

Octane Response in a Downsized, Highly Boosted Direct Injection Spark Ignition Engine

S.M. Remmert, R.F. Cracknell, R. Head, and A. Schuetze
Shell Global Solutions

A.G.J. Lewis and S. Akehurst
Univ. of Bath

J.W.G. Turner and A. Popplewell
Jaguar Land Rover

ABSTRACT

Increasingly strict government emissions regulations in combination with consumer demand for high performance vehicles is driving gasoline engine development towards highly downsized, boosted direct injection technologies. In these engines, fuel consumption is improved by reducing pumping, friction and heat losses, yet performance is maintained by operating at higher brake mean effective pressure. However, the in-cylinder conditions of these engines continue to diverge from traditional naturally aspirated technologies, and especially from the Cooperative Fuels Research engine used to define the octane rating scales. Engine concepts are thus key platforms with which to screen the influence of fundamental fuel properties on future engine performance.

'ULTRABOOST', a collaborative research project which is co-funded by the Technology Strategy Board (TSB), the UK's innovation agency, is a downsized, highly boosted, 2.0L in-line 4 cylinder prototype engine, designed to achieve 35% CO₂ emissions reduction without compromising the performance of a 5.0L V8 naturally aspirated production engine. To probe engine response to fuel, a matrix of 14 formulations was tested at several engine conditions. This is the first in a series of fuel related papers and focuses on the engine's response to the research octane number (RON). The knock limited spark advance was determined for a series of fuels with RON varying from 95 to 112; octane was shown to provide 5 or 10° crank angle advance in knock limited spark advance at 2000 and 3000 rpm, respectively. This study demonstrates that fuel octane quality continues to be important for the performance of emerging downsized engine technologies. Furthermore, the trend for continued engine downsizing will increase the potential performance benefit associated with knock resistant fuels.

CITATION: Remmert, S., Cracknell, R., Head, R., Schuetze, A. et al., "Octane Response in a Downsized, Highly Boosted Direct Injection Spark Ignition Engine," *SAE Int. J. Fuels Lubr.* 7(1):2014, doi:10.4271/2014-01-1397.

INTRODUCTION

Gasoline spark ignition (SI) engine development is driven in part by increasingly ambitious global targets for fleet-average CO₂ emissions. For example, European emissions legislation requires fleet average CO₂ emissions to meet 130g/km by 2015 and 95 g/km by 2020 [1]; while US policies will require CO₂ emissions targets of 101 g/km (163 g/mile) by 2025 [2]. Conversely, maintaining a vehicle's power and performance credentials is important to customers, especially in the premium vehicle market [3]. Therefore, a key area of engine research and development relies on improving combustion

efficiency and reducing losses, such that an engine's fuel consumption targets can be met without compromising performance.

Engine Downsizing and Ultraboost

While a variety of strategies exist for engine development to achieve improved efficiency [4], engine downsizing is a major industry trend that - in combination with pressure charging of the intake air - enables improved efficiency by running the engine at a higher specific output for the same torque at a given engine speed, yet reducing pumping and frictional losses [5, 6]. Similar or improved engine performance is often

maintained across the engine map through intake air charging strategies (super- and turbocharging), variable valve events, and cooled external exhaust gas recirculation (EGR) [4, 6].

'ULTRABOOST' is a collaborative research program, co-funded by the Technology Strategy Board (TSB), the UK's innovation agency, involving the following technical consortium partners: Jaguar Land Rover (JLR), Shell Global Solutions, Lotus Engineering, GE Precision Engineering, CD-Adapco, University of Bath, Imperial College London, and the University of Leeds, as outlined in [Table A.1](#).

The aim of the Ultraboost project was to develop an engine concept that - relative to a baseline 5.0L, naturally aspirated (NA) V8 Euro 5 production engine (the Jaguar Land Rover AJ133[Z]) - would be able to reduce tailpipe CO₂ emissions by 35% over the New European Drive Cycle (NEDC) in a Sports Utility Vehicle, without compromising performance. This ambitious CO₂ reduction target places the Ultraboost engine in the Euro 6-7 emissions class [8].

Fuel Octane & Engine Performance

Fuel chemistry, and particular fuel octane quality, can play a large role in the performance of SI engines, which can be achieved in part via optimal combustion phasing; namely, a sufficiently advanced spark timing (Minimum (advance) for Best Torque, MBT). Advancing the spark timing to MBT can be restricted by an abnormal combustion process known as knock - auto-ignition of the end gas ahead of the flame front - which limits performance and can cause engine damage in extreme cases [9]. Knock resistance of a fuel formulation is traditionally characterized by the Research Octane Number (RON) and Motor Octane Number (MON) scales as determined in a Cooperative Fuels Research (CFR) engine [10]. The RON and MON ratings for a fuel are defined by the volume percent of iso-octane mixed with *n*-heptane required to achieve the same knocking behavior.

