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Technical Articles > **Turbo 101**

We've all heard the saying, "There's no replacement for displacement," and "You just can't beat cubic inches." The basis for these statements is that the greater an engine's displacement, the more air and fuel can be squeezed into the cylinders, and the higher its potential power output. But they're not entirely accurate: There is another way to stuff more air and fuel into the cylinders--lots more, in fact--without increasing an engine's size. It's called supercharging, which is a way to force more air into an engine than it could normally take in by atmospheric pressure alone. Only the most efficient normally aspirated race engines with very specialized induction tuning can exceed 100 percent volumetric efficiency (VE), but a supercharger's forced induction makes exceeding 100 percent easy; 15 pounds of boost pressure (defined as pressure above the normal 14.7 psi atmospheric pressure) effectively doubles an engine's displacement--with correspondingly huge potential horsepower increases.

"Supercharger" is a generic term for any forced-induction compressor that is driven by a belt, gears, or a turbine. The turbine-driven version is known as a turbocharger, and it has the potential to be the most efficient power-adder for an internal-combustion engine on the planet. An internal-combustion engine is notoriously inefficient: Only about one-third of the energy released during combustion actually drives the crank. Of the remaining two-thirds, one-third goes into the cooling system, and one-third goes out the exhaust as heat. In fact, a 200hp engine dumps the equivalent of about 70 hp of raw heat straight out the tailpipe! However, a turbo's turbine-wheel is driven by the engine's own exhaust gases as they exit the motor, so some of the heat that normally goes to waste is now used to power a compressor that pumps more air into the engine.

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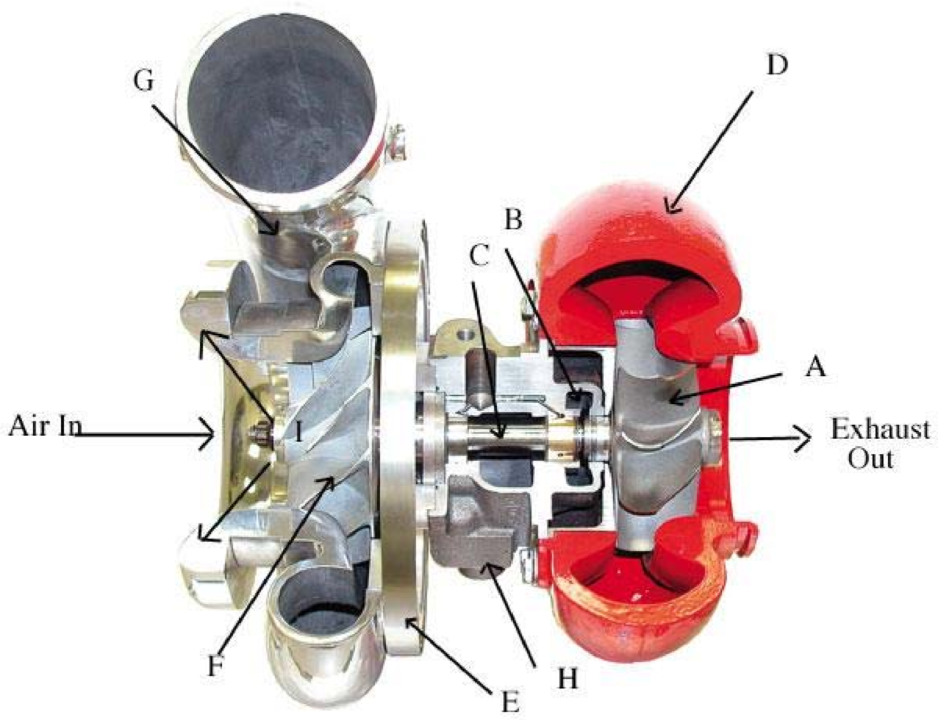

Turbos have three major subassemblies: an exhaust turbine housing, a bearing housing, and a compressor housing. The exhaust and bearing housings each have a wheel with integral blades, and are connected together by a shaft mounted on bearings. Some turbos--like this Turbonetics Super Thumper that can support over 2,400 hp--offer a ceramic ball bearing option. A: Turbine wheel, B: Bearing and seal, C: Turbo shaft, D: Exhaust turbine housing, E: Backplate, F: Compressor wheel, G: Compressor housing, H: Bearing housing, I: Inducer bore, J: Exducer bore

Although a turbo's position in the exhaust stream does restrict exhaust flow potential to some extent, the pumping losses are much less than the parasitic drag induced by a conventional supercharger's belt or gears. In a typical gasoline-fueled engine, it's common to see 30 out of every 100 hp added by a beltdriven supercharger being wasted turning the drive pulleys and belts; this compares to about 5-10 hp per every 100 suffered as pumping losses by a typical well-designed turbo installation. Considered as a system, the turbo setup has less heat buildup than an old-style Roots blower, and its smaller size compared to a centrifugal supercharger permits higher compressor-wheel rotational speeds and more radical blade-tip curvature that collectively translate into greater pumping efficiency.

