

Inherent in the technique of exhaust gas turbo-supercharging is a delay between pressing the throttle pedal and the arrival of increased power at the driven wheels. **John Coxon** investigates means to overcome this phenomenon of turbo lag

Quick as a

Ever since the Swiss engineer, Alfred Buchi invented the exhaust driven turbo-supercharger in the nineteen twenties, engineers have been trying to tailor the delivery characteristics of the device to suit the air demands of the reciprocating piston engine.

Depending upon the size of the unit, the exhaust driven turbocharger can operate at speeds up to and sometimes in excess of 200,000 rpm and the matching of the compressor to the turbine and then again to the engine application can be critical. The compressor's airflow characteristics, varying much as to the square of the turbine shaft speed, would seem to be fundamentally at odds with the breathing characteristics of the piston engine which are roughly proportional to crankshaft speed only.

In heavy-duty diesel engines, where turbochargers first became popular the matching process is not such a major issue. With transient engine speeds rarely considered of great importance, the turbocharger is matched over a relatively narrow range of engine operating speeds. A simple turbocharger system is readily accepted as a way of not only boosting power but also of increasing specific fuel economy, improving emissions, reducing noise and so forth.

Later applications benefited from variable geometry turbines to improve matching and allow the units to produce better boost characteristics over a wider speed range. However, in essence the turbo was generally seen as a diesel engine "thing" up until the mid sixties. All that changed in the late sixties and early seventies when Chevrolet with its Corvair and later Porsche and others, introduced turbocharging to gasoline-fuelled vehicles.

Matching an exhaust driven turbocharger to the demands of the spark ignition engine is much more difficult than the case for its compression ignition equivalent. Even in its simplest mode, the gasoline engine has a much wider range of operating speed and consequently, together with its throttling, a very much wider range of airflow requirement.

Along with the demand for faster transient response to match that of the gasoline engine, this meant that additional devices, limiting the

exhaust flow to the turbine or venting excessive boost pressure were necessary to match both the turbine and the compressor safely to the engine. Enter the exhaust gas wastegate and the intake manifold "dump" valve to assist during transient operation.

The aim was always to approach the turbocharging ideal of having performance equivalent to that of a naturally aspirated engine of correspondingly larger displacement. A 1.5 litre turbocharged engine with a plenum pressure of 2.0 bar corresponds to a 3.0 litre naturally aspirated engine. The days of the 3.0 litre Formula One engine were numbered when those engineering 1.5 litre turbos found they could exploit significantly more than 2.0 bar absolute!

But turbocharging is about more than horsepower. During transient operation a simple turbocharger system will inevitably suffer from poor transient response: this is widely known as 'turbo lag'. In part, it is a direct characteristic of the system dependent on the amount of energy in the exhaust manifold at the time of the demand. However it is also a function of the rotational inertia of the turbine and compressor assembly.

While careful design of the intake and exhaust manifold system minimising volumes can reduce this effect, in practice there are certain constraints. On the intake side a charge cooler will almost certainly be required to offset the increased air intake temperature as a result of compression and on the exhaust side, the packaging of a cherry red-hot turbine housing can present many problems.

If that were not all, the engine designer has little control over the rotational inertia of the turbo unit and often requires even larger units to match the greater airflow demanded by competition units. For these reasons traditionally engineers have looked to other ways of minimising lag.

One obvious method of countering lag is for the driver to compensate for it and anticipate the reaction of the engine by opening the throttle well before full torque is required. This is highly counter-instinctive and is feasible for only the bravest of drivers, although by necessity it was often practised in the early days of turbocharging.

Trimming the brakes with the left foot while keeping the throttle



“Alfa Romeo did experiment with a twin turbo arrangement blowing into a common intake manifold”

slightly open with the right foot, gave more assurance and kept the inlet manifold pressure higher than it otherwise would have been. Remember, though, this was before the advent of paddle change gearboxes and it was very hard on the brakes anyway.

