

A New Generation Lean Gasoline Engine for Premium Vehicle CO₂ Reduction

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Abstract

In an era of rapidly increasing vehicle electrification, the gasoline engine remains a vital part of the passenger car powertrain portfolio. Lean-burn combustion is a formidable means for reducing the CO₂ emissions of gasoline engines but demands the use of sophisticated emissions control.

A 2.0 litre turbocharged direct-injection gasoline engine has been developed with a lean homogeneous combustion system matched to a robust lean and stoichiometric-capable exhaust aftertreatment. The aftertreatment system includes an SCR system and a GPF with filtration down to 10 nm particle size. The engine is equipped with a continuously variable valve-lift system, high-tumble ports and a high-energy ignition system; the boosting system comprises a variable geometry turbocharger and a 48 V electrical supercharger.

The work reported formed part of the PaREGEEn (Particle Reduced, Efficient Gasoline Engines) project under the Horizon 2020 framework programme. In this project, further development of gasoline engines as used in mid to premium-sized cars was undertaken, with the objective to reduce CO₂ emissions by 15% under Euro 6d RDE (Real Driving Emissions) legislation and with particle number emissions measured down to 10 nm.

This paper will give a detailed treatment of the multi-cylinder engine and vehicle development undertaken. The engine delivered BSFC benefits exceeding 10% and a peak brake thermal efficiency of 42%, while the vehicle demonstrated a NO_x conformity factor below 1.0 in independent RDE tests.

Introduction

Growing road traffic in Europe has resulted in detrimental effects on the environment and on public health, despite increasingly stringent emission standards. Carbon dioxide (CO₂) and noxious emissions may not be sufficiently reduced in real driving, whilst some engine technologies may have led to increases in the emissions of nanoparticles that are not detected by current certification procedures. In the European Green Vehicles Initiative call GV-02-2016, within the Horizon 2020 framework programme, the objective was to develop a new generation of engine technologies that are significantly more fuel efficient than the best 2015 equivalent vehicles under real driving conditions, and to demonstrate pollutant emissions levels compliant with the Euro 6 RDE limits and particle number emissions measured down to a 10 nm size threshold [1].

In the PaREGEEn (Particle Reduced, Efficient Gasoline Engines) project [2,3], a consortium including OEMs, research institutions, Tier 1 suppliers and engineering service providers, has focussed on gasoline engines as used in mid-sized and premium-sized passenger cars. An overview of the complete project is shown in Figure 1. With the electrification of smaller vehicle's powertrains (suitable for zero tailpipe emissions in urban environments), addressing larger cars was especially important. The requirement for clean, efficient and economic engines for cars regularly used for inter-urban and regional transport was urgent, and the solutions addressed the societal challenges of air quality, decarbonisation and cost-effective mobility.

Lean-burn operation has been known to improve fuel economy since the earliest internal-combustion engines were developed [4]. Enleanment can reduce both heat losses and pumping work and increase the ratio of specific heats of the working fluids. The first direct-injection (DI) gasoline engines to enter mass production utilised lean-stratified operation [5-8], their wall-guided combustion systems were superseded by spray-guided engines with piezo-electric injectors [9-12]. Boosted lean direct-injection gasoline engines were first demonstrated almost 20 years ago [13,14], they entered series production in 2012 [15].

In order to meet the combined climate and air quality challenges described above with lean gasoline engines, a new generation of technology solutions is required. The focus has returned to lean-homogeneous combustion systems, which produce the lowest engine-out NO_x emissions. Advanced fuel-injection, ignition, valvetrain and boosting technologies have been employed to increase the air-fuel ratio possible with stable combustion [16-22]. This paper presents an experimental study of both multi-cylinder engine and vehicle performance with a lean-homogeneous combustion system. The engine and aftertreatment system have delivered improved brake thermal efficiency and CO₂ emissions, while also controlling drive-cycle and real-world NO_x emissions.

Engine and Vehicle Concept

The work reported sought to advance the state-of-the-art for lean-burn engine technology by combining developments in fuel-injection, boosting and continuously variable valve-lift (CVVL) technologies in a high compression-ratio Miller Cycle engine. As mentioned above, fine sub-23 nm particles are also a special focus; work has concentrated on maintaining low levels during real-world transient driving conditions. Key elements of the project and engine have been introduced in an earlier paper by the authors [23].

