A Methodology to Develop a Sustainable, Highly Efficient Hybrid Propulsion System: the PHOENICE Project

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ABSTRACT: Nowadays the availability of a wide portfolio of powertrain solutions represents the most effective approach to reduce the environmental impact of the transport sector. In such a framework, the PHOENICE project aims at assessing the capabilities of a plug-in hybrid electric powertrain to minimize the fuel consumption of a C-class Sport Utility Vehicle (SUV) while ensuring its compliance with the upcoming EU7 regulations. The achievement of these ambitious goals required the development of an innovative Spark Ignition (SI) engine concept able to maximize its efficiency and, at the same time, minimize its emissions through the synergetic use of advanced in-cylinder charge motion, lean mixture with cooled EGR, electrified turbocharged and a dedicated aftertreatment composed by an electrically heated TWC, a GPF and a SCR. This paper will therefore provide a comprehensive overview of the powertrain design and optimization process which requires a hierarchical exploitation of both numerical simulations and experimental measurements to handle the increased complexity derived from the integration of the abovementioned technologies. More in details, simplified map-based models were preliminary used to assess the potential of selected powertrain configuration while detailed 3D CFD simulations allowed the optimization of combustion concept in highly diluted mixture conditions. Then, a 1D digital twin of the whole engine was developed to investigate a wide range of the operating parameters and to define their best calibration. The paper will pay particular attention to the analysis of the double diluted combustion system and of the aftertreatment performance. At the present state of the research activity, the preliminary experimental tests carried out on the first engine prototype under steady state conditions showed promising results achieving a maximum gross indicated efficiency of about 47%.

KEY WORDS: high-efficiency spark ignition engine, PHEV, EURO7, Horizon2020

1. Introduction

Nowadays the speed of deploying a wide portfolio of sustainable mobility solutions represents one of the key aspects to achieve the carbon neutrality of the transport sector within 2050 [1]. As a matter of fact, the huge variety of applications present on the market may have requirements which can be hardly tackled by a single technology. In such a framework, the development of a new generation of environmentally friendly Internal Combustion Engines (ICEs) can still represent a promising path to effectively curb Green House Gas (GHG) and pollutant emissions. To this aim, the development and exploitation of innovative engine technologies capable to raise the peak indicated efficiency beyond 45% [2] is mandatory. Among the possible options, the ultra-lean combustion concept stands out as one of the most favorable thanks to the decreased thermal and exhaust energy losses caused by the reduction of the combustion temperature. Further enhancements in engine efficiency can also be achieved by increasing the compression ratio and improving the combustion phasing, both of which are made possible by the lower knock likelihood of lean-burn operation [3,4]. An additional solution to effectively reduce the charge reactivity is the Exhuast Gas Recirculation (EGR) [5,6] which can also be used at part load where the reduction in volumetric efficiency caused by the inert gas recirculation allows engine de-throttling and, consequently, a reduction in pumping losses [7]. Finally, the integration of Variable Valve Actuation

(VVA) systems can also allow further efficiency enhancements on the whole engine operating map. Indeed, the capability to completely control the valve lift profile not only avoids the engine throttling at part load, but also enables a reduction of the knock likelihood through the engine cycle Millerization [8,9]. Nevertheless, the synergetic use of the abovementioned technologies may need the development of advanced charging systems. Electrified turbochargers, in particular, can represent a promising solution to provide the boost levels required by a lean and highly-diluted combustion process, while enabling, at the same time, a faster transient response, and a partial recovery of the waste enthalpy of the exhaust gases [10]. This recuperated energy allows reducing the alternator load, thus offering additional fuel consumption reductions, which have been demonstrated to reach up to 2-3 % on WLTC [11].

From the emission perspective, the stringent limit imposed by the upcoming EU7 legislation [12] on the NOx levels, in conjunction with the exploitation of lean mixtures, implies the use of a Selective Catalyst Reduction (SCR) system. Its formulation, differently from Diesel applications, needs also to tolerate stoichiometric mixtures and high temperatures when the engine is operating at high load. The SCR catalyst has to be combined with a Three-Way Catalyst (TWC), which has to be properly designed in order to achieve an excellent conversion efficiency for CO, HC, and NOx at $\lambda=1$, while showing good oxidation capabilities for carbon monoxide and unburnt hydrocarbons under lean conditions. Finally, as far as Particle Number (PN) emissions are concerned, the use of a dedicated Gasoline Particulate Filter (GPF) seems to be mandatory in light of the tightening limits prescribed by the upcoming EU7 standards, which also reduced the lower particle size to be detected to 10 nm. Nevertheless, GPF geometry has to be optimized in order to achieve good filtration capabilities without an excessive backpressure which could partially jeopardize the engine efficiency improvements. Finally, since in a hybrid powertrain the engine can be frequently switched on and off, the catalysts composition has also to ensure the lowest possible light off temperature with further improvements achievable by means of an Electrically Heated Catalyst (EHC).

According to this scenario, the PHOENICE (PHev towards zerO EmissioNs & ultimate ICE efficiency) H2020 European project aims to create a C SUV-class plug-in hybrid demonstrator capable of achieving a 10% fuel economy improvement compared to the current baseline vehicle available on the market, while being fully compliant with the upcoming EU7 regulation [12], as summarized in Table 1 and Table 2, respectively. To boost the economic and environmental benefits, the technologies developed as part of the PHOENICE project are targeted to Technology Readiness Level (TRL) 7, thus carefully considering the costs of industrialization and the application potential for different vehicle classes.

Table 1: Efficiency Target of the PHOENICE project.

