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Electrified road transport through plug-in hybrid powertrains: Compliance by simulation of CO_2 specific emission targets with real driving cycles

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ABSTRACT

Worldwide targets on specific CO_2 emissions (g/km) seem to make the use of internal combustion engines (ICE) prohibitive when adopting conventional driving cycles concerning road transport.

This research comes therefore from the necessity of an accurate analysis of the real driving habits in order to evaluate whether its implementation on an alternative powertrain, suitable to differentiate urban (local zero emissions) and extra-urban travels (highest performances of ICEs, even better than electric motors when contemplating the entire energy chain), can guarantee the compliance with specific CO_2 emissions reduction legislation; this last has been introduced with the aim of containing or even erasing global emissions from the transport sector in next years.

After an overview of all the main available technological alternatives, as regards powertrains, the Plug-in Hybrid (PHEV) solution has been analysed.

An experimental driving cycle is proposed by combining representative cycles obtained from a previous study, based on data provided by FCA, now Stellantis, where a clustering procedure has been applied to a sample of over two-thousand real journeys made in 2015 and 2016 in all Europe with conventional automobiles; appropriate ranges of distance, time, average speed in urban and extra urban conditions, idle times and stops have been identified thanks to a statistical analysis and the cycle has been created with all of these requirements to be as similar as possible to most of daily trips by road transport.

PHEV market has been examined in order to identify the components and architectures that characterize the most registered automobiles; a realistic model has therefore been created and used for the experimental cycle simulation.

Simulation results show that PHEV technology has the potential to consume 69% less fuel than a conventional vehicle counterpart with a consequent reduction of 71% in emitted tank-to-wheel (TTW) tons of CO_2 and significant reductions in fuel expenditure, in one year, because of the different source of energy.

1. Introduction

Global warming thematic is abundantly treated by literature, having become more and more important in the last years; our planet may reach a critical point, since current temperature is declared 1,5 °C higher than in the pre-industrial era; in any case, it results imperative to limit the human contributions to the rise of global temperature by containing CO_2 emissions by transport systems, as far as possible (IEA - Energy Technology Perspectives, 2017).

According to Mock and Diaz (2021), transport systems in Europe were responsible, in 2018, of about 21 % of total greenhouse gas emissions; other sources vary between this value and 27 %, being carbon dioxide emissions anyway an estimation, more or less rough. This variability depends upon different factors, namely: the efficiency of combustion and the actual composition of burnt fuel, which differ from well to well (different benzene rings from different wells imply different amounts of Carbon). Regardless the accuracy in determining such values, in order to reduce global GHG emissions, authorities established limits to specific CO_2 emissions for road vehicles in most countries of the world, based on the WLTC (Worldwide Harmonized Light Vehicles Test Cycle) conventional cycle: specific emissions limit, for private cars, is nowadays set at 95 g of CO_2/km in some parts of the world, including

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the European Union; a progressive percentage reduction is expected in next seven years: a 15 % reduction in 2025 and a 37,5% in 2030 are the current target, with a decision (by the EU Parliament, June 2022) even to erase them at 2035, though this decision is still and will be much discussed.

Conventional thermal engine-based powertrains are not sufficient to reach such an ambitious target, even with further improvements; therefore electrification – in general terms - is a key factor in order to achieve CO_2 emission reduction (**L.** Byrne et al., 2021, analysing transports in Germany, found that 65 % of BEVs and PHEVs in 2030 car fleet could reduce traffic-related CO_2 by 41 %). Different technological solutions for powertrains are currently available, but there are various aspects that should be evaluated to find the best solution or a viable and sustainable one: as a matter of fact, the automotive field is nowadays scattered and manufacturers declare different investing strategies. Some of them are pursuing two separated production lines: one concentrated on traditional ICEs, though assisted to some extent through electrification, and the other on BEVs (Battery Electric Vehicles); other carmakers have decided to move into a more flexible production line with the possibility to produce any kind of electrified powertrain for vehicles (HEV, Hybrid Electric Vehicles; PHEV, Plug-in Electric Vehicles; BEV; micro and mild hybrid; 48-V hybridisation) according to customers desires. The implementation of electricity, as alternative carrier of energy, gives the opportunity to take advantage of various functions (e.g. coasting, sailing, start and stop, regenerative braking, etc.) with the aim of reducing low efficiency driving phases; moreover, in hybrid powertrains ICE can work mainly close to the optimal operating line with a clear influence on the overall CO_2 emissions.

The main challenge is to plan a reasoned technological transition without neglecting all critical aspects that characterise the use of electricity alone for road transportation, in particular the following factors should be considered:

a. Batteries have an energy density per mass 35–50 times lower than gasoline (200–250 Wh/kg, expected values around 300–350 Wh/kg by 2024/25 versus crude oil with 42 MJ/kg or indicatively 11,67 kWh/kg);
b. Any recharging time is considerably slower than refuelling time;
c. Distribution networks of oil derived fuels are consolidated;
d. The impact on infrastructure is relevant; according to Falchetta and Noussan (2021), the average value of the ratio between BEVs and public charging points in European countries has increased from 1.6 to 7.2 in last five years. Still in most regions there are less than 0.5 EV charging points per 1000 inhabitants, so a huge number of new installations should be required to support EVs growth while contrasting unacceptable queuing phenomena accompanying the scaling up the market of BEV;
e. The impact on driving habits results relevant.

The main purpose of this research is to analyse real driving habits and discovering, by simulating different scenarios, if any alternative powertrain technology and drive cycle can make possible the achievement of low emission targets by 2030. Typical journey lengths, durations and locations (urban, extra urban, highway) have been examined and the evaluation of the best technological solution has been done through comparison between pros and cons.

1.1. *CO_2 emission trends and regulations in Europe*

Given the high impact of light-duty vehicles on global CO_2 emissions,[1] a sequence of regulations has been published in last ten years by the European government; in 2017, the vehicle type-approval cycle has changed, shifting from NEDC (*New European Driving Cycle*) to WLTP (*Worldwide Harmonized Light-duty Vehicle Test Procedure*), a definitely more aggressive cycle, that is considered to be more representative of real driving cycles. In fact, with NEDC there was a consistent gap between type approval specific emissions and real-life emissions. In 2021, the limit has been set on 95 gCO_2/km for passenger cars, with a scalable variation based on vehicle mass. The coefficient of the line emission threshold (gCO_2/km) - vehicle mass (kg), which adapts the limit proportionally to the weight, is 0,0333 but it has already been decided that it will be lower in 2025. If thresholds are not respected, some penalties have to been payed to European Community by the infringing carmaker. Starting from 2019, a penalty of 95€ for each gram of exceeding CO_2/km emission has been applied to every new registered vehicle. Manufacturers are struggling to stay under this threshold: most common strategies are pooling operations or investing in electrification because recent (2018–2022) eco bonuses are provided for car makers that produce low or zero emission vehicles.

Starting from 2019, the WLTP procedure has been applied to vehicles equipped with hybrid powertrains; considering PHEV procedure, two different phases are distinguished:

A. Charge depleting test; WLTP cycle is run continuously until break-off condition of the battery is reached; afterwards the current cycle is concluded but is not counted;
B. Charge sustaining test; only one WLTP cycle is run with constant low battery state of charge.

Total specific emissions are calculated through weighted average depending on UF (*Utility Factor*), a coefficient that is related to the km of electric range of the vehicle.

The application of WLTP to hybrid powertrains has been a fundamental improvement in type-approval procedures because quantifying specific emission levels at best operating conditions is the first step to understand the role of the driver. In fact, this technological solution is highly influenced by use and frequency of recharges, consequently the interaction between human and vehicle is what makes the difference between an effective reduction of emissions or just the potential to realise it.

In next paragraphs an evaluation on CO_2 emissions based on the initial state of charge has been carried out in order to highlight this important factor.

According to ICCT (*International Council on Clean Transportation*), CO_2 specific emissions are growing in last years; there is not any manufacturer which is under the 2021 limit curve and even if WLTP has been introduced there is a gap of 17 % between tested CO_2 specific emissions and those measured in real conditions. This gap is the reason why the research synthesised in this paper was directed to identify an experimental driving cycle, according to realistic driving conditions, in order to obtain reliable data on effective emissions. An accurate analysis of this kind has a crucial role in this moment of transition; results must be as realistic as possible in order to aim to the right direction. Time to make decisions is limited and the margin of error is practically nonexistent.

1.2. *Vehicle electrification and actual usage*

The main innovative powertrain configurations on vehicles are (in addition to ICEs) HEVs, BEVs and PHEVs. A higher level of

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[1] In EU, the whole road transport share of the overall energy consumption by all transport modes at continental level represents around 83–84%, expressed in t.o.e.; out of these the heavy duty falls between the 35 and 40%; the remaining amount is represented by all light-duty vehicles.

electrification means more effective use of fuel saving functions – on board - with benefits on overall emissions at local level; according to Mock and Diaz (2021), considering electricity mix in Europe in 2020, BEVs can allow GHG savings compared to ICEs in the range of 50–60 % by 2030. However, the efficiency of an electric motor has a value oscillating around 90 % (normal thermal engines have instead a maximum efficiency of nearly 33%, though higher values are expected for the next years, and only 18–20% in acceleration and low load phases, at traffic lights, when searching parking, in traffic jams) so, in hybrid solutions, it can work as a support in critical phases (e.g. start, acceleration, etc.). In electric vehicles, the electric motor is instead the only source of power with local zero emissions, i.e. just the tank-to-wheel (TTW). PHEVs and BEVs are the powertrains architectures that include every function (start & stop, coasting, sailing, e-assist, e-boost, electric drive, regenerative braking and, for PHEVs, load-point shift to recharge the battery), they are characterised by battery packs with a capacity that extends from indicatively 8–12 kWh (PHEVs with a declared range of 50–70 km) to more than 80 kWh (BEVs with a declared range of 550 km).

Despite the fact that BEVs are local-zero-emission vehicles, there are different problems that are involved in their usage. Besides the aspects related to the queuing phenomena for recharging of public soil generated whenever the market scaled up, the main doubts are related to the electric range besides to the differences between declared autonomy and effective duration, due to the fact that phenomena as battery degradation and activation of auxiliaries (air conditioning, heating) cannot be well considered. Moreover, having only one source of energy implies that there is no solution if the battery is completely discharged (a skilled person, a booster and another vehicle need to be present in this unpleasant case), this induces the driver to feel the so-called "*recharge anxiety*" besides the "*range anxiety*": a psychological stress which occurs when the driver anticipates insufficient driving range for the remaining travel distance (Hasan and Simsekoglu, 2020). To solve *range anxiety* problem for BEVs, Melliger et al. (2018) suggest an amazing infrastructure improvement, in particular regarding home charging, although a substitutive conventional vehicle is also necessary in case of planned long trips. PHEVs represent evidently a more versatile solution; the availability of two different simultaneous sources of energy allows the driver to be sure that his destination will be reached and, through a very evolved control system, the best of both technologies can be exploited. In urban contexts, electric drive can be regularly used; in extra urban or highway travels, ICE can work at maximum efficiency points even in power-split mode. It is true that only considering TTW emissions BEVs are the least pollutant vehicles (together with those burning hydrogen) but considering total lifecycle this assumption has to be investigated: according to Xiong et al. (2019), considering vehicle lifecycle in all aspects – i.e. production of raw materials, manufacturing of components, assembly stage, maintenance and end-of-life - total emissions between BEVs and PHEVs are comparable, even if it should be highlighted that the energy mix in China is worse than European one. Generally speaking, in average, PHEVs seem to still have higher life cycle emissions, but a correct vehicle usage could change the situation. There are also studies which show the risks of new powertrains: Gan et al. (2021) found that, especially considering super-credits, both technologies could lead to a GHG emissions increase. In particular, the cost of the battery, in terms of equivalent grams of CO_2, is substantial; hence the relation between bigger battery packs and higher lifecycle emissions. Furthermore some researchers found that if the battery pack catches fire for accident, it is very difficult to extinguish it because the position is not easy to access, moreover the components of the battery make it burn until everything is consumed. Some electrified motor vehicles are equipped with a system which isolate the battery in case of strong impact or deceleration (with consequent airbag opening), in order to avoid dangerous situations due to battery fire; this process is irreversible therefore the battery pack has to be substituted. In case of small battery packs, the replacing does not impact excessively on overall vehicle costs; but when it comes to BEVs, replacing the battery pack is an onerous expense, comparing with the purchase of a new vehicle. As a fact, according to Conway et al. (2021), the current battery-pack cost is 137$/kWh. In conclusion, BEVs have to be equipped with a large battery pack to guarantee long journeys with a negative effect on recharging time and overall CO_2 emissions, besides, the need to substitute a predominant and expensive part of the vehicle in case of accident, is an economic risk. On the other side, PHEVs need a smaller battery pack (e.g. 8–12 kWh) and, with their correct usage, they guarantee low emissions (around 30 WLTP gCO_2/km), versatility, and a reasonable recharging time of 5–8 h with usual or standard (improperly defined as slow) domestic recharge including the contemporaneous consumption of electricity for other uses. This is the reason why this research is focused on this type of vehicles.

As mentioned before, main difficulties related to PHEVs effectiveness are related to usage and drivers' habits, in addition the high costs of this technological solution do not make it accessible to the majority of the population. Plotz et al. (2020) studied real world usage of PHEVs and following factors have been extrapolated considering an UF proportional to km travelled in electric drive (so different from WLTP UF, but useful to understand the influence of many factors on real PHEV's performances):

- There is a geographical influence; countries with higher population density show lower UFs, this is due to the less availability of private recharging stations; according to Funke et al. (2019), home charging is the main option in most countries, in regions with low potential home charging availability, public infrastructure is fundamental;
- Driving habits have an important role, in fact long journeys tend to discharge the battery with a result of a more frequent use of ICE and lower UF;
- There is a considerable gap between WLTP UFs and real world ones, this means that even for PHEVs type-approval tests are quite different from real driving conditions;
- Vehicles with bigger size of battery pack have longer ranges, consequently annual electric drive mileage is more extended with a positive result on UF, despite that positive effect, bigger battery size implies more weight so higher powertrain power is required and this aspect has a negative influence on UF. In design phases this trade-off should be evaluated;
- Charging frequency has a key role, without recharging properly UF falls down with a negative result in emissions.

This last point has been closely evaluated in simulations of this research; four different scenarios have been set by diversifying charging frequency and results confirmed what has been found in Plotz's study.