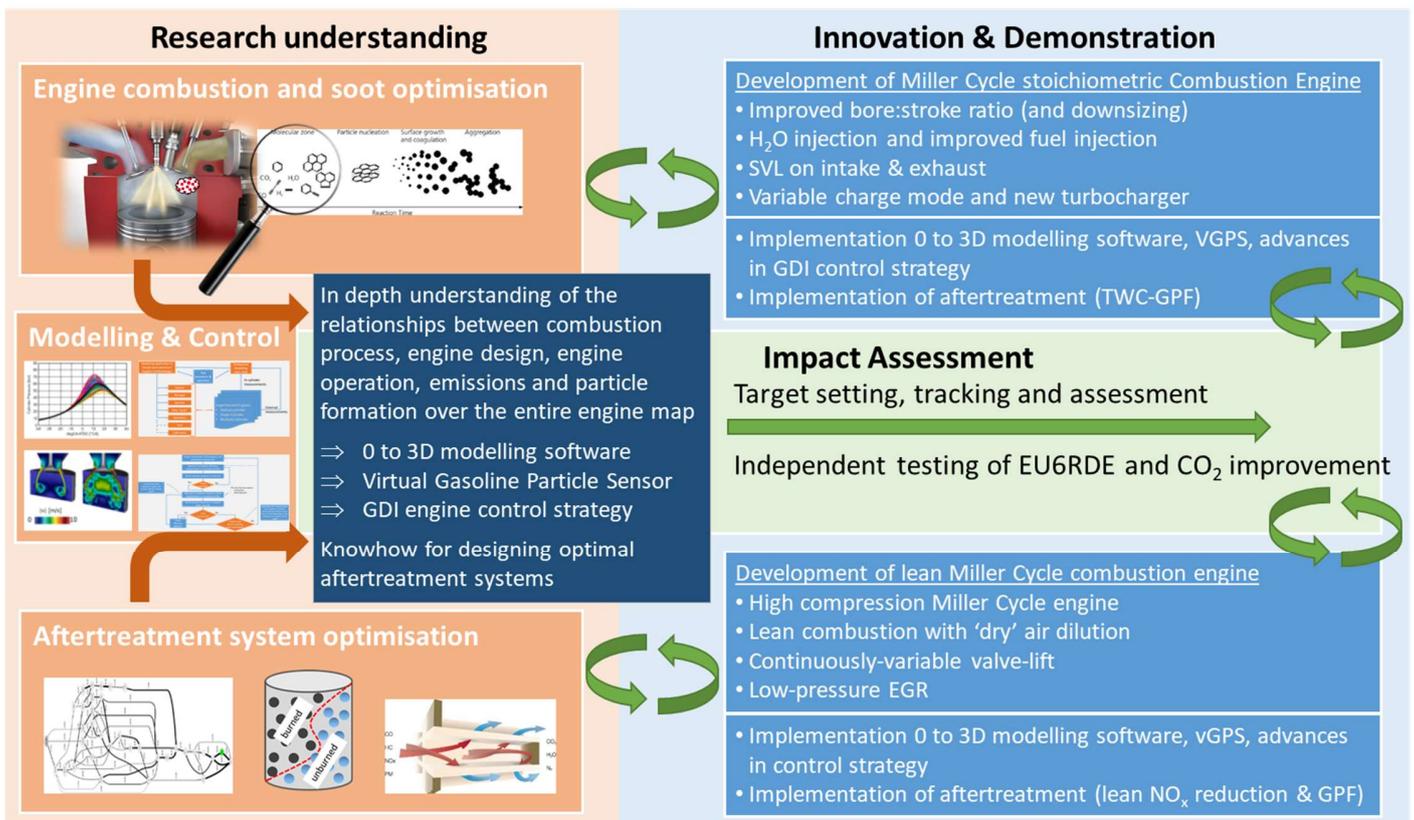


Figure 1 Overview of the PaREGE project

The base engine for this study was Jaguar Land Rover's Ingenium four-cylinder gasoline engine at a 200 PS (147 kW) performance level [24]. The project engine contains a revised combustion system combined with a range of technology to meet future legislative emissions and CO₂ requirements, whilst delivering competitive engine performance and premium refinement. The project engine specification is presented in Table 1.

Table 1 Engine specification

Bore	[mm]	83
Stroke	[mm]	92
Number of cylinders	[-]	4
Engine displacement	[cm ³]	1997
Compression ratio (nominal)	[-]	11.0:1 (interim) 12.5:1 (final)
Rated power	kW	147 (at 5500 rev/min)
Peak torque	Nm	320 (at 1200 – 4500 rev/min)
Valvetrain	[-]	DOHC, dual VCT, intake CVVL
Boosting system	[-]	VNT turbo, 48 V electric supercharger

The geometric compression ratio of the engine as-designed was 12.5:1 (shown in Table 1 as 'final'), but the correct pistons were not available until later in the project, so some engine testing and the vehicle development work were undertaken with lower compression ratio pistons. For this reason, 11.0:1 is shown as the 'interim' compression ratio.

The combustion system is implemented with a multi-mode approach, as shown in Figure 2. Lean-homogeneous operation is used at lower speeds and loads, with stoichiometric operation elsewhere to balance high performance with the most straightforward emissions control. The size of the lean window depends both on the combustion system and on emissions considerations. If lean operation can be maximised while meeting the required RDE conformity factors, the CO₂ benefit is also maximised.

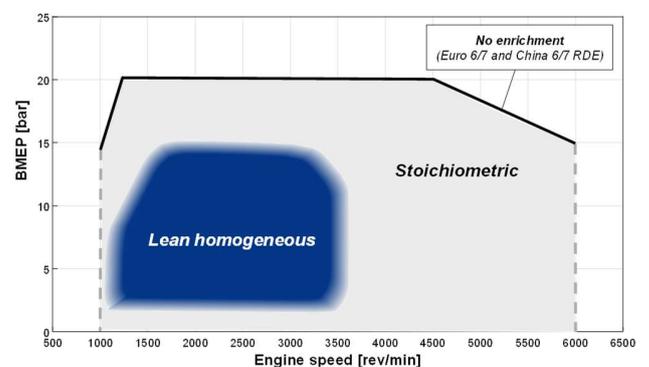


Figure 2 Torque curve and lambda modes

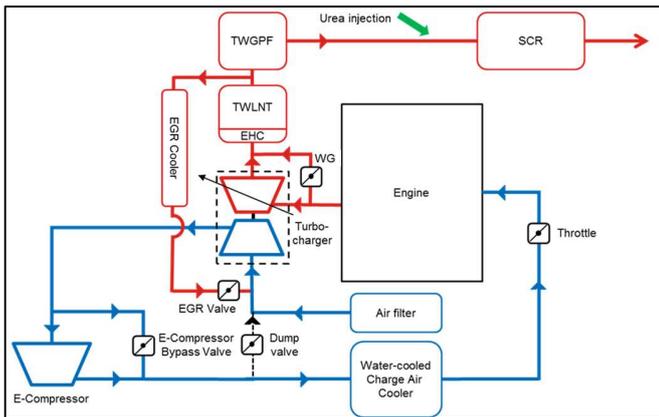


Figure 3 Engine intake and exhaust schematic

A schematic of the intake and exhaust layout is shown in Figure 3. The main components of these systems will be described in the following sections.

Combustion System

To support high thermal efficiency and provide the combustion stability necessary to operate at very lean mixtures, the combustion system was designed for an increased geometric compression ratio and increased levels of charge motion. The increased charge motion was achieved while ensuring the high air-mass flow necessary for lean operation could be delivered with low pumping losses. A representation of the ports and combustion chamber is shown in Figure 4. The intake ports were updated so that air flow over the top of the intake valves was promoted and flow below the valves (close to the cylinder wall) was reduced. This led to turbulence intensity being increased by 17% at the rated power condition, according to 3-D CFD calculations.

The CVVL system was used in conjunction with dual VCT, providing maximum flexibility of intake valve lift profiles to achieve the optimum balance of pumping losses, effective compression ratio, charge motion and internal residuals. The high level of flexibility also allows independent optimisation for stoichiometric and lean operation [21].

In common with the Ingenium family, the PaREGE engine retained a centrally-mounted 6-hole fuel injector. However, the specification of the injector, fuel system and ignition system were all modified or upgraded for this engine. In conjunction with Bosch, the injection spray pattern has been optimised for this engine, and the FIE updated to operate at pressures of up to 350 bar. The injector spray pattern was designed to maximise mixture homogeneity while not increasing wall or valve wetting.

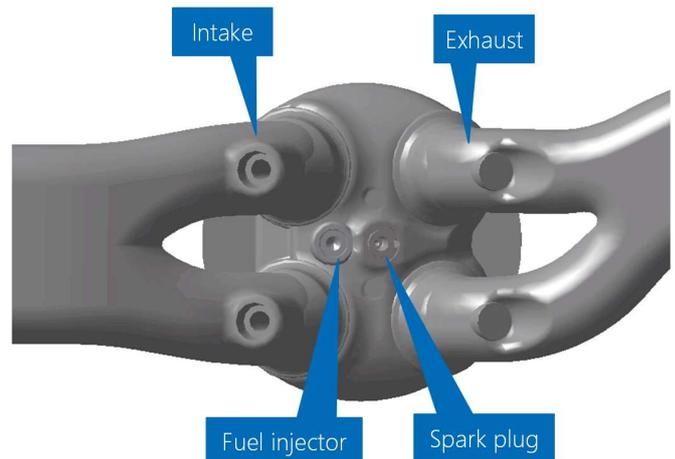


Figure 4 Combustion system geometry

To improve combustion stability and enable operation at leaner conditions, an advanced high-energy ignition system was supplied by Bosch [25]. This system is capable of running with up to 500 mJ ignition energy and can operate in a number of different ignition modes, including single-strike, multiple-strike, and continuous ignition modes. The system can promote early flame kernel development and reduce the likelihood of spark blow-out at high spark stretch rates, such as under high gas flow conditions with the increased levels of charge motion. Initial studies on a single-cylinder research engine found the continuous ignition mode had particular promise, increasing the EGR tolerance of the engine by up to 5 % and reducing the burn duration by several degrees, relative to the other modes tested.

