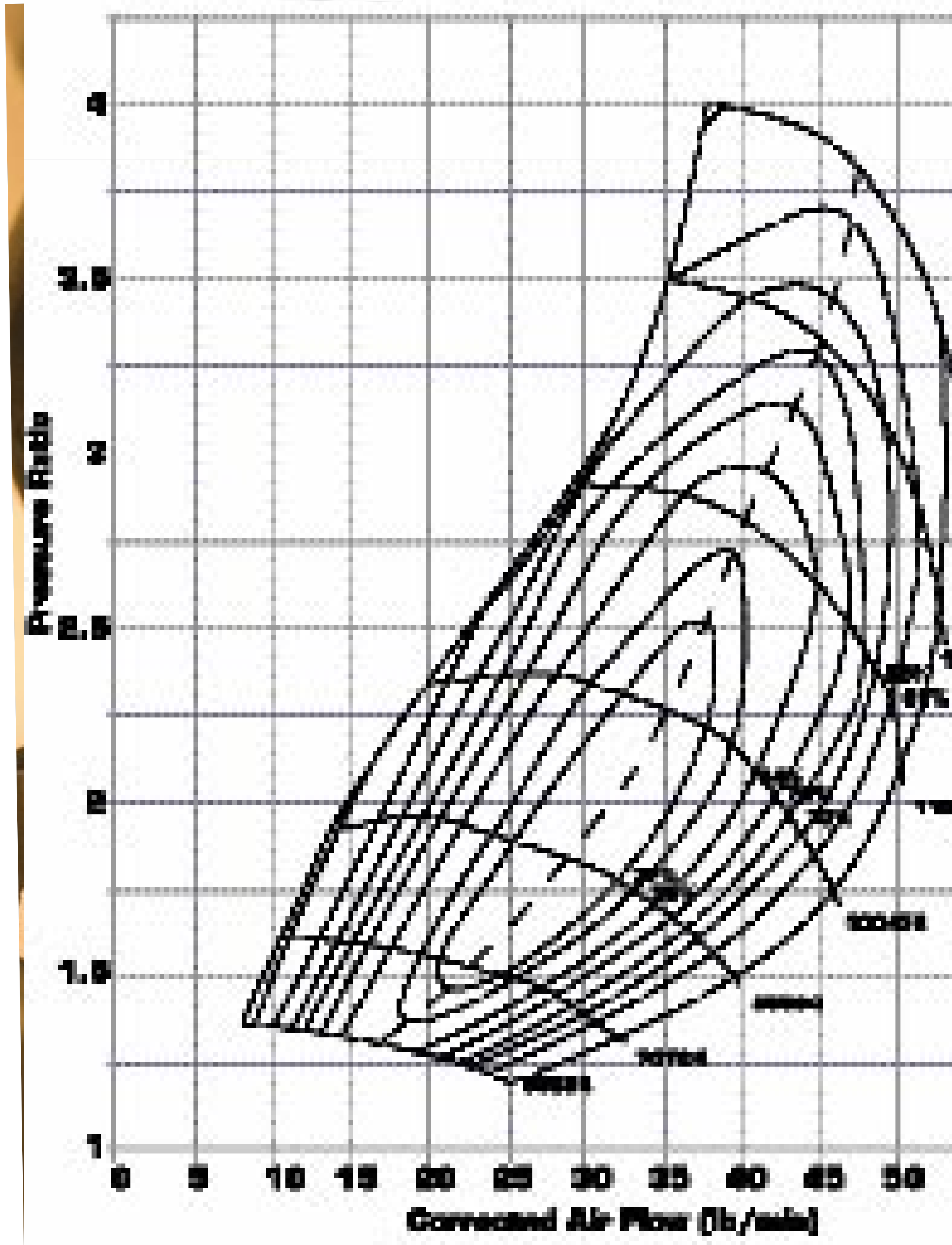


BEFORE STARTING...

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
Photos: Jon Hill, Honeywell Turbo Technologies, Ford

OFF THE MAP

How and why you should bone up on Compressor Maps before choosing that expensive turbo for your big-power engine.

