Powerful final report

Executive Summary

In 2007 and 2008 the European Commission has agreed on a far-reaching package of proposals that will deliver the European Council's commitments to fight climate change and promote renewable energy. Among these, there are proposed legislations establishing mandatory limits on CO2 emissions from new passenger cars.

The large scale collaborative project “Powertrain of future light-duty vehicles (POWERFUL)” addresses research, development, validation and demonstration of future engines for road transport and based on three vertical sub-projects aiming to :
V1. An advanced four-stroke SI engine concept characterized by low-cost / low emissions;
V2. An advanced four-stroke CI engine concept able to run also on new tailored fuels and integrating the LTC (low temperature combustion) mode in the CI combustion system;
V3. An advanced two-stroke CI engine concept running on diesel fuel and integrating the LTHC (low thermal homogeneous combustion) mode in the CI system.
These advanced engine concepts was accompanied by a transversal sub-project T1 taking care of the development of:

- new simulation tools describing the strong interactions between combustion systems and engine architecture;
- means for reducing engine frictions and performing an intelligent energy management;
- PEMS (portable emissions measurement system) approach.

The main objective of POWERFUL was, under pollutant emissions lower than EU6, to meet 40% lower CO2 emissions with respect to the 2005 figures for spark ignited (SI) engines powered vehicles and 20% lower CO2 than the 2005 level for compression ignition (CI) engine powered vehicles with comparable fun-to-drive.

The team has most of the best European companies/universities in engine development :

Renault SAS,	AVL List GmbH	Universidad Politécnica de Valencia
Volkswagen AG	IFPEN	Universita di Genova
Centro Ricerche Fiat	FEV Motorentechnik GmbH	Poznan University
DELPHI Diesel Systems	Le Moteur Moderne	Prag University
MAGNETI MARELLI	Fundación TEKNIKER	POLITECHNIKA LODZKA
Dinex ECOCAT Oy	RWTH-VKA	Joint Research Centre (EC)

Budget/funding 24.34/13.49
Start/end dates 1^{st} of January 2010 to June 30^{th} 2014

Main Results : 4 demo vehicles were delivered, 3 of which were sufficiently developed for NEDC measurements. The SPV2 car fully reached its targets, while SPV1 reached them partially (CO2 reduction of 30% instead of 40%).

Summary description of project context and objectives – SPV1

The **aim of sub-project V1 "Extreme Downsized Low Cost SI Engine"** was the development of a 4-stroke 2-cyl SI TC extremely downsized engine, integrating the electronic valve control and other add-on technologies, in order to reduce drastically CO2 emissions, to improve driveability and fun-to-drive, and maintaining its intrinsic characteristics of comfort. The CO2 target reduction was 40% respect to 2005 figures.

In the following table, the main targets for SPV1 are shown:

Item	Targets	Reference
CO_2	80 g/km	- 40% of today 133 g/km
THC	90 mg/km(*)	- 10% of Euro 6
NO_x	54 mg/km(*)	- 10% of Euro 6
Euro 6 (enforced in 2014): THC/NMHC/NOx/PM = 100/68/60/5 mg/km		
(*) Engineering targets.		
(**) Measured w/ manual transmission; calculated value w/ Automated Manual Transmission 93 g/km		

The down-sizing approach is based on turbo-charging technology: the activities performed by University of Genova were organized according to the following main objectives:

- identification of technology solutions and application problems linked to small gasoline engine turbocharging and guide lines for the best design of the turbocharger system: contribution to the fuel consumption reduction from the adoption of turbochargers purposely designed for engines using a multi-air system
- optimization of the design, assisted by analytical and experimental evaluations of the single components, of the engine inlet and exhaust systems integrating the turbocharger system

Summary description of project context and objectives – SPV2

The **aim of sub-project V2 "New CI Engines with low temperature combustion and integrated aftertreatment system for alternative fuels"** was the development of a 4-stroke Diesel downsized engine achieving emissions 10% lower than EU6 pollutant limits and CO2 emissions 20% lower than 2005 levels.

After redefinition of the targets in period 2 it has been agreed to build a demonstrator vehicle based on the Golf 6 Variant BMT and to reduce CO2 emissions below 98g/km in NEDC under respect of the mentioned emission limits and considering the increase of vehicle weight..

CO_2	NO_x	CO	HC + NO_x	PM
98	**0,072**	**0,45**	**0,153**	**0,0045**

Tab1: emission limits EU6 -10% [g/km] in NEDC

One of the core elements of the technical approach is the low temperature combustion (LTC) to reduce NOx and soot simultaneously. This combustion is supported by a dedicated fuel blend to enhance the operating limits (temperature, pressure) to more usable values.
The downsizing of the engine is accompanied by improvements of the boosting system to guarantee comparable fun to drive figures. New approaches on hardware and software to increase the engine efficiency should be performed in this subproject.

A novel exhaust gas aftertreatment system (EATS) has been developed using a combination of LNT and SCR catalysts and creating the required reformate by on-board-reforming.
A development of an experimental rate shaping fuel injector and 1 cylinder testing to investigate fuel properties contributed to the 1 cylinder tests to investigate LTC.

The final step was the build of the demo-vehicle. This included the electronical integration of the new and of the additional components and the separate control units, e.g. for the EATS. The vehicle had to perform numeral tests to calibrate engine and EATS, leading to the PEMS-tests in cooperation with SP T1.

Summary description of project context and objectives – SPV3

The **aim of sub-project V3 "Extreme Downsized Low Cost CI Engine"** was the development of a 2-stroke 2-cyl Diesel extremely downsized engine achieving emissions 10% lower than EU6 pollutant limits and CO2 emissions 20% lower than 2005 levels.

Table Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**-2 EU Emission Standards for diesel fuelled passenger cars and LCVs**

Passenger Car / LCV	Date	CO	HC	HC + NOx in g/km	NOx	PM	PN #/km
Euro 5b	2011.09	0.50 / 0.74	-	0.23 / 0.35	0.18 / 0.28	0.005	6.0×10^{11}
Euro 6	2014.09	0.50 / 0.74	-	0.17 / 0.215	0.08 / 0.125	0.005	6.0×10^{11}

The down-sizing approach is based on turbo-charging and supercharging technology and the opportunities of the 2-Stroke cycle :

- Extreme downsizing (730cc).
- Twin-cylinders without NVH penalties.
- Efficient after-treatment by exhaust temperature management.
- Control of compression/expansion ratio with Variable Valve Timing.

The work split between the partners is as follows :

Scavenge concept and optimization	RNO
Combustion system concept, design and simulation	RNO
Combustion system testing and optimization	CMT
Injection system design, manufacturing and integration	Delphi
Injection system characterization	CMT
Engine Mechanical design, manufacturing and assembly	RNO
Demo car realization	RNO, IFPEN
Engine testing and optimization	IFPEN
Engine mapping and control	IFPEN

Air system calculations	LMM,RNO,JBRC
Air system design	LMM, RNO
Air system testing and optimization	JBRC

This sub-project is an opportunity to use tools, methodologies and technologies that were not available when the 2-Stroke Diesel engines had a significant share of the industrial engine market (Trucks, locomotives, ships and power generation) :

-1D modelisations (GT-Power/ Amesym)
-CFD calculations (internal aerodynamic and combustion)
-FEA calculation
- Common Rail Diesel fuel injection system
-Electronic control for VVT, Fuel injection, EGR flow, Turbine vanes
-Analysis of test by DOE

Summary description of project context and objectives – SPT1

The **aim of sub-project T1** was to develop tools and technologies for efficient powertrain integration. As these topics are of general interest this sub-project is arranged transversal, which means that there was strong interaction with all vertical sub-projects.

SPT1 included three main topics:

(1) **The development of new simulation tools for powertrain integration**
The objective of this work package was to develop computer models for simulation of engines, which can be integrated to larger environments for simulation of powertrains and vehicles ("virtual engine integration"). These models must be capable to predict engine characteristics under real world driving conditions. The aim is to use them for a projection of innovative aspects to real world driving conditions in order to support an assessment of these innovations. Emphasis is laid on trobological topics (friction, wear).

(2) **Friction reduction**
This work package considered several aspects of friction reduction such as the enhancement of surfaces friction performances, low viscosity oils, thermal management and design aspects. Research on surfaces friction was very fundamental and covered new materials, coatings and surface textures. Tribological characteristics were evaluated in labs and could be introduced to models.

(3) **PEMS for passenger cars and final results assessment**
The objective was to develop and assess the procedure of real-life emission measurements of light duty vehicles with PEMS. These investigations involved three major parts: (i) developing a protocol to measure the emissions of light-duty vehicles in the laboratory and on the road, (ii) applying this protocol to measure the emissions of a baseline vehicle, and (iii) applying the protocol, and if necessary to develop it further, to measure the emissions of one final validator vehicle.

Main S/T results SPV1

The SPV1 partners (CRF, MM, AVL and Unige) worked on the extreme downsized gasoline engine. CRF was involved in the procurement and testing of the new engine and its new innovative components: LP-EGR, WCAC (Water Charge Air Cooler), new CR, new camshaft profile. The expected benefits were:

- Fuel efficiency increase at high loads
- Improvement of combustion cycle efficiency and transient operation
- Pumping loss reduction at part load conditions
- Emissions reductions
- No power derating thanks to intake air temperature reduction

The experimental investigations developed at the University of Genoa turbocharger test rig allowed better understanding compressor and turbine steady and unsteady flow performance.

In particular, experimental investigations developed during the project regarded different aspects following reported:

- measurements of steady flow performance maps of two different turbocharger turbines
- measurements of steady flow performance of two different turbocharger compressors
- test rig upgrade for the installation of two different cylinder heads (4 cylinders and 2 cylinders configuration)
- investigation on unsteady flow compressor performance in 4-cylinder configuration
- investigation on unsteady flow performance of two compressors in 2-cylinder configuration
- experimental investigation on turbine unsteady flow performance
- study on the influence of downstream circuit geometry on compressor steady and unsteady flow performance (three different configurations)

All activities developed allowed to reach the following main results:

- in order to improve matching calculations in the case of waste-gated turbocharger, turbine maps implemented within simulation models should be referred to different by-pass opening positions
- importance of optimizing turbine entry casing design to achieve a higher turbocharger peak efficiency
- turbine steady state maps do not describe real unsteady behaviour, especially at higher levels of mean inlet pressure and engine rotational speed and when the regulating device is open
- unsteady flow effects are also significant for the turbocharger compressor in the case of downsized engines with a reduced number of cylinders
- under strong unsteady flow condition the compressor is capable of average stable operation even if it instantaneously works on the left of the surge line
- the compressor rotor design can significantly affect the extension of stable operation zone under unsteady flow conditions
- importance to test the compressor with the typical automotive circuit in order to assess its real performance (with special reference to the surge limit).

Concerning MM, they carried out the engine calibration at test bench with the target of optimizing the engine performances, to make available a final engine calibration dataset suitable for vehicle, as base calibration to optimize the vehicle performances in transient

conditions. The work focused on base engine calibration process definition and optimization; the calibration was carried out via commercial tools (i.e. PAP Puma 5.6.1 e Cameo 2.4) which allow automated tests performed at the test engine benches, and via specific calibration tool (named MCT) properly developed by MM.
The starting engine was the downsized turbocharged VVA engine with the specs defined in the following table:

Displacement	875 cc
Power / Torque	62 kW / 145 Nm
Bore / Stroke	80.5 mm / 86 mm
Compression Ratio	10:1
Cylinder & Valves numbers	2 cyl & 4 valve per cyl
Injection system	Port Fuel Injection
Distribution	Variable Valve Actuation (MultiAir)
Boost	Conventional Turbocharger

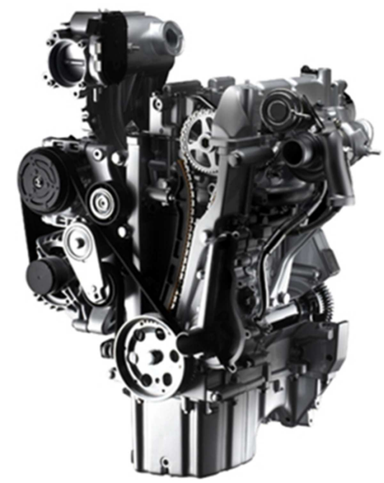


Table 1- 2 cylinders downsized VVA engine specs

The validator has to demonstrate the specified targets concerning fuel consumption, CO_2-reduction, emissions, power and torque respect to the reference engine: several technologies were used and validated to fulfill the goals.

- Cylinder Head Integrated Manifold to cool exhaust gas at extend lambda 1; this hardware modification works mostly at high load from 3000 rpm.
- Intake valve masking elimination to reduce knocking tendency from medium to full load
- Geometric compression ratio increased to 10.5 :1 to improve efficiency at lower load
- Late Intake Valve Closing (LIVC) to use Atkinson cycle and reducing knocking tendency by effective compression ratio decrease: it works mostly at higher load starting from 2000 rpm, where turbocharger has enough energy to compensate the loss of volumetric efficiency due to the delay in valve closing. A new intake profile was designed and realized
- Low Pressure cooled Exhaust Gas Recirculation (LP-EGR) to improve combustion thanks to mitigation of knocking: it has the same working area of LIVC.
- Water Cooled Charge Air Cooler (WCAC) to reduce air intake temperature: this component had several problem and different prototyped were built.