A cooled Low-Pressure Exhaust Gas Recirculation (LPEGR) system has also been employed to manage exhaust temperature at rated power conditions and minimise (or completely eliminate) fuel enrichment in this region.

Boosting System

A Garrett Variable Nozzle Turbine (VNT) was chosen as the main boosting device (Figure 5), supplemented by a 48 V electric compressor also manufactured by Garrett. This boosting system was found to offer the best compromise between low turbine inlet pressures and transient response [26], the low turbine inlet pressures thereby reducing pumping losses and trapped residuals and, in turn, reducing boost pressure requirement, an important consideration for a lean boosted engine.

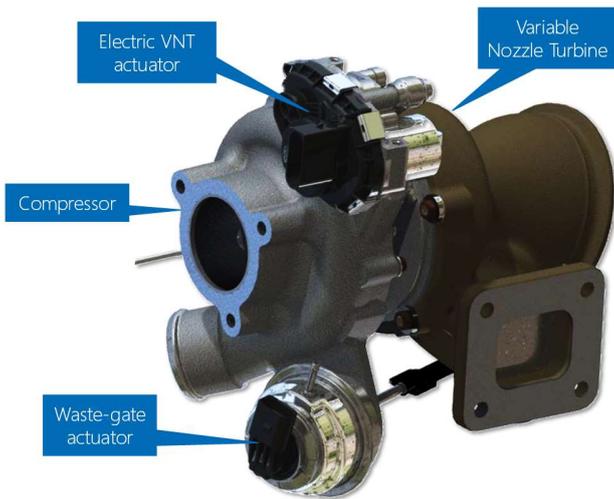


Figure 5 Variable Nozzle Turbine turbocharger

A 48 V electric compressor (Figure 6) is used in conjunction with and downstream of the VNT compressor, to provide increased boost pressure capability when the turbocharger is surge- or turbine-power limited. In addition, the electric compressor is also used during stoichiometric-to-lean mode switching, where it helps to deliver the additional air required to achieve lean homogeneous combustion whilst maintaining engine torque.

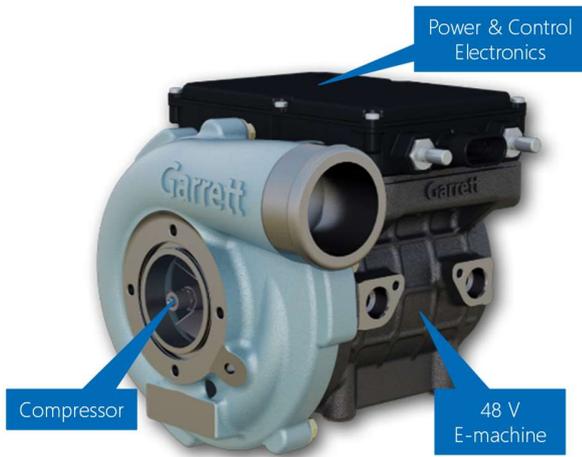


Figure 6 48 V electric compressor

Emissions Control

The aftertreatment is designed to operate under both lean and stoichiometric conditions. Lean NO_x reduction is facilitated by a Lean NO_x Trap (LNT) in combination with a downstream active Selective Catalytic Reduction (SCR) system. A Gasoline Particulate Filter (GPF) has been selected to allow particle reduction down to 10 nm without significantly increasing the overall system back-pressure. Both LNT and GPF have been coated to facilitate three-way (NO_x, CO and HC) catalytic converter capability under stoichiometric conditions, they are herein referred to as TWLNT and TWGPF respectively. All three catalysts have been supplied by Johnson Matthey.

System Layout



Figure 7 Layout of the aftertreatment system

The aftertreatment layout is shown in Figure 7. In order to optimise the catalyst response time from cold-start conditions and during the transitions between lean and stoichiometric operation, the TWLNT was coated onto an electrically-heated catalyst (EHC). Specific requirements of the EHC were for it to run from a 48 V supply, to deliver a heating power output of up to 3 kW. The TWGPF is located closely behind the TWLNT to maximise exhaust gas temperatures at TWGPF inlet, assisting both gaseous emissions performance and the regeneration of accumulated soot through combustion. The SCR catalyst is located in an underfloor position, downstream of the urea dosing module; gas temperatures at the inlet to the SCR are typically expected to be ~140 °C cooler than those at the exhaust manifold. Compared with copper-based technologies, an iron-based SCR (Fe-SCR) technology was chosen based on its higher durability under environments with little or no oxygen present (as will be the case under stoichiometric operation) and low selectivity towards forming nitrous oxide (N₂O).

Gasoline Particle Filter Development

A key requirement for the PaREGEN project was to deliver compliance with the particle number legislation for Euro 6d down to a particle size of 10 nm (below the 23 nm threshold currently defined). Evaluation of the filtration performance of different TWGPF catalyst formulations was carried out using a 2017 model year Jaguar XE 2.0 litre GTDi on a chassis dynamometer. Particulate numbers at the tailpipe were measured using a Horiba MEXA-2000 SPCS analyser to give an accurate reading down to 23 nm, as well as a Cambustion DMS500 to provide representative data on particle size distribution down to 10 nm.

Figure 8 compares the filtration efficiency of two development formulations against a Baseline formulation when evaluated over the World-Harmonised Light-Duty Test Cycle (WLTC); filtration efficiencies for different diameter ranges are shown. Dev1 was developed using new materials with the goal of minimising pressure drop across the GPF (backpressure), which is desirable for enabling the engine to deliver peak power and optimised driveability. Dev2 uses a combination of new materials and processing methods with the goal of optimising filtration efficiency whilst still providing some improvements in backpressure relative to the reference. All three formulations show higher filtration efficiencies at 10-23 nm compared with 23 nm+, likely due to the dominance of the diffusion filtration mechanism at smaller particle sizes. However, both development formulations show an improvement in filtration efficiency at 10-23 nm, with Dev2 showing the best overall filtration efficiency at all particle sizes.

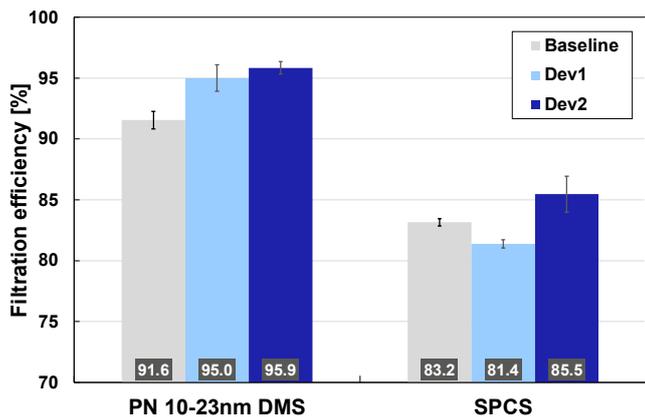


Figure 8 Filtration efficiency summary at different particle size ranges measured over WLTC

Dev2 was also shown to demonstrate favourable back-pressure characteristics (Figure 9) compared with the Baseline formulation. Hence, Dev2 was chosen as the preferred TWGPF formulation.

