Emissions reduction from passenger cars with RCCI plug-in hybrid electric vehicle technology

Jesús Benajes, Antonio García, Javier Monsalve-Serrano* and Santiago Martínez-Boggio

CMT - Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

Applied Thermal Engineering
Volume 164, 5 January 2020, 114430
https://doi.org/10.1016/j.applthermaleng.2019.114430

Corresponding author (*):
Dr. Javier Monsalve-Serrano (jamonse1@mot.upv.es)
Phone: +34 963876559
Fax: +34 963876559

Abstract

Hybrid Electric Vehicles (HEVs) can be considered as a potential technology to promote the change from conventional mobility to e-mobility. However, the real benefits in terms of CO_2 emissions depend on a great extent on their mode of use, vehicle design and electricity source. On the other hand, in the last few years, advanced combustion modes as Reactivity Controlled Compression Ignition (RCCI) showed great advantages in terms of NOx and soot emissions reduction. This paper has the purpose of assessing, through numerical simulations fed with experimental results, the potential of different hybrid vehicles when used together with a low temperature combustion mode. In particular, the dual-fuel Mild (MHEV), Full (FHEV) and Plug-in (PHEV) hybrid electric vehicles are tested and compared to the original equipment manufacturer (OEM) and the conventional dual-fuel powertrain, both no-Hybrid vehicles. The powertrains are optimized to meet the current European homologation legislation Worldwide Harmonized Light Vehicle Test Procedure (WLTP). After that, a deep analysis is performed in terms of performance and emissions. Lastly, a life-cycle analysis (LCA) is performed to evaluate the real potential of the different technologies. The results show that the PHEV has the highest benefits in terms of fuel consumption and engine-out emissions. With this technology, it is possible to achieve the 50 g/km CO_2 target for the PHEVs with a medium battery size (15 kWh), while NOx and soot levels are under the Euro 6 limits. In addition, the RCCI technology shows great benefits to achieve the Euro 6 soot level for the other hybrid platforms. The LCA shows that the PHEVs can achieve 12% reduction of the total CO_2 with respect to the FHEVs, and 30% with respect to the no-hybrid diesel platform.

Keywords

Hybrid powertrain; Diesel Internal Combustion Engines; Emissions regulations; Driving cycles

1. Introduction

The exposition of the human being to particles and gaseous pollutants produced in transport vehicles such as NOx and CO leads to serious health problems. The review of Rahman show that the idling phase of conventional vehicles can cause cardiac events, difficulty breathing, asthma, or even possibly death [1]. In general, the specialists call this phenomenon as local air pollution. On the other hand, the CO_2 emissions, inherent in any combustion process of fossil fuels, contribute to the effect known as global warming. One possible solution to minimize this problem is to change all the transport vehicles propelled by internal combustion engines (ICE) to electric motors. In this way, the tailpipe emissions will be reduced to zero. However, several authors [2–4] have demonstrated that this change will introduce other several problems as a lack of electrical energy from clean sources, rejection of users to the change and lack of infrastructure. In addition, the generation of complementary energy to meet the increase of the electricity demand brings in many cases greater emissions than using the current technologies [5,6]. Therefore, one potential solution is to implement an intermediate scenario, in which both concepts (ICE and electric motors) with higher efficiency than actual, are used to reduce the local and global emissions.

The conventional ICEs operating under conventional combustion modes present a trade-off between the CO_2, NOx and soot emissions by which it is not possible to reduce all of them at the same time [7]. By contrast, the alternative combustion modes, as the low temperature combustion (LTC) strategies, are able to reduce these three pollutants simultaneously [8]. At present, the passenger cars market is shared by diesel and gasoline engines in similar proportion, while diesel engines dominate medium and heavy-duty transportation [9]. The low fuel consumption of diesel engines it is well known, however the higher NOx and soot levels emitted than the gasoline spark ignition (SI) engines makes necessary to include expensive aftertreatment system (ATS) leading to more expensive cars [10]. This is consequence of the strict reduction of the legislation targets in the last years. Thus, a diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalyst reduction (SCR) are needed to achieve Euro 6 in diesel engines [11]. The LTC approaches combine advanced combustion strategies to reduce the ATS necessities. The use of high amounts of exhaust gas recirculation (EGR) with highly advanced injection strategies that improve the mixing process and reduce the combustion temperature allows ultra-low NOx and Soot emissions [12]. Among the different LTC concepts, it is well demonstrated that the RCCI strategy offers the best control over the combustion process by tailoring the mixture reactivity inside the combustion chamber. This is achieved by using two fuels with different reactivity [13]. Usually, the low reactivity fuel (LRF) (gasoline, ethanol, etc.) is injected at low pressures with a port fuel injector (PFI) while the high reactivity fuel (HRF) (diesel, oxymethylene dimethyl ether – OMEx, etc.) is directly injected into the cylinder at high pressures. Tin spite of the gains in NOx and Soot emissions, the benefits in efficiency with RCCI considering all the engine map is not as much as needed to produce a significant fuel consumption reduction compared to the state-of-the-art diesel engines [14]. Since the fuel consumption is proportional to the CO_2 emissions, this means that the single application of RCCI is not enough to reach the future CO_2 targets, being necessary the update of the powertrain system.

In this context, the electrification of the powertrain shows potential to complement the benefits of the RCCI dual fuel mode. The main advantages of the electrification are the improvement of the global efficiency during the transient operation of the vehicle and the use of the braking energy to produce electricity [15]. In addition, the hybrid electric vehicles have as potential to serve as a bridge technology between the current ICE powered vehicles and the "zero tailpipe emissions" vehicles such as battery electric vehicles (BEVs) and fuel cell hybrid electric vehicles (FCHEV). The electrification of the powertrain can be done at several levels, generally divided in mild (MHEV), full (FHEV), and plug-in (PHEV) hybrid electric vehicles. The main conceptual difference between them is that the PHEVs have an external charge source (electricity grid), meanwhile the MHEV and FHEV re-charge the batteries with the ICE. The MHEVs equip batteries with voltages below 60 V and capacities around 1 kWh. The electric motor replaces the conventional alternator to perform the energy recovery and power assist mode. The main advantage of this architecture is the simplicity to be applied in the already developed vehicles. A step further in the electrification degree is the increment of the battery capacity (>300 V and >5 kWh) and the use of electric motors in the driveline to operate in pure electric mode, as is the case of the FHEV. The pure electric mode allows producing zero emissions during a certain travel distance. After that, the ICE is turned-on to re-charge the battery. Lastly, the PHEV could use similar powertrain architectures than the FHEV, but with a higher battery capacity (>10 kWh). This last point allows performing large trips in charge depleting mode (pure electric mode if the power required is below electric motor capacity) due to the external charge of the battery package from the electricity grid. This allows the flexibility to use liquid fuels or electric power with a high range of zero-emissions vehicle operation. In addition, the PHEV has advantages in the market penetration compared to BEVs due to its lower initial cost, higher driving range and the necessity of lower infrastructure investment because of the dual energy source [16]. This means that the change from petrol station to electric charge zones could be done progressively, making the user adaptation and city modifications easily.

Considering this big scenario, one of the main challenges of the homologation normative is to establish a comparative procedure between the different technologies. The current homologation procedures have been updated to reduce the differences between the real-life cycles and the homologation cycles. Moreover, it has been found that the analysis of the PHEVs must be done independently to other vehicle architectures since the opportunity to be re-charge with the electric grid. The split between the liquid and electric energy depends on the electric range of the vehicle. Therefore, the current regulations in Europe (WLTP) [17] adapted the current normative to regulate this type of vehicles with two differentiated modes: a charge-depleting mode where the propulsive energy comes from the stored energy in the battery, and a charge-sustaining mode in which the ICE propels the vehicle and maintains the battery charge at a minimum level. The final consumption is a mix of both tests weighted by a utility factor (UF) [18]. The UF is defined as the proportion of vehicle distance travelled that can be allocated to a vehicle test condition so as to represent the real-world driving habits of a vehicle fleet. These tests are performed in a chassis dynamometer and controlled conditions.

Several works show that if the PHEVs are used appropriately, they have lower energy consumption than the conventional vehicles [19,20]. However, the main question that arises is if this advantage is also observed in terms of total greenhouse gas emissions (GHG). Therefore, the studies that want to answer this question need to include the electricity source, electric components productions, mainly the battery package, vehicle usage and owner responsibility among others [21]. In the last years, due to the increase of the global warming concern, several companies, governmental organizations and researchers put their focus in life cycle analysis (LCA) [22] to quantify the impact of the new versus old technologies in terms of GHG emissions and other parameters (energy use, NOx and other pollutant emissions). The more relevant GHGs emitted to the atmosphere due to anthropological action are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases [23]. Among all these GHGs, the CO_2 is considered the main responsible for the global warming. The time period usually used for GHGs is 100 years and it is called GHG-100 [24]. To estimate the total GHG impact several databases were created along the last few years as GREET, Gabi, Bionergiedat and Psilca, among others. All of this source considers some of the parameters necessary to perform a complete LCA for a passenger vehicle as: fuel and vehicle production, vehicle use, maintenance, etc. Specifically GREET [25] from Argon National Laboratory is a free database used in several works from literature [24,26,27] due to the availability of different components for hybrid vehicles as battery and electric motors [28].

In spite of these studies, the impact of different factors (electric energy source, vehicle use and charge times, user responsibility, etc.) on the fuel economy and emissions of the PHEVs is not extensively addressed in the literature. Also, it exists a lack of results about the real benefits in terms of GHG emissions with the different electrification degrees, and the gains of using advanced combustion modes with respect to conventional combustion modes as diesel. Moreover, few works show this behavior in electrified powertrains [29,30] and none in plug-in electric vehicles. Considering this, the aim of this study is to characterize several powertrains with different hybrid platforms layout using a thermal engine operating in RCCI combustion mode in a passenger car. Numerical and experimental work is performed to account the fuel consumption and emissions in the new European homologation procedure. Also, a cradle-to-grave life cycle analysis is performed to account all the stages of the vehicle production, use and disposal. To do this, the effect of the fuel production (liquid and electricity), conventional and hybrid electric components (electric motors, batteries, etc.) production, maintenance, re-cycling and disposal process are included.

2. Materials and methods

The evaluation of the different hybrid powertrains combined with the dual-fuel RCCI combustion mode were performed in a numerical 0-D vehicle model. The main input of the model is the ICE calibration map of the conventional diesel combustion mode and the advanced diesel-gasoline dual-fuel combustion mode. In addition, several modules are added to the model to set the driving cycle required and simulate the vehicle behavior and all the hybrid components. This section is divided into two subsections. First, the experimental campaign to obtain the stationary engine maps is explained. Later, the details of the vehicle and numerical model are provided.

2.1. Engine and test cell

The first step in the study of a vehicle in transient condition is the measurement of the engine maps in stationary conditions. Several operating points were measured at the test bench for different engine speed and loads. Two engine maps were obtained. The first one corresponds to the conventional diesel combustion using the manufacturer calibration. The second map corresponds to the dual-fuel RCCI diesel-gasoline mode, calibrated by the authors [31].

The experimental tests were carried out in an active dynamometer using a GM 1.9L light-duty engine originally calibrated to operate under conventional diesel combustion (CDC) to pass the Euro 4 normative in terms of emissions in the NEDC. For this work, the 4-cylinder engine was modified to operate as a single-cylinder engine (SCE) because this type of configuration allows a complete control of the parameters (input and output) that are important in the calibration of an advanced combustion mode as RCCI. More information about the original base engine modification can be found in [18]. Two fuels were used, the high reactivity fuel is a commercial diesel (EN590) and the low reactivity one is a commercial gasoline (EN 228), both representative of the European market. In this combustion mode, the fuels are injected separately. The diesel is injected by means of a direct injector (DI) and the gasoline is injected by means of a port fuel injector (PFI). Therefore, two different fuel lines and reservoir tanks are necessary. The cylinder head is composed of four valves (2 intake and 2 exhaust) operated by double cams, and the piston used is the serial one provided by the manufacturer. The engine compression ratio is 17.1:1 and the swirl ratio was fixed at 1.4 by using tangential and helical valves located at the intake port. Table 1 summarizes the most relevant characteristics of the engine. More details of the test bed configuration and characteristics can be found in previous work [32].

All the results were scaled to a 4-cylinder engine, which is the engine configuration that will be used in the vehicle simulation. The passage from the 1-cylinder to the 4-cylinder engine was done by assuming that the other three cylinders have the same behavior than the measured cylinder [32]. This approach was already used by other authors and for verification purpose the original manufactured conventional diesel combustion (CDC) calibration was compared with the results of the SCE in diesel mode with error below the 5% [33].

Table 1. Single cylinder GM engine characteristics.

Engine Type	4 stroke, 4 valves, direct injection
Number of cylinders	1
Displaced volume	477 cm^3
Stroke	90.4 mm
Bore	82 mm
Piston bowl geometry	Re-entrant
Compression ratio	17.1:1
Rated power @ 4000 rpm	27.5 kW
Rated torque@ 2000-2750 rpm	80 Nm

Figure 1a show the CDC engine map that was originally calibrated and programmed in the engine control unit (ECU) by the manufacturer. The engine used was designed to operate with a conventional powertrain and meet Euro 4 emissions limits. The use of this engine in the work was due to the availability of this platform in the research institute. Figure 1b shows the achievable RCCI operating range with the original engine components. It is well known that this type of combustion allows ultra-low NOx emissions operation as seen in the medium map zone of Figure 1b. The same behavior is seen for the soot emissions [34].

