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VIRTUAL CALIBRATION OF CO2 AND POLLUTANT EMISSIONS OF A HIGH-PERFORMANCE PHEV USING MODEL-IN-THE-LOOP METHODOLOGY

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0.1 Abstract

The study analyses the calibration process of a newly developed high-performance plug-in hybrid electric passenger car powertrain. The complexity of modern powertrains and the more and more restrictive regulations regarding pollutant emissions are the primary challenges for the calibration of a vehicle's powertrain. In addition, the managers of OEM need to know as earlier as possible if the vehicle under development will meet the target technical features (emission included). This leads to the necessity for advanced calibration methodologies, in order to keep the development of the powertrain robust, time and cost effective. The suggested solution is the virtual calibration, that allows the tuning of control functions of a powertrain before having it built. The aim of this study is to calibrate virtually the hybrid control unit functions in order to optimize the pollutant emissions and the fuel consumption. Starting from the model of the conventional vehicle, the powertrain is then hybridized and integrated with emissions and aftertreatments models. After its validation, the hybrid control unit strategies are optimized using the Model-in-the-Loop testing methodology. The calibration activities will proceed thanks to the implementation of a Hardware-in-the-Loop environment, that will allow to test and calibrate the Engine and Transmission control units effectively, besides in a time and cost saving manner.

0.2 Acknowledgment

This work is dedicated to all my friends and colleagues that supported me and believed in me during the activities and the thesis redaction. Firstly I want to mention Lorenzo B., that since the beginning transmitted me all the necessary know-how in a very paternal and caring way. A special thanks for Lorenzo M. that patiently supported and guided me through the activities performed in difficult period of the 03-06/2020 Covid-19 lockdown. Thanks to Mauro, that from the beginning believed in me and encouraged me on keeping up with the thesis project. I thank Michele, for having shown me the right direction to follow and for giving me the possibility to participate to this project (and to the future ones).

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1 Introduction

The aim of this chapter is to give the reader an overview of the functioning principles and architecture of conventional and hybrid propulsion powertrain, as well as the current regulations concerning emission and an introduction of the process of powertrain calibration.

1.1 Powertrain evolution in hystory

The definition of powertrain is a mechanical system composed of an energy generator, a transmission and a utilizer. For a light duty vehicle (i.e. passenger car), the most common energy generator is an internal combustion engine, that for nowadays powertrain can be coupled also with electric motors. The transmission is the complex of gearbox, friction clutch, shafts and differentials. The utilizer are the wheels and with them the entire vehicle. This architecture remained standard since the beginning of the automotive industry, what changed during time is the technology itself: it became more efficient and performant, but on the other side more complex to build and to control, as long as more difficult to adapt to environment's necessities.

1.1.1 The internal combustion engine

The internal combustion engine (ICE in short) is certainly the most complex and important part of a vehicle's powertrain. It is considered as a motive thermal machine, that converts in mechanical power the highest quantity of energy coming from fuel combustion inside the machine itself. The working fluid, that compresses and expands in the machine, exchanges the energy with the mobile organs of the engine. This fluid consists in a mixture of air and petrol before the combustion in the chamber, oxidation products after the combustion itself, that must be treated in order to be as harmless as possible before reaching the external ambient. Therefore, the "internal" name means that the combustion actually occurs internally to the machine, without the usage of external components like burners, in which to make the oxidation reactions happens, or heat exchangers.

The internal combustion engine is also a volumetric machine: the working fluid is elaborated in separated chambers called cylinders. The primary characteristic of a volumetric machine is its cyclical functioning: each cylinder intakes a certain amount of mixture, then after the combustion end expansion, expels the combustion products to the external ambient before a new aspiration phase occurs.

The most important classifications relative to the control of internal combustion engines are based on the charge ignition modality and the mixture of air/fuel supply:

1- Spark ignited engines: the mixture of air and petrol is ignited by an electronically controlled spark, coming from the electrodes of a plug. This combustion is very fast and ideally performed with constant volume.

2- Spontaneously ignited engines (Diesel engines): the fuel is injected through an highly pulverized spray into the hot air, causing self-ignition that leads in a slower and more gradual combustion than the one ignited by a spark. Ideally, the combustion is performed at a constant pressure.

3- Naturally aspirated engines: the movements of pistons inside cylinders determines a natural suction of air, coming from the external ambient.

4- Supercharged/turbocharged engines: the air is compressed through the use of a compressor coupled to a turbine and forced inside the combustion chamber.

5- Carburettor supplied engines: a fully mechanical component controls the amount of fuel and mixes it to the air for creating the fresh charge that flows inside the cylinder

6- Injection supplied engines: an electric impulse controls a injector needle that allows the spraying of the fuel or directly inside the chamber or just in front of it.

The focus of this dissertation is on a naturally aspirated, petrol (gasoline) powered, spark ignited, direct injection high-performance engine.

1.1.2 From mechanically to electronically controlled powertrains

A passenger car powertrain is a system that must be controlled continuously in order to satisfy both utilizer, safety and environmental needs. The control methods of a vehicle's powertrain is strictly dependant to its technology. In the past, the method for controlling a standard powertrain was simply mechanical. This means that the driver was directly connected in a physical way to the ICE and transmission subsystems (called actuators) that controls their functioning. The driver by the depression of the accelerator pedal was deciding directly the amount of air and subsequently fuel to be sent into the internal combustion engine.

This was happening with vehicles equipped with carburettors: the accelerator pedal was directly wired with the throttle butterfly valve: the depression of the pedal directly determined the amount of air sucked by the carburettors, that thanks to Bernoulli's law was able to provide the right amount of fuel for a stoichiometric combustion.

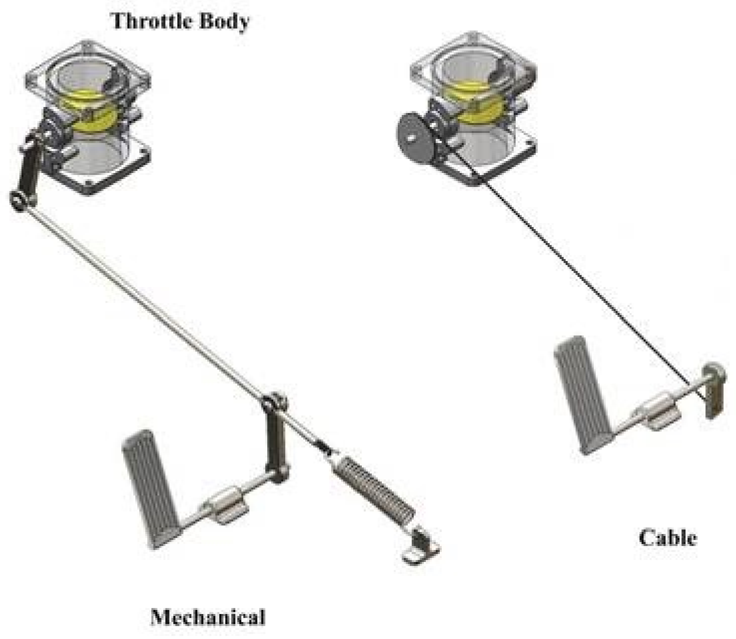


Figure 1: Example of mechanically controlled throttle valve

However, his way of controlling the internal combustion engine lacks in flexibility and elasticity, because it doesn't take into consideration external variables (temperature, altitude, etc…) and the necessity to control the pollutant emissions. This last need, in special, lead the development of the electronically controlled carburettor. With this device, the driver was physically detached to the throttle valve. This means that an electronic control unit was interposed between the accelerator pedal and the actual throttle valve. This control unit, stimulated by additional sensors on the ICE, was able to modify the throttle valve opening for responding to some conditions (like cold starts), but still there was a direct proportionality between the accelerator depression and the amount of opening of the valve. That meant better fuel dosing and preparation of the mixture, but still remained the necessity to control the combustion efficiently.

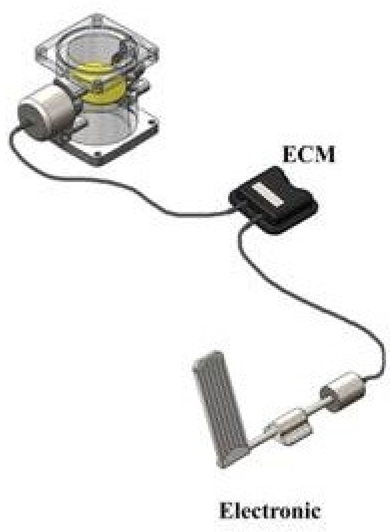


Figure 2: Example of electronically controlled throttle valve

A major control over the combustion phase was achieved by the introduction of the fuel injection system: the amount of fuel is now provided thanks to an electronically controlled nozzle (called injector) that sprays the fuel within the air, creating the necessary mixture for the combustion. This system is controllable in a multitude of parameters, reaching peaks of combustion efficiency without compromising driver's needs.

With the passing of time, the legislations regarding pollutants became much more restrictive and new technologies has been developed, like turbocharging and hybrid powertrain, but especially regarding emission aftertreatment systems like exhaust gas recirculation and three-way catalyst. These systems require the control of mixture to be as accurate as possible. Now, by depressing the accelerator pedal the driver doesn't choose anymore the amount of throttle opening, but he sends a signal of a torque requested at the wheel to the control units of the powertrain. With this information, the electronic control units manage the actuation of all the powertrain's sub-components, with the objective to satisfy both the torque requested by the driver and the combustion emissions requirements.

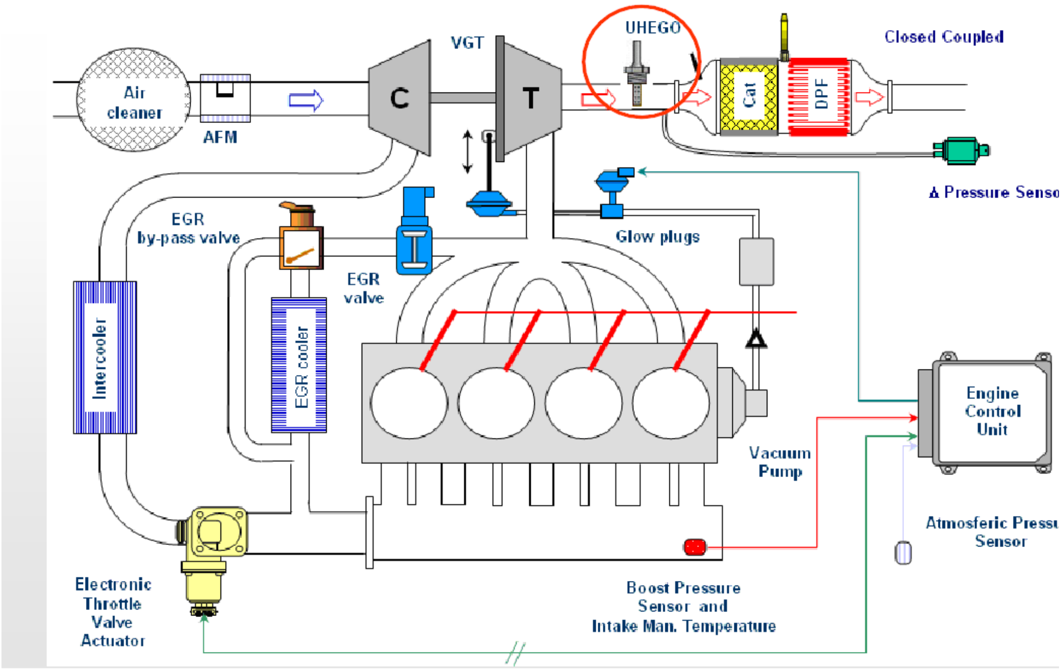


Figure 3: example of a modern powertrain

This way of controlling a powertrain reached nowadays the peak in difficulty and required effort, especially after the introduction of the hybrid powertrains.

1.1.3 Hybrid vehicles – architectures and functioning principles

Automobile manufacturers and engineers have spent the last decade trying to develop innovative solutions with the double purpose of satisfying the market request and complying to the constantly restrictive environmental regulations.

This research led the decision to modify the way in which a vehicle is propelled. The aim was to reduce the impact of the ICE on the ambient, by supporting it with additional, more clean power sources. The result was the development of hybrid vehicles, in which the primary energy source is still the internal combustion engine, assisted by various secondary power sources. The main types are:

- Hydraulic Hybrid: that kind of vehicles have a hydraulic pump as secondary mover or generator, which stores the energy in an auxiliary hydraulic accumulator where oil is used as operator fluid. For their weight and their characteristics, this powertrain is particularly indicated for heavy-duty vehicles;
- Kinetic Hybrid: kinetic hybrid powertrain contains a driveline with a high speed flywheel as auxiliary mover, with the possibility of storing kinetic energy, especially during regenerative braking.
- Compressed-air Hybrid: these vehicles are powered by motors which produce power thanks to the compressed-air expansion in a similar way of the steam engine. As a non-flammable fluid, the compressed-air can stored in pressurized tank up to 30MPa;
- Electric Hybrid here, the auxiliary energy source is the electro-chemical energy provided by Electric Motors, stored in typically high voltage batteries, which can be recharged thanks to the internal combustion engine coupling or during breaking/downhill phases.

The more promising technology in term of CO_2 reduction is the Hybrid Electric (these vehicles in short are defined HEVs). Focusing on this type of hybridization, its level depends on the range of influence of the electric motor over the entire vehicle propulsion. This level is indicated by the Hybridization Factor and described by the following equation:

$$HF = \frac{P_{EM,max}}{P_{ICE,max} + P_{EM,max}}$$

Table 1: Hybridization factor

Parameter name	***Description***

$P_{EM,max}$ [kW]	Maximum power of the secondary source of energy (electric motors – EM – for HEVs)
$P_{ICE,max}$ [kW]	Maximum power provided by the internal combustion engine

Where $P_{EM,max}$ is the maximum power of the secondary source of energy (electric motors – EM – for HEVs) while $P_{ICE,max}$ is the maximum power provided by the internal combustion engine. Based on this factor, the following typologies of Hybrid Electric Vehicles are identified:

- Micro Hybrid: with a HF of about 5%, it's a vehicle equipped with an electric motor linked to the ICE, that usually has only Start and Stop functionality. Most of the them have also some sort of Energy Management function, which optimizes the consumption of the low voltage (12 V) battery energy;
- Mild Hybrid: with a HF of about 15%, these types generally use a compact electric motor (power < 20kW) to provide auto-stop/start features, extra power assist during accelerations and to work as a generator on decelerations (regenerative braking). The battery is a low voltage battery of 48V, whose purpose is to actuate an Energy Management Strategy (EMS). Usually it allows only a minimum range of full electric drive.
- Full Hybrid: where the HF is about 35%, the electric machines and batteries are increased in size, allowing an extended full-electric drive. The recharging of the batteries can happen only with breaking recuperation and with the help of the ICE, because it isn't possible to do from external sources;
- Plug-in Hybrid (PHEV): is usually a general fuel-electric Off-Vehicle Charging (OVC) hybrid with increased energy storage capacity and a HF of 50%. This allows the vehicle to drive on all-electric mode a distance that depends on the battery size and its mechanical layout (series or parallel). At the end of the journey, it may be connected to mains electricity supply through a socket to avoid recharging using the on-board internal combustion engine. This concept is attractive to those seeking to

minimize on-road emissions by avoiding - or at least minimizing - the use of ICE during daily driving. As with pure electric vehicles, the total emissions saving, for example in CO2 terms, is dependent upon the source of the energy produced by the provider company;

- Range Extender (REEV): A range extender is a fuel-based auxiliary power unit (a small but efficient internal combustion engine) that extends the range of a battery electric vehicle by driving an electric generator that charges the vehicle's battery. This arrangement is known as a series hybrid drivetrain.

Electric Hybrid vehicles rely a lot over the usage of batteries. Unfortunately, their intrinsic characteristic is to have a low specific energy in comparison with volumetric density. For instance, the same energy needed for a drive of about 500km is stocked in 46 litres (about 43kg) of gasoline but is required more than 700kg of batteries. Nevertheless, from the dawn of the batteries for automotive purpose, thanks to the improvement in technology their cost becomes cheaper and cheaper, while their energy density increases, as shown in Figure 4.

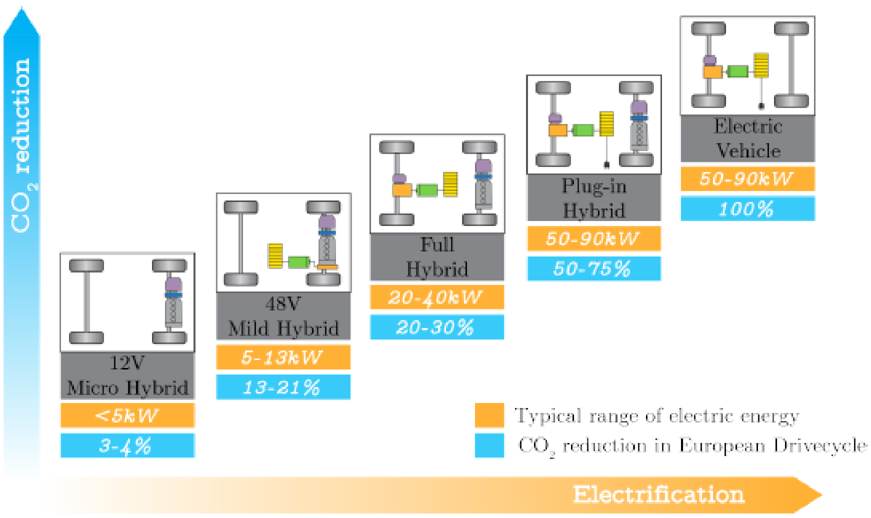


Figure 4: Hybrid Electric Vehicle types

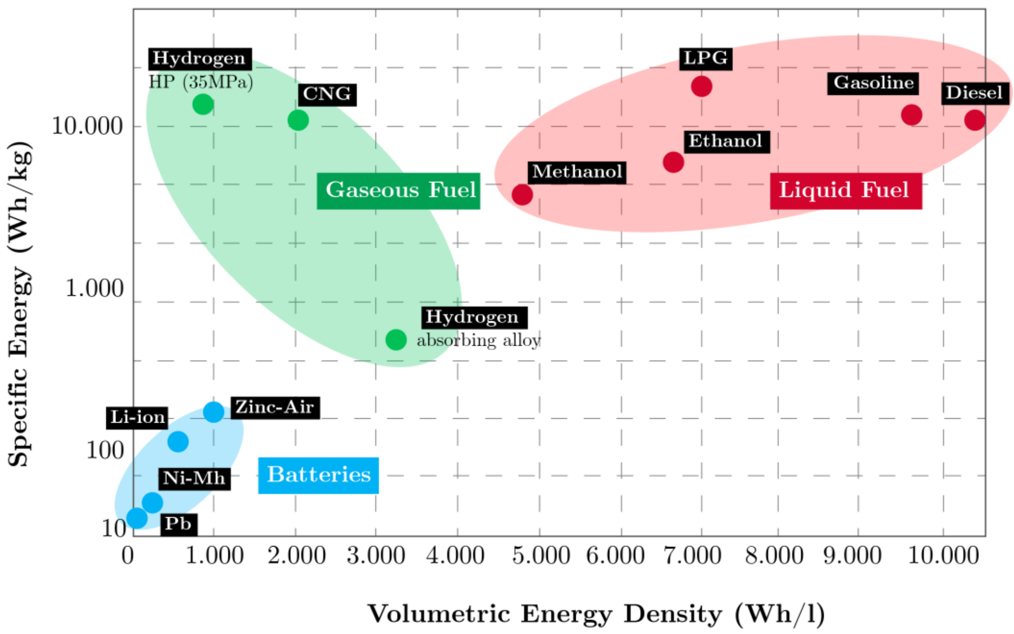


Figure 5: Specific energy w.r.t. volumetric energy density

Once the typology has been defined, another distinction can be made on how the energy flow is transferred from the energy storage (coming from the ICE or batteries for the EMs) to the wheels. Three paths are possible:

- Parallel: the engine is the main power source while the electric motor provides assistance as needed, delivering torque from zero rpm during standing starts and accelerations. This cooperation consent to avoid engine working points where the specific fuel consumption is high. The powertrain can be adapted simply by adding an electric motor and batteries to an existing vehicle, as the scheme of Figure 6

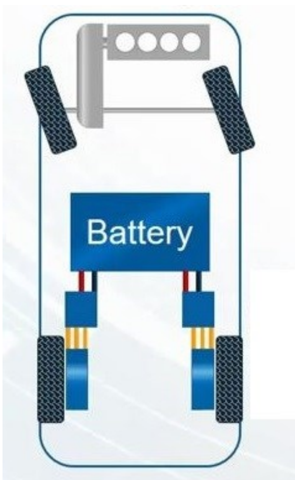


Figure 6: Hybrid parallel layout

- Series: the series layout provides torque to the wheels just by the usage of electric motors, like electric vehicles. The aim of ICE is to recharge the batteries with the generator. The powertrain is equivalent to an EVs and in fact is called Range Extender Electric Vehicle, but because the vehicle also includes an engine, it is considered a hybrid (scheme in Figure 7)

