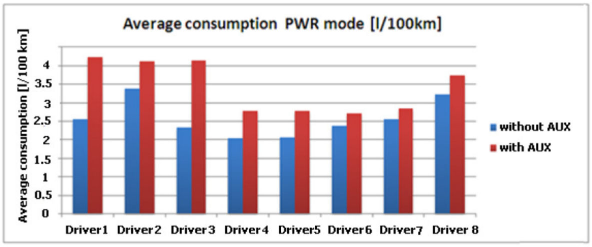

Figure 5: Comparison of individual consumption with and without auxiliary in Power mode

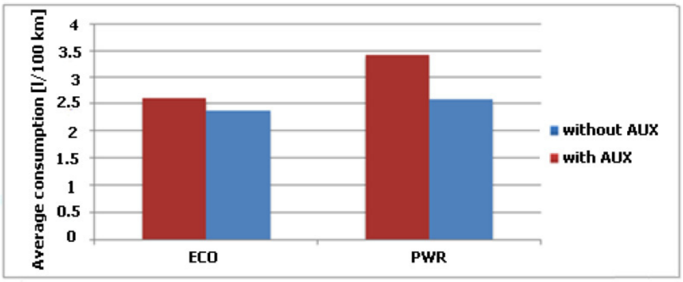

Figure 6: Comparison of average consumption in Eco and Power mode

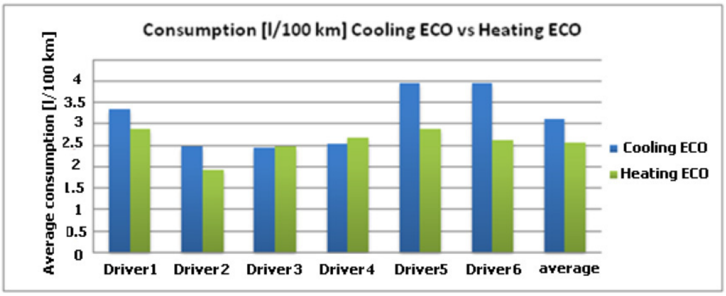

Figure 7: - Global consumption with air conditioning for cooling Eco and heating Eco in comparison

Percentage difference on consumption

	Without cooling/heating ECO	Heating ECO	Cooling ECO
Average consumption [l/100km]	2,4	2,6	3,1
Percentage surplus [%]	0%	8,3%	29%

Table 2: Additional percentage values of consumption in tests of heating and cooling compared to driving in Eco mode without air conditioning

4.2. Autonomy auxiliary incidence in mode EV (Electric Vehicle)

As stressed before, during the EV mode the ICE will start working under specific conditions. For this reason such a mode cannot be strictly considered a ZEV mode. In order to evaluate the consumptions and the autonomy in ZEV mode, the data taken into account are only such a data acquired during the first 8.5 km of each Eco mode mission. In fact, during this range never the ICE has been observed on. By static tests (vehicle not moving with warming/cooling and other aux systems on, and ICE off) the electrical power of the auxiliaries systems has been experimentally measured. In such a way, the electrical consumptions in ZEV mode have been evaluated with and without the auxiliaries (warming/cooling) and the results are shown in table 3. The data reported by the brand are confirmed by the acquisitions showing that driving in EV is possible for a value of SOC ranging from 20% to about 80%. As described above, because the consumption necessary for the traction and the auxiliary system has been assessed, the actual average autonomy available for driving in ZEV mode (keeping the ICE off) with and without auxiliary activated, has been estimated by using the following expression (1) and reported in Table 4:

$$D_e = \frac{(SOC_{\max} - SOC_{\min}) \cdot TBC}{C_e} = \frac{0.6 \cdot TBC}{C_e} \tag{1}$$

where:

- SOCmin: minimum value of SOC (0.2)
- SOCmax: maximum value of SOC (0.8)
- TBC: total battery capacity (5.2 kWh)
- Ce: consumption in kWh / km obtained

Average consumption [Wh/km]	
Without AUX	157
With AUX Heating	186
With AUX Cooling	221

Table 3: Average values of electric consumption in Eco mode in the full electric length

Distance practicable in electric mode [km]	
Without AUX	19,91
With AUX Heating	16,73
With AUX Cooling	14,12

Table 4: Distance practicable in electric mode [km] calculated on the basis of consumption previously obtained

It is possible to confirm, through the experimental data obtained, the autonomy in zero-emissions driving, even in the real driving cycle, at least with auxiliary turned off. In fact this autonomy is the same declared by the brand, while the use of heating and cooling system affects the distance traveled in EV mode of about 16% and 29% respectively. The analysis proposed in this work highlights how it can be possible to increase the autonomy even with the auxiliaries on, for example enhancing its efficiency, or using a preconditioning system at home (using the energy grid).

5. Conclusions

The present study focuses on the evaluation of the performance of plug-in hybrid-electric vehicle on a real urban driving cycle, especially taking into account the driving style influence, the traffic level, the path slope and the comfort level requested inside the vehicle. Indeed all of these aspects are not considered in the homologation cycle, nor in terms of consumption, nor in term of consequent emissions. Indeed the tests carried out on a real urban cycle have given an interesting feedback on the difference among the vehicle performance in real conditions, in urban areas, and the performance in the homologation tests. Fuel consumption and emissions result greater in real case.

Particular emphasis has been given to the impact of A/C and to the comfort inside the vehicle, on average consumption and autonomy with Zero Emission.

The average consumption observed in the tests, in Eco mode, is 2.6 l/100 km and 2.4 l/100 km with and without A/C respectively, while the average consumption in Power mode is 3.4 l/100 km and 2.6 l/100 km respectively. Therefore the influence of the use of heating system in the tests performed, on the global consumption, stands at around 8.3% and 30.7% respectively in Eco and Power mode. However when, the energy request from auxiliaries system is higher, as in cooling case, the contribution of the ICE increases, determining a consumption even 20% higher than the heating case. The influence of the auxiliary on the electric autonomy in ECO mode (EV mode) is found to be about 16% less in the case of heating and about 29% less in the case of cooling, respect to the case without auxiliary. It is important to highlight that the originality of this study consists in the tests carried out on real driving cycles, in urban area, for the evaluation of the incidence percentage of the auxiliaries on the total energy consumption of the vehicle. This analysis gave the possibility to compare the actual values of the parameters of interest with those reported by the automaker. The knowledge of the percentage of incidence of the auxiliaries on the total consumption of the vehicle would allow to use the auxiliaries in a "more rational" way, to use auxiliary systems that consume less amount of energy and to manage the flows of energy on-board in order to optimize operations of the auxiliary system.

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