One way of reducing the rotating inertia of the turbo assembly is of course to reduce the size of the unit itself but increase the number of units.

In the early years of turbocharger development in Formula One, the initial single turbo applications quickly made way for twin turbo systems, as soon as these smaller units became available.

The V6 1.5 litre engines were admirably suited to the packaging of one turbo unit per bank, which could be mounted low down in each of the sidepods. The situation was not so straightforward for those running in line four cylinder engines. While Alfa Romeo did experiment with a twin turbo arrangement blowing into a common intake manifold, other users such as BMW and Hart, felt they had to accept the penalties of a larger turbo and overcome their transient response issues in other ways.

The reduced inertia of smaller turbo units clearly doesn't eradicate turbo lag and may only be part of the solution. Once at an optimum size it is then necessary to look towards increasing the amount of energy in the exhaust manifold for the ultimate solution.

But there is another way. In the mid eighties, the works Lancia rally team produced a lag free engine by using a supercharger and a turbocharger in series. The low speed pressure charging of the

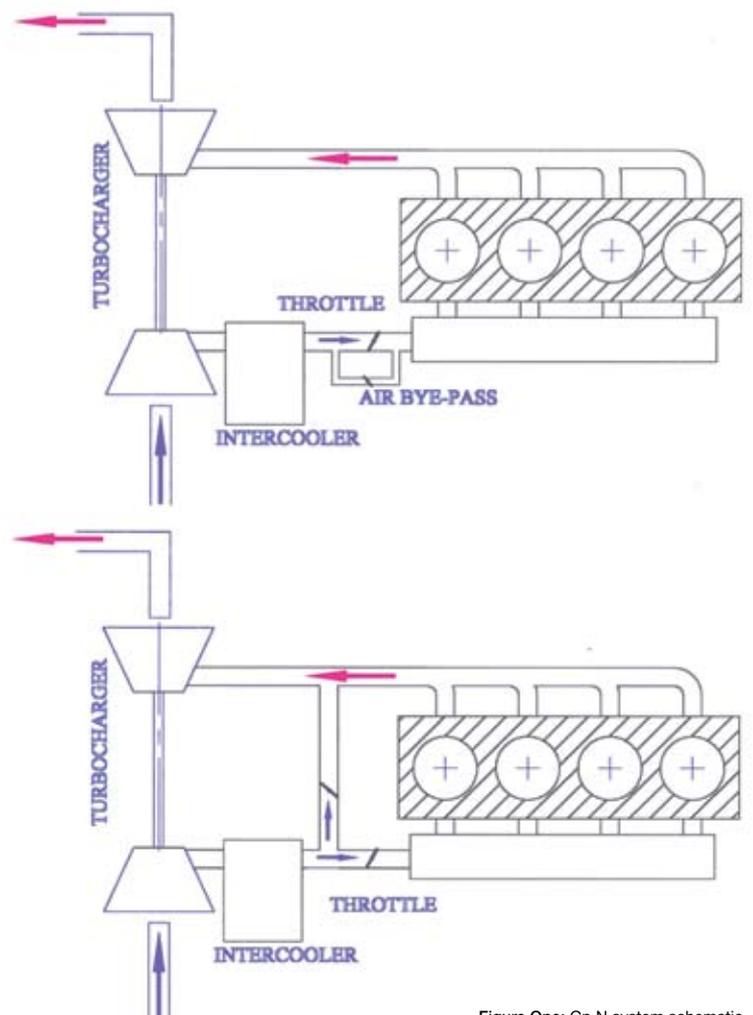
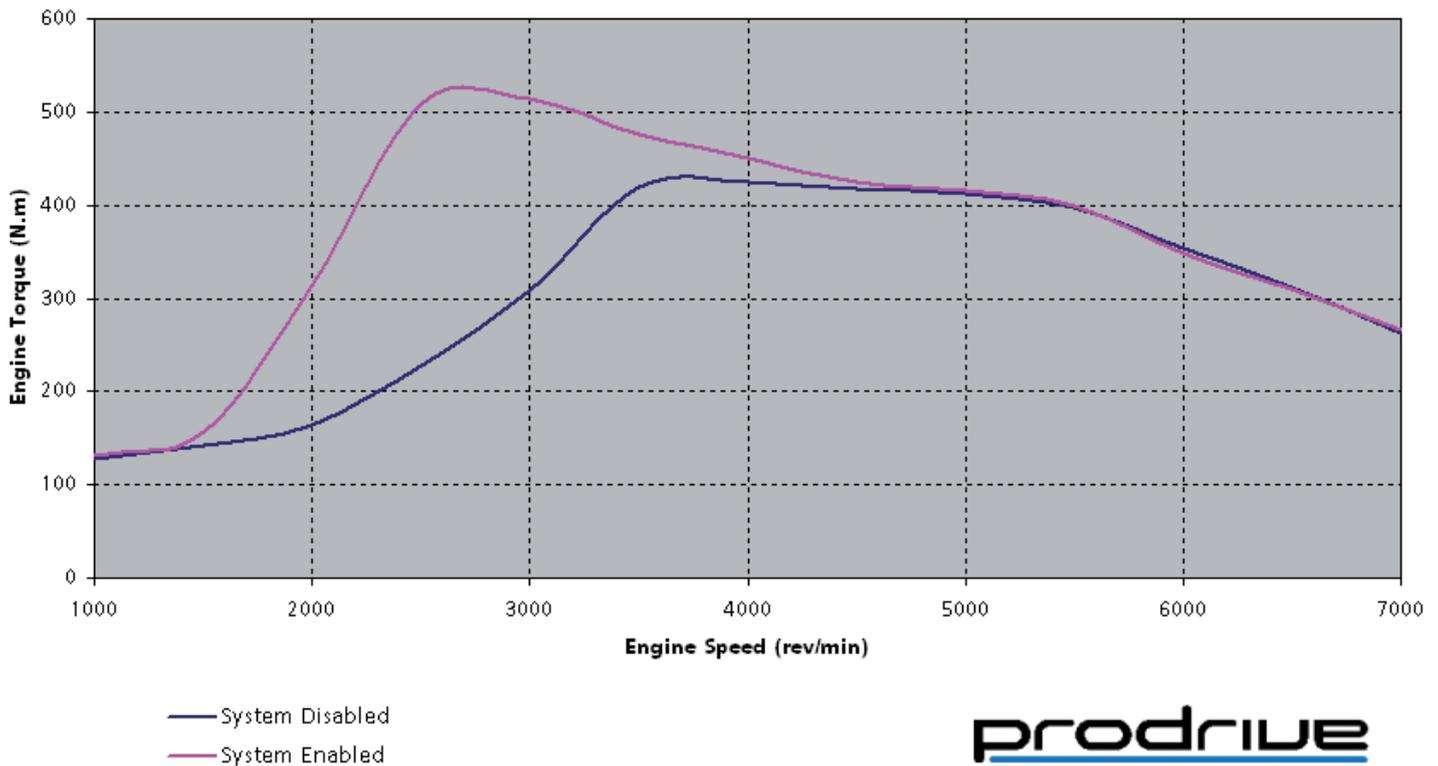


Figure One: Gp N system schematic

Figure Two: Prodrive Subaru torque curve



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engine was taken care of by a Volumex supercharger driven from the crankshaft. Once a certain boost pressure was attained this device was bypassed, using a simple rotary valve and then all of the boost was supplied by the turbo unit. Simple - but not without its problems.

During upshifts, it was claimed, the mechanical system could often be caught out, a phenomenon that was overcome by the addition of a "pneumatic" damper. In fact this was a calibrated hole which reduced the pressure fluctuation in the manifold during the changeover period. However, engineers since have looked to other ways to counter lag, without the complication of using an additional supercharger.