All the technologies described above were validated on the engine installed at test bench. The second step was to install the engine and its new components on the vehicle: the vehicle chosen for the Powerful engine is a Fiat Panda, originally equipped with the base 2 cylinder downsized turbocharged VVA engine.
Fuel consumption benefit was evaluated in homologation NEDC cycle and in IQC and the results are shown in fig. 1 and 2 in comparison with the reference (1,2 liter 4-cyl PFI engine on a Fiat

Panda built in 2005 respecting euro 4 emission limits). Data in the graphs are relative to the base downsized turbocharged VVA engine , Powerful engine and the last is a simulation of the possible benefit due to the use of an automatic transmission. The Powerful engine is different from the downsized turbocharged engine for the following contents:

- Increased compression ratio to 10.5:1
- Elimination of intake valve masking
- Cylinder Head Integrated exhaust Manifold
- New intake profile for Late Intake Valve Closing strategies
- Use of cooled exhaust gas recirculation
- Water CAC

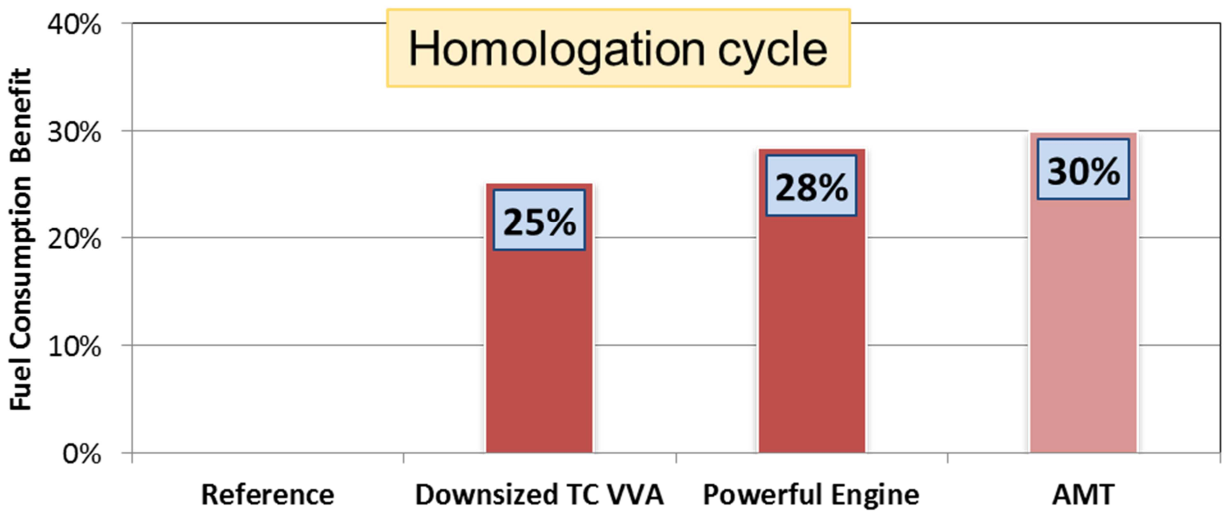


Fig. 1 NEDC cycle fuel consumption benefit

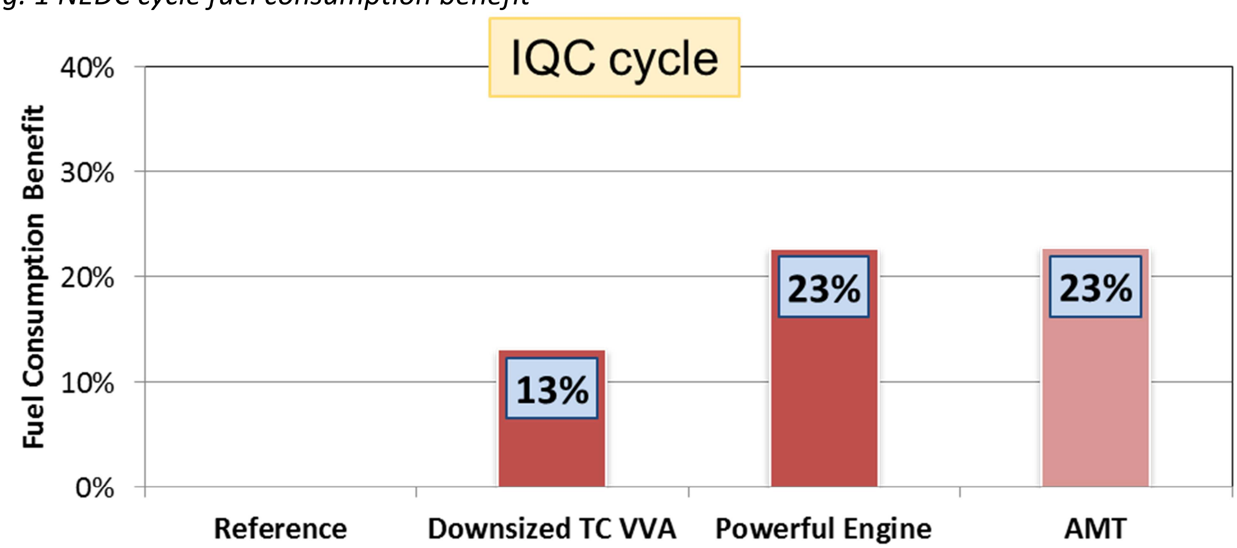


Fig. 2 IQC cycle fuel consumption benefit

The net fuel consumption benefit measured in NEDC cycle is 3% and it is obtained in particular thanks to the increase of compression ratio, as it is the main content used to improve efficiency under 8 bar BMEP.
But the most important improvement is **the gain of 10% measured in IQC** cycle and representative of real life fuel economy benefit. The overall benefit comprehends all the contents added to improve the engine.
For the performance there is no variation respect to the starting 2 cylinder engine because the full load curve was maintained at the same level also with the penalization due to compression ratio increase.
As conclusion, the Powerful vehicle respects Euro 6 limitations for the exhaust emission, as shown in table 4, and also reaches the goals of the project to have THC and NOx emission lower than 10% respect what imposed by the legislation.
As already announced, the **final result of the project is the reduction of CO2 emission on the homologation cycle is 30%** (with automatic transmission), respect to the reference 2005 vehicle.

	NEDC Emissions				
	THC [mg/km]	**NMHC [mg/km]**	**CO [mg/km]**	**CO2 [g/km]**	**NOx [mg/km]**
Powerful Engine	**72**	**41**	**170**	**95**	**28**
Euro 6	100	68	1000	-	60
Target	90	-	-	80	54

Main S/T results SPV2

The efforts undertaken in SP V2 by the partners PUT, FEV, RWTH Aachen, Dinex-Ecocat and Volkswagen, were focused on NOx and CO2 reduction of CI engines and delivered results for five technological areas:

- catalyst
- EATS with onboard reforming
- rate shaping injector
- Low Temperature Combustion with alternative fuel
- downsizing CI engine

The Exhaust Gas Aftertreatment System (EATS) of SPV2 is based on the serial combination of a NSC and a SCR, a bypass for the NSC and the external feed of H2 by a fuel reformer. This could substitute common active SCR systems that depend on the dosing of urea. It would be a great benefit for the customer, who doesn´t need to take care of an additional fluid.
A special focus of this research was the conversion of NOx, which is a challenge of CI downsizing engines.

In light-duty diesel application temperatures are extremely low (<200°C). That was a key driving force in the development of the LNT and SCR catalyst for the novel EATS. At the same time temperatures may reach 700, even up to 900°C during the active DPF regeneration.

The use of higher Pt loading in LNT resulted in improved low temperature activity with a low ammonia emission when the developed Cu-SCR catalyst was located after LNT unit. The best LNT is composed of Pt as the main active metal and in addition a small amount of rhodium to promote reactions in rich side. The developed new Cu-SCR catalyst was able to catalyze SCR reactions in the absence of NO_2 and it was durable up to 800°C.

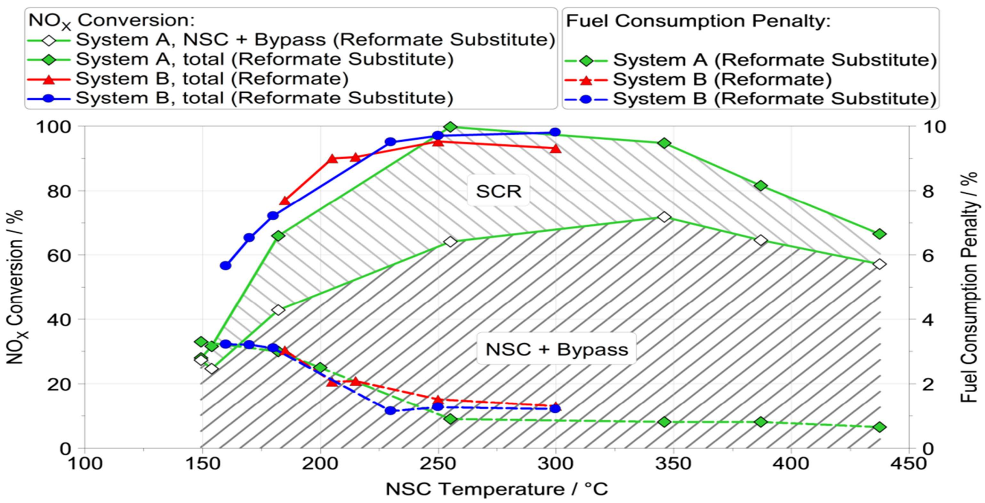


Figure 1: Steady-state NO_X conversion and fuel consumption penalty of NSC + SCR system with reformate and reformate substitute as function of NSC temperature; EU4 NO_X raw emission level

The attained steady-state NO_X conversion of the complete EATS is shown in Figure 1. At 250 °C almost complete conversion is achieved at fuel consumption penalty of ≈ 1.5 %. At T < 250°C the total steady-state NO_X conversion drops due to reduced NSC activity as well as NH_3 yield. The fuel consumption penalty increases due to higher NSC regeneration frequency as well as lower engine fuel consumption due to lower engine load. During transient operation, complete conversion can still be maintained by the SCR for short time, e.g. during DPF regeneration, by consuming previously stored NH_3 depending on SCR NH_3 load and NO_X mass flow. This represents high NO_X performance benefits compared to conventional NSC application.

A parallel, supportive research was the HiFORS injector. It is characterized by a rapid opening and closing action of the nozzle needle, that ensures short times in the area of small needle lifts even at small injection rates, so that the harmful influence of needle seat throttling can be largely minimized.

The continuous rate shaping functionality opens additional potential for combustion sound reduction at moderately increased soot emissions. At full load operation, the injector's high pressure capability enables both increased engine performance and improved indicated efficiency.

One of the core topics of SP V2 was the homogeneous combustion process LTC. The aim of this combustion type is to create low soot and low NOx simultaneously, which is usually a trade-off on common Diesel combustion. LTC has been supported by technical measures like a combustion control and a low pressure EGR (to reach 60% EGR). The operating range (limited

load) has been enhanced by an alternative fuel (naphta/ HVO blend) due to its chemical properties, which enlarge the ignition delay.
The use of LTC directly increases the fuel consumption due to reduced combustion efficiency, though it is used in the final application for being the most efficient measure of engine internal NOx-reduction.

The aimed CO_2-target in this subproject has been redefined in the second year. The new target was 98g CO_2 in a Golf6 Variant BMT, that is homologated with 109g CO_2 and EU5 emission level. The challenge of reducing CO_2 and emissions (below EU6 minus 10%) is increased by additional weight. The validator has been tested on a higher inertia class (3500lbs instead of 3250lbs) than the base vehicle.
To reach these CO_2 levels Volkswagen has built a 1.4l 3cyl TDI® research engine to replace the base engine. This engine contains numerous technical features in all technical areas including special software solutions. The most important and beneficial ones are:

- steel piston
- ball bearing turbo charger
- 3 cam high pressure fuel pump
- increased compression ratio (17,5)
- decoupled auxiliary belt
- seat hole injectors

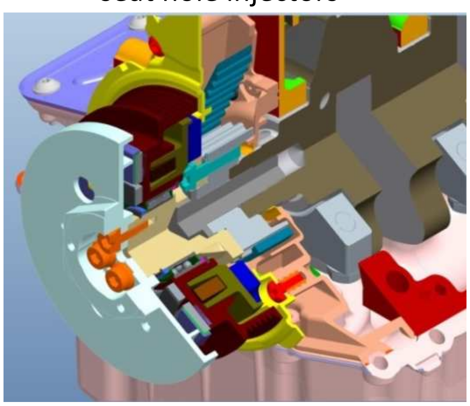


Fig. 2: Decoupled Belt

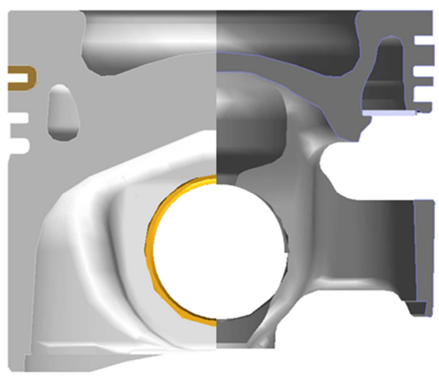


Fig. 3: Comparison alu/ steel piston

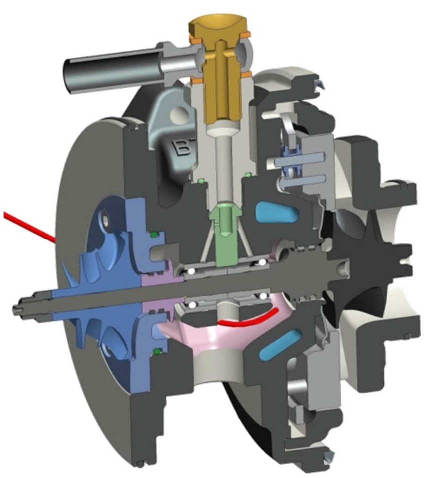


Fig. 4: Ball bearing turbo charger

Steel pistons show an increase of fuel efficiency by two effects: friction reduction and thermodynamic influence. Ball bearings in the turbo charger reduce friction and inertia and increase both, efficiency and transient performance. The redesigned cam-profile of the high pressure pump was beneficial for the engine calibration because of the perfect synchronization between rail pressure and injection events. A huge positive effect has been found by the decoupled belt, which is taking the belt, the compressor and the generator off the crankshaft when not needed. It reduced CO_2 emissions by 5g/km in NEDC. It is significant, that it´s benefit is mainly produced by cold starts. It´s less in longer test cycles like WLTC.