It is not easy to predict how and when PHEV and BEV technology will become the predominant part of new passenger car fleet, notwithstanding the decisions by policy: in their paper Mock and Diaz (2021) considered different scenarios, with a new registrations market share of the sum of BEVs and PHEVs between 53% (current adopted policies) and 99% by 2035; in particular the most extreme prediction consists of a total penetration of BEVs, but - given for the negative aspects of full electric vehicles mentioned before - it is really hard to consider it possible.

2. Experimental driving cycle

In this section the building process of the experimental driving cycle is shown; in order to obtain a realistic driving profile, different activities have been carried out. First of all, important information about real driving habits have been taken by Dalla Chiara et al. (2019) research; secondly, an important source of driving profiles has been the paper *"Analysis of real driving data to explore travelling needs in relation to hybrid–electric vehicle solutions"* where a dataset of more than two-

Table 1
Driving cycle requirements.

Total distance [km]	25–40
Total duration [s]	1740–3420
Urban drive distance [km]	2,5–7,5
Urban drive duration [s]	100–700
Extra urban distance [km]	10–30
Average urban drive speed [km/h]	10–40
Average extra urban drive speed [km/h]	20–80

Table 2
Experimental UEUC parameters.

Total distance [km]	25.8
Total duration [s]	2685
Urban drive distance [km]	2.6
Urban drive duration [s]	475
Extra urban distance [km]	23.2
Extra urban duration[s]	2210
Urban drive speed range [km/h]	0–50
Extra urban drive speed range [km/h]	0–101
Maximum speed [km/h]	101
Average speed [km/h]	34.6
Maximum acceleration [m/s^2]	3.6
Maximum deceleration [m/s^2]	−3.5
Constant speed time (s)	43 (1.6%)
Acceleration time (s)	1115 (41.5%)
Deceleration time (s)	1152 (42.9%)
Stop time (s)	375 (14%)

hundred thousand journeys travelled in Europe, between 2015 and 2016, by conventional ICE vehicles has been analysed and, by hierarchical clustering, converted in a set of sixteen cycles, each of them classified according to following parameters: trip duration, trip distance, maximum speed, journey type, average fuel consumption; finally from sixteen cycles, four have been extrapolated and linked together in order to create only one cycle with characteristics which correspond to requirements deriving from statistical studies on typical journeys.

2.1. Cycle requirements

In order to build a realistic cycle, the first step has been the derivation of journey distance, duration, type and average speed requirements from statistical studies. In examined papers, data from different countries have been compared, except for the average speed which is based only on mentioned data. A first important consideration is that – as commonly known to some extent - high frequency of travels is characterised by - primarily - urban mobility and – secondarily – the extra urban one; this is a key information because it is the driving context where electrification can be exploited at his best potential. Urban mobility is related to low speed, frequent stops, cold starts, conditions where conventional powertrains suffer and are more pollutant, due to low load and low efficiency points. When deepening in the detail, it is necessary to make a distinction between urban and extra urban daily typical ranges of distance, duration and average speed. More than 90% of daily urban journeys have a distance of less than 10 km, most frequent ones are in the range 2,5 – 7,5 km. Typical daily urban driving duration is in the range between 5 and 10 min. Average speed of urban journeys is in the 99% of cases under 40 km/h, with a most frequent value around 20 km/h. Extra urban mobility is characterised by 90% of daily distance under 30 km, most frequent distances are in the range 8–15 km. The typical average speed of extra-urban journeys is in the 90% of cases under 70 km/h, with a most frequent value around 50 km/h.

Total daily driving distance, comparing data of four different European countries, stays in the range 20–40 km with a duration between 29 and 57 min. Summing up all of this information, the list of requirements has been compiled (Table 1). After targets setting, the cycle has been built trying to accomplish all of them.

2.2. Cycle construction

From the extrapolated set of 16 cycles, a selection of the first four, in order of statistical relevance, has been made; the result is a mixed cycle, which includes an urban section and an extra urban one, that is named ***UEUC*** (Urban - Extra Urban Cycle). Technically this is much interesting because its parameters perfectly fit with previous requirements and represent a daily trip with high acceleration and deceleration phases, whose key data are reported in Table 2. The single four cycles that have been assembled represent more than 50% of all the samples; one is an urban cycle of 2,6 km, other three are short extra urban cycles that have characteristics similar to statistical information, another proof of

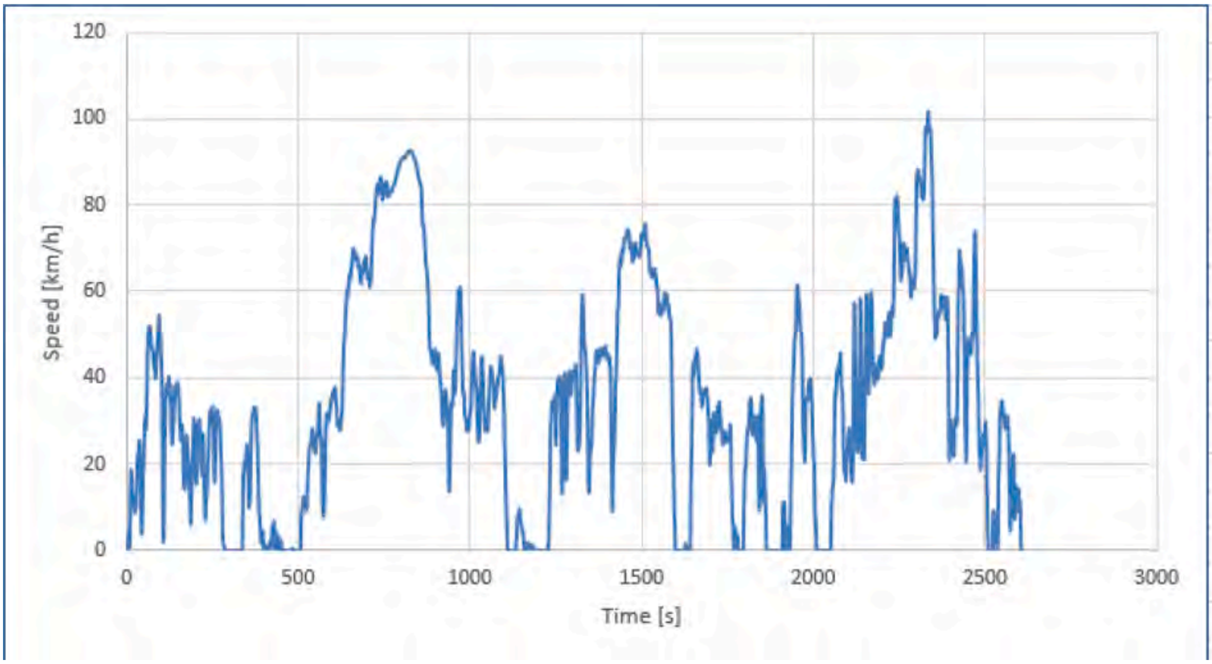

Fig. 1. Experimental driving cycle.

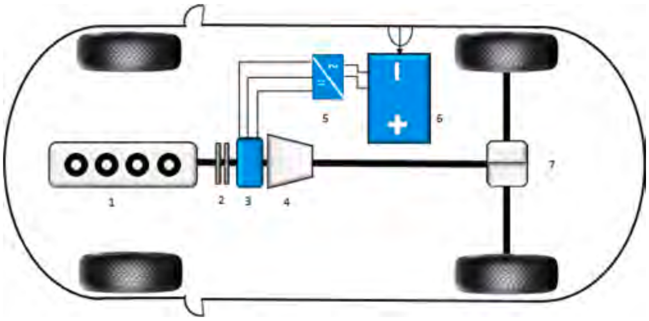

Fig. 2. PHEV model scheme.

Table 3
Vehicle parameters.

Traction	Rear-wheel drive
Curb weight [kg]	1100
Maximum load [kg]	525
Tyre diameter [m]	0,657
# wheels	4
Wheel inertia [kg*m^2]	1,05
Rolling resistance [N/kg]	0,0879
Cx (drag coefficient) [-]	0,25
Frontal area [m^2]	2,22
Braking force distribution (front/back) [-]	0,5
Accessory mean power demand ICE [W]	0
Accessory mean power demand Battery [W]	0
Vehicle Miles of Travel (VMT) [km]	33,000
Vehicle expected years [*anni* or years]	10
Cardan inertia coefficient [kg*m^2]	0,001
Gb-ICE shaft inertia [kg*m^2]	0,01
Average battery energy consumption [kWh/km]	0,2
Wheel-differential efficiency [-]	1

solidity for this research. As it will be shown in the paragraph dedicated to simulations, this experimental driving cycle is more aggressive than WLTP, in fact the type-approval cycle has a maximum acceleration of 1,7 m/s^2, while UEUC's max acceleration is 3,6 m/s^2; regarding time percentage in driving phases, values are quite similar: in WLTP constant speed, acceleration, deceleration and stop time are respectively 3,5%, 44%, 40%, 12,5%, while in UEUC they are 1,6%, 41,5%, 42,9% and 14%. Despite the fact that in the experimental cycle there are more standstill and deceleration phases, which results in a more frequent use of regenerative braking and start & stop, even for a Plug-in Hybrid Electric Vehicle there will be a consistent gap between declared WLTP specific CO$_2$ emissions and UEUC emissions; this result is due to the more aggressiveness of the real cycle; UEUC is plotted in Fig. 1.

3. Simulation setup

After UEUC construction, information on car market EU has been taken by "The pocketbook" by ICCT; a model of typical PHEV has been built in a second moment according to market indications and by software programming various simulations have been processed in order to acquire reliable results.

3.1. Model building

PHEV model is based on a medium segment car; it is characterised by a so-called **P2** configuration; this means that the ICE and the electric motor work in parallel with the electric power unit located between clutch and gearbox; it is one of the most common plug-in hybrid configurations and it allows the powertrain to work with different strategies; a simple schematisation is shown in Fig. 2, where:

1. Internal Combustion Engine
2. Disconnection clutch
3. Electric machine
4. Automatic transmission
5. Power electronics
6. High voltage battery
7. Rear differential

Table 4
ICE parameters.

Displacement [cm^3]	1000
Power [kW]	135
ICE inertia coeff. [kg*m^2]	0,14
Idle speed [rpm]	1000
Max speed [rpm]	6250

Table 5
EM parameters.

Power [kW]	110
Max speed [rpm]	13,000
EM inertia coeff. [kg*m^2]	0,015

Table 6
Battery parameters.

Cell nominal voltage [V]	3,6
Number of cells in a unit	6
Cell capacity [Ah]	2,9
Battery nominal voltage [V]	300
Battery mass [kg]	170
Overall number of cells	1680
Inverter efficiency [%]	95
Energy capacity [kWh]	12

In order to build a realistic model it is necessary to set a large number of parameters; in the next tables the main values are specified: Vehicle parameters are shown in Table 3, ICE parameters in Table 4, EM parameters in Table 5, battery parameters in Table 6 and gearbox parameters in Table 7.

3.2. Software

Simulations have been executed through MATLAB® coding, in particular the algorithm (Miretti et al., 2021) is based on dynamic programming, one of global optimization methods; after establishing a given driving cycle, this method allows to realize an objective function (e.g. minimum equivalent fuel consumption) over a specific mission of the vehicle. It is mandatory to arrange control variables, for example power flow distribution (e.g. pure thermal, powersplit, etc.) or gear number, which are chosen by the algorithm to minimize the selected objective function; state variables, for example the state of charge (SOC) of the battery or the state of the engine (on, off) are also essential to define the state of the main components of the architecture.

Time axis is discretised in intervals and each state variable assumes a specific value at the beginning and at the end of each interval; it is important to select the right time discretisation in order to perform accurate computation without requiring excessive computational time. The program makes use of *configuration matrices approach*: a single configuration is defined as the combination of a gear number, a power flow and an engine state. The space of configurations is defined as [3.1] while the number of possible configurations is expressed in [3.2] where N_{GN} is the number of gear ratios of the transmission, N_{PF} is the number of powerflows and N_{ES} is the number of allowable engine states (two).

$$S_{Conf} = S_{GN} x S_{PF} x S_{ES} \qquad [3.1]$$

$$N_{Conf} = N_{GN} x N_{PF} x N_{ES} \qquad [3.2]$$

Table 7
Gearbox parameters.

# Gears	1	2	3	4	5	6	7	8
Gear ratios [-]	4,714	3,143	2,106	1,667	1,285	1,000	0,839	0,667
Gear Efficiency [-]	0,9675	0,9673	0,9685	0,971	0,99	0,98	0,98	0,98
Gearbox inertia coeff. [kg*m^2]			0,15					
Wheel side gearbox inertia coefficient [kg*m^2]			0,03					
Powertrain side gearbox inertia coefficient [kg*m^2]			0,03					
Gearbox mass [kg]			87					

The mission is discretised in N_{int} time intervals, each time interval has a duration of one second. A configuration matrix associated to a specific variable is so a $N_{int}xN_{Conf}$ matrix, which contains the values of the selected specific variable at each time interval for each possible configuration; two configuration matrices are associated to each input variable: one to store the value of the variable at the *beginning* of each time interval and for each configuration, and another one to store the value of the variable at the *end* of each time interval and for each configuration. At this point the optimization tool works in two phases:

- Pre-processing phase, where a zero-dimensional kinematic model of the vehicle is built and its equations are written at the beginning and at the end of each interval through the configuration matrices;
- Optimization phase, after a feasibility check for every component, the deterministic dynamic programming (DDP) is used in order to find the optimal control strategy, exploiting the results of the pre-processing phase.

3.3. Deterministic dynamic programming

DDP is used to find the optimal control strategy, that is the control sequence $\{u_0^*, \cdots, u_{N-1}^*\}$, that minimizes the cost function J over N stages; given an initial state x_o, the cost function can be written as [3.3]:

$$J(x_0, u_0, \cdots, u_{N-1}) = f_N(x_N) + \sum_{k=0}^{N-1} f_k(x_k, u_k), \tag{3.3}$$

where $f_k(x_k, u_k)$ is the stage cost associated to *current* state x_k and selected control u_k at stage k, while $f_N(x_N)$ is the *terminal* cost incurred depending on the terminal state x_N value at stage N.

The optimal control sequence is the one that minimises J, as shown in [3.4]:

$$\{u_0^*, \cdots, u_{N-1}^*\} = \underset{u_k \in U_k(x_k)}{\operatorname{argmin}} J_k(x_0, u_0, \cdots, u_{N-1}) \tag{3.4}$$

$U_k(x_k)$ is the set of admissible control strategies at stage k, the DDP works in two phases.

