ABSTRACT

This paper describes the design and development of an engine with constant power for SAE's student Formula race-car competition, allowing the avoidance of gear shifting for much of the Autocross event. To achieve constant power for over 50% of the speed range, turbocharging was adopted with a boost pressure ratio of 2.8 at mid-range speeds and applied to an engine capacity of 430 cc. This engine was specifically designed and configured for the purpose, being a twin cylinder in-line arrangement with double overhead camshafts. Most of the engine components were specially cast or machined from billets. The capacity was selected to minimise frictional losses and thus increase delivered power along with dry sump lubrication and a three speed gear box. The engine manifolds and plenums were designed using a CAE application and proved to be well suited to the task resulting in excellent agreement between predicted and actual performance. One of the major challenges of the experimental development was overcoming the turbocharger oil consumption under throttled operation at part load conditions and at full power when the FSAE restrictor is choked. For the 2004 Australian competition the engine was run with slightly reduced mid speed power to avoid excessive use of the traction control system and was very competitive finishing first in the fuel economy event.

INTRODUCTION

Formula SAE has proven itself to be a problem based learning exercise that employers regard as being equivalent to up to eighteen months of work-place training. It can also be an opportunity for undergraduate students to learn research skills in preparation for a career in research and teaching.

This paper focuses on the design, research and development of a purpose designed engine for FSAE and demonstrates that the challenge of looking for new ways to meet the FSAE rules and requirements can be more than a training experience.

The Formula Rules limit the engine capacity and air consumption by means of a restriction in the intake system. Specifically the engine should:

- Be a four-stroke piston engine
- Be limited to a maximum displacement of 610cc
- Use gasoline fuel limited to 98 RON
- Have all intake air passing through a 20mm restriction
- Have the throttle located upstream of the restrictor
- Allow supercharging

The major event in FSAE is the Autocross, which has an average speed of around 55 km/h which typically involves a speed range varying from 30 to 90 km/h. In vehicle acceleration over this speed range, typically two or more gear up shifts (and downshifts) will be needed. It is noted that automatic gear shifting in motor sport major-competition typically takes about 30 milliseconds, so in one lap up to 0.5 seconds may be 'lost' to gear shifting. Even if gearshifts are made clutchless, with the drive train absorbing the shocks, the torque pulsations unsettle the vehicle stability particularly in turns. It follows that an engine with constant power over the speed range has a potential advantage in the autocross event by eliminating gear shifting and running in only one gear. However in the acceleration event, a gear change may be required depending on traction limitations.

Thus the objectives of a turbocharged engine design compared with a 4-cylinder 600 cc reference engine were set as follows:

- The engine should be capable of operating at constant maximum airflow (choked) over at least half of the speed range to maximum
- Power increased by 5-10% through reduced FMEP (friction) through using a smaller than 610cc capacity
- 25% reduction in mass
- 50% reduction in physical size
- 25% reduction in the height of the COG
Design to suit a FSAE styled race-car with regards to packaging

Maximum throttle response making the engine as tractable as possible

The design drew on the team’s previous experience in producing small turbocharged engines for a larger engine task, except that FSAE engines are significantly smaller and there was much to learn [1,2,3]. In practice this concept involved a design from scratch approach since no suitable production engine could be adapted. In reality, production items from a range of different engines were sourced as parts together with the design and manufacture of many major and minor components.

THEORETICAL ANALYSIS

CHOICE OF ENGINE CAPACITY AND CONFIGURATION

The engine capacity was selected with the aid of Figure 1, which shows the volumetric efficiency (as achieved by increasing boost pressure as the engine size reduces to achieve the same power output as a 600 cc engine. A validation point for the simple model simulation is shown with an experimental result from the team’s previous Suzuki GSX-R600 engine at the speed at which the restrictor limits power. On the basis that achieving boost pressures ratios of 3.2 (or VE of 250% assuming losses) is the expected limit from the relatively small, and therefore less efficient turbocharger, an engine size of between 400 and 450 cc was the design brief with an operating speed range of 6000-10000 rev/min.

![Figure 1: Influence of engine capacity on VE (or compressor delivery pressure) needed to achieve sonic flow in the restrictor.](image)

An increase in the number of cylinders reduces the flow velocity fluctuations experienced by the exhaust turbine. However, with frictional losses increasing with an increase in the number of cylinders and resultant piston rubbing area, a compromise between one and four was needed, yielding a two cylinder configuration.

MANIFOLD DESIGNS

The design of the plenums in between the compressor, engine and turbine were an important consideration to offset the flow pulses especially as an uneven firing order was selected for engine balance reasons. Each of the plenums adopted Watson’s KEC rolling flow design where the kinetic energy of the flow is conserved in a vortex about the axis of the plenum. The design can be seen pictorially in the CAD image of Figure 2. To determine the size of the plenums, manifold design and valve timing events, an extensive series of simulations were undertaken using Ricardo’s WAVE®. The predicted results with relatively large plenums are shown in Figure 3.

