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A Fresh Approach to the Design of Clean Engines for the Performance Motorcycle Market

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Until the early to mid 1990’s the engine of choice for off road and recreational vehicles were mainly 2-stroke engines due to the superior power density and Wide Open Throttle (WOT) torque characteristics. With the introduction of increasingly more stringent emission control requirements there has been a large swing to 4-stroke engines. In recent years there has been significant development to improve the power density of the 4-stroke engine in an effort to match the performance 2-stroke engine, however at a compromise to the torque characteristics and the manufacturing and maintenance cost of the engine. This paper looks at a fresh approach to develop a new concept engine to deliver a better compromise between the 4-stroke and existing carburettor 2-stroke characteristics, and provides early experimental results from the development work for a preferred WOT torque characteristic.

Keywords: Performance Engine, 2–stroke, 4-stroke, Direct Injection, Recreational Vehicle Application

1. INTRODUCTION

The past 20 years has seen a significant evolution of engines to suit the off-road motorcycle and All Terrain Vehicle (ATV) markets.

Not only has the introduction of increasingly more stringent emission requirements driven the engine development, but also the customer expectations in terms of functionality, ease of use, Noise Vibration and Harshness (NVH) and performance. The introduction of Engine Management Systems (EMS) has further enabled increased functionality such as transmission control, braking systems in some applications. Given that today’s customer is much more familiar with the added functionality and refinement of the automotive products, the expectation of refinement and ease of use of the off-road and ATV products is increasing, with the expectation that the performance and ‘fun’ factor is not compromised.

Prior to the introduction of emission requirements, the 2-stroke engine was the preferred engine for these applications, due to the superior power density, the superior WOT peak torque and lower manufacturing cost. The drawbacks of the 2-stroke engine were in the emissions, the exhaust smoke, poor fuel consumption and frequent ‘4-stroking’ uneven combustion.

As the emission requirements were introduced, there has been a swing to high performance larger displacement 4-stroke engines. The basic 4–stroke engine has exhaust emission control and fuel economy/range advantages, however with compromised engine power and torque density. In recent years, in order to generate the explosive power to weight ratios achieved by highly tuned 2-stroke engines, the manufacturers have developed 4-stroke engines with higher displacement in conjunction with high engine speeds in order to compete with their 2-stroke counterpart. The requirement for light weight and high engine speeds to achieve the power requirement has also ultimately led to the development of multi-valve 4-stroke engines which call for the use of high cost materials and complex assembly which in turn require very regular service intervals to ensure engine performance and durability.

During the same period as the high performance 4-stroke engines were being developed, in response to the emission regulations practical and affordable direct injection was also being developed for 2-stroke engines (ref 1, 2, 3, 4). Direct injection (DI) addressed many of the issues of the traditional 2-stroke engine such as the short circuiting of unburnt hydrocarbons and the misfiring combustion under light load conditions. Subsequently, further investigations and developments have been carried out to enhance the power density capabilities of the direct injected 2-stroke engine (ref 5, 6) with specific power densities of 120 kW/litre shown whilst providing emission control (ref 5).

Recent research and development into improved efficiency engines have proposed new concepts that take in the best parts of various engine types, rather than dividing into the traditional thinking of 2 or 4-stroke, spark ignition or compression ignition. Concepts such as engine upsizing of direct injected 4-stroke motorcycle engines for fuel efficiency gains (as opposed to downsizing) and alternative engine configurations for efficiency gains have been examined and presented (ref 7 and 8).

This paper includes a basic comparison of the key performance characteristics of the existing high performance carburetor 2-stroke and 4-stroke products in the range of 250-450cc displacement single cylinder engines. These characteristics are then compared to those of a proposed new Orbital concept engine. This new engine concept study covers the advantages of the low emissions and fuel economy benefits of direct injection, and goes on to demonstrate the potential for a fresh approach to the design of a lightweight high performance single cylinder engine, which could deliver significant benefits over the equivalent powered 4-stroke and 2-stroke engines of today. This has the potential to open up opportunities to develop new DI engines for both off-road and on-road applications.

