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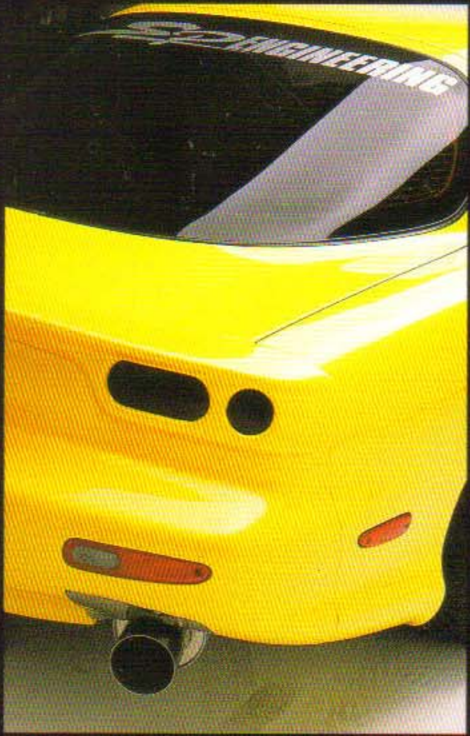
STREET TURBOCHARGING

Design, Fabrication, Installation, and Tuning of High-Performance Turbocharger Systems

Mark Warner, P.E.

Are you looking for more power and performance from your car? Are you interested in turbochargers and forced induction but are unsure where to begin? Whether you're an amateur enthusiast or a skilled professional, you can design, build, install, test, tune, and drive the vehicle of your wildest dreams with this book.

Street Turbocharging offers equal parts theory and practical hands-on advice, with step-by-step procedures and techniques explained in layman's terms, and illustrated with nearly 500 photos and technical drawings.



Street Turbocharging includes:

- The fundamentals of power production
- The theory behind turbocharger systems and how they work in the real world
- Advice on equipment selection, sizing, purchase, and installation
- In-depth coverage of every major component in a turbo system, including compressors, turbines, bearings and lubrication, exhaust, boost control, intercoolers, water injection, fuel injection, ignition, and electronic control systems
- Guidance on engine building, dyno testing, and modern tuning methods
- How-to advice and detailed instructions for fabricating turbo equipment, including the construction of exhaust manifolds and intercoolers
- Project vehicles that demonstrate in detail what can be achieved with the proper application of forced induction
- A comprehensive glossary containing hundreds of often misused and misunderstood turbocharger concepts and terms.

Designing, building and testing turbocharged engines has never been easier. For the enthusiast searching for an accurate, easy-to-understand source of information on turbochargers, *Street Turbocharging* is the perfect tool for the job.

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Finally, I want to thank my wife, Sonya, for her support and patience. I could not have written this without you.

Creating high levels of reliable horsepower and torque from a naturally aspirated internal combustion engine is well understood and well documented. Let's say that another way: creating naturally aspirated engine power is a science. Twenty years ago, this wasn't exactly the case. But today, armed with expert knowledge and reams of test data, we can confidently design and build powerful, naturally aspirated engines that behave exactly as we predict they should. We can build long-running, reliable, fuel-efficient engines that start the first time we turn the key. And these engines can produce enormous quantities of torque and horsepower in exactly the rpm ranges that we desire. There are countless books available that tell the reader precisely how to do this for any number of naturally aspirated engine makes and models.

It is time for turbocharged engines to be treated the same way.

Turbochargers are simple devices. The problem is that they are deceptively simple. Turbochargers are also misunderstood by far too many old-school engine builders and backyard experimenters. Just as the science behind naturally aspirated engines took time to mature, so has the technology behind forced induction taken time to trickle down from turbo manufacturers and engineers to the mainstream public. But those days are over; the science of turbocharging is now both well understood and accessible. No longer is the process of bolting on a turbocharger to an engine an act of faith and finger-crossing. With the proper forethought and technical know-how, just about anyone can design, build, install, test, and drive the turbocharged vehicle of their wildest dreams.

And that's what this book is all about—explaining in layman's terms the inner complexities of turbochargers and the step-by-step procedures necessary to create a properly engineered turbocharger system. For ease of use, the book has been separated into four major parts.

Part I of the book walks through the fundamentals of how power is created in an engine, how and why turbocharger systems work, and some critical concepts and equations necessary to fully understand and size all the various turbocharger components.

Part II discusses—in detail—each of the major subsystems of a turbocharged engine. It explains how to size and select turbo equipment. All of the specialized information, from turbines and compressors, through boost control, intercoolers, fuel injection, exhaust, and electronic control systems, is presented in an easy-to-read format. These chapters cover theory, equipment choices, basic and advanced calculations, material selections, suppliers, do's and don'ts, and all the basic nuts and bolts that hold it together. This section also examines the engine and drivetrain modifications required for turbocharged vehicles. And it describes the necessary steps to safely and effectively dynamometer-test a completed turbocharger system, and how to get the most from an engine during the tuning process.

Part III of the book then examines ten real-world applications, from a mild-mannered Toyota MR2 built with little money and a lot of ingenuity, to a 1000-horsepower twin-turbocharged fire-breathing Chevrolet small block. These chapters discuss what makes each of these particular vehicles work so well. Often the best way to understand how a turbocharger system should be put together is to look at how others have done it before you.

Finally, Part IV of the book includes a large glossary of oft misused and misunderstood turbocharger terms. Also included are a number of appendices that show how to build a turbo exhaust manifold and intercooler, as well as some additional thoughts on turbo applications. Understanding and designing a powerful turbocharger system has never been easier.

A CAUTION BEFORE PROCEEDING

Before you start designing, collecting, or building any parts for your turbocharger project, you must do your homework. This book is intended as a starting point for that research. There are other reliable resources available, and I encourage you to take advantage of all of them. Many people before you have gone down this same performance road in search of power and torque. Just as the key to success is knowledge, the key to failure is ignorance. Learn all that you can before proceeding.

You also need to set goals for your vehicle—and prioritize them—early in the planning process. Ask yourself these questions: What is the objective of this vehicle? Is it to be the ultimate street car, or just a powerful boulevard cruiser? Will it ever see a race track? Will it only see a racetrack? What kind of racetrack? Autocross, road course, or quarter mile? Bonneville, anyone? Will you be the only one driving the car, or will your significant other ever get behind the wheel? Be sure to keep in mind how much you want to spend versus how much power you want to create. Speed, power, and torque all cost money. How fast do you really want to go?

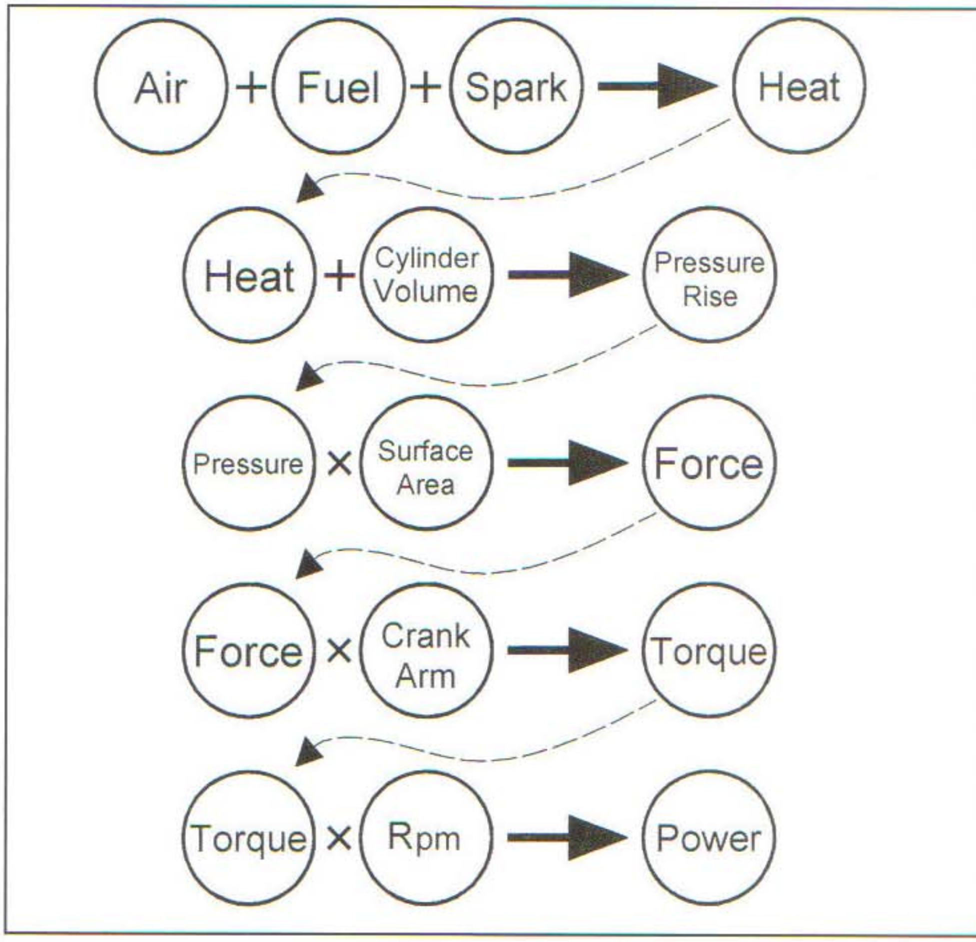
Remember, this may be one of the most frustrating stages of your entire project. You want to start buying equipment and bolting it together, but this is actually the time to slow down. Read everything you can. Talk to people. Study technical data. Run the calculations. Figure out your budget. Write it all down and then go through it again. Patience is the secret to building the best turbocharger system possible.

PART I:

POWER BASICS

1 INTERNAL COMBUSTION BASICS

This book is about turbochargers and forced induction. But before we can discuss turbos in an intelligent manner, it is necessary to understand some fundamental concepts of internal combustion power production. Comprehending these basics is the key to making high levels of reliable torque and horsepower with a turbocharger system. Let's start with the four basic strokes of an engine. For many readers, this will be elementary information, but it is vitally important, even for the most experienced engine builder.



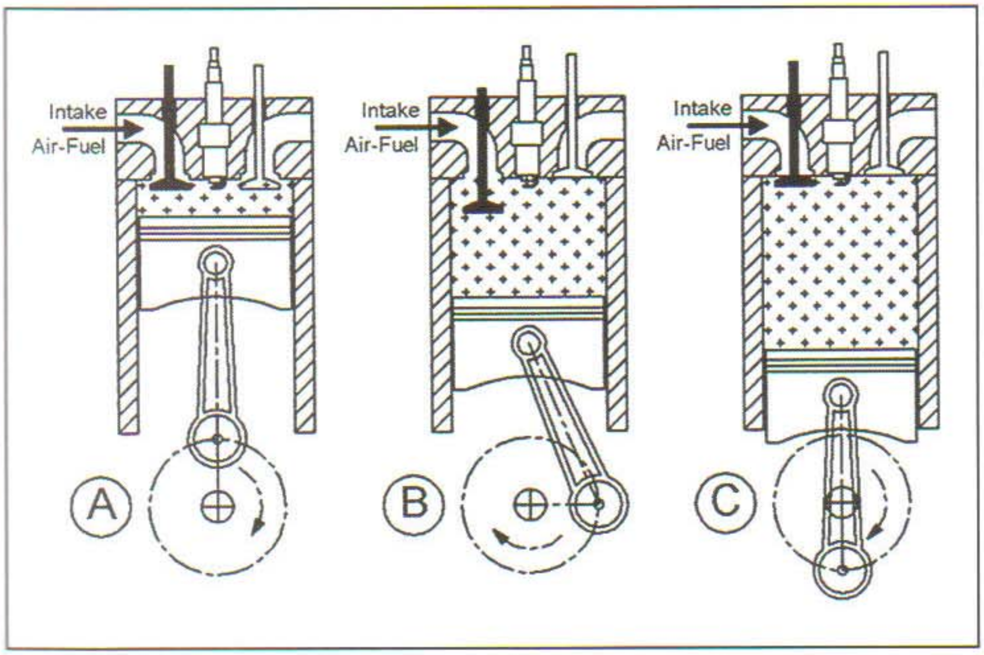
Creating horsepower is directly proportional to the amount of air that can be moved into and out of an engine.

HOW POWER IS CREATED

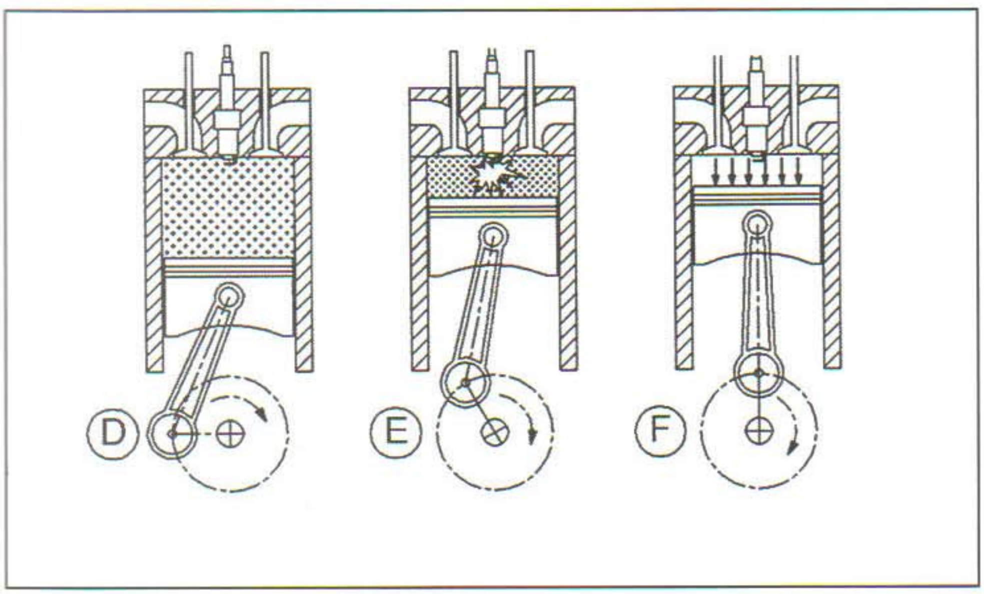
The first part of a naturally aspirated four-stroke engine cycle is called the *intake* stroke. This is the period of time when the piston moves downward in the cylinder, and the intake valve is open. Because the chamber volume increases, a partial vacuum is formed. The difference between the higher pressure air inside the intake plenum and the lower pressure inside the chamber literally pulls a stream of air from the intake manifold into the combustion chamber. The fuel injector adds a precisely metered squirt of gasoline to this incoming air charge. (For now we're going to ignore complexities like camshaft overlap. We'll talk more about this later in Chapter 13. Note also that we're discussing a modern fuel-injected engine. We'll cover carburetor-equipped engines in Appendix E.)

At the end of the intake stroke, the piston has traveled down to the bottom of its cylinder. This position is called bottom dead center, or BDC. At this point, the intake valve is closed, and the cylinder is filled with a volatile mixture of air and gasoline. The crankshaft continues to rotate, causing the piston to rise back upward in the cylinder. This movement is called the *compression* stroke. As the piston rises, the air-fuel mixture is squeezed into an increasingly smaller volume. This causes a rise in pressure. The density of the air-fuel mixture also increases.

As the piston nears the top of its stroke (top dead center, or TDC),



Intake Stroke. The first stroke of a 4-stroke Otto cycle is the intake stroke. The intake valve opens and a partial vacuum is formed by the downward-traveling piston. This pulls in the air-fuel mixture. Note that the positions A-C correspond to the points in the Pressure Volume Plot illustration on page 5.



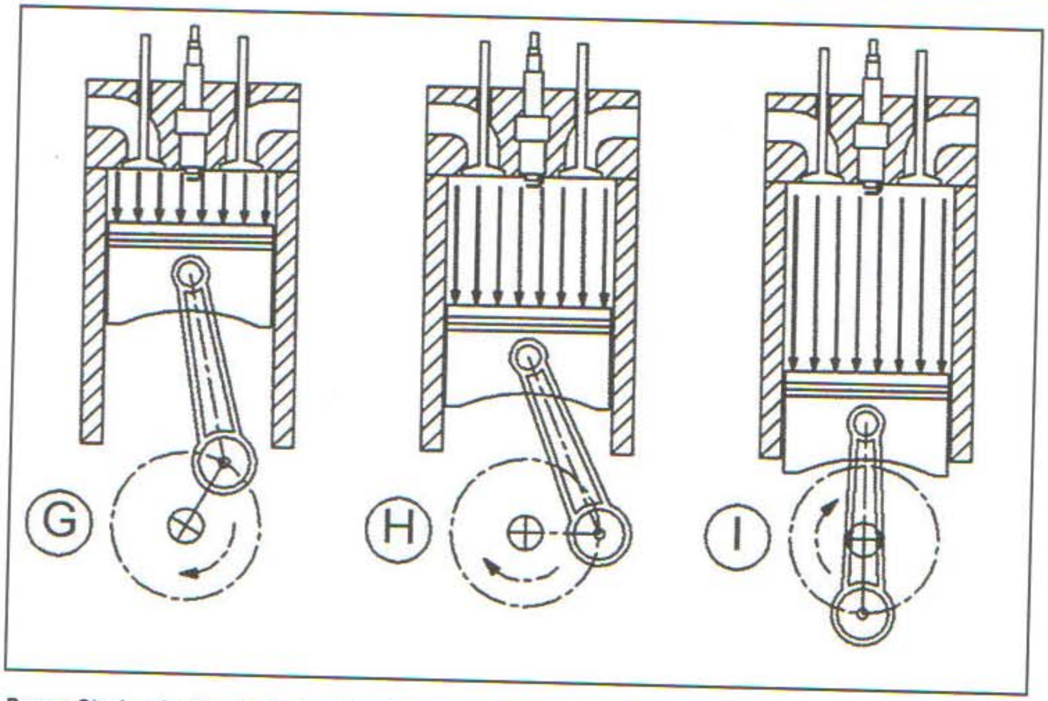
Compression Stroke. During the compression stroke, the valves are closed. The upward-moving piston squeezes (compresses) the air-fuel mixture into a volume that is roughly 10% of the original volume. Ignition occurs near the end of this stroke.

an electrical spark is created across the tip of the spark plug. The result of this spark is ignition and the rapid burning of the air-fuel mixture. Note that I did not write "explosion" of the air-fuel mixture. An explosion is an uncontrolled detonation that does not behave in a predictable manner. Detonation and its evil brother pre-ignition cause damage to engine components and are things we want to avoid at all cost. In contrast, the proper burning of an air-fuel mixture inside a combustion chamber is a well-controlled event. Detonation happens on time scales that are measured in microseconds, or millionths of a second. Normal combustion occurs on the scale of milliseconds, which is thousands of times slower than detonation.

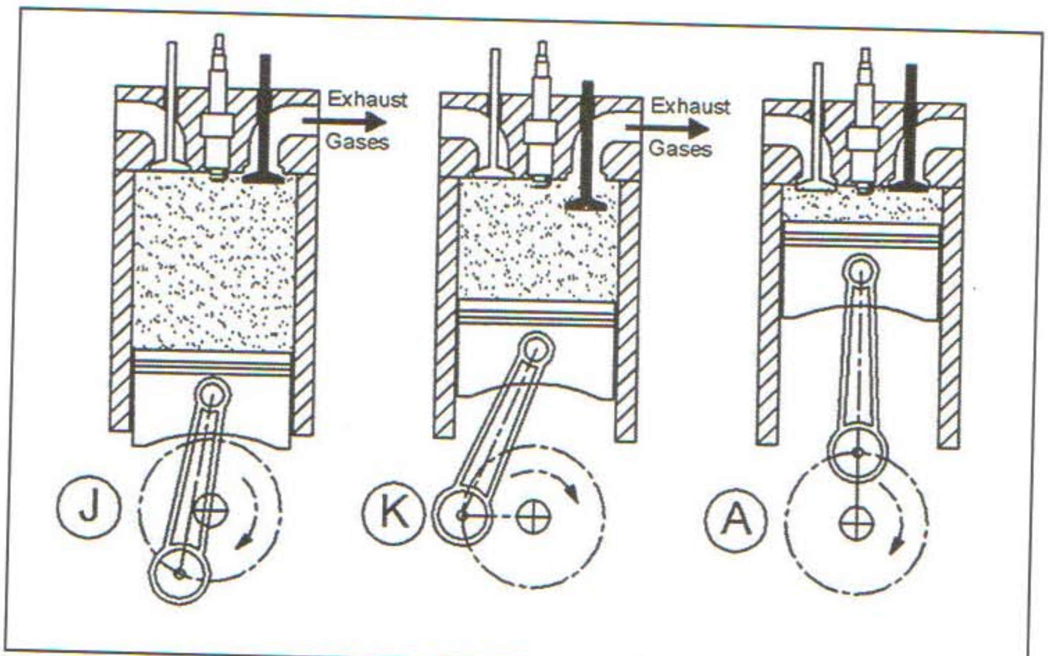
Once ignited, the burning of the air/fuel mixture converts its stored chemical energy to heat energy. This results in a temperature increase, which in turn causes a rapid increase in gas pressure. This pressure rise acts in all directions, including downward, on the piston face. Pressure, acting over an area, results in a force. The force on the face of the piston accelerates it down on its *power* stroke. The piston's linear, or straight-line movement in the cylinder bore is converted into rotational energy by way of the crankshaft.

The final cycle of a four-stroke engine is the *exhaust* stroke, and it begins when the piston has reached BDC again. The exhaust valve opens and the piston moves upward in the cylinder, just like it did on the compression stroke. But this time, instead of compressing anything, the burnt combustion gases are allowed to escape out past the exhaust valve and into the exhaust manifold. When the piston reaches TDC for the second time, the four-stroke "cycle" is complete, and the entire process starts over again.

Intake, compression, power, and exhaust. Suck, squish, bang, blow. Inhale, squeeze, push, exhale. However you want to label it, the four-stroke cycle of creating power in an internal combustion engine is nothing more than the mixing of the right amount of air with the



Power Stroke. As the air-fuel mixture burns during the power stroke, chemical energy is converted to heat energy. This causes a rapid rise in temperature and pressure, which pushes downward on the piston face. The crankshaft harnesses this downward force as a torque.



Exhaust Stroke. The last stroke of a complete cycle is the exhaust stroke, in which the burnt gases are expelled from the combustion chamber via the exhaust valve.

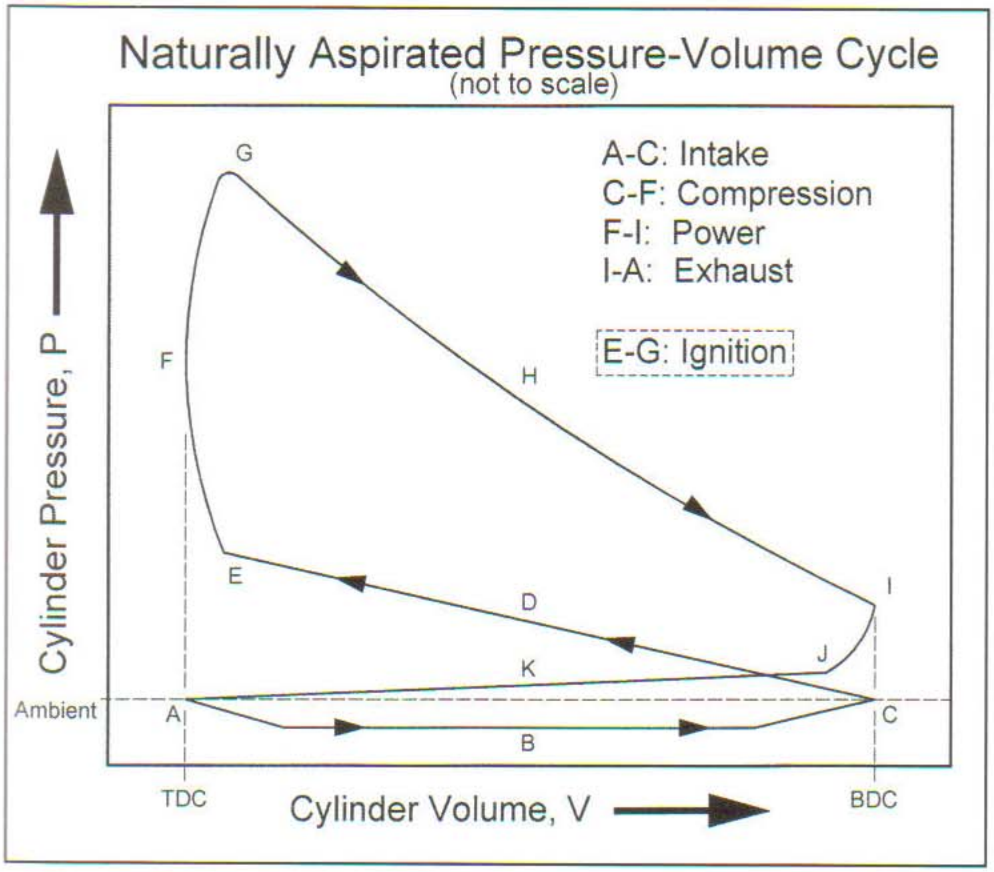
right amount of fuel in the cylinder, compressing it, igniting it at just the right moment, harnessing the energy released, and then expelling the burnt gases. Simple, right? Well, let's make it even simpler. Most professional engine builders tend to think of their engines as nothing more than big air pumps, pulling air in and then pushing it out again. It turns out that this is a great way to look at the challenge of increasing power output. Here's why:

THE ENGINE AS AIR PUMP

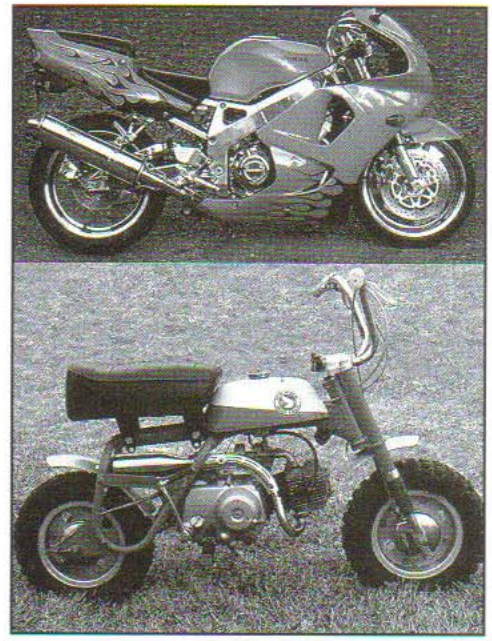
Looking back at the power stroke for a moment, it's clear that liquid fuel (gasoline) is the source of the energy release that ultimately moves the piston downward on its power stroke. But as we learned back in high school science class, oxygen is required to burn a fuel. For every 1 pound of gasoline we inject into a cylinder, we need to draw in roughly 14.7 pounds of air to chemically initiate and support fuel combustion. The technical term for this 14.7-to-1 ratio of air-to-fuel mass is called *stoichiometry*, and we'll discuss it more in a moment. For now, however, just keep in mind that the more air we bring into each cylinder on each intake stroke, the more gasoline we can burn. And the more gasoline we burn means the more power we produce. In other words, maximizing airflow ultimately means maximizing engine power.

Of course we need to accurately add the correct amount of fuel along with the intake air, but when compared to the difficulty of metering and moving all that air mass in and out of an engine, the addition of the right amount of fuel is relatively easy. The real problem lies in getting the large quantities of air into and out of the engine cylinders in an efficient manner.

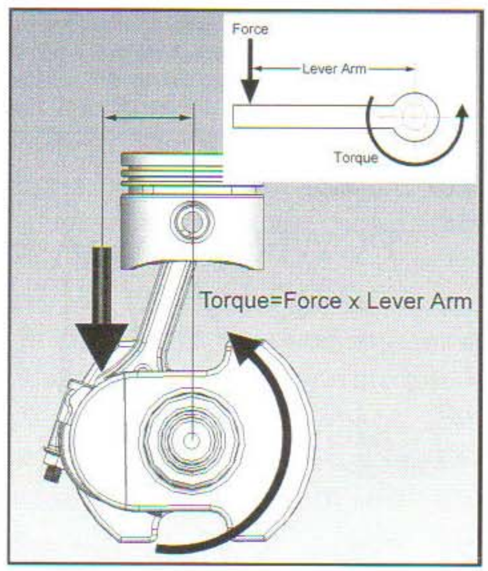
Put another way, the amount of horsepower an engine creates is directly proportional to how many pounds of air are moved into and out of it during a given amount of time. There is no getting around this fact; it is fundamental to power production. An engine is an air pump, and the more air moving in and out of it, the more power it can produce because more fuel can be burned. This is the reason why



Pressure-Volume Plot. A pressure-volume (P-V) plot shows the relationship between cylinder pressure and cylinder volume during the entire engine cycle. The points on the curve (A-K) correspond to the piston stroke positions shown in the preceeding Intake, Compression, Power and Exhaust illustrations. One complete cycle = 2 crankshaft revolutions = 4 strokes.



Even though the power levels may be radically different, all four-cycle engines work the same way: intake, compression, power, and exhaust.



Crankshaft torque is a function of the force delivered by the piston, multiplied by the effective crank arm length. The piston force is equal to the cylinder pressure times the piston face area.

engine builders spend so much time and effort on porting and polishing, stroking and boring, installing bigger valves, bolting on freer flowing exhausts, raising engine speed (rpm) limits, and so on. They are simply trying to move as much air into and out of the engine as they possibly can. Once they've accomplished that, they can increase the amount of fuel injected, and, voilá, they've created more power.

THE FOUR WAYS TO INCREASE AIRFLOW

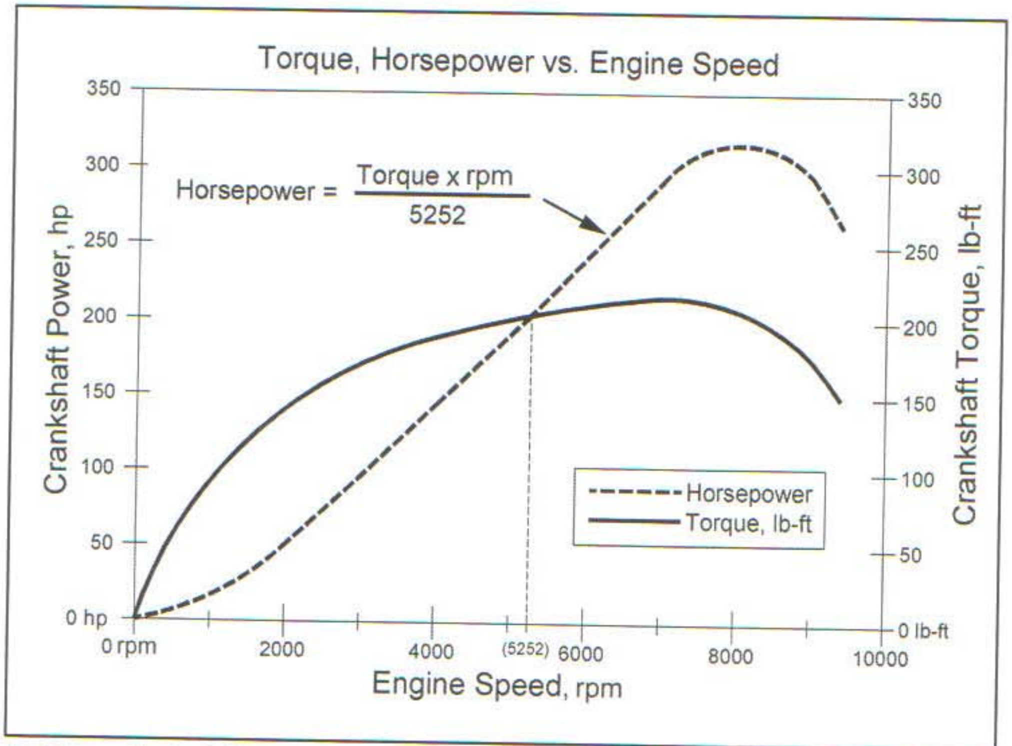
So let's look in more detail at the various means at our disposal for increasing the airflow into and out of an engine. As it turns out, there are only four basic ways to do this: displacement, engine speed, volumetric efficiency, and air density increases.

Displacement

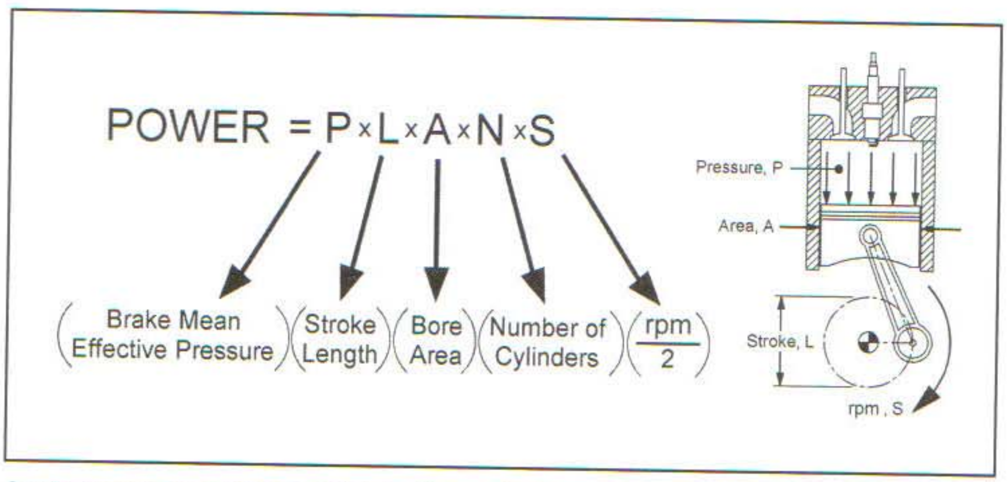
The most obvious way to increase the airflow into an engine is to increase the physical volume that is displaced between top dead center and bottom dead center. You will often hear old-time hot-rodders refer to this as the "there's no replacement for displacement" rule. Everything else being equal, a larger displacement engine will draw in more air on the intake stroke than a smaller engine.

Increasing the volume of an engine can be done in three different ways. First, we can increase the bore, or diameter of each cylinder. Not surprisingly, this is called boring out an engine, and it results in a larger piston face area. Circular area is calculated by:

$$\text{Area} = (\text{Pi})(R)^2 = \tfrac{1}{4}(\text{Pi})(D)^2$$



Horsepower is simply the rate at which torque is produced by an engine. In a sense, the faster an engine revs, the more frequently torque (due to the connecting rod imparting force into the crank arm) is able to do useful work. Note that when torque is measured in lb-ft and plotted on the same scale as horsepower, the two curves will always cross at 5252 rpm.



Creating power is sometimes said to be the result of a good set of PLANS, where: P=Brake Mean Effective Pressure, L= Length of Stroke, A=Piston Face Area, N=Number of Cylinders, and S=Engine Speed/2.

From this, we can see that a small increase in diameter can have a relatively large effect on displacement.

We can also increase the stroke length to increase displacement. Stroke length is just the distance the piston travels between TDC to BDC. Increasing this length, of course, is called stroking an engine. It usually entails offset grinding the crankshaft or fitting an entirely different crankshaft with longer crank arm throws.

Finally, in our quest for more displacement, we can add more cylinders. This, as you might expect, is usually only feasible by switching to a completely different engine.

Engine Speed

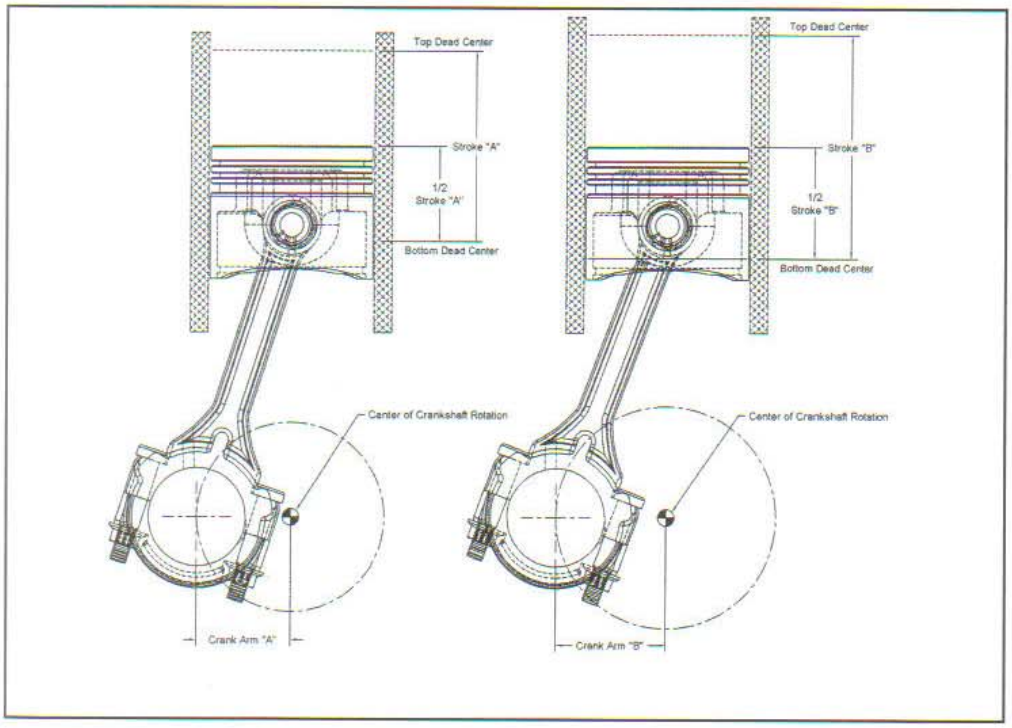
The second method of pumping more air through an engine in a given amount of time is to increase the rotational speed at which the engine operates. By definition, higher rpm means that the four-stroke cycle is occurring at a faster rate. This means that each engine cylinder is filled more frequently with fresh air, which of course means that more fuel per minute can be burned, and therefore more power created.

Volumetric Efficiency

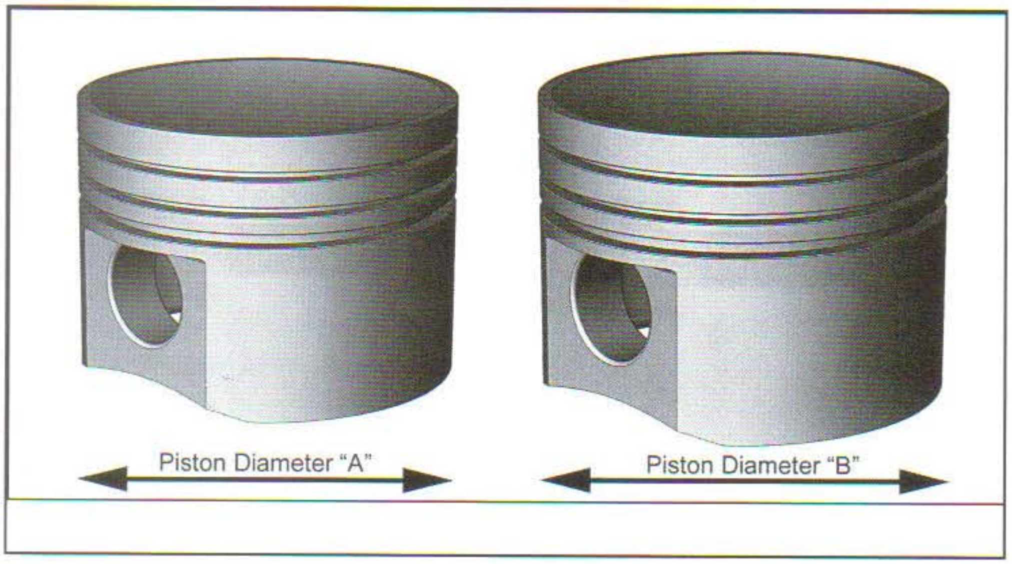
Most engines don't take in as much air during normal operation as they are theoretically capable of ingesting. Restrictions in the intake and exhaust path, valve overlap effects, and airflow inertias all combine to reduce the actual amount of fresh air entering a cylinder during each intake stroke. The quantity of air that does physically make it into an engine on each intake stroke, divided by the theoretical displacement, is called the engine's volumetric efficiency, or VE:

$$VE = \frac{\text{Actual Intake Volume}}{\text{Engine Displacement}}$$

An engine's VE changes with rpm and engine load. Most of the time, however, it falls in a range between 0.8 and 0.9 for average naturally aspirated engines. This means that the typical street engine ingests between 80% and 90% of the potential amount of air that it theoretically is capable of moving at full throttle. Some specialty race



Everything else being equal, increasing the stroke of an engine will proportionally increase the amount of air it draws in during intake. More air means more fuel, which means higher combustion pressures. This of course means the force acting downward on the piston is increased. Also, because the crank arm is longer, the mechanical advantage of the crankshaft is increased. Crankshaft torque is a function of piston force multiplied by crank arm length.



Similarly, boring an engine out to a larger piston size will increase the amount of air drawn into the cylinder.

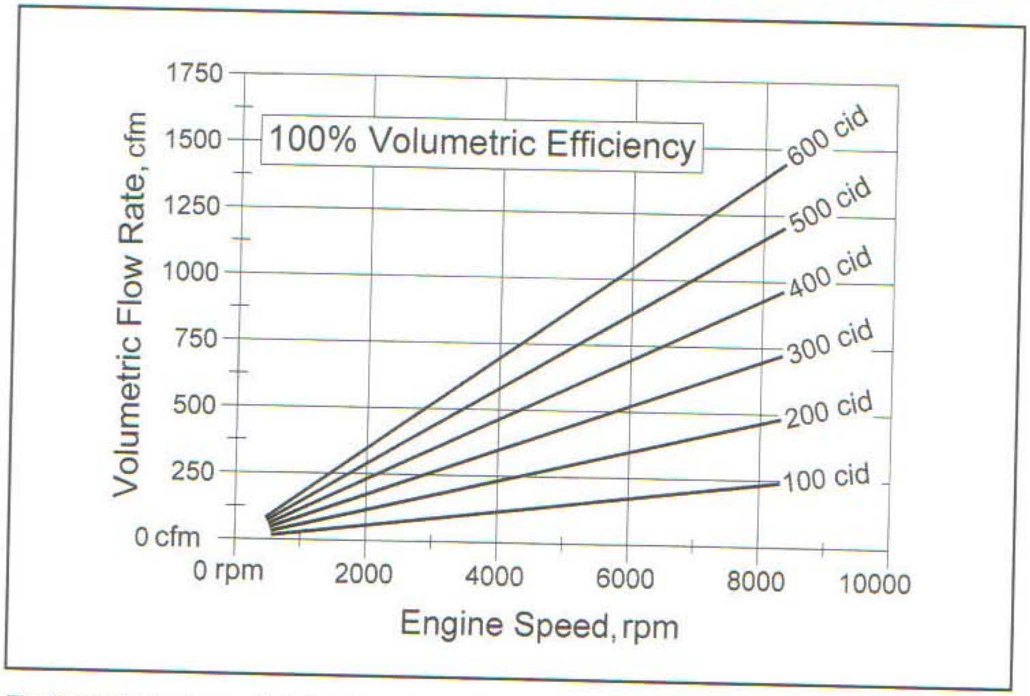
engines can actually exceed 100% at certain engine speeds and conditions, given special acoustic tuning and cylinder scavenging. NHRA Pro Stock engines, for instance, can achieve VE levels as high as 115–120% within narrow rpm ranges at their torque peak.

This VE effect gives the engine builder a clear way to increase the mass of air moving through an engine: increase its volumetric efficiency. This is typically accomplished by way of a variety of traditional hot-rod tricks, such as reshaping, smoothing, and enlarging (porting) the intake and exhaust paths, enlarging intake and exhaust valves, unshrouding valves in the combustion chamber, increasing camshaft lift, duration and overlap, adding freer-flowing exhaust systems, and changing the length of intake runners to improve dynamic inertial effects.

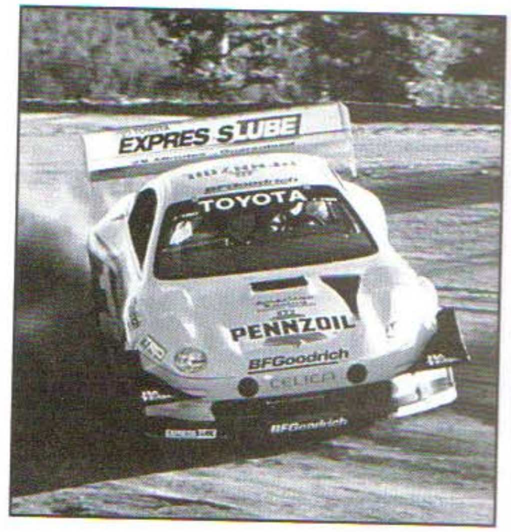
Air Density

The fourth and final way to increase the amount of air that moves through an engine is to increase the density of the incoming air itself. In other words, squeeze more air into a given volume. There are two ways to do this. The first is to lower the temperature of the air. Going back to high school science class again for a moment, we learned that when most things are cooled, they shrink in volume. This is true for air, too. Of course a cooled mass of air still weighs the same amount as it did when it was warm, but it now takes up less space. Put another way, the lower the temperature of a gas, the denser it is. This is why engines make more power on cold days than warm days. They draw in the same *volume* of air, but that volume weighs more. In other words, it contains more oxygen molecules.

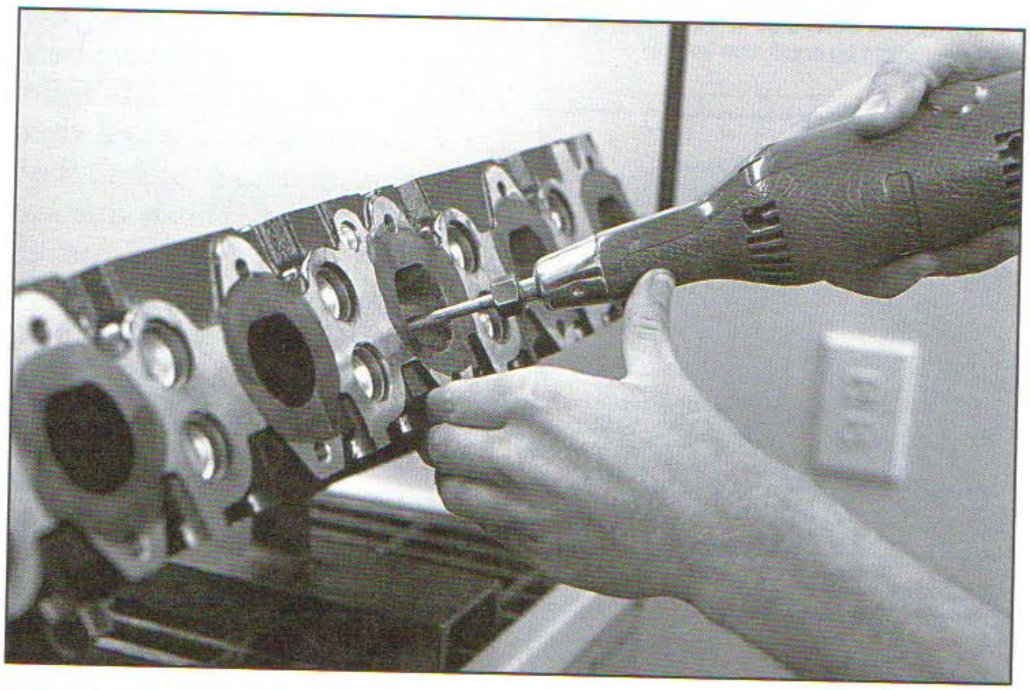
Of course it's hard to control the weather. But there is a second way to physically increase the density of the air charge drawn into an engine: pressure. Normal atmospheric air pressure is about 14.7 pounds of force per square inch (psi), when measured at sea level. The higher the elevation, the



The theoretical volume of air that flows through an engine is solely a function of engine speed and displacement. To calculate the actual amount of air ingested, this theoretical value must be multiplied by the volumetric efficiency (VE) of the engine at that particular engine speed. For modern engines, maximum VE usually falls somewhere between 80% and 90%.



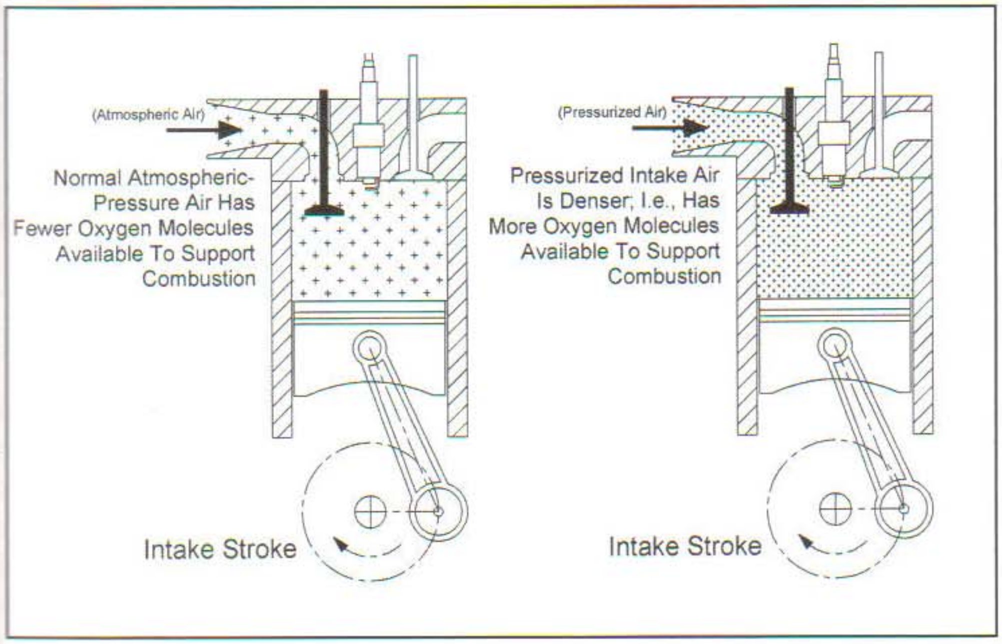
Elevation reduces effective air density, which means fewer oxygen molecules are present in a given volume of air. Conversely, colder ambient temperatures increase air density. Hillclimb racers, like world champion Rod Millen shown here setting a record on the way up Pikes Peak, have to deal with these changing conditions to maximize power. (Photo courtesy MillenWorks).



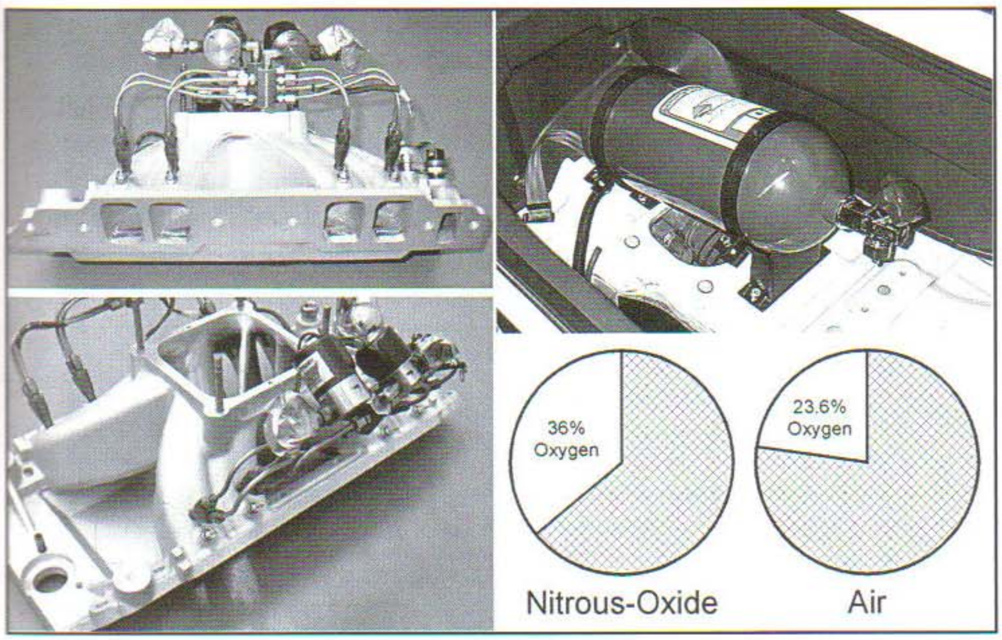
Hot-rodders resort to many tricks to improve the volumetric efficiency of an engine, such as reshaping, smoothing, and enlarging (porting) the intake and exhaust paths, enlarging intake and exhaust valves, unshrouding valves in the combustion chamber, increasing camshaft lift, duration and overlap, adding freer-flowing exhaust systems, and changing the length of intake runners to improve dynamic inertial effects. All this and more—solely in the quest to move more and more air into the chamber. (Photo courtesy Gale Banks)

lower the air pressure. Air is less dense at high altitude than it is at lower altitude. With everything else being equal, a car will make less power in the mountains than it will at sea level. This is because there are fewer air molecules present in the fixed volume of air each cylinder ingests on its intake stroke. Similarly, moving down in elevation (e.g., Death Valley, California, more than 200 feet below sea level) will result in higher air pressure and, therefore, increased air density. Higher pressure means higher density, which means higher levels of torque and horsepower.

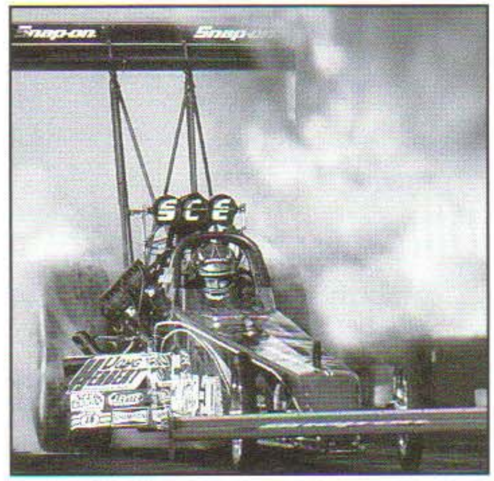
And this of course brings us to the main topic of this book: turbocharger systems. A turbocharger is a type of forced-induction device, which is nothing more than a mechanism used to increase the pressure (and consequently the density) of the air flowing into an engine cylinder. This pressure increase is accomplished by way of mechanical compression. Superchargers and turbochargers are the most common forced-induction devices. Through a variety of



One of the most effective methods to increase the mass of air drawn into the cylinder is to pressurize the intake air charge. Everything else being equal, higher air pressure means higher density, which in turn means more oxygen molecules per unit volume.



While not technically a means of increasing airflow through an engine, there is a fifth method of increasing power production in an internal combustion engine: oxygen enrichment. Because it is really oxygen, not air, that is ultimately required to support and sustain combustion, increasing the percentage of oxygen in the incoming charge stream means that more fuel can be burned. The air humans and engines normally breathe is comprised of roughly 23% oxygen by mass (or 21% by volume). The remainder of our air is mostly nitrogen, with a smattering of argon and other trace elements. Replacing some of the incoming air charge with a gas that contains a higher percentage of oxygen molecules means that more fuel can be burned. Enter nitrous oxide, with around 36% oxygen by mass.



Oxygen enrichment can also be achieved via the use of so-called oxygen-bearing fuels, such as nitromethane, propylene oxide, or other exotic blends. These fuels are often dangerous to handle, require special controls and plumbing, are hard to source, and can be very expensive. Most oxygen-bearing fuels are also corrosive and/or unstable. But in the right hands, the power outputs can be phenomenal.

different physical means, both these devices do the same basic thing: they raise the pressure of the intake air well above ambient atmospheric pressure, thereby increasing the charge density, and thereby increasing the amount of air flowing into an engine. And by now you know what this means: more power!

STOICHIOMETRY AND AIR-TO-FUEL RATIOS

The theoretical, chemically ideal air/fuel mixture for a gasoline-powered internal combustion engine is roughly 14.7 parts (by mass) of air to 1 part (by mass) of gasoline. This ratio of 14.7:1 is called the *stoichiometric* condition. Another way to say this is that for every one gram, ounce, or pound of gasoline that is injected into an engine, 14.7 grams, ounces, or pounds of air are required to initiate and support combustion of the fuel. Mixtures that have higher air-to-fuel ratios than this number (e.g., 16:1) are called "lean," while ones that have lower ratios (e.g., 12:1) are called "rich."

Although the 14.7:1 stoichiometric ratio is chemically ideal, it is not always the ratio that is required for various engine operating conditions. Real-world air/fuel mixture requirements for an engine are a function of many things, including rpm, load, and temperature. In startup and cold conditions, for example, the required air-to-fuel ratio is usually much lower (richer) than 14.7. Similarly, for maximum power and wide open throttle (WOT), the ideal air-to-fuel ratio for an engine is often in the range of 11:1 to 13:1.

For maximum fuel economy, however, such as during part-throttle conditions on a stretch of highway, higher air/fuel ratios are usually required. At part throttle and high loads, the necessary ratio is also usually higher than 14.7:1.

The hotter the combustion gases in the cylinder, the more pressure they produce. This of course results in a larger piston force during the power stroke, and therefore more torque. But there are limits to how hot you can allow the combustion gases to get. Adjusting the air/fuel mixture to keep combustion temperatures in the best possible range—while not destroying the engine—is critical. We'll talk more about this tuning process in Chapter 14. For now, however, it's important simply to remember that we are trying to move as much air through an engine as possible, but not at the expense of an inappropriate air/fuel ratio. You have to add the right amount of fuel along with all that air. Getting it wrong, especially if you lean an engine out too much, can cause detonation. This can result in shattered and melted pistons, destroyed spark plugs, burnt valves, damaged bearings… and depleted wallets.

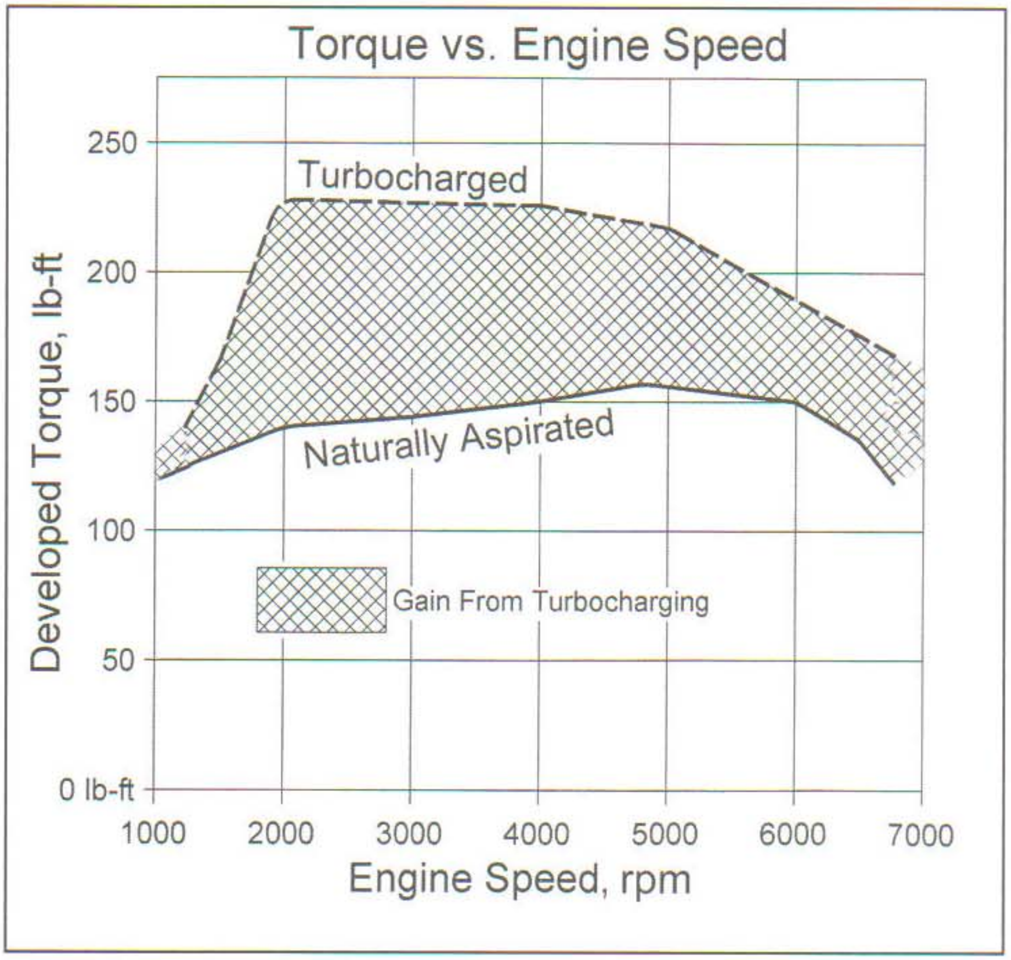
One pound of gasoline contains roughly 19,000 BTU of stored chemical energy. Just as 60 seconds equals 1 minute, and 16 ounces is a pound, 2,545 BTU burned in 1 hour is equivalent to 1 horsepower. In other words, the more fuel that is burned every minute inside an engine, the more horsepower produced.

FORCED INDUCTION BASICS

2

In the preceding chapter, we saw that an effective method to increase the power output of an internal combustion engine is to increase the density of its intake air charge. In 1901, inventor Sir Dugald Clark employed this principle on a one-cylinder test engine in his lab. He demonstrated that he could use a compressor to force more air into an engine than it would normally draw in on its own accord. The result of this experiment was that the engine created more power.

A year later, Louis Renault in France patented this same basic idea by using a centrifugal pump to create pressurized air, which was then fed into the throat of a one-barrel carburetor. Soon, a number of enthusiasts and inventors were experimenting with this new-fangled idea of "forced induction." In 1908, Lee Chadwick of the United States bolted a 3-stage centrifugal compressor onto the side of his racecar, entered it in the Wilkes-Barr hillclimb and won. Chadwick's device used three 12-bladed impellers that were driven by a leather belt attached to the engine crankshaft. The automotive supercharger was born.

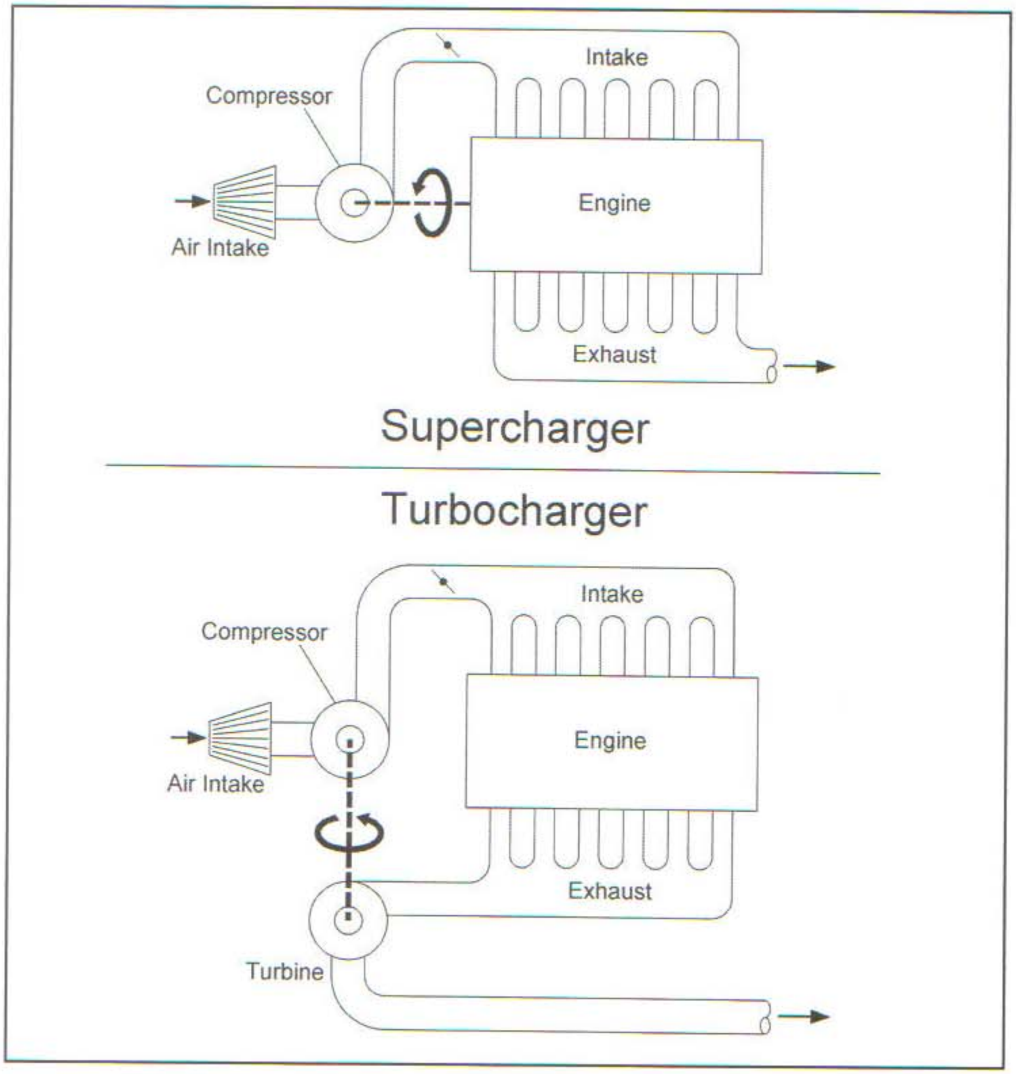


A well-designed forced-induction system for a street-driven vehicle will provide torque and horsepower gains across a wide rpm range. Shown here are engine dyno results for two Audi engines. The naturally aspirated (NA) plot on the bottom shows torque versus engine speed for a 1991 Audi inline 5-cylinder 2.2-liter engine with 4-valves per cylinder. The turbocharged curve on the top is for the same engine fitted with the factory turbocharger. The forced-induction engine has a slightly lowered static compression ratio and camshafts with reduced overlap, but is otherwise identical to the NA engine. The difference in torque and horsepower between the two engines, however, is considerable. (Fahlgren)

Today's modern supercharger may look very different from Chadwick's antiquated device, but the operating principle remains the same. A belt or chain-driven compressor creates a flow of pressurized air. This pressurized airflow is fed to the intake plenum. When the intake valves open, the "boosted" air fills the engine cylinders with more air molecules than would normally be drawn in without the device. From that point on, combustion is no different than it is in a naturally aspirated engine—except that more fuel is burned on each power stroke, and the torque and horsepower outputs are increased.

SUPERCHARGERS

Modern superchargers are capable



Both supercharged and turbocharged engines utilize some type of air pump (compressor) to supply a flow of pressurized air to the engine. The difference lies in how each provides power to the compressor. A supercharger is usually belt or gear driven off the crankshaft of the engine. A turbocharger harnesses energy in the exhaust stream (via a turbine) to supply power to the compressor. Not shown in this schematic are the wastegate, intercooler, blow-off valves, or other miscellaneous equipment required to complete a forced-induction system.

of generating phenomenal horsepower numbers. Witness the estimated 7000+ hp output from a 500 cid NHRA Top Fuel dragster. The types of superchargers these vehicles use are called "roots" blowers, and they offer near-instantaneous boost production. Torque output is immense; there is essentially no throttle lag; and the best part is they're simple devices. What could be more straightforward than a belt-driven compressor?

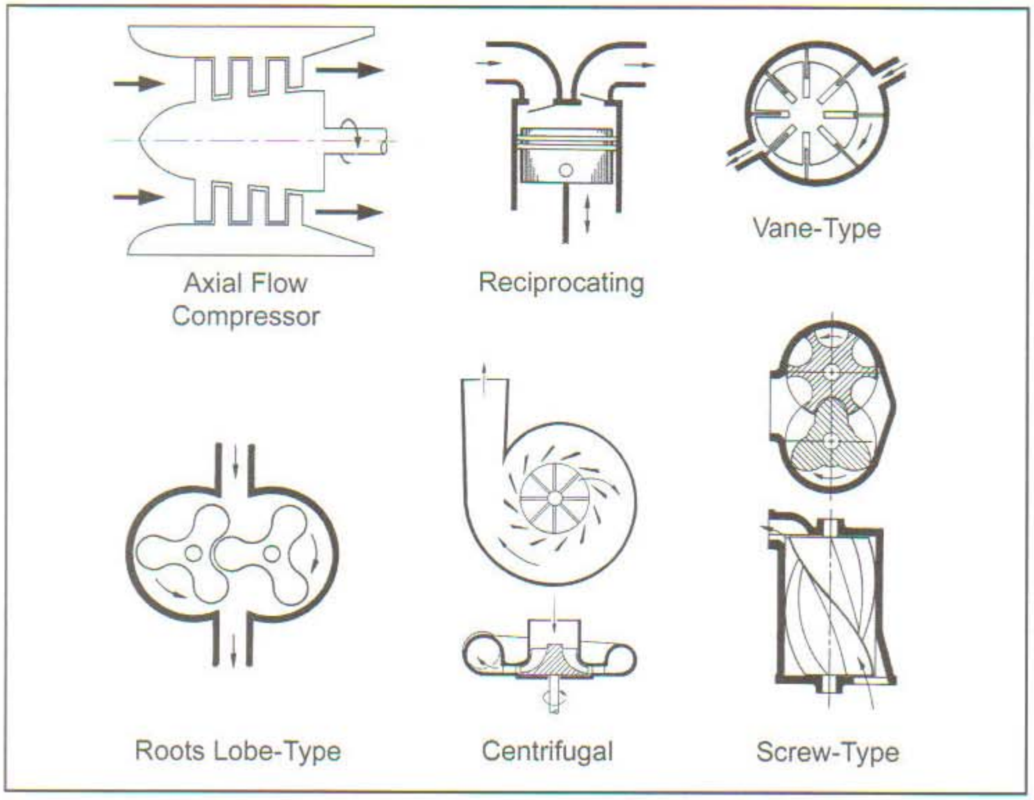
There are problems with superchargers, however, and the biggest is efficiency—or lack thereof. It takes a relatively large amount of crankshaft horsepower to drive an automotive supercharger. Depending on the type of supercharger, between 15% and 50% of the crankshaft energy created by a "blown" engine needs to go back into the task of driving the blower. It takes an estimated 750 to 1000 hp simply to power a Top Fuel supercharger to the required 3000 cfm at the 50 psi output required for a sub-5 second run down the quarter mile. A V-10 Dodge Viper does not develop enough horsepower to run the blower of a Top Fuel dragster engine!

Supercharged vehicles can be excellent performers, but they do come at an efficiency cost. If you want the most efficient form of forced induction, you have to consider turbocharging.

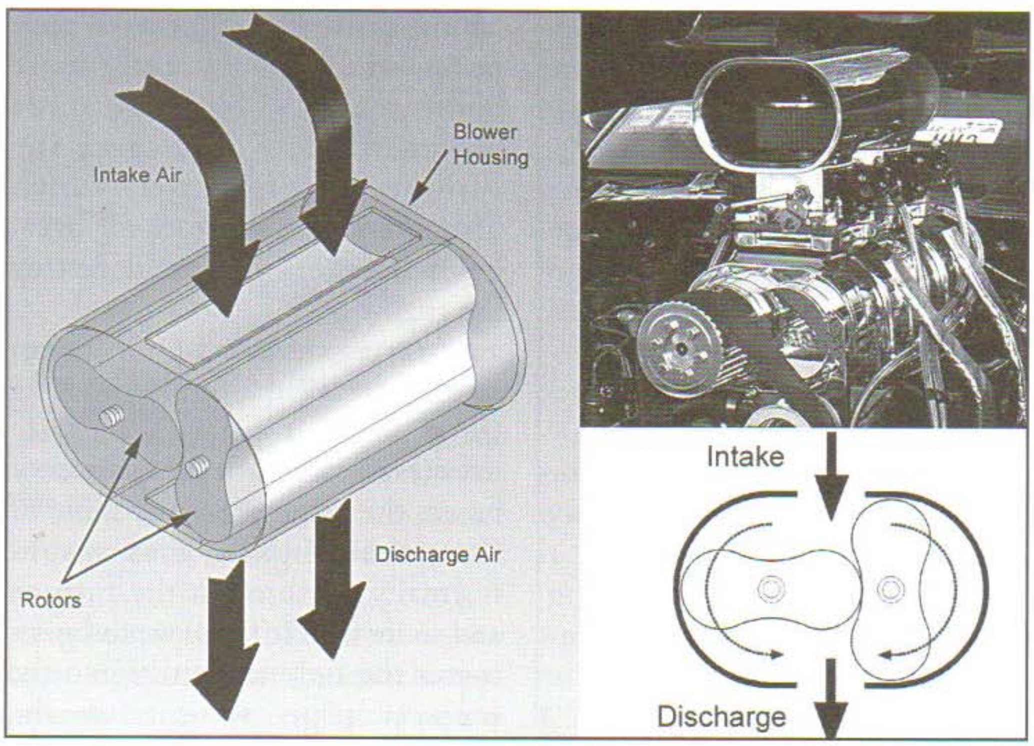
TURBOCHARGERS

Rewind back to the early 20th century. In 1909, a Swiss inventor named Alfred Buchi, building on what the supercharger guys were learning, demonstrated that he could harness some of the energy remaining in the exhaust stream of a diesel engine and use it to drive a compressor. He correctly reasoned that a significant quantity of the combustion energy was literally wasted out the tailpipe at the end of every exhaust stroke. If he could harness some of this "waste heat" energy with, say, a turbine, he could power a compressor and have the benefits of a supercharger, without the corresponding huge crankshaft horsepower drain. With this simple revelation, the turbocharger was born.

The primary moving parts of a modern turbocharger consist of two wheels with blades, mounted on a common shaft that is supported by a set of bearings. One wheel is essentially an air pump (compressor) and the other is a drive unit (turbine). Hot exhaust gases from the engine are routed to the turbine wheel side of the turbocharger. This exhaust stream impinges on, or strikes the turbine wheel and makes it spin, much like the water flowing in a stream can



There are a variety of compressors available for supercharged applications. The most common types in automotive applications are the three shown on the bottom: Roots, centrifugal, and screw. Turbocharged vehicles almost exclusively use the centrifugal type compressor.



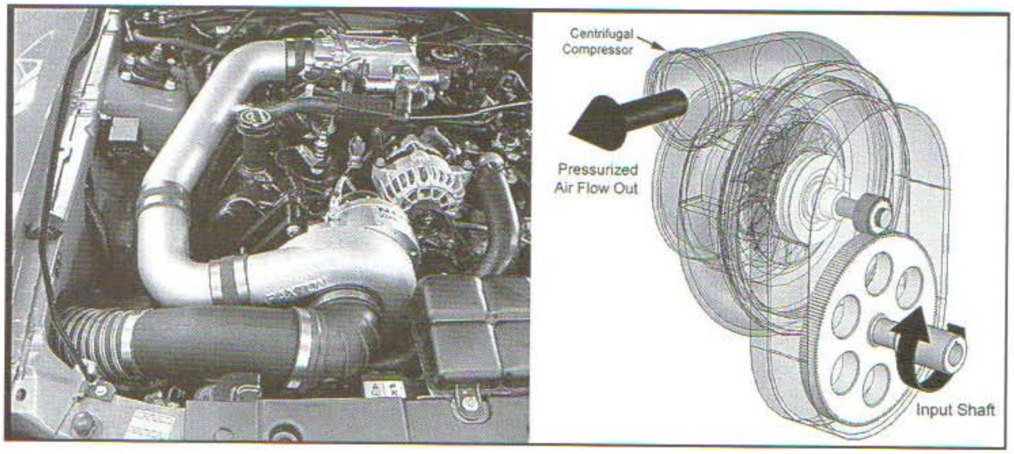
The Roots lobe-type supercharger is a "positive displacement" air pump, which means that it delivers the same quantity of air charge for each revolution of the engine, regardless of speed. Assuming the compressor displacement is twice that of a naturally-aspirated engine, the intake-manifold pressure must rise to enable the engine to flow the same mass of charge delivered by the compressor. This type of supercharger has the advantage of delivering the same manifold pressure at all engine speeds. Boost is nearly instantaneous, even at low engine speeds. The disadvantage is that crankshaft power is used to drive the device. These types of compressors also have inherently low thermal efficiencies—typically 50% or so. This means the air charge is heated considerably as it passes through the unit.

turn a waterwheel.

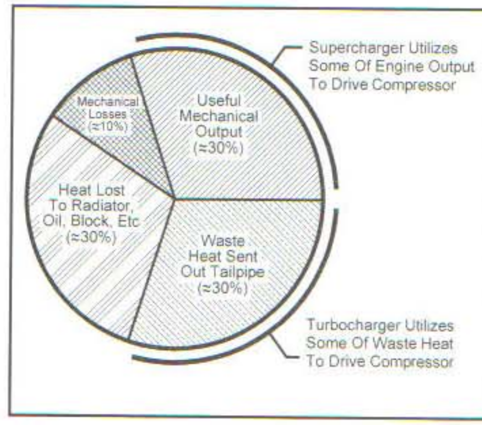
As the turbine wheel begins to spin, or "spool," the compressor wheel also begins to spin. This is because the compressor wheel is connected to the output shaft of the turbine. The spinning compressor wheel draws in, or "inducts" ambient air in an axial direction into its housing and pumps it out in a radial flow. The air molecules scooped up by the spinning blades of the compressor wheel are accelerated to a high radial speed. Next, because of flow resistance of the compressor housing geometry itself, this airflow is immediately slowed down. The velocity energy of the air stream is converted to pressure during this process. The pressure rise of the air is called boost, and is typically measured in units of pounds per square inch (psi) or multiples of atmospheric pressure (Bar). A typical automotive turbocharger can rotate at speeds of 100,000 rpm (or more) and create 5 to 25 psi of boost.

Once created, the flow of pressurized air from the compressor is usually routed through an intercooler, which helps reduce the increased air temperature that has just been imparted by the turbocharger. From there, the air is directed to the intake manifold, down the runners, past the intake valves, and finally into the combustion cylinders.

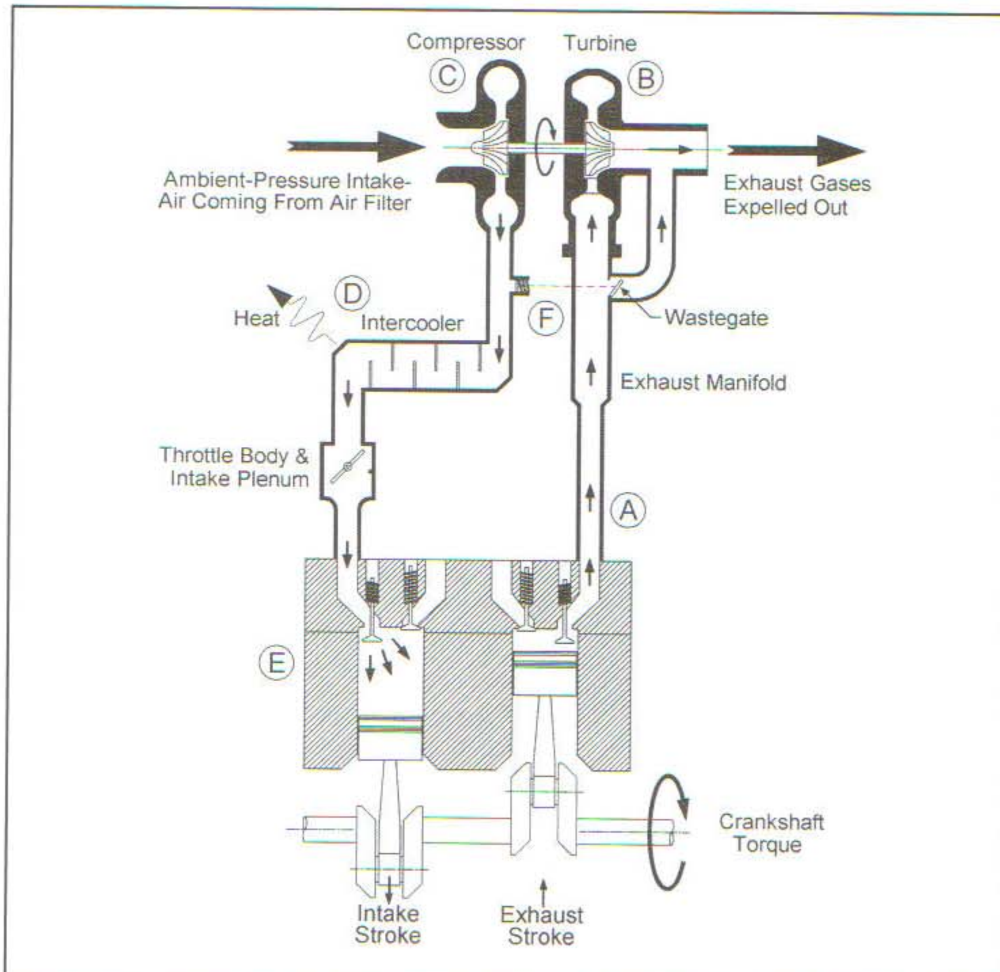
To control the amount of boost pressure created by the turbocharger, a device called a wastegate is used. Remember that the dense airflow from the compressor ultimately results in more engine power and, therefore,



Centrifugal-type compressors are also used quite often in modern supercharger applications. Typically a belt or gear-drive system provides input power to the unit. An internal step-up gear or belt system is then used to spin the compressor wheel at the appropriate speed. Rotational velocities of 50,000 rpm or more are required for most street-driven applications.



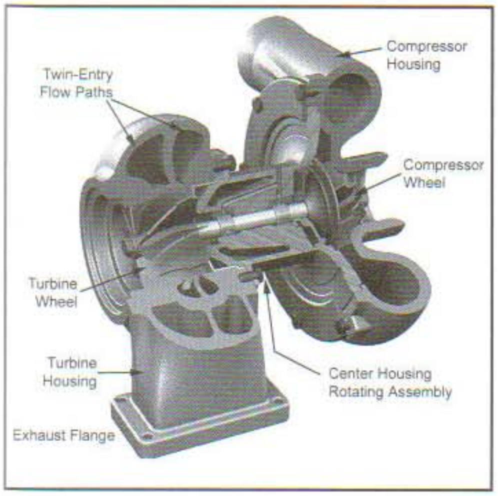
A supercharger is inherently simpler in design than a turbocharger, but it robs crankshaft horsepower that would otherwise be delivered to the drive wheels. In contrast, a turbocharger uses some of the heat and kinetic energy of the exhaust stream that would otherwise be lost out the tailpipe. Not all of this exhaust energy is "free," however. A turbocharger restricts exhaust flow and creates some extra backpressure that the engine must overcome. In a sense, a small part of the energy used to power a turbocharger is also robbed from the crankshaft.



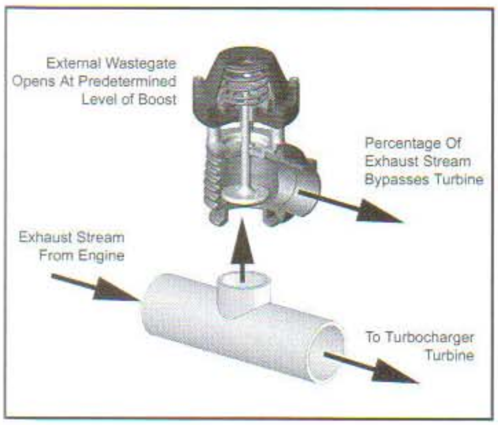
A turbocharger system flow schematic. Exhaust gases exiting the combustion chamber (A) are routed to a turbine (B), where they spin a turbine rotor, or wheel. A steel shaft connected to this turbine wheel is also attached to a compressor impeller (C). The spinning impeller draws in air and compresses it. This flow of pressurized air is then passed through an intercooler (D), which is simply a large heat exchanger that removes unwanted thermal energy from the pressurized air stream. The cooled airflow is then directed to the intake plenum, where it is used to support combustion of gasoline (E). A wastegate (F) bleeds off some of the exhaust gases before they reach the turbine. This governs the speed at which the turbine wheel rotates, thereby limiting the amount of boost created by the compressor. A pressure signal from the compressor outlet is used to control the position of the wastegate door.

more exhaust gas flow and pressure. Left unchecked, this would cause the turbine to spin faster, which would create more boost, which would cause more power, which would cause the turbine to spin faster, which ultimately would create an over-boost situation that could destroy the engine.

A wastegate can be either an integral part of the turbine housing (internal) or it can be a separate unit (external). At a preset level of boost, the wastegate vents some of the exhaust gases that would normally go through the turbine and to its wheel. These vented gases bypass the turbine directly into the exhaust pipe or out to the atmosphere. By cracking open the wastegate at a predetermined level of output boost, the speed of the turbine wheel can be controlled, or governed. This directly affects the output from the compressor, and engine performance is maintained



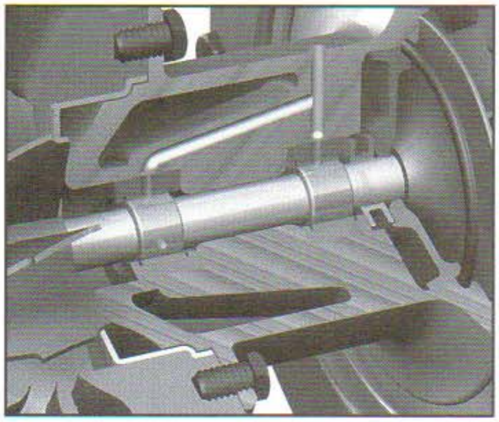
A typical turbocharger consists of three major subassemblies: turbine, compressor, and center housing and rotating assembly, or CHRA. There are a myriad of configurations, variations, and sizes available for each of these three. Predetermining the performance requirements of the turbocharger application is vital in selecting the correct system components for your particular vehicle. (Richard Brehm / RAB Digital 3D)



A flow schematic for a simple external-style wastegate. Most OEM turbochargers employ an internal "door-style" wastegate, while aftermarket turbos often utilize this external-style wastegate.

without overpressurizing the intake air.

And that's really all there is to the basic operation of a turbocharger system. Exhaust energy that would otherwise be wasted out the tailpipe is used to power a compressor and increase the density of the intake air. The more air that is forced into a cylinder, the more fuel that can be burned. A turbocharger is a simple device

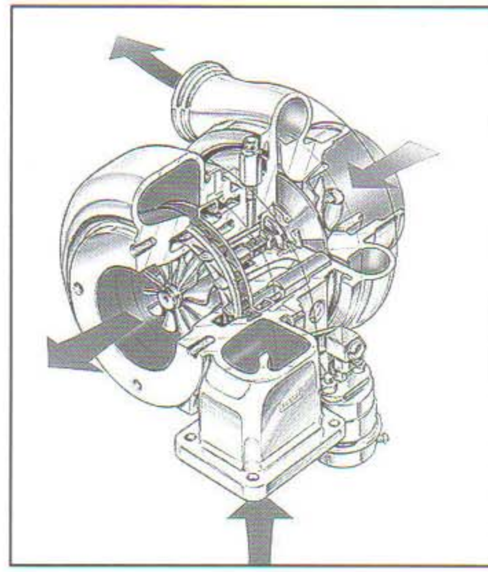


There are two major types of turbo bearings in use today: journal (oil film) bearings and rolling element (ball bearings). Both have advantages and disadvantages, including cost, performance, and complexity. (Richard Brehm / RAB Digital 3D)

in concept, but a properly designed turbocharged engine can be very complex. Not only must the components of the turbocharger itself be precisely sized, but the rest of the engine must be evenly matched to the turbo. Getting any one of the parts wrong can result in poor engine efficiency, weak power production, and possible engine damage. Designing, selecting, and putting all the system components together so that they work in the most efficient and safe manner is the purpose of this book.

ASKING HARD QUESTIONS

Okay, now let's talk about the generalities of a turbocharger system for your particular vehicle. It doesn't matter if you are improving an existing original equipment manufacturer (OEM) turbo system, buying and installing a conversion kit, or building a complete turnkey system from scratch. You still have to do your homework and make certain the system components are going to do what you expect them to do for your application. Which brings up the very first question you need to

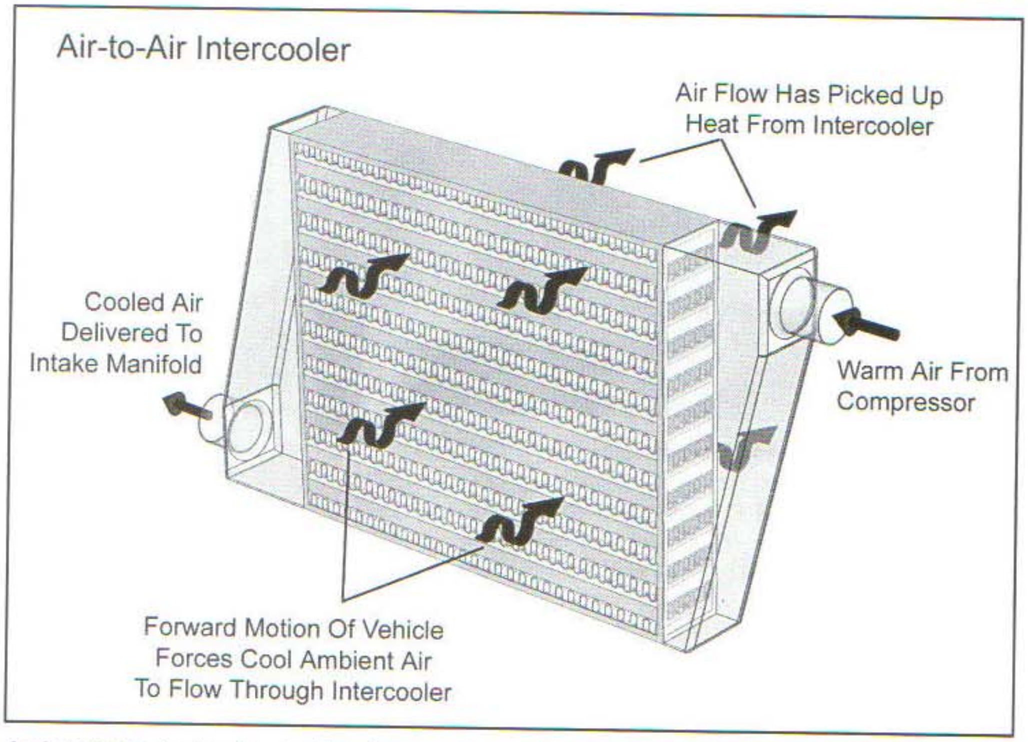


Exhaust gases flow tangentially into the turbine housing, and then exit axially (parallel to the shaft axis). Conversely, intake air is drawn into the compressor housing in an axial direction, and then exits tangentially. (Gale Banks)

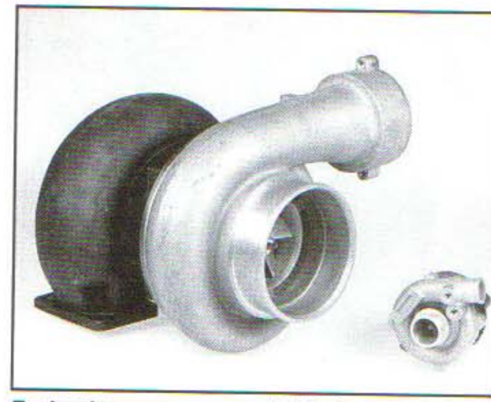
ask yourself: What exactly do you want to achieve with a turbocharger system? You need to be honest with yourself. While the thought of a 400 hp Honda Civic or 1000 hp Chevrolet Camaro may appeal to the egotist within you, does this really make sense for the vehicle, you, and/or your wallet?

Knowledgable enthusiasts understand that a race-spec engine is usually a poor choice for use on the street. Is your car driven daily around town? If so, then low speed, low-boost torque is more important that high-end power. Is it an autocross racer? Will it see time on a road-racing track? Do you want a Saturday night cruiser with a big dyno sheet to impress your friends? Will the car live most of its life a quarter mile at a time? Who will be driving it? Just you? Or perhaps also your significant other, who needs "turn-the-key-and-drive" simplicity and linear power delivery?

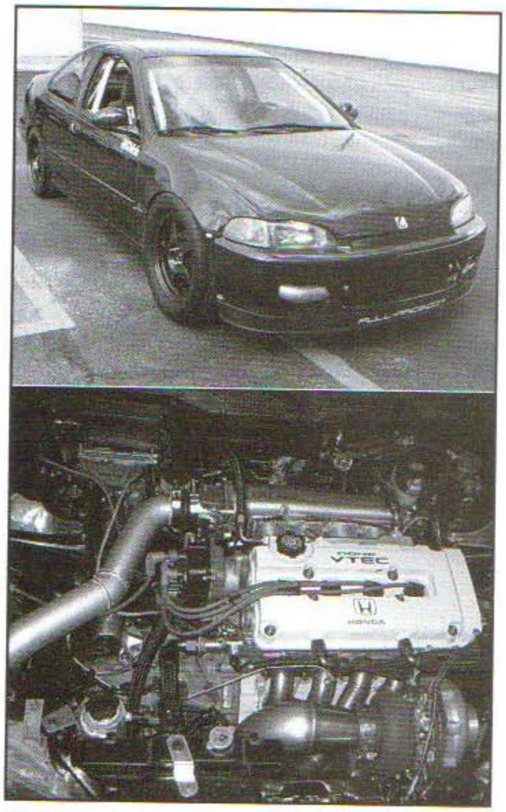
A good street engine should start



An intercooler is simply a heat exchanger. When air is pressurized by the compressor, it also is heated. Hot air is less dense than cooler air, which means less power. Hot air also is more likely to cause detonation and/or pre-ignition. An intercooler helps lower the temperature of the pressurized air stream



Turbochargers are available in a variety of sizes and can be installed on almost any internal combustion engine. Shown here are the massive Garrett GT60 and the diminutive Garrett GT12 assemblies. (Honeywell Turbo Technologies)

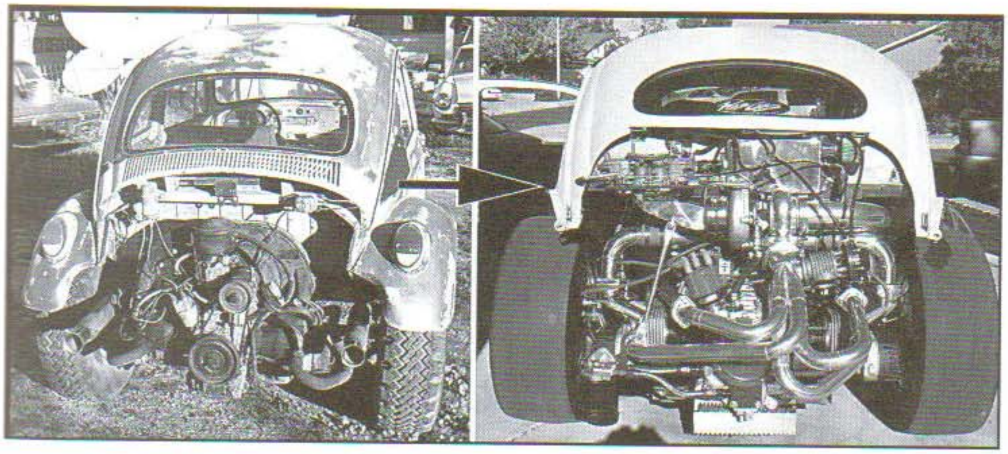


Turbochargers are capable of high specific-power outputs. Witness the 600+ wheel horsepower delivered from this 1.8-liter Honda engine. (Full-Race)

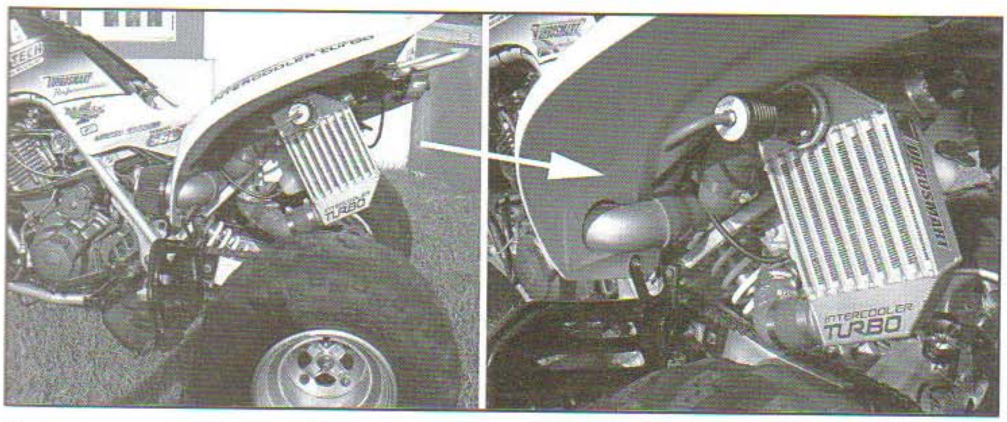
easily, have a smooth idle, run on pump gas, and deliver plenty of low-end torque with a relatively wide powerband. It should also exhibit high reliability, have a long life expectancy, and provide excellent fuel economy. It shouldn't produce excessive emissions, nor create too much noise and vibration. In comparison, a race engine can sacrifice some or all of these traits in the interest of ultra-high power production. For example, many purpose-built turbo racing engines survive only one or two races before requiring a complete teardown and rebuild. Most serious road race engines have life expectancies measured in hours, or even minutes. Witness the BMW M12/13-1 Formula 1 engines from the mid 1980s. In qualifying trim, these amazing devices produced 1300 hp from 1.5 liters— but were only good for a few laps at full tilt. These types of fire-breathing beasts are hard to start, run on expensive race gas, and can barely idle. But they're perfect for their particular application.

Okay, next you have to ask yourself some monetary questions: How much do you have to spend on a system? The old racer's adage holds doubly true for turbocharged engines: Speed costs money, friend. How fast do you want to go? Will you be doing your own work? Again, be honest. Just because you've rebuilt an engine or two before doesn't mean you have the skills to hand-fabricate a custom stainless steel turbo exhaust manifold. You need to determine all the parts you need, and how much they will cost to make or purchase.

Talk to knowledgeable turbo owners before jumping in with both feet. Most experts have learned their lessons the hard way; they've built vehicles that didn't work the way they thought they should—and they probably learned from those mistakes. Look around, see what works, visit dyno shops and performance builders, and, above all, ask questions. Almost



When it comes to turbocharged project vehicles, it seems that nothing is too wild. Just remember that it takes time, money, and a well-considered strategy to achieve results like this. (McCarley/Turbosmart)



A turbocharger can make a small engine act like a much larger one. (Turbosmart)

without exception, owners of turbocharged cars love to show and explain the inner workings of their vehicles to interested onlookers. Don't just ask how they did it, either. Ask what they like about the system, what they don't, what they would do differently the next time—and why.

Evaluating Your Car and Engine

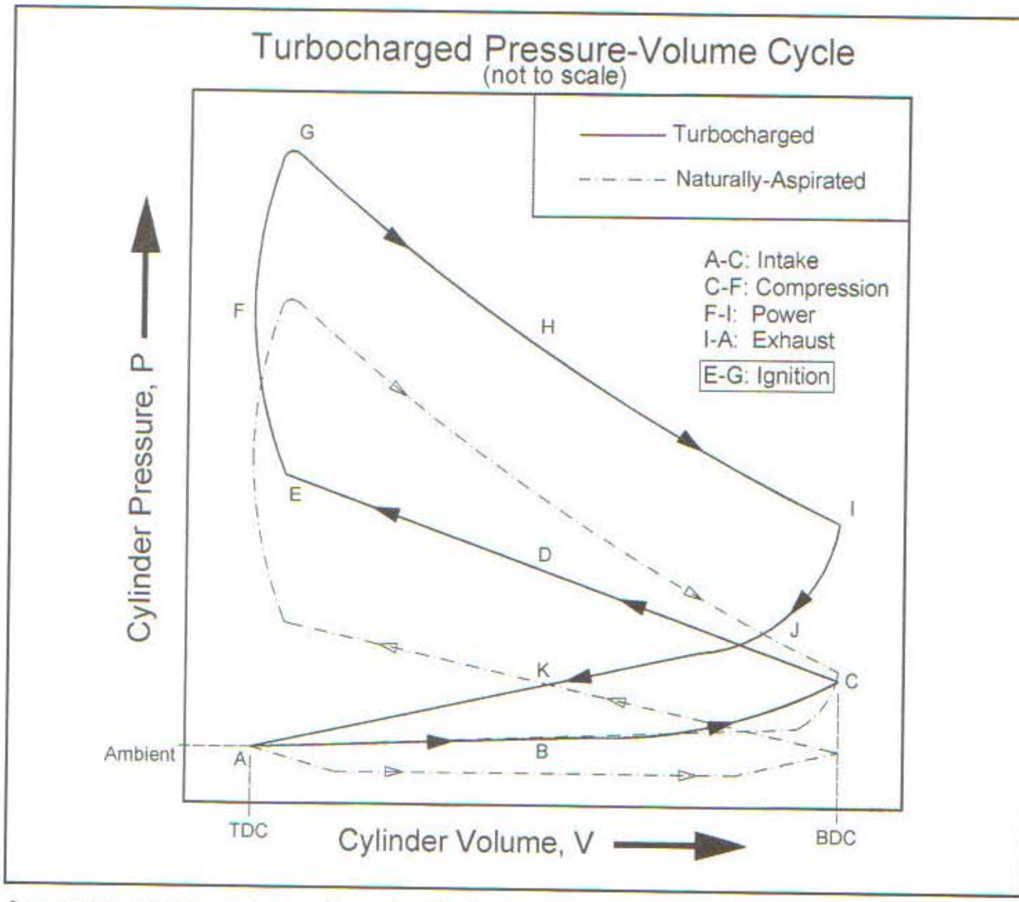
The next item to address before jumping into the design and construction of a turbocharger system is the evaluation of the state of your current vehicle. Is the engine compatible with the type of turbocharger system you want to install or build? All engines can be turbocharged, but not all engines should be. For example, if your vehicle has high mileage and a lot of wear and tear, your money may be better spent rebuilding the engine and drivetrain before you invest in a turbo system. The same is true of the chassis, brakes, and suspension. The added stress and strain put on a tired vehicle by a turbocharger may spell a quick death—to either the vehicle or the driver.

The fuel delivery and the ignition systems also need to be suited to the turbo. Can the ignition adjust the spark timing under boost if required? Can the fuel injection deliver enough fuel to keep the air-fuel mixture within safe bounds? And what about the static compression ratio? You need to determine whether the compression permits the addition of a turbo, particularly in light of the amount of boost and horsepower you want to produce. The higher the static compression, the greater the tendency of the engine to knock (detonate). In other words, for a given fuel octane, the higher the compression, the less boost you can run, and, ultimately, the less torque and horsepower the engine can produce.

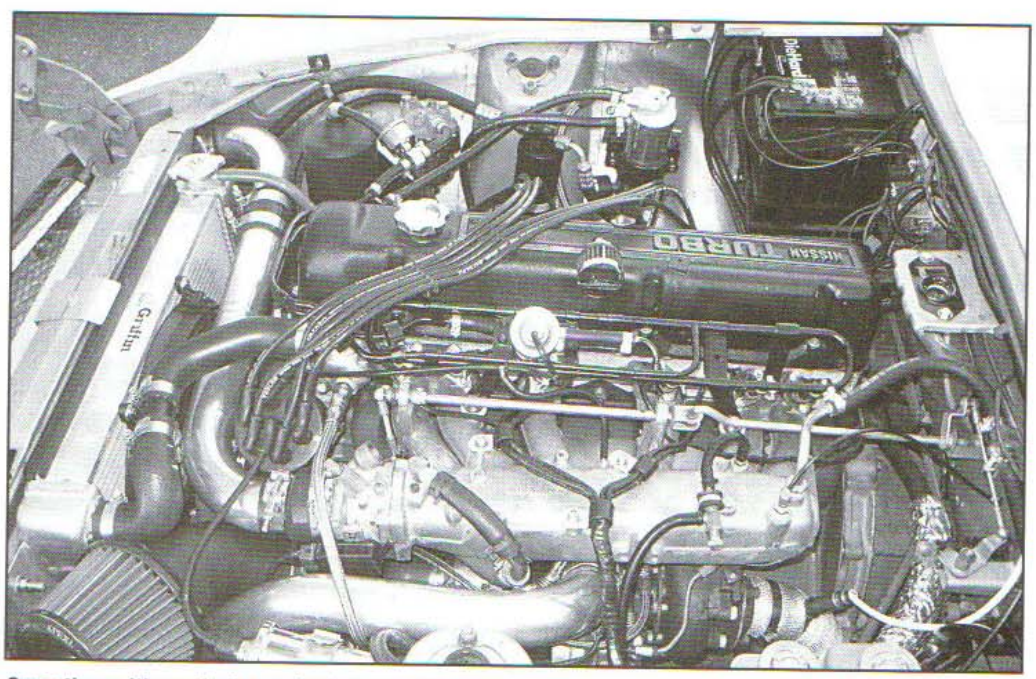
We will cover all these items in more detail later in this book. But you have to start thinking of them now, in the beginning, before the first dollar is spent or the first wrench turned. You don't take a test in school without studying. This holds true when buying or designing a turbo system too, especially when considering the amount of time, money, and effort that will go into the construction and installation of the system.

KITS VS. CUSTOM SYSTEMS

Turbocharged engines can produce incredible power gains and a driving experience that will put a smile on your face every time you turn the key. For this reason, turbocharging has become very popular. The aftermarket is crowded with suppliers selling kits, upgrades, components, and advice. Buying a complete turbo kit is certainly easier than constructing a system from scratch. There are many excellent kits available from reputable suppliers. But there are just as many ill-informed outfits selling mismatched components and substandard equipment. In addition, the one-size-fits-all approach to kits may not match



A pressure-volume plot for a forced-induction engine. Note the general shape is similar to a naturally aspirated engine, but the overall peak and mean cylinder pressures (G- I) are considerably higher. Recall that cylinder pressure, multiplied by the surface area of the piston, is equal to the force that causes the crankshaft to turn. Higher cylinder pressure means higher engine torque. Unfortunately, pumping losses (I–A) are higher, too, which tends to subtract from the overall power gain of a turbo. This can be addressed, however, by various methods such as installing a higher A/R turbine housing, which will be covered later in Chapter 5.