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If turbos are so cool, why don't we see more of them on street machines outside of imports? In racing, it's discrimination, plain and simple. Turbos are dominant anywhere they're allowed to compete against beltdriven blowers (as well as nitrous oxide), so rule-makers almost always legislate against them, adding weight, reducing displacement, or relegating them to a separate class. On the street, it's due to perceived complexity and installation difficulty. While these issues certainly aren't trifles, in these pages--with help from Innovative Turbo, Turbonetics, and other turbo specialists--HOT ROD will attempt to demystify some of these complexities and get you started on the road to making some serious horsepressure.

The little brother of the TO4 (far right) is the T3 (far left). The T3's envelope is about 25 percent smaller, making it easier to package. Turbonetics says many street V-8s run OK with T3 or T3/TO4 hybrids, which is a real godsend in a tight engine compartment.

The Feedback Loop

There are a bewildering variety of turbo configurations, but they're all similar in appearance and function: During engine operation, hot exhaust gases blow out of the engine's exhaust ports, into the exhaust manifold, through connecting tubing, and into the turbo's turbine housing. They strike the blades on the turbine wheel and make it spin. When the turbine wheel spins, so does the compressor wheel. As the compressor wheel rotates, it sucks air (or both air and fuel in the case of a draw-through carbureted setup) into the compressor housing. Centrifugal force throws the air outward, causing it to flow out of the turbo into the intake manifold under pressure.

There are four TO4 turbine wheel trims (rear row)--N, O, P, and Q. The large Q-trim reduces backpressure, but being heavier, it spools up slower. Each trim level is available in two shaft diameters and with a choice of ball or plain bearings. In the front and middle rows are just 10 of the literally dozens of TO4 compressor wheel trims; they're ID'ed by numbers.

As engine speed and boost increase, the turbo becomes self-feeding: The more air the compressor packs into the engine, the more exhaust gas is generated, which causes the turbine wheel to spin faster, in turn spinning the compressor faster and packing more air into the engine.

The key is getting the wheels spinning fast enough in the first place to start generating boost and a feedback loop. Turbos are load-sensitive and need energy to work. If the compressor and turbine wheels are not spinning fast enough when the accelerator pedal is mashed, there will be a slight delay before the turbo develops sufficient boost, a phenomenon known as turbo lag. Factors contributing to turbo lag include improper turbocharger selection, the turbo's physical location within the system, and the inherent limitations of nonelectronically managed engine packages.

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Turbo bearings are subject to tremendous heat. The water-cooled housing (above left) is recommended for prolonged highway use. Short-duration competition engines often use an air-cooled housing (above right) for less complexity.

No Junkyard Dogs

The most critical aspect of a successful turbocharger installation is the proper selection of the basic turbocharger unit itself. Conventional superchargers come in only a few different size variations, and their output is easily adjustable by changing the drive-pulley ratio. Turbochargers come in an enormous array of sizes and shapes to confuse you, and if you select the wrong one, the engine won't function at anywhere near its potential.

First, you can't just go down to the salvage yard, pick up an OEM unit, and bolt it onto your hot rod. Its size and design characteristics almost certainly won't be right for your custom engine from a flow and efficiency standpoint. Its physical layout may also be hard to adapt: The wastegate may be integral with the turbo, making it hard to mate with other engines' exhaust systems, and the compressor and turbine halves may not be clockable as is the case with high-performance aftermarket units intended for use on custom installations.