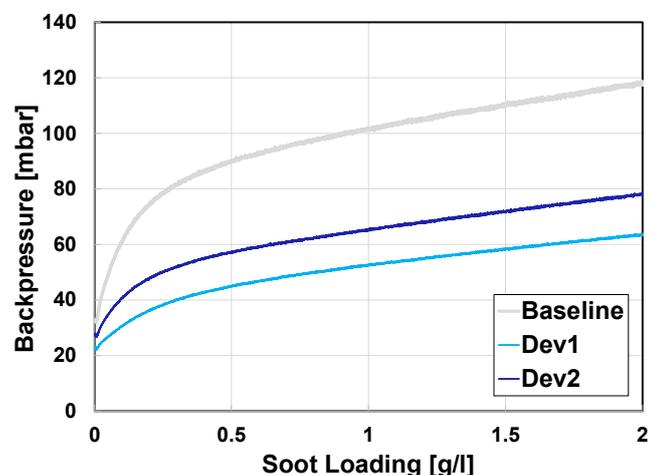


Figure 9 Comparison of soot loaded backpressure

GPF substrates of varying web thicknesses, supplied by NGK, were also considered. Both the Baseline and Dev2 TWGPF formulations were coated on 300 cpsi substrates with web thicknesses of 8 mil and 12 mil, hereafter referred to as 300/8 and 300/12, respectively; there were evaluated over the WLTC, as shown in Figure 10. The Baseline formulation showed increased filtration efficiency when the thicker walled substrate was used. The Dev2 formulation showed less sensitivity of PN filtration efficiency to wall thickness, as seen in the DMS data. In both instances the higher web thickness resulted in a penalty in backpressure. Overall, the Dev2 formulation on a 300/8 substrate remained the best compromise of PN filtration efficiency and backpressure.

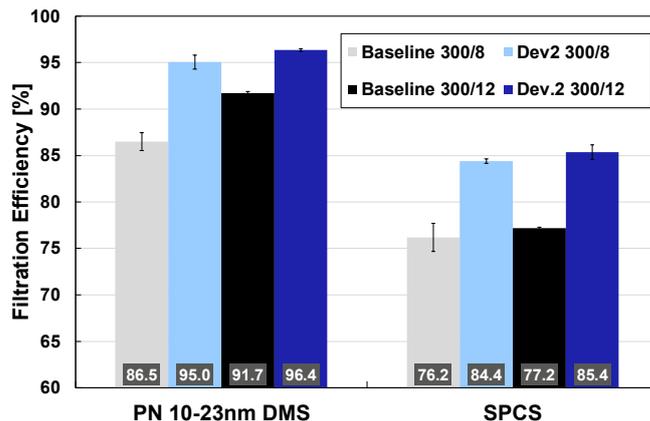


Figure 10 Filtration efficiency summary for different TWGPF and substrate combinations over WLTC

Lean NO_x Aftertreatment Development

The ratio of NO₂:NO in the exhaust gas can have a significant bearing on the SCR conversion efficiency (SCR reactions were described in detail in [20]). Figure 11 shows the effect of temperature and NO₂:NO_x ratio on SCR conversion efficiency for an Fe-SCR catalyst, aged hydrothermally for 4 hours at 900 °C in a gas mix of 2 % O₂ : 10 % H₂O : N₂ balance. The tests were carried out on a synthetic gas rig using a gas mix containing 500 ppm total NO_x (NO+NO₂) and an NH₃:NO_x ratio of 1.5:1, at a gas-hourly space velocity (GHSV) of 60,000 hr⁻¹. The results show that having a high proportion of NO₂ (preferably up to 50% of total NO_x) greatly improves SCR conversion, especially at low temperatures. For the lean-burn gasoline application, however, NO₂:NO_x ratios at SCR inlet are not expected to exceed 10 %, due to the tendency for the upstream TWLNT to consume NO₂ before it reaches the SCR.

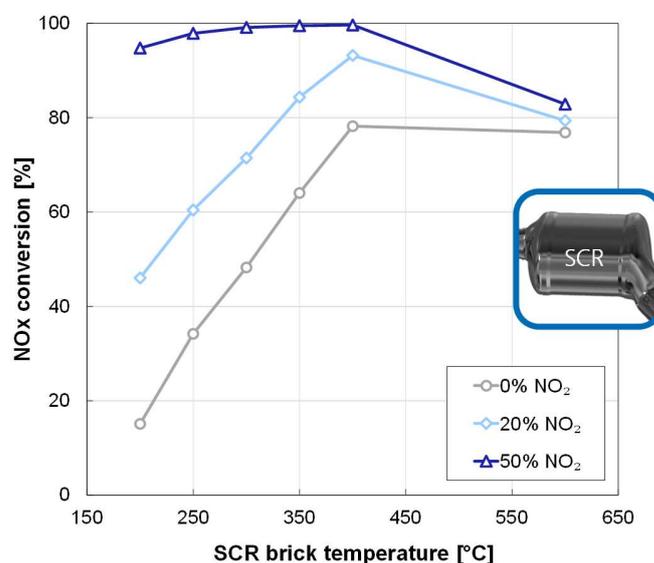


Figure 11 Impact of NO₂:NO_x ratio on SCR performance

As a means of boosting the NO₂:NO_x at the SCR inlet, trials were carried out using a modification of the Dev2 TWGPF formulation to include an additional component to promote NO₂ make, as shown in Figure 12. The benefits of the modified TWGPF design on the

downstream SCR conversion efficiency when evaluated on the multi-cylinder engine are shown in Figure 13.

