Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Vehicle Demonstration of Performance and Economy of a Comprehensive B/C class Diesel Engine and Aftertreatment System Approach for Emissions beyond Euro 6

Ofner Herwig [a], Bürgler Ludwig [a], Wieser Martin [a], Marie-Sophie Gande [a]
Mallet Philippe [b], Gidney Jeremy [c], Houel Valerie [c], Leroy Thomas [d]

AVL List GmbH, Hans List Platz 1, Graz 8020, Austria [a]
GROUPE RENAULT, 1 Avenue du Golf, F78084 Guyancourt Cedex, France [b]
JM Johnson Matthey Orchard Road, Royston SG8 5HE, UK [c]
IFPEN IFP Energies nouvelles, 1-4 avenue de Bois Préau, 92852 Rueil-Malmaison, France [d]

Abstract

Engines for A/B/C class vehicles place high emphasis on economic viability. Thus, many innovations focus on optimum system integration of cost effective technologies, which are individually optimized and controlled within the interrelations of engine, exhaust gas aftertreatment system and vehicle. The European project REWARD conducted such a comprehensive approach with a 1.6 liter diesel engine for a small SUV class vehicle. The core of this development is a new combustion concept which is combined with a specifically tailored aftertreatment system. The goal is the demonstration of an increased fuel economy and a reduction of emissions significantly below the Euro 6 limits under real driving conditions. These targets are demonstrated with a vehicle emphasizing that the improvements refer exclusively to the new engine and aftertreatment system development.
The approach focuses on conventional combustion parameters such as the optimum design matching of new combustion bowls with advanced fuel injectors, injection characteristics and a reduced in-cylinder charge motion (swirl). Outside of these core features further parameters refer to high-pressure/ low-pressure EGR and the charging system. The target is to minimize engine-out emissions and to provide specific exhaust characteristics which are optimum matched to particular aftertreatment system concepts.
Various aftertreatment concepts have been systematically evaluated in view of their performance, reliability and economy. Initially, NOx reduction with a single NOx Storage Catalyst (NSC) was considered. However, even if combined with the low engine-out NOx solution, this initial approach requires excessive NSC purging at elevated exhaust temperatures, which severely deteriorates the fuel economy. Thus, NSC has been completely omitted and replaced by Selective Catalytic Reduction (SCR) with economically “active” urea dosing. Due to a sophisticated temperature management system low temperature operation can be bridged by a diesel Cold Start Concept (dCSC^{TM}) catalyst. The paper describes the comprehensive approach and presents some projected results.

Keywords: passenger car diesel engine, combustion development methodology, calibration, aftertreatemnt concept

Nomenclature, Abbreviations

RDE	Real driving emissions
REWARD	REal World Advanced technologies foR Diesel engines
HP/ LP EGR	High Pressure/ Low Pressure Exhaust Gas Recirculation
WLTC	Worldwide harmonized light vehicles test cycle
MVEG	Motor vehicle emission group – synonym for NEDC

* Herwig OFNER. Tel.: +43 (0)316787613
E-mail address: herwig.ofner@avl.com

1 Introduction

The development work described in this paper is carried out in the European project REWARD (2015-2018 www.reward-project.eu). The main objective of this project is to develop the knowhow, intellectual property rights and technical capabilities to produce cleaner, highly efficient Diesel powertrains and aftertreatment technologies for future cleaner class B to E passenger cars that go beyond Euro 6 limits under real driving conditions (EU6 RDE). Basically, two different development routs are pursued: Engine technology for larger vehicles (class D/E) focuses on the increase of the specific power rating (≈ 100 kW/l) which aims at an increase of the thermodynamic efficiency from a "downsizing" concept. In contrast, engines for class B/C vehicles with a swept volume in the range of 1.6 l currently have a power density around 60 kW/l. These pursue a "right sizing" approach which even may lead to a reduction of performance but offers potential for friction reduction in a cost-efficient way. This latter approach is denominated as "efficiency concept" and subject of this paper.

2 Low NOx Combustion System

2.1. Base Powertrain Description

The concept development is based on the RENAULT Energy dCi 130 engine installed in a RENAULT Kadjar, see Figure 2-1. For this application, a new cost competitive engine concept is developed for an optimized efficiency and a specific target rated power of 62.5 kW/l. This requires the improvement of both hardware and control of charging and charge air cooling (flexibility & efficiency), EGR (high / low pressure), fuel injection and the exhaust gas aftertreatment concept. A new holistic development approach considers all these issues simultaneously and thus also focuses on new methods for a reduction of development time.