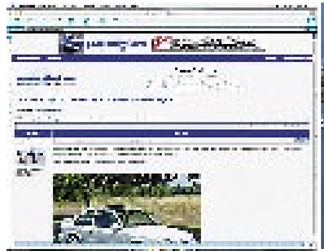
WHO IS STU?

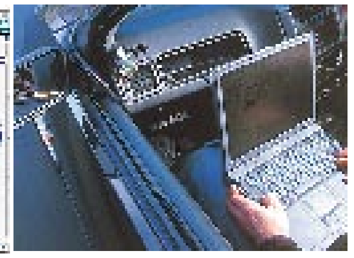
Having worked as a tuner for over 16 years, Stewart 'Stu' Sanderson is one of the most respected names in the business.

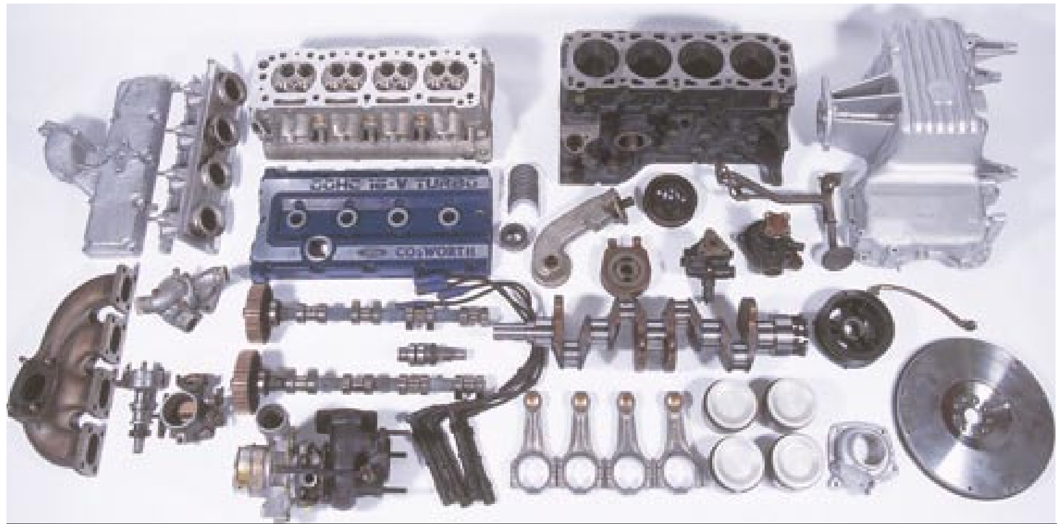
A Level 5-trained fuel-injection technician, in the past Ford nut Stu's worked for a Ford RS dealer, a well-known fuel-injection specialist and various tuning companies. Then six years ago, he joined forces with Kenny Walker and opened up Motorsport Developments near Blackpool, specialising in engine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

He's also jointly responsible with Webmaster, Petrucci for www.passionford.com. Started in 2003, it's grown rapidly from a few friends 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!







Deciding on the spec of your engine — whether it be a blown CVH, Zetec or YB like above — is relatively easy compared to choosing the right-spec turbo, as there are so many variables to consider

LAST month we looked at how a large turbo makes more power than a small one with the same boost pressure. Plus where that power comes from and how it affects the volumetric efficiency (VE) of the engine.

I'm sure that by the end of the article many of you ended up thinking, 'Why don't we just fit the biggest possible turbo and reap the rewards?" That's what we're going to look at this month: how to choose the correct-size turbo for your engine and avoid the common mismatches that can lead, at best, to a poor throttle response and driving experience, and at worst, terminal engine or turbo damage.

The first thing we must do is work out what kind of airflow we'll need the turbo to process in order to achieve our target horsepower figure.

Let's pretend we are building ourselves a 440 bhp Cosworth YB lump. We have already chosen the intake manifolds, compression ratio, headwork and cams to flow the required amount of air, so all we need to do now is find a turbo capable of supplying it without exceeding its design parameters and becoming unreliable. The way to do this, as is quite often the case, is with a little maths.