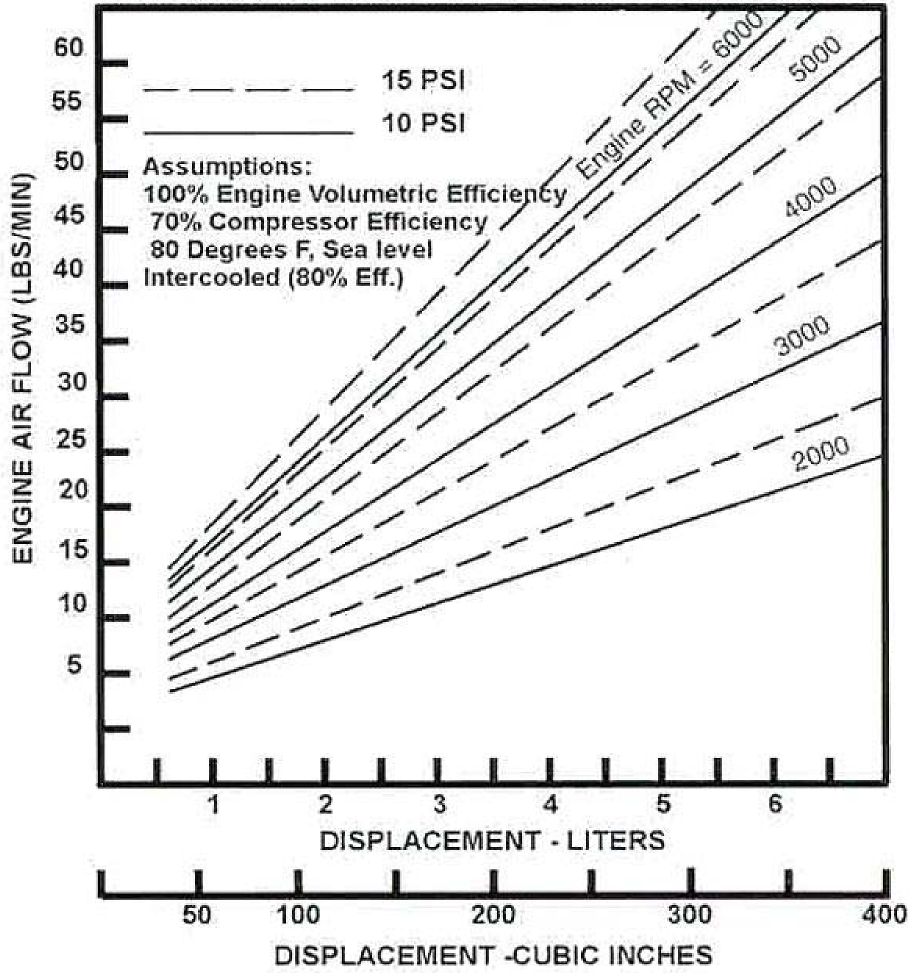
This 358ci small-block Chevy is about as rad as it can get and still use conventional 23-degree-valve-angle heads. Electronically managed by ACCEL Gen 7 DFI, the 10.0:1 engine runs a single large-frame Innovative GTB88 turbo and makes over 1,400 hp on C-16 race gas. Big race turbos are typically identified by the inducer orifice size--in this case 88 mm.

Specifically intended for custom installations, aftermarket units like AirResearch's popular TO4 series are modular and assemble like an erector set, allowing for variable combinations of turbine housings, compressor housings, turbine wheels, and compressor wheels within a given turbo series. Just like cams, there are so many factors governing turbo selection that consulting an expert is highly recommended. However, the following overview will get you close.

Compressor Housing

Turbo size selection begins with choosing the compressor housing (the air-into-engine side of the turbo). Racers operating with high-octane fuel usually base this on how much horsepower is required to be competitive in their particular racing venue. Street-driven cars operating on available pump gas are boost-limited, so their primary selection criterion is based on how much turbo their engine combination can accept at a specified boost level. Generally, 10 psi without an intercooler, or 15 psi with an intercooler (on a well-tuned, electronically managed 8.0:1-compression engine) is about the best a street guy can hope for on pump gas.

Figure 2
Engine airflow requirements for 10 PSI and 15 PSI boost levels.

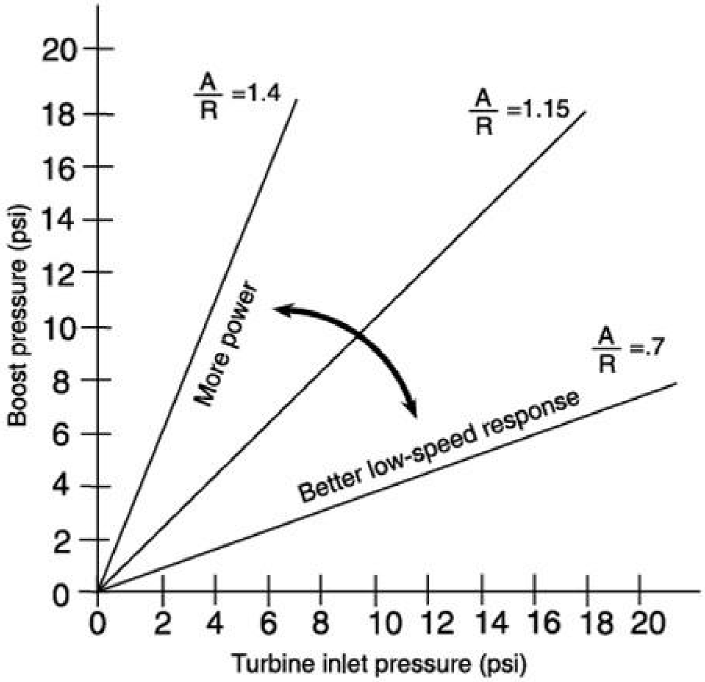


This graph can be used to determine engine airflow requirements for 10- and 15-psi boost levels.

