

Octane Appetite: The Relevance of a Lower Limit to the MON Specification in a Downsized, Highly Boosted DISI Engine

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ABSTRACT

Market demand for high performance gasoline vehicles and increasingly strict government emissions regulations are driving the development of highly downsized, boosted direct injection engines. The in-cylinder temperatures and pressures of these emerging technologies tend to no longer adhere to the test conditions defining the RON and MON octane rating scales. This divergence between fuel knock rating methods and fuel performance in modern engines has previously led to the development of an engine and operating condition dependent scaling factor, K, which allows for extrapolation of RON and MON values. Downsized, boosted DISI engines have been generally shown to have negative K-values when knock limited, indicating a preference for fuels of higher sensitivity and challenging the relevance of a lower limit to the MON specification.

The Ultraboost engine is an inline-4 downsized, highly boosted prototype DISI engine designed to achieve a 35% reduction in CO₂ emissions whilst maintaining performance of a production V8. A series of 14 fuel formulations were tested to probe engine response to various fuel properties. This paper presents results from a 7 fuel RON and MON decorrelated matrix at four high-load engine conditions. The K-value was found to be negative at all engine conditions; fuels of higher sensitivity were found to yield improved engine performance. Furthermore, in-cylinder experimental data from high load knocking conditions with a single standard octane fuel were used to simulate the K-value; a similar trend between theory and experiment was observed.

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INTRODUCTION

Octane Appetite

Modern spark-ignition engine development is driven by the balance between meeting emissions legislation and maintaining vehicle performance to meet consumer demand. For a given engine configuration and operating condition, efficiency and performance can best be achieved via a sufficiently advanced spark timing (Minimum (advance) for Best Torque, MBT) that allows for optimal combustion phasing. Fuel formulation can have a direct impact on an engine's ability

to achieve MBT and hence optimal performance, as the spark advance can be restricted by potentially damaging auto-ignition of the end-gas ahead of the flame front, known as knock [1].

A fuel's knock resistance is historically characterised by the research octane number (RON) and motor octane number (MON) determined in a Cooperative Fuels Research (CFR) engine [2]. RON and MON are assigned by determining the volume percent of iso-octane in a binary mixture with n-heptane -the resulting mixture known as a primary reference fuel (PRF) - required to reproduce the knocking behaviour of a

real fuel. The MON test uses a higher temperature, lower manifold pressure and higher engine speed condition than RON, as shown in [Table 1](#).

Table 1. CFR Engine Conditions for RON and MON Tests

Property	RON Test	MON Test
ASTM Method	D-2699	D-2700
Engine Speed (rpm)	600	900
Intake Temperature (°C)	52	149
Spark Advance (CAD aTDC)	-13	-19 to -26

Due to specific equilibrium chemistry resulting in non-Arrhenius reaction rate for the ignition delay behaviour between 650-900 K, paraffinic fuels exhibit increased knock-resistance under MON conditions and therefore have low sensitivity, defined as $S = RON - MON$ [2, 3]. Real fuels - which also contain olefins and aromatics - do not exhibit negative temperature coefficient (NTC) behaviour and thus have higher fuel sensitivity. This phenomenon highlights two problems with the industry standard octane rating method: (1) the rating scale is defined by paraffins, which do not represent the auto-ignition behaviour of a real fuel, and (2) the knock propensity of a real, sensitive fuel depends on the in-cylinder temperature and pressure history which can change with engine design and operating condition.

Modern engines tend towards downsized, direct injection technologies, with increased charging, and employ the highest compression ratios consistent with this charging. Direct injection, more efficient breathing and improved inlet system, head and block design to reduce charge heating, all result in higher pressures and lower temperatures in-cylinder for modern engines relative to the traditional RON and MON tests [4]. Furthermore, inter-cooling and the introduction of cooled external EGR to the cylinder will decrease the temperature for a given pressure even further [5]. Due to the apparent disconnect between modern engine conditions and the CFR engine - on which the octane rating scales are defined - a series of recent studies have called into question the relevance of the RON and especially MON specifications in predicting fuel knocking propensity [1, 3, 4, 6, 7, 8, 9].