ENGINE AIRFLOW

Engine airflow can be directly related to the amount of bhp the engine develops. The VE of an engine is almost always highest at the point in its rpm range that it makes its peak torque figure. Above this rpm, pumping efficiency per stroke starts to fall away but work done by the engine as a whole is still increasing due to the ever-increasing speed it is making torque at.

Generally, engine airflow is measured using the 'mass airflow' principle and this method of measurement usually has its results stated as pounds of air per minute (lb/min). It is both normal and acceptable to simply estimate your airflow requirements for a new engine installation where the new turbo, or indeed entire engine, will be used for the first time and no airflow data is available.

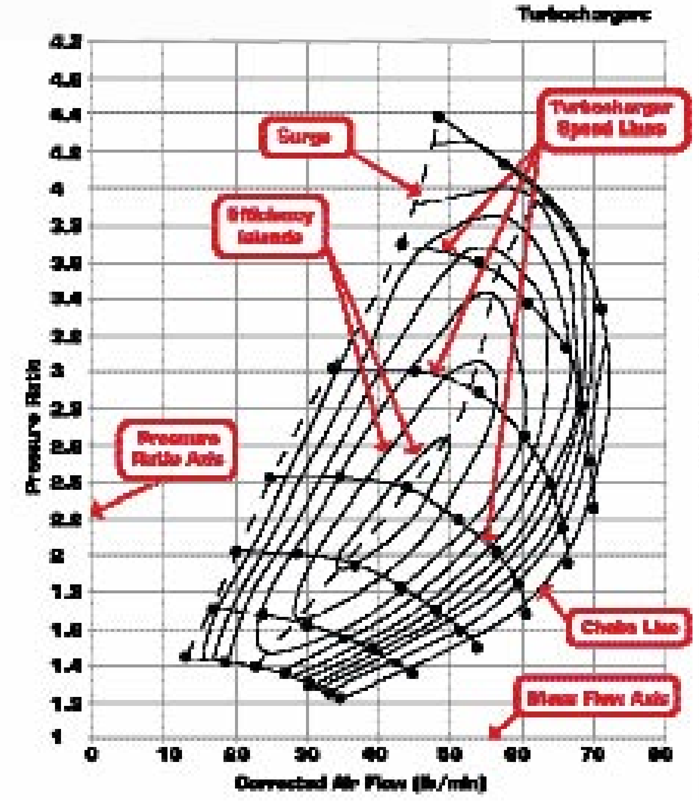
For the record, another method of airflow measurement is also in use today, this alternative method being the 'volumetric flow'. This method of calculation has its results expressed as cubic feet per minute (cfm). If you wish to convert this volumetric flow rate back to mass airflow, you need to simply multiply it by the air density. Air density at sea level is 0.076 lb/ft.

A golden rule always worth remembering, is that a reasonable average consumption figure for an engine — using the mass airflow rating of lb/min — is 1 lb of air will be consumed for every 9.5-10.5 bhp produced by the engine. So we can safely calculate our estimates using the figure of 1 bhp = 10 lb of airflow and normally be within 10 per cent of accurate.

