

A Miller Cycle Engine without Compromise - The Magma Concept

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ABSTRACT

The Magma engine concept is characterised by a high compression ratio, central injector combustion system employed in a downsized direct-injection gasoline engine. An advanced boosting system and Miller cycle intake-valve closing strategies are used to control combustion knock while maintaining specific performance. A key feature of the Magma concept is the use of high CR without compromise to mainstream full-load performance levels. This paper focuses on development of the Magma combustion system using a single-cylinder engine, including valve event, air motion and injection strategies.

Key findings are that Early Intake Valve Closing (EIVC) is effective both in mitigating knock and improving fuel consumption. A Net Indicated Mean Effective Pressure (NIMEP) equivalent to 23.6 bar Brake Mean Effective Pressure (BMEP) on a multi-cylinder engine has been achieved with a geometric compression ratio of 13:1.

Comparison of weighted key point cycle predictions for the downsized Magma concept vs a contemporary baseline engine, indicates fuel consumption savings over WLTC and FTP-75 of 12.5% and 16.4% respectively.

The cost / benefit trade-off is currently being refined, but the position in terms of cost per gram per mile of CO₂ benefit appears to favour a Magma solution over other options. Part of the benefit arises from the current assumption that a 2.0 litre L4 engine is replaced with a 1.5 litre L3 which is enabled by the higher specific rating of the Magma concept. The reduction in base engine cost offsets some of the additional air handling equipment.

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INTRODUCTION

Improvements in gasoline engine fuel economy are a key element in achieving fleet average vehicle CO₂ requirements. Many approaches for improved efficiency have been proposed, with varying implications for vehicle cost, performance, packaging, and after-treatment requirement. Two main solutions have evolved in production engines in recent years [1]:

- High efficiency naturally aspirated engines utilising high compression ratio, modified inlet valve closing strategies, and/or cooled exhaust gas recirculation, for high efficiency at lower specific rating

- Highly boosted, downsized engines for part load efficiency with relatively high specific rating

If a high compression ratio and advanced valve-timing strategy could be combined with downsizing and boosting, it may be possible to obtain the efficiency benefits of both approaches, without compromising full-load performance.

There are nevertheless challenges with this approach, particularly combustion knock which increases with compression ratio [2]. This would typically entail reduced load and retarded combustion phasing, leading to poor specific performance and the thermodynamic efficiency. The solution originally proposed by Ralph Miller is to mitigate knock

by using valve timing to reduce in-cylinder effective compression ratio, whilst maintaining the efficiency benefits of a high expansion ratio [3].

The history of Atkinson and Miller cycle engines is reported by the authors in a previous Magma technical paper [2], and in a number of comprehensive review papers [4,5]. Contemporary application of the Miller cycle can be seen in a number of recent production engines [6, 7, 8, 9, 10, 11, 12, 13]. Some of these engines employ a conventional geometric compression ratio and use LIVC in order to reduce pumping losses under part-load conditions [6, 7, 8]. LIVC is achieved using a hydraulic cam phaser with an intermediate lock position that allows moderate retard angles. The boosting systems employed are conventional, consisting of a single waste-gated turbocharger.

In other current engines the geometric compression ratio is increased significantly, to 11.7, 12.5 or even 13:1 [9, 10, 11, 12, 13]. These engines use either short intake-valve opening durations to achieve EIVC (in some cases with cam-profile switching), or LIVC again through retarded intake cam phasing. Thermodynamic efficiency improvements from an increased compression ratio are reported, but generally with reduced specific performance.

The Magma concept seeks to deliver these part-load fuel efficiency benefits while maintaining full-load specific performance. This paper presents results achieved using a single-cylinder research engine, over a wide operating range. Test methodology is outlined, and results are presented and discussed. It explains where the benefits of the concept originate from based on the phenomena observed. Where limitations exist, mitigating actions are considered. It concludes by comparing fuel consumption on a drive cycle basis with a baseline engine using weighted key point results.

ENGINE CONCEPT

The Magma engine is the subject of previous Ricardo papers [1,2,14], where development of the concept is described using simulation tools and initial engine testing. Key elements include:

- High compression ratio
- Miller cycle inlet valve closing strategy
- Increased boost pressure

It can be described as a deeper application of existing Miller cycle concepts, using the high boost pressure to further enable increased compression ratio and more extreme valve events at higher loads. The compression ratio was chosen to deliver maximum benefit from increased expansion work, before the negative effects of heat loss via increased surface to volume ratio begin to dominate.