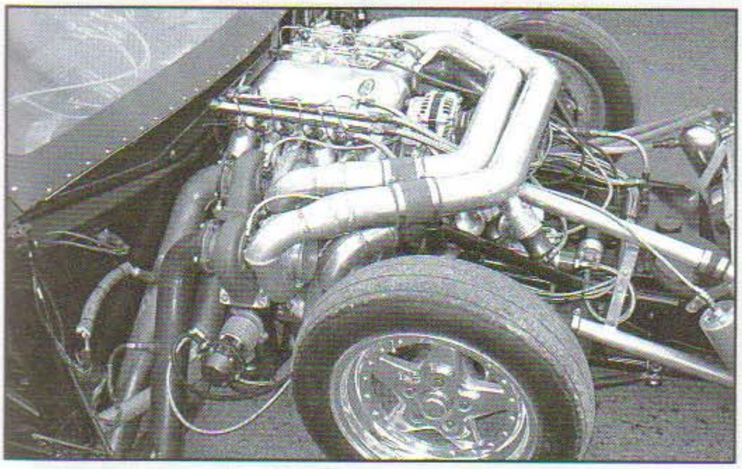


Sometimes it's a challenge just squeezing all the necessary components of a basic turbocharger system into the engine bay. An older-style non-cross flow engine, like this Datsun L28, makes matters worse. Creative packaging and good fabrication skills are required to make a system work well. (Sean McManus)

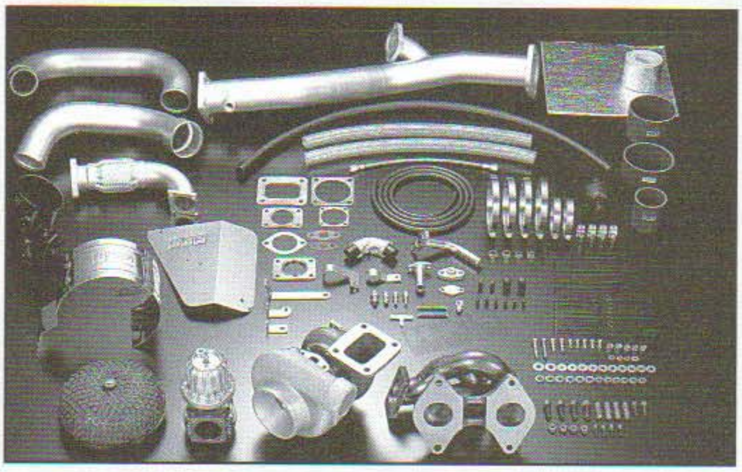
your personal expectations. Again, homework is the key when shopping for a kit. Learn all you can and then evaluate the systems carefully. Given your own goals and resources, you may or may not be able to simply purchase an appropriate system and bolt it on.

You also need to talk to other owners who are running a particular kit you might be interested in. Were they happy with the customer support from the supplier? What was provided—and what wasn't? How difficult was the installation? What worked and what didn't? Price is certainly important, but like most things in this world, you often get what you pay for. Don't misunderstand me; I've seen plenty of good inexpensive kits installed on many vehicles with great success. You just need to be careful and realize that what you don't pay for in dollars you often pay for in man-hours of labor.

As far as custom setups are concerned, it really depends on your skill and comfort level before deciding to go down this road. Turbochargers may be simple, but a turbocharged engine system is complex. Building a well-tuned system from scratch can be very enjoyable and result in an incredibly strong, well-running engine. But there are serious pitfalls along the way to avoid. There is also a lot of marketing hype and misinformation circulating from component suppliers. Whether you're building a system from scratch or buying a full kit and having a shop install it, you have to understand the ins and outs of each and every part of the system.



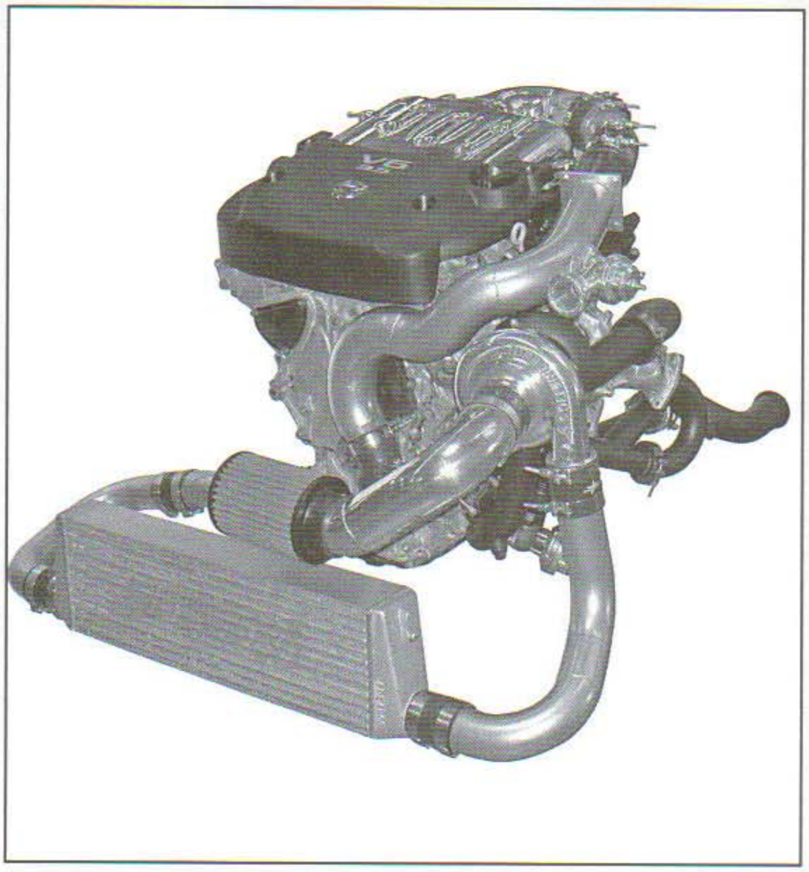
Turbocharging taken seriously. Somewhere underneath all this piping is a fire-breathing 3-rotor 20b Mazda rotary engine. Note the complex plumbing required on even a simple engine fitted with multiple turbochargers. Note, too, the lack of an intercooler. This is a singular-purpose machine, designed with only ultra-fast quarter-mile timeslips in mind. (Turbosmart)



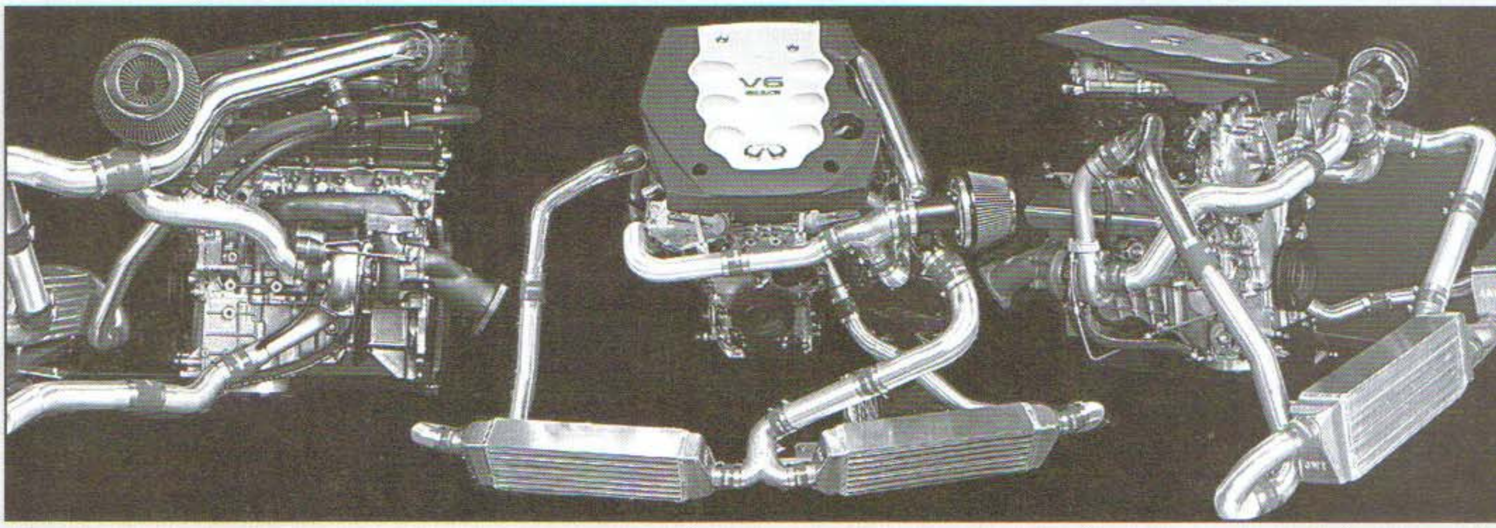
A turbocharger kit should come with all equipment and parts required to install the system and get it running properly. Here's a nice example of a T04R upgrade kit for the FD3S 1993–95 Mazda RX7. (HKS)

UPGRADING

A great way for beginners to learn about turbochargers is to purchase an existing OEM turbocharged vehicle and upgrade it. Vehicles such as the Subaru WRX, Mazda RX-7, and Buick Grand National are very responsive to turbo system modifications and improvements. The engines in these cars generally have strong internals and appropriately-lowered static compression. Factory knock detectors are also common. And there are big power and torque gains to be had by bolting on aftermarket-supplied improvements in so-called "stages." Typically, staged upgrades from suppliers improve exhaust, fuel, and intake systems, as well as control systems and compressor and turbine upgrades. These stages can be addressed as finances allow. This offers a rewarding experience for the owner, who is able to drive and enjoy the vehicle between each step in the process, and stop at a level that is appropriate for him or her.

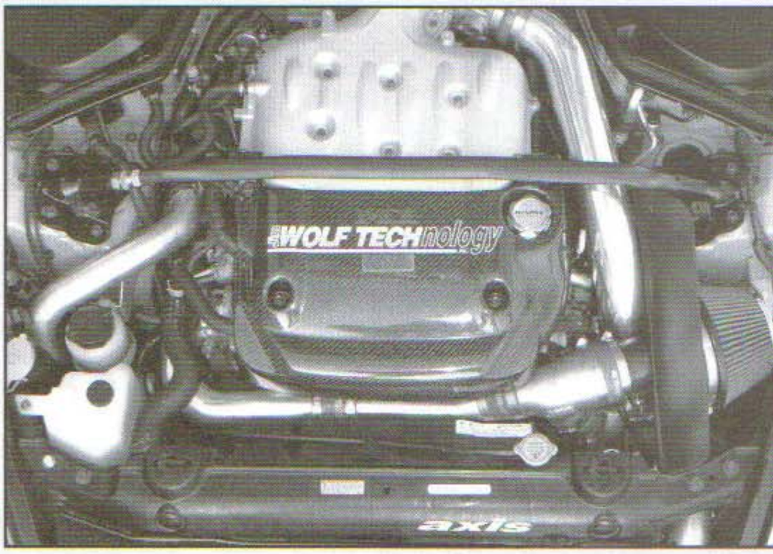


Turbonetics' powerful single-turbo conversion system installed on a Nissan 350Z VQ35 six-cylinder engine. (Turbonetics)



Jim Wolf's tour-de-force twin-turbo kit for the Infiniti G35 and Nissan 350Z. (Jim Wolf Technology)

A well-engineered system for a 4-cylinder Honda engine. Note the simple but effective log-type exhaust manifold, and short, direct plumbing runs from compressor to intercooler, and from intercooler to intake manifold. (Turbonetics)



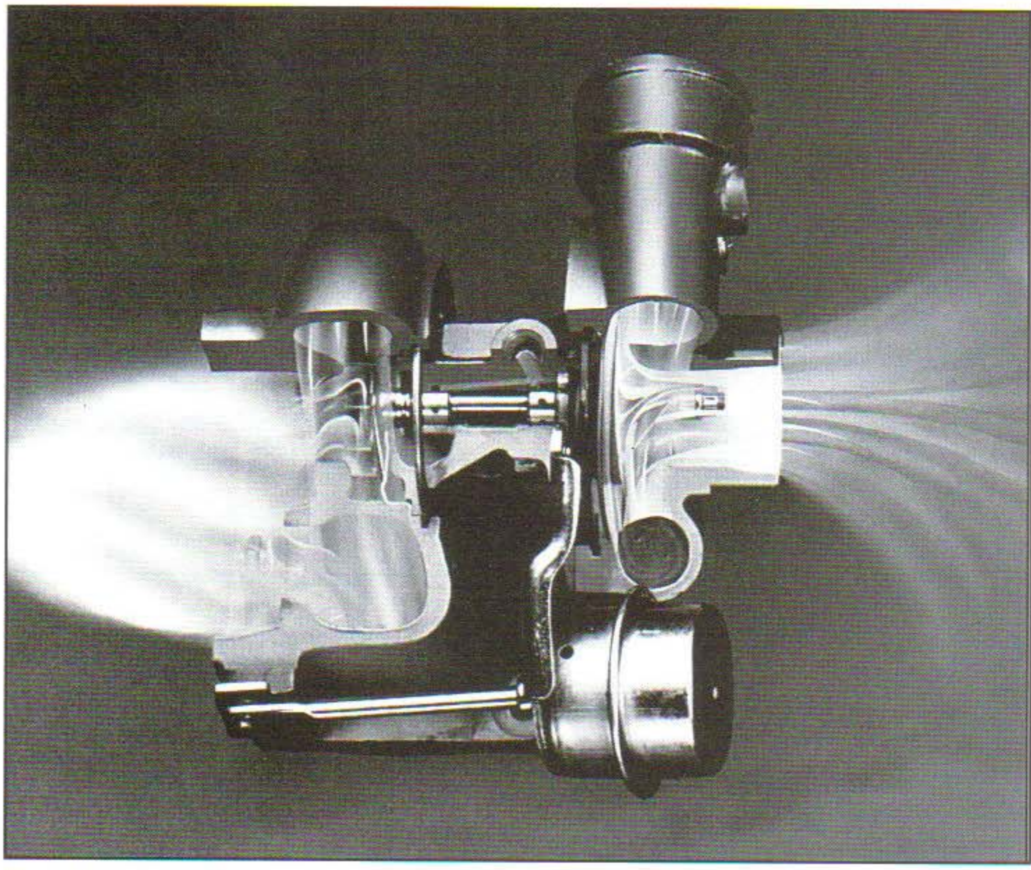
Here is the Jim Wolf system installed in a Nissan. Clever packaging and attention to details are evident everywhere you look. This system has OEM fit and finish, and is emissions-legal. It will also blow the doors off a naturally aspirated Z-car. (Jim Wolf Technology)

PRESSURE, TEMPERATURE, AND AIRFLOW

3

Because the sole purpose of a turbocharger is to increase the mass flow rate of air into an engine, it's important to understand what we mean by flow. And to understand flow, we also have to know a little bit about pressure and temperature.

This section of the book has a number of equations and formulas. Don't worry; the topics are explained in layman's terms and use only basic math skills. Understanding these concepts is critical to designing and building turbo systems that produce optimal power and torque. Let's start with pressure.



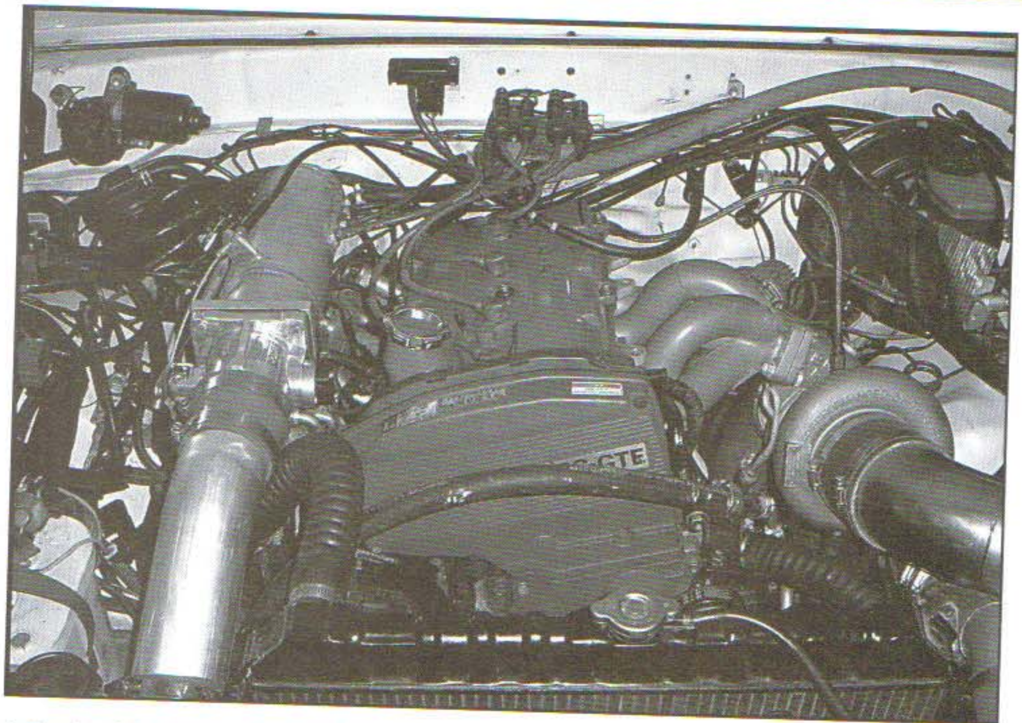
Designing a turbocharger system requires a basic understanding of pressure, temperature, and flow of gas. (Honeywell Turbo Technologies)

MEASURING PRESSURE

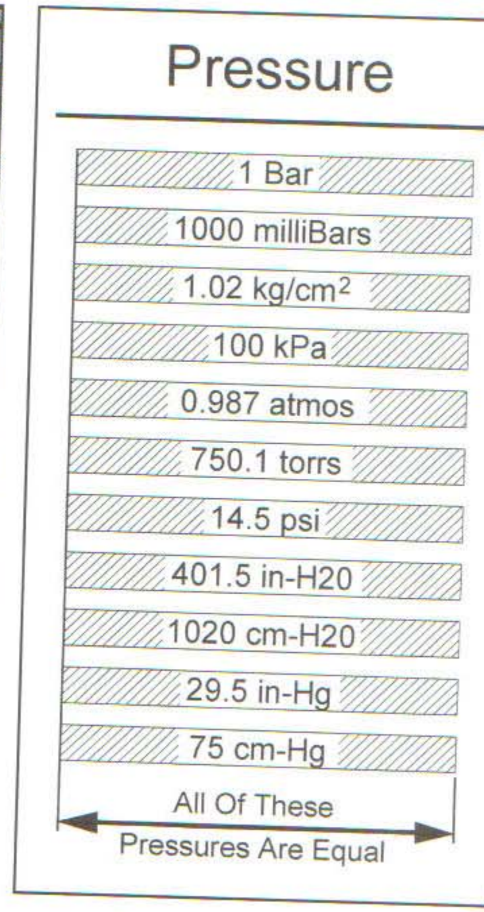
Standing on the surface of the earth, there are literally miles of air resting on top of us. This ocean of air extends all the way up into the fringes of outer space, reaching hundreds of miles above our heads. Compared to water or steel, air has very little density, or mass per unit volume, but a 100-mile tall column of air is a huge volume nonetheless and results in a significant mass of air. We call the effect of all this weight pressing down on a body the *ambient* air pressure. At sea level, this ambient air pressure is roughly 14.7 psi, or pounds of force per square inch. In other words, there are 14.7 pounds of force pressing inward on every square inch of exposed surface of a body at sea level. An empty soda can, your body, a block of wood—it doesn't matter. At sea level all three of these experience a force of 14.7 pounds directed against every square inch of their exposed surfaces. The higher we move up into the atmosphere (for example, driving up into the mountains), the lower this ambient air pressure.

Expressing Pressure

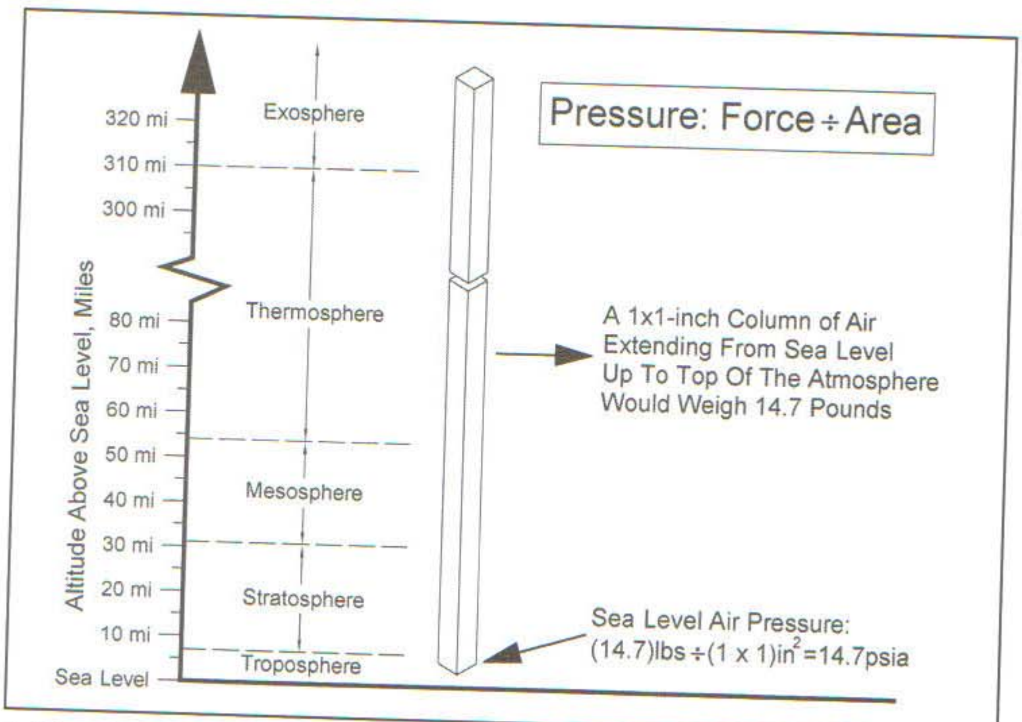
To make experimental measurements simpler to understand and equations easier to manipulate, engineers sometimes ignore this base 14.7 psi of ambient pressure in their data. For example, if we take an engine cylinder filled with air and then start compressing it by moving the piston upward, we're usually only interested in the change of pressure from one position in the stroke to the next. We don't really care about the ambient pressure effect because it adds the same amount of pressure to the measurements at both the beginning of the stroke and at the end. For this reason, there are often



A Toyota pickup truck that develops 440 rear wheel horsepower from its 2.0-liter 3SGTE engine. This type of performance is not achieved via guesswork; the builders did their homework when selecting the turbo components. (The Power Group)



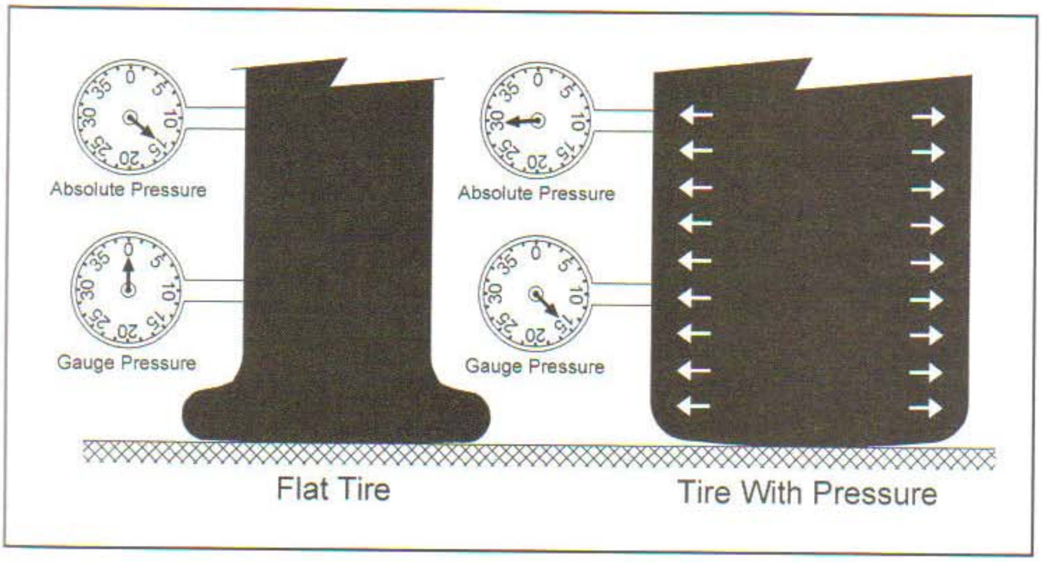
Just as distance can be measured in feet, inches, centimeters, or miles, pressure can be expressed in a variety of different units. Unfortunately, turbocharger engineers often use different pressure units for different aspects of a turbo system, and a lot of confusion arises from this.



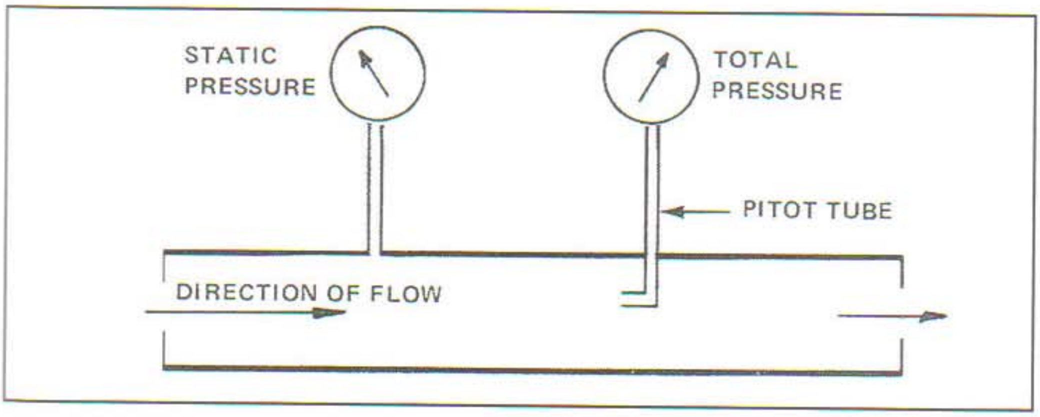
Ambient air pressure is just the weight of the air above a body pressing downward on it. The higher the body travels in elevation, the lower the ambient air pressure acting on it.

two different ways to express pressure: absolute pounds per square inch (psia) and gauged pounds per square inch (psig). The first one, psia, is a measure of the total air pressure, including the ambient pressure effect. The second one, psig, has the ambient pressure subtracted from it.

Let's go back to our engine cylinder example for a moment to see how this works. Let's fit two measurement devices to the cylinder, one reading the internal pressure in psia, and the other measuring it in psig. When the cylinder is filled with normal ambient pressure air, but before the piston moves up and further pressurizes the air, the psia-device would display 14.7 psi. This is the absolute air pressure. The psig device, on the other hand, would display 0 psi, because it has the ambient part of the air pressure subtracted out. Now, after moving the piston up and pressurizing the air by some fixed amount, the gauges will always show a



A pressure monitor displaying the absolute pressure at sea level will always be 14.7 psi greater than a pressure monitor that displays the gauge pressure.



There are two ways to measure pressure: static and total. Static pressure is not affected by the velocity of the gas. Total pressure consists of static pressure plus the velocity pressure of the gas. Consequently, total pressure is always greater than static.

difference of 14.7 pounds per square inch between them. For example, if we increased the pressure inside the cylinder until the psig measurement device displayed 100 psi, the psia-device would show 114.7 psi. Both devices are measuring the air pressure inside the cylinder, but one includes the ambient effect and the other doesn't.

PRESSURE RATIOS AND BOOST

So what does this absolute- and gauge-pressure mumbo-jumbo have to do with turbochargers? Unfortunately, a lot. Some educated folks, such as the MegaSquirt EFI crowd (which we will learn about in Chapter 12), work almost exclusively in absolute pressure units when specifying turbo equipment. But many turbo engineers and experts mix and match units. When they talk about turbocharger boost pressure, for example, turbo engineers speak in terms of gauge pressure, or psig. But when specifying the pressure ratio of a compressor, they often use absolute, or psia units. Not knowing what type of gauge was used to measure pressure can result in serious mismatching of components.

The pressure ratio (PR) of a turbocharger compressor is equal to the boost pressure it produces in locally-corrected psia-units, divided by the local ambient pressure.

Eq. 3-1

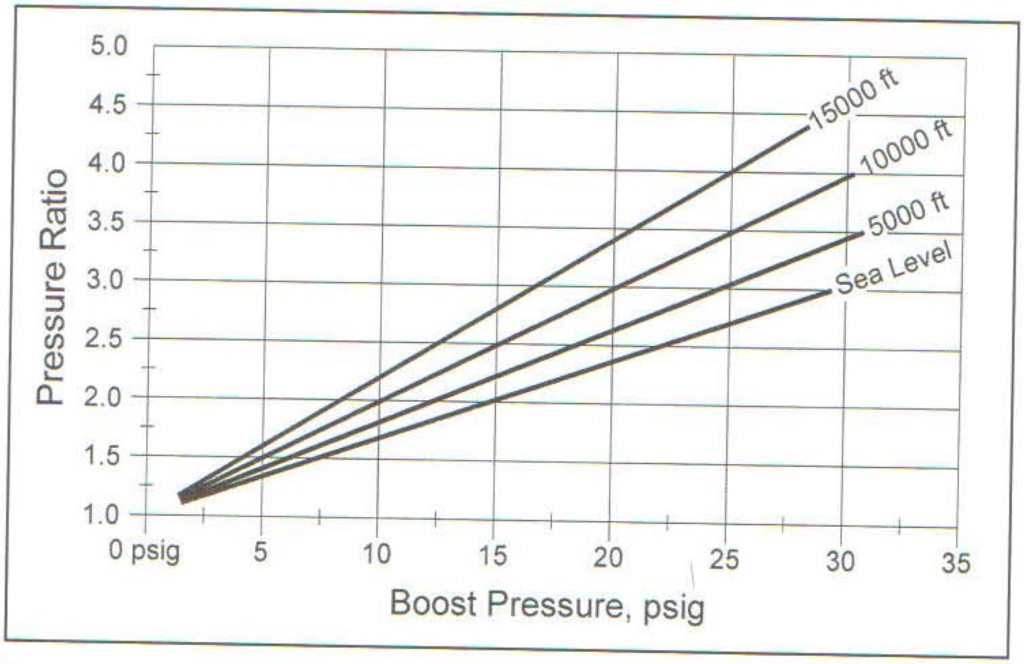
$$PR_{Compressor} = \frac{(boost + ambient)}{ambient}$$

For instance, if we want to determine the nominal pressure ratio for a compressor creating 10 psig of boost at sea level, we would calculate:

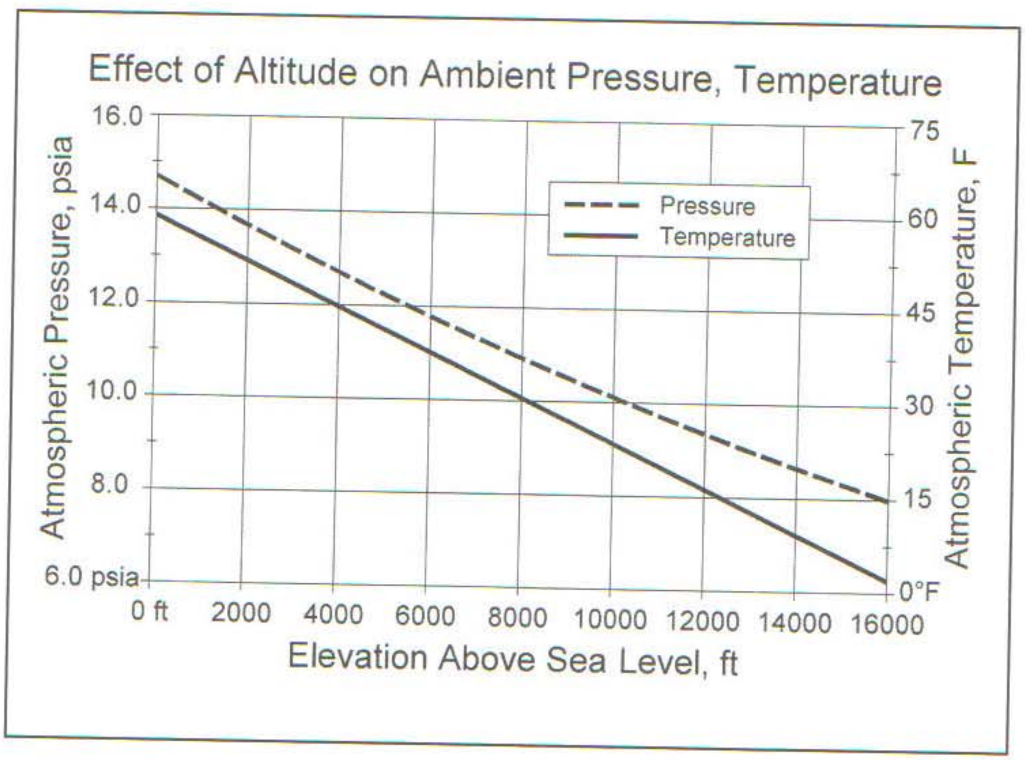
$$PR_{Compressor} = (10.0+14.7) / 14.7$$
$$PR_{Compressor} = 1.68$$

We'll see one reason why knowing the PR is important when we go through a compressor map and size a turbo in the next chapter. The PR also gives us an initial rough indication of how much the airflow rate into an engine can be increased by using forced induction. Our system, with a PR of 1.68, will flow roughly 68% more air than its naturally aspirated brethren.

It's important to note that the PR of the complete intake system, including intercooler (IC), may be slightly lower than the compressor PR. This is because the intercooler introduces its own drop in pressure, usually on the order of 0.5–1.5 psi, depending on the quality of the unit. The same is true for air filters on the inlet side of the compressor. In other words, the boost pressure term in the equation needs to be adjusted downward slightly by the amount of pressure drop across the air filter and intercooler. If our turbo system



When sizing a compressor for a forced-induction application, the pressure ratio has to be calculated. Pressure Ratio = (Boost Pressure + Ambient Pressure) / Ambient Pressure.



Both temperature and pressure are reduced with increasing elevation. Recall that lower pressure means lower air density, but colder air is denser than warm air.

had a total drop of 1 psi across these items, the PR of the system would be:

$PR_{Compressor+IC+AirFilter}$ = (10.0-1.0+14.7) / 14.7 = 1.61

TEMPERATURE

In a perfect world, the temperature of the air exiting a turbocharger compressor could be estimated strictly by so-called "ideal" gas equations. Working through the math, we could calculate the theoretical outlet air temperature with the following simple equation (note that all temperatures in these equations are in degrees Fahrenheit):

Eq. 3-2

$$T_{Out} = [(T_{In} + 460) \times PR^{0.283}] - 460$$

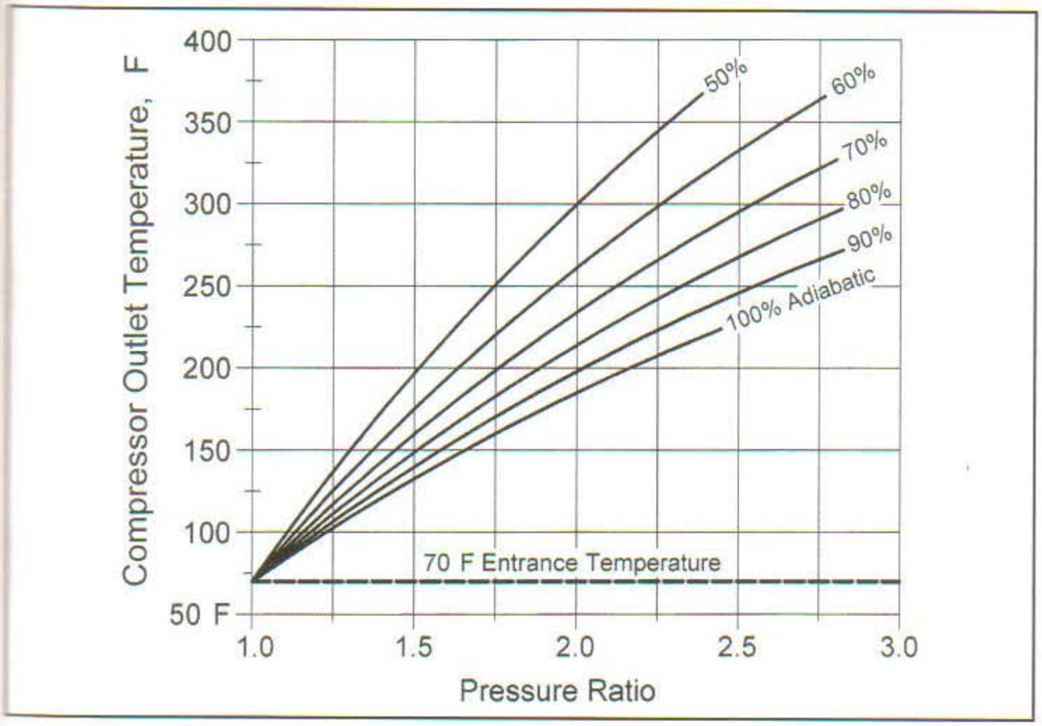
For the 10 psig compressor example above, assuming 85 F ambient intake air, our theoretical compressor outlet air temperature would be:

$$T_{Out,\ ideal} = [(85 + 460) \times 1.68^{0.283}] — 460 = 171° F$$

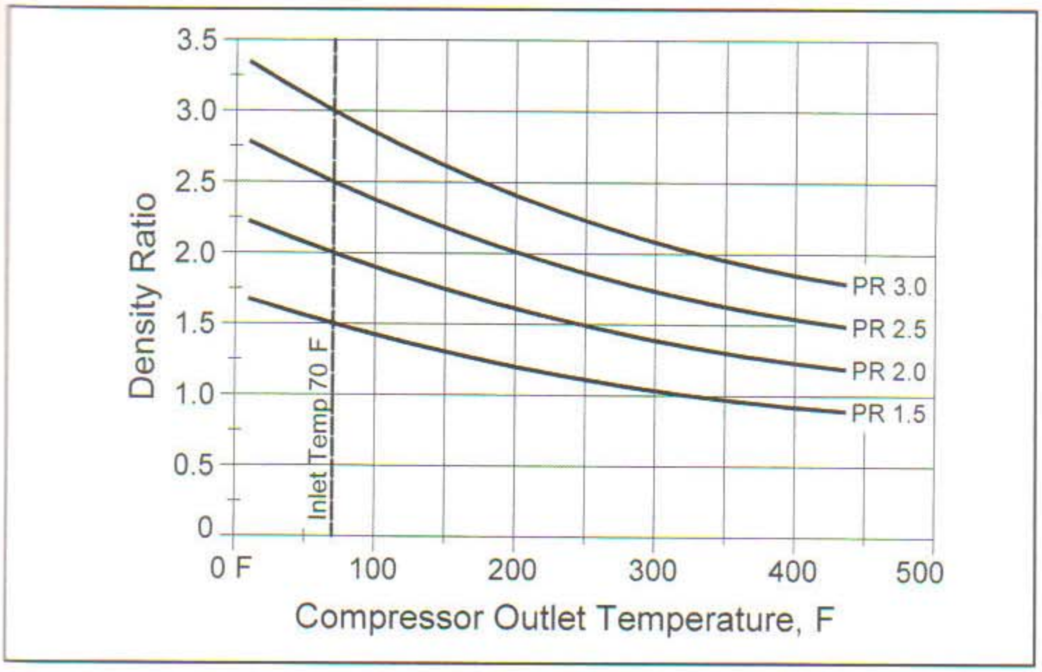
Of course this assumes an ideal, 100% efficient compressor. As we will see when we learn about

"IDEAL" CONDITIONS

Under ideal conditions, intake manifold pressure at full throttle in a naturally aspirated engine is the same as ambient (outside) air pressure. At sea level, ambient air pressure is considered to be 14.7 pounds per square inch (psi), or 29.92 inches of mercury (in-Hg). Notice the word "ideal." Any restriction in the induction system reduces the amount of pressure available to each cylinder. For example, a 1-psi drop through a carburetor or throttle-body means that pressure in the intake manifold is 1 psi less than ambient. At sea level, this means only 13.7 psi of pressure is available to fill the cylinders.



If the air inlet temperature, the pressure ratio, and the compressor efficiency are known, the outlet air temperature from the compressor can be determined. Most modern compressors can operate at 70–80% peak efficiency. This particular chart is for a 70°F entrance air temperature.



The density ratio is a useful value to know when calculating air mass flow rates. It is a function of the compressor inlet and outlet air temperatures, and the pressure ratio.

compressor maps in the next chapter, the maximum efficiency of a compressor isn't 100%, but more like 70–80%. With that in mind, the actual temperature of air exiting a compressor can be calculated as follows:

Eq. 3-3

$$T_{Out\ Actual} = \frac{(T_{Out\ Ideal} - T_{In})}{efficiency} + T_{In}$$

Assuming a 75% efficient compressor, the actual outlet air temperature of our example would be:

$T_{Out,\ Actual} = [(171 - 85) / 0.75] + 85 = 200°F$

Note that this is more than 29°F hotter than the ideal calculation, and 115°F hotter than the incoming 85°F air. No wonder we need intercoolers.

DENSITY RATIOS

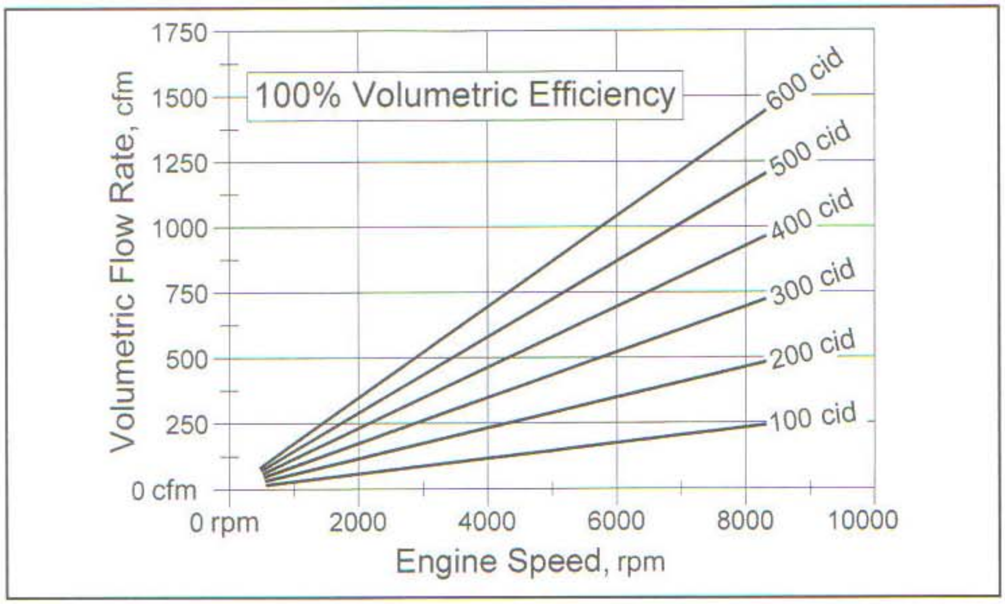
Now that we understand pressure ratios and temperatures, let's look at something called the *density ratio*. After all is said and done, the actual power produced by a turbocharged engine depends on the number of air molecules we can deliver into a cylinder on the intake stroke. The number of air molecules in a cubic inch of air increases with increasing pressure. Unfortunately, it also decreases with the rise in temperature. And as we just saw, compressors tend to warm the air at the same time they pressurize it.

If we know the temperature of the air entering a turbocharger, and the temperature of the air after it's been compressed, intercooled, and transported to the intake manifold, we can calculate its density ratio:

Eq. 3-4

$$DR = PR \times \frac{(T_{In} + 460)}{(T_{Out} + 460)}$$

For example, assume our inlet air temperature is 85°F and the PR is 1.61. Further assume that the temperature of the air after compression and intercooling is 120°F (we'll see how to calculate



The actual volumetric airflow rate of an engine is found by multiplying the theoretical airflow rate by the volumetric efficiency of the engine at that particular speed. For example, a 300 cid engine at 6000 rpm theoretically flows 521 cfm. But if the actual VE at that speed was, say, 85%, the real volumetric flow rate would be 0.85 x 521 = 443 cfm.

the effectiveness of intercoolers later; for now let's just use this value, which isn't too bad of a guess for a typical street intercooled turbo system):

Density Ratio = 1.61 x [(85+460)/(120+460)] = 1.51

This value will be useful to us when we calculate the actual air mass flow rate moving through an engine.

ENGINE DISPLACEMENT

The next thing that we need to learn how to calculate is the displacement of the engine. We can do so with the following equation:

Eq. 3-5

$$\text{Disp.} = \frac{(\#\,\text{Cyl})(\text{Stroke})(\text{Bore})^2}{1.27}$$

For example, a 4-cylinder Honda engine with 3.425 inch diameter pistons and a stroke of 3.571 inches theoretically displaces:

Honda Displacement = 4 x 3.571 x (3.425 x 3.425)/1.27 = 131.9 cid

A small-block Chevy engine might have a bore of 4.0 inches and a stroke of 3.48 inches. It of course has 8 cylinders, so the displacement is:

Chevy Displacement = 8 x 3.48 x 4.0^2/1.27 = 350.7 cid

When calculating displacement, it's important to use consistent units. Plugging inches into the displacement equation will give displacement in cubic inch displacement (cid). If the bore and stroke were measured in millimeters, you could still multiply them in the equation, but you would get cubic millimeters. You would then have to divide this result by 1000 to get the more common unit of cubic centimeters (cc). And once you know the cubic centimeter displacement, you could divide it by 16.39 to get cubic inches. Similarly, if you know the displacement in cid, you can convert to cubic centimeters by multiplying by 16.39. In the case of our Honda engine:

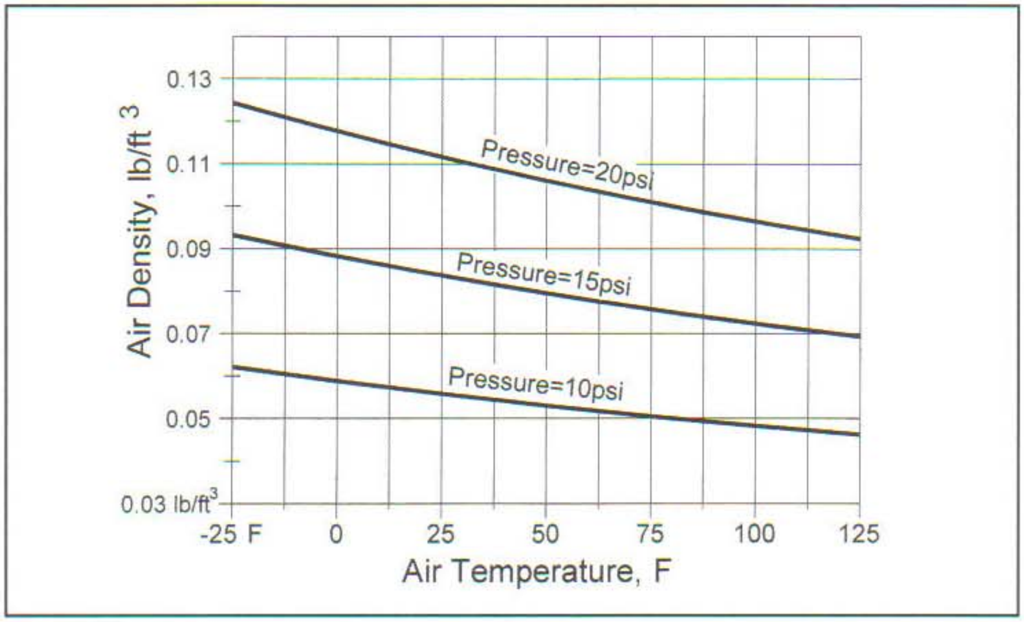
Honda Displacement = 131.9 cid x 16.39 = 2155 cubic centimeters

VOLUMETRIC EFFICIENCY VARIATIONS

In a perfect engine, we could completely fill each of the cylinders of a naturally aspirated engine with fresh incoming air. Unfortunately, we usually can't. With some of the exhaust remaining in the engine cylinders after the exhaust stroke, and with all of the restrictions in the intake tract (valves, intake runners, air filter, etc.), the actual amount of air that flows in each cylinder is somewhat less than ideal. This actual quantity, divided by the theoretical amount, is called the volumetric efficiency, or VE.

The VE of an engine varies somewhat with rpm. A low-performance OEM street engine might have a VE somewhere between 0.75 and 0.80, depending on engine speed. A high-performance engine might be somewhere between 0.80 and 0.85. An all-out racing engine might have a VE as high as 0.90 to 0.95. It's actually possible to get a VE greater than 1.00 for specialty race engines with highly tuned intake and exhaust systems and other engine modifications.

The bottles shown are the same size and volumes. If we fill one with air and the other with water, however, they will have vastly different masses. The density of an object is its mass divided by its volume. The density of the water bottle is therefore higher than the density of the air-filled bottle. Similarly, air at higher pressure is denser than air at lower pressure. This is the fundamental reason forced induction works so well; boosted air in the combustion chamber has more mass than non-boosted air. More mass means more oxygen available to support the burning of additional fuel. Boost means power.



If you know the absolute pressure (psia) and temperature (F) of air, you can calculate its density in lb/ft^3: Air Density = (2.703 x Pressure) ÷ (Temperature +460)

VOLUMETRIC FLOW RATES

Once we know the displacement in cubic inches, we can calculate how much air volume flows into an engine every minute. This flow rate is often stated in terms of cubic feet per minute (cfm), and is a function of how fast the engine is running. The equation for the volumetric flow rate (VFR) of a 100% efficient 4-stroke naturally aspirated engine is as follows:

Eq. 3-6

$$VFR_{100\%} = \frac{(Displacement)(RPM)}{3456}$$

This theoretical VFR then needs to be adjusted by the actual volumetric efficiency (VE) of the engine at that rpm:

Eq. 3-7

$$VFR_{Actual} = (VFR_{100\%})(VE)$$

For example, let's assume our 131.9 cid Honda engine, spinning at 6000 rpm has a VE of 0.9. The volumetric flow rate of air into this engine would be:

$VFR_{100\%}$ = (131.9 cid x 6000 rpm ÷ 3456 = 228.3 cfm

VFR_{Actual} = (228.3 cfm x 0.9) = 205.5 cfm

AIR DENSITY AND MASS FLOW RATES

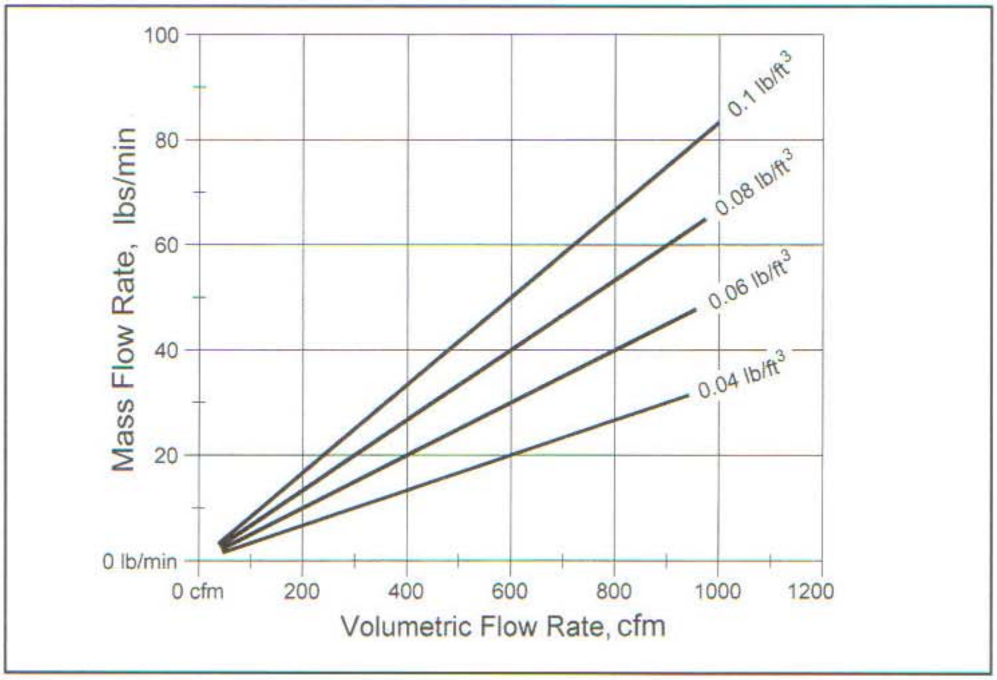
Now that we know how much volume per minute (e.g., cfm) of air is flowing into an engine, we can calculate how many actual pounds of air we're ingesting. This of course is dependent on the density of the air, which in turn is a function of its pressure and temperature. The higher the pressure, the more molecules of air present in a given volume of air. In other words, higher pressure means higher density. Conversely, the higher the air temperature, the fewer air molecules we have. Higher temperature means lower density.

If you know the absolute pressure (psia) and temperature (F) of air, you can calculate its density:

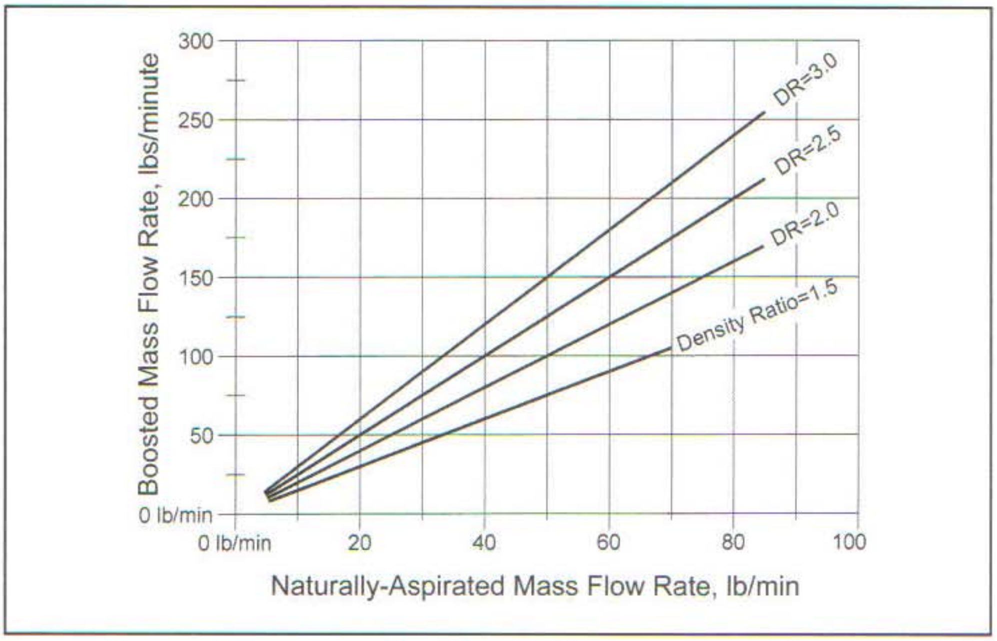
Eq. 3-8

$$\text{Air Density} = \frac{(2.703)(\text{Pressure})}{(\text{Temp} + 460)}$$

For our case of 85° F ambient



The mass flow rate of air moving through a naturally aspirated engine is a function of the volumetric flow rate and the incoming air density.



The mass flow rate of the air moving through a turbocharged engine can be found by multiplying the naturally aspirated mass flow rate by the density ratio.

intake air at sea level pressure, the density is:

Air Density = (2.703 x 14.7)/(85 + 460) = 0.073 lb/ft^3

The mass flow rate (MFR) then is just the VFR multiplied by the air density. Therefore the mass airflow rate for a naturally-aspirated engine can be written as:

Mass Flow Rate = VFR x Air Density or:

Eq. 3-9

$$MFR = \frac{(2.703)(P_{Ambient})(VFR)}{(T_{Ambient} + 460)}$$

For our Honda engine example, the MFR on an 85°F day at sea level pressure would be:

MFR = [2.703 x 14.7psia x 205.5 cfm] / (85 + 460) = 14.98 lb/minute.

For forced-induction applications (e.g., turbocharged), the MFR needs to be further adjusted by the density ratio (DR):

Eq. 3-10

$$MFR_{Turbo} = (MFR_{NA})(DR)$$

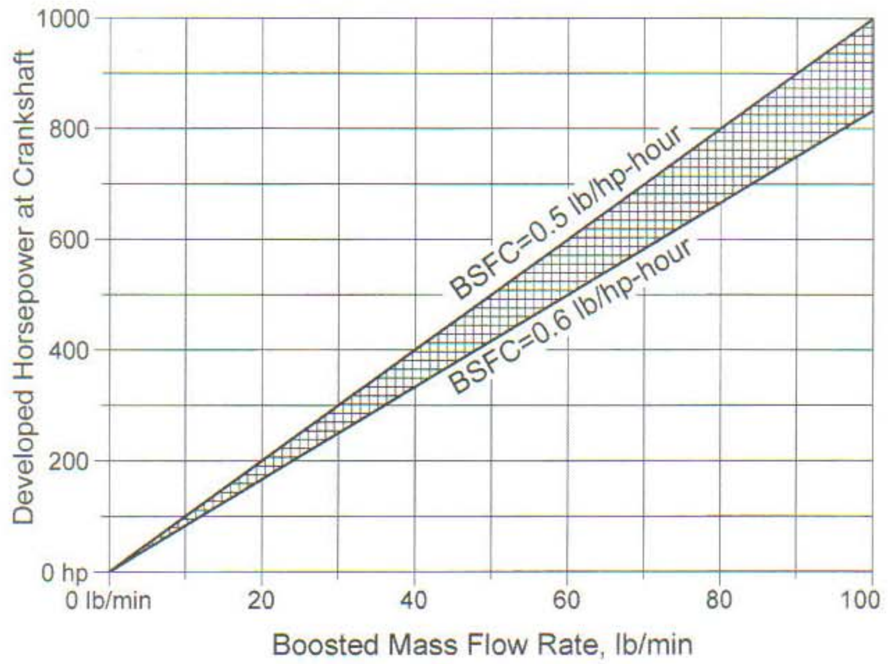
For our Honda example above, assuming a density ratio of 1.51, the boosted MFR would be:

MFR, boosted = 14.98 x 1.51 = 22.6 lb/minute

HORSEPOWER

We can approximate how much horsepower is produced with a properly turbocharged engine. There are a number of ways to estimate horsepower, but an easy and conservative formula is known as the standard brake specific fuel consumption equation, or BSFC method.

The BSFC method relies on knowing the mass flow rate of air into the engine after turbocharging, the final air/fuel ratio, and an arcane constant called, you guessed it, the brake specific fuel consumption value, or BSFC. For properly tuned street-driven turbocharged engines, maximum power air/fuel ratios will range from 11:1 to 13:1. The BSFC value for this type of engine will range from 0.50 to 0.60.



If the boosted air mass flow rate is known, the crankshaft horsepower can be estimated by way of brake specific fuel consumption, or BSFC. Most street-driven turbocharged engines burn between 0.5–0.6 pounds of gasoline every hour for each horsepower developed.

Eq. 3-11

$$HP_{Crankshaft} = \frac{(MFR)(60)}{(A/F\ Ratio)(BSFC)}$$

For our Honda example, if we assume a turbocharged mass flow rate of 22.6 lb/minute of air at 6000 rpm, a well-tuned air-fuel ratio of 12:1, and a BSFC of 0.5, we get:

Crankshaft Horsepower = 22.6 x 60 / 12 x 0.5 = 226 hp

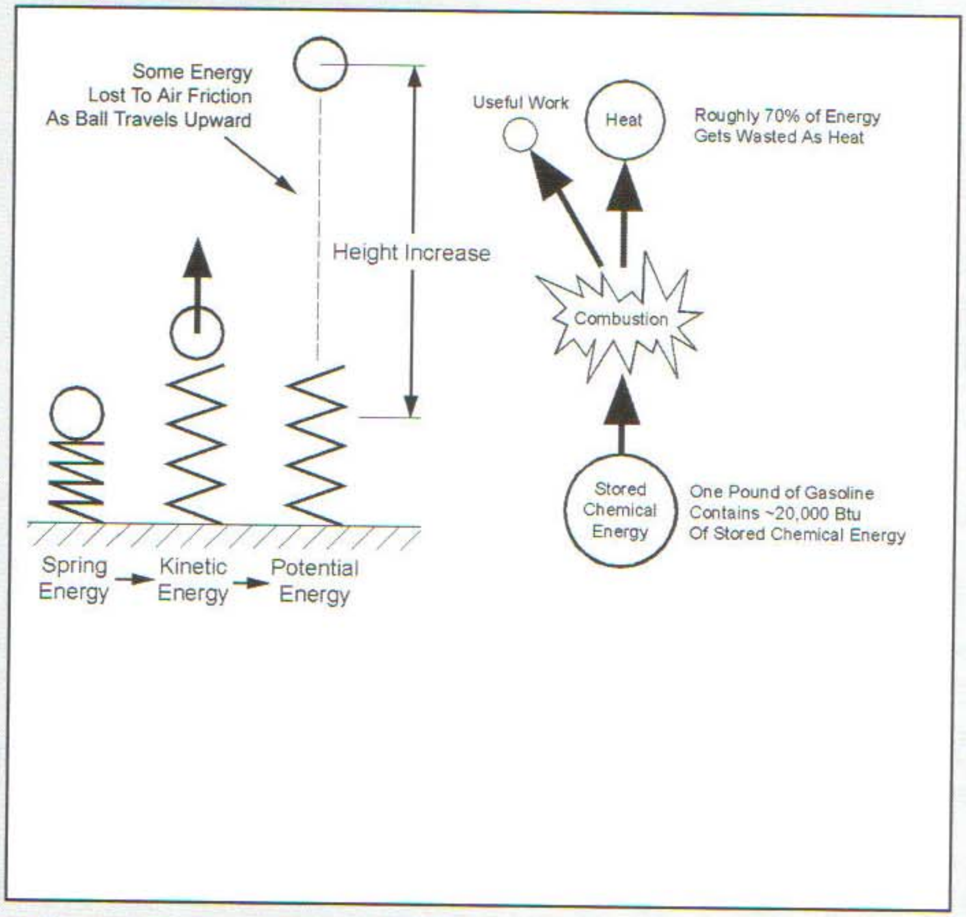
This value is strictly an estimate and is obviously dependent on a number of assumptions. In fact, many of the equations in this chapter are based on assumptions. In other words, the calculations are subject to the old computer programming rule of "GIGO," or garbage in = garbage out. If you make good, well-reasoned and researched estimates for volumetric efficiencies, boost pressures, compressor efficiencies, intercooler losses, etc., the equations will give reasonable results. On the other hand, if you make unrealistic or outrageous assumptions, the results will be meaningless. Not only do you have to understand the mechanics of the equations, but also how to use them appropriately, too.

Once the mass flow rate (MFR) into an engine is known, you can multiply it by 10 to get an approximation of crankshaft horsepower. For instance, if the MFR is 32.5 lb/min, the approximate horsepower developed is 32.5 x 10 = 325 hp.

HEAT, ENERGY, AND ENGINES

Throughout this book, we will often use the terms *heat* and *energy*. Did you know that heat is a form of energy? You may not even know what energy is, let alone heat. No problem. Energy is simply the capacity of a physical system to do useful work. It can take a wide variety of forms. For example, a compressed coil spring has the ability to perform work when it is released. Likewise, an object raised to a large height has an inherent amount of so-called potential energy associated with it. Attach a rope to that elevated object, feed it through a pulley or two, and when you let the object fall back to earth, the pull on the end of the rope can be used to perform some type of work. Similarly, a moving object has a certain amount of kinetic energy. Imagine a wagon filled with bricks rolling down the street. The energy associated with the mass and velocity of the loaded wagon is called its kinetic energy.

You probably learned in high school science class that energy can neither be created nor destroyed. We can, however, convert energy from one form to another. Put a rock on the top of that compressed spring and let it go. Spring energy will be converted to kinetic energy and the rock will fly up in the air. At the top of its trajectory, the rock will momentarily stop moving. In this position, it has built up potential energy due to its height above the ground. When it falls back to earth, the rock



Usually when one form of energy is converted to another, some of the original amount is lost, often to heat. In the case of internal combustion engines, only 30% of the original chemical energy stored in the gasoline that is burned gets converted to useful work. The remainder is lost to various heat sinks.

again speeds up, trading its potential energy back for kinetic energy.

So what does all this have to do with turbochargers and automobile engines? A lot, actually. A gallon of gasoline has a certain amount of chemical energy stored within it that can be put to use when it is burned. When we operate an engine, we are essentially converting one form of energy (chemical) into another (heat). This heat energy manifests itself as pressure and temperature, and it can be converted to kinetic energy (the movement of the piston).

Unfortunately, whenever you convert one form of energy to another, some of it almost always escapes or changes to a form that can't be easily recovered. Machines like internal combustion engines aren't very good at converting chemical energy to useful work. In fact, they're downright lousy at it. For every one unit of kinetic energy we get from the fuel, we also make about 2 to 2.5 units of "waste" heat. In other words, we throw away about 70% of the energy from the gasoline as waste heat into the coolant, the engine block, and of course the exhaust stream. Only 30% or so of the original chemical energy gets converted into useful mechanical work. A turbocharger is used to partially recapture some of this waste heat. It does so by converting back some of the heat and kinetic energy contained in the exhaust stream into the kinetic energy of the turbine wheel.

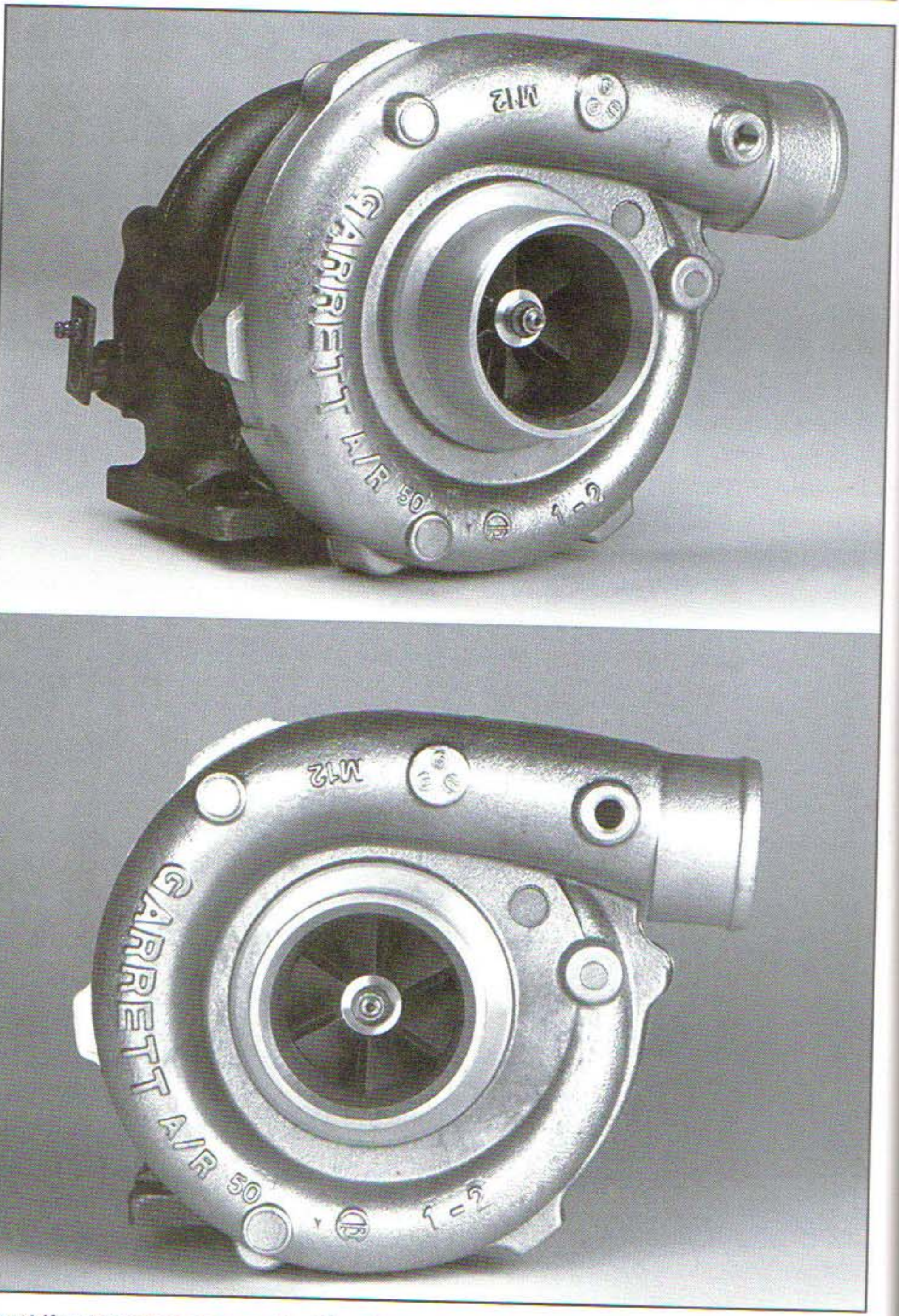
PART II:
TURBOCHARGER COMPONENTS

4 COMPRESSORS

The two fundamental parts of any turbocharger are its compressor and turbine. The requirements for the sizes and shapes of these two items can vary radically depending on the vehicle application. The turbocharger required for a street-driven Honda that is used for commuting and the occasional autocross is quite different than that of an IDRC Outlaw-class 9-second CRX. The sizes and specifications of the compressor and turbine dictate the amount of power that can be delivered, the amount of time required to create that power, the rpm range in which the engine can be safely run, and even the reliability of the system.

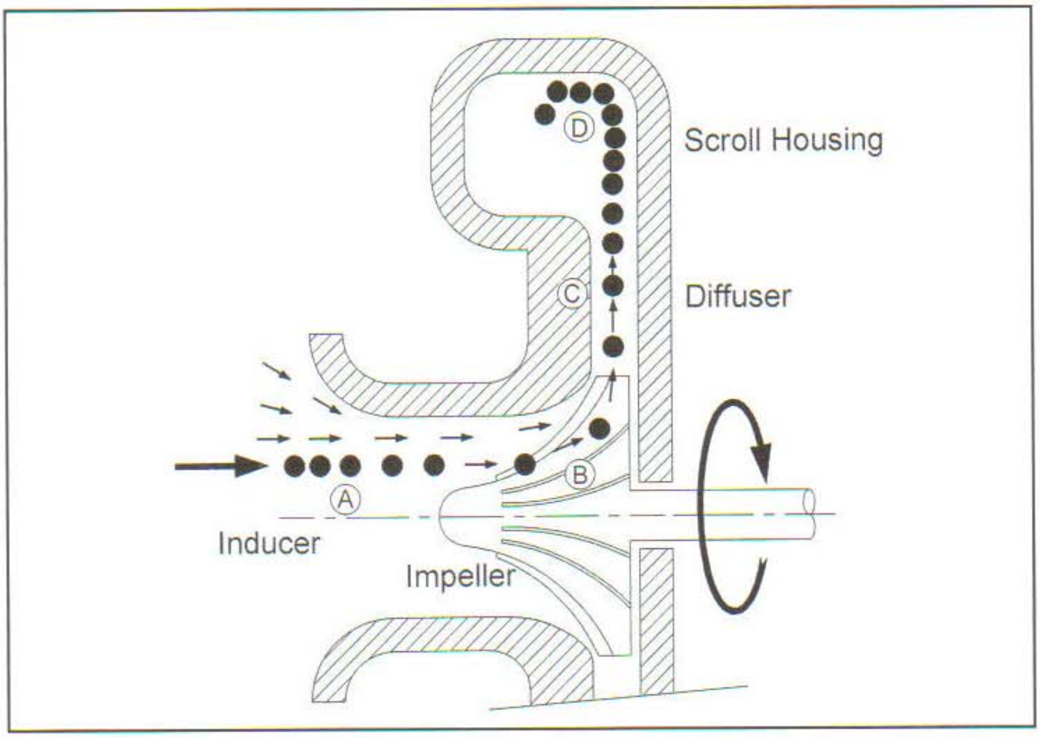
As a general rule, larger turbines and compressors create more power on the upper end of an engine rpm range than smaller units. In contrast, smaller turbos can often spool faster and therefore create boost faster and lower in the rpm range (i.e., reduce the boost threshold). Because they're smaller, however, these turbos tend to exhibit more backpressure across the turbine and higher outlet temps from the compressor. This is the reason they often don't perform as well when engine speeds increase.

The moral of this story is that both the compressor and turbine must be properly matched to the vehicle's engine and application. In



A centrifugal compressor assembly. All modern turbochargers use this type of high-speed device to create pressurized intake charge air. In contrast to positive-displacement compressors, a centrifugal compressor is a "dynamic" device. It accelerates air to a high velocity and then slows it down internally by diffusion. This process converts kinetic energy into pressure energy. (Honeywell Turbo Technologies)

A compressor housing for Turbonetics' versatile T04E turbocharger. (Turbonetics)



A centrifugal compressor draws in air axially via a low pressure zone created at the inducer entrance (A). From here, the rapidly spinning impeller wheel (B) accelerates the stream of air and changes its direction to radial flow. As the air moves out through the parallel-wall diffuser (C), it is slowed down. The initial high kinetic energy of the gas molecules gets converted to pressure energy. The scroll housing (D) helps channel the flow tangentially out of the housing. It also further slows down the air stream, creating more pressure at the expense of velocity. In layman's terms, the constrained geometry of the housing causes the high-speed air molecules flowing out through the diffuser and scroll to pile up on top of each other, creating higher air density, or boost.

the next chapter, we will look at turbine selection. For now, let's start with the compressor.

COMPRESSOR BASICS

In principle, a compressor impeller functions the same way a common room fan does: a series of blades or fins spin rapidly around a rotational axis, scooping up and accelerating a flow of air. In the case of centrifugal compressors like those used in turbochargers, the air is drawn axially into the compressor housing (i.e., parallel to the shaft) and then flung outward in a tangential/radial direction by the impeller blades. Some of the rotational energy of the compressor wheel is transferred to kinetic energy of the air molecules.

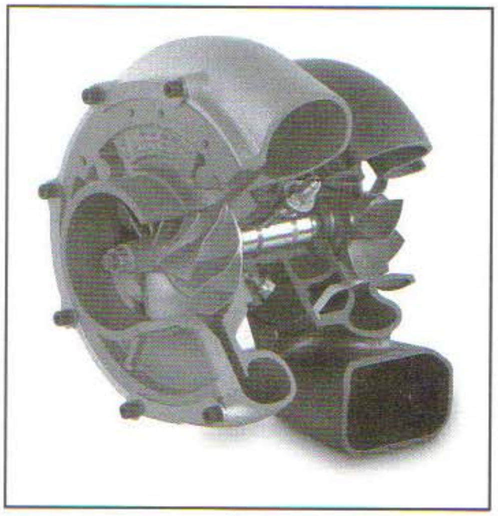
The air being scooped up is forced radially outward by what backyard physicists like to call centrifugal action. (This isn't technically accurate, but to explain why would take another full chapter. For now let's just accept it and move on.)

The diffuser section and the spiral shape of the outer compressor housing helps channel the fast-moving airflow from the spinning blades of the wheel in a direction that will ultimately exit the discharge orifice of the compressor. The housing shape and diffuser geometry also slows down the flow of air, which builds pressure energy in the air stream at the expense of its newly created kinetic energy.

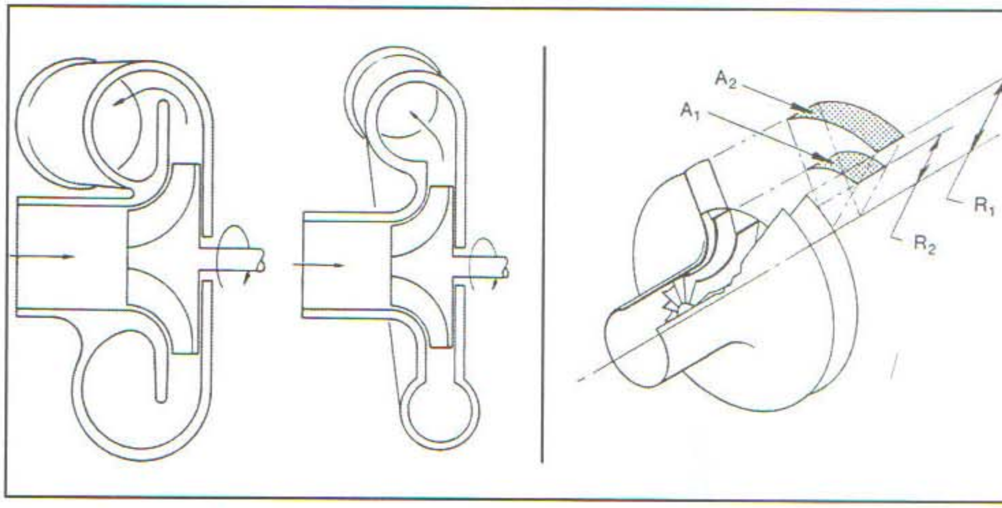
From the outlet of the compressor, the air is directed toward the engine. The airflow is restricted by the throttle plate and the engine itself. This has the effect of further slowing and backing up the flow, building more pressure energy in the air stream while sacrificing more kinetic energy. Voilá, a supply of pressurized air is created by a spinning wheel.

This is all fine and dandy, except there's a problem. Remember when we said that raising the temperature of a constrained gas also raises its pressure? The same is true in reverse: raising the pressure results in a temperature increase. This is a thermodynamic fact from which there is no escape. Worse, air pumps and compressors are inefficient devices, and they always add their own additional heat to the air they're compressing. If we could build perfect machines, perpetual motion would be possible and compressors wouldn't add this extra heat. But we can't and they do.

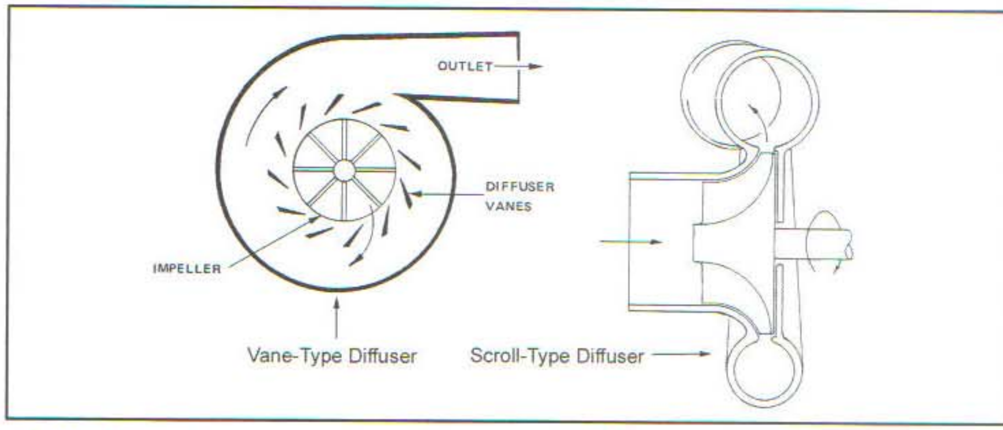
The basic act of spinning a fan blade through air causes heat. This is due to the friction between the



The narrow parallel-wall diffuser channel is visible in this sectioned compressor housing. (Honeywell Turbo Technologies)



Most contemporary turbocharger compressors utilize parallel-wall diffusers. (MacInnes/Monroe)



The less common vane- and scroll-type diffuser designs. (MacInnes)

moving fan blade and all those air molecules. It is often said that a turbocharger compressor "beats up" the air it compresses, much like a chef's electric mixer whips the batter in a cake mix. For a compressor, the result of all this air friction is, of course, a temperature rise.

COMPRESSOR EFFICIENCIES

Compressors are evaluated by their efficiencies. Technically speaking, the efficiency of a compressor is the amount of energy that the unit converts to pressure in the airflow, divided by the total shaft energy required to drive the impeller. At the low end of the efficiency scale, compressors can be as poor as 30–40% efficient for old-fashioned "roots"-type positive-displacement superchargers. At the other end of the scale, efficiencies can be as high as 75% or more for modern centrifugal compressors like those used in turbocharger systems. For these latter types of compressors, roughly 75% of the turbine shaft power transferred to the compressor is used to compress air. A large part of the remaining 25% is transformed into extra heat in the air stream.

The higher the compressor efficiency, the less the airflow will be heated during pressurization. How much the air temperature rises can be calculated by combining the Equations 3-2 and 3-3 on pages 24–25 from the last chapter into a new equation:

Eq. 4-1

$$T_{Out} = \frac{(T_{In}+460)(PR)^{0.283} - (T_{In}+460)}{Efficiency_{Compressor}} + T_{In}$$

Rearranging this formula, we can solve for compressor efficiency as a function of inlet and outlet temperatures and pressure ratio:

Eq. 4-2

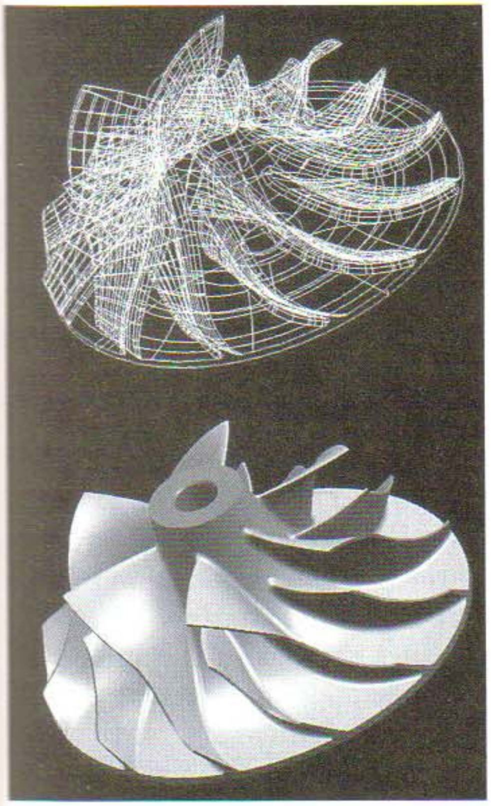
$$Eff_{Comp} = \frac{(T_{In}+460)(PR)^{0.283} - (T_{In}+460)}{(T_{Out} - T_{In})}$$

For example, a system that has an inlet temperature of 85° F, an outlet temperature of 200° F, and a pressure ratio of 1.7, would have a compressor efficiency of:

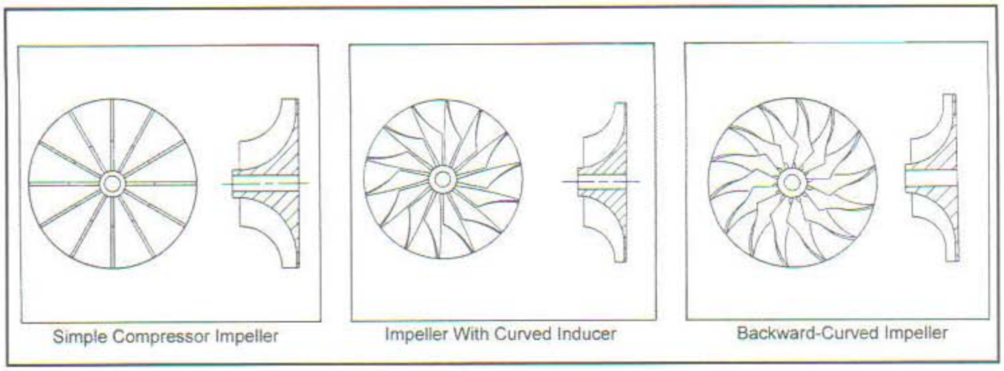
Efficiency Compressor = $[(85 + 460) \times 1.7^{0.283} - (85 + 460)]/(200 - 85)$
= 76.8%

Why is this important? Because selecting a compressor for a given application requires understanding its efficiency characteristics across a large operating regime of airflow and boost pressure combinations.

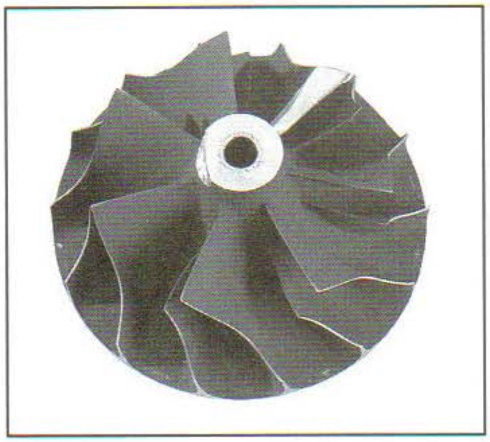
If we instrument a compressor



Modern compressor wheels are designed and built with computer-aided engineering tools, including computational fluid dynamics (CFD), finite element analyses (FEA), and various computer-numerical control (CNC) processes. (Honeywell Turbo Technologies)



Compressor wheels have evolved from simple straight blades to highly-sophisticated designs that incorporate backward curving impeller blades. (MacInnes)



A typical compressor wheel, or impeller, used in a modern turbocharger. (Turbonetics)

> **ADIABATIC**
>
> The word "adiabatic" describes a process in which no heat is gained or lost from the surroundings. The temperature rise of the air passing through a forced-induction device that is 100% adiabatically efficient would be solely due to the pressure rise of the gas; no additional heat would be added from the housing, wheel, or surroundings. In practice, this effect is impossible to achieve. In most cases, a modern centrifugal compressor can achieve only 80–85% efficiency for certain specialized operating regimes.

with sensors that measure the air temperatures into and out of the unit and then spin up the assembly in a laboratory at various pressure ratios and flow rates, we can calculate and chart the efficiency results across a range of operating conditions. The plotted result is something known as a compressor map, and it's a very useful tool.

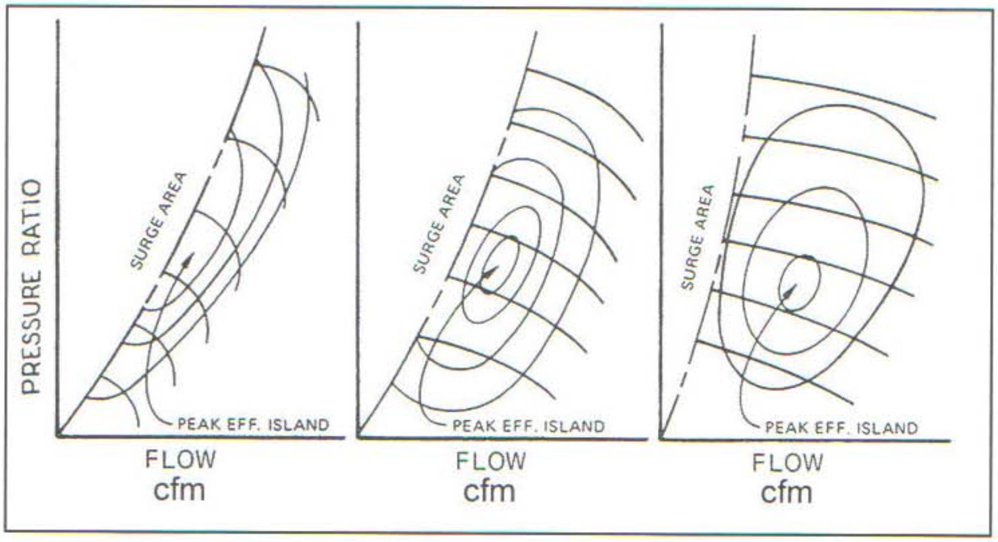
COMPRESSOR MAPS

Ask a turbocharger engineer how to select the best compressor for a given application, and the first place he will turn is to a set of compressor efficiency maps. Let's break down one of these maps to see what all the numbers mean and, more importantly, how to use it to our advantage.

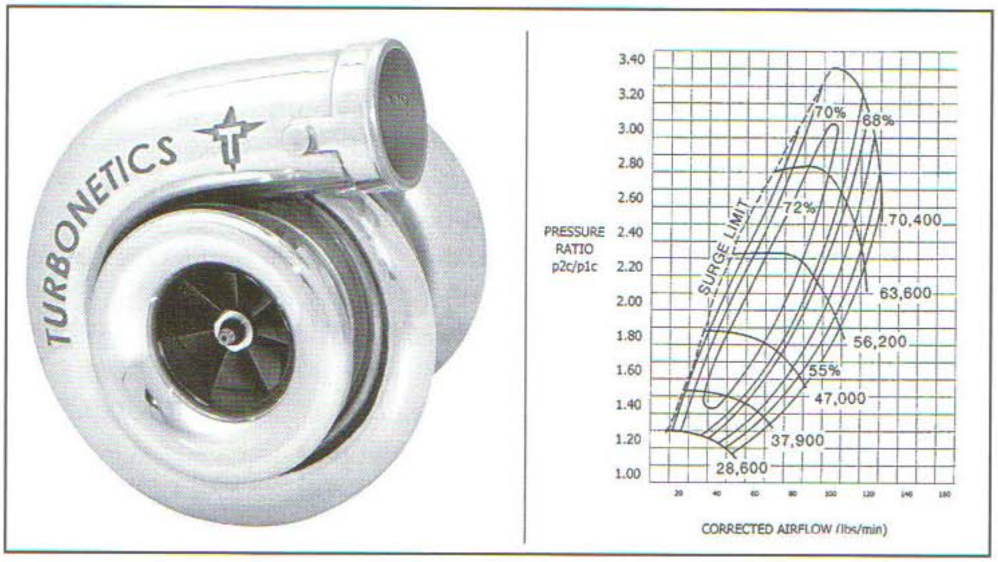
The horizontal axis on the bottom of a typical map expresses airflow rate. Sometimes the units of this axis are in pounds per minute, and sometimes they're shown in cubic feet per minute, or cfm. If your map is in lbs/minute, you can convert to cfm by multiplying the values shown by 13.7 (this assumes the map was created at a standard 85°F inlet temperature, which, fortunately, most of them are). Likewise, converting from cfm to lbs/min is accomplished by dividing by 13.7.

Now let's look on the vertical line on the left of the chart. This axis denotes the pressure ratio, or PR, which you will recall is equal to the boost pressure (in locally-corrected psia units), divided by the local ambient pressure (also in psia). At zero boost, the PR is equal to 1, which is normally the bottommost value on the left vertical axis. As boost pressure rises, the PR increases proportionally upward.

Now let's imagine an actual compressor we want to evaluate. First, we bolt it down to a test bench and connect the impeller shaft to a large, variable-speed drive motor, or perhaps to an actual turbine. In either case, we attach a short piece of tubing on the compressor outlet port and connect it to a flow-control valve.



Compressor maps of three different centrifugal compressors with (left to right) narrow, medium, and broad efficiency ranges. (MacInnes)



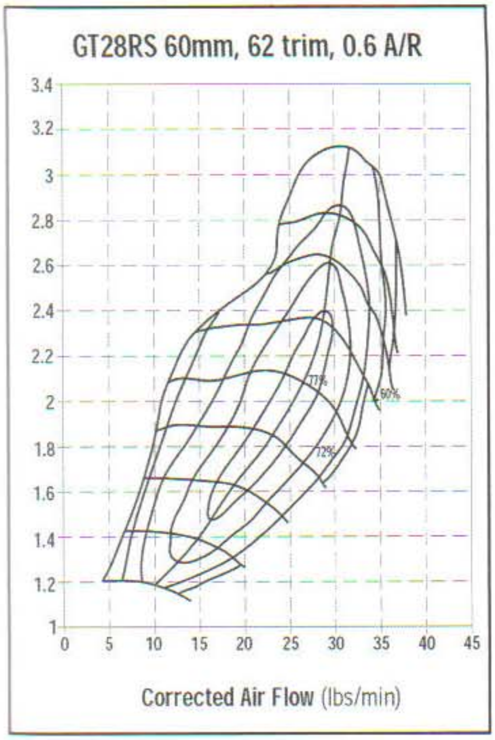
Turbonetics giant Y2K compressor can support an honest 1000+ horsepower. (Turbonetics)

This valve can be set wide open, fully closed, or anywhere in between. If the valve is fully open, and we spin the impeller at a constant speed, the compressor creates a certain amount of airflow from its outlet port. With no external flow restriction (i.e., the flow control valve is open), the pressure rise in the air stream (i.e., boost) that is created is due only to the compressor diffuser and housing.

Now, as we begin to close the flow-control valve, we create a flow restriction. Accordingly, the boost pressure begins to rise and the flow rate drops. The further we close the valve, the higher the boost rises—but not linearly. The boost pressure increase slowly tapers off the farther we go, roughly approaching a constant pressure ratio value. The more we close the valve, the less effect on boost pressure we have. This continues until we hit an airflow rate, called the surge limit, where the flow from the compressor begins to be unstable. The air is restricted so much that it literally backs up and surges in reverse through the compressor. This causes a stall, and the pressure drops. The airflow then resumes in a forward direction but immediately surges again. The flow is unstable at the surge point, so we stop the test. (Letting a compressor surge for extended periods of time can damage the thrust bearing of the turbocharger and even destroy the impeller wheel itself.)

While we were running this "throttle-down" test, we were also recording the airflow rate, the pressure ratio, and the inlet and outlet temperature data of the air stream. Knowing all this information, we can not only plot a curve on our chart that shows the pressure ratio as a function of flow rate, but we also know exactly what the outlet air temperature was anywhere along that curve. In other words, by using some basic mathematical equations, we can characterize the compressor efficiency for one discrete impeller speed. If we repeat the same test at many different wheel speeds, we can assemble all the information required to create a compressor map. Furthermore, if we join all the points of equal efficiencies on the chart, grouping the regions of equal compressor efficiencies into "islands," we can see in a graphical sense where the compressor works most optimally, and also where it doesn't.

Think of the efficiency islands on a compressor map as areas of unwanted heat, or temperature rise. The higher the efficiency, the less heat we will add to the air stream during pressurization. This is why we want large islands of



Compressor map for the popular Garrett GT28RS "Disco Potato" turbocharger. This unit is well-suited for engines displacing between 1.8 to 2.7 liters and generating 250 to 320 horsepower. (Honeywell Turbo Technologies)

high efficiency, and why we want to stay at or near the central (highest) efficiency island as much of the time during engine operation as possible. We also want to ensure that, in all the other parts of the engine rpm range, the efficiency doesn't drop too much or put us off the map or into the surge limit.

As we'll see shortly, the process of evaluating a compressor based on its efficiency map involves a number of formulas. Fortunately, the math isn't too hard if we go through it slowly.

SIZING A COMPRESSOR

The first step in selecting a compressor is to determine what we ultimately want to get out of the system and how much boost the engine can safely take. This requires us to make some assumptions and educated choices, starting with the engine itself. Let's work through an example to see how the numbers play out.

Our theoretical engine for this exercise is a modern 2-liter (122 cid) 4-cylinder with dual overhead cams and 4 valves per cylinder. Let's assume the engine is fairly well designed, with a volumetric efficiency that ranges from 80%–90% in its useful rpm range. We will also assume an 8.5:1 static compression ratio. This is important because if the compression ratio is too large, we will have to limit boost to lower levels and worry about detonation. For this engine, however, because it has a relatively low compression ratio, we can run up to 15 psig of boost without too much difficulty.

Let's further assume that our hypothetical engine idles at 800 rpm and has a redline of 7500 rpm. We operate the engine primarily at sea level, and the outside weather conditions are, on average, moderately warm. We want good street performance, with full boost occurring at, say, 3500 rpm and above. We'll incorporate a high-quality intercooler that has reasonably good efficiency, and we'll also assume our EFI system is capable of supplying sufficient fuel to support this horsepower goal. (Don't worry, we'll cover intercoolers and EFI sizing in later chapters.)

Now, knowing these facts will ultimately allow us to determine the pressure ratio and mass flow rate through engine. These two values will then be plotted on our compressor map to check the compressor efficiency. To do this, we'll be using many of the equations we learned about in the last chapter.

First, let's assume that in addition to the 15 psig of boost from the compressor, we will have a 1 psig pressure drop through the intercooler. From our equation 3-1 for pressure ratio, we have:

$$PR_{Compressor} = (15.0 + 14.7) / 14.7 = 2.02$$

$$PR_{System} = (15.0 - 1.0 + 14.7) / 14.7 = 1.95$$

Next, from our equation 3-2, we can calculate the adiabatic "ideal" temperature rise through the compressor at this pressure ratio:

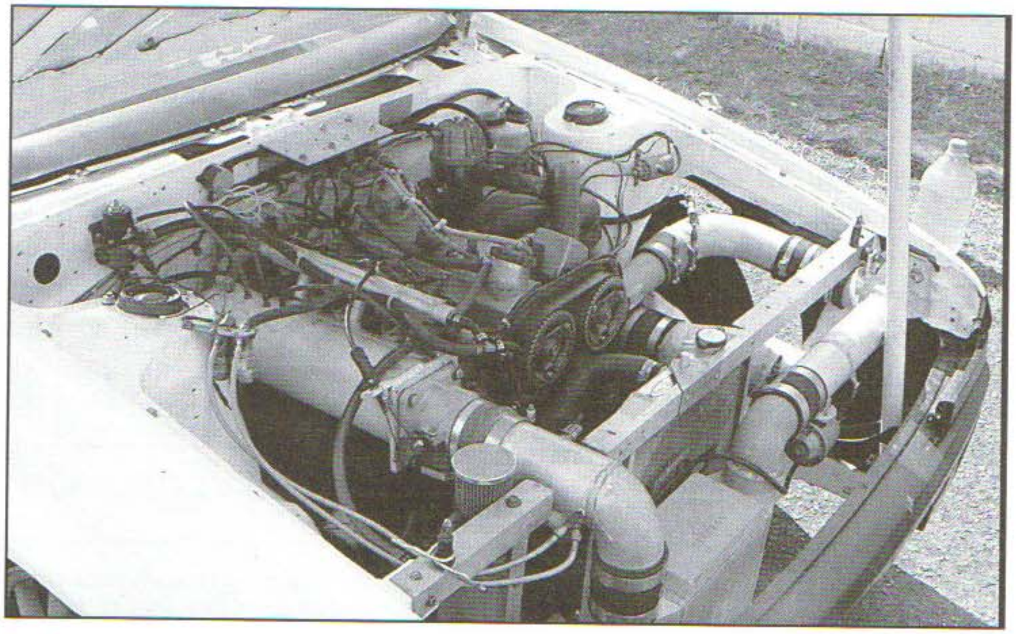
$$T_{Out,\ ideal} = [(85 + 460) \times 2.02^{0.283}] - 460 = 205°F$$

Recall that this temperature rise is for a perfect compressor. Ours won't be, of course, but we'll strive to select a high-quality unit. Let's assume that we will end up using a compressor that has a peak efficiency of 75%. With this information in hand, we can now estimate how hot the air will become when passing through the compressor. This is done with the Equation 3-3:

$$T_{Out,\ actual} = [(205 - 85) / 0.75] + 85 = 245°\ F$$

Intercooler Effect

Next is the effect of the intercooler. We'll go into the mechanics of sizing intercoolers and determining their efficiencies later, but for now let's assume our



Careful compressor selection is required when you want to run the quarter mile in 9 seconds with a 2-liter engine, like this 3SGTE-equipped Toyota. (The Power Group)

intercooler is pretty good, with an efficiency of 70%. The equation for the air temperature exiting an intercooler is:

Eq. 4-3

$$T_{IC\ Out} = T_{Comp\ Out} - (Eff_{IC})(T_{Comp\ Out} - T_{Amb})$$

$T_{Out,\ IC} = 245 - [0.70 \times (245 - 85)] = 133°F$

In other words, the temperature of the air leaving the intercooler—and, therefore, entering the engine—will be 133°F. We can now calculate the density ratio from Equation 3-4:

$DR = 1.95 \times [(85 + 460) / (133 + 460)] = 1.79$

Next is the non-boosted volumetric flow rate at redline. We will assume a volumetric efficiency of 85% at this engine speed, and we'll combine Equations 3-6 and 3-7:

$VFR = 122 \times 7500 \times 0.85/3456 = 225cfm$

A rule of thumb is boost pressure rises as the square of the compressor wheel speed.

And, finally, since we know the boosted density ratio, we can calculate the actual mass flow rate at this engine speed from Equations 3-9 and 3-10:

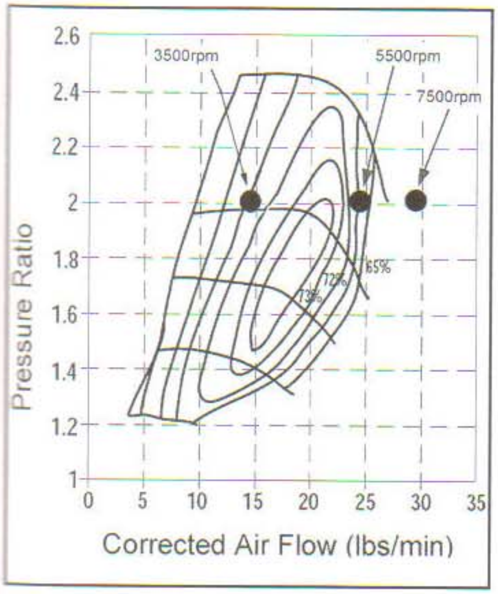
$MFR = (2.703 \times 14.7 \times 225 \times 1.79) / (85 + 460) = 29.4$ lb/min.

And there we have it. For an engine speed of 7500 rpm, we have calculated the pressure ratio and the mass flow rate, which we can plot on a compressor map. We can also repeat this exercise at a few different operating speeds and conditions. For instance, we should probably calculate the mass flow rate for at least two more points that fall within the rpm range where full boost is expected. For example, we plan to select a turbine that is fully spooled at 3500 rpm. In other words, from 3500 rpm up to redline, we expect a fixed system PR of 1.95. In this range, however, the mass flow rate will be less than at 7500 rpm.

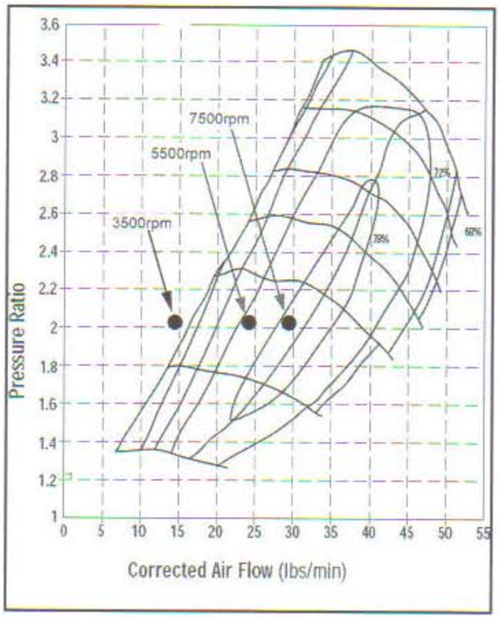
Using a turbocharger from a junkyard can be a tricky proposition. Unless you know what its operating characteristics are, it will be difficult to assess the end result when installed on your engine. It's better if you can source its compressor map and run the numbers to be sure how it will perform.

For our engine, we might calculate the MFR at, say, 3500 rpm and 5500 rpm. Unfortunately, this is both easy and not so easy to do. It's easy because the outlet temperatures and density ratios don't change with rpm (assuming the PR is fixed). This means the only additional calculations that need to be made are for the VFR and MFR. But this brings up the not so easy part: we have to make some assumptions for volumetric efficiency at these two new rpm points.

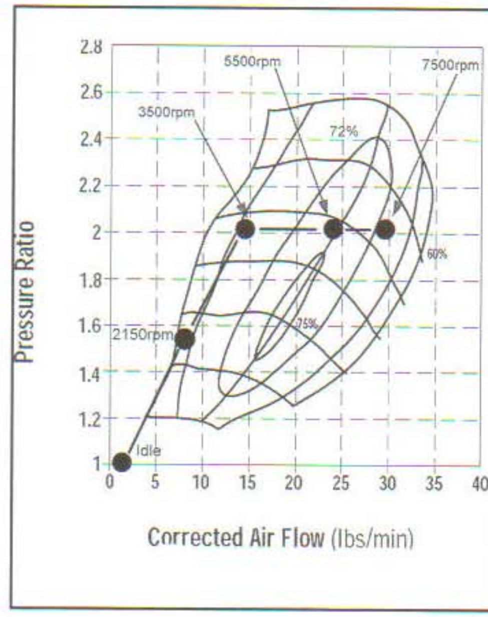
Volumetric efficiency (VE) varies with engine rpm. It is at a maximum where the torque peak occurs in the rev range, and it falls off on either side of this point. For our example, let's assume that the engine torque peak occurs between 3500 and 5500 rpm. At 3500 rpm we'll assume a VE of 90% and at 5500 rpm we'll assume a VE of 95%. (The actual values for your own engine may be higher or lower; it depends on many factors.) Running through the numbers gives us a decent look at the MFR requirements for our engine over a



Garrett GT25R compressor map. Plotting the three example operational points on this map shows that the compressor is too small for the application. At 7500 rpm, the plot is well off the map into the choke zone. When a compressor is run deep into choke, wheel speeds increase dramatically, while compressor efficiency plunges. This means high-outlet air temperatures, reduced power, and increased chances of detonation occurring in the combustion chamber. Durability of the turbocharger itself can be compromised, too, if the compressor is allowed to continue operating in this region. (Honeywell Turbo Technologies)



Garrett GT30R compressor map. Similarly, plotting the three operating points on this map indicates that the compressor is too large for the application. At 3500 rpm, the compressor is operating in the surge zone. Surge is basically an area of flow instability caused by compressor inducer stall. Running a turbocharger in this region for extended periods of time can cause turbo damage, such as bearing failure. (Honeywell Turbo Technologies)



Garrett GT28R compressor map. This particular compressor is a good fit for our example application, with all three points comfortably within the map and at relatively high compressor efficiencies. The idle and mid-boost points also fall within acceptable limits of the map. (Honeywell Turbo Technologies)

3500–7500 rpm range, with a PR of 2.02:

MFR 3500 rpm = 14.55 lb/min
MFR 5500 rpm = 24.13 lb/min
MFR 7500 rpm = 29.40 lb/min

PLOTTING MAP POINTS

Now we're ready to go to the maps and actually select a compressor. While some suppliers don't like to publish their compressor maps, others, such as BorgWarner, Garrett, Holset, and Turbonetics will be happy to give you copies.

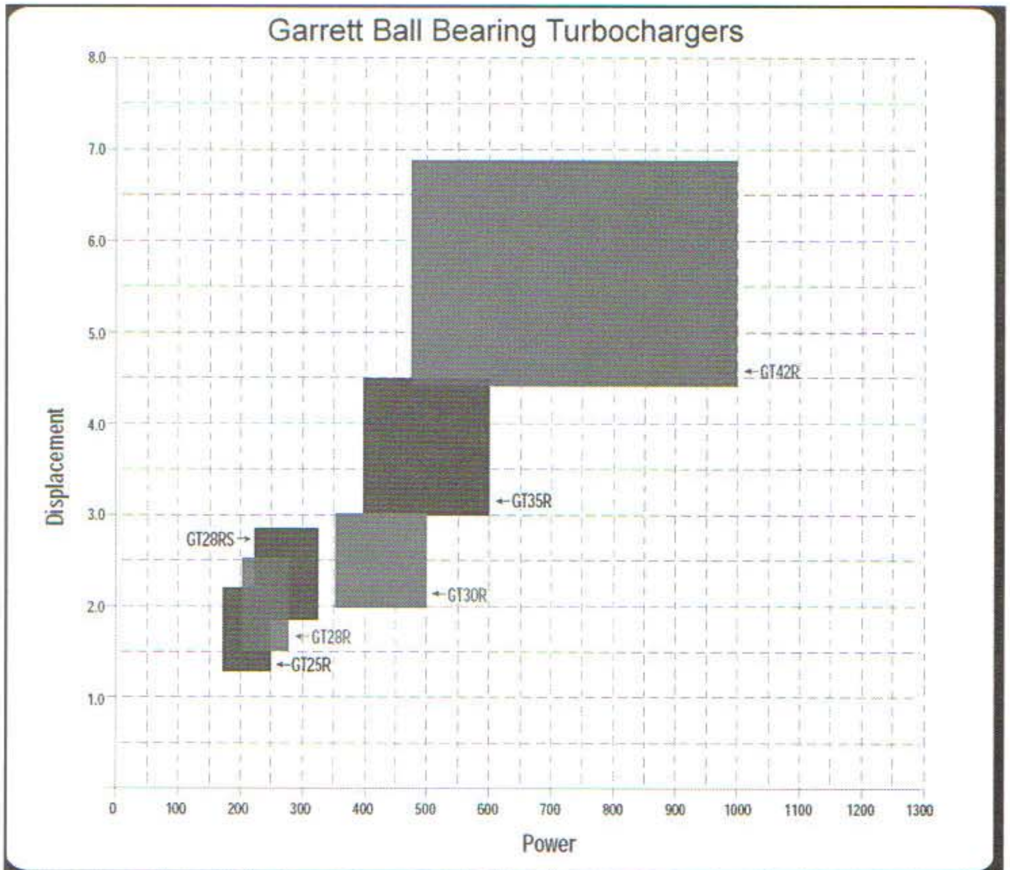
For our example, let's pick three separate maps from Garrett and plot our values of PR and MFR on them. The first compressor map we will look at is a GT25R, as shown in the illustration at left. Note that 3500 rpm and 5500 rpm fall comfortably within the bounds of the map, but 7500 rpm is out into the choke regime. This is a clear indication that the compressor is too small for our application. Using this turbo for our application would result in the creation of a lot of hot air in the upper rpm operating range. This would result in poor performance and, possibly, engine damage due to detonation.