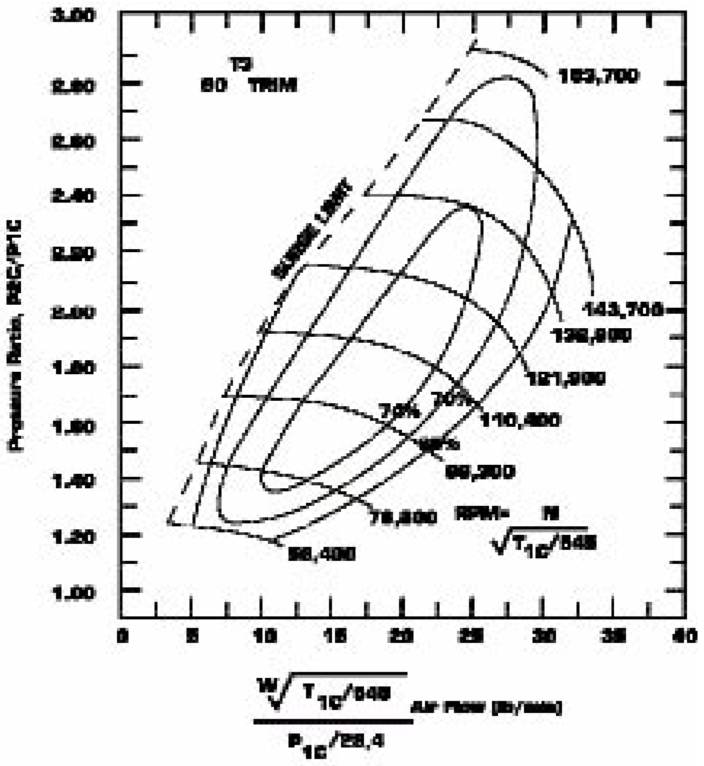
So, if we take an engine from the standard 4wd Sierra Cosworth, we can see it consumes approximately 22.4 lb of air every minute while it is flat out, producing its maximum power of 224 bhp.

Remember that these calculations are subject to air temperature variations since our air changes density if it is heated or cooled. The colder the air, the denser it becomes and the more oxygen is available. This temperature variation has an obvious effect on engine power output, too.

Back to our new engine. We have built it to make 440 bhp and we



All turbos come with a compressor map like this. They compare the compressor's rotational speed to its output airflow



Here's the map from a T3. It shows that the peak volume of air available is 30 lb/min — little use for anything over 300 bhp

now know, using the calculation above, that it is consuming approximately 44 lb/min of air. How do we find out what turbo we need to purchase and fit using this info?

COMPRESSOR MAPS

All turbochargers have a chart known as a compressor map available for them. These are small charts with a mine of incredibly useful information within them. They relate the compressor's rotational speed to its output airflow, and also its actual efficiency. Choosing a turbocharger without these charts is impossible. We know already from our previous estimations that we want a turbocharger that can flow 44 lb of air per minute in a reliable fashion to give us our target bhp figure, and of course we need it to easily flow *less* than this for all other engine operational modes below wide open throttle.

So, how do we read a compressor map and determine that a turbocharger is indeed suitable for our needs?

Let's take a look at the compressor map (above right) from a Garrett T3 60 trim compressor, as fitted to the 4wd Sierra Cosworth, and see how all the information on the map is interpreted.

Immediately we can see that it has two axes:

The vertical axis is what's known as a pressure ratio axis. The pressure ratio is the air pressure out of the turbo plus the atmospheric pressure. Translated, this indicates that a pressure ratio of 1.5 means the air leaving the turbocharger has 1.5 times the pressure it entered with.

This is a brand-new GT3076R turbo. It's shown minus the turbine housing as this is how they're supplied by Garrett

As you can see, the pressure ratio depends totally on the ambient air pressure. For example, at sea level, if a turbo boosts at 14.7 psi, the ambient pressure is also 14.7 psi so that's 2.00 on the compressor map. Take that turbo to a higher elevation where the ambient pressure is less than 14.7 psi and still have the turbo boosting at 14.7 psi and you will find the pressure ratio would be higher (this method of working is called Absolute Pressure).

Incidentally, turbo efficiency almost always decreases as the elevation increases (the pressure ratio increases). In other words, turbochargers lose performance and become less efficient as elevation gets higher.

The horizontal axis is the airflow axis. This shows us airflow out of the compressor in pounds of air per minute. We can see by following these lines vertically, that we move through little islands with percentage ratios tagged to them.

EFFICIENCY ISLANDS

We now have the chart content itself, and this content is presented to us as a series of elliptical circles. These circles are known as Efficiency Islands and relate to the turbo's Adiabatic Efficiency (see boxout). If we look at the island in the centre, this has a rating of 74 per cent. This means, that if we keep our airflow within this island, we will have a compressor efficiency of 74 per cent, meaning we only lose 26 per cent of our turbo's effort to heat. This is good.