Early in the days of turbocharging in Formula One Ferrari bypassed compressor air directly to the hot turbine wheel whenever the throttle was closed. Some fuel was introduced to turn the exhaust side of the turbocharger into a little gas turbine engine! This strategy became less attractive when the rules started to limit the fuel allocation.

The turbocharger manufacturers weren't standing idle. Developments with variable geometry turbine housings mainly for the diesel market and ball bearing systems combined to extract maximum energy from the exhaust gas flow and decrease spool up times.

During the Formula One turbo era, which went on until the end of 1987, significant advances were made in electronic engine management systems. This development work led to control systems and strategies that made turbo lag a thing of the past for the V6 engines. Today, there would appear to be few aftermarket engine management systems that do not offer some kind of anti-lag capability.

Sometimes abbreviated to ALS and made popular through their use in four wheel drive and turbocharged WRC rally cars, these are often also known as 'bang-bang' systems due to their aural characteristics. They are brought into play when the throttle returns to the 'off' position. As well as when shifting up and down the gearbox and when accelerating out of corners, more sophisticated derivatives of these

systems can be designed to be effective even from a standing start, as we shall see when we look at the Subaru World Rally Car.

There are a number of different variations on the ALS theme but essentially the requirement as ever is to keep the turbine shaft spinning at or near the required speed using hot exhaust gas.

On engine over-run when the driver's foot is 'off' the pedal, the throttle must be modified so that it can continue to pass sufficient air to power the turbine. This requires an air bypass system which can either bypass the throttle plate entirely, much like an idle air control valve, or a throttle 'kicker' plate (a solenoid operated device that jacks open the throttle plate) added to produce the same effect.

The air bypass system can be either internal allowing air to pass into the engine or external, rather like the 1981 Formula One Ferrari above and bypassing the engine entirely.

GROUP N ANTI LAG SYSTEM

For the purpose of this discussion I shall refer to Figure One which is a typical Group N turbo system with an external air bypass fitted

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as standard.

When the engine is running at speed with the throttle closed as is the case on the over-run, the ignition will be heavily retarded or even cut completely and the fuel mixture slightly enriched. At the same time the air bypass solenoid will be activated and pressurized air upstream of the throttle will be diverted directly to the exhaust turbine. The fuel rich exhaust when meeting the by-passed air will then burn and expand into the turbine which will speed up again.

If an external air bypass is not possible then on the overrun the throttle may have to be jacked or kept open by as much as 12 to 20 degrees. Retarding the ignition to 35-45 degrees ATDC (around 70 degree off map) will ensure that the fuel enriched exhaust gas burns slowly in the manifold well after the exhaust valve has opened. With little or no expansion in the cylinder the engine will be delivering no torque and the flame front will move down the exhaust manifold to be expanded through the turbine unit.

By keeping the turbine/compressor assembly spinning quickly, transient response is significantly improved when the throttle is again tipped in. Remembering that the whole point is to keep the turbo spinning as near to operating speed as possible, by adjusting the throttle opening, fuelling and ignition retard the best compromise between excessive pre-turbine exhaust temperature and desired anti-lag action can be obtained.

Clearly a system like this has its downsides, the most obvious of which is that it gives no engine braking, making the vehicle brakes work harder. In addition the cylinder bore walls are exposed to greater heat flux and therefore the coolant temperature will increase rapidly. Consequently in most applications, a coolant temperature sensor ALS inhibit switch will be necessary with a trip temperature of around 110 - 115°C. When the coolant temperature reaches this figure the anti-lag system will be automatically switched out.

Using an ALS the engine exhaust valve will see much greater heat and the pre-turbine temperature will increase substantially. Since it is essentially uncontrolled the turbine speed will fluctuate rapidly. There is a danger of overspeed, resulting in damaged blades and ultimately failed units.

The exhaust manifold will obviously see both greatly increased

thermal and mechanical loading. This will need to be addressed at the design stage if considerably reduced durability is not to be encountered. A logical choice of material is stainless steel or even Inconel (a family of trademarked high strength austenitic nickel-chromium-iron alloys with exceptional heat resistant and anti-corrosion properties).

