06SETC-173

Experimental optimisation of manifold and camshaft geometries for a restricted 600cc four-cylinder four-stroke engine

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ABSTRACT

Restricting the airflow to the engine is a convenient, and therefore common, method of regulating engine performance in many forms of motor sport. Formula SAE, and its European counterpart Formula Student, impose such restrictions on engine configuration. The capacity of the engines must not exceed 610cc but, more specifically to this study, the intake system must be fitted with a 20mm diameter restrictor through which all the air must pass.

There are, however, a number of geometrical parameters which can be changed to maximise the performance of the restricted engine. In this study, the effects of modifying the restrictor design, intake runner length, intake camshaft profile, exhaust geometry, and silencer design were measured using a transient dynamometer. These tests were performed on a 600cc four-stroke, four-cylinder Yamaha YZF R6 engine. For each configuration examined, the ignition timing and fuel maps of the DTA engine management system were optimised using torque and emissions readings.

The optimum engine configuration produced an increase in peak power of 12kW (16hp), 23.5% greater than the standard engine in restricted format. In addition, the torque curve was significantly improved with 90% of the peak engine torque available over the useful speed range of 6,000 - 12,000rpm. This provides progressive torque delivery and makes the engine much more suitable for FSAE and Formula Student applications.

INTRODUCTION

The Formula SAE series rules [1] specify that cars must be powered by four-stroke piston engines which must not have a displacement larger than 610cc. With careful tuning, an engine of this description would be capable of producing in excess of 120hp. In order to limit vehicle performance to reasonably safe levels for the non-professional drivers who take part in the competition, while simultaneously ensuring that the power output from the engines are evenly matched, the Formula SAE regulations require that all air to the engine must pass through a Ø20mm air intake restrictor. This reduces the amount of air which the engine can induce and hence restricts the maximum power capability of the engines to a much safer level.

Forced induction may seem like the obvious solution to get round an intake restriction. However, for this application, the weight implication of a super-charger or turbo-charger is not necessarily met by the gains in engine performance. It should also be noted that the vehicle must be driven round a narrow, twisty autocross style race track, and so the engine must provide a smooth and responsive application of power so that the vehicle is driveable. Turbo-charger lag would cause the car to be unpredictable during cornering and require intensive driver training. Consequently a well tuned, naturally aspirated engine is considered to be more suited to the FSAE application.

The main objective of the study outlined in this paper is to optimise the engine configuration and thereby maximise its performance across the wide speed range available. This is achieved through a set of carefully designed dynamometer experiments which examine the effects of intake and exhaust manifold design, intake plenum volume and intake camshaft profile on the resulting torque output. The geometries of these components were guided by predictions from an un-validated computer simulation [2] of the engine, together with published data from similar restricted competition engines [3,4,5,6,7].

The recommendations provided by Blair [8,9], who performed an extensive simulation study of the design of intake manifolds fitted with air restrictors, were also incorporated within the designs. These simulations are based on fundamental unsteady gas dynamic theory, details of which can by found in Blair [10], Winterbone [11], Heywood [12] and Stone [13].

ENGINE GEOMETRY

A 1999 Yamaha R6 motorcycle engine was used in this investigation. This model of engine is used by the Queen's University Formula Student team because it is a lightweight, reliable engine with an excellent power to weight ratio. Originally the engine was fuelled by four 37mm carburettors, however in order to meet the FSAE regulations on engine restriction, the carburettors have been replaced with a multipoint fuel injection system controlled by a customisable engine management system. The standard capacitive discharge ignition system was replaced by a coil pack with two double-ended coils to suit the wasted spark capabilities of the engine management system. Further general specifications of the engine in its standard form are given in Table 1.