The validator as a result of the subproject V2 has been prepared to combine all new technologies. Modifications to chassis, electric and fuel system have been integrated as well as an intense safety program to ensure a safety level during testing and demo-events comparable to standard road cars. This includes some special efforts for the integration of a gas system, which supplies H2-containing gas to the EATS.

Fig. 5: Validator: Golf 6 Variant BMT with Powerful engine and Powerful EATS

With the research engine applied to the validator vehicle it was possible to reduce CO_2-emissions below 95g/km in NEDC under respect of the increased weight and reduced emission targets. The project targets have been completely accomplished.
Besides NEDC, which is the cycle to define the project targets, other cycles have been investigated. A comparison of NEDC and WLTC is shown below:

Parameter	Target (NEDC)	Result (NEDC)	Result (WLTC)	unit
CO_2	98	**94,4**	**99,6**	g/km
NO_x	0,072	**0,045**	**0,053**	g/km
CO	0,45	**0,082**	**0,007**	g/km
HC + NO_x	0,153	**0,100**	**0,070**	g/km
PM	0,0045	**0**	**----**	g/km

Tab. 1: project targets and results for CO_2 and emissions (EU6 minus 10%) in NEDC and WLTC

An overview of the performed cycles and the measured CO2 emissions is shown in the next table, taking the different weight situations into account:

Test	Inertia class (lbs)	Method	CO_2 (g/km)	NOx (g/km)
NEDC	3500	Test Bench	**94,4**	**0,045**
WLTC	3500	Test Bench	**99,6**	**0,053**
RDC soft	3500	Test Bench	**86,2**	**0,067**

RDC normal	3500	Test Bench	**95,1**	**0,099**
RDC aggressive	3500	Test Bench	**141,9**	**0,138**
RDE (w/o PEMS)	4000	Public Road 1	**104 - 139**	**0,056 – 0,250**
RDE (PEMS)	"4250"	Public Road 2	**126 - 135**	**0,037 – 0,122**

Tab. 2: comparison of the performed test cycles

The attained transient EATS system performance in the validator vehicle on chassis roller test bench as well as on road is shown in Figure 4. In NEDC, WLTC and RDE operation up to "normal" driving, the NO_X emission target of 72 mg/km is reached. In high load the NO_X emission rises significantly due to high temperature, space velocity and NO_X engine out emission. The fuel consumption penalty is generally low compared to a conventional engine internal enrichment and conventional NSC operation, due to higher reductant formation efficiency of the applied reforming approach.

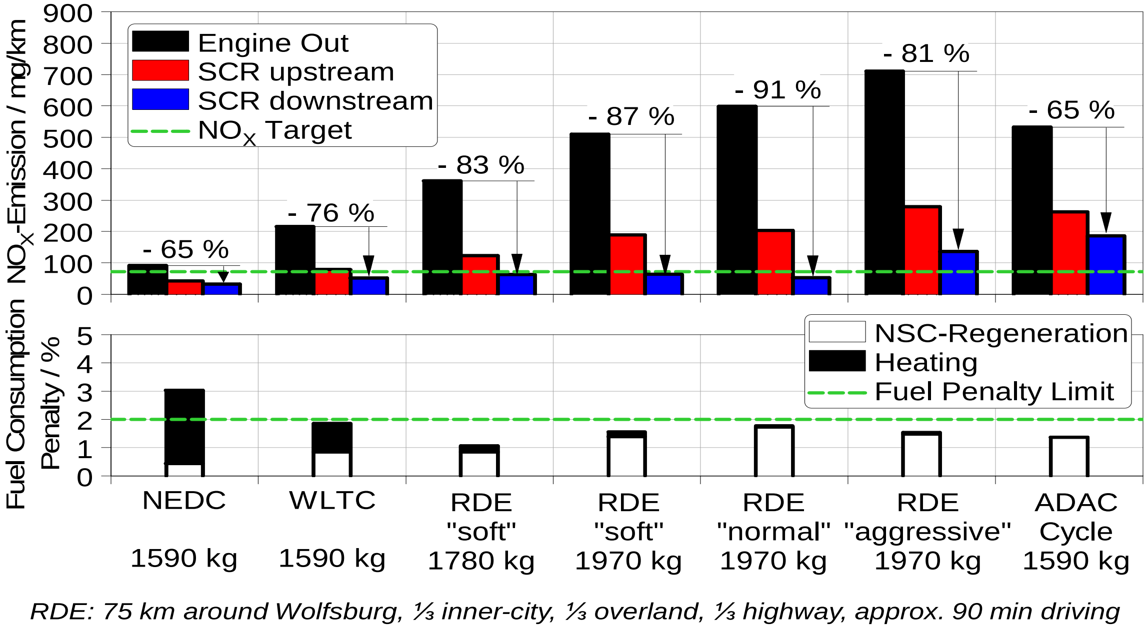


Figure 4: Summary of transient aftertreatment investigation results and validation of emission and fuel consumption targets

The combination of a high efficient Diesel engine, creating very low exhaust gas temperatures with the LTC and the developed EATS leads to a number of parameters, which influence the overall performance in several driving conditions. The importance of the control strategy and when using different technical measures for CO_2 and NOx reduction can be demonstrated with a diagram, showing some main values in a RDE run with the validator (fig 5).

While internal heating measures in the engine are required at the beginning to create a certain temperature in the catalyst (light off) it is a combination of using LTC and/ or the EATS-regeneration. The balance of using the most efficient measure in each situation is a crucial factor for minimised CO_2 and NOx emission.

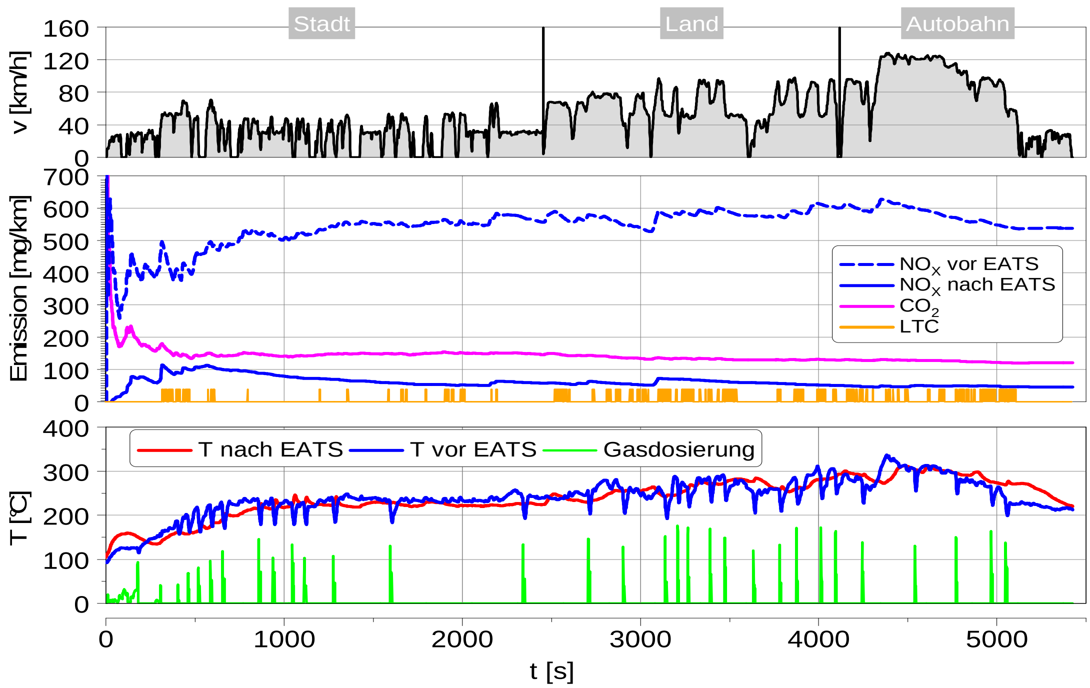


Figure 5: CO_2, NOx, Temperatures and use of technical measures in a RDE-drive around Wolfsburg

Main S/T results SPV3

(we shall express what we've learnt during the project, what works, what doesn't and why)

Mechanical Design

The mechanical design of such a Diesel 2-Stroke has some specificities when compared to 4-Stroke state of the art :

-The twin-cylinder can be fully balanced by adding simple counterweights to one of the camshaft. Typical automotive NVH is achieved with a Twin-cylinder.

-The valve-train requires unusual valve-lift and valve spring because of the High camshaft rpm, but it is definitely doable by using knowledge from Sport/racing engines. Standard plain bearing with oil film leads to high friction, and full roller bearing camshaft is required.

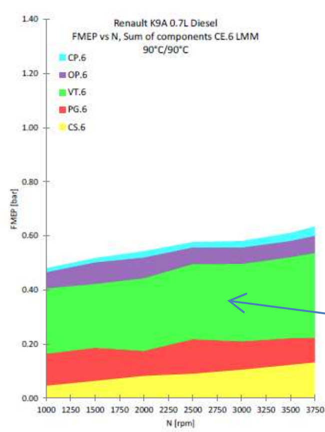
-The friction contacts with the piston pins require either a very special design or the use of state of the art surface treatments and materials.

-The dynamic behaviour of the camshaft drive use conventional technology, but with dedicated dimensions and settings.

General reliability can be achieve without doubt by a competent team of engine developers.

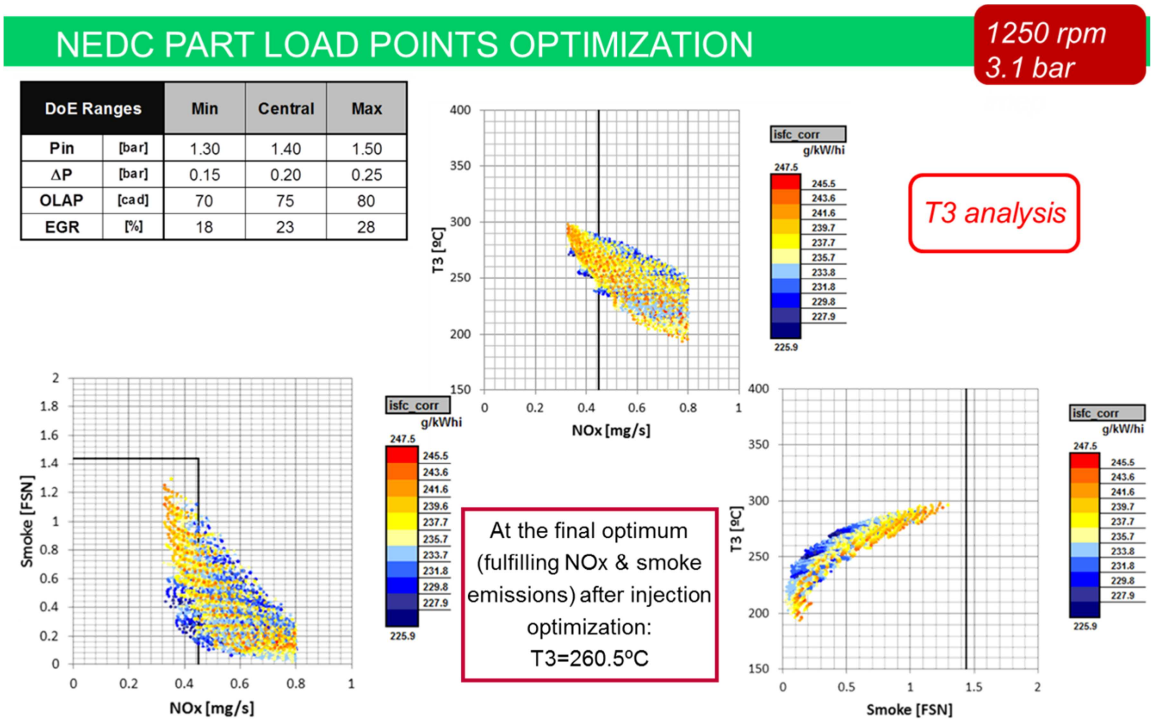
Friction
For all the engine sub-systems to the exception of valve train, the fmep friction is roughly half the 4-Stroke value (as hoped). Future friction work has to concentrate on the valve train friction reduction.