With such high compression ratio, knock mitigation becomes essential in order to maintain specific load. In this case, knock is mitigated via early closing of the inlet valve to reduce the effective compression ratio in the cylinder.

At low-load operating points, short inlet-valve opening duration is used to regulate airflow with less throttling required. This leads to a reduction in pumping work, further increasing the fuel consumption benefit.

In order to maintain the required airflow with shorter inlet cam duration charge pressure is increased substantially. The air system configuration was the subject of a previous 1-D simulation study [2], using compressor maps from series production turbochargers and superchargers. This study concluded that a supercharger and turbocharger in series would provide the necessary pressure and flow rate without excessive exhaust back-pressure.

Inter-stage charge cooling is used to counteract the expected temperature rise associated with a high overall pressure ratio. This means inlet manifold temperature is no higher than with a single-stage boost system. It is significant that this additional cooling occurs outside the cylinder. Some of the extra piston compression work associated with the higher compression ratio is transferred to the boost system, thereby allowing cooling to occur before the air enters. The net result is a charge temperature at the end of compression that is lower than would be the case if all the compression work had been carried out by the piston. Charge temperature at end of compression is a key factor in propensity to knock.

The overall effect of these combined elements is an engine with significantly reduced fuel consumption across the speed load range, whilst maintaining peak BMEP.

EXPERIMENTAL SET UP

Experiments were conducted using a Ricardo Hydra single-cylinder spark-ignited research engine with direct injection and dual variable valve timing. The piston crown, cylinder head, and cam profiles were specifically designed for the Magma concept.

The engine was controlled using a Ricardo r-Cube2 engine control unit via calibration tool software and an injector driver. Fuel injection equipment comprised a centrally mounted multi-hole solenoid fuel injector and pump delivering 200 bar fuel pressure. The injector has six holes and a static flow-rate of 17.5 cc/s.

Key parameters of the test engine are shown below:

Displacement volume / No. cylinders	0.5 litres / 1 cylinder
Stroke	90 mm
Bore	84 mm
Number of valves	4
Compression ratio	13:1
Tumble ratio, R_t	0.8 - 2.8

Valve timing is illustrated in Fig. 1, showing inlet and exhaust cam in both parked and fully phased positions.

The engine (Fig. 2) was installed in a research test facility with an external high-pressure air supply. Suitable measures were put in place to reduce the air system pulsation associated with a single-cylinder engine. An inlet throttle was used to control airflow at the non-

boosted test points where necessary. A high-speed data acquisition system was installed to accurately measure cylinder pressure, and inlet / exhaust pressures on a crank angle basis.

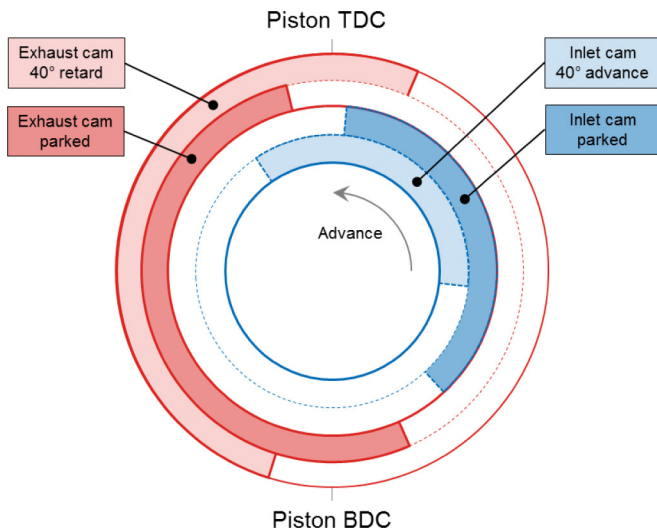


Figure 1. Cam timing diagram including phasing range; opening and closing points are shown for 1 mm valve lift