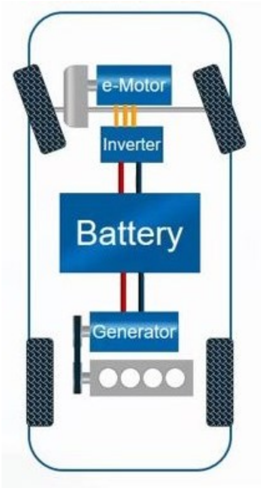


Figure 7: Hybrid series layout

- Power split: also known as series-parallel hybrid, this powertrain shares characteristics of both series and parallel layouts. In particular, the EM powers the vehicle from a standing start and at low speed whereas, as the speed increases, ICE and EM work together to efficiently provide the power required. As can be expected, the system is more complex featuring a power split device, friction clutches and a generator. An exemplification scheme is shown in Figure 8

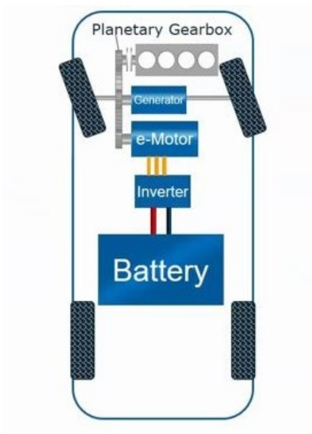


Figure 8: Hybrid power-split layout

The most common hybrid architecture for passenger vehicles is serial-parallel. For this architecture several configurations are possible, depending on the position of the electric machines within the driveline. As shown in Figure 9 they are as follow:

- P0: the combustion engine is coupled to the electric motor through a belt, so the electric machines is called Belt-driven Starter Generator (BSG);
- P1: the EM is directly mounted on the crankshaft, upstream of the clutch, and it is named Integrated Starter Generator (ISG);
- P2: the EM is separated from the engine by a clutch, that allows the pure electric drive;
- P2.5: the EM is mounted on the primary shaft of the gearbox, right after the friction clutch. This configuration is mostly used in high performance cars.
- P3 the EM is mounted on the secondary shaft, just out of the gearbox;
- P4 the EM is connected directly to the front or rear axles, moving the wheels by means of a transmission ratio;

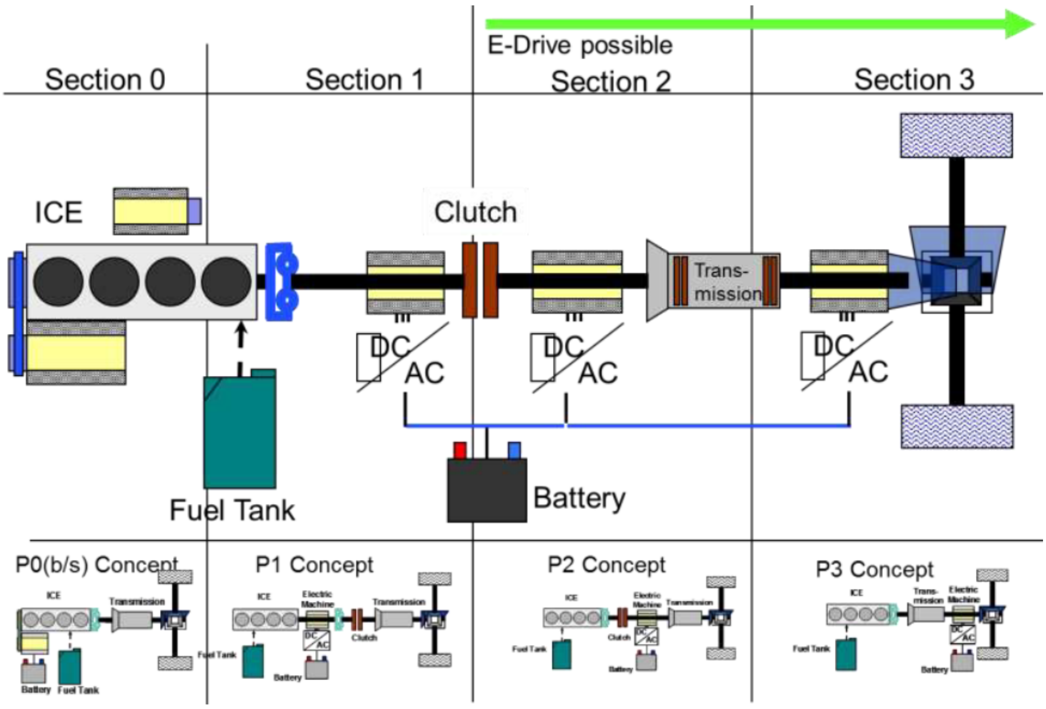


Figure 9: Hybrid topology

Introducing a different type of energy ow (electrical energy) additional to the chemical one, engineers have to face new challenging problems. In fact, while the available space remains the same, the components rise in number: one or more electric motors, a bigger battery, a more powerful control unit and the inverters have to be rationally placed inside the vehicle. Adding new components doesn't imply only a different spacing configuration but it also means a more complex control at system level and also regarding the safety. On one hand, it's possible to achieve similar performance to standard vehicle with internal combustion engine while greatly improving fuel efficiency and tailpipe emission, recovering the energy from braking. On the other hand, the torque split (so how the torque request is fulfilled) becomes the new control variable and it is complicated to handle. The challenge is to find the more efficient split that covers the torque request among the possible solutions. As a matter of fact, the computational effort of the control unit becomes heavier. For proceeding on the work, a deep analysis of the environmental legislations is needed

1.2 Legislation study

The European Union maintains its focus on achieving pollutants and Greenhouse Gas emission reductions planned for the second commitment period of the Kyoto protocol. The target to achieve by the end of 2020 20% of emission reduction compared to the base year 1990. For the following years, the European Union committed within the Paris agreement (COP21) to a pollutant and GHG reduction target for the period from 2021 to 2030. The commitment for 2030 is a reduction of 40% of emissions compared to 1990. Finally, for 2050 the European Union set itself a target of net-zero greenhouse gas emissions.

The road transport sector has a big part in the European energy consumption, representative for the pollutants and CO2 emission share for non-regenerative energies. Therefore, the EU continues to tighten the emissions limits for passenger cars and light commercial vehicles. The evolution of the regulations remains the main driver for changes in vehicle technology. The need for 0-emission powertrains drives the electrified architectures and the search for realistic solutions for alternative, low-carbon fuel.

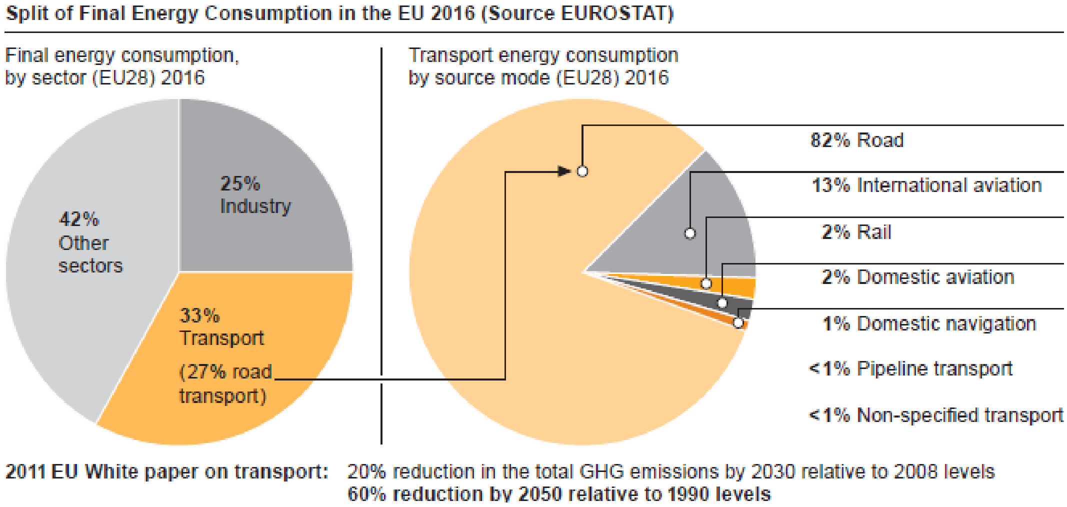


Figure 10: Split of final energy consumption in EU 2016

1.2.1 Regulations and aims

Pollutant emissions are harmful to human health and affect local air quality. Air quality standards are defined by the World Health Organisation (WHO) and applied in different world regions. These standards are still exceeded in many main European cities, especially for the pollutants Ozone, CO, HC, NOx and fine particles. Passenger cars and light duty commercial vehicles are contributing to pollutants and fine particle emissions and with this indirectly to the ozone formation. Pollutant emissions from light duty vehicles, also called criteria emissions, are mainly:

- Carbon monoxide (CO), highly toxic, measured in g/km
- Unburned hydrocarbons (HC), toxicity depends on the detailed chemical composition, measured in g/km
- Nitrogen oxides NO and NO 2 (commonly treated as NOx) harmful to human health and photochemical effects in the atmosphere measured in g/km
- Particulates (soot and ash) measured as PM in mg/km and PN measured in number/km
- In the future additional harmful emissions may be regulated, as there are NH 3 and specific hydrocarbon components as aldehydes.

These emissions are regulated in the world regions by different legislation packages (known as EU5, EU6, ULEV, LEVII, LEVII etc.). There are 3 main clusters:

- The US and some Central and South-American countries using the US test procedure (FTP) or parts of it
- Europe and the countries following the EU legislation, which will be based from 2017 on the new WLTP and the newly created Real Driving Emission test (RDE) Japan has its own test procedure, but will also move to the new WLTP and is evaluating the possibility to introduce the RDE
- China combining elements from Europe (today NEDC but moving to WLTP and RDE) and elements of the US legislation.

All regulations limit the maximum emissions in g/km for each vehicle sold. This means that each vehicle to be certified, a big luxury car or a small car must respect the same defined maximum emissions. The most stringent pollutant emission regulation is the US American one, from 2023 China will be more stringent than Europe. Greenhouse gas emissions are mainly CO_2, but also CH_4 and N_2O. CO_2 is the natural result of the combustion process of carbon containing fuels (Gasoline, Diesel, but also alcohols and natural gas).

CO_2 is by far the most important greenhouse gas. Methane (CH_4) can be a bi-product of the combustion as other unburned hydrocarbons. A second source is the unburned fuel for natural gas engines. N_2O is formed during the exhaust gas aftertreatment process under not optimal temperature conditions. Greenhouse gases affect the world climate and the overall emissions into the atmosphere are important, not the local emissions. For this reason, all major world regions limit the CO_2 emissions as average for the new vehicle fleet sold in a given year. Bigger vehicles can emit more greenhouse gases if the emissions are leveraged by lower emissions of smaller vehicles in the fleet.

The details of the regulations in the world regions are different, but the target converges for the main regions to around 100 gCO_2/km in the time frame 2020-2025. Europe has the most ambitious targets with 95 g CO_2/km in 2020/2021, again reduced by 15 % in 2025 and by 37,5 % in 2030. The average CO_2 emissions of the European fleet diminished since 2010 until 2016 by 22 g CO_2

/km (16 %). In 2017 the European fleet average increased for the first time since 2010 to 118.5 gCO2 /km, 0,4 gCO2 /km more than in 2016. Reason for this are increased vehicle weight, decreasing Diesel share and the shift to the WLTP.

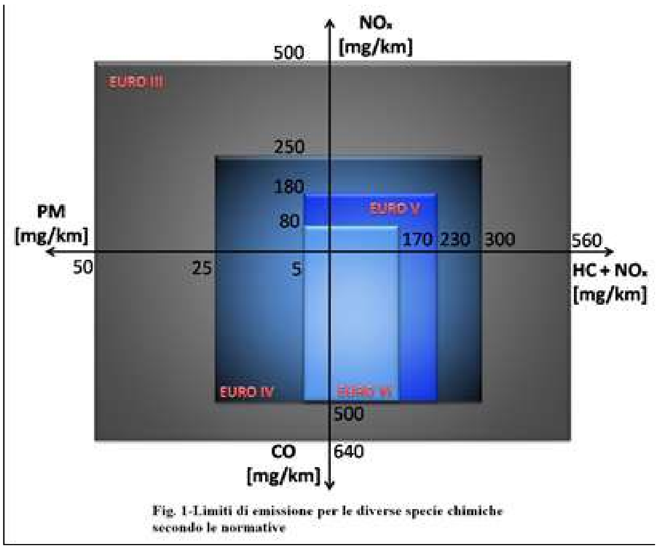


Figure 11: Pollutants emission limits according to EURO 3, 4, 5, 6

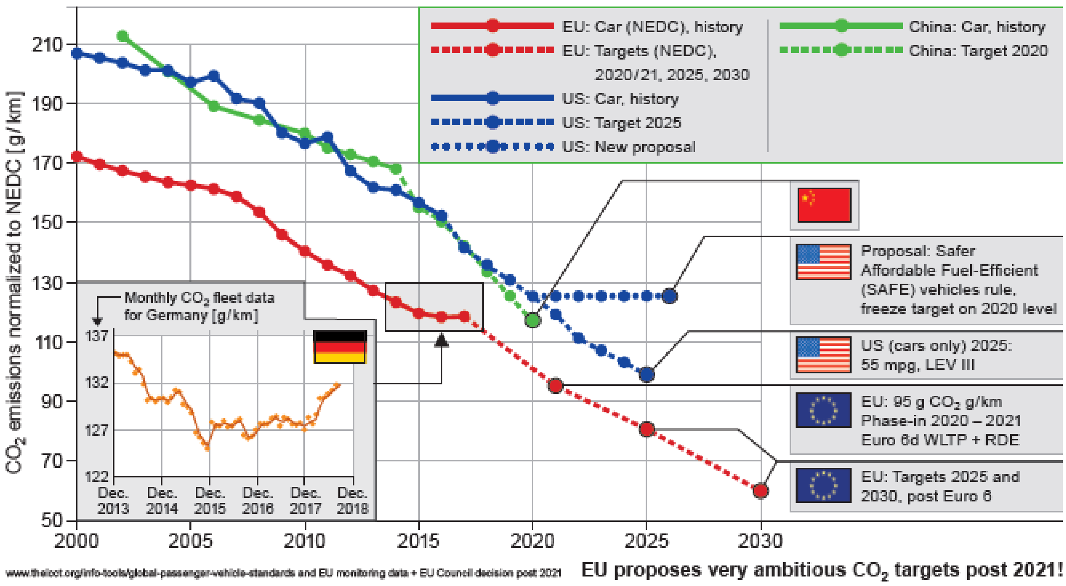


Figure 12: CO2 emission trend EU/US

The UNECE (United Nations Economic Commission for Europe) Regulation 83 describes the test procedure for exhaust emissions at normal and low ambient temperature, evaporative emissions, emissions of crankcase gases, the durability of pollution control exhaust devices and on-board diagnostic (OBD) systems for light duty vehicles. The test cycle as defined in UNECE regulation 83 2 is equal to the New European Driving Cycle (NEDC). The NEDC 2000 is valid for emission testing as of Euro 3 (2000).

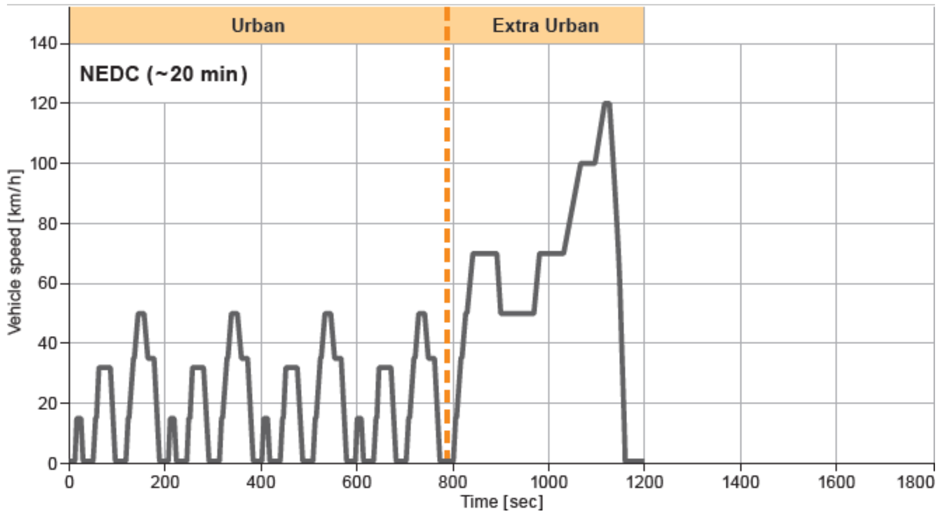


Figure 13: NEDC speed profile

It was known for many years that the NEDC test cycle as defined in regulation (EU) 692/2008 and UNECE regulation 83 does not represent real driving behaviour correctly. Pollutant emissions, fuel consumption and CO2 emissions determined by this procedure do not correspond to the real world (greenhouse gas) emissions. For this reason, the UNECE decided in to prepare a road map for the development of the WLTP. The group developed from 2009 to 2015 the worldwide harmonized light duty driving cycle (WLTC) and the associated test procedures (WLTP) for the common measurement of criteria compounds (regulated pollutants), CO2, fuel and energy consumption.

This Global Technical Regulation (GTR) aims at providing a worldwide harmonized method to determine the levels of emissions of gaseous compounds, particulate matter, particle number, CO 2 emissions, fuel consumption, electric energy consumption and electric range from light-duty vehicles in a repeatable and reproducible manner designed to be representative of real-world vehicle operation. In addition, it has been developed a world-wide harmonized test procedure for real driving emission tests (RDE). The WLTP defines a test cycle (WLTC) which represents a more realistic vehicle speed profile than the NEDC, actually based on an international database of really driven drive sequences. Vehicle mass, rolling resistance, vehicle conditioning and environmental conditions are more precisely defined.

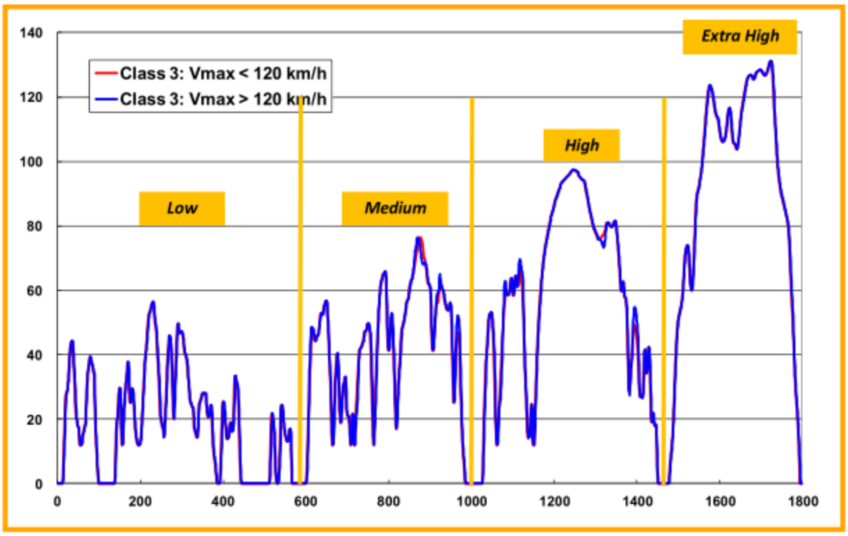


Figure 14: WLTC speed profile

Already before the emissions scandal broke, the EU Commission had proposed to measure emissions in real driving conditions. This test procedure further tightens the rules since it checks the emissions of NOx and ultrafine particles (Particle Number – PN) from vehicles on the road and significantly reduces the discrepancy between emissions measured in real driving and those measured in a laboratory.

The Real Driving Emissions (RDE) procedure complements the laboratory test. In the RDE procedure pollutant emissions are measured by portable emission measuring systems (PEMS) that are attached to the car while driving in real conditions on the road. This means that the car is driven outside and on a real road according to random variations of parameters such as acceleration, deceleration, ambient temperature, and payloads.