Whether you're seeking to reach a desired power level (for racing) or a specific boost level (on the street), first determine how much airflow is needed to reach your goal at a given engine displacement and engine rpm. A normally aspirated four-stroke engine's cfm requirements are expressed by the classic formula: VE is at least 100 percent for a turbocharged engine, so use 1.0 for VE.

Generally on a high-performance EFI engine, every 1 lb/min of airflow is worth about 10 hp, so to find the required lb/min for a race-only application, start with the horsepower requirement, then divide by 10:

Lb/min = hp / 10



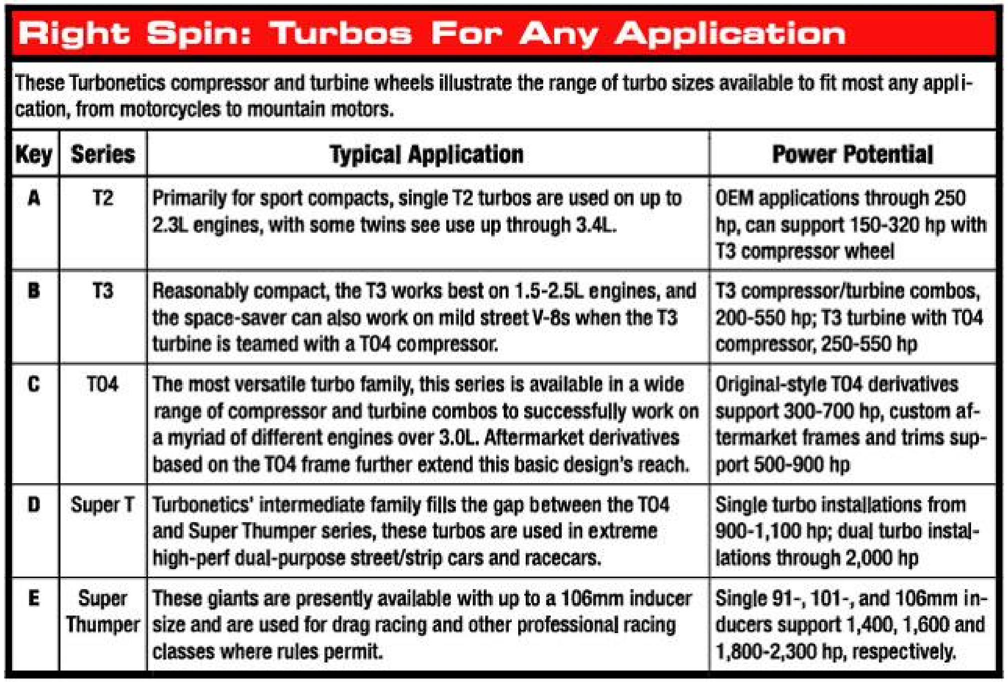
For any turbo series, the higher the A/R ratio, the better the top-end performance. The lower the A/R ratio, the better the low-speed response.

Every compressor has a definite combination of airflow and boost pressure at which it is most efficient. When choosing a compressor, you want to position the point of maximum efficiency in the most useful part of the engine's operating range. As efficiency drops off, heat transferred to the air-induction side of the turbo goes up. That's bad for both power and durability.

Turbo manufacturers publish compressor maps that establish the peak efficiencies of every turbo unit and its variations. These maps are an extremely important part of compressor selection because popular turbo series like the TO4 and its custom aftermarket derivatives have many different available wheel trims--a classification system that defines the relationship between the compressor's inducer (inlet orifice) and the compressor wheel overall diameter and tip shape. At first glance, these maps resemble a topographic contour map, and in a sense the map's bands are describing a turbo's output geography, but in terms of boost and airflow instead of elevation. They may look complex, but don't be put off. The accompanying sidebar shows how to read a compressor map and use it to select a compressor for some hypothetical engine combos.

A tangential turbine housing (left) offers about 4 percent higher flow but has less mounting and packaging flexibility than the on-center housing (right). In the ubiquitous TO4 line, each design is available in a choice of four different trim levels (which must match the turbine wheel trim), and up to eight A/R ratios.

