Boosting Horsepower with a Turbocharger, Part 1

What a concept! The idea may be a century old, but it can still make a small engine put out like a big one. This two-part series will prepare you for high-performance modifications with information on operating principles, design fundamentals, diagnostic info, and replacement and upgrade alternatives.

Once a car reaches cruising speed, it doesn't need very much power to keep up the pace. But acceleration -- especially the thrilling sort that makes driving fun -- requires plenty of output. Wouldn't it be great if you could have a small engine to propel you down the highway economically, but with the ability to grow miraculously in displacement when you ask it to do so by the action of your right foot?

To carmakers pursuing this seemingly magical combination of small-powerplant mpg and gorilla-motor 0 to 60 times, that's been the basic idea behind the turbocharger. HOT ROD Professional readers, on the other hand, are mostly on a quest for the latter, and squeezing a whole lot of power out of an engine can be greatly facilitated by tuning the stock turbo, upgrading the system, or adding one to replace normal aspiration. Before you embark on such a project, however, you'd better know the whole story, beginning with basic principles.

Well-proven

The turbocharger is a proven technology that's been used in heavy-duty trucking, agriculture, heavy equipment, marine applications, railroad engines, aircraft, etc. for many decades. In the automotive world, the term conjures up images of exotics, pure racing cars, and high-end Europeans and Asians, although it's boosted the power of many more mundane vehicles over the years.

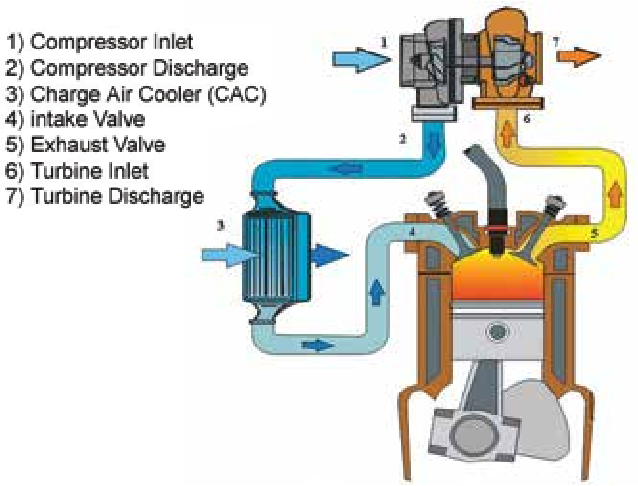
On the street scene, the basic idea has always been to use turbochargers to produce tire-shredding horsepower numbers from relatively small displacements, essentially causing the engine to grow miraculously whenever you put your foot in it. Now, the emphasis is changing to getting acceptable power out of the smallest, most fuel-efficient powerplants possible. The market system is nothing if not responsive, so high fuel prices are about to make turbos explode in popularity. More and more new cars will be appearing powered by small, clean-running turbo-diesels and T-charged gas engines. So, what exactly is a turbocharger and how long has it been around?

1905!

The history of turbochargers begins in 1905 when Swiss engineer Alfred J. Buchi patented the first supercharger powered by exhaust heat. Some time thereafter, a prototype turbocharged diesel engine was developed, but the industrial processes and materials did not yet exist that would allow the manufacture of a true production model. The first working turbocharged engine was created in 1910 -- a two-cycle "rotary" diesel for aircraft built by Murray-Willat (at that time, a rotary engine meant one that had the crankshaft bolted to the airframe so that the entire engine spun with the propeller, so it's not to be confused with the modern Mazda rotary).

By 1920 the first turbocharged diesel locomotives and ship engines appeared, and General Electric introduced its turbo on a LePere biplane that set an altitude record of over 33,000 feet. That same year Mercedes-Benz and Fiat began turbocharging cars, and in 1936 J.C. Garrett formed Garrett Corporation. By World War II, turbochargers -- often equipped with charge air coolers manufactured by Garrett -- were used in warplanes like the Lockheed P-38 Lighting and B-17 Flying Fortress to overcome the lack of oxygen per cubic foot at high altitude. The demonstrated reliability of turbocharging as used on aircraft opened the door to automotive and diesel truck use after the war.