Table 1. 1999 Yamaha R6 Engine Specification

Engine Configuration	Inline Four, 4-Stroke, DOHC
Engine Displacement	599 cc
Engine Cooling System	Liquid
Compression Ratio	12.4:1
Valves Per Cylinder	4
Bore	65.5 mm
Stroke	44.5 mm
Claimed Peak Horsepower	89.5 kW @ 13,000 RPM
Claimed Peak Torque	68.1 Nm @ 11,500 RPM
Engine Redline	15,500 rpm
Fuel Delivery System	(4) Keihin CVRD37 Flat-side CV carburetors
Carburetor Venturi Size	36.5 mm
Exhaust System Type	Four-into-two-into-one
Lubrication System	Wet Sump
Oil Capacity	3.5 litres
Transmission Type	6-speed, Constant Mesh
Clutch Type	Multi-plate, Wet

The distance which the air must travel from the bell-mouths inside the plenum to the back of the inlet valves is known as the runner length. This value is known to significantly affect the performance of the engine and, of particular significance to this study, determine the engine speed at which peak torque is produced. Model predictions suggested that the optimum length for the runners was in the region of 200 - 300mm. Consequently, an experimental inlet manifold was designed to allow the length of the runners to be easily adjusted by replacing sections of straight pipe. Figure 1 illustrates the adjustability of the variable inlet manifold.

The volume of the plenum chamber downstream of the intake restrictor is also known to influence the performance of restricted engines. This is demonstrated by Blair [8] who recommended that plenum volume should be as large as possible. Model predictions of the Yamaha R6 engine suggested that plenum volume did not cause major changes to the performance of the engine beyond a certain volume. It was for this reason that an optimum volume of 3.5L was selected and not varied during the tests.

The existence of a diffuser after the restrictor is essential [8] as it allows a higher air flow rate to be achieved which, in turn, allows the engine to develop more power. In fact removing the diffuser section can result in a 20% reduction in power output [8, 9]. The angle of taper in the diffuser must be between 4º and 7º if the flow is to remain attached to the walls [4, 5, 8]. However, if the taper angle is increased or overall diffuser length is increased, then so too is the exposed surface area of the diffuser. This results in higher friction losses as pressure waves propagate along the diffuser [8, 9]. A comparison of restrictors with both long and short diffusers was therefore undertaken in this study to determine whether the pressure gains from better diffusion are offset by pressure losses due to friction in the pipe.

Model simulations [14] suggested that significant gains could be made to engine performance by altering the duration of inlet valve opening from 338º CA to 298º CA, a reduction of 12%. Based on these predictions, a new intake camshaft profile was generated and subsequently manufactured by Piper Cams [15]. The opening time of the inlet valves was also changed from the standard 64º CA to 19º CA BTDC. The performance of the engine fitted with the modified camshaft was compared with the standard camshaft fitted to the engine. The exhaust camshaft was kept standard.

The design of the exhaust manifold is also known to affect engine performance and can be tuned to provide a broad torque curve [6]. The experimental program therefore included tests on two exhaust manifolds with 4-2-1 and 4-1 configurations.

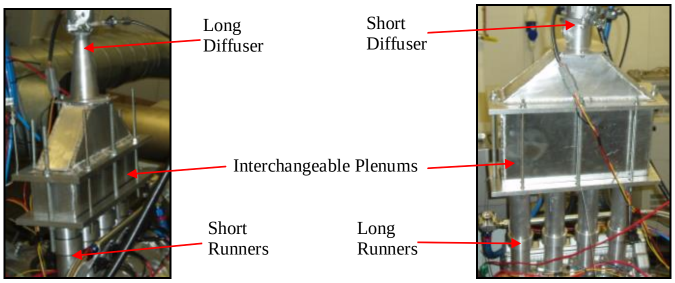

Figure 1. Variable Inlet Manifold

ENGINE TESTING PLAN

The purpose of the engine test plan was to evaluate each of the parameters discussed above, namely diffuser design, intake runner length, intake camshaft profile and exhaust system geometry. The engine configurations were carefully chosen to yield the maximum amount of information regarding the effects of each of these parameters, while minimising the testing time. Consequently, five engine configurations were investigated as outlined in Table 2.