Turbine Housing



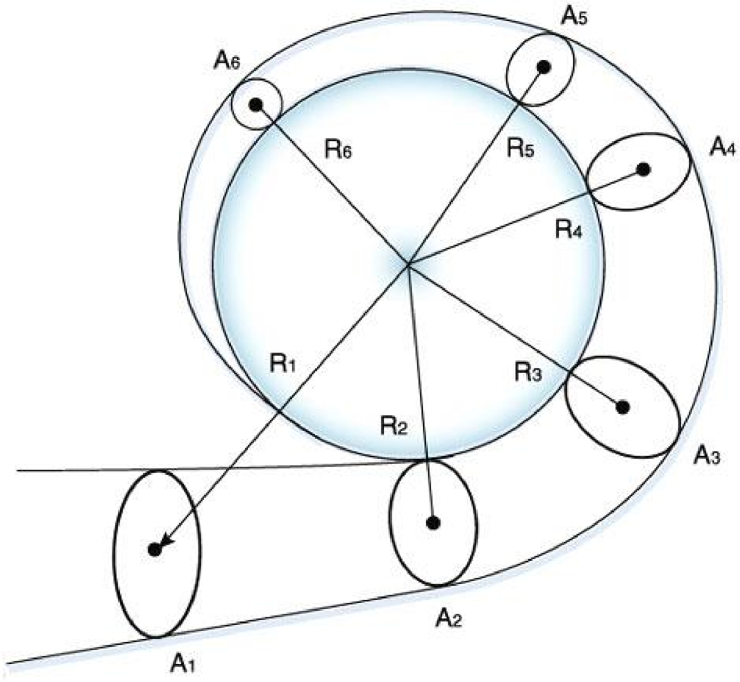
Right Spin: Turbos For Any Application

These Turbonetics compressor and turbine wheels illustrate the range of turbo sizes available to fit most any application, from motorcycles to mountain motors.

Key	Series	Typical Application	Power Potential
A	T2	Primarily for sport compacts, single T2 turbos are used on up to 2.3L engines, with some twins see use up through 3.4L.	OEM applications through 250 hp, can support 150-320 hp with T3 compressor wheel
B	T3	Reasonably compact, the T3 works best on 1.5-2.5L engines, and the space-saver can also work on mild street V-8s when the T3 turbine is teamed with a T04 compressor.	T3 compressor/turbine combos, 200-550 hp; T3 turbine with T04 compressor, 250-550 hp
C	T04	The most versatile turbo family, this series is available in a wide range of compressor and turbine combos to successfully work on a myriad of different engines over 3.0L. Aftermarket derivatives based on the T04 frame further extend this basic design's reach.	Original-style T04 derivatives support 300-700 hp, custom aftermarket frames and trims support 500-900 hp
D	Super T	Turbonetics' intermediate family fills the gap between the T04 and Super Thumper series, these turbos are used in extreme high-perf dual-purpose street/strip cars and racecars.	Single turbo installations from 900-1,100 hp; dual turbo installations through 2,000 hp
E	Super Thumper	These giants are presently available with up to a 106mm inducer size and are used for drag racing and other professional racing classes where rules permit.	Single 91-, 101-, and 106mm inducers support 1,400, 1,600 and 1,800-2,300 hp, respectively.

Because of the turbocharger's modular nature, in many instances it is possible to mix and match different turbine housings (the exhaust side of the turbo) with a given compressor housing. This permits tailoring the turbo specifically to the individual engine's operating characteristics and the vehicle's intended usage.

The turbine must make the compressor spin fast enough to produce the required airflow at the specified boost level. A small turbine spins faster than a larger turbine (which reduces lag), but develops more backpressure (which restricts exhaust flow). The goal is a turbine that spins fast enough to generate the necessary response and airflow while minimizing backpressure in the exhaust.



The turbine housing A/R (area/radius) ratio is the area (A) of any turbine inlet scroll cross-section divided by the distance from the center of that cross-section to the center of the turbine shaft (R). For any given turbine housing, A and R vary in the same proportions, so all As divided by their corresponding Rs yield the same dividend--which is the A/R ratio.

But brute size is not all that matters. The turbine's A/R (area/radius) ratio basically determines where the turbo starts to accelerate. A turbine housing looks kinda like a big snail shell. Unwrap the shell and it resembles a cone. Cutting off the tip of the cone leaves a hole--the cross-sectional area of this hole is the A in A/R. The hole size is important since it determines the velocity at which the exhaust gases exit the turbine scroll and enter the turbine blades. For a given flow rate, the smaller the hole, the higher the velocity--but the greater the restriction to exhaust-gas flow

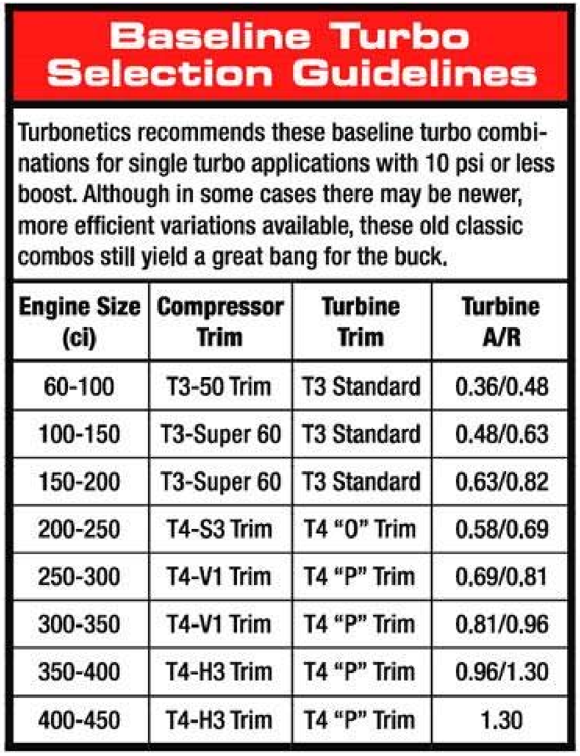
The R in A/R is the distance from the center of the cone's cross-section to the center of the turbine shaft. A smaller R imparts a higher rotating speed to the turbine; a larger R gives the turbine shaft greater torque to drive the compressor wheel (because the lever arm R is longer).