WHAT'S COMPRESSOR SURGE?

When a compressor is processing air and our engine is consuming it, all is fine. We have torque on our turbine wheel generated by the airflow from the compressor in the first stage. However, when we generate more airflow than we can consume, things begin to get messy. The air pressure is backing up at the compressor, slowing it somewhat and the resistance at the compressor wheel starts to exceed the energy available at the turbine wheel, so our compressor starts to stall (a rapid decrease in rotational speed).

This puts the turbo into a vicious circle of events, as the stalling compressor drops our airflow back into an area that the engine can consume, and the turbine starts once again to spin back up, until it hits the flow limit and again starts to stall… so we have a surge of sudden speed and boost, followed again by a sudden stall. This is repeated many times a second and is known as compressor surge. This isn't the only form — a full technical feature could be written on surge alone, but this basic description serves our purpose for this month.

SPEED LINES

Crossing the circular efficiency islands are the turbine speed lines. The numbers next to these lines represent the approximate turbine speed required to make the compressor generate that particular airflow. Hopefully, this is self explanatory.

SURGE LINE

To the far left of our chart is the surge line. Operating to the left of this line represents a region of severe flow instability. Surge is recognized by the driver as anything from a small fluttering noise to a wildly fluctuating boost with a harsh chattering noise from the turbo. Continued operation within this region can lead to premature turbo failure due to huge thrust loading.

Surge is most commonly experienced when one of two situations exist. The first and most damaging is surge under load. It can be an indication that your compressor is too large and is often experienced at low rpm where the engine's air consumption is still low.

Surge is also experienced when the throttle is quickly closed after boosting. A lot of people incorrectly refer to the sound as 'wastegate chatter' — in fact it's the compressor going into surge and stalling. This occurs because the air consumption by the engine is drastically reduced to almost nil as the throttle is closed, but the turbo is still spinning and generating the airflow. This immediately drives the operating point to the far left of the compressor map, the low consumption area, right into surge. For a more detailed explanation of surge, have a look at the boxout.

Surge will stop only when the compressor speed slows enough to reduce the boost pressure and move the operating point back into an area of stability. This situation is commonly addressed by using dump valves to deal with the closed throttle issue. These valves vent intake pressure to atmosphere so that the mass flow ramps down smoothly, keeping the compressor out of surge. In the case of a recalculating bypass valve, the airflow is recalculated back to the compressor inlet.

CHOKE AREA

The area to the right of the outer most elliptical circle is the least-efficient area of a compressor — known as the choke area. When the compressor reaches a certain rpm, the air moved by the compressor wheel in the diffuser area of the compressor housing is moving at or past the speed of sound. When the air speed reaches sonic speed, the amount of airflow increase is very small, as compressor wheel rpm increases as the compressor has effectively now reached its limit.

The choke area is rarely noted on a compressor map, but can usually be found by dropping a vertical line down from where the fastest wheel speed curve ends on the right hand side of the map. This vertical line is the approximate max airflow the compressor is capable of, regardless of efficiency or pressure ratio.

COMPRESSOR MAX FLOW

The maximum flow capability of any compressor is shown on the map. Look for the point where the compressor wheel speed reaches maximum and passes through the least efficient island. The horizontal reading here is the maximum that the compressor can flow.

COMPRESSOR MAX PRESSURE

If you take a look at the pressure column, and find the pressure that corresponds with the highest point on the efficiency islands, this is the maximum pressure that the compressor can produce. 2.9 PR at sea level is 1.9 bar of boost, for example. The compressor's maximum pressure is governed by the compressor wheel's rotational speed.

It's worth noting that the pressure the engine actually receives is further influenced by various things such as intercooler efficiency and air temperature, so the pressure read at the engine itself may be somewhat lower than is generated at the compressor outlet of the turbo-charger. Always bear that in mind.