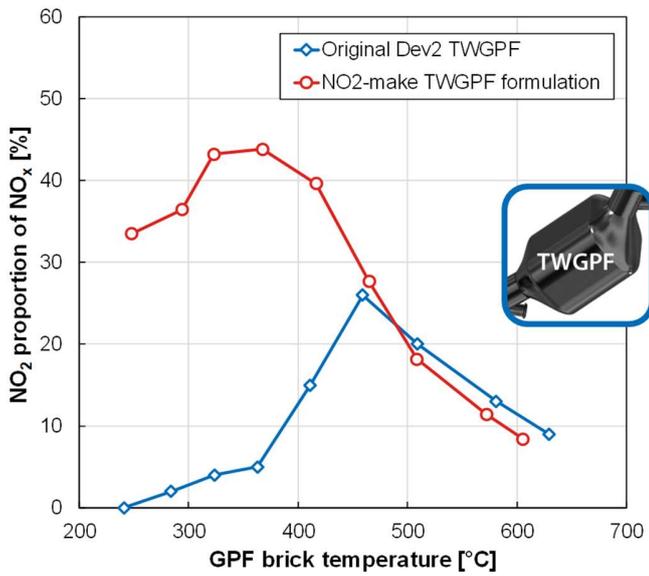


Figure 12 Comparison of original Dev 2 and NO₂ make TWGPF

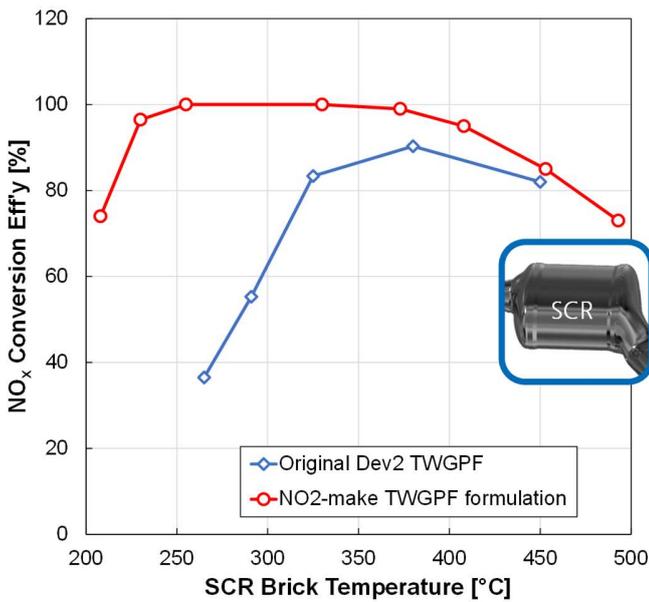


Figure 13 SCR NO_x conversion efficiency with different upstream TWGPFs

The revised filter was evaluated on the chassis dynamometer on the same Jaguar XE 2.0 litre GTDi. The second-by-second PN measurements pre- and post-TWGPF, as measured using the Horiba SPCS, for both filters are shown in Figure 14. The new TWGPF design demonstrated high filtration efficiency (~90 %). Following further revisions of the coating to optimise both filtration and backpressure characteristics, the new TWGPF design was taken forward for demonstration on the engine.

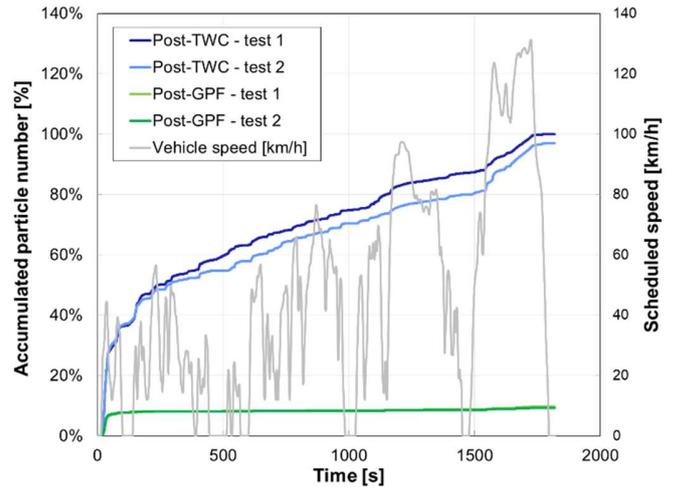


Figure 14 WLTC PN emissions – TWGPF with NO₂-make functionality

Control System

The engine control unit (ECU) platform adopted for the project is the Schaeffler PROtronic system. This system provides a high degree of flexibility when designing the control approach for the engine, actuators and aftertreatment. Key elements of the control system have been implemented and tested successfully on both engine testbed and vehicle. The ECU is also set up to communicate with the rest of the vehicle network, enabling the car to be driven in a variety of operating conditions.

Combustion control is enhanced with the adoption of cylinder pressure feedback, allowing improved control of combustion phasing and indicated mean effective pressure (IMEP). A 48 V system architecture is also configured to drive the electric compressor and EHC. Smooth coordination of all these systems is critical to achieving good transient performance, fuel consumption and emissions control.

Under lean conditions, the optimal settings can differ significantly from those used under stoichiometric conditions. To allow for this, the control system has been specified with separate setpoints for all major actuators under lean conditions. Calibration of these setpoints is described further in the Lean Mode Mapping section. The “enable” criteria for lean operation are based on a number of conditions including: engine coolant temperature, engine speed and load, aftertreatment operating temperature and the 48 V system status. When the threshold values for parameters relating to each of these criteria are met, a switch from stoichiometric to lean is permitted. The control strategy allows for flexibility to define the transition between one mode and the other. The optimal solution involves a rapid change, to minimise time spent within the high-NO_x-generating lambda region between lambda 1.05 and 1.30, whilst minimising any torque disturbances associated with the combustion mode change.

Engine Testing

The multi-cylinder lean-burn engine was installed on a transient dynamometer testbed at the University of Brighton. The test facility included the full vehicle-level exhaust aftertreatment system to accurately reflect the associated backpressure and provide early results for the aftertreatment performance.

The results from the stoichiometric full load power curve (FLPC) testing are presented in Figure 15. In previous testing without the

electric compressor, the target torque curve was not achieved at engine speeds below 2500 rpm. Combinations of valve events which would have led to scavenging were avoided. Testing with the electric compressor resulted in the target torque curve being met at all engine speeds. As the engine speed increases, the VNT was able to generate more boost pressure from the increasing exhaust mass flow and enthalpy, therefore the electric compressor speed required to achieve the target brake torque reduces until, at 2500 rpm, the electric compressor is no longer required. The increased mass flow from using the electric compressor at low engine speeds also allows the VNT to run at higher speed and generate more boost. This can be seen in the difference between the red and blue dashed lines in Figure 15.

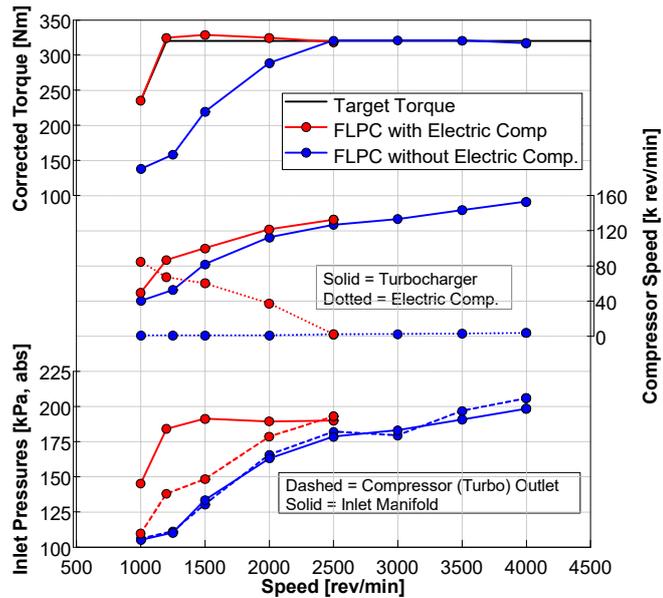


Figure 15 Full load power curve with and without electric compressor

Lean Mode Mapping

The engine was mapped using a Design of Experiments (DoE) approach with Stochastic Process Methods (SPM) modelling [31]. The experimental design included lambda, combustion phasing, intake and exhaust cam timing and CVVL closing angle as input variables. Exhaust lambda for the lean homogeneous mode is shown in Figure 16, based on 51 key-points. The air-fuel ratio (or lambda) employed is a balance between the desire to run as lean as possible, in order to minimise NOx emissions and improve fuel economy, and the requirement to maintain acceptable combustion stability and vehicle driveability. CVVL settings were also an important consideration: in many cases the best fuel economy was achieved with more aggressive EIVC settings and a slightly less lean mixture. Under the most favourable conditions, lambda values close to 1.6 were selected, but at low loads the lambda was reduced in order to maintain combustion stability.