- *Backward phase*

The problem is divided into a number of tail subproblems equal to the number of stages N. Solving each tail subproblem equates to find the optimal control sequence that minimizes the cost function of the truncated problem defined from stage k to stage N. In equation [3.5] the optimal control at a given stage k is expressed:

$$u_k^*(x_k) = \min_{u_k \in U_k(x_k)} \left(f_k(x_k, u_k) + J_{k+1}^*(g_k(x_k, u_k))\right) \tag{3.5}$$

The state dynamics are represented by a model equation $x_{k+1} = g_k(x_k, u_k)$. The optimal control $u_k^*(x_k)$ is the one that minimizes the sum of the stage cost $f_k(x_k, u_k)$ and $J_{k+1}^*(g_k(x_k, u_k))$, which is the cost associated to the optimal solution of the subproblem defined from stage $k+1$ to stage N. Thus, the optimal control sequence for the whole problem is built iteratively solving all tail subproblems until the first stage of the whole problem is reached. The cost function is initialized and set to 0 if the SOC is larger than the vehicle's initial SOC and the engine is off, otherwise, it is set to infinity.

Then, for each possible combination of state variables at the end of the previous interval and each possible combination of control variable used during the last interval, the tool computes the fuel consumption in the last interval by reading the instantaneous fuel consumption at the beginning and at the end of the last interval from the configuration matrices and performing an integration over that time interval. **The fuel consumption represents the cost function**. Moreover, the tool determines also the engine state at the end of that interval and the value of the SOC at the end of the interval. Then, the tool computes the cost function for each combination of gridded state variables and control variables.

The optimal cost-to-go is expressed in [3.6]:

$$J_k^*(x_k) = \min_{u_k \in U_k} J_k(x_k, u_k) \tag{3.6}$$

where *Uk* is the set of feasible control variables (e.g. the engine and e-machines power limits are not violated) at time interval k.

The values for $J_k^*(x_k)$ can be stored to build the optimal control sequence in the forward phase. The optimal control $u_k^*(x_k)$ can be selected for each interval in the forward phase as the one that minimises $J_k(x_k, u_k)$.

Since x_k may be a continuous variable, $J_k(x_k, u_k)$ must be available for any value of x_k, and not only for the gridded values for which it has been explicitly computed. For this reason, an approximating function for $J_k(x_k, u_k)$ must be constructed based on the values available for the gridded state variables. In this application, this approximating function, $\widetilde{J}_k(x_k, u_k)$ is built with a piecewise linear interpolation function. The tool moves on to analyse the previous interval and it repeats the same procedure again, until it reaches the first interval.

The result of the backward phase is a set of approximating functions $\widetilde{J}_k(x_k, u_k)$, one for each time interval, which allow the evaluation of the cost function for any value of the state variables. In other words, the optimal control policy, that is a sequence of functions ([3.7]) that for each interval give the optimal set of control variables u_k^* at the given state x_k, has been obtained.

$u_k^*(x_k), k = 1, \cdots, N$ [3.7], where N is the number of intervals.

- *Forward phase*

The tool reads the results of the pre-processing phase from the configuration matrices in order to get the fuel consumption, on that interval for all control variables and computes the possible values of the state variables at the end of the interval through the battery model, then the optimal control value for the *current* step is evaluated as eq. 3.8.

$$u_k^*(x_k) = \underset{u_k \in U_k}{\operatorname{argmin}} \widetilde{J}_{k+1}(g_k(x_k, u_k)) + f_k(u_k) \tag{3.8}$$

It has to be noted that, since J_{k+1}^* is not available for any possible value of the state variables $x_{k+1} = g_k(x_k, u_k)$, the approximating functions, built in the backward phase, $\widetilde{J}_k(x_k, u_k)$ are used.

Finally, the simulation is advanced to the next step, updating the values for the state variables, and the procedure is repeated until the simulation reaches the last time interval. In Fig. 4 the flow chart of the optimization tool is shown.

Table 8
Highway cycle parameters.

Total distance [km]	107,61
Total duration [s]	4804
Maximum speed [km/h]	138
Average speed [km/h]	80,62
Maximum acceleration [m/s^2]	2.34
Maximum deceleration [m/s^2]	−3.71
Constant speed time (s)	87 (1,8%)
Acceleration time (s)	2390 (49,8%)
Deceleration time (s)	2110 (43,9%)
Stop time (s)	217 (4,5%)

3.4. *Output data*

The software requires all the vehicle parameters shown before and driving mission as input data; simulations in urban/extra urban context have been executed running UEUC cycle. Furthermore, in order to obtain results in every road context, a highway cycle has been selected from the sixteen cycles list; its parameters are shown in Table 8, while cycle plot is in Fig. 3. At the end of simulations, the program provided the following set of output data that have been reputed crucial for the final results:

- FC (fuel consumption) in kg at the end of the mission, then converted in l/100 km;
- CO_2 specific emissions tank-to-wheel (TTW) in gCO_2/km (variable name in the code: **CO2TTW**), fundamental for regulation targets;
- Global Energetic consumption in Wh/km (**ECTTW**), to evaluate the amount of energy spent without a distinction between gasoline and electricity;
- Final SOC, to evaluate the rate of discharge after a single cycle.

In addition, the program provides some useful graphics:

- The Driving Cycle with a detail on powertrain strategy;
- Instantaneous SOC;
- ICE map with a detail on different powertrain strategy;
- EM map with a detail on different powertrain strategy;
- Histogram of spent and recovered energy for all of the powertrain modes;
- Histogram of time share percentage for all of the powertrain modes.

Twelve powerflow strategies are considered: PT (pure thermal), that is the exclusive activation of the conventional engine to move the vehicle, which happens for a PHEV in case of low state of charge or high loads (for example highway trips); PE (pure electric), that is the use of electric motor to move the vehicle (for example in urban contexts with low speed and frequent stops); five levels of PS (powersplit), that is the activation of both engines to move the vehicle; finally-five levels of BC (battery charging), that is the activation of thermal engine to charge the battery; levels of PS and BC modes are differentiated by the α parameter (eq. 3.9), which represents the ratio between power that derives from electric motor and total power provided to move the vehicle; α values are 0,1; 0,25; 0,5; 0,75 and 0,9 and become negative if the strategy is BC.

$$\alpha = \frac{EMpower}{totalpower} \quad [3.9]$$

(in the powerflow figures, the parameter "ϕ" indicates PS strategies for an architecture *P*4; in this paper is set to zero because the model is a *P*2 vehicle, but the code can be used for different architectures).

3.5. *Scenarios*

As mentioned before, one of the main problems of PHEVs is the effect of real habits and usage on effective emissions. In this research the theme of misuse has been evaluated, running UEUC and calculating specific emissions with four different initial SOCs; the algorithm is shown in Fig. 5: firstly a state of charge of 95% has been set, and the first mission was completed. After first step, initial SOC of the second mission has been replaced with the final SOC of the first; this operation has been iterated until battery's state of charge reached the value of 10%; it required three cycles. The last mission has been initialised with SOC kept constant at 10%, in order to quantify emissions in the case of a completely discharged PHEV, representing the worst misuse. Regarding highway cycle, only two scenarios have been evaluated; the first one

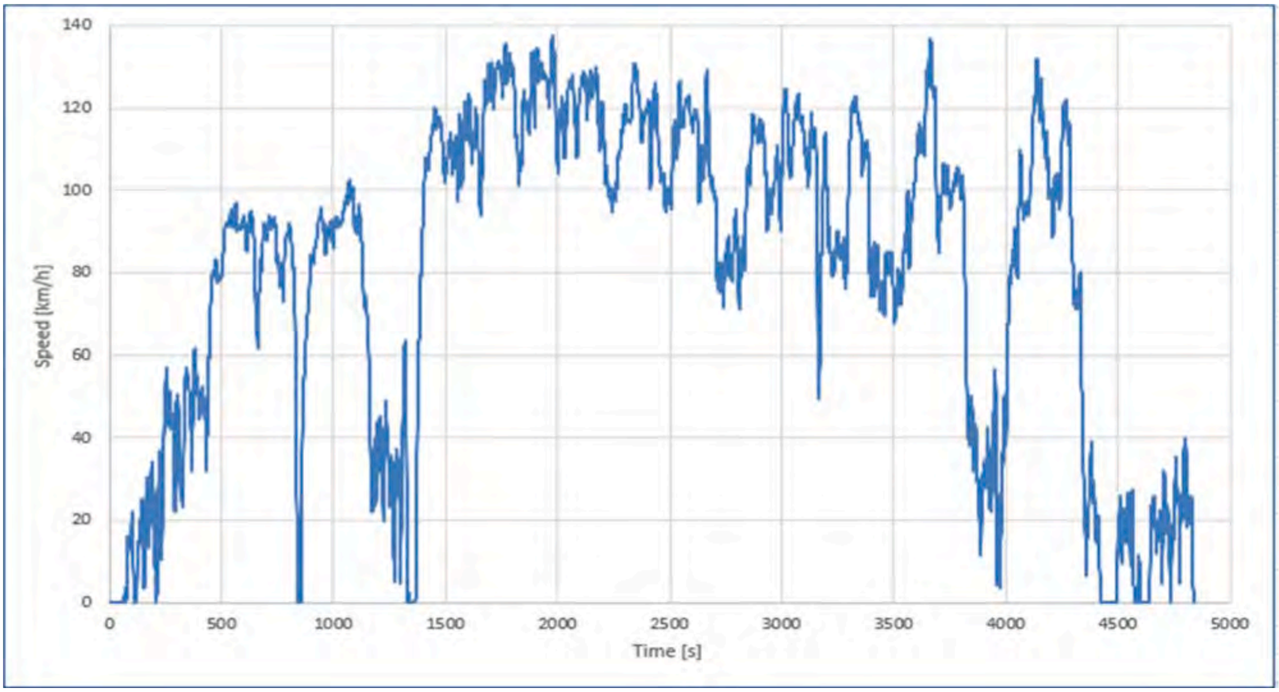

Fig. 3. Highway cycle.

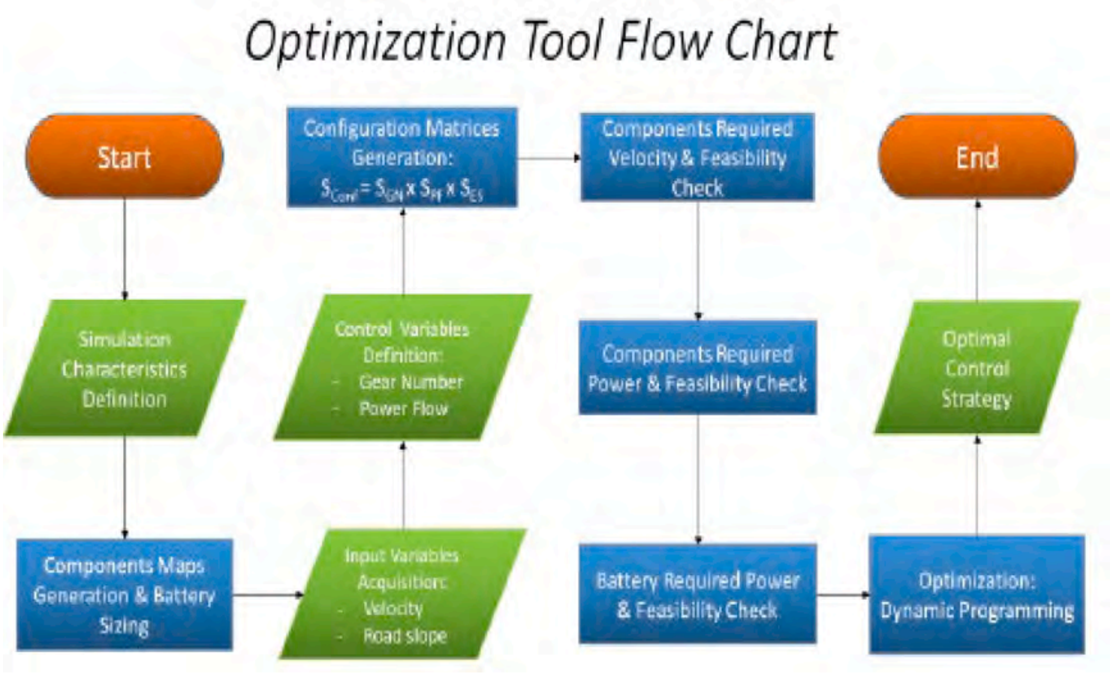

Fig. 4. Optimization tool flow chart.

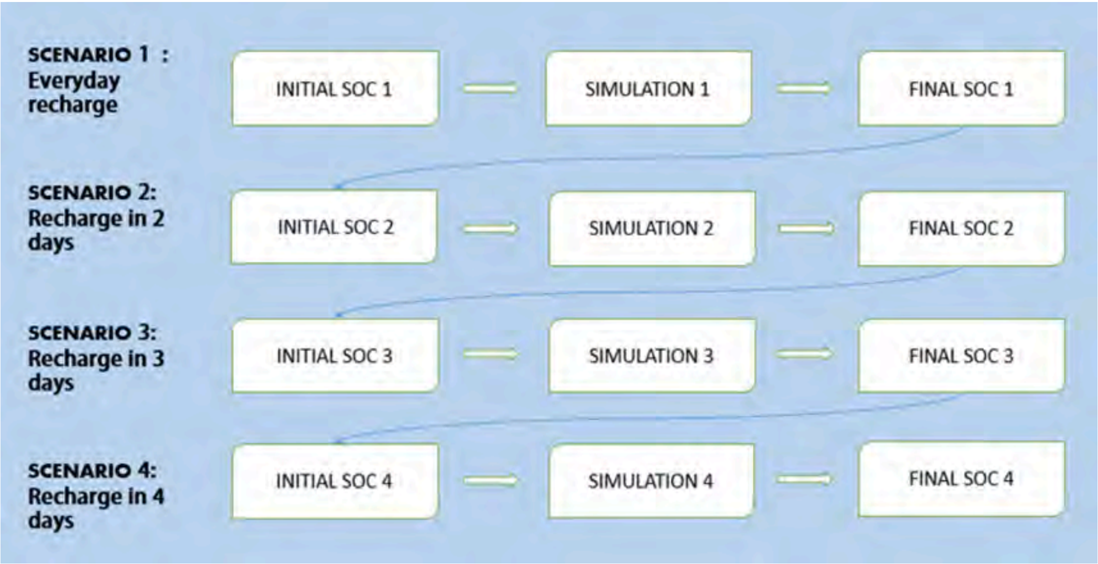

Fig. 5. Scenarios of UEUC simulations.

with completely charged battery, while the second with completely discharged battery. Finally an annual based evaluation has been taken with the aim of quantify benefits in terms of global emissions and fuel cost savings, comparing PHEV and the conventional version of the same vehicle.