Fuel Consumption	-10% vs Baseline Vehicle (CS on WLTC)
ICE Efficiency	47% Peak Gross Indicated Efficiency

Table 2: Emission targets of the PHOENICE project.

CO	400 mg/km	**CH_4**	10 mg/km
NMOG	25 mg/km	**HCOH**	5 mg/km
NOx	20 mg/km	**N_2O**	10 mg/km
PM	2 mg/km	**NH_3**	10 mg/km
PN (>10nm)		5×10^{10} #/km	

This paper will therefore provide a comprehensive overview of the project and of the powertrain optimization process, which requires a hierarchical exploitation of both numerical simulations and experimental measurements to handle the increased complexity derived from the integration of the abovementioned technologies.

2. Project Overview

The PHOENICE concept will be developed upon a currently in production C-Class SUV, featuring a parallel-Through-The-Road plug-in hybrid architecture, the main specifications of which are summarized in Table 3. The type of vehicle was selected according to the relevance of this segment in the European market [13].

Table 3: Reference Powertrain Specification.

Baseline Vehicle Specifications	
Curb weight	1935 kg
Max. Speed	200 km/h
Acc. 0-100 km/h	7.3 s
Fuel Consumption	2.1 L/100km (WLTP)
Battery SoC for CS mode	4.4%
CO_2 emissions	45 g/km (WLTP)
EV range	49 km (WLTP)
Emissions Standard	Euro 6d-final

	Hybrid Powertrain Parameters	
ICE	Specs	1.3L 4-cyl in-line 16v
	Features	MultiAir VVA, GDI, TC with WG
	Bore x Stroke	70 x 86.5 mm
	Stroke/Bore	1.24
	Compression Ratio	10.5
	Max. Power	132 kW @ 5750 RPM
	Max. Torque	270 Nm @ 1850 RPM
	Transmission	6-speed AT
E-Motors	Location	P0 + P4
	Power (P4)	70/44 kW [peak/continuous]
	Torque (P4)	250 Nm [peak]
HV Battery	Spec.	Li-Ion
	Capacity	11.4 kWh

To achieve the project targets, the original propulsion system of the vehicle, as well as its Energy Management System (EMS), need to be strongly upgraded. The most relevant changes will focus on the engine, aiming to achieve a peak gross indicated efficiency of 47% while minimizing, at the same time, the pollutant emissions across its entire operating map. Moreover, to guarantee EU7-compliant tail-pipe emission levels, the Exhaust After-Treatment System (EATS) will be deeply revised with a new generation of high performance TWC and GPF and with the introduction of an SCR. An EHC will be also integrated in the exhaust line to reduce the duration of the catalyst heating phase and to minimize the light-out risks when the vehicle operates in pure electric mode.

3. Engine Concept

The base engine of the reference vehicle is a state-of-the-art 4-cylinder 1.3L turbocharged Direct Injection Spark Ignition (DISI) engine [14] featuring a high stroke-to-bore ratio, a compact 4-valve combustion chamber with high pressure side fuel injectors, a MultiAir VVA system [15] and a cylinder head with integrated exhaust manifold. Such a baseline configuration will be upgraded with the technologies mentioned in the paper introduction and outlined in Figure 1.

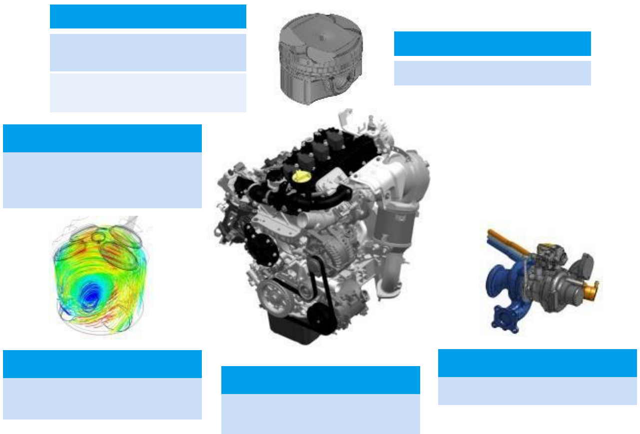

Figure 1: Summary of the new PHOENICE engine features.

First, the piston has been redesigned to increase the Compression Ratio (CR) up to 13.6 and to enable lean burn operation thanks to a Dual Dilution Combustion Approach (DDCA) which synergetically exploits excess air and cooled low pressure EGR. The fuel injection system has been upgraded and it is now able to reach an injection pressure of 350 bar to support the ultra-lean combustion approach. Furthermore, the intake ducts and ports geometries have been optimized to implement the Swumble™, a newly developed charge motion concept able to enhance turbulence levels thus significantly improving the flame propagation even for highly diluted lean mixtures [16]. On the charging system side, a 48V electrified turbocharger embedding a Variable Nozzle Turbine (VNT) replaced the baseline Wastegate (WG) turbocharger. Its specifications were optimized in a previous work of the authors [17] to be compliant with the requirements of highly diluted mixtures and aggressive Miller cycle. Finally, the fully variable Multiair valve actuation system, already integrated in the base engine configuration, enables Miller cycle exploitation through Early Intake Valve Closing (EIVC) or Late Intake Valve Closing (LIVC).

