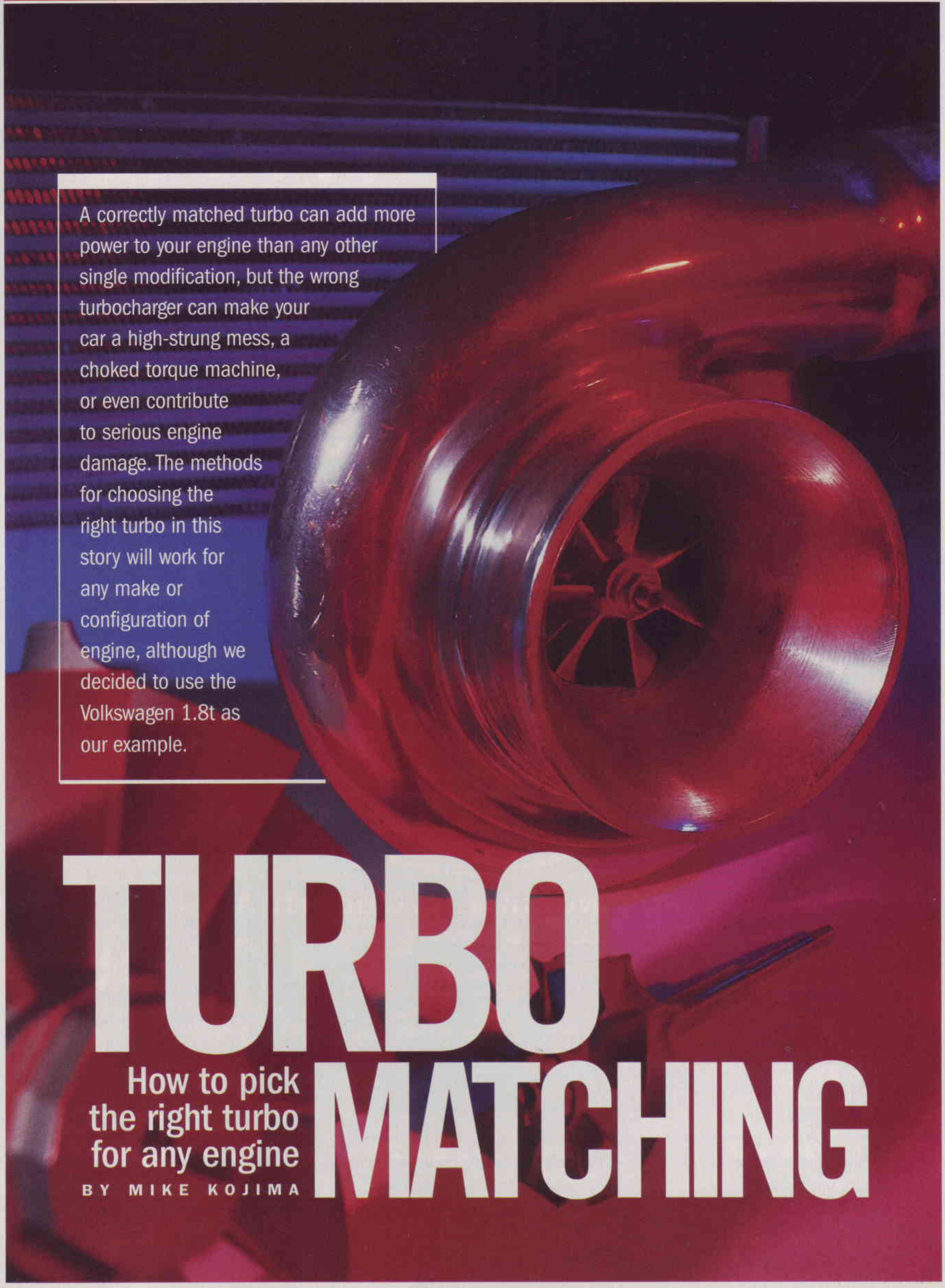


A correctly matched turbo can add more power to your engine than any other single modification, but the wrong turbocharger can make your car a high-strung mess, a choked torque machine, or even contribute to serious engine damage. The methods for choosing the right turbo in this story will work for any make or configuration of engine, although we decided to use the Volkswagen 1.8t as our example.