4. Results

In this section, the final findings are shown and commented; firstly UEUC is taken into exam, comparing results of different scenarios; secondly, Highway cycle is analysed; finally, initial hypotheses and results of the annual based evaluation are shown.

4.1. UEUC: Scenario 1

In current scenario, which represents a daily total recharge scenario, initial SOC is set to 95%. (Fig. 6); the most used powerflow strategy is PE: battery capacity allows running all the cycle exploiting electric motor; PS strategy is activated only in steep acceleration phases. At the end of the cycle, final SOC is 61% (this will be initial SOC of scenario 2), this a first important information: in a single daily driving cycle, which includes urban and extra urban contexts but a short total distance, battery's SOC decreases gradually.

In Fig. 7 time percentage in every powerflow strategy is shown: ICE is never switched on, except for few low loads points in PS phases ($\alpha =$ 0,9); PE is the most used strategy with 80% of time share. In Fig. 8 the amount of energy spent in traction and recovered in braking phases (EM works also as a generator) can be observed. For completing the cycle,

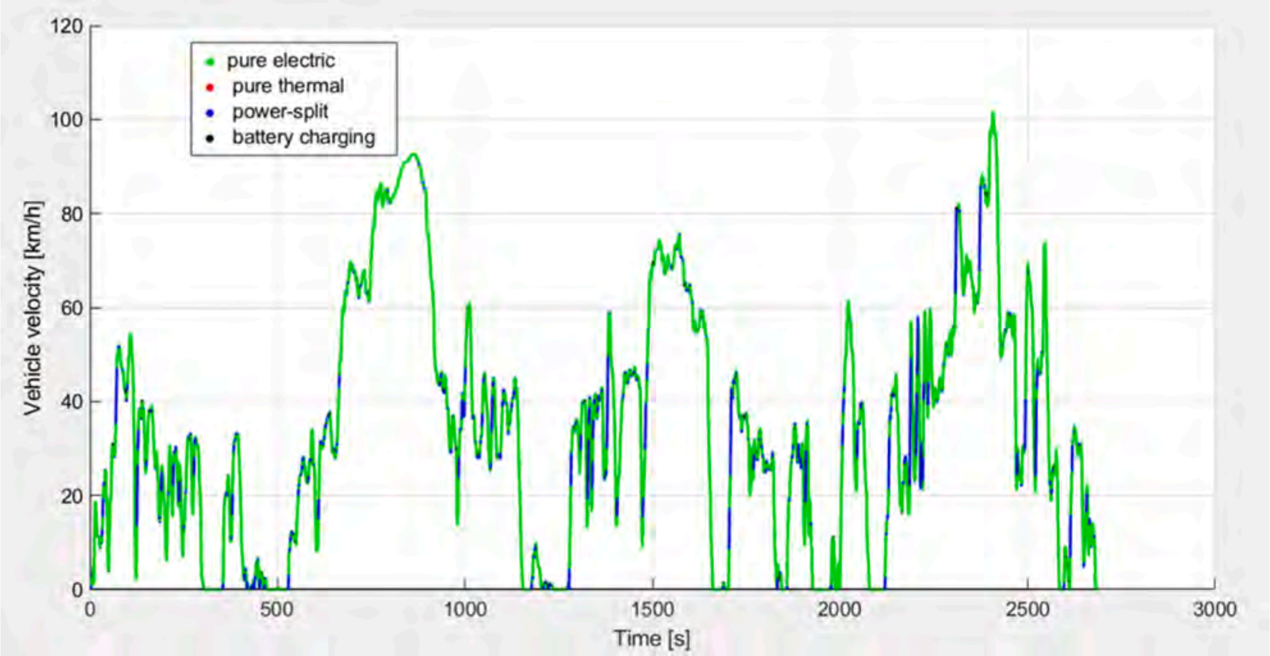

Fig. 6. Scenario 1: UEUC – strategies.

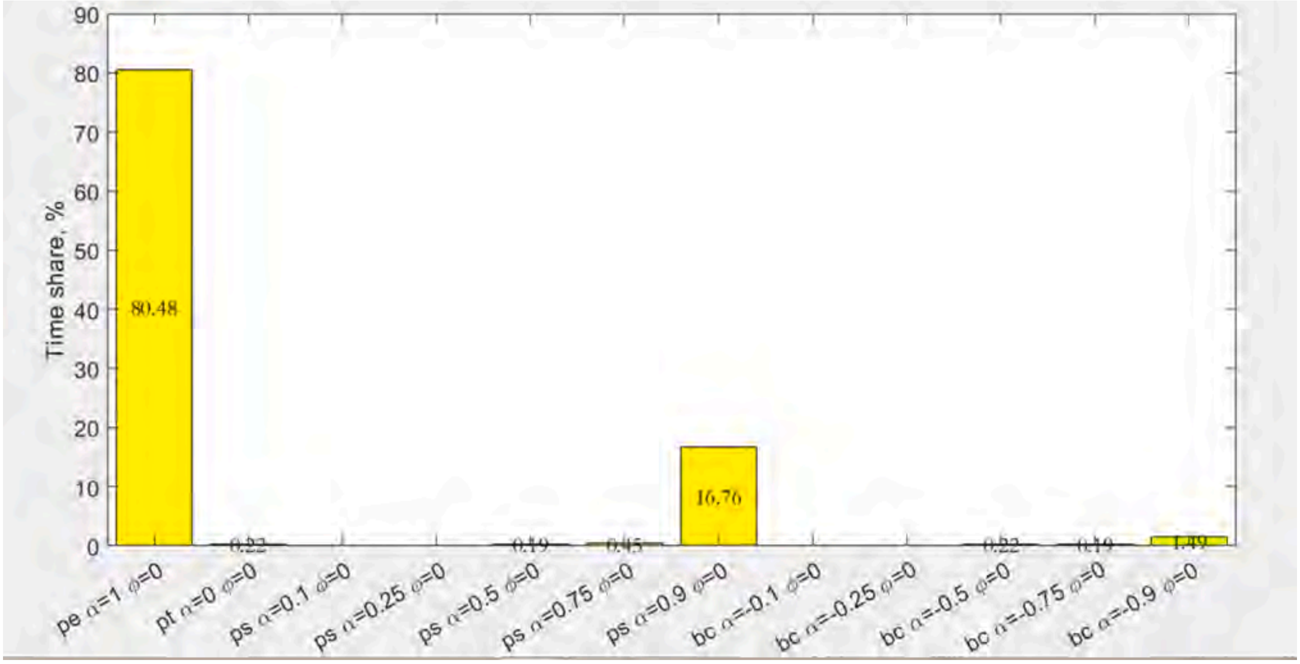

Fig. 7. Scenario 1: UEUC time share for every strategy.

2,56 kWh have been spent in PE and 0,82 kWh in PS, α = 0,9. 1,72 kWh of energy have been recovered in braking phases, the value is the same in every UEUC scenario because it depends only on deceleration rate. Numerical output results of scenario 1 are:

- CO2TTW = 44,1 g/km
- FC = 1,9 l/100 km
- ECTTW = 339,8 Wh/km

Emission level, even in real driving conditions, is under 50gCO_2/km, the ZLEV threshold; but the declared WLTP emissions for the same vehicle are 35,3gCO_2/km; according to paragraph 1.2, there is a gap between type-approval procedure and real emissions (in this specific case WLTP declared emissions are 25% lower).

4.2. UEUC: Scenario 2

In current scenario, which represents a recharge every-two days, initial SOC is set to 61%. The powerflow strategies are quite similar to scenario 1; PE is still the preferential mode (Fig. 9), PS is used in the same phases but in this case α = 0,75 mode provides a small amount of energy (Fig. 10); final SOC is 25%; this means that battery's autonomy is sufficient to work for two days exclusively in electric drive but not three. ICE and EM work almost like scenario 1, numerical output results after

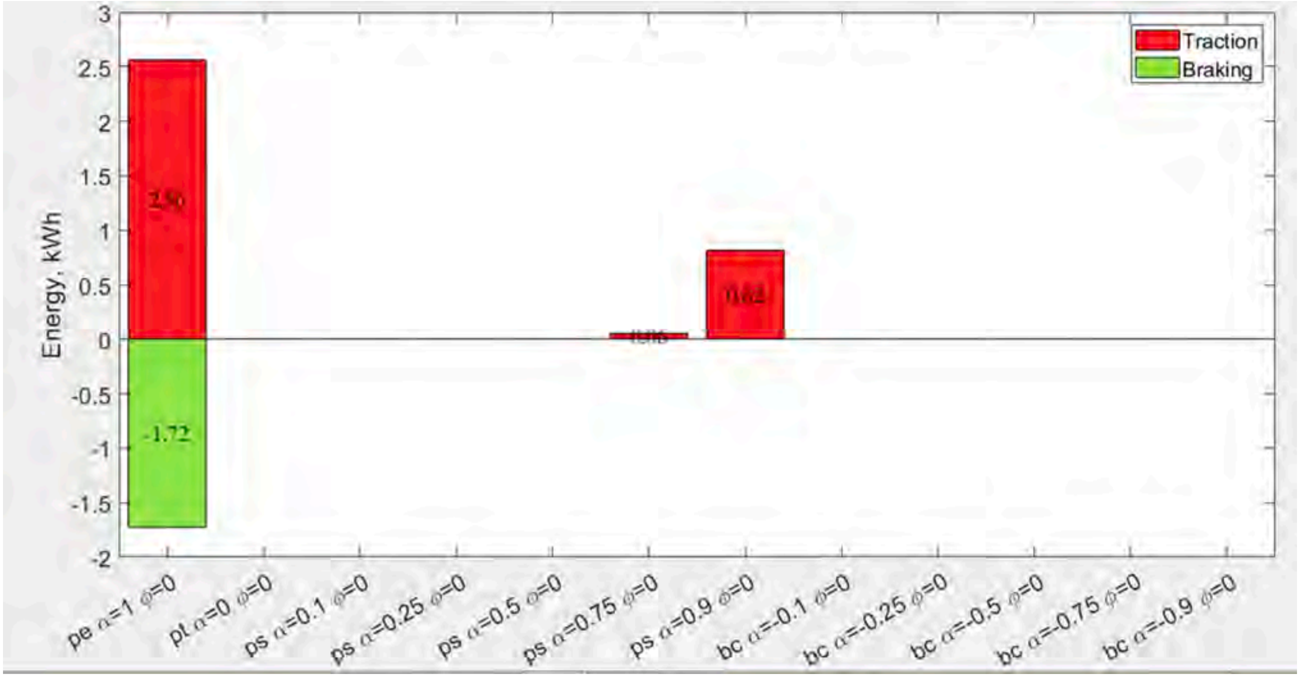

Fig. 8. Scenario 1: UEUC energy amount for every strategy.

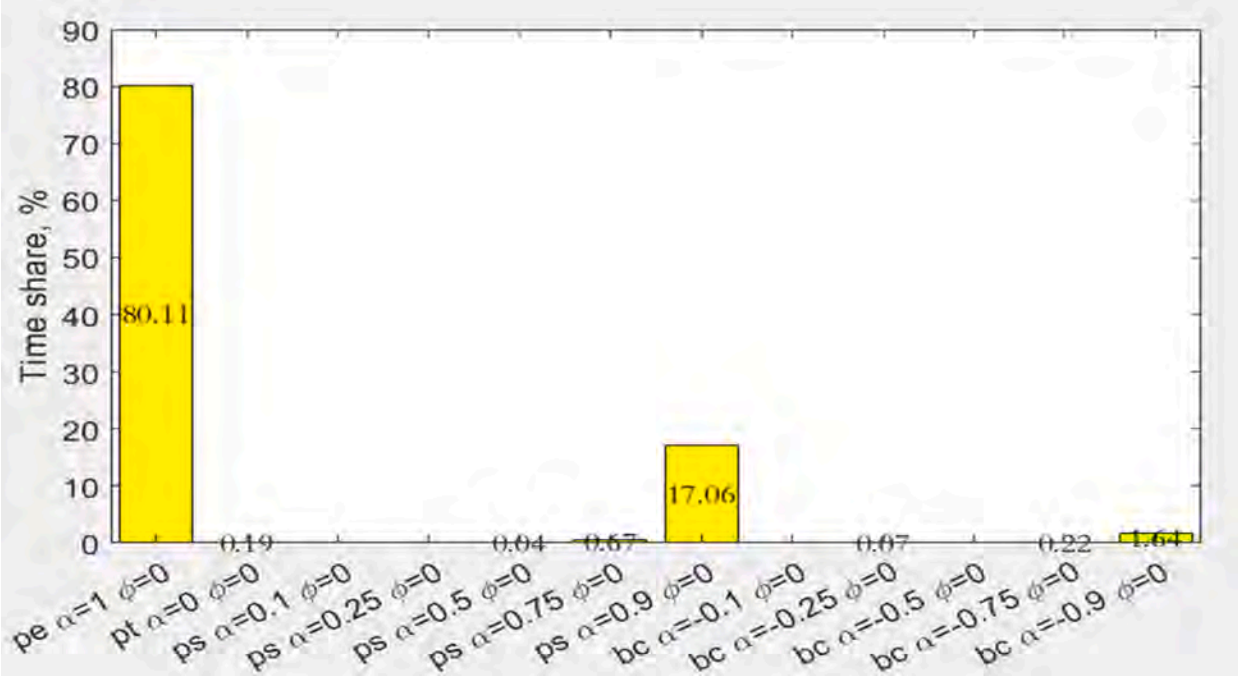

Fig. 9. Scenario 2: UEUC time share for every strategy.

the simulation are:

- CO2TTW = 47,9 g/km
- FC = 2,1 l/100 km
- ECTTW = 357,3 Wh/km

Emission level is circa 8 % higher than first scenario due to a slight increase in ICE usage.

