THE EXPERT
STEWART SANDERSON

Having worked as a tuner for over 20 years, Stewart 'Stu' Sanderson is one of the most-respected names in the business.

A Level 5-trained fuel-injection technician, Stu has worked for a Ford Rallye Sport dealer, a well-known fuel-injection specialist and various tuning companies.

11 years ago he joined forces with Kenny Walker and opened up Motorsport Developments near Blackpool (01253 508400, **www. remapping.co.uk**), specialising in engine management live remapping, as well as developing a range of Evolution chips which are now sold all over the world.

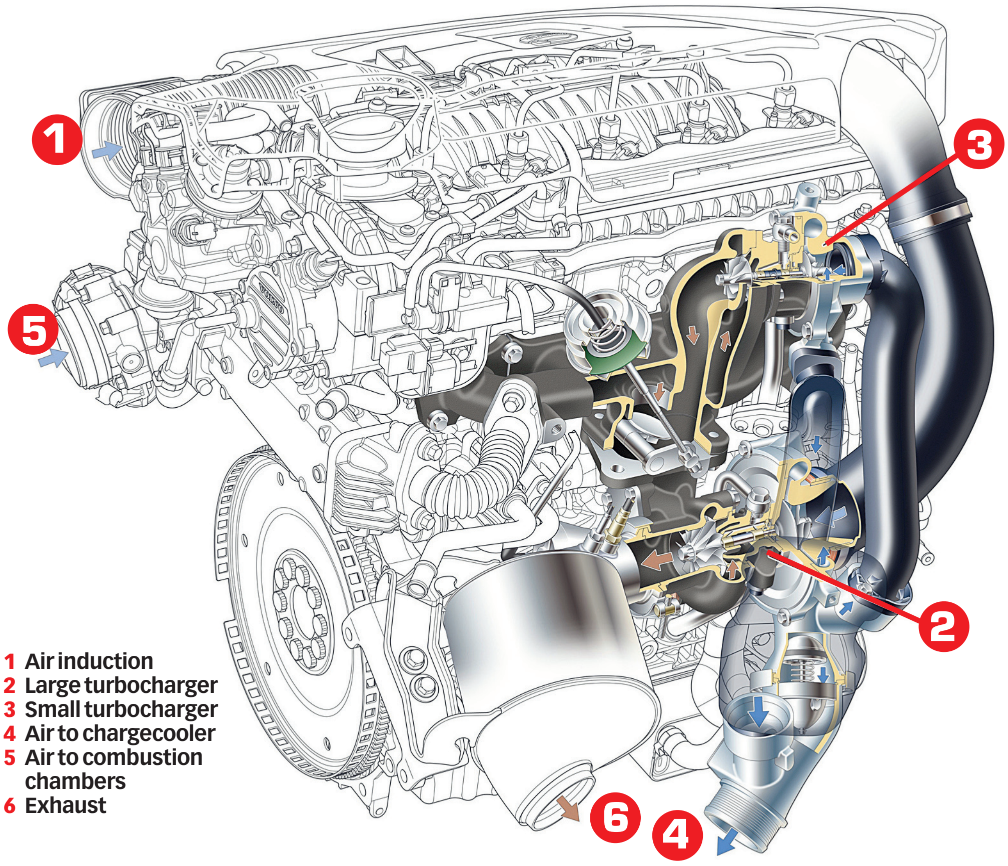
He is the creator and administrator of **www. passionford.com**, which he started in 2003. It has grown rapidly from a few friends contributing, to one of the biggest Ford communities on the web.

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

Words: Stewart Sanderson

COMPOUND CHARGING

We've all heard of cars with two turbos, but there are different ways to get 'chargers to work in tandem. One is compound charging, and here's how it's done.



1 Air induction
2 Large turbocharger
3 Small turbocharger
4 Air to chargecooler
5 Air to combustion chambers
6 Exhaust

Hopefully after last month's article you now fully understand the differences between supercharging and turbocharging. Well, I wonder how many of you have heard of 'compound charging'?

I suspect it's a term you've come across over the years and never really understood, so this month let's take a look at what is involved with compound charging.

WHAT IS IT?

Compound charging is where two turbochargers (or superchargers, but for simplicity let's look at turbochargers because the principle's almost the same) are used on an engine and mounted in such a way as the output from one turbo is fed into the second.

In most installations you will have one large low-pressure turbo installed which draws in ambient air and compresses it as normal before sending it to the inlet of the second turbocharger, which is usually smaller and intended to run a higher pressure. That smaller turbocharger then compresses the air a second time and pushes it towards your intake manifold.

WHY SHOULD YOU COMPOUND CHARGE?