3.1 Swumble™ In-Cylinder Charge Motion

The IFPEN Swumble™ concept is an innovative approach to improve the engine efficiency under a wide range of engine operating conditions. By redesigning the combustion chamber and the intake ducts, Swumble™ can enhance in-cylinder turbulent motion with only minor flow capacity degradation. Moreover, it is particularly well suited to early and late intake valve closing strategies with high dilution rates [18]. It is common knowledge that the charge motion within an internal combustion engine may be represented in terms of the three reference axes, (X, Y, and Z), as shown in Figure 2. The Swumble™ combines a high level of tumble motion around the Y axis with swirl motion around the Z axis.

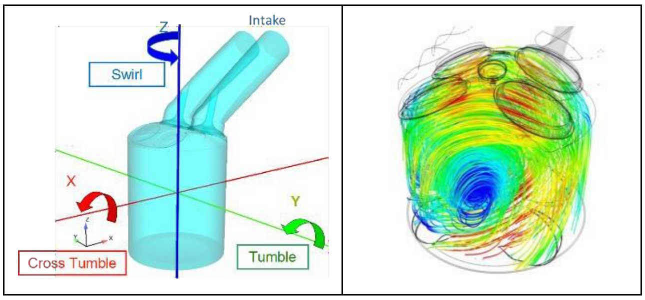

Figure 2: Left: Axes of in-cylinder charge motion. – Right: Swumble™ fluid motion as a combination of tumble (Y) and swirl (Z) motions.

For an optimal integration of the Swumble™ concept with the baseline cylinder geometry, a 3D-CFD analysis of a motored engine test was carried out to determine the impact of several geometrical modifications on the internal fluid dynamics. In the design optimization loops, two intake valve lift profiles were considered for each geometrical modification. These valve lift profiles, shown in Figure 3 together with the computational model for the 3D-CFD simulations, were extracted from the available Multi-Air system dataset.

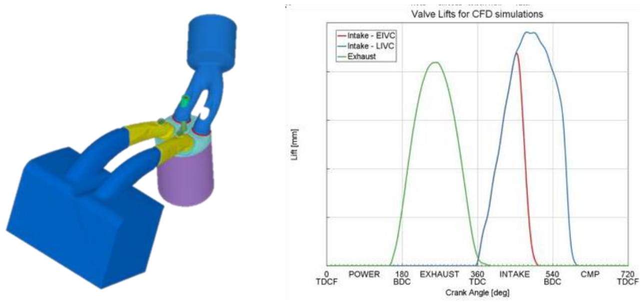

Figure 3: Left: 3D CFD model. – Right: valve lifts profiles (right) used for 3D-CFD simulations.

The cylinder head, piston, intake ports and valve seats geometries were then selected as variables of the optimization process of the combustion chamber design.

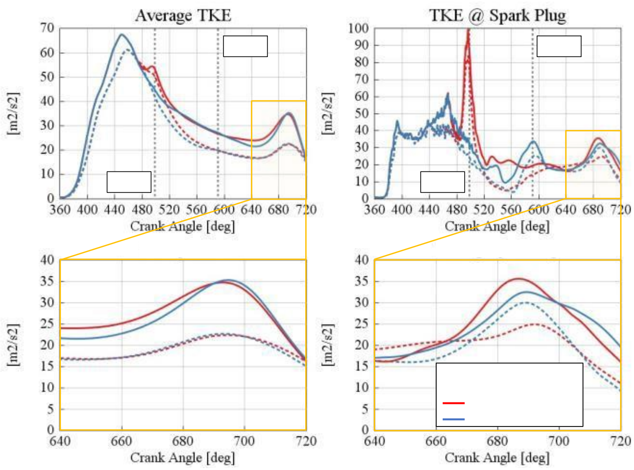

Figure 4: Left: average TKE in the cylinder – Right: TKE at the spark plug, averaged on a 5 mm box. EIVC and LIVC configurations

Figure 4 provides some insights on the increased turbulence motion for the two considered intake valve strategies, EIVC and LIVC. Numerical values in terms of Turbulent Kinetics Energy (TKE) improvements are also reported in Table 4. The enhanced tumble flow motion converted into turbulence leads to a higher TKE on average in the cylinder, as well as locally at the spark plug. This relative increase in average TKE of about 50% for both valve strategies contributes to a reduction in the combustion duration, therefore increasing engine efficiency.

Table 4: TKE improvements after Swumble™ concept optimization. Comparison with baseline for Early and Late Miller configurations.

TKE improvements	**EIVC**	**LIVC**
Average at 690 CAD	**+53%**	**+55.8%**
Average at 700 CAD	**+54.4%**	**+49.7%**
Average at 720 CAD	**+11%**	**+0.33%**
@ spark plug at 690 CAD	**+8.4%**	**+41.8%**
@ spark plug at 700 CAD	**+24.3%**	**+32.2%**
@ spark plug at 720 CAD	**+112%**	**+46.3%**

3.2. E-Turbocharger Development

A new prototype of electric turbocharger has been specifically developed by Garrett for the PHOENICE project. It features a high temperature resistance VNT replacing the wastegate turbine of the baseline engine. Furthermore, a 48V e-Motor has been integrated on the turbo shaft, providing electrical assistance as well as power generation capabilities. The main parameters of this component can be found in Table 5.

Table 5: Main E-Turbo Specifications

Boost Control	**Variable Nozzle Turbine**
Max. Compressor Outlet P	**4 bar**
Max. Turbine Inlet T	**1020 °C**
System Voltage	**48 V**
eMotor Continuous Rating	**2.5 kW**

Beside the functionality already mentioned in the paper introduction, in the PHOENICE concept, the E-Turbo can synergically operate with the EHC to reduce the duration of its warm-up phases operating as a secondary air flow generator.