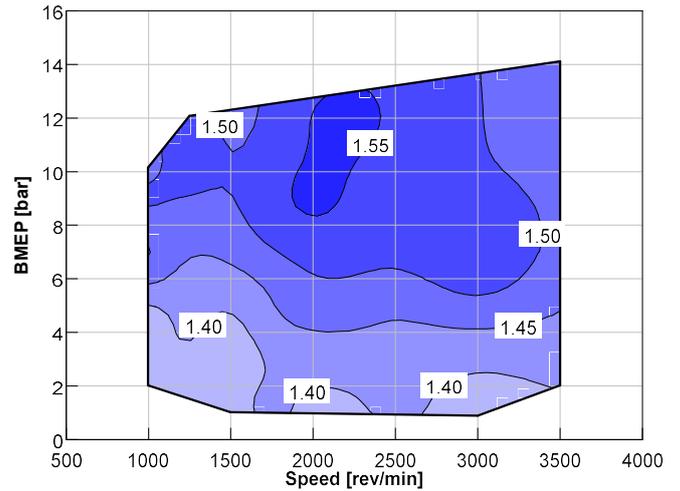


Figure 16 Exhaust lambda under lean operation

Burn durations (10-90% mass fraction burned (MFB)) for lean operation are shown in Figure 17. This data confirms that the efforts made to provide high air motion succeeded, as the burn durations for lean combustion are comparable to the baseline stoichiometric engine.

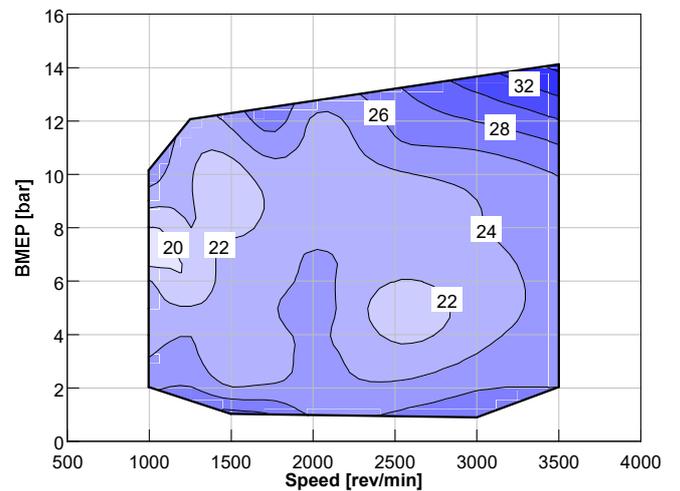


Figure 17 10-90% Mean Fraction Burn duration under lean operation

Figure 18 shows the volume concentration of engine-out NOx emissions in the lean mode, which is up to 90% lower than that for the stoichiometric baseline engine. It is critical to reduce the engine-out NOx emissions as much as possible in order to reduce the burden on the lean aftertreatment system.

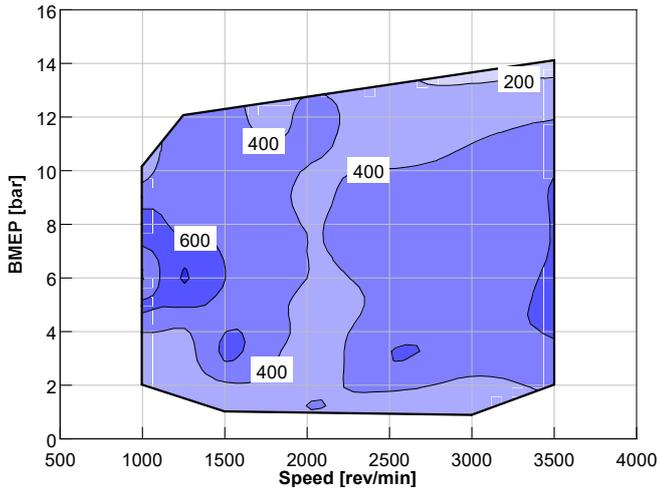


Figure 18 Engine out NOx concentration [ppm] under lean operation

Figure 19 presents the BSFC benefit of the PaREGEN prototype engine over the stoichiometric baseline engine. The BSFC benefit (which includes the impact of increased compression ratio) is greater than 10% over a wide range of loads, in a high-residency region for the project vehicle. This benefit arises largely from reductions in in-cylinder and exhaust heat losses. The low pumping losses of the CVVL baseline engine are highlighted by the relatively small BSFC benefit at low loads.

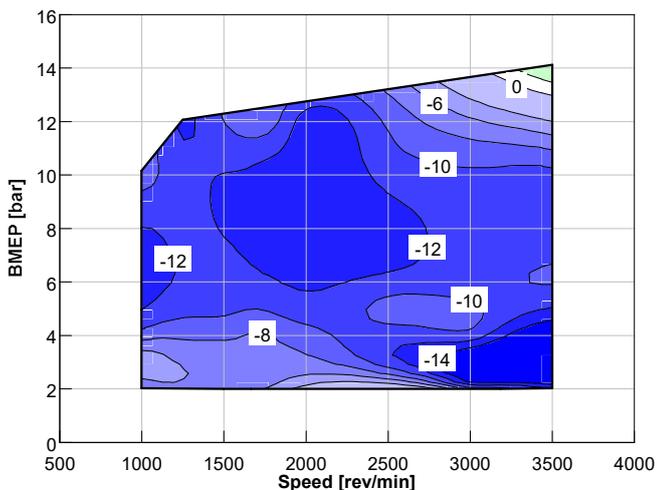


Figure 19 BSFC difference [%] between lean operation PaREGEN and stoichiometric operation baseline engine

Key-Point Optimisation

Key-point optimisation was then undertaken to see if the lean air-fuel ratio could be further increased and BSFC improved, while maintaining combustion stability (a limit of 3% for CoV NIMEP was applied).

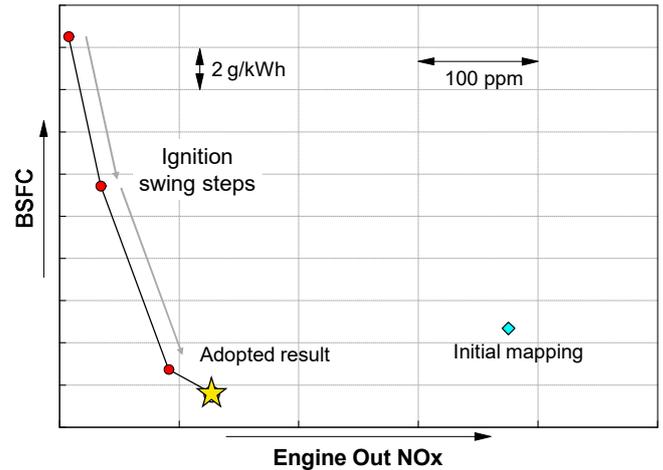


Figure 20 BSFC vs. NOx trade-off with varying ignition timing at 2000 rev/min, 12 bar BMEP

At each key-point the following sequence of tests was undertaken:

1. Lambda swings were undertaken at a range of cam timing settings
2. The cam timing and lambda settings achieving the best BSFC (within combustion stability limits) were then selected
3. An ignition timing swing was carried out to study the trade-off between BSFC and NOx emissions
4. Finally CVVL closing angle was optimised

In Figure 20 the output from step 3 of this process is shown: an ignition swing at 2000 rev/min, 12 bar BMEP. The fixed lambda value for the ignition swing is 1.7, a leaner mixture than was achieved in the mapping exercise. Through this process of optimisation, a best brake thermal efficiency (BTE) of 42% was achieved for the 2000 rev/min, 12 bar BMEP operating condition, while NOx emissions were also reduced by more than 50% at this condition compared with the data shown in Figure 16.