NEW 'CHARGER

So, we already have our target airflow figure, and we have our compressor map and are now equipped to read it. Now what?

We now need to look at the map, and see where we will be on it when the engine is consuming 44 lb/min of air.

Sadly, a quick look on that T3 60 trim compressor map shows us that the peak volume of air available from that turbo is around the 30 lb/min of air mark, so little use at all for anything over 300 bhp, and it's not much good at that either, showing a compressor efficiency of 65 per cent at best. So we need to look a little further a field… Let's try the newer style of turbochargers and examine a GT3076R compressor map.

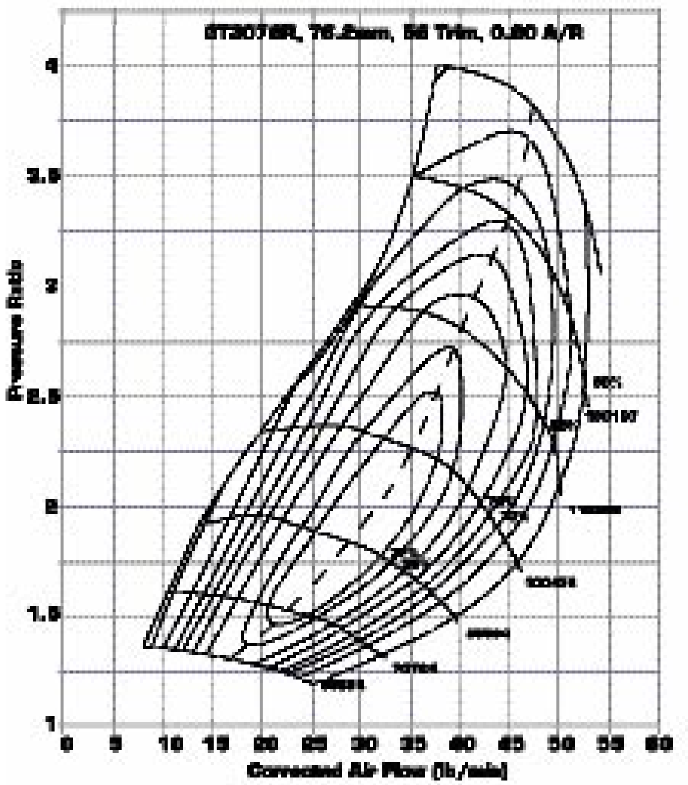
We can see from this compressor map that we can shift our peak of 44 lb/min of air with this compressor at as little as 0.75 bar of boost (1.75 PR).

Although the efficiency isn't at its best at this low pressure, it's unlikely our engine will make 440 bhp at such a low boost pressure anyway, so this could well be a good compromise turbo choice for us if it doesn't surge or cause any other issues with our engine. But how do we know what boost pressure is required to make the power on our target engine, so we can plot the compressor map properly?

WHAT'S ADIABATIC EFFICIENCY?

When a compressor compresses the air, it heats it up. This is a fact with all air compressors, even the simple bicycle tyre pump — remember how it used to burn your hands if you pumped too fast? Adiabatic efficiency is a measure of just how much we heat the air when we compress it. The more efficient the compressor, the less heat is created by the compression process.

Thanks to the large turbine housing needed, the T4-shod RS500 was a nightmare to drive on the road, with little performance below 4000 rpm



The GT3076R compressor map shows us that it can supply the required 44 lb/min easily

Sadly, without access to some very serious equipment, we can't easily, so it will be an exercise in trial and error. All you can really do as enthusiasts is undertake some research and see how much power a comparable engine spec makes on an engine dyno at the points you're interested in and work from there.

So, although we know the GT3076R is almost certainly going to provide our 44 lb/min of air with ease, we still don't know if it will surge at any point. How do we estimate this?

WHAT RPM?

Well, we know that our chosen turbo requires approximately 100,000 rpm to flow 44 lb/min of air with approx 60-65 per cent efficiency at 0.75 bar of boost. We can also see from the compressor map that if we actually need 2 bar of boost to make our 440 bhp, the turbo will be spinning at over 120,000 rpm yet actually be working more efficiently than if it were generating only 0.75 bar. So how do we now figure out what rpm the turbo will be rotating at on our engine? Is it not best to have it spinning up at maximum speed as soon as possible? Can that create further headaches?

