Inside the boxer heart of a leading World Rally Championship contender

Designed and developed by Prodrive in conjunction with factory department Subaru Tecnica International (STI) the current Impreza World Rally Car is an evolution of a model first introduced in 1993. Our sister publication Race Tech looked in depth at the technology of the Impreza in 1995, by which stage it was already established as a winner in World Rally Championship events.

Here we discuss the development of the Impreza's engine with David Lapworth, Technical Director at Prodrive, the UK-based concern that runs the Subaru factory World Rally Championship programme. It is a programme that embraces events as diverse as the ice cold of the Monte Carlo Rally and the heat of the high altitude Rally Mexico. Through a busy season the car will run in a huge range of conditions, ranging from ice and snow to gravel to smooth tarmac stages.

Throughout its life the Prodrive-fielded Impreza WRC has been powered by a modified version of the model's four-cylinder production engine. The horizontally-opposed engine is a true 'boxer', having four crankpins arranged so that opposing pistons 'box' towards each other. It has four valves per cylinder operated by double overhead camshafts, with the WRC car confined to the production 43-degree included valve angle and production valve sizes.

As per WRC regulations, the engine has a 2.0-litre displacement and is equipped with a single turbocharger that breathes through a single 34 mm diameter air restrictor. It runs on the mandatory 98-octane 'Super Unleaded' 'control' fuel.

In 1995 the modifications to the engine were governed by FIA Group A regulations whereas now they are governed by both those rules and additional WRC regulations, which take precedent over them. As a consequence the turbocharger no longer has to be a standard production model, although exotic materials and variable geometry are not permitted. At the same time reciprocating and rotating components are now bespoke rather than mandatory production items.

Lapworth notes that the base engine has been developed to run to a five figure engine speed in other applications. However, given the presence of the restrictor he says that there is no point in developing the current WRC engine to run beyond 7500 rpm. Given the restrictor and the use of turbocharging, Lapworth says that it is not necessary to snap the valves open, nor to use high lift valves.

"The gain would be small compared to a normally aspirated engine. Our valve timing is not wild."

The restrictor rations the supply of air to the turbo compressor and up to a point charge pressure and crankshaft speed are interchangeable. The 34 mm restrictor flows in the region of 10 cubic metres of air per minute and in simple terms as engine speed increases the plenum pressure generated by the turbocharger decreases accordingly.

In practice, says Lapworth, boost is indeed inversely proportional to crankshaft speed and consequently there is twice the boost at 3000 rpm as there is at 6000 rpm. Given the effect of the restrictor the turbo wastegate is a secondary boost control. If it did not operate there is a real danger that the turbine would overspeed and exhaust back pressure would become unnecessarily high.

The Impreza WRC's wastegate is pneumatically activated and is electronically controlled, as part of the engine management system. The turbocharger itself is a bespoke IHI model. Lapworth observes that it doesn't differ massively from a production model but crucially it is tailored to the WRC operating environment, in which the air comes through a restrictor and in which the plenum pressure can be as high as 4.0 bar absolute. In contrast, the production turbocharger used in 1995 provided a maximum of 3.0 bar absolute.

> "It is a programme that embraces events as diverse as the ice cold of the Monte Carlo Rally and the heat of the high altitude Rally Mexico"

The WRC engine's operating speed range is 2000 rpm to 7500 rpm and Lapworth notes that it is hard to make a turbocharger efficient over such a wide speed range. He also notes that the inverse relationship between plenum pressure and engine speed makes the compression ratio something of a compromise.

In 1995 the compression ratio was 9:1. Now it is "over 10:1" and an (undisclosed) figure that is altered from rally to rally. In particular it is tailored to altitude - a higher than normal ratio was used on the new high altitude WRC event in Mexico. In spite of the high ratio the Impreza WRC engine does not employ oil gallery pistons, merely a single oil jet spray to the underside of each of its "regular aluminium racing pistons".

Water injection has been introduced since we looked at the engine in 1995 and has assisted the exploitation of a higher compression ratio, although Lapworth says that its use is not critical in this respect. At the same time the current WRC regulations permit the use of a significantly larger air:air aftercooler than was employed in 1995. As a consequence of these factors the charge air temperature is typically around ambient as measured in the plenum, whereas in 1995 it could often be 30 degrees above ambient in the plenum.

Lapworth notes, however, that ambient temperature varies widely between rallies - from extreme cold to extreme hot - and that some rallies are markedly faster than others: "The intercooler naturally works more efficiently on the high speed events, such as Finland and New Zealand."

Nevertheless, thanks in part to water injection, these days charge air temperatures are typically close to optimum. (See sidebar: WATER INJECTION.) In theory by slowing the burn rate, the water injection system helps suppress detonation. In practice, says Lapworth, the effect is marginal and is only significant at lower engine speeds.