To extrapolate RON and MON test results to relevant engine conditions, it is useful to define the octane index (OI) as a linear combination of RON and MON with an engine condition dependent weighting factor, K [1]:

$$OI = RON - K \times (RON - MON) = RON - K \times S \quad (1)$$

The K-value is thought to be dependent only on the in-cylinder temperature and pressure history experienced by the end-gas prior to the onset of auto-ignition. OI defines a PRF composition with the same auto-ignition behaviour as a real fuel *at a given engine operating condition*; the higher the OI of a given fuel, the more resistant it is to knock [7].

As can be seen in [equation \(1\)](#), the OI is equivalent to RON or MON when $K=0$ or $K=1$, respectively. K is traditionally assumed to be positive; indeed, the anti-knock index (AKI) of the US market is equivalent to OI when $K=0.5$. However, studies in research engines [1, 3, 9] and a fleet of 23 vehicles (model years 1994-2001) [6] have shown that K is often negative. A negative value of K implies that OI exceeds RON for fuels of greater sensitivity, indicating a lower MON value yields greater knock resistance and hence engine performance [10]. Past studies on direct injection spark-ignition (DISI) vehicles [3] have indicated that K decreases for more knock-prone engine conditions, increases with engine speed, and decreases with end-gas temperature for a given pressure. Furthermore, a recent study in a 2007 turbo-charged, direct injection vehicle showed a dependence of the K-value on boosting conditions despite part-load conditions indicating a positive K-value: at full load, wide open throttle (WOT) test conditions, the K-value was found to be negative. As knock is more prevalent at WOT these results are consistent with improved vehicle performance with fuels of high sensitivity [11].

Ultraboost

The Ultraboost project was a collaborative research program involving five industry partners and three universities as specified in [Table A.1](#), co-funded by the UK's innovation agency, the Technology Strategy Board. The aim of the programme was to develop a downsized, boosted engine technology capable of offering a 35% reduction in fuel consumption relative to a production V8 engine, the AJ133 [12], over the New European Drive Cycle (NEDC) in a 2010MY Range Rover vehicle, while maintaining performance and transient response.

Engine design and control system are presented in detail in references [13, 14, 15] and therefore only briefly described here. To achieve a 35% reduction in CO₂ emissions yet maintain the performance of the baseline AJ133 engine (5.0L, naturally aspirated, V8), an inline-4, 2.0L (60% downsized) engine was constructed from one bank of the base engine. A new cylinder head and combustion system were designed, with variable valve timing, cam profile switching, high flow and tumble inlet ports, and both direct injection (DI) and port fuel injection (PFI) capabilities. Cooled external exhaust gas recirculation (EGR) and a water cooled exhaust manifold (WCEM) were also incorporated. Much research has gone into the boosting system, which was designed to be a two-stage series super and turbocharger configuration with an inter- and after-cooler. However, early combustion system optimisation was performed with a charge air handling unit (CAHU) at the University of Bath to simulate the effects of integrated super and turbochargers. To meet the performance target, the first phase of engine development performed with the CAHU was required to meet a 35 and 28 bar BMEP target at 3000 and 2000 rpm, respectively, requiring air charging up to 3.5 bar absolute.

As the Ultraboost concept engine is at the leading edge of downsized, boosted engine technologies, it is useful to understand fuel effects and their impact on performance. In particular, as Ultraboost is expected to have reduced in-cylinder temperature and increased pressure compared to current engines, understanding the octane appetite of this engine provides the opportunity to evaluate the relevance of RON and MON specifications in emerging engine technologies.

In this paper, a series of fuels experiments are described in which air is delivered to the Ultraboost concept engine using a CAHU to simulate the boosting process. An overview of the results on engine response to RON and final engine performance results have been presented in references [16, 17]; this paper follows [16] to describe experimental and theoretical evaluation of the engine's K-value at key regions of engine performance.