The availability of new materials more resistant to high temperatures sped the development of the turbocharger. In 1952, Fred Agabashian qualified the first turbocharged diesel engine race car entered in the Indianapolis 500 for the pole position and led the race for just under 100 miles. His day ended when the turbo ingested tire debris left on the track. Practical turbo powered diesel trucks appeared in 1957, and today the majority of both light- and heavy-duty diesel trucks are turbocharged, as are most diesel-powered tractors and heavy equipment.



Turbocharging is all about making use of energy that would otherwise be wasted to pack the cylinders and make a little engine act like a big one (courtesy Garrett).

In WWII, turbocharging gave many of our warplanes, such as this Lockheed P-38 Lightning, superior performance at high altitudes (courtesy Airforce Image Gallery).

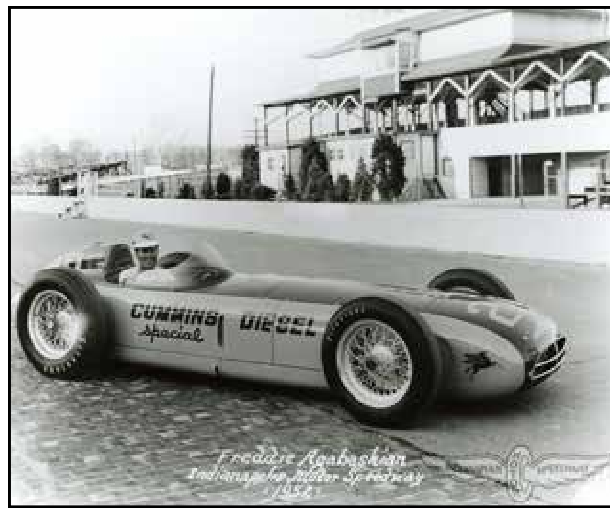
The Oldsmobile Jetfire Turbo Rocket and Chevrolet Corvair Monza appeared in 1962. They were not big sellers, so were short-lived. Turbos re-emerged in the early 1970s on the German-built BMW 2002 Turbo and Porsche 911 Turbo. Soon after that, turbocharged race cars were dominating every venue where they were legal. Beginning in the late '70s, most car manufacturers offered a model or two with turbochargers, but consumers didn't readily accept the extra expense and the complications, nor the turbo lag inherent in those designs -- the power increase wasn't enough to justify the handicaps. The shining exception to this was the Buick 3.8 V6 turbo, which was a great car all around. In 1978 the first turbocharged diesel engine passenger car, the Mercedes-Benz 300 SD, was introduced, and in 1981 the VW Golf Turbodiesel became one of the most desirable cars in Europe. In 1980, the 301 Turbo Pontiac debuted. Turbocharged passenger cars had become commercially viable. Soon, however, multiple valves, variable cam timing, and all the many performance benefits of electronic engine management made naturally-aspirated engines so lively that the addition of turbochargers was deemed unnecessary and superfluous, and their popularity waned.