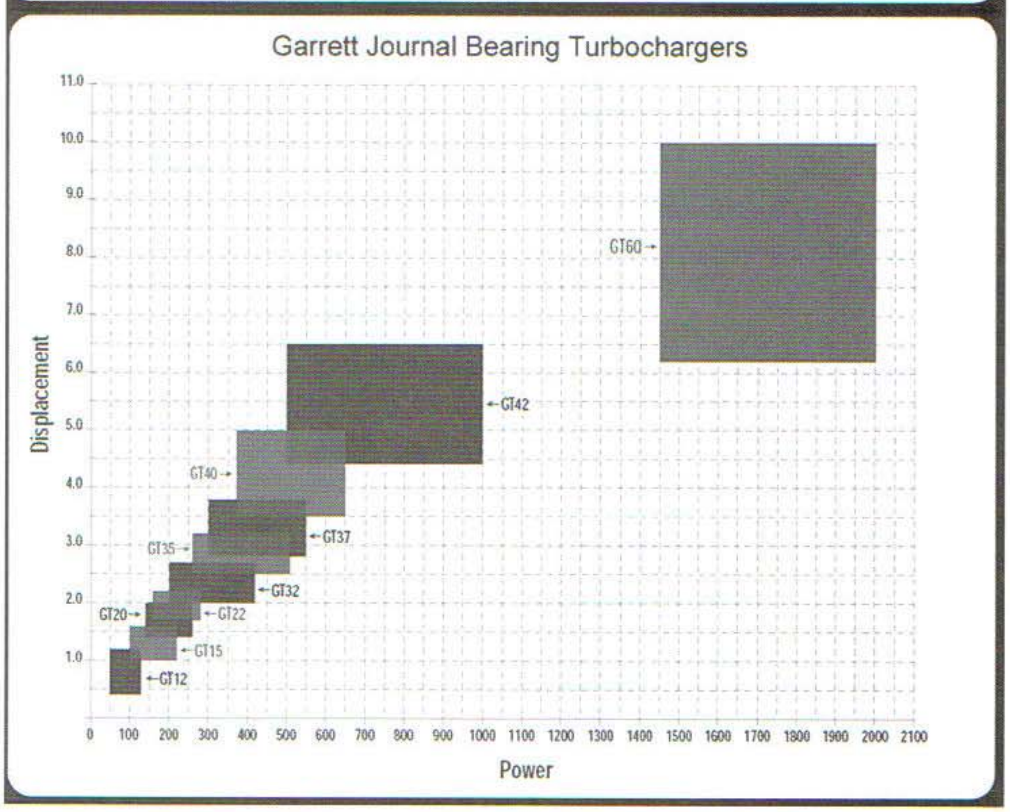
Next we'll look at a GT30R compressor (above center). Again, two of the operating points look reasonable, but the 3500 rpm point is off the left side of the map into the surge zone. This indicates that the compressor is too large. If we were to use this compressor, it could be operating in an unstable regime and could cause damage to itself.

Finally, we'll try a GT28R compressor that, from a size point of view, is situated in between the GT25R and the GT30R. Plotting our three points of the curve (above right), indicates that we have a pretty good match. We're comfortably within the bounds of the map, with all three points falling on relatively high efficiency islands. So far, so good.

Other Points On The Curve

We now have a good candidate compressor of our particular application. But before we run off to the next chapter and select a turbine, we should take a look at a few other points on the chart. Specifically, we need to calculate the PRs and MFRs for this compressor down in the rev range before it becomes fully spooled. This will give us an indication of whether we're in the surge zone of





Does all this compressor map math have your head spinning? Not to worry. Reputable turbocharger suppliers, such as Honeywell Turbo Technologies (Garrett) and Turbonetics, can help you walk through their maze of housings, wheels, and trims. It's still recommended, however, that you run the numbers on the final selected compressor to ensure the turbo will meet your expectations. (Honeywell Turbo Technologies)

the compressor or not.

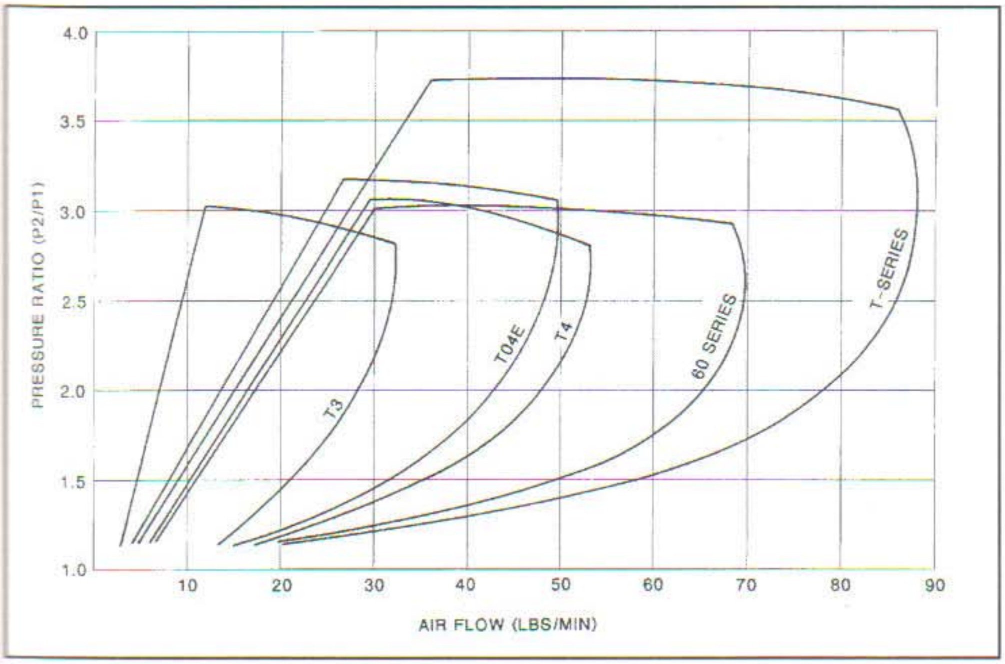
To calculate these low rpm values, we need to make some more assumptions about boost pressure. At idle, for example, we might assume that the boost is essentially zero. At a mid-point between idle and full-spool, however, it's a little harder to guess boost pressure. The actual PR here depends on a number of factors, including the design of the turbine, how efficient the exhaust system is, and how we set up any boost control devices. For a first pass, however, we'll simply guess that the boost rises linearly with engine speed between idle and 3500 rpm. In other words, the boost at a midway point between 800 rpm (idle) and 3500 rpm will be roughly half of the full boost, or 7.5 psig.

We'll also assume a VE of 80% down in this rpm range. Running through all the equations again gives the following:

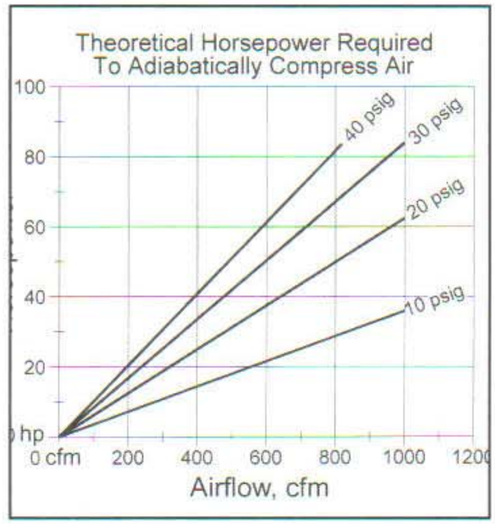
800 rpm: PR = 1.0 and MFR = 1.54 lb/min

2150 rpm: PR = 1.54 and MFR = 6.21 lb/min

Plotting these points on the GT28R compressor map shows us that, while we're getting close to the surge line, we're still marginally within the acceptable limits of compressor performance. Some careful setting of boost versus rpm via the wastegate control device (which we'll cover in Chapter 8) should ensure that we stay out of trouble with this compressor.



The popular Turbonetics compressor family. Charts like this can serve as a good starting point in the process of selecting the right compressor for a specific application. (Turbonetics)



It takes horsepower to compress air. On a turbocharged-equipped engine, the power is harnessed from otherwise-wasted energy flowing out the tailpipe. This plot shows the theoretical amount of power required to compress air, as a function of the flow rate and pressure. It assumes that the incoming air is dry and at 14.7 psia ambient, and that the compression takes place via a single stage, adiabatic process. This means the actual horsepower required to achieve these pressures and flow rates on a turbocharged engine will be somewhat higher than this chart predicts, due primarily to the actual thermal and mechanical inefficiencies of the compressor, friction of the bearings, and the overall inefficiency of the turbine assembly.

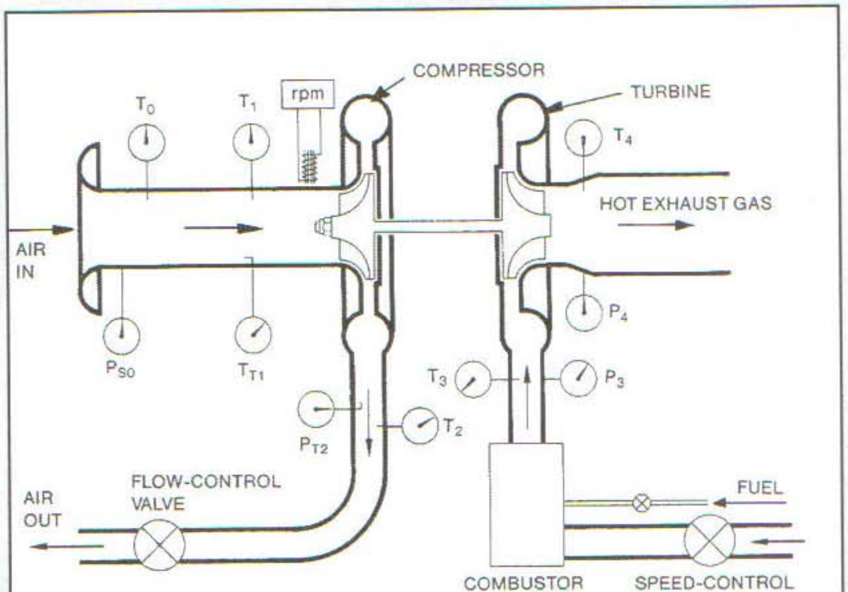
COMPRESSOR SUMMARY

A compressor is a turbocharger's lungs. Get it sized correctly for your application, and you are well on your way to building big power. Get it wrong, however, and your engine will gasp for breath, never creating the performance you want to achieve. It might also be the cause of detonation that can lead to engine damage.

There are a lot of advertising claims and marketing hype surrounding compressors. There are also a lot of old wives' tales and false information. To correctly size and select a compressor for your application, you must work through formulas and plot your points on compressor maps. Each and every compressor has its own distinct map, and any reputable compressor manufacturer will be able to produce maps for all of the products in their line. Without the map, you are left guessing whether your turbocharger will behave the way you expect it to.

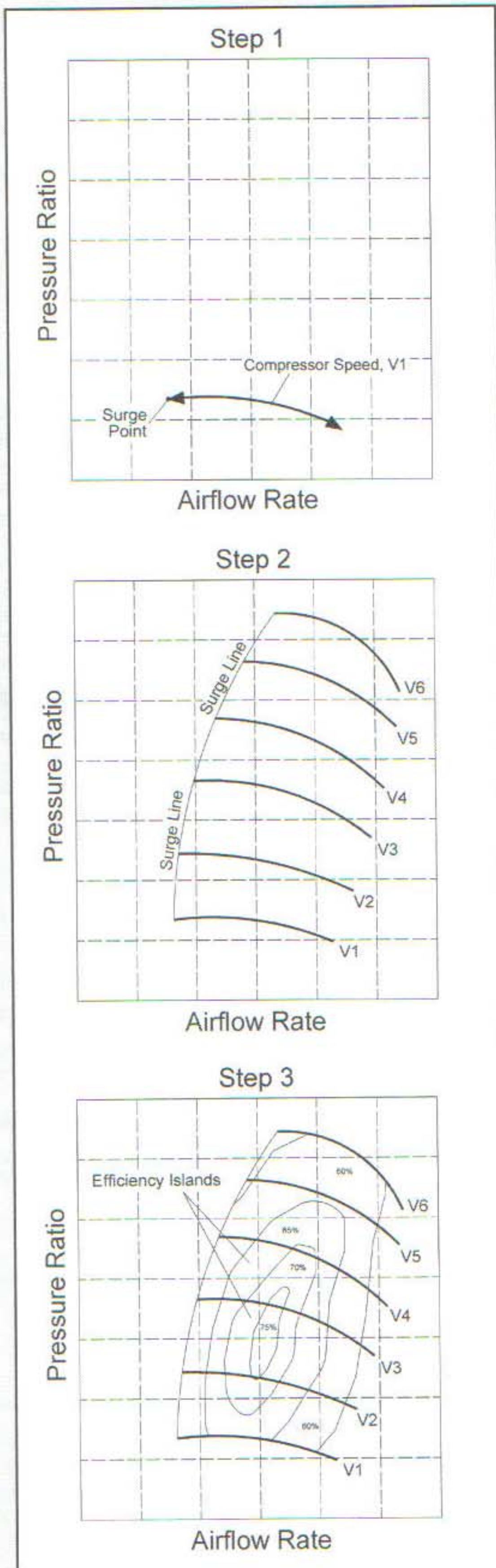
Finally, it's important to remember that the first pass through all these equations are based on a number of assumptions and educated guesses. Once you've narrowed down the choice to a single compressor and turbine (which we'll show how to do in the next chapter), as well as the choice of intercoolers and such, you should go through all the calculations again. Remember that this is an iterative process; you make assumptions and calculations for individual turbo components and then put them all together and reevaluate.

CENTRIFUGAL COMPRESSOR TESTING



Compressor test stand

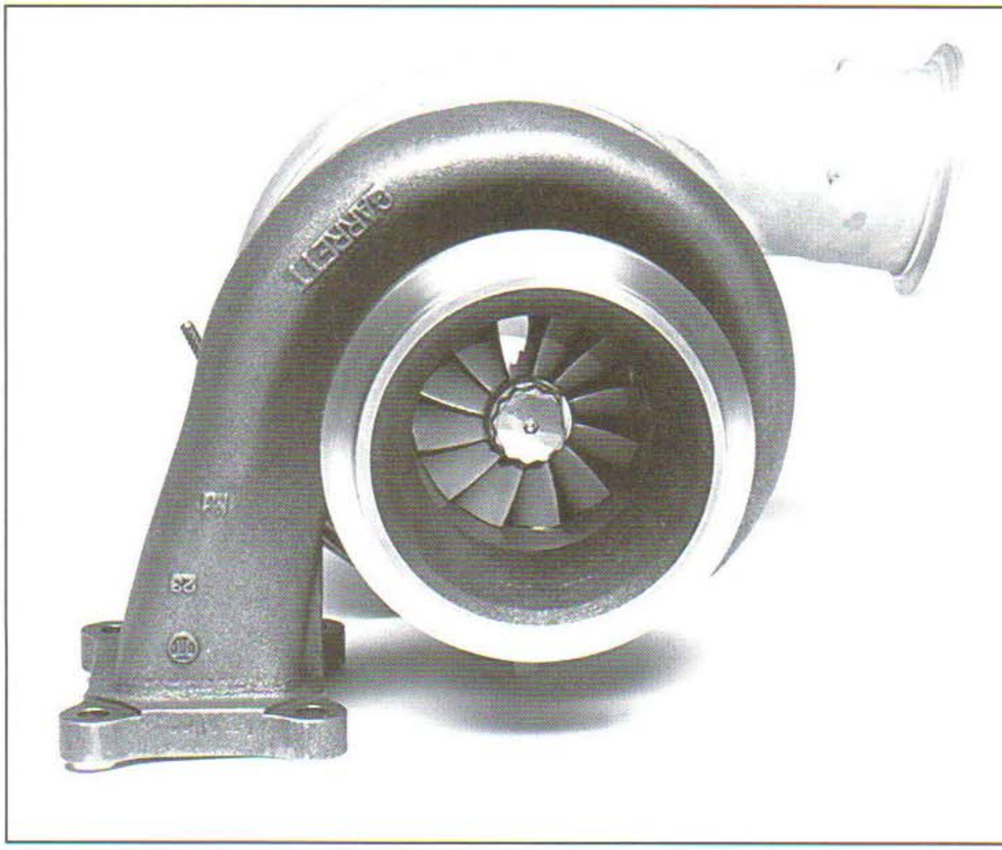
Reading and understanding compressor efficiency maps is the key to selecting the correct turbocharger for a given application. The typical map is created by running the compressor on a test rig like this. The equipment is instrumented and a variety of data collected, including shaft speed, inlet and outlet temperatures, inlet and outlet pressures, and flow rate. (MacInnes)



The testing begins by running the compressor at a fixed speed, V1. The airflow rate is reduced by throttling the compressor discharge. Where the compressor outlet pressure and flow become unsteady is called the surge point. This surge point determines the minimum usable flow at that shaft speed. Below this airflow, the compressor will not operate without pulsing or surging. The flow rate is then increased until the compressor-discharge gauge pressure is about one half the gauge pressure at the surge point. This is usually referred to as the choke condition and is above the maximum usable flow of the compressor. The same test is then repeated for 6 to 8 different shaft speeds, usually in increments of 10,000 rpm. Sometimes aerodynamic experts insist on running compressors at particular rotor-tip speeds, which result in speed line values like 96,250 rpm. Once the runs are completed, the pressure ratios and efficiencies are calculated, and then the results plotted. Areas of equal efficiencies are grouped together to form "efficiency islands."

TURBINES 5

The typical turbocharger turbine is comprised of little more than a cast iron housing and a turbine wheel. The wheel consists of a central hub with an array of blades projecting radially outward from it. It is usually constructed from a special high-temperature material such as Inconel or Mar-M steel. (Strictly speaking the turbine wheel and its integral shaft are part of the center housing rotating assembly, or CHRA, which we will discuss in the next chapter. For now, however, we will treat the turbine wheel as part of the turbine assembly. This will help in the understanding of how power is extracted from the exhaust stream.)



It's clear where the slang expression "snail" comes from when looking at a classic tangential-style turbine housing. A turbine is a device that harnesses otherwise wasted exhaust stream energy to power the compressor. (Turbonetics)

A turbine is an elegantly simple device used to harness energy in the exhaust stream. Hot gases from the exhaust manifold flow tangentially into the turbine housing and spiral inward through the scroll-shaped volute. The volute necks down in both cross-sectional area and distance from the center (radius) as it circles the turbine. This has the effect of speeding up the flow of hot gas, much like the act of crimping down the end of a garden hose with your thumb causes the water to spray out at a higher speed.

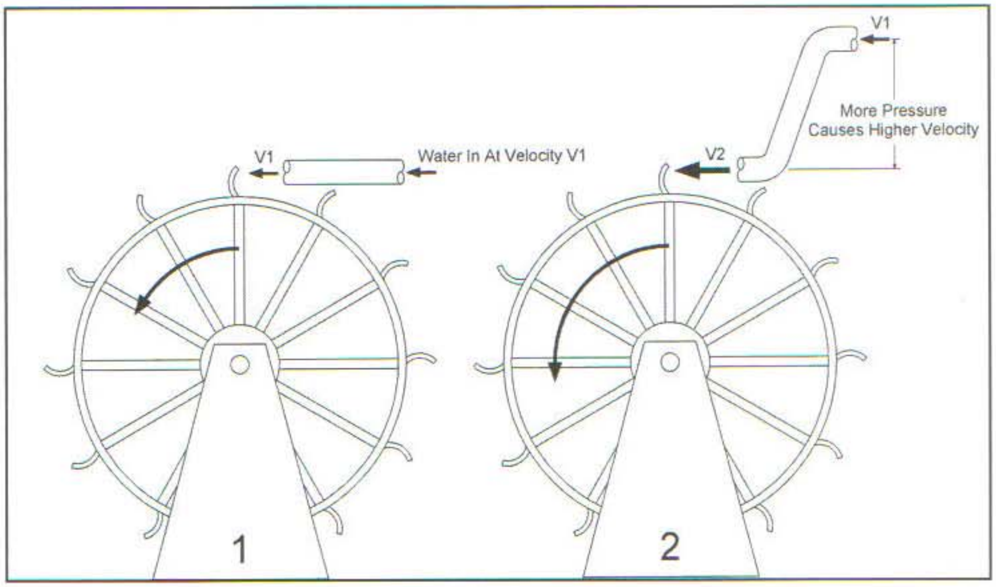
Near the end of the spiral volute, the fast moving exhaust gases exit into the central main chamber of the turbine housing. Here they impinge on, or strike, the blades of the turbine wheel. The momentum of the exhaust stream accelerates the wheel, causing it to rotate.

The turbine wheel blades then redirect the flow of exhaust gases radially inward and, ultimately, out of the turbine in an axial direction near the center of the assembly. From here, the exhaust stream flows through the downpipe and continues into the remainder of the exhaust system. The turbine works by converting the kinetic and thermal energy contained in the exhaust stream gases into the rotational energy of the wheel. Let's look a little closer at how this process works.

TURBINE BASICS

Momentum transfer is the physical process that ultimately causes the turbocharger shaft to spin. Momentum is defined as mass multiplied by velocity. For a turbo, this means that the speed of the gas molecules striking, or impinging on the turbine wheel is critical in the process of making

A high-performance turbine housing for use on a Buick Grand National. Note the large external wastegate mounting flange that is cast directly into the housing. (Turbonetics)



In much the same way as a water wheel operates, momentum transfer between the exhaust gas and the turbine wheel is what powers a turbocharger. Momentum is defined as mass multiplied by velocity. It takes gas molecules moving at speed and striking the turbine wheel to make it rotate. The bulk gas speed comes from the initial blow-down velocity when the exhaust valve opens in the cylinder head, plus an additional acceleration as the gas moves from the high-pressure manifold side of the turbine through to the low pressure exhaust outlet.

the wheel rotate. But armchair engineers often point out that it's the "heat" of the exhaust stream that spins the turbine. Others say that it's the kinetic energy. What's the difference? Or is there one?

Simple physics show us that the only thing that can physically accelerate a turbine wheel is a gas stream with a velocity. It literally takes moving gas particles impinging on the blades of the turbine wheel to make it rotate. This is momentum transfer. Kinetic energy of the gas stream is converted to the kinetic energy of the wheel. The faster the gas flows, the faster the wheel can spin.

There are two main sources to the velocity of the gas flow through the turbine. First is the basic exit velocity of the exhaust flowing from each exhaust port during blow-down and the piston's exhaust stroke.

Blow-down occurs when the exhaust valve opens as the piston approaches BDC. The pressure difference between the hot, pressurized gas in the combustion chamber and the cooler, more expansive exhaust manifold cause a flow of gas. Added to this flow velocity is the effect of the piston rising and physically pushing the gas outward. The speed of the gases flowing into the exhaust manifold at this point can be 350 ft/second or more. Let's call this blow-down speed Vb.

The exhaust gas that has left the cylinder also has heat energy contained within it. The heat energy of any physical substance is a measure of how active its molecules are. The higher the temperature of a gas, the more excited its molecules behave. And when excited, gas molecules tend to move apart, or expand. If constrained, say by the fixed volume of an exhaust manifold runner that is "blocked" downstream by a turbine wheel, pressure is conserved.

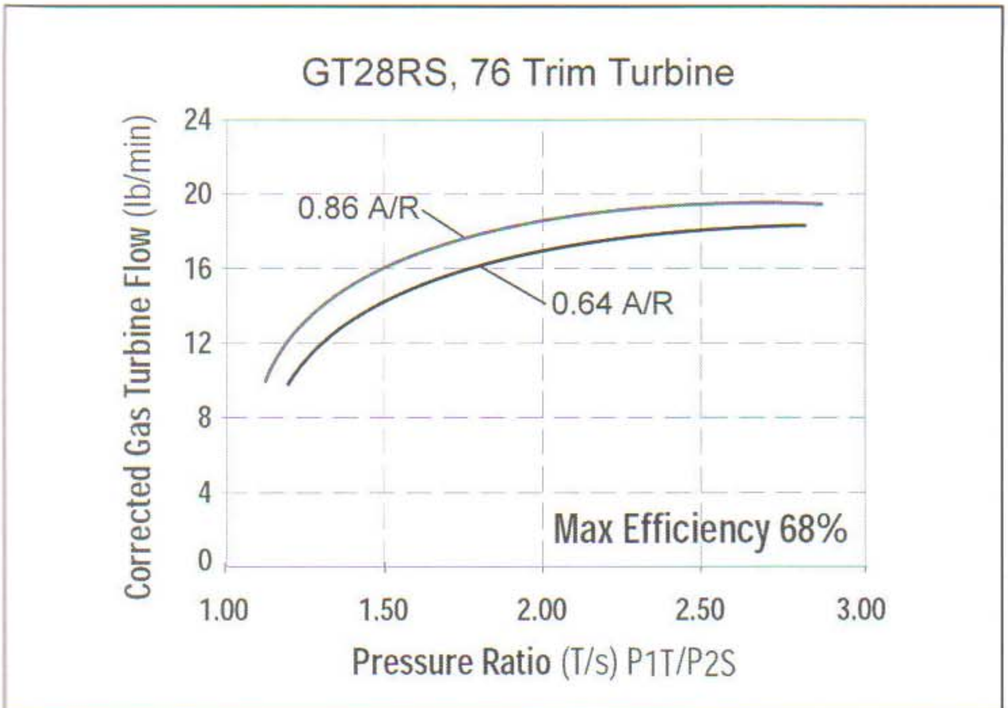
The upstream side of the turbine is subjected to this relatively high gas pressure, while the downstream side of the turbine is at a lower pressure. This is because the downstream side is essentially open

TER

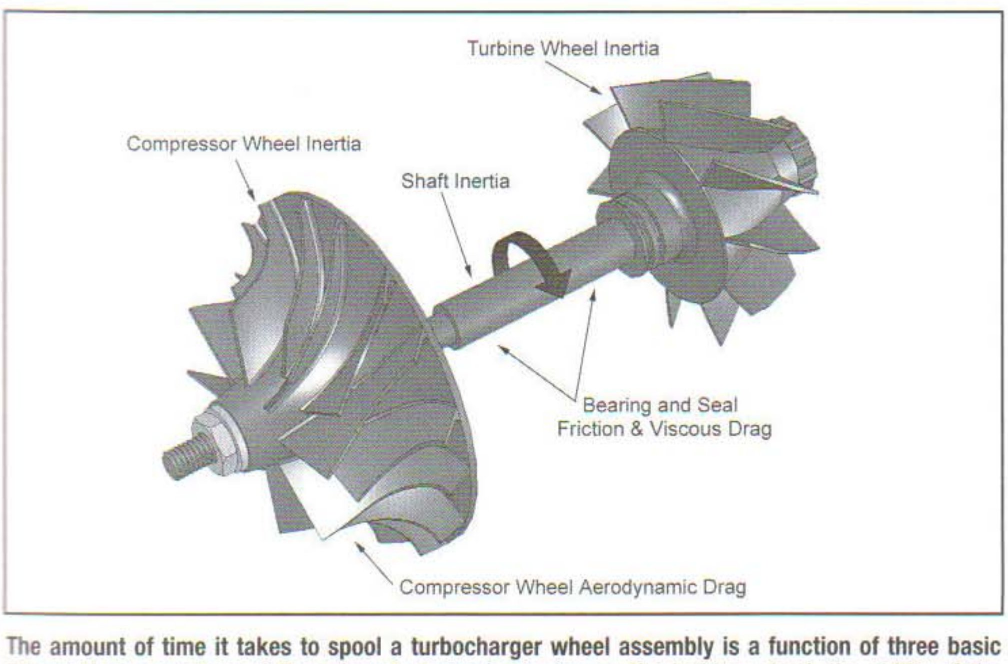
The term "Turbine Expansion Ratio" or TER is a measure of how much the exhaust expands as it passes through the turbine. TER is defined by:

Exhaust Manifold Pressure (psia)/Outlet Pressure (psia)

For example, if the exhaust manifold pressure is 20 psig, and turbine outlet pressure is 1 psig, the TER would be (20 + 14.7)/(1+14.7) = 2.21.



To provide a specific airflow rate and pressure ratio, a compressor requires a certain level of energy input from the turbine. The amount of work a turbine is capable of providing is dependent on a number of basic variables, including the exhaust flow rate, the heat energy contained in the gas, the expansion (pressure) ratio across the turbine, and the efficiency of the turbine itself. Turbine maps quantify the relationship between some or all of these variables. These types of charts are used by turbocharger engineers to size a turbine based on the compressor requirements. For the average layman, however, trying to make use of a set of turbine maps is very difficult. This is because the maps available to the consumer are usually overly simplified, without individual shaft speed lines or efficiency contours included. And even if you can get your hands on an actual engineering map with all the correct data, the math involved to use it requires complex iteration between compressor requirements, shaft speeds, and turbine efficiencies. (Honeywell Turbo Technologies)



The amount of time it takes to spool a turbocharger wheel assembly is a function of three basic things: the momentum of the exhaust stream impinging on the turbine wheel, the ability of the turbine wheel to "capture" this momentum, and the resistance of the wheel and bearing assembly to rotation. This last item, rotational resistance, is dependent on the bearing and seal friction, the aerodynamic drag of the compressor wheel, and the inertial properties of the compressor and turbine wheels and connecting shaft.

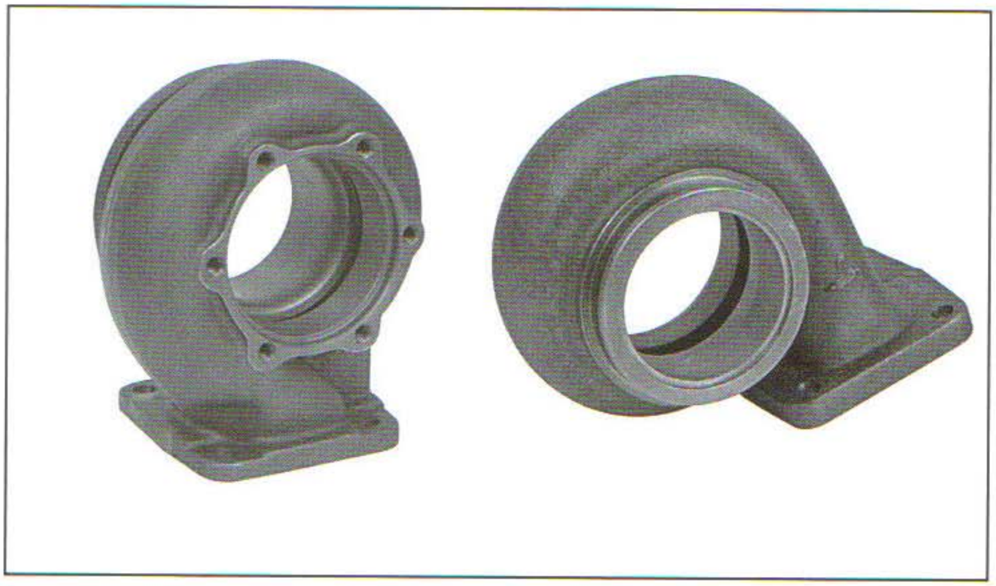
to the outside, or ambient environment via the exhaust pipe and muffler. In other words, there is a pressure gradient, or drop across the turbine. This in itself causes an acceleration of the gas flow that is added to its initial velocity, Vb. (Simply crack open the outlet valve of a pressurized air tank to understand how this pressure-driven type of flow acceleration works. The air inside will rush rapidly out of the tank, equilibrating from high pressure to low.)

The higher the pressure difference between the upstream and downstream side of a turbine, the faster the exhaust gas will accelerate above Vb as it passes across the wheel. Legendary turbo engineer Hugh MacInnes once estimated that the total gas velocity across a turbine assembly was 1500 to 2000 feet per second.

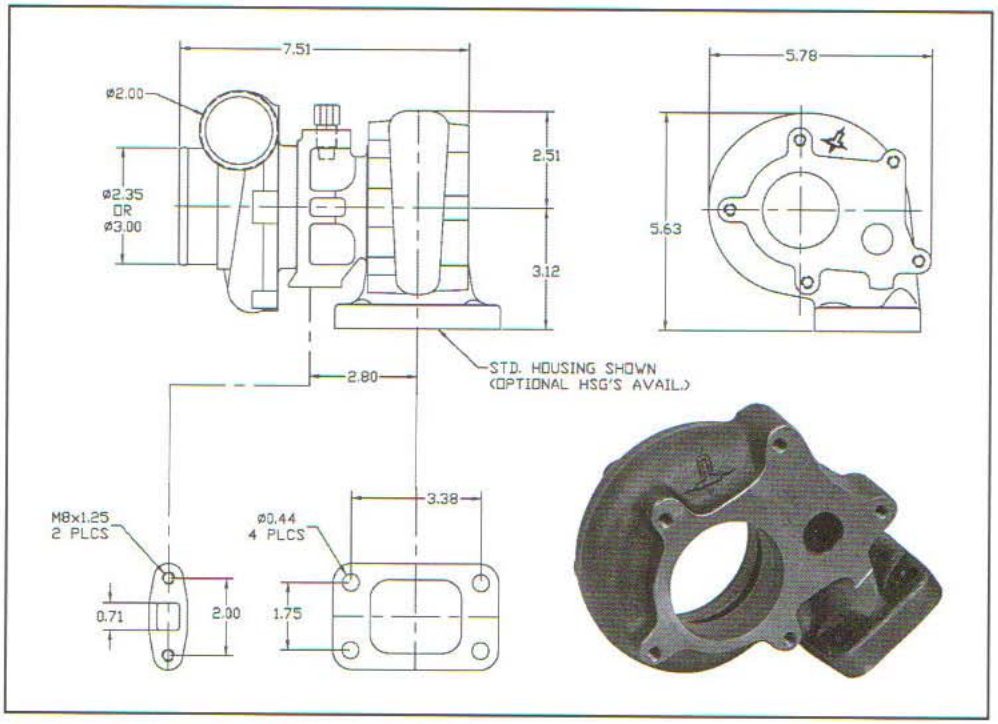
What this all means is that the flow of hot exhaust gas that crosses a turbine can be at a relatively high velocity. And this of course means that the momentum transfer can be high, and the turbine wheel can rapidly accelerate. A combination of the initial bulk gas kinetic energy, and the thermal (heat) energy contained in the exhaust stream, is transformed into rotational (kinetic) energy of the turbine wheel.

TURBINE HOUSINGS

Selecting the correct turbine is not as mathematically straightforward as it is for compressors. Indeed, like compressors, turbine maps do exist. But for the average layman, these maps are difficult to get copies of. Worse, the math involved in working through a



Turbine housings are available in many different shapes and sizes, but they all serve the same purpose: to channel hot exhaust gases to the turbine wheel and then exhaust them with minimal backpressure and turbulence. Shown at the left is a so-called "on-center" housing; at right is a "tangential" housing. (Turbonetics)



The timeless T3 turbine housing. Note the separate wastegate flow opening on the exhaust flange face. (Turbonetics)

turbine map is iterative in nature and can be very difficult, even for experienced turbo engineers. The good news, however, is that turbine selection, while important, is not nearly as sensitive as the selection of the proper compressor. Because of this, there are some general guidelines and rules of thumb that can be used with good results. Let's start with the basic size and shape of the turbine housing:

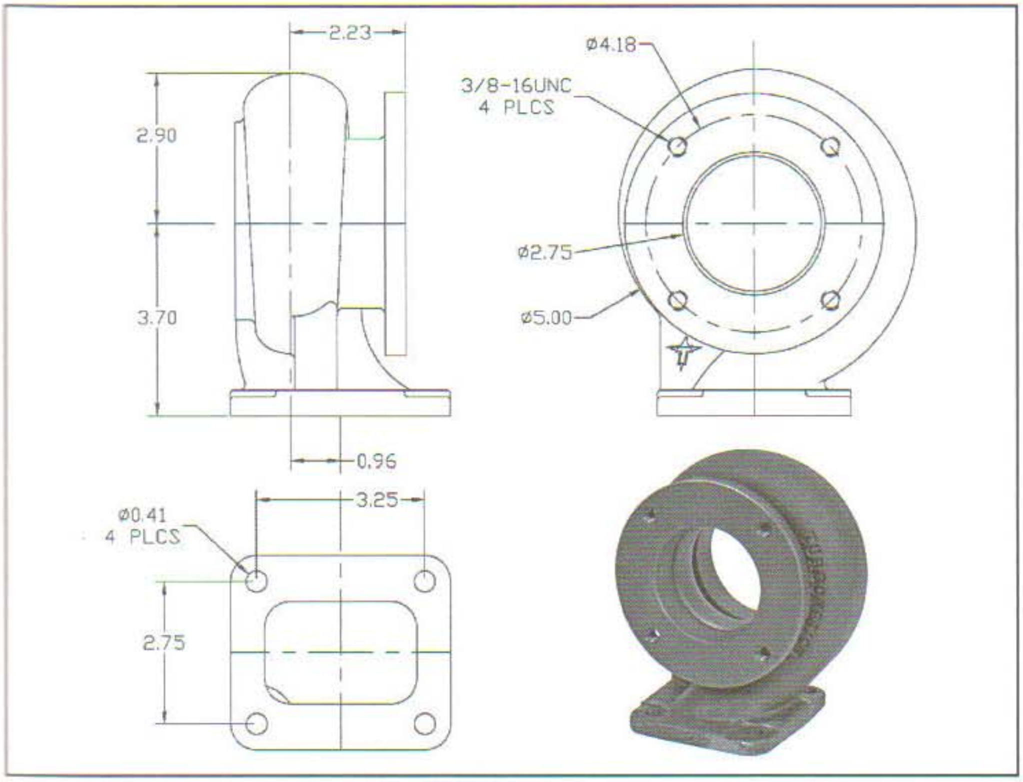
Most turbocharger manufacturers group their turbine housing product lines into different "families" or basic sizes. For example, the smaller turbochargers that the supplier Turbonetics markets falls under the "T3" heading. Moving up in size, Turbonetics carries lines under the categories T04, T4, 60-series, and so on. Other manufacturers follow similar classifications.

Turbine housing families are also grouped according to horsepower ranges. Using Garrett as an example, their GT2x family is generally suitable for horsepower outputs in the 150 to 300 hp range. The GT3x family is best suited for 350–600 hp, and the GT4x family is intended for 500–1000 hp or so. These are just general guidelines, however. The best way to actually select a housing size is to speak with turbocharger manufacturers and start with their recommendations. Talk also with owners and racers of vehicles with similar equipment to yours to see what does and doesn't work. Unfortunately, for the typical street application, it doesn't really get more scientific than this.

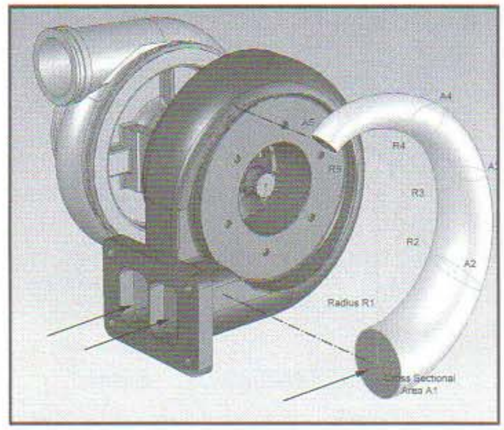
Okay, so once the basic housing size is selected, the next step is to look at different geometries within that family. The internal geometry of a turbine housing can have a significant effect on how quickly the engine responds to throttle input, as well as how much horsepower can ultimately be created. The most important geometrical consideration is something called the area/radius ratio.

Area/Radius Ratio

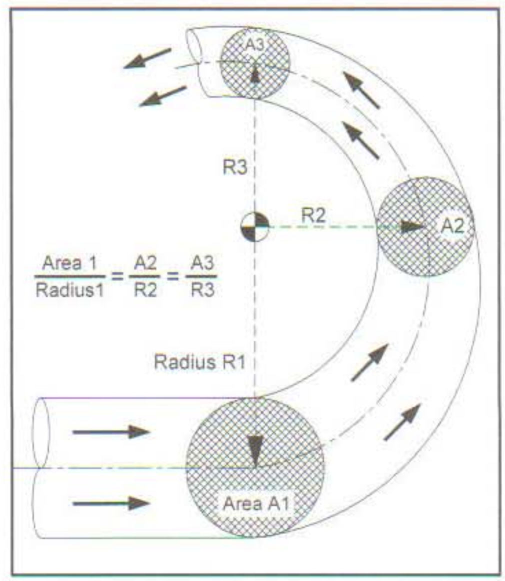
The area/radius ratio is commonly referred to as the "A/R" of a turbine. Sometimes it is simply called the area ratio. In any case,



An on-center T4 turbine housing. On-center housings like this theoretically exhibit worse flow efficiencies than equivalent tangential-style housings, but the difference is normally just a few percent. The decision to use one over the other is often made on installation and space concerns within the engine compartment. On-center housings require slightly less mounting space than a tangential housing. (Turbonetics)



The A/R ratio of a turbine housing is one of the most critical aspects in turbine selection. How the engine responds to throttle inputs is strongly dependent on this value. Larger A/R housings have good flow, less backpressure, and create more top-end power at the same boost pressure. Conversely, smaller A/R housings support less flow and have more backpressure, but offer quicker turbo spool-up characteristics when coming up from idle and off-boost.



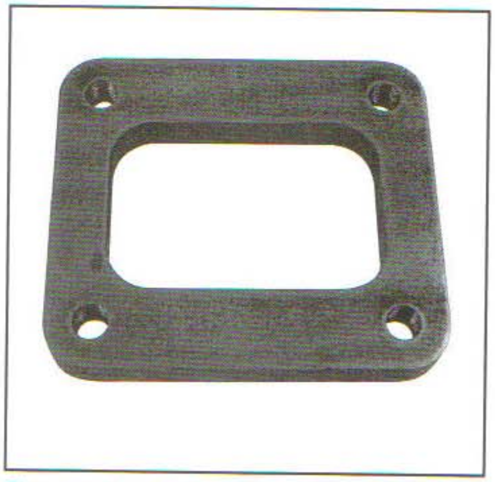
The A/R ratio of a turbine housing is a mathematical description of the cross-sectional area of the turbine housing inlet divided by the radius, or distance from the center of the housing to the center of the inlet area. This ratio stays constant throughout most of the volute of the housing as it tapers inward from the turbine inlet.

the area/radius ratio is a numeric value that is equal to the cross-sectional size (area) of the turbine housing inlet inside the volute, divided by the distance from the center of that area to the center of the turbine (radius). Astute readers will note that the turbine inlet follows an inward spiraling volute, with both the area and radius values getting smaller at the same rate, the farther along the path they are measured. Anywhere along the inlet path, the A/R ratio will be a constant, unchanging number.

Values for turbine A/R ratios range from 0.4 at the small end, to well over 1.4 at the upper end, with the most common street applications falling somewhere in the 0.6 to 0.9 range. Generally speaking, the smaller the A/R ratio, the faster the turbo will spool. This results in a reduced lag time and faster throttle response. The downside of a small A/R ratio, however, is that exhaust flow will encounter higher backpressure as flow increases. This will cause more "choking" of the flow in the upper part of an engine's rpm range. Selecting too small of an A/R ratio can also result in poor drivability, in which the turbo is "trigger happy," exhibiting a sudden on-and-off feeling when the throttle is applied.

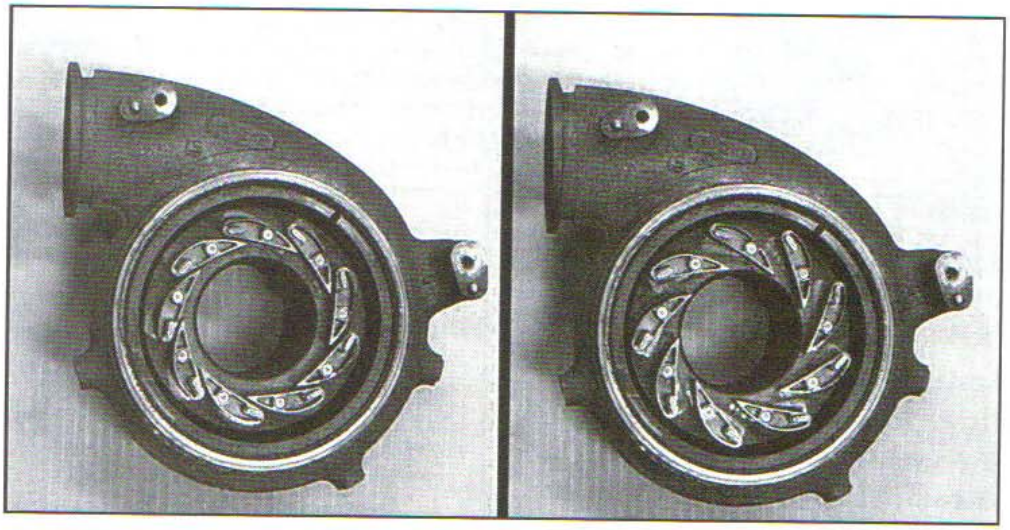
Larger A/R ratios, on the other hand, can be relatively "laggy" at low speeds and off boost, but at higher rpm ranges they will exhibit lower backpressure and can support higher horsepower levels.

The A/R ratio of a turbine is relatively independent of the overall size of the turbine. A small turbine that is suitable for a small engine can have an identical A/R value as a much larger turbine intended for a larger engine. The A/R ratio is just that: a ratio. A small Garrett T25 turbine can have an A/R ranging anywhere from 0.5 to 0.86. Likewise, a larger T04 turbine can have a similar range of



The ubiquitous T4 turbine housing inlet flange, available from many aftermarket suppliers. (Turbonetics)

V-band turbine exit clamps like this offer the fabricator a lot of flexibility in orienting the exhaust down pipe. (Turbonetics)



A variable area nozzle turbine (VATN) employs a set of vanes that can change position to alter the exhaust gas velocity as it enters the turbine. This permits the turbine to behave like a small A/R housing at low flow rates, and a high A/R housing at the upper end of the rpm range, with a smooth transition between the two. The durability of early VATN assemblies was reportedly poor, but manufacturers have since greatly improved the reliability of the units.

possible A/R configurations.

WHEELS, TRIMS, AND CLIPS

Along with choosing a basic housing is the process of selecting the turbine wheel. A turbine wheel must be matched to its housing. But like the process of selecting the housing, the sizing of a wheel for a given application requires advanced mathematics. That said, there are some basic rules of thumb.

Wheel Selection

For example, it is commonly understood that the selection of a turbine wheel can be based somewhat on the size of the previously selected compressor wheel. A good first guess at the major diameter of a turbine wheel is to keep it within 10% of the major diameter of the compressor wheel. If a 2.5-inch nominal diameter compressor wheel is used, for example, a 2.25- to 2.75-inch nominal diameter turbine wheel should be targeted as a starting point. Because inertia plays such an important role in transient response, it's better to err on the smaller side and work your way up to larger wheels, than vice versa.

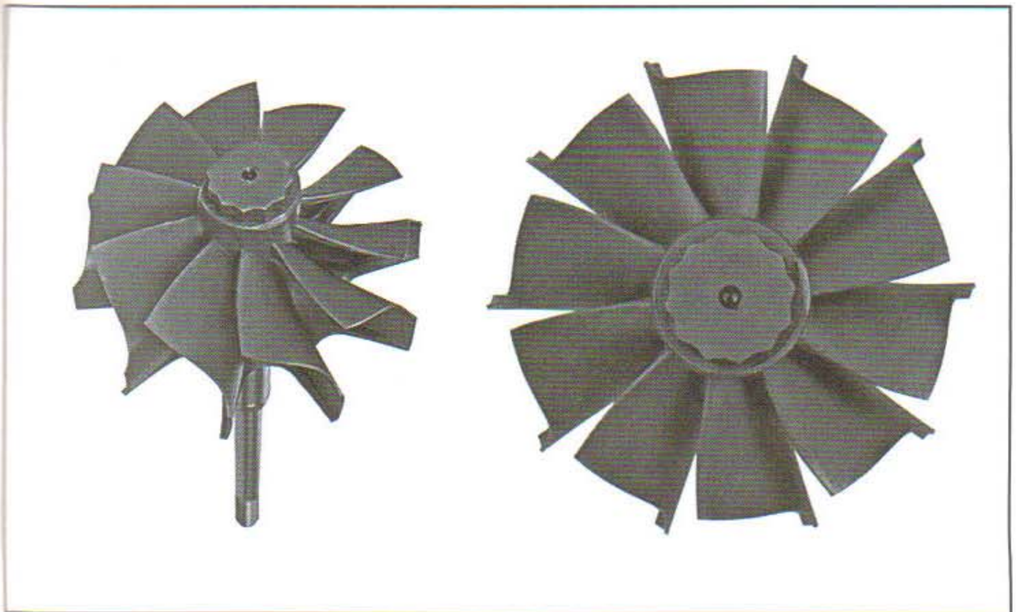
Wheel Trim—Once a nominal wheel size is selected, there are a myriad of options and configurations for that wheel available. The most important of these options is something called wheel trim. Strictly speaking, trim is a term used to define the shape of both compressor and turbine wheels. It is more commonly used when referring to turbines, however. In mathematical terms, trim is determined by the following equation:

Eq. 5-1

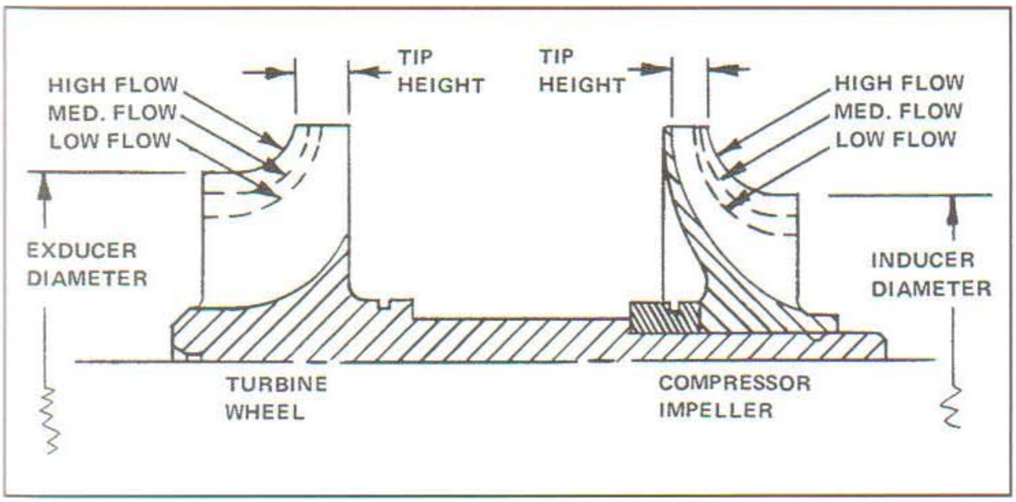
$$\text{Trim} = (100)\left(\frac{\text{Wheel Diam.}_{\text{Small End}}}{\text{Wheel Diam.}_{\text{Big End}}}\right)^2$$

Generally speaking, the larger the trim, the more gas flow a wheel can support. Larger trims mean more horsepower production at higher engine speeds. On the other hand, larger trims imply more rotational inertia, and the turbine will therefore spool slower and result in more lag.

The mathematical designation of trim numbers is useful, but, unfortunately, manufacturers often replace the number with a letter or word, making it difficult for the layman to know what the actual value is. For example, you can purchase either "P," "O," or "Q" trim turbine wheels from one popular manufacturer. The "Q" trim wheel is larger than the "P" trim, but by how much? You will have to ask the manufacturer or consult a conversion table.



As with turbine housings, turbine wheel assemblies come in many different sizes and shapes (trims). Generally speaking, larger wheels and trims support higher horsepower outputs at higher engine rpm ranges, while smaller wheels and trims offer lower mass moments of inertia, or resistance to rotation. This means they spool up more quickly. (Turbonetics)



Contour relationships for different flows. (MacInnes)

TURBINE WHEEL MATERIALS

There are high thermal stresses working on the components of a turbine. Choosing the best materials is important for the long-term durability of the system.

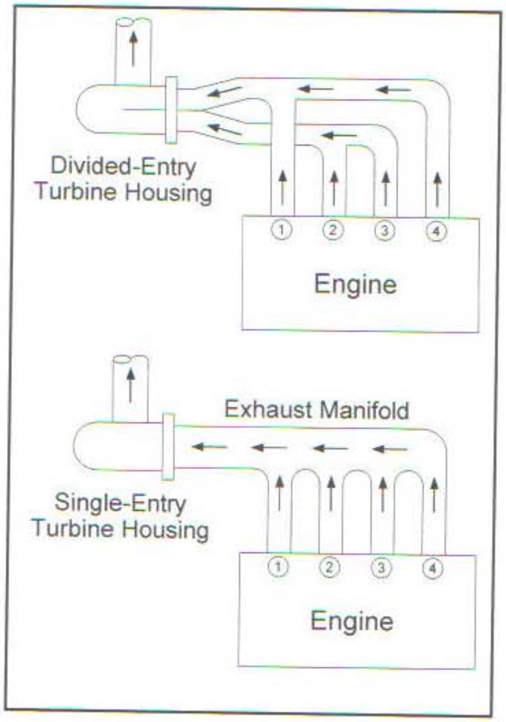
Many turbine wheels are constructed from high-strength alloys such as Inconel or Mar-M. Of these, Inconel is more common and provides excellent temperature resistance. Mar-M is even better, but tends to be more expensive. Turbine housings are usually fabricated from ductile cast iron or "Ni Resist," which is an alloy of iron with high nickel content.

Wheel Clip—In addition to trim, another term that is commonly used to describe turbine wheels is "clip." A clipped turbine wheel is one in which the outer edges of its blades have been machined down. This is often done at a slight 5 to 15 degree angle. This has the effect of reducing the flow resistance across the turbine and therefore boosting upper rpm horsepower. The downside of clipping, however, is that it tends to reduce the effectiveness of the wheel at slower speeds, which in turn tends to increase lag. Some turbo suppliers proudly state that they supply clipped wheels with their turbochargers; other suppliers, just as proudly, state that they would never sell a clipped wheel.

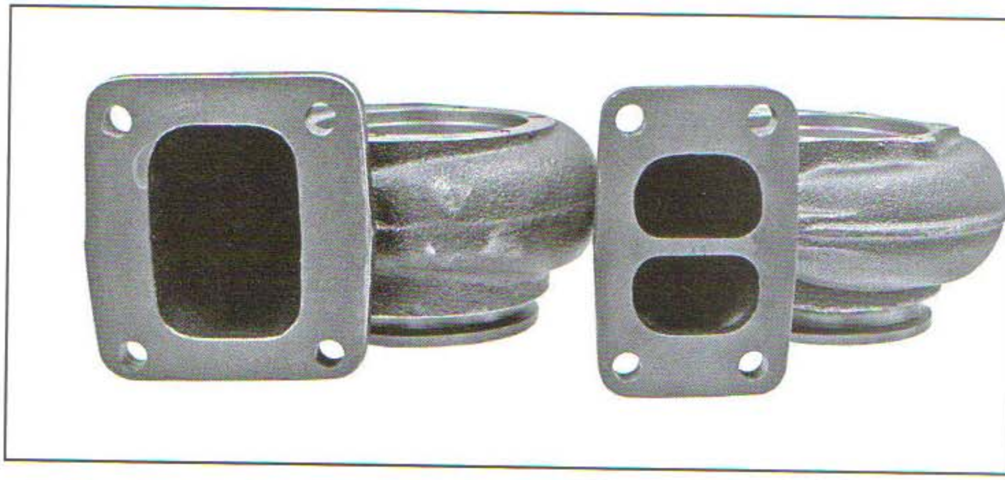
DIVIDED-ENTRY TURBINES

In a perfect world, the hot combustion gases expelled with each exhaust stroke from an engine cylinder would travel as well-defined, homogenous "pulses" of energy (sometimes referred to as "putts") all the way from the combustion chamber, through the exhaust manifold, to the turbine. Unfortunately, the other engine cylinders are also expelling their own energy pulses in sequence. In a typical turbocharger exhaust manifold, all these pulses come together in a collector upstream of the turbine. The gas pulses can and do interfere with each other, robbing the total gas flow of kinetic energy that would otherwise be put to use accelerating the turbine wheel. Worse, as one chamber is on its exhaust stroke, another is on its intake stroke. The exhaust stream from one cylinder can in fact find itself drawn into another cylinder due to valve overlap. This obviously has a detrimental effect on volumetric efficiency. It also increases the likelihood of detonation.

One solution to this problem is



A divided-entry turbine housing offers a small, but measurable advantage for small-displacement four- and six-cylinder engines. In the schematic shown here, the engine has a firing order of 1-3-4-2. Cylinders 1 and 4, and 2 and 3 are furthest away from each other in the firing order and are therefore grouped together in the exhaust manifold.



These two housings use identical trim turbine wheels, but have different A/R ratios and entry styles. The housing on the left is a single-entry with a 0.96 A/R ratio. The housing on the right is a divided entry 0.84 A/R unit. (Turbonetics)

A typical divided-entry turbine housing. (Turbonetics)

to keep each cylinder's exhaust stream separate from the others for as long as possible, right up to—and into—the turbine itself. To accomplish this, some turbine housings are constructed with divided, or twin-entry inlets. Originally developed for large diesel applications, these divided-entry turbine housings have gained favor among smaller displacement four- and six-cylinder engines. On these smaller engines, the detrimental effect of one cylinder's pulse interfering with another is more significant than on eight-cylinder engines.

A typical divided-entry turbine utilizes two separate volutes, or spiral flow paths into the turbine housing. Both of these volutes empty into the same central portion of the housing, and both supply their hot exhaust gases to the same turbine wheel. The difference is that the exhaust paths on a divided-entry turbine are separated for a longer effective distance than on a traditional single-entry turbine.

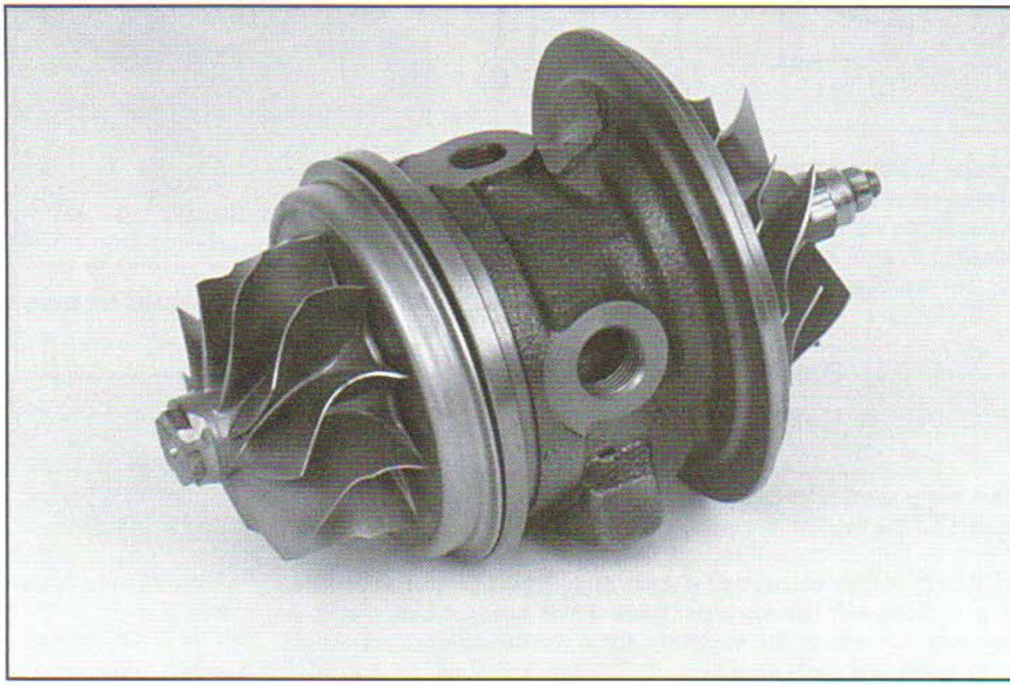
Four-cylinder engines that employ a divided-entry turbine are usually plumbed to combine cylinders 1 and 4 together. These two cylinders are used to feed one of the turbine volutes. Cylinders 2 and 3 are then combined to feed the other volute. For a 1-3-4-2 firing order, this ensures the maximum separation between cylinder pulses. (We'll talk more about this in Chapter 7 when we discuss exhaust manifolds.)

Divided-entry turbines can result in slightly faster spool-up at low engine speeds, lower backpressure at higher speeds, and small but measurable gains in fuel mileage. They can offer a performance advantage for 4- and 6-cylinder engines, typically on the order of 5% or higher.

CENTER HOUSING AND ROTATING ASSEMBLIES

6

Turbochargers spin at rates of 100,000 rpm or more. Clearly, a well-designed bearing system is necessary to support these incredible rotation speeds. And the bearings themselves require a solid housing and a reliable supply of lubricant to keep them alive. Many turbo bearings also require a flow of coolant to keep temperatures down and protect the oil from breaking down. The entire bearing/housing/lubrication unit that connects the turbine to the compressor is known as the *center housing*. The central spinning shaft, including the compressor and turbine wheels, is collectively known as the *rotating assembly*. When combined with all the seals, gaskets, and other items used to keep lubricant inside the unit and hot gases and compressed air out, the entire assembly is known as the *center housing and rotating assembly*, or CHRA for short.



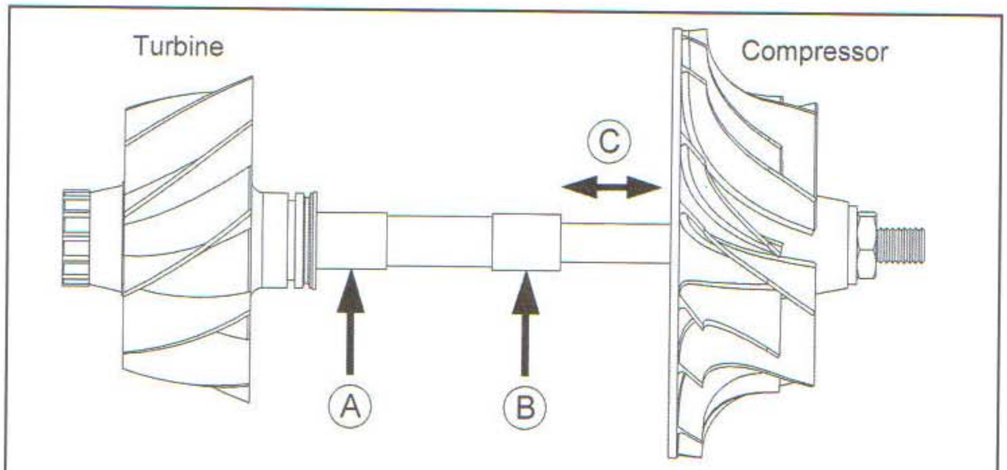
The center housing and rotating assembly (CHRA) is the major structural element of a turbocharger, tying the compressor assembly to the turbine and providing for high-speed rotation and support of the shaft and wheels. A CHRA is called "wet" if it is plumbed into the water cooling system of the engine; otherwise it is called "dry," relying solely on engine oil for cooling. (Honeywell Turbo Technologies)

There are two types of bearings used in modern turbocharger CHRAs. These are the ubiquitous oil journal-type bearings, and the less common rolling element type (ball bearings). The latter, ball bearings, are relatively new on the marketplace. They offer the advantages of less rolling resistance and, hence, faster spool-up than journal bearings. The tried-and-true oil journal bearing, however, has proven itself for decades. Let's look first a little closer at journal bearings.

OIL JOURNAL BEARINGS

An oil journal-type turbo bearing looks somewhat similar to the journal bearings that support an engine crankshaft and connecting rods. Unlike those bearings, however, the loading in a CHRA is significantly less, but the rotation rate is much higher. The turbo bearing must accurately and precisely position the compressor and turbine wheels in very close proximity to their respective housings. The smaller the gap between the wheels and the housings, the more efficient the hot and cold sides of the turbocharger are going to perform. And efficiency is the name of the game in designing and building a high-performance turbo system.

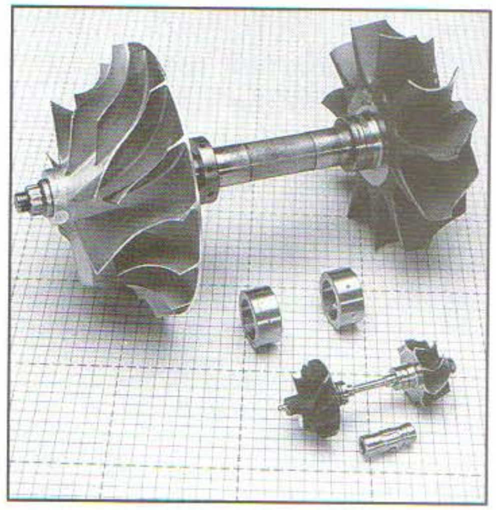
The key to such accurate positioning of the wheels with a journal-type bearing is the oil film that builds up between the spinning shaft and the journal. This thin layer of oil is known as an elasto-hydrodynamic, or EHD film. Lubrication engineers spend entire careers studying and designing EHD bearing systems. The physics behind these units are incredibly complex, but for the sake of simplicity, we're going to



A (radial)	B (radial)	C (thrust)
Journal	Journal	Oil Washer
Journal	Ball Bearing	← None
Ball Bearing	Ball Bearing	← None
Ball Bearing	Ball Bearing	Ball Bearing

There are a number of bearing schemes used to provide the necessary radial and axial (thrust) support for the rotating components of a CHRA. The most common system is a pair of traditional journal, or bronze sleeve bearings used with a thrust washer. High performance units use ball bearings to reduce friction and viscous drag. Thrust control on these units is often accomplished via one of the ball bearing assemblies. Some manufacturers, such as Turbonetics, use a ball bearing at one end of the assembly and a journal bearing at the other. Each of these systems works quite well, and, depending on the application, all have a place in modern turbocharger designs.

CHRAs may look simple, but they're engineered, machined, and assembled to extremely tight mechanical tolerances. This is necessary when spinning at rates of 100,000 rpm or more for tens of thousands of vehicle miles. (Turbonetics)



Bronze journal bearings have been used successfully on thousands of different turbochargers throughout the years. Note the small Garrett GT12 rotating assembly, with its one-piece journal bearing. In comparison, the individual journal bearings of the large Garrett GT60 turbocharger are nearly the same size as the GT12 turbine and compressor wheels! (Honeywell Turbo Technologies)

distill the issue down to a single word of importance: oil.

On most turbocharged engines, the flow of pressurized oil supplied to the CHRA comes from a high-pressure feed out of the main oil galley. A common place for aftermarket turbocharger installations to tap, or "tee" into the oil system is at the sending port used for the oil pressure warning system.

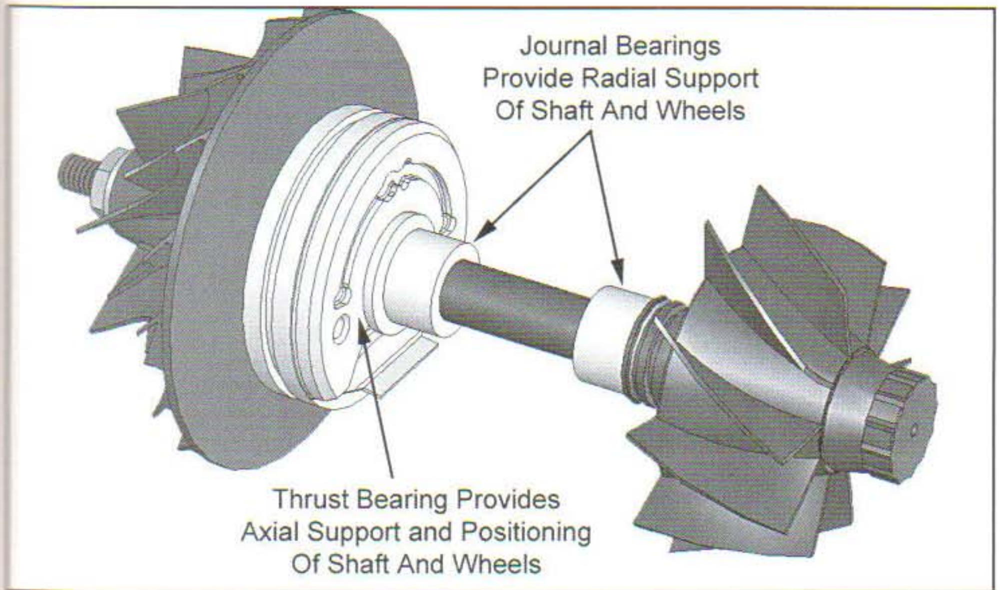
The pressurized oil routed from this tap is injected into the top of the CHRA. From there, it flows down into the bearing journal, where the spinning shaft causes the buildup of the EHD layer of lubricant on the journal. The spinning shaft literally creates the necessary layer of oil that it rotates on.

Once the oil passes through the bearing journal, it drains back either to a return galley in the block, or directly to the oil pan. Most aftermarket turbo installations employ this latter method. Usually a hose fitting is brazed or welded to the side of the oil pan, and a large diameter drain hose is connected between it and the CHRA. A bulkhead fitting can also be used to connect to the pan.

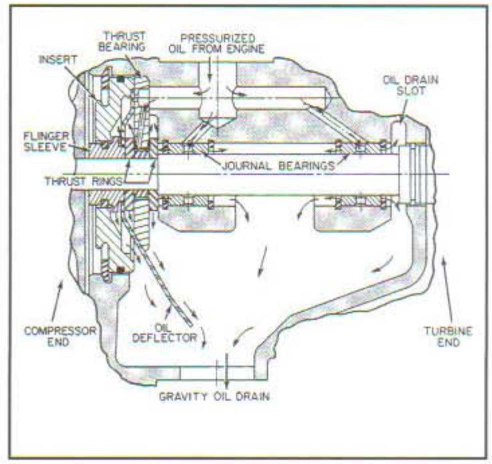
A well-engineered CHRA will have all the correct bearing surface finishes, clearances, and material choices already included in its design. The only real effect most of us have on the performance and longevity of the CHRA is with the oil supply system itself. Clean, filtered, and relatively cool oil is critical for the life of journal bearings.

BALL BEARINGS

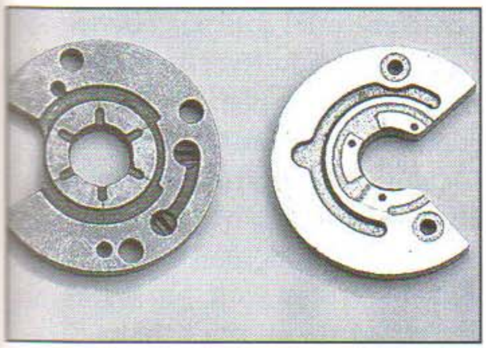
As mentioned earlier, ball bearing–equipped CHRAs are somewhat superior to journal-type bearings from a performance point of view. They're also more costly, however. Let's take a closer look at



A typical journal bearing layout. The most common place for failure in a turbocharger CHRA is at the thrust bearing.



The oil flow path through a typical journal bearing housing. This particular arrangement uses piston rings to seal oil at the compressor- and turbine-ends of the shaft. Note oil deflector and large area for oil drain. (MacInnes)



Most conventional journal bearing turbos use a 270-degree thrust-bearing washer (shown at right), while many of the new breed of turbos employ 360-degree thrust bearings (left). The advantages of a 360-degree bearing include a full circle of lubrication, more orifices on the washer, and an updated pad strategy to better disperse oil where it's needed.

A conventional journal bearing stack up. Note the 360-degree thrust bearing. (Turbonetics)

these units that are gaining in popularity.

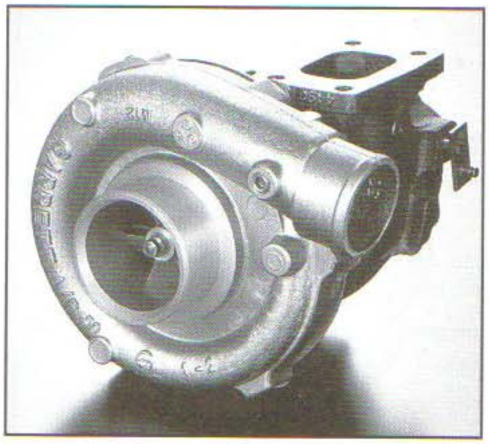
Ball-bearing turbochargers were originally developed for diesel engines used in long-haul trucking and certain marine applications. The technology was needed to help shorten spool-up times and create boost earlier in a diesel's relatively limited rpm range. Shortly thereafter, the word got out to the rest of the automotive world: ball bearings could offer a performance advantage for gasoline engine enthusiasts.

The biggest advantage of ball bearing–equipped CHRAs in gasoline applications is their ability to create boost sooner in the engine's rpm range—sometimes 500–700 rpm sooner. This is due almost solely to their lower rotating friction. It's been shown that reducing friction in a CHRA is functionally equivalent to improving turbine efficiency.

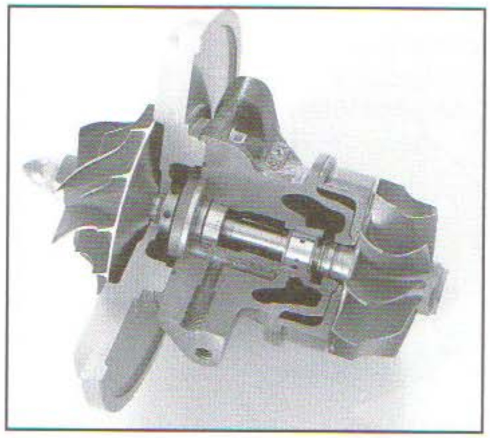
Ball bearing CHRAs also work well with lower oil flow rates. They're also assembled to very high tolerances, which means a closer fit between the rotating wheels and housings is possible. In addition, angular-contact ball bearings offer an inherent axial, or thrust load capacity, that can eliminate a separate thrust bearing altogether.

OIL FEED PRESSURE LEVEL

The oil feed pressure level required for a ball bearing–equipped turbocharger is generally lower than the pressure required for journal bearing turbos. Journal bearing oil-feed pressure levels can damage a ball bearing turbo.



It's difficult to tell just by looking at the outside, but this fast-spooling GT2540R turbocharger is equipped with dual ball bearings. Ball bearing center sections were originally developed for turbo-diesel engines but have found use in high-performance motor sport and street applications. Ball bearings don't require as much lubricant as journal bearings and are less sensitive to oil starvation. They also offer lower rolling resistance, which allows the turbocharger to spool faster. A ball bearing–equipped turbo can often make full boost 500 rpm or more sooner than a journal bearing–equipped unit. (HKS)



This unique Turbonetics hybrid CHRA uses a single angular contact ball bearing on the compressor side (thrust side) and a conventional journal bearing on the turbine side. (Turbonetics)

Depending on the application and mounting configuration, a ball bearing CHRA can withstand 2 to 50 times the thrust loads that a conventional washer-type journal thrust bearing can tolerate. This in turn means greater resistance to compressor surge and other transient backpressure events in the intake and exhaust tracts.

Typically, ball bearings are mounted in pairs in essentially the same locations that two journal bearings would be mounted. Some manufacturers simply machine pockets in the CHRA housing into which the bearings sit, while others, such as Garrett, mount the bearings in a cartridge, which in turn is suspended in a thin oil film. It is claimed that this latter type of system allows for damping of damaging "harmonic" resonant frequencies that can occur at various shaft speeds.

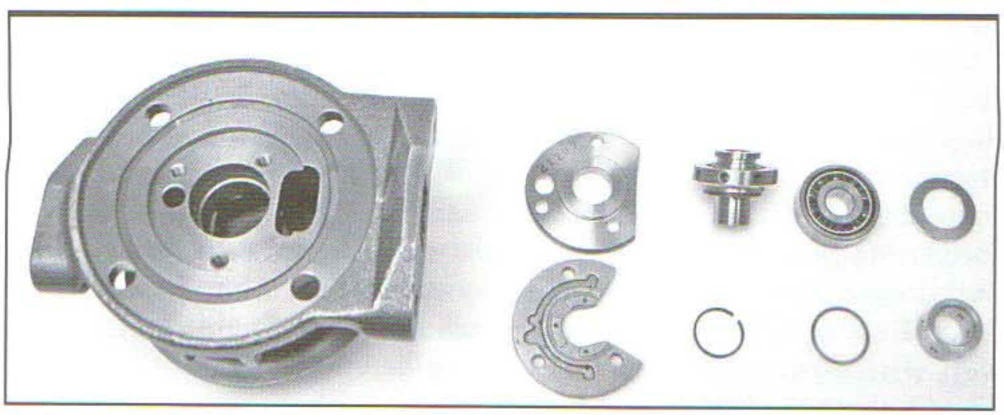
While dual-type bearings make up the majority of ball bearing CHRAs sold today, other manufacturers are experimenting with single bearing designs. Others, such as Turbonetics, utilize "hybrid" configurations that incorporate a ball bearing at the compressor side of the CHRA, and a conventional journal bearing at the other end. Excellent performance has been demonstrated with all of these systems.

Manufacturers are also providing ceramic bearings in their high-end units. Traditional ball bearings are machined from high-strength hardened steel, which offers durability and is readily machined. Ceramics are somewhat more difficult to manufacture, but they offer reduced friction, as well as lower rotating mass. All things being equal, a properly engineered ceramic bearing-equipped CHRA is almost always superior to the other types of rolling element bearings.

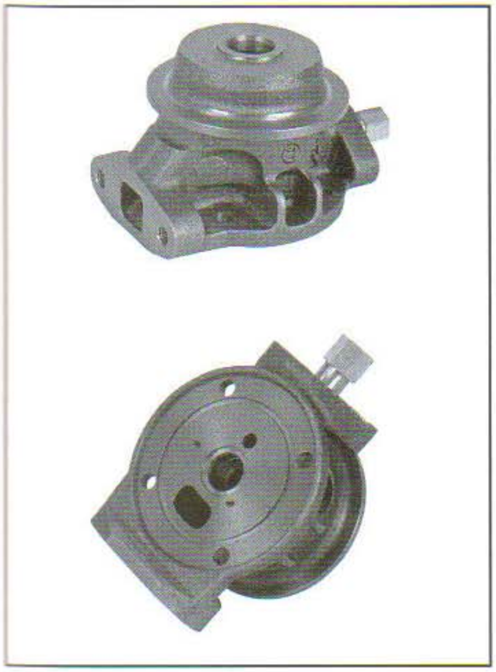
While seemingly ideal in most respects, the biggest downside of ball bearing CHRAs, of course, is their cost. They're also trickier to service and troubleshoot if a problem occurs and usually have to be sent back to a service center for repairs, or replaced altogether.

ADVANTAGES OF BALL-BEARING CHRAS

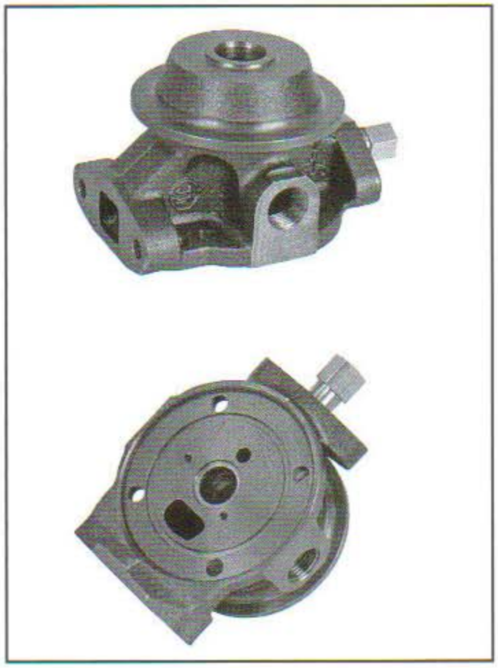
One of the benefits of ball bearing CHRAs is their ability to absorb large thrust loads due to surge. Ball bearing–equipped turbos also can keep the turbo "idling" at higher average speeds than a similar journal bearing–equipped turbo. This helps reduce the spool-up time of the unit.



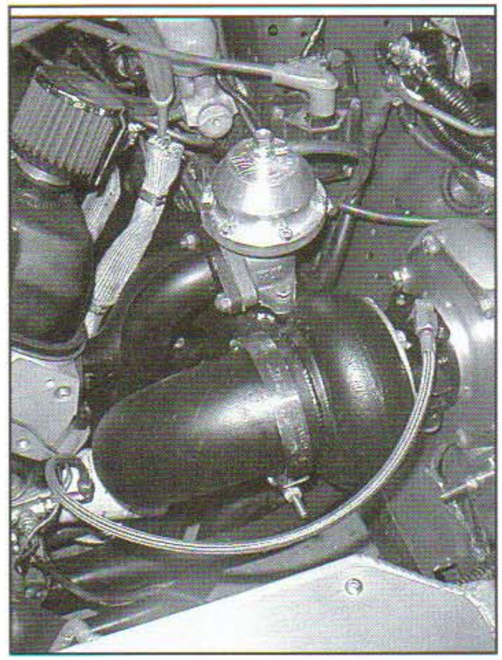
The components that make up the hybrid journal–ball bearing system. (Turbonetics)



A typical dry CHRA center section. (Turbonetics)



A wet CHRA center section. Note the port for coolant water to flow through the assembly. Generally speaking, wet CHRAs provide better protection to the internal bearings than a dry assembly, but they also require more complex plumbing. (Turbonetics)



Whether journal or ball bearing-equipped, all CHRAs require a steady supply of clean, filtered oil. Many aftermarket turbo systems tap into the oil pressure sending port on the side of the engine block. A simple "T" arrangement ensures sufficient oil to the turbocharger. Note the use of a high-quality braided stainless steel hose on this single-turbo Ford Mustang. (Kendall)

OIL SUPPLY SYSTEMS

Whether journal- or ball bearing–equipped, all CHRAs require a supply of lubricating oil that is clean and exhibits proper viscosity and flow characteristics. Oil degrades due to three things: contaminants, age, and heat. The first two of these, contaminants and age, are easy to address via good filtration and frequent oil changes. Use only high-quality filters and change the engine oil no less than once every 2500–3000 miles. Yes, this is more frequent than what is usually recommended for naturally aspirated engines, but a turbo imparts a significant amount of heat into the oil, which has the effect of breaking it down sooner than usual.

Use either synthetic or traditional mineral-based oils. Synthetics are slightly better, but they're also more costly. Studies have shown that there is essentially no difference in engine or turbo wear if either type of oil is used and changed on a frequent basis. The main advantage of synthetics is their resistance to heat effects (i.e., coking), which means you can wait somewhat longer between oil changes than with mineral-based oils. Synthetics also exhibit slightly lower frictional drag (which helps spool-up times), but the effect is small.

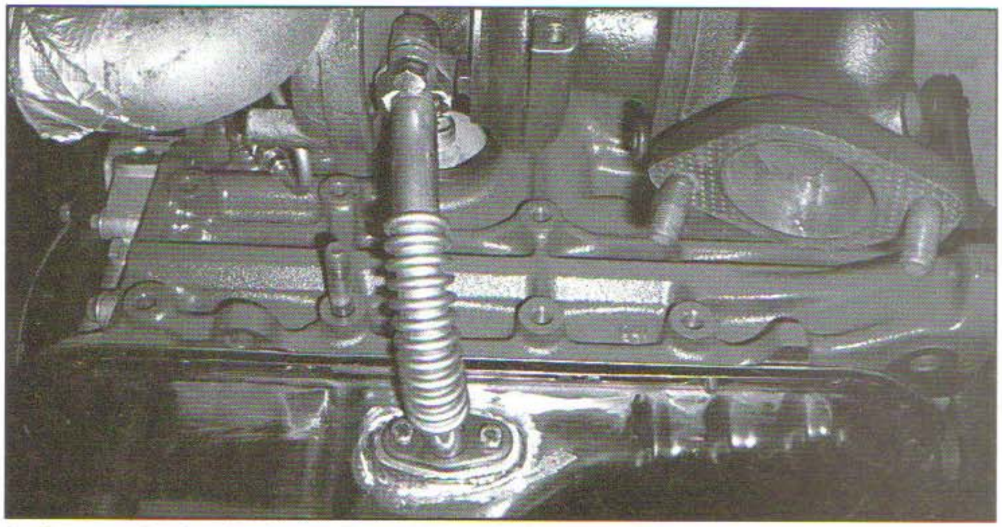
Besides frequent changes, keeping the system oil temperature down is also an important factor in bearing life. Hang around turbo engineers long enough and you will undoubtedly hear the terms "oil coking" and "coked-up bearings" bandied about. Oil coking refers to a process in which oil essentially self-distills due to excess heat. This leaves a deposit of sludge-like oil and carbon (coke) buildup on the journal bearing.

The important thing to remember here is that excess heat is the enemy. So-called "wet" CHRAs that employ water cooling jackets around their bearing sections are superior to "dry" units that don't. A well-engineered water-cooled CHRA will almost never reach the temperatures required to coke the oil (approximately 500°F). Similarly, another excellent addition to a turbocharged engine is a high-quality external oil cooler.

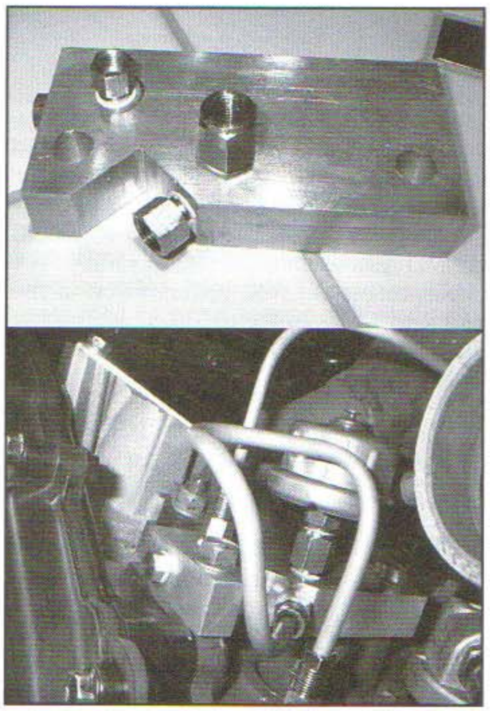
Oil and Water Lines

If a compressor is the lungs of a turbocharger, and a turbine is its heart, then the oil and water lines feeding the CHRA are the system's main arteries. Too often turbochargers fail prematurely due to inferior hoses and/or end fittings. There is no excuse for this. The water and oil supply and return lines feeding your turbocharger may not be as sexy as a polished

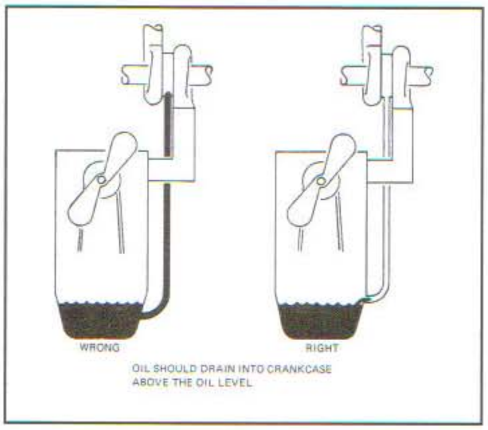
Miniature oil filters are often used to keep contaminants out of the CHRA. This unit features an internal filtration screen. It screws into the inlet port at the top of the CHRA. (Turbonetics)



A nice example of a simple and direct oil drain back system. Note the large diameter steel tubing with integral flex bellows that allows for differential movement of the turbocharger and the engine block due to thermal expansion. (Picasso)



Sometimes you have to be creative to find a supply of high-pressure oil. The owner of this vehicle machined an oil-supply manifold block, into which he could tap any number of outlet ports. One port feeds the turbocharger, while a second supplies an oil pressure sending unit. A third port could be added for a direct-feed oil line to a mechanical pressure gauge or to a second turbocharger. (Picasso)



The right and wrong ways of draining oil from the turbocharger back to the oil pan. The oil drain hose diameter should be as large as possible. A good rule of thumb says that the tubing should be at least five times the diameter of the supply line. The oil is returned to the pan via gravity only; it is imperative to return the hot oil as efficiently and quickly as possible. (MacInnes)

blow-off valve or big intercooler, but they are more important. Get the design or installation of either of these liquid lines wrong, and you can guarantee your turbocharger—and possibly the engine itself—will die a quick death.

Use only hard steel lines and braided-stainless hoses. No ifs, ands, or buts. AN-type fittings are the best. These are not inexpensive, and, yes, specialty tools are required to bend and install them, but for rock-solid reliability, there is no substitute.

The goal is to build a robust, very functional, highly reliable lubrication and cooling system. Plan the routing of the lines as far from hot components like the exhaust manifold as possible. Use braces and supports to keep vibration loads off the end fittings. Use ties, c-clips, and clamps to hold the lines in their proper places.

And don't forget the oil drain line, either. It should be just as well-engineered as the supply lines. Gravity is the main force getting the oil back to the pan. Keep this line as straight, short, and vertical as possible. A good rule of thumb is to make the return line at least five times the diameter of the supply line into the CHRA. You don't want to skimp on quality here. I once saw an engine grenade when it ran out of oil due to a faulty turbo oil return line. The oil supply line was braided stainless steel with high quality AN fittings, but the return was just a cheap rubber hose not rated for hot oil. It split in half during an endurance race. Five quarts of oil were dumped on the track when the engine was at redline. The owner paid a big price for that cheap hose. Don't let this happen to you.

Heat is an oil killer, and turbos, by their very nature, are hot devices. When run hard and then immediately shut down, the oil left inside a CHRA can overheat and turn into a black, tar-like substance called coke. The obvious solution to this problem is to allow the engine to idle for a few minutes prior to switching it off. Turbo timers are for those without the patience to sit in a car, waiting for this requisite cool-down period to occur. A turbo timer keeps the engine idling after the key has been removed from the ignition. And yes, integrated security circuits in the unit keep thieves from driving off in the car during the cool-down period. (GReddy)

TURBO TIMERS

When you shut down a turbocharged engine, the turbine and compressor wheels spool down relatively quickly, typically within seconds. In contrast, the heat absorbed during operation by the turbo housing can take many minutes to drop even a small amount. Coking of petroleum oil inside a CHRA quickly happens at temperatures above 500°F. These conditions can occur if a turbocharger is run hard and then immediately shut down. The oil that has just flowed into the bearing housing during shutdown is at a lower temperature than the housing and will begin to absorb heat until its bulk temperature matches that of the turbocharger's. Worse, depending on the mounting conditions under the hood, the peak temperature of the turbine housing and CHRA can actually continue to rise for a few minutes after shutdown.

Many modern OEM turbocharger setups route the water lines that feed the CHRA so that natural convection will keep the water flowing a little bit even after the car has been shut down. Other vehicles, such as certain turbo Audis, have temperature switches and an auxiliary pump to force circulation through the CHRA after engine shutdown. While these strategies help, they don't completely alleviate the problem. More importantly, many custom turbocharger systems are assembled without this consideration.

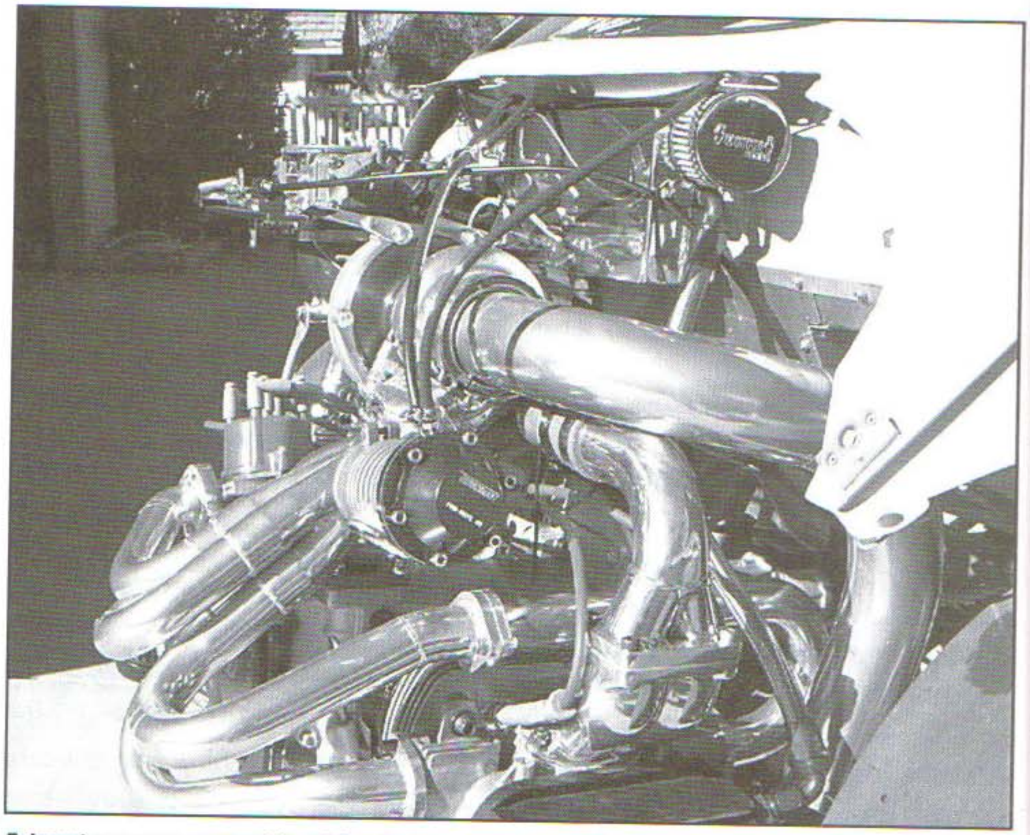
If you've run your car hard immediately before parking, one solution is to keep the engine running for a few minutes at idle before shutdown. This keeps both oil and water flowing through the CHRA, wicking away heat and helping to cool down the turbocharger. A rule of thumb is that three to five minutes of idling off-boost will bring a typical turbo down below the coking point.

The question then is how best to achieve these few minutes of idling. If you're the patient type of driver, willing to wait in the car in the parking lot or driveway for the amount of time it takes to play your favorite song on the radio, this shouldn't be a problem. On the other hand, if you're a type-A personality who wants to get on with your life, a turbo timer might be an idea worth considering.

A turbo timer serves to keep your engine running for a predetermined amount of time after you've switched off and removed the key. The timer accomplishes this by intercepting the ignition switch signal to the engine control unit, effectively keeping the engine running after you've left the vehicle. These units typically come with security features that disable (i.e., turn off) the engine if the clutch pedal is depressed or the parking lever released. Many turbo timers also have integrated circuitry that interfaces to common car alarm systems, which allow the alarm to be activated while the engine is still running.

7 THE EXHAUST SYSTEM

A turbocharger exhaust system can be thought of as two separate parts: the manifold connected to the cylinder head upstream of the turbine, and the exhaust tubing, catalytic converter, and mufflers downstream of the turbine. The design and implementation of both of these parts can have a large influence on engine performance, affecting everything from when usable boost begins to build in the engine rpm range, to ultimately how much horsepower the engine can develop. (Astute readers will note that there is actually a third part of a turbo exhaust system; namely the wastegate flow path that directs hot gases around, or bypasses the turbine. We'll cover wastegate plumbing in the next chapter on boost control.)



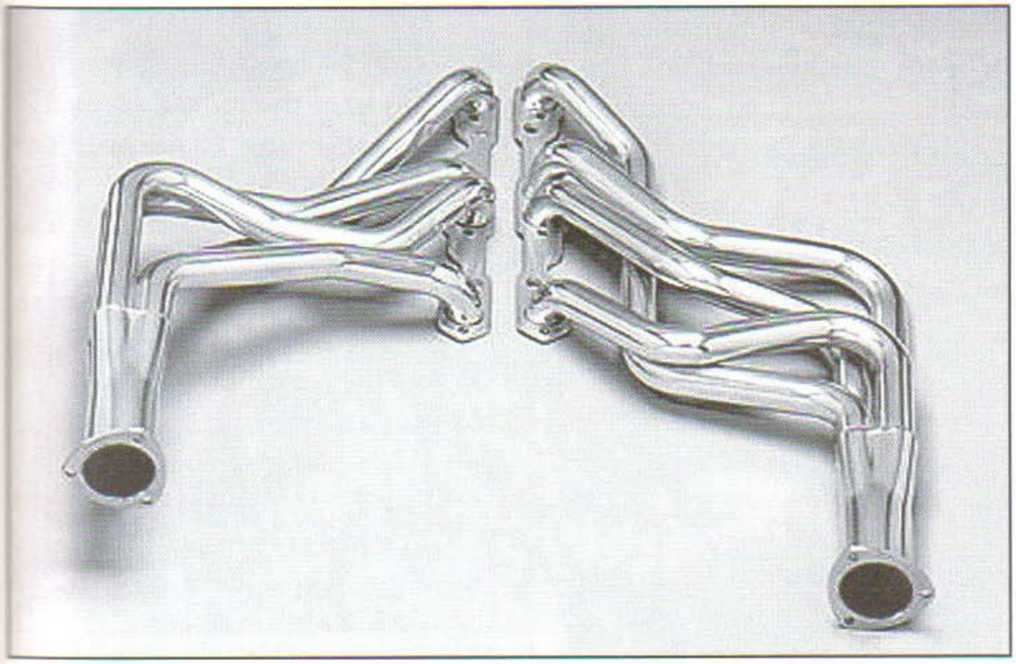
Exhaust gas management is critical to the performance of a turbocharger system, both upstream and downstream of the turbine. (Turbosmart)

EXHAUST BASICS

Many so-called "experts" design turbo exhaust manifolds using the physics of naturally aspirated engines. Unfortunately, the design of a naturally aspirated (NA) exhaust manifold or header has almost nothing to do with that of a properly engineered turbo manifold. This is a case of apple engineering applied to an orange juice application.

A header designed for use on an NA engine relies strongly on exhaust velocity in the collector to scavenge the exhaust gases from the other cylinders. A well-designed NA header employs primary exhaust tubes that are sized both in diameter and length to help this scavenging process. The collector exit diameter also has to be sized appropriately. Get it correct, and a pulse of gas energy from one cylinder will pass through the collector at just the right moment in time and at the right speed, thereby creating a partial vacuum that will help pull along the next pulse of gas energy that is traveling down its own primary tube toward the collector. A well-designed header can dramatically increase the volumetric efficiency of an NA engine. Get the design wrong, however, and the header won't scavenge. Too small of a collector discharge diameter will result in high gas velocity, but also excessive backpressure. And too large of an exit diameter will slow the gas stream too much, also causing a dramatic drop in scavenging.

In contrast, any scavenging in a turbocharged exhaust manifold is of secondary importance. In fact, scavenging is almost nonexistent in the design of most high-



A naturally aspirated (NA) exhaust header is a poor choice for a turbo exhaust manifold. The NA header is designed to maximize cylinder scavenging, not to maximize pressure and flow velocity. The materials used in a typical header aren't designed to withstand the high temperatures and stresses of turbocharging, either. The manifold will fail—it's not a question of if, but rather when.

Even in this black-and-white photo, the heat absorbed by an exhaust manifold under full-boost conditions is clearly evident. If this doesn't convince you that thermal stresses are an important consideration when designing a turbo manifold, nothing will. (Honeywell Turbo Technologies)

performance turbo manifolds. The most important thing is to get the turbo spooling as soon and with as little backpressure as possible. On a turbocharged engine, it is much more important to create boost efficiently and quickly than it is to scavenge cylinders.

As we saw earlier, a turbine wheel operates on the principle of momentum transfer from the exhaust gas stream to the turbine wheel. Momentum is the product of mass multiplied by velocity. To maximize turbocharger performance, we want to maximize both the mass flow rate and the velocity of the exhaust gas stream as it passes through the turbine.

There is little we can do about increasing the mass flow rate of the exhaust (short of ensuring that we don't "throw away" any useful gases by opening the wastegate too early), but we can do some things to ensure the exhaust is at its maximum speed when it passes into and through the turbine.

Recall from our discussion about turbines that the velocity of exhaust gases flowing across a turbine wheel is due to two things: blow-down and the pressure drop across the turbine wheel itself. In other words, we want to ensure high gas velocity and pressure upstream of the turbine, and low pressure downstream.

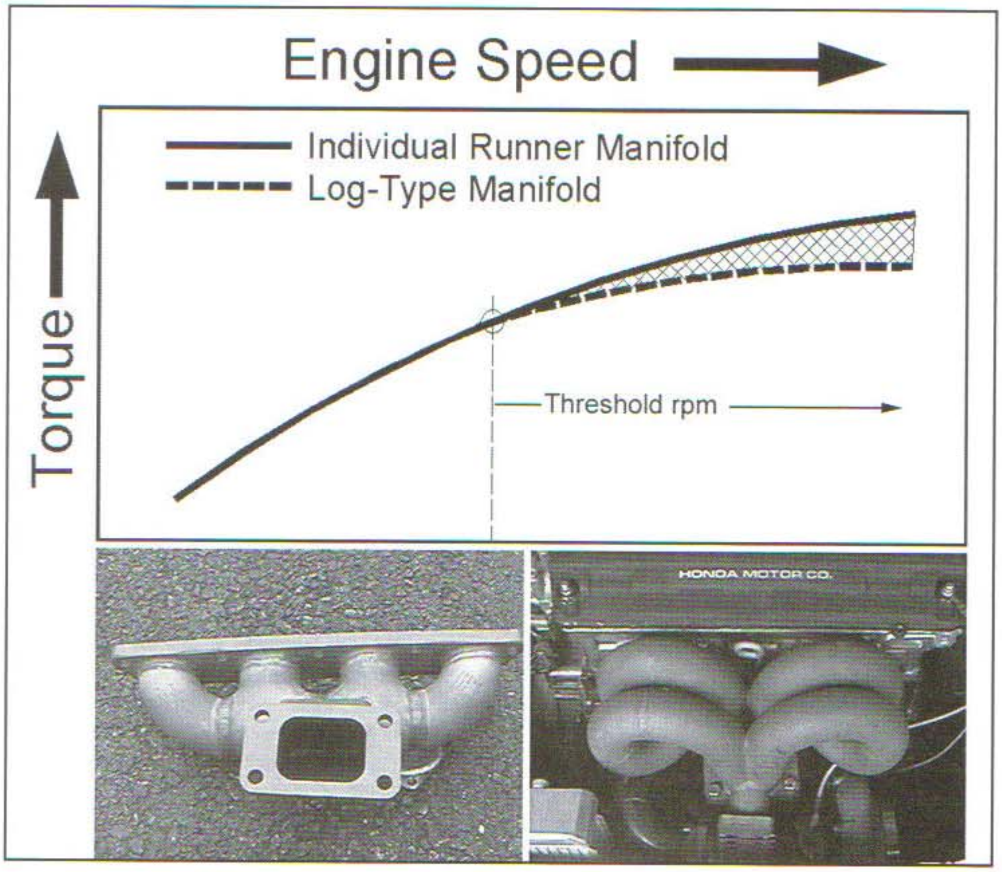
TURBO EXHAUST MANIFOLDS

There are essentially two basic types of manifolds available for use on turbocharged engines: log and individual runner.

Log Manifolds

Most factory (OEM) turbo manifolds are of the log variety. This is because they are inexpensive to produce. They are also very durable, particularly when constructed from thick cast iron. Log manifolds sacrifice some performance potential, but for moderate-boost street engines they can perform within 75% to 90% as well as a purpose-built individual runner manifold. Log manifolds are desirable from a packaging point of view, too. A typical log manifold can conform very closely to the cylinder head, allowing room for air conditioning, power steering, and other ancillary engine components.

A log manifold will never be as efficient as an individual runner-type manifold, but its performance can be maximized by paying attention to smooth bends and well-directed gas flow. When designing a log manifold, it is best to avoid sharp, right-angle feeds of the individual ports into the log. It is better to angle, or sweep the port feeds into the log as gradually as possible. It is also important to keep the flow moving in only one



Up to a certain rpm point, log-type manifolds can perform as well as individual-runner manifolds, but above that threshold engine speed, the individual-runner manifold almost always outperforms the log. (Full-Race)

direction: toward the turbine. Anytime the flow from one exhaust port "tee's" into the log at a right angle, or is pointed back in a direction that is the opposite of the flow from another port, the result will be a loss of efficiency. A log manifold already starts with a handicap; don't exacerbate the situation with poorly designed flow paths.

Tubular Manifolds

The second major type of exhaust manifold is the individual runner, or tubular manifold. This type of manifold is *de rigueur* for ultimate performance applications; when the goal is minimum spool time and maximum horsepower, a tube-type is the only way to go.

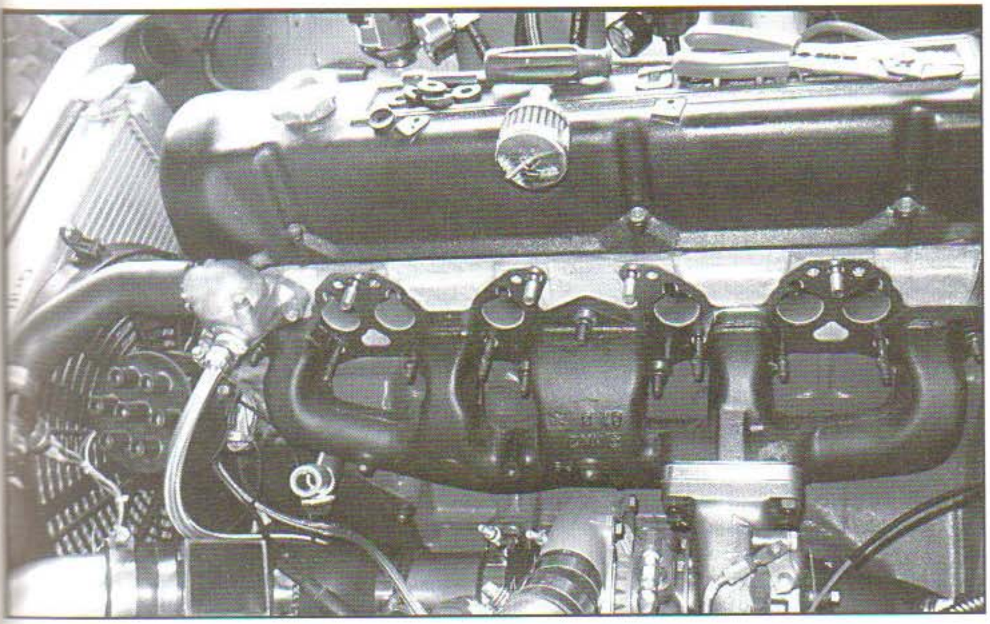
When designing a tubular manifold, the goal is to maintain as much thermal and kinetic energy in each exhaust stream as possible. The key is to keep the hot, pressurized gases from the combustion chambers fully heated and at maximum speed all the way from the cylinder head to the turbocharger. Short tube lengths are better than long ones. A minimal number of bends is also preferred. The goal is to conserve as much gas momentum as possible and to discourage heat transfer to and through the walls of the tubular runners.