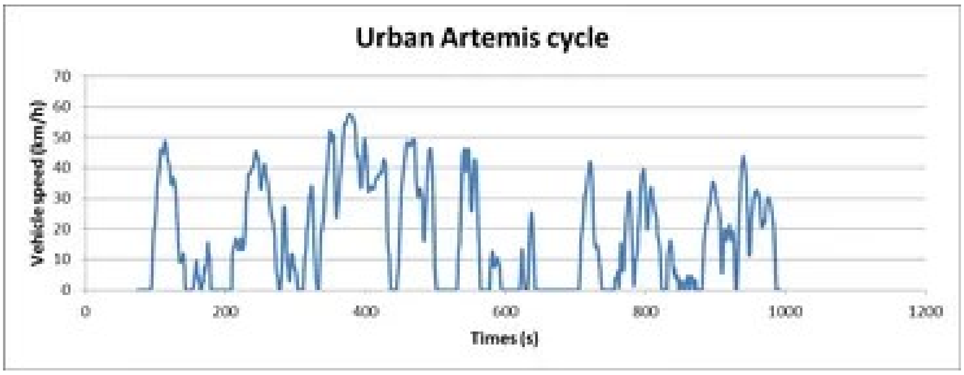


Figure 15: Example of a RDE speed profile

1.2.2 Methodologies for emission testing

For performing the WLTP procedure, the following test equipment is required:

- chassis dynamometer
- exhaust gas dilution system
- constant volume sampling (CVS)
- Emission measurement equipment

The protocol states also standard parameters to follow for the execution of the test. The major ones are:

- The velocity profile that the tested vehicle must repeat (indicating one speed value for each of the 1800 seconds)
- Laboratory instrumentation parameters, such as the calibration of dynamometers, gas analysers, anemometers, speedometers or the rolling resistance of the test bench
- Environmental conditions, such as room temperature, air density, wind
- Fuel type: gasoline, diesel, LPG, natural gas, electricity, etc.
- Fuel quality, and its chemical properties
- The tolerances under which the measures are valid
- The set-up process for vehicles ahead of the test

The procedure doesn't indicate fixed gear shift point, as it was in the NEDC, letting each vehicle use its optimal shift points. If after one test the regulated emissions are under 90% of the Euro 6 limits and the measured CO2 value is under 99% of the manufacturer declared value, the test is valid. If these criteria are not fulfilled, a second test is required, and the arithmetic average of the results is calculated and compared to the criteria for the second test. If these are not fulfilled, a third test is allowed. In any case all pollutant emissions have to stay under the Euro 6 limits, if any of them fails, the test will be invalid.

Detailed test conditions are specified, including background concentration of all measured compounds, ambient conditions and test cell equipment. The ambient air is specified as 23°C ± 3° and the test cell temperature as 23°C ± 5°C. The vehicle is then driven following the applicable WLTC.

The CVS dilution method (Constant Volume Sampling) is the established procedure to collect the combustion gases emitted from the vehicle. Introduced in 1972, it has evolved until today and is still universally used. The concept on which it is based is the dilution of the gases emitted by the vehicle with ambient air, at a ratio of about 1: 5 ... 1: 10. The gases are extracted from a pump system designed to maintain a precise and constant volumetric ratio between the flow rate of ambient air and the flow rate of the exhaust gases. During the test, a sample of the diluted flow is taken and stored in bags (“sampling bags"). At the end of the test, the concentration present in the bags corresponds to the average concentration in the diluted flow. As the total volume of diluted gas is measured, the concentration measured in the bags allows the calculation of the total mass emitted during the test (then compared to the kilometres travelled).

This procedure reproduces the actual flow in the atmosphere of the exhaust gases (mix with ambient air). Thanks to the dilution, condensation of water vapor present in the exhaust gases inside the bags is avoided, thus strongly inhibiting reactions of "loss" of NOx during the time spent in the bags. The dilution strongly inhibits secondary reactions between exhaust gases, particularly among HCs. The main disadvantage consists in reducing the concentration of the given component in the diluted flow, thus requiring much more accurate and sensitive instrumentation/sensors.

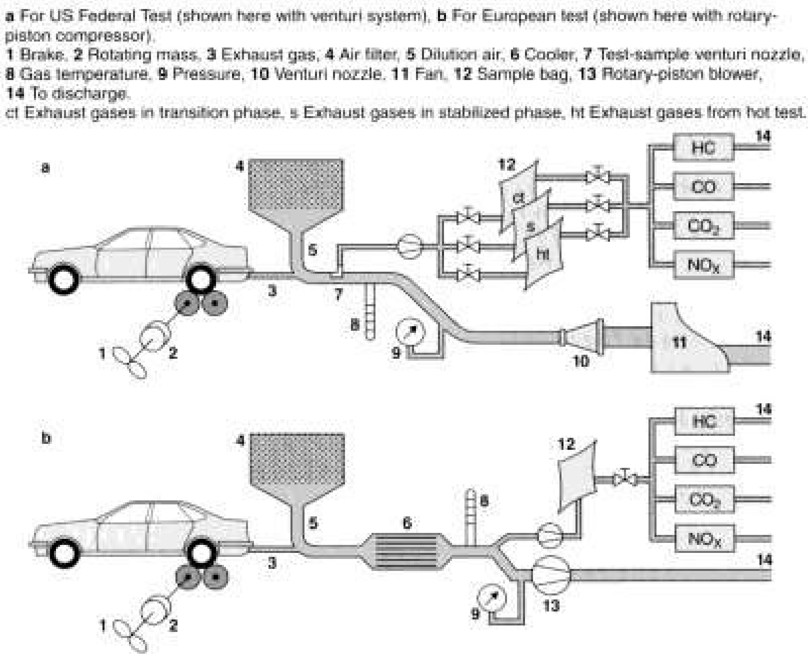


Figure 16: tailpipe emission sampling for EU/US

Along with the lab-based procedure, the UNECE introduced a test in real driving conditions for NOx and other particulate emissions, which are a major cause of air pollution. This procedure is called Real Drive Emissions test (RDE) and verifies that legislative caps for pollutants are not exceeded under real use. RDE does not substitute the laboratory test (the only one that holds a legal value), but they complement it.

During RDE the vehicle is being tested under various driving and external conditions, that include different heights, temperatures, extra payload, uphill and downhill driving, slow roads, fast roads, etc. In addition, the freestream air that the vehicle receives is not conditioned by the wind blower position, which could cause alterations in the measured emissions of laboratory tests. To measure the emissions during the on-road test, vehicles are equipped with a portable emissions measurement system (PEMS) that monitors pollutants and CO2 values in real time.

The PEMS consists in a complex instrumentation that includes: advanced gas analysers, exhaust gas flowmeters, an integrated weather station, a Global Positioning System (GPS), as well as a connection to the network. The protocol does not indicate a single PEMS as reference, but indicates the set of parameters that its equipment has to satisfy. The collected data are analysed to verify that the

external conditions under which the measures are taken satisfy the tolerances and guarantee a legal validity.
The limits on the harmful emissions are the same as the WLTP, multiplied by a conformity factor. The conformity factors consider the error of the instrumentation, that can't guarantee the same level of accuracy and repeatability of the laboratory test, as well as the influence of the PEMS itself on the vehicle that is being tested. For example, during the validation of the NOx emissions, a conformity factor of 2.1 (110% tolerance) is used.

1.2.3 Hybrid vehicle emission testing

For pure electric, hybrid electric and compressed hydrogen fuel cell hybrid vehicles, specific definitions needs to be explained:

- State of Charge (SoC): instantaneous percentage of available energy stored in the high voltage battery
- Charge depleting (CD): strategy selected by the hybrid control unit, that consists in driving thanks to electric motors, that consumes all the available energy of the high voltage battery. These last are not recharged by the ICE, that activates only once the energy has been all drained out.
- Charge sustaining (CS): strategy selected by the hybrid control unit that consists in driving with the ICE that constantly recharges the battery, keeping its SoC almost constant along the drive.

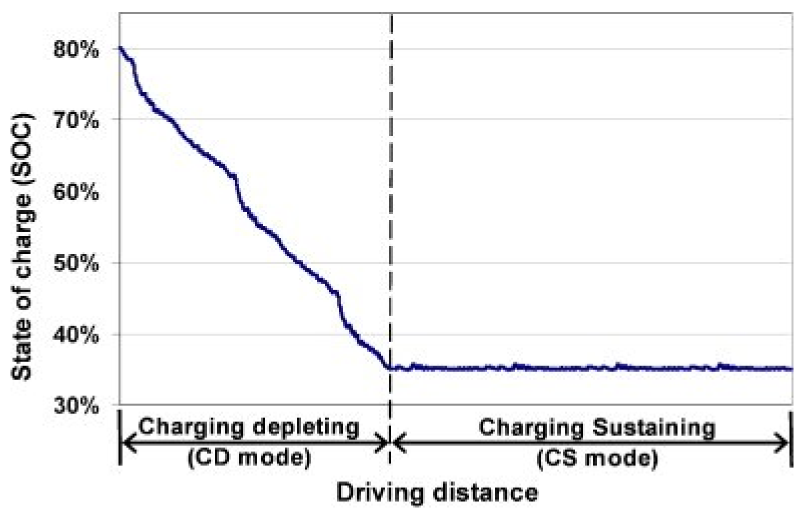


Figure 17: Example of charge depleting/sustaining strategy

Now, specific parameters need to be measured:

- All-electric range (AER): the total distance travelled by an Off Vehicle Charging Hybrid Electric Vehicle (OVC-HEV) from the beginning of the charge-depleting test to the point in time during the test when the combustion engine starts to consume fuel.
- Charge-depleting actual range: the distance travelled in a series of WLTCs in charge-depleting operating condition until the rechargeable electric energy storage system is depleted
- Equivalent all-electric range: the portion of the total charge-depleting actual range attributable to the use of electricity from the electric storage system over the charge-depleting range test.
- Pure Electric range: the total distance travelled by a EV from the beginning of the charge-depleting test until the break-off criterion is reached.

The Plug-In Hybrid Electric Vehicles (PHEVs) shall be tested under charge-depleting and charge-sustaining operating condition. Pollutant and CO2 emissions must be measured for both, in addition to electrical energy consumption and electrical range. The final emissions values will be weighted by a utility factor which is function of electrical range.

The charge-depleting test procedure consists of several consecutive cycles, each followed by a soak period of no more than 30 minutes until charge-sustaining operating condition is achieved. The end of the charge-depleting test is considered to have been reached when the break-off criterion is reached for the first time. The number of applicable WLTP test cycles up to and including the one where the break-off criterion was reached for the first time is set to n+1. The break-off criterion is reached when the difference in electrical energy of the electric energy storage devices between two consecutive WLTP cycles is less than 4%. Each individual applicable WLTP test cycle within the charge- depleting test shall fulfil the applicable criteria emission limits.

The charge sustaining test is preconditioned to set charge sustaining electric energy storage conditions by either setting the charge to a predefined level or by driving WLTP tests, preconditioning shall be stopped at the end of the applicable WLTP test cycle during which the break-off criterion is fulfilled. 4 options for testing sequences are possible, the difference lies in the sequence for the final charging and determination of electrical energy consumption:

- Charge depleting tests only
- Charge sustaining tests only
- Charge depleting test followed by charge sustaining test
- Charge sustaining test followed by charge depleting test

Utility Factors (UFs) are ratios based on driving statistics and the ranges achieved in charge depleting mode and charge-sustaining modes for OVC-HEVs and are used for weighting emissions, CO2 emissions and fuel consumptions.

1.3 Powertrain calibration of a high-performance PHEV

As previously mentioned, nowadays hybrid passenger vehicles comprehend several components – such as internal combustion engine, transmission and gearbox, batteries, inverters, electric motors, auxiliaries – that needs to work synergistically managing hundreds of different variables under many different working conditions. For instance, these components must cooperate in order to satisfy the requested performance, the tailpipe emission, the safety, the drivability of the vehicle in every ambient condition. For a high-performance vehicle this cooperation between components and between external condition has to be focused and stressed even more. This process of fine-tuning is described in the following paragraphs.

1.3.1 Definition and aims of calibration

The calibration phase of a modern spark ignition engine consists into the identification and setting, for different operating points, of the optimal values for control parameters of a vehicle’s powertrain. Example of control variables are the spark ignition timing, air-to-fuel ratio, valve opening and closing strategies, eventual turbocharger setting, etc. The aim of this search of optimal values is to reach the vehicle project’s specifications, such as maximum power/torque, minimum fuel consumption, minimum noise, vibration and harshness emissions. Powertrain calibration it is also mandatory for compelling the legislations that limits the pollutants and GHG emissions.

It is really common that those two requirements (project's specifications and emission limit) go against each other, making the calibration procedure really time consuming. In addition, some operative constraints (maximum levels of in-cylinder pressure, boost level, exhaust temperature, turbocharger speed, knock absence, etc.) have to be respected to ensure engine and sub-components safety as long as driver's and passenger's one. Modern engine architecture shows a large number of degrees of freedom, and each control parameter has to be varied around a presumed set point for predefined operating conditions. This means that the overall procedure of calibration can last up to 50 months with several steps to follow in order to arrive to the start of production (SoP) of the powertrain.

With time, the way and method to calibrate a powertrain consolidated in a well-known process, that requires the usage of dynamometers test bench, standardized procedures to follow and finally in-vehicle calibrations. Recently, the automotive-based research is oriented in improving the efficiency – in terms of costs and time – of the calibration process, developing new methods and tools to perform the calibration activities.

1.3.2 Classic / conventional method

The classic method involved in powertrain calibration is divided in subsequent phases, with increasing in detail depth and complexity.

1) Phase 1: once individuated the concept parameters of the ICE and after feasibility study, is required a very first calibration in order to be able to run the engine. This calibration involves the necessary parameters for making the internal combustion engine complete the entire working cycle, comprehensive of intake, compression, expansion, exhaust phases, for a total of 720° of crankshaft rotation, equal to 2 full revolutions. This means defining the matching positions between crankshaft and camshaft (that control the intake/exhaust valves): is called engine synchronization.
2) Phase 2: once the internal combustion engine is able to perform correctly the working cycle, the following passage is the individuation and calibration of the most significant control parameters of an internal combustion engine. The main base parameter for an ICE is the spark ignition timing, or more

commonly defined Spark Advance (SA). It is defined as the angle before the top dead centre (BTDC) of the compression phase at which the spark plug must release the spark necessary to ignite the fresh charge. Each value of SA is optimal only at a certain engine operative point (in terms of torque and speed). This means that is required a map of SA values for each working point of the ICE. Theoretically, these last ones are infinite, so is required a discretization. The mapping of the SA is performed in an engine test bench with a dynamometer brake, that is able to reproduce the discretized working points by "keeping" the ICE at a defined rotational speed while torque is provided. The search for the operating point of an internal combustion engine with the usage of the dynamometric brake is strictly performed under test standards (like the ISO 3046), that states the external conditions (in terms of air temperature and pressure), equipment needed for the testing, auxiliaries attached to the ICE, procedure to follow and accuracy of results.

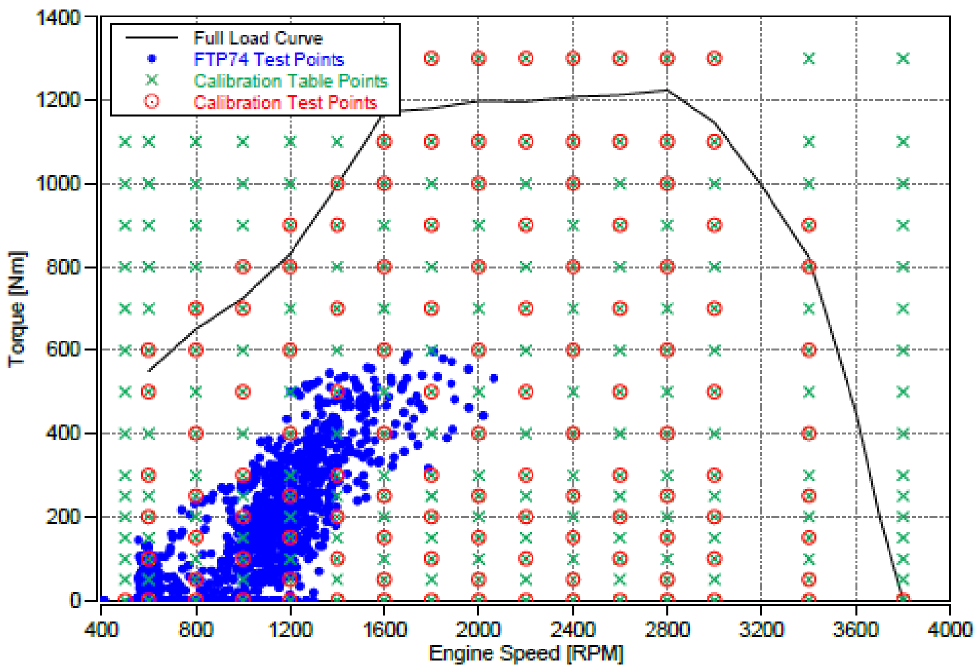


Figure 18: Example of engine mapping

3) Phase 3: when completed the base engine calibration, the level of detail in the process of calibration can get deeper: for instance, the start and warm up event are calibrated, with a special regard again to the SA, that needs to provide a

certain amount of “torque reserve” in order to satisfy the driver’s needs at cold starts or idle conditions. Those calibration can be performed directly on the vehicle, because it comprehends all the auxiliaries and component that can be turned on and off for providing the additional torque. For example, if the A/C compressor or the steering pump are turned on, they require an amount of extra torque from the ICE. It is immediately visible that this calibration phase is costly and risky because it requires a full vehicle in order to be performed. Other on-board calibration examples can be vehicle’s drivability, engine emissions, vehicle functions (like drive assist, thermal management, crash functions, driver information) and on-board diagnostics – OBD for failure detection. The in-vehicle calibration marks the end of the calibration process, because whenever the optimal configuration of control parameters is reached, it is deployed in the control units of the production vehicles. This entire process as seen requires many complicate and expensive equipment, such as test bench, dynamometer, several prototype vehicles etc. This means that the classic calibration process is affected by high costs and time consumption. So much, that new technologies for making the calibration more cost, effort and time effective has been recently developed.

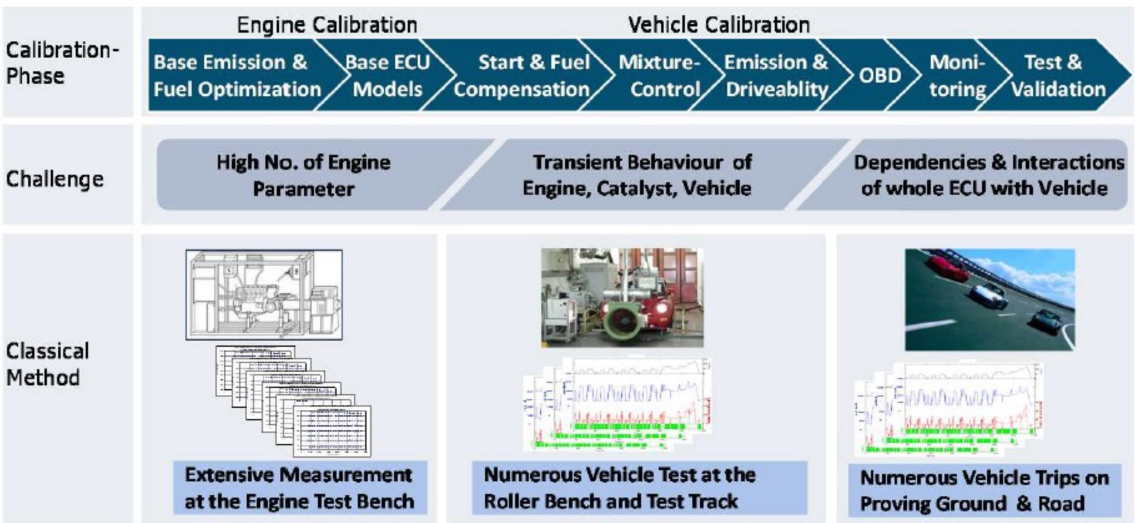


Figure 19: Example of traditional calibration workflow

1.3.3 Virtual calibration method

The calibration of engine management systems requires considerable engineering resources during the development of modern engines. Traditional calibration methods use a combination of engine dynamometer and vehicle testing, but pressure to reduce powertrain development cost and time is driving development of more advanced calibration techniques. The largest part of powertrain calibration, which denotes the optimal adjustment of parameters of the electronic control units (ECUs) of the powertrain, is still done very late in the process, and predominantly in the car. This severely compromises the flexibility to implement changes, and the freedom to experiment with a sufficiently large number of parameter settings.

Front-loading of development activities to earlier phases demands the intensive use of simulation. The principle of system simulation lies in the decomposition of a complex system into the several sub-systems. A modelling representation is made for each elementary sub-system. The model's fidelity to the real process is always a trade-off between the required precision and the short computational time. Afterwards, the sub-models are assembled together and all the interactions among them are taken into account. The second phase is the identification and the calibration of the model's parameters. The database of numerical results and experimental measurements is used during the calibration phase. The final model calibration is performed either by validating separately each sub-model or by a global model validation. Ideally, both global and partial validations are desired.

