## BEFORE STARTING...

The first rule of working on cars and using tools of any kind is don't ever skimp on decent protection. Goggles, gloves, ear defenders, masks and a set of overalls should be in your garage. Use them.

When using power tools, protective gear is essential — grinders and welders can make a real mess of your soft skin and bone if you get it wrong.

Never work under a car without supporting it using axle stands. A car falling on you is not something you'll be laughing about down the pub.

**Words:** Stewart Sanderson



# SUPERSIZE ME

Turbochargers: big or small? How does a bigger one make the power difference without a boost pressure increase?

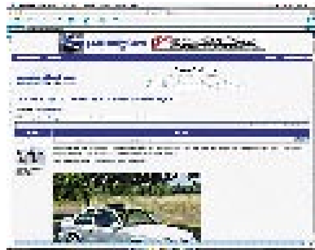
## WHO IS STU?

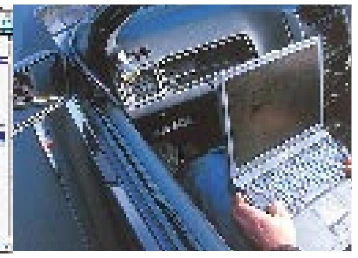
Having worked as a tuner for over 16 years, Stewart 'Stu' Sanderson is one of the most respected names in the business.

A Level 5-trained fuel-injection technician, in the past Ford nut Stu's worked for a Ford RS dealer, a well-known fuel-injection specialist and various tuning companies. Then six years ago, he joined forces with Kenny Walker and opened up Motorsport Developments near Blackpool, specialising in engine management live remapping, as well as developing a range of Evolution chips which are now sold all over the world.

He's also the brains behind www.passionford.com. Started in 2003, it's grown rapidly from a few friends and customers contributing, to one of the biggest Ford communities on the web.

Stu's enviable knowledge of the workings of modern-day Ford performance engines means that he's just the man to explain how and why things work, and most importantly, how they can be improved!



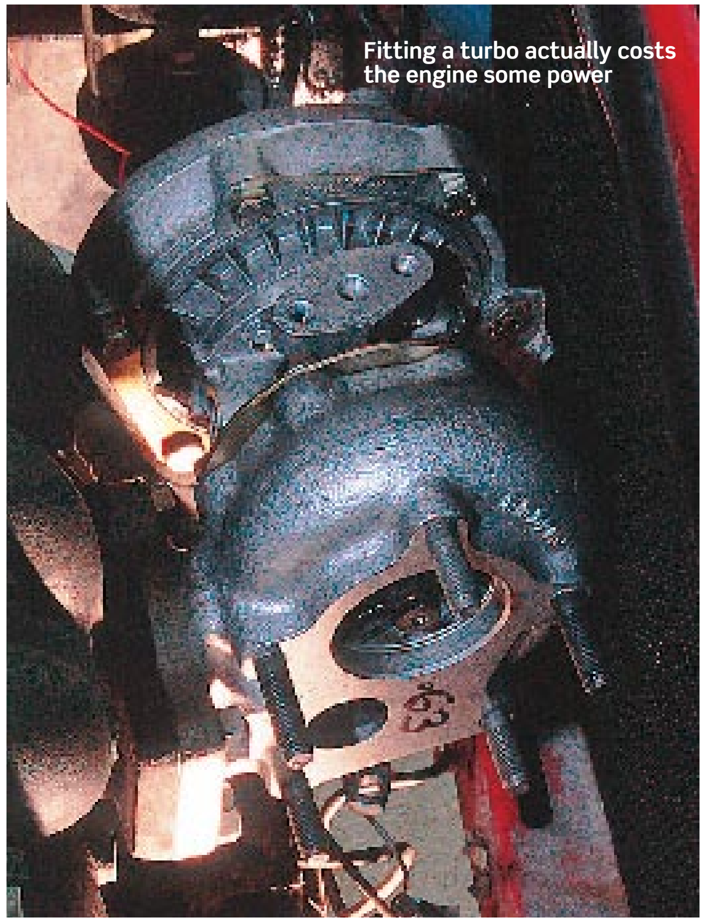


**DURING** my day-to-day work as an engine tuner, I've learnt that there are various concepts that most car enthusiasts (and some professionals!) can't get their heads around. One of these is turbo sizing. When I recommend it's time a customer increases the size of the turbo on their engine as part of a power upgrade package, it's almost guaranteed the very first question asked is, "Does this mean we can run more boost, Stu?".