4.3. UEUC: Scenario 3

In current scenario, which represents a recharge every-three days, initial SOC is set to 25%. Strategy in this case is different from previous scenarios: battery discharges before the end of cycle and ICE is switched on in steep acceleration phases in order to keep SOC constant at 10 % (Fig. 11). Observing Fig. 12, PT is frequently activated, as well as BC in last seconds of the mission. ICE map at Fig. 13 is useful to understand the potentiality of PHEV technology: ICE in this case works, both in PT and PS, at operating points close to the optimal operating line (OOL); even if it is switched on more frequently than first two scenarios, in this case it

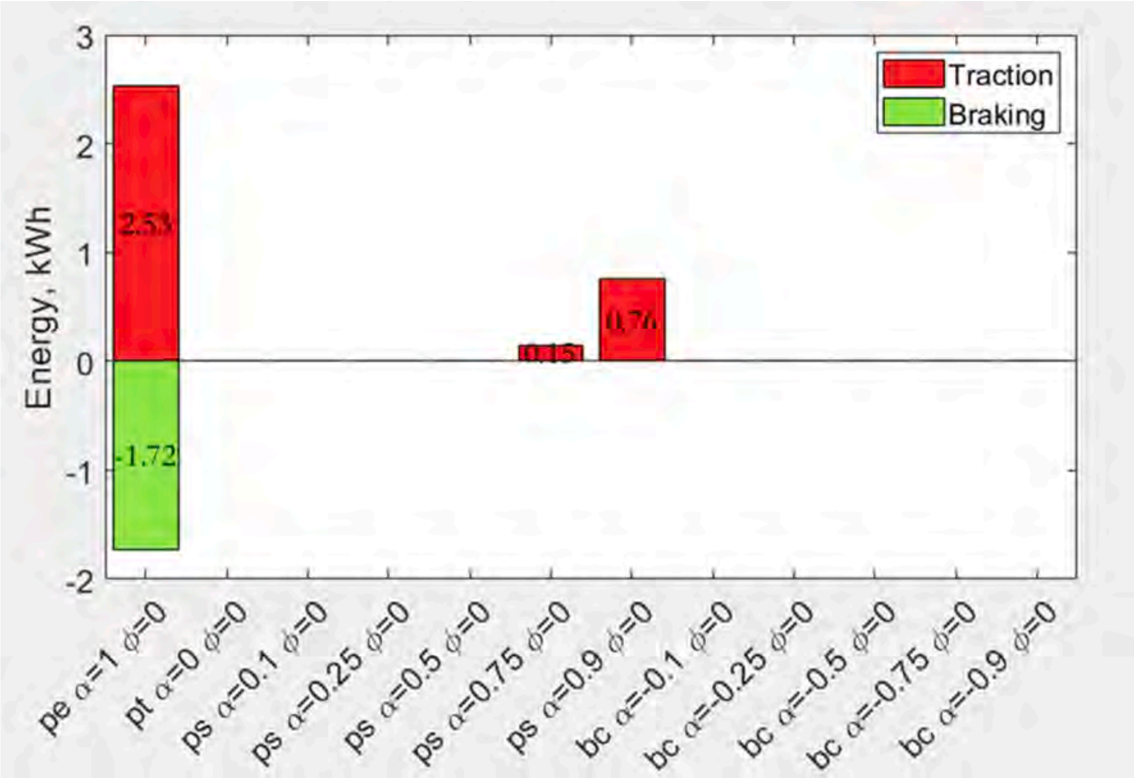

Fig. 10. Scenario 2: UEUC energy amount for every strategy.

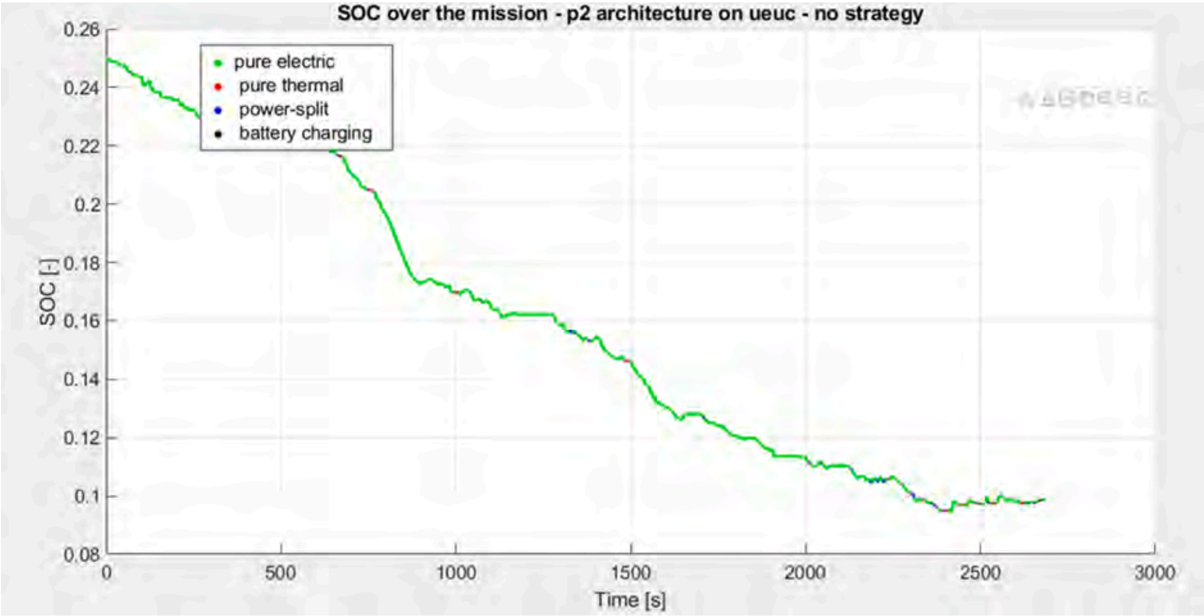

Fig. 11. Scenario 3: instantaneous SOC.

works with higher efficiency with a resulting reduction of fuel consumption and specific emissions. EM is more stressed because of low battery, and works almost exclusively in PE and in some phases in BC; in fact, as shown in Fig. 14, PE time share raises at 90% because in other strategies EM is not substantially used. About this last point, PS is characterised by higher use of thermal engine (α = 0,1 and α = 0,25). The energy spent for traction in PE diminishes under 2 kWh, the remaining energy amount is provided in PT and PS (Fig. 15). Regarding output numerical results of the simulation:

- CO2TTW = 42,8 g/km
- FC = 1,8 l/100 km
- ECTTW = 244,8 Wh/km

Specific emissions are 3% lower than the first scenario and 10% lower than the second scenario, but still 21% higher than WLTP emissions. The principal motivation is that if ICE works at low efficiency points, even for a short amount of time during a driving cycle (as in scenarios 1 and 2), there is an relevant negative effect on environmental

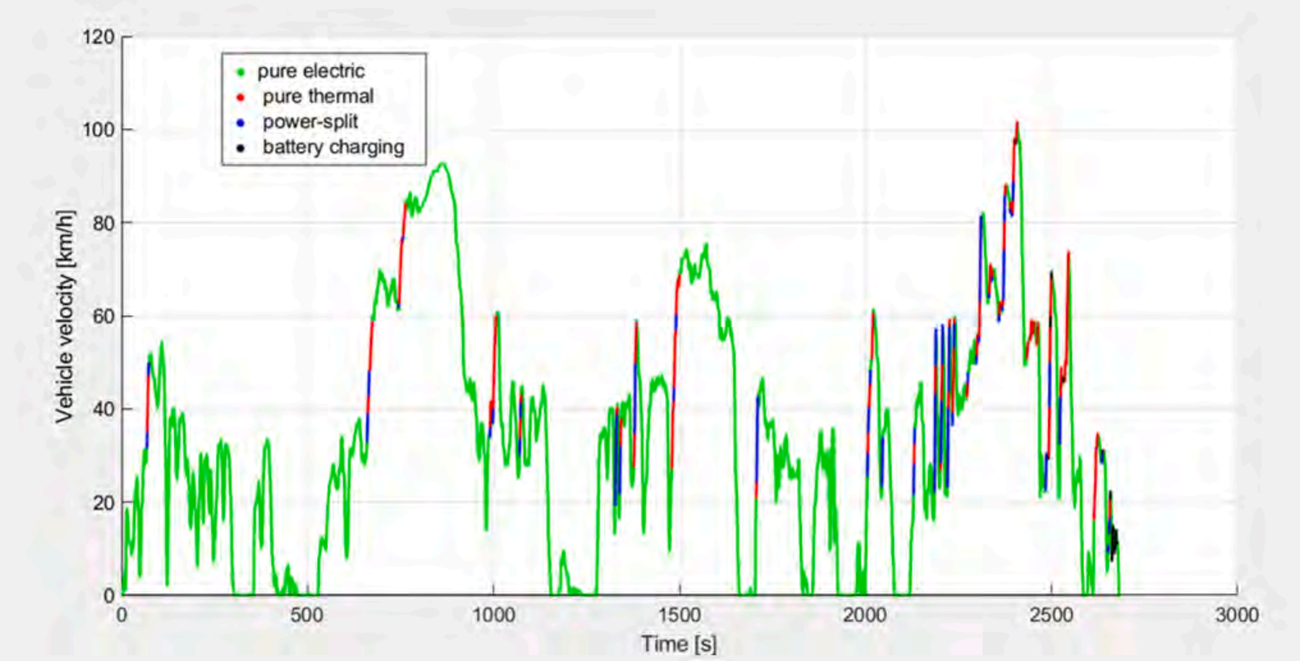

Fig. 12. Scenario 3: UEUC – strategies.

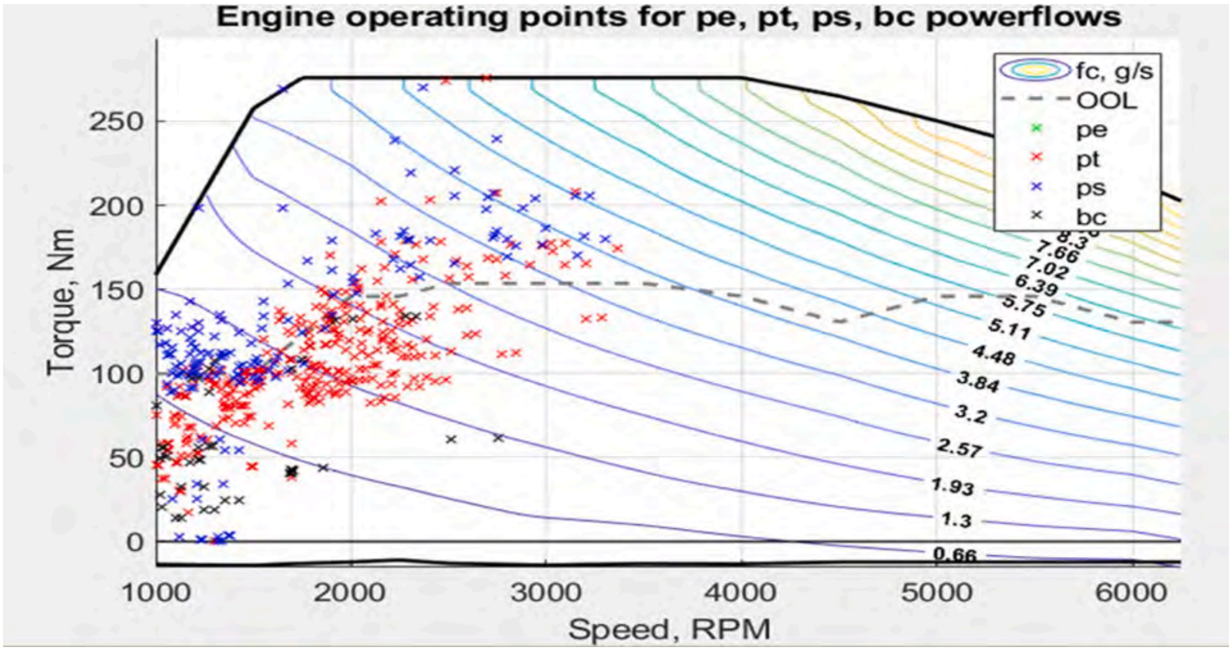

Fig. 13. Scenario 3: ICE map.

impact. EC is lower because this scenario is characterised by the least value of fuel consumption.

4.4. UEUC: Scenario 4

This last scenario represents the worst misuse, a driver that uses a PHEV as a conventional vehicle, emissions level and fuel consumption are considerably higher than previous scenarios because EM works most of the time as a generator while ICE is switched on for most of the mission (Fig. 16). In this case battery is completely discharged at the beginning of the cycle.

Despite the fact that BC mode is activated more frequently, almost for all the mission, SOC level drops under the lower limit (Fig. 17). The difficulty for the battery control system to keep SOC constant at minimum value is the reason why lower limit is set to 10%; if it were set to 0%, the battery would suffer irreversible damage due to complete discharge. ICE map in Fig. 18 shows a certain density of BC points, and a remarkable occurrence of operating points - especially when PT strategy is activated - distant from OOL (high loads area); the higher FC of all of the examined scenarios is a consequence of this last observation. Fig. 19 is useful to observe which strategies are adopted to move the vehicle, PE strategy provides half of the energy spent in traction in first two scenarios (only 0,73 kWh vs more than 2 kWh in the case of completely charged battery); PT is the powerflow strategy which provides the

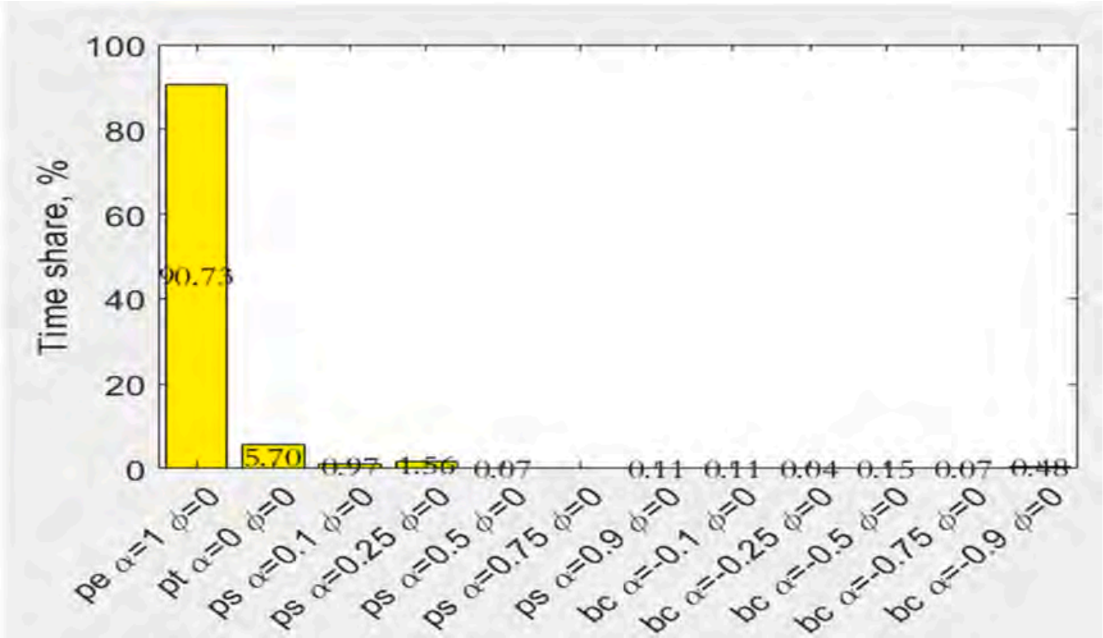

Fig. 14. Scenario 3: UEUC time share for every strategy.