Lapworth notes that the air-restricted Impreza WRC engine is more prone to detonation at low crankshaft speed than at high speed.

"We are compression ratio limited at low speed whereas we are not detonation limited at high rpm. We can find the optimum ignition point at 7000 rpm whereas at low rpm if we run too much advance, it is all too easy to destroy the engine!"

Lapworth reports that the Impreza's ignition advance is in the region of 30 degrees at 7500 rpm whereas at 2000 rpm it can be as low as 5 degrees. In essence, advance increases progressively from 5 to 30 degrees across the engine's operational speed range.

In 1995 the peak power was quoted as 300 bhp at 5500 rpm and the power output was within 10 bhp of that figure from 5000 to 6000 rpm. Maximum torque was produced at 4000 rpm and the driver generally operated within the band of 4000-6500 rpm. Power declined steeply beyond 6500 rpm and the red line was set at 7500 rpm.

A key gain since 1995 has been the power output at lower engine speeds thanks primarily to the higher boost obtainable with the bespoke turbo. Of course, there has also been a lot of painstaking development work on all aspects of the engine, assisted by the greater freedom of internal modifications ➤

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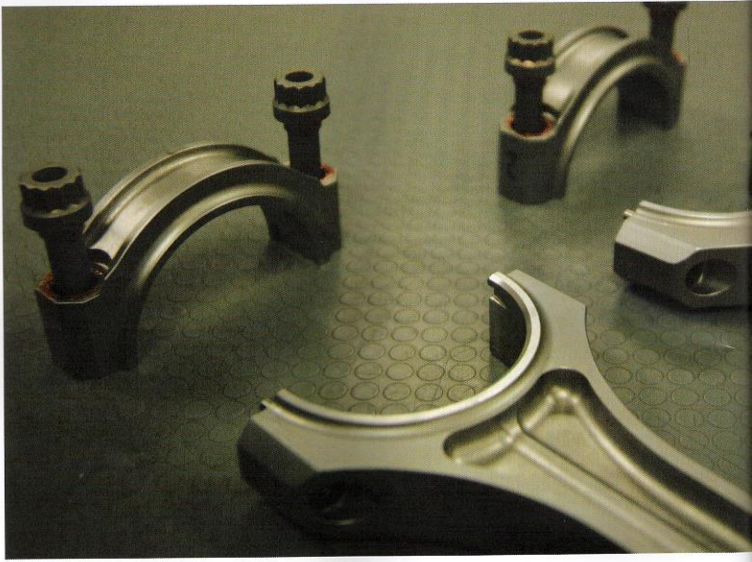

introduced with the 1997 WRC regulations.

Lapworth says that since 1995 there has been a 10% gain in top end power. The peak power speed is still 5500 rpm and power is within 10 bhp of the peak figure of 330 bhp from 4500 to 6000 rpm. It is now 300 bhp-plus all the way from 3000 rpm to the red line at 7500 rpm, beyond which it declines. The current WRC engine pulls strongly from 2000 rpm, which is its idling speed in 'stage' mode. It is an engine speed only experienced in slow hairpins.

A key to success in rallying is driveability. Lapworth notes that a turbocharged air restricted engine such as this, with its flat, wide power curve, is inherently driveable. In this respect significant developments over the last decade have been not only the strengthening of the power curve on both sides of peak torque but also the introduction of an anti lag system, which has effectively eliminated turbo lag. (See sidebar: ANTI LAG.)

Lapworth says that it is a "close call" between the single throttle butterfly employed since the engine was introduced and a four-throttle system. "There would be a tiny response advantage with four throttles but the single butterfly is simple, reliable and gives a weight advantage".

Thanks to the anti lag system, the turbocharger will provide useful boost from 2000 rpm, with at that speed power already in excess of 200 bhp. The plenum pressure will be as high as 3.0 bar absolute at 2500 rpm and peak torque - in excess of 700 Nm - is seen at 3000 rpm, pumping around 4.0 bar absolute.

Lapworth reports that there has been a 25% reduction in engine inertia since 1995. This is primarily a function of the introduction of the WRC rules, which permitted the use of bespoke reciprocating and rotating components. However, Lapworth notes that the lightweight components have only had a marginal effect upon engine output and that in some circumstances less inertia can be a bad thing - for example, over the bumps that characterise some rally stages. "But the engine does feel nice and sharp with less inertia."

The current Impreza WRC engine uses essentially the same block as the original - some minor modifications were made in 1999. The latest Impreza road car uses a further development of the original block. Lapworth explains that this was not adopted for the current WRC car for reasons of cost and continuity. It was not perceived as the basis of a performance enhancement.

Naturally part of the increase in engine performance since 1995 has come from the reduction of frictional and other internal losses.