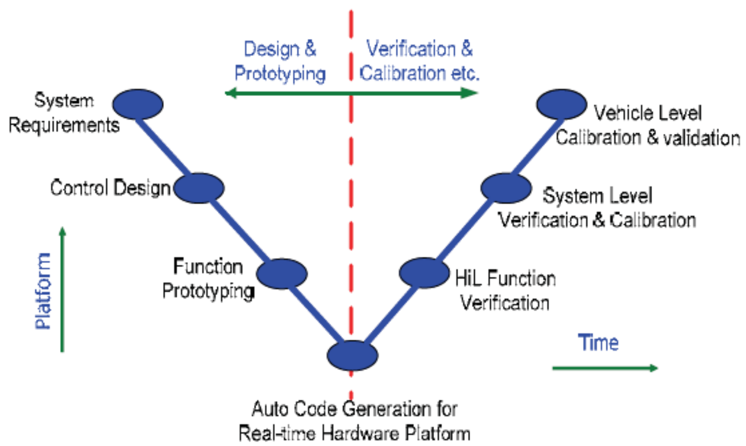


Figure 20: V-model

In the automobile industry the projects are systematically organized with the aid of a “V” process. This process is based on the decomposition of the global complex system (vehicle) into less complex sub-systems. This decomposition is usually made in terms of functionality. Each sub-system is evaluated by its performance while it always retains its links with the main system. The gain of this kind of modelling is visible since each sub-system can be modelled separately and may be integrated in the simulator of the global system. This methodology, defined Model-in-the-Loop, permits the rapid verification of the system response and shows if modifications are needed. Any potential modifications may be applied with minor delays from the beginning of the development phase, resulting in a huge amount of time and cost saved.

Model-in-the-Loop is used in various levels and phases of an engineering project. For a given sub-system, several system models can be used depending on the conceived engineering application. For example, a detailed phenomenological model is used for the prediction of combustion in a spark ignited engine and another model is used for the control of the engine, which is more mathematical but quicker than the physical model. Virtual calibration is very attractive to the automobile industry thanks to its modest needs of computational time, its possibility to analyse various systems and to the facility of construction of a global model from the basic submodels.

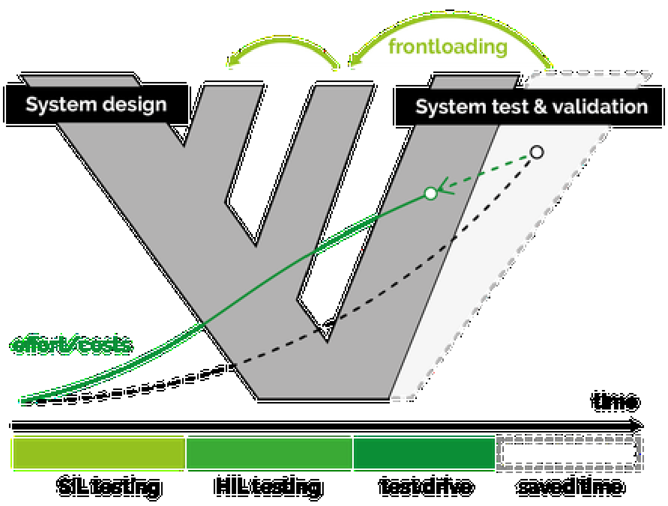


Figure 21: V-model frontloading

Virtual Calibration can delay as much as possible the still necessary road test calibration by performing for example the following activities:

- pre-testing ECU software,
- plausibility checks of ECU parameters,
- pre-calibration of the adjustment parameters with respect to all relevant target functions,
- investigation of the quality and stability of trade-off calibrations,
- stability checks of best parameter settings,
- pre-check of the effects of hardware-modifications,
- virtual variant investigations,
- preparation of test procedures in the office.

In the ideal case of the Virtual Calibration, the real road tests should only be required for the verification of the calibration that has been determined in the simulation environment. As was shown above, on the way to this ultimate aim there are numerous small steps forward, that already have enormous economic potentials in terms of shortening the development process, improving quality, and saving costs by avoiding failures and late modifications. The Model-in-the-Loop methodology is adopted in this dissertation for virtually calibrating the hybrid control unit in question. The next chapter will analyse this process.

2 MiL Calibration: plant model and HCU integration

In this chapter it will be analysed the simulation model of the high-performance plug-in hybrid powertrain used for the emissions and aftertreatment Virtual Calibration, the so called Plant Model. It will be described the components of the model and their mutual interaction, as long as the process of integrating the hybrid modules and controls.

2.1 PHEV powertrain plant model in study

A simulation model representing a powertrain is commonly divided in two main blocks:

1) the physical block, that contains the physical model of the powertrain's components (including the driver and the vehicle dynamic, in order to perform test cycles)
2) the controller block, that comprehends the electronic control units and other supervisors of the vehicle's components.

Those two blocks mutually exchange data in order to perform a closed loop powertrain model: values calculated by the single physical models are then sent to the controller models, that applies controls strategies and correct them for the optimal functioning of the system. Once the controllers made their calculations, the updated control values are sent back to the physical model, closing the simulation loop.

An easily understandable example of such a loop is the simulation of the pressure of fuel injected in the cylinder: the engine control unit (ECU) calculates the injection's pressure (indirectly) basing upon torque requested to the engine. The control value is then transmitted to the physical model of the injector that thanks to modelled physical laws converts that signal into fuel pressure. The result is a torque actuated by the engine, that is read by the ECU and subsequently elaborates the updated value of the injection's pressure, closing the simulative loop.

2.1.1 Physical models – engine, transmission, batteries, driver, vehicle, other models

The main core for powertrain model-based simulations is the internal combustion engine model. The design and monitoring of modern hybrid hi-performance engines require reliable models that can validly substitute experimental tests and predict their operating characteristics under different load conditions. Although there exists a multitude of models for positive ignited engines (spark ignition, gasoline ones), the so called Zero Dimensional (0-D) models present the advantages of giving fast and accurate computed results. These models are useful for predicting fuel spray characteristics and instantaneous gas state.

Numerical simulation of gasoline engine operating cycle is based on the application of mathematical models that describe different physical processes occurring throughout the engine cycle. The elaboration of a mathematical model of combustion processes in gasoline engines gives the possibility to run multiple scenario and optimization procedures in order to predict engine behaviour under different conditions, thus reducing the expenditure linked with experimental researches. Mathematical models for spark ignited engine combustion processes have been widely investigated around the world, simulation models of those engine are mostly divided in three groups:

- Zero-dimensional models (thermodynamic and phenomenological models);
- Quasi dimensional or 1D models;
- Multidimensional models (Computational Fluid Dynamics, CFD).

Zero-dimensional thermodynamic models are based on the laws of thermodynamics and semi empirical relationships describing the rate of combustion of the injected fuel. These models are also known as system models. These types of models take their attractiveness from their relative simplicity of implementation and speed they offer in terms of computational speed and accuracy. In zero dimensional phenomenological models, details of various phenomena occurring during the fuel combustion are added to the basic equations of mass and energy conservation. 0-D combustion models are convenient to describe combustion of fresh mixture and to perform parametric studies of engines. This is because the injection process, which can be relatively well simulated by a phenomenological approach, has a dominant effect on the formation of the reagent mixture and the subsequent combustion process. These models are usually subdivided into sub-models coupled to each other, each one describing phenomena occurring during each cycle. The main sub-models of the studied high-performance PHEV internal combustion engine are divided as follows:

1) air path through intake system submodel,
2) multi-port injection submodel,

3) thermodynamic submodel,
4) efficiencies submodel,
5) emissions and aftertreatments submodels.

Quasi dimensional or 1D models and Computational Fluid Dynamics models describe better the inner phenomena involved in the gasoline engine combustion. In 1D models, the combustion chamber as well as the spray are divided in multiple (hundreds) zones, the reactive flow field is solved only in time for each zone of the combustion chamber (ordinary differential equations) while in Computational Fluid Dynamics models the field is solved in time and volume (partial differential equations). Computer time and memory constraints severely limit the use of these models.

Computational Fluid dynamics models are mainly based on solving Navier–Stokes equations; the whole process is usually broken down into a number of parts to be solved: the dynamic liquid phase of the jet dynamics of gas-phase and gas phase chemical kinetics. In terms of engine parameterization, optimization and computing speed, 0D phenomenological model provide fairly good results.

Numerous research studies on 0D models of spark ignited engine combustion were reported recently with different approaches and complexity.

For the high-performance PHEV in study, transmission model is the other principal object of its powertrain model-based simulation. In the market there are typically two types of internal combustion engine, gasoline or diesel, but for the transmission and gearbox several technologies are currently equipping vehicles. A transmission can be

- fully manual, with a lever-operated set of gears that apply the required transmission ratio between the crankshaft and the axis of the wheels;
- semiautomatic or automatic, with the set of gears – usually a planetary set – that is governed by electric motors under control of the transmission control unit (TCU);
- single clutch transmission, with a single couple of friction disks commanded by the pedal;

- double clutch transmission (DCT) with 2 couples of friction gears and shafts engaged alternatively by the TCU;
- continuously variated transmissions (CVT), functioning thanks to centrifugal forces and movable sprockets.

Transmission obviously lacks the combustion process and the fluid dynamics, so it's modelling is (almost) purely mechanical. The multitude of typologies of transmission and their lack of phenomenological behaviour leads to the development of specific models for each type of gearbox and transmission. In the case of the high-performance PHEV in study, the transmission type is an electronically controlled dual clutch gearbox (DCT). This means that the submodels of the transmission model contains the physical behaviour of the DCT components:

1) the hydraulic submodel reproduces the actuation valves of the synchronizers and their movements, the operation of the clutch hydraulic actuator and the safety valves.
2) the friction clutches submodel represents the physics under the engaging of the friction disks, comprehending the transmitted torque and the lost torque during the engagement.
3) synchronizer's operations submodel, for controlling the hybrid drive during the different driving modes.

Other important component whose physics must be modelled for an high-performance PHEV model-based simulation is the Integrated Starter Generator (ISG). For this electric machine is modelled the rotational speed and the torque and provided to the crankshaft, as long as it's efficiency.

High voltage electric components must be added to the simulation, such as high voltage battery, electric machines and junction box. The high voltage battery is simulated in terms of voltage, power, temperature and state of charge. Like the ISG, the electric machine that directly propels the wheels is modelled in terms of torque provided and revolutions per minute.

Model based simulations that can sustain a test or homologation cycle requires also physical models (even simple ones) of the vehicle itself, and of the driver.

For the vehicle's model, just longitudinal dynamic of a 4-wheeled vehicle is represented, because there's no interest in the lateral one. The driver model is important because it gives the speed profile that is needed for preforming any simulated cycle. Usually for model based simulations the speed profiles that the driver model can request are the homologation cycles ones (such as ECE, NEDC, WLTC, FTP); for the case of a high-performance PHEV it's also recommended to request particular speed profiles, validated through experimental data, such as RDE cycles or even circuit reproduction. Is then necessary to model the actuation of the shift lever, the accelerator pedal and the brake one, as long as the actuation on the ignition/starter key for turning on the car system and firing up the internal control engine.

These models were already present at the start of the work, based on Customer's specification for its prototype. After the description of the physical models of the hi-performance PHEV, are described the major electronic control units acting on the virtual components.

2.1.2 Control models – ECU, TCU, BMS, other controllers

Every physical component needs an electronic controller that manages its functioning. Nowadays cars, and specially the high-performance PHEVs, have a single electronic control unit for almost each component. The most relevant is naturally the engine control unit (ECU). As like as the engine physical model, the engine control unit has several ways and modality for being implemented. For this dissertation case, a custom ECU has been developed prior the beginning of this work, as long as the other control modules. It consists in three different submodels:

1) engine mode selection: its inputs are the ICE rotational speed, the vehicle's velocity, the requested gear and hybrid drive modality, the engine brake mean effective pressure (BMEP) that represents the ratio between the effective work extracted at the crankshaft and the engine displacement. The engine mode selection consists in determining the possible cases in which the ICE must operate, for instance at idle, drive

away, cut-off (accelerator pedal is suddenly released), coast down (vehicle moving only for inertia), upshift and downshift, etc…

2) engine torque request: in this submodel is calculated the necessary torque for performing that manoeuvre in that time instant. The BMEP is converted in torque considering the friction resistances that some components generate if active, and the torque requested by the hybrid module supervisor (analysed in next chapter).
3) Virtual ECU (or Soft-ECU): here is where the torque calculated is translated in throttle angle (drive by wire – DBW – angle), in spark advance (SA), variable valve timing delays and quantity of fuel requested to the injectors.

As explained before, these variables are read by the physical models of the actuators, closing the simulation loop. The high-performance PHEV requires a complex gearbox management, that can ensure high-performance with short time for shifting gears and under all hybrid conditions. This control is left to the transmission control unit, or TCU:

1) desired gear request: this submodel identifies the correct gear for performing the manoeuvre of that time instant. Once the correct gear is individuated, the TCU applies a defined control strategy for deciding whether to change gear or not.
2) Friction clutches torque: the shifting signal is sent to a submodel that calculates the torque necessary for the friction clutches in order to perform the engagement. This request is then traduced into current intensity and sent to the clutch actuators (physical transmission model).
3) Synchros submodel: basing on the shifting strategy determined, the TCU calculates the positions that the gear synchronizers must adopt for selecting the gear. This set of position is then translated in current intensity and sent to the physical model of the synchronizers. Once the synchros are in the right position and the clutches managed the engagement, the new gear is finally in place and operative.

Other important controllers are the modules for the electric machines. According to the driver's request and to the hybrid supervisor, they calculate the amount of torque that needs to be provided for driving the vehicle and/or recharging the batteris. All the control models were already implemented at the beginning of the work.

The last controller present in the models of the hi-performance PHEV that needs to be analysed is related to the hybrid nature of the vehicle: is the hybrid supervisor module, or more commonly hybrid control unit, HCU. This is described in the following chapter

2.1.3 Emissions and aftertreatment models

As seen in chapter 1, the principal and most dangerous emissions of an internal combustion engine are the CO, the HC, the NOx and the greenhouse gas CO2, measured at the tailpipe. The nowadays challenge for the manufacturer is to reduce them under the homologation limit. Two ways are possible to follow: acting on the parameters that regulates the combustion process, but that's almost always not suggested, or avoiding their diffusion in the external ambient. This last solution is the most adopted by the manufacturer, and it is called *aftertreatment.* For performing the aftertreatment of the pollutants it's highly used the so called Three-Way-Catalyst (TWC).

Emission and aftertreatment models can be modelled in SimuLink environment in order to perform a Model-in-the-Loop virtual calibration for powertrain homologation. For the high-performance PHEV in object, the starting point is a fully functioning and validated emission model, that represents the production and the flow of the main ICE pollutants. For the aim of this study, it has been decided not to consider the particulate emissions, in terms of PM (particulate matter) and PN (particulate number). This because lack of experimental data to be inserted in the model as calculation and validation.

The powertrain models used for virtual simulations and calibration using Model-in-the-Loop of this work is unable to reproduce the physic and the chemical reactions that occurs inside the combustion chamber. Because of the lack of those information, it's impossible to model the behaviour and characteristics of the pollutant and the CO2 in a physical way. It's necessary to adopt an empirical approach, based on the confrontation of experimental measurements on an engine during a test performed on dynamometer bench. The experiment (performed in a precedent activity) had the following characteristic:

- An ICE mapping (in terms of torque and speed) has been performed
- Tailpipe emissions have been sampled in terms of mass flow [g/s]
- Exhaust temperature have been sampled [°C]
- ECU fixed parameters of spark advance [°BDTC] and lambda [] have been also sampled

The obtained maps of pollutants and gases mass flows are directly utilized for the model-based simulation. They are fed by the simulated values of torque and speed coming from the engine physical model. The result is a raw emission model for the powertrain in question, because the maps are referred to a different vehicle performing a different test cycle.

This means that the extrapolated values of the map must be corrected to fit the simulated operating condition of the PHEV. Because the calculated emission values are representative only of the engine mapping conditions in terms of SA and lambda, they require to be corrected with the values of the simulation loop. Thus, from previous activities has been collected correction maps, in terms of lambda, ΔSA and pollutant's mass flow variation. Then, the parameters from the physical engine model of that precise timestep enters the map, identifying the correction factor that need to be applied to the raw values.

The corrected results are now representative only right after the exhaust valves of the ICE. For reaching the aftertreatment system, such emissions must flow through the exhaust manifold, which therefore needs to be modelled as well. The exhaust manifold has been previously modelled only in terms of temperature, because the mass flows have been considered constant through it. The manifold model is split in subsequent submodels representing different volume sections. For each volume section is defined a conduction factor through the external environment: the exhaust gas temperature then decreases for every volume section passed through.

At this point it's possible to integrate the aftertreatment models. Once the engine-out emissions are corrected, it's required to simulate the three-way catalyst that converts them and output the tailpipe emissions, the ones that are sampled for performing the homologation. The aftertreatment model in combination to the engine emission model needs then to be experimentally validated. For the purpose of this work, such models have been taken from previous activities and fitted in the powertrain model for the MiL calibration. The mass flow values coming from the exhaust manifold are now directed toward the Three-way-catalyst. The TWC for converting the tailpipe pollutants into harmless emissions, needs to oxidize the CO and HC with the help of Platinum and Palladium molecules, but needs to reduce the NOx with the help of Rhodium molecules. It is clearly impossible to perform two oxidation and reduction reactions at the same time, meaning that the TWC must find a trade-off operational point. The need of a trade-off implies necessarily the presence of a conversion efficiency, that for a TWC is shown in the following formula:

$$\eta_{TWC,x} = \frac{[\%]_{x,inlet} - [\%]_{x,outlet}}{[\%]_{x,inlet}}$$

Table 2: Three-way-catalyst efficiency

Parameter name	***Description***
$\eta_{TWC,x}$	Three-way catalyst efficiency of the x pollutant (x = CO, HC, NOx)
$[\%]_{x,inlet}$	Percentage of pollutant x entering the three-way catalyst
$[\%]_{x,outlet}$	Percentage of pollutant x exiting from the three way catalyst (tailpipe)

This conversion efficiency highly depends on the actuated lambda value. A typical TWC conversion efficiency varies as follow:

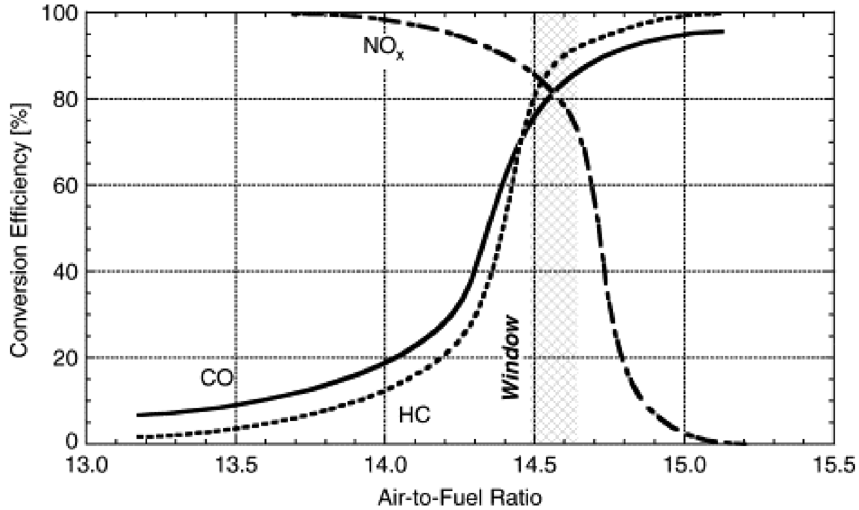


Figure 22: Three-way-catalyst efficiency w.r.t. lambda

To perform the two types of chemical reactions, in a three-way catalyst are present also Cerium-Oxide molecules, that acts like a “sponge” for the O2: in fact, if inside the TWC is present oxygen, the Cerium-Oxide molecules absorbs it, allowing the reduction reaction to happen; vice versa it releases it if the ambient has a low oxygen concentration, allowing the oxidation reaction to happen. It’s then required to define the oxygen storage capacity (OSC) of the Cerium-Oxide. This capacity to store the oxygen can be lost during time, making the conversion efficiency very low. The conversion efficiency depends also on the internal temperature of the TWC itself:

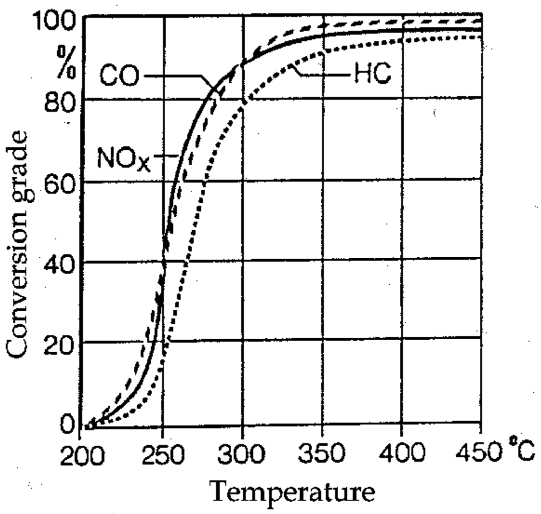


Figure 23: Three-way-catalyst efficiency w.r.t. temperature

It can be defined a point of about 270°C called *light-off temperature*: this point represents the threshold for an efficient pollutant's conversion. The TWC has the same thermal model of the exhaust manifold (based on external heat exchange) and takes into account the exothermy of the chemical reactions. For reproducing the behaviour of the conversion efficiency, the input variables of the TWC model are:

- Pollutant's space velocity:

$$v_s = \dot{m}_x * \frac{P_x}{\rho_{gas} T_{gas}} * \frac{1}{V_{TWC}}$$

- Temperature of TWC:

$$T_{TWC} = T_{gas}$$

Table 3: Three-way-catalyst space velocity

Parameter name	***Description***
$\dot{m}_x$	Mass flow of *x* pollutant (*x* = CO, HC, NOx) [g/s]
P_{gas}, T_{gas}	Pressure and temperature of the exhaust gases
V_{TWC}	Three-way-Catalyst volume

For the calculation of the conversion efficiency, a map-based method is utilized: conversion efficiency maps are collected from previous activities, and fed with the values of temperature and space velocity. The result is a raw conversion efficiency, representative only of the lambda and spark advance set for obtaining the maps. It is necessary a correction, like for the engine emission model.