By far the biggest advantage of compound charging is the wide spread of power it can create along with the rise in power available. The wide spread of power is available because you can virtually have your cake and eat it.

Think of it this way... Normally, when you choose a turbocharger, you have to choose one to suit your maximum required power otherwise you will never achieve that power. If you choose one that is too small, it will be responsive and great to drive, but when you push it hard it simply won't make the power you want, or you will have to run such high levels of

PETROL OR DIESEL?

Some people would assume you could only compound charge a petrol engine, but that is not true!

Most applications that use these systems are diesel. Companies like Cummins have used several compound charged units over the years and many commercial vehicles are compound charged and run large boost pressures. The diesels are easier to implement however, as they don't have to worry about compression induced detonation to the same extent as a petrol engine vehicle does, but recently VW has been using it to great effect on some of their newer TSi petrol engined models.

INTERCOOLING

So, should you run one or two intercoolers? A good question, and the only way to be totally sure is to set it all up and see. Generally speaking though, because we run the large turbo at such a low boost pressure, the adiabatic efficiency is very high indeed and doesn't heat the air up too much at all.

We are also running the second turbo at a much higher efficiency figure as well so in the real world; you often find that the intercooling required is less than was required to run a single small turbo at the same power level.

boost to make the target power that the turbo will have huge reliability problems and also create a lot of heat that requires more cooling thought to go into the install, not to mention money.

Conversely, a turbocharger capable of big power will be hard to spool up low down in the rev range due to its physical size, it will be unresponsive to throttle adjustment and once it finally starts to make boost it often runs into surge issues because it is moving so much air that the engine cannot consume it all throughout its whole power band.

Compound charging alleviates these issues and combines the best of both worlds but without any of the drawbacks. You can have the great spool and low speed response of the small turbo, with the power of a large one further up the rev range, but probably not for the reasons you think as you will soon learn.

SO WHY DON'T ALL ENGINES USE THIS SYSTEM THEN?

There are of course disadvantages to all systems and in the case of compound charging, the biggest issue is cost because you need two turbos, two wastegates and lots of complex plumbing. Cost issues aside, the next biggest disadvantage is the pure complexity of the system. You have to manage each turbocharger's boost level individually and also supply both with oil and water.

There is also the space issue… When was the last time you saw a modern engine bay with enough room to pop another turbo in there? Finally, there is also a weight issue, as turbos and manifolds are not light objects!

SO HOW EXACTLY DOES COMPOUND CHARGING WORK?

OK, pay attention at the back as this one is quite complex… The air going into your turbocharger (at sea level) is always 14.7psi (1bar) because that is our atmospheric pressure. On a boost gauge that is represented as zero. To elaborate on that, when your boost gauge reads 1bar or 14.7psi, we are really pushing the air into the engine with 2bar. The first bar is our atmospheric pressure and the second bar is from the extra compression by the turbocharger.

So, no matter how big the turbocharger, or how fast we spin it, the air coming into it is only being pushed in at 14.7psi. If we spin it too fast, it becomes inefficient at bringing new air in and it becomes increasingly harder to get the exhaust gas out. To overcome this with a single turbocharger, people increase the size of turbines, housings and compressors. While this does of course increase the amount of airflow, it ultimately hurts the low-end drivability, response and spool-up times. This is because you cannot fight the laws of physics. A certain size of hole (the turbocharger's air inlet) will only flow a limited amount of air at a given pressure, so hopefully you can see that a limiting factor to our airflow is in fact our own planet's atmospheric pressure. So what's the solution? Compound charging!

When we plumb two turbochargers into an engine bay sequentially (one flowing into the other), we can overcome the aforementioned limitation. Obviously we cannot just throw any two turbochargers into the engine bay and pipe them together, they must be sized correctly to complement each other or they can and will simply fight each other and probably end up much worse than using just one turbo.

These two turbochargers will almost always consist of one small turbocharger and one large turbocharger. The smaller unit is usually the first to get exhaust gas from the engine and the last one to receive any fresh air from the atmosphere.

PLUMBING THEM IN

The beauty of the whole compound turbocharger system is that you can have all of the benefits of a small quick-spooling turbo with more than all of the benefits of a very large turbocharger. But why exactly is this? Well it's largely about the plumbing and how each turbocharger affects the other one.