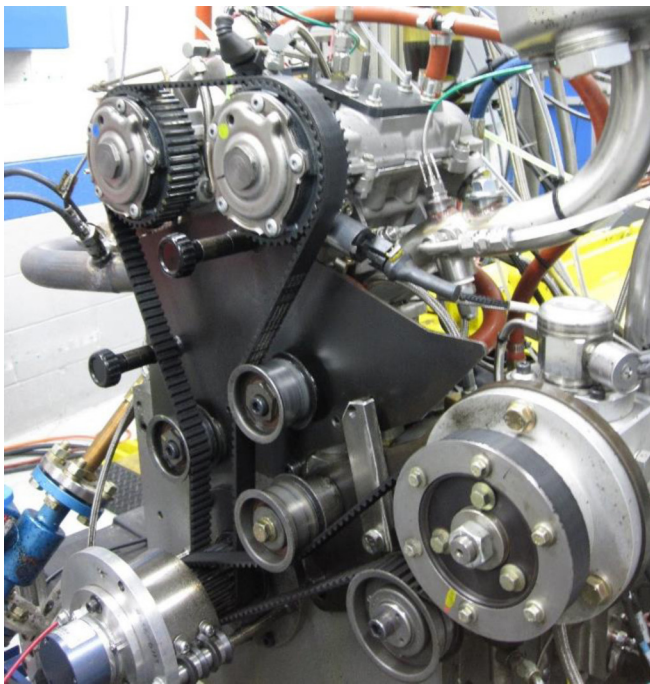


Figure 2. Hydra single-cylinder research engine installed in the research test facility

METHODOLOGY

Testing Approach

A range of steady-state tests were carried out at key operating points in order to characterise the combustion system and provide data for comparison. At each point the following parameters were optimised for best net indicated specific fuel consumption at part load, or highest achievable IMEP at full load:

- Exhaust and inlet cam phasing
- Injection timing
- Ignition timing

Fuel and air flow were controlled to maintain load and air-fuel ratio to stoichiometry measured by downstream lambda sensor. Air flow was controlled using an inlet throttle at lower loads, and inlet air pressure control at higher loads when the throttle was fully open.

All optimisations were carried out in adherence to Ricardo guidelines for parameters such as knock and combustion stability. For full-load operation at 2000 rev/min a peak knock amplitude of 2 bar was applied (measured over 300 cycles), and at 4000 rev/min the limit was 4 bar. A limit of 3% for coefficient of variation (CoV) of NIMEP was applied in all cases.

Key Point Selection

Using the Ricardo internal tool V-SIM, a vehicle model was created in a MATLAB / SIMULINK environment for a D-segment vehicle and simulated over the WLTC and FTP-75 drive cycles.

V-SIM models are forward looking models and operate by the following computation process: a drive cycle or any other vehicle cycle is entered into the driver model; the driver model returns a torque demand from the powertrain; torque propagation is then performed between the engine - acting as the power source - and the vehicle wheels, using vehicle energy balance equations accounting for vehicle systems friction and efficiency, aerodynamic drag and road gradient.

The output from this simulation was an engine speed vs. load trace. A common set of key-points was generated based on residency time and cycle fuel consumption contribution. For each cycle, a set of key-point weighting factors were derived (Table 1).

In addition to the six part-load key points, a further three points were chosen at full load:

Table 1. Key points selected for testing and comparisons with baseline

	Engine speed [rev/min]	BMEP [bar]	FMEP [bar]
Part load	1500	4	0.63
	1500	10	0.67
	2000	2	0.71
	2000	8	0.74
	2000	14	0.77
	3000	8	0.93
Full load	1500	20	0.90
	2000	25	1.07
	4000	25	1.25

The part load points were used to predict cycle fuel consumption over the WLTC and FTP-75 drive cycles for the D-segment vehicle, using the weighted key point method.

For single cylinder engine testing, IMEP operating conditions equivalent to the appropriate BMEP levels for a multi-cylinder engine were set.

A friction model was built of the Magma concept using the Ricardo internal toolset for friction analysis known as FAST. The FAST model provided a Friction Mean Effective Pressure value for each key point.

The FAST methodology uses a semi-empirical equation approach to build a friction model for engine architectures in a time efficient way. FAST builds on the methods of Sandoval, Heywood et al. [15, 16], with the following enhancements:

- Correlated to measured data from modern engines
- Ability to calculate friction under fired conditions as well as motored
- Ability to deal with systems not otherwise considered (e.g. balancer shafts, vacuum pump)
- Physics-based treatment of piston and rings (enables user to examine effects of ring tension, connecting rod length etc.)