The answer is usually: "While we could if we wanted to, we aren't going to — we're going to run the same boost or less, and get much more power!"

This reply normally leads — via confused looks — to a discussion about how a large turbo (Garrett T4, for example) can produce more power with a 20 psi intake plenum pressure, than a much smaller turbo like a Garrett T3 does at exactly the same 20 psi intake plenum pressure.

The facts are quite simple, if not a little tricky to explain, so let's look at a few things shall we?



Fitting a turbo actually costs the engine some power

## VOLUMETRIC EFFICIENCY?

VE is the amount a cylinder fills itself with mixture on the induction stroke. If a 500cc cylinder draws in 500cc of air/fuel on the induction stroke, it achieves 100 per cent VE.

### FORCE THE ISSUE

The first question I have to ask you is this: "Are you aware that a turbocharger is universally recognised as a form of forced-induction that initially costs the engine some power?"

Let's look at this carefully with a little tuning scenario. For the sake of discussion, we'll take a 1994 RS2000 I4 unit that's had the breathing improved by the fitment of some sensible camshaft profiles and a nice porting job on the cylinder head to produce a healthy 170 bhp.

To make this 170 bhp we are utilising the air pumping ability of our 2-litre engine, via its four 500cc cylinders.

These cylinders are drawing in, through the inlet valves, enough air and fuel at the correct ratio to burn safely and, importantly, expelling it once burnt and processed via the exhaust valves, to produce a power at the crankshaft of 170 bhp.

The air processed and power produced is related to the engine's volumetric efficiency (VE). (See boxout for how this is calculated.)

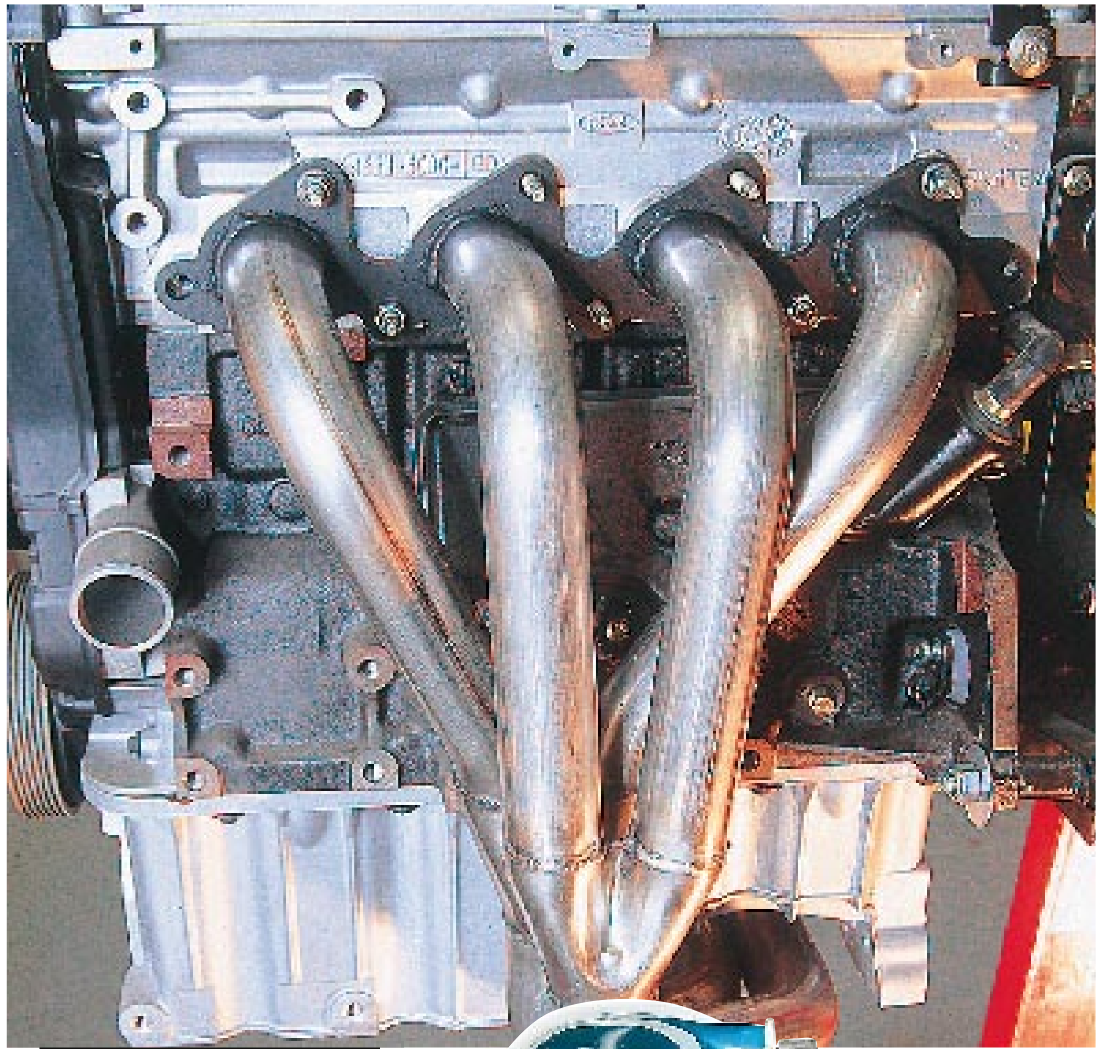
So the engine in question is making its 170 bhp with its nice, well-designed standard 4-2-1 exhaust system. So, now let's redesign this engine and make it turbocharged.