Engine code	-	R9M
Max. Power	kW	96
Max. Torque	Nm	320
Displacement	L	1.598
Bore x Stroke	mm	80 x 79.5
Compression Ratio	-	15.4
Valves/cyl.	-	4
EGR-System	-	LP / HP hot
Emission standard(s)	-	EU5
After treatement	-	DOC/DPF
Biodiesel	-	B30

Vehicle	-	Kadjar
Class	-	B/C
ITW	kg	1700
0 – 100	s	9.9
Gear box	-	MT6

Figure 2-1: Main engine and vehicle data (low pressure EGR + uncooled HPEGR)

2.2. Combustion Concept for Reduced Swirl

Specific engine hardware such as the compression ratio, combustion bowl, intake ports, the fuel injector features together with the nozzle specification (number/ cone angle/ cross section shape of nozzle holes and flowrate) determine the combustion concept. Turbochargers, EGR systems and the fuel injection system are peripheral units which provide the thermodynamic state of the charge and the fuel injection characteristics. While the peripheral units can be flexibly controlled any single change of a hardware parameter is a severe intervention which requires a comprehensive optimization of the whole concept. Such an approach was carried out by reducing the swirl. It may reduce the air flow resistance in the ports and the heat losses in the combustion chamber. Furthermore, it simplifies the intake ports design. To compensate for a worse air/fuel mixing an improved fuel injection system with increased injection pressure and reduced nozzle flow was installed.

In general, the development of a new combustion concept focuses on rated power conditions. At this extreme engine operating point the target power must be achieved while keeping all the limitations of the design such as the peak firing pressure and the thermal load on piston and cylinder head. This requires a certain heat release characteristic which demands for a fast and complete fuel-air mixing, fast and smooth ignition, and an abrupt end of combustion.

A good indicator for the combustion quality are the NOx emissions. Usually higher NOx indicate an improved thermodynamic efficiency. Based on this, the soot emissions can value the quality of fuel-air mixing. As a diffusion flame unavoidably produces soot, high emphasis is laid on the phase immediately after end of fuel injection. In this late phase, all intermediate combustion products should be burned which requires good mixing with the remaining oxygen and a high local temperature. Figure 2-1 outlines this with CFD simulations of the combustion process. The diagram shows typical soot formation/oxidation characteristics. Different measures such as a reduction of swirl and a change of the combustion bowl geometry both affect the soot maximum and the gradient of the declining soot concentration. As demonstrated by the CFD plots, local soot "clouds" are formed in the late phase of combustion which usually cannot be degraded by singular measures. This rather requires a comprehensive optimization of all parameters of the combustion concept. A similar development approach is described in detail by Machold et.al. (2017).

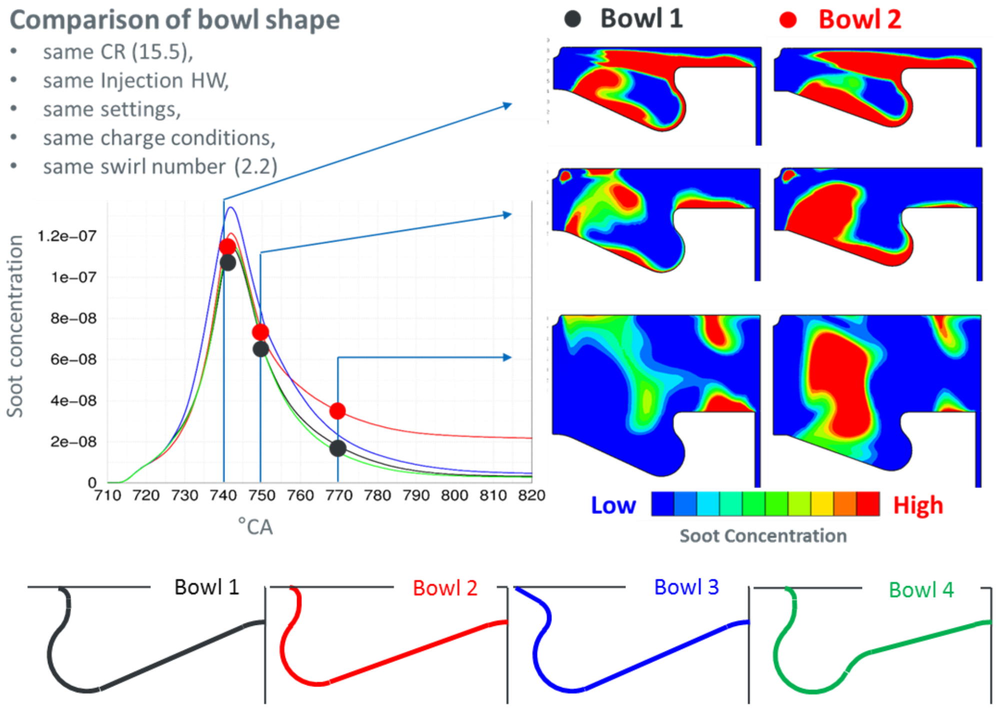

Figure 2-2: Development of a combustion concept with reduced swirl; Soot formation/ oxidation characteristics in different combustion bowl geometries