THE CAR ENVIRONMENT

The Impreza WRC is has a paddle-shift, semi-automatic six-speed gearbox, automatic clutch operation and four wheel drive with active differentials. Nevertheless, Lapworth says that this sophisticated transmission system has not greatly influenced engine development, compared to the use of a simple, mechanically-controlled, two-wheel drive drivetrain.

"With our engine the torque falls dramatically as the engine rpm increases. That makes it easy to control the amount of wheelspin - break traction and the engine torque drops. The engine should work very well in a two wheel drive car."

ANTI LAG

In 1995 we were told that 'the engine does suffer from a certain amount of lag'. Now, says Lapworth, lag is essentially a thing of the past.

The anti lag system sees, in closed throttle conditions a certain proportion of the compressed charge air directed from the charge plumbing into the exhaust manifold, by-passing the cylinders. At the same time the cylinders are fed an over-rich mixture so that unburned fuel is ignited in the exhaust. This ploy maintains turbine speed at the full throttle level, so that when the driver opens the throttle again the required boost is on tap.

Given that the plenum pressure is inversely proportional to crank speed the required turbine speed varies accordingly. In practice, with the anti lag system the only lag occurs after a gear shift, as the turbocharger adjusts to the new engine operating speed. For example, if a shift means that the revs drop from 6000 rpm to 4000 rpm the boost might need to increase from 2.0 bar to 3.0 bar. Lapworth says that the delay while the turbo spools up is only noticeable on data logging - the driver will not perceive it.

WATER INJECTION

All of the factory WRC teams employ either water injection or a water spray to the air:air aftercooler to keep charge temperature under control. Lapworth says that the use of an ERL Aquamist water injection system helps keep the Impreza's charge air temperature to around ambient, even though the engine can be pumping a charge pressure as high as 4.0 bar absolute.

"Water injection can help us take the plenum temperature down to around 40 degrees Centigrade, even on hot rallies. The benefits of reducing the temperature below that sort of figure are marginal and the trade off is the quantity of water carried on board the car. Typically we carry about five litres for a 60 kilometre stage."

Prodrive uses ERL system bespoke-2C, which permits the Impreza's engine management system to incorporate a water injection map. System 2C provides a pre-pressurised water line that runs at up to 10 bar, while the flow rate is metered by ERL's own High Speed Valve.

Made of stainless steel, this in-line HSV is capable of achieving a cycling rate of over 250Hz and is directly driven by the Impreza's ems. A signal from the 2C pump is used to

"Currently only development engines employ any DLC coatings"

The introduction of bespoke reciprocating and rotating components has helped, for example with smaller bearing widths, improved lubrication and the use of coatings. The likes of camshafts, followers and pistons have all benefited from coatings. The piston skirt is coated, albeit not with a DLC. Currently only development engines employ any DLC coatings.

The current bespoke crankshaft retains the production bearing diameters whereas it has reduced bearing widths. Says Lapworth: "the gain from reducing bearing diameter would be marginal and the penalty would be a loss of crank stiffness. Thanks to our 'boxer' configuration we have an inherently light crankshaft."

The rules still call for a wet sump but these days the crankcase runs less oil. Lapworth remarks that the speeds at which the engine operates do not justify sealing the crankcase off into four separate chambers.

The sump is now a bespoke production, whereas it was a modified standard component in 1995. It is still steel. Some rivals use a Kevlar sump but Prodrive prefers steel for its deformability: although the car runs a sump guard, many are the occasions when the sump is attacked by a rock or suchlike.

"It must be designed to sustain some damage," remarks Lapworth. ■

WATER INJECTION (cont)

determine the status of the system in real time and the output drive signal can be made directly proportional to the flow rate.

The water is injected into the charge air pipe that connects the Impreza's single air:air aftercooler with the plenum chamber. It is introduced as a fine spray. Lapworth observes that the ERL injector does not need to be as sophisticated as a typical fuel injector and that its positioning is not critical, provided that the fine spray is reasonably well distributed between the four cylinders.

In theory the use of water injection helps suppress detonation by slowing the burn rate. According to Lapworth the key benefit is its effect upon charge temperature and he reports that the drivers do notice a difference when the water injection system is not working.

Richard Lamb of Prodrive water injection system supplier ERL recalls that a couple of years ago one of the Prodrive 'customer' World Rally Cars had to limp to the next service location on 'safe operation mode' when its water tank ran dry in hot conditions.

"The tank was filled and the system re-primed and he ended

up finishing fourth at the end of the day after having dropped beyond 10th position due that incident. Water injection is crucial in high ambient temperature events," remarks Lamb.

Running without water injection in cooler conditions there might only be a slight reduction in engine output due to higher manifold temperatures but Lapworth remarks that the driver will detect a drop off and that he will typically note that the engine has lost its edge."