2. CURRENT ENGINE CAPABILITY

Current FIM regulations (ref. 9) for enduro motorcycles define the classes according to displacement and engine type, in the Enduro 2 category the designation is up to 250cc 2-stroke or up to 450cc 4-stroke. These race class designations have had a significant influence over the design and development of the products in this motorcycle market, which does not always lead to the best outcome for the customer outside of the racing field. The typical specific power and torque for a modern 450 cc high performance 4-stroke engine is shown in figure 1.

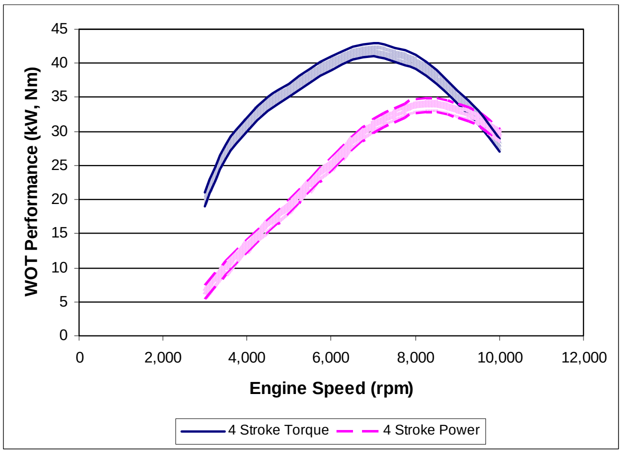

Figure 1: Typical WOT Power and Torque of a Modern High Performance Single Cylinder 4-Stroke Engine

As discussed previously to achieve these power levels significant engine development has been carried out to increase the power density. The peak power engine speed has increased, and use of high cost materials such as titanium valves (ref 10) are becoming common to assist the engine in achieving durability at high engine speeds.

Whilst the torque curve is certainly flatter than a high performance 250cc 2-stroke engine, it is still 'peaky' compared to many lower powered conventional 4-stroke engines, and does not offer the flat torque curve which can be beneficial for many off highway applications where torque and control are equally as important as power.

In comparison, the typical specific power and torque of a smaller displacement 2-stroke engine competing in the same racing classification as the 450 cc 4-stroke is shown in figure 2. High rpm and highly tuned exhaust systems produce a more narrow power band common in this type of engine.

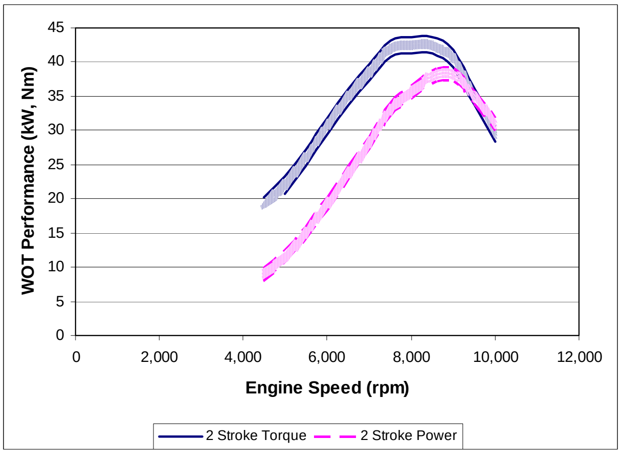

Figure 2: Typical Power and Toque of equivalent classification Single Cylinder 2-Stroke Engine

3. CONCEPT ENGINE

3.1 DESIRED CHARACTERISTICS

Given the opportunity of a 'clean sheet of paper' start to an engine specification and design process, the following base engine functionality is targeted in a proposed new concept engine:

(1) Performance and Functionality

- Maximum power similar to that of today's high performance 450 cc 4-stroke engine but at lower engine speed
- Flat torque curve over a wide speed range – to provide a more user friendly vehicle, with increased driveability across a broad range of engine speeds, leading to reduced requirement for gear changing.