2.3. Experimental Optimization of Peripheral Engine Combustion Units; Low and High Pressure EGR

The general term "peripheral engine combustion units" includes all devices, which provide the thermodynamic state of the cylinder charge (boost pressure, EGR rate and charge temperature) and the injection characteristics (timings / quantities of multiple injections) that can be controlled from the ECU. For the work under discussion it concerns the actuators of the VGT turbocharger, the high and low pressure EGR systems and the common rail fuel injection system.

After the computational layout of some promising combustion concepts they were tested in an engine on engine test bed. This task was carried out by optimizing all peripheral engine units for stationary engine operation in the entire engine operating field. The optimization was supported by Design of Experiments (DoE) using the software CAMEO (AVL 2016).

One of these activities evaluated optimum engine operating conditions for high pressure EGR and low pressure EGR. For this purpose, local DoE models were set up in a number of operating points in both EGR modes. Optimized NOx/BSFC trade-offs ("pareto fronts") with additional limitations for soot and combustion noise - based on the results from the base engine - were extracted. These defined the specific operating strategies (a mixed operation of HP and LP EGR is not considered). However, in general also condensation of water and its impact on durability must be considered.

A further issue investigated different combustion bowl geometries in combination with nozzle specifications. As CFD simulations predicted high soot emissions with bowl#2 (see Figure 2-2), this bowl was not further investigated on engine test bed.

In some selected operating points, the part load performances of bowl#3 and bowl#4 were compared to the base bowl#1 by the DoE approach. As an example, Figure 2-3 depicts the result of an extensive variation of main calibration parameters (main timing, boost pressure, rail pressure, EGR-Rate) for constant swirl, one fixed nozzle configuration and different combustion bowls. Considering limitations for soot and combustion noise, the target function for minimum BSFC versus NOx indicates best overall performance with bowl#3.

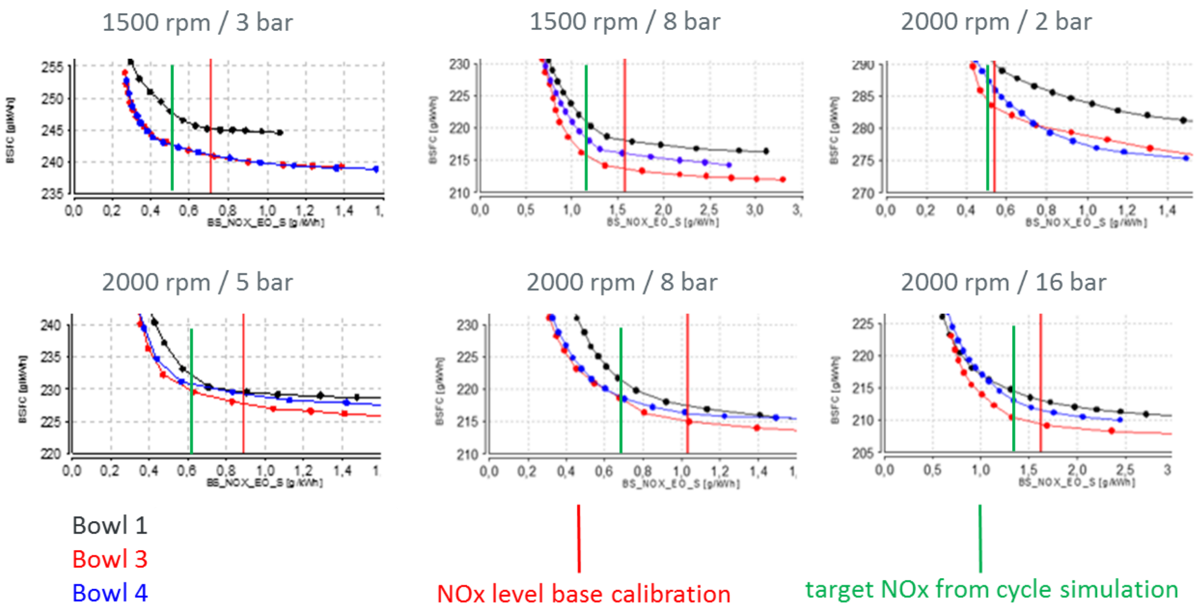

Figure 2-3: Comparison of DoE optimization results ("pareto fronts") for different bowl shapes

The red cursors in Figure 2-3 show the NOx engine-out levels of the initial engine calibration and the green cursors show the target NOx engine out levels. These cursers point out that the target NOx levels can be reached without significant deterioration in BSFC.

