

Observations on the Measurement and Performance Impact of Catalyzed vs. Non Catalyzed EGR on a Heavily Downsized DISI Engine

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ABSTRACT

Increasingly stringent regulations and rising fuel costs require that automotive manufacturers reduce their fleet CO₂ emissions. Gasoline engine downsizing is one such technology at the forefront of improvements in fuel economy. As engine downsizing becomes more aggressive, normal engine operating points are moving into higher load regions, typically requiring over-fuelling to maintain exhaust gas temperatures within component protection limits and retarded ignition timings in order to mitigate knock and pre-ignition events. These two mechanisms are counterproductive, since the retarded ignition timing delays combustion, in turn raising exhaust gas temperature.

A key process being used to inhibit the occurrence of these knock and pre-ignition phenomena is cooled exhaust gas recirculation (EGR). Cooled EGR lowers temperatures during the combustion process, reducing the possibility of knock, and can thus reduce or eliminate the need for over-fuelling. It has also been shown to reduce exhaust gas temperature and improve combustion efficiency through improved combustion phasing. This paper reviews data collected on 'ULTRABOOST', a collaborative research project which is co-funded by the Technology Strategy Board, the UK's innovation agency. The project is based on a prototype, heavily downsized 2.0L DISI engine running under controlled boost conditions, featuring low pressure or 'long route' EGR. This allows for the EGR feed gas to be fed from either pre- or post-catalyst sampling points.

This paper will present data collected at equivalent operating conditions using both catalyzed and un-catalyzed exhaust gas to feed the EGR system. Some comparison of equivalent BMEP levels will be made but this is not the focus of the investigation. Current standards utilize a CO₂ ratio for EGR measurement, but the results presented highlight inaccuracies in this measurement method when repeatable test conditions for pre- and post-catalyst EGR routes are required due to the significant changes in gas composition pre- and post-catalyst. The test engine was artificially boosted utilizing a Combustion Air Handling Unit to simulate commercially available turbo-machinery, which allowed for the catalyst effects to be assessed in isolation. Results from the engine are presented for constant intake manifold pressure and constant EGR mass flow to highlight the effects of the EGR feed gas composition on a range of engine performance metrics.

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INTRODUCTION

Future emissions legislation is the main driving force behind engine research and development. Previously the focus of development has been on the reduction of PM and CO emissions, however there has been a shift towards reducing fuel consumption and hence CO₂ emissions in particular. EU legislation stipulates an OEM fleet average of carbon dioxide emissions of 130 g/km by 2015. This legislation was phased in

from 2012 and will incur a sliding penalty system for vehicles which exceed this figure. The result of this legislation is the rapid development of new and more efficient technologies. An increasingly common method of improving fuel economy is by using a boost system coupled with a downsized engine. Turbocharged gasoline engines are becoming a common replacement for larger naturally aspirated engines, however pushing the boundaries of the boost levels and the extent of the engine downsizing may still provide increased savings.

Researchers seeking to increase the levels of boost in an internal combustion engine will inevitably be faced with a large number of difficulties. These technical challenges are well known and include increasing an engine's tolerance to higher mean peak cylinder pressures without incurring the need for significant compression ratio reduction. The increased inlet manifold temperatures and pressures have a knock-on effect on all ensuing processes, increasing the likelihood of pre-ignition (PI) or self-ignition (knock). In order to prevent these phenomena, more careful control of the combustion process is necessary. The most common method of knock prevention is spark retard. Unfortunately this has a significant trade-off with power and economy through poor combustion phasing, in addition to raising the exhaust gas temperature and causing problems with higher rates of heat transfer in the engine and turbo-machinery.

A collaborative research program, co-funded by the Technology Strategy Board (TSB), the UK's innovation agency, named 'ULTRABOOST' aims to produce an engine which pushes the boundaries of engine downsizing and charging. It draws on the expertise from a consortium of technical partners including Jaguar Land Rover (JLR), Lotus Engineering, Shell Fuels, GE Precision Engineering, CD-Adapco, Imperial College London, University of Leeds and University of Bath, as outlined in [Table 3](#). The primary objective of the project was to achieve a 35% reduction in tailpipe CO₂ emissions relative to JLR's 5.0 litre naturally aspirated V8 engine, whilst maintaining the original engine's torque and power delivery characteristics. The peak Brake Mean Effective Pressure (BMEP) target was set at 35bar but the transient performance was also critical, leading to a requirement for a flat torque curve and thus a target of 25bar BMEP to be available at both 1000 and 6000rpm. Performance targets of this magnitude result in challenging combustion conditions with high probabilities of detrimental abnormal combustion effects such as pre-ignition and knock taking place. [Figure 1](#) shows the current engines on the market and in development that are aiming to achieve high BMEP targets. The baseline AJ133 engine is also shown for comparison to the targets set out for Ultraboost.