EXPERIMENTAL PROCEDURE

Engine Details

The details of the Ultraboost engine and University of Bath test cell are given in [Table 2](#) and the engine installed on the CAHU is shown in [Figure 1](#).

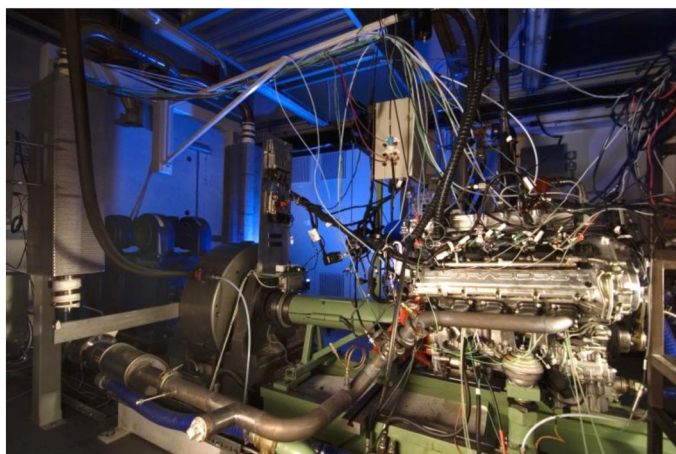


Figure 1. Ultraboost Engine on the dynamometer at the University of Bath

In [17], the engine was shown to provide a 15% improvement in fully-warmed-up fuel economy over the baseline AJ133 V8 which; when friction and engine warm-up were taken into account, together with other secondary vehicle changes, this translated into a >35% reduction in vehicle tailpipe CO₂ on the NEDC. This was achieved using the standard 95 RON pump gasoline which Shell provided throughout the programme for the base engine development programme. Full details of the project and the technologies employed on the Ultraboost engine are provided in [17].

Table 2. Ultraboost Engine and Test Facility Details [18]

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 Auxillary 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 in-cylinder 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

Fuel Properties

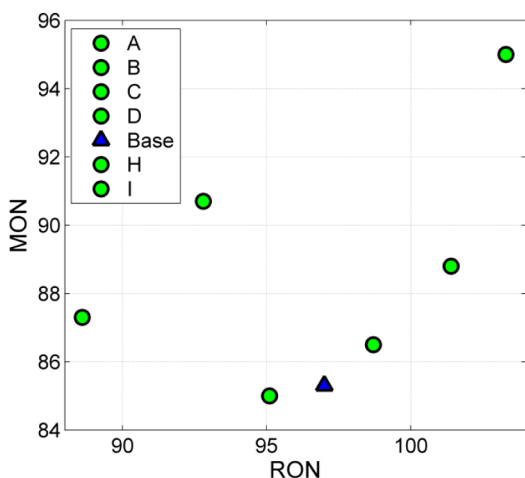
This experiment involved a matrix of 14 fuels designed to screen the Ultraboost engine for performance response to various fuel properties. A subset of 7 of these fuels ([Table 3](#)) were formulated to investigate the octane appetite of Ultraboost via decorrelated RON and MON properties ($R < 0.43$), as shown in [Figure 2](#). Though the influence of RON and MON were considered to be the dominant factors in determining engine performance at the knock limit, it should be noted that these fuels also differ by other properties. Base and H are EN228 compliant E5 gasoline fuels; I is an EN228 compliant E0 gasoline. A-D were specifically formulated for maximum RON and MON differences, and are generally not EN228 compliant: A, C and D have low E70¹ and Reid Vapour Pressure (RVP) values; C and D have low densities, and B has slightly high aromatic content. Furthermore, A and B contain methyl-*tert*-butyl ether (MTBE). To further understand fuel differences, the distillation properties of the fuels are listed