Based on these DoE results, the engine was calibrated for the NOx engine out target values in the entire map – see Figure 2-4.

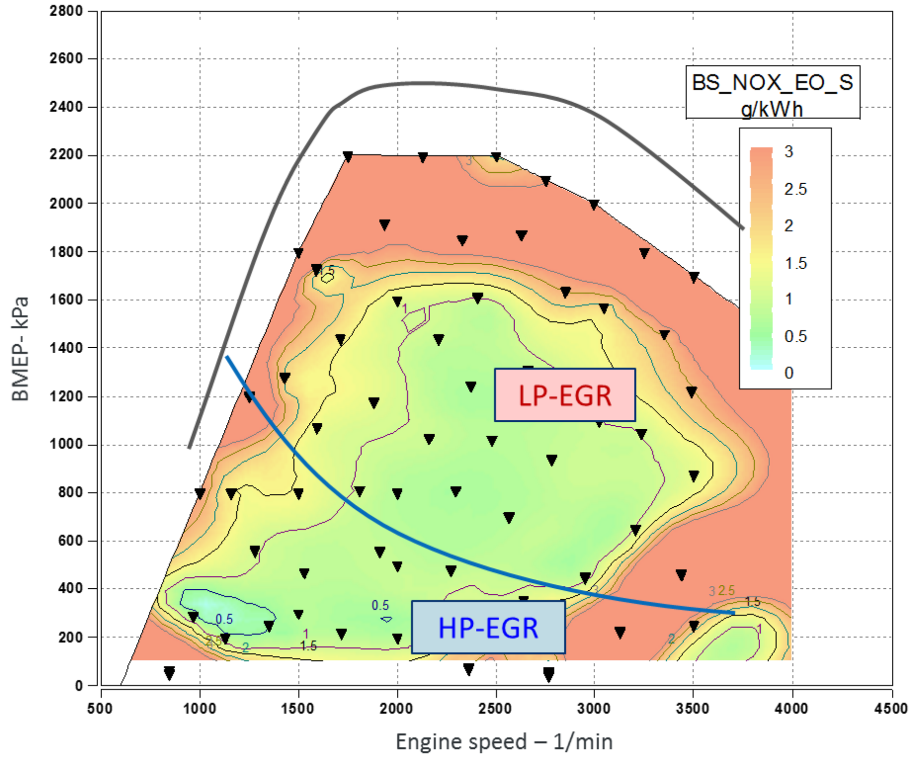

Figure 2-4: Intermediate result for NOx engine-out and operating points for global DoE set up

The speed load area in the centre of the map, which provides most engine operating points for real driving conditions, shows engine out NOx emissions of less than 1 g/kWh. Near engine full load and at high speeds the NOx emissions increase to 3 g/kWh. This engine characteristic was considered as a basis for the subsequent calibration work which additionally must result in low soot emissions, low noise, and improved fuel economy. Quasi-stationary projections to dynamic driving cycles of vehicles demonstrate the quality of this new combustion concept below. These projections used different calibrations which were optimized by different "global DoE" approaches as described in the next chapter.

3 Engine Calibration by a Global DoE Approach

3.1. The Global DoE Approach

In a global DoE test design engine speed and load are included as variation parameters to the common ECU parameters. The target ranges for speed and load were approximated from the emission cycles which finally are optimized. The covered engine operating area is the colored field in Figure 2-4. The dots (black triangles) indicate the discrete engine operating points derived from the test plan for the global DoE with measurements which were used for projecting the map. The variation of the ECU parameters at these individual engine operating points were calculated by a space-filling design (S-optimal) which considers the parameter distribution of the whole design space.

The optimization considers the following 10 variables:

- Engine speed
- Engine torque (respectively brake mean effective pressure - BMEP)
- Start of Injection
- Fresh Air Mass Flow (either with HP or LP-EGR)
- Boost Pressure
- Rail Pressure
- Pilot Injection 1 Quantity
- Pilot Injection 2 Quantity
- Pilot Injection 1 Timing
- Pilot Injection 2 Timing

Due to this high degree of freedom, the total number of variation points, plus repetition points for statistical evaluation, resulted in approximately 1200 points. For such high degrees of automation, the data collection leads to long runtimes (several hours on PC).