Recent engine developments are increasing the gap between modern direct injection (DI), boosted technology and that of the CFR engine [11, 12]; especially in terms of the in-cylinder temperature and pressure history experienced by the end-gas ahead of the flame front, which drives engine knock response [4, 9, 11, 13, 14, 15, 16]. The Ultraboost concept engine is at the leading edge of downsized, boosted engine technologies, and is therefore a key platform from which to understand the impact of fuel octane quality on performance.

A series of experiments were performed with the Ultraboost engine on a Combustion Air Handling Unit (CAHU), for full control of experimental conditions, to probe the engine's response to various fuel properties. This paper is the first in a series of publications on fuel experiments with the Ultraboost engine. The focus of this study was to ascertain the influence of RON on engine performance, in order to evaluate the impact of octane in emerging, downsized engine technologies¹.

1. Fuels of varying RON and approximately fixed sensitivity (S=RON-MON) are

EXPERIMENTAL DESIGN

Engine Configuration

The Ultraboost engine design and control systems are described in detail in references [3, 6, 8, 17, 18], and therefore only briefly summarized here. The Ultraboost concept engine is a 2.0L (60%) downsized in-line, 4 cylinder engine constructed from one bank of the base AJ133 engine. The engine has a new cylinder head and combustion system, with variable valve timing, cam profile switching, both direct injection and port fuel injection (PFI) capabilities, and high flow and tumble inlet ports. Low pressure, cooled external EGR and a water cooled exhaust manifold (WCEM) are also key design features enabling the engine to be run under stoichiometric conditions for improved fuel economy.

Table 1. Ultraboost Engine Details [6]

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

Various boosting strategies have been investigated; to achieve performance across all engine speeds, a two-stage series super and turbocharger configuration with an inter- and after-cooler was chosen [8]. The CAHU at the University of

the subject of this investigation. A future communication will explore the effects of decoupling RON and MON.

Bath was used to simulate the integrated super- and turbo-charger system, for early-stage optimization of the combustion system and for the duration of the fuels experiments. Furthermore, throughout the fuels experiment, the engine was run in direct injection mode only (no PFI). Details of the engine and test cell are shown in [Table 1](#) and [Figure 1](#).

To meet the performance target of the base AJ133 engine, the Ultraboost engine was required to be charged up to 3.5 bar absolute and meet challenging brake mean effective pressure (BMEP) targets. The performance target of the Ultraboost engine in comparison to other engine concepts is shown in [Figure 2](#). Ultraboost engine development progress is presented elsewhere [3, 6, 8, 17, 18]; tests have shown that the Ultraboost target torque curve is achievable with the selected boosting system above 1500rpm due to the steep turbocharger run-up line [6, 19].

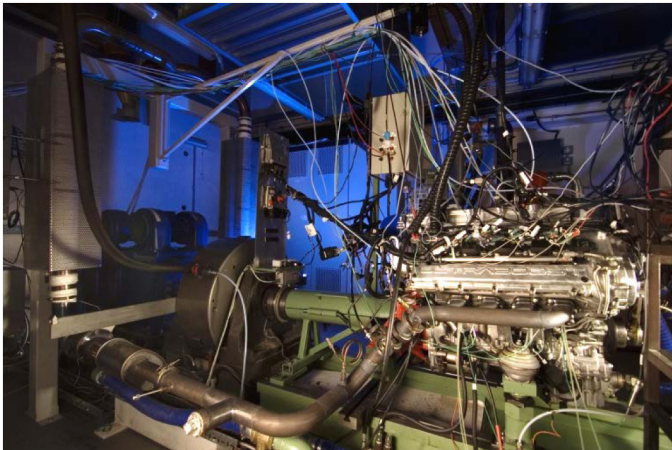


Figure 1. Ultraboost Engine Installed at University of Bath Test Facilities.