The main constraints that restrict the use of RCCI in the all map are the mechanical limitations and the elevated HC and CO emissions. At high loads, the excessive pressure rises rates (PRR) found due to the autoignition of the gasoline in the compression stroke limit the RCCI operation. This problem could be solved by adding higher EGR rates, but the air management system limited this ratio to 50%. At low loads, the CO and HC are too high due to low temperature during the combustion event. Therefore, the engine thermal efficiency suffers an important drop. Lastly, at high engine speeds it is not possible to work with a single-cylinder engine due to mechanical limitations. All these limitations were resume in Figure 1b. After that a multi-mode map was generated combining RCCI and CDC, as shown in Figure 2. In addition, the fuel consumption and gasoline percentage used in the RCCI zone is added in the Appendix A (Figure A1 and Figure A2).

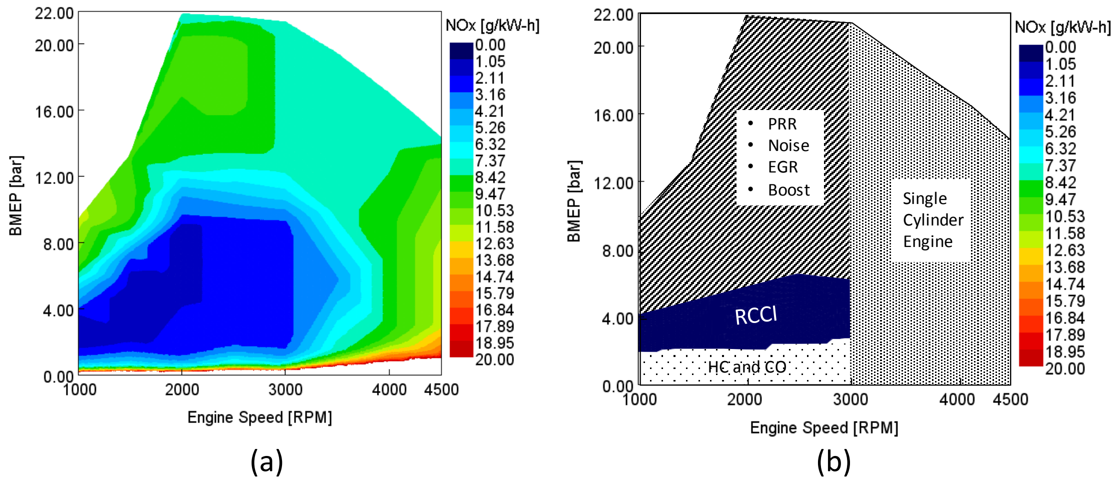


Figure 1 – NOx emissions for the Conventional Diesel Combustion (CDC) calibration map (a) and reactivity-controlled compression ignition (RCCI) gasoline calibration map (b).

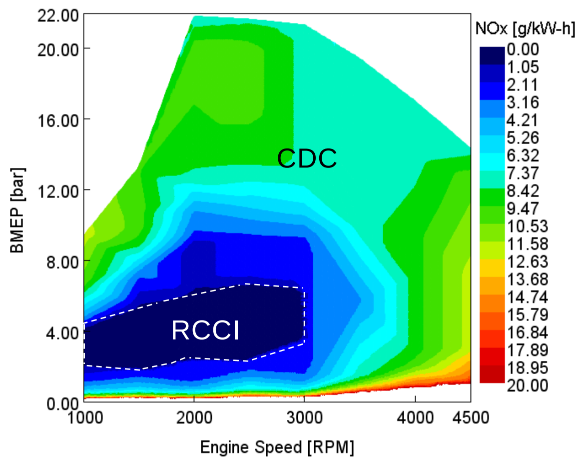


Figure 2 – Engine-out NOx emissions for the coupled CDC-RCCI engine map.

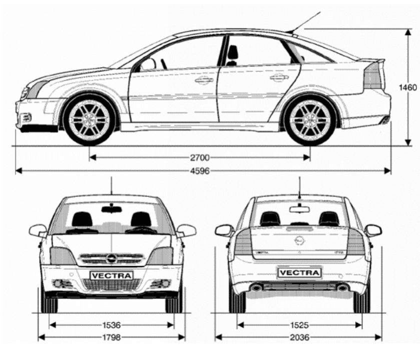
2.2. Vehicle, Computational Model and Homologation Cycle Specifications

The vehicle selected to perform the simulation is a passenger car Class D (Opel Vectra), which equips the compression ignition (CI) engine used in the experimental test bench. The main parameters of the vehicle are described in

Table 2. This vehicle has a conventional powertrain architecture (no-hybrid) with the ICE coupled to a manual 6-gear transmission by a clutch. The final coupling is done by the differential with the front wheels.

Table 2. Vehicle specifications.

Vehicle type [-]	OEM
Base vehicle Mass [kg]	1523
Passenger and Cargo Mass [kg]	100
Fuel Mass [kg]	45
Vehicle Drag Coefficient [-]	0.28
Frontal Area [m²]	2.04
Tires Size [mm/%/inch]	225/45/R118
Differential ratio [-]	3.2



The electrification of the powertrain in the numerical models was performed by the addition of an electric motor and an additional battery package to the conventional powertrain layout. Several hybrid powertrain architectures were designed along the last years. One of the most used architecture is the belt alternator starter hybrid powertrain (BAS or P0), in which a small electric motor (EM) replaces the traditional alternator. Generally, it is called belt alternator starter due to the position in the ICE package [35]. With this configuration, the main vehicle modes are regenerative braking, power assist and the re-charge of the battery. The EM never propels the vehicle because it is not connected directly to the camshaft. Instead, it is inserted in the engine group replacing the well-known alternator in the serpentine belt. Therefore, the power that the EM is capable to transmit is low (<20 kW) and generally a low battery package capacity is necessary (<2kWh and <60v). These are the main reasons that this technology is associated with the mild hybrid electric vehicle (MHEV). For this work, a 48 V battery voltage was used due to availability of components (EM, battery, cables, etc.) already developed to work with this voltage source in the passenger car sector [36].

Other powertrain layouts are the parallel hybrid electric vehicle (P2), series (or range extender) and series-parallel (or power split) architectures [37]. P2 it is referred to the parallel pre-transmission system in which the EM is placed between the ICE and the gear transmission. Some specialists called the P2 to be an upgrade of the P0 architecture to allow more electric capabilities to the vehicle [38]. The P1 is an intermediate powertrain layout in terms of complexity, in which the EM is coupled in the crankshaft. However, the P2 adds an additional clutch to have the pure electric mode in which the EM propels the vehicle without the ICE. Therefore, this last layout allows to drive in “zero emission” mode (pure electric), re-charge the batteries, regenerative braking and power assist mode. In addition, this powertrain could be used with (PHEV) and without (FHEV) external grid battery re-charge. The main difference between PHEV and FHEV is the charge port for the electric grid and the higher battery capacity used, which theoretically could allow additional fuel consumption benefits. As the aim of this work is to test several hybrid platforms, the P2-FHEV and P2-PHEV were selected to be compared with the P0-MHEV and the no-hybrid platforms (diesel and dual fuel engines).

The GT-suite [39] (v2019, Gamma Technologies, LLC., Westmont, IL, USA) was used with an in-house rule-based control (RBC) system specially designed to perform transient operation to the modeling and control of the hybrid and no-hybrid vehicles. A complete description of the RBC strategy development and the limits imposed in each parameter is described in a previous work of the research group [31]. Dedicated modules are used to simulate the behavior of the different components as EM, battery, transmission, wheels among others. The transient simulation model consists of a driver sub-model trying to follow a predetermined speed profile used as input. Therefore, the desired torque is calculated by the vehicle traction equations considering the road friction and aerodynamic forces, among others [15]. This signal is then processed to determine the required accelerator pedal, brake pedal and gear position. The advantage of this approach is the causative behavior since the driver takes an action and then it is corrected depending on the speed reached with respect to the required one. Thus, if more speed is necessary, the action will be to increase accelerator pedal demand, and if the vehicle speed is over the target, the brake pedal will increase too. This gives a more real behavior than that obtained with simple vehicle models. It is important to note that the weight of all the additional electric components (motors, batteries and controllers) was considered and added to the base vehicle weight (OEM) presented in Table 2. This allows to perform a more realistic comparison, in which each additional electric capacity penalizes with more fuel consumption due to the extra weight.

The worldwide harmonized light-duty vehicles test procedure is the currently in force protocol to measure the emissions and fuel consumption for homologating the passenger cars in Europe. The technical regulation No. 15 published by the United Nations Economic Commission for Europe (UNECE) [17] has all the details of the new legislation. The WLTC cycle is performed in a vehicle test bench at controlled conditions and under a pre-defined cycle. As shown in Figure 3, the WLTC has four different zones called low, medium, high and extra-high. The first two are representative of urban driving and the last two are representative of rural and highway areas, respectively. The Opel Vectra tested in this work is a class 3b due to a power-mass ratio of 60 W/kg that is over the 34 W/kg, and maximum vehicle speed over 120 km/h.

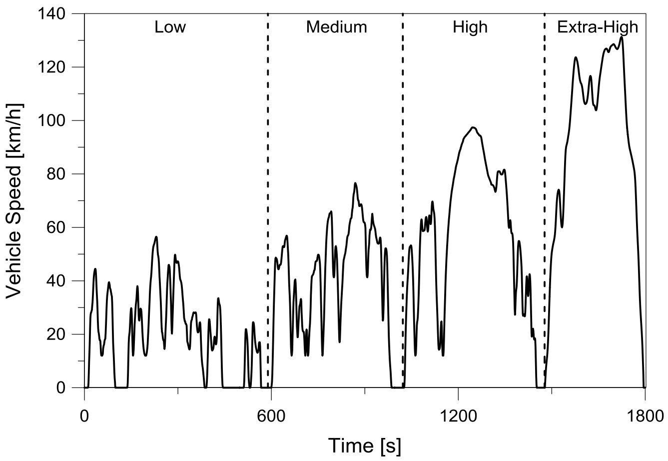


Figure 3 – Homologation cycle under the new WLTP legislation for light duty vehicles.

The current European Union (UE) regulates the NOx, CO, HC and particulate mass (PM) and particulate number (PN) emissions limits of the WLTC under the Euro 6 normative. Additionally, since 2009, the EU legislation sets mandatory CO_2 emissions reduction targets for new cars. The first target was applied in 2015 with a limit of 130 g/km. Later, a stricter value was set to be achieved in 2021 with a limit of 95 g/km. This implies a reduction of 26% in 6 years (4.5%/year). In addition, it is stipulated that the limit is going to be reduced even more in the next years, with 15% lower in 2025 and 37.5% lower in 2030, compared to the 2021 CO_2 emission limits [40]. A summary table with all the Euro 6 emissions limits and the tentative CO_2 targets is shown in Table 3. Fees will be applied to the car manufacturers if the average CO_2 emissions of their fleet exceeds the target in a given year. The European Parliament and the European Council also agreed to apply mechanisms to encourage the sales of more zero and ultra-low emission vehicles. Moreover, it is also probable that will be added in-service conformity testing to follow the emissions of a vehicle along its use and not only when is new. Lastly, the European Commission will evaluate the possibility of developing a common EU methodology for the assessment and reporting of lifecycle emissions (also called life-cycle analysis) of the vehicles.

Table 3 – Euro 6 limits and tentative CO_2 targets

Parameter	Limit [g/km]
CO	0.5
HC *	0.09
NOx	0.08
PM	0.005
CO_2 2021 Target	95
CO_2 2025 Target	80
CO_2 2030 Target	67
CO_2 Taxes incentive	50

*The Euro 6 limit establish the limit for HC+NOx<0.17 g/km

In terms of conventional and hybrid vehicles, the homologation normative has several particular aspects. The MHEVs and FHEVs have the same homologation procedure than the conventional powertrains due to the absence of an external electric charge source. The main constrain imposed during the cycle is that the battery charge level at the end of the cycle must be equal or higher to the state of charge (SOC) at the beginning of the test.

On the other hand, the PHEVs are hybrid electric vehicles that can be fueled from both conventional liquid fuels and grid electricity. Therefore, an annex of the actual WLTP normative was created to have a similar comparison with respect to the conventional and other hybrid vehicles. For the PHEVs, there are stablished two operation modes: charge depleting (CD) and charge sustaining (CS). In charge depleting mode, the electric motor is mainly responsible for the vehicle propulsion due to the full battery charge (SOC at 100%), while the ICE is switched off. In this mode, the battery is completely charged before starting. In charge sustaining mode, as the battery has been fully depleted up to the lower limit (SOC around 30%) in the previous mode, the internal combustion engine is turned on and used to propel the vehicle and keep the battery SOC within a small window around 30%. After that, the battery is charged with electricity from the grid. Finally, the sum of the charge depleting and charge sustaining fuel consumptions corrected by the UF (i.e., weighted fuel consumption), intends to estimate the fuel consumption of the vehicle in a worldwide representative vehicle use scenario. As the trip length increases with the battery size, the fuel consumption of the vehicle will change, eventually asymptotically approaching the charge sustaining fuel consumption for trips of distances much greater than the charge depleting range. The rule that defines the start of the charge depleting mode is described in Equation 1:

$$REEC_i = \frac{\left|\Delta E_{\text{Battery},i}\right|}{E_{cycle}} * 100 < 4.0\% \qquad (1)$$

with $REEC_i$ being the relative electric energy change in cycle i [%], $\Delta E_{BATT\,\mathrm{i}}$ the change of battery energy content i [Wh] and E_{cycle} the energy required to complete one WLTC [Wh].