TURBO MATCHING

How to pick the right turbo for any engine

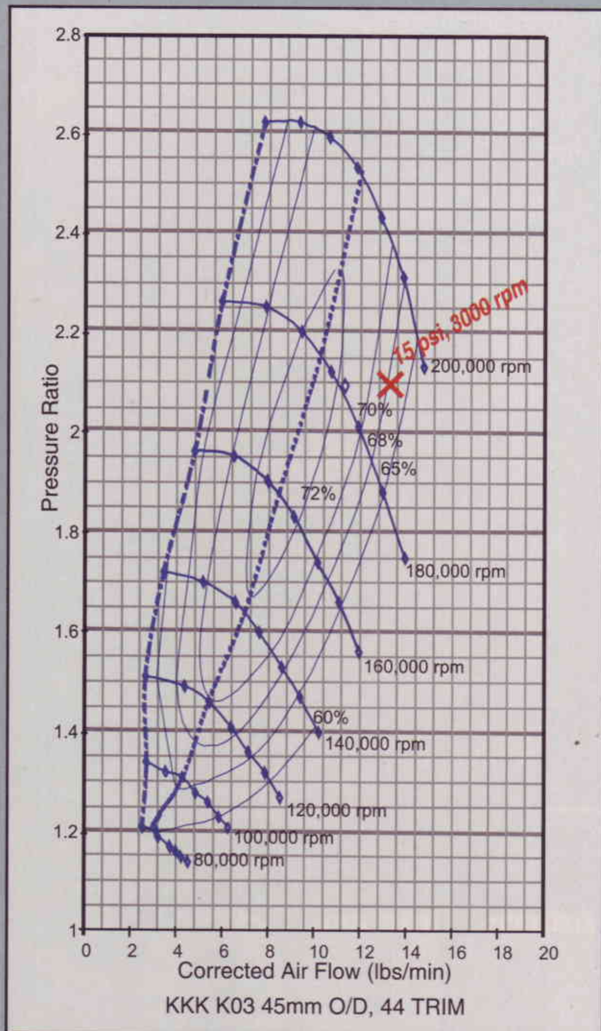
BY MIKE KOJIMA

Before we get into finding the ideal match for your engine, we should explain some basics of turbo matching. Choosing the right compressor (that's the intake side of the turbo that compresses the intake air) is probably the most critical step in selecting which turbo you should use. Compressor matching to the engine is also where most beginner mistakes are made. By using the formulas we'll soon discuss, and looking at various compressor maps, you'll be able to closely estimate which compressor will be best for your intended use.

The math involved in choosing the correct turbocharger can be reduced to simple algebra while still retaining enough accuracy to make good matching choices. Matching also requires that the manufacturer publishes some important data, the most critical being the compressor map. Compressor maps are available from the Turbonetics catalog, The Innovative Turbo Systems catalog and from the Garrett Engine Boosting Systems Web site, www.egarrett.com.

The compressor map is a graph of the compressor's efficiency plotted against boost (expressed as pressure ratio on the Y-axis) and the mass airflow (expressed as pounds of air per minute on the X-axis). The compressor map is two-dimensional and reads like a topographical map, but with the islands representing compressor efficiency rather than altitude. Bisecting the islands moving from left to right across the map are the speed lines. These show the speed of the compressor/turbine in rpm.

But what is compressor efficiency? When air is compressed, it gets hotter. That's just physics, and there's nothing you can do about it. But ideally, it only has to get as hot as the ideal gas law (PV=nRT) says. When we speak about compressor efficiency, we're referring to adiabatic efficiency or how much hotter air gets than it has to by law.



This is the tiny, KKK K03 compressor from the stock 1.8t. We took the liberty of putting it on the same scale as the Disco Potato turbo on the next page. The K03's map looks tiny because it is. At 14 lb/min of corrected airflow, where the K03 is falling off the map, the Disco Potato is just getting started. Plotting any airflow and boost points we calculated for the Disco Potato turns out to be impossible on the K03. Making 15 psi with this turbo means doing it way down at 3000 rpm.