Abbreviation	Component
CE	Complete Engine
BE	Base Engine
CT	Cranktrain
CS	Crankshaft
PG	Piston group
VT	Valvetrain
OP	Oil pump
CP	Coolant pump



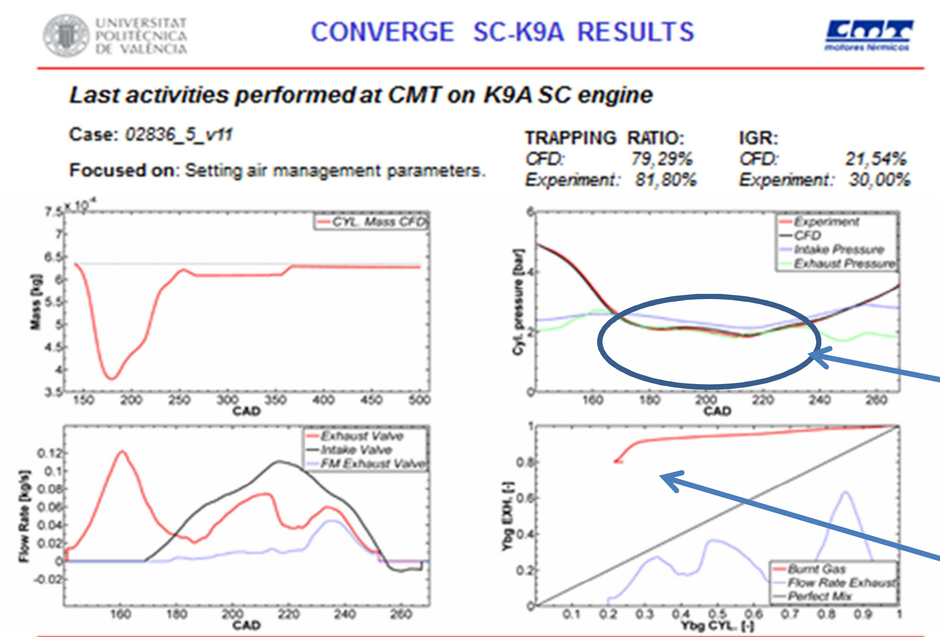
Valvetrain friction is abnormally high

After-treatment (RNO)
The demonstrated ability of this 2-stroke to manage the exhaust temperature would boost the after-treatment efficiency at light loads typical of NEDC cycle.



Scavenge (RNO)

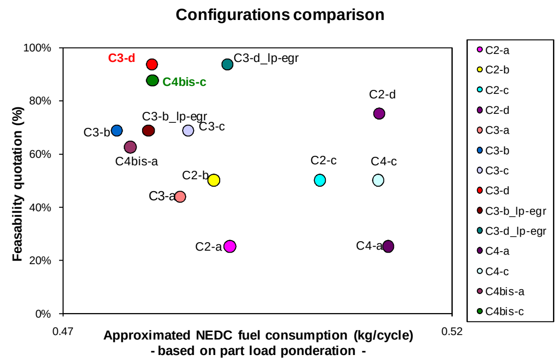
By intense CFD calculations and engine testing, we could reach a very good scavenge efficiency. The scavenge curve is better than expected at project beginning. The biggest problem we had with scavenging is its interaction with exhaust acoustic. We've learnt that acoustic can destroy the scavenge characteristic, and the preferred situation is with a near constant pressure difference between exhaust and intake during the scavenge event.



Provided the pressure difference is near constant during the scavenge phase

Excellent scavenge characteristic

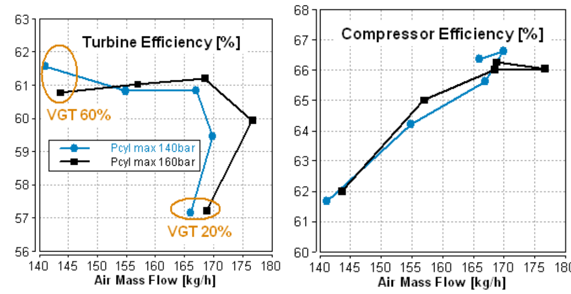
Air systems



Configurations	
C2	Pos. displ. charger upstream TC
C3	Pos. displ. charger downstream TC
C4	Centrifugal charger uptream TC
C4bis	Centrifugal charger downstream TC

Configurations break down	
-a	variable drive + VGT
-b	dual drive + VGT
-c	variable drive + turbine WG
-d	dual drive + turbine WG

Picture 1: Final configurations comparison



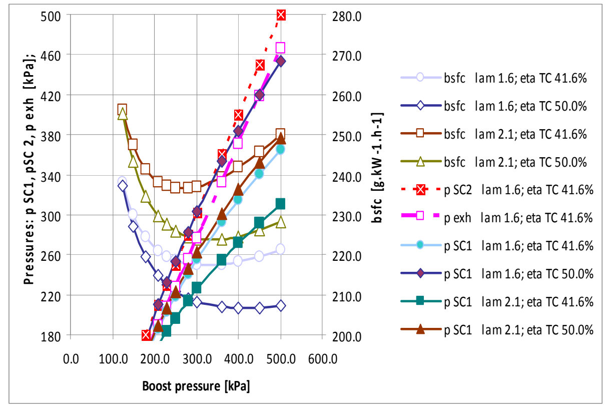
Picture 2: Efficiency of Honeywell turbine and compressor at 1500rpm Full Load

Work on Powerful project started with huge amount of simulations targeting on appropriate air loop layout and turbocharger and supercharger devices. The final comparison of all engine air loops taken into account based on BSFC in NEDC reveals that the configuration C3-d with the mechanical positive displacement charger downstream of the waste gate turbocharger appears to be the best compromise. Turbocharger and supercharger tests in CZ Strakonice revealed in case of MHI turbocharger tests rough disagreement between measured efficiency and that proclaimed by MHI (about 10%) due to turbine overload and thus too low BSR. CZ Strakonice has delivered in very short time their own two prototypes of wastegated turbine (C09 series). Good agreement has been achieved between measured turbine maps and results from engine testing (Picture 3) in terms of turbine efficiency. Honeywell has delivered turbocharger with VNT turbine (GTD1038VNT) proposed based on 1D simulation. The Honeywell VNT turbine (”VGT”) and compressor efficiencies, measured on the engine, are shown in
Picture **2**. As expected the VNT settings strongly modify the turbine efficiency. The values higher than 61% are promising with respect to waste gate turbines, tested previously in the Powerful project, which had featured higher nominal efficiency but lack of controllability with good efficiency.

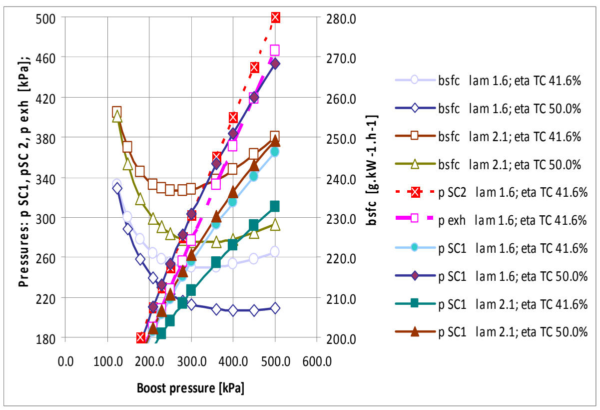
The real engine tests at IFPEN show that the turbocharger choice, made through 1D simulation, is validated. Indeed, at 1500rpm and 3000rpm, compressor and turbine efficiencies fulfil the original project targets.

Finally, as appropriate air loop layout and devices have been chosen engine exhaust piping has to be optimized with target to minimize supercharger input power and thus engine BSFC. The main task was to ensure the highest possible pressure drop over the engine which would ensure sufficient scavenging with lowest possible demand on supercharger input power. From huge amount of different exhaust layouts simulated (Helmholtz resonator, blind pipe, exhaust muffler with perforated runners etc.) short exhaust runners connected to a big volume pipe have been chosen as the final solution. The results of this solution with almost constant intake and exhaust pressure are presented in Picture 4.

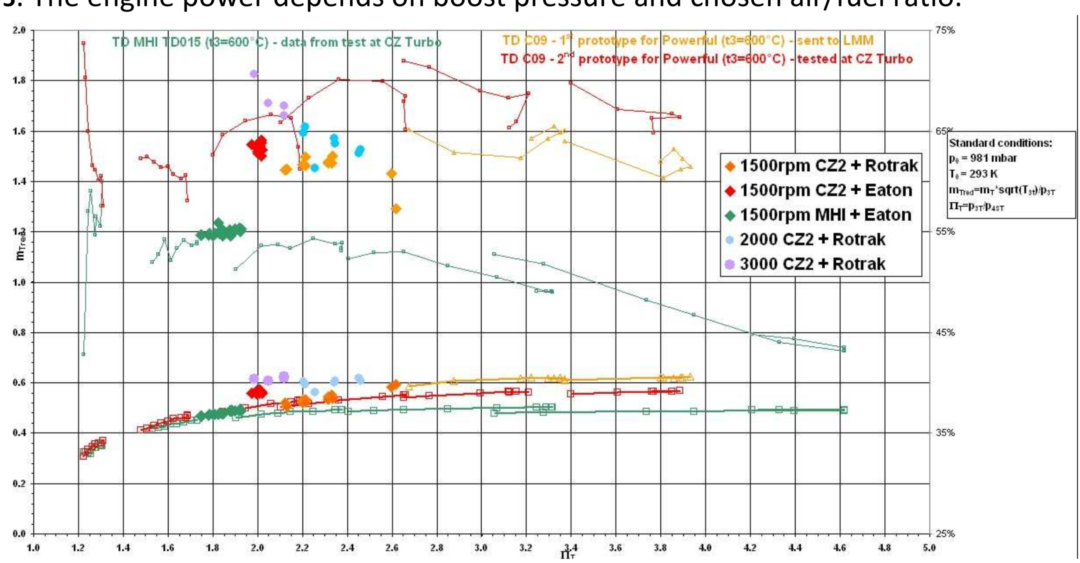
The current lack of sufficiently efficient turbochargers and superchargers posed the question how to proceed. The general analysis has been done and published. The influence of rated air excess and turbocharger efficiency while other parameters were fixed to values found from experiments and simulations of an extremely downsized two-



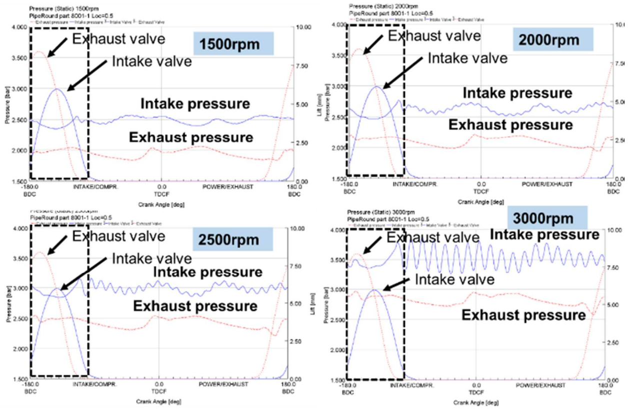
cylinder diesel engine is presented in



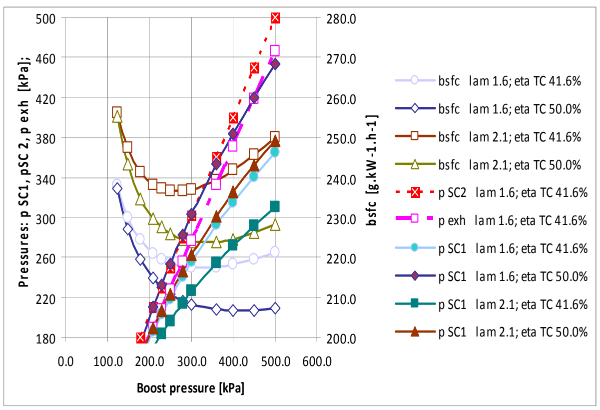
Picture 5. The engine power depends on boost pressure and chosen air/fuel ratio.



Picture 3: Global comparison of MHI and both CZ C09 turbine prototypes data and turbine operating points resulting from the engine testing on IFPEN test bed. The good agreement between CZ tests of both turbines is evident while the MHI manufacturer map (black lines is far from the reality.



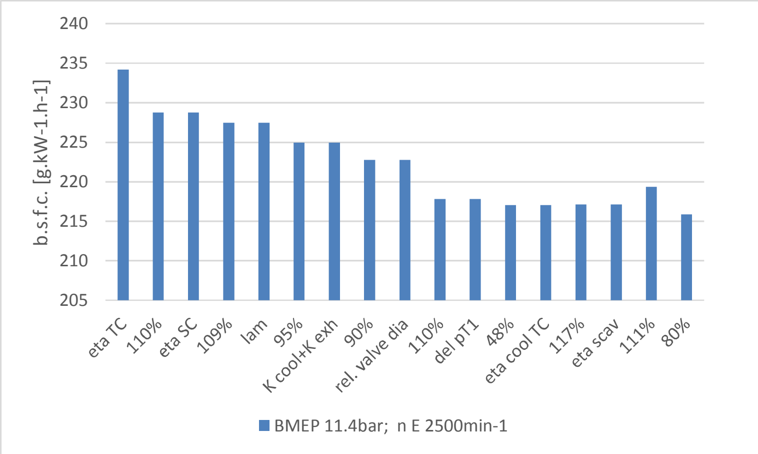
Picture 4: Engine exhaust final solution results



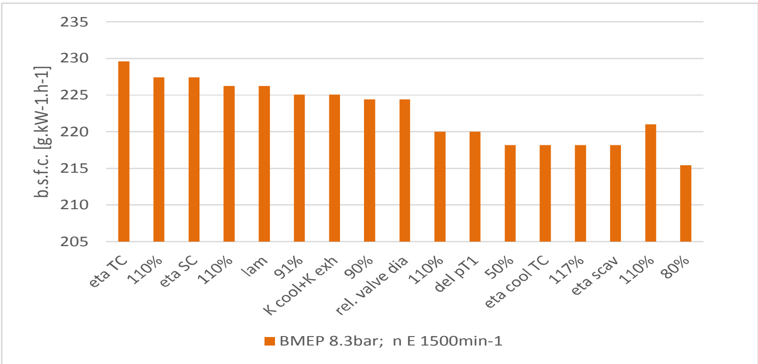
Picture 5 Required averaged pressures at a supercharger and in exhaust manifold and net brake specific fuel consumption in dependence on boost pressure and air excess

The comparison of pressure reached by a turbocompressor (superchrager inlet, p SC1) and supercharger outlet (PSC2) shows clearly that there might be no need for a supercharger in some range of power if the efficiency of a turbocharger is high enough and if the excess air is fixed at reasonable mixture strength level.