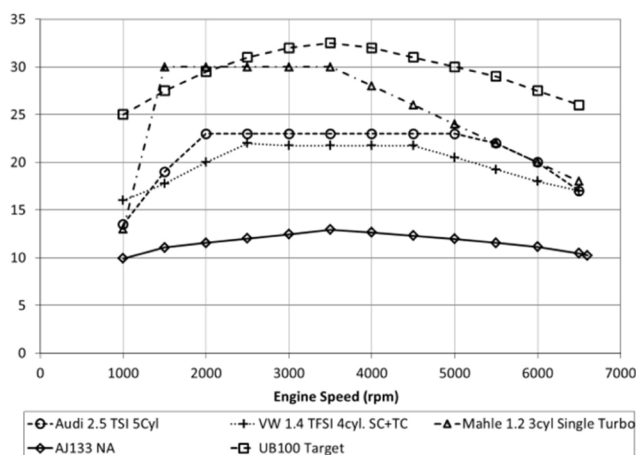


Figure 1. Engine competitors

TEST EQUIPMENT AND METHODOLOGY

The Ultraboost project was structured into three phases; Phase 2 comprised of testing the prototype engine, known as UB100, with simulated boosting control from a Combustion Air Handling Unit (CAHU) emulating the expected inlet and exhaust manifold conditions from the chosen boosting hardware. The third phase, UB200, included the specified boosting hardware on the prototype engine. Development progress is presented elsewhere with the work discussed in this paper from Phase 2 [1,2,3,4,5,6].

The engine was designed primarily by JLR and GE Precision Engineering with input from other consortium members and is based on an existing Jaguar Land Rover direct injection naturally aspirated gasoline V8 with extensive modifications having been made to incorporate features required for high output, four cylinder operation [7]. The engine design and control systems are described in detail in a publication by Turner et.al and therefore only briefly summarized here [8]. The downsized engine was equipped with a highly versatile combustion system, comprising of both port fuel injection (PFI) and 200 bar spray-guided direct injection (SGDI) for improved mixture preparation, volumetric efficiency, knock resistance and transient response. Additional features included high flow and tumble inlet ports, variable valve timing and cam profile switching on both the inlet and exhaust cam shafts to reduce the throttling requirement and to improve fuel economy and scavenging. Details of the engine and test cell are shown in [Table 1](#).

The intended boosting system was selected through a detailed investigation into a wide variety of systems available. The assessment criteria were based on both the technical requirements and customer needs. Two-stage, three-stage, parallel and series systems were all considered. A series two-stage system utilising a high-pressure supercharger and a low-pressure turbocharger was selected as the most suitable system. This configuration was found to deliver the required high boost pressure at high speeds whilst maintaining a good transient response at low engine speed. The engine control was performed by a prototype ECU.

The performance envelope of the engine was investigated at the Powertrain and Vehicle Research Centre (PVRC) engine test facility at the University of Bath. The expected high peak power output required the installation of a tandem dynamometer system comprising of an AC and an eddy current machine. The combustion air handling unit (CAHU) actively controls the inlet manifold pressure, air charge temperature and exhaust back pressure. The exhaust back pressure is controlled by a butterfly valve located on the exit of the exhaust manifold and is then used to replicate the pressure that would be expected due to the presence of a turbine. The facility also includes emissions measurement, combustion analysis equipment and dynamic fuel consumption measurement. In addition to these systems a EGR machine was developed to pump the cooled EGR gas into the inlet system.

Due to the CAHU using industrial compressors there is no low pressure point to reintroduce the EGR gas. The schematic in Figure 2 shows the gas path of the EGR pump.