Figure 5 shows a comparison between compressor and turbine maps of the baseline wastegate turbocharger and the PHOENICE VNT E-Turbo by Garrett. The optimized compressor has a higher pressure-ratio capability but a reduced mass flow capacity with respect to the baseline turbocharger. It features a much wider area of high efficiency, with the peak value that has been incremented by 4%. The optimized turbine vanes have been sized to obtain a similar characteristic to the baseline turbine when the VNT rack is 40% open.

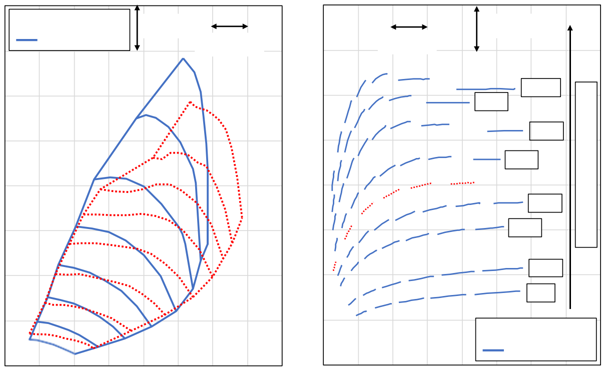

Figure 5: Comparison of Compressor and Turbine Maps.

The performance of the E-Turbo was evaluated exploiting a virtual test rig developed at Politecnico di Torino through the commercially available 1D-CFD code GT-Suite [19]. Two different PHOENICE engine model configurations were analyzed, with the baseline WG turbo and with the optimized VNT E-Turbo, respectively. Full load simulations in the acceptable performance scenario were run. This scenario implies limiting the engine torque and power to an acceptable level capable of ensuring the achievement of the vehicle performance target while simultaneously maximizing the efficiency. Stoichiometric operation was forced, avoiding any mixture enrichment for component protection. For both configurations, the same baseline engine intake valve lift profiles were applied. The different structural limits of the two turbochargers, in terms of maximum turbine inlet temperature and maximum turboshaft speed, were considered by the engine control logic. Finally, no electric boosting was provided. Figure 6 shows the simulated full load curve obtained with the Garrett VNT E-Turbo in comparison with the baseline WG turbo.

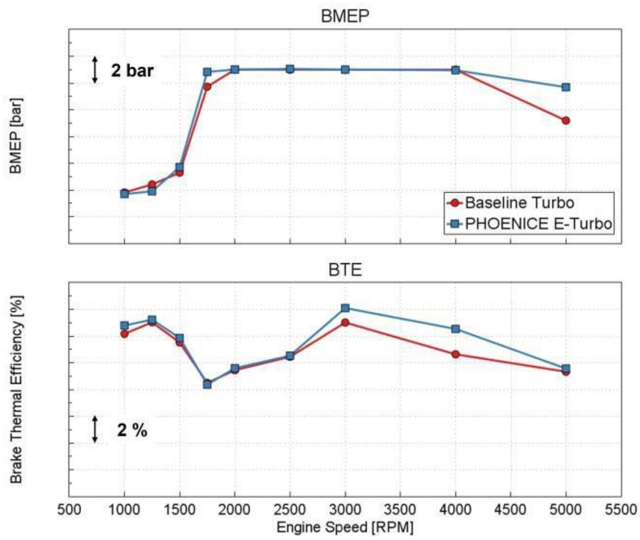

Figure 6: Full Load Curves comparison between baseline WG turbo and Garrett VNT E-Turbo: BMEP and BTE.

The two Brake Mean Effective Pressure (BMEP) profiles are quite close, except for the slightly better low-end torque and for the 15% increase observed at 5000 RPM. This BMEP increase is consistent with the extended turbine inlet temperature (T3) limit of the optimized turbocharger. From 2000 to 4000 RPM, both engine configurations reach the target BMEP. However, thanks to its optimized design, the PHOENICE E-Turbo leads to an improved Brake Thermal Efficiency (BTE) value of up to 2% at 4000 RPM.

4. Aftertreatment Development

The final after treatment system layout for the PHOENICE project is schematized in Figure 7.

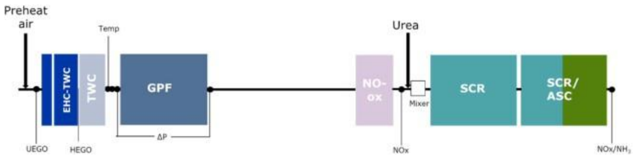

Figure 7: Final Exhaust Aftertreatment Configuration.

The EATS comprises two sections (see Figure 8): a close-coupled section, primarily designed to control gaseous emissions under cold- t rt d to ch o tr c (λ=1) co d t o , particulate matter, and an underfloor section, which is necessary for NOx conversion under lean conditions and to reduce the concentration of additional pollutants such as ammonia.

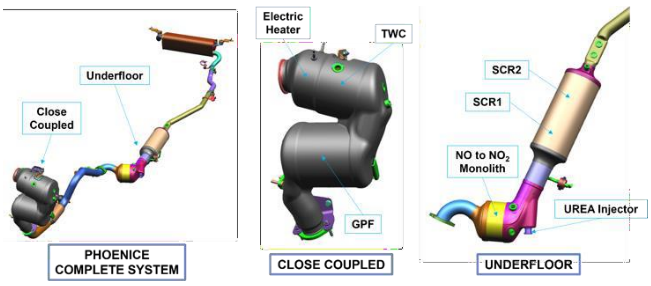

Figure 8: Final Layout of the Exhaust Line.