The turbine unit itself will also suffer if not correctly specified. However even using Maram 247 (a high temperature – up to 1150 degrees Centigrade – Nickel-based aerospace alloy) for the shaft, turbine wheels with cut back blades (to limit turbine speed) and Nimonic wastegate spindles, not surprisingly, durability still suffers.

While an ALS system will not increase the power of the turbocharged engine the improved response will make it much more driveable and should achieve the turbocharging ideal of having an engine of equivalent performance to an naturally aspirated engine of much larger displacement.

WORLD RALLY CAR ANTI LAG SYSTEM

The technology of World Rally Cars in recent years has moved on apace. To understand developments in this area I visited Ben Hoyle of Prodrive at his base at Fen End in Warwickshire, England. Hoyle is responsible for the anti-lag system on the Subaru World Rally Car and for Prodrive Subaru road car systems. Since the Subaru World Rally Team is, in effect, a customer of Prodrive, confidentiality precludes us going into too much detail. Nevertheless Hoyle was prepared to give RET readers a fascinating insight into this intriguing area.

Hoyle explains that instead of a relatively crude 'bang-bang' system the Subaru World Rally Team has introduced what is effectively a much more refined turbocharger speed control system.

"This relies on an external air bypass controlled by a fully proportional, active control valve together with a fly-by-wire throttle in the intake manifold. The air from the bypass is fed into what can be only be described as a canister where continuous controlled combustion takes place."

In reality this is a combustion chamber taking exhaust gas, mixing it with fuel and bypass air. Once ignited, unlike the 'bang-bang' systems, the flame burns continuously. By controlling parameters

including fuel, bypass valve position, throttle, ignition and wastegate it is possible to attain a constant turbo shaft speed independent of the engine.

The Subaru system is driver-selected at the start of the special stage, at which point the engine idle jumps to around 2000 rpm and the turbo speed jumps to a constant figure controlled within +/-1%. Ben is naturally coy about revealing this number. He much prefers talking about the constant 130,000 rpm seen in the Subaru road car demonstrator. ▶

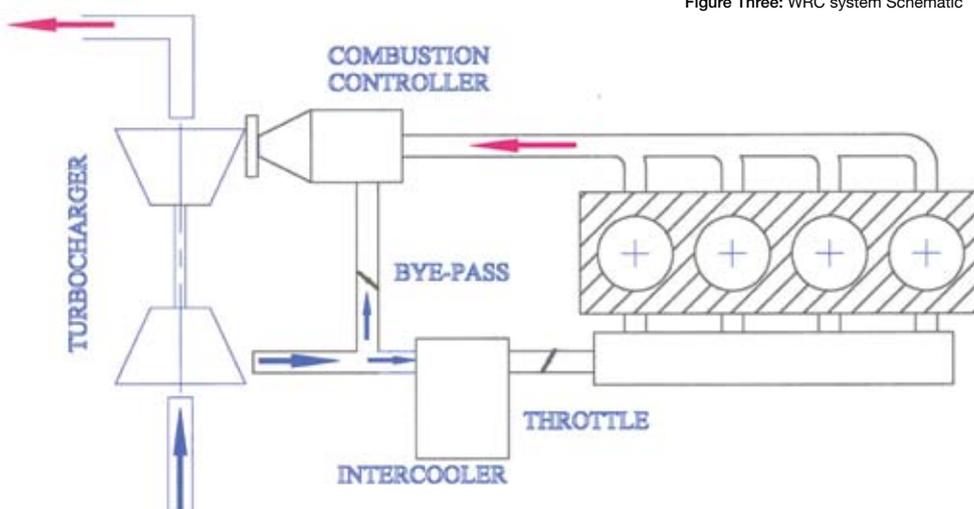
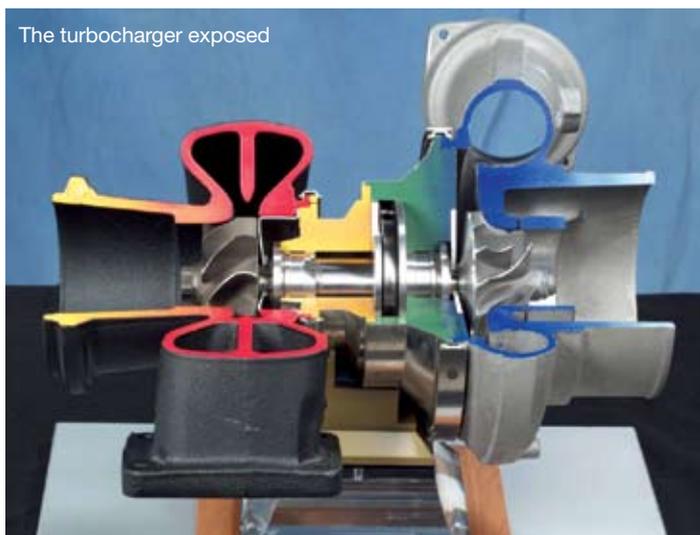