Starting at the exhaust system, we'll remove that 4-2-1 manifold and stick a Garrett T3 turbo with a relatively small turbine housing on it. We'll then jam close the exhaust turbine bypass gate (also known as a wastegate), and weld tight the compressor wheel so it can't spin and pressurise our intake system — just to see what actually bolting the turbo on does to our engine.

In essence, we now have the same, proven 170 bhp engine, but with a far more restrictive exhaust due to the turbo's turbine housing.

Hands up anyone there who thinks this engine will still make 170 bhp?

I'm sure we are all agreed that by restricting our exhaust this way we are now going to be lucky to see 100 bhp! But why does the power



Above. In a perfect world, exhaust gasses would have no restrictions to cause losses, like when a 4-2-1 manifold is fitted to a NA engine

drop? What has actually changed that's cost us 70 bhp?

## LOSE OUT

The answer is that we have dramatically increased pumping losses. Pumping losses are the amount of power used by the power stroke of a cylinder, to pump out the exhaust gas from another cylinder. The harder it is to get the gas out, the more power is lost in doing so.

This is the biggest issue with turbocharged engines. The reason this costs us power, is a great proportion of the energy produced from the power stroke of each cylinder burning the charge of fuel and air is now wasted trying to push the spent gas out of the previously active cylinder's exhaust valve, and through the tiny turbine housing into the exhaust before it can draw in another fresh charge.

We also have some detrimental knock-on effects from this back pressure: the friction on components caused by this pumping loss will now add heat to our engine, too. This heat was part of our power stroke's energy so is wasted power.

This pumping loss has also caused a problem with a phenomenon known as cylinder scavenging. Scavenging is used extensively with normally-aspirated engines, but is reduced to virtually zero on almost all turbocharged engines due to the back pressure in the relatively tiny turbine housing.

This back pressure has now also decreased the amount of air the exhaust pulse drew through the inlet valve at overlap (the point at which both inlet and exhaust valves are slightly open), so the maximum cylinder fill (VE) has reduced. Not only that, but the back pressure created means that some of the exhaust gas no longer escapes at all, thus diluting down our next cylinder of air/fuel with dead (and extremely hot) gases.

Down goes the engine's VE again... things are looking really bad for our power curve now!

So conversely, as we now have less airflow on overlap, we are going to start dumping heat through our exhaust seat and port and are heating our soft alloy head up. Why? Simple: designers use scavenging on overlap as a very simple and effective way of cooling valve seats, guides and ports.