The correction is performed in terms of lambda but also in terms of oxygen store capacity. Another correction is necessary, on the CO2: the chemical reactions that occurs inside the TWC develops also an amount of CO2; this value is then added to the CO2 value coming from the engine emission.

The validation of the tailpipe emissions and aftertreatment models have been performed in a previous activity, through experimental comparison with a real vehicle's emission. The vehicle adopted is the same as the high-performance PHEV in case, but with a conventional powertrain. This vehicle has performed a test cycle, a NEDC, during which tailpipe emissions mass flow have been sampled. The same NEDC has been reproduced with the Model-in-the-Loop methodology. The emissions and aftertreatment models are then considered validated if the simulation and the experimental results are comparable within certain limits. The validation results are shown in the following graphs:

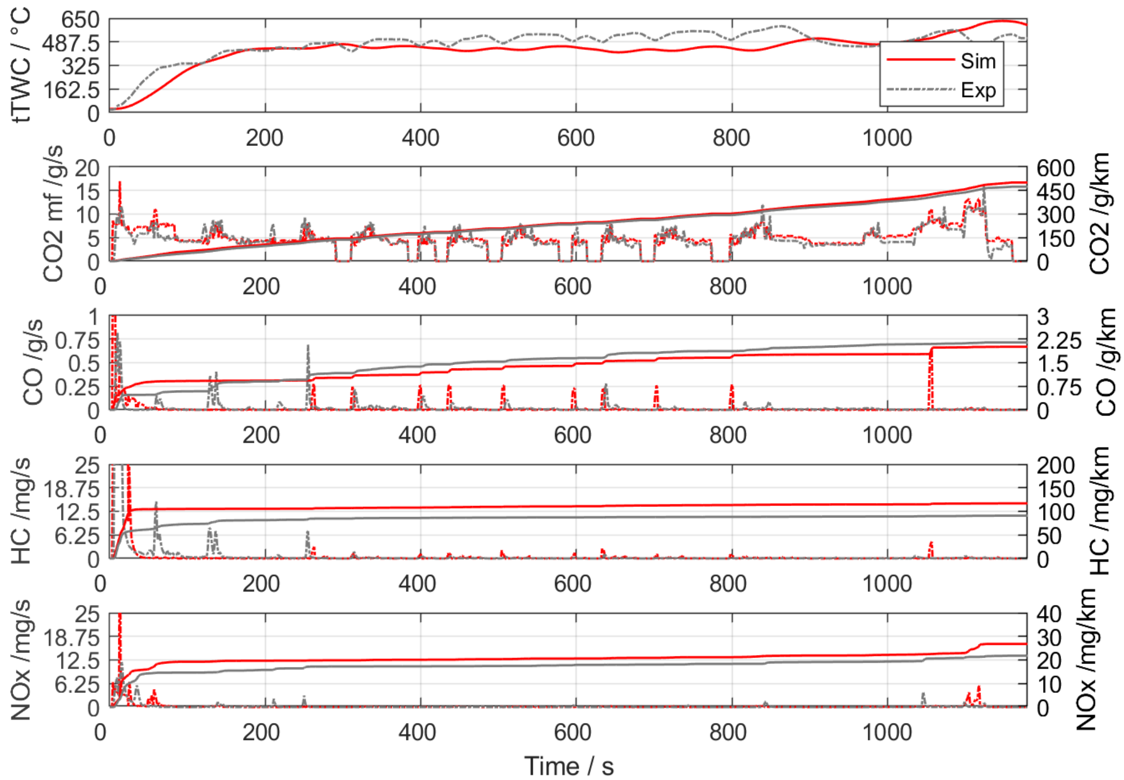


Figure 24: Emission and aftertreatment's models validation

Because such model validation is considered "standalone" and applicable to any test cycle and powertrain operating condition, this validation is considered applicable also for the hybrid powertrain of the study and also for different cycles, such as WLTC. There is also a second type of validation of the Three-way catalyst temperature: through a 1-Dimensional TWC model, developed with GT-

Suite environment developed previously to this work. The result of this validation is the sequent:

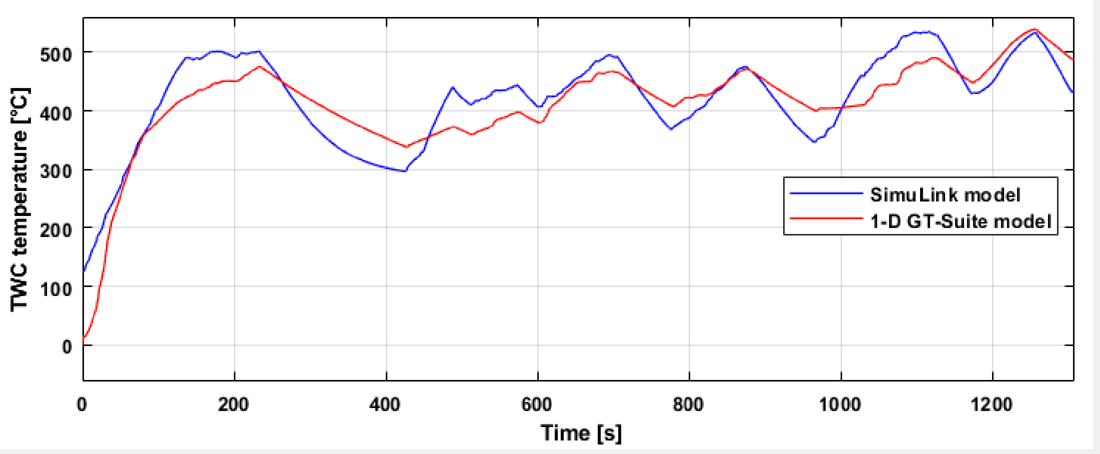


Figure 25: Three-way-catalyst temperature validation

2.2 HCU model description

The intrinsic characteristic of a hybrid electric vehicle is the possibility to run in multiple powertrain configurations, like utilizing only the internal combustion engine to move the wheel, or only the electric machines, or both, etc… In particular, the high-performance PHEV in study is a power-split hybrid. Thus, the powertrain can behave as a parallel hybrid, as a serial hybrid, as a conventional vehicle or a fully electric vehicle. This variety of operating modes requires a control module that decides the correct functioning operation for that given moment.

Almost every hybrid electric vehicle has an additional electronic control unit that governs the hybrid functionalities. In some vehicle it is called Hybrid Supervisor, or Hybrid Module Coordinator, or more simply Hybrid Control Unit (HCU). This electronic control unit model has been developed for the model-in-the-loop simulation of this work. The following chapters will analyse how the HCU has been modelled and integrated with the other models and submodels in order to perform Model-in-the-Loop simulations.

2.2.1 Hybrid mode request submodel

The very first task that a hybrid control unit must perform is the definition of the most suitable driving mode. This involves selecting if driving in a hybrid-parallel mode, hybrid-serial mode or in fully electric mode. It also can be set manually to drive in conventional mode (wheels moved only by the ICE). To perform the selection, the Hybrid Mode Request submodel must evaluate input parameters such as the wheel's velocity, torque requested by the driver, state of charge of the high-voltage battery and status of the internal combustion engine. If those parameters satisfy the following conditions, E-drive modality can be requested:

$$v_{vehicle,ICE\_on} < v_{vehicle,act} < v_{vehicle,ICE\_off}$$

$$T_{EM,lower\_lim} < T_{req@wheels} < T_{EM,upper\_lim}$$

$$P_{discharge,lower\_lim} < P_{battery,act} < P_{discharge,upper\_lim}$$

$$SoC_{ICE\_on} < SoC_{act} < SoC_{ICE\_off}$$

Table 4: Hybrid Mode Request

Parameter name	***Description***
$v_{vehicle,act}$ [m/s]	Actuated vehicle velocity
$v_{vehicle,ICE\_off}$ / $v_{vehicle,ICE\_on}$ [m/s]	Vehicle's velocity threshold for ICE deactivation/activation
$T_{req@wheels}$ [N/m]	Torque requested at the wheels
$T_{EM,lower\_lim}$ / $T_{EM,upper\_lim}$ [N/m]	Maximum/minimum deliverable torque from the EM
$P_{battery,act}$ [kW]	Power provided by the battery
$P_{discharge,lower\_lim}$/ $P_{discharge,upper\_lim}$[kW]	Power's maximum/minimum limit that the battery can provide
SoC_{act} [%]	Actual state of charge of the battery
SoC_{ICE_on} / SoC_{ICE_off}[%]	SoC thresholds for requesting the ICE to be on or off

If one of this condition is not satisfied, then the request is not E-drive but hybrid drive. For the hybrid mode request, it is also computed the start & stop functionality. The output of the submodel is a single bit that enables the following submodel, in where is performed the actual selection of the hybrid mode.

2.2.2 Hybrid mode selection

The bit of the hybrid mode request enters in a SimuLink StateFlow chart, that is a control logic tool used to model reactive systems via state machines and flow charts. StateFlow also provides state transition tables and truth tables. Inside the chart is defined the behaviour that the powertrain must assume according to the hybrid mode previously requested. At first is stated whether the internal combustion engine must be started by the integrated starter generator or not:

$$Hybrid\ drive\ request > time\ threshold$$

If the request is consistent, the StateFlow commands the ISG that cranks the engine. The cranking stops and the ICE is considered running when the following conditions are satisfied:

$$ICE\ rpm\ actuated > ICE\ threshold\ rpm$$

$$Requested\ gear > 0$$

Once the engine is fully running, the HCU must decide whether to drive in parallel hybrid or serial hybrid mode, according to the configuration selected by the driver at the start of the simulation. This selection will trigger other submodels present in the HCU (details provided further on). If the following conditions are fulfilled, the ICE can be turned off if E-drive is requested, returning to the initial state of electric driving operation:

$$Edrive\ request > time\ threshold$$

$$ICE\ rpm\ actuated < ICE\ rpm\ threshold$$

The output of this StateFlow is a series of controlling bits (triggers) that enables other submodels to calculate the conditions of that proper hybrid mode.

2.2.3 E-drive / parallel submodel

In this submodel are calculated the control parameters of the components that must ensure a hybrid parallel drive. For this, are calculated torques requested to the internal combustion engine, the electric motors and the integrated start generator. The first step is the ICE raw torque request, considering also the case of battery recharge necessity: this state is called Load Point Shift (LPS). Thus, if it's necessary to perform the LPS, the HCU must consider the minimum between those values:

$$T_{batt} = \min\left(\frac{P_{requested}}{\omega_{ICE}}, T_{P2,max}, T_{ICE,ECU}\right)$$

Table 5: Hybrid parallel / E-drive

Parameter name	***Description***
T_{batt} [Nm]	Additional torque necessary for performing LPS
$P_{requested}$ [Nm]	Power requested to the ISG for recharging the batteries
ω_{ICE} [rpm]	ICE rotational speed

$T_{P2,max}$ [Nm]	Maximum torque that the P2 electric machine can deliver
$T_{ICE,ECU}$ [Nm]	Torque calculated by the engine control unit

The Load Point Shift power requested for recharging the battery is:

$$P_{requested} = k23 + (SoC_{actual} - SoC_{min}) * k24$$

Table 6: Hybrid parallel Load Point Shift

Parameter name	***Description***
$k23$ [kW]	Requested power for recharging batteries if the state of charge is at minimum
SoC_{min} [%]	State of charge threshold for ICE activation
SoC_{actual} [%]	Actual state of charge of that timestep
$k24$ [% / kW]	Rate that modifies the $P_{requested}$ depending on SoC deviation

Once the raw torque necessary for the parallel drive is calculated, it enters along with other inputs in a StateFlow, that calculates the raw values of torque to be provided to the other components. For the E-drive mode instead, the calculations for the EM are as follow:

$$T_{P4} = T_{tras,in} * \frac{r_{gear,act}}{r_{P4,act}}$$

$$T_{P2} = 0$$

Table 7: E-drive torque calculation

Parameter name	***Description***
T_{P4} [Nm]	Raw torque requested to the P4 motor
$T_{tras,in}$ [Nm]	Raw torque requested from the wheels to the transmission
$r_{gear,act}$ [Nm]	Transmission ratio of the engaged gear
$r_{P4,act}$ [Nm]	Transmission ratio of the P4 gear

For the hybrid mode (parallel drive) the raw torque of the P4 machine is calculated as follow:

$$T_{P4,regenerative\_braking} = T_{tras,in} * \frac{r_{gear,act}}{r_{P4,act}}, \qquad T_{tras,in} < 0$$

$$T_{P4,normal\_drive} = \left(1 - RWD_{split}\right) * \ T_{tras,in} * \frac{r_{gear,act}}{r_{P4,act}}, \qquad T_{tras,in} > 0$$

Table 8: Regenerative braking torque calculation

Parameter name	***Description***
$T_{P4,regenerative\_braking}$	Raw torque provided by the P4 motor during regenerative braking phase
$T_{P4,normal\ drive}$	Raw torque requested to the P4 for normal driving condition
RWD_{split}	Torque split between ICE and P4 motor

$$T_{ICE,recharge} = T_{tras,in} * RWD_{split} + T_{LSP}, \qquad T_{tras,in} < T_{ICE,only\_threshold}$$

$$T_{ICE,only} = T_{tras,in} * RWD_{split}, \qquad T_{tras,in} > T_{ICE,only\_threshold}$$

$$T_{ICE,regenerative\_braking} = 0, \qquad T_{tras,in} > -20$$

Table 9: ICE torque calculation

Parameter name	***Description***
$T_{ICE,recharge}$	Raw torque requested to the ICE for driving and recharging batteries
T_{LSP}	Raw torque requested to the ICE for performing the Load Shift Point
$T_{ICE,only\_threshold}$	Torque threshold for conventional driving mode
$T_{ICE,only}$	Raw torque requested to the ICE for functioning in conventional mode
$T_{ICE,regenerative\_braking}$	Raw torque requested to the ICE for performing a regenerative braking

$$T_{P2,charge} = \min\left(0, T_{tras,in} * RWD_{split} - T_{Edrive}\right) * \frac{r_{gear,act}}{r_{P2,act}}, \qquad T_{tras,in} > -10$$

$$T_{P2,zero\_load} = 0$$

$$T_{P2,regenerative\_braking} = 0, \qquad T_{tras,in} < -10$$

Table 10: P2 torque calculation

Parameter name	***Description***
$T_{P2,charge}$	Raw torque requested to the P2 for recharging batteries
T_{Edrive}	Raw torque requested for driving in Eelectric mode
$T_{P2,zero\_load}$	Torque requested to the P2 if zero load
$T_{P2,regenerative\_braking}$	Torque requested to the P2 in regenerative braking phase

Once all of those calculation are performed, the raw quantities are then corrected in another submodel, according to other parameters coming from the physical models, such power losses and frictions along the drivetrain. These corrections are necessary to state the actual torque/power request that the HCU sends to the controllers of the vehicle's hybrid components.

2.2.4 Series mode submodel

If the driver has chosen the series hybrid driving mode, the StateFlow of the hybrid mode selection enables the series mode submodel, that calculates the torque values necessary to drive in that modality. Like for the previous block, it's necessary to evaluate the Load Point Shift in series mode. Here, the ICE task is just to recharge battery, because it's disconnected from the wheels. For evaluating the ICE torque, it's necessary to determine the minimum value among the following torque requests:

$$T_{LSP,series} = \min\left(\frac{P_{charge}}{\omega_{ICE}}, \frac{T_{P2,min}}{r_{P2}}, T_{ICE,max}\right)$$

Table 11: Hybrid series LPS

Parameter name	***Description***
$T_{LSP,series}$	Raw torque requested for performing the LSP in series mode
P_{charge}	Raw power requested for recharging batteries
ω_{ICE}	Rotational speed of the ICE
$T_{P2,min}$	Minimum continuous torque deliverable by the P2 motor
r_{P2}	Cranking ratio (P2 ratio)
$T_{ICE,max}$	Maximum torque provided by the ICE

Once the torque of the LSP sent to the ICE is defined, the series submodel acts a control on the P2 electric motor in terms of rotational speed. It's defined thanks to a mechanical balance: the electric motor adapts its rotational speed on the base of the torque requested for charging the battery. In the model, this is represented by the following calculation:

$$T_{P2} = T_{LSP,series} + T_{sc}$$

Table 12: P2 speed control

Parameter name	***Description***
T_{P2}	Raw total torque requested to the P2 motor
T_{sc}	Additional torque necessary for achieving the target ICE rpm value

This way, are prevented unwanted sudden accelerations of the P2 motor. The actual torque that is necessary at the wheel given by the P4 motors is calculated in the final submodel, on the basis of the combination of all the other torque requests.

2.3 Model integration

The insertion of a hybrid control unit model inside a conventional powertrain's model requires corrections and integrations of the major participants in the simulation. Specifically, the engine control unit and transmission control unit must be updated in order to respond to the request of the "higher in level" hybrid control unit. In the following paragraphs will be described the modifications made in the engine control unit and in the transmission control unit.

2.3.1 Engine control unit integration

The main modification performed in the ECU is related to the engine mode selection, because it needs to comprehend the several functioning ways during hybrid/Edrive phases. The HCU sends directly a torque request to the ICE necessary to perform the manoeuvre at that moment, that is then converted in brake mean effective pressure (BMEP), via this formula:

$$BMEP_{requested} = \frac{T_{ICE} * 2\pi}{0.5 * 10^5} * \frac{1}{V}$$

Table 13: Brake mean effective pressure

Parameter name	***Description***
$BMEP_{requested}$	Brake mean effected pressure requested at the ICE
T_{ICE}	Raw torque requested at the ICE crankshaft
V	Engine displacement in volume

This calculation intrinsically contains the amount of torque necessary for the LSP. This means that the engine must know whether to perform the load shift point or not. For this, inside the engine mode selection, has been created a proper engine mode that represents this state. Depending on the engine hybrid state, the ECU calculates the torque and subsequently the values of requested air, fuel, spark advance, throttle valve angel etc…In particular, the virtual ECU requires a modified idle control, based on a PI controller that acts on idle target and revolutions per minute actuated. For this, the PI integrator needs to be reset every time the engine performs the load shift point. The same modification is required for controlling the position of the drive-by-wire throttle valve (DBW).

2.3.2 Transmission control unit integration

As long as the ECU, an important integration has been made in the transmission control unit, due to the fact that the gearbox has to behave differently considering all the hybrid modalities. The main modification that has been performed involved the submodel desired gear selection (DGR). In fact, a condition of cranking request became necessary. So, a virtual gear (equal to -1) has been added to the DGR submodel in order to identify the condition of cranking request. This condition is based on a control bit coming directly from the HCU.

Moreover, an additional modification had to be inserted, regarding the electric drive only. The desired gear when this mode is selected by the HCU should be neutral, conventionally identified by the number 0. Also, this condition is directly determined by the hybrid control unit. The hybrid transmission required a re-arrangement of the synchronizer control.

2.3.3 HCU virtual validation via Model-in-the-Loop

After the insertion of the hybrid control unit in the powertrain model, and after the integration of the engine and transmission control units, the powertrain model needs to perform a series of simulations in order to be considered fully functioning. This process is called model virtual validation. There is not a standardized way to validate virtually a powertrain model. The model-in-the-loop simulation selected for performing a virtual validation is a WLTC run for each hybrid and Edrive mode. The hybrid powertrain model can be considered if the virtual car performs the entire cycle correctly, showing reasonable values for the main parameters and comparable results. For the purpose of the model virtual validation, a scope interface has been developed in order to investigate the principal parameters of the simulation. Such parameters are:

- The status of the hybrid control unit that defines the functioning mode
- The actuated torque of the internal combustion engine, the P2 motor and the P4 motor
- The actuated rotational speed of the internal combustion engine, the P2 motor and the P4 motor
- The vehicle's target velocity profile and instantaneous speed

The following simulations are performed to state the validity of the model-in-the-loop:

- Hybrid parallel mode
- Hybrid series mode

Both of them includes some electric driving. Each simulation has been performed varying some parameters of the hybrid control unit, such as minimum state of charge at which the engine must be activated, thresholds for engine deactivation, power requested for performing the load shift point, etc… In the following graphs are shown one example of each simulation performed.