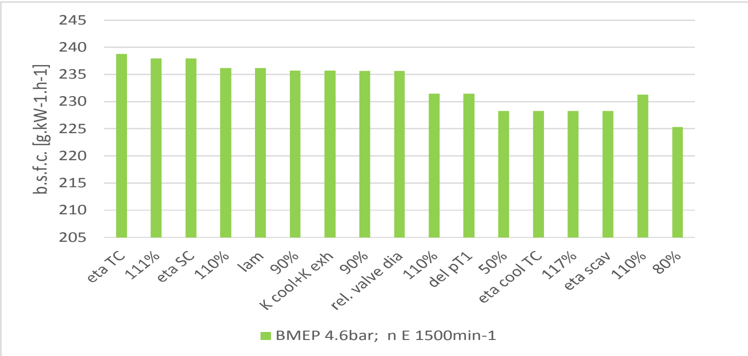
The potential of the further optimization of air-loop parts can be found in example of 3 different NEDC points (high load, high speed and two loads at lower speed) - **Picture 6** - **Picture 8**.



Picture 6 Potential for bsfc improvement in dependence on different engine parameters (numbers in bar description express the relative change of the parameter in consideration, i.e., total turbocharger efficiency eta TC, supercharger isentropic efficiency eta SC, air excess lam, cooling losses in cylinder and exhaust system relative to fuelk enthalpy K cool+K exh, pressure loss at high-pressure DPF del pT1, low-pressure cooler efficiency eta cool and scavenging efficiency eta scav) – high load, high speed



Picture 7 Influence of relative size of valves on bsfc – high load, low speed



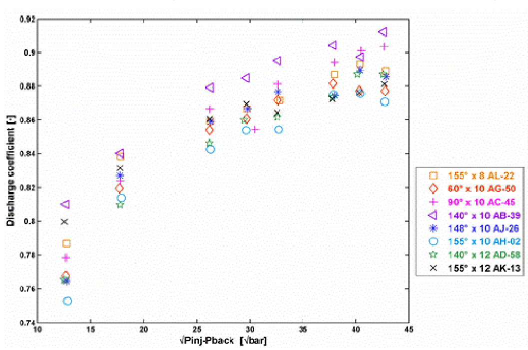
Picture 8 Influence of relative size of valves on bsfc – low load, low speed

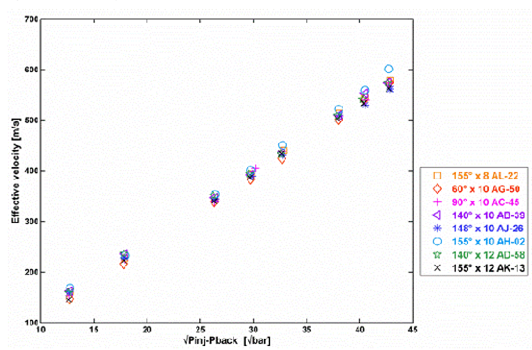
The important conclusion is that with the close future development of turbocharger efficiency, the bsfc can be reduced by another 5-10%. If additionally air excess optimization and avoidance of exhaust cooling loss is realized, another 3-5% reduction may be achieved. The crucial role of air-loop pressure losses has been already mentioned. Quality of scavenging is very important, as well. It seems, that subquadratic cylinder layout may increase loop scavenging efficiency and engine scavenging permeability without reducing trapping ratio. Other parameters, as intercooler cooling efficiencies, play less significant a role.

Combustion system (UPVLC)

Injection system characterization:

A set of potential injector nozzle configurations were experimentally characterized and results show how the discharge coefficient ranges between 0.74 and 0.92 as usual in conical nozzles. Too wide include angle nozzles trend to cavitate since the flow is strongly diverged when entering inside the hole, while too low included angle nozzles trend to cavitate due to a lack of hidrogrinding. As it is well known, results confirm how despite the cavitation phenomena, the effective velocity increases monotonically with the injection pressure.





Regarding the spray macroscopic characteristics, some differences were observed in both the spray angle and its total penetration. As expected, injectors with low momentum flux and high spray angle should show small penetration values.

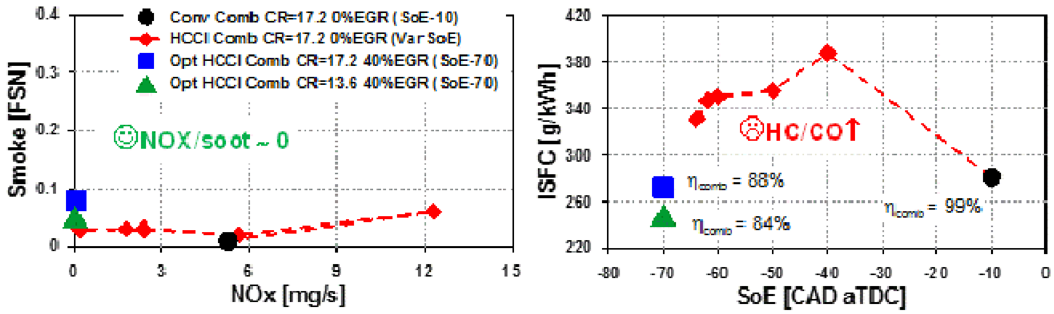
Finally, all the injectors were considered suitable for being tested on the engine along the definition of the final combustion system.

Potential of the early injection HCCI combustion concept:

The potential of this combustion concept was experimentally evaluated at low load (2 bar IMEP) and low speed (1250 rpm), where the concept should provide the best results.

As a summary, this combustion concept was implemented and its potential for controlling simultaneously NOx and Smoke emissions was confirmed. However, even after optimizing the air management settings and the engine geometric compression ratio, the IGR level was too high and then, also the temperature at IVC and along the compression stroke. As a result, combustion is phased too early during the compression stroke having a negative impact on indicated efficiency.

The main conclusion was that the 2-stroke engine architecture under development (with intrinsically high IGR ratio) is not compatible with the early injection HCCI concept when using diesel as fuel (high reactivity or cetane number of diesel).



Final engine hardware definition

This work was performed at medium load (10.4 bar IMEP) and medium speed (1500 rpm).
Camshafts with wide valve lift durations or high valve lifts (intake) are not suitable since they worsen the relation between TR and IGR, while increasing the expansion ratio (exhaust camshafts with narrow opening durations) is critical for improving the engine efficiency. The A80-06 / E95-02 definition provides the best ISFC-ISFCcorr and trade-offs without impacting negatively over the NOx-Smoke trade-off, so this was the final camshaft definition.
Regarding the combustion chamber hardware, nozzles with 80µm hole diameter with more than 10 holes and less than 140º of included angle are not suitable since spray mixing process is compromised, increasing Smoke, CO and ISFC. Additionally, higher nozzle diameters are interesting since they reduce the impact of the observed nozzle coking problems.
The optimum combustion chamber hardware was selected based on ISFC and exhaust emissions, so the final definition consists of a steel piston with compression ratio 17.8 and suitable bowl profile together with 2 nozzle configurations, 8h-90µm-155º and 7h-96µm-148º.

Optimization of the CDC concept

This optimization was carried out sequentially, starting by the air management settings optimization and ending by the injection settings optimization already fixing the optimum air management settings. The DoE-RSM technique was implemented to optimize air management settings while a conventional parametrical approach was followed to optimize injection settings. This research included 5 points representative of the NEDC homologation cycle covering a suitable range of engine speeds and loads.
A great effort was devoted to establish & confirm the physical relations between the air management parameters, in-cylinder conditions, combustion characteristics, and final exhaust emissions and efficiency levels.
Finally, at each operating condition the air management settings which allow to fulfil the desired optimization criteria (lowest NOx, best NOs/soot/ISFC trade-off, minimum ISFCcorr, best ISFC/ISFCcorr trade-off) were defined. An example is included corresponding to the medium-to-high load (10.4 bar IMEP) and medium speed (1500 rpm) operating conditions (Point 5), optimizing for lowest NOx or optimizing for ISFC relaxing NOx limits.

Final results of this optimization are included in the table.

		POINT 1		POINT 3		POINT 4			POINT 5			POINT 6		
		4-stroke K9K	OPT lowNOx	4-stroke K9K	OPT lowNOx	4-stroke K9K	OPT highNOx	OPT highNOx	4-stroke K9K	OPT lowNOx	OPT highNOx	4-stroke K9K	OPT lowNOx	OPT highNOx
Speed	*rpm*	1250		1500		2000			1500			2500		
imep	*bar*	3.1		5.5		5.8			10.4			15.1		
NOx	*mg/s*	0.45	0.44	0.75	0.73	0.55	3.45	5.29	2.15	2.13	5.91	28.2	21.5	33.1
HC	*mg/s*	0.8	0.54	0.65	0.5	1.35	0.54	0.6	0.65	0.36	0.3	1.3	1.85	1.62
CO	*mg/s*	4.95	3.71	4.4	5.77	9.1	2.98	1.57	18.65	13.02	3.75	3.7	20.68	6.76
FSN	-	1.44	0.33	0.56	0.38	0.73	0.8	0	4.6	2.99	0.41	0.27	1.7	0.54
Bruit	*dB*	84.2	84.48	89.9	89.4	90.2	87.8	89.2	88.3	86.4	87.1	91.5	88.3	88.8
isfc	*g/kWh*	237	208.41	210.25	178	210.7	188.5	183.4	213.6	196.6	186.8	196.37	196.3	192.5
isfc_corr	*g/kWh*	-	226.4	-	215.1	-	211.11	211.22	-	238.7	216.1	-	237.81	237.31

For low to medium loads & low speed conditions all emission and noise limits were fulfilled even with lower isfc compared to the base 4-stroke engine and important benefits in isfc were observed when relaxing NOx limits. In general, all emission and noise limits fulfilled, but higher boost pressures than those predicted were needed to get the proper combination of fresh air and external EGR flows.

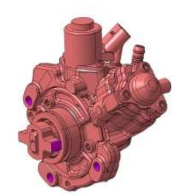
For high load and medium speed fulfilling soot, CO and HC emissions was not possible since combustion process is compromised due to reduced air flow. However important benefits are expected by improving the acoustic characteristics of the intake and especially exhaust systems.

Synthesis of the main scientific breakthroughs:

- New methodologies & tools has been successfully implemented for optimizing the performances of the 2-stroke engine concept.
- The feasibility of the 2-stroke diesel engine concept with scavenge loop architecture in terms of combustion & emissions performance has been experimentally confirmed for CDC concept, but NOT for early injection HCCI concept (with diesel fuel).

Fuel Injection System

The definition of the prototype fuel injection system designed for the POWERFUL SPV3 project twin cylinder focussed on efficiency for fuel consumption reduction, on cost optimization and on packaging constraints and includes the following components :



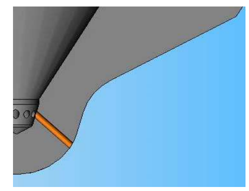
A single plunger with a 1:1 driving ratio was chosen for improved hydraulic efficiency and weight and cost reduction. The HP pump drive was modified from conical to Oldham coupling to have a compact engine packaging (HP pump is directly driven by the camshaft).

A fuel rail was specifically designed for the twin cylinder (reduced volume and outlet ports number). Its new design with an integrated mechanical Pressure Limiting Valve allows avoiding the permanent electrical consumption which would due to a classical HPV solenoid actuator.

A dedicated communication protocol was implemented in Delphi ECU in order to be used as a slave by the IFPEN engine management system. In this architecture, Delphi ECU is in charge of injection and rail pressure control, and receives fuel quantity, timing and rail pressure demands from IFPEN ECU. The injection control software was modified for the 2-stroke twin cylinder firing sequence.

The injector is the fast servo solenoid DFI1.5 2000 bar capable with an adapted outline to fit the engine. Two matrixes of nozzles (see table below) were delivered to enable the combustion system optimization on SCE at CMT.

DELPHI	Spray cone angle (°)				
Nozzle Flow @100bar (ml/min) / # of holes	60	90	140	148	155
320 / 8				o	o
350 / 7				o	
400 / 7				o	
400 / 8				o	x
400 / 10	x	x	x	x	x
480 / 12			x		x
x : first matrix					
o : additional matrix					



Most of these nozzle prototype variants were beyond current production range and are characterised by small injection hole diameters (< 100 µm), high number of holes and sometimes very narrow spray cone angle.
Some nozzle variants showed a fast, significant and reversible loss of flow rate during the single cylinder combustion campaign which could be identified as coking. But this was not confirmed on the twin-cylinder engine. Nevertheless, this point will have to be monitored in the following two stroke project.