3.2. Optimization Procedure and Constrains

In principle, the DoE approach is a smart post processing of the measured data which includes:

(1) The definition of the variation parameters. For this procedure, it is preferred to use actual measured values and no set point values.
(2) The calculation of statistical models. A so-called RNN (Robust Neural Network) has been used which is a neuro-fuzzy. This model is most suitable for the detection of nonlinearities in measured data

The main idea behind RNN is a split of data (or input space) into smaller pieces. Each piece is modeled by a polynomial. The polynomials are then combined to a weighted sum which means that the overall model of an RNN is a link of many local polynomial models (local models...LM_1, LM_2, ... LM_M):

- Each local model LM_i is responsible for a specific fuzzy area of the input space and contributes to the overall model by its weight Φ_i.
- The model's output is calculated based on the following formula:

$$\hat{y}(k) = \sum_{i=1}^{M} \Phi_i(k)\, \hat{y}_i(k)$$

$\hat{y}_i(k)$: local polynomial $\quad \Phi_i(k)$: weight of local polynomial

The outcome of this procedure are mathematical models for noise, fuel consumption, NOx and SOOT emissions which are functions of the 10 variation parameters. With such "DoE-" models, it is possible to predict the stationary engine behavior at all operating conditions with the restriction that the settings vary within the measurement range of the DoE data.

For the development work under discussion global DoE modes were applied to:

- Evaluate the optimization potential in terms of the NOX-SOOT and NOX-FC tradeoffs. An example for such tradeoffs is shown in Figure 3-1 for the engine operating point 1500 rpm/ 8 bar bmep.
- Find optimal settings for best fuel consumption with given constraints for emissions and noise, using numerical optimization algorithms
- Investigate parameter sensitivities on engine responses

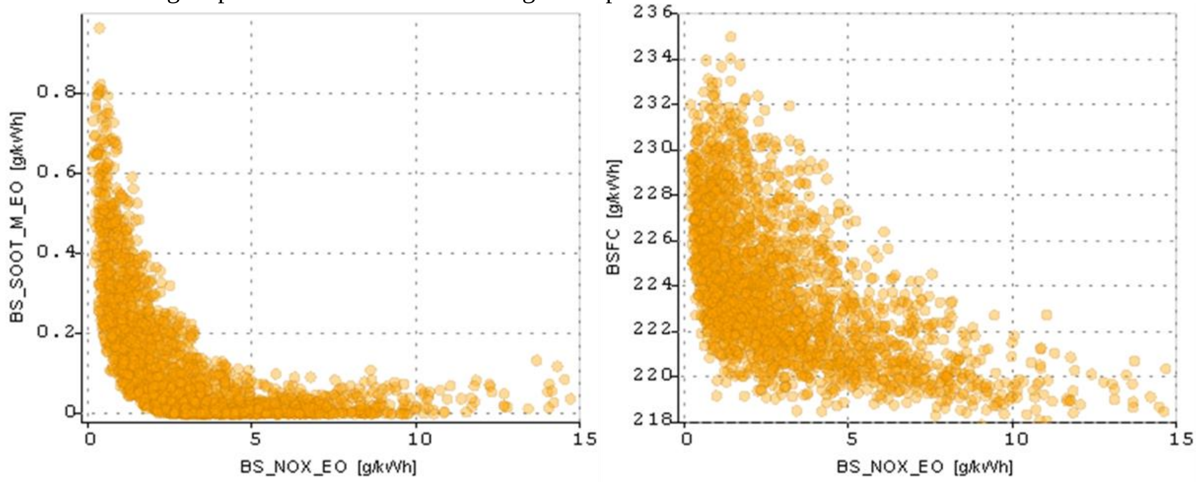

Figure 3-1: Trade-Offs for NOX-SOOT and NOX Fuel Consumption at engine operating point 1500 rpm/ 8 bar BMEP

As the optimization uses the discrete engine operation points with measurements, the optimized settings may fluctuate within the engine operating map which could lead to instable engine operation. To avoid this, CAMEO provides specific "map smoothing" procedures which can be considered as a constraint within an optimization. This procedure limits the gradient difference between nearest neighbor operating points. A map smoothing factor. quantitatively adjusts the degree of smoothing.

3.3. Projections of Engine-Out Characteristics of Low NOx Combustion System to WLTC

For an assessment of the new combustion concept the stationary engine operating characteristics were projected to WLTC results. For this purpose, the WLTC drive was simulated with AVL Cruise (2017) which provided the engine operating trace for the WLTC, see Figure 3-2. Depending on the time, which is spent at (or near) discrete operating points, specific weighting factors were derived and assigned to 67 individual points, equally distributed to cover the emission related area. The considered points cover the whole engine operating area of the WLTC, see Figure 3-2. At each individual point, the engine-out emissions, fuel consumption and noise were calculated from the DoE model. The input parameters for the model were the variables listed in chapter 3.1. Finally the sum of the weighted emission components was calculated, which does not consider transient operation effects, but can be used for relative comparison.