As illustrated in Figure 4, the initial state of charge is set to its maximum (SOC=1.0), then the WLTC is repeated until the battery reaches its minimum allowed charge state (SOC = 0.3). After that, a complete WLTC is performed in charge sustaining operation (the vehicle is propelled by the ICE). One of the most important parameters that defines the main behavior of a hybrid plug-in vehicle is the electric range (ER), which is defined as the distance traveled in 100% electric mode until the ICE is turned on for the first time. Depending on the manufacturer calibration, during the CD test it could be possible to turn on and turn off the ICE without braking the condition that makes the CD mode end (Eq. 1). To manage these cases, the equivalent electric range was created, which is defined as the distance covered in CD mode without counting the part traveled with the ICE switched on. In the CS mode, the energy of the electrical energy storage system can fluctuate, but on average it has to be maintained in a neutral level of load balance while the vehicle is being driven. This test is carried out through a single WLTC cycle as in the conventional vehicles or non-plug in hybrids. As it can be inferred, the vehicle configuration and the user behavior have great impact in the real behavior of the vehicle. Also, as two different tests must be performed, it is necessary to set a balance between both results to have a final fuel and electricity consumption as well as for the evaluation of the final emissions.

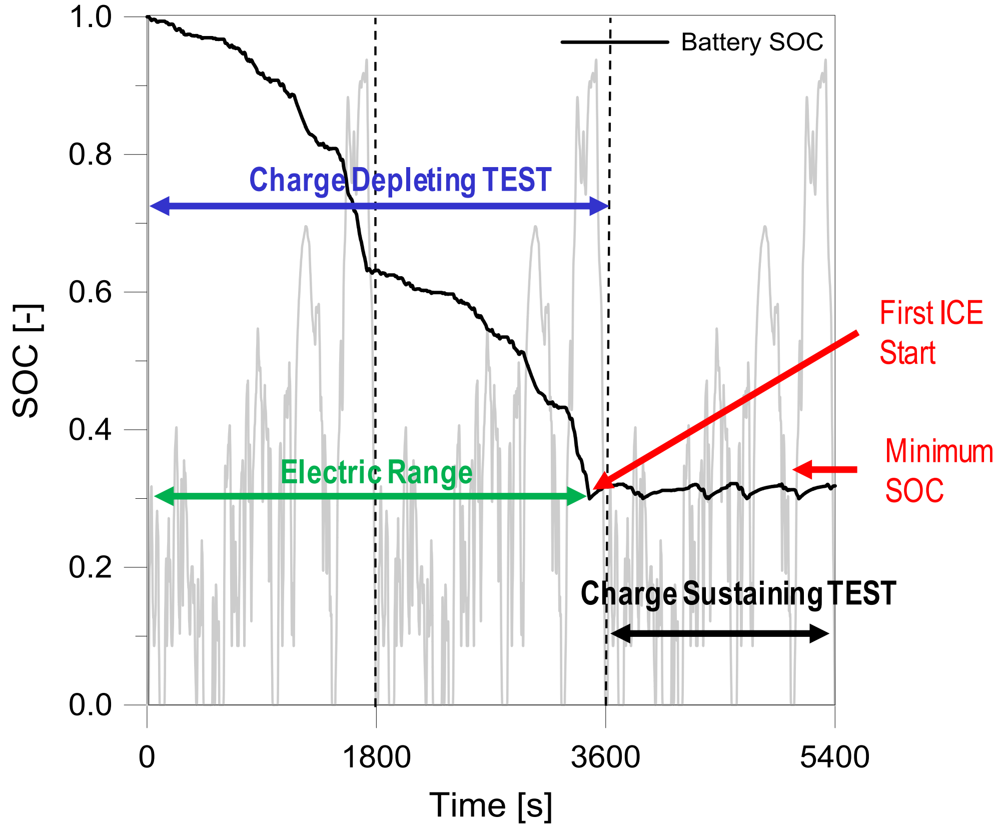


Figure 4 – PHEV homologation test with the CD and CS phases.

The weighting between the CD and CS operations of the drivetrain will also be considered through statistics expressed by a ratio called Utility Factor. The UF represents the fraction of the distance covered in charge depleting over the total distance covered between two battery external charges Figure 5. The Society of Automotive Engineers (SAE) has proposed a standard method (SAE J2841) [41] that defines this weighting between charge depletion driving and charge-sustaining driving as a utility factor that intends to represent the real-world driving habits of a vehicle fleet. The SAE J2841 method assumes that the vehicle is fully charged at the beginning of the test and it is charged only once per day. Moreover, the SAE J2841 method assumes that the driving route is carried out with the same patterns than the national US average vehicles, and considers that the charge depletion represents the primary mode of energy consumption in the PHEVs. Figure 5 shows the UF behavior with the increase of the charge depleting range. Other purpose of the UF is to estimate the fuel consumption of the PHEV, which is collected in the "sticker fuel economy". To obtain the final weighted result, the following formula is used for the gaseous emissions:

$$M_{i,weightened} = \sum_{j=1}^{k} \left(UF_j \times M_{i,CD,j}\right) + \left(1 - \sum_{j=1}^{k} UF_j\right) \times M_{i,CS} \qquad (2)$$

where $M_{i,weightened}$ is the weighted mass emission of the compound i, in g/km; UF_j is the utility factor of the phase j; $M_{i,CD,j}$ is the mass emission of compound i in phase j of the CD mode, in g/km; $M_{i,CS}$ is the mass emission of compound i in CS mode. The weighted fuel consumption has the same calculation structure, with its units in lt/100km:

$$FC_{weightened} = \sum_{j=1}^{k} (UF_j \times M_{CD,j}) + (1 - \sum_{j=1}^{k} UF_j) \times M_{CS} \quad (3)$$

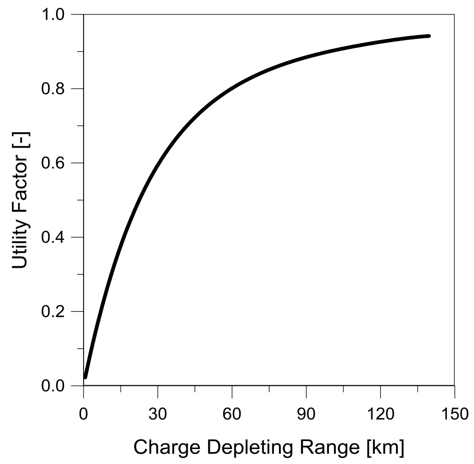


Figure 5 – Utility factor against charge depleting range

2.3. Life Cycle Analysis for passenger vehicles

One of the most used approaches to perform environmental evaluations of product systems is the life-cycle analysis (LCA). The LCA is a method that provides a system-wide perspective of a product or service due to the evaluation of the complete process [42]. It considers all the stages of the life cycle, including material production, system manufacture, assembly, service provision, maintenance, and end-of-life processes. Approaches as gate-to-gate or cradle-to-gate and cradle-to-grave are usually used depends on the scope of the analysis [43]. As in this work it is required an overall view of the vehicle life, cradle-to-grave was performed. Figure 6 shows the different stages of the process.

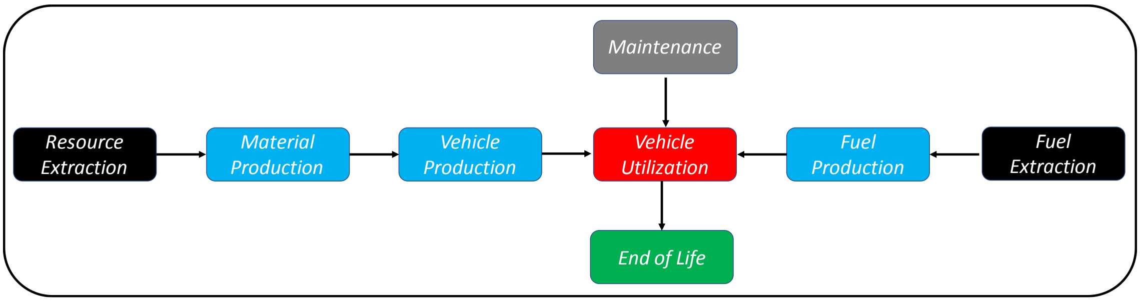


Figure 6 – Diagram of Life cycle analysis data flow

The LCA analysis is performed with the open source calculator developed by Argonne national laboratory. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) life cycle model allows to perform the analysis with several vehicle configurations and considering several energy mixes and materials. The basis of the software is an attributional life cycle analysis (ALCA) in which several bill of materials (BoM) are considered as well as the all process that allows a vehicle to work. Thus, different fuel production, electricity mixes and components productions are already inserted in the database. Also, the software considers the vehicle process and adds the corresponded values for the different emission or consumption parameters. The main calculated parameters are: Total Energy, Fossil, Coal, Natural gas, Biomass, Nuclear and Renewable fuels, Water usage as reservoir, irrigation, cooling, mining and process. Also, different pollutant emissions as, NOx, PM, SO_2, HC, CO_2, CO_2 Biogenic, CO_2 Land Use, CH_4, GHG-100, among others. The categories and information source are specified in Table 4. The lifetime of the vehicle was taken as 150,000 km as the average considered in Europe for hybrid electric vehicles without battery replacement [44].

Table 4 – Main process evaluated in the LCA model by GREET.

Section	Parameter	Model
Well-to-Tank (WTT)	Fuel and electricity production.	Conventional diesel and gasoline [45], EU electricity mix [46].
Tank-to-Wheel (TTW)	Vehicle use.	Data obtained in the simulation section.
Battery	Material extraction and battery assembly.	Lithium-ion battery materials [47] and assembly [48].
Components	Vehicle body, tire replacements, electric motors and electric systems.	Greet database version 13395.
Fluids	Engine oil and coolant, transmission fluid, brake fluid and power steering fluid.	Greet database version 13395.
Vehicle assembly, disposal and recycling	Vehicle assembly, disposal and recycling.	Vehicle production and end of life [49].

3. Results and discussion

The results are divided into three subsections. The first subsection shows the results of the optimization procedure for the different vehicle without plug-in capacity. In a second subsection, the potential of the PHEV is studied by a design of experiment (DoE) of different battery capacities and other hardware specifications. To assess the potential of the PHEVs, a comparison between all the technologies (plug-in and no-plug-in) in terms of energy consumption and engine-out emissions is performed at the end of this subsection. Finally, the last subsection presents a life cycle including all electrification degree to analyze in an overall perspective the benefits of each technology in terms of CO_2 emissions and others pollutant emissions.

3.1. OEM, No-hybrid and No-Plug in Hybrids Dual-fuel Optimization

The optimization approach was performed by testing several hardware and vehicle control parameters [50]. A design of experiments (DoE) with 1500 cases for each hybrid platform and a Latin hypercube sampling (LHS) was used [51]. This allows to generate a near-random sample for a multidimensional problem. As demonstrated in a previous work, this number of cases and sampling method allow to test the vehicle in almost all the possible conditions [31]. Others tools as the kriging fitting method and the Pareto frontier could be applied. However, no improvements were seen for this particular analysis.

Table 5 shows a summary of these parameters and the range tested. It is important to note that for the MHEV, the battery voltage used was 48 V, while for the

FHEV 400 V was preferred due to the capacity to operate in pure electric mode. The gear shift strategy was optimized for each vehicle architecture, as the manufacturers can do to perform the homologation cycle. The optimization was performed taking the OEM shift strategy as a baseline, and applying a shift coefficient that varies between 0.7 and 1.3 ($Speed_{shift\ Optimize} = Speed_{shift\ OEM} * \ Coef_{shift}$), as shown in Table 6. This mean that a more aggressive (low vehicle speed shift change) or more soft gear change can be tested. The maximum vehicle speed is used in the FHEV vehicle to limit the use of the pure electric mode. Basically, at high vehicle speed the ICE achieve acceptable thermal efficiency. Therefore, it is preferred to use liquid fuel instead of electricity. This parameter was change from low vehicle speed to extra high speed to see the behavior of the fuel consumption and emissions. Lastly, the coefficient of power split determines the share between the ICE and the EM when both operate in the mode power assist. This parameter varies between zero assist and complete drive by the electric motor. See previous work for more information in this point [31].

Table 5 – DoE parameters for the optimization of Mild and Full hybrid and OEM and DF No-hybrid vehicles.

Parameter	OEM	Dual-fuel No-Hybrid	Dual-fuel MHEV	Dual-fuel P2-FHEV
Electric Motor Capacity [kW]	-	-	8 - 20	25 - 50
Battery Package Capacity [kWh]	-	-	0.5 – 2.0	2.0 – 12.0
Gear Shift Strategy [-]	0.7 - 1.3			
Max. Speed Pure Electric Mode [km/h]	-	-	-	25-140
Coef. Power Split [%]	-	-	0 - 100	

Table 6 – Shift strategy suggested by the manufacturer

Gear Shift	1-2	2-3	3-4	4-5	5-6
Up (km/h – rpm)	30 - 3040	45 - 2445	70 - 2410	100 - 2545	123 – 2410
Down (km/h – rpm)	26 - 2630	40 - 2175	65 - 2240	95 - 2418	115 - 2255

The selection of the optimum vehicle configuration from the 1500 cases tested depends on the criteria imposed (minimum fuel consumption, achievement of a determined emission value as NOx or soot…). In a previous work of the research group with the same ICE, it was seen that exists a trade-off between fuel and NOx [31]. Also, this behavior is commonly seen in diesel engines [52]. Therefore, it is not possible to minimize both components at the same time. A solution to this problem, is to set a desired NOx value for all the cases and then study the improvements in the other parameters as the fuel consumption, CO_2 or soot. This approach was followed in this work, with the NOx target set at the minimum value achieved by the OEM vehicle. The main reason of this selection is the possibility to use the same aftertreatment system than in already developed diesel engines to achieve the Euro 6 limit in terms of NOx. Thus, the engine-out NOx has an acceptable value that could be reduced with a selective catalyst reduction working with urea to achieve Euro 6 in tailpipe (0.08 g/km). Moreover, this approach allows to compare the fuel consumption without penalties in NOx emissions.