Where bends and turns in the tubes are required, keep them gradual and smooth. Large radii are better than small radius bends. It's also important to keep the individual tubes as equal in length as possible. This will help even out the timing of the individual energy pulses impinging on the turbine wheel and ensure that they don't interfere with each other. This also helps keep exhaust reversions to a minimum. It's often difficult to keep all the runners identical in length, but the closer they are to each other, the faster the turbine spool-up will be.

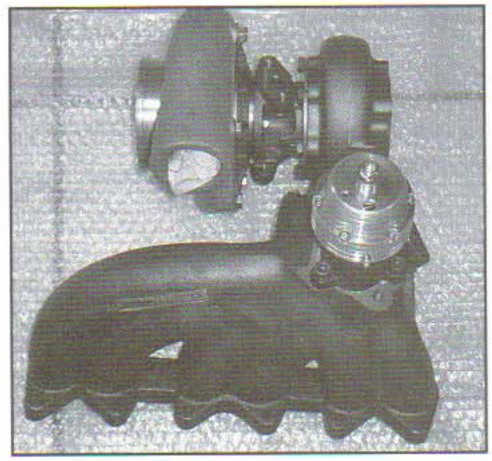
Note, too, that the individual tube diameters on a properly engineered manifold tend to be slightly smaller than on a similar NA engine. Usually the cross-sectional area of the exit port on the cylinder head is a good starting point for sizing the runners. For tubular manifolds, it's better to err on the small side, which will maintain gas velocity and reduce the exterior surface area, helping to minimize heat loss.

The collector design where the tubes come together depends on a number of factors, such as how many cylinders feed the turbo and in what configuration are they arranged (e.g., inline-6 versus V-6). The firing order also plays into the design. This is especially true for smaller four- and six-cylinder engines and in applications that use twin-entry turbine housings. It's better to group cylinders that are far apart in the firing order together in the collector. For example, a 4-cylinder engine with a 1-3-4-2 firing order would benefit from a grouping of 1 and 4 together, and 2 and 3, with each of these pairings feeding separate volutes of a twin-entry turbine.

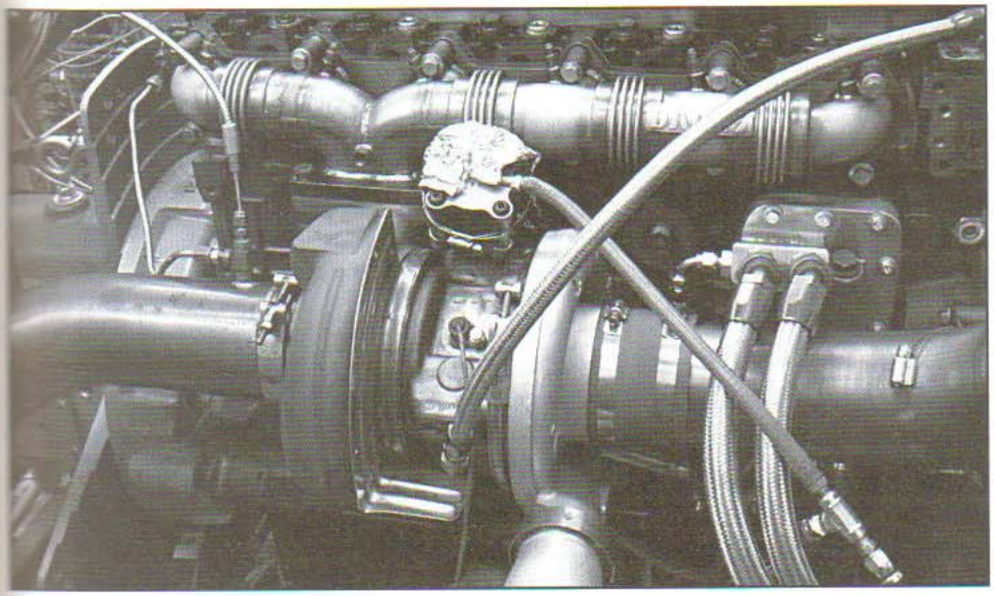
Material choices for a tubular header will be discussed in a moment, but for now it's



A traditional log-type OEM manifold. Note the sharp bends and less-than ideal flow paths. Even with this suboptimal configuration, however, the owner of this Datsun 240Z has managed to squeeze over 300 lb-ft of rear wheel torque from the engine. (McManus)



A compact log manifold for a six-cylinder engine. (The Power Group)

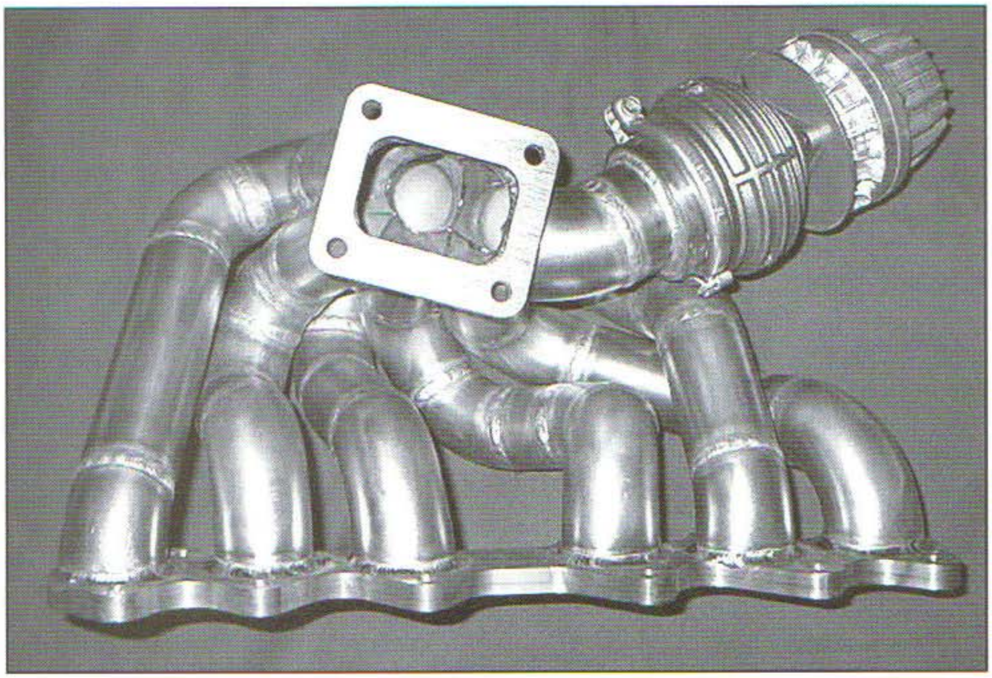


The custom exhaust on this Cummins diesel engine features a 1/4-inch thick wall stainless steel log-type exhaust manifold with four integral expansions bellows. (Gale Banks)

important to remember that a key performance goal is to retain heat energy upstream of the turbine. The thermal conductivity of the manifold material is important, but so is the total exposed surface area and the wall thickness of the tubes. In general, thicker is better from a thermal point of view, even though it carries a weight penalty. Similarly, shorter tube lengths are better because the total surface area is less, and the potential for heat loss is therefore reduced.

Long tube lengths have another disadvantage and that is larger stresses. The heat inside a turbo manifold is high, which adds to the stresses on the material. Unfortunately, it is quite easy to build a turbo manifold that fails prematurely due to stress cracking. If the runner lengths are long enough, it's often helpful to support the turbo itself with a separate bracket. The design of the bracket should allow it to carry the load of the turbo, but still allow the system to expand and contract with temperature.

A tubular manifold almost always has to be hand-fabricated for an application. High quality welds and smooth transitions and internal surfaces are critical. Integrating the wastegate has to be considered, as does a myriad of other factors. In fact, there are a lot of considerations when building an exhaust manifold, whether it's tubular or log. Interference with other engine equipment, heat shields, routing of exhaust and hot components nearby coolant hoses, intercoolers, fuel lines, etc., all have to be factored into the effort. Despite the best of intentions, designing and building a turbo exhaust manifold invariably is a process of give and take, and accepting compromises.



A gorgeous equal-length tubular runner single-turbo conversion manifold for the Toyota Supra 2JZ-GTE engine. (Full-Race)

MATERIALS

Turbo exhaust manifolds have to perform under very high temperatures and thermal stresses. There are only a handful of materials that should be considered, regardless of whether the manifold is tubular or log.

At the low-tech end of the scale is something called high-strength alloy steel NSP-type tubing. A more common name is plumber weld-els and tubes. These thick-walled pipes are used in the industrial plumbing and gas fitting industries. They offer the exhaust manifold fabricator a relatively inexpensive, forgiving material to work with that is easily cut and welded. The penalty, however, is weight.

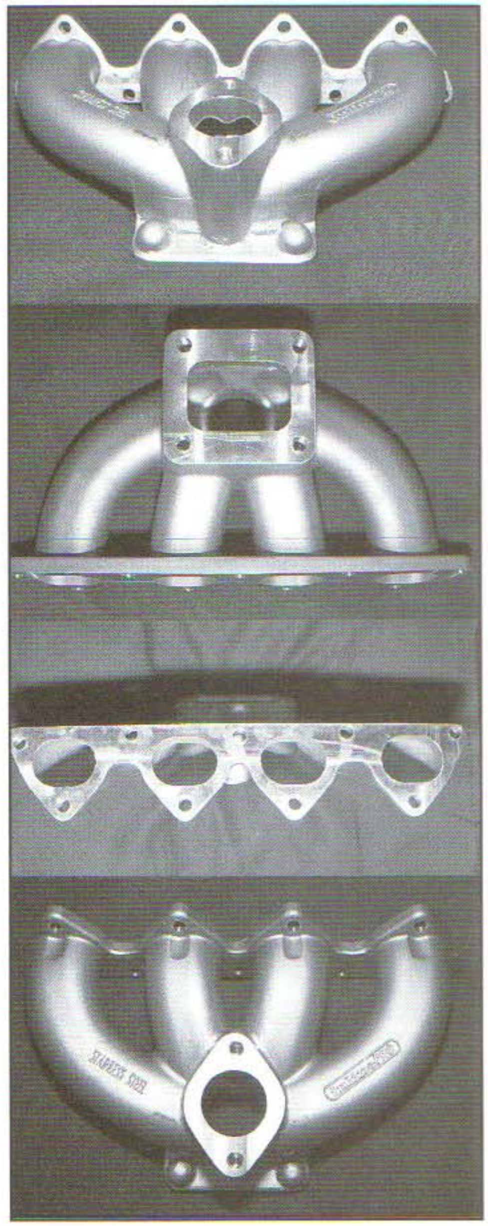
Schedule 40 weld-els are adequate for most turbo applications. Thinner gauge material is available, but for long-term durability and strength at the high temperatures expected in a turbo application, it is generally recommended that schedule 40 or thicker be used. A manifold constructed from thick weld-els should last for many years of hard use. The material is available in sections of straight pipe in various diameters, as well as short- and long-radius bends.

Moving up the cost scale leads us to stainless steel. Technically speaking, "stainless steel" is a trade name applied to what is more accurately termed corrosion-resistant steels. For sake of common usage, however, we'll stick to the "stainless" moniker.

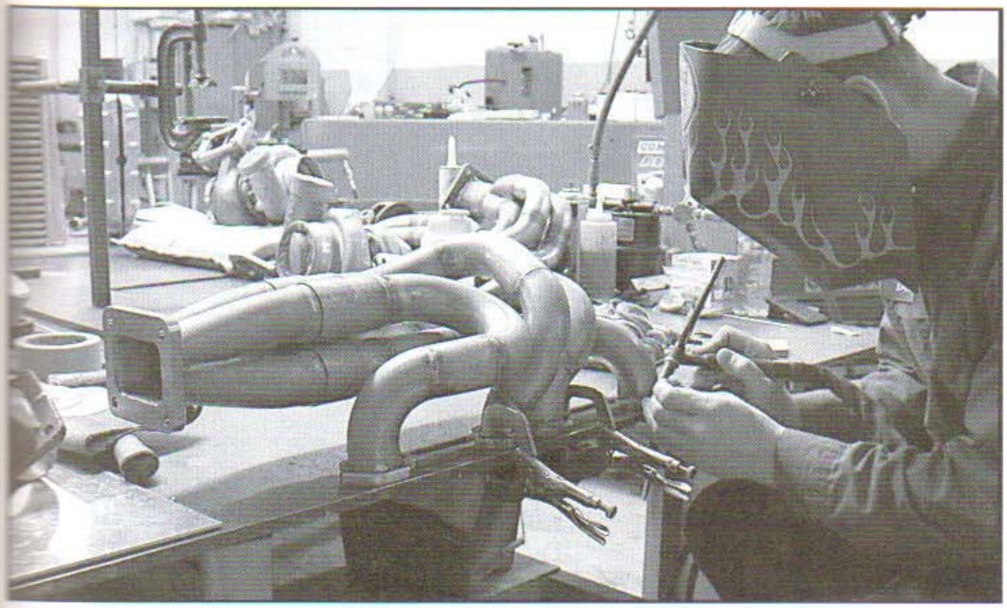
A three-digit numerical system is used to classify most stainless steels. Included in this system are the ubiquitous 300-series steels that are popular with race car fabricators. With a few exceptions, many of the steels that fall under this 300-series category should be avoided for turbo exhaust manifolds. This includes the oft-mentioned 304 series. While 304 is excellent for

PORTING

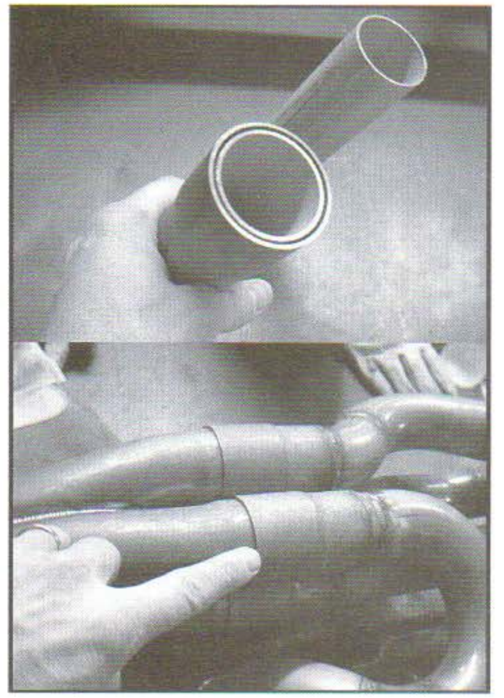
Very good results can often be achieved by porting stock OEM turbo exhaust manifolds. In addition, processes like Extrude Hone can also be very beneficial.



The line between log and fully tubular manifolds is blurred with some modern exhaust manifold designs. This beautiful unit is made by Inline Pro for a Honda application. It features good flow paths from each exhaust port directly to the turbine in a compact package. Note the well-situated wastegate port that sees flow from all four runners. (InlinePro)



The exhaust manifold and downpipe exiting the turbine are two of the most highly stressed components on a turbocharged engine. It's best to use only high-quality materials. Thick-walled cast iron and stainless steel 321 are good choices for the manifold upstream of the turbine. Because the temperatures are somewhat reduced downstream of the turbine, there are more choices available. Stainless 304, 321, 347, 409 and ceramic-coated carbon steel are all possible here. Just don't scrimp on wall thickness in an effort to save weight. Durability is as important as power production. (Stielow)



Expansion of the exhaust manifold can be accommodated by way of slip-fits. The collector shown here has a unique double-wall slip connection that allows good gas containment while still accommodating large expansions and contractions. (Stielow)

Approximate Material Properties At 70 F	Mild Steel	Stainless 304	Stainless 321	Inconel 625
Tensile Strength, psi	55,000	85,000	90,000	140,000
Yield Strength, psi	40,000	35,000	35,000	77,000
Density, lb/in^3	0.283	0.290	0.290	0.305
Modulus of Elasticity, psi x 10^6	29.5	28.0	28.0	30.1
Thermal Expansion, in/in-F x 10^6	7.2	9.9	9.6	5.5
Thermal Conductivity, Btu /ft-hr-F	26.9	9.4	9.3	5.7

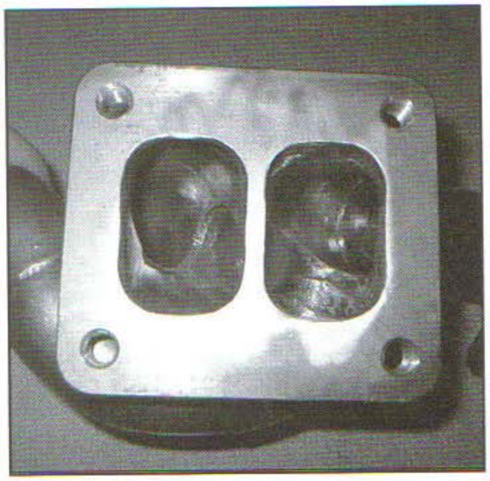
Choosing the right materials for an exhaust system depends on a number of factors, including the amount of heat that will be applied to it. Generally speaking, the farther to the right you move in this table, the higher the resistance to thermal stresses.

many automotive applications, a turbo exhaust manifold is not one of them. Stainless 304 is prone to carbide precipitation when held at the high temperatures experienced in a turbo manifold.

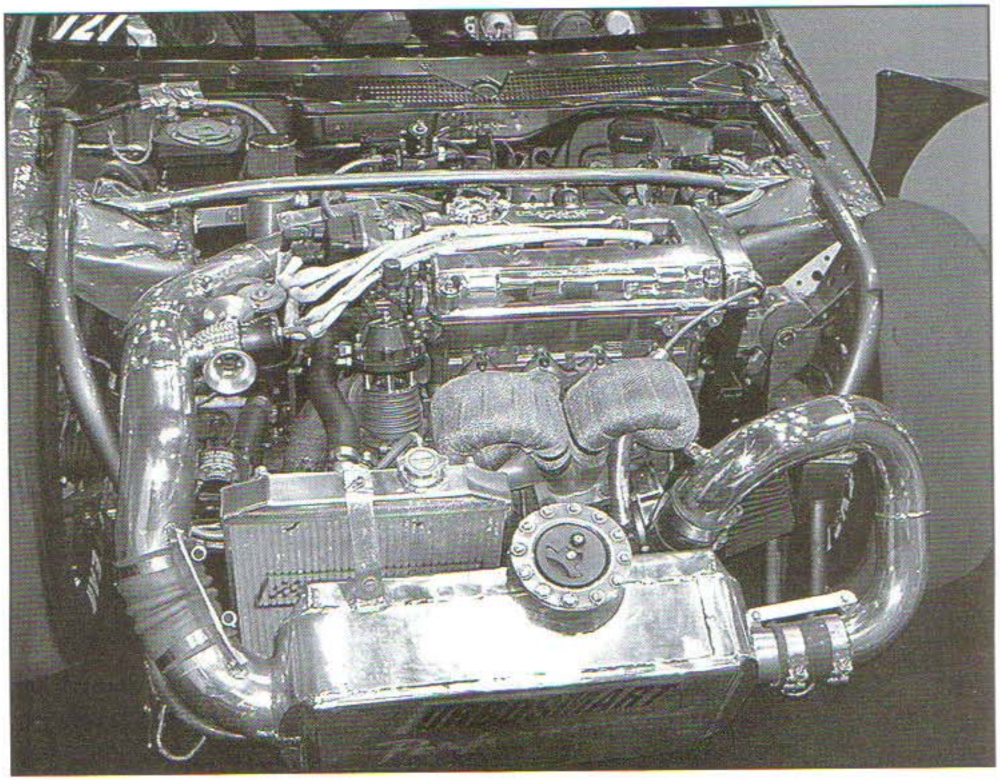
On the other hand, two of the best 300-series stainless steels to use for turbo manifold construction are the 321 and 347-series steels. Stainless 321 and 347 belong to a stabilized grade of corrosion-resistant steel. They are alloyed with either titanium (321) or columbium (347), which helps to eliminate the issue of carbide precipitation.

Typically, stainless 321 is less expensive than 347, but either can be used with good results. They both exhibit excellent mechanical properties, including low thermal conductivity. This results in less heat energy loss from the exhaust stream through the walls of the tubing. These grades of steel are also relatively lightweight and have high strength and resistance to cracking at elevated temperatures. The disadvantages are higher cost and a reputation for being slightly difficult to work with, including welding.

Exotic steels such as 625 Inconel and the like are often used in extreme-duty turbocharger applications. Initially developed for use in jet engines, Inconel contains a high content of nickel and chromium. Other elements, such as molybdenum are also alloyed into the mix. This allows Inconel to maintain high strength and durability at temperatures in excess of 1800°F. Lesser metals, including the aforementioned 321 stainless series, cannot withstand these high temperatures. For ultra-high performance, Inconel is an excellent choice. Unfortunately, Inconel is also expensive, hard to find,



The flow paths from the individual runners should merge gradually and smoothly into the collector. Here is a good example of proper flow management. (RCC Turbos)



Exhaust thermal wrapping keeps heat in, which can help maintain high exhaust gas velocities and reduce under hood temperatures. Unfortunately, the wrap also retains moisture and can rust out a set of primaries quickly. For a purpose-built drag race car like this 400 hp Honda, thermal wrap is a great idea, but probably not for a street machine subjected to rain and long-term abuse. Many manufacturers won't warranty their manifolds if any type of heat wrapping is used. (Turbosmart)

difficult to cut, and is challenging to weld. For this reason, it is usually restricted to professional race teams with large budgets.

DOWNSTREAM EXHAUST

There is one major goal for the design of the exhaust system downstream of a turbocharger: low backpressure. The higher the backpressure in this part of the exhaust system, the slower the wheel speed and the lower the horsepower. There is no getting around this fact. To make the most use of the high gas pressure upstream of the turbine, we need to ensure that there is the lowest possible downstream backpressure.

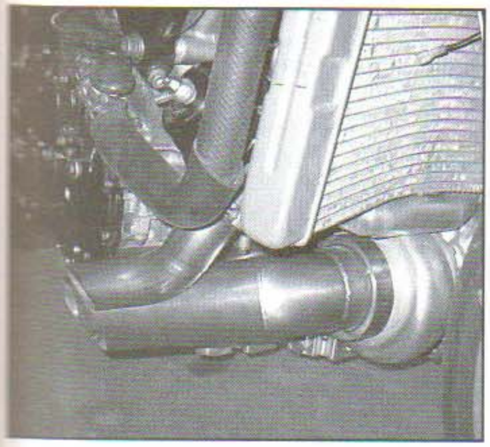
Unfortunately, this is a message that is often lost on many "expert" exhaust fabricators. People who should know better often suggest blatantly bad designs. For example, you should ignore any advice that says some minor choking is required to cause the turbine to spool. This is an old wives' tale that should but won't die. There is also no such thing as cylinder scavenging downstream of the turbine. In other words, there is no reason to try to design for high exhaust velocities downstream by necking down the exhaust or by any other means. You will only introduce backpressure.

Ideal Exhaust System Design

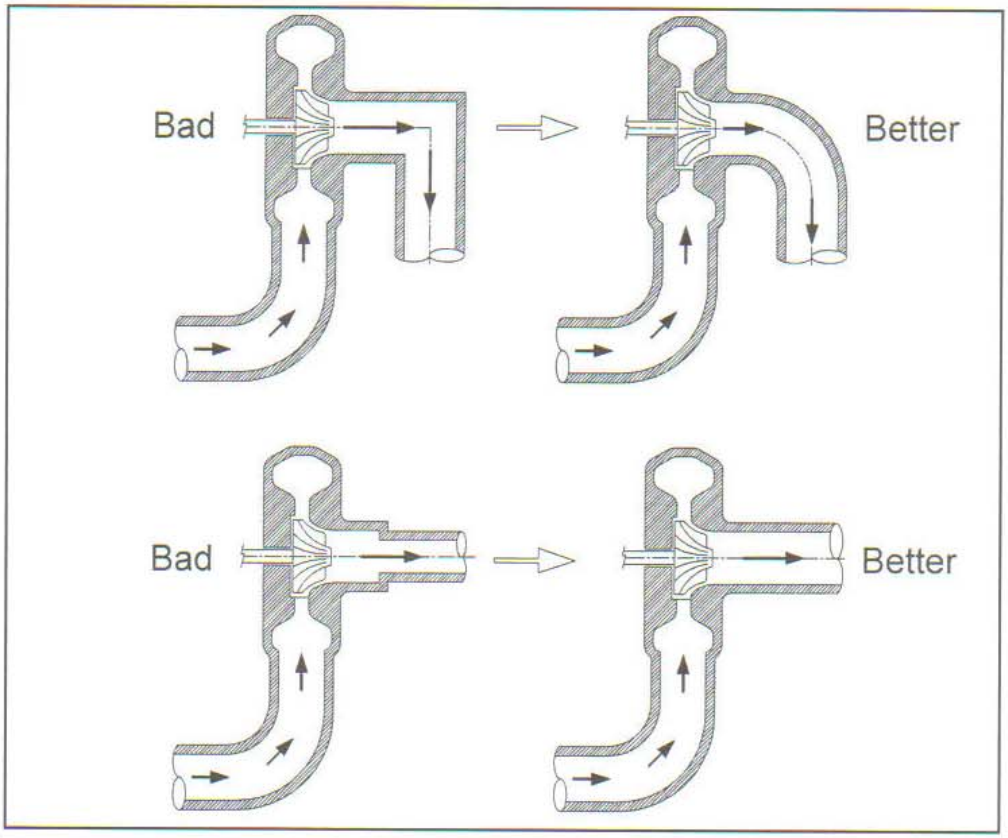
So how do we get low backpressure behind the turbine? To begin with, a larger diameter exhaust tube is better than a small diameter. Shorter is better, too. From a theoretical point-of-view, the ideal exhaust would be a very short "megaphone" pipe attached to a turbine that dumps directly out into the atmosphere. Of course this is wildly impractical for all but the most radical off-highway vehicles. But physics shows that this is the ideal. Less really is more when it comes to downstream exhaust systems.

For most street applications, a proper downpipe, exhaust tubing, muffler, and catalytic converter are required. Where high horsepower and low spool times are the primary performance goals, each of these components should be sized to reduce or eliminate flow obstructions. For example, there is a minimum acceptable pipe diameter required to support a given flow rate of gas. Since the charge air mass flow rate into the engine is directly proportional to the exhaust gas outflow, and horsepower is related to that inflow, it is possible to establish a relationship between horsepower production and a minimum acceptable exhaust diameter (see the graph on page 67).

For optimal performance, you



A nearly ideal exhaust system from a performance point of view—but not necessarily good for noise control. Note the separate exhaust tube used for venting the wastegate. (RCC Turbos)



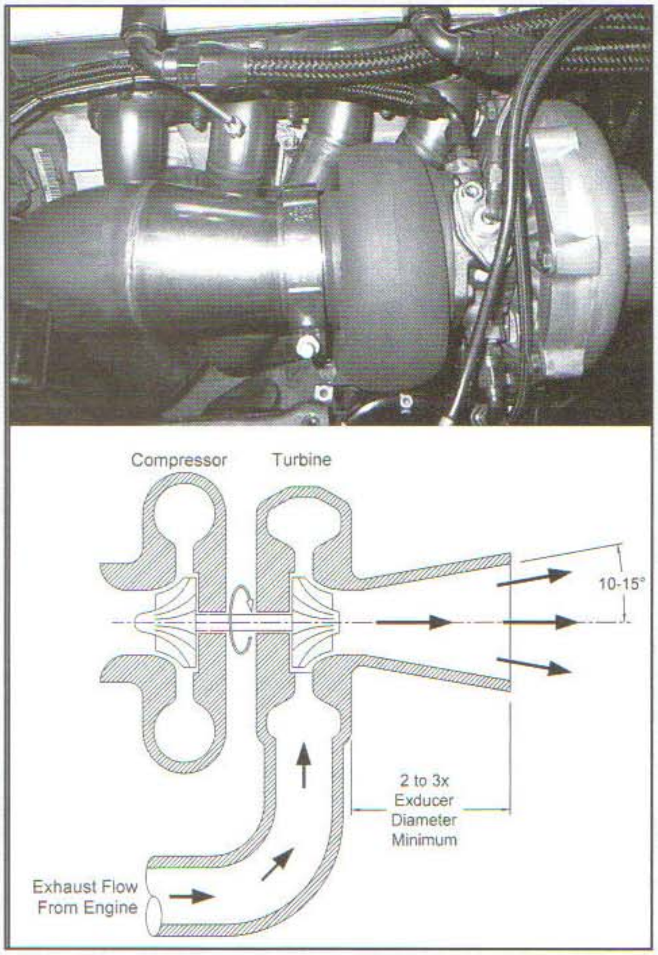
Sharp bends, abrupt flow transitions, and diameter reductions all result in exhaust system backpressure. The goal is to allow exhaust gases leaving the turbine a free and unrestricted pathway to the atmosphere.

also want to minimize any tight bends, sharp edges, abrupt transitions, and other features that cause the exhaust flow to change direction suddenly or, worse, slow down. Any of these features tend to build backpressure, thereby reducing the effectiveness of the turbocharger.

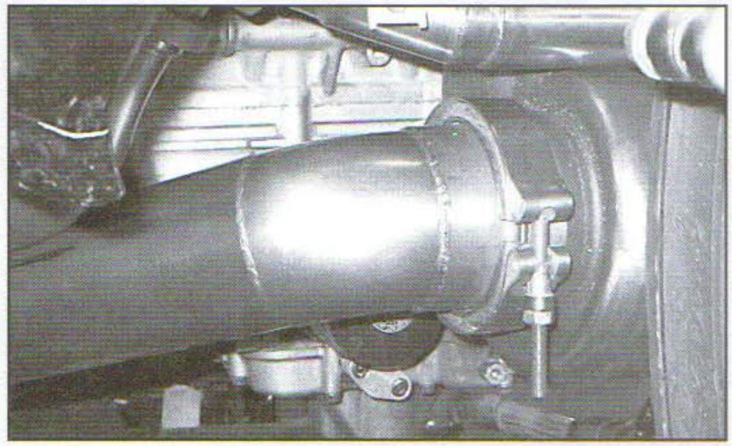
Mandrel bent tubing should be used wherever direction changes or bends are required. A mandrel-bent tube is one in which a shoe or mandrel is inserted into the tube prior to it being formed into a radius on a hydraulic bending machine. The shoe keeps the tubing from collapsing, or necking down during the bending operation. This ensures that the tube inner diameter remains unaffected throughout the entire sweep of the bend. If you start with a two-inch tube, for example, the inner diameter throughout the entire section of a mandrel bend will remain two-inches.

Mandrel-bent tubing is more expensive than other, so-called "crushed" tubing bends, but for maximum performance, there is no substitute. In contrast, crush bending works by, you guessed it, crushing the pipe at the bend. This physically creates an elongated kink in the pipe, reducing the diameter of the pipe through the bend. This is obviously not a good thing. If you absolutely have to use crush-bend tubing, you should go up in size to a larger nominal diameter. While the crush transitions of such a bend will still add some flow resistance, the overall detrimental effect will be less than with a smaller diameter crush bend.

Finally, you need to decide on a muffler system. The best systems offer the least flow resistance. Unfortunately, this usually means more noise. You have to decide what level of noise you can live with—and what level the local police can live with, too. The same is true for catalytic converters. Local noise and pollution ordinances will dictate the minimum allowable standards for these items.

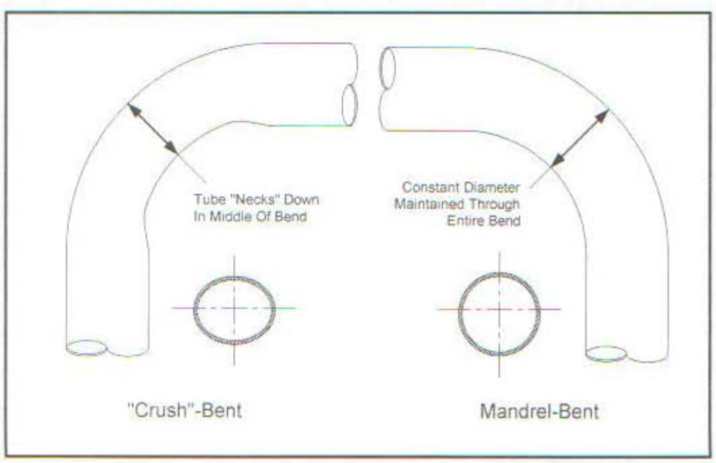


It is often said that the best exhaust for a turbocharged vehicle is no exhaust at all. Actually, from a theoretical performance-based sense, the "best" exhaust for the widest range of operating conditions would be a short (6–10 inch long) megaphone-style exhaust tube, that tapers at roughly 10-degrees out from the turbine outlet. Note that this technique can be combined with a traditional exhaust system to reduce backpressure, as shown in the top photo. The effect is small, but measurable. (Full-Race)

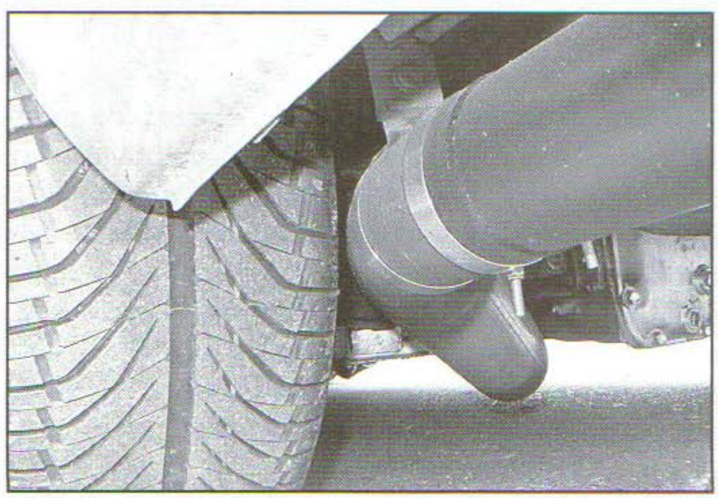


A V-band connector. This simple device allows good sealing between the downpipe and the turbine, while also allowing for rotation adjustability during assembly. (RCC Turbos)

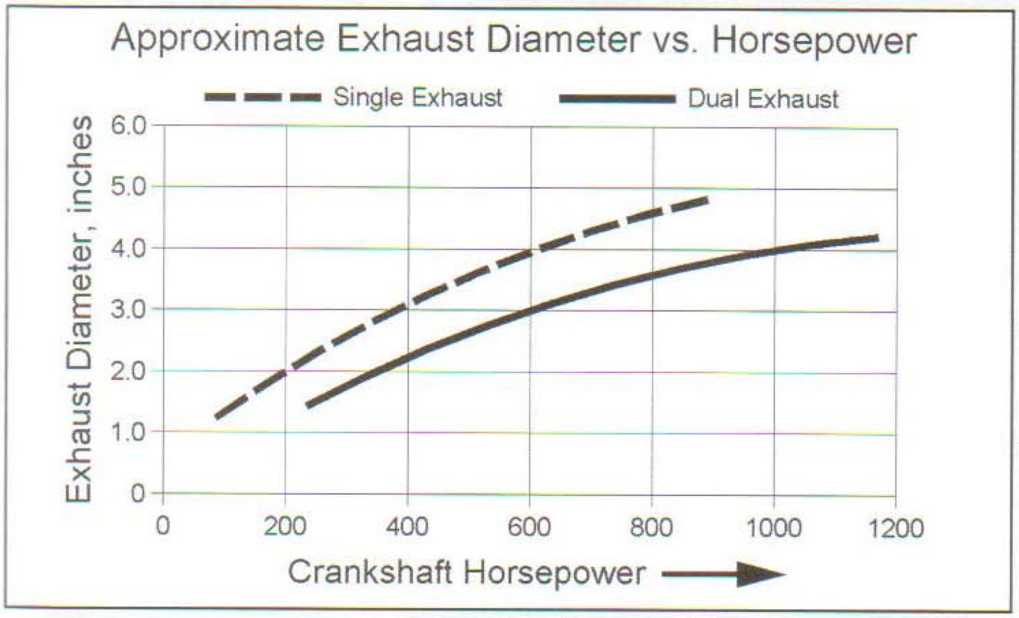
A flex joint is often used between the end of the downpipe and the rest of the exhaust system. This allows the engine and exhaust system to move relative to each other without imparting large stresses. (Turbonetics)



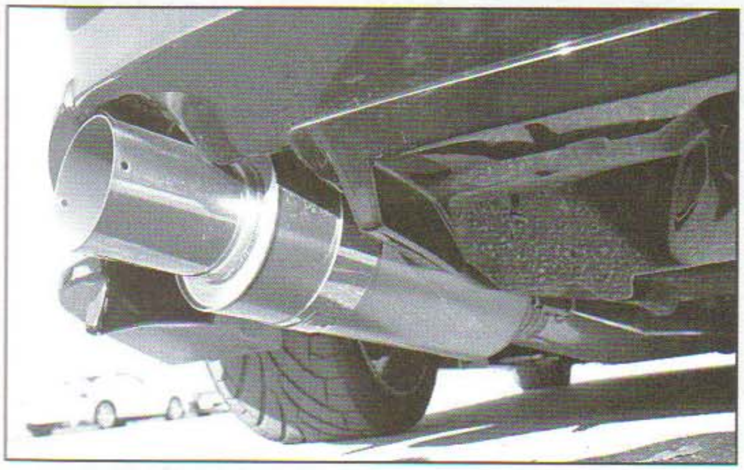
Wherever possible, mandrel-bent tubes should be used for all sweeps and turns in an exhaust system. While more expensive than traditional "crush"-bent tubes, mandrel bends flow better and result in lower pressure losses.



Exhaust diameter and gentle bends were a high priority in the design of this system. The exhaust tubing clears the rear tires by a scant 3/8-inch. (Lum)



Engine performance can be affected strongly by the tubing size used downstream of the turbine. The nominal exhaust system size is essentially determined by the smallest diameter in the entire system. You may have 3-inch tubing and 3-inch diameter mufflers, but if the system necks down to 2.75 inches somewhere along the way, then that's the effective diameter. Performance is in the details. If you absolutely have to reduce the diameter of the exhaust tubing, do it as far from the turbine as possible. This plot shows the approximate required exhaust diameter for a given horsepower goal.



While certainly pretty, the titanium HKS exhaust system on this Supra was chosen solely for its flow characteristics and low backpressure. (Henderson / SP Engineering)

A catalytic converter can be a significant flow restriction in the exhaust system. This is true even of so-called "high flow" cats. It is possible to pick up significant horsepower gains by removing the cat. However, removing the catalytic converter (or any other pollution control device) in most cases violates federal law and can result in a fine. Take it out at your own risk.

Noise Source	Decibel Level
Near Total Silence	0 db
Inside New Car With Engine Off	40-50 db
Residential Street Noises	60-75 db
OEM-muffled Motorcycle @ 30 ft	80-90 db
Lawn Mower @ 5 ft	90-100 db
Motorcycle Without Muffler	100-115 db
Rock Concert (Typical)	110-125 db
Jet Engine @ 100 ft	130 db
Threshold Of Physical Pain	130-140 db

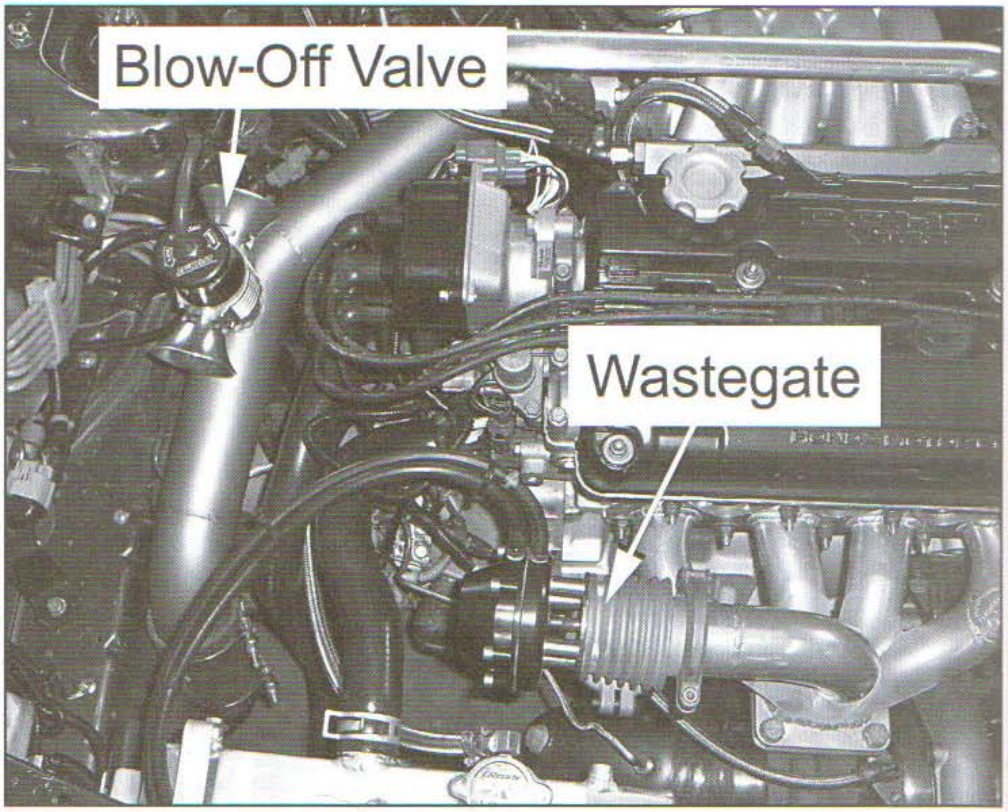
Hearing Protection Required

Low backpressure downstream of the turbine is the goal for any performance-based turbo system. Large diameter piping and free-flowing mufflers are some of the keys to achieving this. But along with less-restrictive mufflers comes an unwanted side effect: noise. Hearing experts say that it's best to avoid any unprotected exposure to sounds above 100 decibels (db). They also say that hearing protection should probably be used whenever you're exposed to levels above 85 db, especially if the exposure is prolonged. A rule of thumb says that if you have to raise your voice to be heard, the sound is at or above 85 db. Racetracks are notorious places for big db's, and it's a good idea to bring along some kind of hearing protection whenever you head out to the races. When in doubt, use sound protection. Hearing damage is both cumulative and irreversible.

8 BOOST CONTROL

Turbochargers create boost, and this is a good thing. Boost means higher intake charge density, which means more power. But there is a limit to the amount of boost pressure that can be safely run in an engine. Above a certain threshold, all sorts of bad things begin to happen, from minor pre-ignition to full scale detonation and, eventually, engine meltdown.

Boost control devices take two forms: those that limit the amount of boost before it gets created, and those that vent or release any excess boost after it is created. The former are sometimes referred to as turbine-side boost control and are primarily comprised of wastegates. The latter (compressor-side boost control) takes the form of blow-off and bypass valves. Let's look at both, starting with turbine-side boost control.



Blow-off valves (BOV) are the most common type of compressor-side boost control used on modern turbocharged engines. Similarly, wastegates are the standard turbine-side boost control device. This Honda engine is fitted with a dual-exit BOV and an external-type wastegate. (Turbosmart)

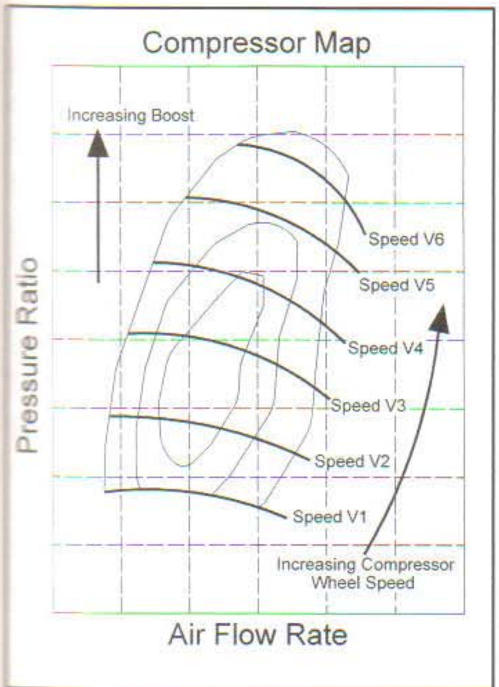
TURBINE-SIDE BOOST CONTROL BASICS

Left unchecked, a turbocharged engine is a type of runaway device. The more power the engine produces, the more exhaust energy it creates. This energy is put directly into the exhaust stream, and more exhaust energy, of course, means a faster spinning turbine. This in turn means a faster spinning compressor, which means more boost and therefore more power. More power results in more exhaust energy, and so on. Left unchecked, boost pressure can continue to rise like this until things go, well, boom!

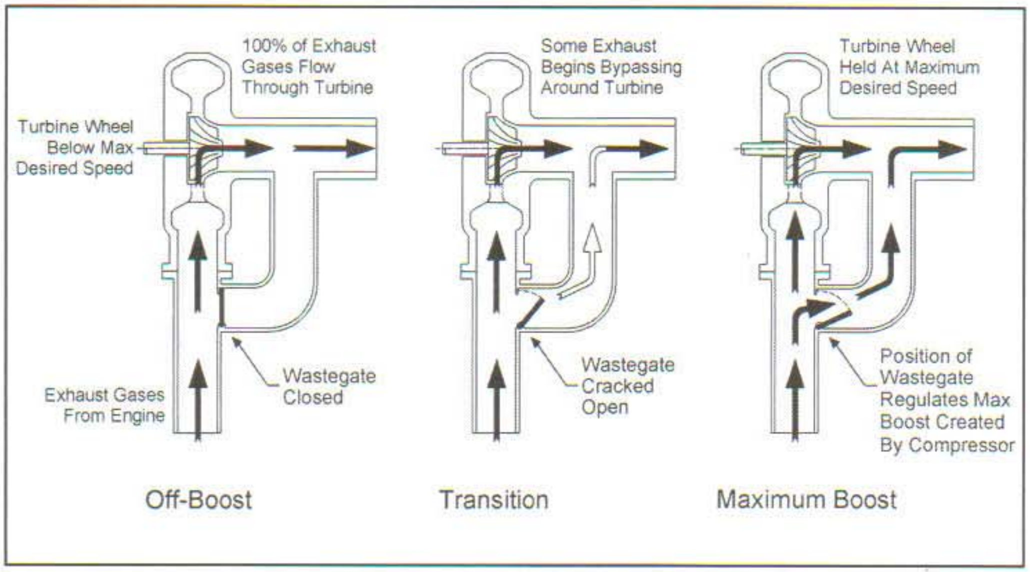
When looking at a compressor map, it can be seen that a compressor's pressure ratio (i.e., the pressure of the compressed air) is more or less proportional to the compressor speed. The faster a compressor spins, the more pressure gets created. A logical way to control boost pressure, then, is to limit the maximum speed that the turbine can spin. Wastegates are devices used to provide this kind of speed control.

Wastegate Theory and Operation

A wastegate is a simple mechanism. Think of it as a door in the exhaust that is upstream of the turbine wheel. This door can be opened on command. It offers hot exhaust gases leaving the engine an alternative path to the normal route through the turbine. A wastegate shunts, or diverts, the exhaust stream around the turbine.



Compressor boost output is strongly related to wheel speed. Because of this, the amount of boost pressure produced by the compressor can be controlled by changing the rotation speed of the turbine wheel.



A wastegate is essentially a door that offers exhaust gases a detour around the turbine. The speed of the turbine wheel is governed by the amount of exhaust energy that passes through it. By adjusting when and how much the wastegate is opened, control of compressor boost is achieved.

When hot gas exits the engine, it can either go through the turbine, which causes the compressor to spin and create boost, or it can be bypassed via the wastegate.

The control of a wastegate is handled by something called the wastegate actuator. The typical actuator is nothing more than a spring-loaded diaphragm connected to the wastegate door with a control arm. A rubber hose is fitted between the pressurized intake tract (i.e., the compressor side) and the wastegate actuator. The air pressure inside this hose is known as the actuator signal.

When there is no boost pressure, the actuator signal is zero, and the spring inside the wastegate actuator is strong enough to keep the wastegate door closed. As boost rises, the actuator signal pressure acting on the diaphragm rises. Actuator force is equal to boost pressure multiplied by the diaphragm area; the higher the actuator signal pressure on the diaphragm, the larger the force. When this force exceeds the spring preload, the actuator begins to move.

During light throttle and low boost situations, a turbocharger wastegate normally stays closed. This keeps all the exhaust moving through the turbine, which results in fast impeller spool-up and good boost response. As boost increases, however, the wastegate actuator sees rising pressure and starts to crack open, thereby letting some exhaust bypass the turbine. The more boost created, the more the valve opens. This continues until the turbo is at full boost and the wastegate is fully open, thereby allowing a predetermined amount of exhaust gas to flow across the turbine.

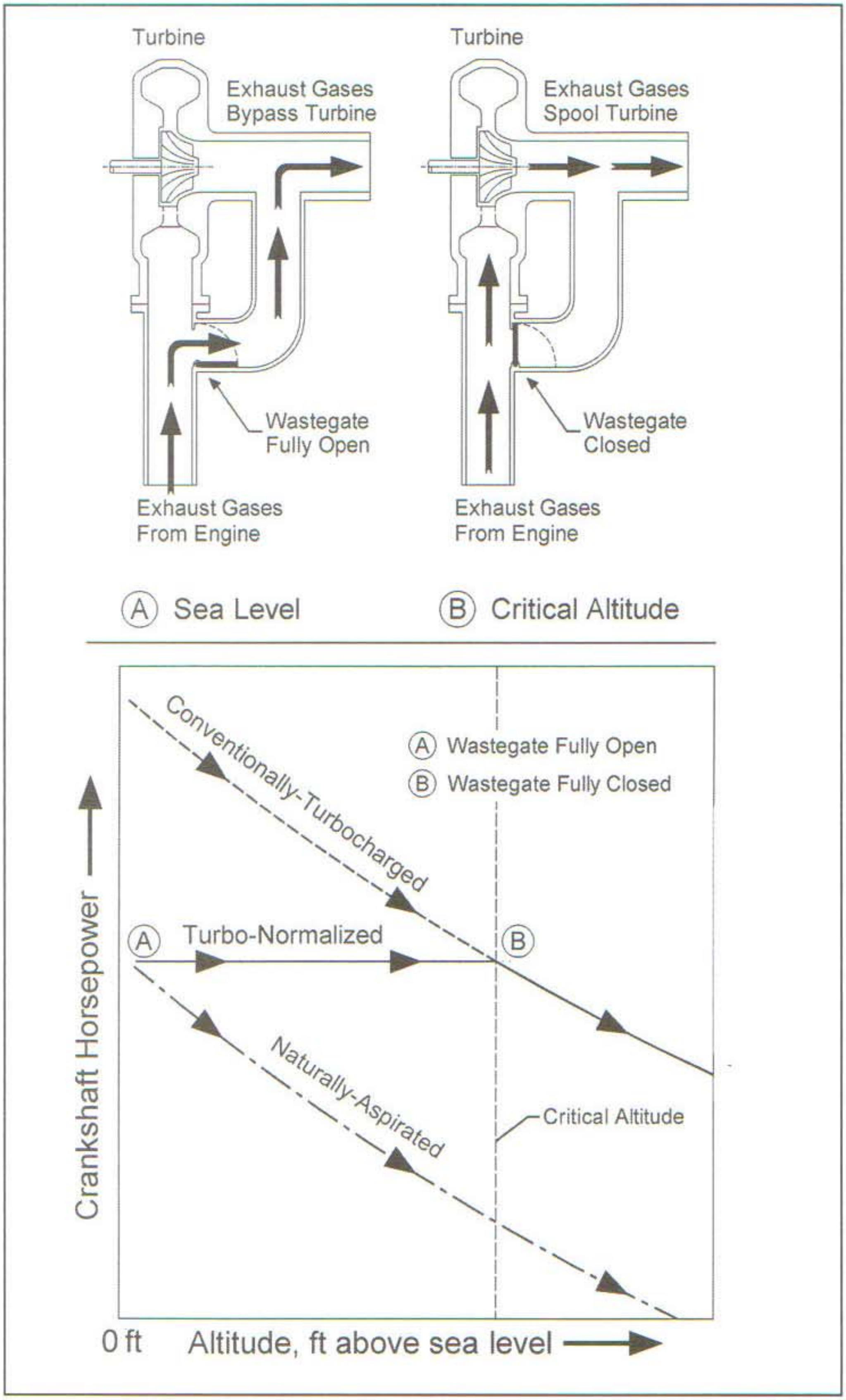
Okay, now that we understand how a wastegate works in theory, let's look at some specifics. There are essentially two types of wastegates: internal (also known as integral) and external (also known as remote).

Internal Wastegates

An internal wastegate is located inside the turbine housing. It has a pivot, or hinge, that passes through the wall of the turbine. A lever is attached to this pivot on the outside of the turbine. A steel rod is then connected to the wastegate actuator, which is typically mounted on the side of the compressor housing.

Most factory (OEM) turbochargers use internal wastegates. This is because they are simple and inexpensive to mass produce. Since the valve is located inside the turbine housing, it can vent the exhaust gases arriving from all the engine cylinders in an efficient manner.

An internal wastegate also offers the advantage of compactness. Because it's built into the turbine housing, no additional tubes or pipes are required to vent the gases entering or exiting the wastegate. Once the turbocharger is mounted



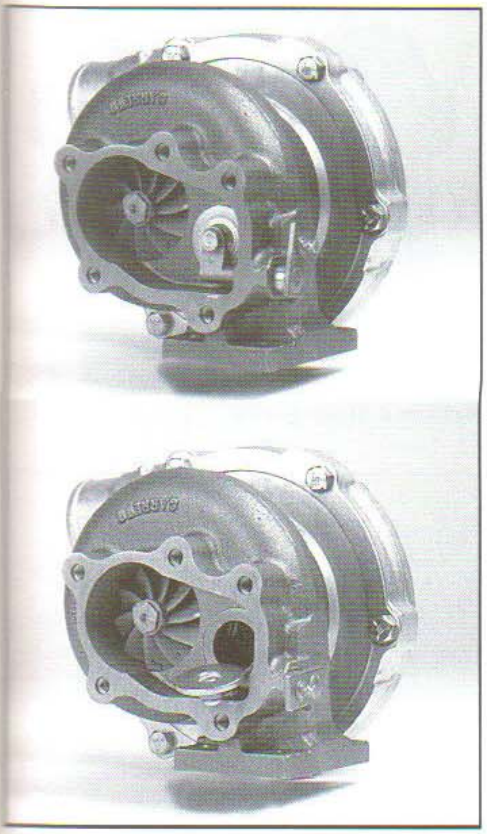
Turbo-normalizing is a boost control technique often used in turbocharged aircraft and some specialty hill- and mountain-racing vehicles. This method allows the engine to produce a constant level of horsepower over a wide range of altitudes. Note that the wastegate is held fully open at sea level and then gradually closes as the vehicle gains altitude. One advantage of this arrangement is that engine stresses are held constant. In effect, the turbocharger functions as a device to maintain sea level horsepower output at altitude.

and plumbed into the exhaust stream, there is nothing more to connect. A properly sized internal wastegate is often sufficient for moderate-boost (i.e., less than 15–20 psi) street applications.

For higher boost and performance levels, however, there are some drawbacks to internal wastegates. For example, the exhaust stream passing through an internal wastegate dumps directly into the exhaust downpipe right next to the exhaust that passes through the turbine. This waste-gate gas stream can interfere with the exhaust stream exiting the turbine, causing increased back-pressure that reduces the effective-ness of the turbine.

Boost Creep—Another issue with internal wastegates is something called boost creep (see sidebar page 72). Because a wastegate door has a finite size, it has a fixed amount of gas that can flow through it. In other words, above a certain level, an internal wastegate cannot flow enough exhaust to maintain a fixed amount of energy passing across the turbine. Turbochargers fitted with internal wastegates are generally not intended to support high levels of boost. They're fine for low-to-moderate pressure applications, but above a certain threshold they begin to choke. Sometimes it is possible to port, or grind open, the wastegate passage to flow more exhaust, but it's easy to go too far and end up with a wastegate door that leaks at low boost levels. This results in a slow spool-up of the turbine.

The factory wastegate actuators typically used with internal wastegates are also not ideal from a



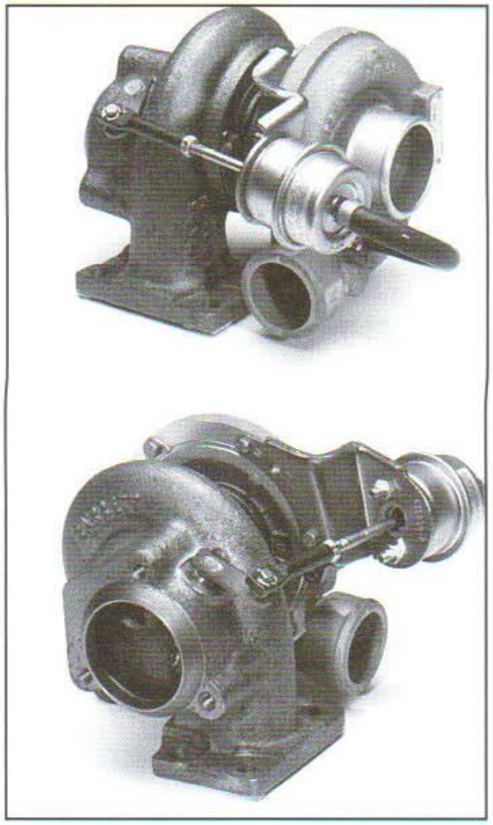
A typical internal-type wastegate, shown in the fully open and closed positions. Internal wastegates offer the advantages of compactness and simplicity. (Honeywell Turbo Technologies)

performance point of view. The springs inside of these devices often cannot easily be changed, and some actuators can be prone to breakage under hard use.

Aftermarket companies sell block-off plates so that the internal wastegate can be removed, and an external wastegate can be added to the system. You can also weld them shut.

External Wastegate

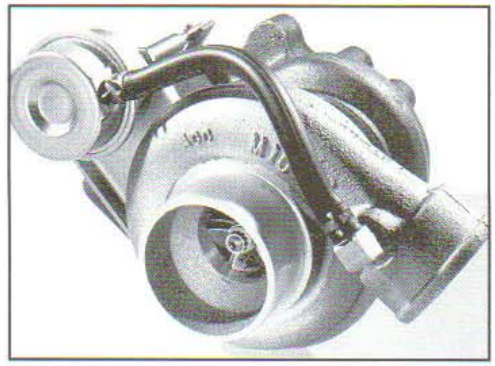
For all-out performance, an external wastegate is the preferred solution for turbine-side boost control. This is due to three things. First, the exhaust from an external wastegate can be routed in a way that it does not interfere with the backpressure directly downstream of the turbine. Second, external wastegates are less prone to boost



An actuator mounted on the compressor controls the internal-type wastegate. Note the pivot (hinge) that passes through the turbine housing body. A pushrod connects the actuator with the wastegate door assembly. (Honeywell Turbo Technologies)

creep than internal units, mainly because they are larger in size and have a much higher flow threshold before they choke. Finally, external wastegates are fitted with their own built-in actuators. These actuators can be fine-tuned with different springs or preload washers to change the rate at which they open the wastegate. They also sometimes have an adjustable preload screw that can be used to set the opening point of the wastegate.

The exhaust exiting from an external wastegate is an interesting problem. The exhaust can be dumped directly to the atmosphere, or it can be routed back into the main exhaust pipe. When dumping directly to the atmosphere, the best solution is to



The wastegate actuator receives its boost signal from the compressor outlet; simple, reliable, and effective. (Honeywell Turbo Technologies)

install a completely separate exhaust path, including small muffler, for the wastegate. This obviously complicates the exhaust system construction, but for all-out performance, a separate flow path offers the best performance.

If you feed the wastegate exhaust back into the main exhaust pipe, you should do so at least 18 to 24 inches downstream of the turbocharger. Another key to minimizing the effect on the turbine-side flow is to keep the angle of the tubing merge as shallow as possible. The turbine exhaust stream should be minimally disturbed by the incoming wastegate exhaust. This will reduce the amount of flow turbulence (which results in turbine back-pressure) and help maintain a fast-spooling turbocharger.

Another consideration is the placement of the wastegate itself. Ideally, the device needs to receive exhaust pulses from all the cylinders of the engine. An internal wastegate (located inside the turbine housing) by default sees flow from all the cylinders. This is not necessarily true for a manifold-mounted external wastegate. Too often, fabricators place the

BOOST CREEP

A common problem with modifying turbocharger-equipped vehicles is one of boost creep. Boost creep occurs when the wastegate is improperly sized and cannot dump enough exhaust gases to keep the turbine from accelerating beyond an allowable maximum speed. The result is uncontrolled rising boost.

Exhaust from the engine has two ways out: through the turbine or through the wastegate. The wastegate is closed at low engine speeds, and all the exhaust passes through the turbine. When boost pressure on the compressor side reaches a predetermined level, the boost controller starts opening the wastegate to give the exhaust gases an alternate way out without passing through the turbine. Factory (OEM) wastegates are sized to bleed a nominal amount of exhaust pressure to control boost. They have a very small margin of error built into their size. The advantage of this is that the wastegate door can use more of its range of motion to control flow.

If the wastegate door is too large for the system, it ends up being more of an on-off switch than a smooth regulator. On the other hand, if the door is too small for the engine, it can't relieve enough pressure. The result is boost creep. This is a common occurrence on engines that have had free-flowing exhaust systems installed downstream of the turbocharger. Lower backpressure increases exhaust gas velocity across the turbine. This makes more boost, which ultimately means more exhaust gas flow than the stock wastegate is designed to handled.

There are a number of solutions to boost creep. The most common involve porting the internal wastegate orifice to increase its flow. If this is insufficient, it is possible to plug the internal wastegate orifice and install an aftermarket external unit that has higher flow abilities.

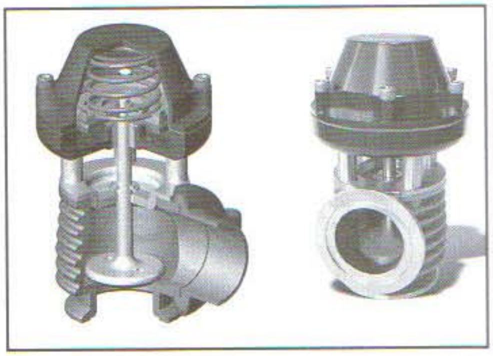
wastegate on a single runner of the exhaust manifold before it merges with the other exhaust streams. Designs that do this are inferior; they can make boost control difficult and should be avoided if possible.

Finally, the flow from the exhaust manifold needs to smoothly transition to both the wastegate and the turbine. Sharp angles, ninety-degree bends, and arrangements that require exhaust flow reversals should be avoided.

Wastegate Boost Controllers

A wastegate actuator has a fixed pressure at which it is designed to start opening. If we want to increase the boost output from a turbocharger, we have to delay this opening point. The devices that accomplish this task are known as boost controllers. Most boost controllers work by reducing the actuator signal supplied to the actuator. This keeps the wastegate from opening until a higher boost level has been reached. Boost controllers can be either manually or electrically operated.

Manual Boost Controllers—Manual boost controllers, or



A high-quality aftermarket external-type wastegate. (Turbosmart)

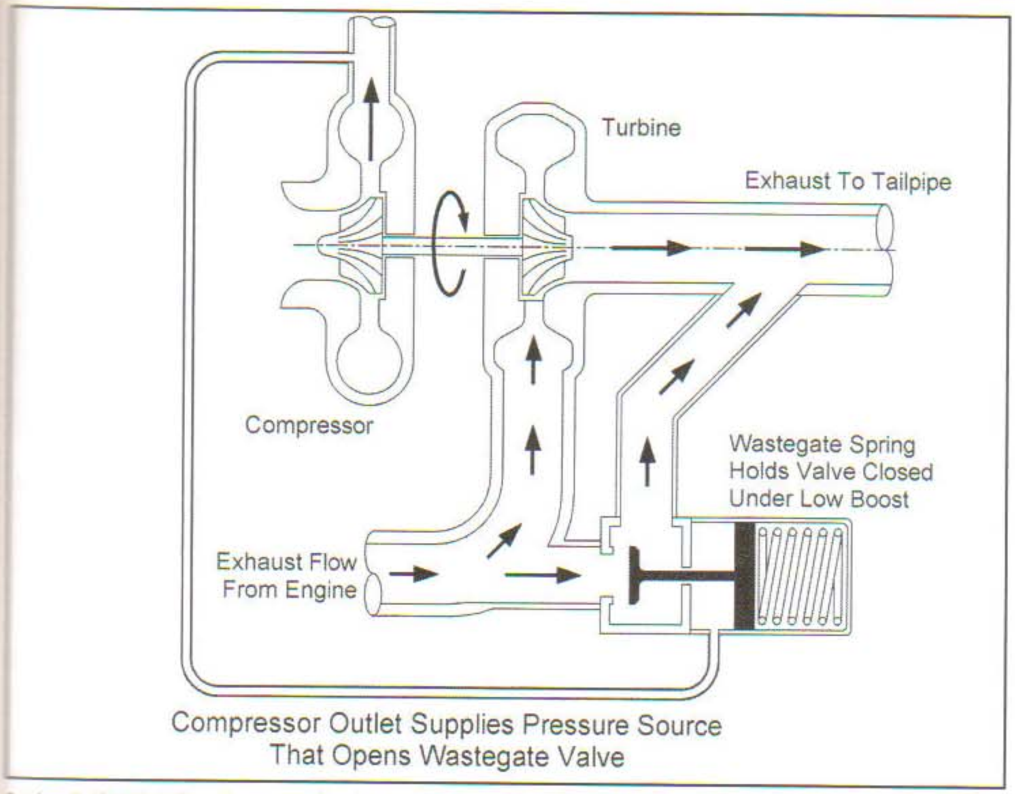
STREET LEGALITY

Adding an external wastegate is not usually a street-legal option, unless it is plumbed back into the exhaust upstream of any emissions-control devices, such as catalytic converters.

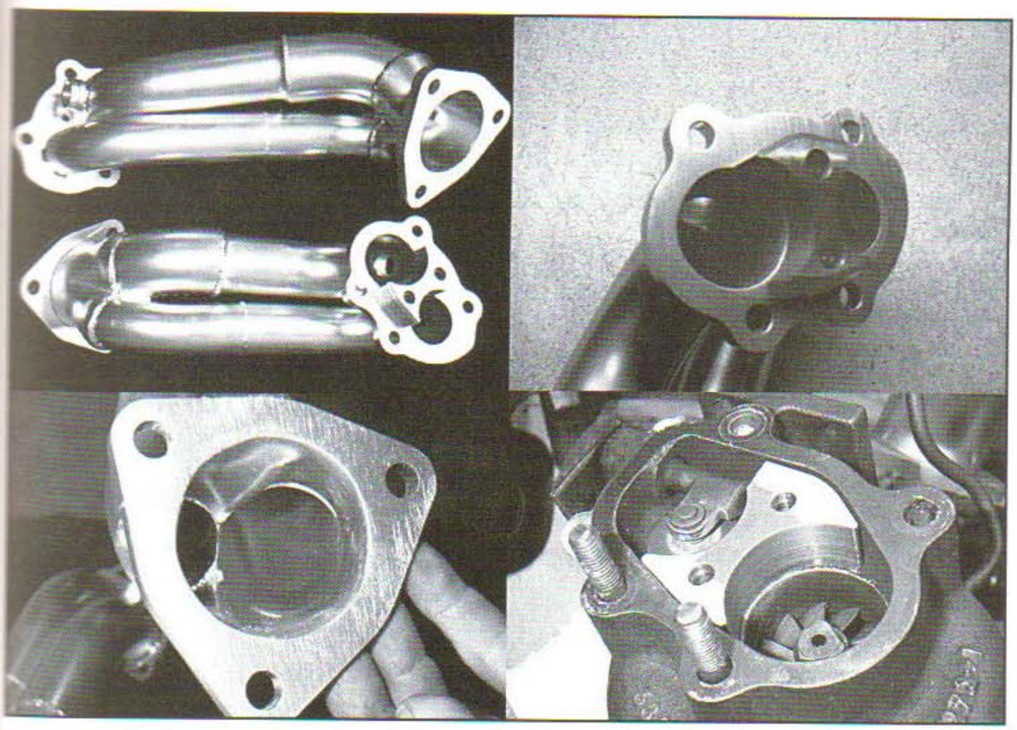
MBCs, are simple devices. They are reliable and are relatively inexpensive. In fact many enterprising enthusiasts build their own MBCs for less than $20.00 with supplies purchased from a hardware store.

That's the good news. The (sort of) bad news is that MBCs tend to be non-linear devices that can be difficult to set up properly. Trial-and-error is often called for when adjusting and tuning the devices. This usually involves starting with fairly low levels of boost and then slowly increasing it in incremental steps.

MBCs work on the principle of manipulating the actuator pressure signal from the compressor before it reaches the wastegate actuator. They do this by either blocking the airflow to the actuator, or by bleeding off some of that flow. Both of these types are usually mounted inside the engine compartment, close to the

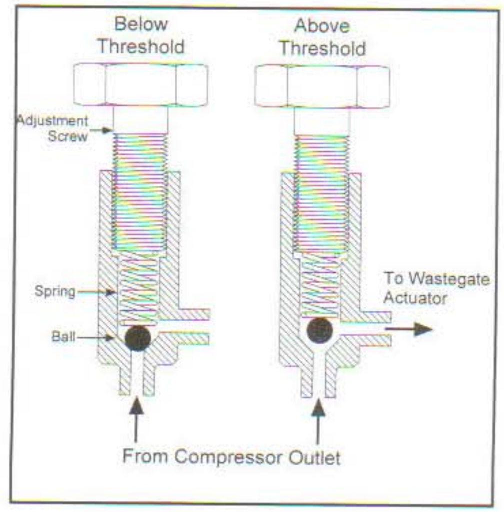


Instead of a pivoting door, most external-type wastegates use a linear-action valve to vent exhaust gases. External wastegates can often flow more exhaust gases (and thereby support higher levels of boost production) than internal wastegates.



One disadvantage of an internal-type wastegate is the interference its exit flow has on the exhaust passing out of the turbine. Because the two exhaust streams vent to a common area immediately downstream of the turbine wheel, turbulence can be created. This can cause a rise in backpressure, which will reduce the performance of the turbine. A so-called "divorced" wastegate downpipe, like the unit shown here, can reduce this power-robbing effect. Note the flow divider in the turbine housing that keeps the two exhaust streams separated until they enter their respective pipes. Also note the smooth transition at the other end of the downpipe, where the flows merge together. Eighteen to 24 inches is a typical downpipe length of a divorced tube before recombining the flows. (Specialty-Z)

An aftermarket manual boost controller (MBC) can be used to change the output characteristics of a turbocharger. (Turbosmart)



A simple spring-and-ball type manual boost controller. The wastegate actuator will not see boost (and therefore will not begin opening) until a minimum threshold pressure is created by the compressor. This threshold value can be changed by adjusting the spring preload.

wastegate, but some higher-end models can be mounted within the driver's reach inside the cabin.

The blocking type of MBC typically consists of a ball and spring assembly that keeps any pressurized air from reaching the wastegate until a threshold psi value is reached. These are the simplest of MBC devices and tend to work very reliably. They keep the wastegate shut until the desired

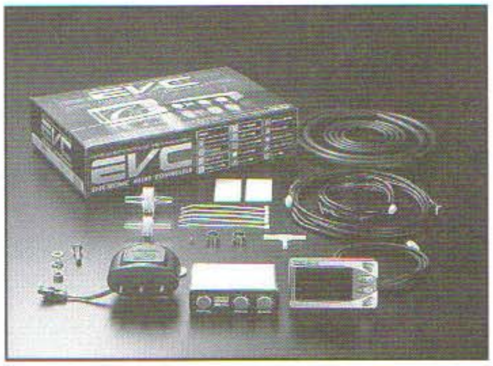
An electronic boost controller offers the advantage of in-cockpit adjustment of wastegate settings. (Turbosmart)

boost is reached, and then they open relatively quickly.

The second type of MBC is a bleed controller. These devices work by bleeding, or leaking off boost pressure to the atmosphere so that the wastegate sees less boost being produced than there really is. Bleeder MBCs let the wastegate partly open at lower boost and result in a slower, more gradual transition to full boost.

Electronic Boost Controllers—Electronic boost controllers (EBCs) are essentially computer-controlled versions of manual boost controllers. In other words, EBCs use modern electronics to take the place of a hand-twisting dial.

Most electronic boost controllers are comprised of three basic components. These are an air pressure sensor, a solenoid valve or stepper motor, and a cockpit-mounted control unit. The pressure sensor and solenoid valve (or stepper motor) are installed in the engine compartment, normally very close to the turbocharger and wastegate, with short hose lengths for fast response. The control unit is mounted in the cabin near the driver.

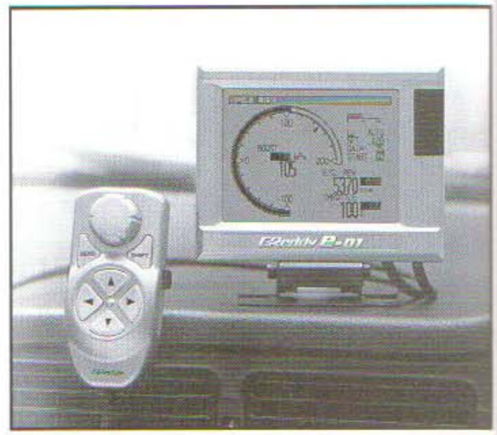


HKS offers this electronic boost control kit, complete with everything required to install and set up an in-cabin control system. (HKS)

The air pressure sensor generates and sends a voltage signal to the control unit. The control unit reads this signal and, depending on a variety of conditions and other sensor inputs, sends a command signal to the solenoid valve or stepper motor. In the case of a solenoid valve system, the valve opens and closes very rapidly, bleeding off the actuator signal pressure. The stepper motor units work by varying the position of a precision bleed valve. The big advantage of both these types of devices is the elimination of boost creep.

In addition, electronic boost controllers offer some other advantages over MBCs. Firstly, because they are electronic and remotely-controlled, the solenoid and sensor units can be located inside the engine bay, next to the wastegate. MBCs that are remote-mounted in the cabin can suffer from slow response, especially if the remote vacuum/pressure hose is routed a long distance through small diameter hose.

The second advantage of EBCs is the fact that they can improve turbo response by keeping the wastegate closed longer during spool-up, which allows more efficient use of the exhaust stream

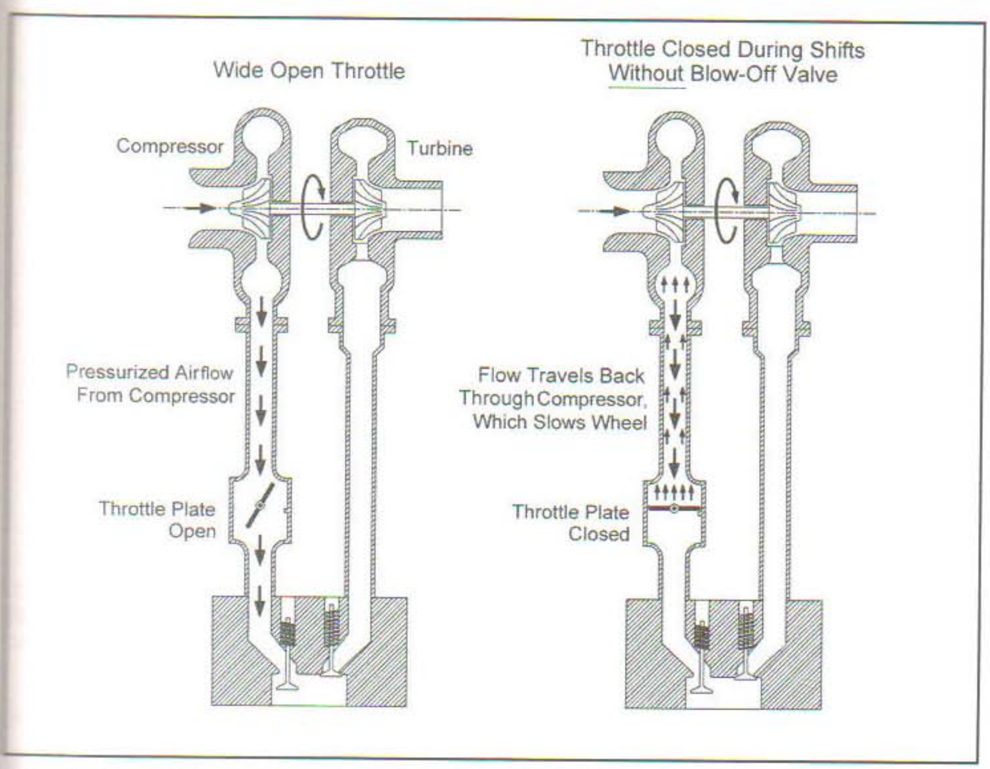


This Profec e-01 unit combines electronic boost control, data logging and display, as well as programmable fuel management control. (GReddy)

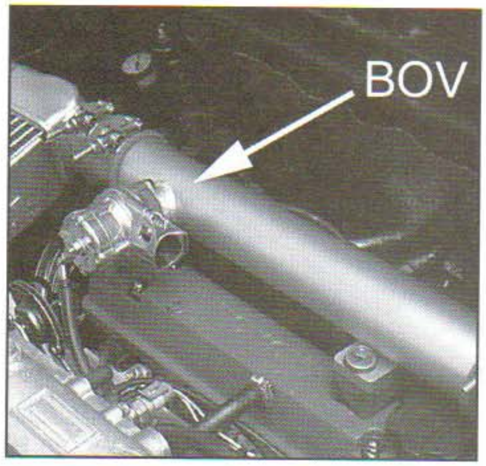
energy. Most OEM and many MBC units actually have to start opening the wastegate far in advance of the desired boost pressure. For example, if a wastegate is set to open at 12 psi, it may have to start opening at 7 or 8 psi, so as to not overshoot the final desired boost level. Many EBC units also begin opening early, but because they are faster acting and more controllable, the opening point can be delayed much farther into spool-up.

Finally, EBC manufacturers offer a myriad of extra features, such as stored multiple boost settings and gear- and rpm-dependent boost levels. Some even have fuzzy boost logic that "self-learns" how you drive. EBCs are also available with full engine sensor monitoring and a variety of real-time and stored display abilities. EBCs are useful when you want to have precise control over the boost output under a variety of conditions. The downside of these units, of course, is that they tend to be pricey.

Electronic boost controllers are gaining in popularity. A number of aftermarket companies such as



When the throttle is closed suddenly during boost, such as during gear shifts, a pressure spike can be created inside the intake tract. This can cause the airflow to stop, or even travel back through the compressor, slowing the impeller and sometimes causing damage. A pressure-relief valve fitted to this portion of the intake tract can vent the excess pressure, thereby maintaining the turbocharger at the correct rotational speed.



This Toyota MR2 MK1 is fitted with a Blitz BOV directly upstream of the intercooler. (Picasso)

A'pexi, Blitz, GReddy, HKS, and Turbosmart make high-quality EBCs. Several of these are also available with pollution exemption stickers, so you can run them legally on the street. Some stand-alone electronic control units (ECU) also have EBC capabilities built in. These have the advantage that they are integrated with the other engine functions, which means that if, say, the ECU detects high coolant temperatures, it can shut down the boost and protect the engine.

COMPRESSOR-SIDE BOOST CONTROL BASICS

Turbochargers can spin at over 100,000 rpm and create hundreds of cubic feet per minute of highly pressurized airflow. There is a large amount of internal energy contained in the airstream that flows from a compressor. What happens to all that energy during gear shifts or other moments when the accelerator pedal is suddenly lifted and the throttle plate snaps shut? The answer is that a very large pressure spike is created that essentially has nowhere to go.

This pressure spike that is created can actually cause a flow of air to pass backward through the compressor and, in doing so, impart a load on the impeller, the shaft, and the turbocharger bearings. It can also slow the compressor wheel rotation (and hence the turbine, too). This is like applying an air brake to the turbocharger.

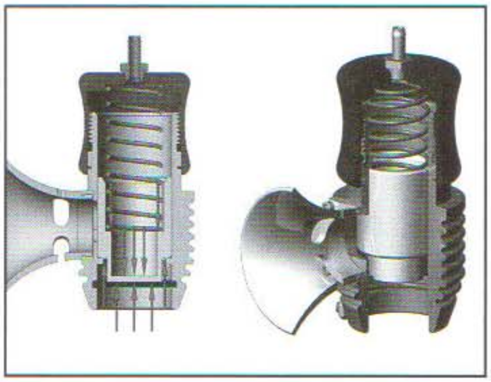
Besides the excessive loading this places on the turbocharger components, the slowing of the compressor ultimately results in turbo lag. When the driver opens the throttle again to accelerate, the turbine and compressor wheels have to spool-up again to create the same level of boost pressure.

Blow-Off Valves (BOV)

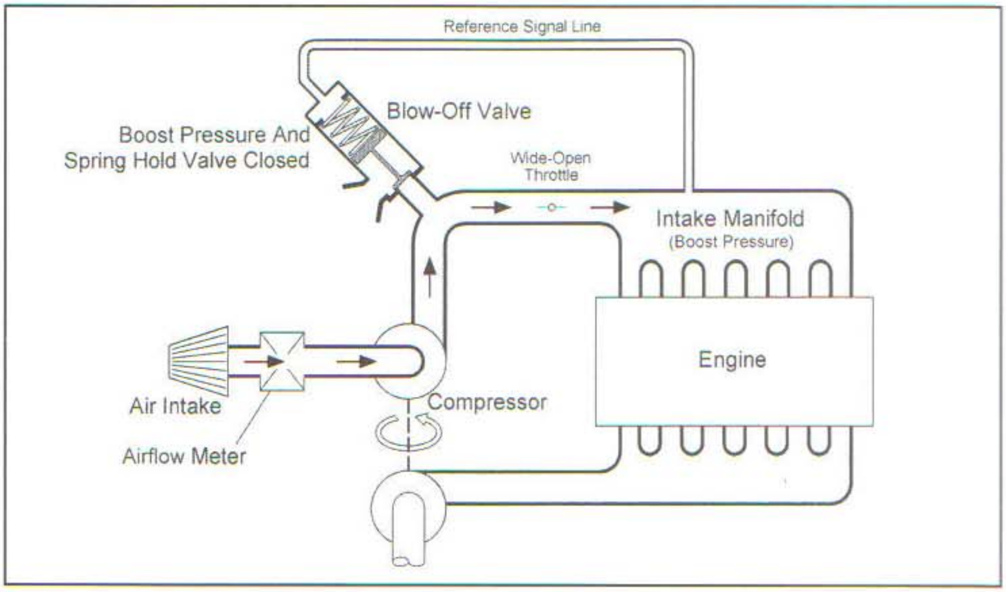
The solution to lift-throttle pressure spikes is a blow-off valve, or BOV. Unfortunately, the BOV is probably one of the most misunderstood parts in a turbo system. Everyone wants one for their vehicle. Aftermarket suppliers sell thousands of them, and few people understand what they do or how they work.

A blow-off valve is nothing more than a pressure-relief valve. When pressure rises too high inside the intake tract, the vent opens and allows airflow to escape. This helps to eliminate the pressure spike, thereby allowing the compressor to "freewheel" so there is no significant loss of impeller speed.

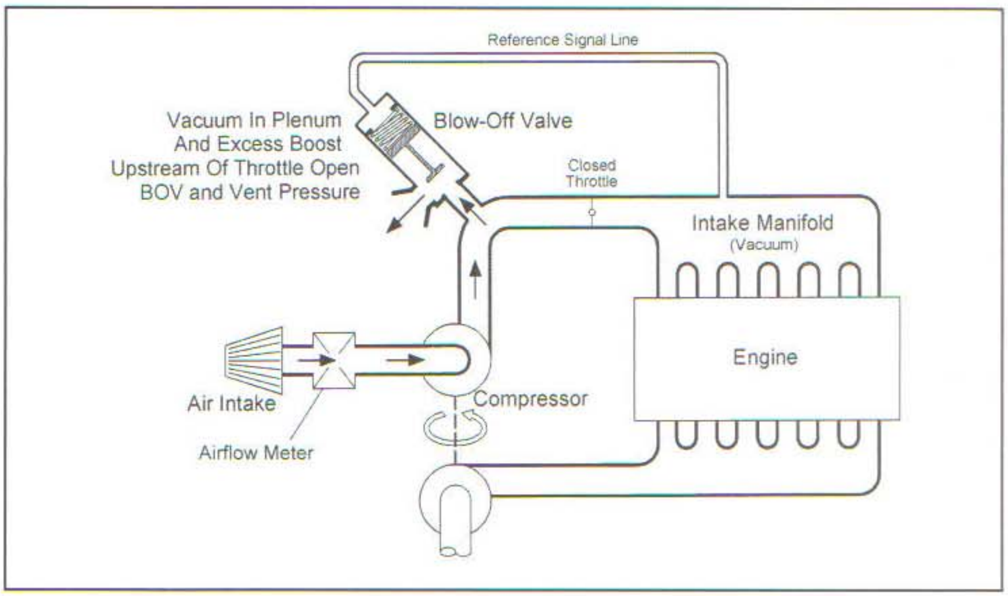
Many people—too many, it seems—buy BOVs simply because of the noise they make when shifting. Some BOV suppliers even include descriptions of the cool noise a BOV makes in their product literature. A BOV is a safety and performance device. It is



A typical blow-off valve. Note the pressure signal port on the top of the unit. This port is connected to the intake plenum. (Turbosmart)



During normal boost production, the air pressure in the intake plenum, along with the integral spring, keeps the blow-off valve closed. Full boost pressure is available throughout the intake tract.



During gear shifts, when the throttle plate is closed, a temporary vacuum is created in the intake plenum. This vacuum downstream of the throttle works with the high pressure upstream of the throttle to lift the valve seat. The excess pressure is then vented out of the BOV.

not intended to be a noisemaker. Yes, they sound kind of nifty when they vent. But this is a byproduct of their real function: pressure relief.

Most aftermarket valves operate on a spring versus pressure principle. Boost pressure on one side of the valve presses against the force of a compression spring on the other side. Often a pressure line is also used to direct manifold pressure to the spring side of the valve. Under normal boost conditions, the spring and manifold pressure are sufficient to keep the valve seated. When the throttle closes, however, the manifold-side pressure reverts to vacuum. This, in combination with the upstream throttle-plate pressure, works to lift the valve and vent air.

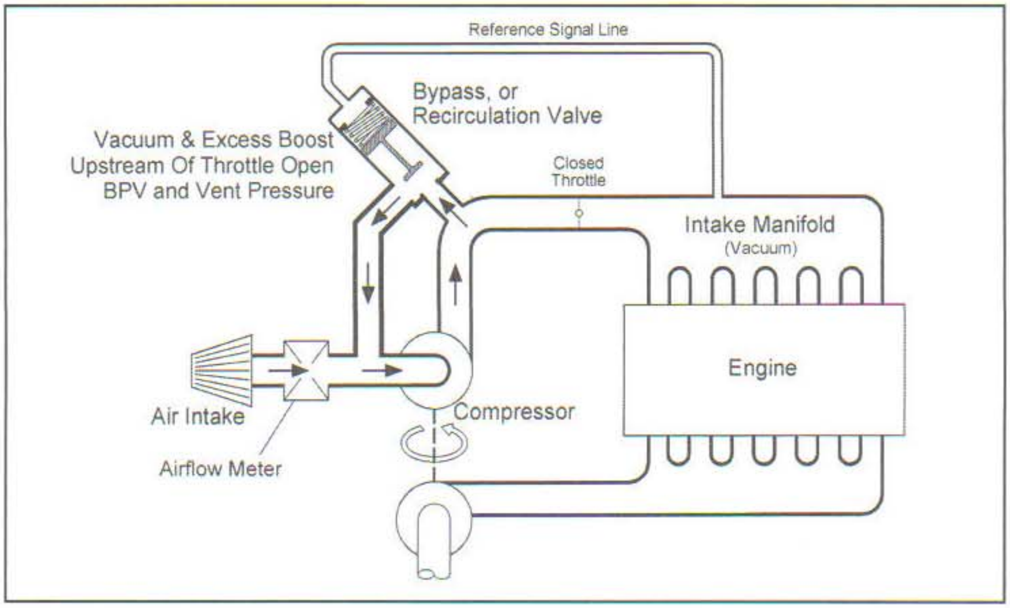
Bypass Valves (BPV)

Many original equipment manufacturers (OEM) don't utilize BOVs, but instead use something called a bypass valve, or BPV, to handle pressure spikes caused during the sudden closing of the throttle plate. A bypass valve functions in essentially the same way an aftermarket BOV does, but there is a difference in how the vented air is handled.

Most aftermarket BOVs exhaust or vent directly to the atmosphere. Of course this is the reason that they make the much sought-after "Pssshhhht" noise—the air is dumped into the engine bay. Venting air like this, however, can cause a minor problem on cars equipped with airflow meters that are mounted upstream of the BOV. When intake air passes by the airflow meter, a signal is sent to the ECU that determines how much injected fuel is required to support combustion. If some of this air is vented after metering, the ECU does not have any way of accounting for the loss. In other words, the air/fuel mixture will be wrong.

Bypass valves solve this problem

A configurable blow-off valve. This unit can be changed from BOV to BPV by simply switching the outlet port fitting. (Turbosmart)



A boost bypass valve, or BPV, is often used in OEM applications. It differs from a BOV in that it redirects vented air back to the intake side of the compressor rather than simply releasing it to the atmosphere. There are two advantages of a BPV over a BOV. The first is that there is no loss of air from the intake tract. Many engine electronic control units (ECUs) determine the amount of fuel required based on the quantity of air that has passed by an airflow meter upstream of the compressor. Venting air from the intake tract downstream of the air meter can fool the ECU into thinking more air is being ingested by the engine than actually is. This results in intermittent over-rich air-fuel mixture conditions. The second benefit of a BPV is that of noise. A BPV is typically much quieter than a BOV—however, some enthusiasts don't consider this to be an advantage at all.

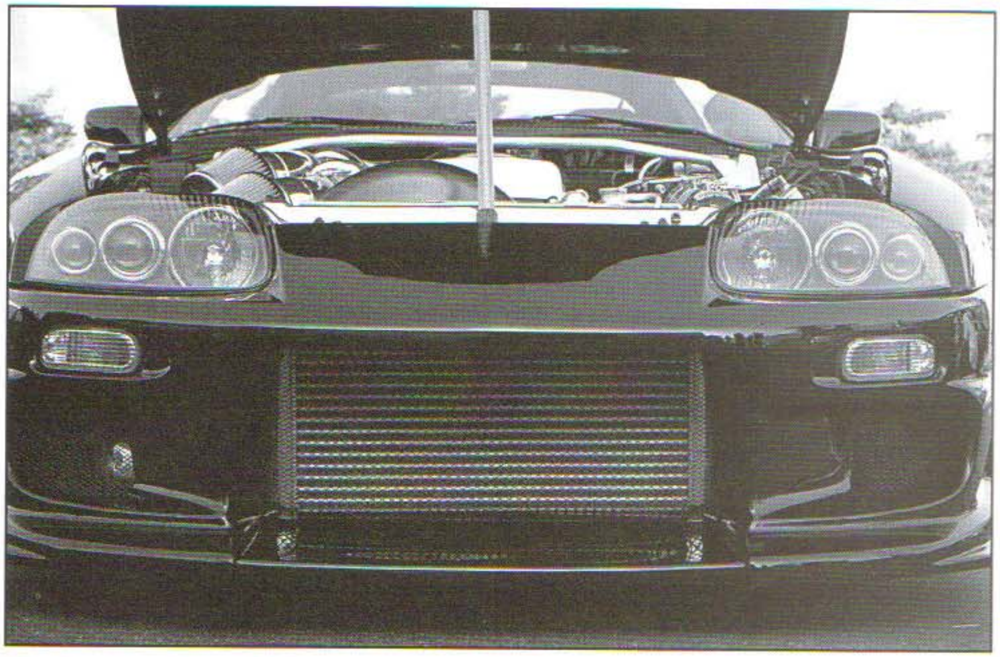
by directing the vented air back into the intake tract, usually directly upstream of the compressor (but downstream of the airflow meter). This retains all the air accounted for by the ECU but still results in a pressure relief in the systems. BPVs also have the benefit of being less noisy than BOVs. This is another reason why they're used by OEMs; they're more suitable for someone who wants a quiet turbocharged vehicle—not one that goes "Pssshhhht" every time he or she shifts gears.

For those using BOVs, the good news is that the air/fuel error is only a momentary effect, and it generally results in an overly rich mixture. Other than wasting gasoline, there is not generally a big safety risk associated with BOVs.

When selecting either a BOV or BPV, a few things need to be considered. First, the reaction time to vent air is important. A slow-acting valve can allow a significant fraction of the pressure spike to make it back to the compressor impeller—and slow it down. The next thing to consider is how quickly the device will close after venting. How fast boost pressure is restored is directly affected by the time it takes to close the valve. And finally, a BOV or BPV must stay closed under all normal boost conditions. It is a safety device, but you don't want it venting useful—and safe—boost during normal engine operations.

A dual-port unit features sequentially staged venting. During normal driving, excess pressure is returned to the intake tract via the BPV port shown here on the right side of the unit. During higher pressure events, the left-side BOV-type port is also opened, allowing additional venting. (Turbosmart)

9 INTERCOOLERS


The classic front-mounted air-to-air intercooler. At 37 psig of boost, this Supra develops over 1100 hp at the rear wheels. A large intercooler with excellent airflow characteristics and low pressure drop are an absolute requirement. (Henderson/SP Engineering)

The pressurized air that exits a compressor is hot, and hot air is less dense than cold air. The horsepower an engine produces is directly related to the density of the intake, or charge air stream. If we don't remove some or all of the extra heat added by the compressor to the charge air, we sacrifice horsepower. We also risk engine damage. Hot intake air is more likely to allow detonation in the combustion chamber than cold air. In other words, cooling the air after compression can have a major effect on both engine performance and safety.

There are essentially two different types of devices that fall under the general heading of charge cooling equipment: intercoolers and water injectors. Let's look at how these devices work, starting with the intercooler. We'll examine water injection systems in the next chapter.

INTERCOOLER BASICS

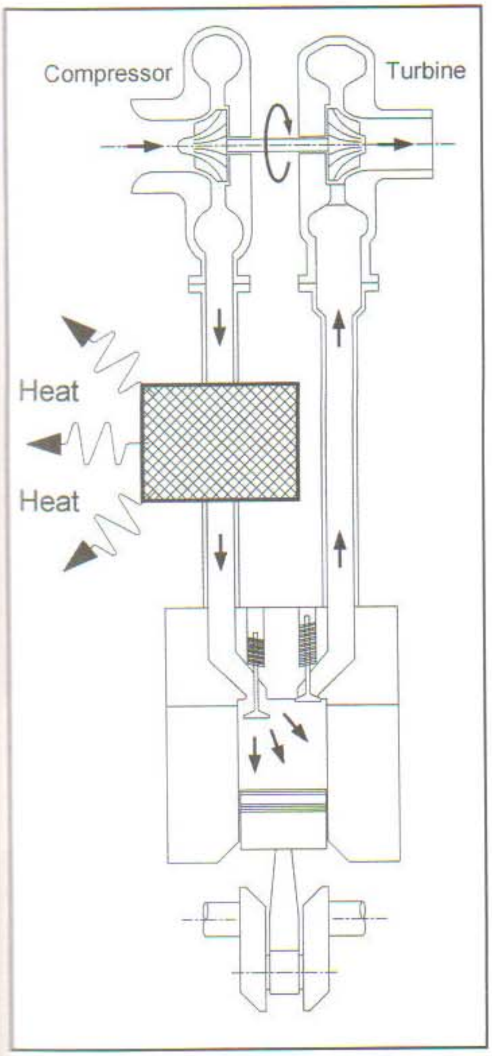
Picture a basic, run-of-the-mill engine radiator. Now imagine warm intake air flowing through the interior of the unit instead of hot engine coolant. Congratulations, you've just invented the intercooler!

A radiator is a heat exchanger, and an intercooler is a heat exchanger. One of these devices flows a liquid (coolant), and the other flows a gas (air), but they're both heat exchangers that work via indirect-contact heat transfer to cool, or remove heat from the fluid that is flowing inside of it.

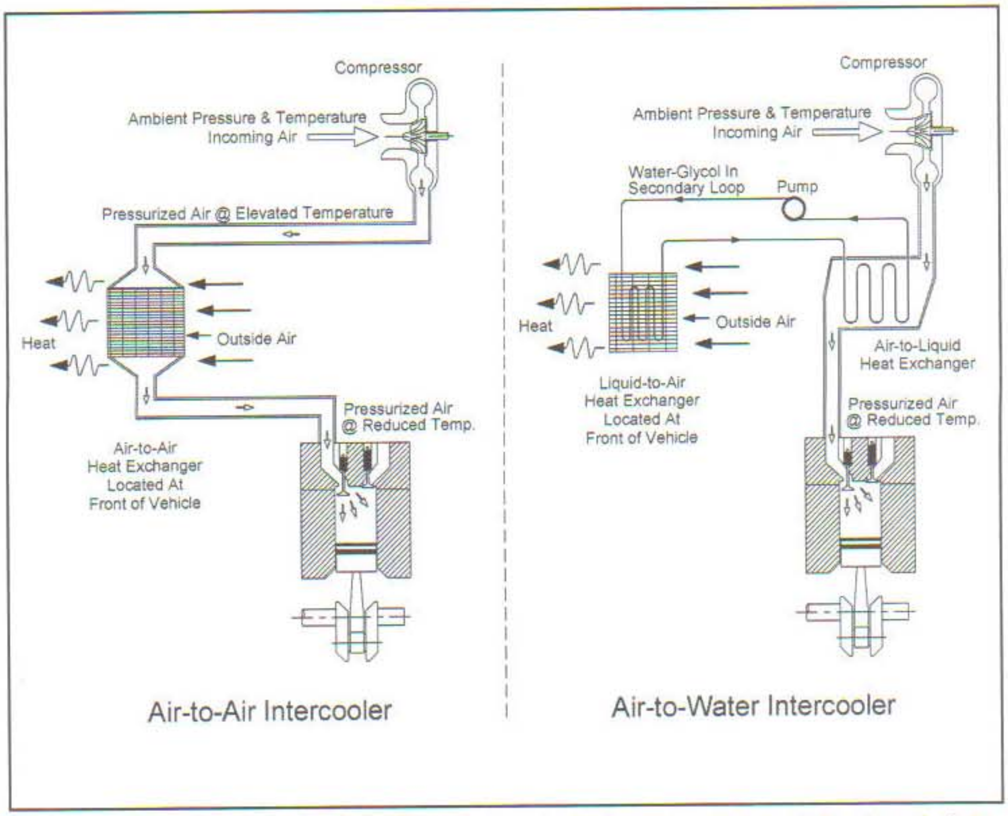
A heat exchanger is a device that transfers energy (heat) from a warm fluid (either a liquid or a gas) to another cooler fluid (again, either a liquid or gas). In the case of an air-to-air intercooler, heat contained in the pressurized charge air is transferred to the cooler outside ambient airstream by way of a series of fins and tubes that are made from a thermally conductive metal such as aluminum. The warm interior charge air and the cooler exterior ambient air never touch each other. Instead, they rely on the conductive properties of the tubes and fins to transfer the actual energy.

Now, before we go any further, it's important to note that heat flows only in one direction: from hot to cold. If you put a warm hand on top of a block of cold steel, heat from the hand will be transferred to the steel. There is no such thing as "cold" flowing from the steel to the hand. Heat always moves from a warmer body to a colder one. Intercoolers exploit this principle by a combination of *conduction* and *convection*.

The hot air charge that flows through the interior channels and tubes of an intercooler sheds its heat to the relatively cooler interior walls of those channels and tubes. This takes place through a process called convection. Once transferred to the interior surfaces of the



An intercooler is a heat removal device. Compressors warm the intake air during pressurization. The lower the compressor efficiency, the hotter the outlet air. Intercoolers are used to remove some or all of this added heat. The cooling medium can be air, water, ice, or any other fluid that is colder than the charge airstream

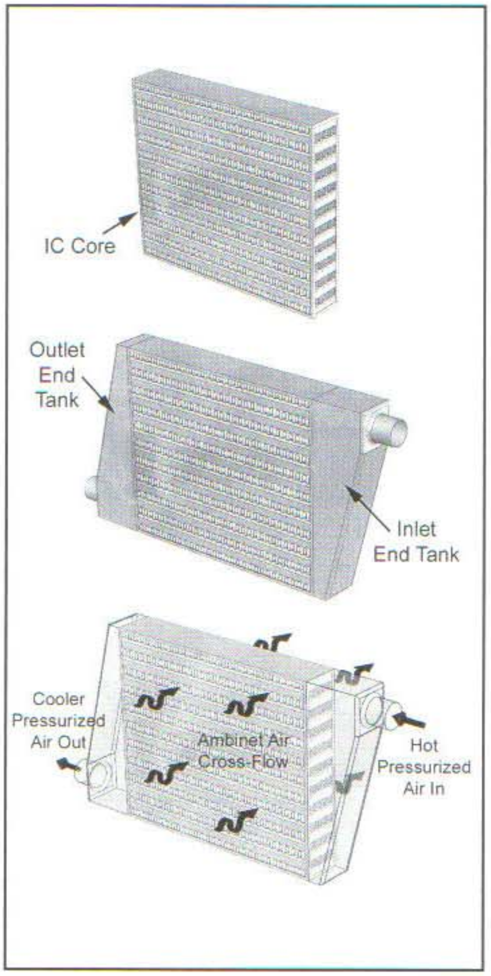


There are two main types of intercoolers used on turbocharged vehicles: air-to-air and air-to-water.

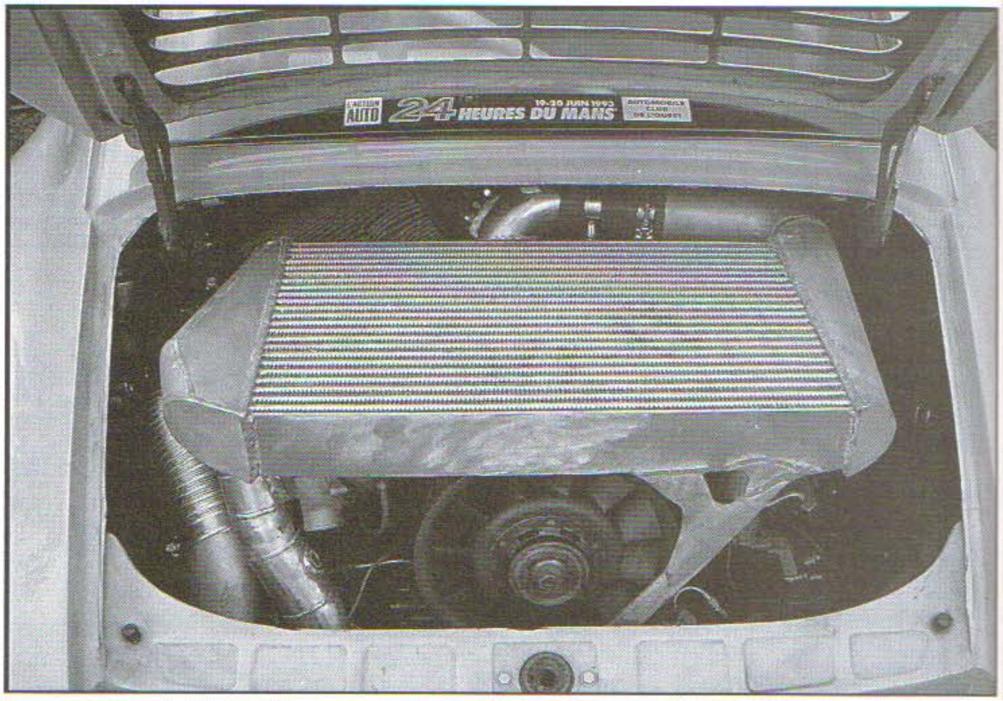
intercooler, the heat is conducted through the walls and fins to the exterior, or ambient side. This happens—of course—because the exterior side of the intercooler is cooler than the interior (remember, heat flows from warm to cool). Once the heat arrives at the exterior fins and surfaces, the cooler outside ambient air picks up the heat and carries it away, again by convection. (To learn more about conduction and convection, see the sidebar on heat transfer.)

Now, the important thing to note is that if there is no temperature difference, there can be no heat flow. This means that if the walls and fins of the intercooler get too hot, heat in the charge air stream cannot be transferred to those walls. This phenomena is known as "heat soak," and it often occurs in poorly or underdesigned intercoolers. It also occurs in static situations such as during prolonged idling or repeated pulls on a dynamometer, where there is insufficient ambient airflow to keep the intercooler temperature down. In a sense, heat soak means there is no temperature difference to keep the intercooler working. In fact, an intercooler can get hot enough that it actually adds heat to the intake air, rather than remove it. Heat will always flow from a warm location to a cold one; if the intercooler is warmer than the air leaving the compressor, it will give up heat to the airflow.

Another problem with intercoolers is that they cause a drop in boost pressure. Any obstruction or restriction that an air stream encounters, no matter how small, will bleed off pressure energy from the flow. Sharp bends, tight passageways, and narrow tubes will quickly rob an airflow of its pressure. Unfortunately, for an intercooler to efficiently convect energy from the charge air to the interior walls, it has to have lots of these types of features. In other words, the fins, tubes, and passageways that help an intercooler transfer energy by forcing the airflow into intimate contact with the walls, also serve to rob the air stream of some of its valuable boost pressure. An intercooler helps charge density by cooling the air, but it can also hurt



The basic air-to-air intercooler is comprised of a core and two end tanks.



Intercooling a rear-mounted engine like this Porsche 3.3-liter flat six-cylinder requires a large efficient intercooler. The rear spoiler aids in managing the external ambient airflow through the unit. (The Power Group)

the density by lowering the pressure. The secret then, obviously, is to maximize heat transfer, while minimizing pressure drop.