Engine testing

A first task of the twin cylinder engine testing campaign was the assessment of the air loop, defined through 1-D simulation.
Several configurations and components were tested:

- On low pressure side : WG and VNT turbocharger
- On high pressure side : roots supercharger and centrifugal compressor coupled with a CVT transmission

Even if, due to the failures of the superchargers, it was not possible to perform extensive experimental campaigns with all the boosting configurations, the VNT turbocharger was chosen thanks to the slightly higher performances and wider flexibility.
In the figure here below, it can be observed the higher performances at low end torque, in terms of IMEP, and at partial load in terms of BSFC with equivalent smoke/NOx.

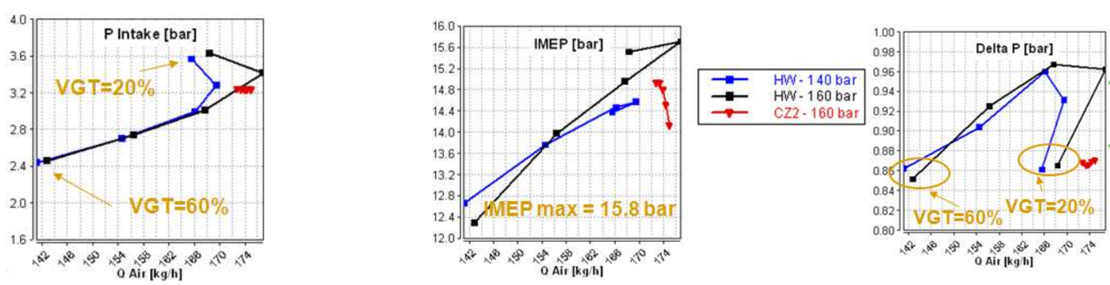


Figure : VNT and WG performances at 1500 rpm full load conditions

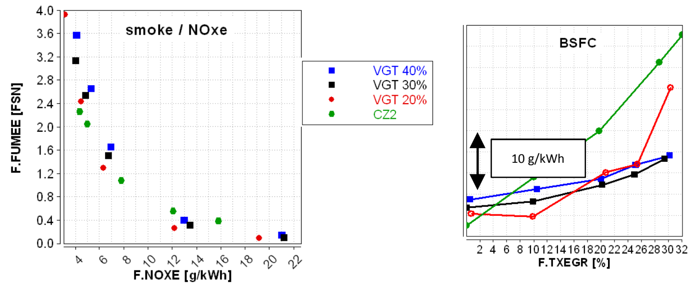


Figure : VNT and WG performances at 1500 rpm 7.7 bar BMEP

Regarding the supercharger, a double speed root compressor was chosen after several failures on all the different components tested.
The centrifugal compressor coupled with a CVT transmission performed well in terms of maximum compressor ratio, but the demanded compressor work resulted too high: at high load, almost half of the piston work (represented by the IMEP) was consumed for driving the compressor.
Before starting the engine calibration through DoE, a specific work was done to reduce the pressure waves in both intake and exhaust manifold.
The final design, allowed a very flat intake and exhaust pressure, as shown in the figure here below.

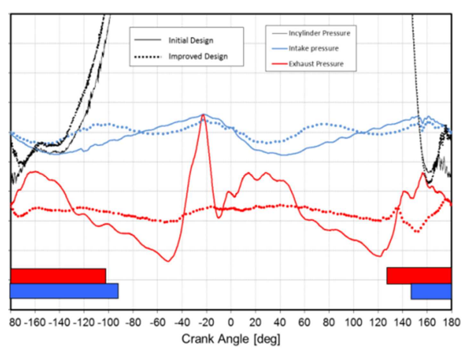


Figure: Pressure wave in intake and exhaust manifolds

Three engine points were characterised using statistical models (DoE method), through the in-house IFPEN software ICE²TM.
In figures below, response/response diagrams present the optimal points under constraints in blue but also the set of possible results when covering the whole domain in red points; grey points represent the constrained domain; green point corresponds to the optimal fuel consumption without any constraint.
The results show that to limit NOxe emissions, EGR and IGR are essential. In the same time, intake pressure (Pplenum) and differential pressure at upstream and at downstream of the engine (deltaP) increase, and supercharger power asked raises due to overlap reduction. This results in higher BSFC, despite a lower ISFC. A better optimization with this architecture could be expected if EGR were increased and IGR reduced. Notwithstanding, improvements should be place in the area drawn by grey points.

To reduce trade-off Smoke/NOxe without having a large impact on BSFC, we need to improve scavenging efficiency and delivery ratio while maintaining an acceptable level of trapping ratio. This will reduce IGR rate, increase EGR rate and limit the use of the supercharger. Therefore, trade-off should be respected and have a small impact on fuel consumption. These recommendations should be incorporated on future studies in order to make a viable two-stroke engine concept with only valves.

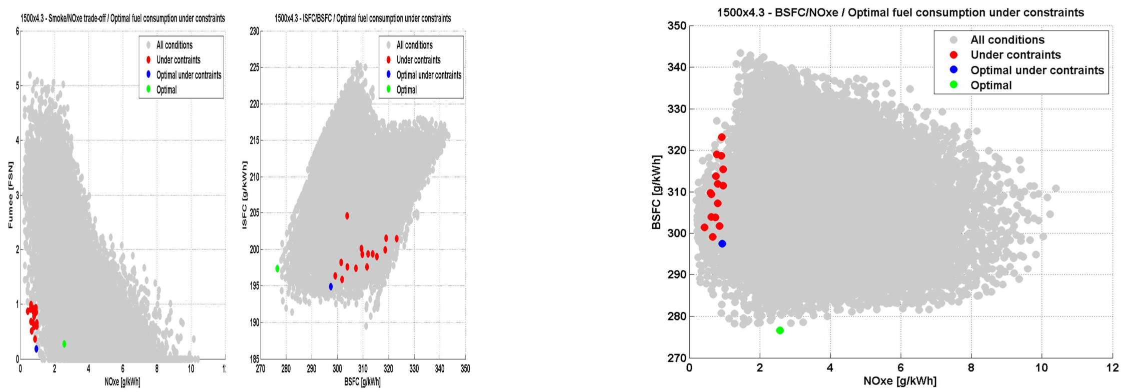


Figure: 1500-4.3 Fuel optimisation under NOxe / Smoke constraints

Engine Control

The hardware architecture developed for controlling the engine into the demo-car is given in the following figure*Figure*. Engine control software is integrated into the IFPEN control unit. It communicates via CAN with the Delphi injection control unit and with the vehicle control units (necessary to enable vehicle start up).

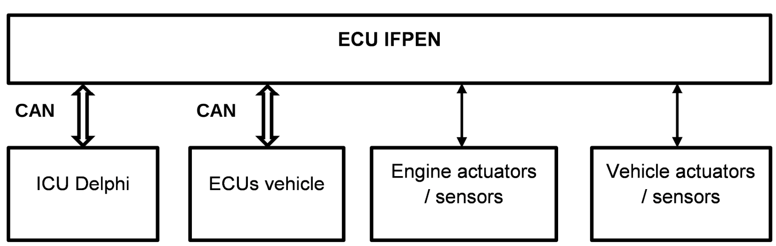


Figure: Electronic architecture.

A special model has been developed for taking into account the friction and thermodynamical losses of the compressor: $\mathrm{FMEP}^{\mathrm{est}} = \mathrm{f}(\mathrm{Ne}, \mathrm{Pupcomp}, \mathrm{Pdowncomp}, \mathrm{Tupcomp})$,
where Ne is the engine speed, Pupcomp and Pdowncomp are the upstream and downstream supercharger pressures and Tupcomp is the upstream supercharger temperature.
A dedicated pressure controller is implemented to manage the supercharger bypass. This strategy (*T. Leroy, J. Chauvin and A. Chasse. "Procédé de commande d'un moteur thermique équipé d'une double suralimentation". Patent FR, 12/02.420, delivered on 14/03/2014*) has been adapted to the Powerful engine.

Because of the several failures affecting the experiments, it was not possible to develop an entire 2-stroke dedicated control strategy. Nevertheless, first results allowed defining and exploring preliminary strategies and anticipating future needs. Firstly the control will has to provide an estimation and control of the burned gas rate in the intake manifold. Secondly, it is necessary to well manage the pressure difference and the VVT to get the desired scavenging / trapping compromise. Finally, the smoke limitation is complicated by the fact that the trapped air mass is not measured. It is certainly the most challenging issue the control will need to address.

Vehicle testing

The encountered failures on the engine at the testbench didn't allow a full calibration of the vehicle.

Nevertheless, a first calibration has been made, allowing a first level of demonstration on the vehicle of the potential of this two-stroke diesel engine, especially in terms of engine integration and NVH.

To reduce the damage risk on the demo-car, particularly on the mechanical compressor, the operating area of the engine was limited in load and speed.

The figure below shows the current maximum torque, and an example of the operating points of the two-stroke Diesel engine during a road test.

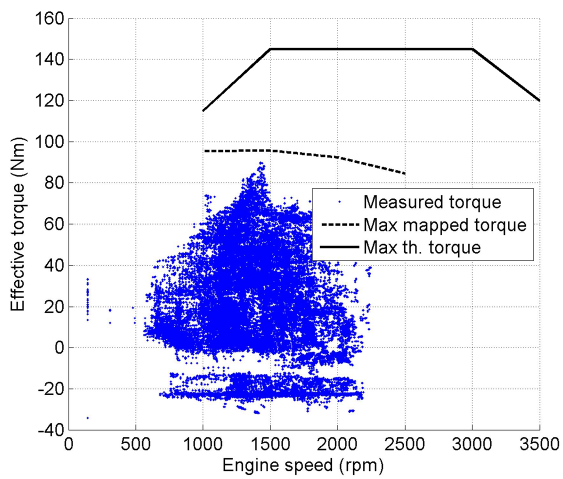
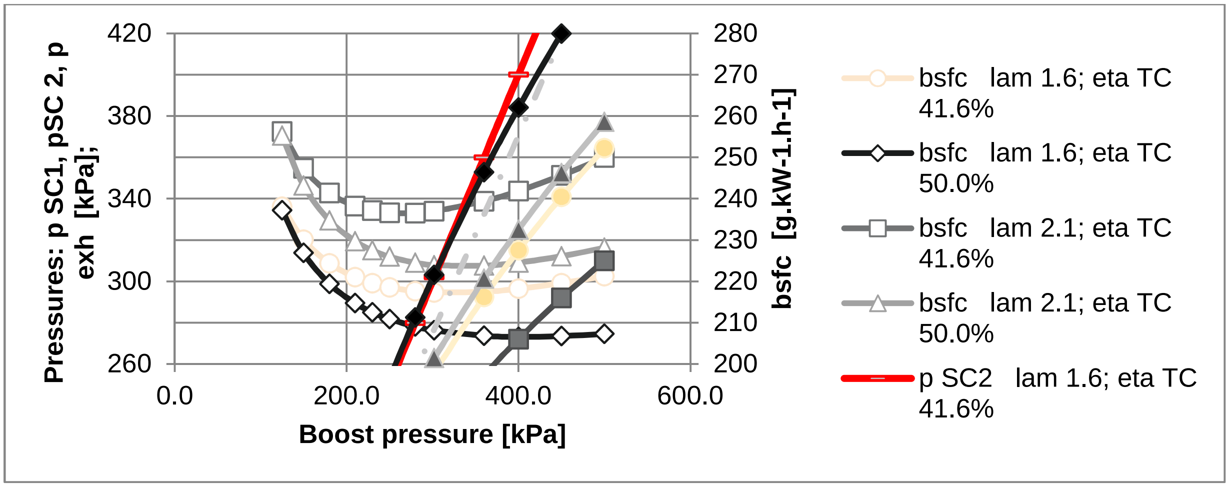


Figure: Operating points on road test and current limitations

SPV3 technical conclusion at the end of the project :

-Some more work has to be done for reducing the valve train friction. Roller bearing camshaft should do the job.

-2-stroke Diesel engine overall efficiency depends more on its airloop efficiency than an equivalent 4-Stroke. For small engines to have a competitive BSFC, the use of exhaust acoustic is probably an obligation.



Main S/T results SPT1

The transversal sub-project SPT1 (partners AVL, CRF, TEKNIKER, TUL, JRC) worked on universal topics such as friction, lubrication, wear and cooling. These included fundamental research on materials and coatings, experimental work in tribological labs and component test rigs, modeling of friction and wear at various sliding contacts (primarily of the crank mechanism), modeling of entire vehicles and simulations of engine friction and wear under real driving conditions. Furthermore, comprehensive testing and assessment procedures have been developed which apply portable emissions measurement systems (PEMS).

SPT1 was structured into three tasks which worked on the following topics:

(I) Tribological investigations

CRF, TEKNIKER and TUL worked on tribological topics (coordinated by CRF). These activities concentrated on tasks related to an enhancement of surfaces friction performances and the application of low viscosity lubricants. The starting point was the preparation of a friction contact pairs map in IC engines to identify the most relevant mechanical losses sources due to friction. After that a tribological test plan was prepared to simulate the selected contact pairs at lab scale in order to evaluate the friction and wear performances of the standard surfaces compared with the performances of engineered surfaces, in particular coated or treated by partners TEKNIKER and the University Lodz (TUL). The tribological tests, which were included in this test plan, referred to: Piston ring/liner, piston skirt/liner, valve/valve guide, crankpin/sliding bearing, camshaft/head supports, piston pin/piston (see Fig.1).