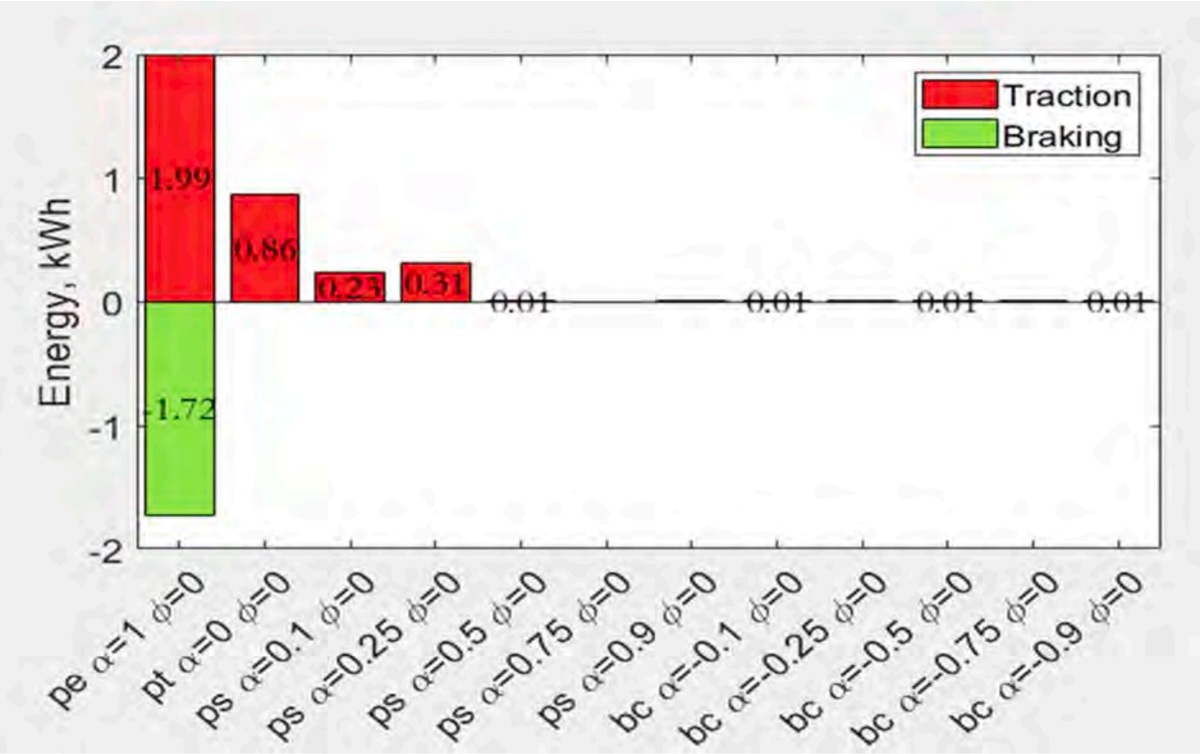

Fig. 15. Scenario 3: UEUC energy amount for every strategy.

higher amount of energy (2,1 kWh); BC in other scenarios was not relevant, in this case there are 0,41 kWh spent in traction to recharge the battery. The conclusion is that low battery SOC implies more activation of BC at the expense of PS.

The output numerical results of the simulation:

- CO2TTW = 89,6 g/km
- FC = 3,9 l/100 km
- ECTTW = 368,1 Wh/km

Emission level is more than doubled compared to scenario 3, but still under 2021 target of 95 gCO_2/km. This means that, even if the driver must be responsible and has to recharge the battery, PHEVs are not as pollutant as conventional vehicles even with low battery conditions because of the possibility to activate BC and braking recovery.

4.5. Highway cycle

After an accurate analysis of UEUC, another important question is

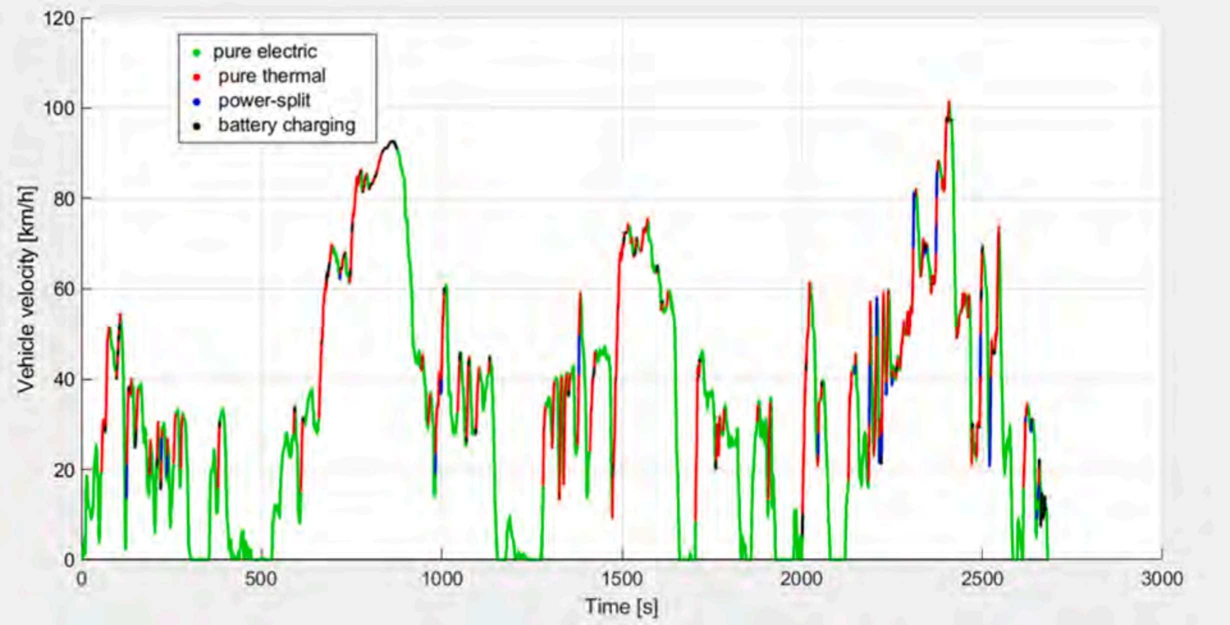

Fig. 16. Scenario 4: UEUC – strategies.

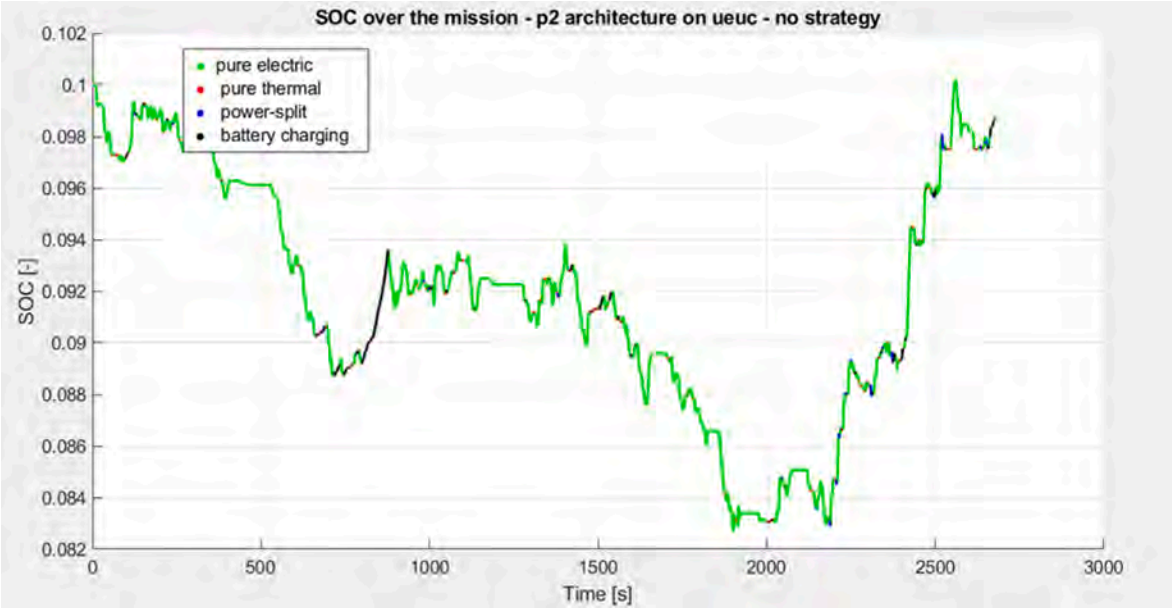

Fig. 17. Scenario 4: instantaneous SOC.

the behaviour of PHEVs in a realistic highway cycle. About this context, only the graphics that refer to an initial SOC value of 95% are reported, because it is reasonable to think that long distance trips are well programmed by drivers so recharge should not be forgotten in most part of the cases. At the end of the analysis, values in case of low initial SOC are reported just for completeness. The cycle examined is 108 km long, so the autonomy of the battery does not allow the vehicle to travel in electric drive for all the mission; the difference with UEUC is that in this case the synergy of all strategies is mandatory to optimise fuel consumption. In Fig. 20 instantaneous SOC can be observed; battery falls to 10% nearly at the end because control strategy predicts to discharge it the more gradually possible; in steep acceleration phases PS or PT modes are activated; PE is preferred by control system in low speed phases and BC is used only in the final part, Fig. 21 shows the trend. In Fig. 22 ICE and EM maps are plotted. Regarding the thermal engine, is clearly visible an extended area of high efficiency points, close to OOL; EM works as a generator in BC and supplies power at high efficiency in case of PE or PS. Fig. 23 gives important information on time share: PE is adopted 83% of the time, PT and PS are preferred in remaining time, BC is practically not relevant. As can be seen in Fig. 24, even if initially the battery is fully charged, PS selected modes are α = 0,1 and α = 0,25; there is an evident difference with UEUC cycle: in case of long distances the control system selects powersplit strategies which involve mostly the thermal engine.

Numerical output results in the case of completely charged battery are:

- CO2TTW = 45,4 g/km
- FC = 2 l/100 km
- ECTTW = 278,2 Wh/km

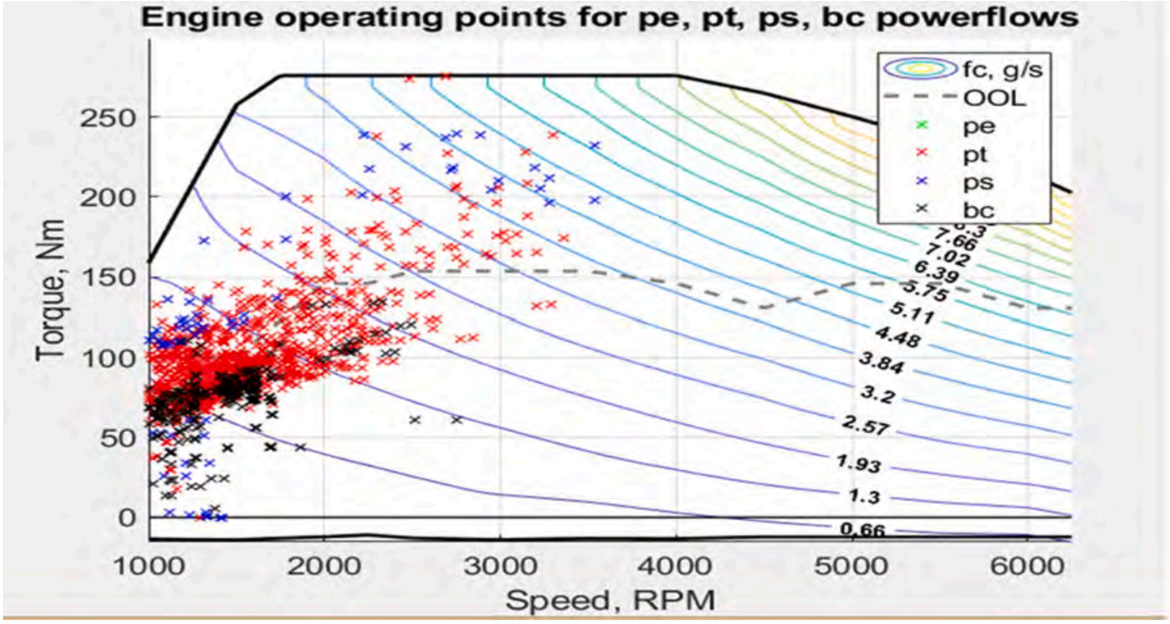

Fig. 18. Scenario 4: ICE map.

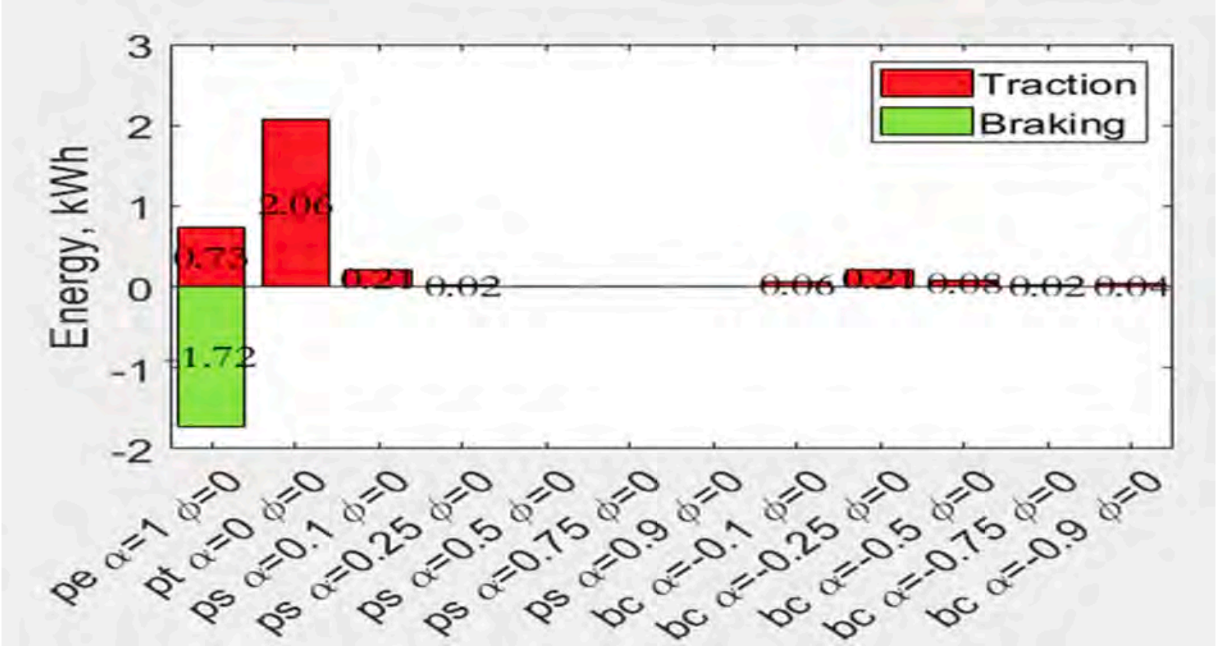

Fig. 19. Scenario 4: UEUC energy amount for every strategy.