The BMEP value minus the FAST FMEP lead to an NIMEP for each key point. The Ricardo 1-D WAVE model of the Magma concept was interrogated to provide Pumping Mean Effective Pressure (PMEP) at each key point and supercharger impact on GIMEP if a contribution was required. Therefore, the initial boosting conditions and GIMEP level were defined.

Baseline Comparison

A comparison was made with conventional engine technology by replacing the Magma fuel consumption data with that of a baseline engine from the Ricardo benchmark database.

Trend analysis suggests that the mainstream (i.e. highest manufactured volume) 2016 rating for such a product in a D-segment vehicle is ~135 kW. In 2022 it will be ~140 kW (neglecting the impact of incoming electrification).

The baseline selected is thus a representative downsized, boosted gasoline direct injection engine, of 2.0 litres and 140 kW. It has dual variable valve-timing and a compression ratio of 10.5:1. Comparisons between Magma and the baseline were made at a number of key operating points, and WLTC and FTP-75 cycle prediction comparisons were made.

Tests Conducted

Exhaust Orifice Selection

An initial set of tests were carried out to assess the exhaust blow-down phase, comparing high-speed cylinder pressure data to that of a multi-cylinder engine. An exhaust orifice was fitted to better simulate the damping characteristics of a turbine and waste-gate. A range of exhaust orifice sizes were tested, and a 28 mm diameter orifice was selected as this gave effective damping of the pressure pulses without excessive restriction.

Cam Phasing Matrices

At all key-points the effect of cam timing was investigated. Inlet cam phasing swings were conducted at a range of exhaust cam phasing positions.

Injection / Ignition Timing Swings

To ensure comparison at optimum settings, an injection timing swing was performed at each key-point using the previously defined optimum cam phasing. At each point in the swing the ignition timing was set according to best SFC, or limited by knock in some cases. A further ignition timing swing was performed at the optimum injection timing to fully characterise the response at the optimum point.

RESULTS AND DISCUSSION

Test results achieved using the single cylinder research engine are presented and discussed here.

Air Motion

One of the key challenges arising from the application of EIVC is the impact on air motion. The combination of EIVC and high geometric compression ratio can impact air motion as follows:

- Short cam duration - reduced period for tumble formation
- Early valve closing - increased period for tumble decay
- Reduced peak lift - tumble formation is reduced at lower lifts
- Flatter combustion chamber - affects the transition from solid body rotation to turbulence, increasing collapse of air motion leading to lower turbulent kinetic energy at ignition timing

Each of these factors needs to be addressed to avoid challenges associated with insufficient air motion. These could include extended ignition delay, slower combustion, and greater cycle to cycle variability. Consequences manifest themselves as unstable combustion, particularly at low load, and increased peak knock at higher load. The measures required to mitigate this, such as retarded combustion phasing, increase fuel consumption.

To assess this impact of air motion in the context of EIVC and high compression, two port designs were developed as shown in Figs. 3 and 4.

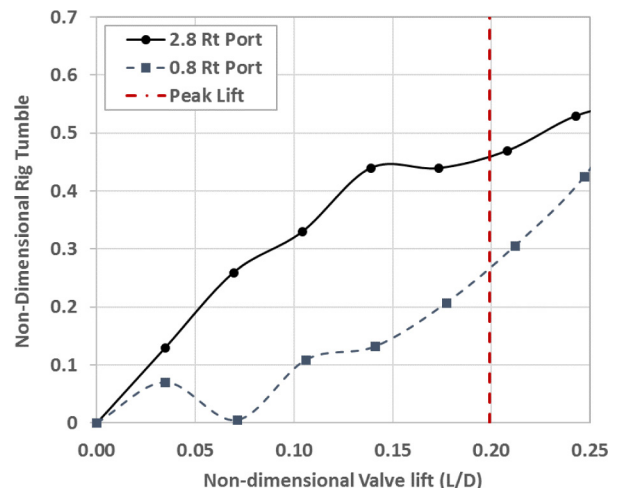


Figure 3. Port tumble ratio (measured on an airflow rig) vs non-dimensional valve lift, for two ports compared