Vehicle Testing



Figure 21 The PaREGEN lean demonstrator vehicle

The PaREGEN lean demonstrator vehicle is shown in Figure 21 and the engine installation is shown in Figure 22. Due to the duration of

the project, the vehicle was fitted with the 11.0:1 compression ratio interim pistons, instead of the 12.5:1 compression ratio pistons fitted to the testbed engine.

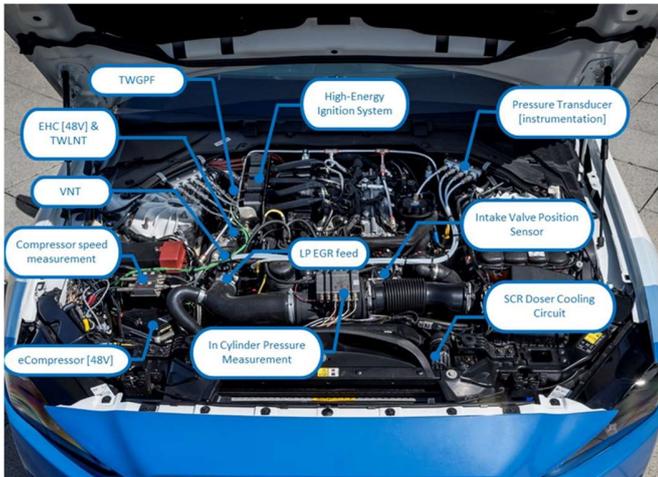


Figure 22 Under bonnet layout with the key systems identified

The vehicle has been developed and calibrated in order to meet the RDE emissions objectives and to demonstrate the CO₂ benefits of the engine technology package. The vehicle is able to successfully transition between stoichiometric and lean operation during transient manoeuvres. Figure 23 shows an example of this. The switch event is completed rapidly, within 0.4 seconds. During the switch the in-cylinder charge setpoint is managed by a combination of CVVL, manifold pressure and boost pressure targets. The response of the boost actuators is shown, as the control set-points are modified, triggered by the transition mode switch. Fuelling is adjusted according to a lambda target trajectory, with the closed-loop fuelling control active throughout. Precise lambda control is required to enable effective use of the aftertreatment system and control of tailpipe emissions. This remains a challenge under transient conditions and highlights the requirement for an accurate air-path model to predict the in-cylinder charge.

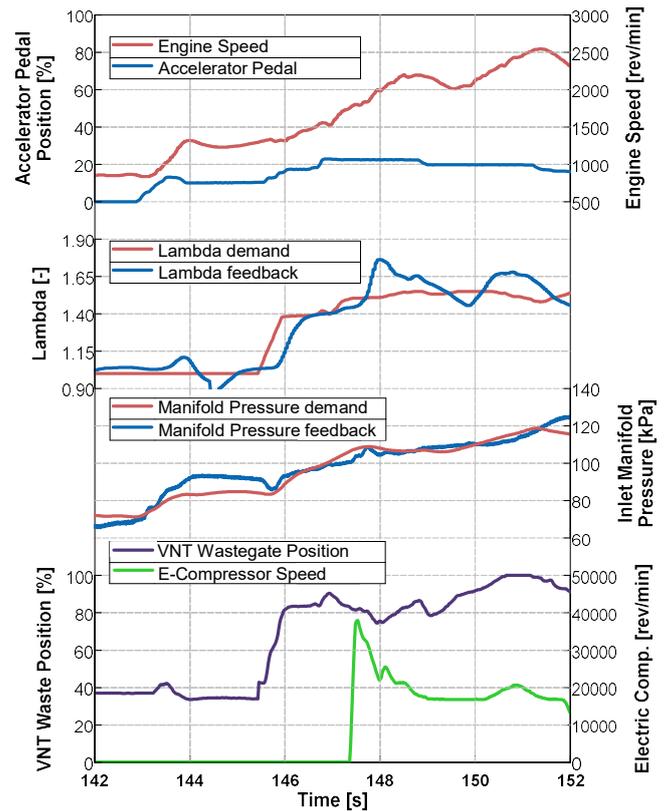


Figure 23 Example combustion mode switch in vehicle

To minimise tailpipe emissions following a cold start, it is vital that the exhaust aftertreatment is brought up to operating temperature as soon as possible. To enable this quick light-off of the three-way catalysts, a catalyst heating mode was developed, to be used in conjunction with activating the EHC. Figure 24 shows a comparison of the demonstrator vehicle with and without the EHC active. The use of the EHC led to a ~40 % reduction in the time the vehicle spent in catalyst heating mode and ~40 % reduction in the cumulative tailpipe NO_x.

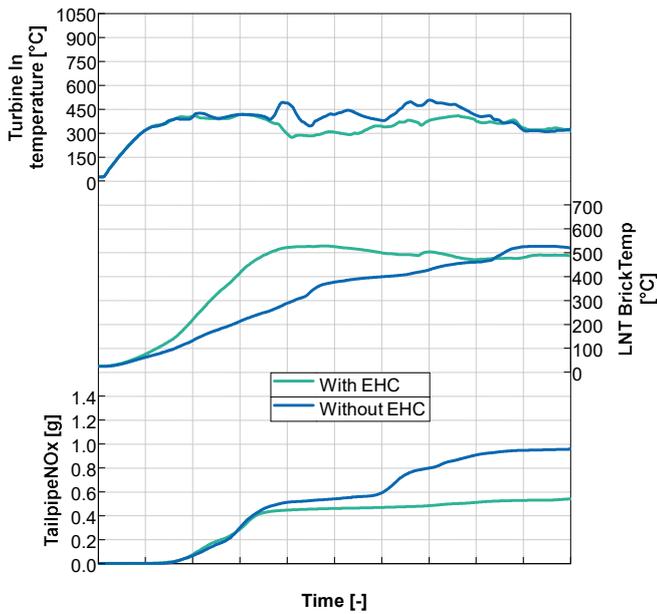


Figure 24 Vehicle catalyst light-off performance with and without EHC

In Figure 25, the final 1200 seconds of a WLTC are shown. During this period lean operation is maximised to exploit the fuel consumption benefits. A large proportion of the measured tailpipe NO_x emissions are from the initial 600 seconds of the cycle, during which the engine operates only in a stoichiometric mode. The primary reason for this is the immature status of the control system. Therefore, the performance during the first 600s has been matched that of the donor XE production vehicle. With this correction made, it is estimated that the PaREGEN demonstrator can achieve the project target of 0.060 g/km NO_x over the cycle.