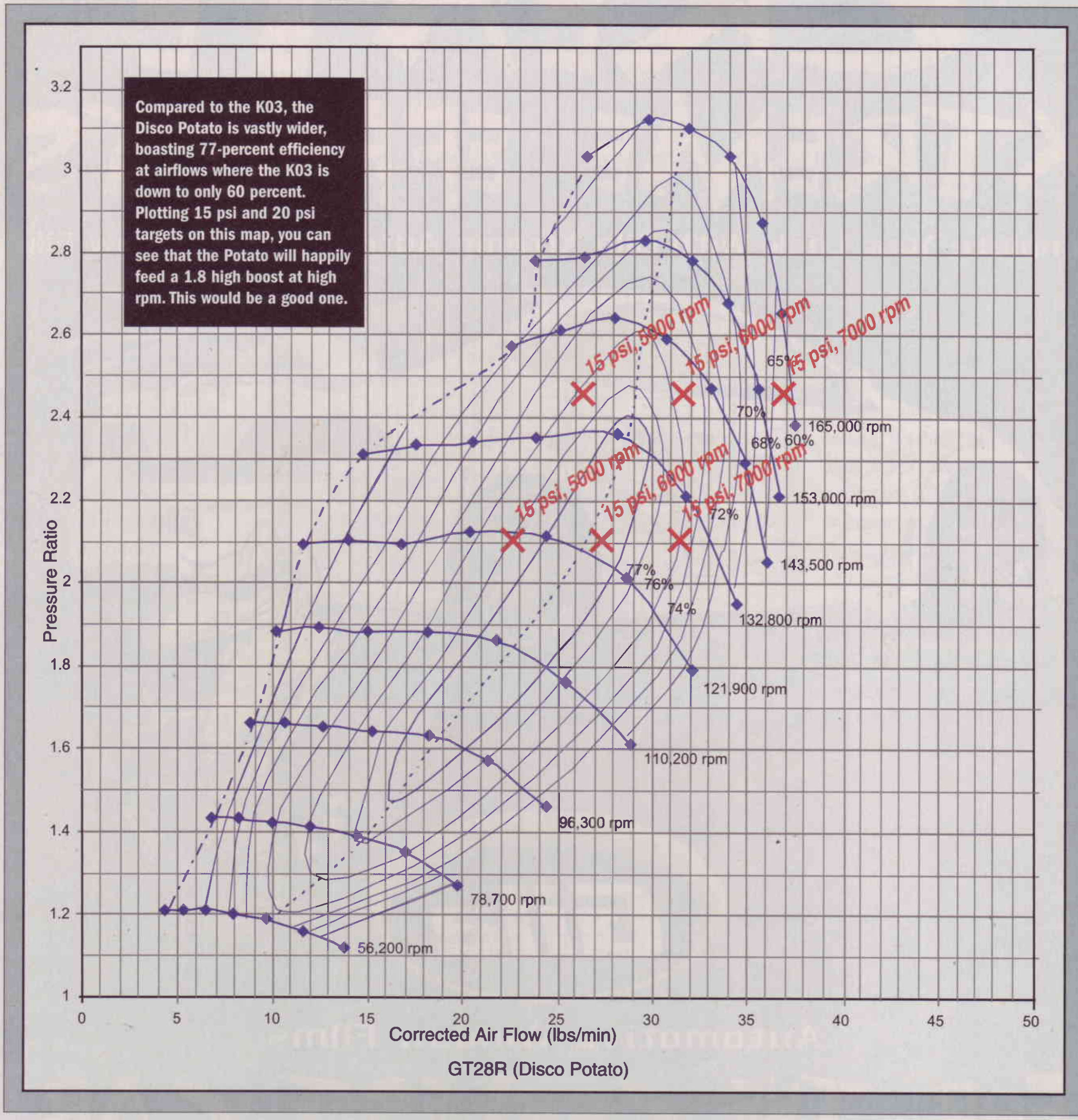
The thermodynamically impossible nirvana of 100-percent efficiency would mean the compressor discharge temperature was perfectly predicted by the ideal gas law. Less than 100-percent efficiency means the compressed air is hotter.

The compressor map also has an important landmark, the surge line. The area of compressor surge is a line bordering the islands on the far left side of the map. Surge is when the air pressure after the compressor is higher than the compressor can generate. This causes the airflow in the compressor wheel to back up and stall. This, in turn, causes the pressure to drop, allowing flow to resume until pressure builds up and it stalls again. In severe surge, this can become a violent oscillation that destroys the thrust bearing of the turbo and can even cause mechanical failure of the wheel. Any compressor match should avoid crossing over the surge line.