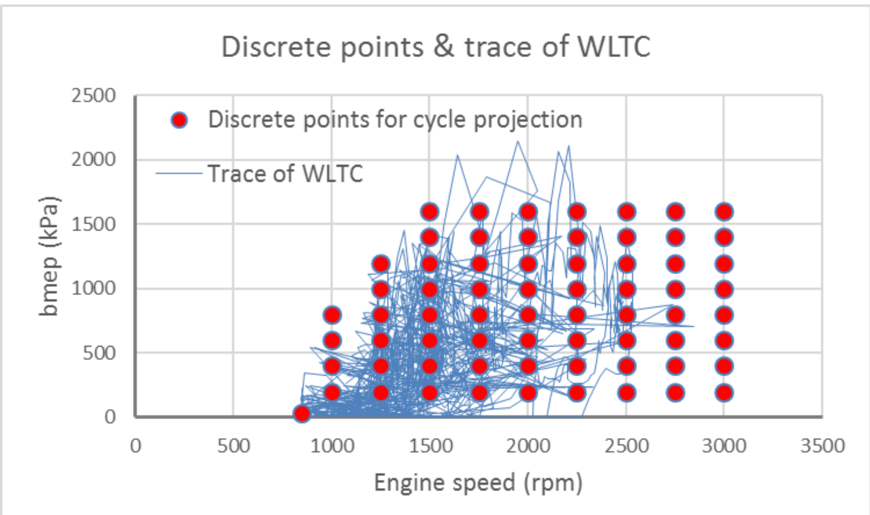

Figure 3-2: Trace of WLTC and discrete engine operating points for cycle projection in engine operating map

Even though the optimization space, defined by the 67 discrete points of the map, approximately covers the WLTC trace, some areas at the boundary towards low loads could not take part at the optimization. This distorted the quantitative cycle results. Therefore, a reference WLTC result was calculated from the measured engine map (Figure 2-4) and all relative tradeoffs of the cycle optimization were pinned to this absolute reference point.

Figure 3-3 shows the results of the WLTC projections in the diagram WLTC NOx (engine-out) versus WLTC Fuel Consumption (FC). First, the discrete engine operating points were projected with the engine settings (= input parameters given in chapter 3.1), which were used for the measurements (see blue square in Figure 3-3). This point was pinned to the reference WLTC result as described above. Then, the FC was successively minimized with lowered NOx constrains but without any additional constrains for map smoothing – see Figure 3-3, green line. This green line clearly shows the tradeoff between NOx and FC. Finally, the FC was minimized with the additional constraints for map smoothing, SOOT and combustion noise, see red dot. For this optimization, an extensive optimization procedure had to be carried out which took several hours of computation time.

Figure 3-3 clearly indicates the WLTC tradeoff between NOx and FC with a smoothed map. It shows a NOx reduction of -25% versus 2% increase in FC. Besides of that, the SOOT emissions were also lowered (the red dot resulted in 20% lower SOOT compared to the blue square) and the combustion noise stayed approximately at the same level (-1%).