Table 2. Engine Test Configurations

Set-up	1	2	3	4	5
Diffuser Design	Short	Short	Long	Long	Long
Intake Runner Length (mm)	330	215	215	215	215
Intake Camshaft	Standard	Standard	Standard	Customised Profile	Customised Profile
Exhaust System Geometry	4-2-1	4-2-1	4-2-1	4-2-1	4-1

Set-ups 1 and 2 compared the effect of the length of the inlet manifold runners on engine performance. Set-up 1 had 330mm runners fitted whereas set-up 2 had 215mm runners fitted. Set-ups 2 and 3 compared the effect of restrictor diffuser design on engine performance, set-up 2 having a short 25mm diffuser fitted, while set-up 3 had a longer 100mm diffuser fitted. Set-ups 3 and 4 compared the effect of inlet camshaft profile on engine performance. Set-up 3 had the standard Yamaha R6 inlet camshaft fitted with the standard timing, whereas set-up 4 had the camshaft with the modified profile fitted with an inlet valve opening angle of 19º BTDC. Set-ups 4 and 5 compared the effect of the exhaust design on engine performance. Set-up 4 had the 4-2-1 exhaust system fitted whereas set-up 5 had the 4-1 exhaust system fitted.

EXPERIMENTAL APPARATUS

The engine was connected to a 145kW Schenck AC asynchronous, four quadrant dynamometer [16] by a driveshaft connected to the gearbox output shaft of the engine. The driveshaft was not connected to the crankshaft of the engine because the dynamometer was unable to cope with the high engine speeds which reached 13,000rpm. Therefore all performance figures quoted in this paper are produced at the gearbox. Engine performance figures will obviously be slightly higher than the figures quoted. Exhaust emissions were analysed using a Horiba MEXA 7000 Exhaust gas analyser. The engine was fitted with custom fuel injection and ignition systems controlled by a DTA engine management system. This allowed adjustments to be readily made to the fuel and ignition maps.

Engine performance under full load was the primary concern of this investigation, therefore only the wide open throttle (WOT) points of the engine management system were mapped for each configuration. Each cell was first mapped to an air/fuel ratio of 13:1. The ignition was then adjusted to minimum advance for best torque. Once mapping was complete, cycle-averaged performance and emissions data were collected over the usable speed range of 3,000rpm to 12,500rpm at 500rpm intervals. All measurements were corrected to take account of varying atmospheric pressure, temperature and relative humidity using the SAE J1349 correction factor.

ENGINE TEST RESULTS AND DISCUSSION

<u>Effect of Runner Length (Set-up 1 vs. Set-up 2)</u>

Figures 2 and 3 show how changing the length of the runners of the inlet manifold affected the torque and power output of the engine.

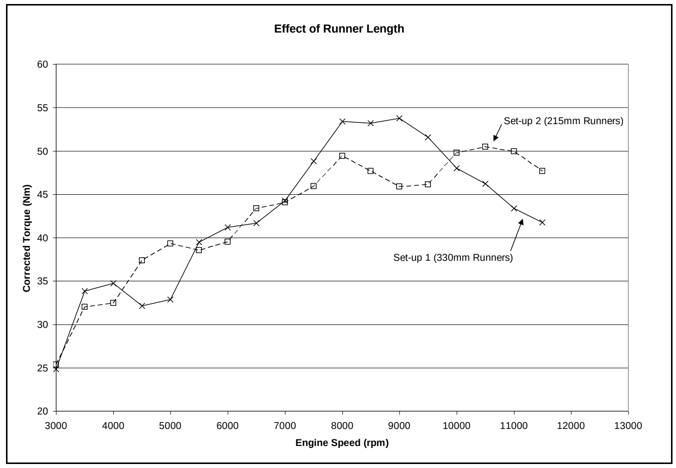

Figure 2. Effect of Runner Length on Engine Torque

Figure 2 shows how the long 330mm runners used in set-up 1 produced the highest peak torque output from the engine of 54Nm, but this dropped off suddenly at 9,000rpm. The shorter 215mm runners used in set-up 2 improved the torque output of the engine between 4,000 and 5,000rpm by 18% and, although it didn't reach the same peak torque as achieved by set-up 1, it achieves a much longer, flatter area of torque from 8,000rpm reaching 50Nm of torque at 11,000rpm.

Figure 3 shows that the power curve produced by the engine with set-up 2 was also much better than that produced by set-up 1. The long runners of set-up 1 caused the engine to reach a maximum power output of 51kW at 9,000rpm, whereas the shorter runners boosted this peak power to 57kW at 11,000rpm.