1. Evaporated volume at 70 °C

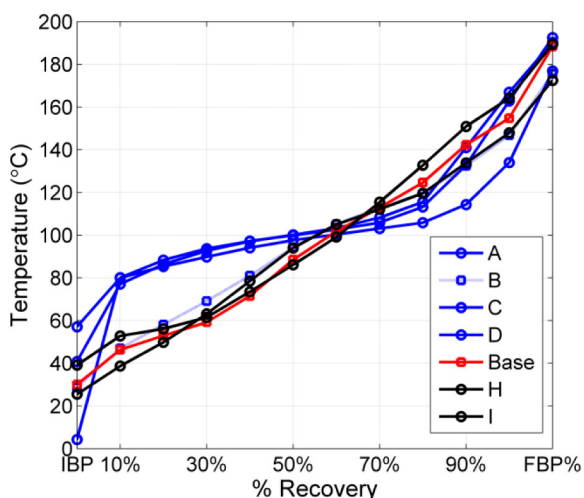
are shown in Figure 2. While Base, B, H and I show similar distillation behaviour, A, C and D are less volatile at low temperatures.

Table 3. Select Properties of Fuel Test Matrix

Fuel	Base	A	B	C	D	H	I
RON	97	103.3	101.4	92.8	88.6	95.1	98.7
MON	85.3	95	88.8	90.7	87.3	85	86.5
S	11.7	8.3	12.6	2.1	1.3	10.1	12.2
Oxygenate Content	E5	14% MTBE	10.5% MTBE	E0	E0	E5	E0
LHV (MJ/kg, gas)	43.1	42.6	42.2	44.3	44.2	43.0	43.3
Density (g/cm ³)	0.743	0.732	0.754	0.703	0.704	0.748	0.735



a. Decorrelated Matrix of RON and MON Fuels. (Correlation coefficient 0.43).



b. Distillation Properties of K-Value Matrix Fuels

Figure 2. Fuel Properties. (a) RON and MON correlation and (b) Distillation properties

Experimental Design

Engine Test Cycle

Four target torque-speed conditions of the engine map were chosen for the fuels experiments, as shown in Figure 3. These conditions were chosen to reflect (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 turbo-charged region of engine operation at mid-speed, high load², and (4) the turbo-charged region of engine operation at high speed, high load.

For each of the four torque-speed conditions, one parameter was varied to probe:

1. The effect of external EGR at (1), via test 1A (low) and 1B (high).
2. The influence of boost temperature at (2), via 2A (low) and 2B (high).
3. Back pressure effects at (3) via test 3A (low) and 3B (high).
4. Effect of lambda at (4), via test 4A (stoichiometric) and 4B (rich).

Though the full experimental procedure is described here, the results of test region (1) and (3) only are the focus of the current paper, as these knocking regions of the engine map were used to determine the engine K-values. The detailed engine test conditions are given in Table 4. The target torque was set to be slightly lower than the torque curve target at this engine speed due to in-cylinder pressure limitations. The boost pressures used for the 0% and 10% EGR conditions at test point (1) were set such that similar torques could be achieved at both EGR rates. The boost pressures were initially set with the engine running on base fuel and the chosen boost pressures were subsequently imposed for all remaining fuel formulations

Each fuel was run through the test cycle in a fixed order: 1A, 1B, 2A, 2B, 3A, 3B, 4A and 4B. At test conditions (1) and (3), spark timing (ST) was varied until knock limited spark advance (KLSA) was approximately reached. KLSA was determined by the average knock peak (KP) of the four cylinders as computed via the standard AVL algorithm for knock identification³; 10 data points from the initial ST to the KLSA were collected. Within each test condition and ST value the engine was stabilised for 30 seconds before measurement. In-cylinder data (ST, KP, mean effective pressure, maximum in-cylinder pressure, and combustion phasing) was collected and averaged over 10 seconds

2. Due to material limitations of in-cylinder pressure limits at the 3000 rpm condition, the engine operation condition was adjusted to allow for knock limited, rather than in-cylinder 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 maximum BMEP at this operating condition is 32 bar BMEP; the BMEP at this test condition ranged from 19 to 27 bar across the 50% to 90% recovery range.

3. Knock peak is defined as the maximum knock amplitude of the 5kHz - 25kHz band-pass filtered in-cylinder pressure trace.