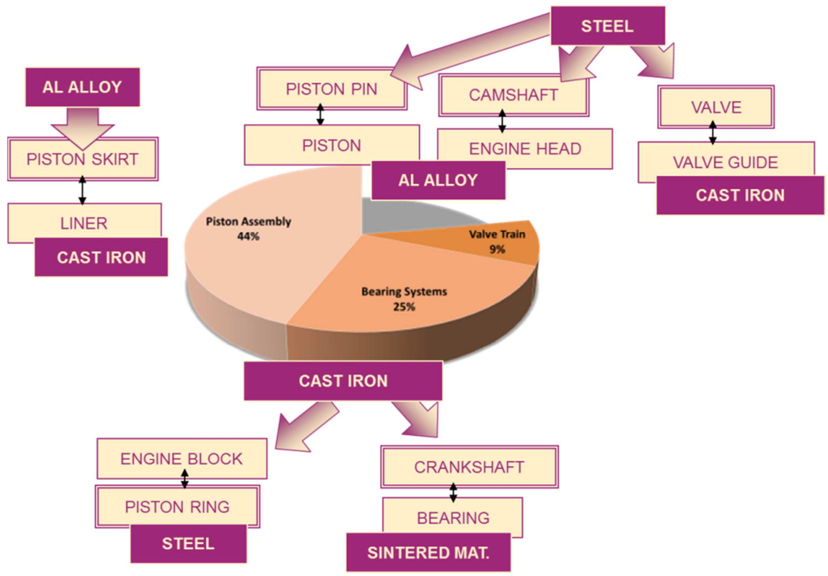


Fig. 1 IC Engine Friction Losses and considered sliding contact pairs in Powerful

At the end of the project the activities of TEKNIKER and CRF were mainly focused on laser texturing of coated pistons and bearings and their tribological performances; moreover TEKNIKER completed the tribological study of piston ring/liner contact and modeling by AVL-EXCITE. TUL delivered an improved version of a-C:Si:Cr:H coating for piston pin application whose coefficient of friction was reduced by 50% in comparison with previously deposited coatings. Finally, a specific cost and environmental analysis concerning the production and application of two new coatings for piston rings was carried out (nc-WC/a-C:H developed by TUL and CrN/ZrN/ZrCN developed by TEKNIKER).

(II) Modelling

AVL worked on new simulation tools for combustion engines and linked them to a platform for simulation of powertrains and vehicles (“virtual engine integration”). The new tools depict various innovative aspects of new engine concepts, which were developed in the vertical sub-projects of POWERFUL. The new concepts have been analyzed and assessed by comparison with relevant baselines vehicles.

The activities started with a detailed modelling of a series-production Fiat Punto EVO 1.4L (baseline SI engine concept). This vehicle meets the Eu5 emissions regulations. Within Powerful it represented typical ‘state of the art’ technology for class B cars with gasoline engines, thus it was used as a baseline for the assessment of advanced concepts which were developed by AVL in SPV1. The modelling approach reached a level of sophistication which includes the thermodynamic cycle of the combustion engine, the drive train, the cooling and lubrication systems, auxiliaries and also detailed tribological models for sliding surfaces within specific component groups of the engine.

In parallel, JRC used the same vehicle for on-road tests with PEMS. Thus, recorded data from two different test routs around Ispra (Italy) were provided and could be used for validation of the vehicle model. Ongoing studies concentrated on one of these drives between Ispra and

Milano which represents a meaningful mix of urban and highway sections. Based on this drive (denominated as “Milano cycle”) individual advancements such as the improved friction characteristics at specific sliding surfaces, oil characteristics and the power consumption of auxiliary drives were systematically analyzed with the Fiat Punto baseline model.
Next, a model for an improved version of the Fiat Punto EVO 1.4L was set up which was the AVL demonstrator vehicle in SPV1. This vehicle is characterized by the following improvements:

- Electronic cylinder deactivation
- Reduction of engine friction and parasitic losses
- Electric supercharging
- Thermal management (cooled exhaust manifold, rev. thermostat)
- Robotized gearbox with long gear ratios
- Drag reduction (underbody cover, low friction tires)

This model was validated with test data from chassis dynamometer tests (NEDC) and on-road measurements from test drives in the area of Graz; Austria. After that, the “Milano cycle” was simulated and thus the characteristics of the advanced vehicle could be directly compared with those of the baseline vehicle.
For evaluation of the friction and wear characteristics complex simulations of sliding contacts were carried out. These concentrated on the piston group. High emphasis was laid on the contacts between piston rings and liner which are main contributors to engine friction. This modelling approach allowed detailed investigations of materials, oil properties, surface textures and designs. The modelling sophistication was specifically chosen in a way that the experimental results from the tribological labs (see above) could be directly introduced and projected to global characteristics of the engine. At that point the calculations were again validated with friction measurements on component test rigs. Thus, the detailed tribological investigations could be brought together with the integrated vehicle modeling. Finally, friction and wear was systematically analyzed at boundary conditions, which were derived from real on-road vehicle tests such as the “Milano cycle”.
This methodical approach could be completely carried out for the B-class gasoline vehicle. In parallel, the same approach was started with a Renault Twingo dCi 85 which was the reference Diesel vehicle of SPV3 and thus selected for tribological investigations. For this car again a complete vehicle model was set up with the same level of sophistication as for the two Fiat Punto vehicles (baseline and advanced concept). Furthermore, JRC made further on-road measurements with a Renault Twingo. Finally, the characteristics of the Diesel and Gasoline vehicles could be directly compared among each other.
A comprehensive analysis of the Renault K9A engine, which was the advanced concept of SPV3, could not be finished. However, by the end of the project intensive friction measurements were carried out with a K9A engine by AVL. These also included measurements with specific coatings.

Main results of the analysis and assessment:

- The application of new friction reducing measures such as new materials, coatings, lubricants etc. reduce the friction losses of an engine (FMEP) by approximately 20-30%. The projection of this improvement to real world driving conditions results in a fuel saving in an order of 1-1.5%.

- Additional measures such as the application of flow controlled oil pumps, improved coolant pumps, the reduction of engine speed, etc. results in an additional fuel saving of approximately 1%.
- The development of new engine concepts cannot be considered independently from the complete power train (transmission etc.) and the vehicle because it must provide a comparable driveability, durability, safety, comfort etc. However, completely improved concepts depict a much higher improvement in fuel economy than individual measures for reduction of friction and parasitic losses. With the concept vehicle of AVL ("Fiat Punto Advanced") a fuel saving of 20% in NEDC was demonstrated (basis = Euro 5 technology). The projection of this concept to real world driving conditions depicted a fuel saving of approximately 15%.
- In many cases advanced materials and coatings are not the prime originators for friction reduction but rather enable the application of effective measures such as the usage of low viscosity oils and the development of new engine concepts which usually have higher demands on the tribology of sliding contacts.

(III) Real life emissions investigations with PEMS

JRC worked on real life emissions investigations with PEMS. The objective of the first part of this work package was to develop a protocol for measuring on-road emissions of light-duty vehicles with PEMS, including the design of suitable test routes, the selection of test parameters to be measured, and the definition of test modalities. To comprehensively characterize the CO_2 and pollutant emissions requires complementing laboratory tests over the NEDC, WLTC, and the Artemis cycle with on-road emissions tests. The emission tests on the road covered shares of urban, rural, and motorway driving to represent as far as possible the wide range of normal driving conditions. The on-road emission testing in POWERFUL was closely related to the work of the Real-Driving Emissions of Light-Duty Vehicles (RDE-LDV) working group of DG Enterprise that develops a complementary on-road test procedure for light-duty vehicles.

The predefined test protocol was used to measure the on-road emissions of the first baseline vehicle, i.e., a Fiat Punto equipped with a gasoline engine as provided by CRF. The PEMS tests were conducted on two test routes around Turin and Ispra, respectively, representing urban, uphill/downhill, and motorway driving. The tests on each route were replicated three times. The on-road PEMS tests were complemented by extensive laboratory emissions testing at different ambient and engine temperatures based on the New European Driving Cycle (NEDC, 18 tests), the Artemis driving cycle (11 tests), the Worldwide Harmonized Motorcycle Test Cycle (WMTC, 2 tests) and a newly designed driving cycle designed at the JRC based on driving patterns identified during PEMS on-road testing (8 tests). These results indicated that PEMS is applicable to light-duty vehicles and yields reliable measurements of on-road NO_X, CO, THC, and CO_2 emissions.

Later on, the JRC tested another base-line vehicle (Renault Twingo) in the laboratory and on the road. The laboratory tests were carried out as for the Fiat Punto at 20-30 degrees Centigrade ambient temperature by using various driving cycles (NEDC, WLTC, Artemis). These tests were

not mandatory; for reasons of brevity, the test results can be obtained upon request from the JRC.
At the end of POWERFUL, the emissions of the final validator vehicle, provided by the Volkswagen AG, have been measured in the laboratory and on the road in close cooperation of JRC and the Volkswagen AG. All tests were conducted with a test fuel consisting of a 25% in volume blend of Hydro-treated Vegetable Oil (HVO) and 75% in volume blend of naphtha. The performance of the final validator vehicle was verified: (i) in the laboratory over five cycles, i.e., the NEDC, WLTC, and three random cycles (developed by the RDE-LDV working group) as well as (ii) during six on-road tests, driven in three different styles and conducted over one test route that fulfils the requirements specified by the RDE-LDV working group.

With respect to the application of PEMS for real life emissions investigations, the following is concluded:

- The successfully completed tests demonstrate that PEMS equipment is applicable to light-duty vehicles. This finding confirms existing possibilities for a robust assessment of on-road emissions, which can complement the current emissions testing conducted over the NEDC and the WLTC. In fact, type approval based on the NEDC does not accurately capture the efficiency and emissions performance of light-duty vehicles under a wide range of normal on-road operating conditions. It has been shown that PEMS can be used to address this shortcoming, e.g., when type-approving the emissions of new vehicles.
- Guidelines on how to conduct on-road tests, including the selection of test routes and the handling of analytical equipment were provided. The proposed combination of laboratory tests and on-road emissions testing with PEMS allows capturing vehicle emissions under a wide range of operating conditions.
- The tests of the validator vehicle have confirmed that novel powertrain concepts can be both efficient and clean. Although further fine-tuning in the application of engine and after-treatment systems may be required, the test results demonstrate that substantial potentials exist to reduce both fuel consumption and pollutant emissions of internal combustion engines.

Fig. 2 PEMS installation on the final validator vehicle

Potential impact SPV1

The great challenge to design and develop a gasoline downsized engine is to improve the overall efficiency without penalize any area of operation. It is well known that a bad downsizing can worsen high load engine operation points due to an increasing knocking tendency. As a relative high compression ratio (>10) is necessary to improve efficiency at low loads, an integrated approach is necessary to do not compromise high load operation: technologies developed in SPV1 have demonstrated the huge potential in lowering noxious and CO2 emissions by matching downsized engine with new approach to the air and thermal management.

The compression ratio increase allowed improving fuel economy in homologation cycle because it works at low load (BMEP<8) in the NEDC working area. To improve higher load efficiency many interventions were done on Powerful engine validator: the use of LIVC strategies permitted to control the effective compression ratio and by reducing it, due to a shorter compression stroke and hence achieving lower charge temperatures inside the cylinder, significant mitigation of knock tendency could be obtained, thus allowing the adoption of more advanced spark timings and the achievement of lower exhaust temperatures. As a consequence, the enrichment of the mixture could significantly be reduced, thus obtaining impressive efficiency improvements. However, at lower engine speeds, despite these operating conditions being generally the most critical for knock occurrence, only minor positive effects were obtained, since the lack of an adequate boost pressure did not allow further delays of the IVC. In low speed – high load area, where it was not possible to increase boost pressure, it was important to have a combustion chamber that reduced the possibility of knocking. During the test it was demonstrated that the use of cooled exhaust gas recirculation to reduce knocking tendency could be very effective only when LIVC strategies are not used, even if it was possible to see a small improvement with the overlapping of the two contents

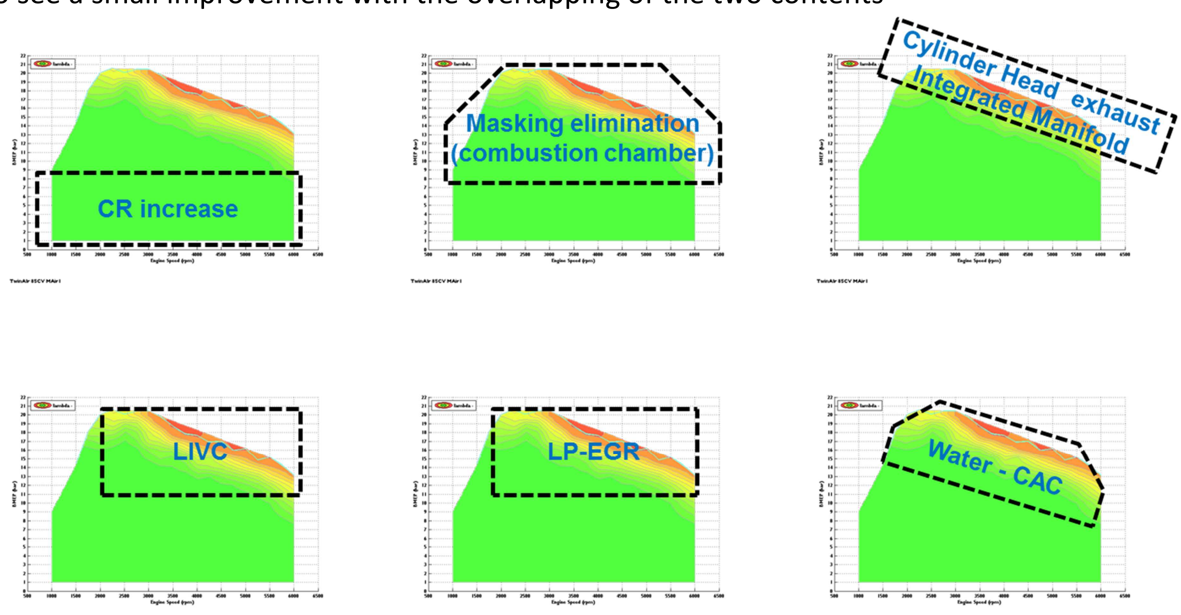


Fig. 3 Working area for downsized engine contents

The integration of exhaust manifold in cylinder head took good advantages thanks to the extension of lambda 1 area and the use of a water CAC, with a better control of intake temperatures and the possibility to lower them; it was very important because had an impact on knocking (when lower temperature are achieved) and also on time to boost (thanks to optimization of intake system and reduction of volumes). It has to be taken into account that the last two contents have an impact at vehicle level, because all the thermal management has to be studied in order to be able to additionally cool exhaust gas and maintain good efficiency to maintain low intake temperatures.
Finally, the technologies developed in SPV1 have demonstrated a huge potential for a short medium term strategy where gasoline engines could play a growing role in the EU transportation fuels panel; this potential is also supported by the economical sustainability of this approach as most of the engine technologies are in sharing with all the other gasoline engine platforms (downsizing / turbocharging / variable valve actuation system / LP-EGR / WCAC/ CHIM) offering higher production volumes to contain the variable costs.