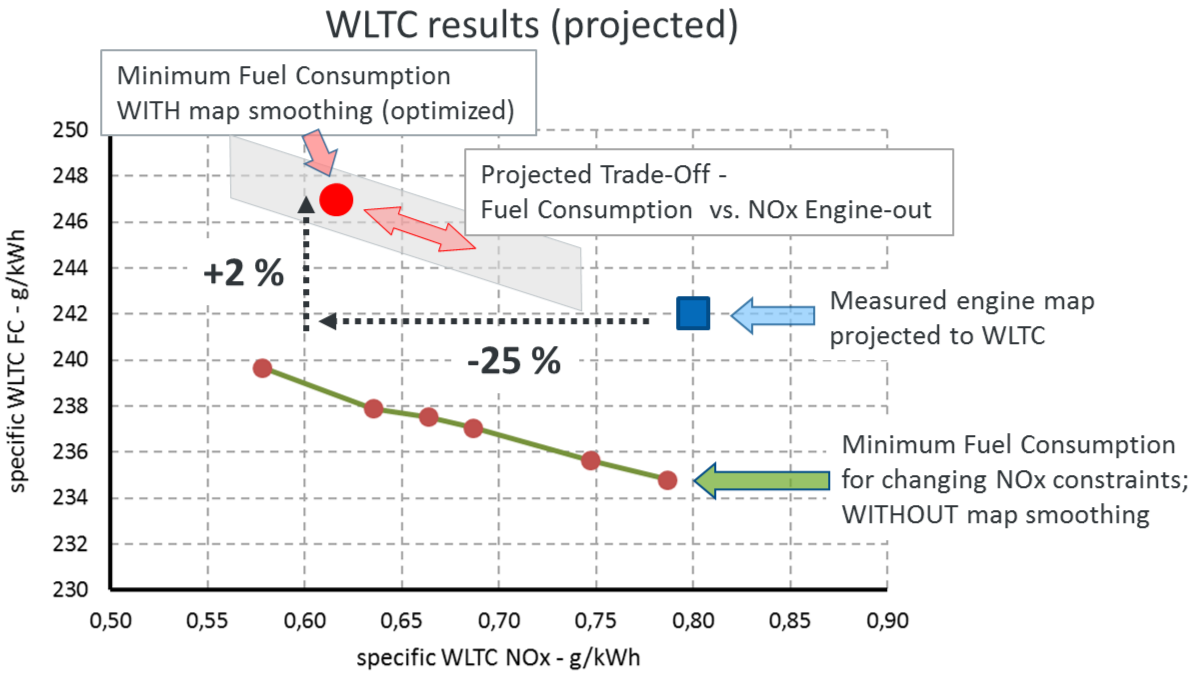

Figure 3-3: Stationary engine map projected to WLTC: Trade-Off Fuel consumption vs. NOx-Engine-out; Projections show minimum Fuel Consumption for changing NOx constrains; with and without map smoothing constrains

4 Exhaust Aftertreatment System

To maximise the NOx efficiency, the aftertreatment system is a combination of three technologies, all installed close-coupled on the engine, to have a very fast heat-up. The first catalyst (1.6 litre volume) allows oxidation and NOx absorption function. Downstream this catalyst, the urea is injected in front of a mixer which gives a very uniform repartition of the urea (and of the formed NH3) in front of the 1,0 litre SCR and finally of the 4.0 litre SCR on DPF. At the end of this system, positioned in the underfloor position, a clean-up catalyst eliminates the remaining NH3 which could slip from the SCR on DPF catalyst.

The aftertreatment system is a key part of the solution of achieving the REWARD targets, so various aftertreatment concepts have been evaluated in view of their performance, reliability and economy. Initially, NOx reduction with a single NOx Storage Catalyst (NSC) was considered. However, even if combined with the low engine-out NOx solution, this initial approach requires active management of the NSC (purging to regenerate the NSC, deSOx), which deteriorates the fuel economy. Thus, NSC has been completely omitted and replaced by Selective Catalytic Reduction (SCR) with urea dosing. A novel improved SCR on filter (SCRF®) was developed, to provide high conversion efficiency windows at low as well at high temperatures, to comply with Real Driving conditions and post Euro 6 emissions standard. The arrangement of an SCR upstream the SCRF is the optimum balance between transient response and thermal inertia of the system. Figure 4-1 shows increased performance of this novel SCRF catalyst evaluated on engine bench on several test cycles.

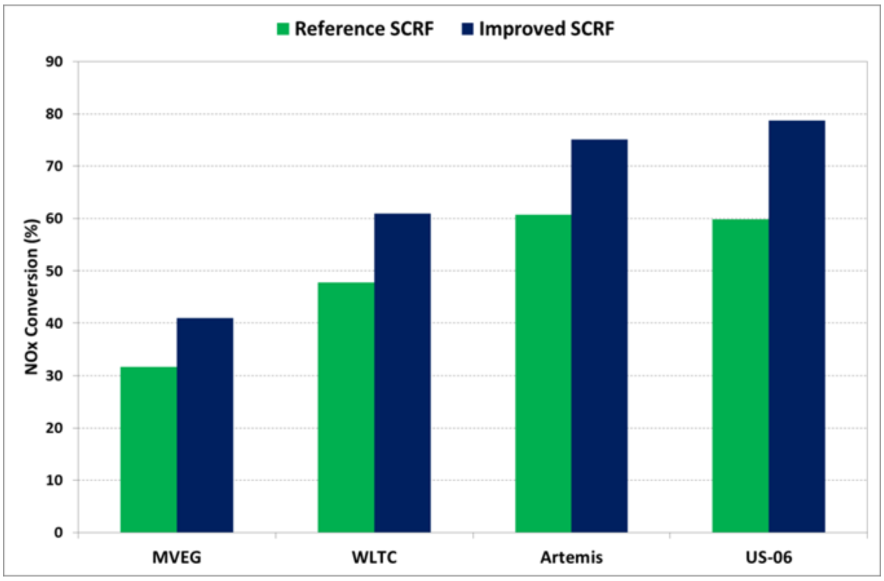

Figure 4-1: NOx conversion for Reference SCRF vs. Improved SCRF on various test cycles – engine bench