More in detail, the close-coupled aftertreatment section comprises TWC components for the abatement of CO, HC and, under stoichiometric conditions, NOx. The first component, i.e. the EHC, features a coated metallic substrate which can be electrically heated to greatly reduce light-off duration. In principle this process could be performed before the engine is switched on for the first time, if the vehicle is able to drive off under electrical power alone. A GPF coated with a TWC technology to provide additional gaseous emissions control is then used to abate the particulate emissions. To meet the demanding PN emissions limits prescribed by EU7, an innovative coating technology was used to deliver a step gain in filtration efficiency over the current EU6d-level technologies with an equivalent penalty in backpressure.

In the underfloor part, an urea injector provides the NH_3 required to convert the NOx in the SCR. Its conversion efficiency at low temperature is further enhanced by an upstream oxidation catalyst (NO-ox) which converts a portion of the NO to NO_2. An Ammonia-Slip Catalyst (ASC) is finally integrated in order to abate NH_3 tailpipe slip which may otherwise appear, due to overdosing of urea solution or as a by-product of the reactions in the upstream catalyst components und r to ch o tr c or r ch (λ<1) op r t g conditions.

The main features of the EATS components are reported in the Table 6.

Table 6: Summary of the PHOENICE Aftertreatment Specifications.

o po t	P rpo	o (tr)
H	o d t rt o p rfor c th ctr c (pr)h t g tr t gy O, H , λ=1 NOx.	0.7
W	o d t rt o p rfor c (O, H , λ=1 NOx).	0.75
GPF	H gh f tr t o do to PN10 Add t o g o o co v r o (O, H , λ=1 NOx).	~2.5
NO Ox	o v r o of NO to NO_2 h λ>1 for opt R NOx co v r o ff c cy.	~1
R	NOx co v r o g r j ct o .	2.5
A	Add t o NOx vo NH_3 o co tro d r g co d t rt d λ>1. Add t o O, H , NOx c t y t vo t h gh GH , d o tr t d for λ=1 co d t o .	2.5

Additional details about the design process and the performance of the main monoliths are reported in the next paper subsections. The analysis will mainly focus on the NOx conversion, which represents the main challenge for the PHOENICE project.

Three-Way Catalysts

A state-of-the-art TWC technology whose PGM-loading was optimized for future EU7 gasoline applications, was selected for both the EHC and second TWC components of the PHOENICE system. Since it was developed for different substrate media, it suitable for both the metallic EHC and the cordierite TWC.

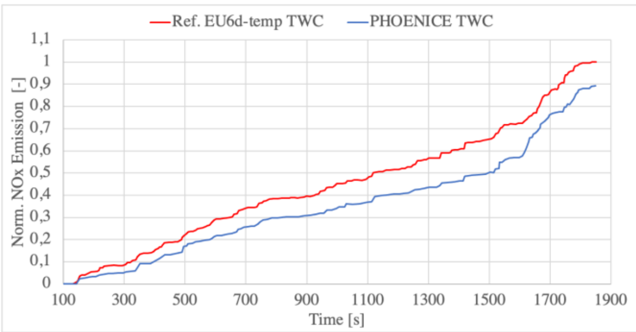

Figure 9: NOx Emission reduction of the PHOENICE TWC on an aggressive RDE cycle with respect to a state-of-the-art EU6d-temp catalyst.

Despite no further details about the TWC composition can be disclosed due to confidentiality reasons, Figure 9 demonstrates the improvement in performance of the selected technology against the previous best-in-class reference. The measurements were performed on a similar turbocharged DISI engine over an aggressive RDE cycle and highlights 10% improvements in NOx performance after the first 100s when the catalyst is fully lit off.

Gasoline Particulate Filter

As for the TWC, the technology selected for the GPF is a state-of-the-art targeted to EU7 gasoline applications. The coating was tailored for porous cordierite filter substrates, while the loading was designed in order to achieve a sufficient conversion efficiency for the species slipped from the TWCs. Furthermore, the catalytic coating technology may further improve the filtration capabilities and can enable the regeneration of the filter, which is expected to occur passively during normal vehicle operation, at low exhaust gas temperatures.

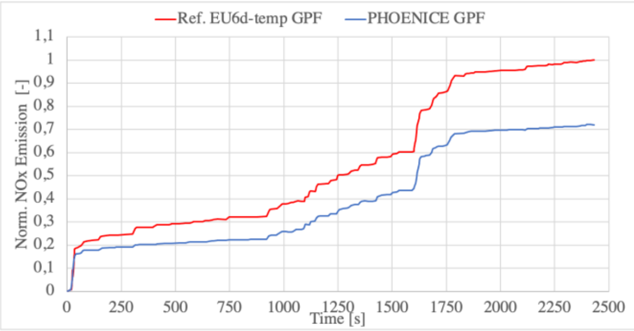

Figure 10: NOx emission reduction of the coated GPF on an aggressive RDE cycle with respect to a state-of-the-art EU6d-temp GPF.

Also in this case, the performance of the GPF was benchmarked against a reference Eu6d-final technology on a PHOENICE-equivalent turbocharged DISI engine over an aggressive RDE cycle. The results presented in Figure 10 highlight a clear improvement in the NOx tailpipe emissions with a reduction of about 28%.

From the filtration perspective the stringent limit of 5×10^{10}#/km for PN >10nm which has been set for EU7, requires a huge improvement of the filtration capabilities with respect to the Eu6d baseline. Figure 11, which shows the relationship between backpressure and filtration efficiency expected for Eu6d-equivalent coating technologies, proved that the GPF proposed for the PHOENICE concept achieves filtration efficiencies in excess of 90%, whilst greatly mitigating the penalty in terms of backpressure.