Figure 7 shows the fuel consumption and engine-out CO_2 against the engine-out NOx emissions for the different hybrid (no plug-in) and no-hybrid vehicles. From the figure, it is possible to see that the dual-fuel mode allows to reduce the NOx emissions in most of the cases. This is due to the ultra-low NOx zone of the engine map (Figure 2). The minimum NOx of the baseline case was 0.56 g/km with intermediate fuel consumption (5.5 lt/100km). On the other hand, the combination of dual-fuel combustion and hybrid powertrain capabilities allows to achieve minimum NOx levels of 0.28 g/km in the WLTC. Moreover, the dual-fuel with the same powertrain architecture (no-hybrid) could reduce up to 34% the NOx emissions. In spite of the improvements in engine-out NOx using the combination of both technologies, it is not possible to achieve the Euro 6 limit without using an aftertreatment device. This is mainly due to the small RCCI zone found in the calibration map.

The square points in Figure 7 show the best configuration for each powertrain, with the target condition of 0.56 g/km in NOx emissions (OEM minimum). Figure 7a show that the combination of dual-fuel operation and hybrid powertrain allows reducing the fuel consumption. In spite of the RCCI mode does not allow a direct fuel consumption reduction (Figure in the Appendix), it allows to reduce the NOx emissions at low engine speed and middle load zone. Therefore, with RCCI it is possible to use a more aggressive gear strategy to reduce the fuel consumption while maintaining the same emissions levels. Table **7** shows the hardware and control optimum parameters to achieve these results. The table shows that the implementation of the dual-fuel mode enables a fuel consumption reduction of 5% and adding the electrification of the powertrain gives additionally 5% for MHEV and 20% for FHEV. Overall, it is possible to achieve 4.2 lt/100km with the most complex vehicle set up (25% lower with respect to OEM).

In terms of CO_2 emissions, the desired target imposed by the legislation is 95 g/km for 2021, as marked in Figure 7b. The FHEV dual-fuel achieves 104 g/km. In spite of the great improvements, it is necessary to develop additional technologies to achieve the target. It is important to note that the study starts with an ICE calibrated to achieve the Euro 4 regulation with CO_2 emissions of 147 g/km (above 2015 target).

The gear shift strategy is one of the parameters that have more influence in the trade of between fuel and NOx emissions [31]. Looking at the results shown in Table 7, the dual-fuel operation was optimized with a coefficient below 1.0. This means the engine working at lower rpm (around 2300 rpm) and higher load (BMEP). On the other hand, to achieve low NOx emissions, the pure diesel mode needs to work with intermediate engine speed and load (coefficient 1.1, around 2800 rpm). See Figure B1 and Figure B2 to better understand of this point.

Other advantage of the hybrid vehicles is the addition of electric motors that give additional power to the vehicle, providing an increase of the power output of the vehicle with respect to the OEM (17% for MHEV and 28% for FHEV).

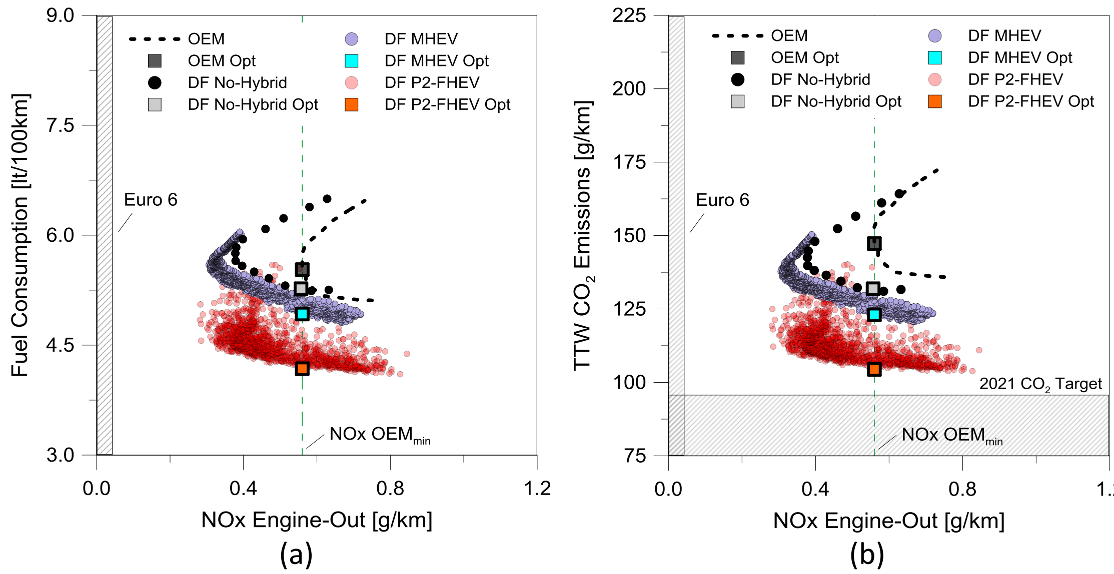


Figure 7 – Fuel consumption (a) and tank-to-wheel (TTW) CO_2 emissions (b) against NOx engine-out emissions for MHEV and FHEV. The baseline cases (OEM, DF No-hybrid) and the optimum value was included.

Table 7 – Optimum hardware and control selection for a MHEV and P2 FHEV to meet WLTC

Parameter	OEM	Dual-fuel No-Hybrid	Dual-fuel MHEV	Dual-fuel P2-FHEV
Electric Motor Capacity [kW]	-	-	18	30
Battery Package Capacity [kWh]	-	-	0.5	5.1
Total Vehicle Weight [kg]	1523	1523	1574	1612
Gear Shift Strategy [-]	1.10	0.87	0.78	0.87
Max. Speed Pure Electric Mode [km/h]	-	-	-	100
Coef. Power Split [%]	-	-	76	50
Homologate Fuel Consumption [lt/100km]	5.53	5.27	4.93	4.18
Homologate CO_2 Emissions [g/km]	147	132	123	104

An advantage of the dual-fuel combustion is the possibility to reduce the NOx and soot emissions at the same time. This is not possible with the conventional diesel combustion because the increase of the EGR rate, that allows a decrease in NOx, increases the soot emissions, mainly due to the lack of air available to the particle oxidation. However, as RCCI combines high EGR rates and full premixed combustion, it avoids the local rich zones that promote the soot formation. Figure 8 shows the gains achieved with the use of both technologies. The additional benefits of the electrification are low and it is seen that the main reason of the decrease is due to the combustion mode. The dual-fuel MHEV and dual-fuel no-hybrid have approximately the same engine-out soot values. Moreover, at the same NOx level, Figure 8 shows that the optimum case is below the Euro 6 limit (0.005 g/km). Therefore, ideally it is not necessary to use diesel particle filter or others ATS in the dual-fuel vehicles compared with the OEM.

One of the main disadvantages of the RCCI dual-fuel combustion is the increase of CO and HC emissions. This behavior was well studied in previous works [53], and the reasons found were the low combustion temperature, that decrease the CO conversion, and the gasoline injection in the intake stroke, that increase the HC emissions due to the crevice trap effect. Figure 9a show that the dual-fuel combustion increases the CO emissions from 0.8 g/km of the OEM to 1.6 g/km in dual-fuel no-hybrid. However, the hybrid vehicles use the upper part of the engine map (high BMEP) due to the recharging of the batteries, where the ICE produces lower CO emissions. Therefore, with the hybrid dual-fuel configuration it is possible to achieve the same engine-out CO values than the OEM. The HC emissions show a similar behavior, with the difference that, even with the electrification of the powertrain, the HC are over the OEM (Figure 9b). In spite of the CDC has lower HC and CO emissions, for all cases it is necessary to use a diesel oxidation catalyst (DOC) to achieve Euro 6 limits. In this sense, as demonstrated in a previous work of the research group, this values of CO and HC will have above 90% of conversion efficiency using a commercial DOC system [52].

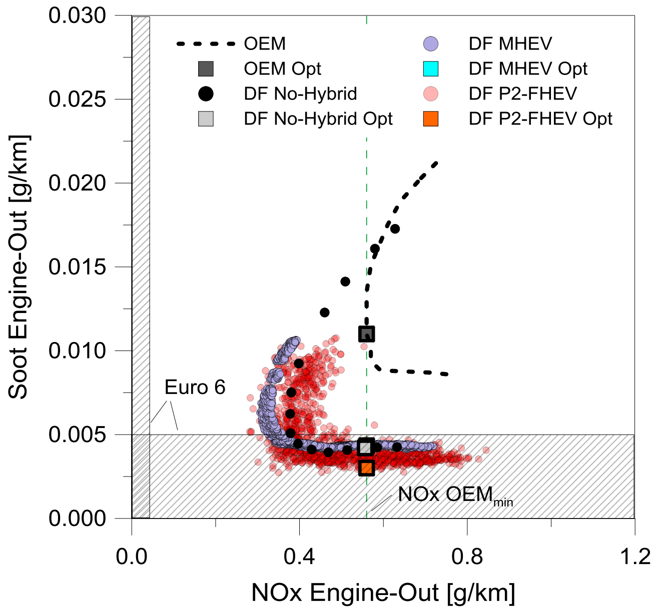


Figure 8 – Soot against NOx engine-out emissions for MHEV and FHEV. The baseline cases (OEM, DF No-hybrid) and the optimum value was included.

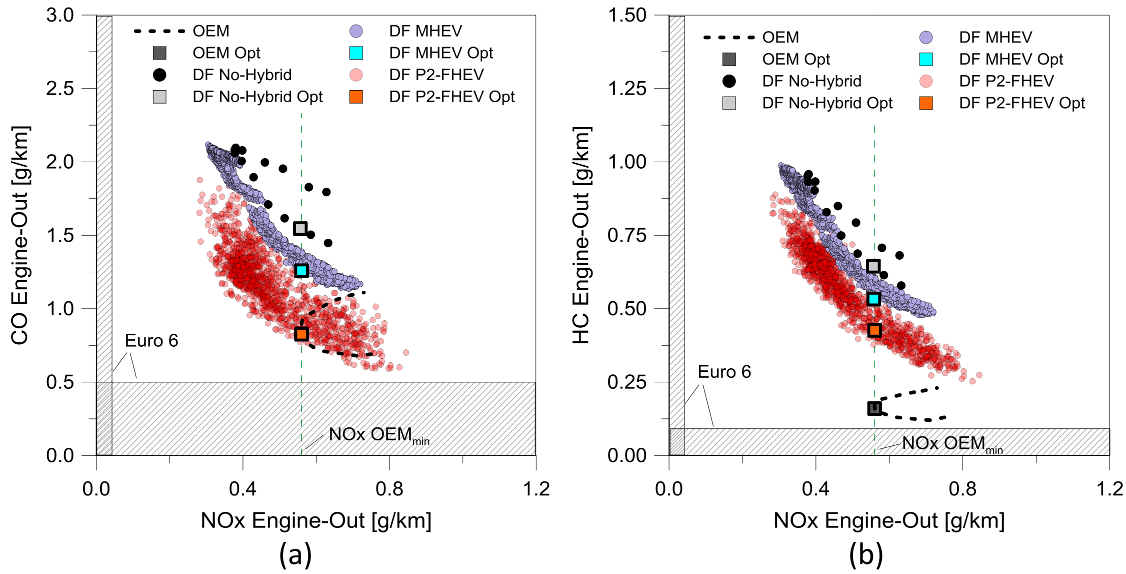


Figure 9 – CO (a) and HC (b) against NOx engine-out emissions for MHEV and FHEV. The baseline cases (OEM, DF No-hybrid) and the optimum value was included.

3.2. Plug-in Hybrid Dual-fuel Optimization

After the analysis of hybrid electric vehicles without the possibility to re-charge the batteries with the electricity grid, the aim of this section is to present the potential of plug-in electric vehicles using dual-fuel combustion mode. As was explained in section 2.2, this type of vehicles needs to perform different type of cycles in the homologation procedure. One type is the charge depleting and the other is the charge sustaining mode. In addition, this behavior is representative of the normal usage when the user starts with 100% of battery charge and drives further than the electric range. So, the ICE starts until a re-charge of the battery with the grid connection is done. Table **8** shows the different parameters and range tested to explore the PHEV behavior. The parameters of Table 7 are the same of Table 4 with the exception of the control of the maximum vehicle speed at pure electric mode and the split of the charge in power assist mode, which have no sense in PHEV.

Table 8 – DoE parameters for the optimization of the dual-fuel Plug-in hybrid electric vehicle.

Parameter	Dual-fuel PHEV
Electric Motor Capacity [kW]	50 - 90
Battery Package Capacity [kWh]	1 - 50
Gear Shift Strategy [-]	0.7 – 1.3

The electric range (ER) is one of the most important parameters in the study of this type of vehicles due to the direct impact in the UF that corrects the fuel consumption and emissions (see Figure 5). Also, countries as Spain give the “zero emission sticker” depending on the electric range. Figure 10 shows that the battery size has the highest impact on the electric range instead of the electric motor or the shift coefficient. Also, the trend is linear (R^2=0.998) with the increment of the battery size. The maximum battery capacity tested (50 kWh) allows a pure electric mode of 179 km. It is important to note that higher battery capacities could improve this range. However, it was not studied in this work due to be not representative of the current passenger vehicles due to the high cost [21]. The utility factor presented in Figure 10 is the UF sum in each phase of the WLTC ($\sum_{j=1}^{k} UF_j$), that is used in Eq. 3.