New, improved

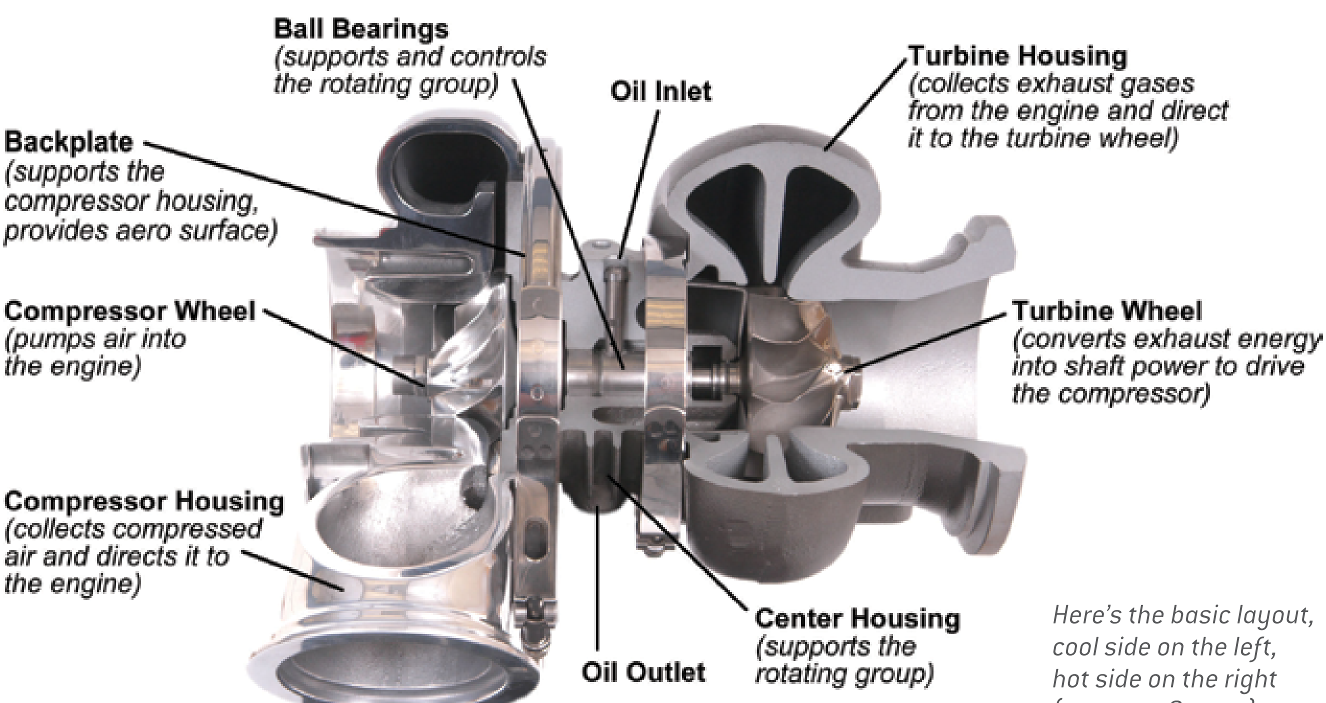
Fast forward to the present day. With energy prices as they are, you shouldn't be surprised to see widespread use of turbocharging occurring now. Turbo lag has been largely cured with ball bearing construction and high-technology turbine designs, including variable vanes on the turbine side. VNTs (Variable Nozzle Turbines) have been in use for years on diesel pickups with the GM Duramax, the 6.0 and 6.4 liter Ford, and the Cummins inline six. Turbocharging offers the power of a large engine on demand with the fuel-sipping qualities of a much smaller engine during low power demands – the best of both worlds. As clean-burning catalyzed and particulate-controlled diesels make inroads, you can expect to see the turbocharger population continue to grow and flourish.

The players and the product

Numerous companies manufacture turbochargers: Garrett, Banks, Borg-Warner, Cummins, Toyota, Rotomaster, Holset, IHI-Warner-Ishi, Rayjay, Schwitzer, Komatsu, and Mitsubishi, to name a few.



Fred Agabashian led the 1952 Indy 500 for almost 100 miles in a car powered by a turbocharged Cummins diesel (courtesy Cummins).



Here's the basic layout, cool side on the left, hot side on the right (courtesy Garrett).

The basic automotive and light truck turbocharger consists of an axial inflow, radial outflow compressor on the intake side coupled on a common shaft with a radial inflow, axial outflow turbine on the exhaust side. "Radial" and "axial" refer to the direction of gas movement. Punch the point of a pencil through the center of a cardboard circle. Radial flow would originate at the rim of the cardboard circle and move inward to the pencil where it penetrates the cardboard circle. Axial flow would originate where the pencil enters the cardboard and would move along the length of the pencil to the eraser end.

The heat and pressure of the exhaust side is harnessed in the turbine, which drives the compressor through the common shaft. The shaft may be supported by a pair of floating bronze journal bearings and a separate thrust system, or by the newer ball bearing system with integral thrust control, and there are good reasons why the former gave away to the latter. Ball bearing center housing rotating assemblies don't need a separate thrust control system since the shouldered thrust faces of the two ball bearings are installed opposing each other, thus controlling thrust in both directions. Plus, ball bearings are more tolerant of lubrication shortcomings, and also spool up more quickly, dramatically reducing the dreaded turbo lag.