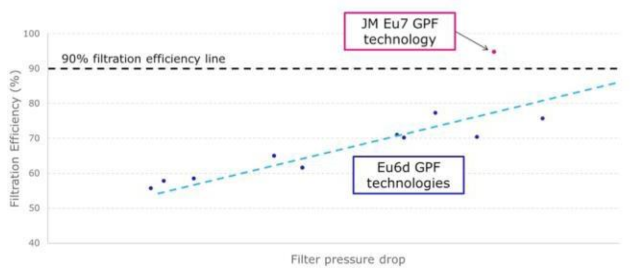

Figure 11: Relationship between filtration efficiency and the backpressure for Euro6d-final compared with the final PHOENICE coated GPF.

NO-ox Oxidation Catalyst

The designed NO-ox catalyst is a derivation of the Diesel Oxidation Catalyst (DOC) technology commonly deployed in light- and heavy-duty diesel aftertreatment systems, with the main purpose to supplement the performance of the downstream NOx conversion of the SCR system. It does this in two ways: (1) by generating an exotherm through the combustion of CO and HC which raises downstream exhaust gas temperatures and enables faster light-off of the downstream SCR and more favourable operating temperature conditions; (2) by oxidising some of the NO in the exhaust gas stream to NO2, which enables more efficient NOx conversion over the SCR system.

In the case of the PHOENICE application, most or all of the CO and HC is expected to be converted over the close-coupled (TWC+GPF) section of the EATS. Therefore, the primary function of the NO-Ox catalyst is the oxidation of NO to NO2. As such, the design intent of the NO-Ox considered is the optimization of the NO oxidation function of a conventional DOC technology. However, an additional consideration for the PHOENICE application is the durability of the technology under a different exhaust gas environment (temperatures, lambdas) than would normally be considered for a conventional diesel application. Therefore, careful selections of raw materials, as well as the ratios in which they are used, is critical to the lifetime performance of the NO-Ox technology.

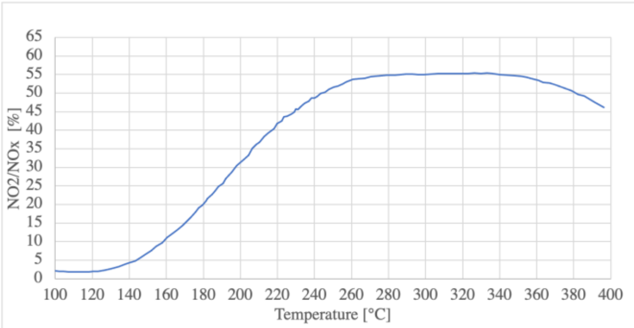

Figure 12: NO-ox conversion efficiency depending on the Temperature

The final performance assessment on the selected coating technology reported in Figure 12 shows a conversion performance above 50% between 240 and 380 [°C].

Selective Catalyst Reduction

The function of the SCR volume is to convert NO_x (NO and NO_2) to N_2 and H_2O during lean mode via the addition of upstream urea injection which provides NH_3 for the reduction reactions. The SCR needs to provide high NO_x conversion over a range of exhaust conditions within the lean-mode operating window, whilst ideally minimising the amount of N_2O produced as a by-product of the SCR reactions. The SCR should also be able to store a certain amount of excess NH_3 which is produced either through urea dosing or as a by-product of one or more of the upstream catalysts, and use the stored NH_3 for the conversion of NOx.

For the PHOENICE engine a Fe-based SCR technology will be selected for this application. The advantages of Fe over Cu (more conventionally used for diesel applications) for this application are its superior durability under low-O2 conditions and reduced selectivity towards N_2O. However, the challenges with using an Fe-based technology are its reduced performance at lower temperatures (though greatly influenced by the proportion of NOx which is in the form of NO_2) and lower NH_3 storage capability compared with Cu; therefore accurate control in the urea dosing strategy will be required.

Figure 14 shows the impact of varying NO_2:NOx over a range of temperatures on the NOx conversion efficiency, measured at the point where NH_3 slip first exceeds 20ppm. Peak conversions in excess of 90% are achieved at 400°C. Below this temperature, NOx conversion efficiency is seen to be strongly dependent on NO_2:NOx, with conversion at 200°C improved by as much as 60% when moving from an NO-only gas mix to a 50% NO_2:NOx gas mix. The temperature region where NO2:NOx strongly affects NOx conversion corresponds well with the temperature window where the NO-Ox catalyst is most effective (see Figure 12) and demonstrate its importance in the proposed aftertreatment configuration.

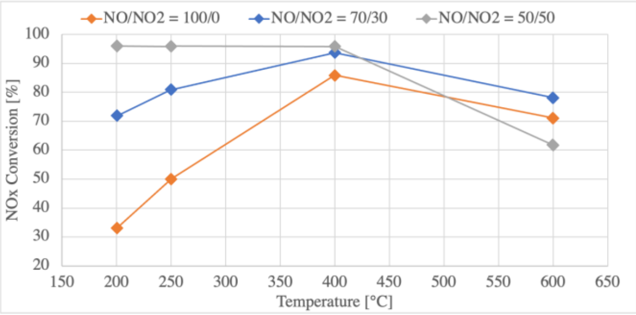

Figure 13: Effect of NO2/NOx on SCR conversion efficiency.