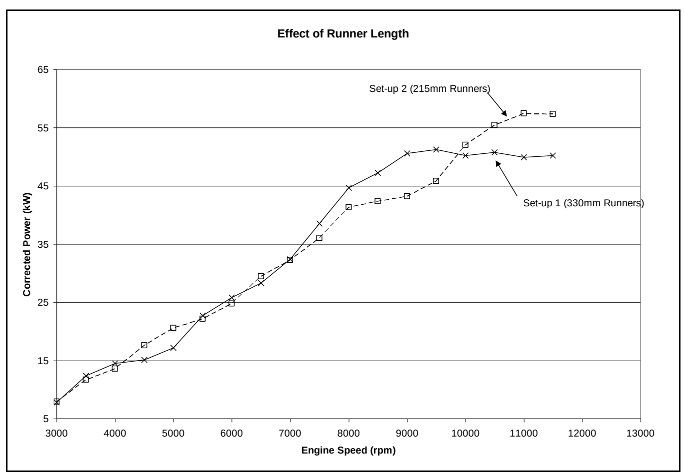

Figure 3. Effect of Runner Length on Engine Power

<u>Effect of Restrictor Design (Set-up 2 vs. Set-up 3)</u>

Figures 4 and 5 compare how the torque and power output of the engine are affected by the design of the diffuser after the restrictor in the inlet system. The diffuser used in set-up 3 is four times longer than the short restrictor used in set-up 2.

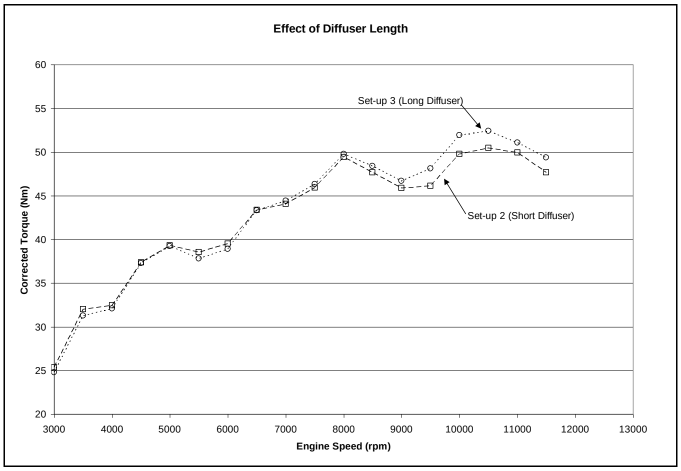

Figure 4. Effect of Diffuser Length on Engine Torque

Figure 4 shows how the longer diffuser used in set-up 3 improved the torque output of the engine above 8,000rpm compared with the shorter diffuser of set-up 2. The peak torque output of the engine was increased by 2Nm (4%) by using a longer diffuser in the restrictor. This improvement was caused by the longer diffuser slowing the flow of the air more as it entered the plenum of the inlet manifold. This improved distribution of air to each of the cylinders at the higher engine speeds. The shorter diffuser was causing the air to ‘jet’ as it entered the plenum through the restrictor. This has two effects which result in a reduction of the performance of the engine; firstly the amount of air able to pass through the restrictor is effectively reduced, and secondly the air is not distributed evenly to all four cylinders - Cylinders 2 and 3 receiving more air than cylinders 1 and 4, causing them to run slightly lean relative to the outer two cylinders. This was confirmed by temperature readings at exhaust ports 2 and 3 which were higher than the temperature readings at ports 1 and 4.

Figure 5 shows that the peak power was also improved by introducing the longer diffuser to the set-up. A gain of 3.5% was achieved at 11,000rpm.