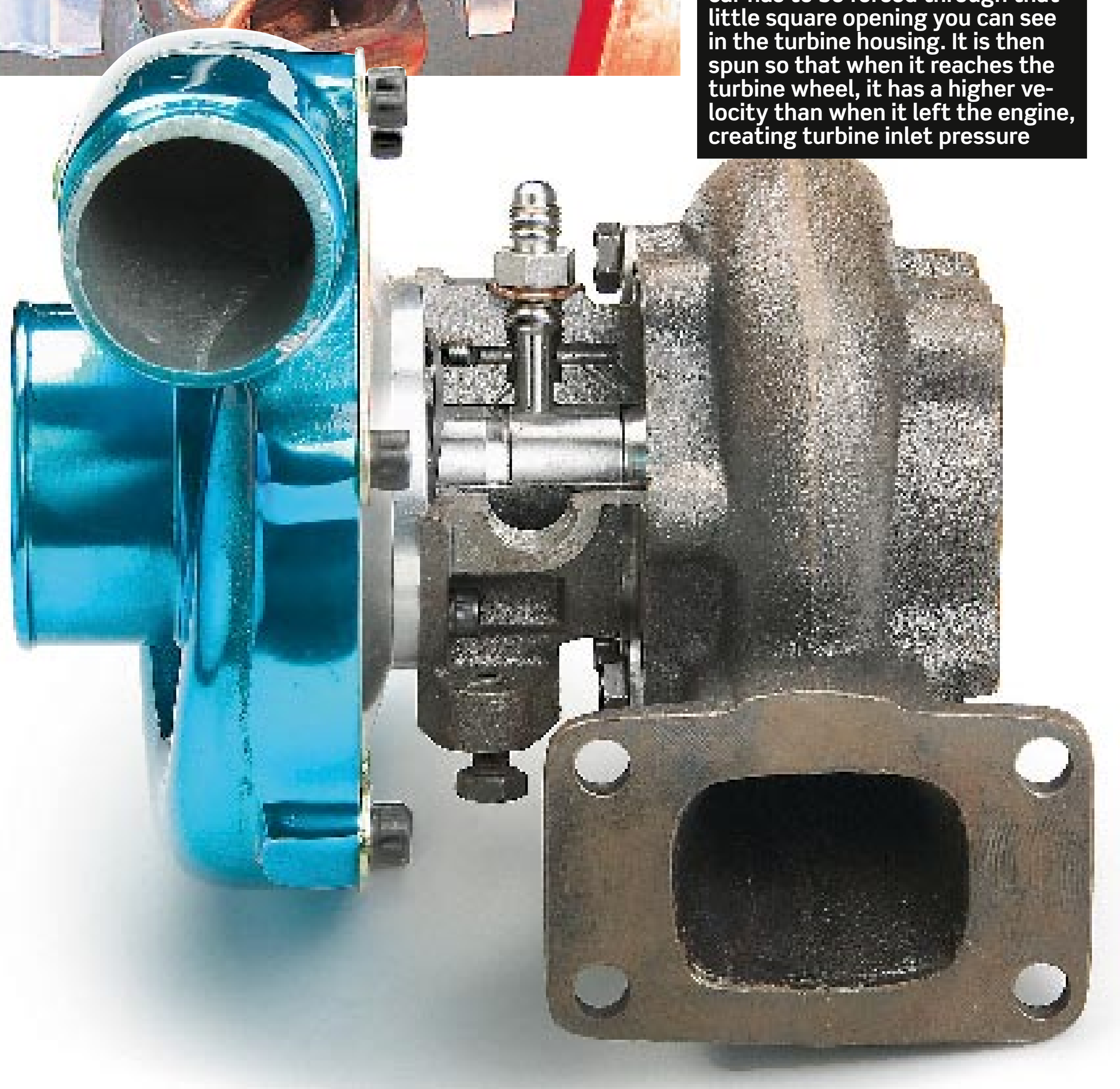
How does that work? Well, it's simply because when we reach overlap in our cam timing event, we have both a *cold* inlet and *hot* exhaust valve open. This gives the exhaust valve and relative components time to cool down from their grievous job only moments after shifting a mass of immensely hot air through its system. So it's a great relief for them to sit in some nice cold-flowing air for a second and transfer a bit of excess heat away!

Our fancy new engine design isn't looking too hot now is it? Well actually, it's getting very hot!

So, hopefully you can now see why the turbo costs an engine horsepower just by its very existence, and if you understand that, you are now well on your way to understanding how a *bigger* turbo will make more power than a smaller one with the same inlet pressure.

## CYLINDER SCAVENGING

This is the extra amount of waste gas drawn out of the exhaust valve at top dead centre (TDC), due to the presence of a slight depression that was created by the evacuation of gas through the exhaust valve.