![Figure 2: CAD image (upper) of the ‘WATTARD’ turbocharged engine showing the turbocharger location and the manifold and plenum designs. Lower picture shows the turbocharger location and exhaust plenum behind the dry sump oil tank.](image)
ENGINE DESIGN AND SPECIFICATION

The specification of the engine can be seen in Table 1.

<table>
<thead>
<tr>
<th>BRAND</th>
<th>UniMelb &quot;WATTARD&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENGINE TYPE</td>
<td>Parallel twin</td>
</tr>
<tr>
<td>4 stroke</td>
<td>Liquid cooled</td>
</tr>
<tr>
<td>FIRING ORDER</td>
<td>Unequal (0°, 180°CA)</td>
</tr>
<tr>
<td>CAPACITY</td>
<td>434 cc</td>
</tr>
<tr>
<td>BORE &amp; STROKE</td>
<td>69 x 58mm</td>
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<tr>
<td>BORE/STROKE RATIO</td>
<td>1:1.2</td>
</tr>
<tr>
<td>COMPRESSION RATIO</td>
<td>10.2:1</td>
</tr>
<tr>
<td>VALVE ACTUATION</td>
<td>8-valve DOHC Bucket shim adjustment</td>
</tr>
<tr>
<td>VALVE TIMING</td>
<td>IVO 24° BTDC</td>
</tr>
<tr>
<td></td>
<td>IVC 72° ABDC</td>
</tr>
<tr>
<td></td>
<td>EVO 57° BBDC</td>
</tr>
<tr>
<td></td>
<td>EVC 9° ATDC</td>
</tr>
<tr>
<td>LUBRICATION</td>
<td>Dry Sump</td>
</tr>
<tr>
<td>OPERATING RANGE</td>
<td>6000 - 10500 rev/min</td>
</tr>
<tr>
<td>CONROD LENGTH</td>
<td>116.5mm</td>
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<tr>
<td>INLET</td>
<td>20mm restrictor- Dall Venturi</td>
</tr>
<tr>
<td></td>
<td>Watson KEC manifold with EFI</td>
</tr>
<tr>
<td></td>
<td>4.5L plenum volume</td>
</tr>
<tr>
<td></td>
<td>350mm primary intake length</td>
</tr>
<tr>
<td>EXHAUST</td>
<td>Watson KEC manifold</td>
</tr>
<tr>
<td></td>
<td>2.5L plenum volume</td>
</tr>
<tr>
<td>ENGINE MANAGEMENT</td>
<td>Motec M4 EMS</td>
</tr>
<tr>
<td>TURBOCHARGER</td>
<td>Modified Garrett GT12</td>
</tr>
<tr>
<td>CLUTCH</td>
<td>Multi wet plate (8)</td>
</tr>
<tr>
<td>TRANSMISSION</td>
<td>3 forward gears</td>
</tr>
</tbody>
</table>

Table 1: Final specification for the 2004 TC ‘WATTARD’ engine for FSAE-A competition.

The initial stroke of the engine was dictated by the selection of a two-cylinder Kawasaki ER500 crankshaft as an interim measure prior to machining a new item. The gears and change mechanism in the crankcase were significantly modified with new gear sets to give a wide ratio 3 speed box, compatible with the constant power concept of the engine.

PISTON AND CYLINDER

The twin cylinder barrel was machined from solid featuring a gasketless interface used with success to contain the high combustion pressures and temperatures associated with turbocharging, with the arrangement as depicted in Figure 4. The oil jet cooled custom forged pistons received considerable development. The third and final design featured a reduced compression ratio of 10.2:1 with an increase in the number of rings from two to three to reduce blow-by and improve heat rejection at the high boost pressures employed.

![Figure 4: Section view highlighting the novel Barrel liner/cylinder head interface sealing arrangement.](image)

The specially designed and machined connecting rods are shown in Figure 5 together with analysis in Figure 6. At the same mass, the I section rod had lower compressive stresses at peak load, just after peak cylinder pressure and thus was adopted.
CONNECTING ROD ANALYSIS

1) H - Beam
2) I - Beam

A central oil feed was added to the clutch housing together with drillings into the clutch hub to increase oil cooling.

The clutch housing with reinforced basket as shown pictorially in Figure 7.

![Figure 7: Reinforced clutch housing required to transmit the increased torque of the turbocharged engine.](image)

TURBOCHARGER

A well-recognized problem in turbocharging FSAE engines arises from the rules, which dictate that the throttle must be on the suction side of the compressor. Almost all passenger car applications are throttleless (compression ignition engine application) or are upstream of the throttle. The consequence of the upstream throttle is that oil from the compressor side of the journal bearing is sucked into the inlet manifold when the engine is throttled. Not only is this an imposition on the amount of oil that needs to be carried, but the oil causes major combustion problems ranging from plug fouling to pre-ignition and/or increased propensity for knock to occur.

Even though the original metal seal was replaced by a proprietary carbon seal, the vacuum at idle and under restrictor limited choked operating conditions, was such that several litres per hour of oil were consumed. This problem was finally overcome by a novel redesign of the compressor-side seal that normally consists of a split ring seal on the shaft. The seal housing was modified to contain two seals in series with a special venting arrangement between both seals. Because of the turbocharger’s very small size, precision machining of the housing and venting feature were required.