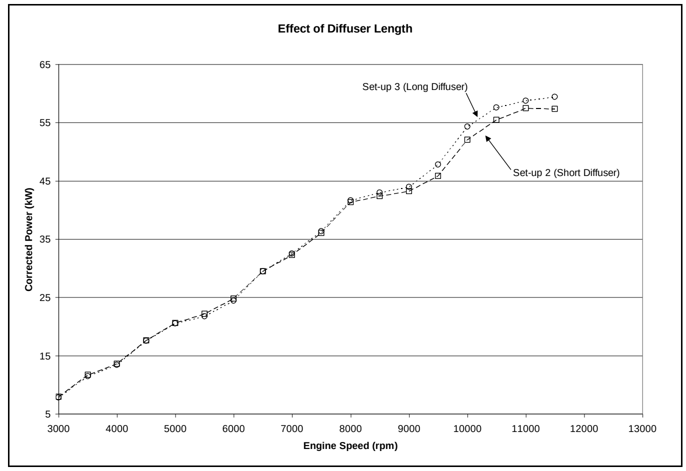

Figure 5. Effect of Diffuser Length on Engine Power

Effect of Inlet Camshaft (Set-up 3 vs. Set-up 4)

Figures 6 and 7 compare the performance of the engine with the standard inlet camshaft, fitted in set-up 3, against the modified inlet camshaft of set-up 4.

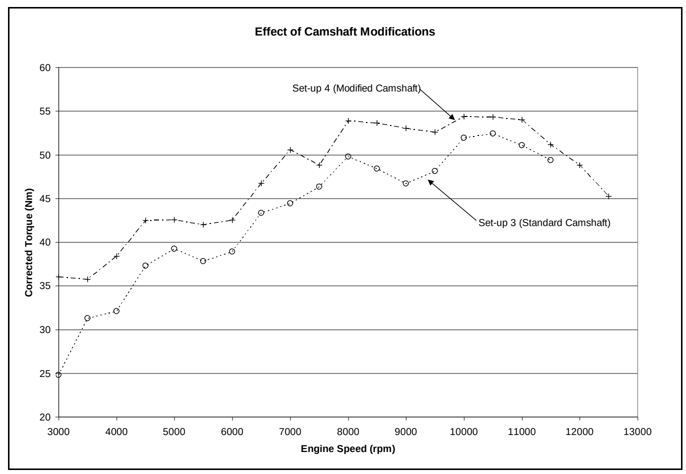

Figure 6. Effect of Inlet Camshaft Modifications on Engine Torque

Normally during engine testing, a gain in one area of the torque and power curves results in a loss in another, but not in this case. Figure 6 shows clearly the huge effect that the modified camshaft had on the performance of the engine. Torque output is increased right across the speed range of the engine, with an impressive 44% increase at 3,000rpm. The peak torque output of the engine was improved by 3.8% to 54Nm at 10,500 RPM. The torque curve is improved further by the flattened area from 8,000 to 11,000rpm which is less ‘peaky’ than the curve produced by set-up 3.

Figure 7 also shows how the power output was improved overall by set-up 4. Peak power was increased by 3kW to 62kW at 11,000rpm. The modifications to the camshaft reduced the duration of inlet valve opening allowing the valves to open much later than standard while maintaining a similar closing time. In other words the amount of overlap between the exhaust valves and inlet valves being open has been reduced. This is important for the restricted engine because at WOT the presence of the restrictor causes part throttle conditions, i.e. the pressure in the inlet is much lower than the pressure in the exhaust. Reducing the valve overlap decreases the amount of exhaust gas drawn into the inlet by this pressure gradient, so that when the induction stroke begins the gas drawn into the cylinder from the inlet is almost completely air/fuel. The obvious result of this is more power. This isn't a problem with the standard unrestricted R6 configuration because at WOT the pressure in the inlet is much more similar to the pressure in the exhaust, so there is less 'backflow' from the exhaust into the inlet during valve overlap.