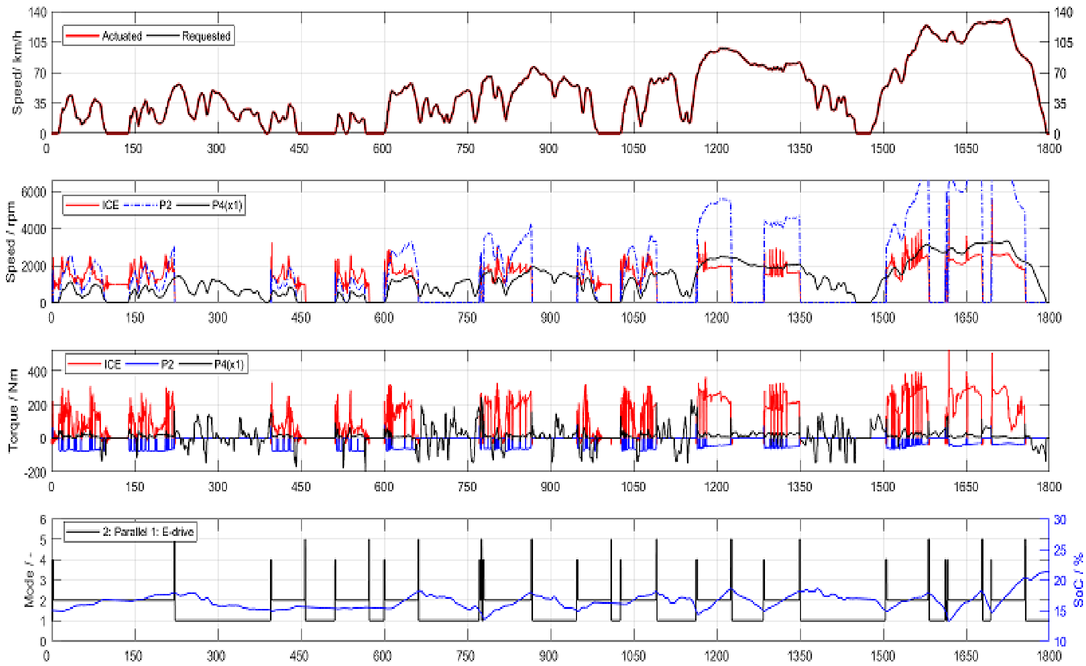


Figure 26: WLTC Mode-in-the-Loop hybrid parallel validation

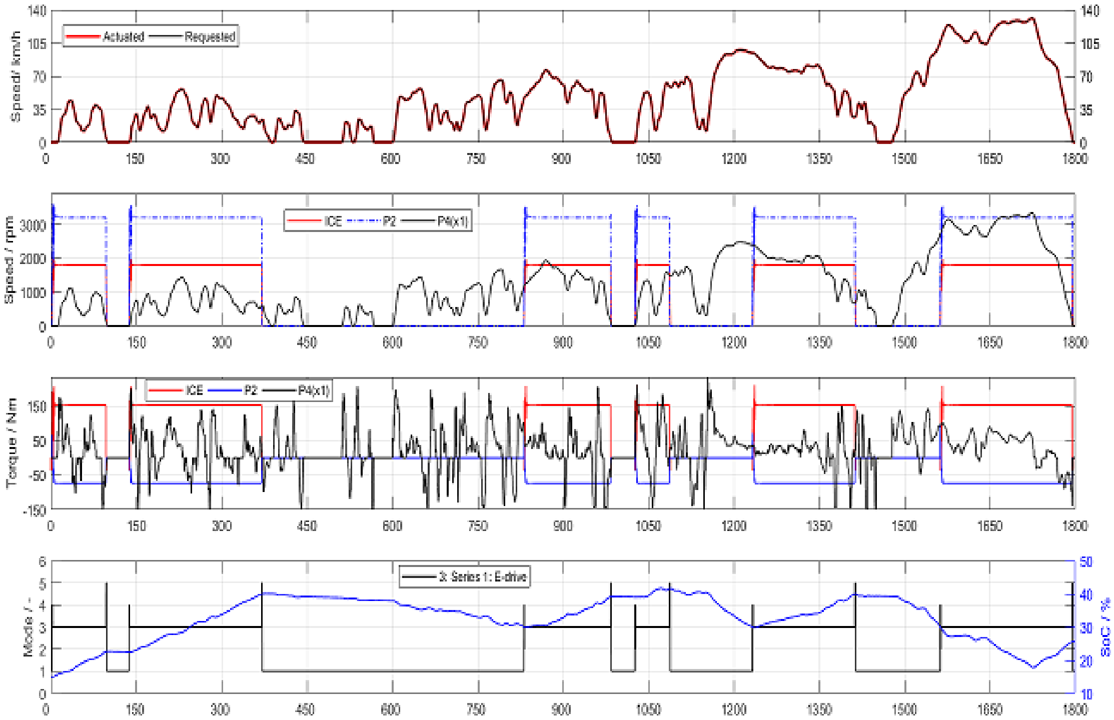


Figure 27: WLTC Mode-in-the-Loop hybrid series validation

3 Virtual calibration of emissions via Model-in-the-Loop

For calibrating the tailpipe emission of a vehicle, a possible way is to modify the parameters of the engine control unit, such as the spark advance, the injection timing etc… This is however considered a very refined emission calibration, because such values are the inner one workable with. For a higher-level pollutant emission and CO2 calibration, especially in a plug-in hybrid electric vehicle, it's possible to act on the hybrid control unit (HCU).

Because the HCU acts on the internal combustion engine functioning, it's possible to set parameters that govern the functioning strategy for calibrating the tailpipe emissions and more evidently the CO2 emission, because the latter are directly proportional on the ICE functioning. In this chapter are analysed the HCU parameters chosen for the virtual calibration, the design of experiment (DoE) selected for the simulation and the evaluation of the optimal HCU values combination.

3.1 Design-of-Experiment based HCU parameter optimization

For performing a virtual calibration of HCU with the aim to contain the pollutant emission under the legislation law and to reduce the CO2 emission as much as possible, it's required to identify the parameters that affect the most the tailpipe emission production. It's necessary to define a test cycle in which to perform the HCU virtual calibration. The selected test is a WLTC, but it has been decided not to perform the entire World Lightweight-vehicle Test Procedure for hybrid electric vehicles. This because it comprehends the performing of several cycles in a battery charge-depleting strategy. The initial SoC is set to the maximum, and thus means that the vehicle drives only in electric mode for most of time. The electric drive of course doesn't give any contribution to tailpipe pollutants or CO2 production, because the ICE is kept almost always deactivated. In other words, a WLTC performed in CS represents the *worst-case scenario* for the production of CO2 and pollutants of a PHEV.

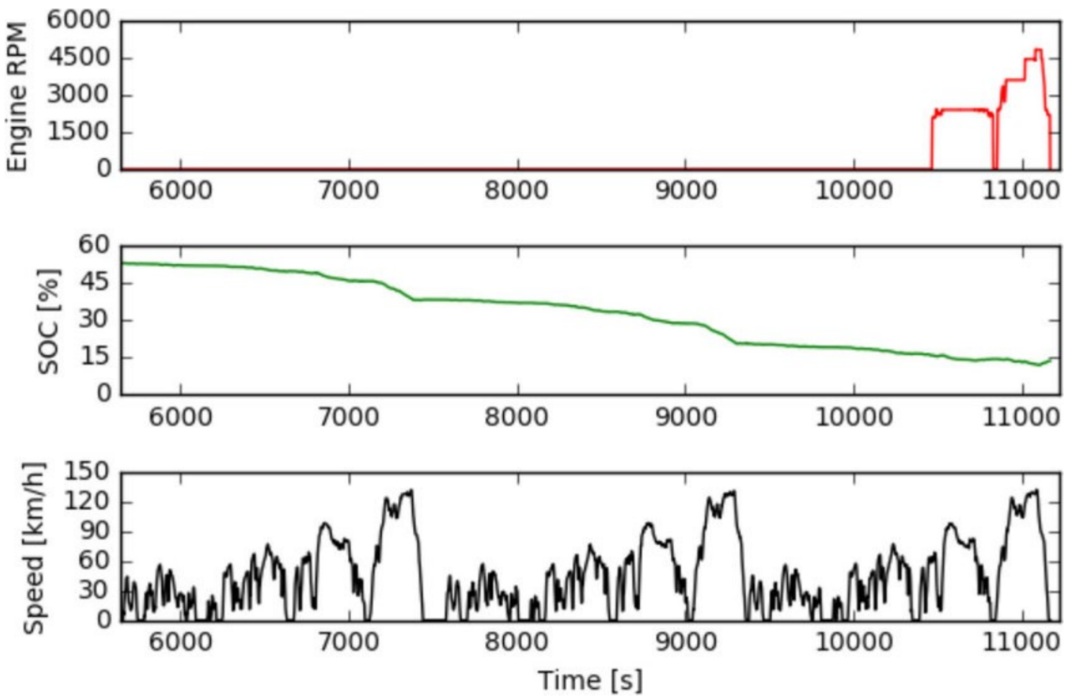


Figure 28: Example of a full charge depleting strategy

It's clearly visible that the ICE starts only at the very end of the cycle, but for the rest is completely shut down due to the electric driving. The ICE contribution to the emission is then too difficult to evaluate in that short time window, so the charge depleting WLTCs are discarded. What is considered more appropriate for performing the present analysis is to select only the charge sustaining cycles of the WLTP. Here the engine operates almost continuously, and because of that the emission evaluation is easier to achieve and the optimal calibration easier to obtain.

Once the cycle and the strategy are defined, it's necessary to identify HCU parameters that affect mostly the tailpipe emission trend. In the HCU there are a multitude of parameters to choose from, but the majority of them won't have a high impact on tailpipe emission, because they don't influence directly the functioning operation of the ICE. For example:

- SoC_{ini}: the initial battery state of charge doesn't influence significantly the emission production, because in a charge sustaining test cycle the electric drive is reduced to a limited amount.
- $SoC_{ICE,on}$: the state of charge value at which the engine is required to activate in order to recharge the battery doesn't have a high impact on the emission, because that value depends on the battery's physical model and because it affects mostly a charge depleting test cycle.
- Shifting strategies (TCU): the transmission control unit receives directly the values of the torque and speed requested from the HCU. The aim is not to interfere between the HCU and the TCU.

On the other side, there are some parameters that affects the behaviour of the hybrid control unit, thus intervening directly on the internal combustion engine functioning strategies. The parameters chosen for virtual calibration are:

- $SoC_{ICE,off}$: it represents the threshold at which the engine must be deactivated after having completed the load shift point. It is fundamental because it defines the operating window of the ICE: increasing this value means a higher window, thus the ICE is required to operate continuously more in a test cycle, but activating and deactivating less times; decreasing the value means that the LSP window is reduced and during a test cycle the ICE runs and stops several times but for a shorter period. This variation can greatly affect the emission production.

- Load Shift Point parameters: for this HCU the LSP is governed by a formula that states the power and state of charge thresholds for activating and deactivating the ICE with the aim to recharge the batteries. The formula is the sequent:

$$P_{charge} = k23 * (SoC_{act} - SoC_{min}) * k24$$

Table 4: Load Point Shift power calculation

Parameter name	***Description***
P_{charge}	Power requested by the P2 motor to the ICE for recharging batteries [kW]
$k23$	Power requested to the ICE for battery charging at minimum state of charge
SoC_{act}	Instant value of state of charge of the battery
SoC_{min}	Minimum state of charge value at which is necessary to perform LSP
$k24$	slope which modifies the ICE power request depending on SoC deviation [kW/ %SoC]

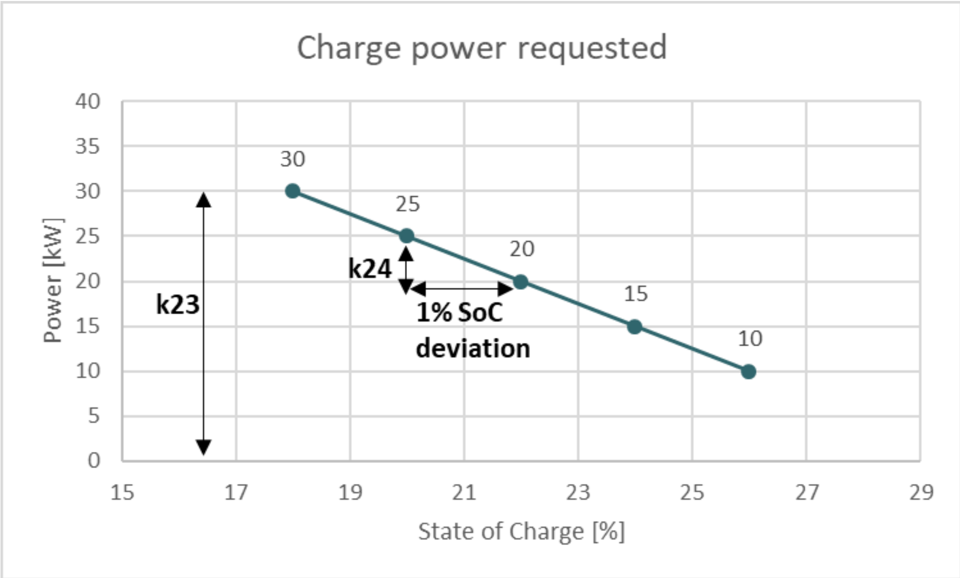


Figure 29: Charge power requested example

The LSP parameters selected for virtual calibration are the following:

- k23: important because the more power is requested for recharging the battery, the more torque must be provided from the ICE, with a high impact on fuel consumption and then on CO2 and pollutants production.
- k24: important because it defines the rate of recharging power depending on the actual state of charge: if the SoC is low, the ICE must apply more torque for providing recharge power; if the SoC is close to the ICE deactivation threshold, the torque provided by the ICE is lower. This behaviour affects the pollutants formation as well.

Once the parameters of the HCU have been selected, it’s necessary to develop a Design of Experiment for performing the virtual calibration. The controlled variables are such parameters, and in order to investigate the final result it’s necessary to define the variation range, the length of the variation step and the number of variations necessary. In addition, the objective of the DoE is set: the minimization of the CO2 tailpipe emission under the constraints of the Euro VI pollutants’ emissions.

After some explorative design of experiments, it was visible that outside a certain range of the selected values, the tailpipe emissions didn’t vary in an appreciable way. Thus, the most significant table of values for the purposes of this study has been found:

Table 5: Design-of-Experiment table

DoE	$SoC_{ICE\ off}$	k23	k24
Value 1	18 %	10 kW	0 kW/%
Value 2	20 %	15 kW	2 kW/%
Value 3	22 %	20 kW	3 kW/%
Value 4	24 %	25 kW	4 kW/%
Value 5	26 %	30 kW	6 kW/%

Once the matrix of values is set, it's possible to run the DoE simulations. It is performed a simulation for each combination of parameters. According to permutation's law, the number of simulations performed is equal to:

$$3\ parametes, 5\ variations \rightarrow 5^3 = 125$$

Each simulation is performed to a sample time of 0.1 seconds, and this means that the amount of simulation time for performing a single WLTC is roughly:

$$WLTC\ sim.time = 0.1 * 1800 = 180\ s = 3\ min$$

For performing 125 test cycles, is then required approximately a total amount of time of:

$$total\ sim. time = 3 * 125 = 375\ min = 6.5\ hours$$

It its already visible how the usage of virtual calibration is extremely time saving for HCU emission calibration purpose. The result of this experiment are the following quantities:

- CO2 mass flow [g/km]
- CO mass flow [g/km]
- HC mass flow [g/km]
- NOx mass flow [g/km]
- TWC temperature trend [°C]

They are expressed in terms of 2D surfaces referred to one parameter at a time. The aim of the experiment is to evaluate the best HCU calibration for fulfilling the legislation limits over CO, HC, NOx pollutants, with a cost function of minimizing the production of CO2. In other words, the best calibration result is the parameter's combination that ensure the fulfilment of pollutant legislation of EURO VI-D and at the same time minimizing the tailpipe CO2 amount.

3.2 CO2 emission correction

By modifying the HCU parameters as stated previously, the hybrid strategy changes significantly from cycle to cycle. This leads often to a non-perfect behaviour of charge sustaining. This means that the initial state of charge and the final one are not perfectly the same, but the cycle shows a ΔSoC, defined as follow:

$$\Delta SoC = SoC_{final} - SoC_{initial}$$

This ΔSoC can be positive or negative. The ΔSoC is generated mainly because the last part of the WLTC spots a LSP performed because of high speeds (140km/h) and some energy recuperated due to the final braking. If the ΔSoC is highly positive, it means that the internal combustion engine recharged the battery in excess with respect to an ideal charge sustaining test cycle. Vice versa, if the ΔSoC is highly negative, it means that the ICE didn't recharge the battery sufficiently, for arriving at the end with a perfect charge sustaining cycle.

All those considerations mean that the CO2 actually produced is not representative of the test cycle performed. Instead, experimental results show that for the pollutant this difference is not significant, therefore it is going to be neglected in the following discussion. It is necessary then to apply a correction on the value of CO2 mass flow, and this can be performed with a correction factor named kCO2. This factor is obtained by a standardized procedure, executed with the following experiment:

- 5 WLTC performed with different initial state of charge:
    - 2 cycles performed with charge sustaining strategy
    - 2 cycles performed with charge depleting strategy
    - 1 cycle performed with balanced strategy
- HCU calibration with averaged parameters

The values selected for performing this experiment are the following

Table 6: HCU calibration for kCO2 experiment

SoC engine off	***k23***	***k24***
22 kW	20 kW	3 kW/%

SoC ini	***15%***	***18%***	***21%***	***24%***	***27%***

Once the 5 simulations are performed, the results (values of each cycle) are:

- CO2 mass flow [g/km]
- SoC end value [%]
- Battery energy consumption [Wh]

The first step for calculating the kCO2 is to state the actual energy consumption of the high-voltage battery. This is performed by integrating over time the actual provided power from the battery:

$$EC = \int_{t=0}^{t=t\_end} P_{batt} \; dt$$

This calculation is required for every of the 5 WLTC performed. Now it's possible to evaluate the correction factor kCO2 with this formula:

$$kCO_2 = \frac{\sum_{n=1}^{5}\left((EC_n - EC_{avg}) * (M_{co2,n} - M_{co2,avg})\right)}{\sum_{n=1}^{5}(EC_n - EC_{avg})^2}$$

Table 7: kCO2 calculation

Parameter name	***Description***
EC_n	Energy consumption of the n-th cycle [W/h]
EC_{avg}	Averaged energy consumption of the whole 5 cycles [W/h]
$M_{co2,n}$	CO2 mass flow of the n-th cycle [W/h]
$M_{co2,avg}$	Averaged CO2 mass flow of the whole 5 cycles [W/h]

The following step is to correct the actual CO2 mass flow on the basis of the correction factor kCO2 and the energy consumption. The corrected value is found for each cycle performed in the Design of Experiment stated in the previous paragraph. The formula for calculating the corrected CO2 mass flow is the sequent:

$$M_{co2,corr\_n} = M_{co2,n} - kCO_2 * EC_n$$

The following graph shows the correlation between the raw and the corrected values of CO2. For copyright reason the axis values are omitted except the axis tick:

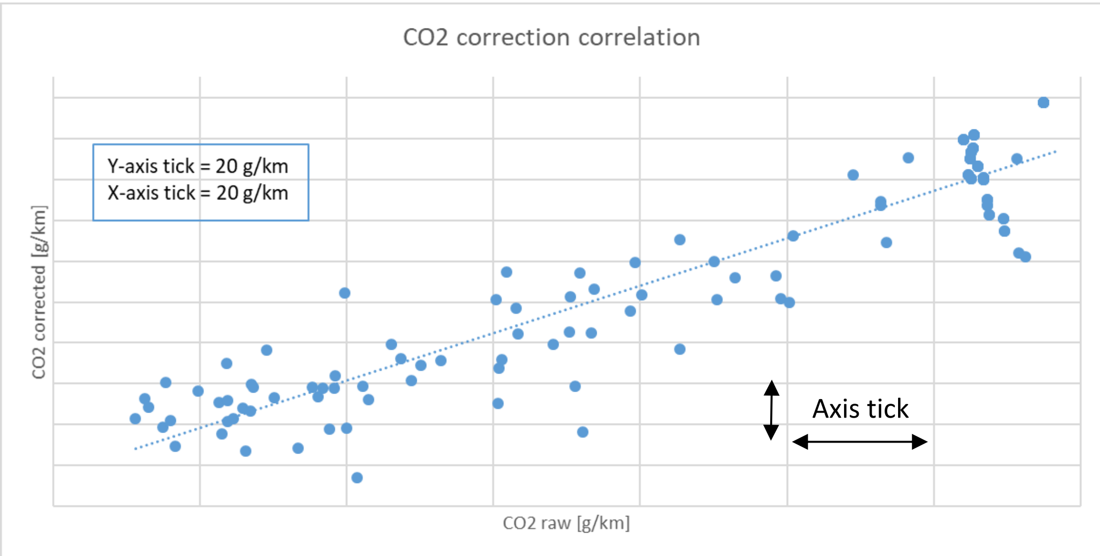


Figure 30: CO2 correction correlation

In the following subchapter are shown and analysed the results of this optimization process.