5. Steady State Engine Calibration

The most relevant engine operating points under real-world conditions were identified through preliminary 0D vehicle simulations of RDE test cycles [20,21]. As shown in Figure 14, a total of 23 operating points were identified for initial steady-state calibration.

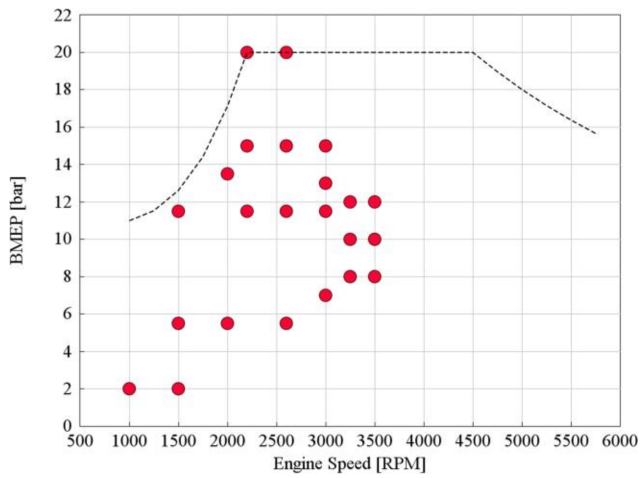

Figure 14. Selected engine operating points for steady-state calibration

The calibration aimed at optimizing the control parameters concerning fuel injection strategy, intake valves actuation, Air/Fuel ratio and EGR rate. The objective was to evaluate the improvements in brake thermal efficiency with respect to the baseline engine and to assess the achievement of the 47% target peak gross indicated thermal efficiency.

A specific sequential methodology, consisting in the following 3 sequential steps, has been adopted:

1. Rail pressure and SOI optimization.
2. IVO and IVC angles optimization.
3. AFR and EGR rate optimization.

Furthermore, in order to support and to speed-up the calibration process at the bench, numerical simulations were exploited. To this purpose, a predictive 1D-CFD engine model was developed and validated over a set of preliminary experimental data. Afterwards, it was used as virtual test rig to explore the benefits of cycle Millerization through EIVC and LIVC strategies, as well as from mixture enleanment with excess air and cooled EGR [17,22]. For sake of brevity, only the findings for one of the chosen operating points, 3000 RPM and 13 bar BMEP, are hereby reported as an example. Figure 15 shows the oucomes in terms of optimal combination of AFR and EGR rates (last step of the optimization process). In particular, fo r d ff r t λ v , , 1.0 – 1.2 – 1.4 – 1.6, together with four different levels of EGR rates, i.e., 0% – 5% – 10% – 15%, were tested.

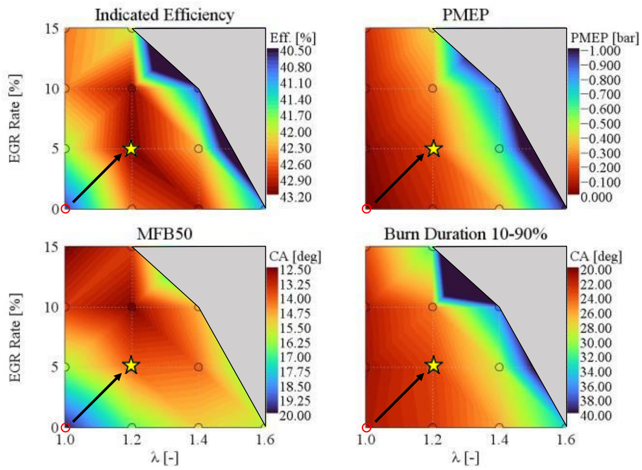

Figure 15. 3000 RPM and 13 bar BMEP. Virtual Calibration results

Evidence from simulation has demonstrated that the highest net indicated efficiency (identified by the star marker in Figure 15) can be achieved running the engine at moderately lean and diluted xt r th λ = 1.2 d th 5% GR. d d, th co t o of λ d GR prov d th t co pro t k ock suppression, increased pumping losses and combustion duration deterioration. Indeed, higher air/fuel ratios or EGR rates could further improve the combustion phasing thanks to the lower knock tendency, but, on the contrary, would increase both the backpressure, because of the higher boost requirements, and the combustion duration due to lower flame propagation speed.

Figure 16 shows the outcomes of the whole optimization process: each of the three rows of the graph correspond to one step of the optimization process, i.e., fuel injection control parameters (first step), valve actuation (second step) and mixture dilution (third step): as far as the 3000 rpm and 13 bar BMEP operating point is concerned (highlighted with a star marker on Figure 16), a pretty good agreement can be observed between the results of the experimental optimization and the optimal lambda and EGR values predicted by the virtual calibration process.