One of the advancements that makes the newest turbos far better than older versions is ball bearings. Lag is reduced and durability is much better than with plain journal bearings (courtesy Garrett).

If you were looking for a word to describe turbochargers, that word would be "precise." The turbine and compressor wheels are carefully positioned in their respective housings with .010-.020 in. of clearance to the contour bores. The precision-machined housings change in volume from inlet to outlet to maximize energy extraction on the turbine side and air movement on the compressor side. The size, shape and contour of the volutes (the spiral, scroll-shaped form of the housing that resembles a ram's horn) are critical to turbocharger flow rates and efficiency.

By convention, the inlet of a turbine or compressor section is called the inducer section and the outlet the exducer section. A ratio of the relative sizes of the inducer and exducer sections is often expressed as a trim number, helpful in sizing the turbo correctly. Since space limitations restrict the use of a more efficient axial-only turbocharger, blade shapes on the turbine and compressor wheels are engineered to reduce the losses generated as gases make the 90 degree turn through the housing. Turbine blade shape constricts at the exducer to extract maximum power from gases that are gradually slowing and cooling. Viewed on end, a turbine blade suspiciously resembles an airfoil -- there's a lot going on here!

Imagine the engineering and manufacturing processes that went into this sophisticated compressor wheel.

Inlet pressure on the turbine (hot) side is generally within a few pounds of the actual boost, about 15-20 psi, which translates into a pressure drop of about 13-18 psi across the turbine wheel at full load if the exhaust system backpressure is two pounds. Expect full load temperatures to drop about 300 deg. F. from a 1,200-1,500 deg. inlet reading. It's that temperature and pressure drop across the turbine wheel that provides the energy necessary to spin the compressor.

On the compressor side, the amount of boost is controlled by a wastegate, or by a variable nozzle arrangement on the turbine side. The wastegate is a simple bypass system. Inlet pressure is routed over to a spring-loaded diaphragm that opens a passage to bleed exhaust gas around the turbine. Less flow and heat through the wheel means slower turbine speed, hence slower compressor speed and less inlet pressure. Simple and elegant.

The VNT system eliminates the wastegate. Vanes mounted on pins and connected by linkage are actuated together to limit exhaust flow or change gas direction through the inducer of the turbine wheel, slowing the rate of rotation and reducing boost.