Figure Three: WRC system Schematic



The turbocharger exposed

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However other sources suggest that this is in the region of about 180-200,000 rpm on the WRC car.

While the WRC programme continues to look for higher performance, developments on the Prodrive Subaru road car are targeting the areas of refinement and control. At the moment the road car system is still driver selectable from a button on the dashboard and once that is pressed, the performance of the car changes immediately, as I saw for myself.

With a reassuring dull thud, the combustion chamber bursts into life and within a split second the turbo speed counter is registering a constant 130,000 rpm from the standard IHI turbo unit. At the same time the engine idle jumps to around 1200-1500 rpm.

Thereafter the control system monitors the throttle pedal position against road speed, selecting a suitable target turbo speed and inlet manifold pressure. Comparing these against the actual parameter an error signal is obtained in the feedback loop. By altering fuel, engine ignition, bypass opening, manifold throttle position and wastegate opening in a series of nested look-up tables, the desired target value is approached.

“In addition,” remarks Hoyle, “there is a supervisory system checking in the background to ensure that the turbo speed is not going out of control. There’s no point in say, demanding low boost when the turbo speed is doing 160,000 rpm or exceeding the 900 deg C turbine inlet temperature. The degree of interaction is very sophisticated in the road car.”

All of this is controlled via the Motorola 565 microprocessor embedded in the Prodrive Proteus engine management system.

The implications to running a system like this are wide ranging as Figure Two goes to show. By boosting the inlet manifold, engine output torque can be substantially modified particularly at low speed. In this case the standard peak torque of 430 Nm at 3700 rpm is changed to a whopping 520 Nm at a more than useful 2700 rpm!

From underneath the bonnet there is very little to distinguish the Subaru ALS system from the standard Prodrive Subaru offering and with a little further development it is hoped that the system will be offered as a kit. That should happen in the not too distant future.

Maybe at that point turbo exponents might finally be able to claim that they have at last reached the Grail of producing performance not just equivalent to but greater than a naturally aspirated engine of correspondingly higher displacement. ■

THE TURBOCHARGER

An exhaust-driven turbocharger consists of a centrifugal air compressor powered by an inward radial flow gas turbine at the other end of a common shaft. The exhaust gas from the engine, sometimes at up 1000 degrees Celsius, is carefully ducted into the turbine housing where it is accelerated through a nozzle and directed at the turbine wheel. Imparting both momentum and expanding through the wheel a torque is consequently applied to the turbine shaft. To counterbalance this, at the other end of the shaft, the centrifugal compressor is accelerating the air from its intake, through the compressor wheel and into a diffuser section. In the diffuser the air is gradually slowed down converting its velocity energy into pressure energy that can be many times greater than the pressure at the inlet.

The turbine generally spins on a set of “fully floating” journal bearings positioned centrally within the unit separating the compressor and the turbine stages. These are fed by oil from the engine lubrication system.

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