You want to pick a compressor in which the engine spends most of its operating range within the highest efficiency islands of the compressor map. You also want to pick the compressor with the highest efficiency. A good compressor means lower intake temperatures, which means higher air density and reduced load on the intercooler. A more efficient compressor requires less shaft power, reducing the energy that the turbine must try to extract from the exhaust. This quickens the turbo spool time and reduces exhaust backpressure, which improves volumetric efficiency.

With less exhaust gas being belched backward into the cylinders, along with drops in combustion temperature, the engine's detonation resistance is increased, allowing tuning to be less compromised. Leaner air/fuel ratios, camshafts with more overlap and more ignition advance are all possible, meaning more power and better fuel economy.

To determine if the compressor is a good match for an engine, determine the engine's airflow over the rpm range and plot it on the



compressor map. Ideally, the plot will fall over the map's best efficiency island and stay out of the surge range. The calculations are somewhat involved, but if you understand high school algebra, they're not too bad. The more computer literate of you may find this a useful tool and can put these equations into an Excel spreadsheet to make it user-friendly.

Using a Volkswagen/Audi 1.8t as an example, we'll use a simple, one-dimensional estimation method that will allow you to see if a turbo you're looking at is even in the ballpark. If your potential compressor choice is way off, you'll find your plot completely off the map. This method is also accurate enough to make a choice between two decent compressors.

This method will not allow you to predict lag, boost fall-off, or allow you to design your own turbo. What it will do, however, is allow you to look at a turbo that someone suggests for your car, and determine if they know what they're talking about.

Lets get straight to the math, then we'll explain what the math tells us. Bust out the calculator and sharpen your pencil.

Step 1

Figure out the maximum level of boost you plan to run. Most stock import engines with proper fueling, etc., on 91-octane pump gas can handle at least 7 to 10 psi. Some very strong stock engines like our proposed VW 1.8t can take up to 20 psi with proper tuning and race gas.

Let's do a basic compressor match at 20 psi on a VW 1.8T

First, you have to make a few assumptions.

- Pick a proposed boost level: For this first match, we've already decided on 20 psi.
- Pressure drop across intercooler: Assume 1.5 psi in most cases. If it's more than this, you should choose another intercooler.
- Atmospheric pressure: For sea level, that's 14.7 psi.

From these assumptions you can calculate absolute pressure out of the compressor (Pco):

$$\text{Pco} = \text{Boost} + \text{Atmospheric Pressure} + \text{Intercooler Pressure drop}$$

Which, in our case, means:

$$\text{Pco} = 20\text{ psi} + 14.7\text{ psi} + 1.5\text{ psi} = 36.2\text{ psi}$$

And now it's a simple matter to find the pressure ratio (Pr):

$$\text{Pr} = \frac{\text{Pco}}{\text{Atmospheric pressure}} = \frac{36.2\text{ psi}}{14.7\text{ psi}} = 2.46$$

Next, we want to calculate the approximate density of the air, after the intercooler. This is called Di.

To do this, we first have to guess what the post-intercooler temperature might be. One hundred thirty degrees Fahrenheit is a good starting point, and it's normally what we see on turbocharged cars with a fairly good aftermarket intercooler.

So, the formula:

$$\text{Di} = \frac{\text{Boost pressure} + \text{Atmospheric pressure}}{\text{R} \times 12 \times (460 + \text{Post-intercooler temp})}$$

In this case, R = 53.3 (this is a constant, and happens to be the same R from the ideal gas law, PV = nRT). The number 12 is there to preserve the inch units in the equation, and 460 is to convert degrees Fahrenheit to degrees Rankin (absolute temperature). Just believe us on these.

So, in our case:

$$\text{Di} = \frac{20\text{ psi} + 14.7\text{ psi}}{53.3 \times 12 \times (460^\circ + 130^\circ)} = 9.19 \times 10^{-5}\text{ pounds per cubic inch}$$

From this we can calculate the mass flow rate (Mf) of the engine at the rpm where we want to do the match:

$$Mf = \frac{\text{Di x Displacement in cubic inches x RPM}}{\text{2 x Volumetric Efficiency}}$$

If you don't know your displacement in cubic inches, divide displacement in cc x 16.387.