One limitation of the SCRF based system is the performance at low temperature, during the cold start period of the vehicle, before the SCRF reaches its operating temperature and urea can be injected. To complement the SCRF, a catalyst such as the diesel Cold Start Concept (dCSC™), Chen et.al. (2013), can be used to store NOx at low temperatures. The dCSC also provides HC and CO oxidation and the partial NO to NO_2 conversion required by the downstream SCRF. If the design of the aftertreatment system and the engine control strategy are optimised, the NOx are released from the dCSC and converted on the SCRF thus improving the overall efficiency of the system. A novel improved dCSC was developed to optimize the NOx storage capacity as shown in Figure 4-2.

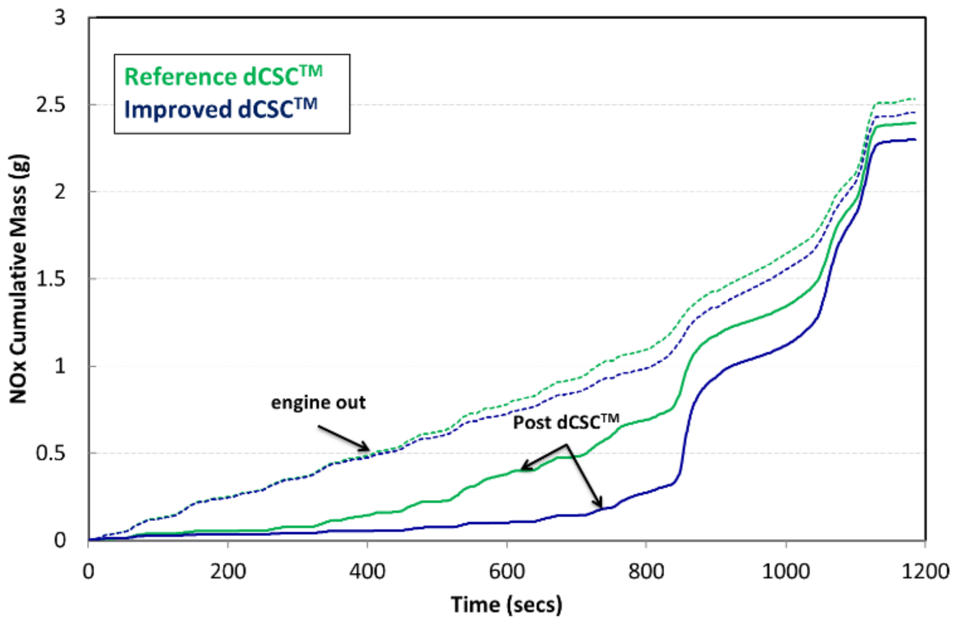

Figure 4-2: Comparison of NOx storage for Reference dCSC™ and Improved dCSC™ on MVEG test on 1.6L engine

5 Summary, Next Steps

A development approach of a high efficiency Diesel engine for B/C class passenger cars is presented. This approach is based on fundamental changes of the combustion concept which require a comprehensive optimization of the engine and its calibration. For the improved engine-out emissions a specific aftertreatment system has been specified. The total approach focuses on cost-efficient solutions.

So far, the new combustion and aftertreatment system concepts have been developed and a calibration has been evaluated which can be used as a basis for the final calibration of a demonstrator vehicle. This will be carried out in the final phase of the project REWARD. The performance and emissions of the vehicle will be demonstrated under real driving conditions (WLTC and on-road tests which correspond to RDE requirements).

6 Acknowledgments

Thanks goes to the partners within the REWARD project consortium for their assistance and permission to publish this paper. The work reported here received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 636380

7 References

REWARD (2015-2018) "REal World Advanced technologies foR Diesel engines"; www.project-reward.eu

Machold, A. et.al. "Model based combustion-chamber layout for passenger car Diesel engines" 4th International Engine Congress, Baden-Baden, 21-22 Feb 2017

AVL List GmbH, "AVL CAMEO", 2016.; www.avl.com /cameo-3

Chen, H., Mulla, S., Weigert, E., Camm, K. et al., "Cold Start Concept (CSC™): A Novel Catalyst for Cold Start Emission Control," SAE Int. J. Fuels Lubr. 6(2):372-381, 2013, doi:10.4271/2013-01-0535.

AVL List GmbH, "AVL CRUISE™ ", 2017.; simulation tool for vehicle driveline system analysis and optimization; www.avl.com /cruise