Dissemination
The main results of the project were published by UNIGE in congress and journal as shown in the table reported below.

N°	* Publication type: Peer reviewed publication	D.O.I.	* Title	* Author(s)	* Journal (Title of the monograph)	Publisher	Publisher location (Place of publication)	ISSN	eISSN	* Volume/Issue	* Date of publication Syntax: dd/mm/yyyy	* Relevant pages	Open access is/will be provided to this publication Yes/No
1	Peer reviewed publication	10.4271/2012-01-0715	Effect of Pulsating Flow Characteristics on Performance and Surge Limit of Automotive Turbocharger Compressors	S. Marelli, C. Carraro, M Capobianco	SAE International Journal of Engines	SAE International	USA	1946-3936	1946-3944	Volume 5/Issue 2	May-12	596-601	No
2	Peer reviewed publication	10.1016/j.ijheatfluidflow.2013.11.001	Pulsating Flow Performance of a Turbocharger Compressor for Automotive Application	S. Marelli, M. Capobianco, G. Zamboni	International Journal of Heat and Fluid Flow	Elsevier	London	0142-727X		Volume 45	Feb-14	158-165	No

N°	* Publication type: Paper in Proceedings of a Conference/Workshop	D.O.I.	* Title	* Author(s)	* Proceedings (Title of the monograph)	* Volume	* Date of publication Syntax: dd/mm/yyyy	Start date of conf/workshop	End date of conf/workshop	* Publisher	Publisher location	ISBN	URL	relevant pages	Open access is/will be provided to this publication Yes/No
1	Paper in Conference Proceedings		Experimental Investigation under Unsteady Flow Conditions on Turbocharger Compressors for Automotive Gasoline Engines	S.Marelli, M.Capobianco	Proceedings of the 10th International Conference on Turbochargers and Turbocharging		May, 2012	15 May, 2012	16 May, 2012	Woodhead Publishing Ltd	London	9780857092090		219-229	No

Potential impact SPV2

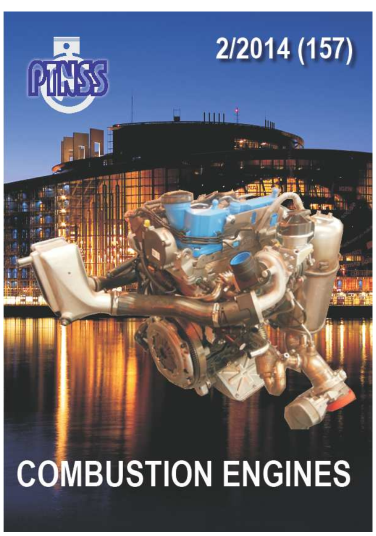
The CO2 and GHG discussion and the emission legislation define the boundary conditions for the continuous development of new combustion systems. Compressed ignited engines have a passenger car market share of about 50 % in Europe. The advantage of CI engines is the lower fuel consumption compared with gasoline engines. The challenge for future CI engines is to reduce the emissions (soot, NOx, HC) and to reduce simultaneously the fuel consumption.

New combustion systems and aftertreatment systems, as investigated in POWERFUL SPV2, will help to achieve these goals. Furthermore the characteristics of future tailored 2nd generation biomass based fuels have a significant impact on CO2 and pollutants.

The technologies applied and tested at the downsizing TDI® engine are reducing energy losses in cold and warm conditions and improve the energetic efficiency of systems like boosting or EGR. It contains measures to reduce friction, throttling, heat losses and to increase combustion efficiency. Such technologies have been transferred to the corresponding departments at Volkswagen and will contribute to the development of future, high efficient vehicles. Due to the high market share of the Volkswagen group in Europe the implementation of the gained knowledge will have a significant, positive effect on the emissions on the one side. On the other side it remains important to stay active on the improvement of CI engines and to further explore their existing potentials.

An additional benefit from SPV2 together with SPT1 is the gained experience with PEMS technology. PEMS will influence the technology in a positive way to further reduce emissions, especially in real world driving and also considering ageing effects of the vehicles with their engines and aftertreatment systems.

Beside the internal use of the results the experiences have been and will be presented to the public by numerous international publications. It contains SAE papers, congresses in Germany, Poland, France, Sweden or USA, presentations to Eucar and Ertrac and will be finalized by presentations at the Aachener Colloquium 2014 in Aachen and Beijing. Additionally many articles in automotive or scientific journals have been published.



In the occasion of the final general assembly respectively the end of the project a complete Powerful-related special edition of the “Combustion Engines” magazine has been created. It contains the most important results of all SP V2 partners and gives a deep insight into the different technologies like injection, catalyst formation, EATS strategies and CI engine.

Figure 5: Special edition of “Combustion Engines” magazine about Powerful SP V2

Potential impact SPV3

The first impact is the network/trust built between all the companies that participated. Cooperation have not finished with the project, we will continue win-win collaborations.
That “bond” between individual and companies would not arose without this kind of collaborative work.

The combined activities on single cylinder engine tests, 1-D air loop development, and twin cylinder engine tests demonstrated that a 2-stroke Diesel engine could be a right architecture for A/B segment cars, especially in terms of compactness, weight, NVH.

The last results obtained on SCE and twin cylinder engine suggested that the emissions are almost equivalent to a 4-stroke Diesel engine, when the BSFC is still higher. The main reason is the high work demanded by the mechanical compressor.

Further studies should be addressed to an innovative air loop: boosting system, dedicated intake and exhaust manifolds, in order to optimize the scavenging phase.
The proposed H2020 project REWARD should be the right project for finally assessing the fully valved 2-stroke technology for automotive applications.

IFPEN Dissemination Activities:

Ternel, C., De Paola, G., & Tribotté, P. (2014). Air Loop Characterization and First Potential of an Automotive Two-Stroke HSDI Diesel Engine. THIESEL Conference on Thermo- and Fluid Dynamic Processes in Direct Injection Engines

JBRC Dissemination Activities:

Pohořelský, L.,Brynych, P., Macek, J., Vallaude, P.-Y.,Ricaud, J.-C., Obernesser, P., Tribotté, P.: Optimization of a Two - Stroke Diesel Engine Air System. XLII. INTERNATIONAL SCIENTIFIC CONFERENCE OF THE CZECH AND SLOVAK UNIVERSITY DEPARTMENTS AND INSTITUTIONS DEALING WITH THE RESEARCH OF INTERNAL COMBUSTION ENGINES 2011.

Pohořelský, L.,Brynych, P., Macek, J., Vallaude, P.-Y.,Ricaud, J.-C., Obernesser, P., Tribotté, P.: *Air System Conception for a Downsized Two-Stroke Diesel Engine*. SAE Paper 2012-01-0831.

Brynych, P. - Macek, J. - Pohořelský, L.: Air System Proposal and Testing for a Downsized Two-Stroke Diesel Engine. In Proceedings of the FISITA 2012 World Automotive Congress. Peking: SAE-China; FISITA (Eds.), 2012, vol. 1, p. 289-314. ISBN 978-3-642-33841-0.

Brynych, P., Macek, J., Vítek, O., Červenka, L.: 1-D Model of Roots-Type Supercharger. SAE Paper Nr. 2013-01-0927.

Brynych, P., Macek, J., Vítek, O., Červenka, L.: 1-D Model of Roots-Type Supercharger. XLIV. INTERNATIONAL SCIENTIFIC CONFERENCE OF THE CZECH AND SLOVAK UNIVERSITY

DEPARTMENTS AND INSTITUTIONS DEALING WITH THE RESEARCH OF INTERNAL COMBUSTION ENGINES 2013.

Macek, J., Vítek, O.: Dimensionless Parameters Characterizing Charge Exchange Of ICE. XLIV. INTERNATIONAL SCIENTIFIC CONFERENCE OF THE CZECH AND SLOVAK UNIVERSITY DEPARTMENTS AND INSTITUTIONS DEALING WITH THE RESEARCH OF INTERNAL COMBUSTION ENGINES 2013.

Exploitation of results:

The basic knowledge, experimental and theoretical tools and technological solutions developed in the FP7 POWERFUL Project have been transferred to the FP8 REWARD Project proposal, where the partners will combine their efforts for further development of this 2-stroke OHV HSDI diesel engine.

In POWERFUL Project, the early injection highly premixed combustion concept was implemented with success using a low volatility/high reactivity (diesel) fuel, reducing simultaneously NOx and Smoke emissions. The high flexibility provided by the 2-stroke engine configuration over the air management settings for controlling the cylinder thermochemical conditions was confirmed. However, the early onset and phasing of the combustion process caused by the intrinsic IGR level, which results in a high gas temperature along the compression stroke, compromised the engine efficiency.

However, the analysis of the results evidenced the great potential of combining the 2-stroke OHV engine architecture and its high air management flexibility with the partially premixed compression ignition (PPCI) combustion concept, but using a high volatility/low reactivity (gasoline ON95) as fuel. It is expected to reproduce or even improve the benefits in terms of ISFC/pollutants trade-off already proven and reported in literature in 4-stroke HD and HSDI diesel engines, but avoiding the limitations introduced by the impossibility of extending the load range below 6 bar IMEP due to problems for igniting this low reactivity gasoline ON95 fuel. Another open question in REWARD relates to the benefits in BSFC since the concept demands medium equivalence ratios, high external EGR rates, and advanced air management.

REWARD will determine the feasibility of the 2-stroke engine operating with the gasoline PPCI concept for substituting the state-of-the-art 4-stroke engine operating with the CDC concept in the short to medium term.

Technical impacts :

A number of technical items were tested on the 2-stroke Diesel, shedding a new light on their benefits, and giving us ideas for possible quick wins on more conventional engines.

-Miller Cycle : it is very easy to test on SPV3 engine, and most of the NEDC load-point were fully Millerised. We relearned its fundamentals, and it is tempting to use it on 4-Stroke engines.

-Variable Valve trains for Diesel : The dual VVT and the 2-Stroke cycle play with the amount of IGR in the combustion chamber, the compression ratio and expansion ratio (Miller)
-Internal Gas Residuals : this engine show that IGR can be welcome for reaching best thermal efficiency together with high exhaust temperature at low loads. A hot EGR loop might work the same on a 4-Strokes engines.

Potential impact SPT1

Friction reduction is a central issue in the context of all initiatives which aim at an increase of the fuel conversion efficiency and a reduction of CO_2 emissions. Currently this topic has gained economic importance because of the legislative guidelines to regulate CO_2. In this context no big step forward can be expected from individual measures for friction reduction, it rather requires a careful matching of many small aspects in order to achieve a remarkable benefit. In the POWERFUL project partners who worked on friction reduction pursued considerably differed approaches and business interests. On the one hand TUL and TEKNIKER conducted fundamental research in the production of new coatings and tailored texturing surfaces, CRF and TEKNIKER systematically tested and assessed new materials and coatings in tribological labs under conditions which simulate their application in engines (temperature, load, lubrication, oscillating motion) and AVL carried out friction measurements on component test rigs (motored engines with different test components and lubricants at various temperatures). Finally, friction and wear characteristics were modelled and projected to real engine conditions. In this respect the friction group of POWERFUL successfully tied fundamental research into tasks of applied engine development. This is also visible from partly common publications of project partners. Such co-operations definitely promote an expansion of knowledge, appreciation and business contacts. They should continue in succeeding projects.

Another aspect, which was demonstrated throughout the whole program, is the interrelation between friction and wear. In many cases advanced materials and coatings are not the prime originators for friction reduction but rather enable the application of effective measures such as the usage of low viscosity oils and the development of new engine concepts which usually have higher demands on the tribology of sliding contacts. Thus, the high importance of research in the tribological characteristics at sliding contacts was emphasized.

Finally, this sub-project of POWERFUL contributed to the development of procedures for measuring and monitoring emissions of light duty vehicles under real driving conditions with PEMS.

All aspects listed contribute to the reduction of emissions (mainly CO2) from light duty vehicles and support the development of new products.