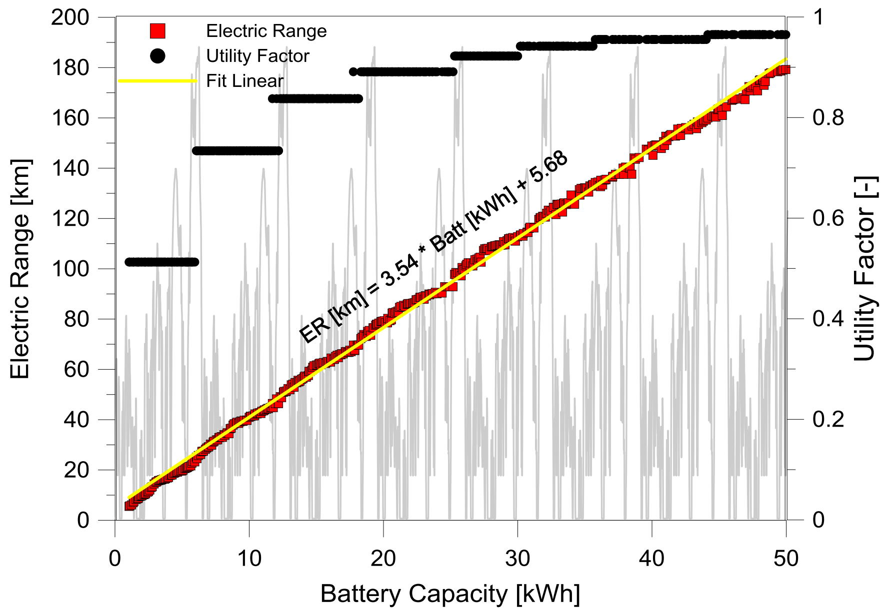


Figure 10 – Electric range and utility factor for all the dual-fuel PHEV configurations against the battery size.

Figure 11 depicts the fuel consumption before (engine-out) and after (weighted) the use of the UF correction. The square points are the all DoE cases with variation of the three parameters depicted in Table 8. The lines are the results for the PHEV varying the battery capacity and using a fixed electric motor size and shift coefficient. It is possible to see that the main parameter that affect the final fuel consumption is the battery size as in the case of the electric range. For Figure 11a, the electric motor selected is a mid-size with 70 kW of capacity and the shift coefficient was selected as the OEM (1.0). When comparing the weighted line with respect to the engine-out line, it is possible to observe that the UF solve the sawtooth behavior of the fuel consumption. This occurs because the vehicle needs an additional WLTC test in charge depleting mode to meet the $REEC_i < 4\%$ (Eq. 1). Therefore, in the next cycle the ICE will be switched on for more time, increasing the fuel consumption. Figure 11b shows the effect of varying the battery size and the shift coefficient in the extremes (0.7-1.3). The lowest value of shift coefficient decreases the fuel consumption and the opposite trend is seen with the highest shift coefficient. The OEM shift strategy is in the middle of these values. As it can be confirmed, the variations are below 0.5%.

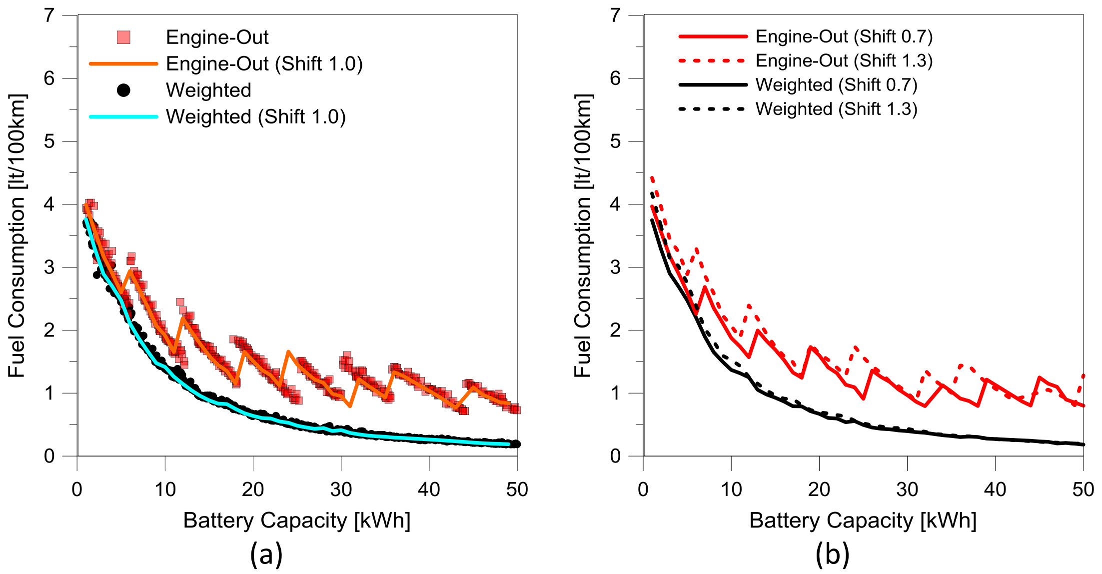


Figure 11 – Fuel consumption against battery capacity for PHEV in the homologation cycle with all DoE cases (a) and changing the shift coefficient (b).

It is also interesting to evaluate the fuel consumption in the two different battery conditions. Figure 12 shows that in charge depleting mode, the fuel consumption is low, below 2.0 lt/100km, for battery sizes over 5 kWh. Also, the sawtooth trend explains the behavior of the total fuel consumption in the cycle. It is possible to observe that for battery sizes with ER near a multiple of the WLTC range (23.2 km), the fuel consumption is almost zero (just below a multiple of the WLTC range) or locally maximum (just above a multiple of the WLTC range). On the other hand, the charge sustaining phase shows a more stable fuel consumption near 4.7 lt/100km, which increases slightly with the battery capacity due to the addition of extra weight. The shift coefficient does not show a great effect in the charge depleting range. However, for the charge depleting range, the differences are almost 0.5 lt/100 km higher for the soft gear shift (1.3) compared to the most aggressive strategy (0.7).

Similar trend was seen for the engine-out CO_2 emissions. The target set for this emission value is 50 g/km, which is generally expected for vehicles with high electrification capacity. Some countries give additional taxes benefits for vehicles with ultra-low CO_2 emissions. Figure 13a show that with a battery capacity above 7 kW/h it is possible to achieve the tax target for this dual-fuel PHEV. On the other hand, Figure 13b shows the CO2 emissions for the depleting and sustaining phases. This figure remarks the importance of the daily charging of the PHEV and the use of the vehicle in the range stipulated by the normative. Otherwise, the charge sustaining mode leads to greater CO_2 than a full and mild hybrid vehicle (Table 7).

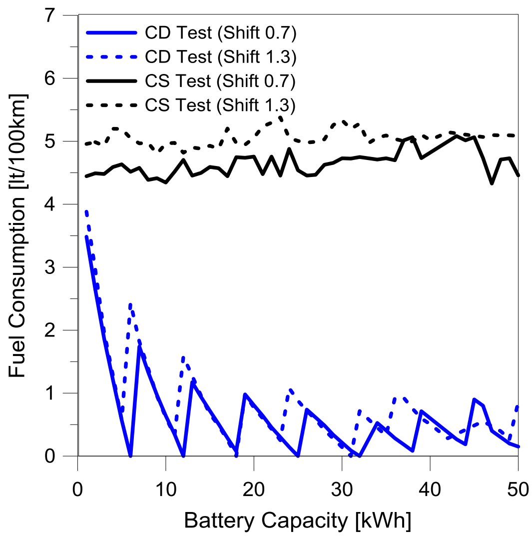


Figure 12 – Fuel consumption against battery capacity for PHEV in the homologation cycle at charge depleting and charge sustaining test.

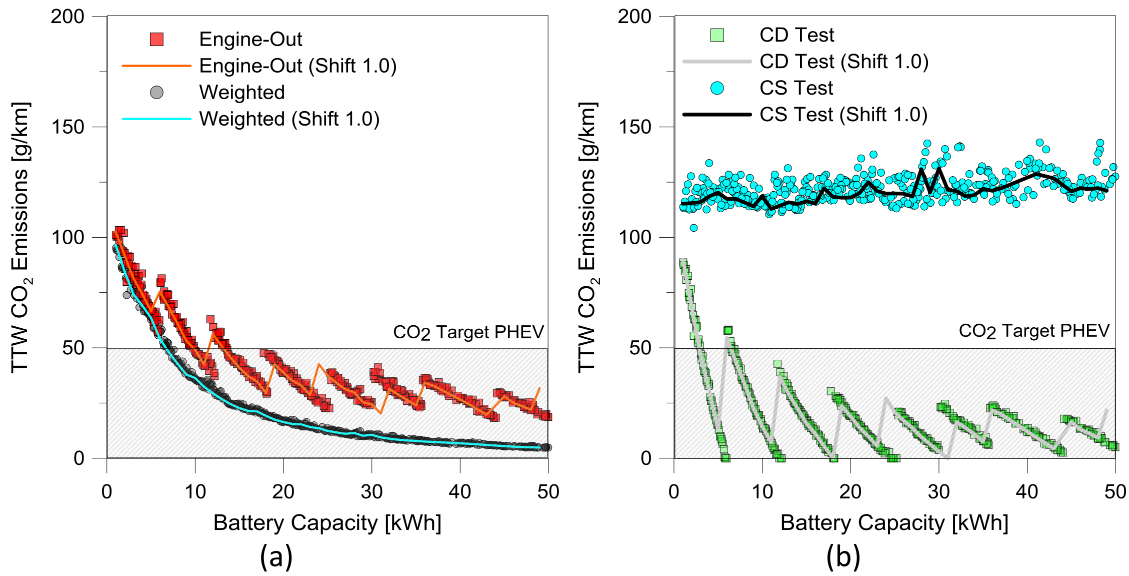
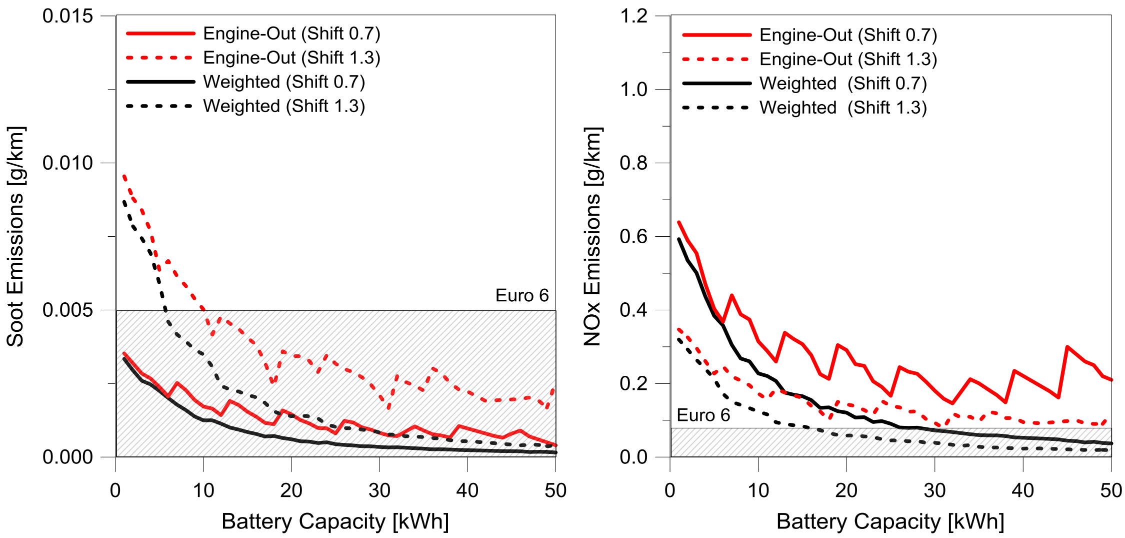


Figure 13 – Tank-to-Wheel (TTW) CO_2 emissions against battery capacity for PHEV in the homologation cycle for the total cycle (a) and for the charge depleting and sustaining test (b).

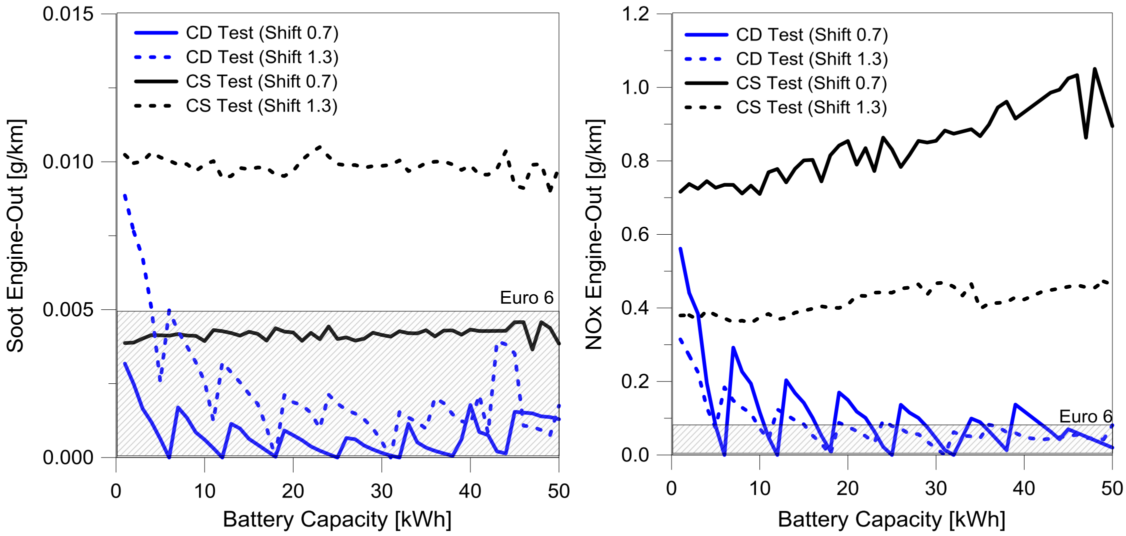
As was seen for the other hybrid vehicles, soot and NOx emission are other main concerns that need to be reduced to achieve the Euro 6 targets in CI engines. Figure 14 shows that it is possible to achieve Euro 6 levels in terms of soot and NOx with the dual-fuel combustion and plug-in powertrain with battery size above 20-30 kWh depending on the gear shift strategy. This is one of the greatest advantages of this type of architecture due to the inability of the other technologies to achieve these ultra-low values (Figure **7**). For the soot emissions (Figure 14a), the weighted values are below euro 6 for all the battery sizes if the gear shift is aggressive and for all the gear strategies if the battery is above 10 kWh. This is in line with the results seen in Figure 8 for the all dual-fuel vehicles. On the other hand, Figure 14b shows that to achieve the Euro 6 NOx emission target is necessary to select a high battery capacity. With a soft shift strategy (1.3) 15 kWh of battery capacity is enough. However, due to the operation zone of the engine map (high BMEP and low rpm) the hard shift strategy needs 25 kWh to achieve the desired NOx target.