The compressor housing is a primary factor in determining how much boost (and power) a turbo is capable of supporting. There are at least nine different housings available for standard shaft-diameter TO4s alone! Here are three of 'em.

Why is A/R ratio important? Consider two extremes: Bonneville land-speed racing (LSR) versus quarter-mile drag racing. In an LSR application, the turbo's rate of acceleration is not critical; the setup can be lazy off-the-line, but the overall acceleration rate, once it begins, should be smooth and linear--this application generally calls for a high A/R ratio. At the drags (and on a street car), you need more aggressive, instant response, which tends to lean toward a lower A/R ratio.

Unfortunately there is no easy scientific method for selecting the proper A/R ratio. Seat-of-the-pants feel is important: If boost rise is sluggish, the ratio is too large. In extreme cases, the ratio gets so big the turbo can't turn fast enough to produce the required boost. But if the ratio is too small, the turbo gets into boost so quickly that the vehicle becomes almost undriveable--and on top, it will feel like a choked-up normally aspirated engine that's under-carbureted. Also, what equates to a low or high A/R ratio varies by turbine series and engine displacement.

Assuming the ubiquitous TO4-style turbo on a typical 350ci engine, Innovative offers these A/R guidelines as a starting point, based on where you want the turbo to work best:



Baseline Turbo Selection Guidelines

Turbonetics recommends these baseline turbo combinations for single turbo applications with 10 psi or less boost. Although in some cases there may be newer, more efficient variations available, these old classic combos still yield a great bang for the buck.

Engine Size (ci)	Compressor Trim	Turbine Trim	Turbine A/R
60-100	T3-50 Trim	T3 Standard	0.36/0.48
100-150	T3-Super 60	T3 Standard	0.48/0.63
150-200	T3-Super 60	T3 Standard	0.63/0.82
200-250	T4-S3 Trim	T4 "O" Trim	0.58/0.69
250-300	T4-V1 Trim	T4 "P" Trim	0.69/0.81
300-350	T4-V1 Trim	T4 "P" Trim	0.81/0.96
350-400	T4-H3 Trim	T4 "P" Trim	0.96/1.30
400-450	T4-H3 Trim	T4 "P" Trim	1.30

Operating Range; A/R Ratio
Low-end; 0.58
Midrange; 0.69-0.81
High-rpm; 0.96

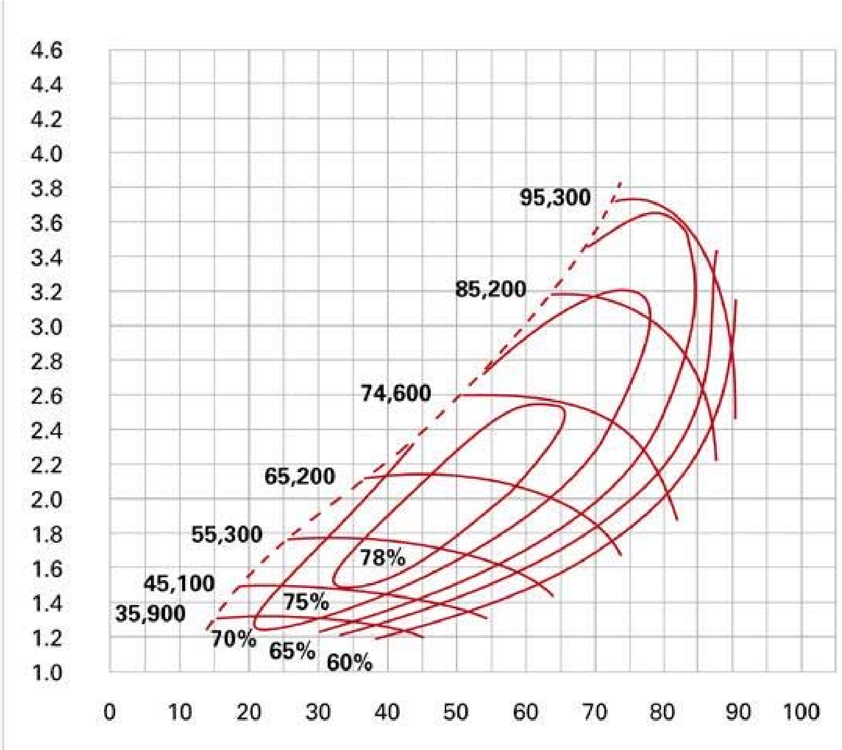
The accompanying Turbonetics table lists its baseline recommendations for a variety of engine displacements.