Given that a key benefit of water injection to a WRC engine is in terms of plenum temperature, an intercooler spray is a less efficient means to the same end but one that can be seen as safer: there is no danger of flooding the engine with water. Prodrive has had no such problem using the ERL system.

In fact, Lamb says that all teams other than Mitsubishi currently run internal water injection. But in the near future the FIA intends to ban both water injection and water sprays. Lapworth observes that this will result in a small cost saving and a slight decrease in engine power. At the same time the weight of the water and the injection system will be saved - around 5 kg in total at the start of a stage.

Says Lamb: "I would like to know the real reason behind the ban. With water injection, the engine can run leaner, cleaner and operate more efficiently. We will be going back to the days when every one uses a 'fuel dumping' strategy for cooling the combustion chamber. It will be a sad decision for the environment." ⭘

PRODRIVE/STI SUBARU IMPREZA WRC flat four ENGINE ANATOMY

IMPREZA WRC flat four 2004
WORLD RALLY CHAMPIONSHIP 2004
Horizontally opposed four cylinder
92 mm x 75 mm = 1994 cc
Single IHI turbocharger
Super unleaded fuel
Aluminium block and heads
Dry Nikasil liners
5 main bearings, plain
Steel crankshaft, 4 pins
Steel con rods
Light alloy pistons; 3 rings
Dohc, belt driven
4 valves/cylinder, 1 plug
Valve angle 43 degrees included
36 mm intake, 32 mm exhaust valve
STI ignition
STI injection
STI engine management system
98 octane Super Unleaded control fuel
Compression ratio undisclosed
Maximum rpm 7500
Weight 175 kg fully dressed

The Impreza's horizontally-opposed four-cylinder 'boxer' engine is based on aluminium alloy production castings. The crankcase is split vertically along the crankshaft axis, the two halves coming together to sandwich the five main bearings. Each crankcase half is formed integrally with its respective block, to which is attached a separate head with integral tappet block.

Ten bolts tie the two halves of the crankcase together with each head attached by a further six bolts and block to head sealing via metal rings. The combustion chamber is of the pent roof type, with an included valve angle of 43 degrees as per the base production engine. The valve sizes are as per the production engine (36 mm and 32 mm in a 92 mm bore) and there is a single central plug.

The bespoke three-ring piston has light valve clearance notches and a more pronounced intruder than its 1995 predecessor, thanks to the higher compression ratio (over 10:1 compared to 9:1). The gudgeon pin is steel and it runs in a bronze-bushed small end, retained by conventional circlips.

The bespoke con rod is still steel in view of the regulations. It is a two-bolt I-section design. The crankshaft, which runs in plain bearings, is now a bespoke production by STI. It has the production bearing diameters - 60 mm main and 52 mm big end - but reduced bearing widths. The crank oiling system has not been fundamentally altered from the stock layout and a steel flywheel is used, as per the regulations.

While production valve sizes are still employed, the steel valves are now bespoke productions. The exhaust valves are sodium cooled. The valve seats are likewise a bespoke material - one that is very hard as dust is the enemy of rally cars.

Twin steel valve springs supplied by STI are run with an interference fit. Solid steel bucket tappets are employed, as in 1995, with shims for adjustment. The tappets are directly-operated by the twin overhead steel camshafts, each running in three journals carried directly by the head. The head is closed by a carbonfibre cover, whereas a plastic cover was originally employed.

The timing drive follows the production system, with a single toothed belt powered by a pulley on the nose of the crankshaft driving both banks and the water pump. However, thanks to WRC rules lightweight pulleys and an up-rated belt can now be employed. The up-rated belt is significant given a 25% reduction in engine inertia since 1995.

Ahead of the timing belt, a vee-belt drives the power steering pump and the alternator. The oil pump is driven directly by the crankshaft. Bolted to the base of the crankcase, the deep steel wet sump is has complex baffling. The WRC engine has modified production oil and water systems. The production oil/water heat exchanger has been switched for an oil/air radiator to suit car packaging requirements.

The intake system sits atop the engine, the exhaust ports emerging underneath. The intake manifolding is magnesium, the exhaust system inconel. The four primaries are routed to the IHI turbocharger's single-entry turbine. The turbo is plugged into the engine oil system.

The compressor feeds through an air:air aftercooler, with a single butterfly throttle positioned between there and the central plenum chamber. The throttle is electronically rather than cable operated. With this fly-by-wire system the throttle pedal operates as a sensor and the engine management system controls the butterfly.

The fuel injectors are now bespoke items and the system runs at 10 bar, compared to 4 bar in 1995. TAG supplies the injectors and the coils, one of which is mounted on each plug. STI supplies the engine management system, which these days exploits significantly higher computing power - in 1995 the car used an 8 bit processor whereas now it has a 32 bit item.