The results divided into depleting and sustaining mode (Figure 14) evidence that high NOx values are emitted if the sustaining mode is used for long periods. Also, for soot emissions and shift strategy of 1.3, the emissions are double than the Euro 6 limits. As was seen in the CO_2 emissions, the user operation of the vehicle is critical to not emitting large amount of pollutants. In this sense, the dual-fuel operation gives some margin when using the charge sustaining mode due to the low emissions as compared to the OEM diesel engine operation.



(a) (b)

Figure 14 – Soot emissions (a) and NOx emissions (b) for a dual-fuel PHEV in the homologation cycle.



(a) (b)

Figure 15 – NOx emissions (a) and soot emissions (b) for a dual-fuel PHEV in charge depleting and charge sustaining mode for different battery capacity and two shift strategies.

The next step in the analysis is the selection of the optimum PHEV configuration. In the case of mild and full hybrid the criteria used was to reach the minimum fuel consumption with the same NOx engine-out emissions levels with respect to the OEM. This selection was done due to the impossibility of the vehicle to achieve the Euro 6 and the CO_2 target. However, the plug-in vehicles allow to achieve the Euro 6 together with ultra-low engine-out CO_2 emissions. Therefore, the best powertrain configuration was considered the one that allows to achieve the Euro 6 NOx target at the engine-out together with 50 g/km of CO_2 (tax benefits). Figure 16a shows all the DoE cases for the PHEV in terms of CO_2 and NOx engine-out emissions. The square black point highlights the first optimum case that achieve the above-mentioned requirements with the minimum battery size. This is important to reduce the final cost of the vehicle. However, Figure 16b shows that it is possible to reduce even more the total energy consumption if higher battery size is used. As was shown in Figure 13 and Figure 14 the CO_2 and NOx also are reduced with the increase of the battery size. This means that the black circle point in Figure 16a allows achieving the desired optimum targets with even more energy consumption benefits than the square point. For this reason, two optimum points were selected for the dual-fuel PHEV. Table 9 shows a summary of the optimum powertrain configuration. The optimum 2 has 12.6 kWh of extra battery capacity and use a soft shift strategy instead of a hard strategy seen for the optimum 1. This result is in line with the two trends in Figure 14a. It is important to note that exist intermediate cases that could improve the energy consumption with NOx at Euro 6 limit. However, for the brevity of the manuscript, the two extremes were studied. In addition, the left points of Euro 6 limits were not selected because have greater battery size without benefits to the manufacturers in terms of NO_X (emissions below Euro 6 have not taxes benefits) and the extra benefits in energy consumption are minimum after optimum 2 (flat trend above 25 kWh in Figure 16b). So, the extra cost of the vehicle due to the higher battery size is not justified. Figure B3 show the operating point in CD and CS modes for the optimum 1. It necessary to take care in the Figure B3a because represents the operation over 70 km (3 WLTC) instead of 23 km (1 WLTC) as the other cases.

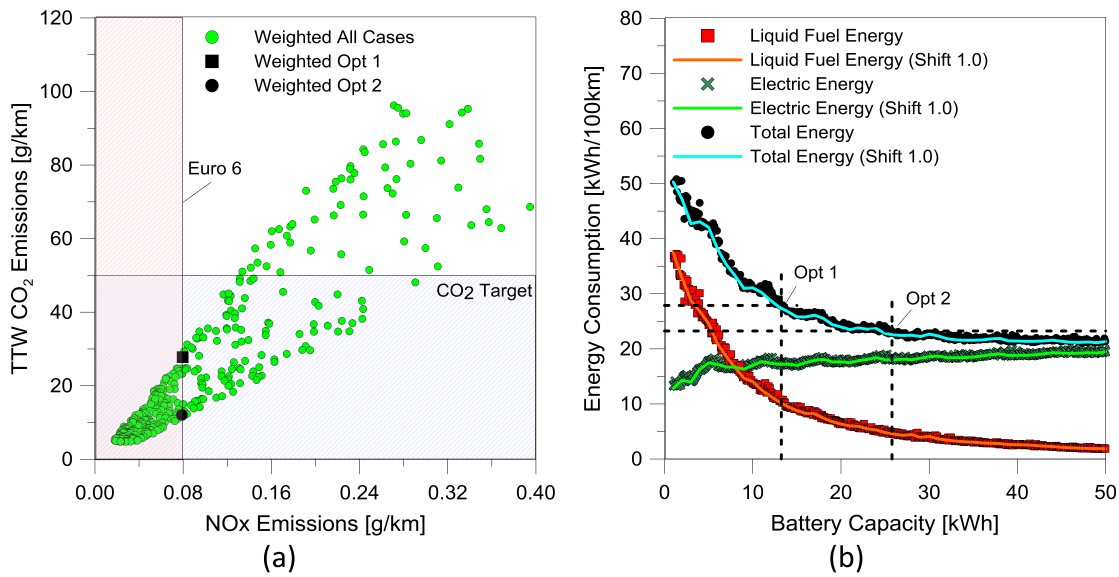


Figure 16 – CO_2 tank-to-wheel against NOx emissions (a) and total, fuel and electric energy consumption (b) for the different DoE cases in a dual-fuel PHEV. The two optimum selection is marked with black points.

Table 9 – Optimum hardware and control selection for dual-fuel PHEV to meet the WLTP.

Parameter	Dual-fuel PHEV Option 1	Dual-fuel PHEV Option 2
Electric Motor Capacity [kW]	88	84
Battery Package Capacity [kWh]	13.2	25.8
Gear Shift Strategy [-]	1.13	0.74
Total Vehicle Weight [kg]	1733	1857
Electric Range [km]	54	97
Homologate Fuel Consumption [lt/100km]	1.08	0.47
Homologate Electric Consumption [kWh/100km]	17.1	18.6
Homologate TTW CO_2 Emissions [g/km]	28	12

To have an overall perspective of the results, Figure 17 shows the total energy consumption of the different powertrain configurations against the engine-out NOx emissions. In addition to the benefits in terms of NOx emissions, the PHEV allows to reduce the energy consumption. This means that the sum of fuel and electricity energy are lower than that for vehicles using only liquid fuels. The benefits are: 50%, 42% and 32% with respect to the OEM, MHEV and FHEV respectively. In addition, the figure shows that the use of ATS for NOx is imperative for non-plug in vehicles to achieve Euro 6 for this ICE operating with CDC or RCCI.

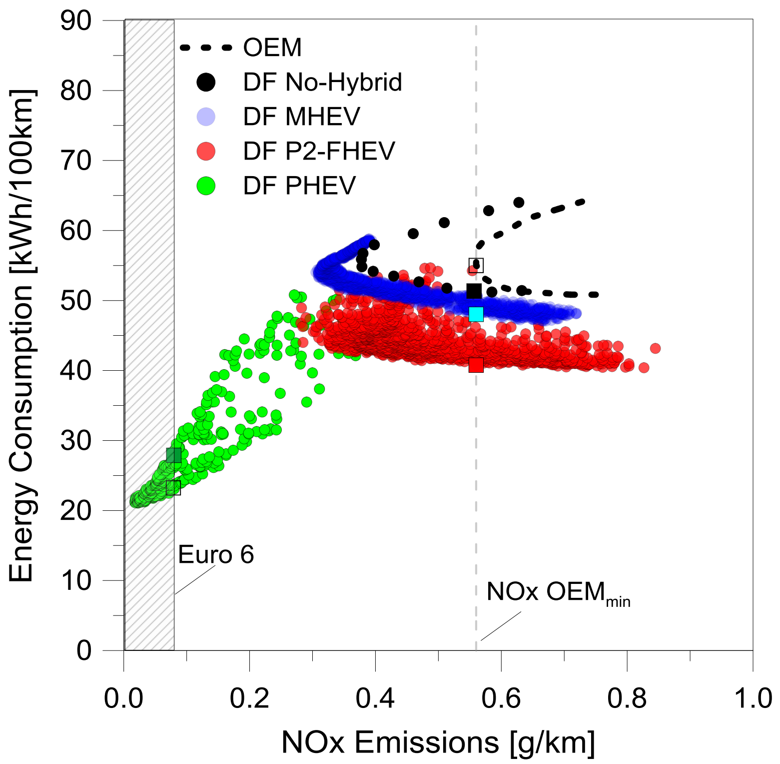
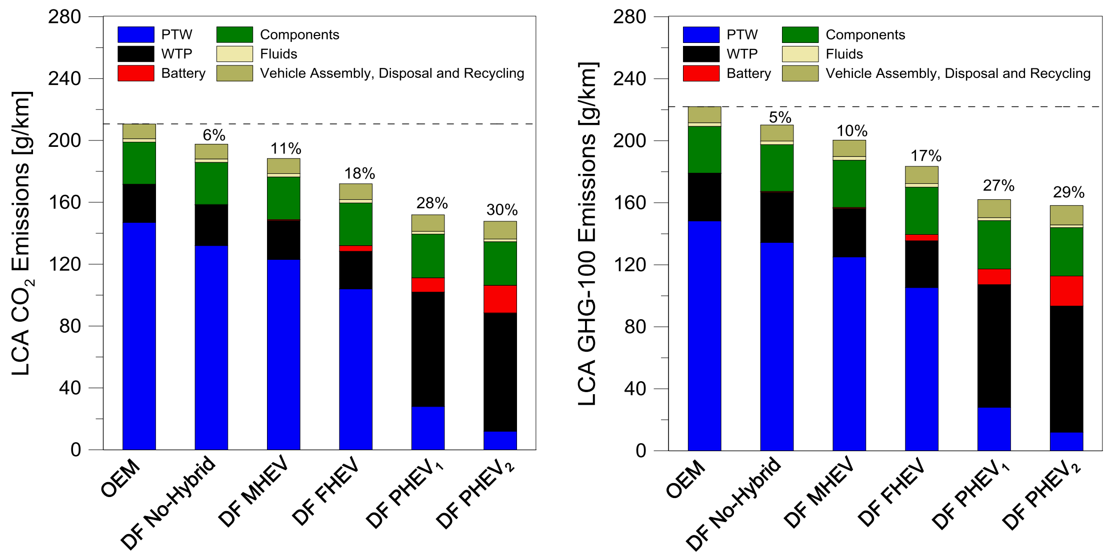


Figure 17 – Total energy consumption for the different DoE cases in a dual-fuel MHEV, FHEV and PHEV. The baseline cases, OEM and No-hybrid cases are included ass the optimum values in square points.

3.3. Life Cycle Results

The LCA results are presented in this section for the main emissions that affect the global and local pollution of the world coming from the vehicle platforms studied in this work. Figure **18** shows the CO_2 emissions and GHG-100 for all hybrid and no-hybrid technologies. The dashed line shows the baseline case of the OEM diesel vehicle. It is possible to see a strong decrease with the electrification capacity with a minimum for PHEV. In spite of the PHEV option 2 has the lowest CO_2 emission at tailpipe (60% lower than the PHEV option 1), the CO_2 LCA was close between both options with only 4 g/km of difference. This effect is the combination of higher CO_2 production in the battery and electricity production (higher WTT than PHEV option 1). In addition, the 86% CO_2 reduction seen in the tailpipe between PHEV and OEM (see difference between Figure 7b and Figure 16a) is seen to decrease down to 30% in the LCA analysis. Mainly by the effect of adding the CO_2 emissions corresponding to the electricity production and the battery production. The difference between CO_2 and GHG-100 are minimum with an increase of around 5 g/km for GHG-100. Also, the dual-fuel vehicles maintain the difference with the OEM approximately. The components CO_2 (green bar) addition is almost constant between the vehicles because the main contribution is produced by the vehicle body fabrication (87%) and tire replacement (9%), which is the same for all vehicle platforms. The EM size do not have a notable effect in this point (4%).



(a) (b)

Figure 18 – CO_2 and GHG-100 emissions results for the different hybrid and no-hybrid vehicle extracted from LCA analysis.

Other results of the LCA as the energy and water consumption are presented in Table **10**. The dual-fuel combustion mode increases slightly the energy consumption due to higher heating value of the gasoline. However, with the electrification of the powertrain this trend is reverted with a minimum for the PHEV vehicle (8% lower than OEM). On the other hand, the water consumption suffers an abrupt increase when passing from the FHEV to the PHEV due to the higher use in the electricity production.