3.3 Response surfaces and result analysis

The Design-of-Experiment simulation results have shown the following considerations:

- WLTC, Charge sustaining: worst case scenario for pollutants and CO2. This means that the results show the highest emission values within the whole homologation procedure.
- HC, NOx emissions for every cycle are well under the legislation limits
- CO emission strongly depends on the Three-way-catalyst temperature trend along the cycle: the heating and cooling phases of the TWC influences greatly the CO production

The objective of the DoE optimization is to find the set of parameters that minimizes the CO2 by keeping the HC, CO, NOx amount under the current EURO 6c legislation limits with a safety coefficient of 20%, also in prevision of future restrictions. For copyright reason, the following results are presented according to the following formulas:

- $\Delta CO_2 = CO_{2,highest\ value} - CO_{2,lowest\ value}$ [g/km]
- $\Delta NO_x = NO_{x,highest\ value} - NO_{x,lowest\ value}$ [g/km]
- $\Delta CO = CO_{highest\ value} - CO_{lowest\ value}$ [g/km]
- $\Delta HC = HC_{highest\ value} - HC_{lowest\ value}$ [g/km]

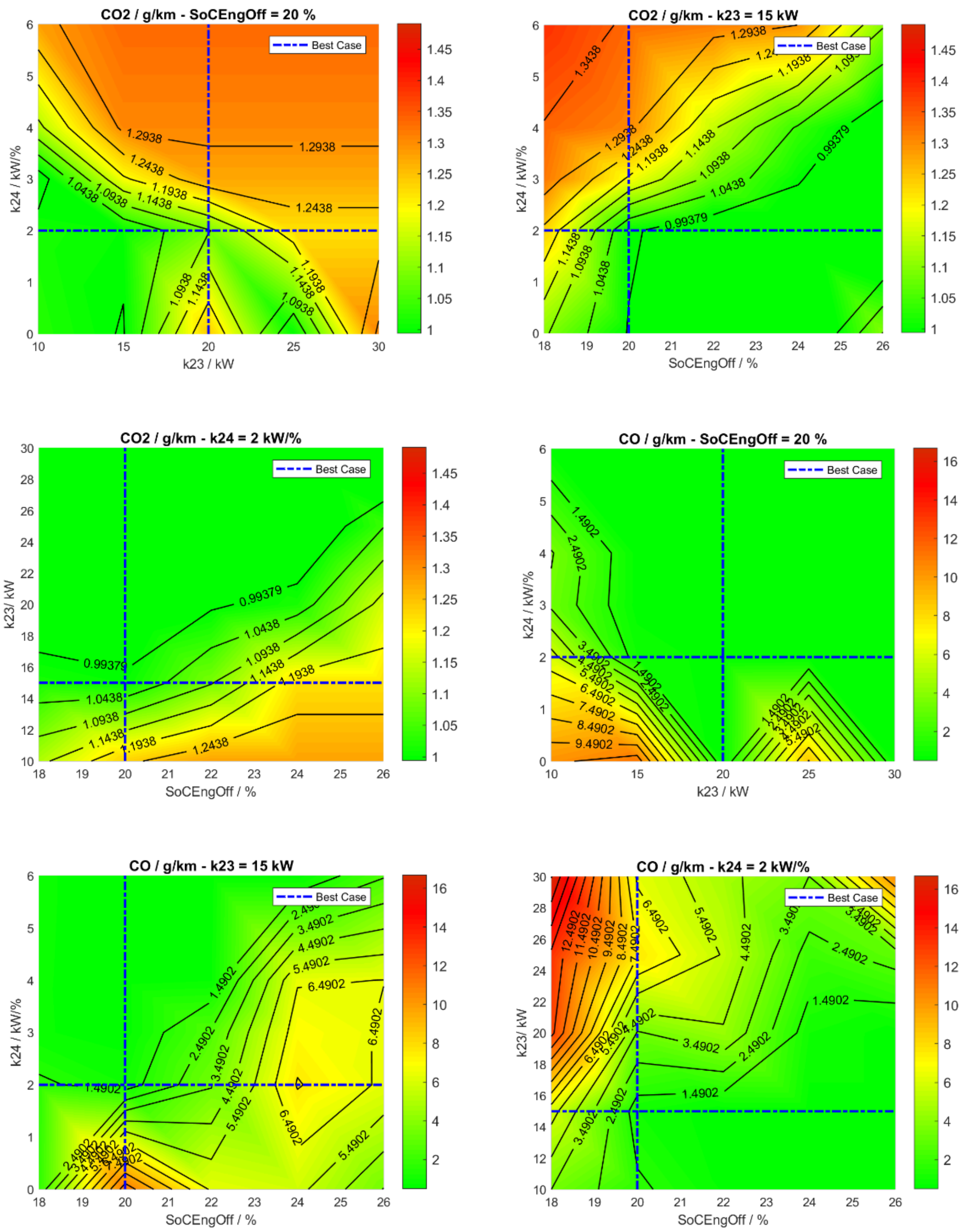
The following table shows how substantial the optimization has been, as long as the set of HCU parameters that have shown the best result:

ΔCO2 [g/km]	ΔCO [g/km]	ΔNOx [g/km]	ΔHC [g/km]
183.3	8.15	0.016	0.039
SoC_off [%]	**k23 [kW]**	**k24 [kW/%]**	
20	15	2	

Table 8: HCU optimized calibration

The actual values are not representative of the possible homologation, because this study has been performed only for the CS part of the WLTP. However, as stated previously, it is expected that the CO2 and pollutants' values could only decrease by performing the entire procedure (comprehensive of charge depleting cycles). This ensures the validity of the optimization

The results of the optimization process are then illustrated in terms of response surfaces. Each parameter analysed (CO2 and pollutant's specific mass flow) depends on three different parameters. A response surface has a 2 variables dependency. This means that each surface is referred to a specified value of one of the three DoE parameters. The values of the surfaces, for copyright reason, are normalized to the optimized HCU calibration



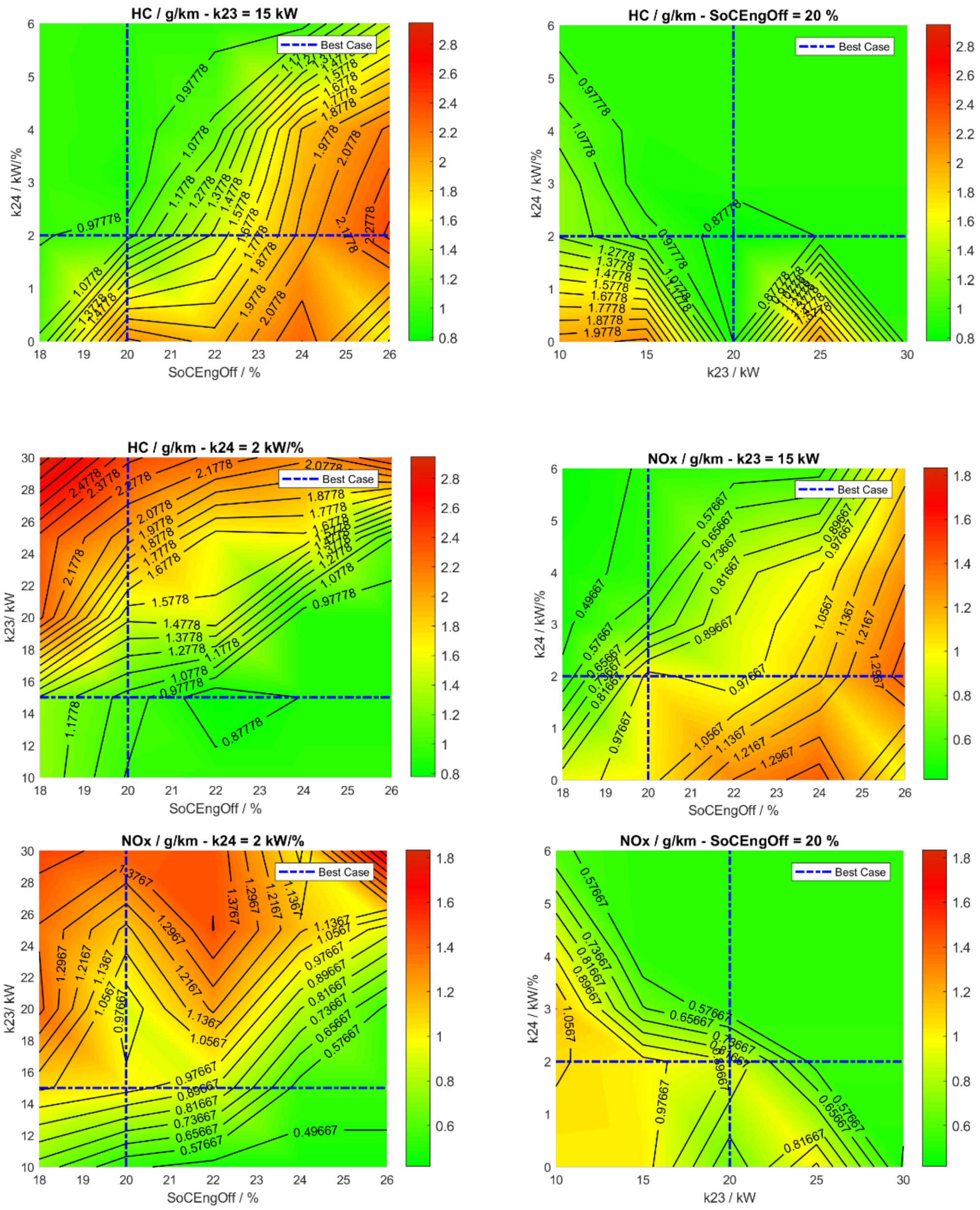


Figure 31: Optimized response surfaces

The corresponding cycle performed with the optimized set of HCU parameters shows the following trend. For copyright reason in the emissions trend are omitted the values of mass flow:

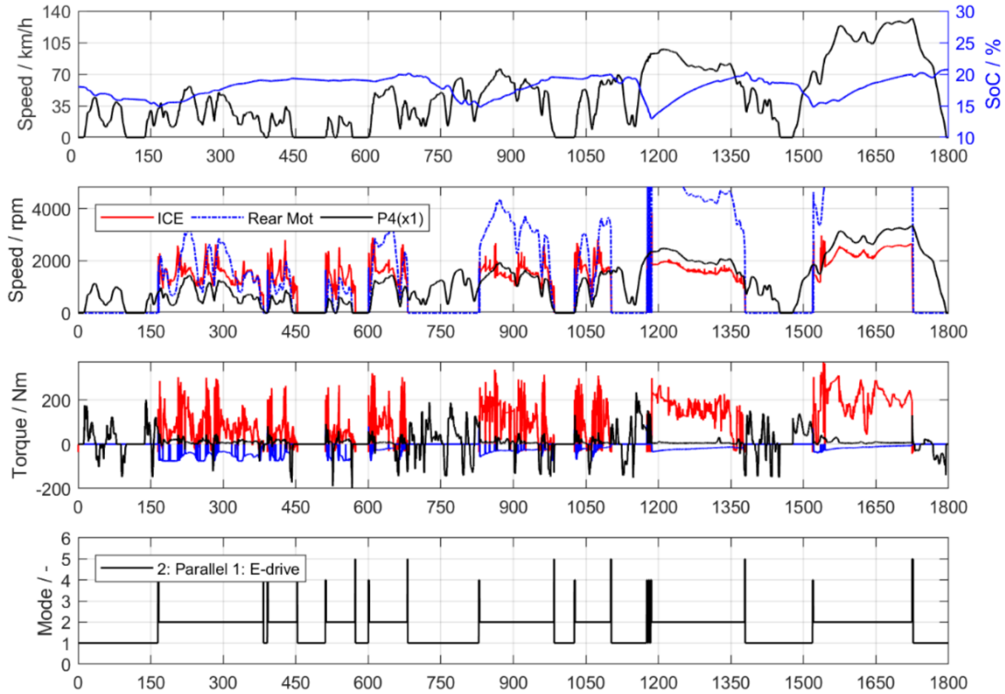


Figure 32: Optimal HCU calibration WLTC

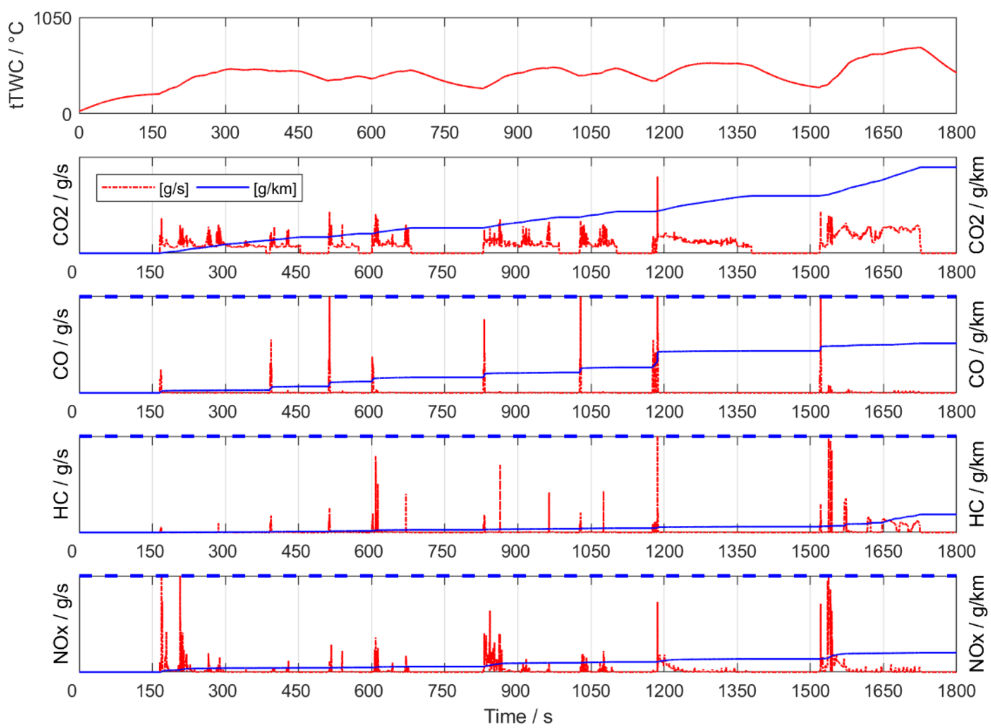


Figure 33: Tailpipe emissions of optimal HCU calibration

Figure 32 in particular shows the TWC temperature w.r.t. time and the instantaneous pollutants mass flow, as long as their specific values. Some considerations can be made on the TWC temperature regarding HC, NOx and CO production:

- NOx and CO contributions are strictly dependant on the TWC temperature: at the first stage of the cycle, the temperature is low and this means a high instantaneous mass flow.
- The HCU driving strategy turns the ICE down in some moments, meaning that during the ICE-off phases the TWC cools down. This leads to high contribution of NOx and CO.

It is possible also to make correlation graphs between pollutants and amount of CO2 produced. For copyright reason the values are omitted, except the axis tick for giving the idea of how wide the optimization range has been:

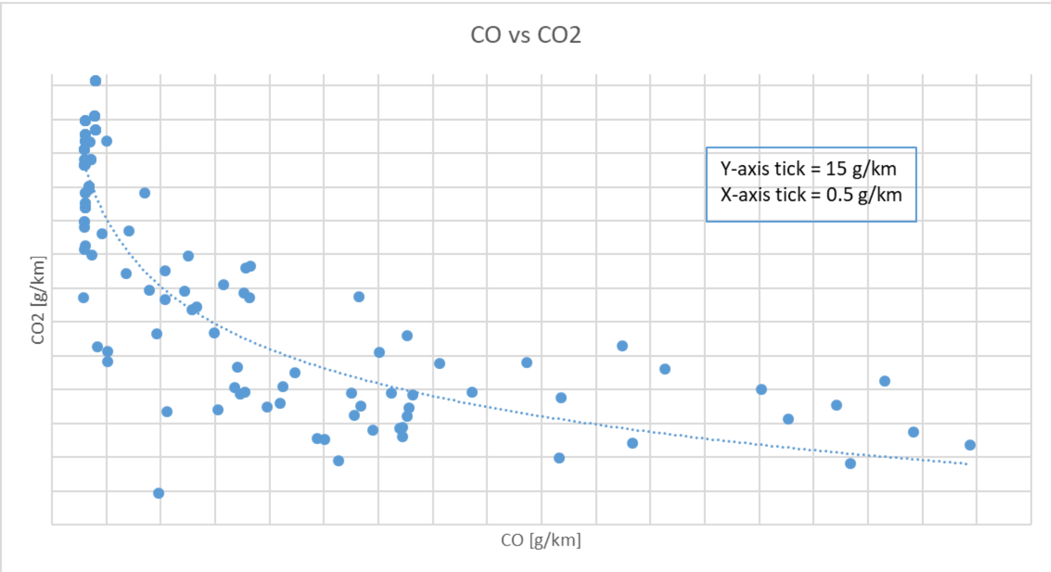


Figure 34: CO w.r.t. CO2

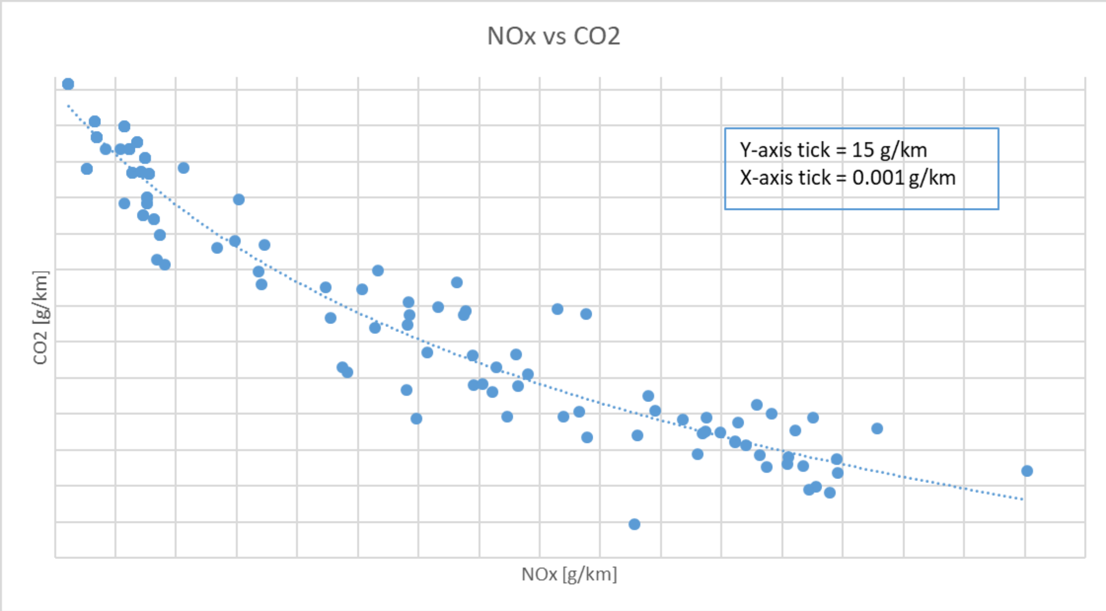


Figure 35: NOx w.r.t. CO2

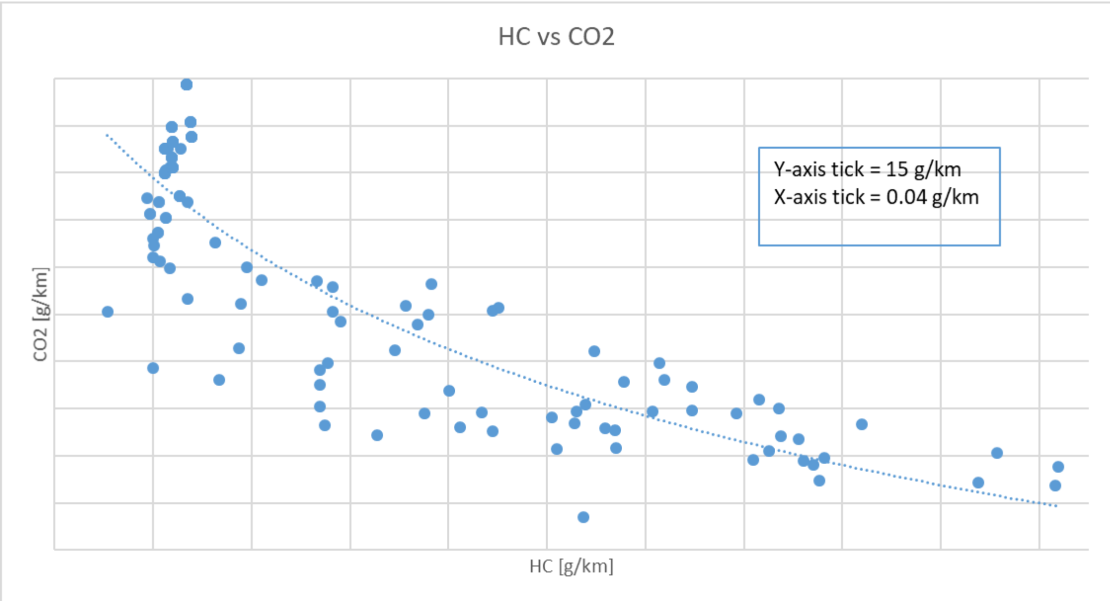


Figure 36: HC w.r.t. CO2

The graphs show a logarithmic line that approximates the correlation trend. It is clearly visible how for high values of CO2, the CO and NOx amount is low. This because high values of CO2 mean that the ICE is actually functioning, thus the related TWC temperature is high, and subsequently it's conversion efficiency. On the other hand, low values of CO2 sign that the internal combustion engine is kept off, leading in a TWC cooling and in a lowering of its conversion efficiency.