INTERCOOLER MATH

Most air-to-air intercoolers are cross-flow–type heat exchangers. This means that the two fluids (the hot air from the compressor, and the cool ambient air passing over/through the intercooler) move at right angles to each other. The math to accurately predict the performance of a cross-flow heat exchanger is quite complicated and beyond the scope of this book. That said, the general equation for the rate at which heat is transferred from one fluid to another in any basic heat exchanger can be approximated by the following equation:

Eq. 9-1

$$Q = (U)(A)(\Delta T_{log})$$

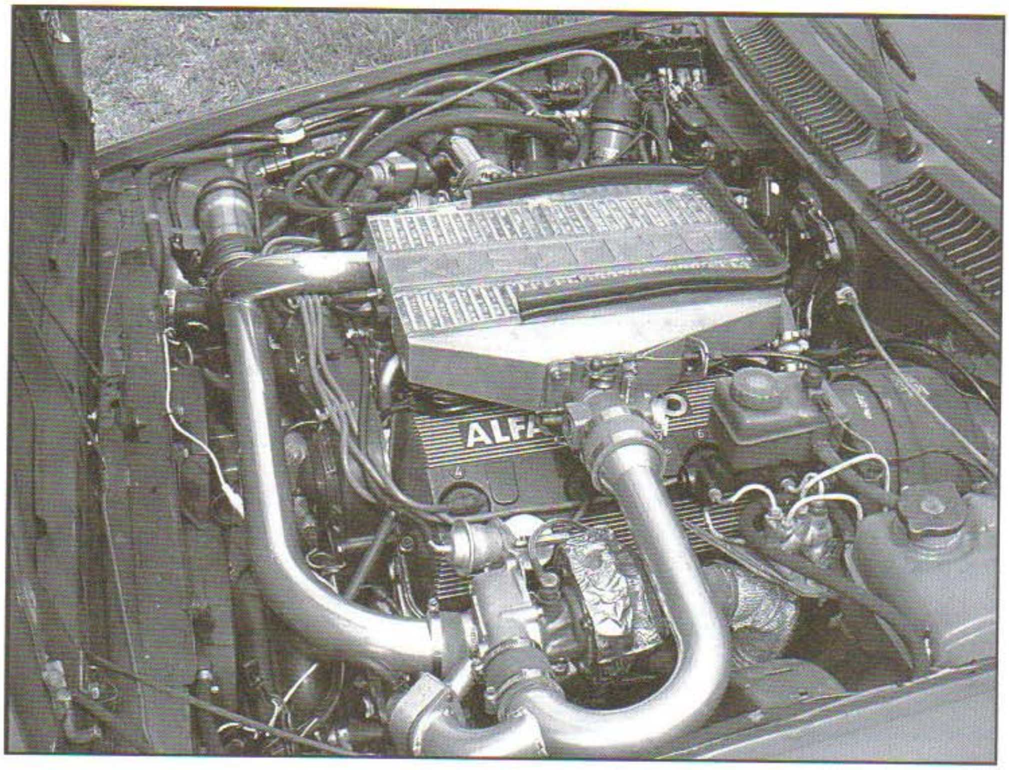
In this formula, Q is the rate at which heat is transferred from the charge air to the ambient air stream. It is usually specified in BTUs per hour. On the right side of the equation we find three

INTERCOOLING VS. AFTERCOOLING

What's the difference between intercooling and aftercooling? It depends on who you talk to. To engineering historians, the difference lies in subtle variations in the placement of the charge cooling device in multi-stage compressor installations. A heat exchanger (charge cooler) located between multi-compressor stages was historically called an "intercooler." A heat exchanger located downstream from all the compressors was called an "aftercooler." But that was then, and this is now. In modern parlance, there seems to be little rhyme or reason in the usage of the different terms. Turbo diesel experts sometimes refer to their charge air cooling devices as "aftercoolers," while gasoline engine enthusiasts usually call theirs "intercoolers." Others seem to think that it depends on whether the unit is an air-to-air or an air-to-water unit. Of course everyone is right, and everyone is wrong, too. For practical purposes, they're both the same basic thing: a charge air cooling device (i.e., heat exchanger) used to remove energy added by the compressor.

HEAT TRANSFER COEFFICIENT

The heat transfer coefficient, U, is dependent on convective film coefficients. The formula for U can be approximated by: U = (hi x ho) / (hi + ho), where hi is the interior wall film coefficient and ho is the outer, or exterior wall film coefficient. Values for hi and ho can range from 1 to 500 BTU/hr-ft^2-°F, depending on flow speed, surface roughness, and cleanliness of the surface.



Top-mounted intercoolers can suffer from poor airflow if not designed right. Note the rubber strip on top of the intercooler that is used to seal the IC to the hood and help the flow of air out the hood vents. Vehicle is an Alfa Romeo GTV6. (The Power Group)

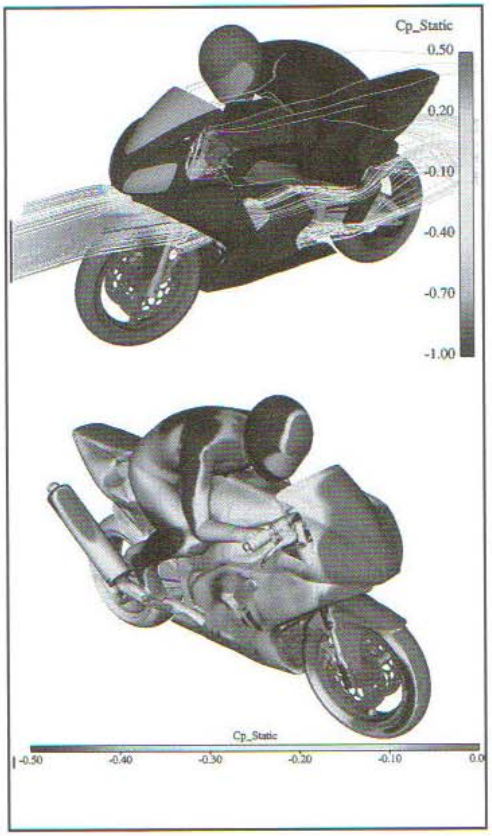
variables: U, A, and ΔT_{log}. U is the heat transfer coefficient, A is the heat transfer area, and ΔT_{log} is something called the logarithmic mean temperature difference. Even if we don't yet know what the terms on the right side of the equation mean, we can see that if we increase any or all of them, the Q on the left side of the equation will get bigger. In other words, when designing/selecting/installing an intercooler, we want to make U, A, and ΔT_{log} as large as we can. This will increase the efficiency of the intercooler and result in lower charge air temperatures.

For example, let's look at U, the heat transfer coefficient. In simple terms, U is a measure of how effectively a heat exchanger can transport energy. It is dependent on a number of design factors, including how turbulent the flows of air are inside and outside the intercooler. This is why so-called "turbulators," "swirlers," and "mixers" are incorporated into the design of many modern intercoolers. Adding these types of flow obstructions inside an intercooler helps to mix up the air, causing swirling turbulence. From a heat transfer point of view, this type of turbulence is a great thing (though it's a bad thing for pressure).

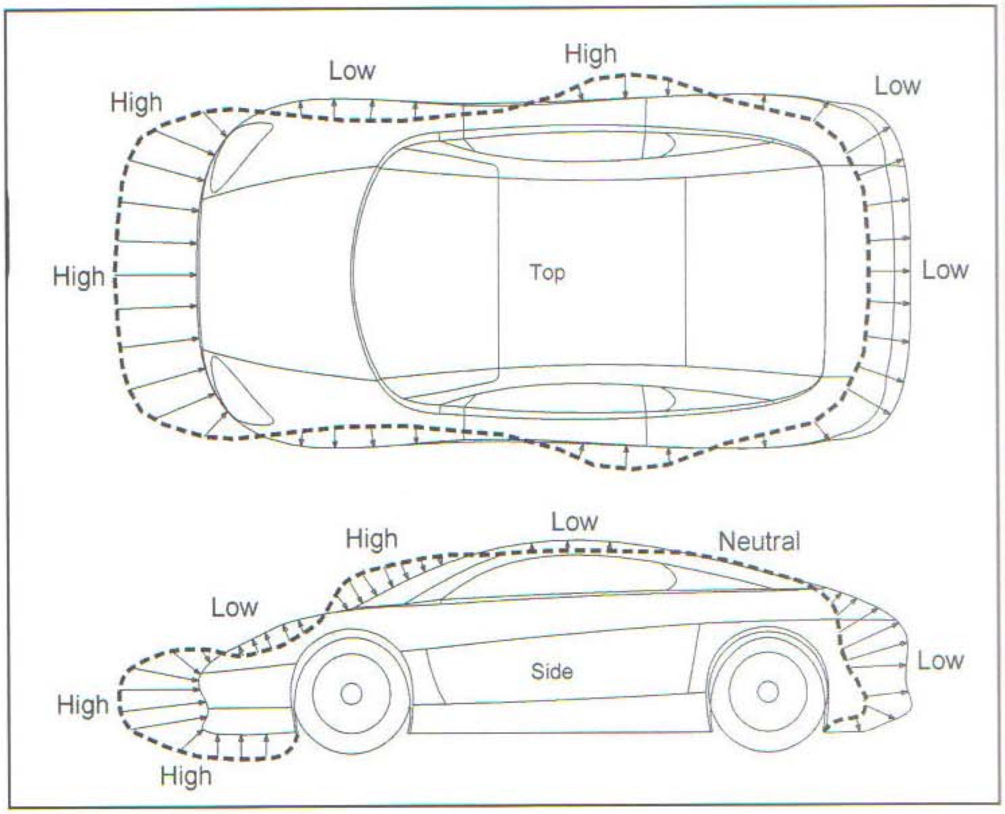
U is also a function of something called convective film coefficients. These coefficients (often designated with the letter "h" by thermal engineers) represent the ability of a warm, moving fluid to transfer heat to a cooler stationary wall. For intercoolers, convective film coefficients are affected by everything from how rough the walls are, to how clean the interior surfaces of the intercooler are. For example, oil and dirt can build up inside an intercooler from bad turbo seals or leaky air filters. This is why you can sometimes gain horsepower by flushing out the inside of your intercooler. The barrier caused by oil and dirt buildup acts like a type of insulation that reduces the convective efficiency of heat transfer.

You can also make U larger by simply increasing the velocity of the exterior ambient air impinging on and through the intercooler. Air scoops and diverters that direct airflow into and through an intercooler are effective at raising U. You can also improve the ambient airflow through an intercooler by ensuring that there is minimal resistance *behind* the unit. For example, it's often better to locate an intercooler beside or below a front-mounted radiator than directly in front of it. This is because airflow through a heat exchanger is affected nearly as much by flow obstructions downstream of the unit as it is by obstruction upstream, or before the unit.

Similar to U, making the area, A, in our formula bigger is fairly straightforward. First, we can bolt on a wider and/or taller intercooler. The same is true for the intercooler



Computational fluid dynamics (CFD) software is used by engineers to determine pressure gradients on race vehicles. Air will flow from high pressure regions to low pressure regions; mounting an intercooler in a manner that takes advantage of pressure differentials on and around a vehicle can improve airflow through the air charge cooler. (Advantage CFD)



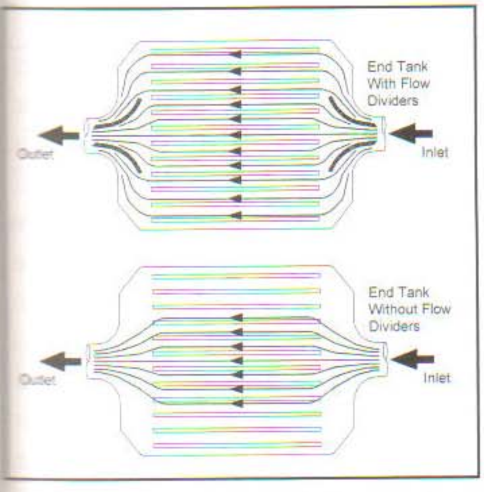
Generally speaking, high pressure occurs in areas where exterior airflow is slowed down. For example, the front of a vehicle, the base of the windshield, and underneath the chin spoiler usually are high pressure zones on the typical car. Conversely, airflow that is accelerated to high speeds will result in low pressures. This typically includes the top of the hood, roof, and sides of the front quarter panel.

core thickness. Bigger is better—but only up to a point. Too much internal flow volume can affect turbo lag, and too thick of a core can actually impede the flow of ambient air through the unit. Above a certain threshold, this becomes a case of diminishing returns.

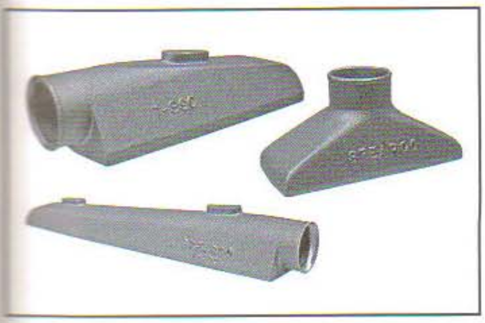
Another way to increase the effective area is to select an intercooler with more fins, especially on the exterior surfaces. The variable "A" in the equation is determined not only by the overall size of the unit, but also by the number and size of fins and tubes. The larger the surface area exposed to cooling airflow, the better. But again, you don't want so many fins that they physically restrict the amount of air that can flow through the unit.

Finally, the last term in the heat transfer equation is the logarithmic mean temperature difference, or ΔT_{log} variable. Don't get too worried about the name of this beast. Physicists can describe how to correctly calculate the value of ΔT_{log}, but this involves a complicated formula and knowledge of airflow directions and temperature gradients. For the sake of simplicity, it's okay to think of $\Delta\Delta T_{log}$ as just the difference in temperatures between the warm incoming charge air, and the average exterior ambient air. The bigger the difference in the numbers, the better.

We obviously can't (and don't want to) increase the charge air temperature to drive up this temperature difference. That would be counterproductive. And at first glance, it doesn't appear that we can do much to improve (i.e., lower) the exterior ambient air temperature either. But it is possible to ensure that we don't make the temperatures of either one worse than they already are. For example, it's often been said that mounting an intercooler in the engine compartment makes it behave more like a charge air heater than a charge air cooling device! Instead of cool ambient air pulling heat out of the intercooler, you can actually end up adding heat to the charge air if the underhood temperatures are higher



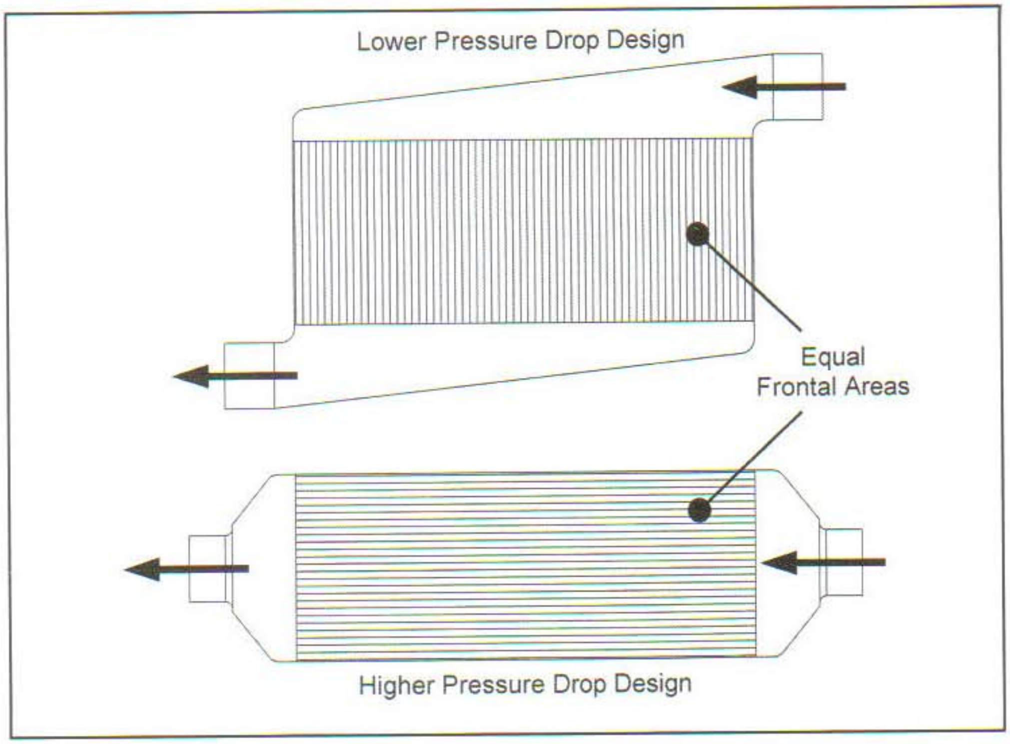
Air is technically a fluid. It will always seek the path of least resistance when flowing from one location to another. This includes flow through an intercooler core. Flow dividers can be used to ensure all of the intercooler frontal area is employed in cooling the intake air charge.



End tanks are available from aftermarket suppliers. Choosing the right design can have a large effect on both thermal efficiency and pressure drop. (Turbonetics)

than the charge air temperatures. Remember, heat moves from a warm environment to a colder one. If the intercooler is located inside a hot engine bay, it can pick up heat instead of shedding it.

You can also inadvertently raise the charge air temperature going into the intercooler by simply running the intercooler piping nearby hot engine components, such as the exhaust manifold or alongside the radiator or engine block. Insulation of this piping can be very effective in alleviating extra heat gains into the charge air stream.



These two intercoolers have equal frontal areas but result in very different pressure drops. It's important to balance the requirements of air charge temperature reduction with pressure drops through the unit. The goal is to deliver cool, highly pressurized air to the engine.

WHAT IS FLUID?

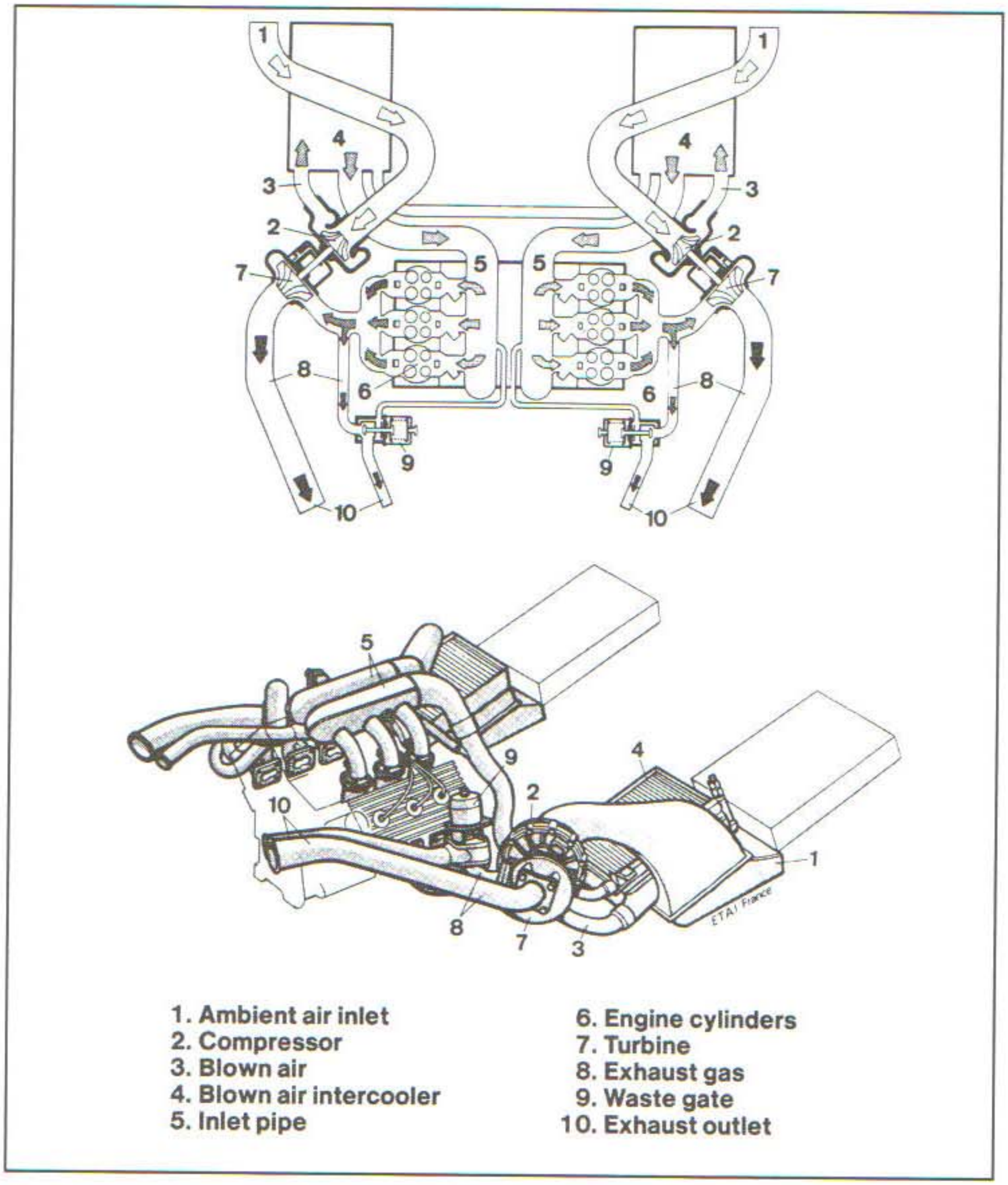
People often get confused when they hear the term "fluid" used by intercooler experts. A fluid can be either a gas or a liquid. For example, the warm intake air flowing through the inside of an intercooler is technically a fluid. This is also true for the outside ambient air that flows through and around the intercooler. Likewise, the liquid water that is used in an air-to-water intercooler is a fluid, too.

AIR-TO-WATER INTERCOOLERS

In addition to air-to-air devices, there is another type of intercooler that has gained popularity in recent years: the air-to-water intercooler.

All physical substances have a certain ability to absorb and store heat. This property is called the specific heat capacity, and is denoted by the symbol C_p. Air has a C_p of roughly 0.24 BTU/lb-°F when it's held at constant pressure. What this means is that it takes 0.24 BTUs of energy to raise the temperature of one pound of air one degree Fahrenheit. In contrast, water has a C_p of roughly 1.0 BTU/lb-°F. In other words, water is four times better at absorbing heat energy than air for a given temperature rise. (Which, by the way, is why most engines are cooled by water than by air; it's much more efficient.)

Because of this property, engineers have learned that they can exploit the C_p of water by liquid cooling intercoolers. Instead of passing ambient air over or through the intercooler, water can be used, which means that four times the energy can be pulled out



A dual intercooler system used on an early turbo-era Formula One race car. (Renault)

of the charge air for roughly the same ΔT_{log}. Also, when convecting heat, water exhibits higher U-value characteristics. Put another way, water has a better ability to collect, store, and transfer heat than air. And these are all good things, right? Well, yes and no.

Air-to-water intercoolers are typically compact and space efficient. It's much easier to route small, flexible water lines to and from an intercooler than it is to route large and bulky air pipes to the unit. As a result, it's often easier to make the induction air path length shorter and more direct than with an air-to-air unit.

Another advantage of air-to-water intercoolers is their use in short-duration, high-power applications. Because water has such a good capacity to absorb heat, air-to-water intercoolers are excellent for short-duration racing applications such as drag racing where they can easily absorb big temperature spikes.

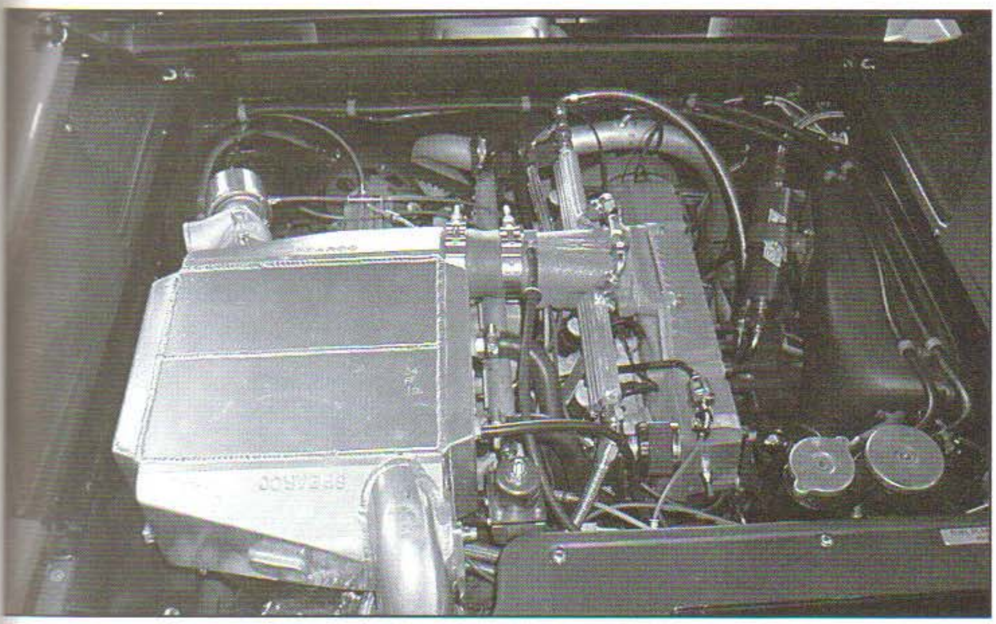
The downside of air-to-water intercoolers, however, is the fact that the heat absorbed by the water has to be removed somewhere else in the system. If we don't reject this absorbed heat, the water will continue to rise in temperature until it no longer can cool the charge air. On street-driven vehicles, this heat rejection is typically done by way of a second cooling loop, with a water-to-air heat exchanger mounted in the ambient air stream.

Air-to-water intercooler systems therefore have two cooling loops. When compared to air-to-air intercoolers, they're more complex, heavier, more expensive, and have more components, such as the water pump, that can fail. Perhaps worse is the fact that there are now two heat exchangers in the system, each with their own inefficiencies. We will talk about intercooler efficiencies in a moment. But for now, just note that the overall system efficiency of the two cooling loops of an air-to-water system is usually lower than that of a well-designed air-to-air intercooler system.

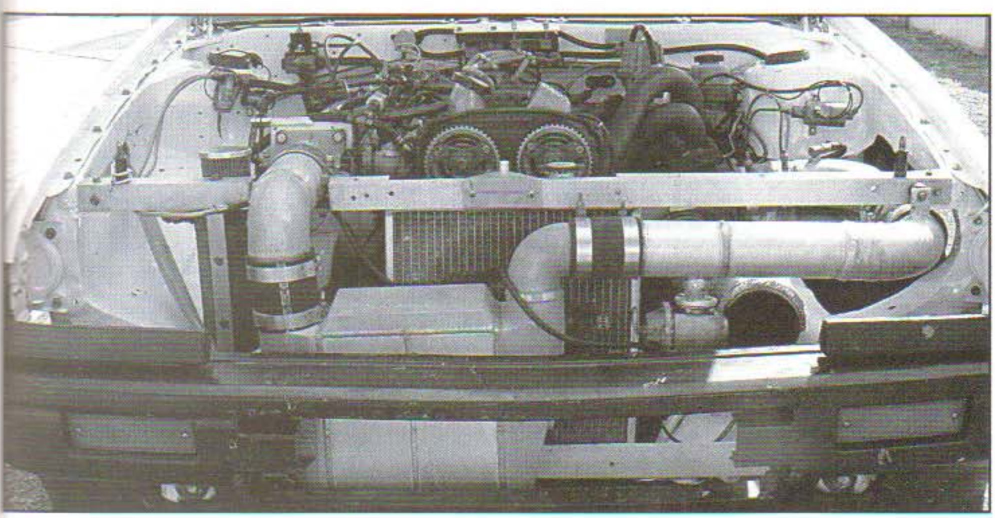
But this doesn't mean that air-to-water intercoolers don't have their place in modern performance turbocharger applications. Drag racers, autocrossers, and land speed racers love air-to-water units. One of the reasons for this is because they can pack the water-to-air heat exchanger in ice, thereby drastically lowering the intake charge air temperature and creating an artificially large ΔT_{log}. Owners of turbocharged vehicle in northern climates, who drive when the temperatures are low, can attest to the significance of this effect. Air-to-water systems are also great for

Type of Intercooler	Advantages	Disadvantages	Recommended For:
Air-to-Air	Inexpensive Simple Robust Recovers From Heat-Soak Quickly	Long Induction Paths More Difficult To Package Higher Pressure Drops Heat Soaks Faster	Street Vehicles Off-Road Long Duration Races
Air-to-Water	Compact Easier To Package Short Induction Paths Can Absorb Large Temperature Spikes Ice Water Usage Heat Soaks Slowly	More Complex More Prone To Failure Heavier More Expensive Recovers From Heat-Soak Slowly	Drag Racing Max Power Contests Land Speed Records Packaging Solutions

The advantages of air-to-water intercoolers are significant, but the disadvantages are noteworthy, too. The choice depends strongly on the application and desired performance goals, not to mention the budget. For most street applications, the common air-to-air intercooler is usually hard to beat.



An air-to-water intercooler installed on a turbocharged Lotus. (Aquamist)



This 3SGTE-powered Corolla uses a large front-mounted air-to-water intercooler to keep charge temperatures down. The Toyota runs 9-second quarter miles. (The Power Group)

marine applications, where the unlimited supply of cold water under the boat can be easily exploited. Very dense intake charges can be created in these applications.

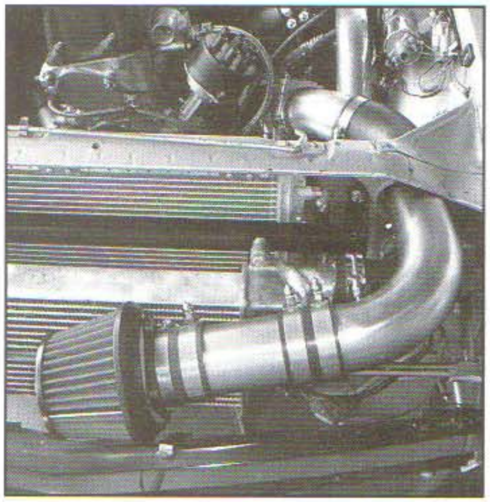
Air-to-water systems are also helpful on street-driven applications where space is at a premium in the engine compartment, or where it's difficult to get good airflow to an air-to-air intercooler. For example, mid-engine vehicles such as the Toyota MR2 that are fitted with side-mounted intercoolers don't often receive good airflow through the heat exchanger. By employing an air-to-water unit in the engine compartment, the induction path length from the compressor to the intake manifold can be very short. The water loop can then extend all the way to the front of the car, where the secondary-loop water-to-air heat exchanger can be placed in a good location in the air stream.

INTERCOOLER PERFORMANCE AND EFFICIENCIES

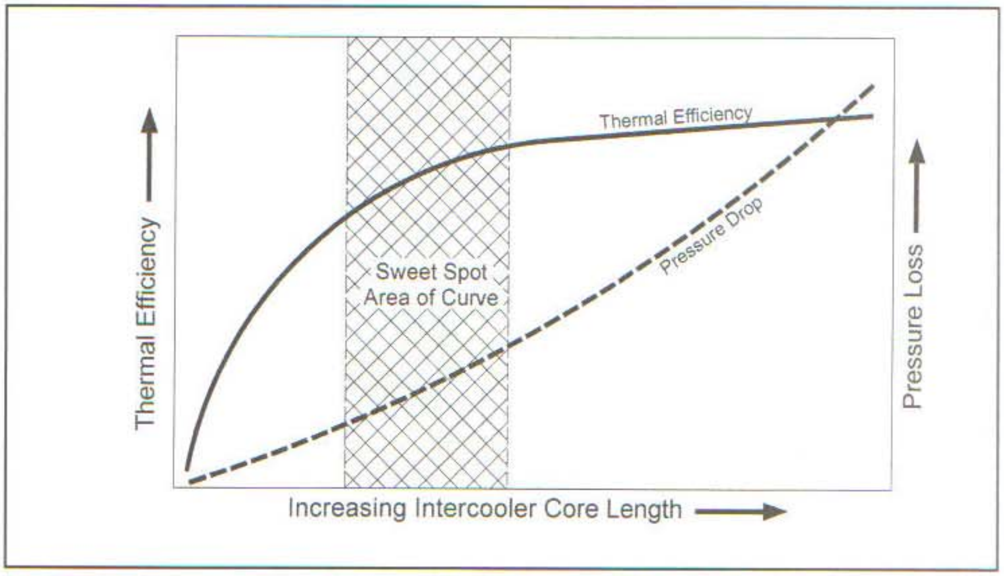
When turbo engineers discuss intercoolers, the topic inevitably turns to efficiency values. Intercooler (IC) efficiency numbers are a measure of how well the heat exchanger removes heat from the charge air. They are given by the following basic equation:

Eq. 9-2

$$Eff_{IC} = \frac{T_{Comp\ Out} - T_{IC\ Out}}{T_{Comp\ Out} - T_{Ambient}}$$



Care must be taken to ensure good airflow to and through the intercooler body. The intake air filter blocks a significant fraction of the intercooler frontal area on this turbocharged Datsun 240Z. (McManus)



Making matters more complicated is the issue of thermal efficiency vs. pressure drop. Generally speaking, the larger the temperature drop delivered by the intercooler (i.e., the higher the thermal efficiency) the more the pressure drops. But thermal efficiency tapers off with increased intercooler length, while pressure drop is more or less linear with length. You want to select a core size that lies in the so-called "sweet-spot" of this curve, with high thermal efficiency, but low pressure drop.

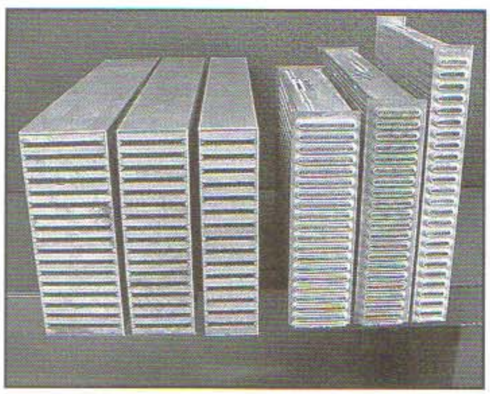
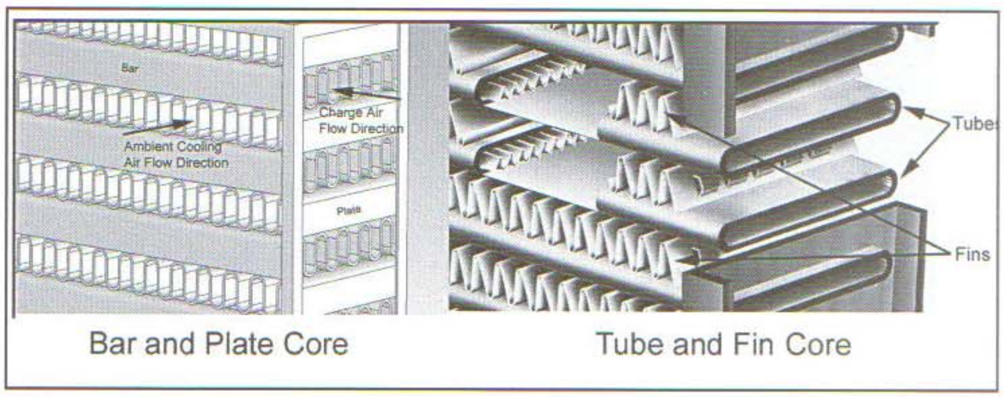


Plate and coil cores shown on the left, tube and fin cores on the right. Generally speaking, tube and fin intercoolers are less expensive, lighter, and produce a smaller pressure drop for the charge air stream passing through it. Bar and plate intercoolers, on the other hand, have higher thermal efficiency and are more resistant to damage from road debris. For most street-type applications, there is no appreciable difference between the two that can be discerned by the average tuner. As long as the core chosen has good thermal efficiency (>70%) and an acceptable (<1–2 psi) pressure drop, either type can be used with excellent results. (ARE)



There are two major types of cores to choose from: bar and plate, and tube and fin. There is much debate among experts as to which is a fundamentally better design. Both have pros and cons, and the truth is that it's very difficult to make an accurate comparison between the two types in operation. This is because efficiency and pressure drops depend so strongly on the length, width, and depth of the core, the design of the end tanks, the number, shape, and density of the internal fins, and the ambient and charge conditions under which each operates. (HKS)

We can also rearrange this equation, solving for the outlet temperature of the intercooler:

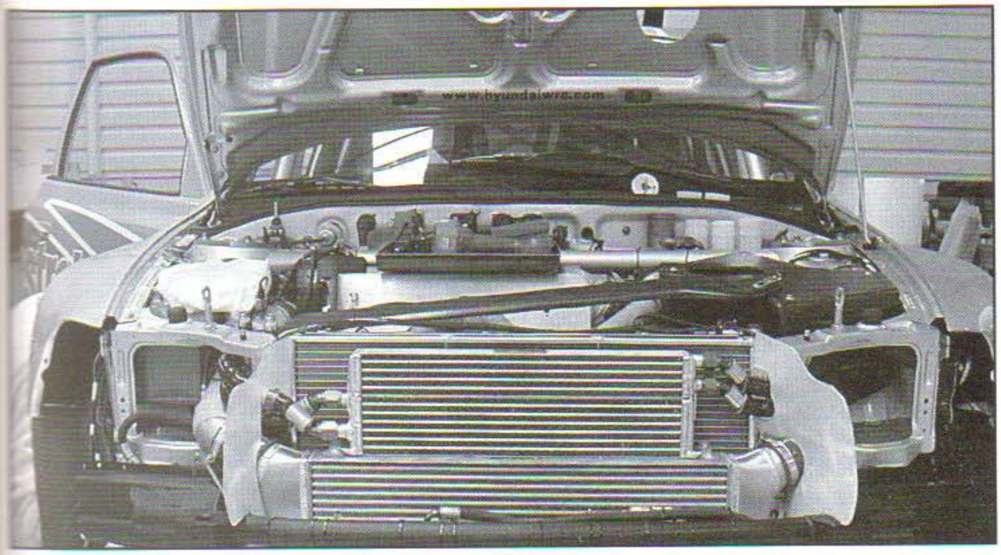
Eq. 9-3

$$T_{IC\ Out} = T_{Comp\ Out} - [(Eff)(T_{Comp\ Out} - T_{Amb})]$$

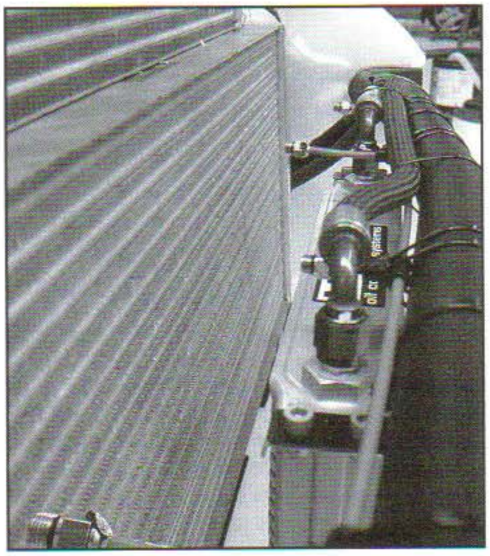
For example, if we have a 70% efficient intercooler, 85 F ambient air flowing on and through the intercooler, and 200 F charge air exiting the compressor, we can compute the temperature of the charge air after intercooling:

$$T_{IC\ out} = 200 - [70\% \times (200 - 85)]$$
$$= 119.5° F$$

Note that if the intercooler is located in the engine compartment, the effective Tambient value can be much higher than the outside ambient temperature. Also note that average, good quality, front-mounted intercoolers will deliver 70–80% efficiency for "standard" ambient and compressor temperatures. Side-mounted intercoolers and those that don't receive good ambient airflow to them can be considerably less. Fifty to sixty percent is not uncommon for these types of units.



The front-mounted intercooler on this rally car competes for airflow with many other heat exchangers, including radiator, and oil transmission coolers. This is an extreme example of calculated tradeoffs between the requirements of the various engine systems. (Aquamist)



A water spray device can increase the effectiveness of an intercooler. In exactly the same way that evaporating sweat removes heat from the skin of a human body, water that is sprayed onto the surface an intercooler will vaporize and remove heat energy. Note, however, that many race venues won't let cars with water spray devices onto their tracks, because the devices are technically considered a fluid leak. There is also the added weight of the water, tank, pump, and supply lines to consider. (Aquamist)

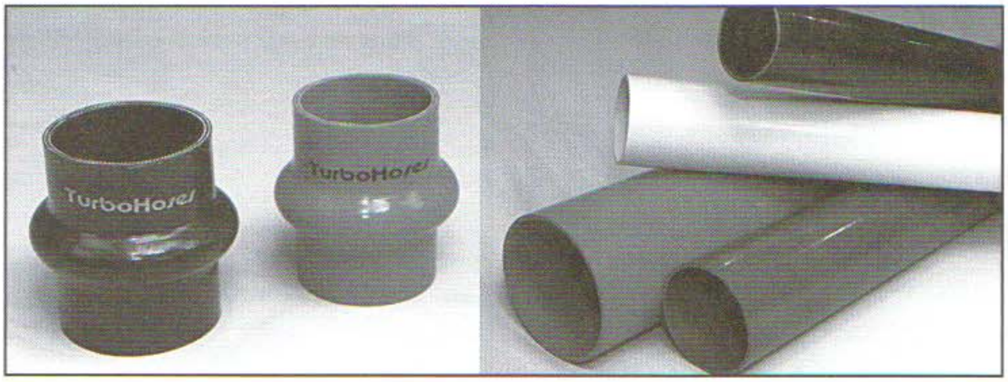
CO_2 spray bars like this can help lower the intercooler core temperature. Just make sure the CO_2 doesn't end up being ingested by the engine intake system. (Design Engineering, Inc.)

Intercoolers are also sometimes rated or characterized by the pressure drop that occurs in the charge air stream under "standard" conditions. A good, high-quality intercooler will reduce the air pressure by only 0.5–1.0 psig or so. Less efficient units can affect the air pressure by much more than this, however. One to two psig is not uncommon and can be a significant charge density loss to account for when sizing a high-performance turbocharger system.

The factors that affect pressure losses in an intercooler include the internal flow area, the number and size of "turbulators" and internal flow tubes, and the mean airflow velocity through the unit. As a general rule, larger internal flow areas, more tubes, and shorter tube lengths are best. The end tank design is also important. When evaluating pressure drops for different intercooler designs, it helps to think of the airflow in terms of minimizing the flow path. The "easier" it is for the air to flow from the inlet to the outlet ports, the lower the pressure drop.

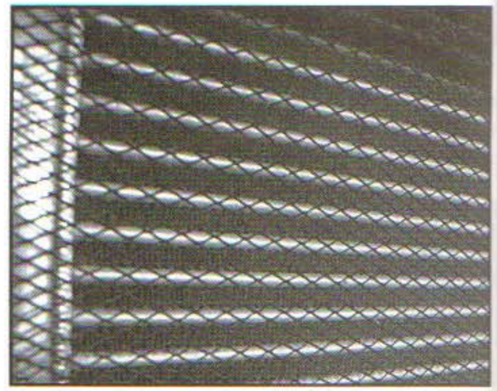
Piping and Connections

Often overlooked—but just as important as the intercooler itself—is the design and implementation of the charge air piping that leads to and from the intercooler. Remember that heat *always* flows from a warmer body to a relatively cooler one. The intercooler piping itself can pick up heat from a number of hot sources in the engine compartment. If you have to make a choice about which runs of tubing should be longest, make the piping from the turbo to the intercooler the long one, and



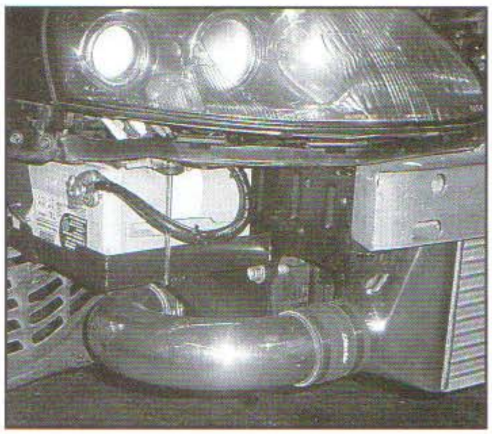
Silicone hoses have good yield temperature limits that are suitable for forced-induction applications. Silicone wrapped in fiberglass is even better, with yield temperatures typically in the 500–600° F range. Silicone hoses can also handle higher boost levels than rubber-based hoses. Keep in mind, however, that any flexible hose, silicone or rubber, will have a diminished burst rating as temperatures increase. Also, the longer the hose and/or larger the diameter, the lower the allowable burst pressure. Also shown here are preformed bends and so-called "hump" hoses. These flexible hump connectors allow differential movement between engine components during operation, reducing stress levels on the intercooler end tanks. (Turbohoses)

A roll-beaded tube end can help ensure that hoses stay put during operation. (Racetech)



A grill screen like this one can be used to protect the delicate fins of a front-mounted intercooler from rocks and road debris. Just don't select a screen with grill openings too small, or airflow can be choked off. (Henderson/SP Engineering)

Spring-loaded T-bolts are a good idea at the compressor outlet connection. Experience has shown that this is a likely place for a connection failure. The spring-loaded design of this type of clamp maintains constant clamping force. (Turbohoses)



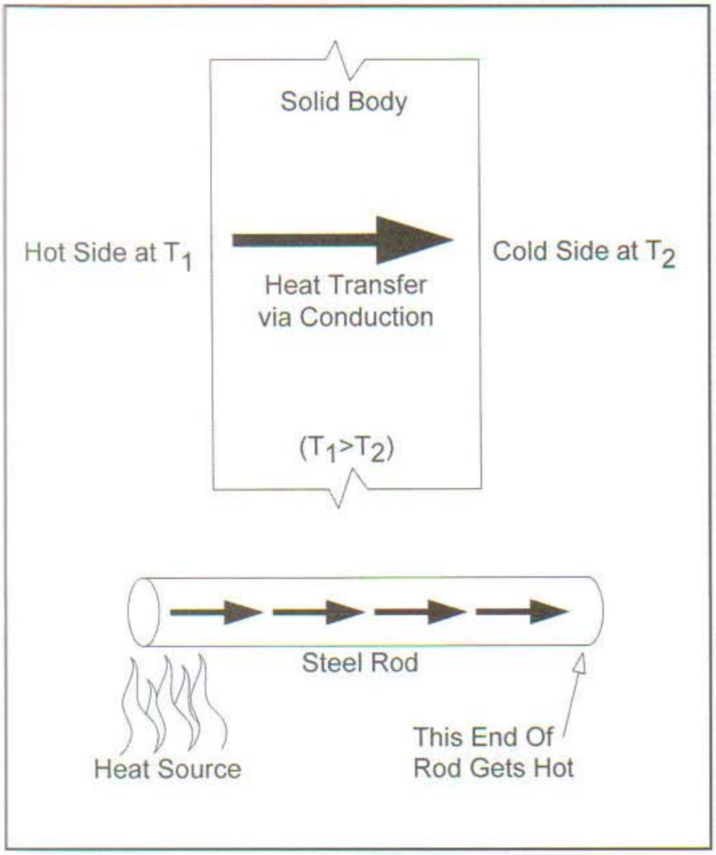
A nice example of large-radius intake bends and intercooler end tank design on a Toyota Supra. (Aquamist)

the piping from the intercooler back to the throttle body the short one.

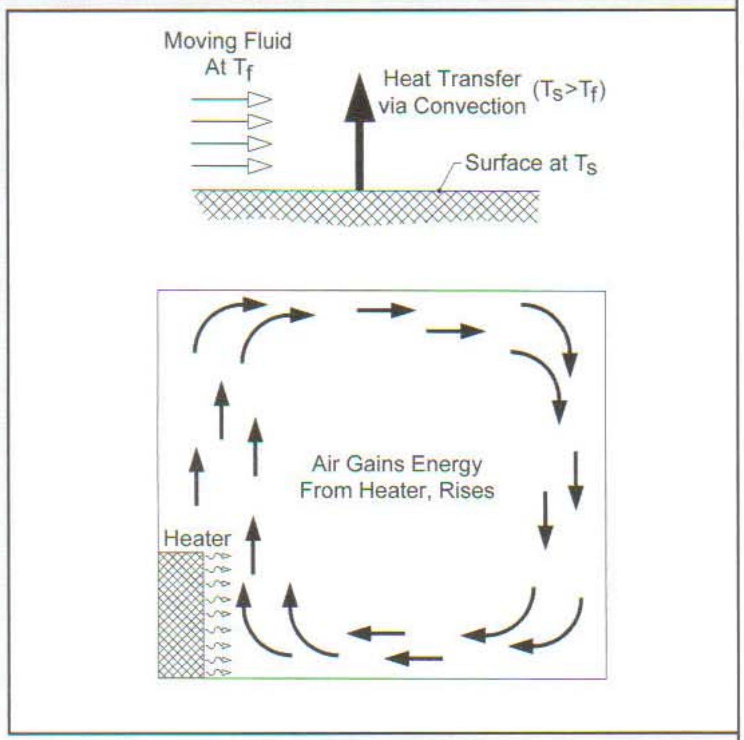
Intercooler piping can also be a source of pressure losses in the charge air stream. Anytime the piping bends or changes directions, there exists a source of pressure loss. And these losses can be significant. It has been estimated that a "tight" 180-degree bend in a 3-inch diameter pipe is equivalent to 8–10 feet of straight pipe. Again, think of the airflow in terms of resistance. Anytime the flow has to turn or change direction abruptly, or neck down into a smaller diameter tube, it is a bad thing. In terms of pressure drops, longer, straighter runs are almost always better than shorter runs that have many bends, turns, and diameter changes. But don't get too carried away, because longer piping is more likely to gain unwanted thermal energy. It's all a matter of balance.

HEAT TRANSFER

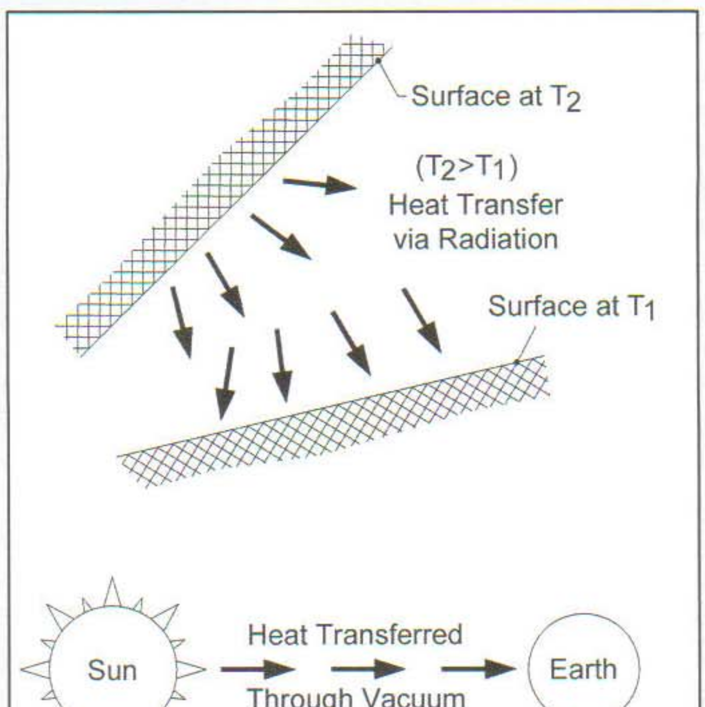
Heat always flows from a hot body to a cold body, and it can do so in three different ways: conduction, convection, and radiation.



Conduction. When one side of a solid body is warmer than the other, heat energy is transported directly through the body by means of internal conduction. For example, when one side of an aluminum fin in an intercooler is warmer than the other side, heat flows through the fin until the whole fin reaches one homogeneous equilibrium temperature. Stated another way, heat continues to flow forever as long as there is a temperature gradient, or difference, from one side of the fin to the other. Factors that affect how well a body conducts heat include the type of material from which the body is constructed, the length and cross-sectional area of the body, and the temperature difference from one side to the other.

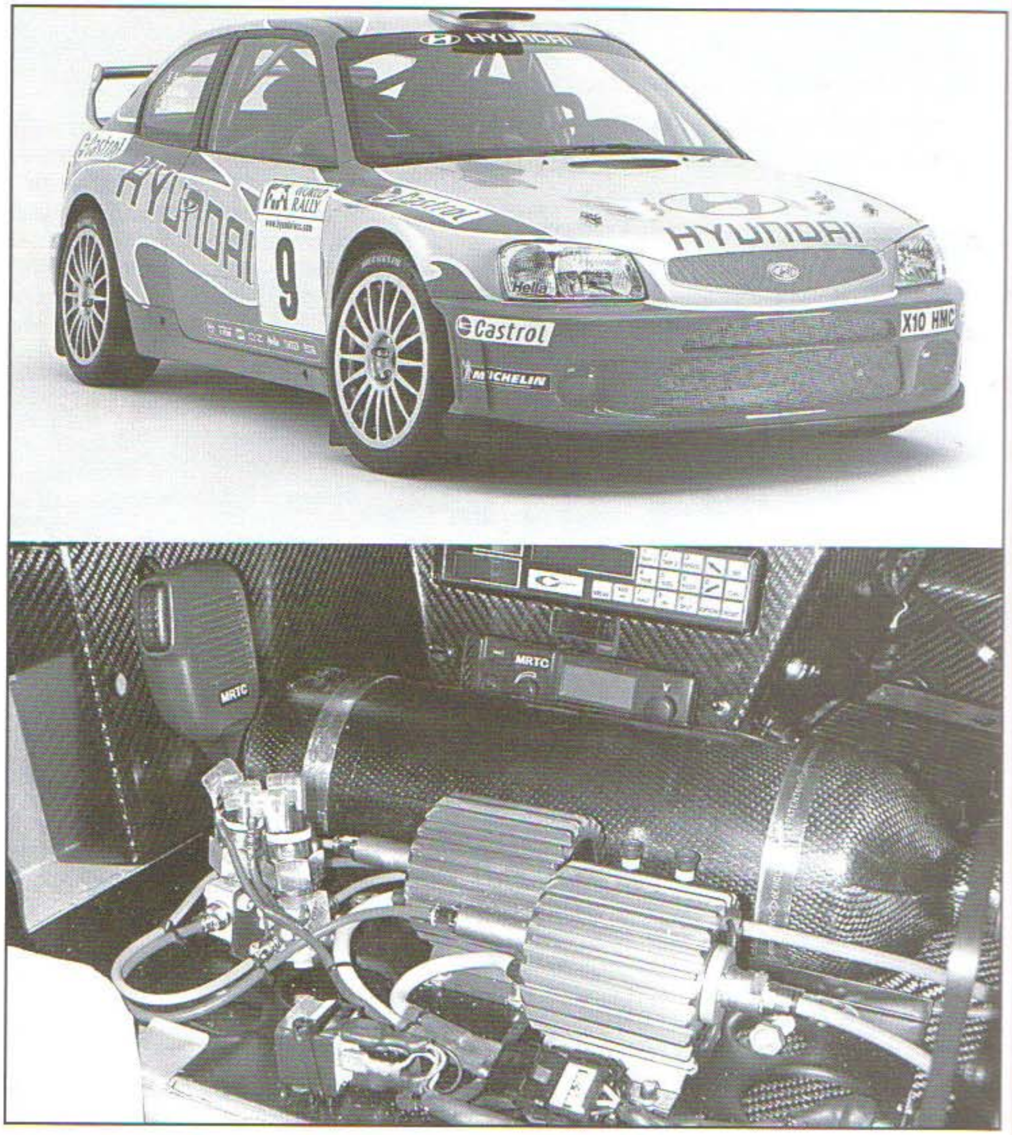


Convection. Imagine warm air blowing over a cooler body. The warm air literally rubs up against the cold object, transferring some of its heat energy to the colder object by means of fluid contact. This is called convection. The transference of heat from the charge stream inside an intercooler to the walls of the intercooler takes place via convection. The factors that affect how well a fluid convects heat include the physical makeup and properties of the fluid, the speed of the fluid, and the roughness and cleanliness of the surface.



Radiation. Another way heat can be transferred from one body to another is via radiation. Your body can be warmed from a campfire via radiation, even when a wind might carry the actual warmed air of the fire away from you. The same thing goes on under the hood of your car; heat from hot surfaces (such as the turbine or engine block) radiates onto cooler objects (like an intercooler or intake manifold). Factors that affect how well two bodies radiate energy between them include the temperature difference between the two bodies, the color of those bodies, and something called a "view factor," which is a measure of how much the geometry of one body is exposed to the other.

10 WATER INJECTION



Many World Rally Championship race teams use water injection as a standard part of their arsenal against detonation and high intake charge temperatures. (Aquamist)

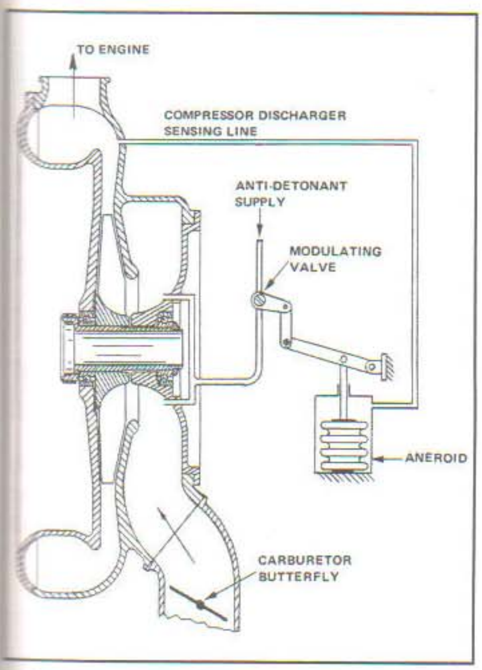
In the previous chapter, we saw how intercoolers reduce charge air temperatures. An alternative to those ubiquitous heat exchangers is something called water- and water/methanol-injection devices. While not as popular as intercoolers, they've been used by hot-rodders for nearly as long.

In 1936, British engineers Anderson and Fedden patented a device that eliminated detonation in a supercharged engine. Their system was based on the principle of injecting "anti-detonant" chemicals into the intake side of the compressor. During World War II, a variety of aircraft engines were fitted with similar devices to improve their power production and detonation thresholds. By the mid-1950s, a half-dozen patents for similar anti-detonation injection devices were issued for general automotive use. Most of these systems relied on the introduction of water into the charge air stream. Today, water injection is a popular technique used on supercharged and turbocharged vehicles to help raise performance and reduce the chance of detonation.

WATER INJECTION BASICS

There are a number of possible locations that water can be injected into the charge air stream, including at the throttle body, down and upstream of the intercooler (if an intercooler is also installed), and even in front of the compressor in some cases. Each of these locations has certain advantages and disadvantages. For now, let's examine a hypothetical system where the injection point takes place somewhere between the intercooler and the throttle body.

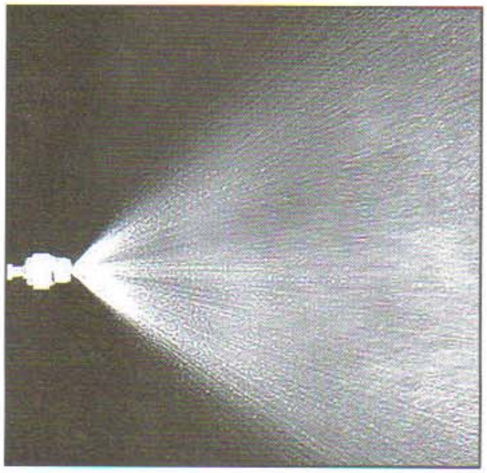
In most water injection systems, liquid water is sprayed into the intake tract by way of *atomization*. The term atomization means that a liquid is converted into a spray of tiny droplets. A perfume spray bottle is a good example of an



Anderson and Fedden patented this "anti-detonant" device in 1936.

atomizer. Note that atomization is not the same thing as *vaporization*. We'll come back to that concept in a moment, but for now the water being sprayed into the intake air is atomized and therefore does not undergo a phase change. That is to say the tiny liquid water droplets remain liquid.

As we saw in the last chapter, the specific heat capacity of liquid water is roughly 1.0 BTU/lb-°F. In other words, it takes one Btu of energy to raise one pound of liquid water one degree in temperature. There is a lot of energy contained in the intake charge air stream. A decent intercooler will lower the temperature of the charge air to 120–140° Fahrenheit after compression. Water does not boil (i.e., vaporize) until 212° F at sea level. The pressure in the charge air stream from a turbocharger is considerably higher than that at sea level, so the vaporization point is even higher than 212° F.

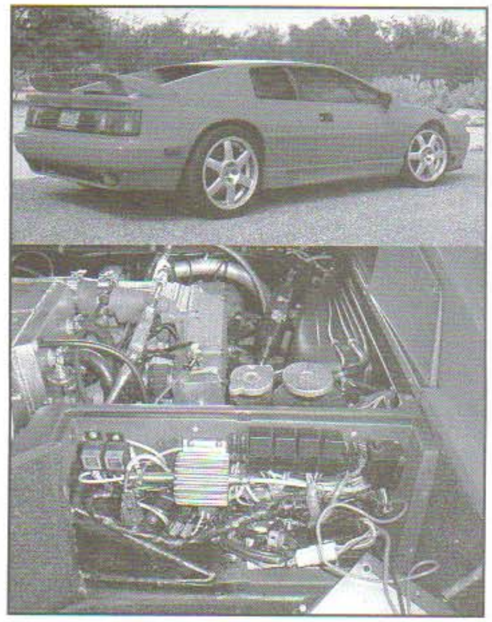


This photo shows proper atomization of the water spray in an injection system. (Aquamist)

What this means is that the atomized water droplets remain liquefied and suspended in the warm air stream. The water that is injected has come from a reservoir that is roughly ambient in temperature. This causes the droplets to absorb heat from the air. In a sense, the warm air gives up, or transfers, some of its heat energy to the cooler water droplets suspended within it. As a result, the bulk air temperature drops, and because water has such a high specific heat capacity, the temperature of the water droplets that are gaining heat does not increase very much. In fact the overall temperature of the air-water mixture can drop considerably depending on the mass flow rate of the water.

The cooled mixture is then transported past the throttle body and into the intake manifold. From there, it is drawn into the combustion chamber and mixed with an appropriate amount of fuel as it normally is.

When the suspended water droplets enter the hot chamber, they begin to vaporize, or turn to steam. Water has a relatively high latent heat of evaporation. This

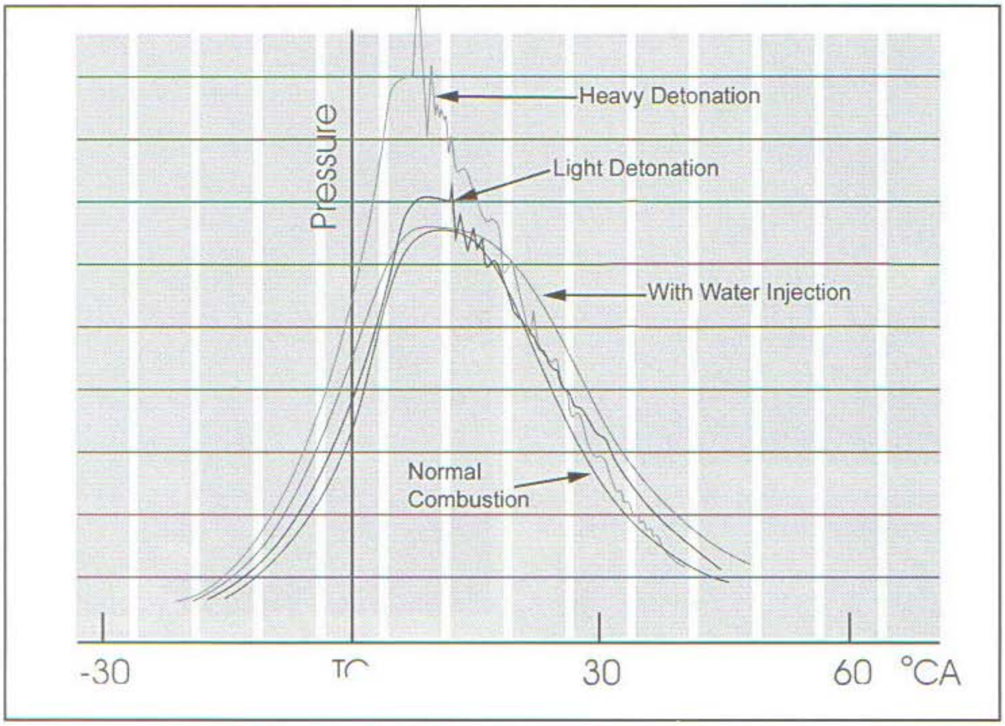


This turbocharged Lotus engine is operated in Arizona, where summer daytime temperatures routinely exceed 100° F. Charge cooling by the air-to-water intercooler is increased by a water injection system. (Aquamist)

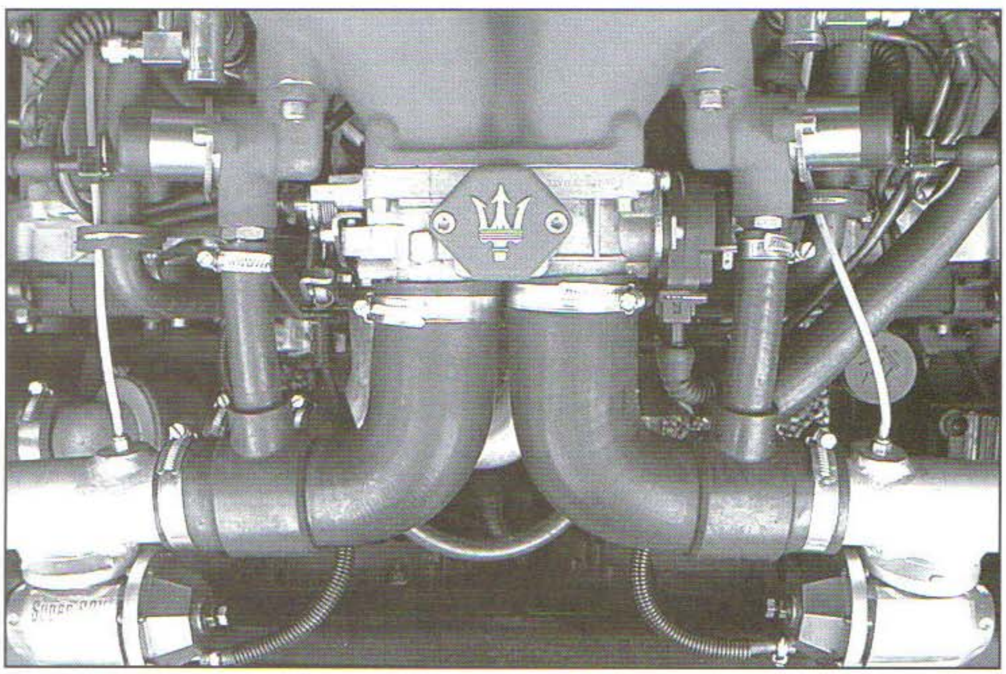
means that a very large amount of heat energy is required to change the water *phase* state from a liquid to a gas. In other words, the water droplets soak up even more heat energy in the combustion chamber when they turn to steam.

The bad news is that vaporized water displaces a large volume when compared to the volume it displaced when it was liquefied. This larger volume takes up space that might otherwise be filled with useful air molecules. The good news, however, is that the lowered temperature of the air/fuel mixture (and corresponding density increase) more than makes up for the loss in volume.

To make a long story short, the charge air mixture is denser with water injection than without, and the combustion chamber temperatures are radically lowered. For a given amount of boost pressure and gasoline octane, detonation is therefore less likely to

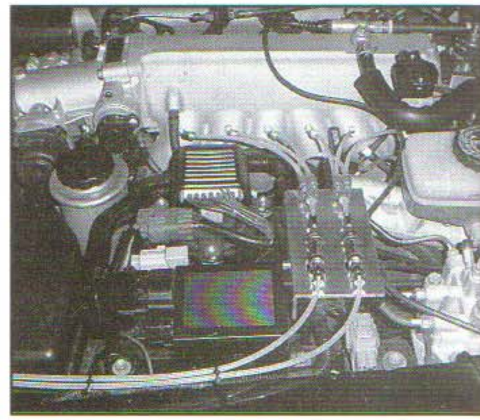


Light detonation was measured on this engine when the ignition timing was advanced approximately three degrees from its optimal position. Heavy detonation occurred when the ignition was advanced a further three degrees. Engine damage would occur if this were allowed to continue. Water injection brought the cylinder pressures back to slightly better than normal values. (Aquamist)



A twin-turbo Maserati fitted with dual water injection ports.

occur. Or, put another way, we can now raise boost pressure and/or run lower octane fuel and have the same detonation threshold or higher. Water injection allows for more boost (and consequently more power) as well as safer combustion if the system is engineered properly.



Water injection is an integral part of this 1000 hp Toyota Supra. Note the individual water port injection lines that are tapped into the intake manifold. Simple and effective.

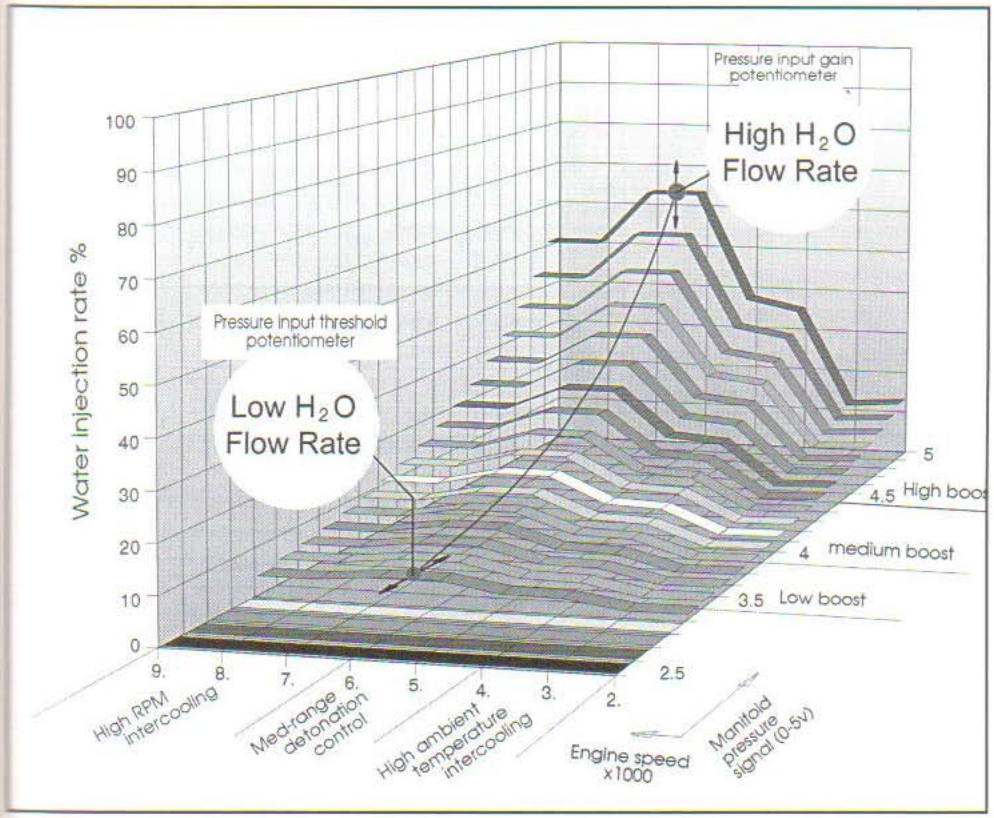
WATER-TO-FUEL RATIO

For moderate boost applications, some water injection manufacturers recommend a 10–15% ratio of water to fuel (i.e., the water injection rate should be 10 to 15% of the fuel injection rate). Under higher boost conditions, 15–25% can be required in the maximum torque region of the engine's rpm range. This is just a guideline, however, and the actual amount needs to be determined via careful tuning.

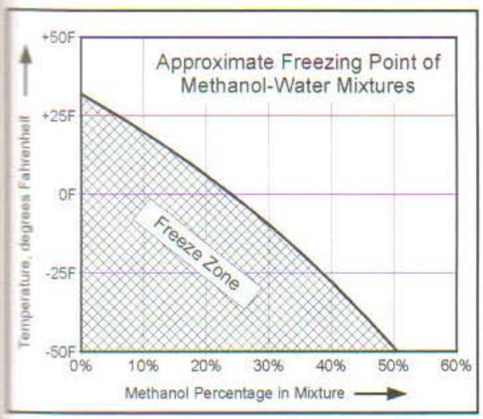
Water vs. Methanol

So far we've discussed the injection of pure water into the charge air stream. But many performance enthusiasts inject a mixture of water and methanol into their engines. There are some good reasons for doing this.

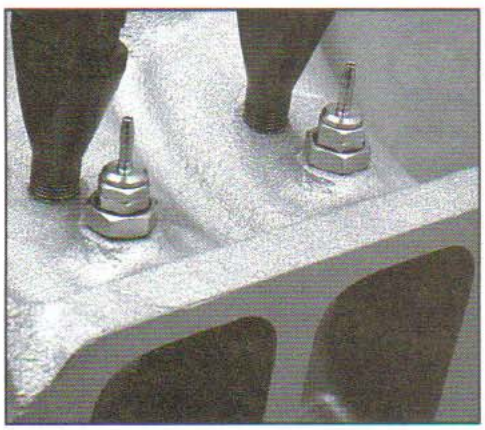
Back in World War II, military engineers experimented with a variety of water injection systems in their quest to squeeze maximum performance from their forced-induction aircraft engines. They discovered that for detonation



Water injection rates increase with rising forced-induction boost levels.



Adding methanol to water can lower its freezing point and help boost performance.



Water injection nozzles mounted next to nitrous oxide injection nozzles on an intake manifold. (Aquamist)

suppression, plain water was ideal. But for maximum horsepower, a mixture of methanol and water was better (typically 50% methanol by weight). This combination yielded excellent power while still retaining good detonation suppression characteristics.

Methanol is volatile, which means it vaporizes very easily. This helps to improve the cooling effect in the charge air stream. Methanol is also considered a fuel, which provides a slight horsepower increase over straight water. It also serves as an anti-freeze agent, keeping the water from turning to ice in its reservoir during cold weather.

METHANOL PROPERTIES

Methanol is both hygroscopic and miscible, which means that it absorbs and mixes very well with water.

INJECTOR NOZZLE CLOGGING

Injector nozzles are prone to clogging by the accumulation of mineral deposits. The best type of water to use is distilled, especially if the local tap water is "hard" or laden with salts and minerals.

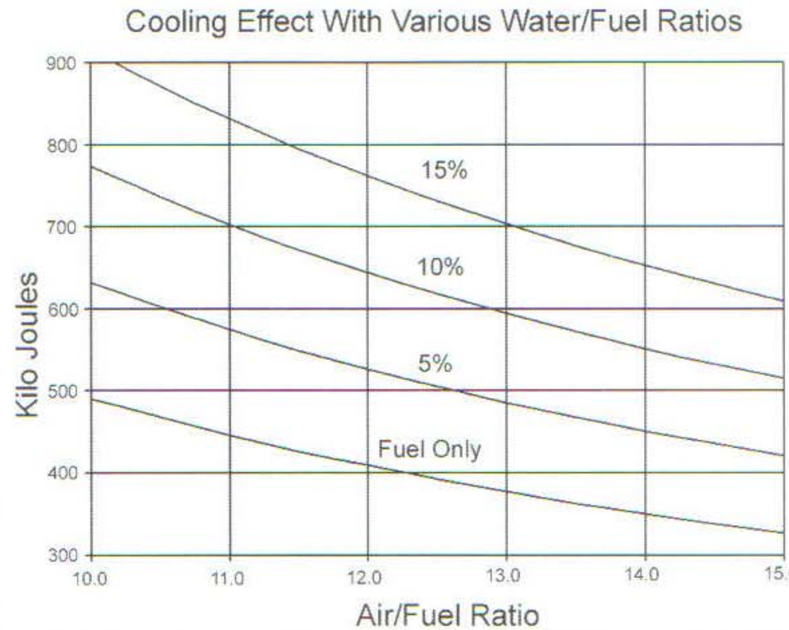
INJECTION SYSTEMS

Most commercial injection systems include a storage tank for the coolant, a high-pressure pump, one or more injector nozzles, and all the requisite hoses and clamps. Many systems also come with solenoids, temperature and pressure sensors, and electronic control units. These types of systems do not initiate injection until a minimum threshold air temperature and/or boost pressure is achieved. Some high-end systems also make real-time adjustments for varying airflows, air/fuel ratios, rpm, and/or throttle position.

The purpose of a water injection system is to reliably deliver a spray of water into the charge air stream. A quality system will feature precise-metering of the injected liquid. It should deliver the fluid in a very fine, well-atomized spray. The smaller the droplets, the better. Small droplets are better at absorbing heat and are less inclined to fall out of suspension from the air. Depending on the characteristics of the manifold, this

WATER VS. FUEL

Dynamometer tests have shown that fairly dramatic changes in air-fuel ratios do not have a significant effect on power output for most turbocharged engines. Certainly, having too lean of a mixture can result in dire consequences. The same is true of extremely rich mixtures, too. But within a fairly wide range of air/fuel ratios, power output is not greatly increased or decreased. So then why do we often want to enrich mixtures under maximum power conditions?



Water has more capacity than fuel in reducing excess heat in the combustion chamber.

Experienced engine tuners understand that rich air-fuel ratios are required not directly for additional power production, but rather for control of chamber temperatures. A significant fraction of the fuel injected into the combustion chamber is used solely to absorb and remove heat from the engine during and after the combustion event takes place. Fuel, like water, has a capacity to absorb heat and lower temperature.

In a sense, rich air/fuel mixtures are employed to relieve engine components of heat. Put another way, selecting the appropriately rich air/fuel mixture is actually a matter of thermal management. (Many OE turbo applications incorporate this type of "rich fuel dump" safety feature in their control algorithms. To help overcome fuel octane variations and provide in-cylinder temperature control, this form of self-protection strategy has been widely practiced by car manufacturers since the first turbocharged car arrived on the commercial market.)

Once a minimally rich air/fuel ratio is found for producing optimum power output (often around 12.5:1), the only benefit of additional fuel is to keep chamber temperatures down. Since water has a higher specific heat capacity than gasoline (and is considerably less expensive), it makes sense to consider water injection as a replacement or supplement to a rich air/fuel strategy. For example, in one engine tested, a 3-percent ratio of water added to fuel had roughly the same cooling effect as running a 10:1 air-fuel mixture. Of course there are practical limitations to the amount of water that can be injected, but nonetheless this technique can be used to actively manage the inlet air and in-cylinder temperatures with good success.

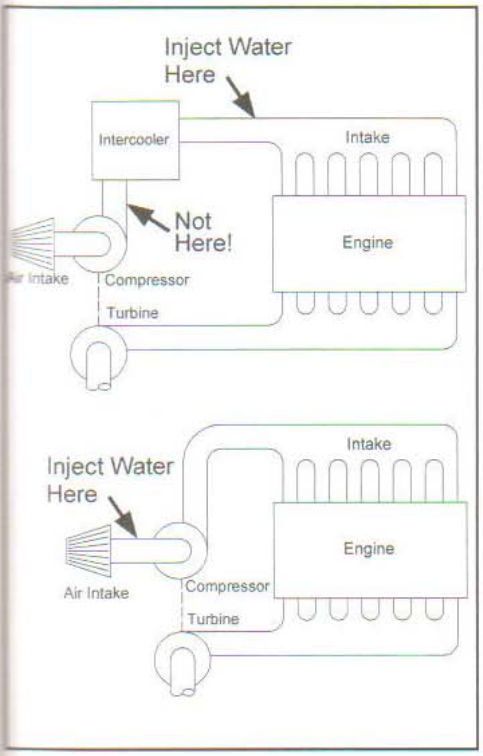
will help ensure that each cylinder receives equal doses of coolant.

Two- or three-stage-type systems are also desirable. These units inject less water at lower boost levels and more at higher levels. Even better are continuously-variable or progressive systems that proportionally increase the water injection rate as boost pressure rises.

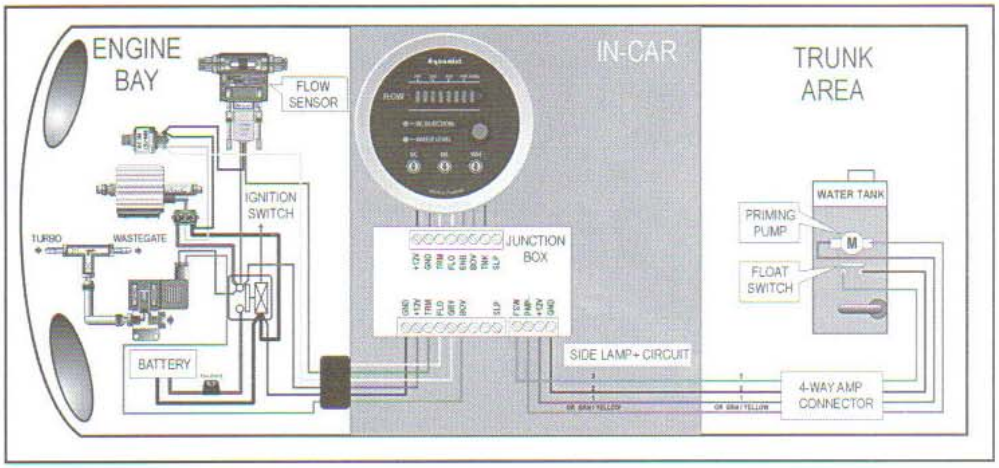
A high-quality injection system will automatically start and stop the flow of liquid as required. It should not require the driver to remember to switch on a pump or activate any electronic circuitry. It should also have a warning system that alerts the driver when the liquid level is running low.

The pump must be capable of supplying more static pressure than the maximum air boost pressure. The pump must also be rated for continuous duty at the flow rates and pressures that are required. Some systems include an accumulator that is used to reduce the amount of time that the pump has to run.

The entire injection system,



Usually when employing water injection with an intercooler, the injection point should be downstream of the intercooler. Rarely, if ever, does it make sense to inject between the compressor and the intercooler. The water can fall out of suspension or, worse, the intercooler can actually heat back up the air that is sub-cooled by the water. When no intercooler is used, it is often preferable to inject the water just upstream of the compressor. The old rodder's tale that water droplets passing through a spinning compressor will damage it are false. If this were true, then draw-through carbureted turbo systems would never work.



A properly engineered water injection system is more than just a pump and a water tank. This particular system includes in-cabin monitoring of the WI system parameters. (Aquamist)

WATER INJECTION USE

For street engines running 91–93 octane fuel and a compression ratio of 9:1 or lower, a rule of thumb to determine if water injection is called for is as follows:

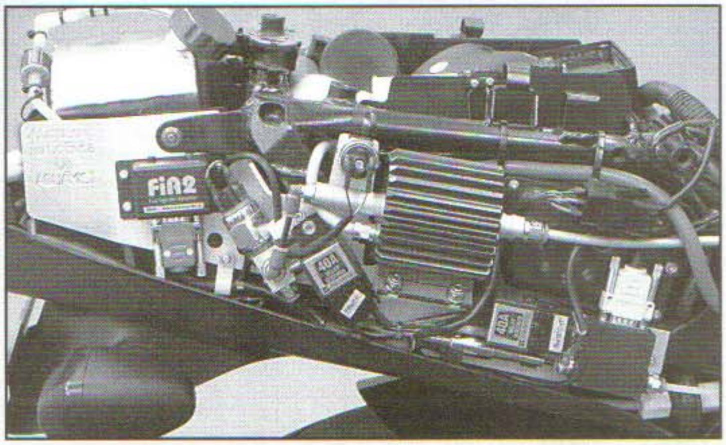
Boost < 5 psi: No Intercooler or Water Injection
Boost 5–12 psi: Intercooler Only
Boost > 12 psi :Intercooler + Water Injection

including the storage tank, should be sized for the vehicle's primary application. Remember that water is heavy; a single gallon weighs more than eight pounds. A drag racer would clearly benefit from as small of a storage system as possible, while the driver of a street vehicle would probably be more concerned with running out of coolant between fill-ups than he would with the total weight of the system.

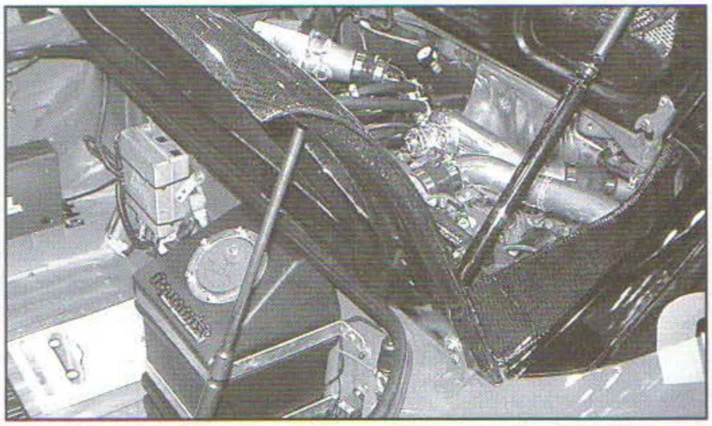
Some commercial water injection systems don't come with a water tank. It's left to the purchaser to supply a tank that is sufficient for his or her vehicle's needs. Often inexpensive windshield washer tanks are used for this reason. It's important to remember, however, that the coolant storage tank needs to be selected with the type of coolant mixture in mind. Systems that use pure water are simple to accommodate. Methanol, on the other hand, is a flammable fuel. It is also highly corrosive with certain materials. Care must be taken to ensure that the storage container, pump, seals, and lines are all compatible with the volatile mixture. Karting fuel tanks make good methanol/water tanks. Most are designed to be used with similar fuels, and they are intended to be used in high-G situations and still deliver the fluid.

Finally, the hoses and clamps used in the system should be of high quality. When routing the lines in the engine compartment, it's important to securely fasten down all the hardware and components. Having an engine melt down because a 75-cent hose clamp or 35-cent cable-tie failed is never a good situation in which to find yourself.

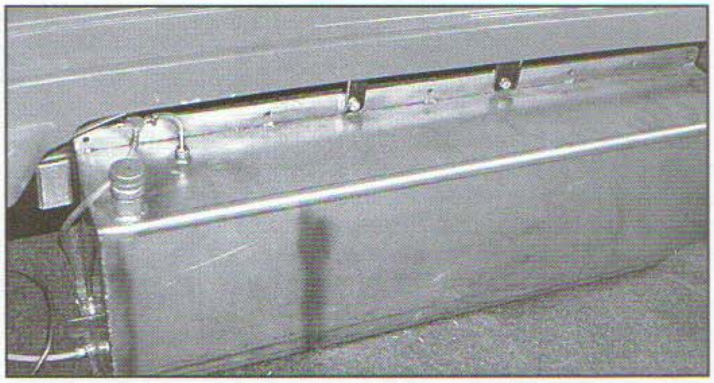
Check valves are used to keep water flowing in only one direction under boost. Good filtration is necessary, however, as small foreign objects can cause these devices to malfunction. (Aquamist)



Where space is tight, clever packaging is required. This Suzuki Hayabusa has a complete water injection system mounted underneath the seat and rear valance. (Aquamist)



Toyota MR2 with trunk-mounted water-injection tank. Water weighs 62.4 lbs/cubic foot, or about 8 lbs per gallon. Note the brackets used to hold the tank in place during hard acceleration and deceleration of the vehicle. (Aquamist)



A trade-off between capacity and weight is part of the planning process for a water injection system. The owner of this car obviously wanted extended periods of operation between water fill-ups. A concern of water injection is that if you ever run out of coolant, charge air temperatures can increase dramatically, which in turn can result in detonation. A safety warning system is often incorporated to alert the driver of low water levels.

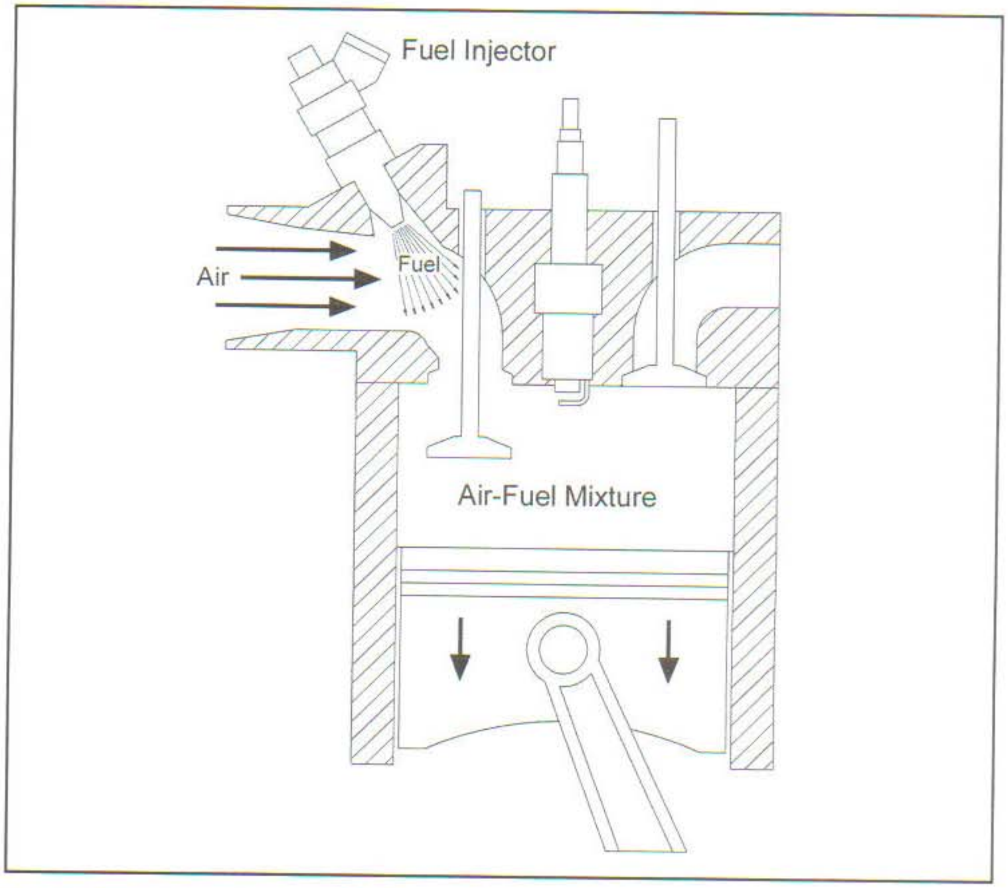
	Advantages	Disadvantages
A2A Intercooler	Simple Reliable No On-Going Maintenance No Fill-ups Required	Bulky Plumbing/Packaging Issues Airflow Pressure Drop Expensive
Water Injection	Not Subject to Heat Soak No Airflow Pressure Drop Simple Compact	Frequent Fill-ups Required Weight of Water Component Failure or Leak Can Be Catastrophic

So, which type of charge cooling system is better, water injection or intercooling? The answer, of course, is that it depends on the application. Each type of system has its pros and its cons. Deciding which is right for a given vehicle requires judgment and compromise.

FUEL INJECTION 11

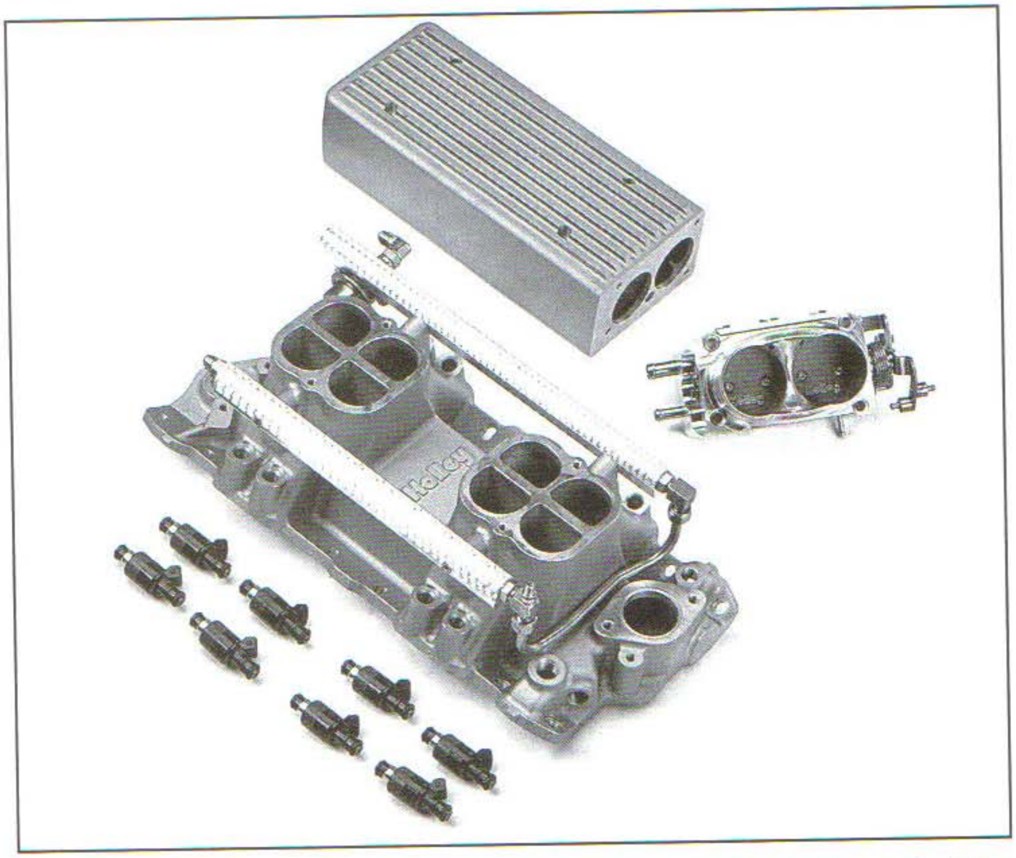
Throughout most of this book, we have focused on the pressurization, cooling, and flow of air into and out of an engine. Back in Chapter 1, in fact, we saw that an excellent way to think of an engine is to consider it as simply a large air pump. Moving and managing all the required air into and out of an engine to support combustion is by far the most difficult aspect of engineering a turbocharger system. In comparison, the addition of fuel is much easier. But that said, fuel management is not trivial—not by a long shot. In fact, all the airflow in the world into and out of an engine will mean nothing if the correct amount of fuel is not provided at the right moment in the four-stroke cycle.

There are two primary methods of delivering fuel to an engine: carburetors and electronic fuel injection (EFI). The last new car in America that came equipped with a carburetor was built back in the late 1980's. Since then, manufacturers have only supplied EFI-equipped vehicles to the public. The reason, of course, is that EFI is superior to carburetors for essentially all consumer vehicle applications. From emissions to fuel economy, especially when factoring in variable ambient conditions, operating elevations, and so on, a properly set up EFI system will outperform a carburetor.

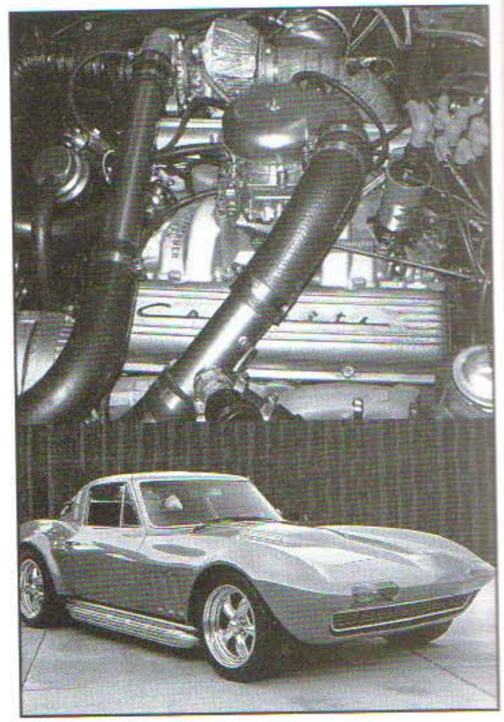


A fuel injector is simply an electrically operated solenoid valve. When the correct voltage and current is delivered by the ECU to the injector, the valve opens. This allows pressurized gasoline (typically at 40–45 psig) to spray out the nozzle tip into the intake tract. On most multi-port injection (MPI) systems, the injector is situated near the intake valve, as shown in this drawing. In contrast, throttle body injection (TBI) systems place injectors much farther upstream at the throttle body. TBI systems deliver fuel in much the same way a carburetor does, and in fact are known as "wet" EFI systems because the fuel and air must travel together through the intake runners (much like a carburetor system). MPI systems are "dry" because the fuel is added at the end of the intake runners, directly in front of the intake valve. MPI systems are generally superior to TBI systems, especially in forced-induction applications.

For ultimate power production, however, the differences are less distinct. Both types of systems can work very well if their respective builders and tuners know what they are doing. This is true for forced-induction applications as well, especially given the availability of modern tuning equipment such as wide-band air/fuel meters and chassis dynamometers. It is possible to dial in a carburetor-equipped turbo system such that it produces identical horsepower and torque to that of a similarly-equipped EFI-based vehicle.



There are a number of quality and affordable aftermarket companies that can supply all the equipment necessary to convert a carbureted engine to electronic fuel injection suitable for forced induction. (Holley)



A properly engineered and tuned carburetor-equipped engine can produce just as much horsepower as a fuel-injected engine. This holds true for turbocharged vehicles, too. This beautiful 1965 Corvette Coupe features a 413 cid small block running 10 psig of intercooled boost from a 60-1 single turbo. Carburetor is an AFB-style unit modified with a sealed throttle shaft and nitrophyl floats. See Appendix E for more information on carburetors and turbochargers. (Sypherd)

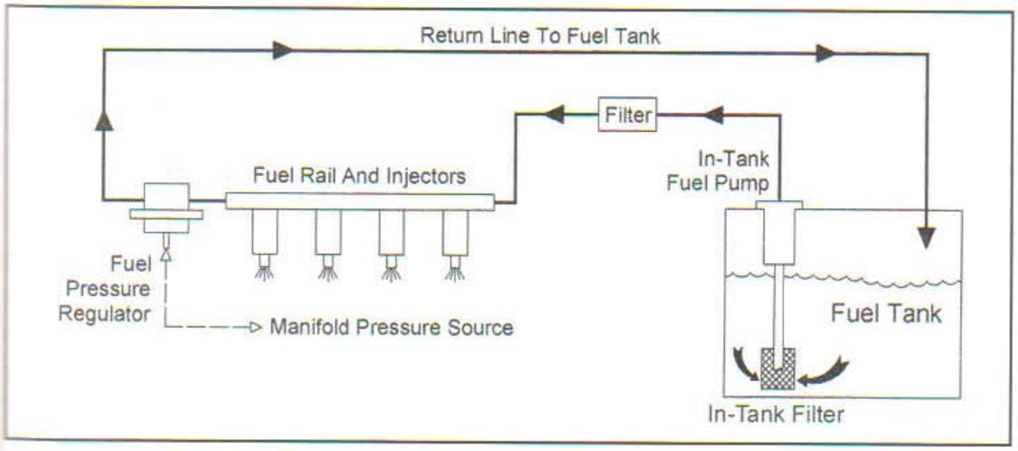
The common Bosch style, or push-in type fuel injector. These types of injectors are used in US, Japanese, and many aftermarket EFI systems. Pressurized fuel is delivered to the injector via a fixed tube, or "fuel rail," which also serves as a mounting device to hold the injector in place.

The bottom line is that turbochargers and carburetors can be mixed together with excellent results, but the techniques for doing so are very different than those required for EFI-equipped engines. If the reader wants to learn more about carburetor-based turbocharger systems, Appendix E covers the basics. There are also excellent web-based sources for learning the ins and outs of carburetor-turbo systems, such as the forums on www.TurboMustangs.com. But because most of the vehicles that are turbocharged today have EFI, and because the future will only see more of this trend, this book focuses on fuel injection. So let's start the discussion with a basic understanding of how EFI works.

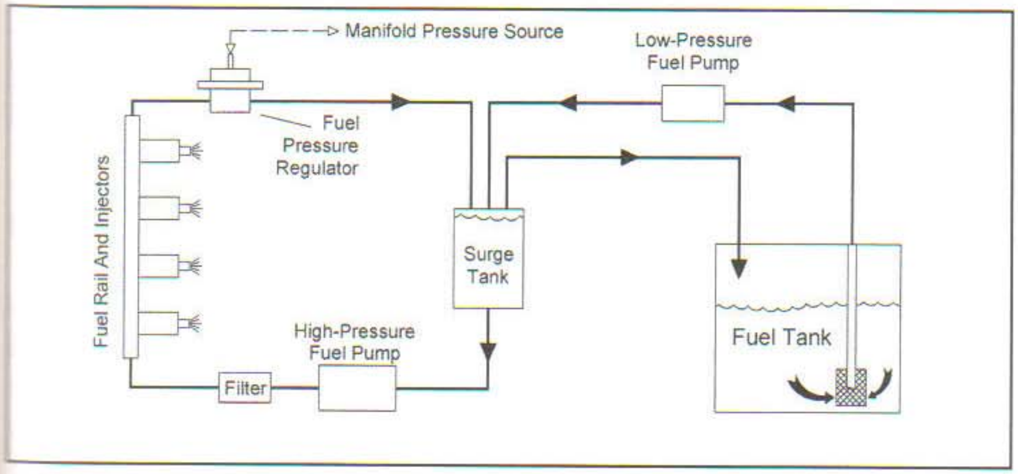
INJECTOR BASICS

A modern fuel injector is little more than an electronic solenoid valve. When electrical power is removed from the injector, the valve is closed. In this position, it physically stops pressurized gasoline from flowing. When the injector receives an electrical signal, however, the solenoid becomes energized and the valve opens. This allows fuel to pass through and out the end of the injector. The shape of the nozzle on the end of the injector causes the fuel to atomize into a fine mist. In most port-injected engines, this spray is aimed directly at the back of the intake valve(s).

The electrical signal from the electronic control unit (ECU) is what activates the solenoid. We will talk more about how the ECU



A basic fuel supply system. A pressure regulator referenced to manifold boost controls the actual pressure of fuel supplied to the injectors. As boost rises, fuel pressure increases proportionally.



Some high-performance fuel injection systems employ a two-stage circuit like the one shown here. A low-pressure pump located near the fuel tank supplies gasoline to a small one or two gallon surge tank located in the engine compartment. A high-pressure pump draws fuel from the surge tank and supplies it to the fuel rail. This type of system is often used on vehicles that undergo high accelerative loads. The surge tank ensures a continuous supply of fuel to the high-pressure circuit under high g's.

There are two basic mounting methods for injectors: flange type and push in, or Bosch-style. Flange-style injectors are less common, but can still be found in some European vehicles and older EFI systems. These injectors employ two small screws to secure the flange to the intake manifold. The fuel "rail" is typically a manifold block with individual flexible fuel hoses feeding each injector.

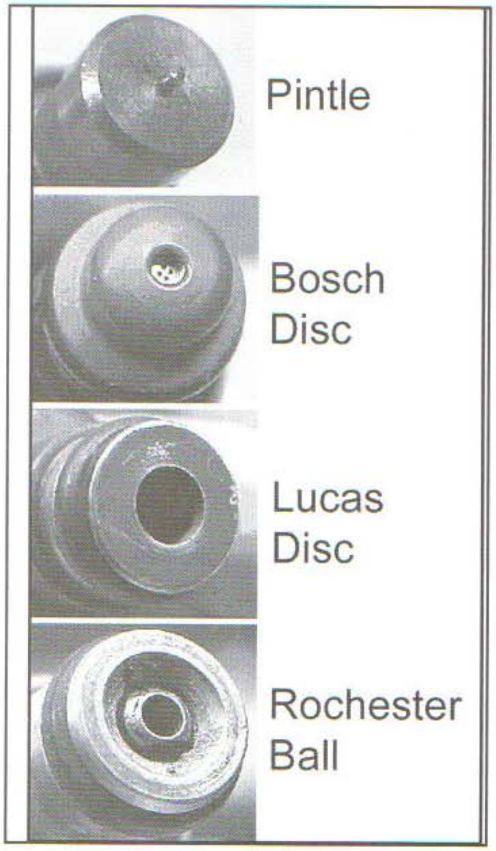
> **INJECTOR RATING**
>
> Injectors are rated by the volume of fuel that they can deliver per minute and by their spray pattern, which specifies the shape of the spray.

determines the timing and duration of the electrical signal to the injector in the next chapter. For now, it's important simply to note that the longer the duration of the electrical pulse, the longer the injector stays open. And the longer the injector stays open, the more fuel flows into the cylinder, and therefore the richer the mixture.

Duty Cycles

Injectors are designed to flow a particular amount of fuel through them in a given period of time. This flow rate is typically measured in either cubic centimeters per minute (cc/min) or pounds per hour (lb/hr). This flow rate is specified at a particular fuel pressure. Most modern fuel pumps supply roughly 44 psi of pressure under normal operations, so this is the standard pressure at which fuel injectors are rated.

When a manufacturer says that a particular fuel injector will flow X cc/min or Y lb/hr, he is also implying that this occurs at a 100% duty cycle rating. This means that the injector will indeed flow that amount of fuel—but only if it remains continuously open. Unfortunately, most fuel injectors don't behave well at a duty cycle greater than 85%; they need some time to close and rest between



There are a number of different injector types to choose from when purchasing fuel injectors. The most common is the pintle-type, in which a small needle rests in a tapered seat at the end of the injector. When the solenoid is energized, the needle is pulled back, allowing fuel to spray out. This is a well-proven design that has been in use for decades. Similarly, the two disc-type injectors work the same basic way, except that a flat disc is retracted from a hole to allow gasoline to spray. The Bosch disc-type employs tiny holes to create a spray pattern. These work well, except they're somewhat more prone to clogging than the standard pintle. The Lucas disc-type exhibits a very fast response, but its spray pattern tends to be narrow. The ball-type injector employs a ball-in-socket arrangement to meter the fuel. These exhibit excellent fuel atomization and spray patterns, but can be affected by varnish deposits. (Racetech)

pulses. The more time that an injector is energized and open, the hotter it will get, and the less reliable it will behave.

The actual amount of time (measured in seconds that the injector is open) is called its pulse width. Duty cycle is therefore defined as the actual pulse width time, divided by the theoretical time the injector could stay open during two complete engine revolutions (for a four-stroke engine). Some OEM systems, such as certain Honda engines, are designed to run at close to 100-percent duty cycle when the engine reaches redline. The thinking behind this is that the engine rarely stays at that rpm, and therefore the injector will not overheat very often.

For performance-based turbo systems, however, the time an injector is at or near redline will probably be more frequent than on stock OEM systems. For this reason, aftermarket injector manufacturers typically recommend that their injectors not exceed 80–85% duty cycle. If your injectors routinely need to be open more than this, you probably need larger injectors.

SIZING FUEL INJECTION SYSTEMS

The standard method used to size fuel injectors for a vehicle relies on something called the brake specific fuel consumption value, or BSFC. This quantity derives from the relationship between the amount of gasoline an engine consumes and the horsepower it produces; i.e., an engine's BSFC is a measure of the rate at which fuel is consumed on a brake dynamometer while the engine produces a particular amount of horsepower.

BSFC is expressed in units of pounds of fuel consumed per hour per horsepower, with typical values ranging from a low of 0.3 all the way up to a high of 0.7 lb/hr-hp. Forced-induction engines, including most typical turbocharged systems, usually have a BSFC that falls somewhere between 0.50 and 0.65 lb/hr-hp.