Firstly, the fresh air enters the larger (slower spooling) turbocharger and is then pressurised and fed into the smaller (and fastest spooling)

"COMPOUND CHARGING COMBINES THE BEST OF BOTH WORLDS BUT WITHOUT ANY DRAWBACKS"

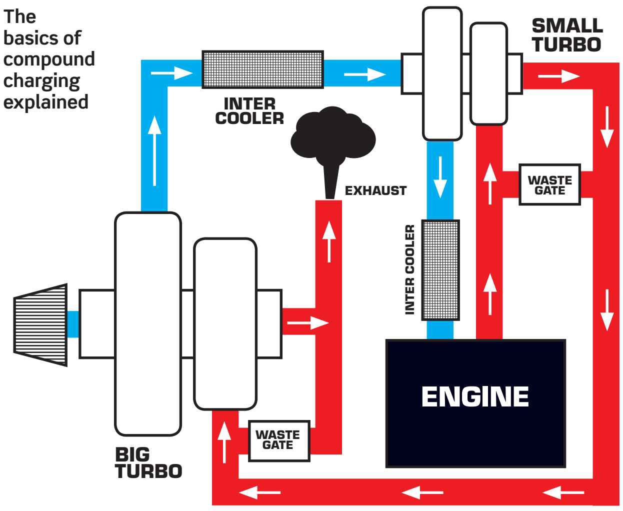
turbocharger, which then multiplies the already pressurised air and feeds it into the engine.

The benefit so far is that the air has been compressed twice instead of once, but this isn't the main party trick, take a deep breath and read on as we get into some maths…

Remember, turbochargers simply multiply atmospheric pressure and feed the resulting higher-pressure and therefore higher-density air into our engines. Look at it this way, if a small turbocharger on its own can take air into itself at 14.7psi (atmospheric pressure at sea level remember?), and produce 40psi boost, then it is multiplying the air coming in by 3.72 times. We get to that figure as follows:

- The intake air pressure is 14.7psi absolute. (1 Atmosphere)
- The outlet air pressure is 54.7psi absolute.
- 54.7psi / 14.7psi = 3.72

(Remember, zero on our boost gauge is already 14.7psi of atmosphere so we only ever see 40psi of the 54.7 on an average boost gauge.)



The basics of compound charging explained

A COMMON COMPOUND CHARGING QUESTION

So... why doesn't the smaller turbo strangle the engine? This is probably the most-asked question when it comes to compound charging. So here's the answer.

The biggest point to understand is a turbocharger is rated by the amount of volume it can deliver, and compound charging doesn't change this number.

To use some conveniently round numbers, let's say the small turbo is rated at 250ft³/min, which ends up being around 25lb/min when fed air at atmospheric pressure. If you then use the big turbo to raise the pressure to double atmospheric pressure, or 15psi boost, the density of that air is doubled. That same 250ft³/min which the small turbo still moves, now weighs 50lb/min.

The small turbo has still moved the same exact same volume of air but with it being twice as dense, it's twice the amount of air, and provides twice the horsepower, so in essence a 250bhp rated turbo can now deliver 500bhp of air due to the simple fact we have doubled the inlet (atmospheric) pressure it is operating at.

"THE VOLUME OF AIR SENT TO THE ENGINE IS THREE TIMES THE SMALL TURBO MANAGES."

Moving on, we know of course that our large turbocharger can do a very similar job. Therefore let's say that the large turbocharger is running less boost and multiplies its 14.7psi inlet pressure by 2.2 times and sends out 32.3psi absolute. (So 17.6psi on your boost gauge) Now the small turbocharger will receive 32.3psi absolute at its air inlet instead of the 14.7psi and that means the small turbocharger is ready to multiply that air coming in by 3.72 just as it did before, but now the pressure output will be a massive 120.16psi for the same compressor speed!

WHAT COMPOUND CHARGING DOES

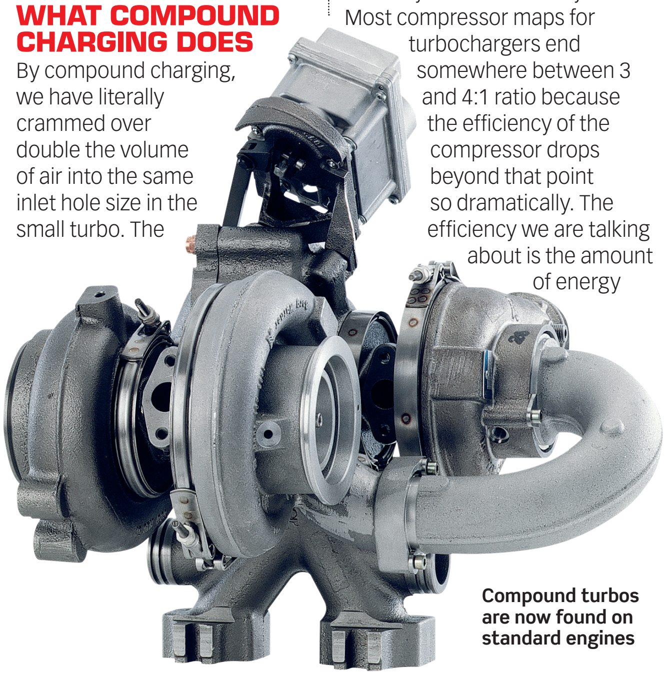
By compound charging, we have literally crammed over double the volume of air into the same inlet hole size in the small turbo. The small turbo spinning at the same speed will now produce 120.16psi instead of only 40psi. The volume of air sent to the engine is three times the small turbo manages.