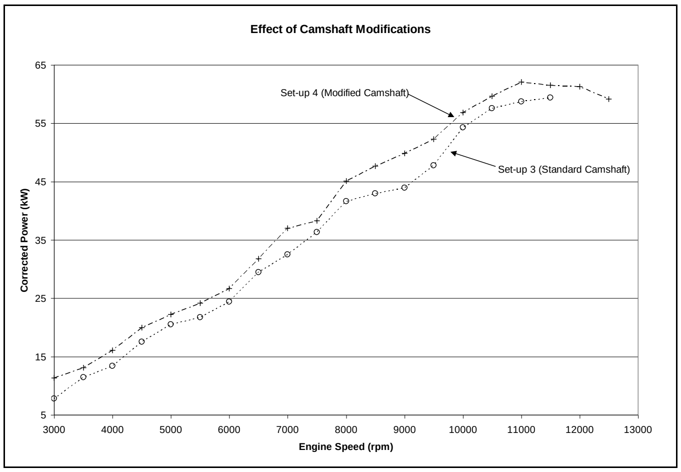

Figure 7. Effect of Inlet Camshaft Modifications on Engine Power

<u>Effect of Exhaust (Set-up 4 vs. Set-up 5)</u>

Figures 8 and 9 show how the exhaust configuration affected the torque and power output of the engine. Set-up 4 had the 4-2-1 exhaust system fitted to the test engine, whereas set-up 5 saw the attachment of the 4-1 exhaust system to the test engine.

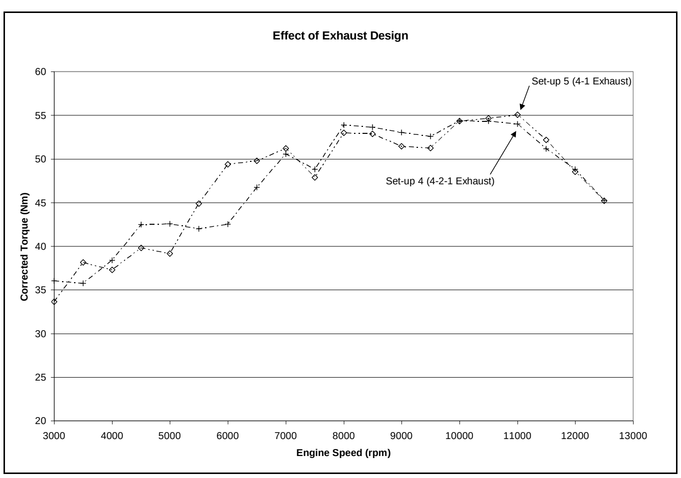

Figure 8. Effect of Exhaust Design on Engine Torque

In Figure 8 it can be seen that set-up 5, with the 4-1 exhaust system, showed an improvement in the torque in the range of 5,500 to 7,000rpm. This increased the length of the flat region of the torque curve by 2,000rpm compared with the torque curve produced by set-up 4, with the 4-2-1 configuration, therefore increasing the actual operating range of the engine from 6,000 to 11,000rpm. Set-up 5 also increased the peak torque of the engine by a further 1Nm to 55Nm.

Figure 9 demonstrates that set-up 5 increased the power produced between 5,500 and 7,000rpm significantly as well as the peak power output of the engine. An extra 1kW of power was found at 11,000rpm with set-up 5 fitted to the engine increasing the peak power to 63kW.

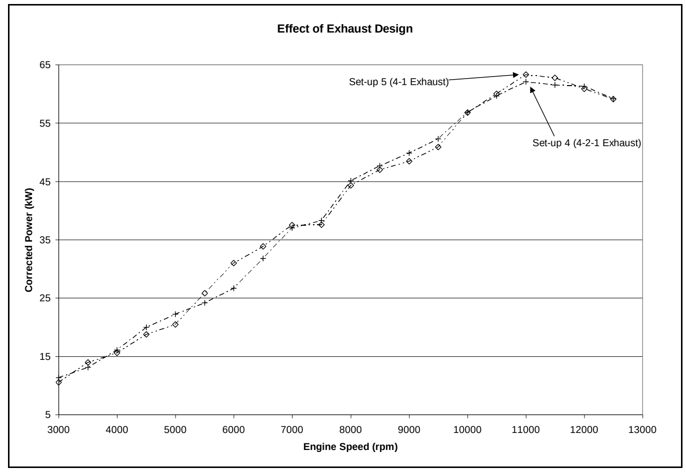

Figure 9. Effect of Exhaust Design on Engine Power

<u>Overall Improvements to Engine Performance (Set-up 1 vs. Set-up 5)</u>

Figures 10 and 11 show the overall improvements to engine performance from set-up 1 to set-up 5. Huge gains are obvious across the engine operating speeds.