Table 10 shows the same NOx levels for the dual-fuel no-hybrid and the MHEV and FHEV dual-fuel vehicle. On the other hand, the NOx emissions for the PHEV are slightly above the mentioned level due to the higher NOx production in the WTT. It is important to note that the engine-out NOx in the vehicles is reduced by the addition of the SCR-Urea to achieve the Euro 6 legislation target. Therefore, Table 10 shows the NOx emissions taking in account 0.08 g/km in the tailpipe and the emissions in the production of the fuels. The Sulphur oxides emissions are mainly due to the presence and burning of Sulphur compound in the fuel production. At the engine-out, the amount of Sulphur oxides is negligible. The PHEV shows higher Sulphur oxides values in the LCA models as well as the particle matters. In both cases, these levels are associated to the no renewable source of the electricity production. Lastly, volatile organic compounds (VOC) are emitted as gases from certain solids or liquids. VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects. The main processes that added this type of compound are the vehicle body fabrication, assembly and discard. For this reason, the values for all vehicle types are close.

Table 10 – LCA parameters consumption and emissions

Parameter	OEM	Dual-fuel No-Hybrid	Dual-fuel MHEV	Dual-fuel P2-FHEV	Dual-fuel PHEV Option 1	Dual-fuel PHEV Option 2
Total Energy [MJ/100km]	284	290	283	282	261	261
Total Water [lt/100km]	34	35	35	38	121	135
NOx [g/km]	0.16	0.16	0.16	0.16	0.23	0.24
SOx [g/km]	0.17	0.17	0.18	0.22	0.33	0.44
PM [g/km]	0.04	0.03	0.03	0.03	0.07	0.08
VOC [g/km]	0.06	0.07	0.07	0.07	0.06	0.06

4. Conclusions

This work investigated the potential of implementing the dual-fuel RCCI combustion mode in a plug-in hybrid vehicle platform. The results are compared against other electrifications levels and no-hybrid vehicles under the WLTP normative.

From this study, it was found that:

- Dual-fuel combustion mode allows to decrease the fuel consumption in 5% if comparing at the same NOx level than conventional diesel combustion. Also, it is possible to reduce 30% the NOx emissions at the same fuel consumption level than the OEM. Moreover, the improvements in soot emissions in the medium load zone of the engine maps allows to achieve Euro 6. This suggest a potential to reduce the DPF system requirements. However, additional future works to measure the particle number is needed.
- The combination of dual-fuel combustion with mild and full hybrid electrified levels allows extra gains in fuel consumption with a maximum for FHEV of 25% with respect to the OEM. This gain is attributed to better ICE engine map use and the regenerative braking capacity. However, it is not possible to achieve the CO_2 target necessary for 2021, with a difference of 9 g/km between the best hybrid (no plug-in) and the 95 g/km target.
- The plug-in technology under the actual WLTP normative allows a strong reduction in fuel consumption and tailpipe emissions. The 50 g/km target for ultra-low CO_2 emissions vehicles and the Euro 6 normative can be achieved in weighted values. The main parameter that allows this achievement is the use of a high battery capacity package. However, in the sustaining mode the NOx targets are not achieved so the SCR-Urea needs to be implemented.

- The PHEV operating with dual-fuel combustion shows a total energy consumption reduction up to 25 kWh of battery capacity. After this value, the total energy trend was flat. However, above 15 kWh the gains are minimum and two options of optimum powertrain were selected.
- The LCA shows that between 15 and 25 kWh of battery the GHGs were minimum (difference of 2%). However, the benefits for the use of PHEV instead of MHEV or FHEV are high, with differences of 19% and 12% respectively.

The results show that PHEV technology together with dual-fuel consumption has strong potential to reduce local and global pollution. However, it is important to note that the vehicle usage and the owner responsibility are crucial to the real benefits of this technology. These impacts are not direct in other hybrid technologies as MHEV or FHEV.

Acknowledgments

The authors acknowledge FEDER and Spanish Ministerio de Economía y Competitividad for partially supporting this research through TRANCO project (TRA2017-87694-R). The authors also acknowledge the Universitat Politècnica de València for partially supporting this research through Convocatoria de ayudas a Primeros Proyectos de Investigación (PAID-06-18).

References

[1] Rahman SMA, Masjuki HH, Kalam MA, Abedin MJ, Sanjid A, Sajjad H. Impact of idling on fuel consumption and exhaust emissions and available idle-reduction technologies for diesel vehicles - A review. Energy Convers Manag 2013;74:171–82. doi:10.1016/j.enconman.2013.05.019.

[2] Chen D, Jiang J, Kim GH, Yang C, Pesaran A. Comparison of different cooling methods for lithium ion battery cells. Appl Therm Eng 2016;94:846–54. doi:10.1016/j.applthermaleng.2015.10.015.

[3] Qiao Q, Zhao F, Liu Z, He X, Hao H. Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle. Energy 2019;177:222–33. doi:10.1016/j.energy.2019.04.080.

[4] Huda M, Aziz M, Tokimatsu K. The future of electric vehicles to grid integration in Indonesia. Energy Procedia 2019;158:4592–7. doi:10.1016/j.egypro.2019.01.749.

[5] Taljegard M, Göransson L, Odenberger M, Johnsson F. Impacts of electric vehicles on the electricity generation portfolio – A Scandinavian-German case study. Appl Energy 2019;235:1637–50. doi:10.1016/j.apenergy.2018.10.133.

[6] González LG, Siavichay E, Espinoza JL. Impact of EV fast charging stations on the power distribution network of a Latin American intermediate city. Renew Sustain Energy Rev 2019;107:309–18. doi:10.1016/j.rser.2019.03.017.

[7] Reijnders J, Boot M, de Goey P. Impact of aromaticity and cetane number on the soot-NOx trade-off in conventional and low temperature combustion. Fuel 2016;186:24–34. doi:10.1016/j.fuel.2016.08.009.

[8] Benajes J, García A, Monsalve-Serrano J, Villalta D. Exploring the limits of the

reactivity controlled compression ignition combustion concept in a light-duty diesel engine and the influence of the direct-injected fuel properties. Energy Convers Manag 2018;157:277–87. doi:10.1016/j.enconman.2017.12.028.

[9] Xu HT, Luo ZQ, Wang N, Qu ZG, Chen J, An L. Experimental study of the selective catalytic reduction after-treatment for the exhaust emission of a diesel engine. Appl Therm Eng 2019;147:198–204. doi:10.1016/j.applthermaleng.2018.10.067.

[10] Guan B, Zhan R, Lin H, Huang Z. Review of state of the art technologies of selective catalytic reduction of NOx from diesel engine exhaust. Appl Therm Eng 2014;66:395–414. doi:10.1016/j.applthermaleng.2014.02.021.

[11] Mera Z, Fonseca N, López J-M, Casanova J. Analysis of the high instantaneous NOx emissions from Euro 6 diesel passenger cars under real driving conditions. Appl Energy 2019;242:1074–89. doi:10.1016/j.apenergy.2019.03.120.

[12] Zehni A, Khoshbakhti Saray R, Poorghasemi K. Numerical comparison of PCCI combustion and emission of diesel and biodiesel fuels at low load conditions using 3D-CFD models coupled with chemical kinetics. Appl Therm Eng 2017;110:1483–99. doi:10.1016/j.applthermaleng.2016.09.056.

[13] Benajes J, García A, Monsalve-Serrano J, Villalta D. Benefits of E85 versus gasoline as low reactivity fuel for an automotive diesel engine operating in reactivity controlled compression ignition combustion mode. Energy Convers Manag 2018;159:85–95. doi:10.1016/j.enconman.2018.01.015.

[14] García A, Monsalve-Serrano J, Rückert Roso V, Santos Martins ME. Evaluating the emissions and performance of two dual-mode RCCI combustion strategies under the World Harmonized Vehicle Cycle (WHVC). Energy Convers Manag 2017;149:263–74. doi:10.1016/j.enconman.2017.07.034.

[15] Huo Y, Yan F, Feng D. A hybrid electric vehicle energy optimization strategy by using fueling control in diesel engines. Proc Inst Mech Eng Part D J Automob Eng 2019;233:517–30. doi:10.1177/0954407017747372.

[16] Williams B, Martin E, Lipman T, Kammen D. Plug-in-hybrid vehicle use, energy consumption, and greenhouse emissions: An analysis of household vehicle placements in northern California. Energies 2011;4:435–57. doi:10.3390/en4030435.

[17] Commission Regulation (EC) No 692/2008 of 18 July 2008 implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial veh. 2008.

[18] Paffumi E, De Gennaro M, Martini G. Alternative utility factor versus the SAE J2841 standard method for PHEV and BEV applications. Transp Policy 2018;68:80–97. doi:10.1016/j.tranpol.2018.02.014.

[19] Xie S, Hu X, Liu T, Qi S, Lang K, Li H. Predictive vehicle-following power management for plug-in hybrid electric vehicles. Energy 2019;166:701–14. doi:10.1016/j.energy.2018.10.129.

[20] Rocco M V., Casalegno A, Colombo E. Modelling road transport technologies in future scenarios: Theoretical comparison and application of Well-to-Wheels and Input-Output analyses. Appl Energy 2018;232:583–97. doi:10.1016/j.apenergy.2018.09.222.

[21] Plötz P, Funke SÁ, Jochem P. The impact of daily and annual driving on fuel economy and CO2emissions of plug-in hybrid electric vehicles. Transp Res Part A Policy Pract 2018;118:331–40. doi:10.1016/j.tra.2018.09.018.

[22] Marmiroli B, Messagie M, Dotelli G, Van Mierlo J. Electricity Generation in LCA of Electric Vehicles: A Review. Appl Sci 2018;8:1384. doi:10.3390/app8081384.

[23] Meisterling K, Samaras C. Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles : Implications for Policy. Environ Sci Technol 2008;42:3170–6.

[24] de Souza LLP, Lora EES, Palacio JCE, Rocha MH, Renó MLG, Venturini OJ. Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. J Clean Prod 2018;203:444–68. doi:10.1016/j.jclepro.2018.08.236.

[25] Burnham A. User Guide for AFLEET Tool 2018 2018:45.

[26] Wang M, Han J, Dunn JB, Cai H, Elgowainy A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environ Res Lett 2012;7:045905. doi:10.1088/1748-9326/7/4/045905.

[27] Lu Z, Han J, Wang M, Cai H, Sun P, Dieffenthaler D, et al. Well-to-Wheels Analysis of the Greenhouse Gas Emissions and Energy Use of Vehicles with Gasoline Compression Ignition Engines on Low Octane Gasoline-Like Fuel. SAE Int J Fuels Lubr 2016;9:527–45. doi:10.4271/2016-01-2208.

[28] Argon. A review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs 2010.

[29] Millo F, Ferraro C V, Rolando L. Analysis of different control strategies for the simultaneous reduction of CO 2 and NO x emissions of a diesel hybrid passenger car. Int J Veh Des 2012;58:427–48. doi:10.1504/IJVD.2012.047393.

[30] Asghar M, Bhatti AI, Ahmed Q, Murtaza G. Energy Management Strategy for Atkinson Cycle Engine Based Parallel Hybrid Electric Vehicle. IEEE Access 2018;6:28008–18. doi:10.1109/ACCESS.2018.2835395.

[31] Benajes J, García A, Monsalve-serrano J, Martínez-boggio S. Optimization of the parallel and mild hybrid vehicle platforms operating under conventional and advanced combustion modes. Energy Convers Manag 2019;190:73–90. doi:10.1016/j.enconman.2019.04.010.

[32] Benajes J, García A, Monsalve-Serrano J, Villalta D. Exploring the limits of the reactivity controlled compression ignition combustion concept in a light-duty diesel engine and the influence of the direct-injected fuel properties. Energy

Convers Manag 2018;157:277–87. doi:10.1016/j.enconman.2017.12.028.

[33] Talibi M, Hellier P, Watkinson M, Ladommatos N. Comparative analysis of H2-diesel co-combustion in a single cylinder engine and a chassis dynamometer vehicle. Int J Hydrogen Energy 2019;44:1239–52. doi:10.1016/j.ijhydene.2018.11.092.

[34] Benajes J, García A, Monsalve-Serrano J, Lago Sari R. Fuel consumption and engine-out emissions estimations of a light-duty engine running in dual-mode RCCI/CDC with different fuels and driving cycles. Energy 2018;157:19–30. doi:10.1016/j.energy.2018.05.144.

[35] Bao R, Avila V, Baxter J. Effect of 48 V Mild Hybrid System Layout on Powertrain System Efficiency and Its Potential of Fuel Economy Improvement. WCX™ 17 SAE World Congr. Exp., SAE International; 2017. doi:https://doi.org/10.4271/2017-01-1175.

[36] Liu Z, Ivanco A, Filipi ZS. Impacts of Real-World Driving and Driver Aggressiveness on Fuel Consumption of 48V Mild Hybrid Vehicle. SAE Int J Altern Powertrains 2016;5:2016-01–1166. doi:10.4271/2016-01-1166.

[37] Sarlioglu B, Morris CT, Han D, Li S. Benchmarking of electric and hybrid vehicle electric machines, power electronics, and batteries. 2015 Intl Aegean Conf. Electr. Mach. Power Electron., IEEE; 2015, p. 519–26. doi:10.1109/OPTIM.2015.7426993.

[38] Solouk A, Shakiba-Herfeh M, Arora J, Shahbakhti M. Fuel consumption assessment of an electrified powertrain with a multi-mode high-efficiency engine in various levels of hybridization. Energy Convers Manag 2018;155:100–15. doi:10.1016/j.enconman.2017.10.073.