(2) Weight and Packaging Size, NVH

- Reduced package size and weight compared to today's high performance 450 cc 4-stroke
- Simplified tuned exhaust system for reduced packaging compared to todays high performance 2-stroke engines
- Reduced BMEP to assist in reduction of exhaust break out noise and assist in improved NVH characteristics.

(3) Durability and Maintenance

- Reduced maximum power rpm and reduced BMEP to assist in engine durability, with significantly less stress on engine components and reduced maintenance.

(4) Fuel Economy and Emissions

- Whilst fuel economy is not seen as a key concern to most off-road applications, the range available per tank of gasoline is important
- The engine must have the capability to satisfy existing and foreseeable future emission requirements.

3.2 PROPOSED ENGINE

The initial approach was to determine a desired WOT torque curve for an engine that could compete directly with the typical high performance 450cc 4-stroke engine. This WOT torque curve, as shown in figure 3 representing the 'target' curve, is competitive on a power basis with the 450 cc 4-stroke engine whist targeting a wide spread of torque over the usable engine speed range i.e. 90% of peak torque to be available over a 5000 rpm speed range.

The proposed development path discussed here investigated the optimization of an air assisted direct injection 2-stroke single cylinder engine by combining the following key aspects:

a) Increasing the engine displacement for reduced BMEP
b) Part load stratified combustion control for linear throttle control
c) New approach to port design time area and exhaust system tuning.

Initial investigations utilizing engine modeling including WAVE and internal proprietary analysis techniques were carried out to assist in the base specification of the engine displacement, porting design and exhaust system.

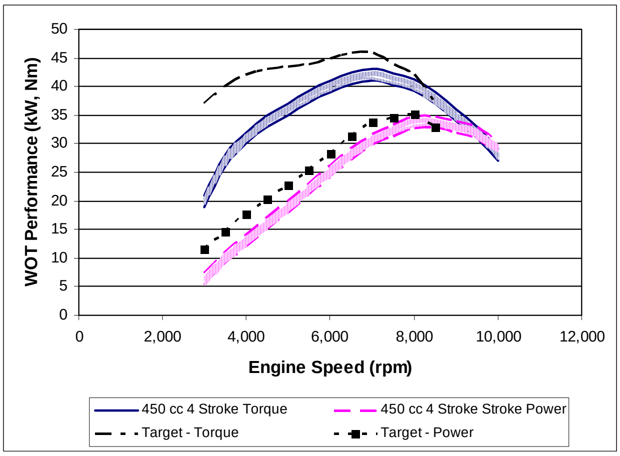

Figure 3: Target WOT torque curve compared to typical high performance 4-stroke engine torque curve

4. TESTING OF CONCEPT and DISCUSSION

The base engine used to test the initial concept was a high performance development 2-stroke air assisted DI engine previously used by the authors (ref 5). To assist in the direct comparison, the target WOT torque as specified in figure 3 was converted to Brake Mean Effective Pressure (BMEP) assuming as a starting point a 450 cc displacement, giving a target WOT BMEP curve as shown in figure 4. The initial investigation presented here was to establish the sensitivity of the WOT torque curve to changes to the exhaust port and exhaust system design as well as confirming the corresponding engine displacement to achieve the target performance.

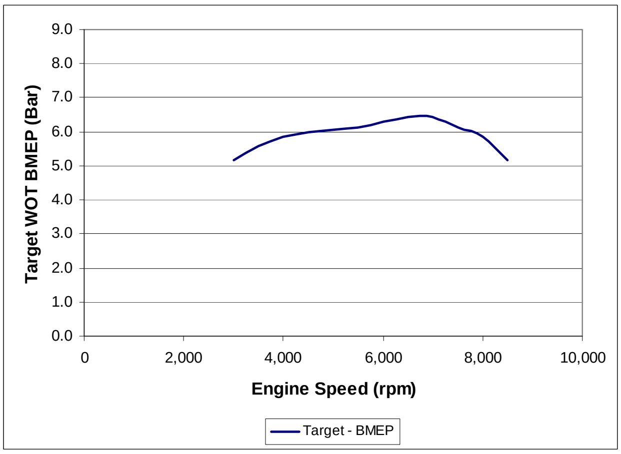

Figure 4: WOT BMEP target curve for the concept engine

The first stage of the test program investigated the following key aspects of the engine exhaust system:

a) Exhaust port opening (EPO) angle
b) Exhaust port shape
c) Exhaust system tuning