Well, this is where the problems really do begin, as it is far more complex to plot how much air the engine will use at a given rpm point *before* it reaches peak power and we really do need to start using some educated guesswork if we are to avoid surge.

Here's an example: if our engine, at wide open throttle, actually moved enough air at 3000 rpm to spin our turbine and compressor up to 100,000 rpm and as a result, we generated the expected 0.75 bar of boost, and the compressor tried to start processing 44 lb of air per min, we would have to be generating 440 bhp at 3000 rpm to consume it. Clearly this won't be the case, so what will actually happen?

To answer this we need to know how much air we will really be consuming at that sort of plenum pressure and engine rpm... So, let's presume we are really making more like 100 bhp. That means, if we take our average consumption figure of 1 lb of air for each 10 bhp, we can also assume we will be consuming 10 lb/min of air at 3000 rpm.

This means though, that if we only make 100 bhp at 3000 rpm, with 0.75 bar of boost pressure, we will actually place ourselves to the far left of the map and into the surge area of the GT3076R, where as on our T3, we were operating efficiently with no problems at all. This surge is very dangerous to both the turbo and the engine and must be avoided at all costs.

This is where a change of turbine housing can come in very useful. Increasing the turbine housing's Area Radius will result in less turbine speed for any given gasflow, thus slowing down our compressor and hopefully putting us into a more efficient area of the compressor map when our boost is made at a slightly more efficient engine speed.

A good example on this compressor map is 55,000 rpm and only 0.35 bar of boost — this will just about keep us on the efficiency map and hopefully solve the surge issue we had with higher turbine speeds and more consequential boost pressure, but of course there is a trade off. Our engine response will have suffered somewhat and feel a little less responsive due to the slower boost climb. Naturally though, a slight lack of response is far more acceptable than deadly compressor surge.

In a nutshell, we need to customize the turbo's response range to keep the compressor away from its surge area until our engine gets to a speed where it can consume enough air for a compressor of that size and keep it away from the choke area once our engine is consuming lots of air.

The future: this is the adjustable turbine housing from a variable-geometry turbo as found on Ford's 2-litre TDCi engine. These turbos can't cope with huge power levels, but it won't be long

PROBLEM AREA

This very tuning is the part of turbo selection that causes us the most problems, as we almost always hurt the turbo's response time by increasing the rear housing size. But it's a necessity with large turbochargers and high power outputs if we want to avoid the dreaded surge (turbine inlet pressure problems aside — see last month).

Anyone who's driven both the Garrett T3-equipped Sierra Cosworth as well as the later Garrett T4-equipped RS500 will know what that larger turbocharger feels like on the road — pretty damn awful in most respects.

But without the large turbine housing, the T4 compressor would run almost immediately into surge, as the standard 2-litre YB engine simply cannot consume enough air in its lower operating range to support a compressor of that immense size. So the turbine housing had to be sized ccordingly to keep the turbine and ompressor speeds down to a sensible speed until the engine was capable of consuming the volume of air from the compressor.

The result was virtually no performance below 4000 rpm, but once that compressor span up to speed, all hell broke loose and the top end performance of the motor with its large compressor and big turbine housing was far sweeter revving than its little T3 sister that was running out of puff around the same time this monster got into its stride.

There you go, you can't have your cake and eat it just yet, although, not too far away are turbochargers with large compressors and a turbine housing that adjusts itself according to how much airflow we want to flow through it at the time, called variable geometry turbochargers.

At the moment, the mechanism isn't quite capable of dealing with the intense heat we experience at huge power levels, but it's working fine on thousands of turbo diesels and I'm confident they will be with us on big-power petrol Fords very soon indeed.

NEXT MONTH

Fuel pressure: why it's important, and why turning it up is sometimes worse than turning it down?