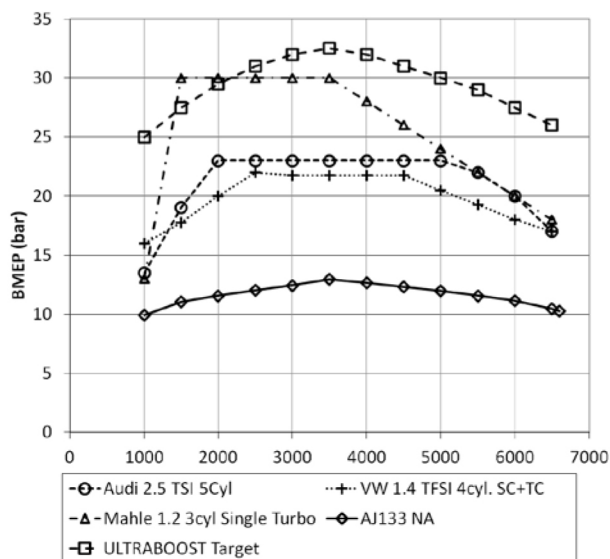


Figure 2. BMEP Performance Target of the Ultraboost Concept Engine in Comparison to Production and Concept Engines

Fuel Properties

A matrix of 14 fuels was tested in the Ultraboost engine, in order to probe the response of a highly boosted, downsized engine to a variety of fuel properties including octane, sensitivity, flame speed, and oxygenate content. The focus of this paper is on a subset of five of these fuels, chosen to probe the engine's response to octane (RON) as a means of understanding the potential performance benefit provided by premium octane fuels in emerging engine technologies. The results of the remaining fuels experiments will be the subject of future communications.

The details of the five fuels chosen for this experiment are shown in [Table 2](#). The "Base" fuel was used throughout the engine development process and is included as a reference case. The fuels vary in RON from the minimum EN228 compliant fuel (H) with a value of 95.1, to a very high octane fuel dosed with a synthetic octane boosting component (G), with a RON value of 111.6. Only fuels of similar levels of sensitivity are presented; from 10.1 to 12.6; the influence of fuel sensitivity on performance in Ultraboost is the subject of a future communication and is not discussed here.

The fuels vary in terms of oxygenate content; the Base fuel used in engine development contained 5% ethanol by volume, as did fuel H. Fuels I and G contained 0% ethanol, and Fuel B contained 10.5% methyl tert-butyl ether (MTBE). This variation in oxygenate content could contribute to differences in engine performance via charge cooling or flame speed; however, the auto-ignition properties of the fuel formulation are considered to be the dominant factor under high load, knocking conditions. Furthermore, the distillation properties of the fuel blends are relatively well matched, as shown in [Figure 3](#), with the exception of fuel G, which has an atypically low level of material boiling below 100°C (10%v cf. 60%v). Again, octane is considered to be the primary fuel property in this experiment, though distillation properties can affect spray formation and hence adequate mixing and efficient combustion [20].

Table 2. Details of Test Fuel Formulations

	H	Base	I	B	G
RON	95.1	97	98.7	101.4	111.6
MON	85	85.3	86.5	88.8	101.2
S	10.1	11.7	12.2	12.6	10.4
LHV (MJ/kg, gas)	43.0	43.1	43.3	42.2	42.4
Density (g/cm³)	0.748	0.743	0.735	0.754	0.795
Oxygenate Content	E5	E5	E0	10.5% MTBE	E0

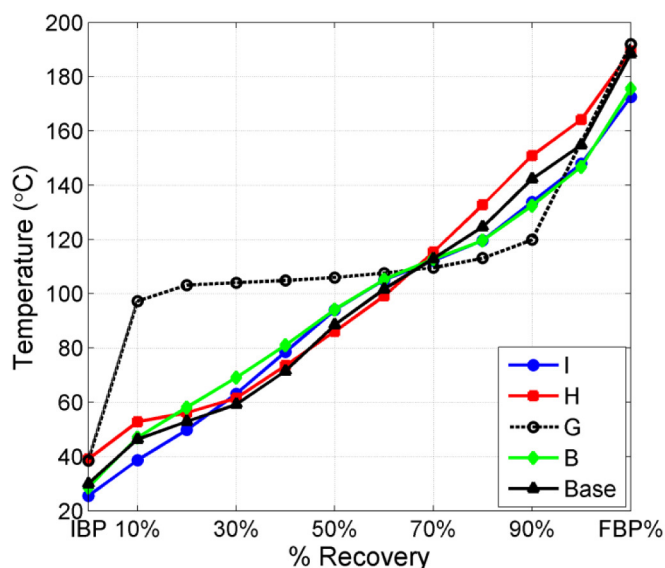


Figure 3. Distillation Properties of Test Fuels. Fuels have similarly matched properties with the exception of Fuel G.