As part of the overall engine concept the exhaust system package and design was simplified from the traditional tuned exhaust system i.e. "expansion chamber". A basic box exhaust system, as shown in figure 5 was set up to investigate the sensitivity of the exhaust design on the WOT BMEP curve. This exhaust system had a 44mm diameter header pipe (no taper) leading to a simple chamber with a 25mm diameter exit tailpipe. The standard muffler and tailpipe (not shown) for this motorcycle engine were fitted to the end of this experimental system. Overall backpressure was comparable to the standard tuned exhaust system.

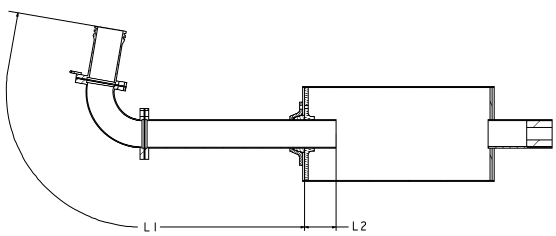

Figure 5: Exhaust System Layout, with variable lengths.

All testing was carried out at WOT with ignition, injection timing and air/fuel ratio optimized for maximum torque calibration.

Initial results, as shown in figure 6, shows the influence of two exhaust port shapes and timing differences. The overall torque curve with both the 104 and 102 deg ATDC main timing edge has a very good low speed torque but this reduces very quickly above 6000 rpm.

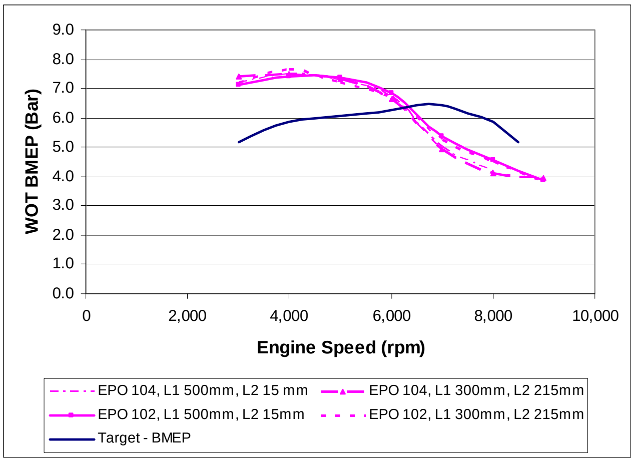

Figure 6: WOT BMEP Testing – Initial testing of EPO and Exhaust System Configuration

With the earlier exhaust port opening time of 102 deg ATDC, further development of the exhaust system configuration, including different combinations of basic header lengths L1 and L2 were assessed. As shown in Fig. 7 the best compromise in regard to overall torque spread was found utilizing header and re-entry pipe lengths of L1=300mm and L2=15mm. This improvement in high speed performance is linked to the improved timing of the rarefaction pulse from the simple box chamber in the exhaust, which along with the high transfer ports and large intake system allows efficient breathing at high speed.