[39] Driveline V. GT-SUITE 2016.

[40] Council GS of the. Proposal for a Regulation of the European Parliament and of the Council setting emission performance standards for new passenger cars and for new light commercial vehicles as part of the Union's integrated approach to reduce CO2 emissions from light-duty. Brussels: 2019.

[41] Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using 2001 U.S. DOT National Household Travel Survey Data 2009. doi:https://doi.org/10.4271/J2841_200903.

[42] Kaushik LK, Muthukumar P. Life cycle Assessment (LCA) and Techno-economic Assessment (TEA) of medium scale (5–10 kW) LPG cooking stove with two-layer porous radiant burner. Appl Therm Eng 2018;133:316–26. doi:10.1016/j.applthermaleng.2018.01.050.

[43] Gnansounou E, Dauriat A, Villegas J, Panichelli L. Life cycle assessment of biofuels: Energy and greenhouse gas balances. Bioresour Technol 2009;100:4919–30. doi:10.1016/j.biortech.2009.05.067.

[44] Deng T, Zhang G, Ran Y, Liu P. Thermal performance of lithium ion battery pack by using cold plate. Appl Therm Eng 2019;160:114088.

doi:10.1016/j.applthermaleng.2019.114088.

[45] Cai H, Han J, Forman G, Divita V, Amgad E, Wang M. Analysis of Petroleum Refining Energy Efficiency of U.S. Refineries. 2013.

[46] Moro A, Lonza L. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transp Res Part D Transp Environ 2018;64:5–14. doi:10.1016/j.trd.2017.07.012.

[47] Dai Q, Kelly JC, Dunn JB, Benavides PT. Update of Bill-of-materials and Cathode Materials Production for Lithium-ion Batteries in the GREET Model. 2018.

[48] Q. Dai, J. Dunn, J. Kelly, A. Elgowainy. Update of Life Cycle Analysis of Lithium-ion Batteries in the GREET Model. 2017.

[49] Stodolsky F, Vyas A, Cuenca R, Gaines L. Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles. SAE Tech Pap Ser 2010;1. doi:10.4271/951837.

[50] Auerbach M, Ruf M, Bargende M, Reuss H-C, Van Doorn R, Friedrich W, et al. Potentials of Phlegmatization in Diesel Hybrid Electric Vehicles. Highlighting Latest Powertrain, Veh. Infomobility Technol., SAE International; 2011. doi:https://doi.org/10.4271/2011-37-0018.

[51] Shields MD, Zhang J. The generalization of Latin hypercube sampling. Reliab Eng Syst Saf 2016;148:96–108. doi:10.1016/j.ress.2015.12.002.

[52] García A, Piqueras P, Monsalve-Serrano J, Lago Sari R. Sizing a conventional diesel oxidation catalyst to be used for RCCI combustion under real driving conditions. Appl Therm Eng 2018;140:62–72. doi:10.1016/j.applthermaleng.2018.05.043.

[53] Benajes J, García A, Monsalve-Serrano J, Sari R. Potential of RCCI Series Hybrid Vehicle Architecture to Meet the Future CO2 Targets with Low Engine-Out Emissions. Appl Sci 2018;8:1472. doi:10.3390/app8091472.

Abbreviations

ATS	Aftertreatment systems	LTC	Low Temperature Combustion
BEV	Battery electric vehicles	MHEV	Mild hybrid electric vehicle
BMEP	Brake mean effective pressure	NEDC	New European Driving Cycle
BoM	Bill of Materials		
$BSCO_2$	Brake specific CO_2 emissions	NOx	Nitrogen Oxides
BSFC	Brake specific fuel consumption	NOxEU6	Nitrogen oxide limit for Euro VI legislation
BSNOx	Brake specific NOx emissions	OEM	Original equipment manufacturer
CDC	Conventional diesel combustion	OMEx	Oxymethylene dimethyl ether
CI	Compression Ignition	P0	Belt alternator starter hybrid powertrain
CO	Carbon Monoxide	P2	Parallel hybrid electric vehicle
DI	Direct Injection	P2-FHEV	Parallel full hybrid electric vehicle
DOC	Diesel Oxidation Catalysts	PFI	Port fuel injection
DoE	Design of Experiments	PHEV	Plug in electric vehicle

DPF	Diesel Particulate Filter	PPCI	Partially premixed compression ignition
ECU	Engine control unit	PRR	pressure rise rates
EGR	Exhaust Gas Recirculation	TTW	tank-to-wheel
EM	Electric motor	RBC	Rule base control
EMS	Energy management system	RCCI	Reactivity Controlled Compression Ignition
EU	European Union	RDE	Real driving emission test
FCHEV	fuel cell hybrid electric vehicles	rpm	Revolution per minute
FHEV	Full hybrid vehicle	SCE	Single Cylinder Engine
GHG	Greenhouse gas emissions	SCR	Selective Catalytic Reduction
HC	Unburned Hydrocarbons	SI	Spark Ignition
HCCI	Homogeneous Charge Compression Ignition	SOC	State of the charge of the battery
HEV	Hybrid electric vehicle	UF	Utility factor
HRF	High Reactivity Fuel	UNECE	United Nations Economic Commission for Europe
ICE	Internal combustion engine	VGT	Variable geometry turbine
LCA	life-cycle analysis	WLTC	Worldwide Harmonized Light Vehicles Cycle
LI-Ion	Lithium Ion batteries	WLTP	Worldwide Harmonized Light Test Procedure
LRF	Low Reactivity Fuel	WTW	Well to wheel

Appendix A

Brake Specific fuel consumption map for the dual mode CDC-RCCI with gasoline as secondary fuel is presented in Figure A1. Also, the proportion between fuels (Diesel/Gasoline) is presented in Figure A2.

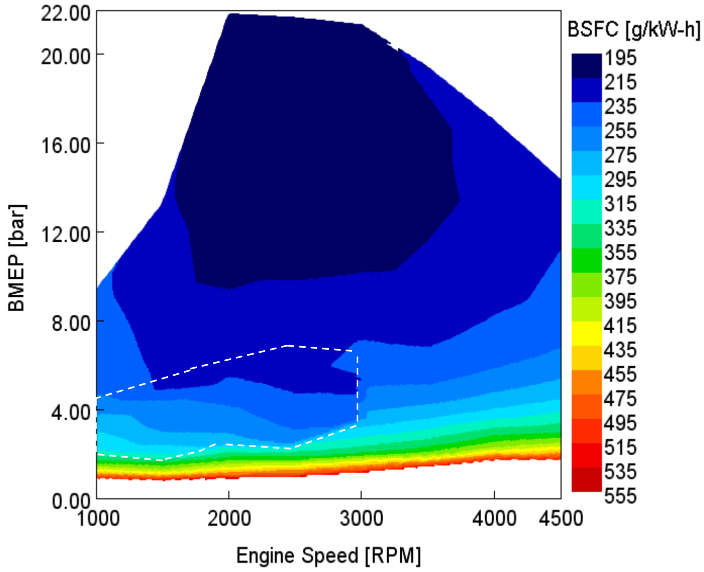


Figure A1 – Brake specific fuel consumption for the coupled CDC-RCCI engine map.

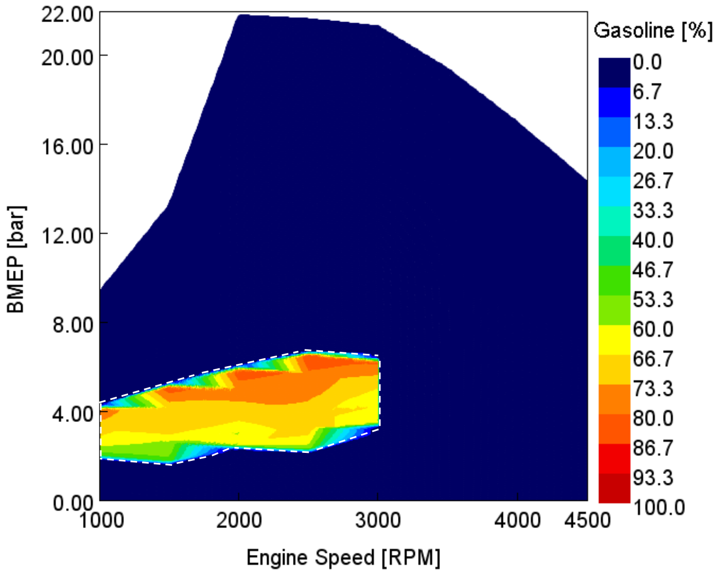
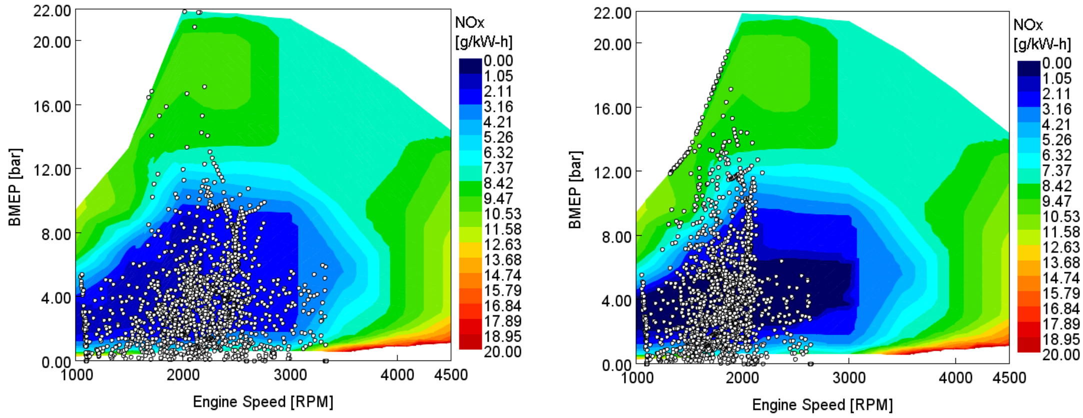


Figure A2 – Gasoline percentage in volume basis with respect to the total injected mass (Diesel + Gasoline).

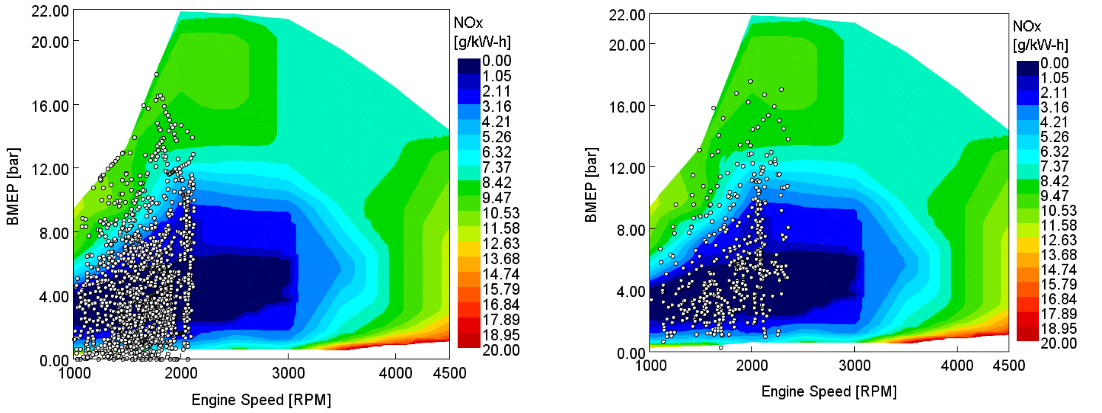
Appendix B

The operating points over the NOx engine map for the optimized vehicle platforms is presented from Figure B1 to Figure B3.



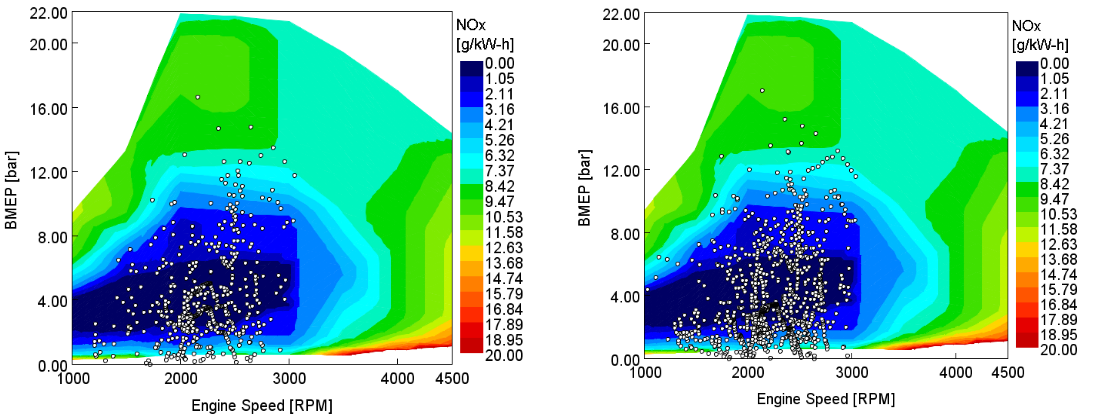
(a) (b)

Figure B1 – Operating points over the NOx calibration map for the OEM (a) and the dual fuel no-hybrid (b) vehicles in the WLTC with the optimum configuration.



(a) (b)

Figure B2 – Operating points over the NOx calibration map for the dual fuel MHEV (a) and P2 FHEV (b) vehicles in the WLTC with the optimum configuration.



(a) (b)

Figure B3 – Operating points over the NOx calibration map for the dual fuel PHEV in the CD(a) and CS (b) tests with the optimum 1 configuration.