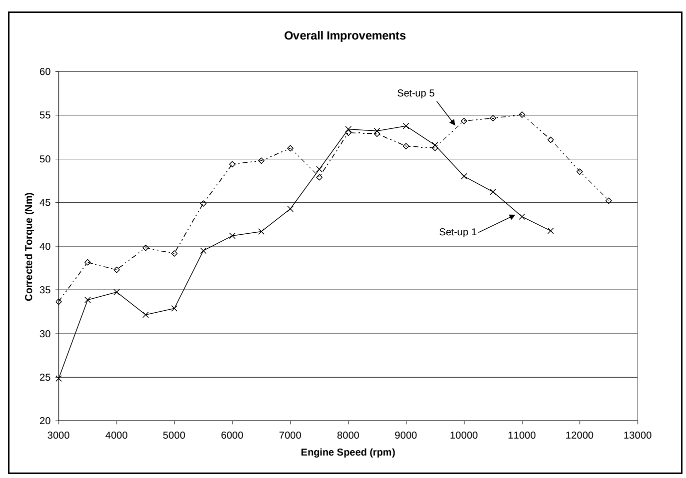

Figure 10. Overall Improvement to Engine Torque

Figure 10 shows how much broader and flatter the torque curve of set-up 5 is compared with set-up 1. Peak torque has been increased from 53Nm at 9,000rpm to 55Nm at 11,000rpm. More importantly though is the increase in useful speed range of the engine's torque, which is now available from 6,000 - 12,000 rpm as opposed to just 7,500 - 10,000rpm.

Figure 11 shows the impressive gains which have been made to the power output of the engine. Peak power has increased from 51kW at 9,500rpm to 63kW at 11,000rpm. This is a 23.5% gain in power.

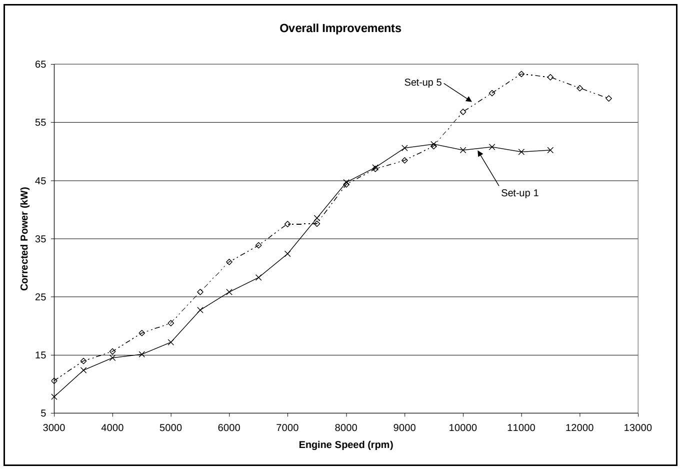

Figure 11. Overall Improvement to Engine Power

Set-up 5 should result in a much more drivable car than previous set-ups where torque curves peaked early and dropped off and power was inconsistent, resulting in a narrow working range for the engine.

For FSAE events acceleration times using the torque and power curves produced on the dynamometer, show a reduction of over 0.2 seconds in the 0 - 75m event at the competition between set-up 1 and 5. For the sprint and endurance events the car will be much easier to drive as the power will be delivered much more smoothly, reducing the likelihood of handling problems such as over steer which can be caused by erratic application of the engine's power.

CONCLUSION

The performance of the restricted Yamaha R6 engine has been dramatically improved by carrying out the tests described in this report. Careful planning and analysis went into deciding on the most influential variables affecting the performance of the engine, and through the use of a simple but effective variable inlet manifold a lot of extremely useful data has been collected and used.

The final engine set-up used by the Queen's University Formula Student team resulted in the car setting the 2nd fastest acceleration time at the 2006 competition.

ACKNOWLEDGEMENTS

The Authors would like to thank the Queen's University of Belfast School of Mechanical & Aerospace Engineering for providing access to engine test facilities. In addition, the support of Optimum Power Technology in providing the Virtual Engines licences is greatly appreciated.

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NOMENCLATURE

ABDC After Bottom Dead Centre

BTDC Before Top Dead Centre

CA Crank Angle

FSAE Formula SAE

rpm Revolutions per minute

SAE Society of Automotive Engineers

WOT Wide Open Throttle