4 Ongoing activities and future steps

As mentioned in chapter 1, for obtaining real benefits in terms of time and cost, following steps are often adopted, such as Hardware-in-the-Loop simulations and Engine-in-the-Loop testing. Those methodologies for virtual calibration are defined and described in the following chapter. In particular, they represent the activities performed in parallel to this work (HiL) and the future task to be performed (EiL) in order to arrive to a small amount of calibrations performed in-vehicle.

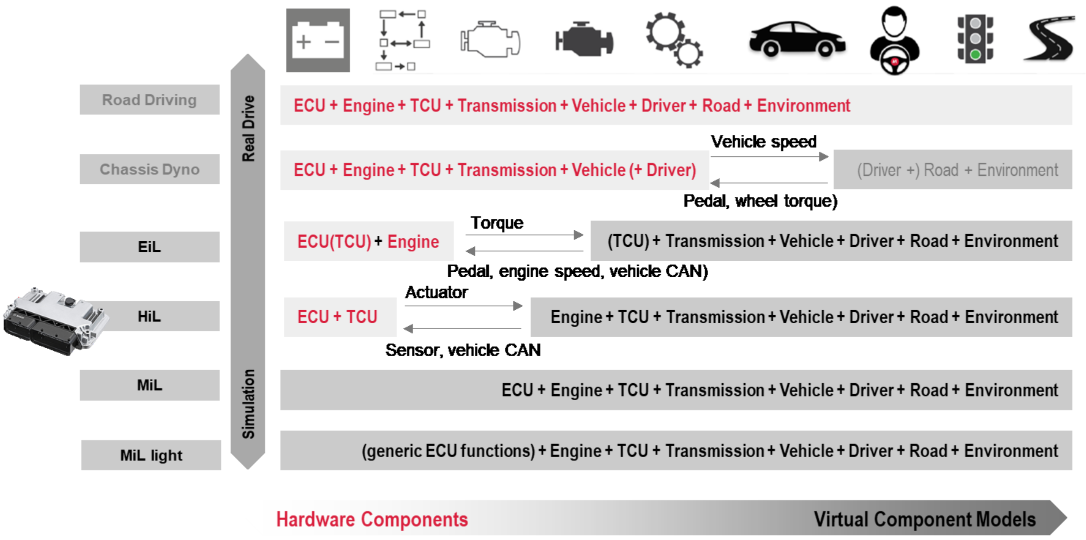


Figure 37: MiL, HiL, EiL workflow

In the following chapter is then analysed the process of Hardware-in-the-Loop configuration and set-up, as well as the planned Engine-in-the-Loop testing environment. To summarize the virtual calibration process and to underline how can be time and cost effective for powertrain's development, a virtual calibration time plan has been studied and redacted.

4.1 Hardware-in-the-Loop configuration

For the high-performance vehicles in general, the need of improving constantly their performance is stressed at maximum level. During their powertrain development, many refinements are achieved, each of them necessarily tested. A method for performing those tests in a reliable and time (as long as cost) effective manner is the usage of the Hardware-in-the-Loop simulations. For the PHEV in study, has been implemented a HiL environment.

4.1.1 Definitions and aims

As mentioned in chapter 1, the Model-in-the-Loop methodology of virtual calibration implies that all the elements of a powertrain are virtualized and tested in a model-based simulation. Once the MiL simulation is verified and functioning (the physical models reproduces the actual behaviour of the components and the controllers acts as desired on them) the next step is the Software-in-the-Loop simulation: at this step, the generated C-code from the MiL is entirely substituted to the controller blocks. Simulations are then performed in a similar way of the MiL. This helps to give an idea of the control logic, and if the input/output of the simulations with controller blocks and with C-code only are comparable, this code can be used for the following step of virtual calibration process. If instead this won't happen, it's required to return back to the Model-in-the-Loop phase to adjust controller strategies and logics.

This means that the SiL enables the following more important step of the virtual calibration process, the Hardware-in-the-Loop. At this stage, the controller model is replaced *in totum* with the real multiple hardware control units. This means that the hardware control units don't act on real physical components but on the simulated environment. In other words, the hardware control units "believe" to operate in real conditions with real components of a real car. It is also possible to insert in the HiL system simple physical components, like engine sensors and actuators (such as throttle valves, injectors, gearbox valves, solenoids etc…). The HiL real-time simulations are performed thanks to a real-time-processor unit that is able to interact with the software models and with the physical controllers/actuators under test. This processor elaborates the signals coming from the simulation models making them readable by the electronic control units, thanks to a digital-to-analogue conversion. It then performs the opposite transformation (analogue-to-digital) when receiving physical signals (like voltage and currents) form the components. This is helpful for evaluating if the control signals coming from the electronic control units are converted correctly into physical signals.

For instance, it is now described the control flow of the throttle valve. The HCU calculates a torque request from the driver model; it is then traduced in throttle angle and sent to real control unit. This control unit converts internally that value in voltage and current intensity, sent to the actual solenoid of the throttle valve. If the control signal chain is correct, the butterfly valves opens at the exact calculated angle (this can be verified with the help of software tools like ETAS INCA). Whenever this process is verified and fully functioning, it is possible to put in production such control modules. In this way, there's no need of a full vehicle for testing an electronic control unit, because it is still simulated.

Another aim of the HiL virtual calibration methodology is to test new releases of the controller module's internal software. For example, if new control strategies have been implemented, by utilizing the HiL is possible to state if they work correctly and controls the actuator in the desired way. This is a logical representation of a Hardware-in-the-Loop environment

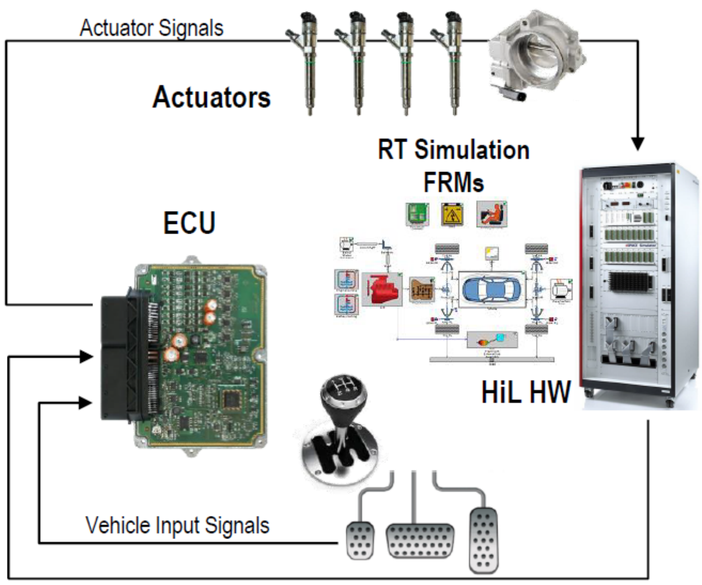


Figure 38; Harware-in-the-Loop scheme

4.1.2 Design of real time simulation environment

For the high-performance PHEV powertrain in study, the starting point of the creation of a Hardware-in-the-Loop environment is the referenced conventional powertrain. Once the HiL is validated, the following step is to add the HCU inside the loop and all the other hybrid functionalities. This paragraph shows the process of real time HiL simulation set up for that mentioned conventional powertrain.

The first step is to adapt the model utilized in the Model-in-the-Loop simulation to the real-time processing unit. This is performed by the complete substitution of the controller model with the interface necessary for the real-time processor. In other words, the input and output ports of the SimuLink controller blocks are not anymore connected with the simulated controller, but with the blocks that represents the physical control unit. For the HiL configuration in study, the following structure is defined:

- Real-time processor output – physical controller input:
    - Digital inputs (ex. cranking requested)
    - Analogue inputs (ex.DBW target)
    - PWM inputs (ex. gearbox valves current)
    - Engine inputs (ex. injection angle, spark advance)
- Real-time processor input – physical controller output
    - Digital outputs (ex. brake pedal pressed/released sensor, ignition key on/off)
    - Analogue outputs (ex. throttle pedal percentage, lambda)
    - PWM outputs (ex. gearbox valves' position, clutch speed)
    - Resistance outputs (ex. intake manifold temperature)
    - Engine output (ex. engine synchronization)

Once the input and output ports has been defined, it is necessary to switch to the interface of the real-time processor for the port configuration. This configuration sets the wirings and their properties between the physical components and the RT processor. For instance, it's configured the pin connection, the RT calculation board, etc…When the process of HiL configuration is ready, it's necessary to build the real time application: it is so defined the C-code that will run through the physical and simulated items of the HiL for performing the test simulation. This C-code is automatically generated by the real-time processing unit on the basis of the configuration performed.

Once the C-code has been generated and downloaded on the HiL RT calculation boards, it is possible to start the test simulations. In order to be able to interact with the simulation, another software tool allows the development of a control interface. In particular, it's possible to gain control to the variables in the real time application, for visualization or modification. For instance, it’s possible to actuate the control variable of the brake pedal actuation, and to visualize in another tool that scopes the ECU if that signal has been correctly received and the subsequent actions performed. This last phase of HiL simulation is commonly called “HiL driving”, because the simulation is performed real-time acting on controls that normally are present in vehicle.

To complete this process of Hardware-in-the-Loop simulation, it is although necessary to implement the communication between the electronic control units and the real-time processor, according to the requested communication protocols, such as CAN, CAN-FD, TTP, LIN, Ethernet, FlexRay and so on.

4.1.3 Communication implementation

For the studied high-performance PHEV, the required communication protocol is FlexRay. FlexRay is much faster and more reliable than existing CAN systems, it is also a deterministic system, which gives high reliability of communications. FlexRay can handle any type of network configuration, it is 10 times faster than CAN, however it is more expensive, hence it is highly suited to high-performance power train, drive-by-wire, active suspension and adaptive cruise control systems. FlexRay can be used as the bus protocol for highly advanced vehicle technologies, requiring absolute reliability, such as drive-by-wire, steer-by-wire and brake-by-wire where the bus and all its components must last the life of the vehicle without even momentary failure.

The FlexRay protocol is a unique time-triggered protocol that provides options for deterministic data that arrives in a predictable time frame (down to a microsecond). CAN uses an arbitration scheme where nodes will yield to other nodes if they see a message with higher priority being sent on a bus. FlexRay prioritizes the messages. Every FlexRay node is synchronized to the same clock, and each node waits for its turn to write on the bus. FlexRay is able to guarantee determinism or the consistency of data delivery to nodes on the network. Low priority data simply has to "wait in a queue". This provides many advantages for systems that depend on up-to-date data between nodes. A FlexRay signal can carry up to 30 times the data of a CAN message and has 3 CRC checks, this gives FlexRay many advantages over CAN bus systems which use a more "flexible" message timing system with less data and less tightly controlled messages & less message verification. Since FlexRay by definition was designed and produced specifically for use in automotive networks, it is highly unlikely to find it in any applications other than automotive.

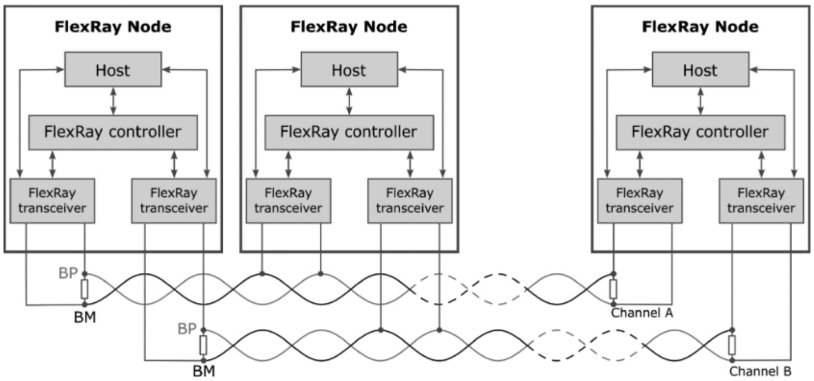


Figure 39: FlexRay scheme

For implementing such communication for the electronic control units of the HiL in question, is necessary to use a dedicated software tool. The implementation starts from the so called FibEX file, in which are present all the message frames and their signals of the network. Those frames are then sorted according to the HiL configuration, in a way that each electronic control units sends and receives the exact messages like if they would be on board of the vehicle.

FlexRay protocol requires also a checksum control for ensuring the signal's transmission (otherwise called cyclic redundancy check, CRC). It consists in an algorithm that detects accidental changes to raw data. Blocks of data entering the

FlexRay network get a short check value attached, based on the remainder of a polynomial division of their contents. On retrieval, the calculation is repeated and, in the event the check values do not match, corrective action can be taken against data corruption, such as signal re-reading or re-sending. The grade of the polynomial defines the type of CRC algorithm. Examples of polynomials used in automotive industry are:

$$CRC.8 = x^8 + x^4 + x^3 + x^2 + 1$$

$$CRC.16 = x^{16} + x^{12} + x^5 + 1$$

$$CRC.24 = x^{24} + x^{22} + x^{20} + x^{19} + x^{18} + x^{16} + x^{14} + x^{13} + x^{11} + x^{10} + x^8 + x^7 + +x^6 + x^3 + x + 1$$

The CRC algorithm implementation is performed internally to the same FlexRay configuration tool, according to the specification provided in the FibEX file. This complete configuration is then deployed in the model used for HiL simulations prior to RT application generation. In this way, the real-time processing unit reads directly the frames of the messages to be exchanges among the electronic control units in the loop and define the communication.

4.2 Engine-in-the-Loop

At this point of the study, it has been deeply analysed the process of virtual calibration, starting from Model-in-the-Loop and arriving to Hardware-in-the-Loop simulation and testing. The following step concludes the entire process of virtual calibration, before entering the final – and most traditional – calibration activities performed in-vehicle. It is clear that passing through the virtual calibration phases, more real components are added to the simulation. Indeed, this step is defined as Engine-in-the-Loop.

4.2.1 Definitions and aims

In Engine-in-the-loop (EiL) vehicle simulation, the "real component" is the engine control hardware and software together with a physical engine; while the "real-time simulated component", or the "virtual simulation", is the vehicle and driver. The interaction between the engine and the vehicle system, which includes the driveline, tire and road interface, and vehicle body etc., is replaced by the engine and a transient dynamometer that emulates a real vehicle. There are specific reasons why such a combination is used. There have been many studies in which both the engine and the vehicle system are modelled. However, high fidelity modelling of engine emission, especially in transient operating mode has been very challenging. For an EiL system, since a physical engine is in the setup, there is no need to make an effort in emission modelling. Moreover, such a system has many other advantages for powertrain control development, as well as engine and vehicle performance evaluation. Some of the benefits brought by the EiL simulations are:

- providing a platform to rapidly and efficiently evaluate, verify and debug engine control software, finding and correcting function errors in the early stages of the design process
- Using EiL, developers can perform transient engine control development before whole vehicle integration is available.
- EiL can support performance-assured controller design. With its help, developers can perform preliminary calibration targeting driveline and vehicle system with specific parameter values.
- An EiL system is very flexible in that the vehicle system parameters can be easily modified such that their impact on engine performance can be studied.
- An EiL platform provides better monitoring of engine behaviour and good repeatability of the test runs. It ensures a reliable and consistent process. Development activities normally executed in highly variable vehicle environment are carried out in controlled engine test cell settings which significantly improve the repeatability.

In summary, with an EiL system, developers can complete as much work as possible for engine control development and performance evaluation in the engine test cell environment, before having to perform at the vehicle level. Because of its numerous advantages, EiL has become a powerful tool and is expected to be more widely used in the near future also for the high-performance PHEV in object. The following image represents the Engine-in-the-Loop simulation flow:

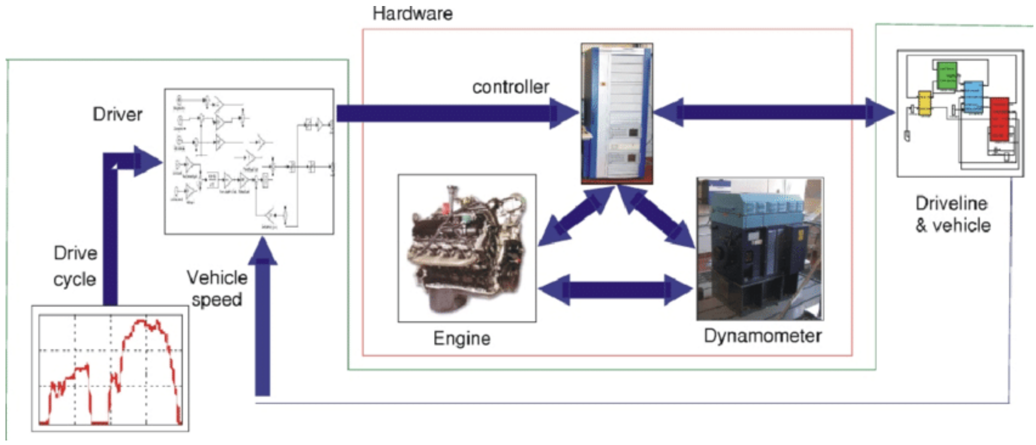


Figure 40: Engine-in-the-Loop scheme

4.2.2 In-vehicle final calibrations

Once the simulations performed at the Engine-in-the-Loop achieve satisfactory results, the powertrain could eventually reach its start of production (SoP). At this point of development, at least one prototype of the vehicle is required to be built, for final validations and testing. It is recommended that at this final stage of the project development, changes and modifications of the hardware/software structures are non-existent or reduced the minimum. This because returning at the project's phase would mean a high cost and an almost certainly delay of the SoP moment of the final vehicle. Nevertheless, if during in-vehicle testing arises necessities of modifications, it's possible to return backward at the phase of Engine-in-the-Loop or Hardware-in-the-Loop. For example, if the manufacturer of the ECU (or whatever other control unit) launches a new release of the software, it would be time and cost consuming testing it in a real vehicle. The most preferable way for performing tests would be returning back at Hardware-in-the-Loop simulation stage.

The in-vehicle calibrations are then seen as ultimate validation before the start of production of the vehicle. It has to be considered also that each step of virtual calibration is useful also after the vehicle’s mass production, for research and development purposes and yet testing of software releases.

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6 List of figures

7 List of tables

8 Glossary

- BEV: Battery Electric Vehicle
- DoE: Design-of-Experiment
- ECU: Engine Control Unit
- EiL: Engine-in-the-Loop
- FCEV: Fuel Cell Electric Vehicle
- GHG: Green House Gas
- HCU: Hybrid Control Unit
- HEV: Hybrid Electric Vehicle
- HiL: Hardware-in-the-Loop
- ICE: Internal Combustion Engine
- ISG: Integrated Starter Generator
- MiL: Model-in-the-Loop
- NEDC: New European Driving Cycle
- OEM: Original Equipment Manufacturer
- OVC: Off Vehicle Charging
- PHEV: Plug-in Hybrid Electric Vehicle
- RDE: Real Driving Environment
- REEV: Range Extender Electric Vehicle
- REEVS: Rechargeable Energy Storage System
- SiL: Software-in-the-Loop
- SoC: State of Charge
- TCU: Transmission Control Unit
- ViL: Vehicle-in-the-Loop
- WLTC: World harmonized Lightweight-vehicle Test Cycle
- WLTP: World harmonized Lightweight-vehicle Test Procedure