If we know the BSFC and the desired horsepower output from an engine, we can calculate how large the fuel injectors need to be to support that power level. Injector size (in pounds per hour) can be given by the following equation:

Eq. 11-1

$$\text{Size} = \frac{(\text{BSFC})(\text{HP}_{\text{Crankshaft}})}{(\text{Duty Cycle})(\text{No. Injectors})}$$

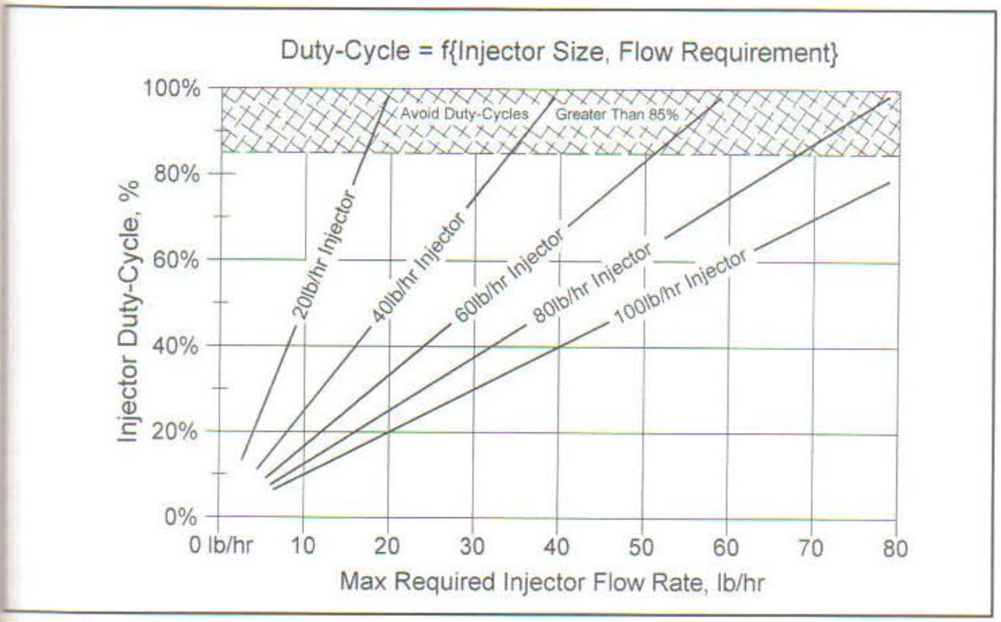
For example, a 6-cylinder turbocharged engine, producing 300 horsepower, with one injector per cylinder, and an injector duty cycle of 85%, would require approximately:

Fuel Injector Size = (0.60 x 300)/(0.85 x 6) = 35.3 lb/hr

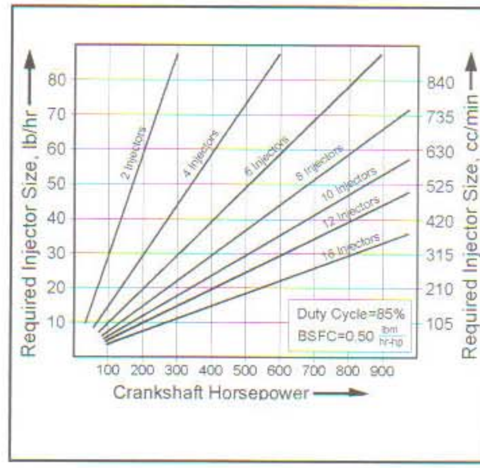
Note that we assumed a BSFC of 0.60 for this calculation. It's important to realize that this is really just an educated guess. Volumetric efficiencies of the engine, how well-sized the turbocharger is, and how well-tuned the EFI system is will all affect this number. The act of estimating fuel injector sizes is only as valid as the values used in the formula.

Okay, that said, to convert from pounds per hour to cubic centimeters per minute, simply multiply by 10.5. For the example shown above, the injector size would be:

Fuel Injector Size = 35.3 x 10.5 = 370 cc/min.



Duty cycle at idle is normally only a few percent, rising as engine rpm increases. Most injector manufacturers recommend that the duty cycle of an injector never exceed 85%.



The nominal size requirement of a fuel injector can be estimated via a brake specific fuel consumption calculation. Turbocharged engines typically exhibit BSFCs around 0.50–0.65 lb/hr-hp. This chart is for a BSFC of 0.50 lb/hr-hp.

Fuel Pressure

Injectors are usually rated by the manufacturer at 44 psi. Raising or lowering the pressure from this nominal value will change the flow rate of the injector. A common hot rod trick to increase flow rate, therefore, is to raise the fuel pressure. And as you might expect, there is a formula for estimating the change in fuel flow rate when the pressure is raised or lowered:

Eq. 11-2

$$Press_{New} = (Press_{Old})\left(\frac{Flow\ Rate_{New}}{Flow\ Rate_{Old}}\right)^2$$

For example, if we wanted to achieve 450 cc/min of flow from our 370 cc/min and 44 psi injectors, the required fuel pressure would be:

$Pressure_{New} = [(450/370)^2 \times 44] = 65$ psi

We can also rearrange the equation to solve for new flow rate as a function of pressure:

Eq. 11-3

$$Flow_{New} = (Flow_{Old})\sqrt{\frac{Pressure_{New}}{Pressure_{Old}}}$$

Note in this equation that the rate of fuel injected is the square root of the fuel pressure ratio. If fuel pressure is doubled, only about 41% more fuel is delivered. It takes a fourfold increase in pressure to double flow rate. And this means a *serious* fuel pump, capable of not only this much higher pressure, but also the resulting doubling of flow rate, too. This is generally not advisable; it's better to simply bite the bullet and install larger injectors if that much flow increase is required.

Injector Pulse Widths

If you know the air mass flow rate into an engine and the size of the fuel injectors, it is possible to calculate the amount of time those injectors have to stay open during engine operation to maintain a desired air/fuel ratio. This period of time is referred to as the injector pulse width.

For example, let's look at the turbocharged and intercooled 1.6-liter Honda engine that was described back in Chapter 3. At 6000 rpm, 10 psig boost, 1 psig intercooler loss, 75% efficient compressor, and 120°F air entering the intake manifold, the air mass flow rate (MFR) was calculated to be 16.86 lb/minute. Or, put another way, this Honda engine, operating under these conditions, ingests nearly 17 pounds of air per minute.

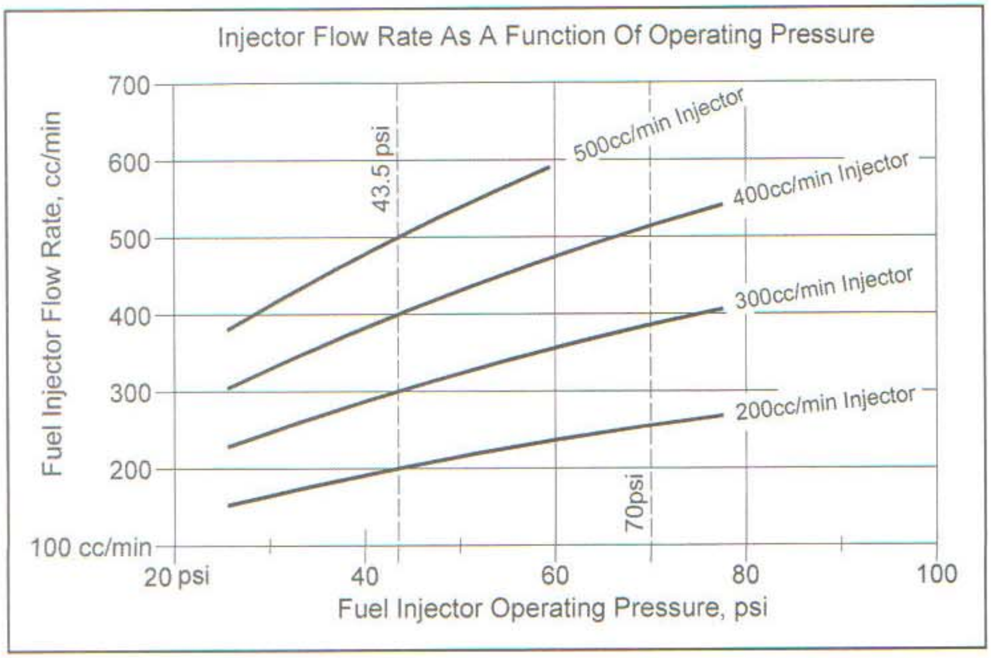
Now recall that this was a four-cylinder engine. Each individual cylinder is therefore drawing in:

Eq. 11-4

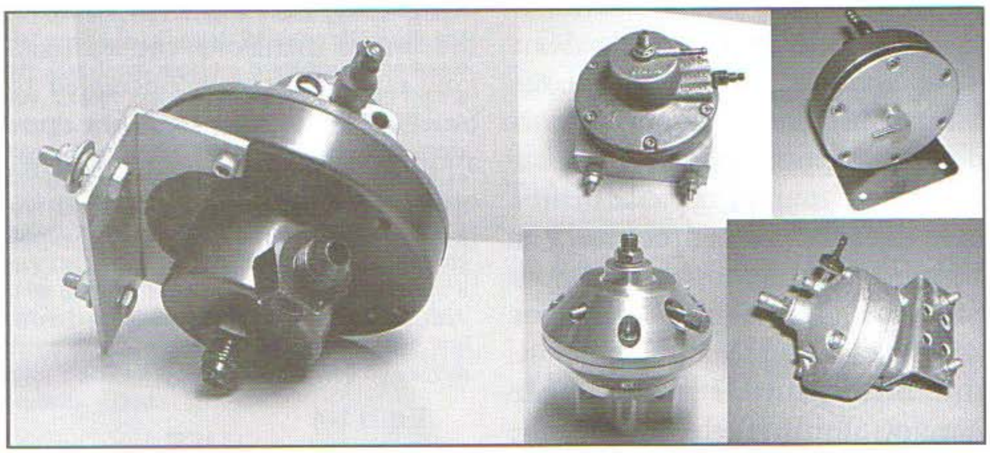
$$MFR_{Cylinder} = \frac{MFR_{Total}}{No.\ Cylinders}$$

For our example:

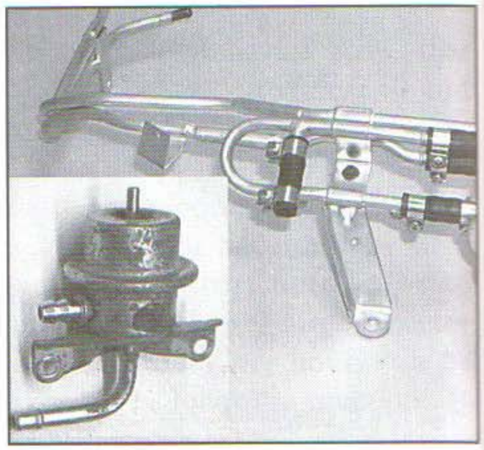
$MFR_{cylinder}$ = 16.86 lb/min / 4 cylinders = 4.2 lb/minute



The rate at which fuel flows through an injector is proportional to the square of the pressure in the rail. In most cases, it is suggested not to run more than 70 psi of fuel pressure, or the injectors may not open and close properly. Similarly, don't install injectors with a larger flow capacity than required. Very large injectors can cause idle problems that are difficult to tune. For street turbo applications, the rule of thumb is that injector flow rate, as measured in cc/min, should not exceed 1.5 to 1.7 times the displacement of a single cylinder in the engine. For example, a 3-liter, 6-cylinder engine has an individual cylinder displacement of 3000cc / 6 cylinders = 500 cc per cylinder. Multiplying this amount by 1.5 results in a recommended injector size of 750cc/min. Larger sizes are possible if you have very high-quality injectors and a well-tuned control system. In general, however, if your vehicle requires injectors larger than this, you should consider multi-staged injectors.



Shown here are a variety of "rising rate" fuel pressure regulators (RRFPR), which are also known as fuel management units (FMU). Unlike standard FPRs, which increase the fuel rail pressure proportionally with boost at a 1:1 rate, an RRFPR increases fuel pressure at much greater rates. The use of RRFPRs on turbocharged engines is constantly debated by tuners. Advocates say that that they offer a simple and inexpensive way to supply the additional fuel required under boost. Opponents counter that fuel flow varies as the square root of fuel pressure, so controlling the desired quantity of fuel throughout the rev range and under all boost conditions can be difficult. Also, as rail pressure rises, injectors take longer to open and/or require additional current to open.



EFI fuel pressure regulators (FPR) come in various sizes and shapes, but their purpose is always the same: to hold fuel pressure at a certain differential above the intake manifold pressure. Most OEM-type regulators employ a 1:1 ratio. At one psi of boost, the regulator adds one additional psi of fuel pressure. This ensures a constant pressure differential across the fuel injector. (Racetech)

Or, converting to pounds per hour:

$MFR_{cylinder}$= 4.2 lb/min x 60 min/hour = 252.9 lb/hour

There are a number of ways to calculate the required fuel injector flow rate, but since we know the MFR, we can simply apply the desired air/fuel ratio to size the injector:

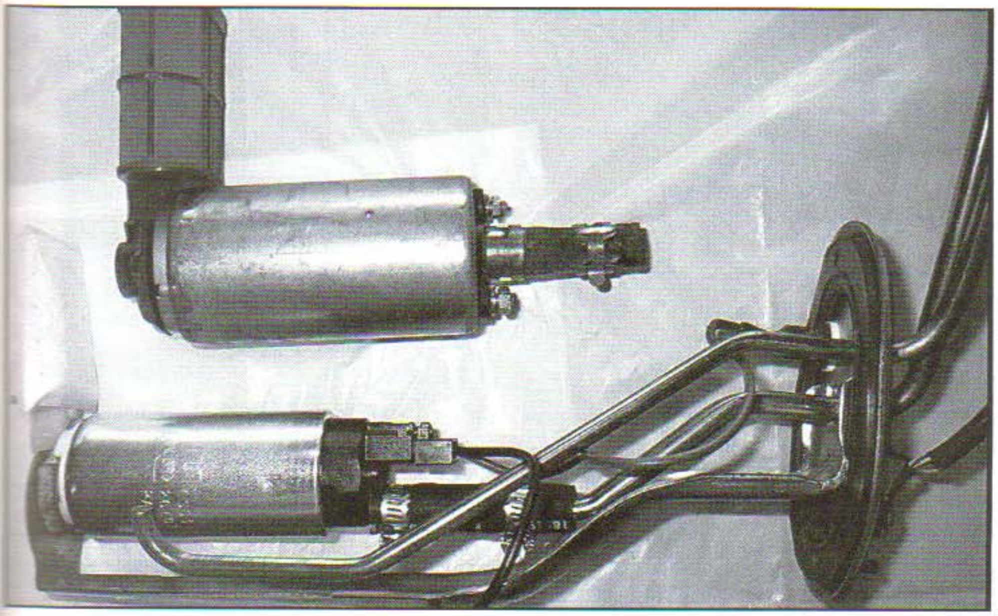
Eq. 11-5

$$\text{Inj. Flow Rate} = \frac{\text{Air MFR}}{\text{Air:Fuel Ratio}}$$

For example, at a slightly rich air-fuel ratio of 13:1 (i.e., rich relative to stoichiometry), we would require the following amount of fuel:

Fuel Injector Mass Rate = 252.9 lb/hr / 13:1 = 19.5 lb/hr of fuel

Next, let's calculate how much time at 6000 rpm is physically available to open each injector and spray fuel into the respective intake



An EFI fuel pump must meet the fuel injector requirements for both pressure and flow rate. This photo shows an OEM in-tank fuel pump on the bottom. It is being replaced with the higher capacity pump on the top. Note the return line that exits near the intake on the OEM pump. An intake "sock" is used to pre-filter the gasoline before it enters the pump. (Picasso)

runner. For a four-stroke engine that has the standard intake-compression-power-exhaust strokes per cycle, we know that engine speed divided by two gives us the number of complete cycles per

Eq. 11-6

$$\text{Cycle Rate} = \frac{\text{Engine Speed}}{120}$$

minute. Dividing that by sixty gives us cycles per second:

Or in our example:

Cycles Rate = 6000 / 120
= 50 cycles per second

Inverting this gives the total elapsed time per cycle as:

Eq. 11-7

$$\text{Avail. Cycle Time} = \frac{1}{\text{Cycle Rate}}$$

Or, for our example:

Available Cycle Time = 1 / 50 cycles per second = 0.02 seconds per cycle

In other words, we have 0.02 seconds, or 20 milliseconds (20 ms) in which to inject fuel for each complete intake-compression-power-exhaust cycle. (Note that holding open an injector for this entire 20 milliseconds is the same thing as operating it at 100% duty cycle.)

Next, let's pick an injector size. Assuming our actual injector used in the engine is, say, rated at 24 lb/hour, we can calculate the required duty cycle. This is possible because we just calculated the required injector mass flow rate:

Eq. 11-8

$$\text{Duty Cycle} = \frac{\text{Req'd Flow Rate}}{\text{Injector Size}}$$

Or, for our example:

Duty Cycle = 19.5 lb/hr / 24 lb/hr
= 0.81 = 81%

Because this falls within the typical recommended max duty cycle rating of 85% for most injectors, we can proceed to calculating the required injector pulse width:

Eq. 11-9

Pulse Width = (Dty Cycle)(Cycle Time)

Or, for our example:

Pulse Width = 0.81 x 20 milliseconds = 16.2 ms

Complicating these calculations somewhat is the fact that fuel injectors take a finite amount of time to physically open and close, which subtracts somewhat from the available cycle time. But for a good approximation of pulse width, these types of calculations aren't too far off.

> It is always a good idea to disconnect your battery when working on the fuel system. It's also recommended that you keep at least two fire extinguishers on hand, one nearby your work, and the other placed somewhere that the fire can't reach. A fire extinguisher that gets engulfed in a fireball won't do you much good.

INTAKE MANIFOLDS

While technically not part of the fuel injection system, the intake manifold design strongly affects how well the EFI system performs. It also affects how much horsepower and torque can ultimately be developed, and where they peak in the rpm range.

A rule of thumb for naturally aspirated EFI manifolds is that long, narrow intake runners result in better low rpm torque, while

To get maximum performance and power from a fuel-injected engine, it's important to have all the fuel injectors matched to the application—and each other. There are a number of companies that specialize in "blueprinting" fuel injectors. For a fee, you can mail your injectors to them and they will disassemble, clean, and reassemble the units. They will also flow test them, providing a before and after report on the injectors. This allows the injectors to all operate similarly in a "balanced" set and with more consistent flow rates and quicker response times. Fuel pumps can be blueprinted, too. (RC Engineering)

After working on a fuel system, take a couple of minutes to check and recheck for fuel leaks before starting the engine. Think safety when working around flammables like gasoline.

short, wide runners give better top-end horsepower. This is precisely why so many OEM manufacturers utilize variable-length intake runner systems in their performance cars. At off-idle and low-rpm conditions, relatively long runner lengths are employed for maximum torque, but at higher speeds, valves or baffles are deployed to effectively shorten the intake paths for better horsepower.

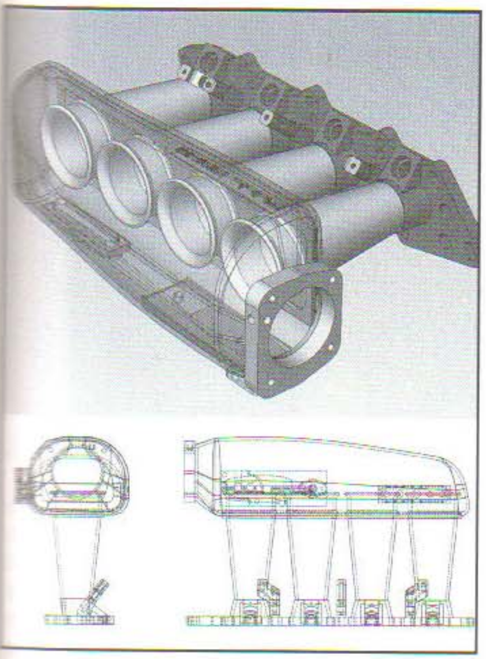
There is some debate about how important it is to worry about intake runner lengths for forced-induction vehicles. Above the boost threshold, one argument goes, long narrow tubes simply add flow resistance and reduce the VE of an engine. For ultimate horsepower production, short and wide is better. The truth, however, is that a fluid is fluid, and gas dynamic effects are present regardless of boost levels. If you want to maximize intake efficiency, you need to pay attention to resonance and inertial effects in the region of interest, including the time spent under boost. Further, for many street-driven turbo vehicles, the amount of time spent below the boost threshold can be significant. Again, we come back to the idea of evaluating turbo system requirements on the basis of vehicle application.

A typical turbo engine will behave a lot like a naturally aspirated engine below the boost threshold. In fact, most turbo engines actually have worse VEs than equivalent naturally aspirated engines at low engine speeds. This is due to the intake (compressor) and exhaust (turbine) flow restrictions that the turbocharger components cause. Remember that below the boost threshold, a turbo engine behaves entirely like a naturally aspirated engine, relying on the partial vacuum created in the cylinder to draw air into the combustion chamber. For good street performance and drivability, an intake manifold optimized for low-end torque is probably the best compromise. This means long and narrow runners. A variable length runner system is even better. Some OEM manufacturers, such as Toyota on their second generation MR2, use a variable length runner system on their turbo engines with excellent results.

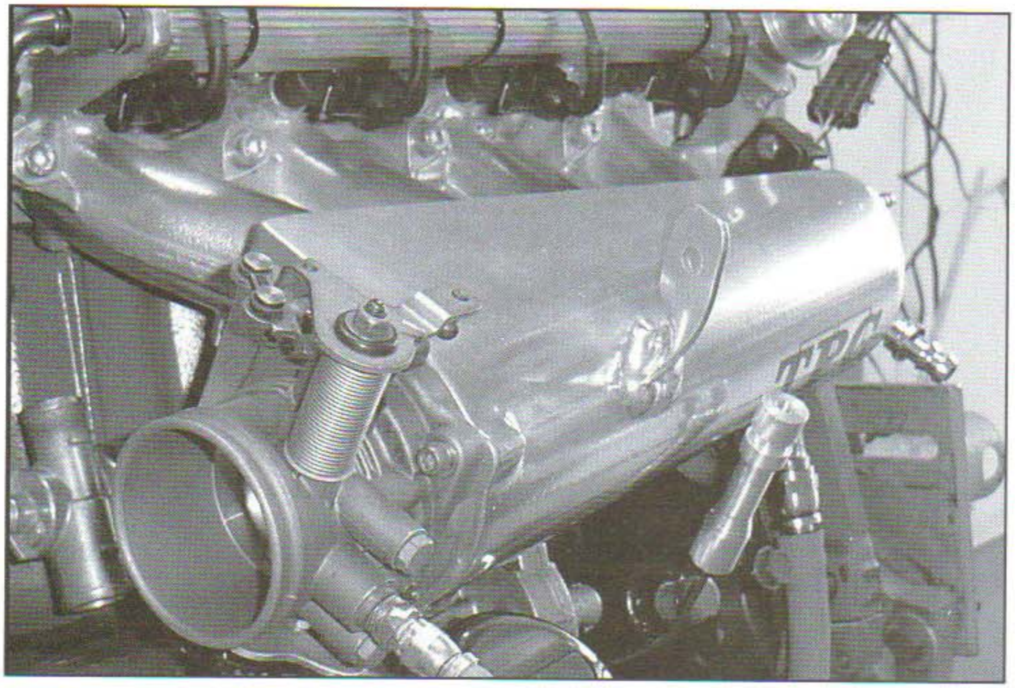
PLENUMS AND THROTTLE BODIES

Moving upstream from the runners gets us to the plenum, or "log" as it's sometimes called on four and straight-six engines. The plenum is the large common volume between the runners and the throttle body. A rule of thumb for street-driven turbo engines is that the plenum volume should be around 40–60% of the total engine size. This will result in a decent compromise between throttle response and maximum flow. For a 2-liter engine, we would want a 1-liter plenum.

At the upstream end of the plenum is, of course, the throttle body. Many people simply bolt on the largest butterfly assembly they can on their vehicles and expect great performance. While good



Fuel injection intake manifolds can range from the simple to the sophisticated. But they all do basically the same thing: provide a supply of fresh air to the engine and allow the injection of the appropriate amount of fuel. The sophisticated manifold shown here was designed and built for a Honda B16 engine. Note the smoothly tapering intake runners that are fitted with entry air horns inside the plenum. A serious amount of engineering and planning goes into a high horsepower design like this. (Full-Race)



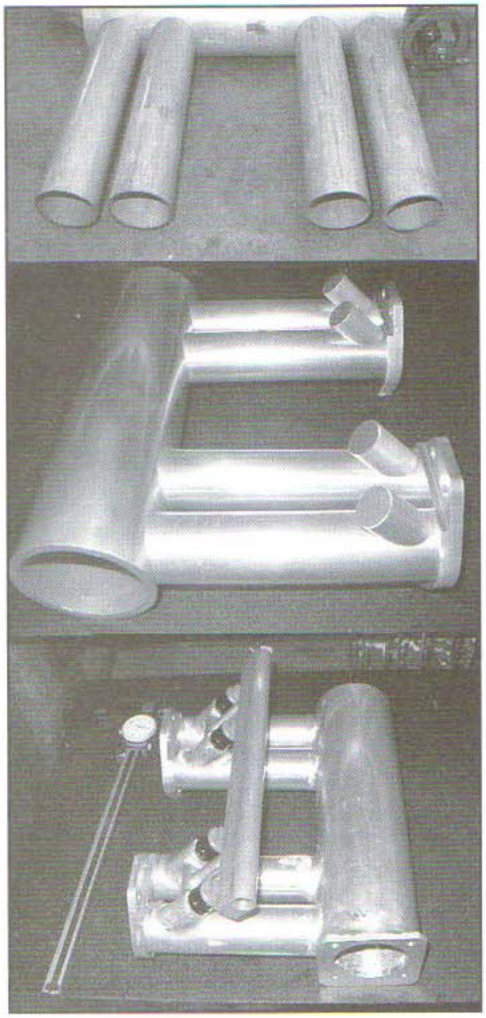
Another well-designed EFI manifold. Note the tapered plenum and short, direct intake runners. Generally speaking, short and wide intake runners are best suited for developing maximum horsepower at high rpm. Long, narrow runners develop better low-speed torque. This maxim holds true for both naturally aspirated and turbocharged engines alike. (The Power Group)

from a flow restriction point of view, larger throttle-bodies are not necessarily the best choice for a street car. The problem is often that off-idle (i.e., what is known as "tip-in") throttle response can be affected by a throttle body that is too large. I know of a late-model Ford Mustang, whose owner had installed a very large diameter throttle body. The car was essentially undrivable on the street; it was either wide-open throttle (WOT), or it was idling. There was essentially no in between. Throttles like this are often referred to as "digital," and the effect when boost is just coming on can be even worse. The tiny throttle opening can change from manageable power to too much in a range of just a couple hundred rpm.

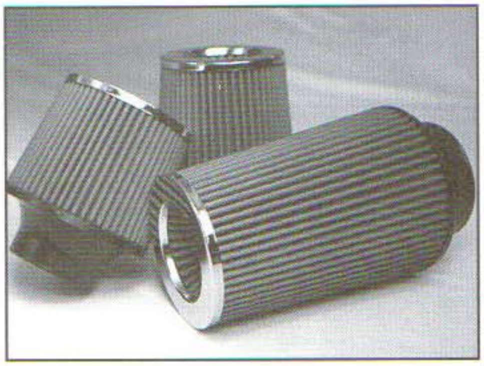
INJECTOR PLACEMENT, FUEL RAILS, AND FITTINGS

The placement of the injectors on the manifold is another area that affects performance. Because of the latent heat of vaporization effect, fuel injection engineers have seen small but measurable improvements in horsepower when fuel injectors are moved to the upstream end of the runner. However, they also point out that most OEM manufacturers position the fuel injectors close to the cylinder head, aimed as close to the backside of the intake valve(s) as possible. Injectors positioned close to the valves improve off-idle throttle response, bottom-end torque, and emissions. For drivability issues alone, emulating this OEM-style approach is recommended.

If you are converting a carburetor manifold to EFI, there are a number of suppliers that sell fuel rail stock, mounting hardware, weld-on injector bosses, and throttle body adapters. Adapters for pressure and temperature sensors required in the manifold are also available. Use only high-quality braided stainless steel supply and return lines, along with AN-style hose fittings. The thought of high-pressure fuel spraying around the inside of your hot engine compartment should convince you to spend the money on quality equipment. The same is true for fuel filters, pumps, and pressure regulators.

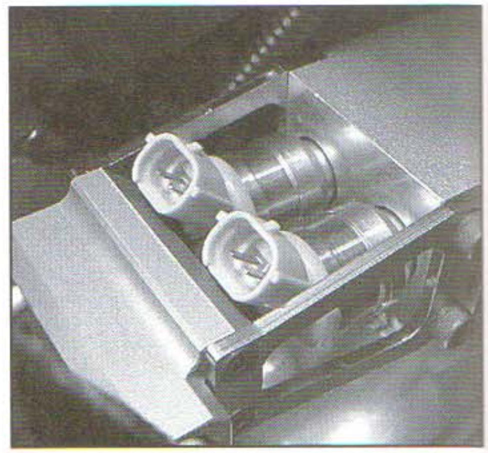


A custom intake manifold for a hybrid 2.2-liter Datsun engine. The long, narrow runners were chosen to maximize torque at off-idle and low engine rpm. (Tyler/Ruschman)

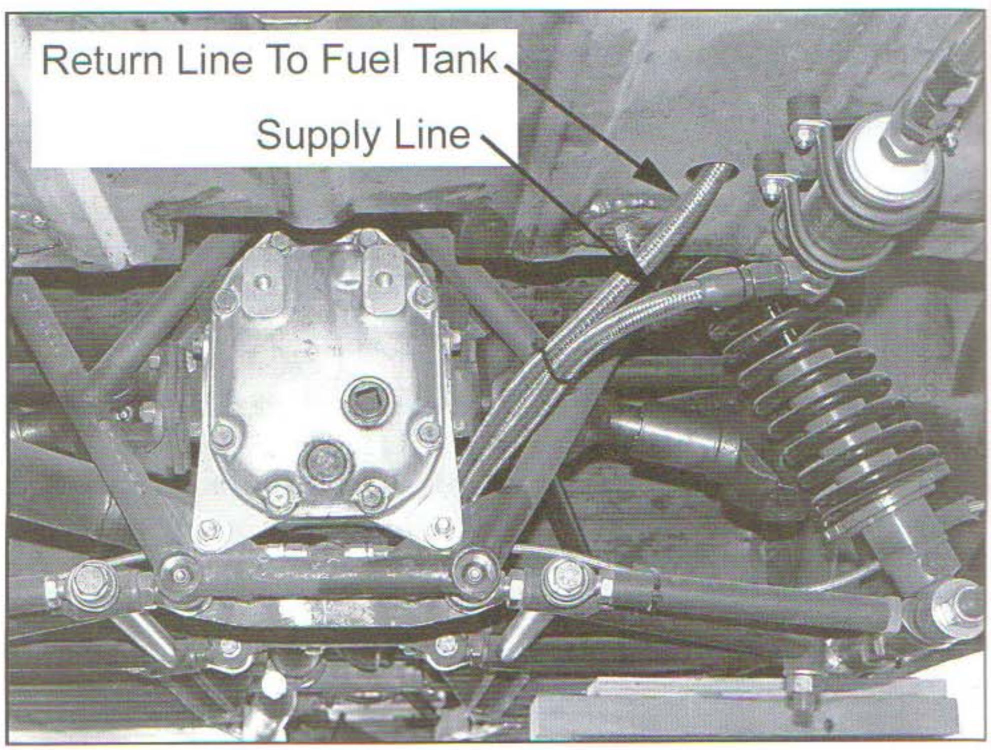


An undersized air filter can cost 1–2 psi of boost pressure or more. Don't skimp—and don't think about running an engine without an air filter, either, unless you have deep pockets and enjoy rebuilding engines and turbocharger compressors. (Turbohoses)

> A general rule of thumb for street-driven turbo engines is that the intake plenum volume should be approximately 40–60% of the total engine size.



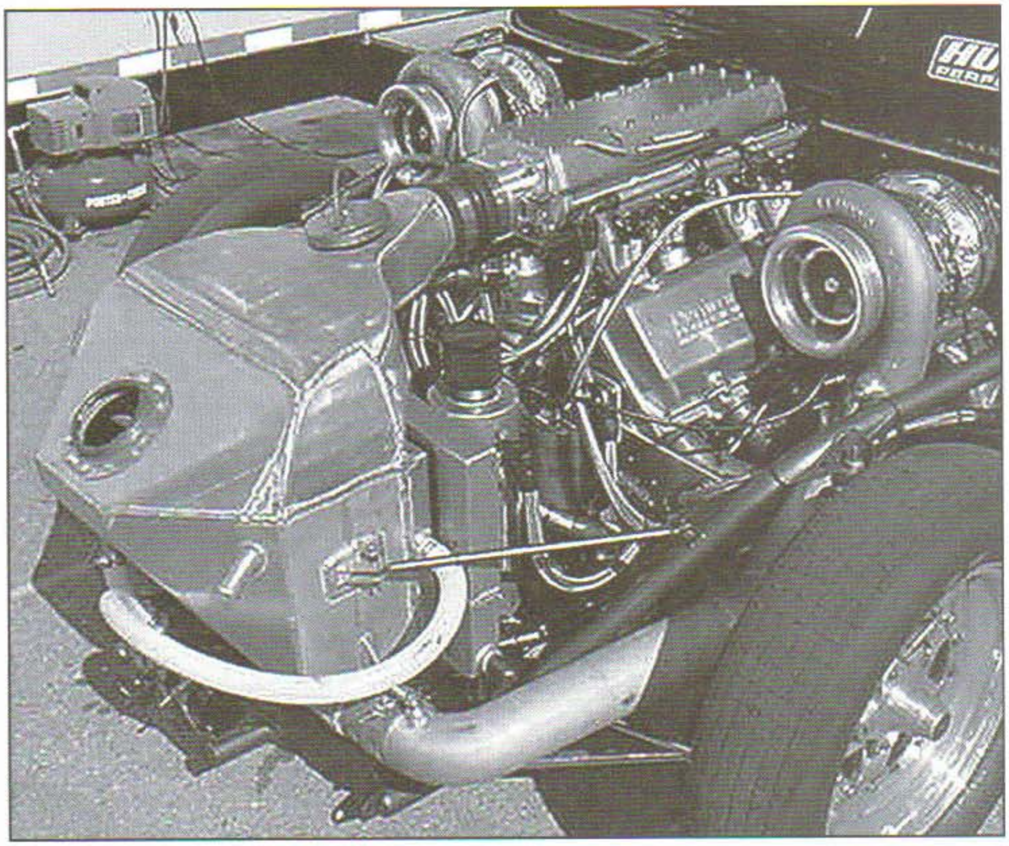
A pair of secondary injectors fitted to the intake tract on a Toyota Supra. OEM engineers often choose the smallest fuel injectors that will supply enough gasoline to meet the maximum target horsepower. Smaller injectors are easier to control off-idle and at lower engine rpm. This same idea can be used in custom high-power applications. Small injectors can be employed as the primary fuel delivery devices, which are used during low boost and rpm situations. Large secondary injectors can then provide the extra required fuel under maximum boost conditions. Typically, the smaller-sized daily-driver injectors are located close to the intake valve, while larger "power" injectors are mounted farther upstream. (Henderson/SP Engineering)



An external-type fuel pump mounted below the tank. Regardless of type, the fuel pump should always generate an excess flow of fuel. The regulator controls the pressure in the fuel rail by returning any fuel not used by the engine back to the fuel tank once the control pressure is met. At idle, perhaps 95% of the fuel delivered to the fuel rail is returned to the tank. At full power, only 5–20% of the fuel may be returned back to the tank. (As a side note, the owner of this vehicle should install a rubber grommet at the point where the return line passes through the bodywork. Even braided stainless steel hoses will wear out quickly if allowed to rub against sharp steel edges like the hole in this trunk floor.)

CONTROL SYSTEMS 12

Engine management systems are responsible for regulating fuel injection and ignition timing in order to achieve maximum engine performance, whether the performance goal is maximum torque output, horsepower, fuel efficiency, or minimum emissions. Some advanced engine management systems also handle boost control, nitrous, and a variety of other functions, but the main purpose of any engine control system is fuel and ignition control. Let's look at fuel control first.



This Pro Street 1957 Chevrolet Bel Air features an aluminum 447 cid big block with twin 88 mm turbos and an ice water-to-air intercooler. Fuel, spark, and boost are all controlled by way of MoTeC engine management, including complete data acquisition. The 2,300 horsepower generated by the engine routinely propels the 3000 lb car through the quarter mile traps in 6.5 seconds and 223 mph. (Tecklenburg)

FUEL CONTROL BASICS

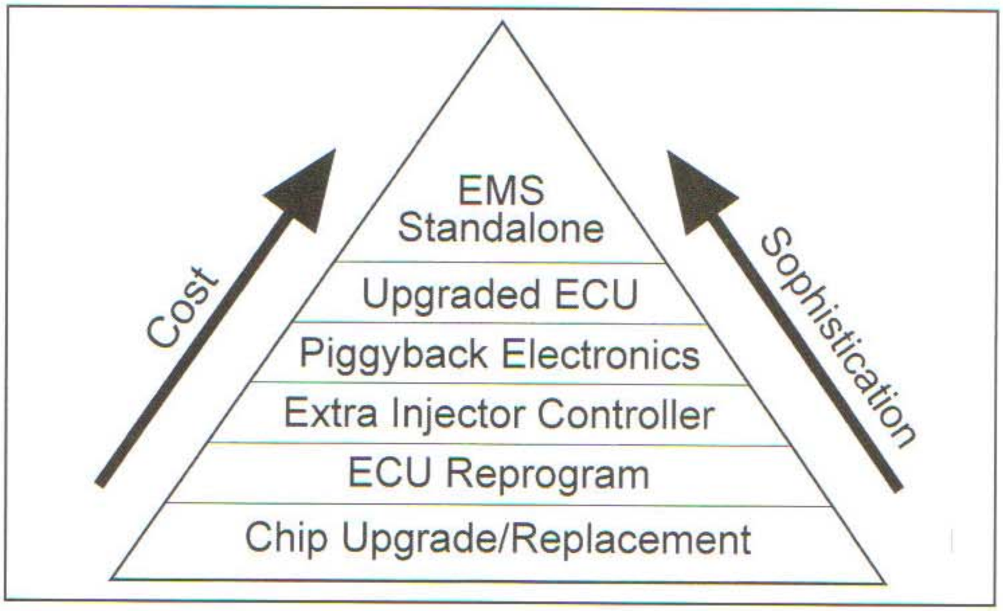
A fuel control system performs three basic functions. First, using electronic data supplied from engine sensors, the control system determines the operational mode of the engine and the instantaneous amount of airflow through it. Second, the control system calculates the correct amount of fuel required to support combustion for that amount of airflow and that particular operating mode. And third, the control system calculates the precise moment in time that is required to inject the fuel and then supplies the electronic trigger to fire the injectors.

An EFI control system performs these tasks by way of a series of algorithms, or mathematical procedures and formulas that are programmed into its computer. These algorithms include a variety of preset operational modes under which the engine might be operating. For example, the amount of fuel required when an engine is fully warmed up will usually be quite different than when it's cold. Similarly, when the engine is in cruise mode, where maximum economy and/or low emissions output is the highest priority, the fuel injection requirements will be different than when the engine is being asked to provide maximum power, as might happen under wide-open throttle.

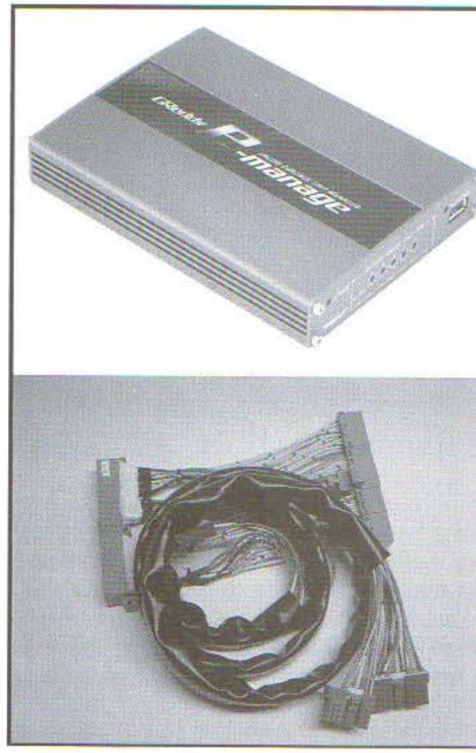
DETERMINING AIRFLOW RATES

A control system can determine how much air is flowing into the engine in three basic ways. First, a control system can directly measure the airflow being ingested with an airflow meter. This technique is commonly referred to as a mass airflow (MAF) system. These types of systems are often used in OEM applications. They are generally very accurate and allow for precise determination of the amount of fuel to inject.

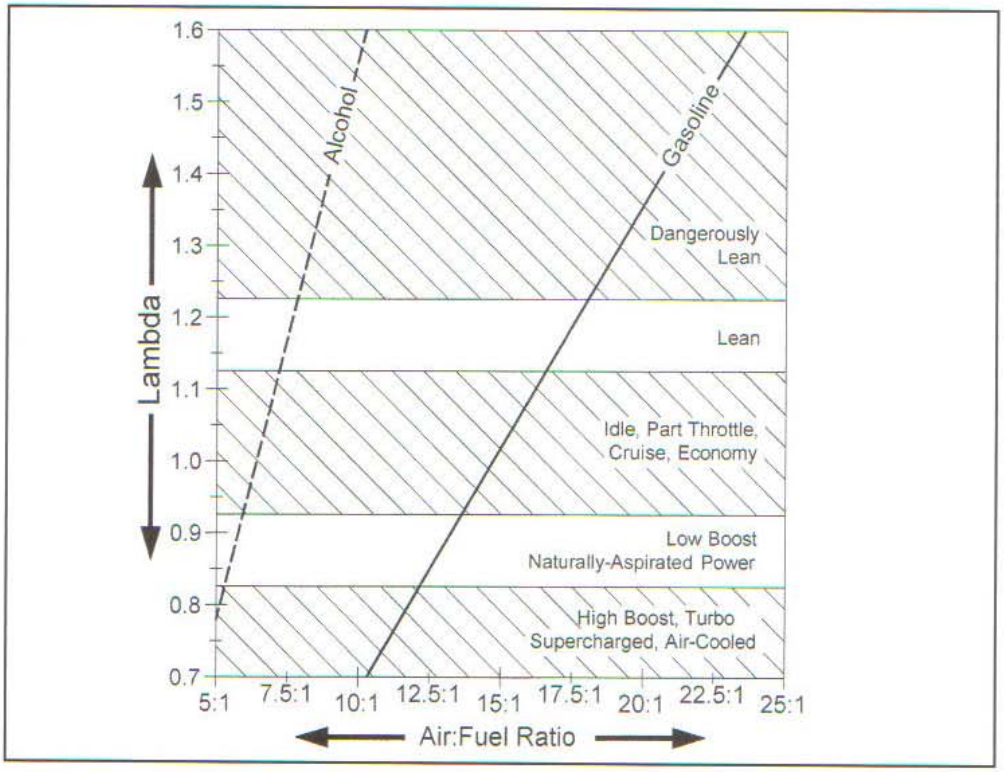
The second way a control system



Higher-than-stock turbo boost means higher charge-air densities. This in turn means that additional fuel needs to be injected into the cylinders to maintain proper air/fuel ratios. There are a number of ways to achieve this extra fuel control, ranging from simple chip upgrades to complex and powerful stand-alone engine management systems that are fully programmable and capable of controlling fuel, spark, boost, and acquiring and storing real-time operating data. The application goals, degree of tuning required, and of course the budget will dictate which system is best for each project.



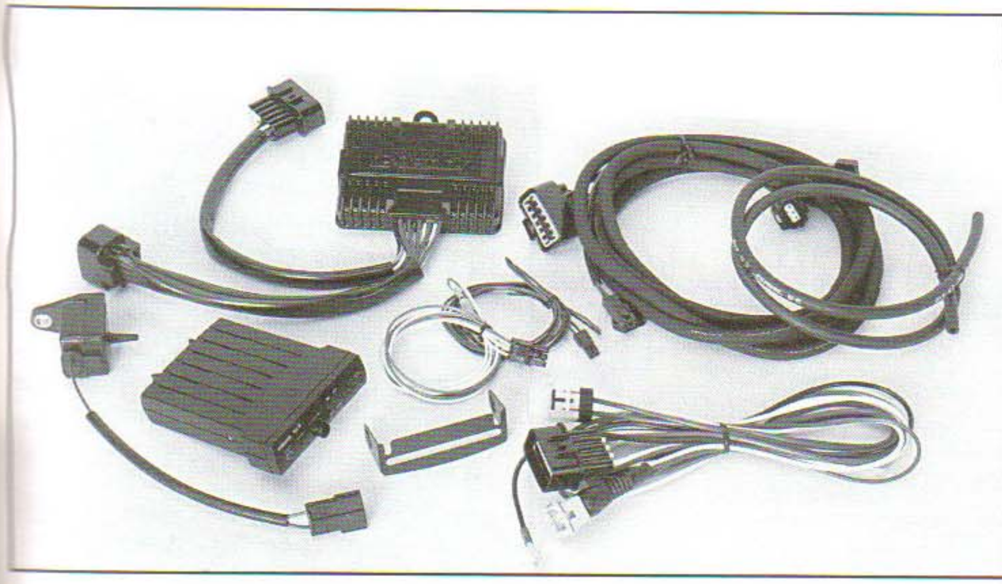
GReddy makes an inexpensive programmable fuel controller that "piggybacks" onto the OEM ECU. This unit allows the user to alter the injector duty cycles up to + or – 20 percent by intercepting and altering airflow or MAP sensor signals on their way to the ECU. (GReddy)



The term "lambda" represents the actual air-to-fuel ratio of combustion, divided by the stoichiometric air-to-fuel value for the type of fuel being burned. For gasoline, stoichiometry occurs at 14.7:1. In a sense, lambda is just another way to express the instantaneous air-to-fuel ratio of the mixture in the chamber. The required ratio (and, consequently, lambda) is dependent on many things, including the operating condition of the engine. Richer mixtures (i.e., lower lambdas and air/fuel ratios) are often required for high-power output conditions, while leaner mixtures (i.e., higher lambdas and air/fuel mixtures) are required for low-power conditions, such as idle and cruise.

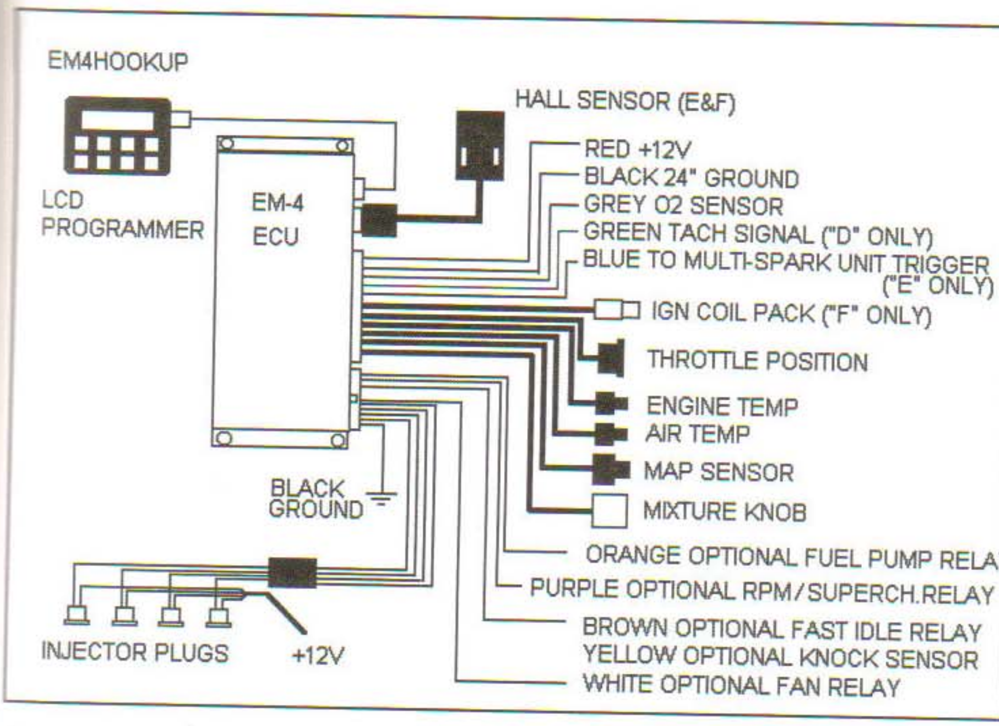
can determine airflow is to infer, or deduce the amount from various secondary parameters like engine speed and air temperature. There are a number of variations on this type of system, including so-called speed-density and alpha-N type systems. Many aftermarket EFI control units are based on this type of "conditional" measurement system.

The third and final technique is one in which the control system doesn't actually measure the amount of incoming air to the engine, but rather it assesses the quality of the exhaust gases leaving the engine. Special sensors located in the exhaust stream are used to determine how much oxygen remains in the spent gases. This information is then fed back to the control system computer, where it is used to make adjustments to the



An aftermarket extra-injector controller. These types of units work independently of the factory ECU. Under boost and high rpm conditions, the system activates and controls the duty cycle of one or more additional fuel injectors mounted either in the intake runners or farther upstream in the plenum. When the engine is not operating under boost, the factory injectors provide the correct amount of fuel to the engine, but under boost, the extra injectors kick in to supply any additional fuel that is required. (GReddy)

Racetech's inexpensive Simple Digital System fuel and spark controller is well-suited to basic street turbocharging needs. (Racetech)



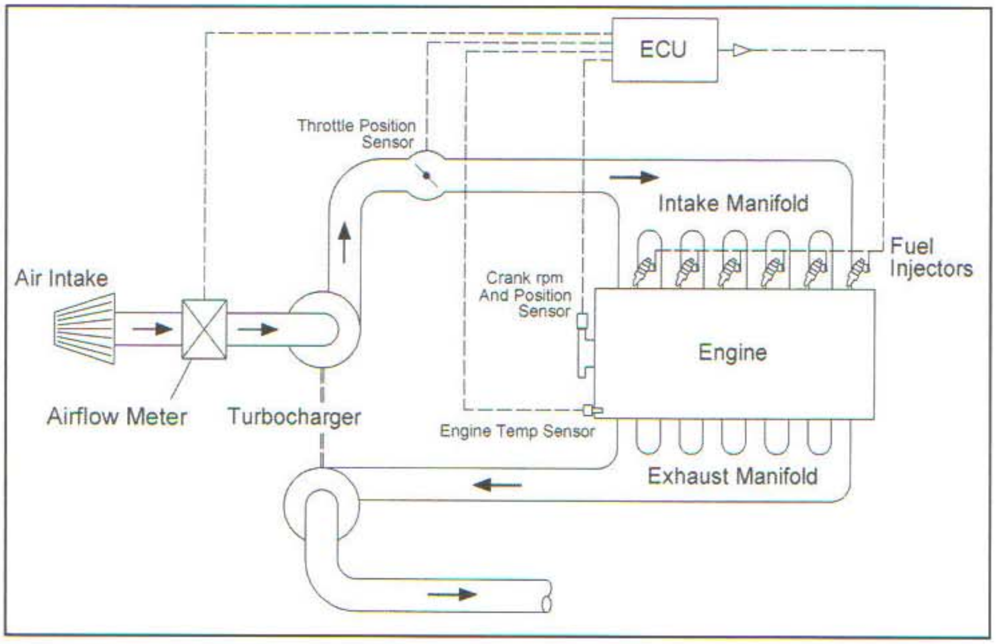
A typical electrical schematic for a speed-density fuel control system. This particular unit by Racetech features a hand-held LCD programmer that is used to tune and set operating parameters such as duty cycle and ignition advance. Other manufacturers require the use of an external computer (e.g., laptop) and specialized software. (Racetech)

fuel injection parameters. The first two methods (MAF and conditional systems) are known as open-loop control systems. The third method is called a closed-loop control system, because output data (e.g., exhaust stream quality) is sent back to the computer, forming a feedback loop. Most modern OEM control systems utilize a combination of these methods, depending on the engine operating modes and engine load.

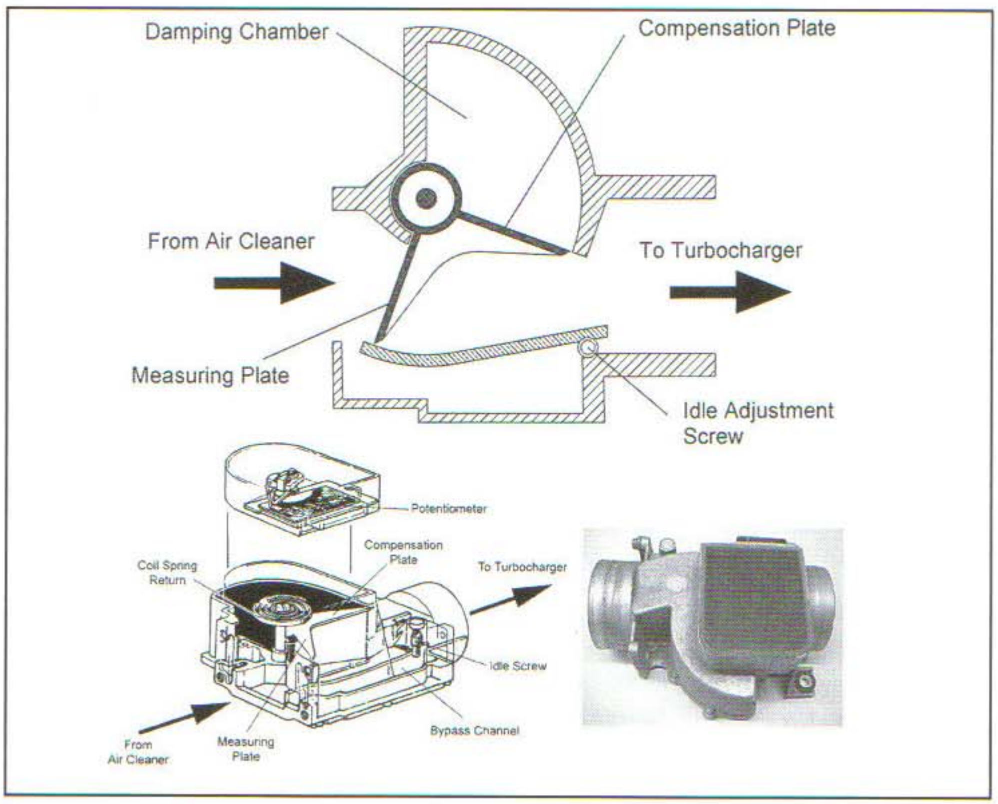
Let's look at these three methods in a little more detail, starting with mass airflow systems.

Mass Airflow Systems

An obvious strategy to determine how much air is flowing into an engine is to directly measure it. Mass airflow systems do just this, utilizing an airflow meter (AFM) to precisely determine the actual amount of air drawn into the engine. There are two main styles of AFMs. The first is the older "flapper door" or vane airflow type. This form of AFM is nothing more than a hinged flow obstruction that is placed in the intake tract. The shaft of the flapper door is connected to a potentiometer, which in turn converts door rotation into a variable resistance. The more air that passes through the intake tract, the more the door is pushed up and out of the way, and therefore the more electrical resistance that gets produced by the potentiometer. A simple calibration ratio between voltage drop across this resistance and airflow rate is all that is needed to supply the control



A typical mass airflow (MAF)-based control system. This type of system forms the basic operating platform for most OEM turbocharger applications. An airflow meter measures the instantaneous amount of air flowing into the engine and adjusts the fuel injector duty cycle accordingly. Throttle position, crankshaft speed, and engine temperature are secondary inputs that fine-tune the fuel requirements.

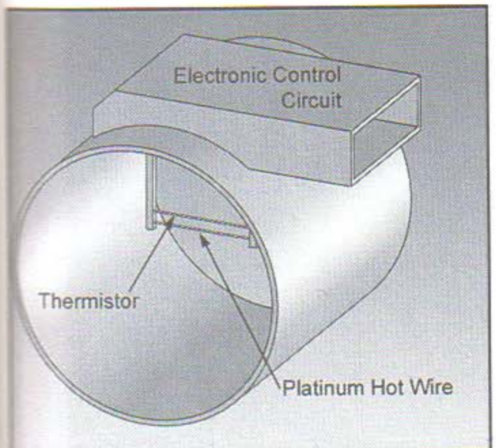


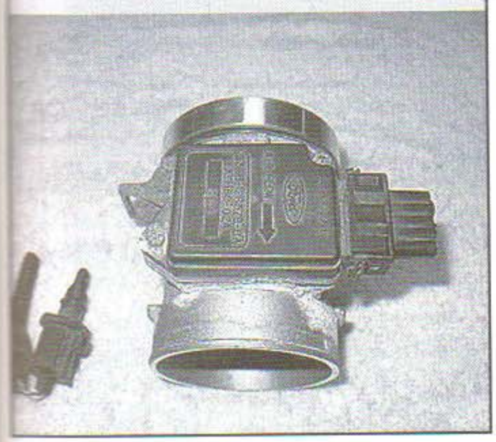
There are two primary types of mass airflow meters: the hot wire type and the vane airflow meter, which is shown here. This unit works by way of a measuring plate, or "flapper door" that swings open in proportion to the amount of air flowing through the unit. A potentiometer connected to the door changes resistance as a function of airflow. The damping chamber and compensation plate help reduce rapid movement of the measuring plate, smoothing out the generated signal. These types of MAF devices are simple and effective but also relatively large and cumbersome. More importantly, the door is a flow obstruction that reduces the overall volumetric efficiency of the engine.

system with the airflow value at any given moment in time.

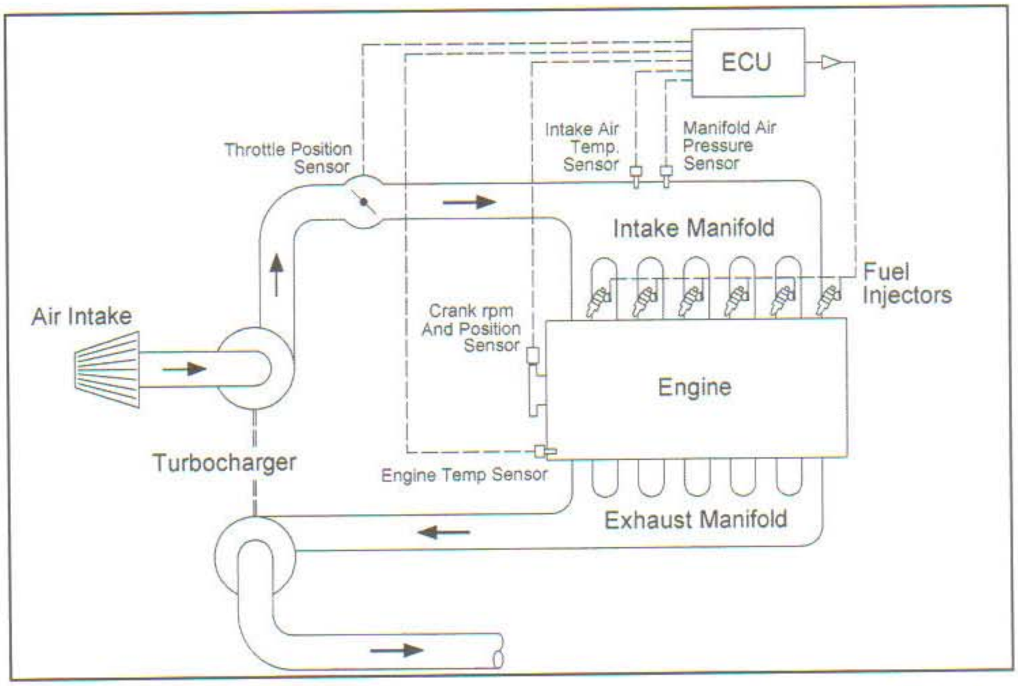
The second common type of AFM is the more sophisticated "hot wire" or "hot film" type. A hot-wire AFM operates on the principle of convective heat transfer. An electrical current is passed through the wire, which lies directly in and perpendicular to the flow of air inside the intake tube. The current causes a temperature rise in the wire. Air flowing over the wire, however, tends to convect, or carry heat away from the wire. The more air that passes over the wire, the bigger this cooling effect is. A small computer module constantly varies the electrical current through the wire to maintain a fixed temperature. The amount of current necessary to maintain this temperature, then, is proportional to the flow of air. Some hot-wire AFMs actually use a heated plate or grid of wires to achieve the same effect. A hot-wire AFM creates far less restriction in the air intake stream than does a flapper door AFM.

The big advantage of MAF-based control systems is their ability to adapt to widely varying air conditions and engine running states. Because it is measuring the actual flow of air into an engine, it lends itself to modified engines. Porting the intake tract and cylinder head, for instance, will increase an engine's volumetric efficiency. This means that the engine breathes more freely and can create more power. The AFM will simply see this for what it is: more airflow. Consequently the appropriate amount of extra fuel will be injected. As long as the injectors are





The other primary type of mass airflow meter is the so-called "hot-wire" MAF. The primary components of this unit are a thermistor, a platinum hot wire, and an electronic control module. The thermistor measures the temperature of the incoming air stream. The temperature of the hot wire is maintained in relation with the thermistor by the electronic module. An increase in the flow of air through the unit causes the hot wire to lose heat at a faster rate. The electronic module compensates for this by supplying more electrical current through the wire to maintain the original temperature. This current is measured, and a proportional voltage signal is then sent to the ECU.



A typical speed-density control system. Most aftermarket ECUs and standalone EFI control systems utilize this type of system. The density of air inside the intake plenum is calculated from the pressure and temperature sensors. The crankshaft speed, coupled with knowledge of the engine's volumetric efficiency, are then factored into an algorithm to determine fuel injection requirements. Depending on whether the system is batch or sequential fire, all of the injectors will then fire simultaneously or separately, respectively.

sized sufficiently to handle the increased power production, an MAF control system will accommodate the increased airflow. This also is true for engine wear and reductions in volumetric efficiency. This is one reason why modern OEM engines fitted with AFMs can maintain their low emissions for 100,000 miles or more.

The MAF benefit is also valid for turbocharged engines. As long as there are no air leaks (e.g., blow-off valves venting to the atmosphere), an MAF sensor can be located anywhere in the intake path, either upstream or downstream of the compressor. The MAF simply measures the mass airflow rate passing through it and sends the information to the control system. The higher the boost (and consequently the higher the airflow rate), the more fuel that gets injected.

Conditional Open-Loop Systems

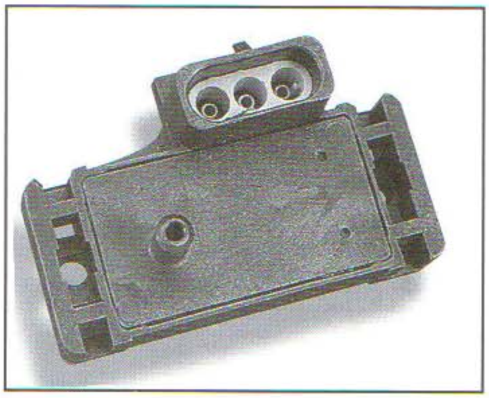
In contrast to MAF-based control system, conditional open-loop systems determine airflow from secondary sensors, such as manifold pressure and engine rpm. The two most popular of these open-loop systems are alpha-N and speed density systems.

An alpha-N fuel control system uses two sensor inputs to infer, or deduce the amount of air flowing into an engine. Throttle position (alpha) is the first input, and engine speed (N) is the second.

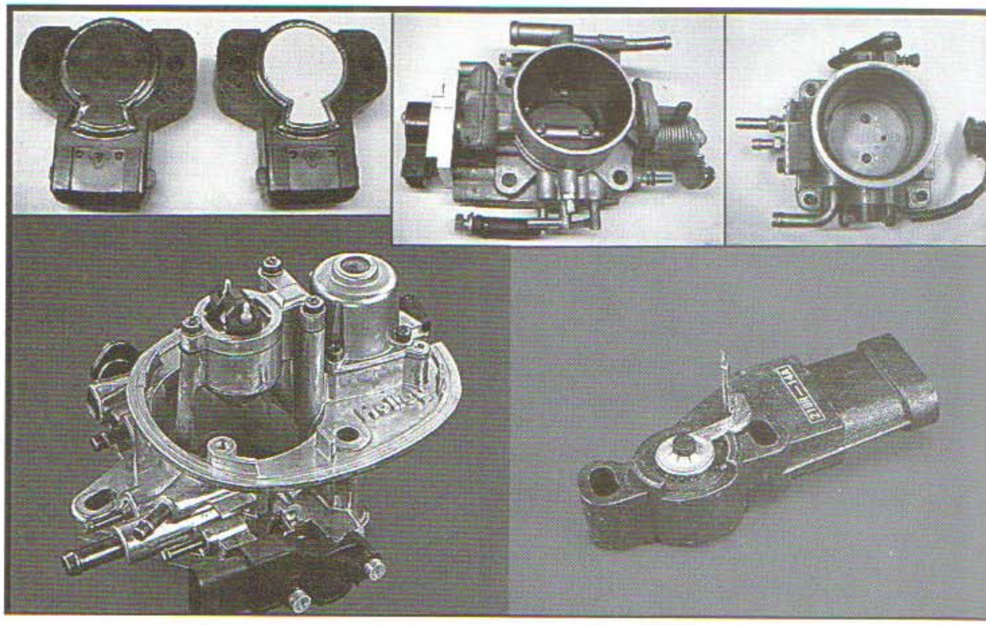
Alpha is determined by way of a throttle position sensor (TPS), which is nothing more than a variable resistance potentiometer mounted to the side of the throttle body. The TPS is connected to the movement of the throttle plate. As the throttle opens and closes, the internal resistance of the potentiometer varies. An electrical current passes through the potentiometer and results in a variable voltage as the throttle plate position is changed.

The second input to an alpha-N system is engine speed. This is determined by either a crankshaft or camshaft sensor, or by a tachometer signal from the ignition system.

Alpha-N systems rely on simple "look-up" tables or equations that



A manifold pressure sensor, or MAP. When combined with the intake air temperature sensor, the output from the MAP is essential in determining the density of the air inside the intake manifold plenum. As the throttle is opened and/or boost pressure rises, the manifold pressure increases, which ultimately means more required fuel. MAP sensors use a solid state pressure transducer to measure the pressure. They are available in 1, 2, 3 and larger "Bar" configurations. For naturally aspirated applications, a 1 Bar unit is appropriate. For turbocharged applications, a 2 Bar or greater MAP sensor will be required. In either case, the MAP should be attached to the plenum; i.e., it should not be attached to a single runner of the intake manifold.



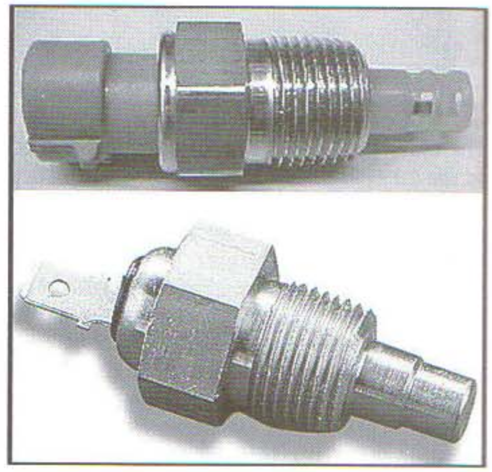
Throttle position sensors, or TPS, come in a variety of shapes and sizes. The TPS is an important control system sensor as it is usually the primary input for acceleration enrichment calculations. (Holley / Racetech)

relate the independent variables (throttle position and engine speed) to the dependent variable (airflow). This relationship is established through experimentation and then programmed into the control system computer. Unfortunately, pure alpha-N systems don't work for turbocharged engines, since neither alpha nor N have any correlation with manifold pressure. For these applications, alpha-N systems need to be augmented with something to correct for boost. This is evidenced in so-called "hybrid" alpha-N systems, such as those used in Ferrari's F40 cars.

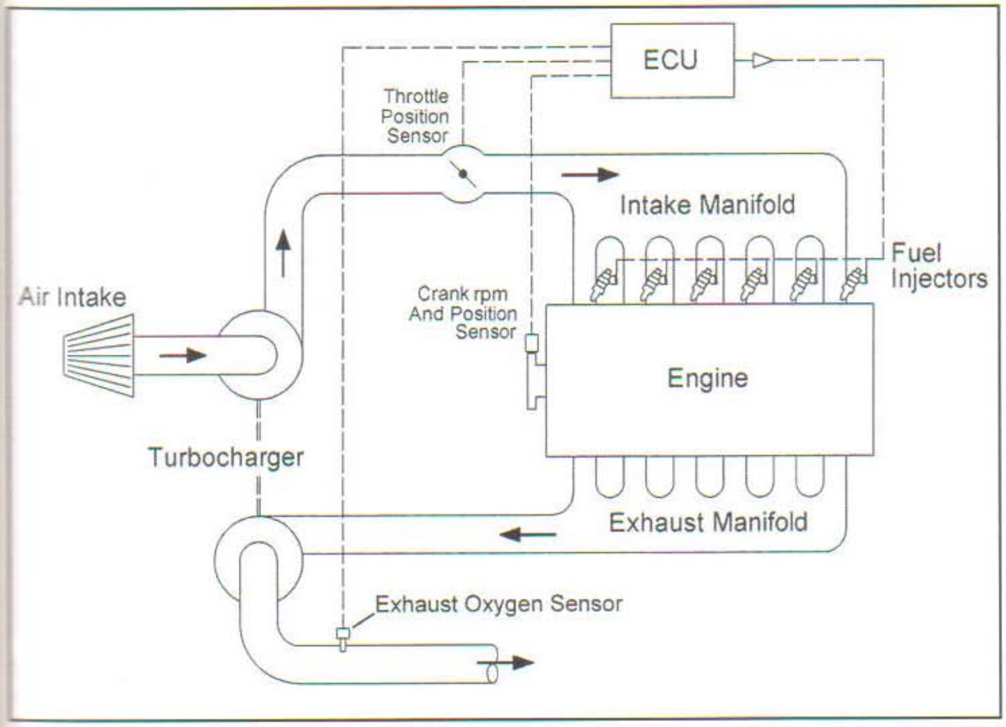
A speed-density control system is the other major type of conditional open-loop system. The operating principle behind speed-density systems is that an ideal gas obeys the relationship PV=nRT, where: P= Pressure; V=Volume; n= Number of moles, which in turn is directly related to the mass of the gas; R= Ideal gas constant; and T= Temperature. To make a long and complicated story short, the air an engine ingests behaves fairly close to the relationships in this equation. Rearranging the terms of the ideal gas equation, we can solve for mass. In other words, if we know the pressure, temperature, and volume of the air in the intake manifold, we can deduce its density, which is another way of

HOSE LENGTHS

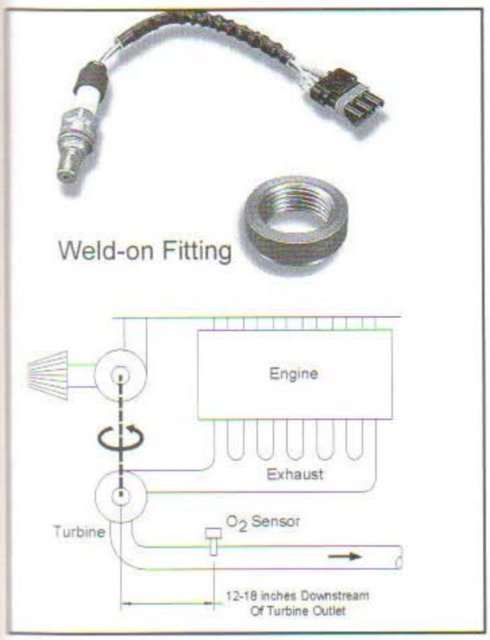
Signal latency tests on MAP sensors have shown that up to 20 ft. of signal hose can be used with nearly no loss in performance. Essentially, any length of hose appears to work fine. Just make sure you connect the MAP to the plenum and not to a single intake runner. (Fahlgren)



Typical air and water temperature sensors. The air temperature output is used in conjunction with the MAP sensor to determine charge density in the intake plenum. The water temperature is a secondary input required mainly to ensure proper starting and warm-up of the engine. When the engine is cold, the air/fuel ratio must be enriched to enable enough fuel to vaporize for proper starting. Analogous to a carburetor choke, the computer increases the injector pulse width to supply extra fuel when the engine is cold, and then tapers off this extra fuel as the water temperature increases. Water temperature sensors are also used in some ECUs as safety devices, feeding information to the boost controller, thereby allowing it to reduce boost before the engine overheats.



The third major type of fuel control system: a closed-loop layout employing an oxygen sensor in the exhaust downstream of the turbocharger turbine. Closed-loop systems are frequently added on top of an open-loop system in OEM applications.



Oxygen sensors are the primary feedback device used in closed-loop systems. By measuring the gas content of the exhaust stream after combustion, the computer can determine if the air/fuel ratio is too rich or too lean for optimum combustion and will then adjust the next few injection quantities accordingly. O_2 sensors are primarily employed for emissions control and to a lesser degree, fuel economy. Under wide-open throttle conditions, the computer temporarily ignores the sensor output so that the engine can produce more power by running a richer mixture.

saying we know its mass per unit volume.

Once we know the engine speed and the air density, and if we know a little bit about the volumetric efficiency of the engine, we can make a good estimation of the mass flow rate of air into the combustion chamber.

The biggest downside of speed-density and alpha-N systems is that they are sensitive to engine changes. Because they rely on advanced knowledge of the volumetric efficiency of the engine, changing the intake and exhaust flow characteristics will affect the accuracy of the fuel injection calculations.

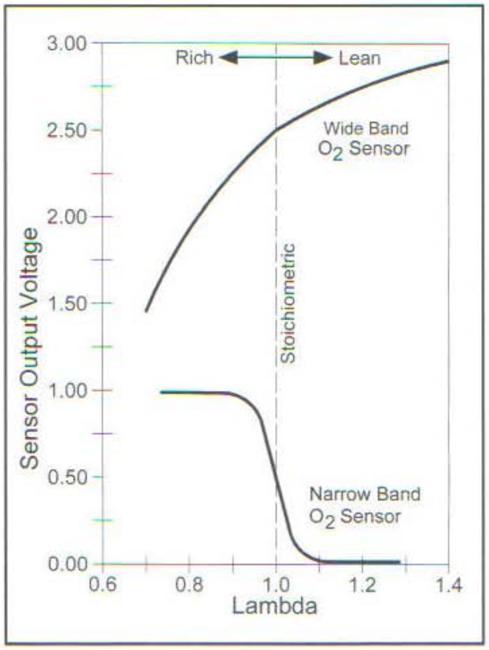
Closed-Loop Systems

A closed-loop control system is one in which a sensor on the output side of the system "feeds back" information to the control unit so that adjustments to the input side of the system can be made. The control unit alters the input to affect the output. Closed-loop fuel injection systems typically utilize an oxygen sensor in the exhaust stream to feed back gas mixture information to the control unit. The amount of fuel (input) is then adjusted to achieve a prescribed amount of oxygen in the exhaust (output). This indirectly results in a desired air/fuel ratio. Exhaust gas temperature is another feedback variable sometimes used, but the most common is "lambda" sensing, which is also known as "oxygen" sensing.

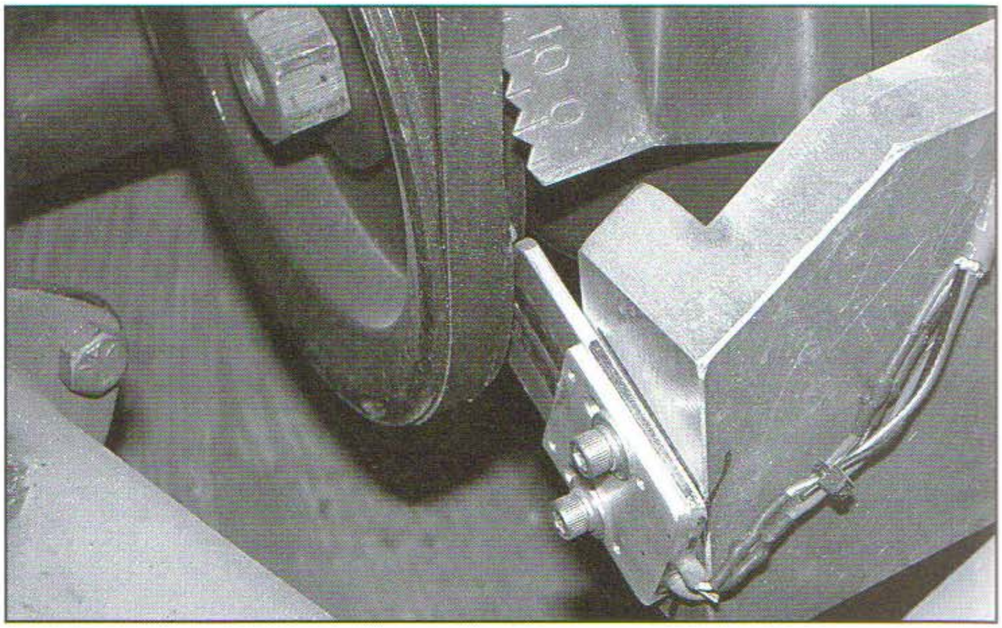
Oxygen Sensors—Standard oxygen sensors used in fuel injection systems are not particularly accurate beyond a narrow range of air/fuel ratios. In fact, they only produce a precise measurement in a very limited band centered about the stoichiometric ratio of 14.7:1. This is why these types of devices are often called narrow-band O_2 sensors and hence are fairly useless for tuning high-performance engines, which can require air/fuel ratios in the range 11–13:1.

Oxygen sensors use special elements such as zirconium dioxide to detect oxygen. They are mounted in one or more locations in the exhaust system. On turbocharged vehicles, the primary oxygen sensor is usually located directly downstream from the turbine. On most all OBD-II OEM vehicles, there is a second sensor just after the catalytic converter.

The oxygen sensor generates a voltage that indirectly is based on the concentration of oxygen in the exhaust gas. These sensors are



In many cases, an air/fuel mixture richer than 12:1 or lower is used to help keep cylinder temperatures down. The extra fuel is used primarily for its latent heat of vaporization properties, rather than for any extra chemical energy released. This helps control detonation and often allows more advanced timing and more power. With a narrow-band O_2 sensor, however, the voltage curve is very flat outside a narrow range centered around stoichiometry. Because of this, it is really only possible to tell for certain whether the mixture is rich or lean, but not by how much. For best power, lambdas of 0.7–0.9 are required, and it is very difficult to use a narrow-band reliably to set mixtures in this range. With a wide-band sensor, however, there is no ambiguity between air/fuel ratios and voltages; the curve has a nice easy-to-read slope over a wide range of lambdas. This is why most tuners insist on using wide-band sensors.



Most aftermarket engine control systems utilize a crankshaft sensor to measure engine speed and angular position. This particular unit utilizes two magnets glued to the crank pulley and an inductive pickup sensor fixed to the block. Another popular type uses a small toothed wheel and an optical sensor assembly.

sensitive to temperature. Most modern units include a heating element that brings the sensor up to operating temperature very quickly after engine startup. Without the heating element, it might take several minutes to fully warm up, which delays the ability to run in closed-loop mode.

Narrow-band oxygen sensors can't tell accurately how lean or rich the exhaust is. Instead, a "lean" condition creates a low voltage signal. Because the control unit doesn't know how lean the mixture is, it simply commands that the mixture be richened by increasing the injector pulse width. This fuel enrichment continues unabated until too much fuel has been added and a high voltage, or "rich" condition signal is generated. At this point, the control unit reduces the pulse width, and the fuel leans out until a lean condition is generated again. For this reason, closed-loop control systems constantly swing back and forth around the stoichiometric point, forever trying to maintain a 14.7:1 air/fuel ratio.

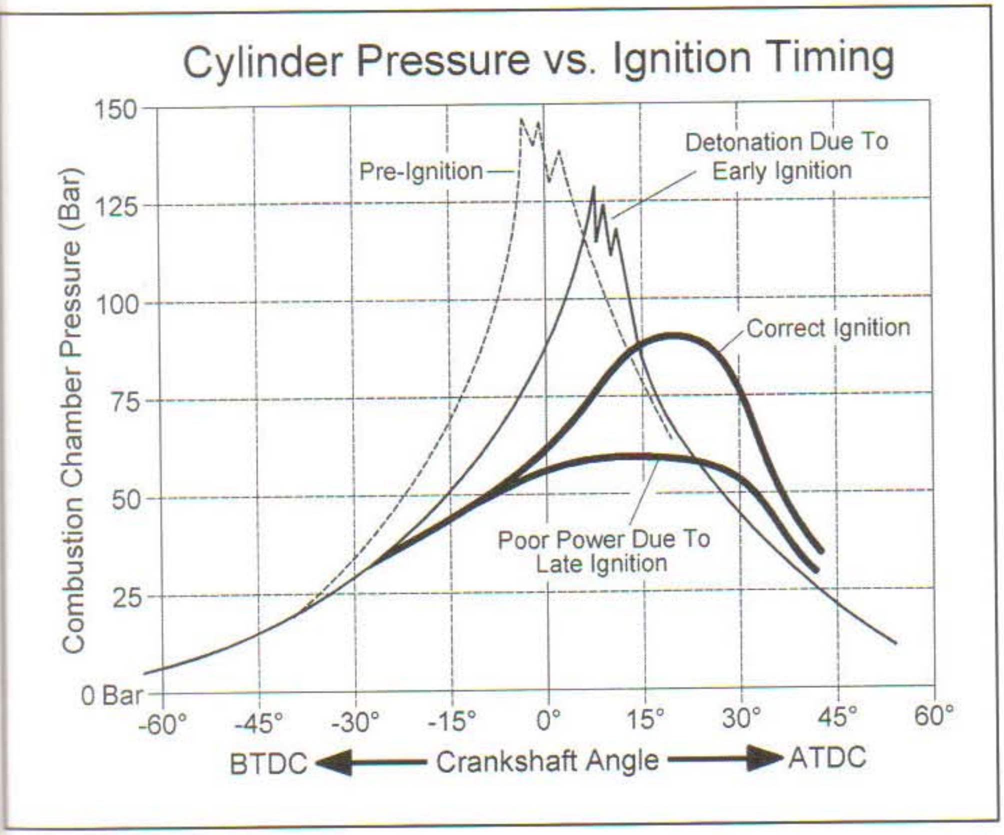
The chief advantage of closed-loop control systems is that they rely on the output to adjust the input. As engine components wear, air filters clog up, and ambient air conditions change, the control system simply adds or subtracts fuel based on the exhaust stream output. The downside of these systems, of course, is that they're based on a 14.7:1 air/fuel ratio that is not ideal for either power or economy, but is great for a catalytic converter.

> Typically, a fuel control system is configured to energize the fuel injectors to spray on the back of the closed intake valves. This is done in order to vaporize the fuel and reduce emissions.

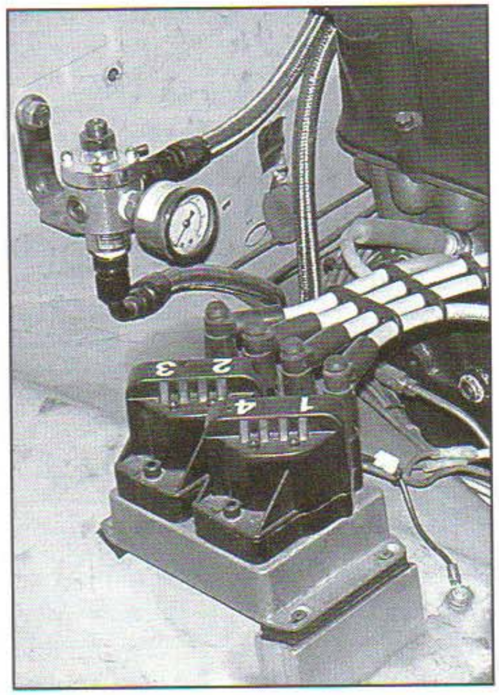
INJECTOR TIMING

Once the amount of intake air (and appropriate amount of fuel to be injected) is determined, the next step a fuel control system performs is determining when and how to inject the fuel. There are essentially two different ways to do this: batch fire and sequential fire.

To understand the difference between these schemes, we must first review some basics. Because most automotive engines are 4-stroke devices, they make two complete 360-degree revolutions of the crankshaft for every one intake-compression-power-exhaust cycle. A crankshaft position sensor (CPS) or



In addition to drawing in the correct amount of air and fuel into the cylinder, it is very important to ignite the mixture at the correct moment in time. A flame front propagates at roughly 100 ft/sec in a naturally aspirated mixture. Knowing this, it should be theoretically possible to calculate the ideal amount of ignition for any given engine speed and cylinder bore. Unfortunately, a number of other factors affect the actual timing requirements, including compression ratio, combustion chamber shape, charge density, charge temperature, relative humidity, and fuel octane. This greatly complicates the calculation of optimal ignition timing.



A "distributorless" ignition system offers wide control over the ignition curve. Ignition advance can be adjusted, depending on both engine speed and load (e.g., boost).

similar device is used to determine the rotational orien-tation of the crankshaft. But with the crankshaft in any one discrete angular position, there are actually two possible states it can be in. For example, for a given crank position that results in a piston moving downward, that particular cylinder can be in either the intake or the power stroke. How does a control system tell the difference? Or does it even have to?

Batch Fire—In a batch-fire injection system, multiple injectors are electronically ganged together in "batches" or "banks." These banked injectors are triggered simultaneously, regardless of whether their individual intake valves are open or not. Typically in a batched fire system, each injector is fired once per crankshaft revolution but delivers fuel only every other time it is fired. In other words, the first pulse of fuel is fired with the intake valve open (intake stroke) and then again when the intake valve is closed (power stroke). This batch system simplifies the control system. Many inexpensive and entry-level aftermarket fuel injection control systems, like Racetech's Simple Digital System, use batch fire control with very good results.

Sequential Mode—In contrast, a sequential fire mode energizes each individual injector separately, and only when its respective cylinder requires it. Each cylinder injector is energized in the sequential firing order of the engine. A sequential fire system needs to rely on more than a simple CPS to determine which cylinder is on which of its four strokes. Many OEM and higher-end aftermarket fuel injection control systems, such as AEM, Autronic, Electromotive, Haltech, HKS, and MoTeC, use sequential fire control with excellent results.

IGNITION CONTROL SYSTEMS

Compared to fuel injection, control of the ignition system is somewhat easier. An air/fuel mixture of a given volume, pressure, temperature, and chamber shape takes a certain amount of time to burn. The flame front has to travel from the spark plug outward through the volume of air/fuel, sweeping through and filling the entire combustion

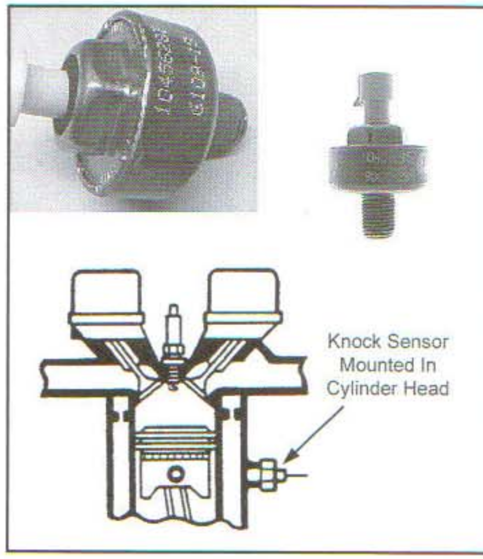
MegaTune Spark Advance Table

File Tools

kPa \ RPM	1000	1325	1675	2000	2375	2675	3000	3325	3675	4000	4325	4675	5000	5500	6000	6375
150.0	22.0	24.0	24.0	24.0	24.0	25.0	25.0	23.0	23.0	22.0	23.0	24.0	25.0	31.0	30.0	30.0
143.0	22.0	24.0	24.0	24.0	24.0	25.0	25.0	23.0	23.0	22.0	23.0	24.0	25.0	31.0	30.0	30.0
135.0	22.0	24.0	24.0	24.0	24.0	25.0	25.0	23.0	23.0	23.0	24.0	25.0	26.0	32.0	32.0	32.0
129.0	22.0	24.0	24.0	24.0	24.0	25.0	26.0	24.0	25.0	25.0	26.0	28.0	26.0	33.0	34.0	34.0
122.0	22.0	24.0	24.0	24.0	22.0	25.0	26.0	25.0	27.0	26.0	27.0	28.0	27.0	33.0	34.0	34.0
115.0	22.0	24.0	24.0	23.0	22.0	26.0	26.0	25.0	28.0	27.0	28.0	28.0	28.0	33.0	34.0	34.0
108.0	22.0	24.0	22.0	23.0	24.0	28.0	27.0	29.0	29.0	29.0	29.0	29.0	29.0	33.0	35.0	35.0
101.0	24.0	25.0	24.0	25.0	27.0	30.0	28.0	30.0	32.0	32.0	32.0	32.0	32.0	36.0	38.0	38.0
94.0	25.0	22.0	25.0	29.0	32.0	34.0	30.0	33.0	34.0	34.0	34.0	34.0	34.0	38.0	40.0	40.0
87.0	26.0	27.0	30.0	31.0	33.0	36.0	35.0	37.0	37.0	37.0	37.0	36.0	35.0	40.0	42.0	42.0
80.0	26.0	32.0	33.0	34.0	37.0	38.0	38.0	40.0	40.0	39.0	39.0	40.0	39.0	42.0	45.0	45.0
73.0	30.0	34.0	33.0	34.0	39.0	42.0	42.0	44.0	45.0	44.0	44.0	44.0	44.0	45.0	48.0	47.0
66.0	34.0	34.0	34.0	35.0	39.0	42.0	44.0	46.0	48.0	48.0	47.0	45.0	46.0	47.0	50.0	50.0
60.0	31.0	33.0	35.0	36.0	41.0	44.0	45.0	48.0	50.0	50.0	50.0	47.0	48.0	50.0	50.0	52.0
50.0	26.0	31.0	38.0	41.0	43.0	45.0	46.0	48.0	50.0	50.0	50.0	47.0	48.0	50.0	52.0	52.0
40.0	22.0	30.0	42.0	44.0	46.0	46.0	46.0	48.0	50.0	50.0	50.0	50.0	50.0	52.0	52.0	52.0

Fetch From ECU | Send To ECU | Close

An ignition advance table used in an aftermarket engine management system (EMS) software package. (Fahlgren)



A knock sensor is a type of acoustic device, tuned to the frequency range of engine "knock" (detonation). The ignition advance can be retarded until knocking ceases, thereby providing a type of closed-loop operation of the ignition system. (Racetech)

> If an engine is operating with a proper air/fuel ratio, the timing required for the maximum best torque (MBT) is not "just this side of knock"!

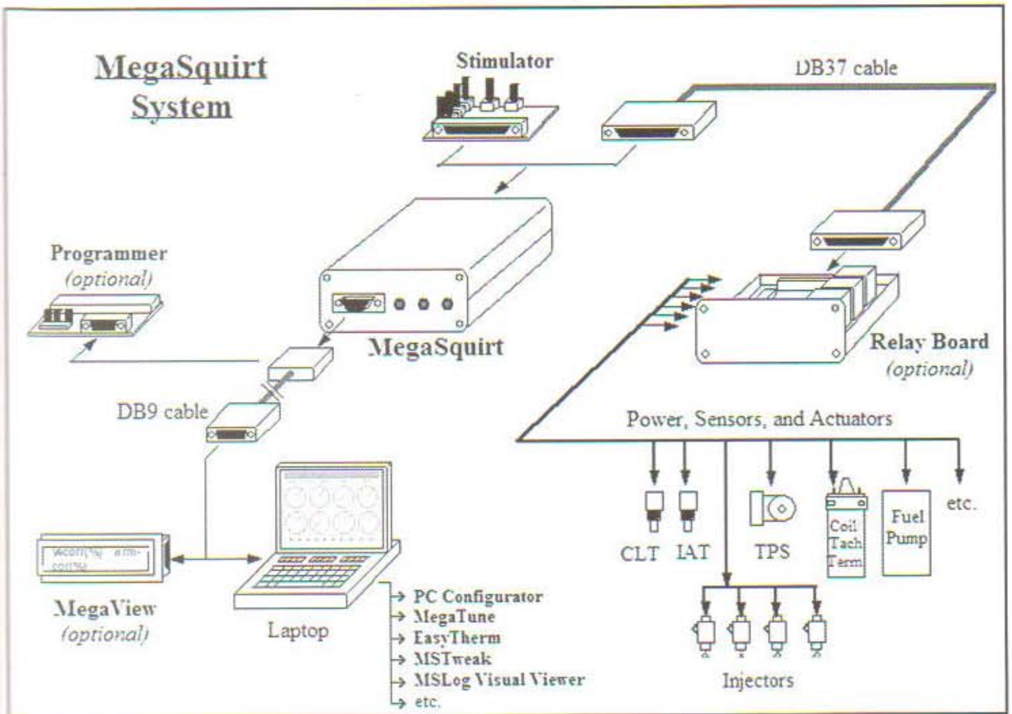
chamber. Complicating how quickly this flame front spreads is the amount of gas turbulence in the chamber, the octane of the fuel being burned, the rate at which the piston is moving upward in the cylinder (rpm), the time it takes to physically initiate a spark across the plug gap, and various other factors. Denser air/fuel mixtures (such as in a turbocharged environment), for example, tend to complicate matters by burning faster than naturally aspirated mixtures.

With the exception of knock control and some relatively high-tech applications (e.g., ion-sensing), ignition control systems typically run in an open-loop mode. For a given engine speed and manifold pressure, there is a specific ignition advance that is "best." This is called the point of maximum best torque, or MBT. Unfortunately, ignition requirements vary from vehicle to vehicle, and application to application. There is no exact science (well, there is, but not within the scope of this book) for determining ignition requirements, but there does exist a best ignition advance for a specific set of cylinder conditions that can usually be determined via testing and tuning. Unfortunately, it can take a lot of trial and error runs to produce an optimal spark advance table. As a general rule, cylinder spark advance should increase with engine rpm (up to a fixed point) and decrease with increased manifold pressure. Turbocharged vehicles require less spark advance than an equivalent naturally aspirated vehicle.

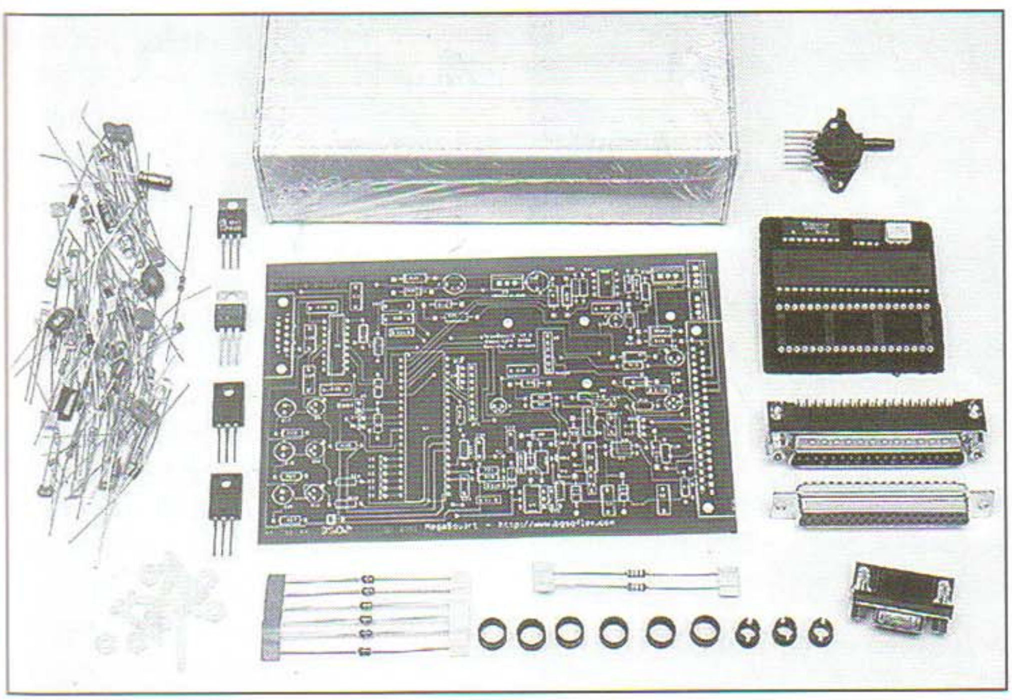
MEGASQUIRT

For the diehard do-it-yourself (DIY) individual in search of an inexpensive control system for their turbocharged vehicle, the MegaSquirt electronic fuel injection computer might be worth a look. Developed by enthusiasts Bruce Bowling and Al Grippo, the MegaSquirt system is an open-source, build-it-yourself kit that offers fully programmable EFI control for a fraction of what turn-key EFI control systems typically cost.

The catch, of course, is that you have to assemble the unit yourself from what is essentially a collection of electronic parts. For roughly $200, Bowling and Gippo will supply the intrepid buyer with a couple of aluminum chassis boxes and a pile of circuit boards, drivers, relays, diodes, and capacitors. If you can solder and follow directions carefully, you should be able to successfully assemble a MegaSquirt system. The comprehensive assembly guide walks you through the entire assembly and testing process with little fanfare. In addition, there is an online community (www.msefi.com and



The MegaSquirt EFI system is simple in concept but quite powerful in execution. Thousands of MegaSquirt units have been implemented on everything from 1-cylinder lawn mower engines to 10-cylinder race engines equipped with multiple turbos. The system has also been run successfully on rotaries, diesels, and engines that operate on propane and natural gas. (Bowling/Grippo)



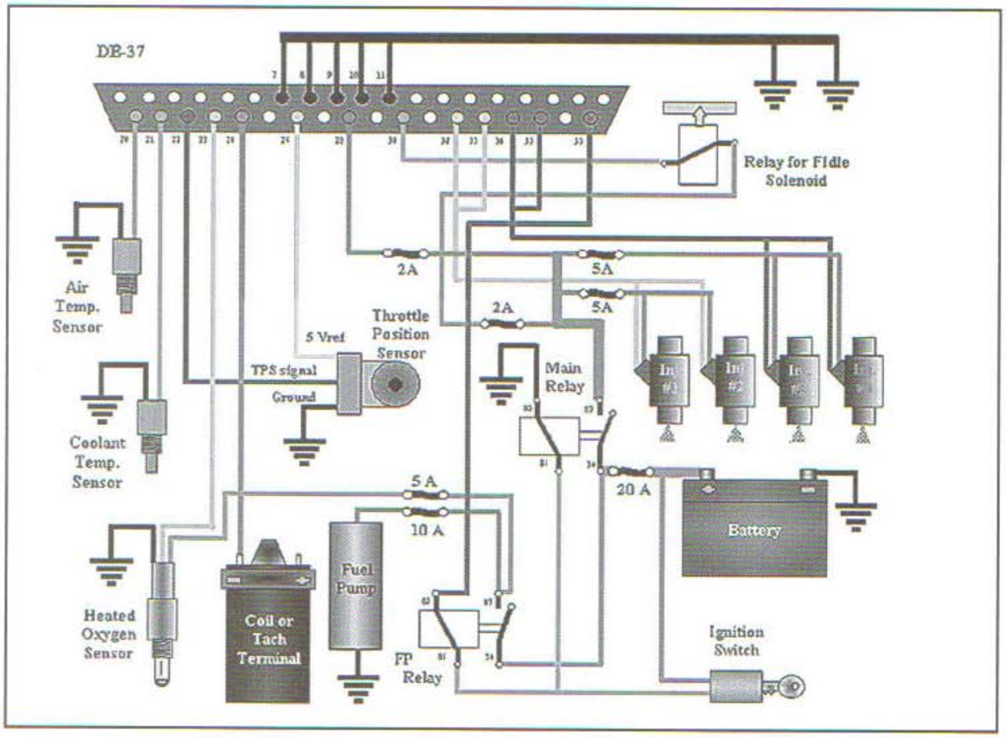
The collection of electronic parts that must be assembled looks daunting, but with patience and the help of an active on-line community of users, building a MegaSquirt is not too difficult. Once constructed, the basic system does not require any modifications in order to use it with a turbocharger, provided that 20 psi of boost is not exceeded. Above this level of boost you will need a different internal MAP sensor and recompiled assembly code to match the new sensor. (Bowling/Grippo)

www.mega-squirt.info) that has helped thousands of MegaSquirt neo-phytes successfully get through the build process.

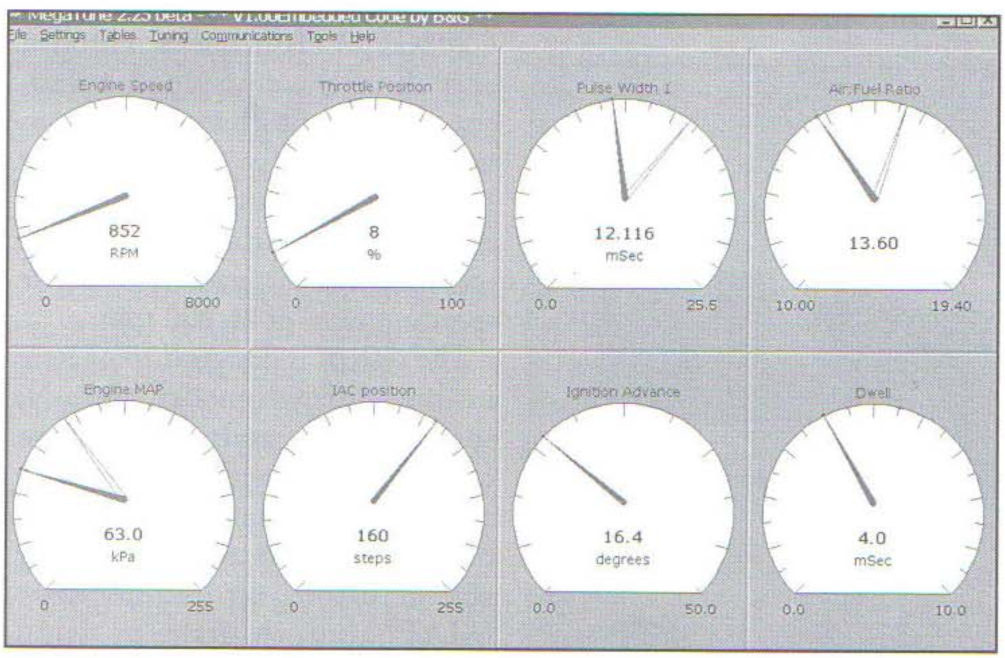
Once the unit is constructed and installed in the vehicle, tuning takes place via a serial cable link to an external laptop computer. Free Windows-based software, such as "MegaTune" can be downloaded from the web. In addition, there are a variety of enthusiast-created software and hardware devices that help the user install, tune, and troubleshoot the basic system. No assembly code writing is required, either, although the EPROM-based ECU certainly allows for customized code and mod-ifications.

The electronic control unit (ECU) used in MegaSquirt is based on the Motorola MC68HC908GP32 Flash microcontroller, and all of the embedded microprocessor code that is used was written directly in assembler language. This results in a very fast-executing code that can provide real-time fuel calculations at engine speeds upward of 16,000 rpm.

The system is designed to operate in three different modes: alpha-N, speed density, and/or O_2-sensor closed-loop. MegaSquirt employs popular (and inexpensive) GM-based connectors and sensors like the manifold air temperature (MAT) and throttle position sensors (TPS). It is also commonly used with the already-existing sensors on many vehicles (i.e., the GM sensors are not a requirement, just a convenience). This helps keep costs down and repairs are easily made via local parts stores. MegaSquirt does, however, use an on-board manifold absolute



While MegaSquirt does not directly support ignition control, there are a number of related DIY-type systems and upgrades available, such as MSnS-Extra, with full ignition, boost control, nitrous control, and so on. (Bowling/Grippo)



Two of the many options available to the builder are MegaTune and the MegaSquirt Stimulator. This latter item is a diagnostic tool that is essentially a signal generator. It uses five potentiometer control knobs to simulate engine rpm, MAP, throttle position, coolant temperature, and intake air temperature. By connecting the Stimulator to the MegaSquirt computer, it's possible to test the unit using the MegaTune software, thereby ensuring that the ECU is functioning properly before connecting it to an actual engine. (Fahlgren)

> The latest Megasquirt processor replacement, called MegaSquirt-II, uses a Motorola 9HCS12C32 that is programmable in C, opening up custom development to a whole new audience.

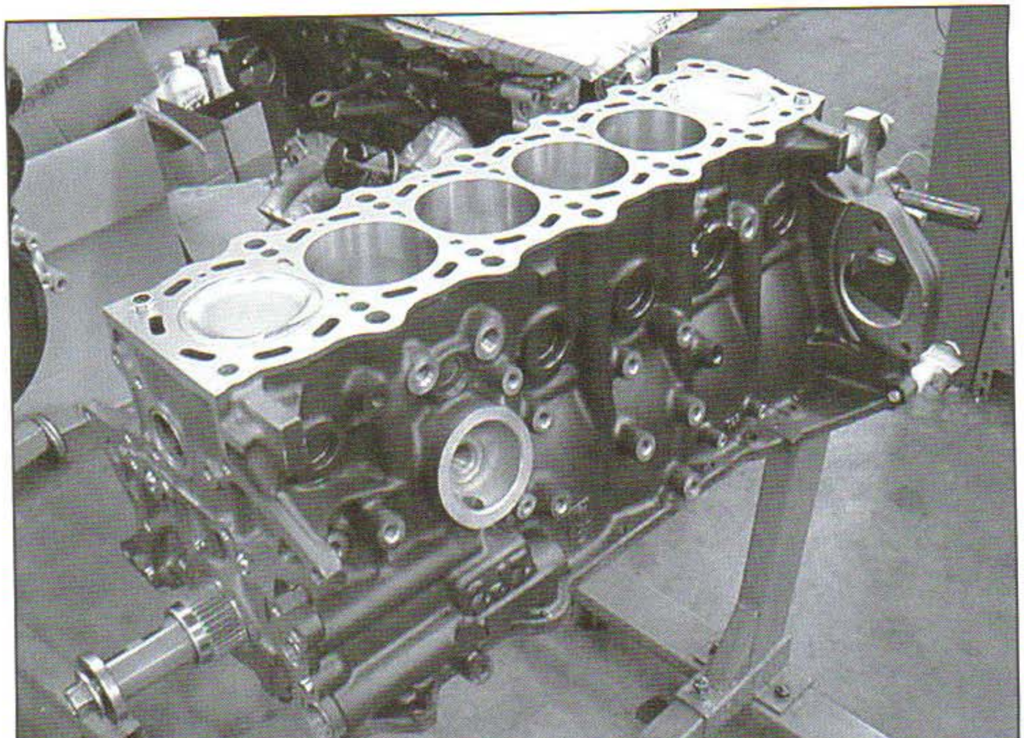
pressure (MAP) sensor built into the box that is a Motorola unit. This MAP (and the standard embedded code) can handle boost pressure ranging from 0 to 20 psig. For intake pressures greater than this, the user has to install a different MAP sensor and reflash the microprocessor code with preexisting code that is available online.

While the cost is very attractive, perhaps the biggest advantage of MegaSquirt is how it teaches the fundamentals of EFI control and theory; it's impossible to put the unit together and get an EFI system running without understanding how the basic system operates. The DIY installer truly takes ownership of their control system, allowing easy handling of future troubleshooting and modifications. The source code is available to anyone who wants it, allowing as much customization as the user is willing to undertake.

ENGINE COMPONENTS 13

The perfect turbocharger system will mean nothing if the engine to which it's bolted is not up to the task of handling the stresses of increased horsepower production. Just as the quality of a foundation underneath a house ultimately determines how long the structure above it remains standing, the conditions inside an engine affect how long it will survive under boost.