For Volumetric Efficiency, we can assume 90 percent, which should be typical for this modern five-valve DOHC engine. Of course, the actual volumetric efficiency will vary from one engine to another and from one rpm point to another, and even depending on which turbo you use, but that's what makes this a simple model.

Also, note this formula is good for only one rpm point. You'll have to do this particular calculation over and over, plugging in different values of engine rpm to generate a useful picture of the turbo's performance across the rpm band. This is where a spreadsheet comes in handy.

Now, for our 1.8t:

$$Mf = \frac{9.19 \times 10^{-5}\ \text{lb/in}^3 \times 108.7\ \text{in}^3 \times 7000\ \text{rpm}}{2 \times .90} = 38.9\ \text{lbs/minute}$$

Now, the compressor map uses corrected mass flow, not the mass flow we calculated. The "corrected" part means it has been adjusted to the standard test conditions used to make the compressor map.

$$CMf = \frac{Mf \times \sqrt{\dfrac{\text{Compressor inlet temp (in °R)}}{545°R}}}{\dfrac{\text{Atmospheric pressure}}{\text{Compressor inlet pressure}}}$$

The °R part is, again, the absolute temperature scale Rankin. 545°R is 85 degrees Fahrenheit, the standard temp Garrett uses in its compressor maps. We will also assume our ambient temp is 545°R, just to make the math easier. You can use whatever temperature you think is appropriate for your car (just take Fahrenheit degrees and add 460 to convert to Rankin) but 85 degrees is a good estimate of average intake temp. Atmospheric pressure is, again, 14.7 psi, and Garrett uses 13.95 psi as the compressor inlet pressure considering the pressure drop across your typical air filter.

Plugging in these numbers, plus the Mf we calculated earlier, we get:

$$CMf = \frac{38.9\ \text{lb/min} \times \sqrt{\dfrac{545°R}{545°R}}}{\dfrac{14.7\ \text{psi}}{13.95\ \text{psi}}} = 36.9.\ \text{lb/min}$$

So you have your pressure ratio of 2.46 and your mass airflow of 36.9 lb/min. Next, plot these points on the compressor map you're considering to see how well your engine matches the compressor map. If you try to plot this point on the map of the 1.8t's stock K03 turbo, you'll find the point way off the page. The K03 simply can't feed a 1.8t 20 psi of boost at 7000 rpm. Don't even try.

If you want to plot more points, you can do so by plugging in different rpm values, remembering that no turbo is going to produce 20 psi at idle. A reasonable powerband to plot would be between 3000 to 7000 rpm for the 1.8t. (Though the 1.8t's redline is lower, most don't actually hit the fuel cut until 7000 rpm.) Juggle boost targets, powerbands and compressor maps until you find one where your powerband falls over the areas of highest efficiency while avoiding crossing the surge line.

Starting with the point we calculated, try and plot it on the stock K03 compressor map. The point won't fit on the map. This means the boost and RPM targets we chose for this turbo are completely unrealistic. Anybody who has driven a 1.8t can tell you the stock turbo won' t make 20 psi at 3000 rpm.

Now, try plotting that point on the GT28R Disco Potato compressor map. The point lands on the map, but barely. Being this close to the edge of the map means our simple model is probably getting a little inaccurate. With compressor efficiency dropping below 65 percent, it's taking a lot more exhaust energy to drive the compressor. This will cause backpressure, which will lower the Volumetric Efficiency, which, in turn, will affect our Corrected Mass Flow calculation. Again, 20 psi at 7000 rpm is not the best choice. It's not impossible, like it was on the K03, but it's not ideal.

If you calculate a few more points with 20 psi at 6000 and 5000 rpm, they'll land in much more efficient parts of the map. The fact that these parts are near the top of the map suggests (but does not guarantee) that this is at the high end of the boost you should be running on this turbo, and that the turbo, being relatively small, should spool quickly and be responsive.

Plotting a few more points at 15 psi, you can see that this would be the happiest turbo in the world.

Now back to the K03. Even the 15 psi and 5000 rpm, we're still completely off the page. You have to back down to 3000 rpm beore you get onto the compressor map. In reality, with the backpressure of the tiny K03, the Volumetric Efficiency is probably lower than the .90 we predicted, and the Corrected Airflow might be lower.

So there it is. Get some maps, do some math, and crank the boost. ■

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