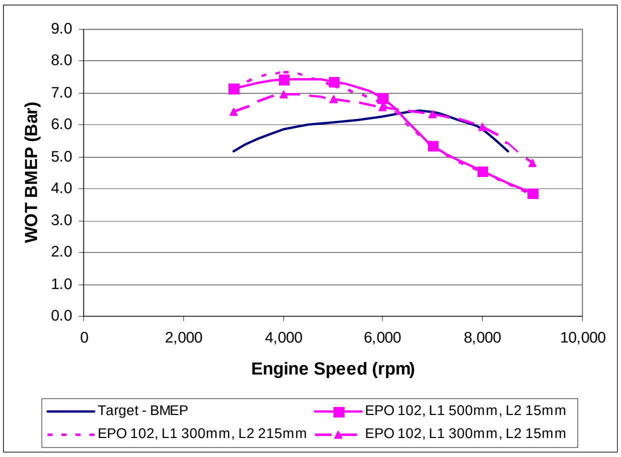

Figure 7: BMEP of varied Exhaust Header Lengths for EPO of 102 degrees ATDC

Based on an optimal exhaust system configuration from the testing with an exhaust port opening of 102 degrees ATDC, a further modified exhaust port with an earlier timing of 100 degrees ATDC was also assessed. The result of this combination of port timing/port area and exhaust system specification achieves above the target BMEP, as shown in figure 8.

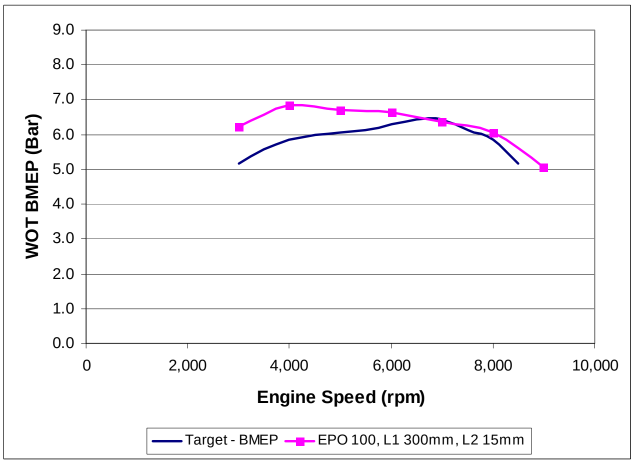

Figure 8: BMEP with EPO of 100 degrees ATDC and preferred exhaust system configuration

In the case of a basic 2-stroke engine factors such as exhaust tuning, port time area and port opening shape influence the cylinder trapping and charging efficiency and hence the available WOT performance of the engine. These three variables all have different influences as a function of speed. The challenge with this motorcycle concept engine was to reduce the effect of engine speed on the trapping and charging efficiency to be able to achieve the desired flat WOT curve across an extended engine rpm range. This is quite different from the more typical peaky torque curve with peak torque at high rpm (and a narrow high torque rpm band) associated with single cylinder performance 2-stroke engines, as discussed by Blair (ref. 11).

In a fresh approach to the development of the new concept engine, the authors adopted an upsizing of the engine displacement to be similar to that allowed for 4-stroke engines which enabled a reduced BMEP target and hence a different approach for the exhaust system tuning. The combination of a reduced exhaust tuning level and optimised exhaust port shape while maintaining the engine breathing capacity with high flow intake and transfer ports have enabled a good spread of torque over a wide speed range.

A further consideration of the reduced exhaust tuning is targeted at reducing the exhaust packaging, noise and the tonal quality which will be the subject of future work.

In terms of matching power to the initial target WOT torque curve, scaling of the base test engine data suggests a displacement of around 450 cc could achieve the desired power. Compared to the typical high performance 450 cc 4-stroke engine, this would enable torque and power curves as shown below in figure 9.

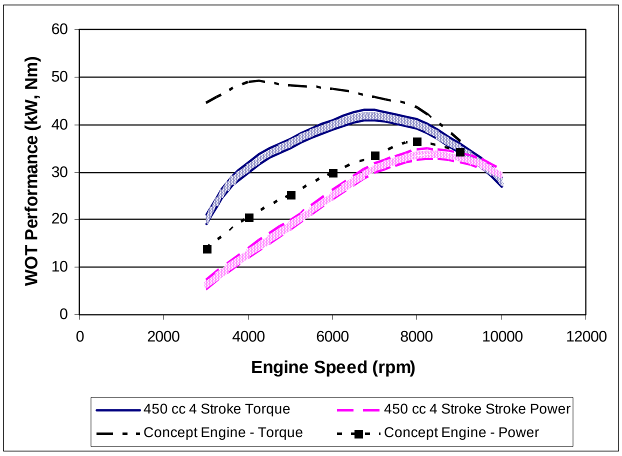

Figure 9: WOT Power and torque of a 450 cc Concept engine compared to typical performance 450 cc 4-stroke engine.