Instead, if initial SOC is set to 10 %, output results are:

- CO2TTW = 107,7 g/km
- FC = 4,7 l/100 km
- ECTTW = 443,1 Wh/km

Considering a charged battery, the emission level is satisfactory and in line with those calculated simulating UEUC; this consideration confirms PHEVs as a versatile technological solution. It must be also emphasised the strong negative effects which are caused by negligence.

4.6. Recap of results

Simulations provided a high number of useful information about PHEVs real behaviour; a recap of numerical output for all the simulated contexts is reported in Table 9, while in Table 10 and Table 11 time share and energy amount are respectively shown. In Fig. 25 the set of simulated specific CO_2 emissions is shown: until three days without recharging, in urban and extra urban contexts (week days), the modelled PHEV showed interesting performances; if the vehicle starts the mission with completely charged battery, even in highway contexts, specific emissions are notably low as well.

This important result clearly represents the remarkable potential of this technological solution; it should be though emphasised that initial assumptions exclude some variables, in order to make the simulation less complex, that can have a negative impact on performances, such as the use of auxiliaries in cold weather, or battery degradation during years; however, as showed in paragraph 1.2, this phenomena affect in a

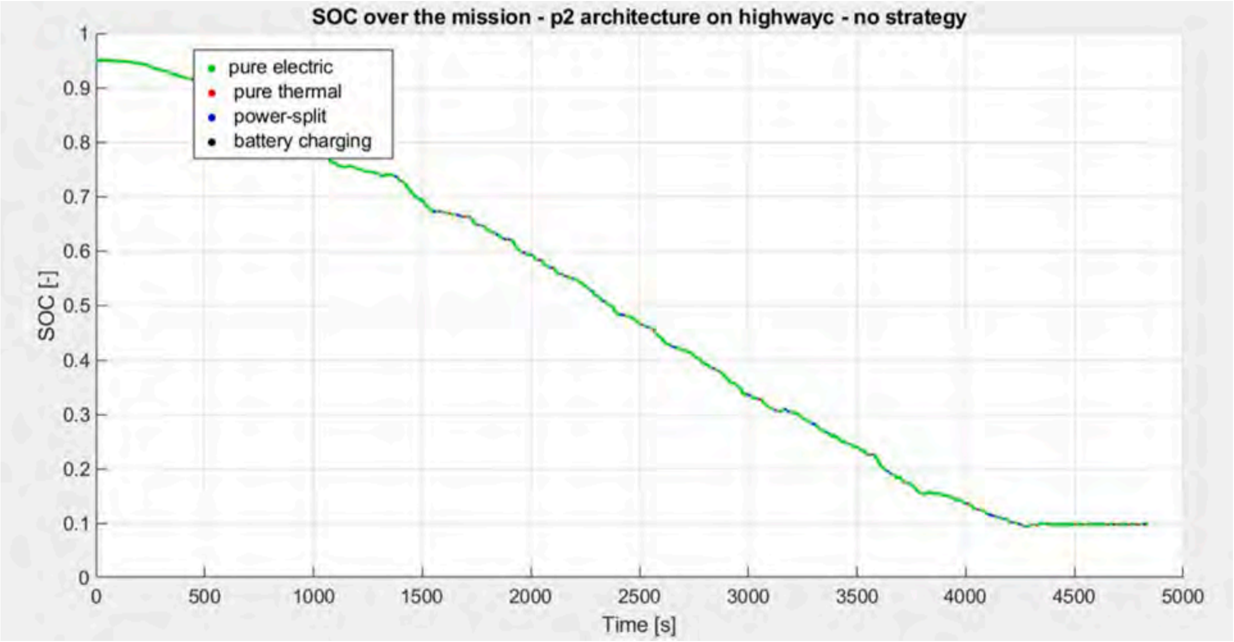

Fig. 20. Highway cycle: instantaneous SOC.

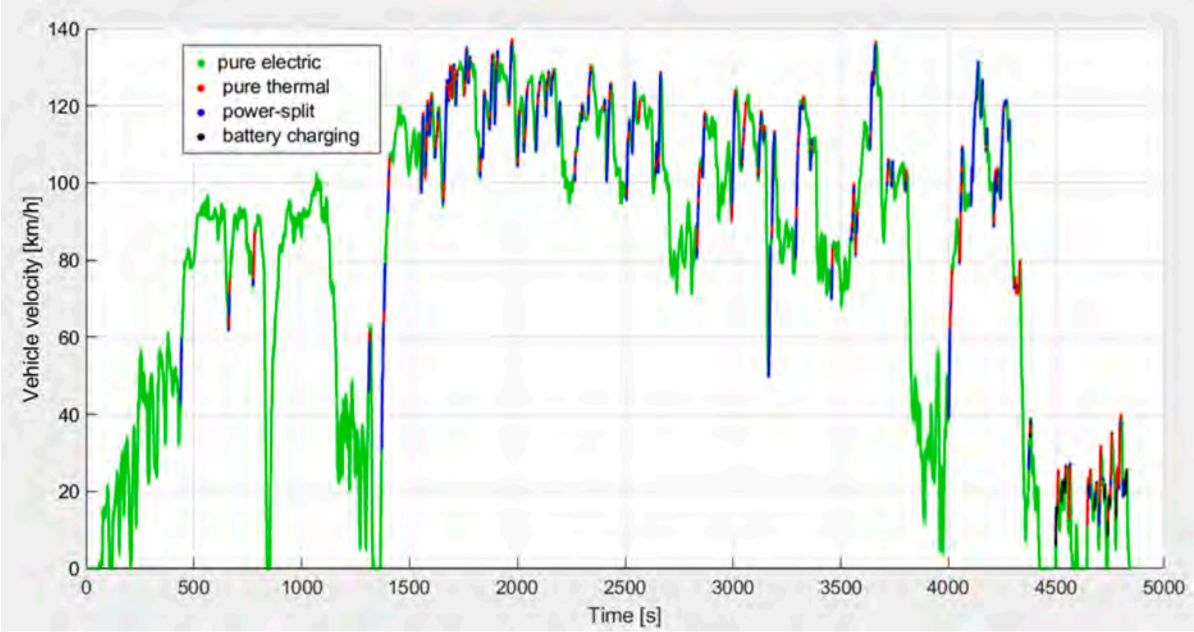

Fig. 21. Highway cycle – strategies.

more relevant way the BEVs.

5. Annual evaluation

Important results obtained in previous paragraphs have made it possible to evaluate, in terms of FC and CO_2 emissions as well as fuel cost saving, annual benefits of switching a conventional vehicle to the corresponding PHEV; following assumptions must be declared:

- A weekly routine, based on 5 days UEUC + 2 days Highway cycle, has been considered;
- Initial SOC before highway cycle is always set equal to95 %;
- In first 5 days, only scenarios 1,2,3 are considered;
- Selected recharge type is the standarrd domestic, called inappropriately slow (3,3 kW);
- Assumed conventional vehicle's average fuel consumption is 6,5 l/100 km;
- Fuel consumption and CO_2 emissions of PHEV, when the mission is UEUC, are calculated as the average between values of scenarios 1,2 and 3;
- Fuel consumption and CO_2 emissions of PHEV, when the mission is the highway cycle, are the values calculated in 95% initial SOC case;
- Fuel cost is assumed 2€/l (Fuel cost in Italy in February-July 2022);

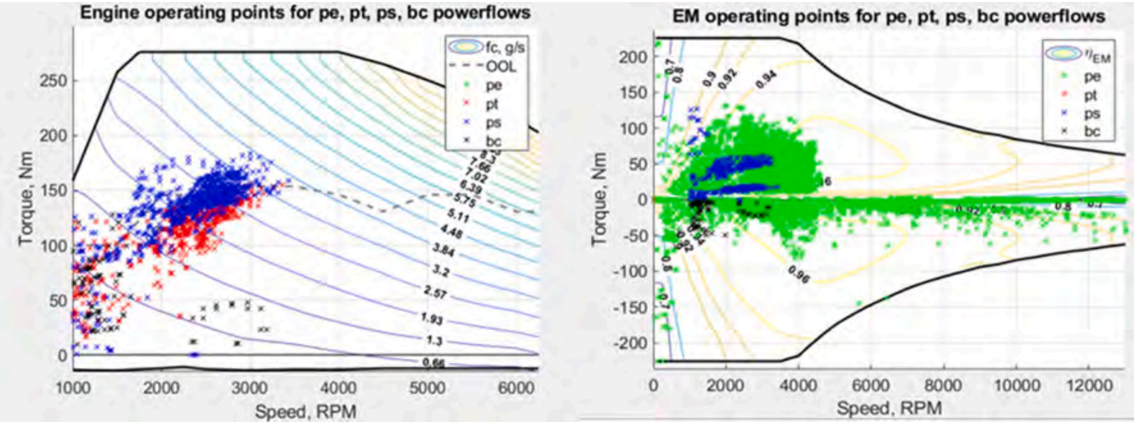

Fig. 22. Highway cycle: ICE and EM maps.

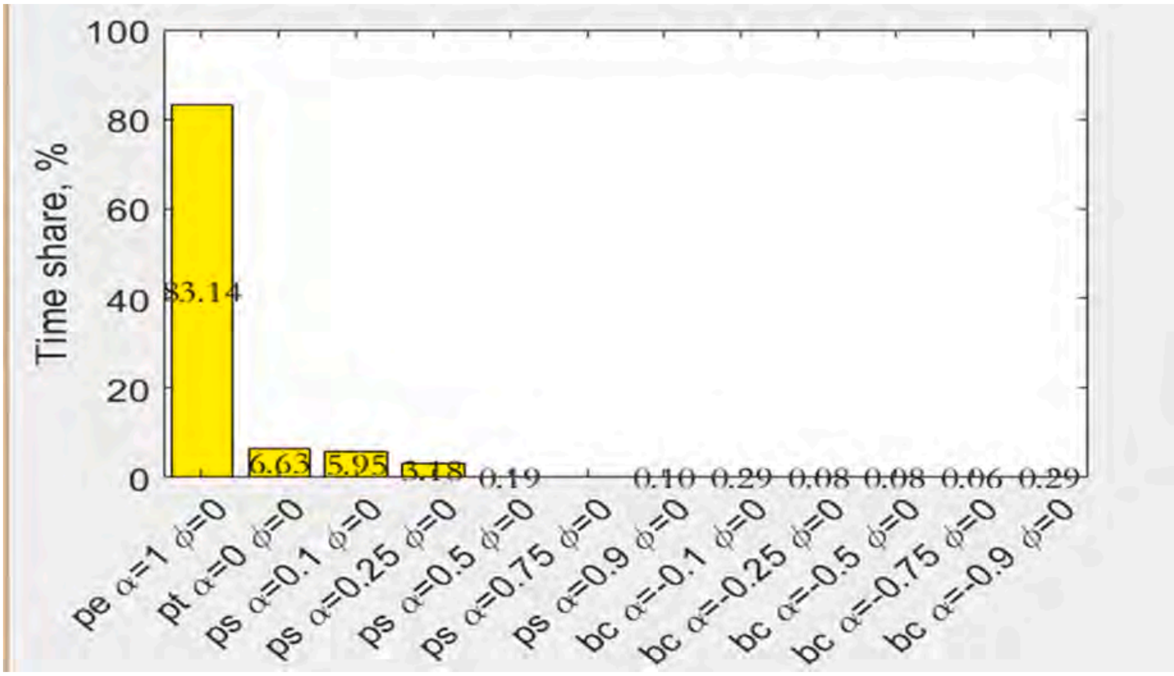

Fig. 23. Highway cycle: time share for every strategy.

- Recharge cost is assumed 0,3 €/kWh (Average electricity cost in Italy in February-July 2022)

5.1. *Fuel consumption and tank-to-wheel CO_2 annual reduction*

According to previous assumptions, for the modelled PHEV, considering 52 weeks with the same routine, annual distance covered is 17899 km with 350,9 *l* of fuel consumed and 0,809 tons of total tank-to-wheel CO_2 emissions.

The same vehicle with conventional powertrain consumes 1163,5 *l* for the same distance, by equation 5.1 a total of 2,84 tons of TTW CO_2 emissions has been calculated, where ρ_f is fuel density and V is fuel consumption in l/100 km:

$$m_{CO_2}[ton] = \frac{\rho_f[kg/dm3]}{31,5} * V\left[\frac{l}{100km}\right] * kmtot \qquad [5.1]$$

As shown in Fig. 26, if long distances are travelled during year, PHEV's emissions are remarkably lower (- 71%) due to less fuel consumption.

5.2. *Fuel cost saving*

According to assumed fuel prize, for travelling 17998 km the conventional vehicle consumes 1163,5 *l* of fuel with a resulting cost of 2327€. Estimating the cost of a PHEV requires more calculations; first of all 350,9 *l* of annual consumed fuel corresponds to 701,80 €, in addition the cost of electric energy has to be calculated and added. From data on Table 11, total annual energy has been derived, taking into account the amount of energy recovered during braking phases: for the first 5 days of the routine the average of scenarios 1,2 and 3 has been considered, for weekend days only the 95% initial SOC case has been considered, the energy provided in PS has been weighted through α parameter. Net electric energy spent in a year to travel 17998 km with the simulated strategies is 964,3 kWh with a consequent cost of 289,30 €. Considering both sources of energy, annual fuel cost for PHEV is 991,10 €, so annual savings of 1335,90 € are expected if the vehicle is used constantly during year, even for long distances.

Considering fuel and recharging cost in Italy in 2020 (respectively 1,54 €/l and 0,25 €/kWh) annual savings would have been of 1010 €; the more the cost of fuel increases, the more convenient PHEVs result.