The boost pressure was regulated using the waste gate to pressures determined by the information received by the Motec engine management unit. The boost pressure was regulated for the competition to less than the engine’s maximum torque capability, as in second gear wheel spin could be induced over almost all of the speed range. This will be shown in the performance graphs which follow.

CLUTCH ASSEMBLY

The increase in torque levels necessitated an improved clutch design. The following changes to the wet clutch were made through a series of development steps:

- The number of friction plates was increased to 8.
- The clutch plate material was changed to Kevlar.
- The clutch pressure plate spring stiffness was increased by 60%.
- The clutch basket was reinforced with a circumferential ring to resist the three-fold increase in torque experienced by the clutch.

![Figure 6: Evaluation of H and I beam connecting rods favoring the adopted latter design.](image)
ENGINE PERFORMANCE

The design and development of the engine took place over a two-year period. For the 2003 Australian competition, the engine ran in NA form and suffered knock/cooling problems, which were eventually overcome.

Figure 8: Performance of the WATTARD TC engine at sonic flow conditions above 6000 rev/min compared with the NA version of the engine that ran in the 2003 FSAE-A competition and the team’s previous four-cylinder engine.

The turbocharged engine development commenced with a separately driven supercharged version to establish parametric constraints, followed by an extensive period of trial and error solutions to overcome the turbocharger on-throttle oil consumption problem mentioned above. Whilst there is much to be learnt from these experiences, the reader is likely interested in the final version of the engine as it was readied for the 2004 competition.

Figure 8 demonstrates the engine’s ability to deliver almost constant power over the 6000 to 10000 rev/min speed range. At 6000 rev/min with a boost pressure of just under two atmospheres, the engine’s peak torque is 2.6 times that of the naturally aspirated version. From this speed upward the torque falls as the power is limited to about 60 kW or 80 HP. The BMEP diagram represented in Figure 9 compares the specific work performance of a range of recently tested engines. The relatively high BMEP of the NA version of the engine was obtained from a combination of optimised port design, cam timing and low engine friction to produce higher BMEP values at lower speeds when compared to engines normally used for this formula. This was known to be important to obtain the best possible torque before the turbocharger produces waste-gate limited boost. [2]

When the car for the 2004 competition was completed and fitted with the 15kg lighter engine, it was apparent that the torque deliverable at low speeds was excessive as can be seen in Figure 10. This shows the torque from the engine with boost controlled via the MOTEC EMS compared with the NA version of the engine and the team’s previous four-cylinder engine. Some wheel spin limited torque requirements for intermediate gear operation are plotted.

Figure 9: BMEP of the WATTARD TC engine at sonic flow conditions above 6000 rev/min compared with the NA version of the engine and the team’s previous engines.
A major undertaking for SAE’s student Formula racecar competition – the development of an engine with constant power has been described. The principal object was to run most of the competition in one gear allowing the avoidance of gear shifting for much of the autocross event. A purpose designed and built two-cylinder engine with a capacity of 430 cc and a Garrett GT12 turbocharger was adopted.

To obtain a constant power of around 60 kW, a boost pressure ratio of 2.8 was adopted at mid-range engine speeds. This was actually larger than required due to the light car into which it was installed and the reduction in engine mass contributing to the overall mass reduction. Thus for the 2004 competition, the engine had its peak torque de-rated from 90 to 70 Nm.

The engine manifolds and plenums were designed using a CAE application and proved to be well suited to the task resulting in excellent agreement between predicted and actual performance. One of the major challenges of the experimental development was overcoming the turbocharger oil consumption under throttled operation at full power when the FSAE restrictor is choked and under part load conditions. This was achieved with a two stage sealing ring with a special venting arrangement between both rings.

In general this was a fun project that most FSAE developers might aspire to. Few would have the dedication and experience to succeed. For the 2004 Australian competition, the engine and car were very competitive finishing first in the fuel economy event. This version of the engine and trophy are seen in Figure 12. More development time was needed for the overall car to achieve its best on track performance.
Figure 12: The University of Melbourne “WATTARD” engine together with the fuel economy trophy from FSAE-A 2004.

ACKNOWLEDGMENTS

When the second author brought the US formula to Australia he had hoped that 10 Universities might eventually participate in this competition. It was hoped that the participating teams would enjoy much of the practical training that the authors brought to this project from their involvement in different aspects of motor racing. We are pleased to report in 2005 that every University in Australia with a relevant department is participating in this competition. A great credit to its US originators and SAE support from the President, officers, and volunteers of SAE-A.

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NOMENCLATURE

- BMEP brake mean effective pressure
- CA crank angle
- COG center of gravity
- DOHC double over head camshafts
- EFI electronic fuel injection
- EMS engine management system
- EVC exhaust valve closed
- EVO exhaust valve open
- FMEP friction mean effective pressure
- IVC inlet valve closed
- IVO inlet valve open
- KEC kinetic energy conservation
- MBT minimum spark advance for best torque
- NA naturally aspirated
- RON research octane number
- TC turbo charged
- VE volumetric efficiency

REFERENCES


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