But this doesn't mean you have to build a skyscraper-class foundation if you're just putting together a moderate-boost engine for street duty. Most modern, stock OEM engines in good condition, whether foreign or domestic, can handle a low level of boost without too much trouble. By "low level," I mean 5–6 psi or so of maximum boost. Note also the words "in good condition." This means the engine should have fewer than 75,000–100,000 miles, a low- to moderate-level of static compression (9:1 or less), and consistent pressure readings between all the cylinders. It also means the engine has successfully passed a leak-down test, and that the cylinder head and valvetrain components are in good shape. Stock OEM-type camshafts with little overlap, a coolant system that is in good repair, and a fuel delivery system that is up to the task of matching the increased airflow are also important. And this is just for low levels of boost; the further you want to boost beyond 5 or 6 psi, the more things have to be addressed when putting together an engine. The rest of this chapter focuses on these higher levels of horsepower production.

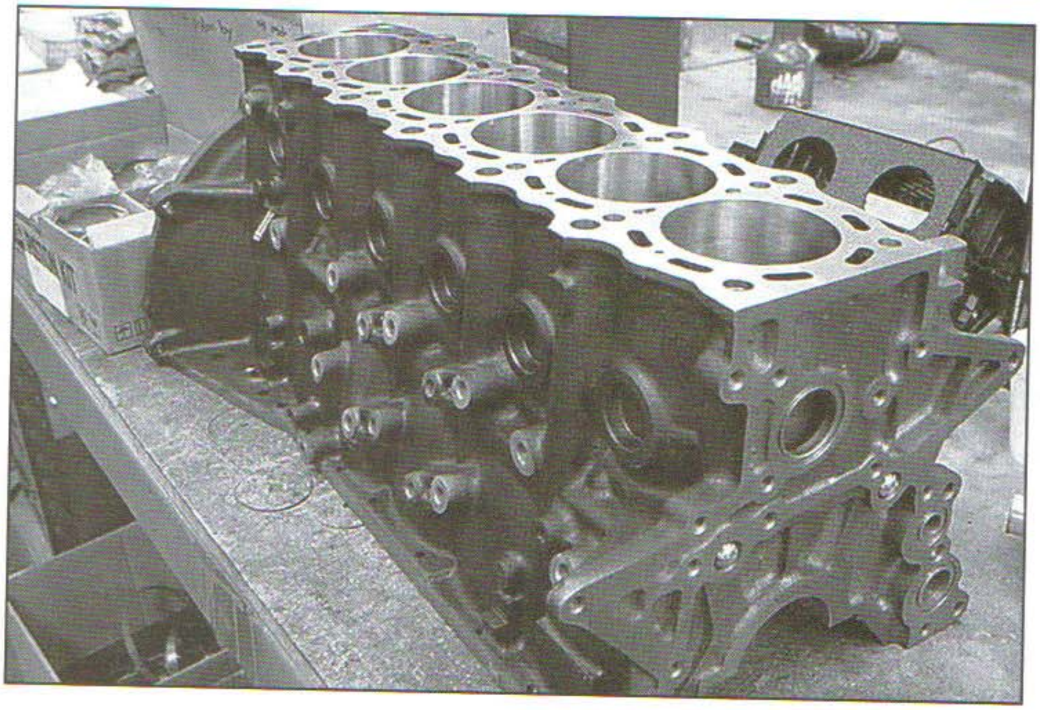


A stout Toyota 2JZ-GTE short block. Serious effort—and money—was spent on this particular engine, but the results are astounding: over 1100 horsepower delivered to the rear wheels from just 3.4-liters (207 cid). (Henderson/SP Engineering)

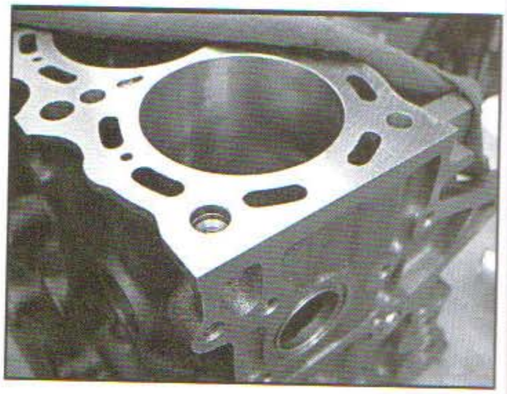
But before we get into that, it's important to note that this is not a book on how to build an engine. There are plenty of excellent references in the marketplace that are make- and model-specific. Instead, this chapter is intended as a starting point of what to keep in mind and what to watch out for when planning an engine that will be subjected to the pressures of forced induction. Remember, when you're building a turbocharged engine, you're bolting together the foundation for your forced-induction project.

ENGINE BLOCKS

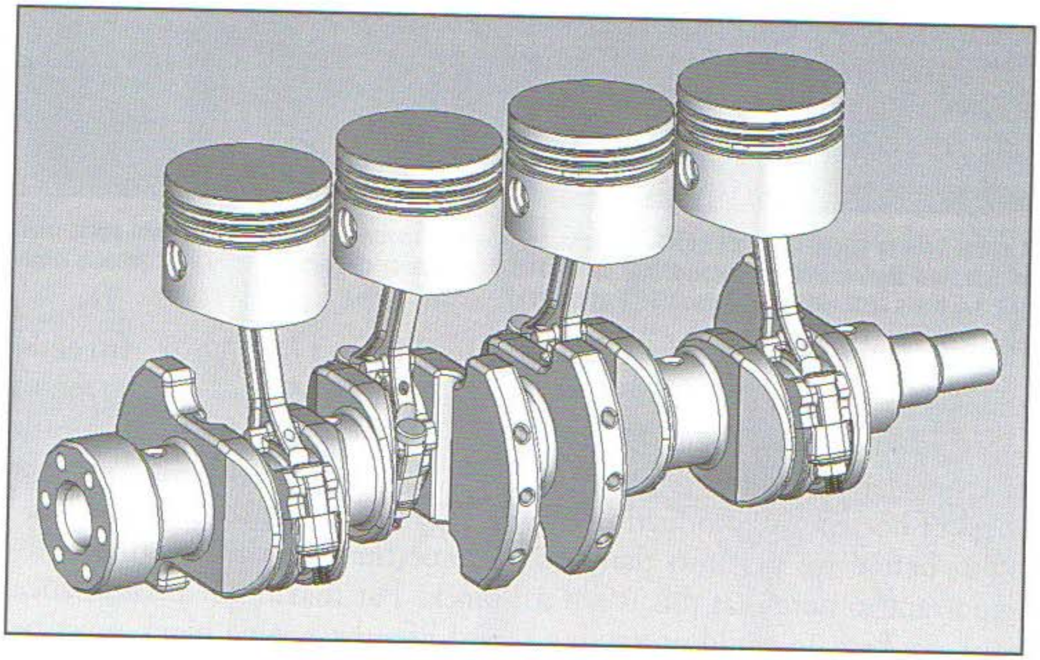
The heart of any high-performance turbocharged engine is its block. For maximum performance and life, the engine block must be in good condition before any components are bolted to it. This means no cracks, defects, or other flaws. To do this right, the block should be fully stripped down, a thorough hot-tank session undertaken, and the engine completely cleaned. A magnetic-particle and/or dye-penetrate examination are required to ensure that the structural integrity of the block



A high-performance turbocharged engine begins with a solid foundation: the engine block. (Henderson/SP Engineering)



Honing cylinder bores is one of many machining processes performed on the block. Performing these steps correctly is critical on engines that are subjected to boost and will ensure longevity and high levels of horsepower production. (Henderson/SP Engineering)



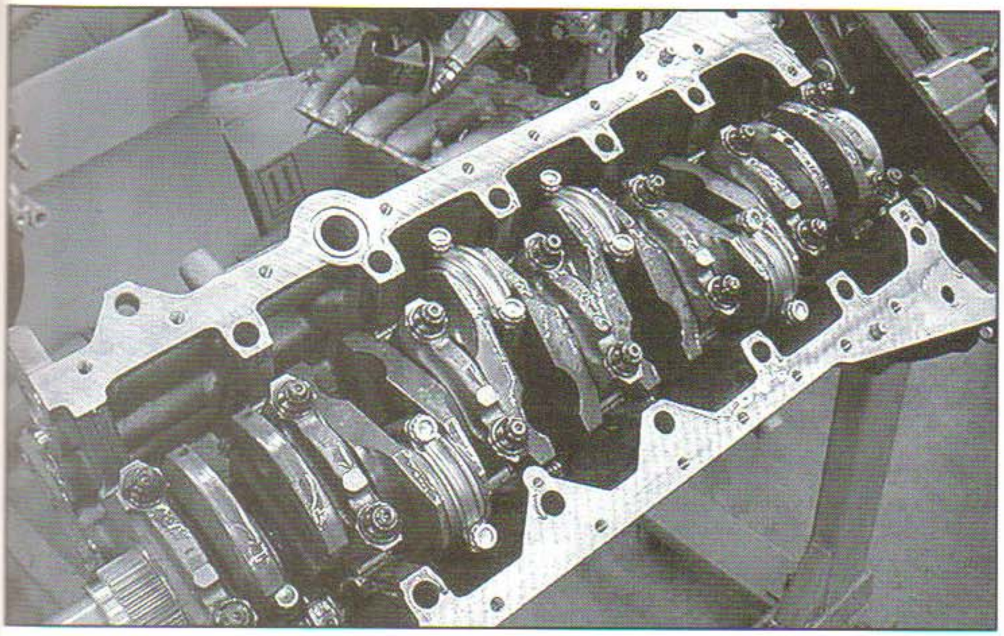
Balancing the reciprocating assembly is an important step on turbocharged engines that will be revved to redline frequently. Cryogenic treatments can also be beneficial, increasing wear, lubricity, and fatigue strength. Performance is in the details.

material is intact. The geometry of the block must also be correct.

Depending on how far the engine will be pushed and how much boost is to be run through it, it may be necessary to blueprint the engine to better than OEM clearances and fits. For example, the block might require align-hone checking and remachining. Normal engine stresses are amplified by boost pressures. The cylinders may require boring and honing to bring their values within specs, often with main bearing caps torqued to the correct values and/or a torque plate installed. Deck surfaces can also be machined with respect to the crankshaft centerline and other datum surfaces.

Following any machine work, the internal block surfaces and edges should be deburred and deflashed, holes chamfered, and oil return paths cleaned up. Keeping a turbocharged engine cool requires oil flow. Remember that oil inside an engine does more than lubricate; it also serves as a secondary coolant fluid, wicking away heat from hot sources inside the engine. Some engine builders recommend that the inside of engine blocks be painted to ensure absolute cleanliness and to aid the return flow of oil to the sump.

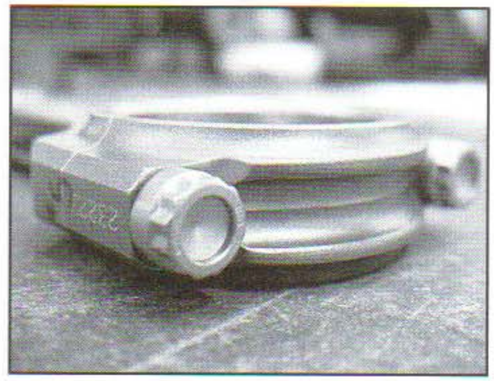
For some street and many race applications, displacement increases should be considered. Recall back in Chapter 1 that a fundamental method for increasing horsepower production is to increase the size of the engine. The old hot-rodder's adage that there is "no replacement for displacement" holds true for turbo engines just as it does for their naturally aspirated brethren. Torque is king on the



Patience is the key to assembling a robust and reliable engine. All the usual steps and tricks employed on a naturally-aspirated engine are doubly important when building an engine for forced-induction use. (Henderson/SP Engineering)

Quality pistons and connecting rods are a must when building a big horsepower engine. The piston shown here is a forged unit that features a thick top ring land suitable for turbocharging. The H-style connecting rod is by Carillo and offers high tensile and compressive strength. (Henderson/SP Engineering)

street and in many types of racing, and torque is proportional to displacement. This will help not only in overall output, but will aid in off-boost performance of the engine. Boring the block is a viable option for increasing the displacement of a turbocharged engine, but care must be taken not to go too far. Because of the increased cylinder pressures of a forced-induction application, there must be adequate room left between cylinder banks for full head gasket sealing.



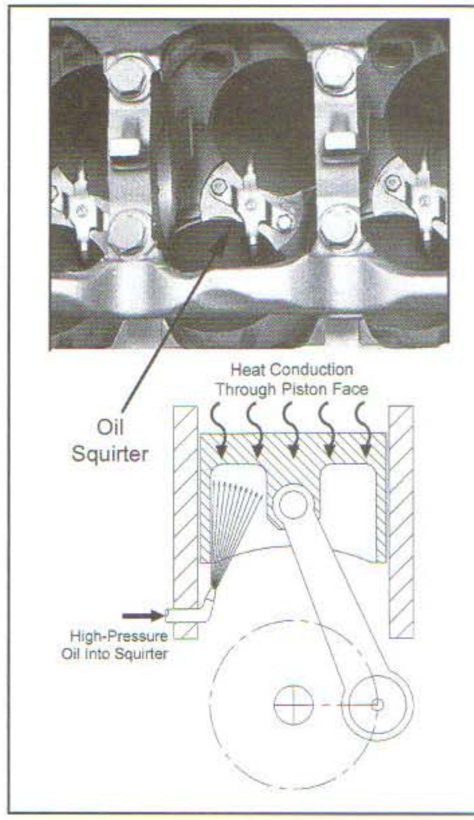
The internal connecting hardware is just as critical as the basic engine components themselves. This includes head studs, rod bolts, and main bearing cap bolts. (Henderson/SP Engineering)

CRANKSHAFT & CONNECTING RODS

There is little different about preparing the crankshaft of a turbocharged engine versus that of a naturally aspirated engine. In both cases, for maximum performance and longevity, the crankshaft needs to be inspected for cracks and flaws and have its journals ground properly if required. The unit itself must be straight, and the angularity and indexing of the rod throws need to be correct and within spec. Of course all the usual hot-rodder tricks can be applied with success, too, such as smoothing the fillet radii, chamfering oil holes, micro-polishing bearing journals, etc. The strength offered by a forged steel crankshaft can be useful at higher boost levels, but for most engines it isn't necessary until boost levels exceed 15 psig or so.

Similarly, there isn't really anything special about connecting rods for a turbocharged engine—at least at lower levels of boost. For all-out performance and maximum boost, forged H-style connecting

A high-quality forged piston kit for a turbocharged application. (HKS)



Oil jets, or "squirters," aimed at the bottom of the piston can greatly aid in chamber cooling. Heat from combustion conducts through the face of the piston, where it is removed by convection into the oil spray. Simple and very effective.

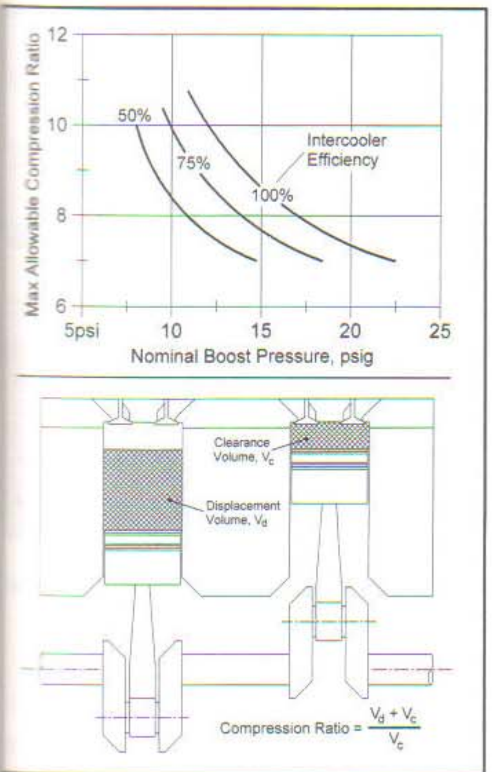
rods should be considered. They offer greater compressive strength than standard OEM I-beam type rods, which can be a helpful at high horsepower levels. Upgraded rod bolts are also beneficial.

PISTONS & COATINGS

There are many myths and hearsay when it comes to piston choices for turbocharging. High among these is the never-ending debate between cast and forged pistons. The truth is that for low-boost applications (e.g., 5–10 psig), most so-called eutectic OEM cast pistons are probably adequate if detonation is avoided. As boost pressure rises, however, hypereutectic pistons should be considered. A hypereutectic piston is nothing more than a cast aluminum unit with an increased silicon content. The amount of silicon in the casting affects the strength, wear, and scuff resistances, as well as the coefficient of thermal expansion. Before the expense of forged pistons is considered, the cost-minded engine builder would be wise to look into hypereutectics.

But that's not to say that forged pistons are always overkill; indeed forged slugs have a definite place in turbocharged engines that run high boost (i.e., >15 psig). In fact, some turbocharged OEM engines come equipped with forged pistons from the factory. As engine stresses increase, forged pistons offer several advantages over cast pistons, including improved ductility and higher yield strength. Forgings also provide a higher thermal conductivity than many castings, which lets them dissipate heat at a higher rate and also be somewhat less sensitive to pre-ignition and detonation. A rule of thumb is that for engines operating above 90–100 hp per liter (1.4 to 1.6 hp per cubic inch) specific output, forged pistons are recommended for turbocharged applications. Below this level, they're probably not required.

Once the choice of materials has been made, there are a few additional things to keep in mind when selecting pistons. Because stresses are magnified by boost, large, thick ring lands are preferable to thin ones. Similarly, piston faces with smooth faces and chamfered edges can reduce the propensity for pre-ignition and/or detonation. If you have a choice as to where the ring is located relative to the face of the piston, move it as far away as possible to reduce the heat transferred to the rings. In contrast, modern OEM pistons typically have the rings placed near the crown, or face, to reduce the unburnt mixture trapped between the



Static compression ratio is the combustion chamber volume at BDC, divided by the chamber volume at TDC. Naturally aspirated engines typically run static compression ratios ranging from 9:1 to 11:1, or higher. Because of the increased cylinder pressure, however, turbocharged engines need to run at lower levels of compression. The actual amount required is dependent on many factors, including intercooler efficiency, chamber design, and so forth. There are no hard and fast rules for the maximum allowable compression ratio, and selecting the appropriate value when building an engine is often a trade between throttle-response and off-boost torque, and maximum allowable cylinder pressure when the engine is on boost. The higher the static compression ratio, the better the low-speed throttle response, but this comes at the expense of not being able to run high levels of boost without the use of high octane race fuels.

piston and the cylinder wall. This is one way manufacturers lower emissions, but it's bad from a high-performance thermal point of view.

The debate is still ongoing on the subject of thermal coatings. On the plus side, they help keep thermal energy contained within the combustion chamber where it can perform useful work. The downside is that it can be expensive to apply, and the performance gains, while measurable, are small.

A good idea, on the other hand, is the use of piston oil squirting jets. Some very successful high performance forced-induction engines, such as Toyota's venerable 4AGZE and Formula Atlantic variants, utilize oil jets that direct a spray of oil on the bottom face of the piston to help keep down piston temperatures.

COMPRESSION RATIOS

An engine's static compression ratio is equal to the combustion chamber volume at BDC, divided by the chamber volume at TDC. Modern, naturally aspirated engines typically have static compression ratios between 9:1 and 11:1, or higher. Because of the increased cylinder pressure, however, turbocharged engines typically need to run at lower compression ratios. For example, an intercooled street-driven turbocharged engine running 92 octane pump gas and 10 psi will likely require a static compression ratio of 8:1 or so.

Unfortunately, there are few hard and fast rules for the maximum allowable compression ratio. This is because there are so many factors that are affected by the amount of static compression, from chamber design, to squish and quench areas, to the volumetric efficiency of the engine itself.

Selecting the appropriate level when building an engine is often a trade between throttle-response and low-end torque on one hand, and maximum allowable boost pressure on the other. The higher the static compression ratio, the better the low-speed throttle response, but this comes at the expense of not being able to run high levels of boost. And all of this must be weighed against the availability of high octane fuel.

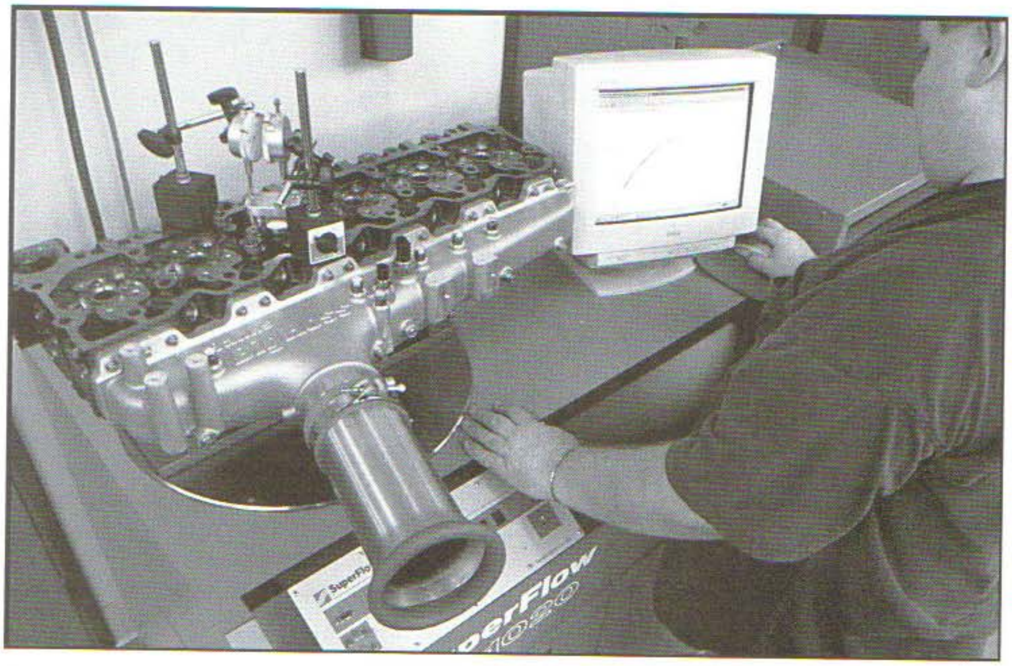
> Generally speaking, modern four-valve per cylinder pent roof combustion chambers have a lower tendency toward detonation and can withstand higher compression ratios than older two-valve designs.

CYLINDER HEADS & GASKETS

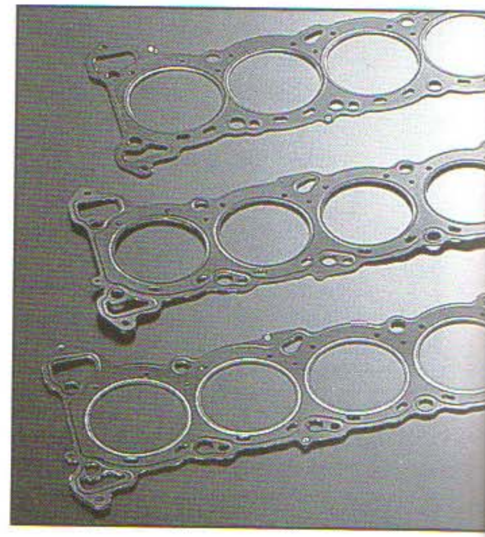
For a maximum performance turbo engine, the cylinder heads should be completely disassembled, cleaned, and carefully inspected for cracks and flaws. Dye penetrant and/or magnetic-particle testing is useful. Care must also be taken to ensure that the cylinder head is perfectly flat. Ensuring a good sealing surface between the head and the block at high levels of boost is critically important; an all-too-common reason for the malfunction of a turbocharged engine is the failure of the head gasket, which in turn is often caused by detonation brought on by poorly machined surfaces on either the block or the cylinder head.

Care should be taken not to mill off too much material if the head is resurfaced. The static compression ratio of the engine will be raised by milling. For a performance engine, this can result in cylinder pressures that are too high and an increased risk of pre-ignition and/or detonation.

Sharp edges and holes should be deburred and chamfered to reduce



Most of the usual cylinder head tricks that work on naturally aspirated engines, such as porting and polishing, can be doubly effective on a turbocharged engine. This Cummins inline six-cylinder turbo-diesel head is shown here being tested on a flow bench. (Gale Banks)



A collection of high-quality aftermarket metal head gaskets. (HKS)

High-quality studs are generally considered cheap insurance by most engine builders.

the chance of pre-ignition. The same is true for any burrs, hot-spots, or other irregularities inside the chamber.

For maximum performance and to help even out exhaust flow pulses to the turbine, the chamber volumes and shapes should be equalized, as should the static compression ratios. This is commonly referred to as "CC-ing" the chambers.

A common misconception is that porting is not cost-effective or even beneficial on a turbocharged engine. The reasoning is that the pressurized airflow from the compressor can and will overcome any flow restrictions that would affect a naturally aspirated engine. The fault with this logic, however, is that any restriction in a flow path results in a pressure loss, which robs boost that you've worked so hard to create with the turbo equipment upstream of the cylinder head. For all-out performance, a proper porting and polishing job can benefit most engines.

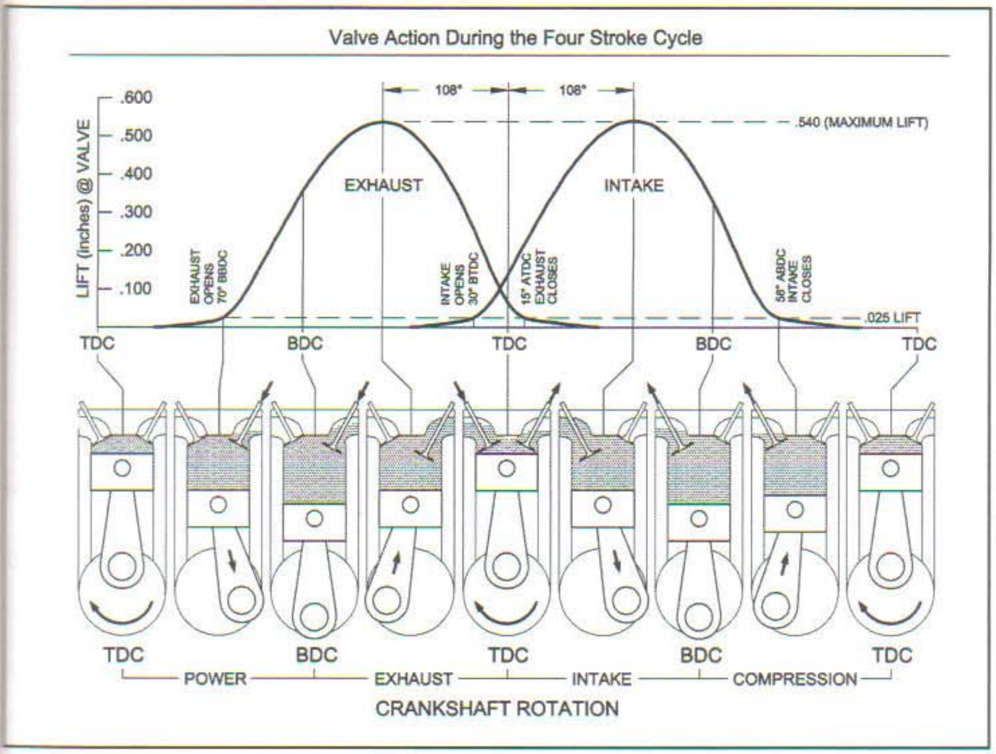
For low boost levels, stock head gasket and cylinder head bolts are usually adequate, provided they are torqued to the proper levels. But as boost levels rise, high-performance metal head gaskets are useful, as are using O-rings around each cylinder. The somewhat popular idea of using a stock head gasket to provide a weakness or mechanical "fuse" that will protect the pistons and rings from detonation is unsound. A blown head gasket can and will result in just as much damage as a destroyed piston ring land. The correct way to address detonation is with intercooling, fuel, and tuning—not mechanical fuses.

Studs are also useful; they allow for more precise control of the head seating forces and better equalization between attachment points than standard head bolts.

CAMSHAFTS & VALVES

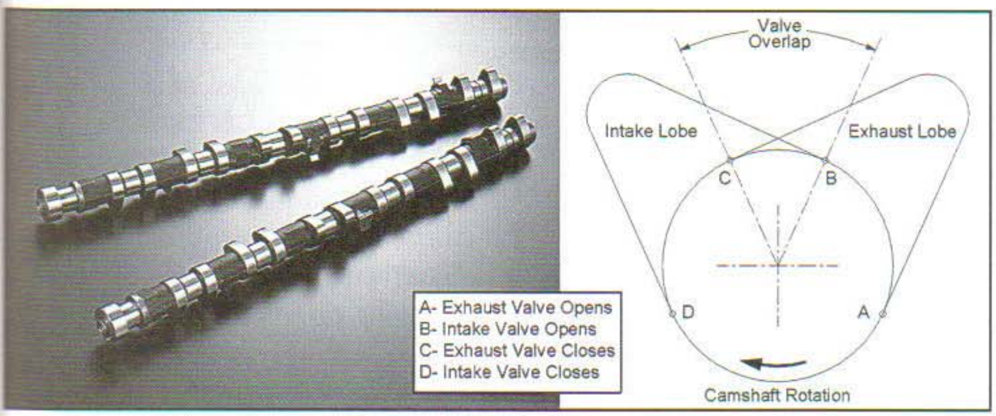
For a turbocharged engine, it's very easy to choose the wrong camshaft, especially if the builder is used to naturally aspirated engines. In fact, proper camshaft selection for a turbocharged engine may be surprising: stock OEM-type cams often are the best choice. The key to good performance is to have little overlap between the intake and exhaust valves opening, which is something that most OEM cams exhibit. Large lift is good, obviously, but too much overlap is what kills many a turbocharged engine's performance. For all-out performance and high levels of boost (e.g., >15 psig), consult with a cam grinder who has extensive experience with turbocharged applications.

An often overlooked step is to "degree" the camshaft. Degreeing is simply the process of measuring and adjusting the timing gears and/or chains to ensure proper

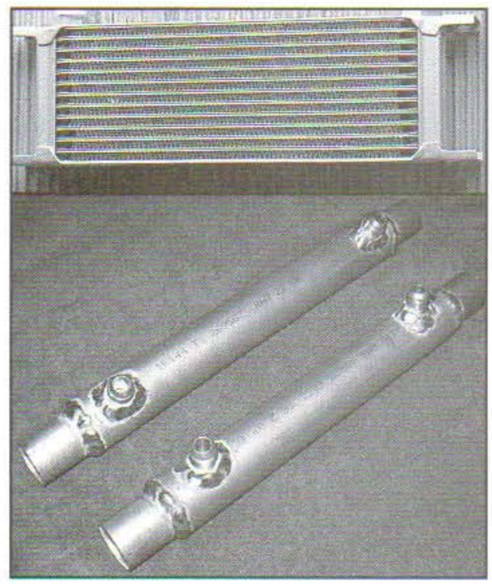


There is a period of time during engine operation, called "overlap," when the exhaust valve hasn't fully closed, yet the intake valve has begun opening. High-performance naturally aspirated engines generally respond well to large amounts of overlap. Turbocharged engines running moderate to high levels of boost, however, don't behave in a similar manner. At high boost and engine speeds, backpressure caused by the turbine can exceed intake manifold pressure. This can cause hot exhaust gases to flow backward through the engine, diluting the intake charge. It can also cause chamber temperatures to rise and detonation to occur. (Saulnier)

The more horsepower an engine makes, the more heat that needs to be dissipated. While a large, efficient intercooler is great for charge cooling, it also tends to block airflow to the radiator. Make sure the engine cooling system is sized to account for the added heat input, as well as any reduction in airflow caused by the intercooler mounting. (Turbonetics)



Camshafts designed for high-performance turbocharged use feature large lift and duration, but small levels of overlap. For lower levels of boost, stock OEM-type camshafts are often quite good. (HKS)

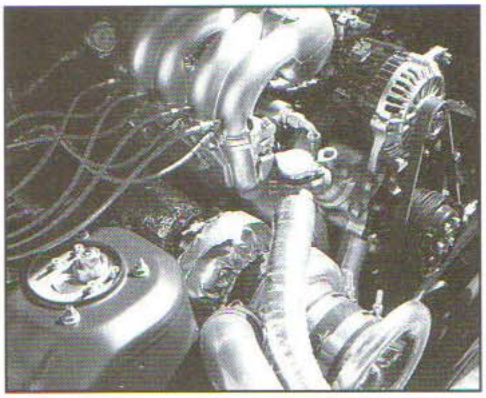


Oil coolers can be an excellent addition to a turbocharged vehicle. Shown at the top is a traditional oil-to-air cooler; at the bottom are two unusual, but quite effective, oil-to-water coolers. (Racing Strong Motorsports)

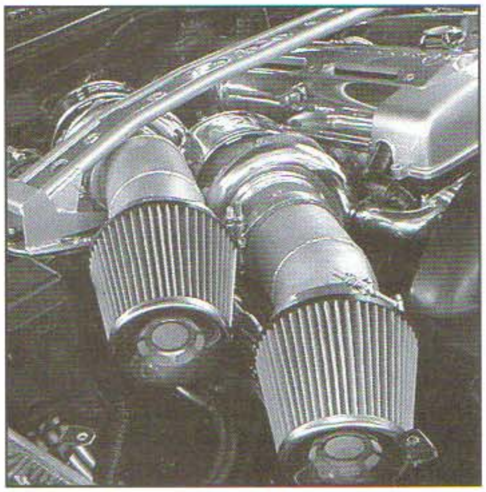
crankshaft-to-camshaft phasing. The effects of improper cam timing is exacerbated by forced induction.

ENGINE COOLING

Only 25–30% of the fuel energy contained in a pound of gasoline gets converted to useful work inside an internal combustion engine. The remaining 75% goes into waste heat, and a significant fraction of it ends up in the cooling system. Consequently, a turbo-charged engine that produces 50% more horsepower than an equiv-alent naturally aspirated engine also produces 50% more waste heat. This means the cooling system has to be sized to handle 50% more heat. Make sure your radiator, hoses, fans, coolant, and other cooling system components are up to the task of handling the horsepower gains that are expected. Also be wary of



Details like proper heat shielding can ensure that an engine performs to its utmost abilities. (The Power Group / Heat Shield Products)



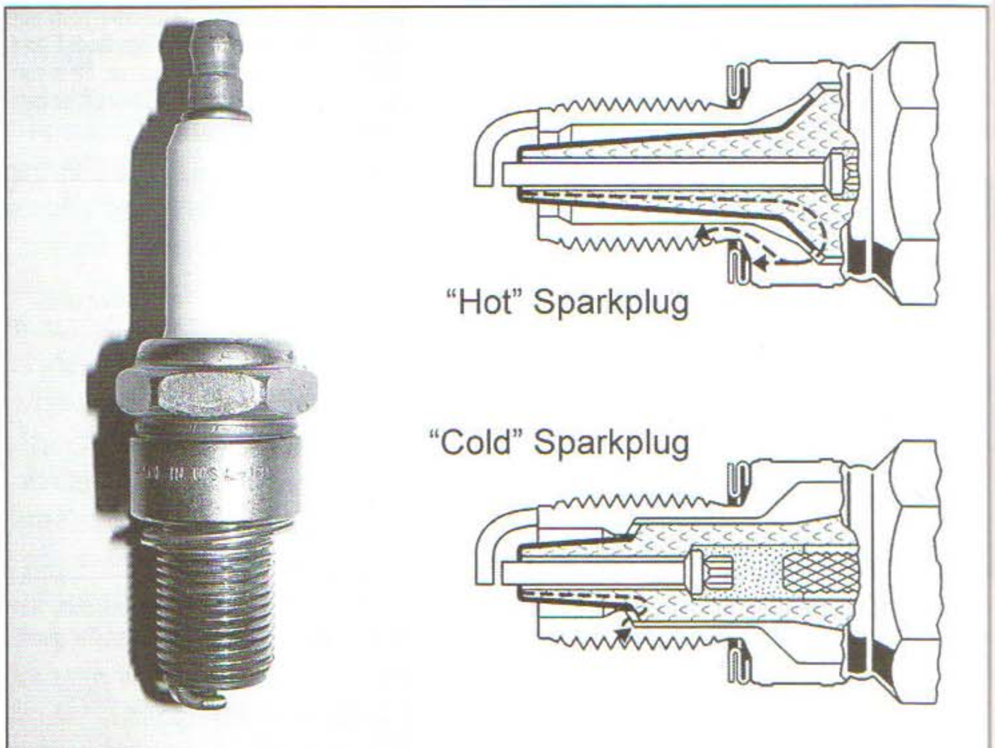
Filtration is more important on a turbocharged engine than it is on a naturally aspirated engine. The reason is the delicate nature of the compressor wheel. Spinning at rates in excess of 100,000 rpm, a compressor wheel has to be perfectly balanced. Impacts from small rocks, bugs, or pieces of dirt can quickly destroy a compressor. Compounding this problem is the fact that a turbocharged engine acts very much like a vacuum cleaner, ingesting huge amounts of air. Invest in a high-quality, free-flowing air filter. (Henderson/SP Engineering)

"high-performance" pulleys, as they can slow down the water pump and drastically affect cooling capacity.

PUTTING IT ALL TOGETHER

The old carpenter's motto of "measure twice, cut once" should be expanded to engine building: "measure three times, torque fasteners twice, start once."

The good news is the use of high-quality braided stainless steel hoses. The bad news is the exposure of these critical hoses to all sorts of road debris kicked up by the front tire on this turbocharged Suzuki. (Turbosmart)

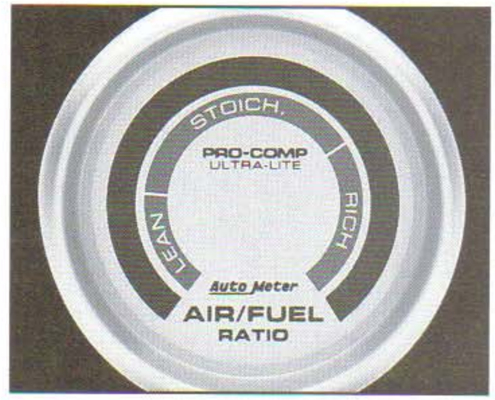


A sparkplug is a sparkplug, right? Wrong. Sparkplugs serve an important function beyond simply igniting the air-fuel mixture. Plugs help remove heat from the combustion chamber. Ranging from "hot" to "cold," sparkplugs are classified by their heat range, or ability to remove thermal energy from the chamber. Heat range is determined by the insulator nose length and the plug's internal design. Hot plugs have longer noses and consequently have longer paths for heat to travel before being absorbed by the cylinder head. Colder plugs have shorter, more direct routes from the chamber to the head. As boost pressure—and therefore cylinder temperatures—rise, colder range sparkplugs are often required on turbocharged engines.

RECOMMENDED SPARKPLUG HEAT RANGES

When it comes to sparkplugs, a rule of thumb that many engine builders use is as follows:

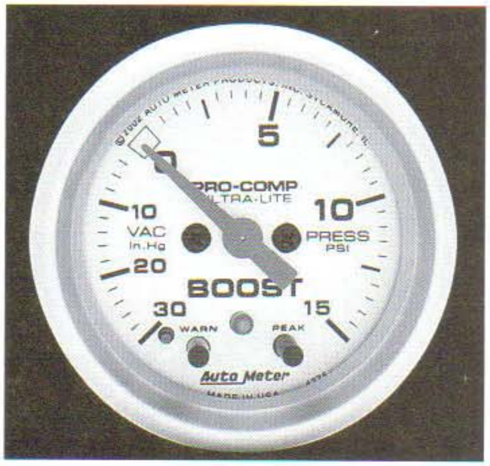
Boost	Heat Range
0–5 psig	Stock
5–10 psig	One Range Colder Than Stock
10–15 psig	Two Ranges Colder Than Stock
> 15 psig	Three Ranges Colder Than Stock



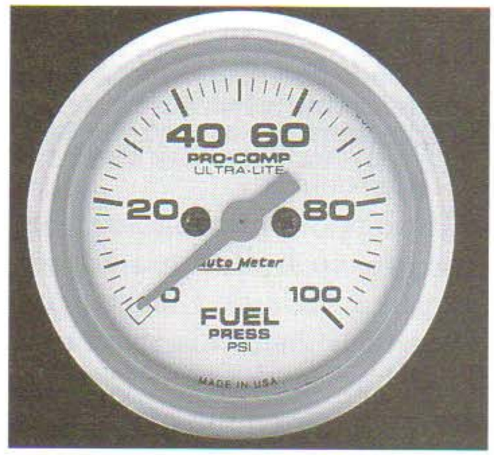
Perhaps the second-most important gauge is the air/fuel ratio meter. Up until recently, only narrow-band air-fuel gauges were available on the aftermarket. While certainly very useful, narrow-band meters cannot tell the operator the full story about what the air/fuel ratio is. In fact, with the exception of mixtures very close to stoichiometry, a narrow-band gauge can only indicate whether the engine is running higher or lower than 14.7:1, but not by how much. (Auto Meter)

Blueprinting a high-performance turbocharged engine is the act of painstakingly measuring and adjusting and measuring again as accurately as possible all of the internal components. For low boost applications, blueprinting is overkill, but for high performance it's a necessity.

Perhaps more important is cleanliness; dirt is the enemy of an engine. Turbocharging an engine amplifies all the internal strains and wear rates. Everything you can do to ensure that the engine is assembled correctly and cleanly will pay dividends later in the engine's life. The goal of building a turbocharged engine is to obtain maximum power and to ensure the longest possible engine reliability and life. Turbochargers build horsepower, but they do so at the cost of added engine stress. If your goal is all-out horsepower and reliability, there are no shortcuts.



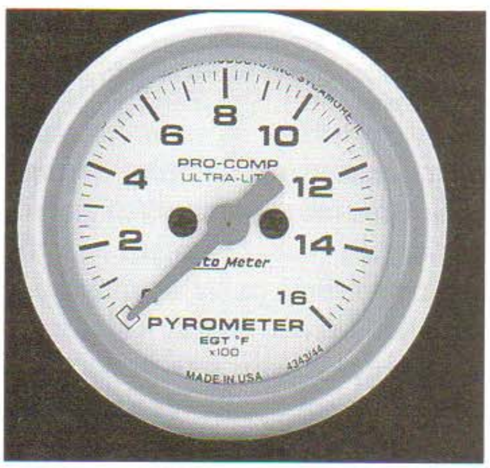
The most important gauge a turbocharged vehicle requires is a quality boost gauge. A quick route to a destroyed engine is a stuck wastegate. Without a quality boost gauge, there is no way to know that you're over-boosting. (Auto Meter)



A fuel pressure gauge can be a useful device. Unstable fuel pressure can result in an air-fuel mixture that changes erratically. Invest in a quality gauge like this one by Auto Meter and sleep well at night. (Auto Meter)

TURBOCHARGER GAUGES

Gauges are what allow you, the owner, to monitor how the engine is performing. Gauges are a key part of breaking in, tuning, maintaining, and operating a turbocharged vehicle. It is always worthwhile to invest in high-quality gauges. While some money may be saved in the short term with inexpensive gauges, you will likely pay for it in the long term with the uncertainty of the measured values.



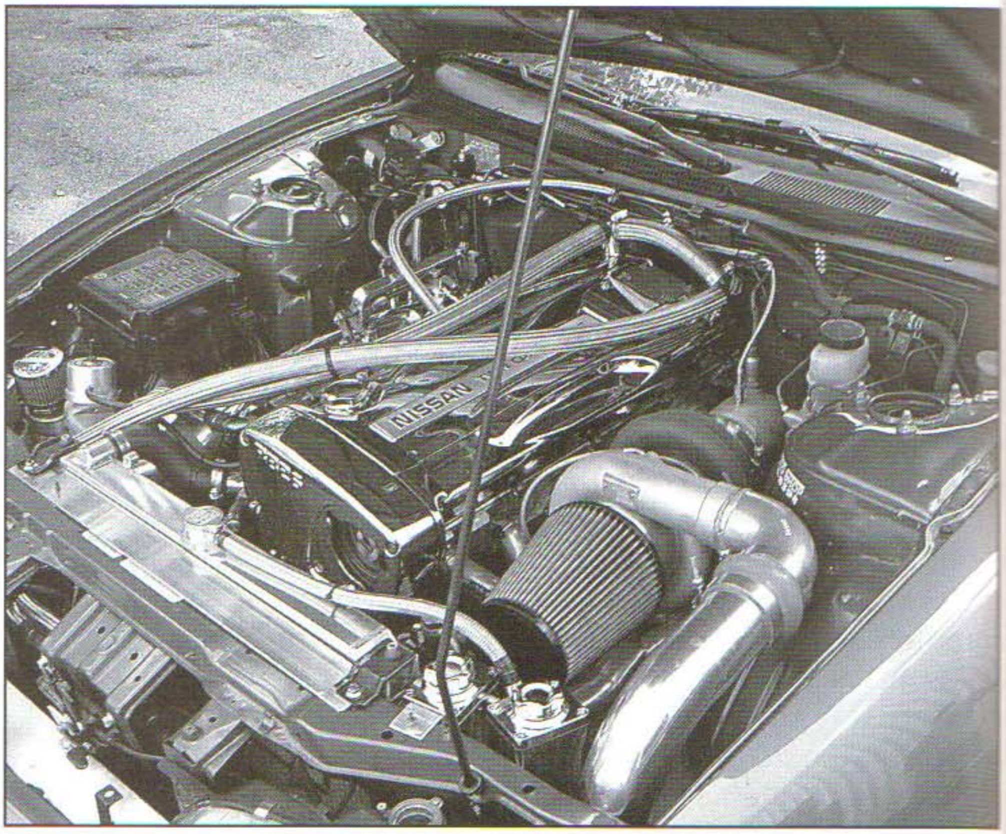
The temperature of the exhaust gases leaving your engine are an indication of the status of your air-fuel ratio and ignition advance. Unfortunately, it's hard to distinguish between the two when simply reading EGT values. In my opinion, an EGT gauge is very useful, but primarily as a warning device that something is amiss with the engine; it should not be used for tuning unless it is done in the hands of an expert. (Auto Meter)

So what gauges are important for forced-induction engines? Beyond the usual tachometer, oil pressure, and water temperature gauges, there are four special gauges that are particularly useful on turbocharged engines: boost, air-fuel ratio, fuel pressure, and exhaust gas temperature.

14 DYNO TESTING AND TUNING

Putting together a turbocharger system for your vehicle doesn't stop when you tighten the last bolt or plug in the final electrical connector. You can purchase, fabricate, and install the best forced-induction parts available, but unless sufficient time and effort is invested in testing, tuning, and adjusting the components to work together properly, it's a certainty your turbocharged engine won't function as you intended. Worse, you may actually cause engine damage if all the components are not set up correctly.

Testing and tuning are key elements to building a turbocharged vehicle that meets your expectations. And while there are a number of methods to test and tune an engine, one of the best possible ways is on a dynamometer, or dyno for short.



A Nissan 240SX with a turbocharged JDM RB26 inline six-cylinder. A radical engine swap like this should almost always be followed by comprehensive tuning on a chassis dynamometer. (The Power Group)

DYNO BASICS

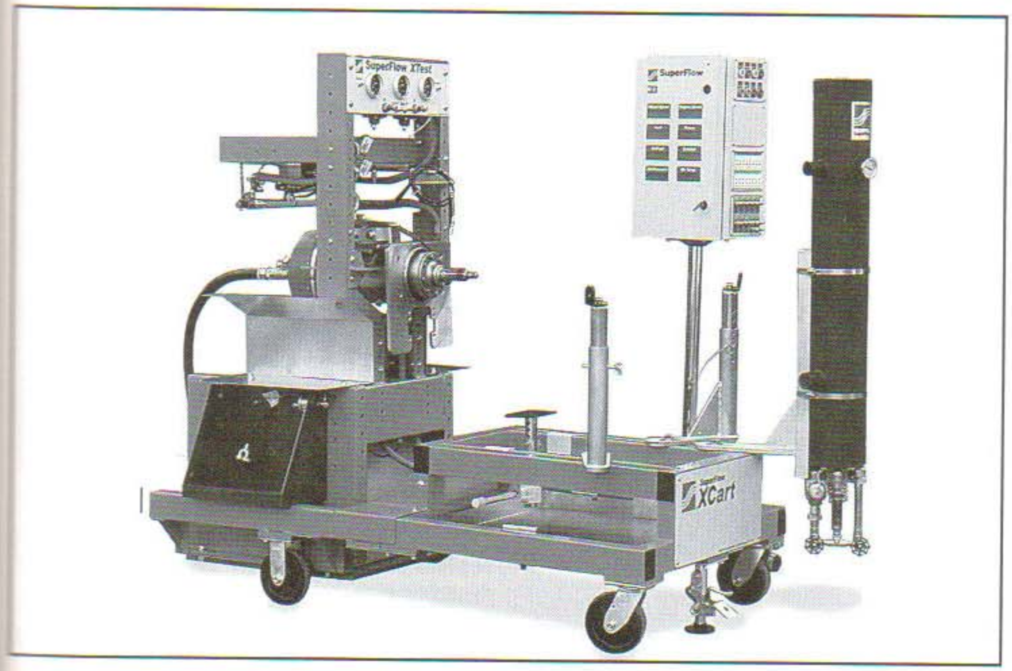
A dynamometer is a device that measures force, torque, or power output from an engine. Dynos come in many different styles and designs, but for automotive purposes they can be distilled down to two basic types: engine dynos and chassis dynos.

Engine dynamometers are ones to which the engine itself is bolted and run. Most engine dynos are "brake"-types, which means that an actively controlled resistance, or braking torque is applied to the engine output shaft during testing. This torque is commonly supplied by way of water, oil, or eddy-current brakes, or by a generator. In order for an engine to run at steady speed, it has to create enough torque to overcome the dynamometer brake torque. When the engine is neither accelerating nor decelerating under this fixed resistance at a specific rpm, the engine output—by definition—exactly matches the brake torque. At this point, the brake torque and engine speed are recorded. From these two values, engine horsepower can be calculated from the following equation:

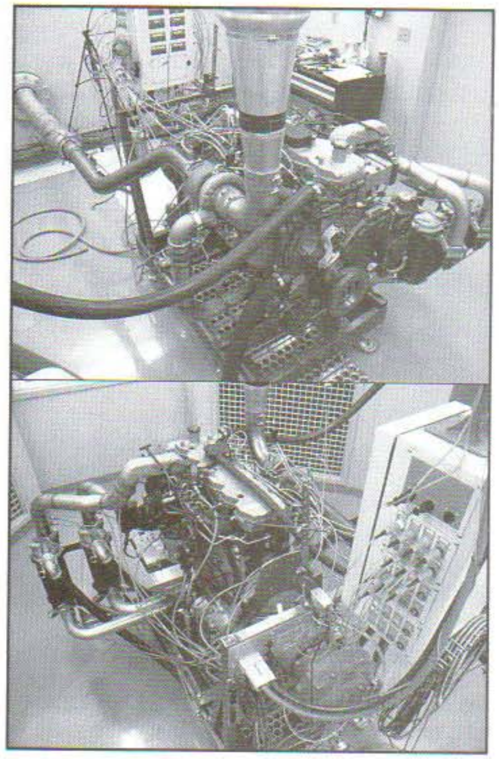
Eq. 14-1

$$\text{Horsepower} = \frac{(\text{Torq}_{\text{lb-ft}})(\text{RPM})}{5250}$$

Engine dynos allow for excellent control over test parameters and, consequently, the measured results. They also provide a direct measurement of engine torque (and therefore horsepower) with no external influence from other vehicle aspects, such as driveline losses. The downside, of course, is that the engine must be removed



An engine dynamometer provides a direct measurement of developed engine torque (and therefore horsepower) with no external influence from other vehicle aspects, such as driveline losses. Engine dynos are most often used for research, endurance testing, reliability measurements, and determining exact engine outputs for engineering and marketing purposes. (SuperFlow)



A fully instrumented inline six-cylinder turbo-diesel being tested on an engine dynamometer. Note the array of sensors and control cables attached to the engine. The brake unit is also visible in the lower photo. (Gale Banks)

from the vehicle for testing and connections must be made for all the engine support utilities, such as fuel, electrical, exhaust, coolant, throttle, etc. Engine dynos are most often used for research, endurance testing, reliability measurements, and determining the exact engine outputs for marketing purposes.

In contrast to an engine dyno, an automotive chassis dynamometer measures engine torque at the drive wheels; i.e., the entire vehicle is physically attached to the dynamometer. These kinds of dynos usually have a set of large steel cylinders, or rollers, upon which the test vehicle is mounted and strapped down. When the operator "drives" the vehicle on the dyno, the car remains stationary, while the tires cause the steel rollers to spin underneath it.

Chassis dynos can be classified in two different categories. The first is known as an "inertial"-type. Inertial dynos rely on the fundamental equation:

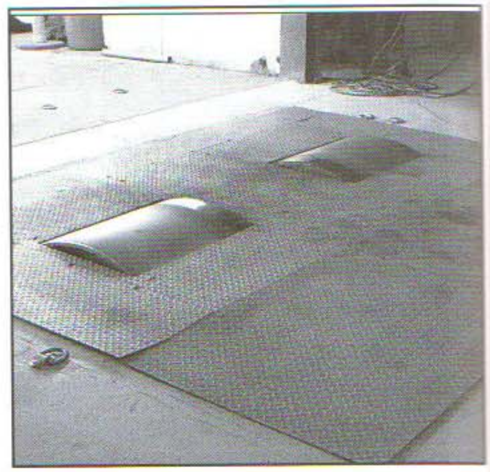
Eq. 14-2

$$\text{Torque} = (\text{PMI})(\text{Acceleration})$$

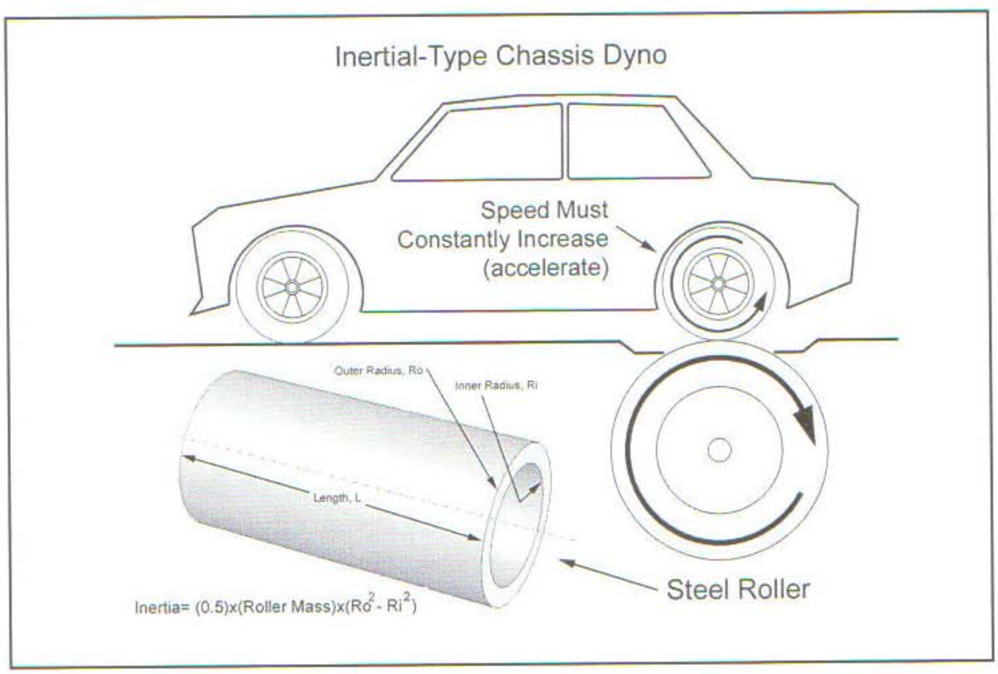
In this equation, the term polar mass moment of inertia, or PMI, can be thought of as the measure of a body's resistance to rotation. The PMI of the steel dyno rollers of an inertial dyno is large, so it tends to strongly resist rotation. By measuring the rate at which the speed of the roller changes as the car "drives" up through its rev range in gear, the instantaneous acceleration rate of the steel roller can be determined at all points throughout the vehicle's rev range. Then, since the acceleration and the PMI of the roller are known, a plot of delivered torque to the rollers versus engine speed can easily be calculated and plotted. To get a chart of horsepower versus engine speed, Equation 14.1 on page 128, can be used.

Inertial type dynos have become very popular. They can be used with good results to baseline the delivered torque and horsepower to a vehicle's drive wheels. They can also be used to measure the effect of changing engine components and vehicle settings. Because the rollers continuously increase in speed (i.e., accelerate) during a run, they're useful for getting a quick and complete snapshot of how well a vehicle is performing from idle up to redline. Unfortunately, this is the same reason why an inertial-type dyno is not well suited for serious tuning and adjusting of fuel and ignition maps. When tuning, an engine needs to be run at constant speeds and loads while the

The same turbo-diesel being tested in its vehicle on a chassis dynamometer. The luxury of testing both on an engine and chassis dyno can allow engineers to quantify driveline losses and help optimize the overall vehicle setup for a specific race application. (Gale Banks)



There is not much to look at above ground, but beneath the steel plates is a highly-sophisticated, computer-controlled chassis dynamometer.



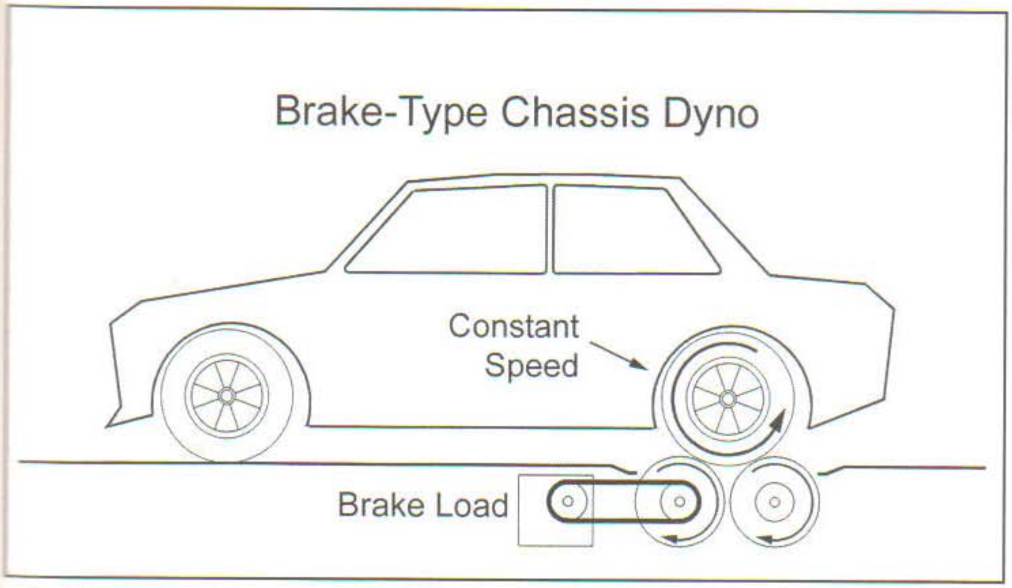
An inertial-type chassis dyno requires the vehicle to continually accelerate from a lower speed to a higher speed during the test. These dynos work on the principle that drive torque is equal to inertia multiplied by acceleration. The faster the acceleration, the higher the delivered drive torque.

air/fuel mixture and ignition maps are tested and adjusted. For this, a brake-type chassis dyno is required.

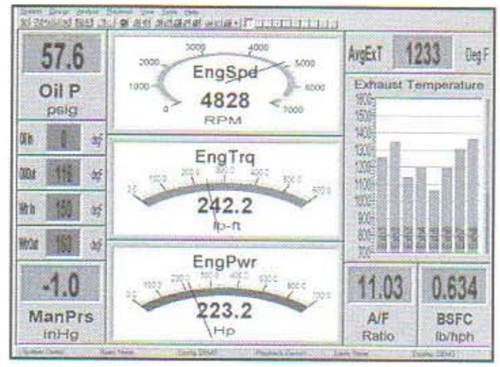
A brake-type chassis dyno works the same way an engine brake dyno works. A variable resistance, or brake load is applied to the steel drive rollers on which the vehicle is strapped down. The vehicle then drives against this load. When the rollers are neither speeding up nor slowing down under that load, the instantaneous brake torque value and engine rpm are recorded, and horsepower is calculated. A brake-type chassis dyno allows engine parameters to be changed in real time at fixed engine speeds and loads, and, consequently, allows the torque output at each of these conditions to be maximized.

TESTING ON A DYNAMOMETER

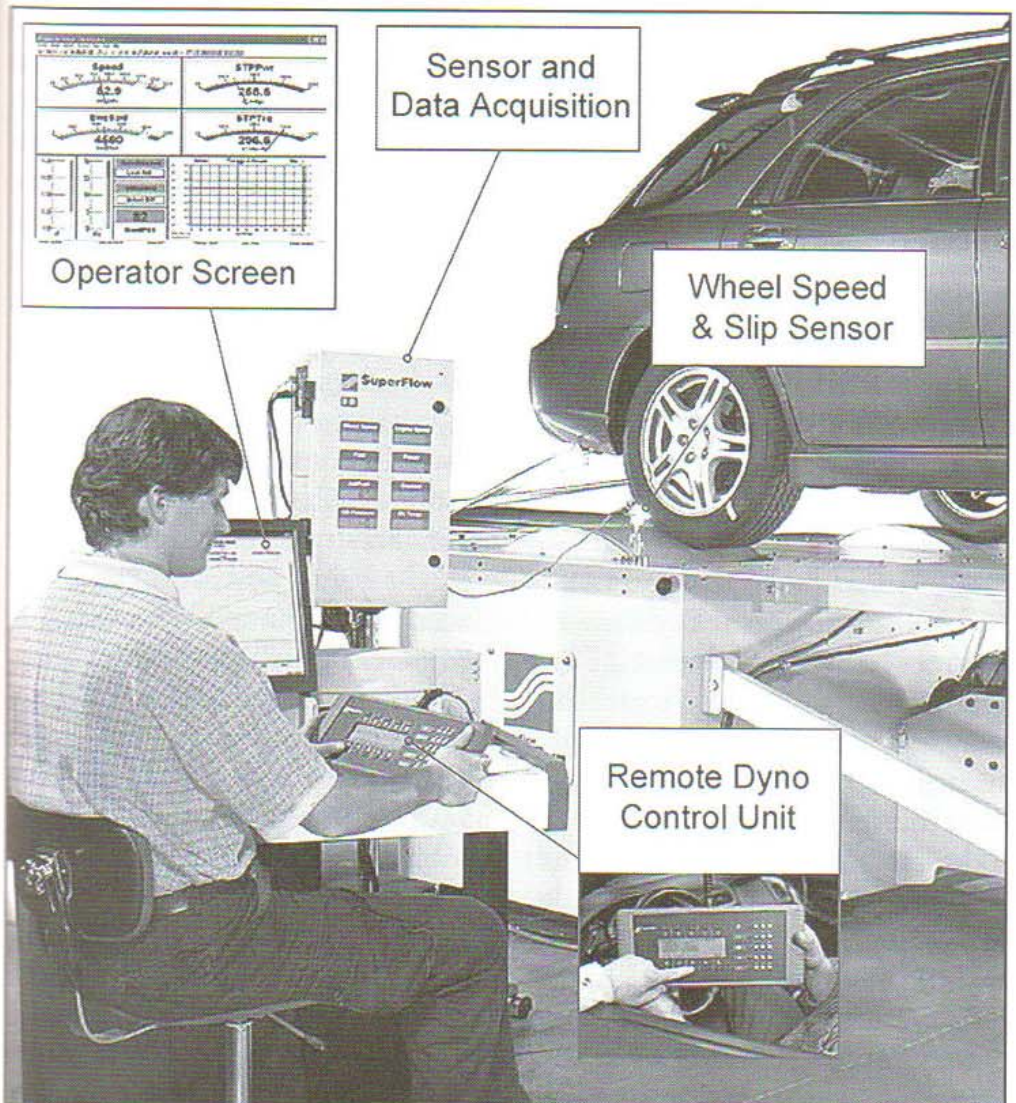
Chassis dynos have the obvious advantage of being able to test the complete vehicle. There is no need to remove the engine from the car, which expedites testing and tuning. Indeed, it's relatively easy to roll a vehicle onto a chassis dyno, strap it down, and begin taking data. The downside, of course, is that there are many variables in the testing and tuning equations. Are the underhood temperatures realistic and constant? In what operating condition are the transmission and differentials? Are the tire pressures correct and equal and are the wheels aligned correctly with the dyno rollers? Is there tire slippage? Is the intercooler heat-soaking and/or cooling the charge intake air sufficiently? Care must be taken



A brake-type chassis dyno allows the vehicle to run at a fixed speed and load, which in turn provides time to precisely adjust and optimize air/fuel ratios and ignition advance amounts.



A typical operator interface for a computer-controlled chassis dynamometer. Note the manifold pressure, exhaust gas temperature, and air-fuel ratio output boxes that should be monitored at all times during testing. A lean mixture can lead to detonation. This can quickly destroy a turbocharged engine, even at relatively low boost levels. Similarly, too much advance can cause problems. When tuning under boost it is important to vigilantly monitor boost levels, air/fuel ratios, and exhaust gas temperatures. (SuperFlow)



A fully equipped chassis dynamometer operator station. (SuperFlow)

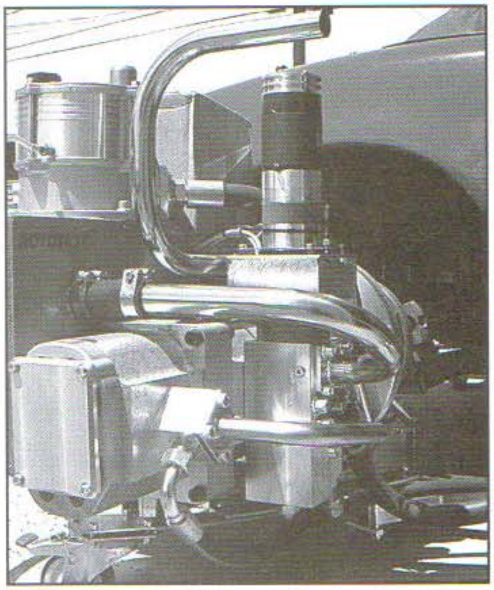
to account for these and many more factors if consistent and meaningful test results are desired.

In any case, by adjusting tuning variables such as ignition timing and air/fuel mixtures in real time, maximum torque and/or horsepower can be quickly dialed in, and this can be done so in a systematic manner. In the hands of a competent operator, a brake-type chassis dynamometer is an excellent tool for dialing in a turbocharged engine.

Like many things, there are right ways and wrongs ways to test and tune a vehicle on a chassis dyno. The following sections highlight some things to keep in mind before, during, and after a chassis dyno session.

Before the Chassis Dyno Session

The first step in preparing for a test-and-tune session on a chassis dynamometer is to locate a reputable shop that can help tune



An alternative to the ubiquitous roller-type chassis dynamometers is Rototest's unique bolt-on system. Flyin' Miata in Colorado uses a pair of these innovative dynos to test and tune their fire-breathing Mazdas. Note the adapter plate that is bolted to the car in place of the wheels. Electronically controlled hydraulic pumps are then attached, which supply a resistance load, which in turn is measured by way of strain gauges. Because the dynamometer is solidly attached to the vehicle, there is no possibility of tire slippage, and the resulting torque measurements are extremely accurate. Better yet, add two more units to the front of the car, and you have an all-wheel drive dyno. (Flyin' Miata)

A highly-tuned Toyota Supra laying down 1000+ horsepower to the rear wheels. Engine dynos will always measure higher torque and power outputs than a chassis dyno testing the same engine. The reason, of course, is due to all the driveline inefficiencies and parasitic losses in the transmission, gears, differentials, CV-joints, and wheel bearings that conspire to rob crankshaft energy. For most street-driven vehicles, a chassis dyno delivers the most useful information to the owner. After all, the amount of torque and power delivered to the drive wheels determines how quickly the vehicle accelerates and how fast it ultimately travels. In a sense, the amount of power generated back at the crankshaft is really just a number to brag about. (Henderson/SP Engineering)

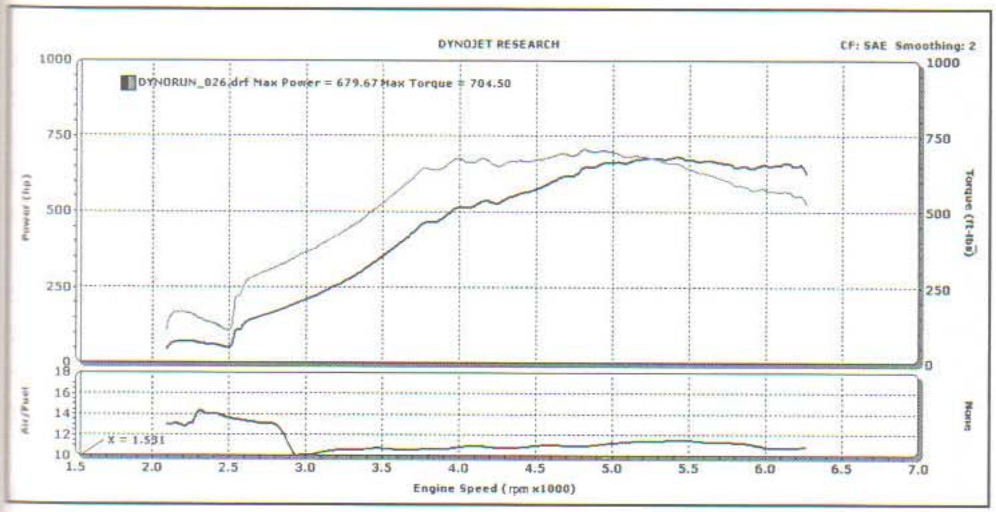
your car. Find out what type of chassis dyno they have and determine what you want to achieve. Is it an inertial-type or a brake-type? Talk to the shop owner and to previous customers. Find out how much experience the shop has with vehicles and turbo systems that are similar to yours. Ask what a typical session entails—and what it doesn't. Find out when the dyno was last calibrated—if it ever was. You've just spent thousands of dollars and hundreds of man-hours building your turbocharger system. Don't take any shortcuts when it comes to tuning. If necessary, don't hesitate to take your car to a dyno facility in the next town or city if you're not satisfied with local equipment.

Choose a facility that has wide-band tuning capability—and knows how to use it. Some dyno shops use a wide-band stick or "wand"-type probe that is inserted in the tailpipe to take measurements of the air/fuel ratio. These wands are fairly accurate, but they're slower to react than a sensor mounted in the exhaust stream near the engine, especially if the exhaust path is long. Consider having an O_2 sensor mount welded to the exhaust system near the engine. (But don't locate one too close; most wide-band sensors have a maximum allowable operating temperature that can be surpassed if it's positioned too close to the engine.) A good compromise is to locate a wide-band O2 sensor a foot or so downstream of the turbocharger.

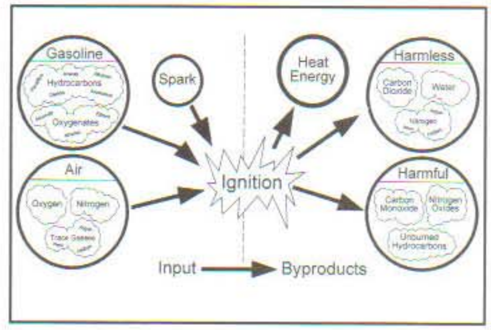
Do not expect to get any meaningful tuning information from a one- or two-shot "dyno day" session with a dozen of your closest friends (and cars) on hand. Reserve one to three dedicated hours of quality time solely for your vehicle on a brake-type chassis dyno. It takes time to safely tune a turbocharged engine, and time costs money. Be prepared to do this right.

Prep Your Vehicle—Time on a chassis dyno passes quickly. It's a good idea to do your homework ahead of the session, adequately preparing yourself and your vehicle prior to arriving at the dyno. For instance, it always makes sense to do all the normal maintenance tasks, such as changing the oil, plugs, plug wires, air filter, etc., a day or two ahead of the appointment. Flush the coolant and check the engine over from top to bottom. A dyno shop is not a repair shop, nor is it a warehouse of spare parts. It is your responsibility to make sure everything on your vehicle is in good working order and that you have all the required equipment installed.

Fluid and exhaust leaks will get a vehicle booted from a dyno faster than your turbine can spool. The same is true for fuel system problems, shoddy electrical wiring, loose suspension and drivetrain components, and anything else that looks suspect to the dyno operator. Remember that you will be strapping your vehicle down on a set of spinning rollers and then driving it up through the rev range, right to redline at full wide-open



Reading a dyno plot is an acquired skill, like learning to speak a foreign language. Spend time examining dyno plots and digesting them. Peak numbers, while important, only tell a small part of the story. It's often the subtle things like the area under the curve and air-fuel ratio fluctuations that are more meaningful.



Tuning is often undertaken to extract the maximum horsepower and torque from a vehicle. But sometimes tuning is focused on minimizing emissions and harmful byproducts of combustion.

throttle. There are literally thousands of BTU's of energy being transferred from your car to the chassis dyno; the result of something going amiss is frightening. Most dyno shops will send you home if they don't think your vehicle can be safely tested on their equipment.

Another thing to do before arriving at the dyno is to purchase a second set of sparkplugs, plus anything else that you think may break or require changing during the session. Make a list and keep checking it. Dyno shops usually charge by the hour, and they don't mind if you run to the store to buy new parts during the session, but they're going to keep the meter running.

Next, set tire pressures to the values you will run on the street. Get a notebook and record these pressures, plus all other relevant "baseline" numbers, including spark plug heat ranges and gaps, initial fuel and timing map variables, etc. This information will be useful later when trying to discern trends and results.

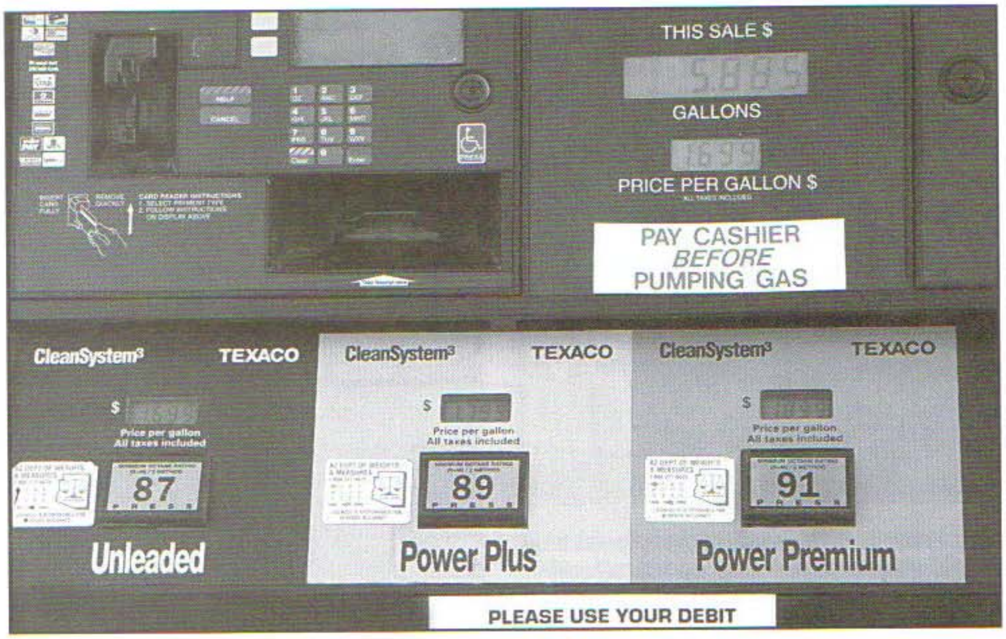
Also test the vehicle's fuel supply system. Replace the fuel filter and measure the delivered fuel pressure to the injector fuel rail. If you're not making full pressure, you're probably not making full horsepower. More importantly, a sudden drop or change in fuel pressure during testing can result in erratic results and can even cause the engine to run dangerously lean. Make sure the fuel delivery system is in good shape before going to the dyno.

While you've got the hood up, it's also worthwhile testing all the sensors and components of the EFI and ignition system. Is the TPS functioning correctly? Are the MAP and IAT sensors reading properly? Are the injector connectors attached firmly? Are there any loose wires or suspect components? There is nothing more frustrating than discovering halfway through a dyno session that a flaky sensor has been giving false readings.

Next up is to determine what your transmission gear ratios are. Specifically, you're looking for the gear ratio that is closest to 1:1. Typically, fourth gear is 1:1 on a 5-speed; fifth gear on a 6-speed. In many transmissions, the 1:1 gear is not a gear set at all; the input and output shafts are simply locked together. This eliminates the losses through the gear teeth and results in a higher power output in that gear. Most dyno tests are done at this 1:1 ratio. Running in too low of a gear can allow the engine to outrun the turbo. Higher gears slow the engine's acceleration and allow the turbo to spool earlier and more consistently. This is why a turbocharged vehicle often "feels" stronger to the driver in higher gears on hills than lower gears.

Another thing to do before the dyno session is to find a reliable friend who is willing to come along and be a gofer during the test. He or she can do all those things you forgot but can't spare the time to do during the runs. They can also act as the record keeper, copying down data, test condi-tions, significant changes and trends, and can also be a second set of eyes on the air/fuel and EGT gauges during the dyno pulls to ensure the mixture doesn't inadvertently go lean.

You should also organize all your



There are two different schools of thought about which octane grade to use during dyno testing. One says that you should test and tune to the octane you expect to run on the street. The logic is that you should tune as you intend to drive it. There is no use dyno tuning a car with 110+ octane race fuel if it is only going to see 91 octane when operating on the street. The other camp advocates running much higher octane than stock—perhaps race gas—to help ensure against detonation while dialing in air/fuel mixtures and ignition maps. Remember that octane is basically a measure of a fuel's resistance to detonation. The higher the octane, the less sensitive the engine will be to pre-ignition and detonation.

tools and equipment that will be brought to the session. Most dyno shops frown on customers who borrow tools. Bring everything that you'll need to make adjustments and changes to the engine setup.

Take the time to learn everything you can about dynos, your car, and tuning before showing up to the shop wide-eyed and naive. The absolute worst thing is to arrive at the dyno uninformed. Ignorance has a way of blowing up engines and emptying wallets.

Finally, consider doing a "street tune," making sure you are already in the ballpark with most of your settings. There's no sense in paying for dyno time when you could get rid of obvious over-rich conditions simply by driving the car around the block and then reading sparkplugs to diagnose the problem.

During The Chassis Dyno Session

Once you've arrived and installed your vehicle on the dyno, it's time to begin testing. But before you fire up anything, take a moment to familiarize yourself with the testing setup. Will the "driver" be able to communicate readily with other personnel, such as the person watching the air/fuel mixture? Is the car aligned correctly on the rollers and adequately strapped down? Has the engine been warmed up and are all systems functioning correctly?

It's also important to ensure there are enough fans that flow a sufficient amount of ambient air onto the front of the car. At a minimum, the fans should simulate the airflow on and over the car during normal driving. This means big fans. Both the intercooler and radiator need to receive sufficient flow. Note also that there needs to be an exit path for the air to flow out of the facility once it has passed over/through the car. It does little good if the air warmed by the intercooler re-circulates right back on to the engine.

Most cars make more power on the first few dyno runs than later in the session. The reason for this is that everything is nice and cool early in the session. Subsequent runs are warmer and therefore not as efficient. When testing, it's important to take sufficient (and equal) periods of time between successive runs to stabilize the intake, coolant, and intercooler temperatures. Consistency is the key to proper tuning. A good way to do this is to measure coolant temperatures. Between runs, let the engine cool down until the coolant temperature falls within a 5–10 degree window before making the next run. Usually a few minutes is required. Comparing runs made at significantly different temperatures is almost meaningless.

Begin testing with a conservative ignition advance map. A somewhat retarded ignition curve is generally more prudent than an advanced one. Don't go overboard with retarding ignition, however. If the ignition timing is significantly retarded, the exhaust manifold and turbo can overheat as the unburned mixture lights off in the exhaust manifold.

Similarly, begin with a conservative air/fuel mixture. Too rich is almost always safer than too

Handheld digital wide-band air/fuel ratio meters are accurate, affordable, and can feature internal data logging like this unit does. (Innovate Motorsports)

A digital temperature probe is a useful tool when tuning. For example, sensors can be mounted on the intercooler inlet and outlet tubes to help diagnose heat soaking and ensure consistent test conditions.

lean, but again don't get carried away. Going too rich with the mixture can lead to fouled spark plugs, carbon build-up, and even pre-ignition.

Also start with no load (i.e., no boost) and low rpm on the first runs, slowly adding engine speed and load in subsequent pulls. Do not make your first (and only) run at a sky-high level of boost. A good tuning philosophy is to dial in the "safest" operating regimes that are easy on the engine before progressing to higher loads and engine speeds.

Modern ECU tuning software usually displays base air/fuel and ignition maps that can be "filled in" in real time on the dyno. For example, rpm may be shown along the horizontal axis at the bottom, and manifold pressure up the vertical axis on the left. If your software is configured this way, start in the lower left hand corner of the maps and slowly work your way to the upper right hand corner as tuning progresses. In other words, start near idle, and then progress out through no-load speed ranges, followed in order by no-load acceleration enrichment, light-load rpm ranges, medium to heavy-loads, and finally full-load rpm ranges.

A technique that generally yields good results is to dial in the air/fuel mixture first with the wide-band output. Following this, ignition timing is advanced until torque is maximized (while keeping an eye out for detonation and pre-ignition). Once a set of adjacent cells are set with their appropriate air/fuel and ignition maps, the tuner can move up and outward to adjust the next higher engine speed and load portions of the map. Again, it's better to be conservative than overly aggressive. Take your time and do this right.

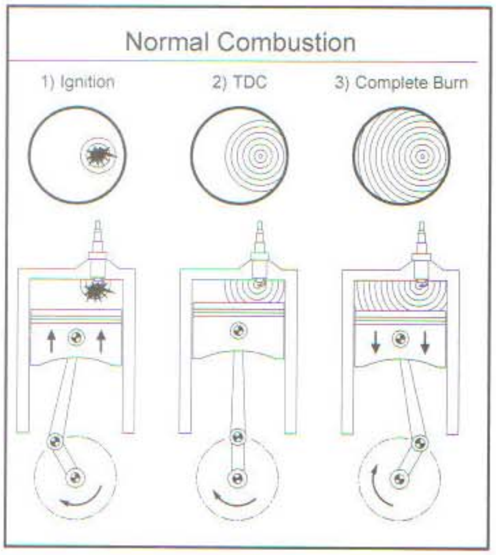
Record everything, from engine settings and tire pressures, to outside air temperature and barometric pressure. Get floppy disk copies of the data. The more information you have accurately recorded, the more scientifically and logically you can make changes and assess the results. If your ECU has datalogging capabilities, be sure to log everything you can.

After the Chassis Dyno Session

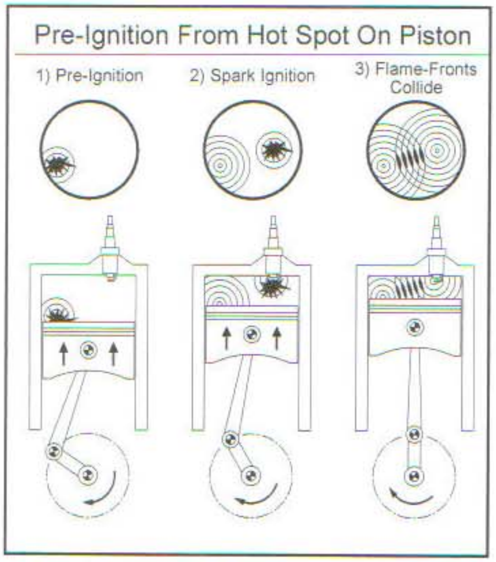
When you are finished with the dyno session, take your vehicle out for a drive and make sure it operates the way you expect it to. The street is no place to make adjustments for maximum power, but it is a great place to test cruise mixture, low-load acceleration enrichments, and other such things. Remember, the street is the ultimate arbiter of whether your tuning session was successful or not.

When you get home, go through your notes from the testing session, studying what changes made what results. The pressure and excitement of a dyno session often makes it difficult to keep track of all the finer points. Now is a good time to step back and digest the information. Reading dyno charts and fuel and ignition maps are learned skills; they don't happen overnight.

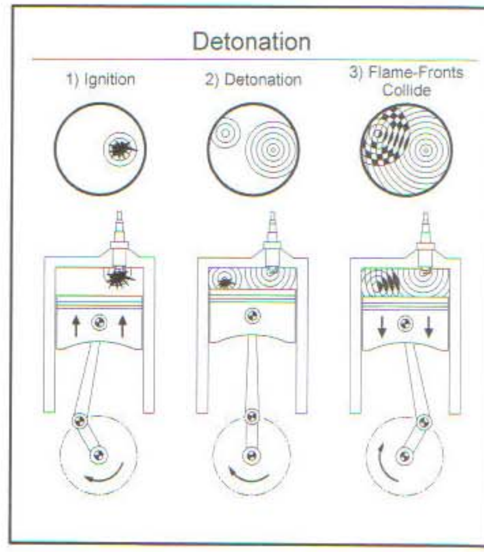
Review your dyno plots carefully. Don't fixate on peak horsepower or torque numbers if the car is going to be street driven. It's the boost threshold point and "area under the curves" that are more important. Look at the air/fuel mixtures and the boost values. Spend the time to understand when and how the engine is performing optimally. Carefully assessing the results will help guide the next set of modifications you're planning for the vehicle. Remember, a turbocharged project car is never finished!



During the normal operation of an engine, the burning of the air/fuel charge is initiated solely by the spark plug. This ignition source produces a controlled burn and pressure rise, and, consequently, a predictable and smooth building force on the piston in the cylinder. The timing of this pressure rise coincides with the downward movement of the piston, maximizing crankshaft torque. Note how the combustion flame front moves rapidly outward from the plug tip, much like a surface wave generated when a stone is dropped into a pool of water.



Pre-ignition, as the name suggests, is the premature ignition of the air/fuel mixture inside the chamber. This occurs *before* regular ignition from the spark plug. If the regular spark happens shortly after the pre-ignition, the two flame fronts can collide. Worse, the rapid increase in cylinder pressure due to the premature burning of the air/fuel mixture can occur when the piston is still moving upward. This damages pistons, rings, and valves. During teardown, a hole in the face of a piston is a tell-tale sign of serious pre-ignition. Pre-ignition can be caused by white-hot carbon deposits on the piston face, sharp edges in the combustion chamber, overheating of the engine, and even the mechanical failure of the sparkplug itself.



In contrast to pre-ignition, detonation is the spontaneous ignition of the air/fuel mixture after the normal spark occurs. While similar to pre-ignition, detonation is more akin to random pockets of air/fuel explosions inside the chamber. Like pre-ignition, detonation can cause serious engine damage, too, but the results are often different in nature. Broken rings and piston ring lands, cylinder scoring, and head gasket failure are common consequences of heavy detonation. The most typical causes of detonation are use of a poor quality (low octane) fuel, an excessively lean air/fuel mixture, improperly advanced ignition timing (early spark), and/or a static compression ratio that is too high.

Finally, don't run off and boast to your friends what your crankshaft horsepower is as gospel. Without a laborious set of driveline tests and coast-down measurements, it's essentially impossible to determine what your actual drivetrain losses are from a set of chassis dyno data. It's empty bragging to claim a crankshaft value if you've only measured the drive-wheel values. Keep the verbal bragging to a minimum—and let the vehicle performance numbers speak for themselves.

EFI UNIVERSITY

Want to learn how to properly test and dial in a turbocharged vehicle? Go to school. Classes like this one offered by EFI University provide students with a solid background and understanding of the fundamentals of engine operation and tuning.

The world of dynamometers and tuning shops is filled with half-truths, innuendos, misunderstandings, and simple ignorance about how engines function and dynos operate. There are countless web sites, magazine articles, and Internet chat rooms that perpetuate these myths and confusion. Many dyno shop owners don't even know how their own dyno equipment actually works. Worse, tuning engines is sometimes left to guesswork and/or dangerous trial-and-error methods. Many an engine has melted down on the dyno because neither the operator nor the vehicle owner really knew what they were doing.

There is no excuse for this. Tuning a turbocharged engine on a chassis dyno can and should be undertaken with a systematic approach. Tuning is a science, and the keys to success are (a) understanding the fundamentals of how air/fuel mixtures, ignition, and boost interact; and (b) knowing how and in what order to do things when you finally do strap your vehicle down on the dyno and begin testing and adjusting.

So how does one attain this elusive knowledge? Simple: go to school. Classes, like those run by EFI University, were founded with one purpose, which is to instruct individual vehicle owners, dyno shop operators, and performance tuners in the science of tuning.

In a weekend or two, students can complete beginning and advanced courses in EFI tuning. The classes teach the basics of EFI, what "tuning" actually entails, how to set mixtures and ignition advance maps, and how to go through a dyno session in a step-by-step manner and safely dial in an engine.

For roughly the same price as a set of performance tires or a new intercooler, students of a tuning school get taught both theory and practical knowledge. This includes hands-on time on an actual chassis dyno. Valuable do's and don'ts are provided, as well as suggestions for improving skills and knowledge after the class is completed.

Whether you're brand new to turbochargers and performance tuning, or you're an experienced race professional with years of experience, an EFI tuning class can be the secret to dialing in your vehicle and obtaining maximum performance. See page 199 for contact information.

PART III:

TURBOCHARGED PROJECT VEHICLES

TURBOCHARGED PROJECT VEHICLES

Now that we understand the theory and operation of turbochargers, it's time to see how all the pieces come together. The following ten projects represent a wide range of vehicles and forced-induction technologies. Each owner had a different set of goals in mind and, consequently, arrived at their own distinctive turbo solution. While the vehicles may appear totally different from each other, all had two things in common: a well thought-out plan and an extraordinary level of attention paid to the details. Study what these ten enthusiasts have done with their vehicles; whether you're new to turbos, or are an old hand in the world of forced-induction, there are valuable lessons to be learned here.

PROJECT VEHICLE 1
1985 TOYOTA MR2—AUTOCROSS DOMINATOR
The DIY Approach to More Power

In stock form, the first generation Toyota MR2 is a fun little car. Nimble and responsive, it's a joy to drive on twisty roads. The mid-engine design results in a low-polar moment of inertia that is ideal for changing directions quickly. And the relatively lightweight nature of the car allows for quick stops from high speed. The MR2 is nearly perfect for the track—except for the problem of anemic power.

The owner of this particular MR2 knew his car had the potential to be a serious Street Mod 2 contender in SCCA Solo2 autocross events. All it would take is a serious dose of forced induction. A minimum output of 200 hp and 200 lb-ft of torque at the drive wheels, coupled with a wide, useable power band was determined to be the secret for fast times on the race course. Getting to those levels of power was accomplished via a low-buck, do-it-yourself (DIY) turbo approach that coupled creativity, research, and frugal eBay shopping for turbo components. This DIY tactic also freed up some of the budget for critical safety and reliability components, such as AN-type fluid lines and high-quality engine internals.

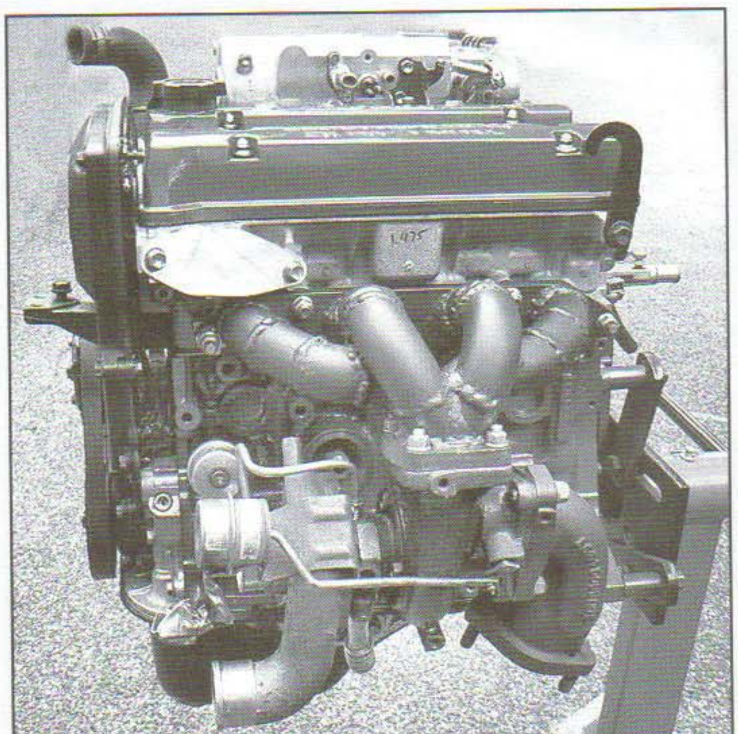
The project began with the procurement of a Japanese domestic model (JDM) variant of the stock Toyota 1.6-liter 4AGZE supercharged engine. The turbocharger that replaced the factory blower was sourced from a second-generation Mitsubishi Eclipse. The supporting hardware was then either fabricated by hand or adapted from other OEM turbo applications. Even the fuel injection and ignition controllers were constructed from basic electronic components. The results are an inexpensive, yet powerful vehicle, with a broad powerband. A side benefit of the project was the knowledge gained by the owner during the build; when constructing a purpose-built machine like this from scratch, you often learn more than you ever planned.

Turbocharger System Details:
• Turbocharger: 1997 Mitsubishi Eclipse T25 @ 15psi
• Exhaust manifold: Custom fabricated; 1.25-inch schedule 40 weld-el runners; 0.50-inch mild steel flange; TD06 turbine flange
• Intercooler: First-generation Ford Probe intercooler with reworked end tanks; cooling fan
• Boost Control: Custom ball-and-spring manual boost controller; ported internal T25 wastegate; Blitz Dual Drive blow-off valve
• Intake System: Stock Toyota 4AGE manifold
•Fuel Injection System: Lucas disc-type 550 cc/min injectors; Aeromotive 1:1 non-rising rate fuel pressure regulator; braided stainless steel fuel lines
• Control System: Owner-built Megasquirt stand-alone EFI controller
• Ignition System: Owner-designed and built MegaJolt Lite Jr standalone controller; Ford EDIS crank-fired ignition module
• Exhaust System: 3-inch; Dynomax muffler

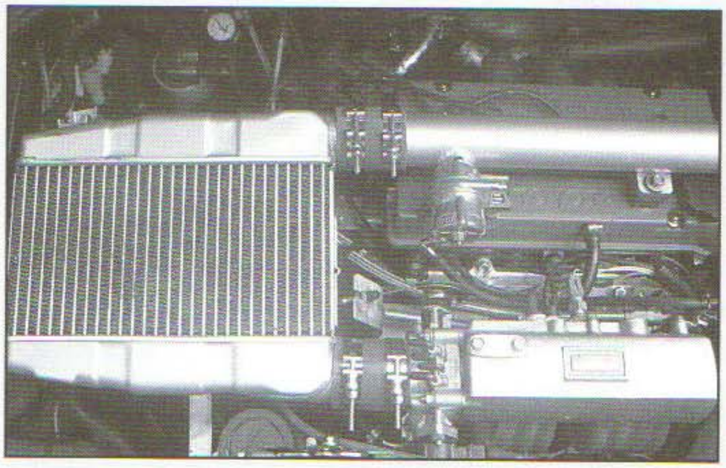
Other Significant Vehicle Details:
• Gauges: VDO Vision series boost gauge; VDO EGT gauge; Tech-Edge wide-band 02 meter; Megasquirt Digital Dashboard
• Engine modifications: 4AGZE OEM forged, coated 8.0:1 pistons; ARP fasteners; balanced and blueprinted long block; mild porting; TED Components 1mm oversized stainless steel valves; stock 4AGZE camshafts
• Drivetrain modifications: KAAZ limited slip differential; Redline MT-80 fluid; Fidanza flywheel; Clutchmasters Stage-3 clutch
• Chassis/Suspension: Wilwood forged 4-piston calipers (front); 1993 Toyota MR2 calipers (rear); Corrado 11-inch rotors (front and rear); Ground Control coil-overs; Koni race shocks; Suspension Techniques anti-roll bars (front and rear)
• Body modifications: Fiberglass rear engine deck lid with dual reverse scoops

Results:
• 15 psi of boost @ 3000 rpm; 18 psi at redline

The MR2 is compact, balanced, light, nimble, and mid-engined. The base vehicle has nearly everything you want in an autocross vehicle—except power. The naturally-aspirated engine generates roughly 95 rwhp and 85 lb-ft of torque. With the addition of a turbocharger and some clever DIY ingenuity, however, this particular MR2 now generates a potent 225 rwhp and 217 lb-ft of torque.

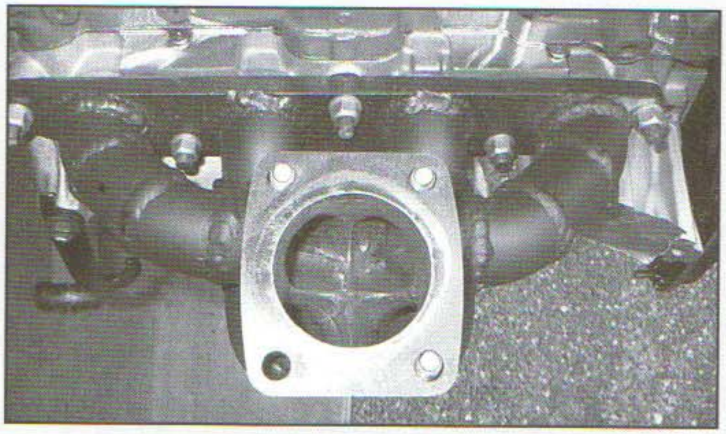


Strong and eager to rev, the Toyota 4AGE is a robust little engine that begs for forced induction. The turbocharger used in the build is from a second-generation Mitsubishi Eclipse. Sometimes dubbed the "T-Too-Small," the diminutive T25 turbo has proven to be nearly ideal for this 1.6-liter Toyota.

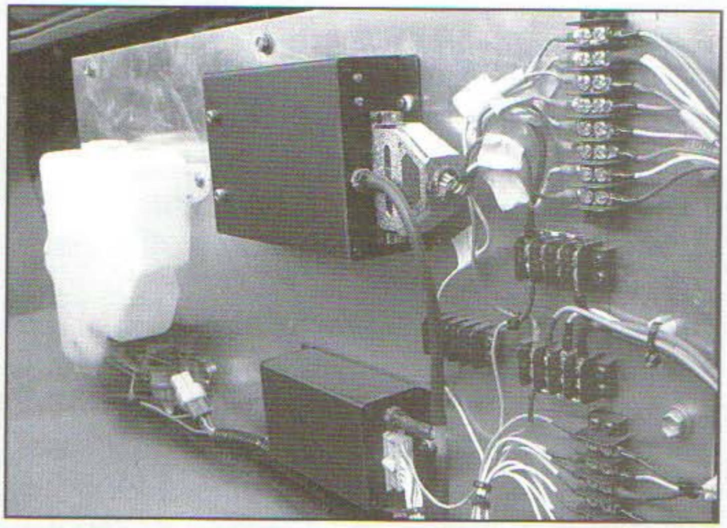


A modified Ford Probe intercooler was chosen for its cost, size, and excellent flow design. The Probe unit offers an efficient core design with good heat transfer characteristics. The top-mount placement is similar to the supercharged MR2 variants. When the car is in motion, air naturally flows from underneath the chassis, up through the intercooler, and out the engine lid. An 11-inch cooling fan boosts cooling at low speeds.

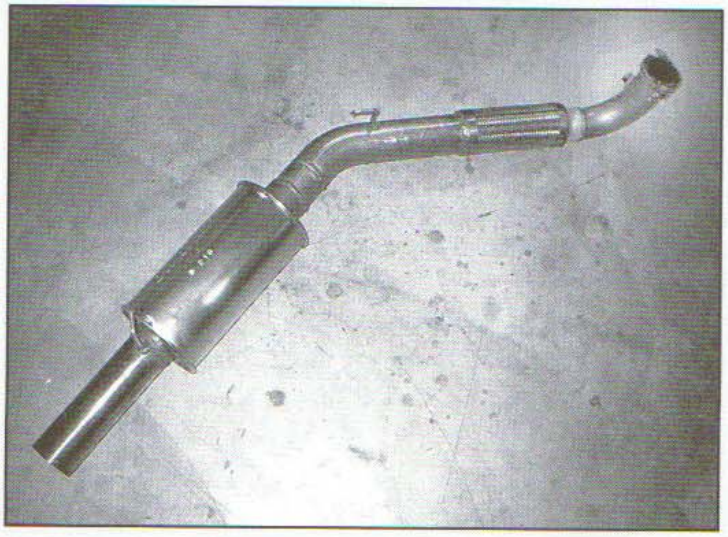
One of the first steps in turbocharging the engine was to fabricate an exhaust manifold from schedule 40 weld-els. The results are compact, durable, and very functional.



Even though the external welds aren't polished to perfection, the internal flow paths are smooth and efficient, with short, direct paths from the exhaust ports to the turbine inlet.

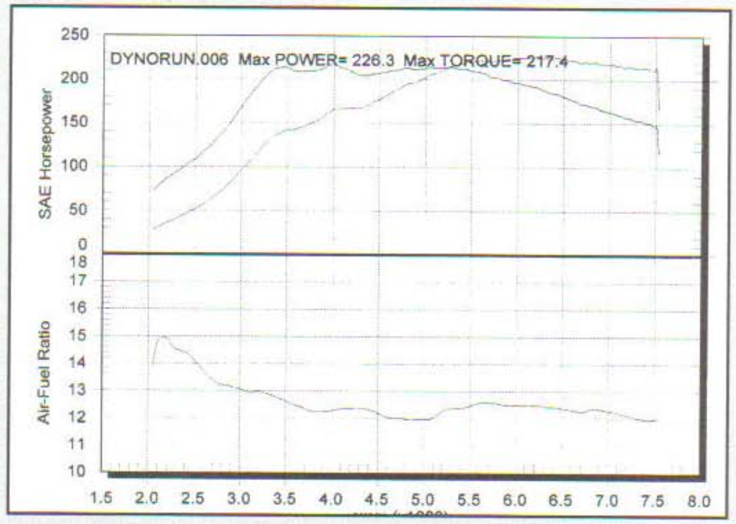


A DIY project like this provides an incredible opportunity to learn. The hand-built Megasquirt EFI controller (top) operates on a speed-density algorithm, allowing removal of the restrictive air-door AFM. Inspired by the success of the Megasquirt system, the vehicle owner designed and built the fully-programmable open-source ignition controller, which is the bottom black box shown here. Dubbed "MegaJolt Lite Jr," it is now in use in over 500 vehicles around the globe.



The exhaust system is a simple design that exits immediately behind the car. Total weight from the downpipe rearward is just 16 lbs. This layout offers little flow restriction and low backpressure.

The MR2 waiting its turn on an autocross starting grid. Note the engine lid with its unusual rearward-facing vents that help remove heat from the engine bay and intercooler.



The tuning and refinement process for the car was both incremental and lengthy, first focusing on idle, then light load, cruise, and then moderate load. The data logging and closed-loop features of the Megasquirt system were used extensively for this first phase of testing. Finally, WOT tuning was undertaken with a wide-band meter installed.

PROJECT VEHICLE 2
1971 DATSUN 510 SEDAN—PERFORMANCE DAILY DRIVER
Swapping in an OEM Turbo Engine From Another Vehicle

1971 2-door Datsun 510 with a surprise lurking under the hood. The license plate gives only a hint that 335+ horsepower is on tap from a twin-turbocharged Nissan V6.

The Datsun 510 sedans of the late sixties and early seventies were renowned for their stellar handling and basic simplicity, beating many larger and more expensive vehicles in the SCCA Trans-Am race series. They were not, however, known to be titanic power producers. The original 1.6-liter OHC powerplant was inexpensive and reliable but generated only 97 horsepower and 100 lb-ft of torque at the crankshaft. The non-crossflow cylinder head and two-valve layout may have been robust, but by modern standards the engines are antiquated. Contemporary owners of these cars routinely swap in larger four- and six-cylinder drivetrains to compete at today's performance standards.

The owner of this particular "dime" wanted a wolf in sheep's clothing, a modern performance vehicle in the guise of 1970s econobox sheet metal. A minimum goal of 250 lb-ft and 250 hp at the wheels was desired, as were fast throttle response, 12-second quarter-mile times on pump gas, and 25+ mpg—tall orders for such a diminutive car, but ones that could be achieved by careful planning and design.

The solution, as shown on these pages, was to replace the existing drivetrain with a twin turbo 3.0-liter DOHC V6 from a mid-nineties Nissan 300ZX. Early in the project, a conscious decision was made to utilize as many OEM Nissan parts as possible. This resulted in a reduction in the time required for shakedown, bug chasing, and fabrication. It was also decided that "form would follow function," that nothing would be added or taken away that might reduce performance—but not at the cost of comfort or convenience.