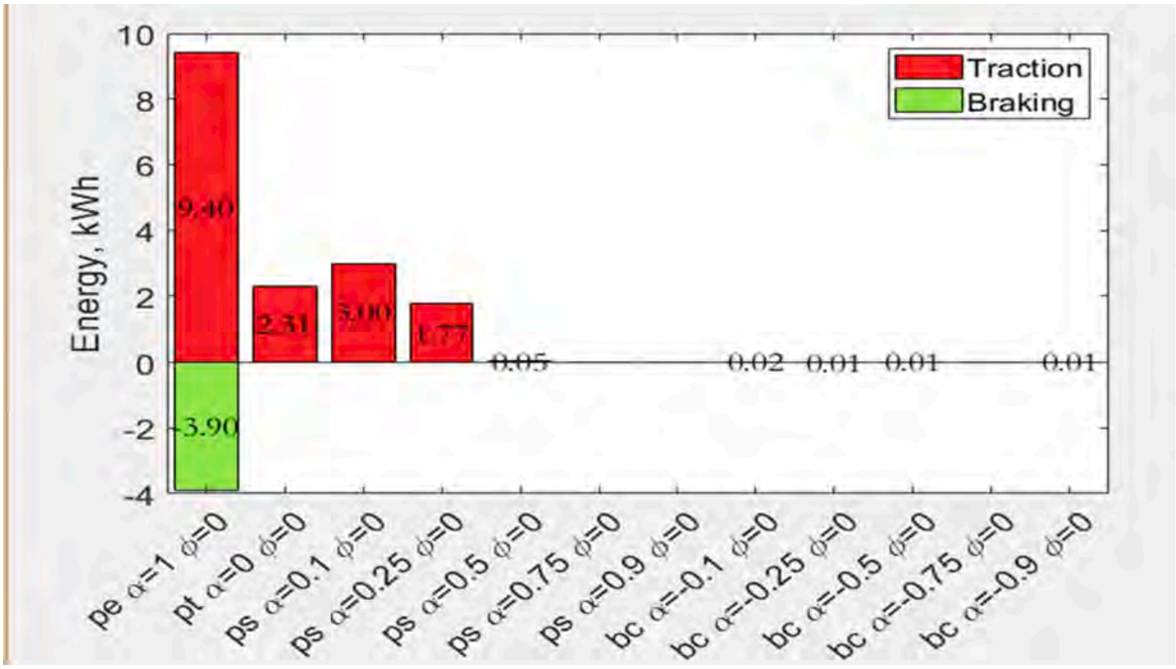

Fig. 24. Highway cycle: energy amount for every strategy.

Table 9
Overall results.

	kmtot	FC [kg]	l/ 100 km	CO2TTW [g/km]	Final SOC	ECTTW [Wh/km]
WLTC (CD + CS)	116,3	1,37	1,5	35,3	0,10	229,3
UEUC	25,8					
Initial SOC [%]						
95		0,38	1,9	44,1	0,61	339,8
61,09		0,41	2,1	47,9	0,25	357,3
24,95		0,37	1,8	42,8	0,10	244,8
10		0,77	3,9	89,6	0,10	368,1
Highway Cycle	107,6					
95		1,63	2,0	45,4	0,10	278,2
10		3,88	4,7	107,7	0,10	443,1

6. Analysis of results

This research provided useful results in a long term view. Various topics have been faced in order to try to understand the complex transition from traditional vehicles to innovative solutions. Powertrain electrification will be fundamental to accomplish emission targets in next years. Among different technical solutions, PHEV has been preferred because it is a versatile vehicle which combines efficiently two different sources of energy and solves the problem of range and recharging anxiety. The battery has smaller dimensions when compared to that of BEVs, and can be completely recharged in 5–8 h allowing a less drastic change in habits. The factors which influence vehicle's lifecycle total CO_2 emissions as the energetic mix of the country, the battery production and recycling, the battery degradation, the autonomy decrease due to auxiliary usage, have a bigger impact on total CO_2 emissions of BEVs rather than of PHEVs. A trade-off between battery size and weight increase has to be taken in consideration in the design phases because even if longer electric range increases UF, a higher weight has a negative effect. Driver's habits and behaviour have a strong influence on PHEVs' use: recharging frequency and the context of journeys (urban, extra-urban, highway) are factors that change the effective value of emissions; another important problem is the objective difficulty of implementing plug-in hybrid technology in low segment vehicles, the consequence is that PHEVs have an high cost. The experimental cycle represents real driving conditions, with both urban and extra urban phases, a total distance of 25 km, frequent stops and changes of speed, an average speed of 35 km/h and a maximum of 101 km/h; this distance fits in PHEVs typical electric ranges of indicatively 40–70 km; from simulations it has been found that even after three days without recharge the vehicle produces a level of specific emissions in the range 42–48 gCO_2/km, under the threshold of ZLEVs (50 gCO_2/km); the gap between real emissions and WLTP emissions is around 20%, a sign that there is still a difference and that in next decade a new type-approval driving cycle should be realized in order to be closer to real driving conditions. The most interesting result of this research is that even if the journey is an highway cycle of more than 100 km, analysed PHEV shows satisfying performances in simulations, in conditions of complete recharge, with a

Table 10
Time share for all the strategies.

Time share [%]	Pe	Pt	Ps α = 0.1	Ps α = 0.25	Ps α = 0.5	Ps α = 0.75	Ps α = 0.9	Bc(-) α = 0.1	Bc(-) α = 0.25	Bc(-) α = 0.5	Bc(-) α = 0.75	Bc(-) α = 0.9
UEUC												
Scenario 1	80,48	0,22				0,45	16,76				0,19	1,49
Scenario 2	80,11	0,19			0,04	0,67	17,06		0,07		0,22	1,64
Scenario 3	90,73	5,7	0,97	1,56	0,07		0,11	0,11	0,04	0,15	0,07	0,48
Scenario 4	74,93	16,95	0,86	0,19	0,04		0,15	0,78	2,91	1,45	0,45	1,3
Highway	83,14	6,63	5,95	3,18	0,19		0,1	0,29	0,08	0,08	0,06	0,29

Table 11
Energy amount for all the strategies.

		Pe	Pt	Ps $\alpha = 0.1$	Ps $\alpha = 0.25$	Ps $\alpha = 0.5$	Ps $\alpha = 0.75$	Ps $\alpha = 0.9$	Bc(-) $\alpha = 0.1$	Bc(-) $\alpha = 0.25$	Bc(-) $\alpha = 0.5$	Bc(-) $\alpha = 0.75$	Bc(-) $\alpha = 0.9$
UEUC													
Scenario 1	Traction [kWh]	2,56					0,06	0,82					
	Braking [kWh]	1,72											
Scenario 2	Traction [kWh]	2,53					0,15	0,76					
	Braking [kWh]	1,72											
Scenario 3	Traction [kWh]	1,99	0,86	0,23	0,31	0,01			0,01		0,01		0,01
	Braking [kWh]	1,72											
Scenario 4	Traction [kWh]	0,73	2,06	0,21	0,02				0,06	0,21	0,08	0,02	0,04
	Braking [kWh]	1,72											
Highway	Traction [kWh]	9,4	2,31	3	1,77	0,05			0,02	0,01	0,01		0,01
	Braking [kWh]	3,9											

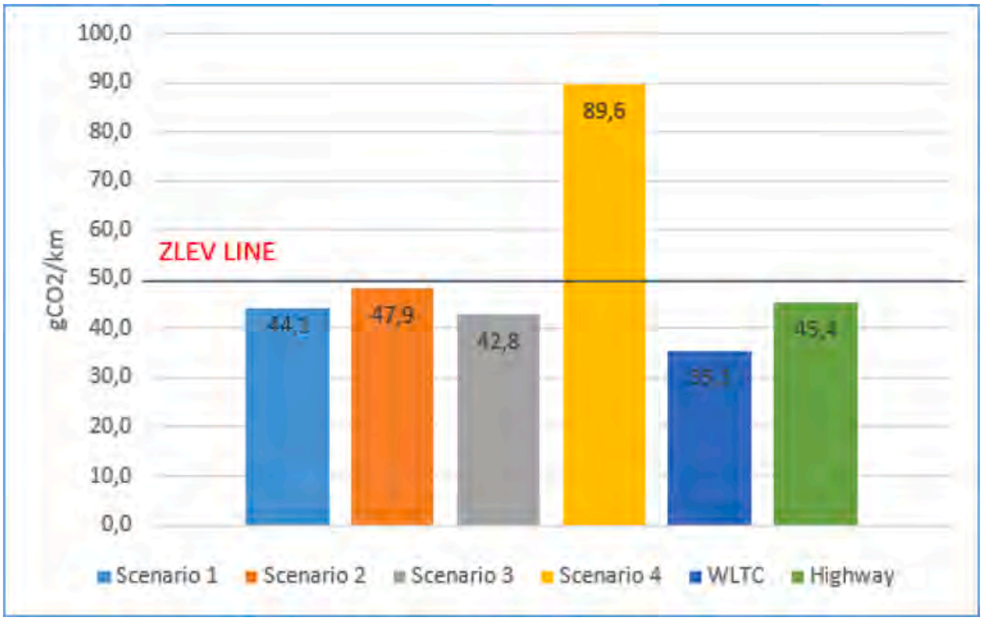

Fig. 25. CO_2 specific emissions in every context.

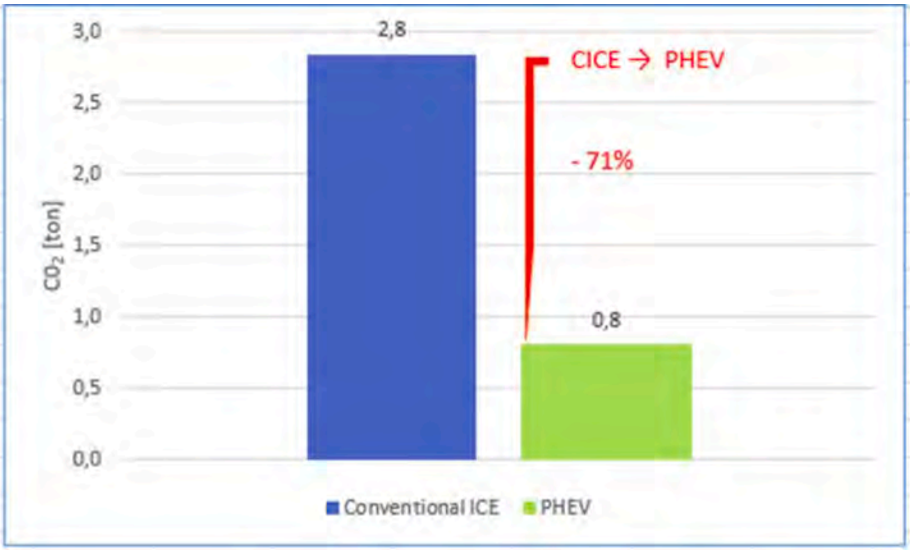

Fig. 26. Annual CO_2 emissions: CICE vs PHEV.

specific emissions level of 45,4 gCO_2/km; a clear demonstration of versatility since the two sources of energy result to guarantee a low emission level even if battery autonomy is not sufficient to travel all the cycle in electric drive. It is although correct to mention negative side effects of this technology in case of irresponsible behaviour or inaccessibility to recharge (absence of domestic wallbox, low availability of public recharge points, etc.); in scenario 4 or in the highway cycle travelled with low battery the emission level is not comparable with ZLEVs; misuse is a topic that has to be considered in an overall analysis. Last considerations have been taken comparing PHEV with the conventional counterpart, according to the hypothesis of a long distance travelled during year, the vehicle with electrified powertrain consumes 69% less fuel with a consequent reduction of 71% in emitted tank-to-wheel tons of CO_2 and indicatively one thousand Euros savings because of the different source of energy.

The current study can be expanded and completed considering:

- Lifecycle emissions;
- Effect of auxiliaries usage on PHEV's performances, for example cold weather effect on batteries;
- A more extended and complex cost analysis;
- A more realistic annual fuel consumption evaluation of CICE powertrain;
- Different PHEV's architectures (e.g. P0-P4, P3, etc.);
- The impact on infrastructure and recharging network;
- A different real driving cycle with recent data (including daily missions travelled properly by BEVs or PHEVs);
- Other pollutant substances (CO, HC, NO_x, etc.).

7. Conclusions

As demonstrated in this research, differentiating driving cycles between urban phases - characterised by higher local pollution due to the low efficiency of the thermal engine - and the extra-urban ones, where thermal engine has an high efficiency, a notable advantage in terms of CO_2 emissions reduction can be reached through PHEV: specific emissions under the threshold of 50 gCO_2/km, with a reasonable recharging frequency, and 71% reduction in global tank-to-wheel tons of CO_2 emitted every year.

A solution such as the one proposed here, which differentiates and enhances the use of batteries coupled with the electric motors in an urban context, with respect to the extra-urban one suitable for the ICE, has a series of beneficial effects that may satisfy in many other contexts as well: those of the lower whole power required to the electric grids, that of shorter recharging times, that of contained recharging power with related energy costs, that of the containment of ageing of batteries according to the recharging method, that of the costs related to battery replacement in the event of a road crash, that of queues waiting to be recharged. All these contexts favor small batteries in slow recharging, i.e. those typical of PHEV. The last issue is perhaps the least marginal, not dealt with in this paper, but a useful complement for concluding and stimulating other researches: to the extent that batteries are contained in terms of accumulable energy (e.g. 8–12 kWh), they not only provide the benefits discussed within this paper but also facilitate the driver with regard to a non-marginal issue inherent to electrification: the scalability of the BEV market; if there is no alternative to the electric grid for recharging batteries, the number of recharging stations must be very high and leads towards quick and fast recharging, more expensive than refueling; the PHEV solution facilitates slow and short recharging, thus limiting queues in the case of accessible stations on public soil.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Glossary

BC: Battery Charging.
BEV: Battery Electric Vehicle.
CICE: Conventional Internal Combustion Engine.
CO_2TTW: CO_2 Tank-To-Wheel.
DDP: Deterministic Dynamic Programming.
ECTTW: Energy Consumption Tank-To-Wheel.
EM: Electric Motor.
ICCT: International Council on Clean Transportation.
FC: Fuel Consumption.
NEDC: New European Driving Cycle.
OOL: Optimal Operating Line.
PE: Pure Electric.
PHEV: Plug-in Hybrid Electric Vehicle.
PS: Power Split.

PT: Pure Thermal.
SOC: State Of Charge.
UEUC: Urban Extra-Urban Cycle.
UF: Utility Factor.
WLTP: Worldwide harmonized Light vehicles Test Procedure.
ZLEV: Zero and Low-Emission Vehicle