Table 1. Ultraboost Engine Details [4]

Engine Details	
Engine Type	4 cylinder in-line, 4 valves per cylinder
Capacity (cc)	1991
Bore (mm)	83
Stroke (mm)	92
Compression Ratio	9.0:1
Firing Order	1-3-4-2
Construction	All-aluminum AJ133 cylinder block (right bank)
Combustion System	Pent-roof combustion chamber Asymmetrical central DI and spark plug High-tumble intake ports Auxiliary port-fuel injection (not used in these experiments)
Valve Train	Chain-driven double overhead camshafts, fast acting dual continuously variable camshaft phasers (DCVCP) Cam profile switching (CPS) tappets on inlet and exhaust
Specific Power	142 (kW/l) @ 6500 rpm
Specific Torque	255 (Nm/l) @ 3500 rpm
Maximum BMEP	~35 bar @ 3500 rpm and ~25 bar @ 1000, 6500 rpm
Other	External cooled EGR, Water cooled exhaust manifold 130-145 bar peak pressure limit
Engine Test Facilities	
Dynamometer	Twin dynamometer arrangement (AVL 215kW AC dynamometer and Froude AG250 Eddy current dynamometer)
Emissions Bench	MEXA 7000 Series with EGR
Cylinder Pressure Sensors	Kistler type 6054 (air cooled)
Cylinder Pressure Acquisition	AVL Indiset advanced 16-channel system

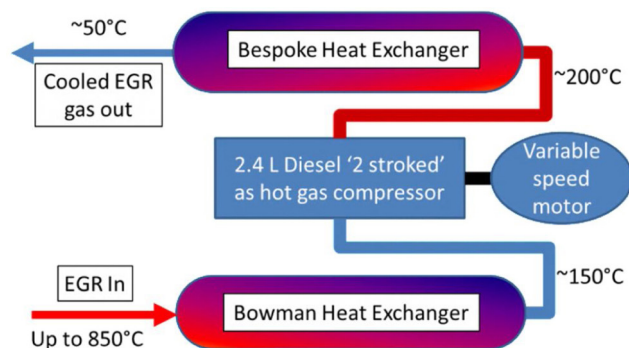


Figure 2. EGR pump schematic

Exhaust gas is sampled from post-exhaust back pressure valve and cooled through a Bowman heat exchanger prior to being compressed in a 2.4 litre diesel engine converted to two-stroke operation. The gas is cooled again before being reintroduced upstream of the inlet manifold to allow for adequate mixing. For catalyzed EGR the three way catalyst (TWC) from a single bank of the baseline V8 engine was placed in the system before the first heat exchanger. The compressor is coupled to a variable speed electric motor so the EGR flow rate can be controlled up to 20% across the engine speed range. The coolant supplied to this pump facility is independent of the engine coolant system therefore there is no additional impact of the cooled EGR on the engine coolant system. This system allows for exhaust gas from the experimental engine to be reintroduced into the high pressure intake system. The combined use of the EGR pump facility and the CAHU allows for a controlled investigation into the effect of different EGR rates at a number of engine speeds with independent control of all engine inputs. Figure 3 shows the engine setup as well as the test bed measurement locations for both temperature and pressure. Exhaust emissions are sampled both after the catalyst and analyzed using two Horiba MEXA 7000 units.

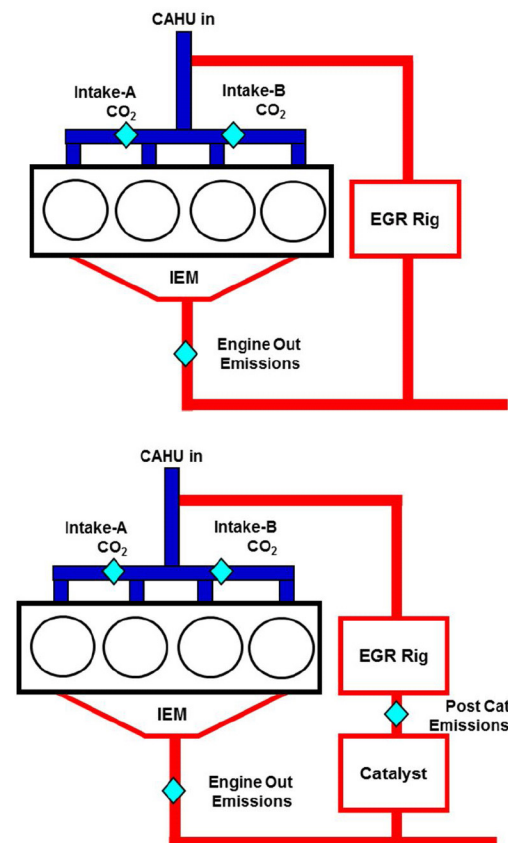


Figure 3. Engine setup and measurement points

For combustion analysis, each cylinder was fitted with an uncooled Kistler Type 6054 piezoelectric pressure transducer. In addition, each of the corresponding intake runners and the exhaust manifold exit were fitted with fast response uncooled and water-cooled pressure transducers respectively. High frequency data was recorded and analyzed using an AVL