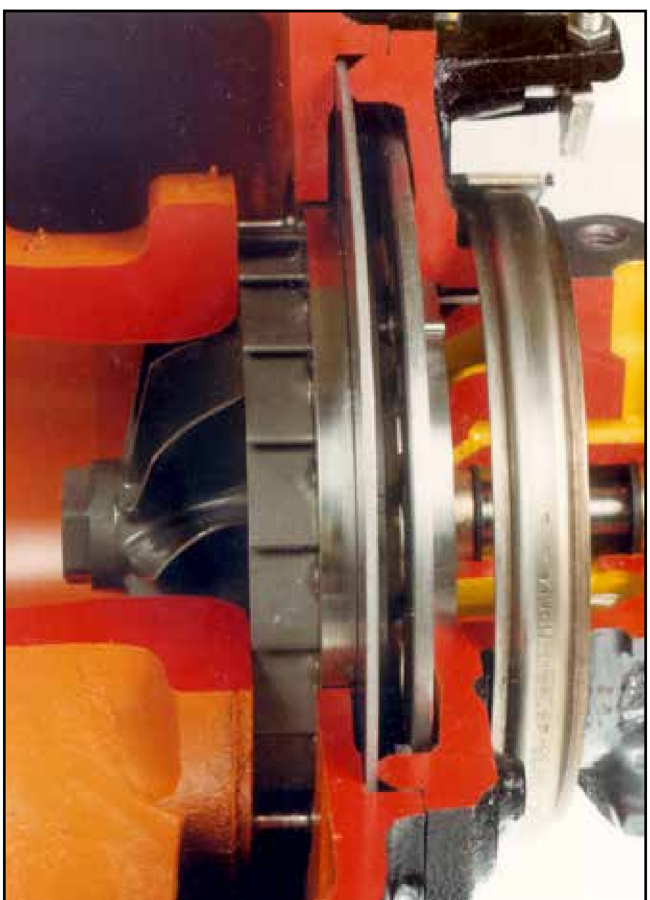
Overdone

There are limits to per-liter internal combustion power output, no matter how exotic the materials and build techniques. With turbocharging (or supercharging, for that matter), you risk changing the timing of the intake valve closing event, taking the engine to detonation, or finding the mechanical limits of the head gasket, block, fasteners, or cylinder head. There's a great picture on the Internet of a tractor puller who yanked the block of his six-cylinder engine in two just where the head studs stopped in the block when his boost gauge hit 300 psi! Let's see, 300 psi times 16:1 is . . . a helluva lot of pounds of force!

Potential intake valve closure issues are really only a problem in all-out performance applications unless there's a failure that creates unregulated boost. In high-performance applications, valve closure issues are overcome by design: limit the boost, increase valve spring pressure, keep intake valve diameter down, grind the cam for boost application, or modify the rpm band.

Assuming cylinder pressure is zero, a two-inch valve with 15 psi intake boost only has about 50 pounds of force counteracting the valve spring. But our pulling tractor at 300 psi? Assuming it's a four-cycle engine, that same two inch valve would need almost 1,040 pounds of spring pressure just to overcome inlet pressure. ■

It's pretty obvious what we're doing here. If you open the gate, exhaust gases bypass the turbine wheel, slowing shaft speed and reducing boost.



Variable Nozzle Turbines (VNTs) don't need a wastegate. Instead, a system of vanes is used to limit and/or change exhaust flow. Here, the vanes are closed, which allows the fastest possible turbine speed.

In this photo, the vanes are open, which slows turbine speed to control boost.

Turbo Waves

Most people don't realize that the first wave of mainstream production turbocharged cars arrived in the early 1960s -- over half a century ago. To be precise, the Olds Jetfire 215 cid/215 hp aluminum V8 was the earliest, introduced in 1962, followed within a matter of months by the Corvair Monza. Both were reasonably successful and dependable, but were blown out of the market by the brutal muscle car V8s of Detroit's horsepower race, and by the public's negative attitude about accepting any new, potentially troublesome technology.

The Olds Jetfire 215 cid aluminum V8 was the first production turbocharged engine from a domestic manufacturer. At 215 hp, it produced the magic one horse per cube.

The mid-1980s saw many manifestations of the concept, such as this 1.6L Mitsubishi.

A second wave hit after the energy crisis of 1979, but that was really just a stopgap, a temporary phenomenon with significant drawbacks. Take throttle lag. T-charged engines just didn't have that right-now feeling. There are safety considerations, too. You might be in a curve with the pedal to the metal, then get enough unexpected kick to put you on a new line, possibly one that intersects an immovable object. If the road's slippery, you could lose it altogether. It's sort of like a hot two-stroke dirt bike with a narrow power band -- you nail it, very little happens, then suddenly the front wheels are pointing at the clouds.

Although turbocharging back then was hyped as the ideal means of putting high-performance excitement back into cars after emissions and fuel mileage regulations took it out, multi-valves, ingenious intake manifold designs, and seriously-efficient engine management systems gave us the sought-after combo of high performance, great fuel mileage, and low emissions without the need for an expensive add-on that takes up precious room under the hood. So, the second generation died quietly.

In the last decade or so, we've been seeing a third wave of turbocharged vehicles with technology that mitigates lag and other drawbacks almost down to nil. Probably the most well-known and successful application of the current gen first appeared on the 2002 Impreza WRX, something about which you may be painfully well aware if you've ever drag raced one. With fuel prices way up, the attraction of the mpg and performance combo has proven irresistible to the automakers, and just about all of them are making the most of turbocharging. ■

The latest generation of turbocharged engines, such as this Subaru STi, offer all of the pros with almost no cons.