Turbonetics latest Inconel Super T turbine wheels (right) feature 10 improved high-efficiency blades in place of the previous 11-blade design. Super T turbines fill the gap between the TO4 family that tops out about 900 hp and the huge Super Thumper family that starts working at 1,400 hp. Inconel is good up to 1,700 degrees F. Need more? Special Mar-M 247 exhaust wheels survive at 2,000 degrees.

One Turbo or Two?

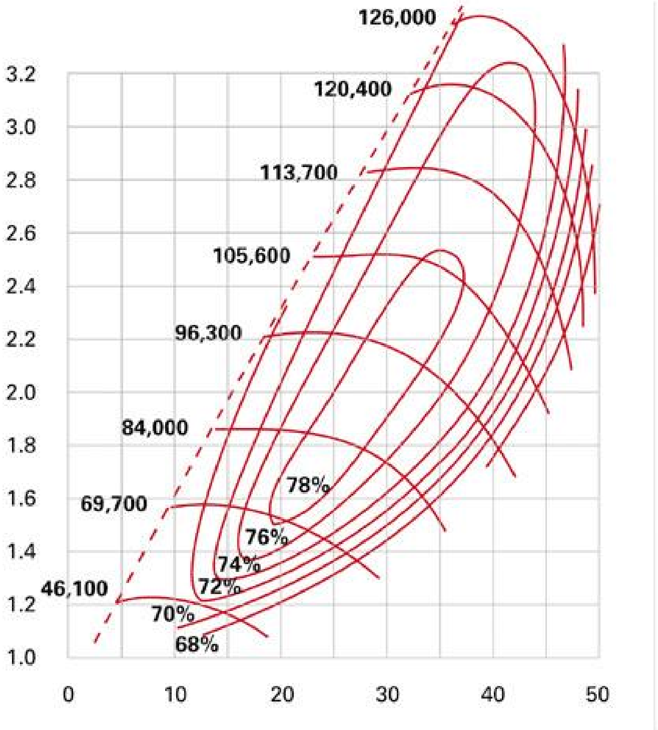
For racing only, there are super-large single turbo setups that can support over 1,500 hp, but they don't work well down low. Generally, when not restricted by sanctioning body rules, the usual crossover point between single and dual installations is in the 900-1,000hp range. Most under-900hp requirements can be met by one turbo, typically the universal TO4 or a custom derivative based on the TO4 frame. However, some claim that even in the under-900hp regime, two smaller turbos reduce lag over one big turbo; others counter that basic physical laws postulate that the reduction in inertia and flow caused by splitting the exhaust energy in half more than outweighs the supposed advantages of lighter, smaller components--or, in English, one big turbo housing is more efficient than two smaller housings.

But turbos must also be considered as part of the overall induction and exhaust system. There's no doubt that twin turbos have certain advantages on V-type engine layouts. The cross-tube on single-turbo V-8 installations can lose a lot of heat, and heat energy powers the turbine; two turbos permit a greater cross-sectional discharge pipe area, and dual wastegates are more efficient.



Ford 302, Actual displacement: 301.59 ci, Peak engine speed: 6,000 rpm, Airflow: 1,057.67 cfm (74.04 lb/min), HP potential: 740 hp, Compressor: GT76, Approx. efficiency: 66%

Finally, there is a special type of dual-turbo setup called compounding, where multiple turbos are mounted in series instead of in parallel, as is normally the case on a multi-turbo setup. Compounding is for extremely high boost pressures (on the order of 50-100 psi!) and is usually only encountered on tractor pullers, big diesels, and aircraft. With one turbo alone making 50 psi under extended operation, the high boost causes shaft overspeed and eventual unit failure. With compounding, a larger unit mounts ahead of a smaller unit. Since it's able to work harder and draw in more air, the larger unit generates an initial 15 psi or so, which the smaller unit then multiplies by three or four times to generate high boost without overspeed. With the air already condensed, the second, smaller turbo is not a restriction.