Below. Unlike the manifold on the left, all the gas on a turbo'd car has to be forced through that little square opening you can see in the turbine housing. It is then spun so that when it reaches the turbine wheel, it has a higher velocity than when it left the engine, creating turbine inlet pressure

A T3 turbo will produce good power at a given boost limit with relatively low lag, giving good response and driveability

The much larger T4 turbo will produce a lot more power at the same boost, but as it has larger housings, it's very laggy

## T3 V T4

The necessary exhaust back pressure caused by the turbine housing assembly is the key element between the T3 and T4 — the T4 flows far more exhaust gas than the T3 so pumping losses are far reduced.

But let's deal with the delivery of our air into the engine now, and for that let's use the Cosworth four-cylinder YB power unit.

A T4 produces far more volume of air at a given pressure from its compressor housing than a T3 — that's universally agreed. And we agree both turbos have the same job — to pressurise our engine's intake system and keep the air flowing through it, mixed with fuel at the correct ratio, to generate power.

So let's look at the route of the air a little closer.

Our turbo's pressurised air has to travel through hoses, intercoolers, throttle bodies and then ultimately the plenum, before it has fuel added to it and it travels through the inlet valve into the awaiting cylinder.

Once combusted and the energy from this mixture is converted into crankshaft energy as best it can be, the piston travels back upwards with the exhaust valve open, and the air is expelled into the turbine housing and exhaust awaiting a fresh charge through the inlet valve...

So, how do we make our engine shift more air and thus create even more bhp?

The engine will only process more air if we do one of the following things:

**1.** Improve the air's route into the cylinders
**2.** Increase the pressure we push it in with
**3.** Improve the volumetric efficiency

What did bolting a T4 onto our engine do? The head hasn't been ported or cams fitted so there's no route improvement.

We are running the same boost pressure as on the smaller turbo, so there's no harder push.

So, have we changed the engine's VE? We must have!

## TECH NOTE

To explain how, I am afraid we have to get a little bit technical. First, the **Compressor Stage:**
On a standard YB, a Garrett T3 equipped with a 50-trim compressor (2wd Cosworth), running our desired boost pressure of 20 psi may be spinning at around 120,000 rpm with a compressor efficiency of 70 per cent (depending on air consumption at the time of measurement).

A Garrett T4 equipped with a 60-trim compressor (RS500), running our desired boost pressure of 20 psi may be spinning at only 90,000 rpm with a compressor efficiency of

Here you can clearly see the difference in size of the T3 (left) and T4 compressor wheels. The T4 will move a far greater volume of air thus improving the engine's VE

The exhaust, or turbine housing as its known will make all the difference to how a car drives — too big and it will be laggy, too small and it won't make big power but will have instant response

82 per cent (depending on the air consumption at the time of the measurement).

**Turbine Stage:**
The T4 P trim turbine wheel flows a lot more air than the standard T3 trim rear wheel. But it conversely takes more energy to spin it to speed, so the first thing to note is we have an exhaust gasflow improvement due to a better flowing rear wheel.

Secondly, we now have a wastegate that will open much sooner and much wider than it would on the T3 turbo, as less exhaust volume is required to spin the turbine and compressor to generate our required inlet pressure, due to improvements made to the efficiency of both the turbine and compressor.

At the turbine we now have a 30,000 rpm improvement in efficiency at our rated 20 psi inlet pressure — hey, and that's another exhaust back pressure improvement there, isn't it?

A nice, wide-open wastegate is also a by-product of a more efficient turbocharger — the wastegate bypasses the restrictive turbine housing as a means to stabilise and regulate boost pressure. This also makes the piston and crank's job of pumping the exhaust gas from the engine a little easier again, so the wider the better please.

Since our T4 is actually using an altogether bigger turbine housing area radius (A/R) as well, we have another exhaust back pressure improvement there at all times, wastegate open or closed.

Let's look now at the boost pressure seen at our intake valves.

Since our exhaust back pressure is now largely reduced, our cylinder's demand for and ability to process air has increased. We have overlap efficiency gains during valve open events, we have thermal efficiency gains in the compressor stage meaning our air is cooler coming out of the bigger turbo and thus denser, and we can suck more air into the cylinder, mix it with more fuel and generate more bhp due to increased cylinder evacuation on the exhaust event. Result: we are now processing more air and this T4 can supply it all in its stride, due to its nice, large compressor.

But we aren't making more power simply because the T4 pumped more air at 20 psi, are we?

I have now proven that we are making more power because this turbo improved the volumetric efficiency of our engine. The improvements are mainly through exhaust back pressure reductions, and an improvement in outlet temperatures at the compressor itself. This temperature improvement is due to a factor known as Adiabatic Efficiency (which we'll discuss in a future issue).