It is expected that further optimization of the porting and exhaust tuning could result in overall increased BMEP capability of the concept engine, potentially reducing the concept engine displacement to further maximize packaging advantages.

5. DISCUSSION OF KEY FEATURES

A comparison of the key features and potential capability of the new concept motorcycle engine compared to the typical high performance 450 cc 4-stroke engine and the typical 250 cc 2-stroke carburetor engine is shown in table 1.

	Relative to Baseline - 450 cc 4-stroke	
Key Features	2-stroke Carburettor (250cc)	New Concept Engine (450cc)
Peak Power	0	0
Peak Torque	+	+
Torque Spread over speed range	-	+
Package Size & Weight	+	+
Fuel Efficiency/range	-	+
Emissions (HC,CO & Nox)	-	0
Maintenance	+	+
Noise quality	-	0
Exhaust Smoke	-	0
Engine Cost	++	+
Oil Consumption	-	+

Table 1: Key feature ratings relative to a baseline high performance 450cc 4-stroke engine (0 same, + improved, - worse)

There are a number of key areas where the latest high technology 4-stroke engine has significant benefits in comparison to the carbureted 2-stroke competitor of today. In the case of the average user of an enduro type of application the 4-stroke provides a flatter spread of torque, more linear part throttle control, lower smoke and smell as well as a longer fuel tank range. The 2-stroke carburetor still delivers benefits in terms of lower weight and package size, explosive performance as well as a lower cost maintenance engine.

In comparison the proposed new concept engine provides the benefits of DI combustion control in combination with a fresh approach to the design of the base engine. Package size and weight of the concept engine would be similar to the current 2-stroke, and the retention of the 2-stroke base engine components would mean low maintenance. Experience at Orbital has shown that the improved low speed torque characteristics of the concept engine can be fully exploited with the fuel led combustion control system of air assisted DI which can provide a linear torque delivery and throttle feel. The benefits of the DI system in combination with the good low speed trapping efficiency should deliver superior fuel economy and fuel tank range based on experience of Leighton et al (ref. 12) from other DI conversions. The addition of electronic oiling would also enable low exhaust smoke and enable the overall oil consumption to be less than the 4-stroke engine.

There are a number of areas which need further work to fully prove out the potential benefits of this new engine concept, in particular the ability to achieve these results on a 450cc displacement engine and confirmation of emissions capability which will be explored in further development and publications.

6. CONCLUSION

(1) A concept engine was developed to provide an alternative engine choice to the existing 4-stroke and carbureted 2-stroke options for Enduro and ATV applications.

(2) Testing of the concept was carried out on an air-assisted direct injected test engine by assessing the effects of exhaust port optimization in combination with a very simple exhaust system at WOT conditions.

(3) The concept engine demonstrated a good spread of torque across a wide speed range with a fixed exhaust port timing of 100 deg ATDC and a basic exhaust header length of 300mm and re-entrant pipe length of 15mm.

(4) This initial assessment indicates that a new engine concept, of around 450cc displacement, based on 2-stroke air assist direct injection operating principles, could offer an attractive alternative to today's carburetor 2-stroke and 4-stroke products.

7. ACKNOWLEDGMENTS

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APPENDIX

Abbreviations:

ATDC – After Top Dead Centre

BTDC – Before Top Dead Centre

BMEP – Brake Mean Effective Pressure

Deg – Degrees

DI – Direct Injection

FIM - Fédération Internationale de Motocyclisme

EPO – Exhaust Port Opening

WOT – Wide Open Throttle