Now, for tractor and commercial engines these sorts of figures aren't even particularly high and we often see engines running 250psi of boost in tractor pulling. But we are interested mainly in performance car engines, so, assuming we don't want to run 120+ psi on this installation, how can we benefit from a compound charging system running more sensible boost levels?

Well, the biggest problem with high boost on any turbocharger is usually loss of efficiency. Most compressor maps for turbochargers end somewhere between 3 and 4:1 ratio because the efficiency of the compressor drops beyond that point so dramatically. The efficiency we are talking about is the amount of energy which is converted into heat during the compression process. The higher the efficiency, the less heat is made from compressing the air. Most compressors have their highest efficiency at below 2.5:1 ratio, so this is where we would like to be when delivering our air into the engine so as to deliver it as cool and dense as possible.

Sadly, most high performance turbochargers of a small size are running right down into the 65 percent efficiency area because we have to spin them so fast. We are of course doing this because we don't want to lose the response a small turbo gives us, so accept that we then have to run huge boost pressures to deliver enough air to our engine to make the power we want.

The net result is a very hot air charge that needs a lot of cooling and will usually still be entering the engine a lot hotter than we would like. Remember: heat is the enemy and every degree of heat in the intake air loses us horsepower.



Compound turbos are now found on standard engines

SO, HOW DOES COMPOUND CHARGING HELP US?

Our first gain is compressor efficiency; that very same turbo in a compound configuration will give the same boost at a much slower rotational speed and therefore at a much higher efficiency level and can therefore provide the same pressure of air to the engine as before but at a much higher efficiency meaning that air will arrive at our cylinder much cooler and therefore much denser. That means more power.

Our second gain is exhaust efficiency. Because of the low pressure ratio required by the small turbo, we can open our wastegate much earlier and much wider than usual as we don't need as much rotational speed on the turbine to make the same boost pressure as before. The fact we have opened our wastegate earlier and wider means that the exhaust back pressure goes down significantly. Less back pressure not only improves the engine's horsepower as pumping losses to get exhaust gas out and fresh gas in are reduced, but it also reduces the exhaust gas temperature too which is another bonus.

All in all, we end up with a more powerful, more efficient and cooler running engine with turbos that will probably last a lot longer. Result!

IS TWIN-TURBO THE SAME AS COMPOUND CHARGING?

No, two turbochargers are commonly referred to as twin turbochargers but twin turbos are just that – 'twins'. They're usually two identically-sized turbos working in the same engine bay but each on either bank of a V-configuration engine or working together and firing into the same inlet.

Typically each turbo is used to do one half of the work and is not in a compound configuration. Remember, a compound installation requires the air to be compressed by one turbocharger and then fed directly into the inlet of a second turbo charger before being compressed again and sent into the engine.

WHAT IS THE PRESSURE RATIO?

A turbocharger is just a pressure multiplier. Its output is not measured in boost pressure, but in pressure ratio. The pressure ratio is simply the pressure at the compressor exducer (P2 – the turbo outlet) versus the pressure at the compressor inducer (P1 – the turbo inlet).

To put this another way, it's the ratio of the pressure of the air after compression versus the pressure before compression (P2/P1).

The pressure ratio calculation depends totally on the ambient pressure you are operating the turbo in. For example, at sea level our ambient intake pressure is 14.7psi. If the turbo compresses this and outputs 29.4psi then that's a pressure ratio (PR) of 2 on a compressor map because 29.4psi is 2 times our ambient pressure which was 14.7psi. Always remember though, these pressures are what we call absolute pressures. On a normal boost gauge, the zero usually represents atmospheric pressure so you would only see 14.7psi boost on your gauge in this scenario.

However, if we now take that very same turbo to a higher elevation where ambient pressure is less than 14.7psi and the turbo still set to output 29.4psi then the pressure ratio to create that output pressure would be higher as the ambient pressure at the intake was less than 14.7psi. In a nutshell, turbos lose performance and become less efficient as elevation gets higher.