## BIGGER = BETTER?

Therefore everything about the bigger turbo is good, isn't it? So why don't we always fit a huge, great turbo and benefit from the greatly flowing turbine stages?

Well, that brings me to the downsides of fitting a larger turbo... Where do we lose out with a larger turbo? And why?

Turbochargers require high back pressures prior to the turbine wheel to drive them correctly. This pressure is referred to as the Turbine Inlet Pressure (TIP), and is the first part you must match when designing a turbocharged installation on an existing engine.

A normal ratio here will be in the order of 2:1 (for example, 40 psi turbine inlet pressure and 20 psi inlet valve boost pressure). The way the turbine housing works is to accelerate the gasflow and concentrate the heat energy, so that it meets the turbine wheel with more velocity and heat energy to drive it hard, thus spinning our compressor hard and generating the maximum boost pressure in minimum time.

This is achieved by narrowing the turbine housing down prior to it terminating at the turbine wheel, increasing the compression of the gas and ultimately releasing maximum heat — but creating the maximum back pressure.

A small turbine housing and wheel will spool the turbo up quickly, but leave you with lots of exhaust back pressure and a torque curve that at high rpm will drop off very quickly due to the pumping losses generated at high rpm when we try and move maximum volume of air in the least possible amount of time.

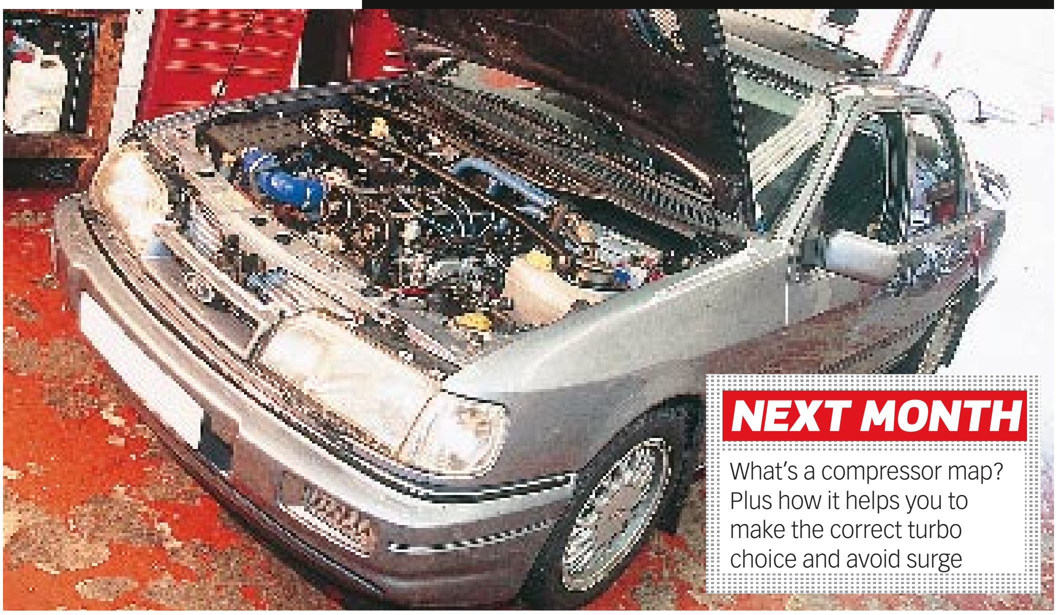
The size of the turbine housing is expressed in an A/R figure, and in most cases, the smaller the number, the smaller the housing, and therefore, the faster the spool will be and the higher the ultimate back pressure.

When we increase the turbine housing A/R, we drop the back pressure, and in doing so, also drop energy and velocity at the turbine wheel, thus slowing the turbine's response, which ultimately harms the compressor's response and making the engine's 'time to boost' worse. Not to mention the possibility of engine and turbo-damaging surge.

This lower TIP and corresponding compressor response has the effect of moving the engine's power band higher, but damaging low-end torque at the same time.

Turbo choice is a science that requires an educated amount of give and take. You cannot yet have your cake and eat it — at least, not until variable geometry turbochargers are ready for us to start reliably bolting to your petrol engines. But that's another story...

Even on Cossies, big turbos don't always make for great road-car installations, simply because of the increased 'time to boost'



**NEXT MONTH**

What's a compressor map? Plus how it helps you to make the correct turbo choice and avoid surge