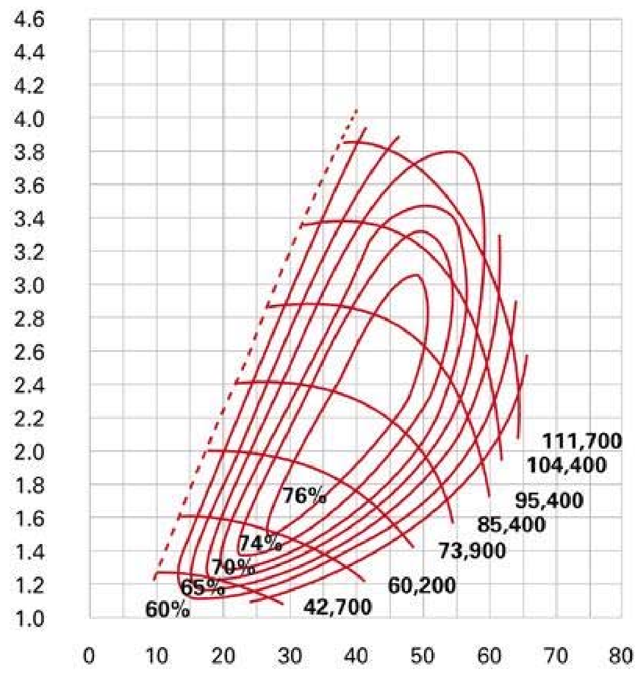
Honda B18, Actual displacement: 1,834 cc (111.95 ci), Peak engine speed: 9,000 rpm, Airflow: 588.88 cfm (41.22 lb/min), HP potential: 412 hp, Compressor: TO4E-50 trim, Approx. efficiency: 72%

We've said that heat is good on the turbine side, but bad on the inlet side. When an engine makes over 10 psi of boost, heat buildup on the inlet side requires cooling the incoming air down using a charge-air cooler (aka "intercooler"). We'll get into 'coolers, wastegates, system layout (including turbo location), and turbo engine-building stuff next month. Stay tuned!

Sample Compressor Maps

These Innovative Turbo maps are just a few examples of some of the many available compressor variations. We've selected them because they meet the needs of common high-performance engine combinations in terms of efficiency and airflow. The selection is based on 15 psi of boost pressure (approximately a 2.0:1 pressure ratio), the absolute maximum for an electronically managed and efficiently intercooled engine running on pump gas.

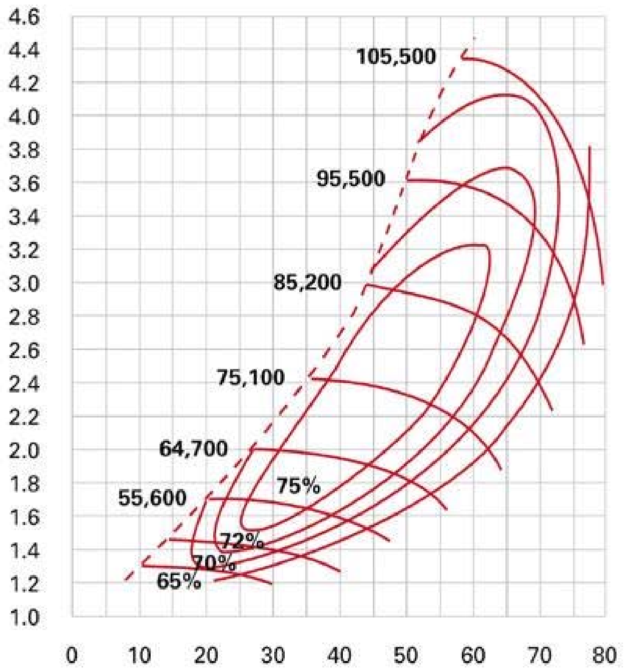
To select a compressor by means of an airflow map, use the engine airflow in lb/min to establish an operating line on the compressor map for the turbo combo in question. Choose a map so that the intersection point of lines drawn from the desired engine airflow in lb/hr (the green vertical line in these examples) and the boost pressure-ratio axis (the blue horizontal line in these examples) ideally falls within the 70-75 percent efficiency region. On an intercooled application, you can scrape by with as low as 60 percent, but higher is better.



Chevy 350 (+0.030), Actual displacement: 355.11 ci, Peak engine speed: 6,500 rpm, Airflow: 1,349.15 cfm (94.44 lb/min), HP potential: 944 hp, Compressors: Two GT61 (47.44 lb/min per turbo), Approx. efficiency: 73%

If several different maps seemingly meet your efficiency goal, choose one that has the intersection point farthest to the right side of the 70-75 percent island. This results in quicker turbo response. You want to play in right field.

In a dual turbo installation, divide the total airflow requirement in half, then select a map that satisfies those conditions. Note that as engine displacement increases, a given turbo still passes the same amount of air, but observed gauge boost pressure will be lower.



Chevy 454, Actual displacement: 453.96 ci, Peak engine speed: 6,000 rpm, Airflow: 1,592.01 (111.44 lb/min), HP potential: 1,114 hp, Compressors: Two GT70 (55.75 lb/min per turbo), Approx. efficiency: 70%

By: WDRacing