Test Design

The full matrix of 14 fuel formulations was tested over a fixed cycle order of 8 engine test conditions, chosen to reflect different areas of engine operation. Each fuel was tested once, with the exception of the Base fuel, which was tested five times over the course of the experiment to evaluate repeatability. At four instances during the engine experiment (before the first four Base fuel repeats), lubricant was flushed to fresh semi-synthetic 5W-20 oil, followed by a 9 hour de-greening procedure with four repeats of the complete engine test cycle.

Approximately two experiments were performed per day; fuel test order was determined according to alternating high and low RON to aid in adequate determination of fuel flushing via engine stabilization of the knock limit. Approximately 1.5L of fuel was required to flush the engine system when running at the daily stabilization condition of 2000 rpm, mid-load.

Engine Test Cycle

The engine test cycle consisted of four target torque-speed conditions of the engine map as shown in Figure 4; a subset of these test conditions is given in detail in Table 3. These conditions were designed to investigate the fuel response properties of (1) the supercharged region of engine operation at low speed, high load, (2) the transition between non-boosted and boosted at low speed, mid load, (3) the transition between the super and turbocharged region of engine operation and mid-speed, high load², and (4) the turbocharged region of engine operation at high speed, high load.

2. Due to material limitations of in-cylinder pressure limits at advanced spark timings at the 3000 rpm high load condition, engine operation was adjusted as follows to allow for knock rather than pressure limited experiments: the air charge temperature was increased from 40°C to 60°C to increase the propensity to knock. The inlet cam phasing was also reduced to retard from 60° to 45° reducing the valve overlap and air flow so that KLSA was reached before maximum pressure limit. The BMEP achieved at 3000rpm for fuel matrix testing ranged from 19 to 27 bar across the spark sweep, whereas peak value for full

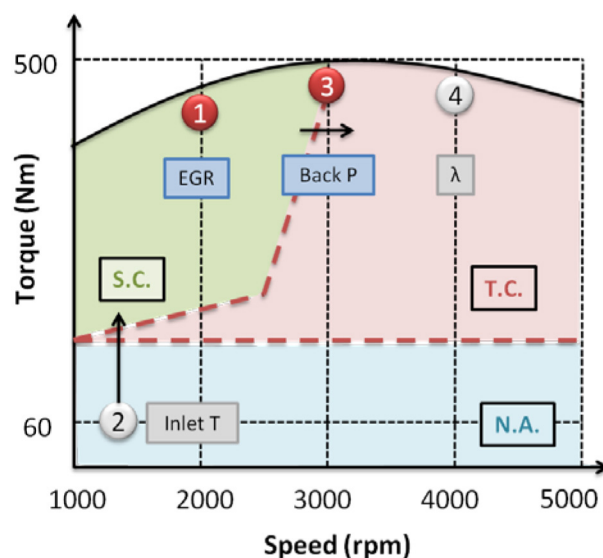


Figure 4. Schematic of Engine Test Cycle. (1) Supercharged bias with variable EGR; (2) Non-boosted with variable inlet air temperature, (3) Transition between super- and turbocharged bias with variable back pressure, and (4) Turbocharged bias with variable λ . (1) and (3) are the focus of the current study.

One parameter was varied at each of the four torque-speed conditions; at condition (1) the effect of percent external EGR was evaluated via test 1A (low) and 1B (high); at condition (2) the influence of boost temperature was investigated via 2A (low) and 2B (high); and at test condition (3) the influence of back pressure was evaluated via test 3A (low) and 3B (high). Finally, at test condition (4) the effect of lambda was evaluated via 4A (stoichiometric) and 4B (rich). Although the details of the full engine test cycle are discussed here for completeness, only the knock limited high load test conditions (1) and (3) are the subject of the current report.

The engine test cycle details for conditions (1) and (3) are given in Table 3. The torque target was set slightly lower than the maximum torque curve to avoid in-cylinder pressure limitations. At each of the four conditions, the boost pressure was set such that the target torque was met with the Base fuel; the boost pressure was subsequently held constant for all remaining fuel formulations tested at that engine condition. For 1B (10% EGR), the boost pressure was increased such that the Base fuel was able to achieve the same target torque as for 1A (0% EGR); this set the boost pressure conditions for all remaining fuels.

Each fuel was run through the test cycle in a fixed order: stabilization condition, 1A, 1B, 2A, 2B, 3A, 3B, 4A and 4B. At test conditions (1) and (3), the spark timing (ST) was advanced until the knock limited spark advance (KLSA) was reached, as determined by the average knock peak (KP) of the 4-cylinders, via the standard AVL algorithm³. At each of the ten recorded ST conditions, the engine was stabilized for 30 seconds before

load engine operation is 32 bar.

3. Knock peak is defined as the maximum knock amplitude of the band-pass filtered in-cylinder pressure trace.