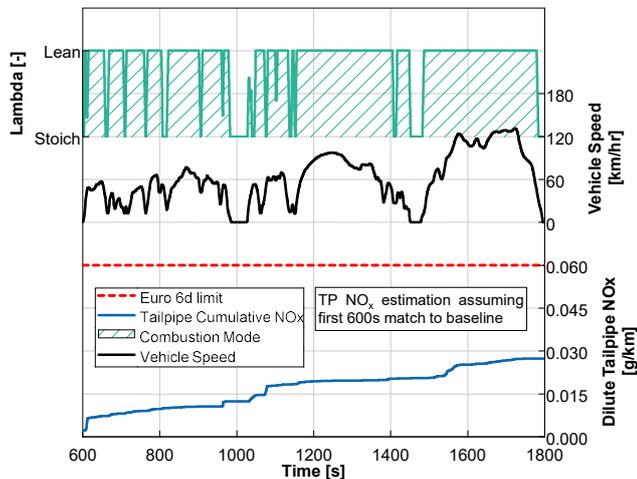


Figure 25 WLTC Lean Phase NO_x emissions

In addition to the WLTC testing conducted at Ricardo, the demonstrator vehicle was also independently tested at IDIADA AUTOMOTIVE TECHNOLOGY as part of the PaREGEN project. RDE simulation testing was carried on the chassis dyno, replicating a real-life RDE cycle that meets the standard homologation conditions. Figure 26 shows the control system's ability to switch between stoichiometric and lean operation automatically. Also shown is the dilute (tailpipe) NO_x emissions. The initial steep rise, 0 – 500 s, is a result of the light-off of the TWC elements of the aftertreatment

system. Whilst this impact has been reduced by the use of the EHC, further benefits would be seen from improvements to the engine control system in this area. The following section, ~500 – 3000 s represents the Urban phase during which the lean combustion mode is active and shows the tailpipe NO_x is well controlled. The Rural phase is represented by ~3000 – 4250 s. During this phase some small but steep rises in the tailpipe NO_x were seen. These represent higher levels of breakthrough and were due to poor AFR control under high load transient conditions. With further development, it is expected that these breakthroughs would be reduced or eliminated. The Motorway section, ~4250 – 5650 s shows some similar NO_x excursions. It can be seen that the system overall has good capability to control NO_x under a variety of transient conditions.

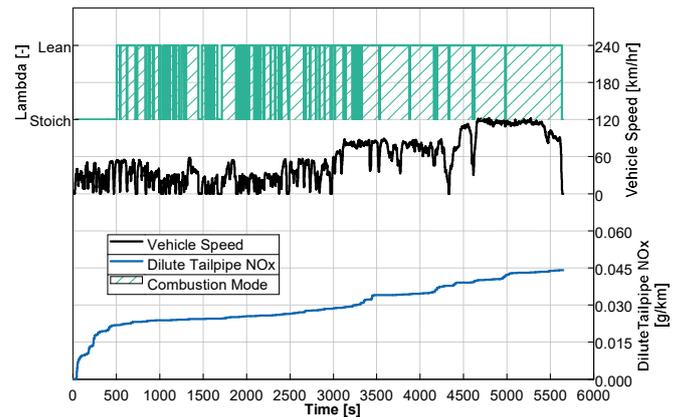


Figure 26 Chassis Dyno RDE NO_x emissions

The average NO_x emissions result from two chassis dyno RDE tests was 0.044 g/km (measured by the standard CVS approach), representing a conformity factor (CF) well below 1.0 [28]. This result is inclusive of the cold-start phase and no corrections were applied to match the baseline vehicle.

The final WLTC CO₂ cycle result is a combination of vehicle results and analysis using testbed data. The demonstrator vehicle by itself was not expected to meet the project target of a 15 % reduction compared to baseline test results, since the timelines for the project precluded full development and optimisation of all CO₂ relevant systems which would be expected on a production vehicle. Therefore, a projection has been generated, as presented in Figure 27. Each step in the projection has been calculated using a mixture of data from the demonstrator and baseline vehicles, the test engine and simulation. It includes allowances for stop-start not functioning, the vehicle being fitted with 11:1 CR pistons instead of 12.5:1, and the immaturity of the control system capability compared to a production level system.

The demonstrator vehicle has shown that, in spite of the challenges of lean operation (such as the requirement for regular mode switching), significant fuel savings have been made along with stringent emissions standards being met or exceeded. The key challenge for future implementation remains the complexity and cost of emissions control.

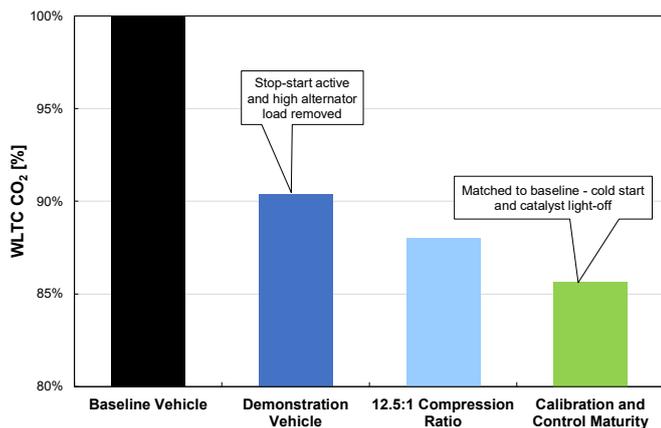


Figure 27 Projection of WLTC CO₂ based on vehicle results and testbed data analysis

Conclusions

- A lean-homogeneous combustion system has been developed, incorporating direct injection, high-tumble ports and a high-energy ignition system
- This combustion system has been implemented in a 2.0 litre four-cylinder engine with a continuously-variable valve-lift system, a variable-geometry turbocharger and an electric compressor
- The engine has delivered BSFC benefits greater than 10% over a wide range of speed and load, and a peak BTE of 42%
- An aftertreatment system suitable for full RDE compliance with this stoichiometric/lean switching engine has been developed, including control of lean NO_x emissions and particle number emissions down to 10 nm diameter
- The project vehicle has demonstrated stoichiometric/lean switching under transient conditions and an independently verified RDE NO_x conformity factor well below 1.0
- The project has also demonstrated a route to deliver close to the 15% reduction in vehicle CO₂ emissions sought by the call within the Horizon 2020 2016 work programme, through a combination of physical prototype testing and analytical approaches

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EIVC	Early Intake Valve Closing
FIE	Fuel Injection Equipment
GPF	Gasoline Particle Filter
IMEP	Indicated Mean Effective Pressure
MFB	Mass Fraction Burned
PaREGEEn	Particle Reduced, Efficient Gasoline Engines
RDE	Real Driving Emissions
SCR	Selective Catalytic Reduction
SPCS	Solid Particle Counting System
SPM	Stochastic Process Model
TWC	Three-Way Catalyst
TWLNT	Three-Way Lean NO _x Trap
TWGPF	Three-Way Gasoline Particulate Filter
VCT	Variable Cam Timing
VNT	Variable Nozzle Turbocharger
WLTC	World Light-duty harmonised Test Cycle

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Abbreviations

AFR	Air-Fuel Ratio
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CF	Conformity Factor
CR	Compression Ratio
CVS	Constant Volume Sampling
CVVL	Continuously-Variable Valve-Lift
DCU	Dosing Control Unit
DOHC	Double Overhead Cam
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EHC	Electrically-Heated Catalyst