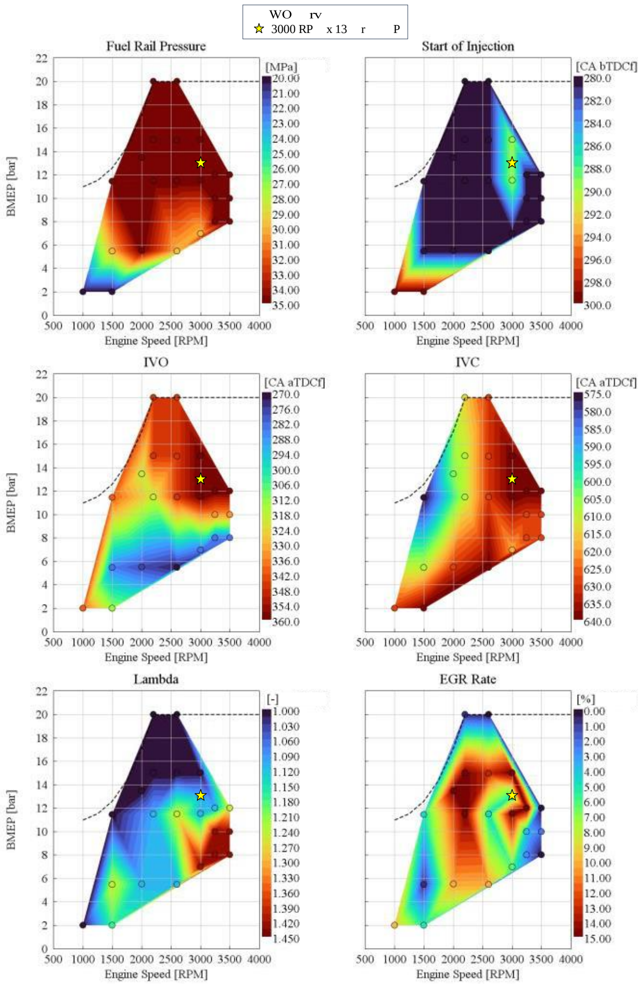

Figure 16: Outcomes of the experimental optimization of engine calibration

Finally, Figure 17 and Figure 18 shows the gross indicated efficiency and the BTE improvements (with reference to the baseline engine) achieved on the tested operating points, respectively. A maximum gross indicated efficiency close to 47% was achieved for the operating points at 3250-3500 rpm x 10 bar BMEP. Furthermore, BTE improvements larger than 10% could be achieved on a large portion of the map (see Figure 18), thus showing that the project ambitious target to reduce by 10% the fuel consumption of the vehicle on CS mode on WLTC can be achieved.

Only the 1500 RPM WOT operating point shows significant worsening in terms of efficiency, due to the increased knock tendency which requires significant spark timing retard, thus leading to a substantial degradation of the combustion process.

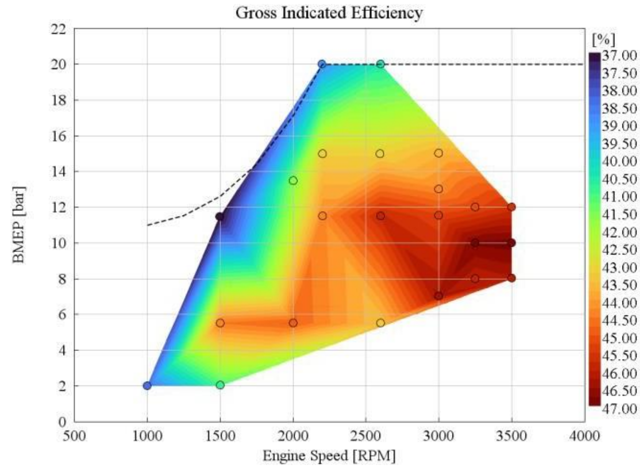

Figure 17: Gross Indicating Efficiency Achieved through the experimental engine Optimization.

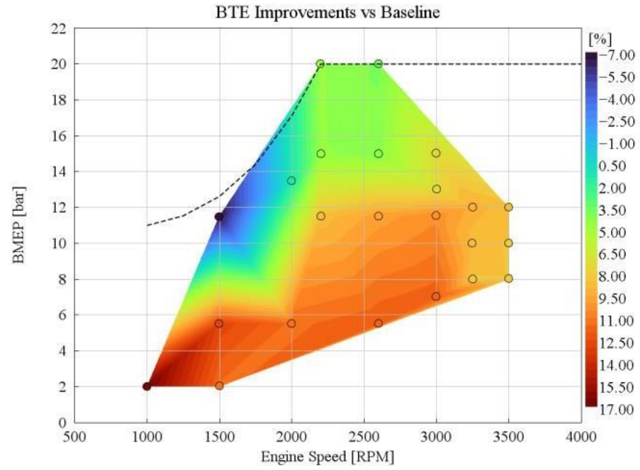

Figure 18: Brake Thermal Efficiency Improvements achieved by the PHOENICE concept with respect to the base engine.

7. Conclusions & Further Development

A new lean-burn spark ignition engine concept was developed based on a state-of-the-art Stellantis 1.3-liter gasoline engine. Several innovative technologies were selected to maximize the synergy with the hybrid architecture of the PHEV demonstrator vehicle. Swumble^{TM} in-cylinder charge motion was exploited to enable dual-dilution combustion approach, that utilizes excess air and EGR. To this extent, 3D-CFD simulations were performed to optimize the intake ports geometries and piston design and to evaluate the benefits of this innovative technology in terms of turbulent motion enhancement. A new charging system featuring an electrically assisted turbocharger allows the engine to operate with high dilution levels and enables strong EIVC and LIVC Miller strategies. Moreover, a new Euro7-ready EATS including a diesel-like SCR and an EHC was developed and optimized for engine lean operation.

Initial testing on the first engine prototype yielded some very encouraging results with a gross indicating efficiency close to the 47% target for the operating points at 3250-3500 rpm x 10 bar BMEP. The comparison of the BTE between the PHOENICE prototype and the baseline engine also showed a promising 10%

improvements on a wide region of the operating map proving that the project ambitious target to reduce by 10% the fuel consumption of the vehicle on CS mode on WLTC can be achieved

Future work will be focused on further optimization of engine calibration exploiting both numerical simulation and physical testing, under both steady state and transient operating conditions. Finally, starting in the first quarter of 2024, a vehicle demonstrator will be available for the final assessment of the project objectives.

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