Turbocharger System Details:

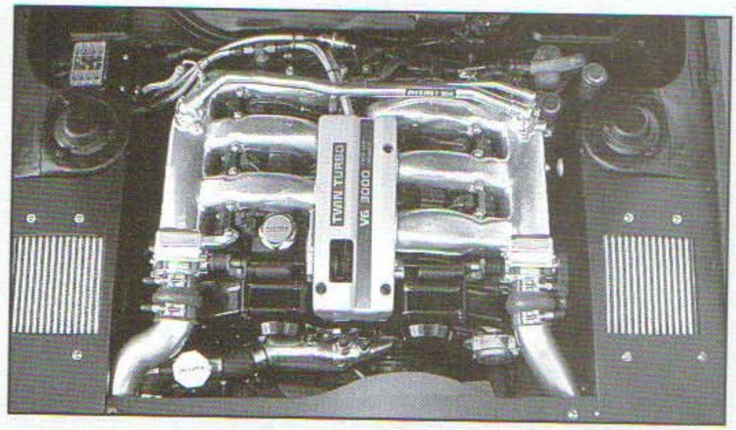
- Turbocharger: Dual Garrett TB22 @ 15psi Compressor: T3 Housing/0.42 AR/50 trim Turbine :T25 Housing / 0.48 AR / 62 trim
- Exhaust manifold: Stock 300ZX twin turbo
- Intercooler: Stock 300ZXTT intercoolers, mounted under the hood to minimize total intake length and improve throttle response
- Boost Control: Greddy Profec-B, Bosch recirculation valves
- Intake System: Custom dual MAF
- Fuel Injection System: Stock 300ZXTT except for Nismo (Nissan Competition) 555 cc/min injectors
- Control System: Reprogrammed factory ECU with Apexi SAFC-II piggyback fuel controller for fine-tuning
- Ignition System: Stock Nissan 300ZX TT crank-triggered ignition
- Exhaust System: Mandrel bent 2.5-inch from turbos, merging into single 3.5-inch exiting at stock location behind vehicle; Magnaflow 3.5-inch straight through muffler

Other Significant Vehicle Details:

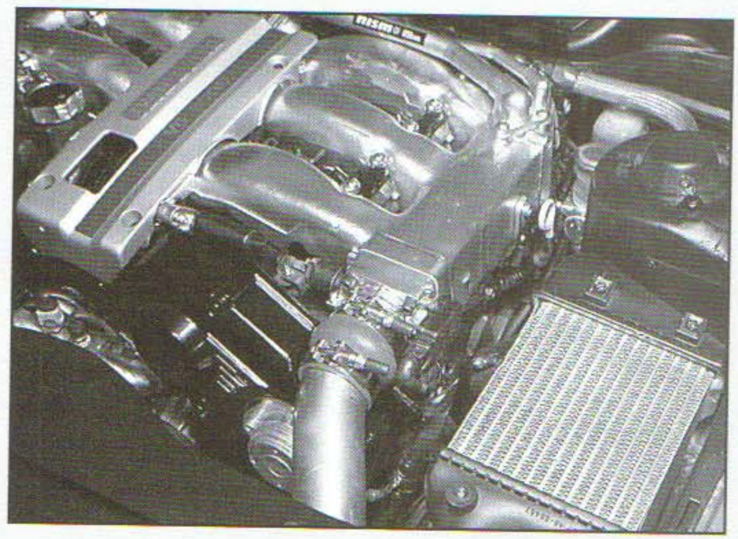
- Gauges: Boost/vacuum and in-cabin fuel pressure gauges
- Engine modifications: None (stock Nissan)
- Drivetrain modifications: Stock 300ZXTT transmission; Datsun 240Z limited slip differential, 300ZXTT wheels, calipers, and rotors; 280ZX brake master cylinder
- Body modifications: Aftermarket air dam added for intercooler intake; vents in hood for intercooler exit flow

Results:

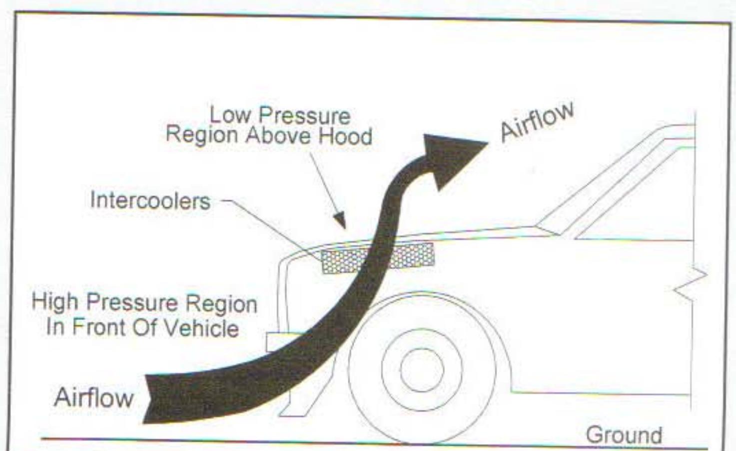
- 10 psi of boost @ 2000 rpm, 15 psi at 2500 rpm
- 336 rwhp @ 6400 rpm, 315 lb-ft @ 3400 rpm at 15 psi boost
- 12.8-second 1/4-mile time at 113.7 mph
- Fuel mileage 27.0 mpg highway



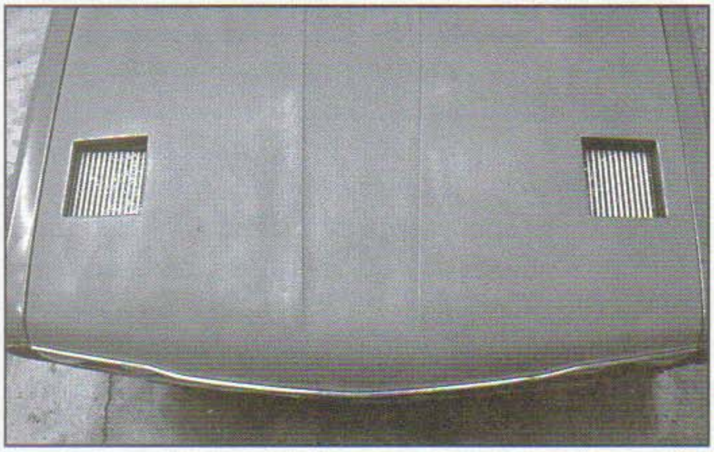
Sometimes the best way to turbocharge a vehicle is to swap in a complete drivetrain from another vehicle. Finding space, however, for such a large powerplant like this Nissan VG30DETT can be challenging. A lot of planning goes into a clean installation like this.



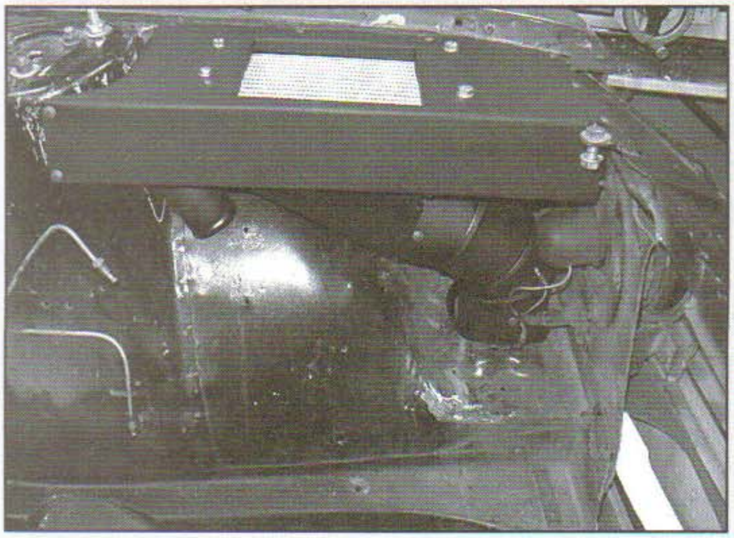
To minimize the total intake tract length from compressor to throttle bodies, the intercoolers were mounted horizontally in the forward corners of the engine bay.



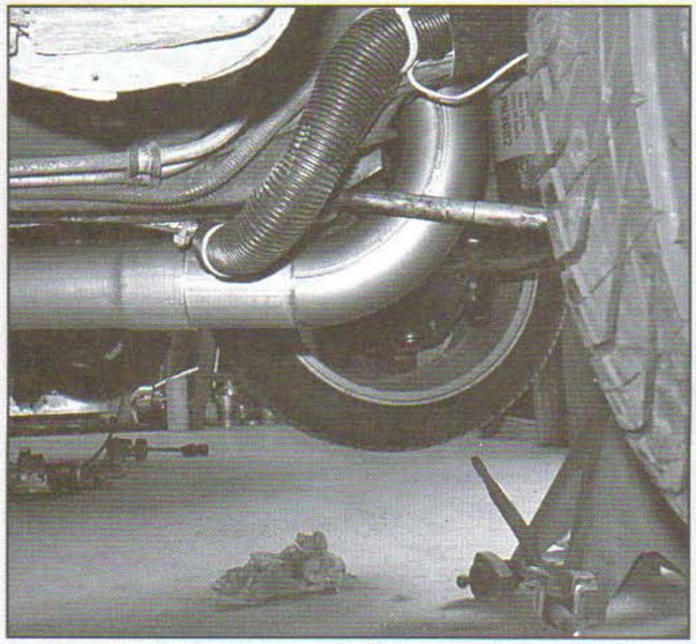
High pressure air in front of the car, coupled with a low pressure region on top of the hood, provide excellent airflow through the intercoolers.



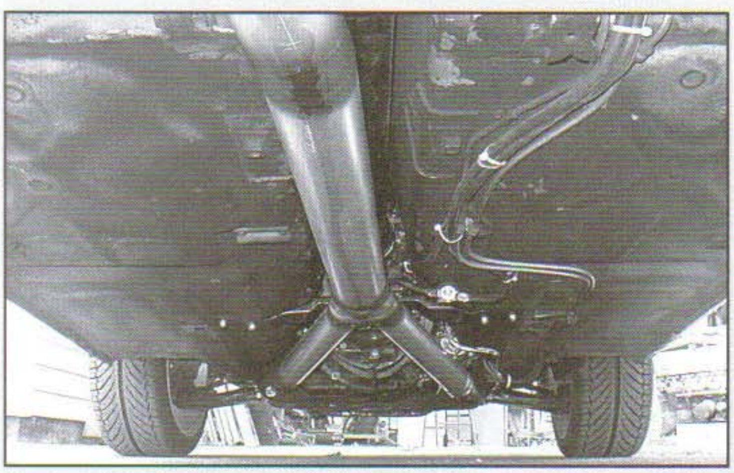
Discrete rectangular holes were cut in the hood to allow air warmed by the intercoolers to escape.



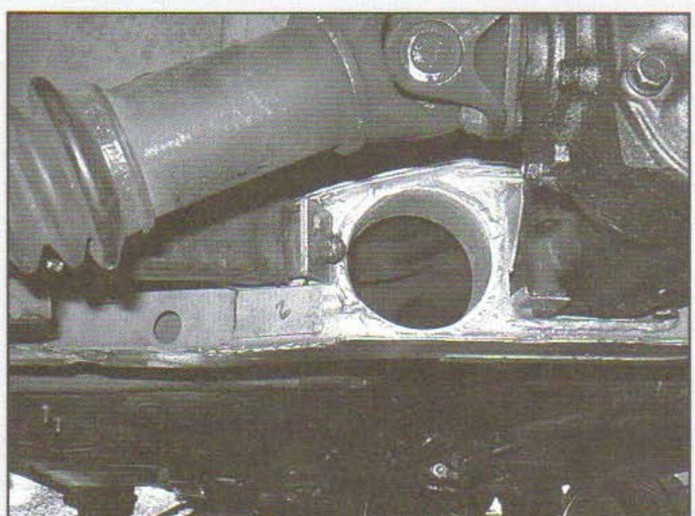
Sheet metal ducting was fabricated to gather and direct air from the lower air dam up to the underside of the intercoolers.



Downpipes from the Garrett T25 turbines were fabricated from 2.5-inch mandrel bent tubing. Note the large radius bends with no significant flow obstructions.



Originally, a 2-inch dual-into-2.5-inch single crushed-bend exhaust was installed. Exhaust flow was choked and only 7 psi of boost created, resulting in 260 rwhp. Switching to the 2.5-inch dual-into-3.5-inch single mandrel-bend system shown here opened up engine breathing, allowing 15 psi of boost and 335+ hp. Exhaust flow is just as important as intake on a performance turbocharged engine.



A large reinforced hole was formed in the rear cross-member for passage of the 3.5-inch diameter exhaust tubing.

PROJECT VEHICLE 3
1969 DATSUN 510 SEDAN—ULTRA-QUICK STREET CAR

Keeping Things Light and Simple

Unlike the other Datsun 510 featured on the previous pages, this particular one was built with a single performance goal in mind: quickness. To achieve the objective of ultra-fast acceleration, the power-to-weight ratio of the car had to be maximized. As Colin Chapman of Lotus fame once pointed out, reducing vehicle weight is just as effective as increasing power in the search for quickness. In fact, it's perhaps more effective, given that braking and cornering also receive the benefits of mass reduction.

The owner of this vehicle selected a Mazda 13B rotary engine as the starting point of the project. These amazingly compact engines have very few moving components and are relatively lightweight. They also respond well to forced induction; a little boost goes a long way toward increased torque output.

The downside, of course, to an ultra-lightweight vehicle project is that every ounce matters. The owner calculated early in the planning stages that charge cooling would not be required if boost production was limited to 10 psi or less. This allowed the planning of the engine bay without consideration of bulky intercooler plumbing or heavy water-injection tanks. Fuel injection was also rejected; a basic draw-through four-barrel carburetor was planned from the beginning to keep things very simple.

Designing a single-purpose project like this entailed careful consideration before the first wrench was lifted or the first weld bead put down. Everything had to be thought out in detail to ensure that no unnecessary compromises would be required late in the game. Incorporating the turbocharger system as an integral part of the overall packaging from the beginning (including the decision not to use charge cooling) was critical. The results for this particular project are 1710 lbs of blindingly quick acceleration.

1969 Datsun 510 with turbocharged Mazda rotary engine. Horsepower was added and vehicle mass reduced, improving both numerator and denominator in the quest for a maximum power-to-weight ratio.

Turbocharger System Details:

- Turbocharger: RotoMaster T04B @ 10 psi; turbine wheel size P, housing A/R 0.81
- Exhaust manifold: Custom, made from Racing Beat header flange, a RotoMaster turbine housing flange, and 0.125-inch mild steel tubing bends
- Intercooler: None
- Boost Control: RotoMaster wastegate, manually adjustable from 5-9 psi
- Intake System: Holley 390 CFM 4-barrel mechanical secondary carburetor; power valve diaphragm chamber connected to the compressor outlet, making the power valve sensitive to boost pressure; racing floats, custom fuel bowl baffles, and vent whistle
- Fuel Supply System: Carter electric fuel pump
- Control System: None
- Ignition System: Stock Mazda
- Exhaust System: Mandrel-bent 3-inch mild steel tubing; 2-chamber Flowmaster muffler with custom sound baffle on tip; all components ceramic coated

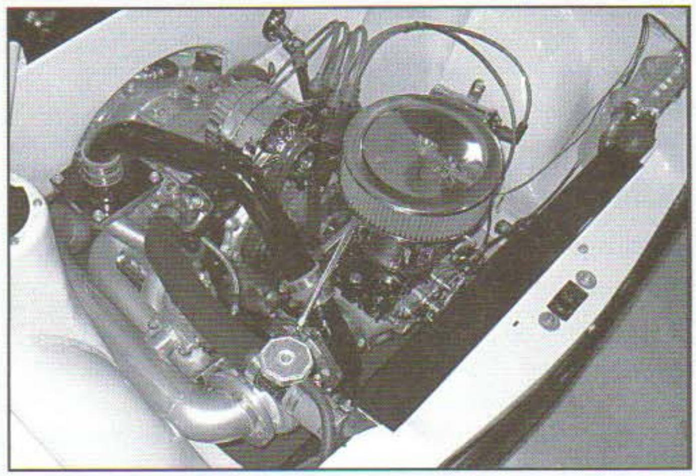
Other Significant Vehicle Details:

- Engine modifications: None (stock Mazda)
- Drivetrain modifications: Stock Mazda transmission; Jaguar rear suspension; custom wheels; Corvette brakes, coil-over suspension; rack and pinion steering
- Body modifications: Smoothing and filling of body panels

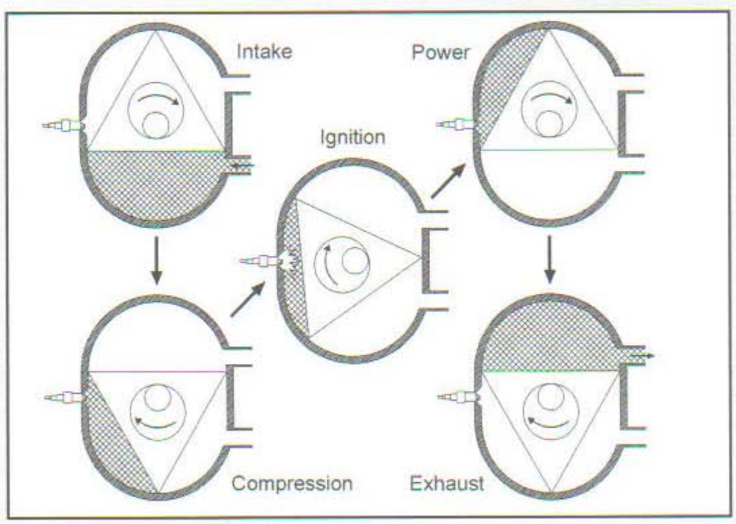
Results:

- 1710 lb total vehicle weight
- 0–60 mph in 4.0 seconds

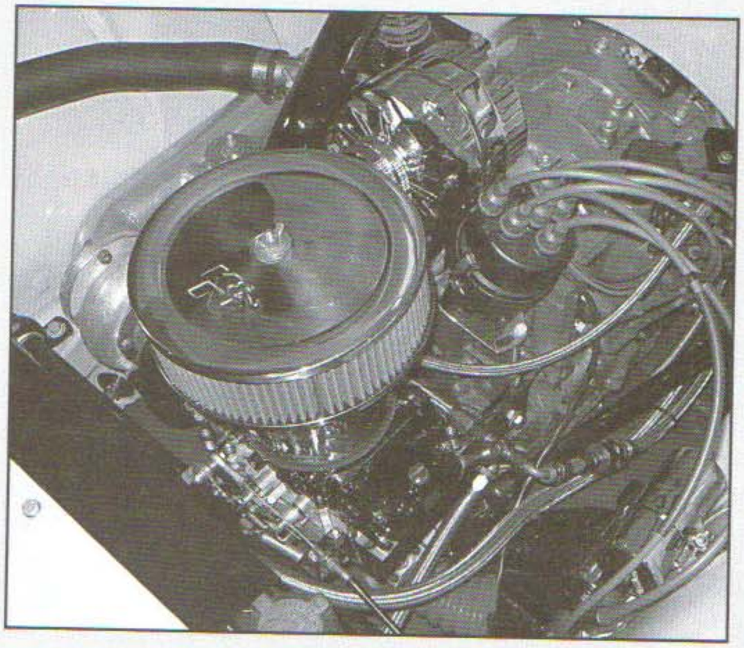
The concept of quickness permeates this car. With 300 lb-ft of torque on tap and only 1710 lbs to move, acceleration is nearly instantaneous.



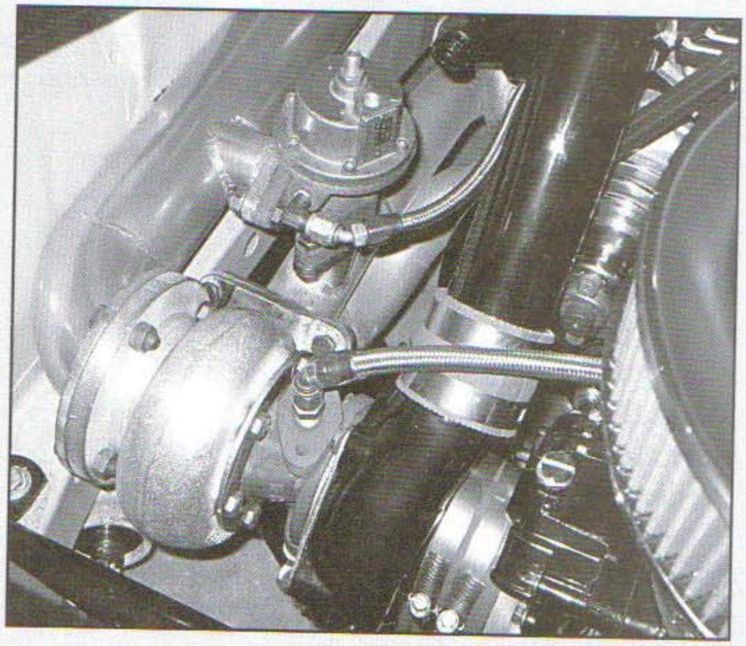
Rotary engines respond very well to forced induction. Just a little boost makes a big difference in output. Note the direct routing from compressor to intake manifold.



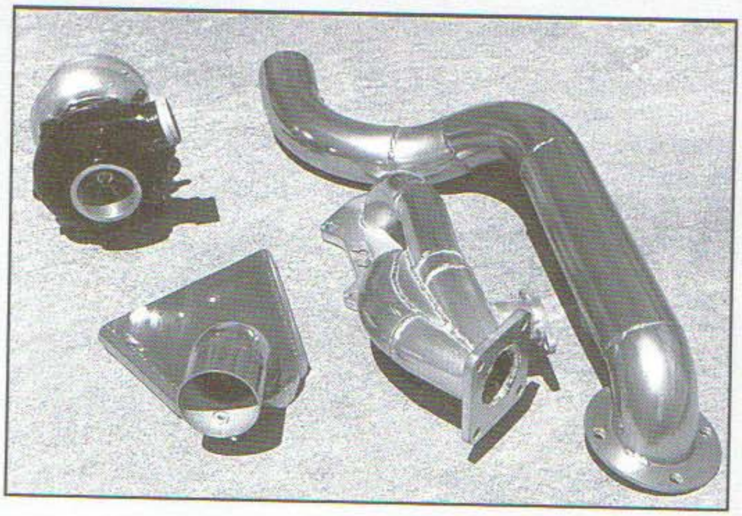
The four "strokes" (plus ignition) of a rotary engine combustion cycle. It looks different than a piston engine, but a rotary has exactly the same four Otto-cycle phases: intake, compression, power, exhaust. It also responds the same way to forced induction; introduce more air into the chamber during the intake phase, and the engine can produce more power.



Careful tuning and limiting boost to 10 psi, detonation is kept in check without the use of an intercooler. The exhaust manifold is designed to mount the turbo in front of the engine, where there is plenty of space and it can be kept low.



A manually adjustable RotoMaster wastegate is used for boost control. Note the braided stainless-steel lines and simple, direct routing of lubrication and control plumbing.



High quality workmanship is evident everywhere on this car. The custom-made setup utilizes a large turbocharger appropriate for the 13B rotary engine. All exhaust components are ceramic coated. Everything was intended to be uncomplicated and direct. "Light and Simple" was the mantra oft repeated during construction.

A narrowed Jaguar rear suspension with 12-inch wide rear tires was required to tame the 300 lb-ft of delivered torque. Note the lack of exhaust tubing. To further reduce weight and simplify the layout, the exhaust system exits in front of the rear wheels.

PROJECT VEHICLE 4

1994 HONDA CIVIC DX COUPE—A DAILY-DRIVEN TRACK CAR

Race-Bred Turbocharger Equipment Applied to a Street-Driven Vehicle

Honda debuted its Civic in 1973, billing the diminutive car as a roomy compact that offered good gas mileage for a low price. Since then, Honda has continually improved the car, releasing a new and improved "generation" of the vehicle every few years. Each of these model releases were accompanied by engine and accessory upgrades, but Honda's basic formula has never changed: build a quality car and couple it with good performance and excellent reliability. It's been a winning combination for decades.

Modern performance enthusiasts, however, see Honda's flagship as something altogether different than a frugal econobox. For these modern day hot-rodders, the solid Civic is a platform upon which serious horsepower can be built. There are literally tens of thousands supercharged, turbocharged, and nitrous-equipped Honda Civics burning up racetracks and thundering down Main streets around the world. The stout B-series engine that powers these ubiquitous "rice rockets" has evolved into the small-block Chevy for an entire generation of go-fast fanatics.

The owner of the 1994 Civic shown here had two specific goals in mind when he started the project. First, he wanted a reliable daily driver that could take him to and from work every day and deliver acceptable mileage. Second, he wanted a competitive drag racer that would post 10-second and faster quarter-mile times in a variety of NOPI/NDRA and NHRA drag classes. To achieve this latter goal, it was calculated that somewhere in the neighborhood of 400 lb-ft and 700 horsepower were required. This in turn meant a very large turbo and fuel system. It also meant serious tuning, testing, and the development of state-of-the-art exhaust and intake manifolds.

The engine selected for the car was a 1.8-liter DOHC inline-4 from an Acura Integra GS-R. The B18C1 stock cylinder liners were bored out and ductile iron sleeves installed and bored, increasing displacement to 2.0-liters. A stock crankshaft with forged internals was then fitted. Next, a massive dual ball bearing Garrett GT4088R turbo was chosen as a basis of the forced-induction project. A fully-engineered top-mount exhaust manifold was installed, as were a race-inspired fuel injection manifold, 1000 cc/min fuel injectors, a 4-inch exhaust system, and a variety of other imposing turbo hardware. The result is a car that clicks off the quarter mile in excess of 144 mph, while remaining mostly streetable and delivering good gas mileage in a nondescript package.

This 1994 Honda Civic is a rolling showcase for the owner's aftermarket turbocharger company. In addition to running 10-second quarter miles at 144 mph, the car is driven to and from work every day, and has been piloted cross country twice.

Turbocharger System Details:

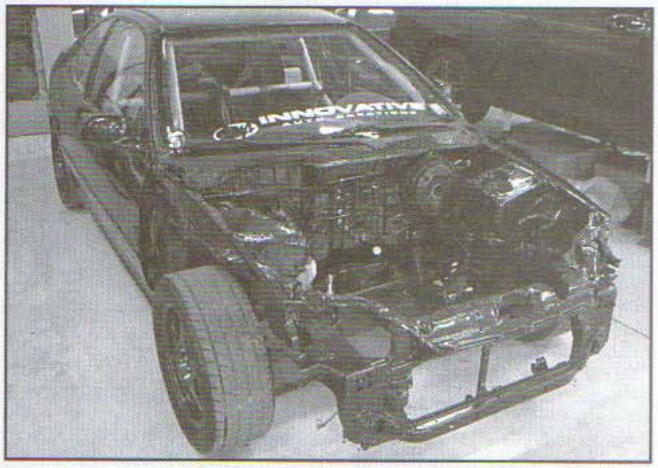
• Turbocharger: Dual ball bearing Garrett GT4088R @ 38 psi. Compressor: 0.58 AR / 88 mm wheel @ 52 trim; Turbine: T4 divided inlet housing / 0.85 AR / 77 mm wheel @ 78 trim
• Exhaust manifold: Full-Race B Series top mount T4/44 manifold with divided merge-pulse collector and robotically TIG welded equal-length and equal-pressure runners
• Intercooler: Full-Race bar and plate, 4.5 x12x18 inch with plenum-style end tank
• Boost Control: MSD Launch Boost Controller; TiAL 50 mm blow-off valve; TiAL 44 mm V-band wastegate
• Intake System: Full-Race B-series intake manifold; 3-inch aluminum 6061-T6 charge pipes; 75 mm throttle body
• Fuel Injection System: Sequential; 5 Bar MAP sensor; 1008 cc/minute injectors
• Control System: NepTune OEM Honda ECU-based system
• Ignition System: ECU Controlled MSD Digital 6
• Exhaust System: Four-inch downpipe with conical diffuser; 4-inch Full-Race aluminum 6061-T6 exhaust; Magnaflow muffler; 4-inch V-band connectors

Other Significant Vehicle Details:

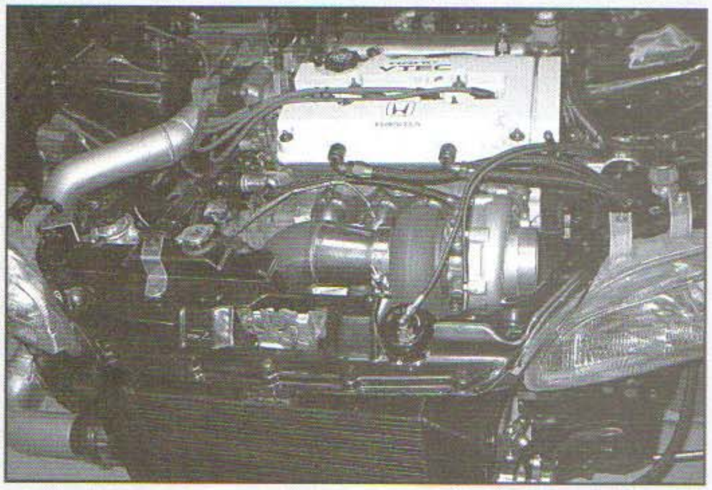
• Gauges: Boost; individual cylinder EGT; fuel pressure; wide-band O_2; water temp; oil temp; oil pressure
• Engine Modifications: ERL-sleeved block; Manley pistons; Full-Race connecting rods; Integra Type R camshafts; Headgames port work and valve job; balanced reciprocating assembly
• Drivetrain modifications: Exedy twin-disc clutch; Quaife helical gear-based limited slip differential; 300M axles; stock gears and transmission case

Results:

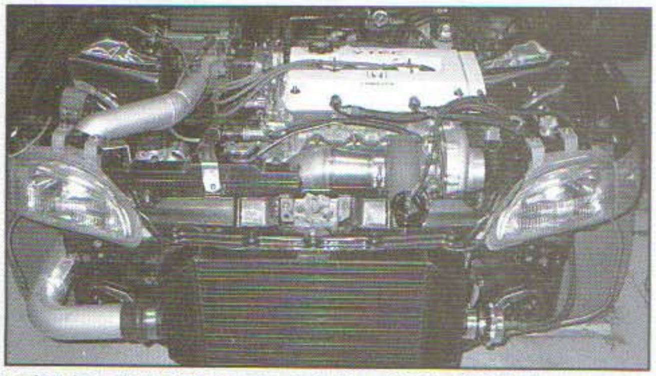
• 700 rwhp @ 7250 rpm, 515 lb-ft @ 7000 rpm at 36 psig boost
• 10.4-second 1/4-mile time at 144 mph



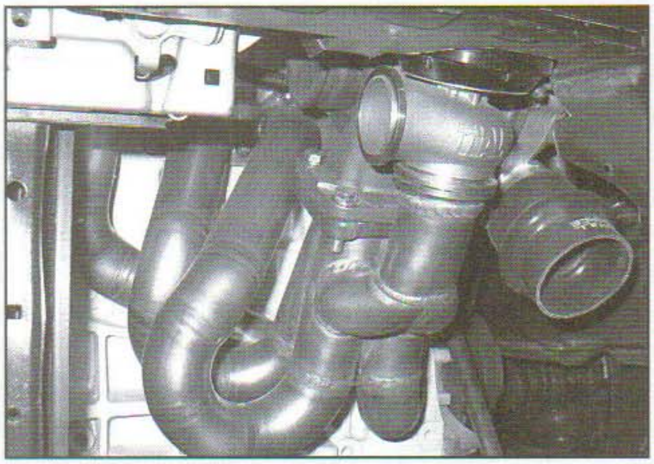
The automotive equivalent of a blank sheet of paper. Anything that was not required for horsepower, torque, or speed production was removed prior to starting.



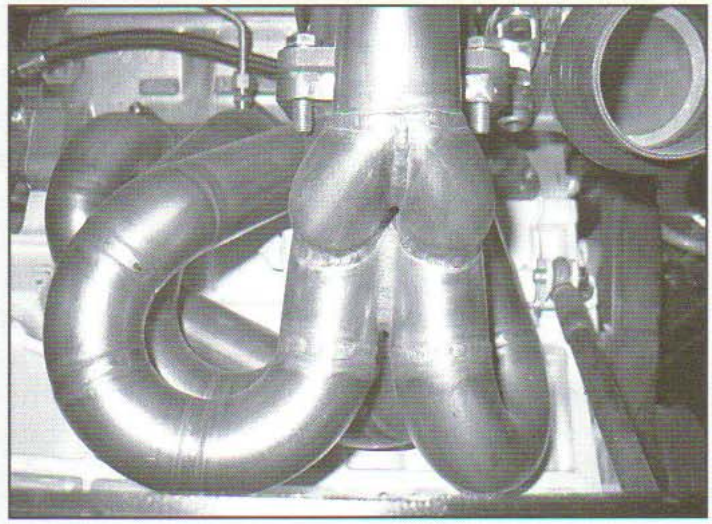
A textbook high-performance Honda turbo setup employing a very large turbocharger and fuel system. The dual ball bearing Garrett GT4088R turbocharger dominates the engine bay. To achieve 700 hp at the drive wheels, the compressor was required to generate 36+ psig of boost.



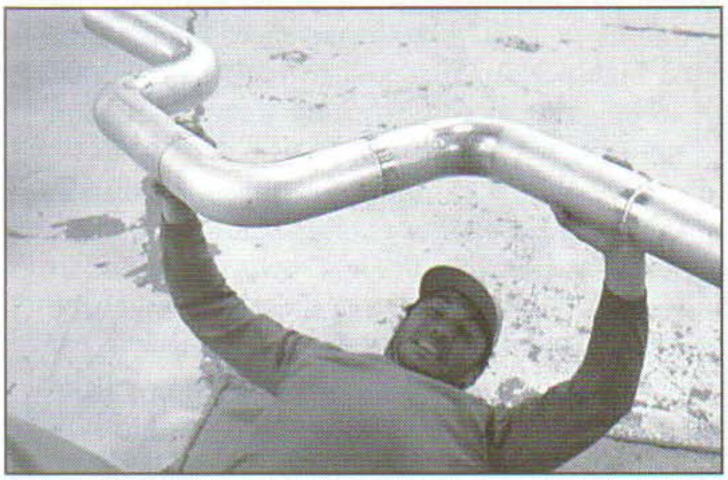
The engine is a far cry from the 1.6-liter, 108 hp/68 lb-ft motor that Honda originally provided in the car. The front-mounted air-to-air intercooler is based on a bar-and-plate core. Custom end tanks were fabricated by Full-Race. Fifty millimeter diameter blow-off valve is by TiAL and is mounted directly on the intercooler end tank. Note the diverging cone-shaped diffuser exiting from the turbine into the downpipe.



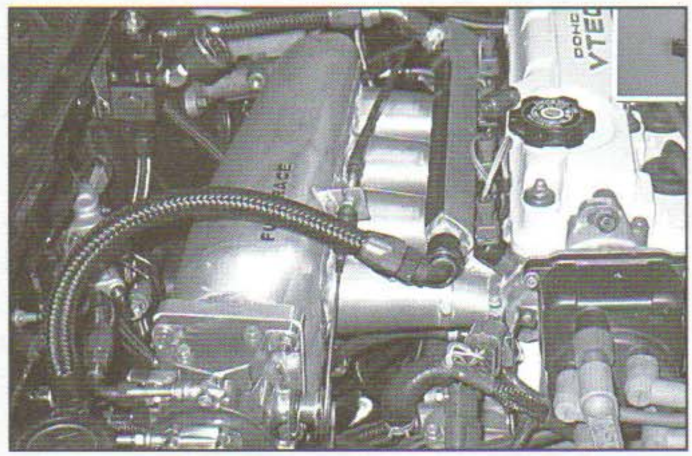
A key part of generating reliable mega-horsepower is a well-engineered exhaust manifold. Individual runners were sized to deliver equal and maximum pressure pulses to the turbine. Wastegate is a TiAL 44 mm unit.



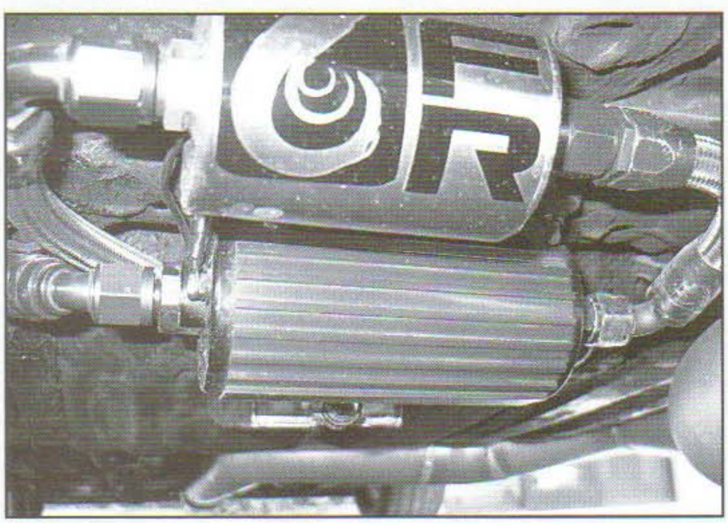
Want your welds to look this good? Hire a robot. The stainless steel 316-type thick-wall tubing is joined with a proprietary robotic welding process.



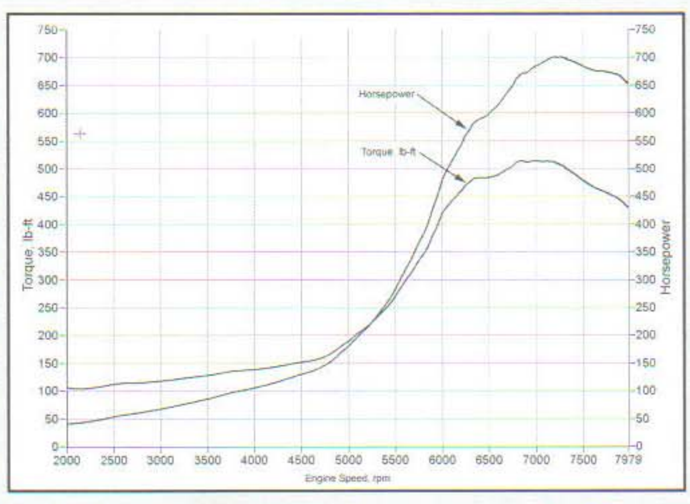
The exhaust system is fabricated from 4-inch aluminum 6061 tubing. Total weight is just 10.5 pounds. It's not as heavy as this guy makes it look.



The intake manifold is constructed of CNC-machined aluminum 6061-T6 billet runners with ASME-type venturis, each with a taper calculated for maximum flow velocities with minimal pressure drop. The Full-Race CFD-designed plenum is cast in aluminum.



It takes a serious amount of fuel to support 700 hp. The external-type fuel pump is an Aeromotive 1000 liter/hour unit attached to a Full-Race external fuel sump.



On the dyno, the little Honda put down an incredible 515 lb-ft of torque and over 700 hp to the front wheels. Boost pressure peaked at 36 psig. Fuel was high octane C16 race gas. If this plot doesn't convince you of the possibilities of forced induction, nothing will.

PROJECT VEHICLE 5
1991 FORD MUSTANG GT—DUAL PURPOSE PERFORMANCE
Custom Single-Turbo Kit for Street and Strip

Early nineties Ford Mustang GTs arrived stock from the factory with roughly 225 hp at the crankshaft. By today's standards, these factory 5.0-liter (302 cubic inch) V8s are underpowered for anything other than grocery-getting work. There are many ways to increase the output from Ford's venerable 302, but choosing the right path depends strongly on the final desired performance goals, as well as the fortitude to not accept compromises along the way.

In his long quest for more horsepower, the owner of the Mustang shown here went through a variety of different engine modifications and configurations, ranging from purpose-built stroker motors, to nitrous-equipped engines, to a poor-quality aftermarket turbo kit that never quite fit correctly and was pushed seriously past its limits. In mid-2003, the owner was fed up with these halfway solutions and expensive repair bills. It was time for a total and focused engine makeover to take place under the hood.

The primary goal of the reconstruction was "streetability," combined with high horsepower. This meant 100% factory-level reliability, near-stock sound output…and a 140mph trap-speed target in the quarter mile. To achieve this ambitious level of refined high-performance and to propel the 3200+ pound vehicle through the quarter-mile traps at such prodigious speeds, a quality forced-induction system was required.

The engine was assembled from the ground up and coupled with a custom single-turbo installation built specifically for the car. A standalone engine management system was also included to allow precise control over the air-fuel mixture under all operating conditions. The GT now sports a Dart engine block, AEM engine management with wide-band O_2 sensing, and a well-engineered turbo system by Rusty Weining of Tucson. More importantly, the car can now routinely run low 10-second/140 mph quarter-mile blasts on the weekends, yet still provide effortless commuting to and from work during the week. This is called having your cake and eating it, and it's the direct result of good planning and no compromises.

This unassuming Fox-bodied Mustang GT serves double duty as a weekday daily driver and weekend racer. A single-turbo system delivers 700 hp and 700 lb-ft of torque to the rear wheels. The only exterior hint of the turbo system is the intercooler nestled into the front bumper.

Turbocharger System Details:

• Turbocharger: Garrett GT42, modified by Limit Engineering. Compressor: T04S housing / 0.70 AR / 74 mm wheel, GTQ trim. Turbine: 0.83 AR tangential exhaust housing with 3.5-inch V-band

• Exhaust Manifold: Custom 14-gauge mild steel 1-3/4-inch tubular primaries that merge into a T4 flange; driver's side manifold accepts 2.5-inch cross-over pipe (16-gauge, mild steel)

• Intercooler: 24x12x3.5-inch extruded core, 3-inch center inlet and outlet built by Mental Addiction Motorsports

• Boost Control: TiAL 35 mm wastegate; GM boost solenoid controlled by engine management system; HKS SS blow-off valve between turbo and intercooler inlet

• Intake System: Trick Flow TFS-R lower intake manifold and Reichard Racing Billet upper manifold

• Fuel Injection System: Siemens Deka 83 lb/hour low impedance injectors; custom low impedance injector driver box (8 x 25 Watt, 8 ohm resistors); dual external Walbro 255 lph high pressure fuel pumps; Modular Mustang Racing sumped fuel tank; Aeromotive fuel pressure regulator

• Control System: AEM engine management system

• Ignition System: AEM capacitive discharge ignition box; Accel/F.A.S.T. Dual Sync Distributor; stock coil

• Exhaust System: 3.5-inch downpipe; 3.5-inch Y-diverging pipe; factory-style 2.5-inch cat-back system with Dynomax Ultraflow mufflers

Other Significant Vehicle Details:

• Gauges: AEM wide-band air/fuel ratio gauge; Autometer boost, water temp, fuel pressure

• Engine Modifications: 1st Performance 316-cubic inch long-block with Dart Iron Eagle Block, Eagle 3.1-inch forged stroker crank, Eagle 5.4-inch forged H-beam connecting rods, TEA-ported TFS Twisted Wedge Heads, Cam Motion turbo cam

• Drivetrain Modifications: Modular Mustang Racing Tremec TKO900 5-speed; Lakewood bellhousing; Ford aluminum driveshaft; 31-spline Moser axles; Detroit Tru-trac differential; 3.27 gear ratio; McCleod twin disk clutch

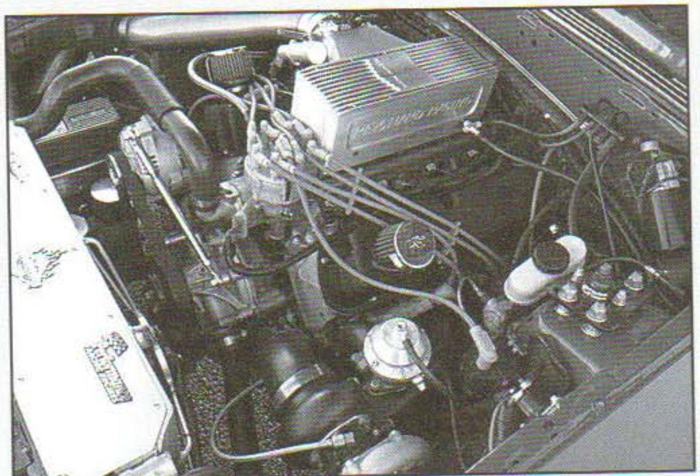
• Body Modifications: Front bumper modified for intercooler airflow

Results:

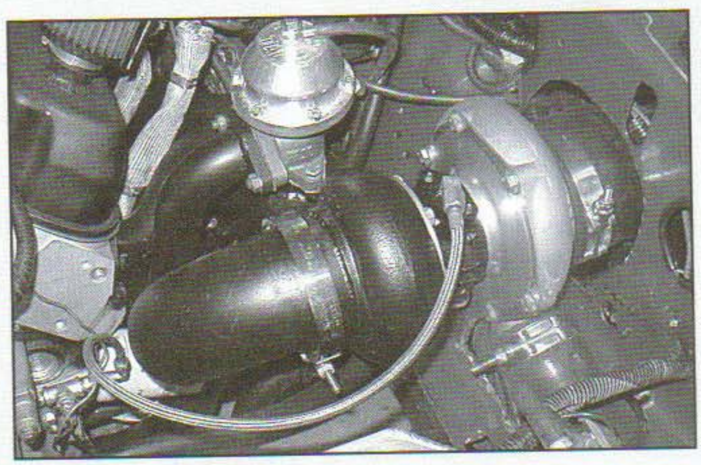
• 15 psi of boost @ 3200 rpm

• 700 rwhp from 5200 to 6000 rpm; 700 lb-ft torque from 4000 to 5200 rpm

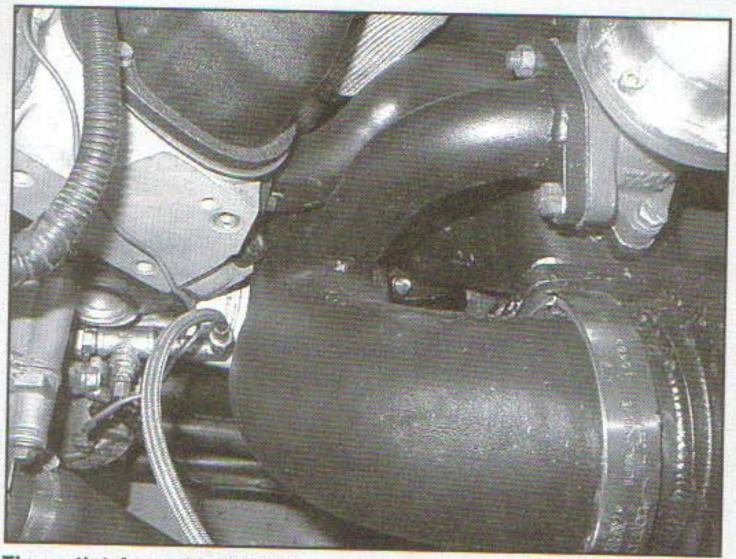
• 10.25-second 1/4-mile time at 141 mph



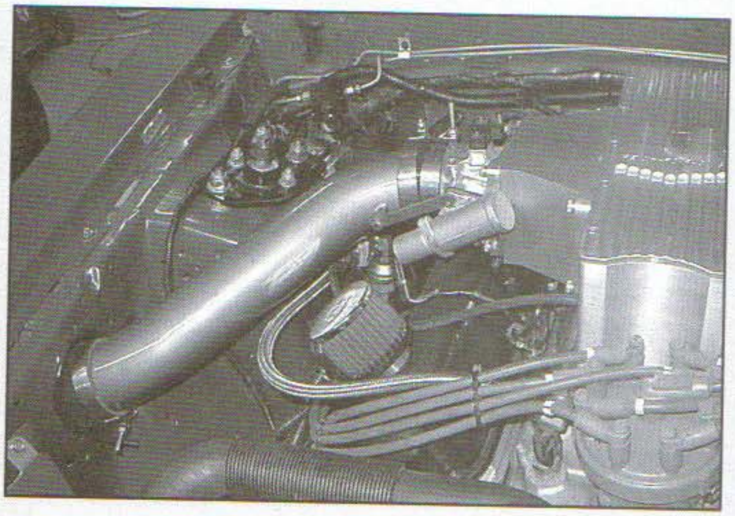
The mounting location of the Garrett GT42 turbocharger provides an uncluttered engine bay, with plenty of room for changing sparkplugs and working around the engine. The car has no trouble idling in 115°F Phoenix traffic. Taking the time to plan a system properly always pays off in the end.



Nothing fancy here, just well-engineered packaging. Note the compressor air intake that is fed cool outside air through a hole in the driver's side fender well.

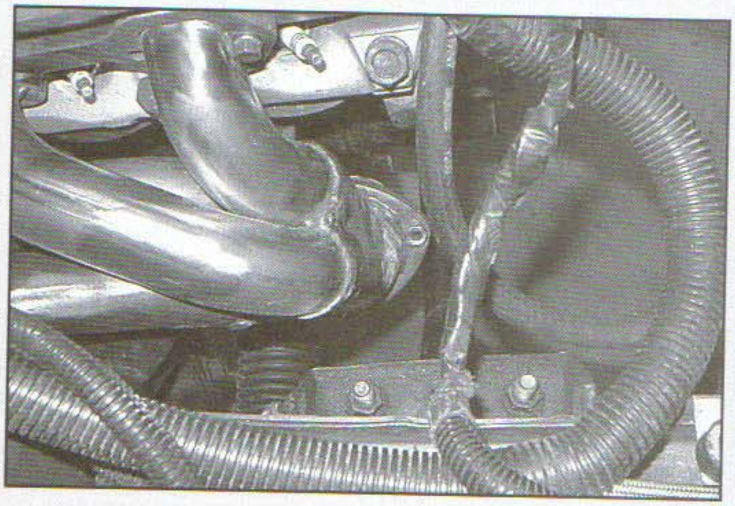


The outlet from the TiAL 35 mm wastegate feeds into the 3.5-inch turbine downpipe.

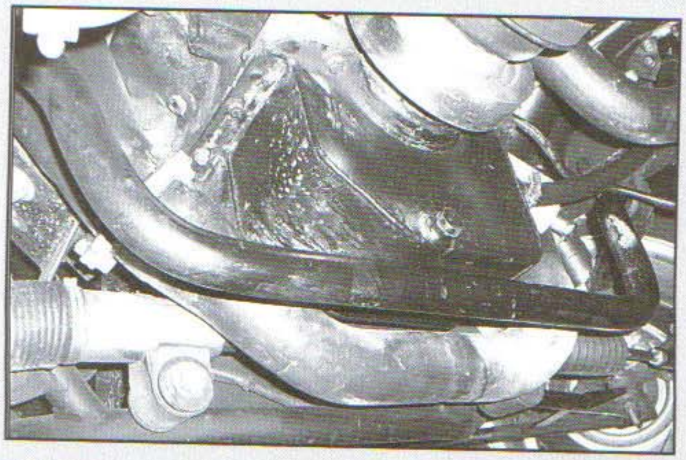


The supply piping from the front-mounted intercooler is routed through the passenger-side fender well. Form follows function.

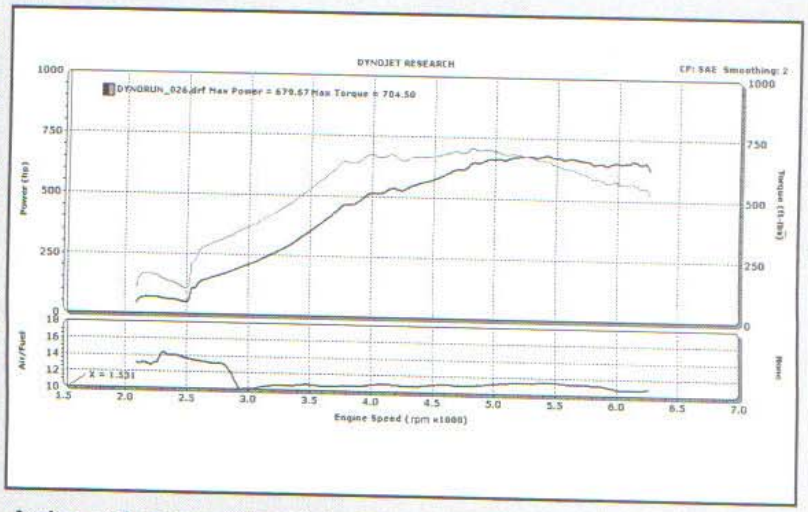
The old driver-side log-style exhaust manifold is shown for comparison with the current tubular-style manifold. Peak boost now occurs 700 rpm earlier in the rev range.



Passenger-side exhaust manifold merges forward and then feeds down below the front of the engine. Note the smooth and gradual tubing bends.



The crossover pipe that connects the passenger-side exhaust manifold to the driver-side is routed between the steering rack and the anti-roll bar. It's a tight squeeze to keep a direct route like this, but worth it for maintaining as much exhaust energy as possible on its way to the turbine.



A nice, wide torque curve that peaks at over 700 lb-ft at the rear wheels. Power output is an equally-impressive 679 hp.

PROJECT VEHICLE 6
1969 CHEVROLET CAMARO—PRO TOURING MUSCLE CAR
Twin Turbocharging a Small-Block Chevy

The 1967–'69 Chevrolet Camaro is one of the greatest incarnations of classic American iron ever to come out of Detroit. Muscular, but not burly; handsome, but not flashy, the Camaro appealed to a wide segment of the populace. That it was available with a variety of engines, ranging from a frugal in-line six-cylinder to a selection of ground-pounding V8s, certainly added to its allure. But the real reason the first-generation Camaro found a permanent place in automotive history was its seemingly endless ability to respond to aftermarket tuners, enthusiasts, and racers. In the right hands, the already-potent muscle car was capable of dominating almost any motorsport event it entered, from drag racing to autocross to road racing.

The beautiful 1969 car shown here is owned by Charley and Shirley Lillard of sunny California. They wanted a street machine with aesthetic appeal, but also one that could be driven reliably for long distances in so-called "power tours" sponsored by hot-rod magazines and sports car clubs. They also wanted performance—and plenty of it. In a previous incarnation, the car was a naturally-aspirated slayer of Mustangs, but once the horsepower addiction took hold, significantly more performance was demanded. A minimum of 800 lb-ft of torque and 1000 flywheel hp were targeted by the owners. This naturally got them thinking about forced induction.

The car's previous owner, Mark Stielow, a performance ride and handling engineer at GM, was summoned back to oversee the twin-turbo transformation. In the engineer's capable hands, the car's racing aluminum engine block was bored out to 4.125-inches and fitted with forged pistons and a de-stroked crankshaft. The resulting 389 cid short block was then capped with aluminum heads and a hand-built fuel injection system. Then the real work began, with a custom twin-turbo induction system built from the groundup. As shown here, the results are stunning, both visually and viscerally. Decades after it rolled off the assembly line, this first-generation Camaro has once again proved its dominance in the never-ending pony car wars.

1969 Chevrolet Camaro: clean, elegant, and wickedly fast. The car was a featured build-up in *Popular Hotrodding* magazine. In its current configuration, the engine generates over 1026 hp at the flywheel. The builder reports that the car is very mild mannered until it comes up on boost, at which point you have to pay attention as things happen very quickly.

Turbocharger System Details:

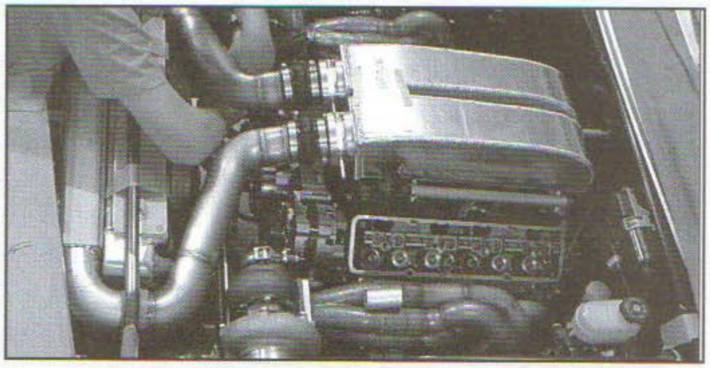
- Turbocharger: Twin 63 mm Precision Turbo units with ball bearing center section, water-cooled, tangential exhaust housing
- Exhaust manifold: Wheel to Wheel–built; stainless 304 3/8-inch thick flanges; stainless 321 1-7/8x0.065-inch thick tubes; stainless 321 merge collector
- Intercooler: 26x24x3-inch Precision Turbo core, Wheel to Wheel top and end tanks
- Boost Control: TiAL blow-off valves
- Intake System: Wheel to Wheel fabricated dual intake plenums and throttle; Kinsler intake
- Fuel Injection System: 65 lb/hr F.A.S.T. injectors; Bosch twin high-pressure fuel pumps; Kinsler fuel pressure regulator
- Control System: F.A.S.T. engine management system
- Ignition System: F.A.S.T.-managed; MSD crank trigger; MSD distributor
- Exhaust System: Stainless 304 3-inch tubing; dual Stainless Works chamber mufflers

Other Significant Vehicle Details:

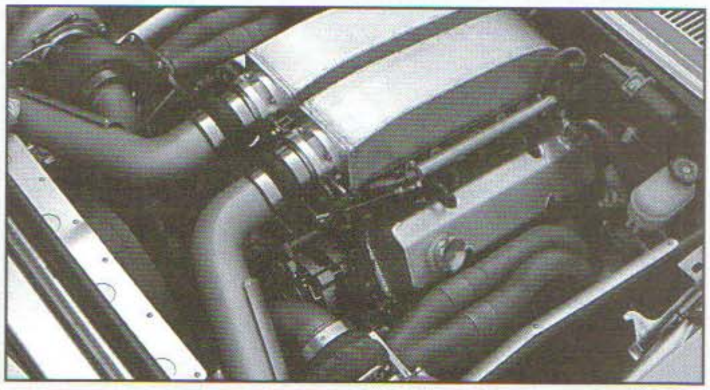
- Gauges: Autometer
- Engine modifications: GM racing aluminum short block; Lunati crankshaft; 6-inch Oliver rods; JE Forged flat-top thermal-coated pistons (8.5:1 static compression); Speed-Pro rings; Cam Motion custom grind solid roller camshaft; 18-degree TFS aluminum cylinder heads
- Drivetrain modifications: Blueprinted Viper T56 transmission; McLeod twin-disk clutch; C-4 Corvette front suspension on Wayne Due sub-frame; 4-link rear suspension with Currie Ford 9-inch; 275/35R18 front, 335/30R18 rear tires on Fikse wheels
- Body modifications: Louvered hood

Results:

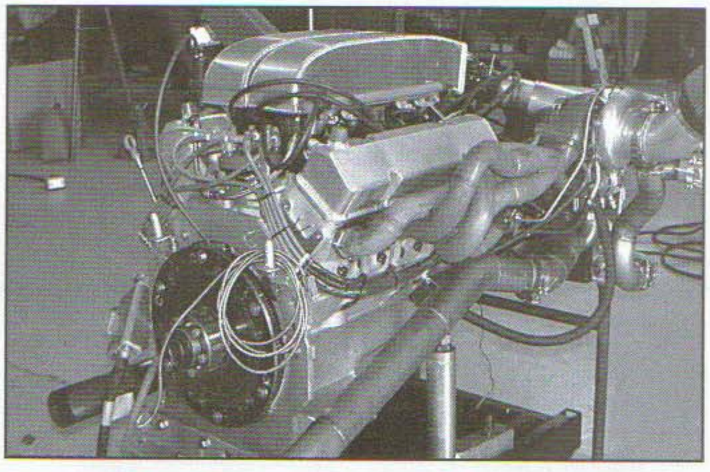
- Horsepower: 1026 hp @ 6800 rpm at 16 psi
- Torque: 810 lb-ft @ 6600 rpm at 16 psi



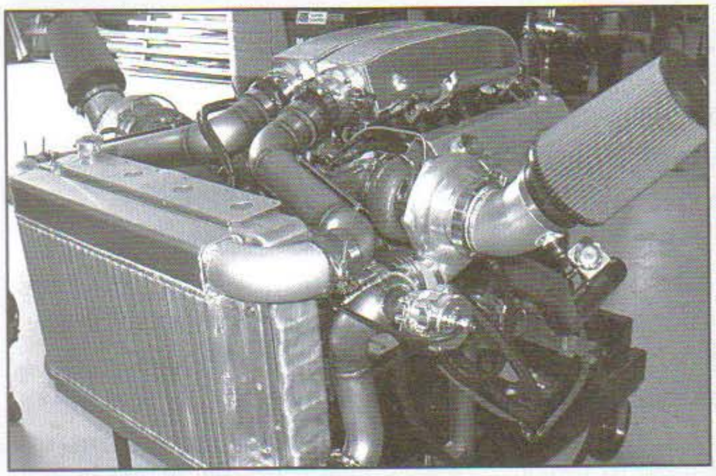
The decision to install twin turbos meant a lot of equipment would be squeezed into the engine bay. Careful consideration of component packaging allows maintenance to be performed with little fanfare.



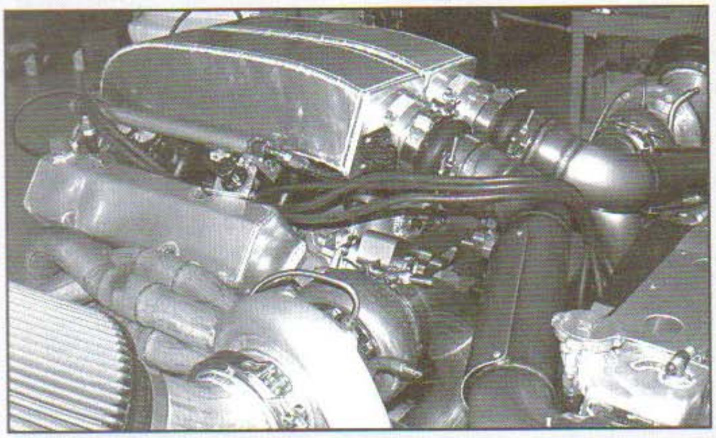
A very sanitary engine bay. The long block consists of an all-aluminum race-style engine block, Lunati de-stroked crankshaft, forged pistons, billet steel connecting rods, and 18-degree TFS aluminum cylinder heads. Twin turbos are from Precision Turbo and feature ball bearing CHRAs.



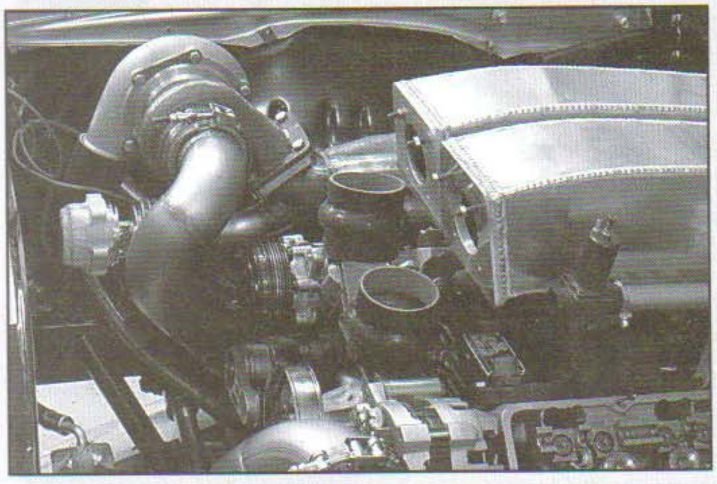
Rear view of the engine on the stand. Exhaust manifolds were fabricated by Wheel to Wheel in Warren, MI, using 3/8-inch thick 304 stainless flanges, 1-7/8-inch diameter 321 tubes, and 321 stainless merge collector. A double-wall slip-fit of the tubes into the collector allows for thermal expansion and contraction.



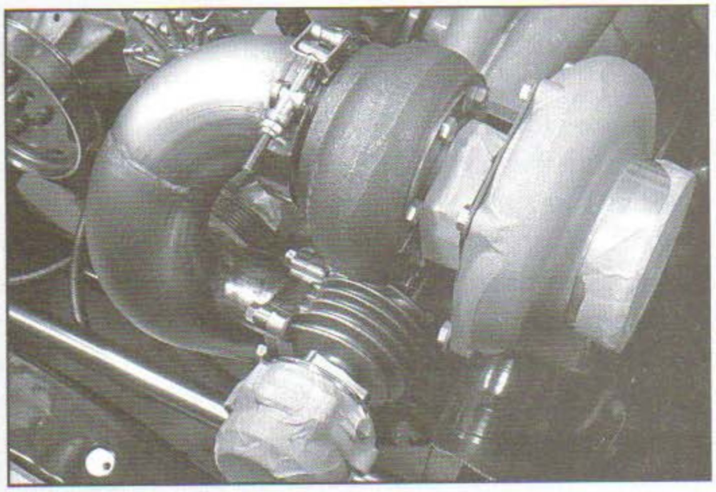
The basic turbo systems layout. A number of iterations were required when mounting the turbos and required plumbing. Originally, the turbine and compressor locations were swapped, with the exhaust exiting outboard. Subsequent work changed the layout to the configuration shown here.



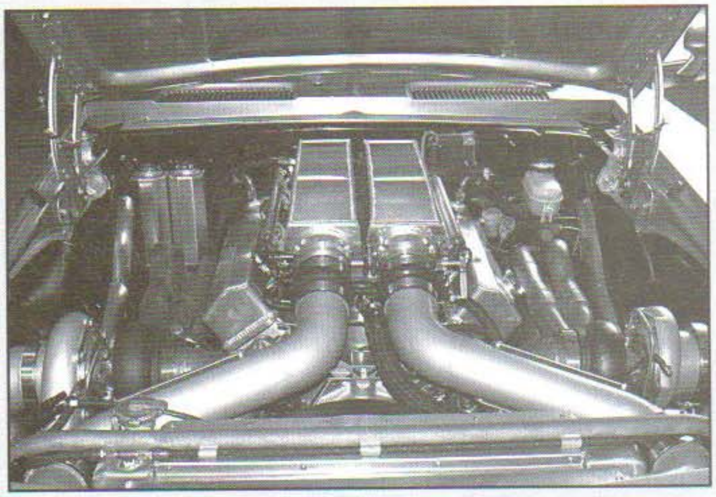
The car originally sported a lightweight fiberglass hood. This was replaced with a louvered steel unit because of the excessive heat rising off the exhaust manifolds and the turbos. Note the stainless steel heat shields that protect the intake tubes from the turbine downpipes.



The downpipes exit toward the midline of the car. Note the dual Wheel to Wheel fabricated intake plenums.



Wastegate plumbing detail. Note that the wastegate gets direct flow from the exhaust manifold collector. Tape shown here was used to protect equipment during layout and fabrication.



Wheel to Wheel fabricated the dual intake plenums and the billet 2-3/8-inch diameter throttle bodies. The intake below the plenums is based on a Kinsler manifold system. The plenums are connected together with a" communicator" tube to balance the intake pressure. Idle air control and the MAP sensor are fed from this tube.

PROJECT VEHICLE 7

1994 TOYOTA SUPRA TURBO—AN ULTIMATE STREET CAR

Professionally Built Twin Turbo System

The inline 6-cylinder 2JZ-GTE from Toyota is arguably one of the best engineered production engines ever put on the street. Silky smooth and nearly bulletproof, these 3-liter DOHC 24-valve machines are world-renowned for their ability to generate—and withstand—amazing levels of horsepower. From the factory, these engines came with a cast-iron block, aluminum head, piston oil squirters, a forged crank and forged connecting rods. A typical 2JZ in a stock mid-nineties Supra would have arrived from the factory with 320 crankshaft horsepower and 315 lb-ft of torque. But, with various modifications, the twin sequentially-turbocharged engine can produce two to three times these output levels at the wheels with little fanfare.

The owner of the Toyota Supra shown here had logically reasoned his car was complete when it generated 801 rwhp and 633 lb-ft of torque on the dyno with its previous turbocharger setup. But then the builder of the car, SP Engineering of City of Industry, California (www.sp-power.com), took delivery of the first HKS 3.4-liter stroker kit in the country for the 2JZ-GTE.

With the increased displacement, and the resulting hotter, more powerful exhaust pulses, the installation of dual ball-bearing HKS GT3240 turbochargers became a possibility. This, in turn, meant that 800 lb-ft of torque and 1100 horsepower at the wheels might be achieved without the use of nitrous. Suddenly, entry into the "200 MPH Club" was within reach, as were various high-speed road course, time-attack and land speed events, such as the Silver State Classic and the Texas Mile. And all this would be possible with minimal turbo lag and no loss of drivability on the street.

The car has been fitted with a body kit with a larger-than-stock intercooler opening and a hood scoop that allows ambient air directly into the engine compartment. The engine generates over 1000 hp at the drive wheels, but the vehicle can operate effortlessly with power windows and the air conditioning without fear of overheating in California's dreaded bumper-to-bumper traffic.

Turbocharger System Details:

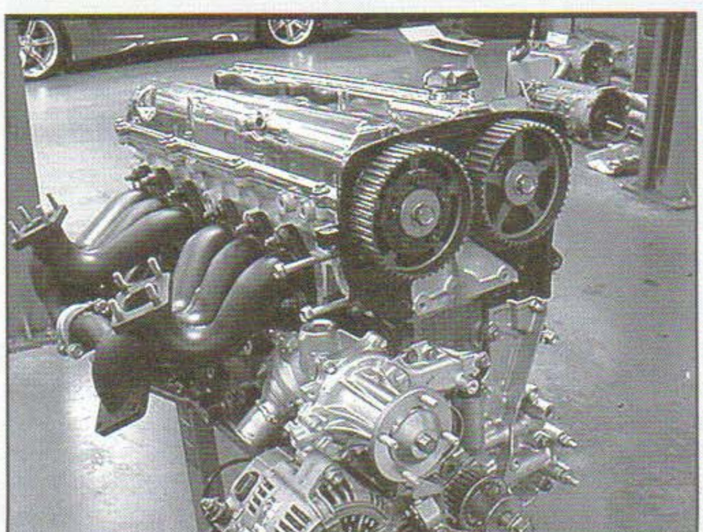
- Turbocharger: Dual Garrett/HKS GT3240 Dual Ball Bearing Units. Compressor: 100 mm Inlet/60 mm Outlet; 0.60 A/R Housing; 54 Trim Wheel. Turbine: GT25 Inlet, GT30 Outlet Housing, 0.87 A/R; 84 Trim Wheel
- Exhaust manifold: HKS SUS304 tubular, equal-length, stainless steel, two-piece exhaust manifolds; flange type: 2 x T25; manifolds are ceramic coated with JetHot 2000
- Intercooler: GReddy 4-row tube & fin front-mount; 25x12x6-inches
- Boost Control: HKS EVC-Pro controller; dual HKS S/S Racing external wastegates (1.6 kg/cm2 wastegate springs); Dual Blitz Racing Dual-Drive blow-off valves
- Intake System: VeilSide intake manifold surge tank, with 100 mm throttle body and internal velocity stacks; VeilSide lower intake manifold; SP Engineering 100 mm intake piping with Blitz Racing stainless steel air filters
- Fuel Injection System: SP Engineering custom fuel system; dual OEM Supra fuel pumps; Earl's stainless steel lines and fittings; VeilSide billet fuel rail; Toyota Racing Development (TRD) fuel pressure regulator; eight 1000 cc/minute low-impedance Denso fuel injectors
- Control System: HKS F-CON V-Pro engine management system piggybacked onto OEM engine control unit; OEM knock sensor; HKS Knock/Amp six-wire wide-band O_2 sensor
- Ignition: Stock Toyota direct-fire coil on plug; HKS Type DLI ignition amplifier with combination capacitive discharge and transistor ignition
- Exhaust: Dual HKS 70 mm downpipes; SP Engineering 75 mm mid pipes; HKS Racing Titanium exhaust; 102 mm internal diameter tubing; 170 mm muffler

Other Significant Vehicle Details:

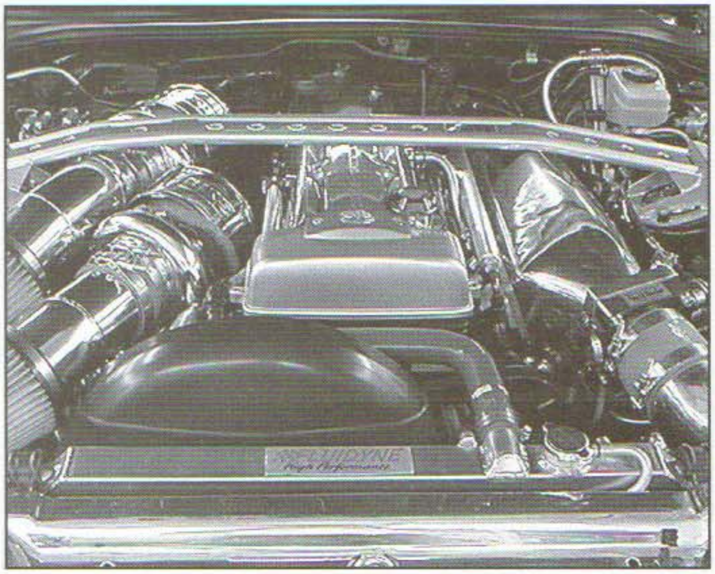
- Gauges: SP Engineering A-pillar pod; GReddy boost gauge; GReddy exhaust gas temperature gauge; SP Engineering intercooler temperature meter; custom four-gauge pod housing 60 mm GReddy peak/hold gauges for fuel pressure, oil temp, oil pressure and water temp
- Ancillary Equipment: HKS turbo timer
- Engine Modifications: HKS 3.4-liter Stroker Kit with forged long-throw crankshaft, forged HKS/Carillo H-beam connecting rods, forged HKS pistons (bored oversize by 1mm); ported cylinder head with HKS 272 duration camshafts, Ferrea dual valve springs, titanium retainers, stainless steel valves, valve guides, locaters and locks; OEM oil cooler and Trust 16-row oil cooler; Fluidyne aluminum radiator; GReddy under-drive pulleys; HKS 1.6 mm metal head gasket
- Drivetrain Modifications: OS Giken quadruple-disc road-race-biased clutch; ACPT 3.25-inch diameter carbon fiber driveshaft; TRD engine and transmission mounts; Getrag 6-speed transmission; Race Logic Adjustable Traction Control system
- Body Modifications: 12-piece Do-Luck Type II body kit with large intercooler inlet; hood scoop

Results:

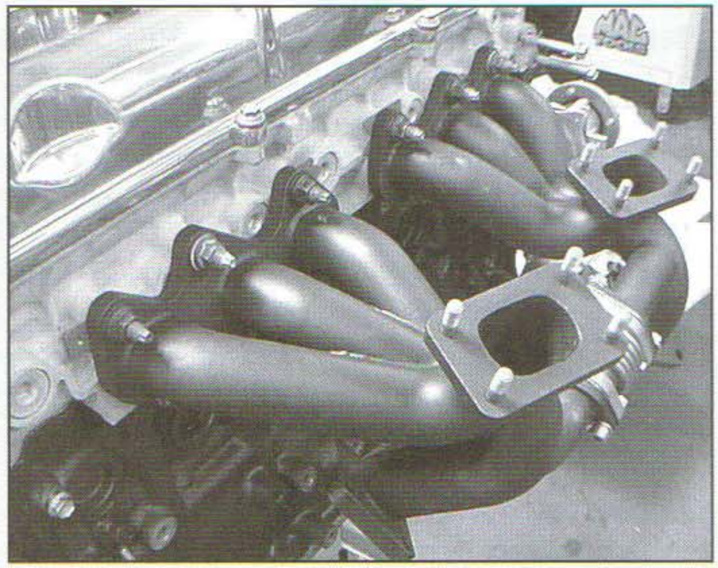
- 37 psi boost; excellent spool-up characteristics
- 1110 rwhp @ 7200 rpm; 839 lb-ft torque @ 6600 rpm, with over 800 lb-ft from 6300 rpm to redline (7500 rpm)



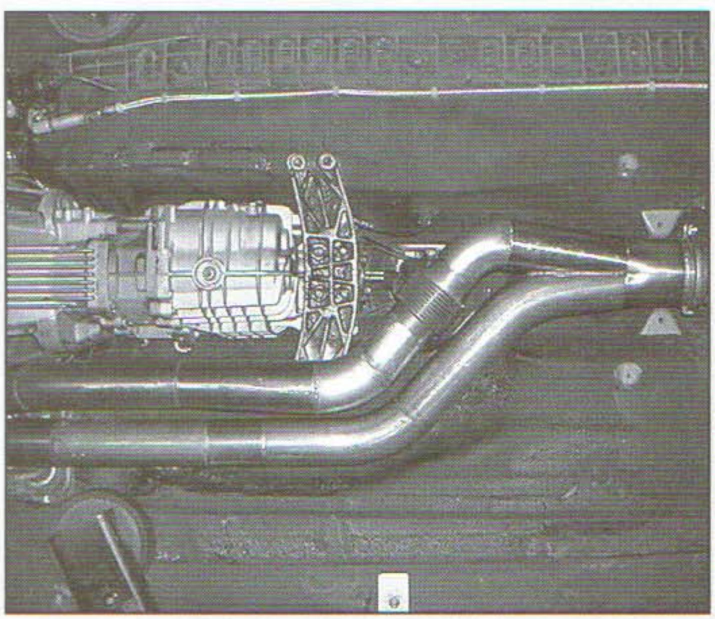
Toyota's amazing 2JZ-GTE engine served as the starting point for the project.



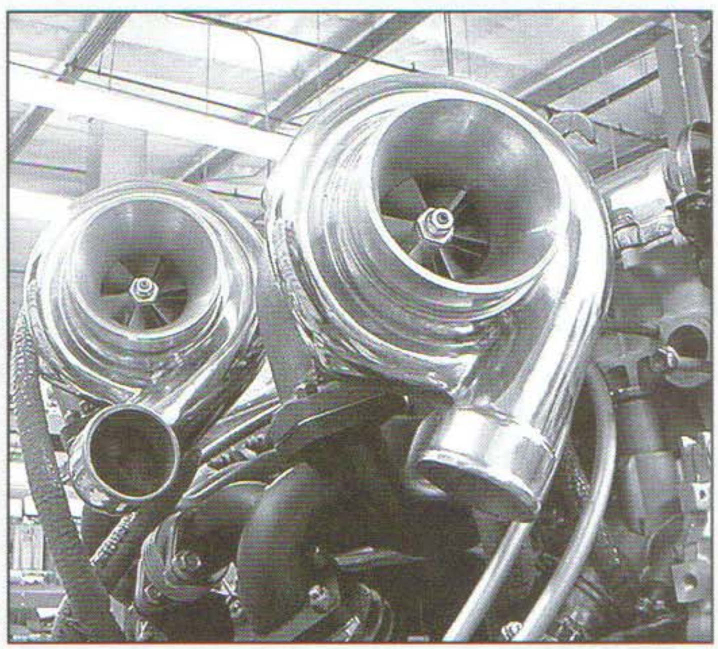
The turbochargers take up nearly as much engine bay real estate as the engine block itself. A car of this complexity and power potential requires expert fabrication and technical prowess. Credit goes to Alex Shen, owner of SP Engineering, and his staff, for constructing and tuning this monster.



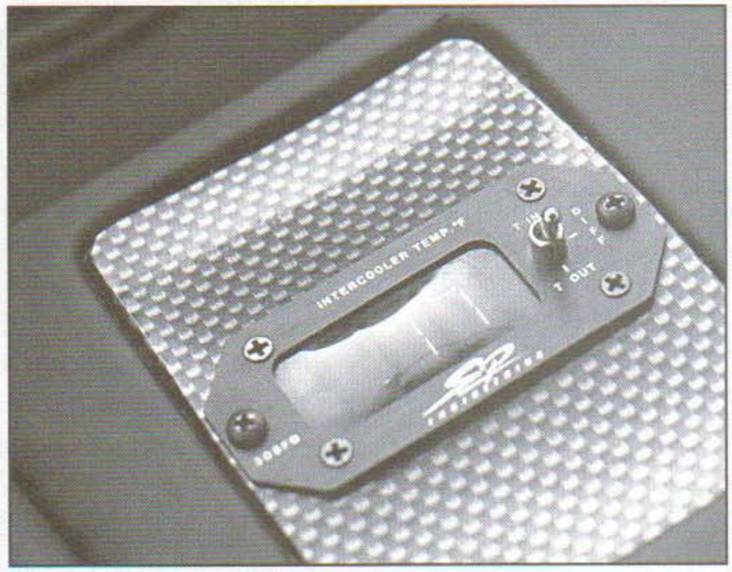
These stainless steel HKS equal-length two-piece exhaust manifolds are works of art. Note the unusual wastegate plumbing with balance tube. The wastegates themselves have fully sealed shafts, high temperature resistant diaphragms, and 50 mm stainless steel valves. Each gate is rated at 1000 hp.



Valuable lessons can be learned by studying this exhaust routing. Note the smooth and efficient bends, the flex bellows in the upper pipe, and the gradual merging of the two exhaust streams into the Y-collector. If you want to develop 1000+ horsepower on boost you have to get these types of details perfect.

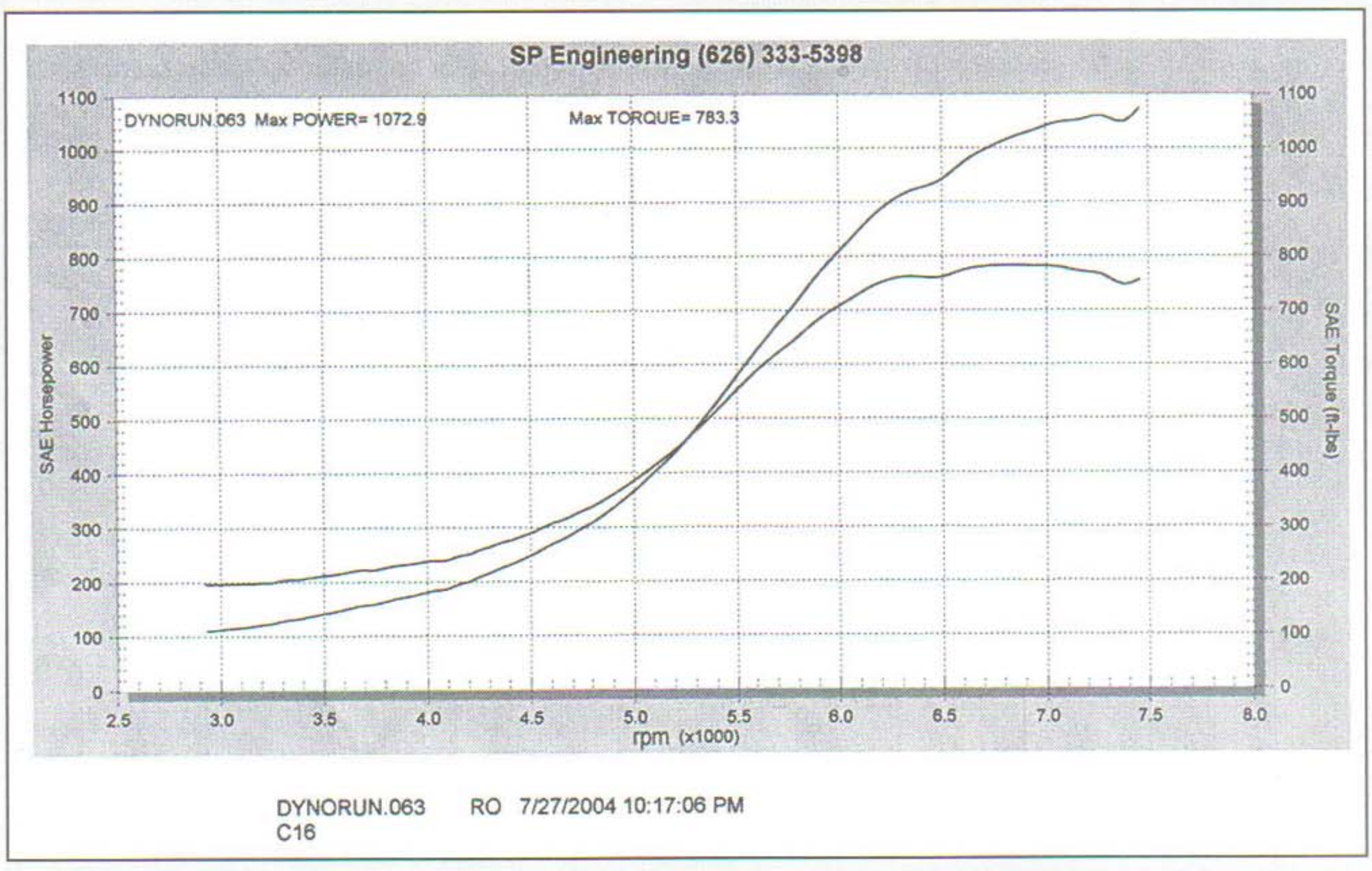


These are the gargantuan Garrett/HKS GT3240 turbochargers used in this application. The compressors feature 100 mm diameter inlets and 60 mm outlets.



Keeping track of the engine operating conditions is critical on a high-dollar machine like this. Boost and EGT gauges are on the A-pillar pod; air-fuel meter to the right of the steering wheel; turbo timer and boost controller to the left; fuel pressure, water temperature, and oil temperature and pressure are on the dash right-side pod; intercooler temperature gauge is below the shift lever. And don't forget the all-important radar detector on top of the dash.

At 25 x 12 x 6 inches thick, the intercooler provides a full 1800 cubic inches of heat-exchanging ability. The efficiency of this unit is constantly monitored by an SP Engineering intercooler temperature meter. This gauge toggles between compressor outlet temperature, intake air temperature (after the intercooler and right before the intake plenum) and the difference between the two by way of the small switch on the right.



For the doubters, here's the money shot. Power delivery just keeps building as the revs climb. While this dyno sheet shows the motor generating 1,073 rwhp, the car, in a subsequent dyno competition, produced 1110 rwhp and 839 lb-ft at 37 psi, using C16 race fuel.

PROJECT VEHICLE 8
2001 DODGE DAKOTA—DIESEL SPORT TRUCK
Installing a High-Performance Turbo-Diesel for Land Speed Racing

To the average person on the street, the term "diesel" conjures up images of black soot- and smoke-producing trucks and tractors that are smelly, loud, and slow. Similarly, the words "pickup truck" have functional but, well, lackluster connotations. A diesel truck is supposed to be a slow-speed workhorse, not a high-performance street vehicle. It's also not supposed to be fast or fuel-efficient. And it certainly isn't supposed to set land speed records, or beat Dodge Vipers and Chevrolet Corvettes in the quarter mile.

In early 2000, Gale Banks Engineering decided to erase these stereotypic and negative perceptions of diesels. They reasoned that a demonstration of the capabilities of a turbo-diesel could best be shown by setting a land speed record at Bonneville—in a pickup truck, no less. A fundamental objective of 210 mph was established early in the project, as were requirements that the vehicle be clean, quiet, and efficient. A goal of twenty or more miles per gallon was targeted, and the vehicle would have to be drivable on the street. And, because it was a truck, it would be required to tow its own support trailer to and from the salt flats. The ambitious project was code-named "Sidewinder."

In 2003, Banks took possession of a '01 Dodge Dakota, complete with its stock 2.5-liter gasoline 4-cylinder engine. The anemic 98 rwhp power plant was removed, and a huge Cummins 24-valve 5.9-liter inline-six cylinder common rail diesel engine was shoehorned in between the frame rails. Then, just about every other mechanical system on the truck was either replaced or seriously upgraded, including drivetrain, chassis, suspension, body, and interior. A custom Holset variable-geometry turbocharger was added, along with all the requisite high-performance life-support equipment needed for the turbo. The result of this automotive project is a relatively stock-appearing Dodge Dakota that generates an astounding 735 hp and 1300 lb-ft of torque, runs the quarter mile in 12+ seconds, set a two-way average Bonneville speed record of 217 mph, and sips fuel at 21 mpg. Not bad for a utilitarian diesel pickup truck.

The Banks Race Shop–prepared 2001 Dodge Dakota, complete with creature comforts inside and 1300 lb-ft of torque on tap under the hood. After chassis dyno and coast down testing, the Banks engineering staff determined that over 800 horsepower would be required to reach the desired speed of 210 miles per hour with the stock Dakota frontal area and coefficient of drag. By lowering the truck to race configuration and cleaning up the aero profile with a front air dam and other allowed modifications, both the frontal area and drag coefficient were reduced enough to lower horsepower requirements to a projected 600 hp.

Turbocharger System Details:

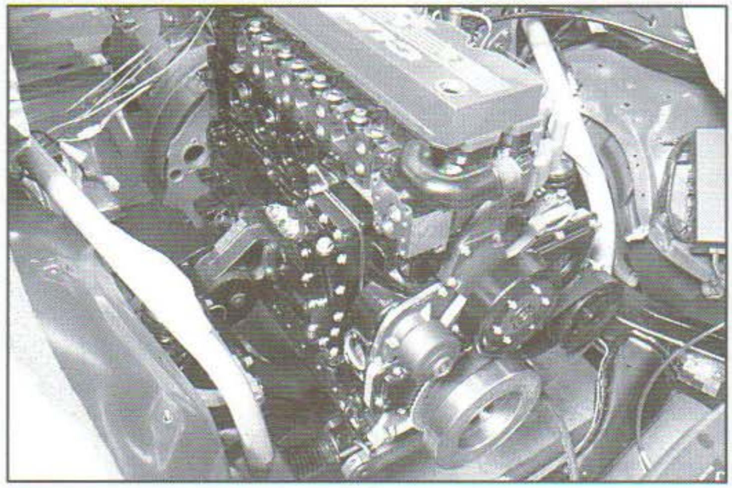
- Turbocharger: Holset HX55 variable-geometry turbine, pneumatic actuator; Banks electronic controller
- Exhaust manifold: Custom 6-into-1 stainless, 0.25-inch wall with expansion bellows
- Intercooler: Dual Cummins marine air-to-water charge air coolers in parallel; ice water circulated from tank in the truck bed
- Boost Control: Indirect control via VGT controller
- Intake System: Banks Big Hoss aluminum manifold
- Fuel Injection System: Common rail; Bosch 780 injectors at 28,000 psi
- Control System: Bosch fuel injection system controller in conjunction with Dodge powertrain controller, programmed via Banks Ottomind and Six-Gun systems
- Ignition System: None (compression ignition diesel)
- Exhaust System: Four-inch stainless steel with single Banks Monster Muffler

Other Significant Vehicle Details:

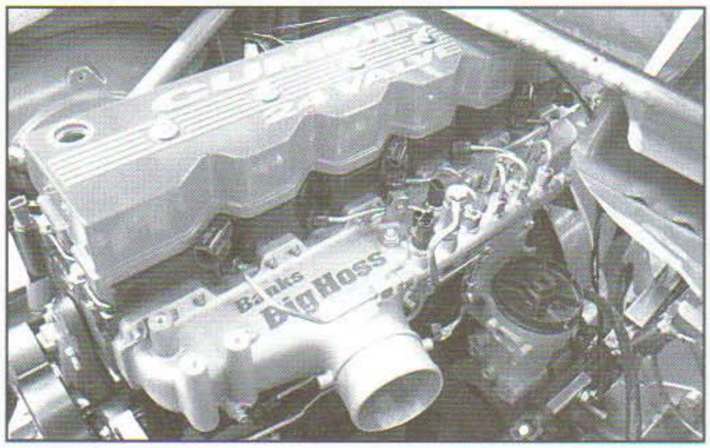
- Gauges: Stand-alone data-acquisition; gauges include rpm, boost, turbo speed, oil pressure, oil and coolant temperatures, and 250 mph speedometer
- Engine modifications: Banks reground cams; ported head with CNC and hand finishing; Fluidamper vibration damper; crankshaft girdle
- Drivetrain modifications: Numerous, including New Venture Gear six speed gearbox; Wilwood braking system; Progress Group coilover spring/shock units
- Body modifications: Lowered body; custom air dam and hood

Results:

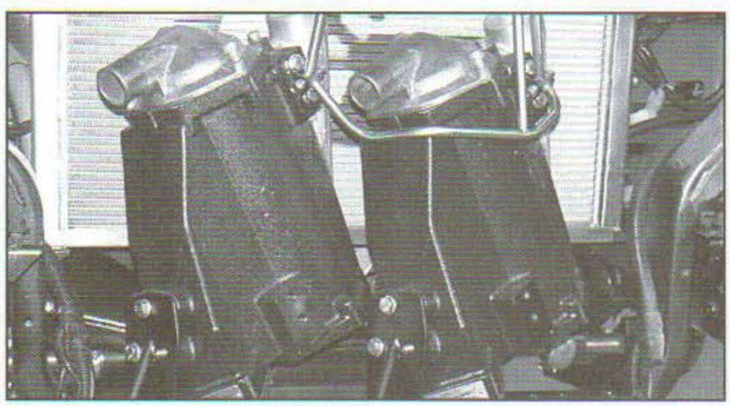
- 50 psi from 2500 to 4000 rpm
- 735 rwhp at 3100 rpm; 1350 lb-ft at 2500 rpm
- 217 mph two-way average at Bonneville
- 12.16-second 1/4-mile time at 115 mph



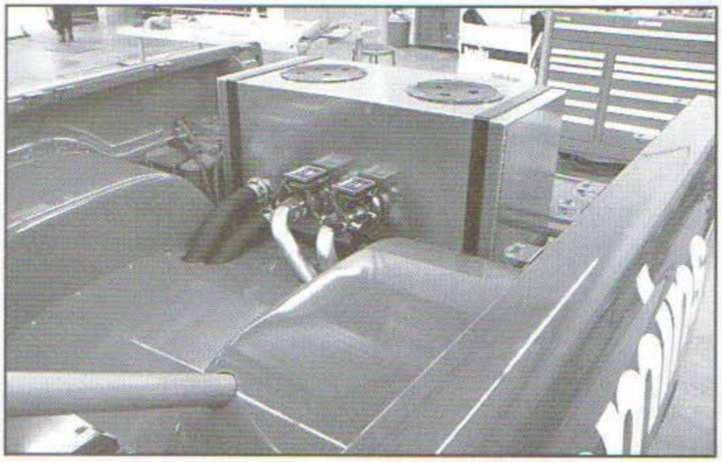
The engine of choice for the project was the "anvil strong" Cummins ISB 24-valve 5.9L engine. Diesel engines have long-held negative performance connotations in many racing circles. Maybe it would help to call them compression ignition engines instead.



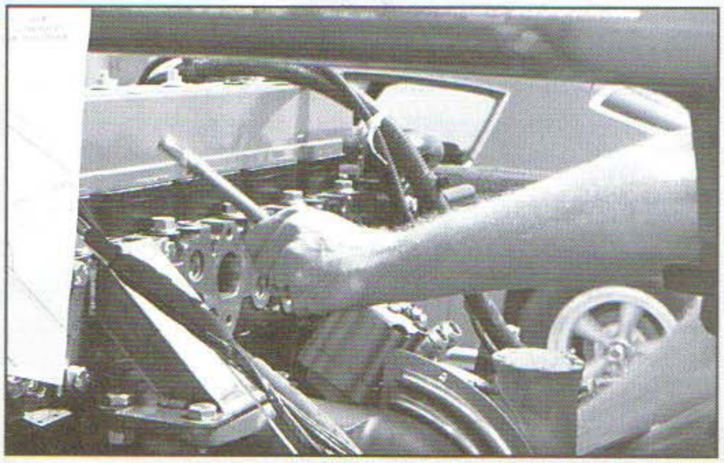
The Banks Big Hoss aluminum intake manifold. Diesel engines don't use a throttle plate to control rpm; engine speed is governed by the amount of injected fuel. A specialized electronic controller also eliminated the need for a wastegate or blow-off valve. The system detects rapid throttle drops during shifts and quickly opens the turbine nozzle to prevent surge as the engine flow suddenly varies with gear changes.



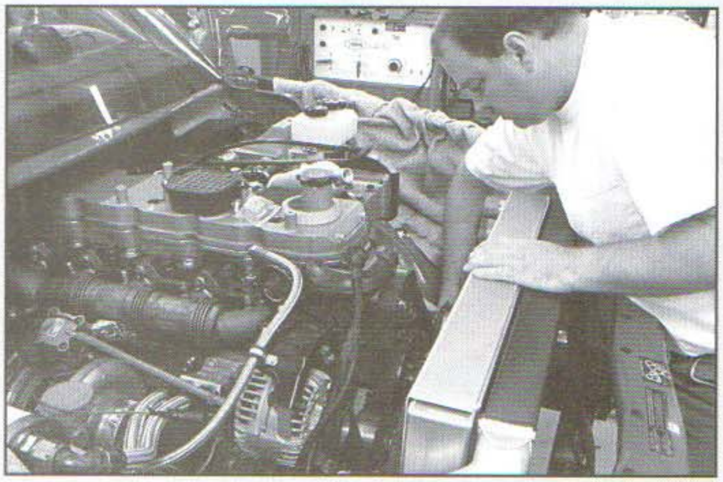
Dual Cummins marine air-to-water charge air coolers, plumbed in parallel. Excellent performance was obtained with efficiencies in the 90% range with less than 0.5 psi total pressure drop. Air temperatures went from over 500 degrees Fahrenheit at the compressor outlet, to approximately 100 degrees F in the intake manifold. These intercoolers cost $5,000 apiece.



The intercooler water tank was mounted in the bed of the truck. An aerodynamic tonneau-type cover was fitted over the bed for the speed record runs.



A technician fabricating custom sheet metal and mounting hardware in the engine bay. Note the massive Holset turbocharger and 4-inch stainless steel downpipe. Because it's a diesel, the engine could be run at very high boost (50+ psig) without concern for detonation. Boost is lowered slightly as engine rpm and flow increase, due to the downward-sloping shape of the speed lines on the compressor map.



An air-to-air intercooler being test fitted. Note the stainless steel exhaust manifold with integral bellows that allows differential expansion between the manifold and the cylinder head. Thousands of man-hours went into the design of the mechanical components on the truck.

Ice being added to intercooler tank prior to a speed attempt on the salt flats. The truck averaged 217 mph in two-way action.

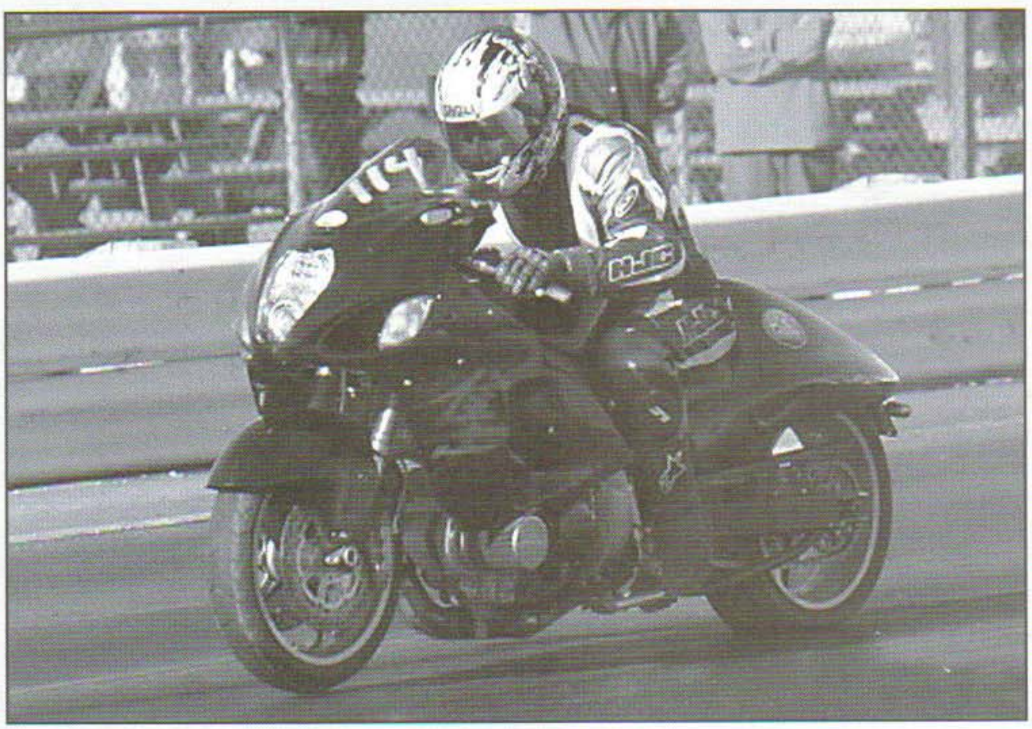
Most land speed record holders arrive at the salt flats on top of trailers. To make a point, Gale Banks insisted that this particular participant tow its own trailer to the event. Banks also required no visible smoke during operations. This was obtained through high boost with the VGT and fuel limiting at low speeds. The maximum air-to-fuel ratio was 25:1 for brief times, and had the exhaust temperature limited to 1350° F.

PROJECT VEHICLE 9
2003 SUZUKI HAYABUSA—MAKING A HORSEPOWER STATEMENT
Building an All-Out Turbo System for Street, Strip, and Bonneville

In stock form, the Suzuki Hayabusa is a very fast motorcycle. With 148 horsepower and 92 lb-ft of torque on tap from its 1.3-liter inline four-cylinder engine, the Busa is known in 2-wheeled circles as a street weapon. For many riders, the bike has more power than can be safely handled. But for others, the stock horsepower output provides just a taste of what they crave. For these select few, there is no such thing as too much power.

The owner of the 2003 Hayabusa shown here also owns a specialty motorcycle shop in Canada. Between testing at the dragstrip and the dyno, the bike has been pushed well beyond anything that the engineers at Suzuki ever intended. In late 2004, the owner decided to up the ante even further. He reasoned that with the right combination of custom components and boost, 600 horsepower could be achieved. Weighing in at a scant 478 pounds dry weight, this meant a low 8-second quarter-mile time was in the cards.

Starting with the factory crankshaft and cases, little else was left stock. A custom exhaust header, a huge Garret GT-40R twin-entry turbocharger, and a hand-built air-to-water intercooler and airbox formed the basis of the project. Modifications to the control system, fuel delivery system, and just about every other internal engine, transmission, and suspension component was also required. The result is a staggering 618 hp at a sky-high 11,000 rpm.



The owner at the race track on his 2003 Suzuki Hayabusa, laying down an 8.22 second quarter-mile blast.

Turbocharger System Details:

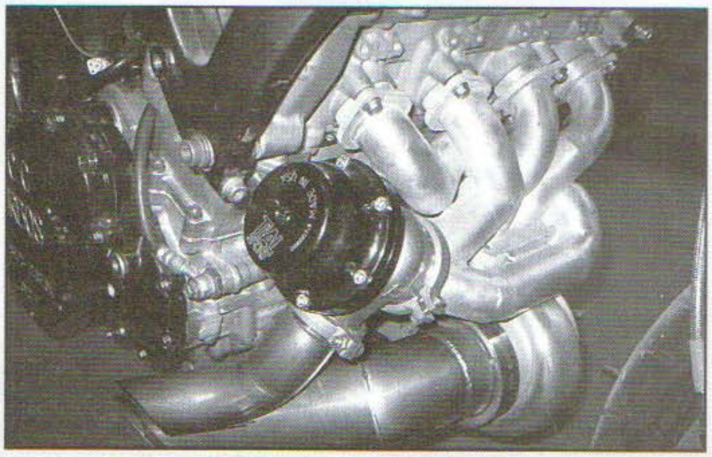
- Turbocharger: Dual ball-bearing Garrett GT-40R @ 35 psi; Compressor: 0.58 AR housing / 88 mm wheel/52 trim; Turbine:Twin-entry housing / 0.95 AR / 77 mm wheel /78 trim
- Exhaust manifold: Custom RCC Turbo manifold; 14-gauge stainless 304; 1.5-inch primaries
- Intercooler/Airbox: Custom RCC Turbo air-to-water unit; 10x4x3-inch Bell core
- Boost Control: TiAL 44 mm V-band wastegate; Innovative electronic boost controller (gear based); TiAL 50 mm blow-off valve
- Fuel Injection System: Stock Suzuki primary injectors; 96 lb/hr secondary injectors; Bosch fuel pump
- Control System: Stock Suzuki for primary injectors; 4-Bar MAP sensor and custom Microtech controller for secondary injectors
- Ignition System: Stock Suzuki
- Exhaust System: 8-inch long x 3-inch diameter open exhaust; separate 1-5/8-inch diameter exhaust for wastegate

Other Significant Vehicle Details:

- Gauges: Autometer gauges; 2-channel air intake temperature sensor; boost gauge with peak recall and over-boost warning
- Engine modifications: 84 mm bored cylinders; JE low compression pistons and base spacer for 8.5:1 static compression ratio; Carrillo H-beam connecting rods; stainless steel valves; Yoshimura Stage-1 camshafts
- Drivetrain modifications: MTC clutch; back-cut gears

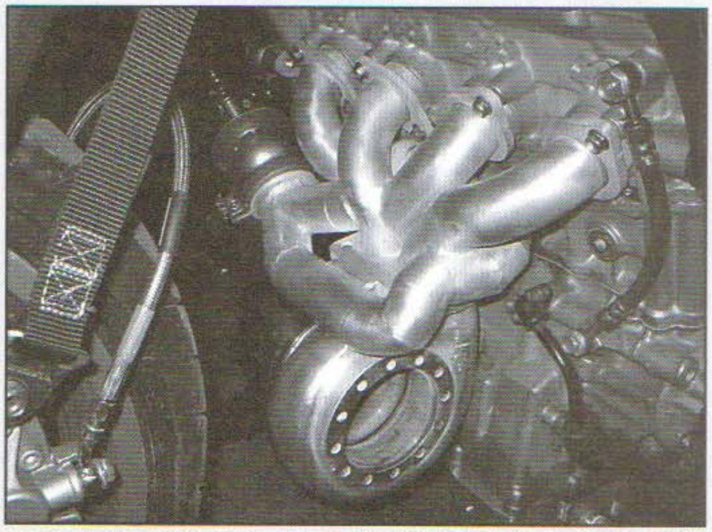
Results:

- 34 psi of boost @ 11,000 rpm
- 618 rwhp @ 11,000 rpm, 300 lb-ft @ 10,000 rpm
- 8.22 second 1/4-mile time at 183 mph



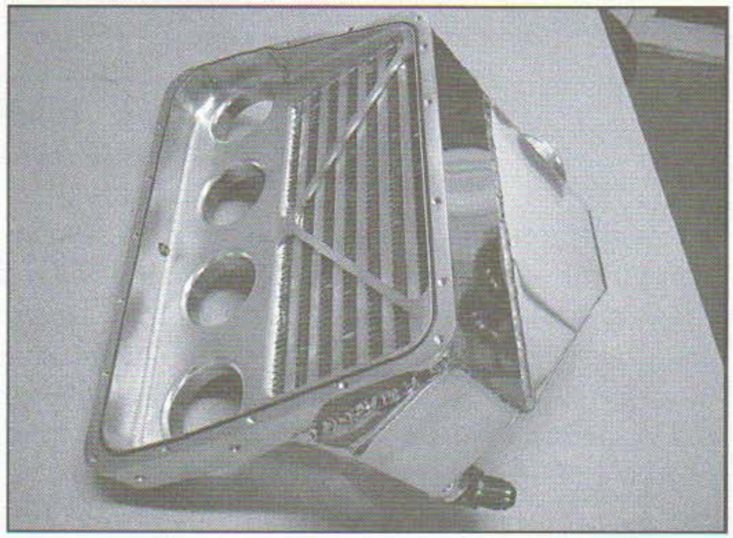
A nearly perfect exhaust system downstream of the turbocharger. Most city and state noise ordinances wouldn't allow this type of system, and neither would the local pollution police. But if you want ultra-low backpressure, it's hard to beat this type of arrangement. Note the separate exhaust pipe for the TiAL wastegate.

The stainless steel exhaust manifold during construction. Tube diameters are 1.5-inches.

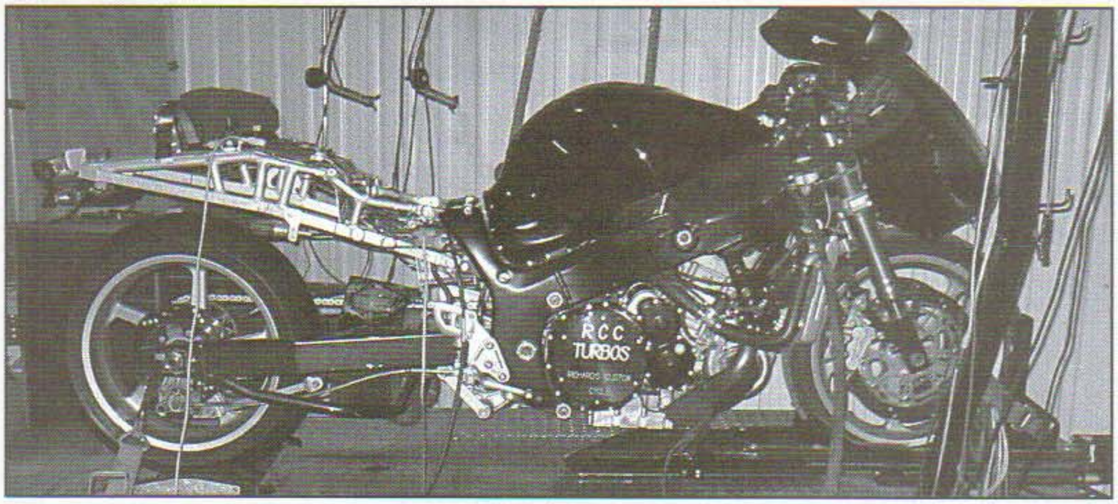


Another view of the exhaust manifold during fabrication. Note the massive the GT-40R turbine housing.

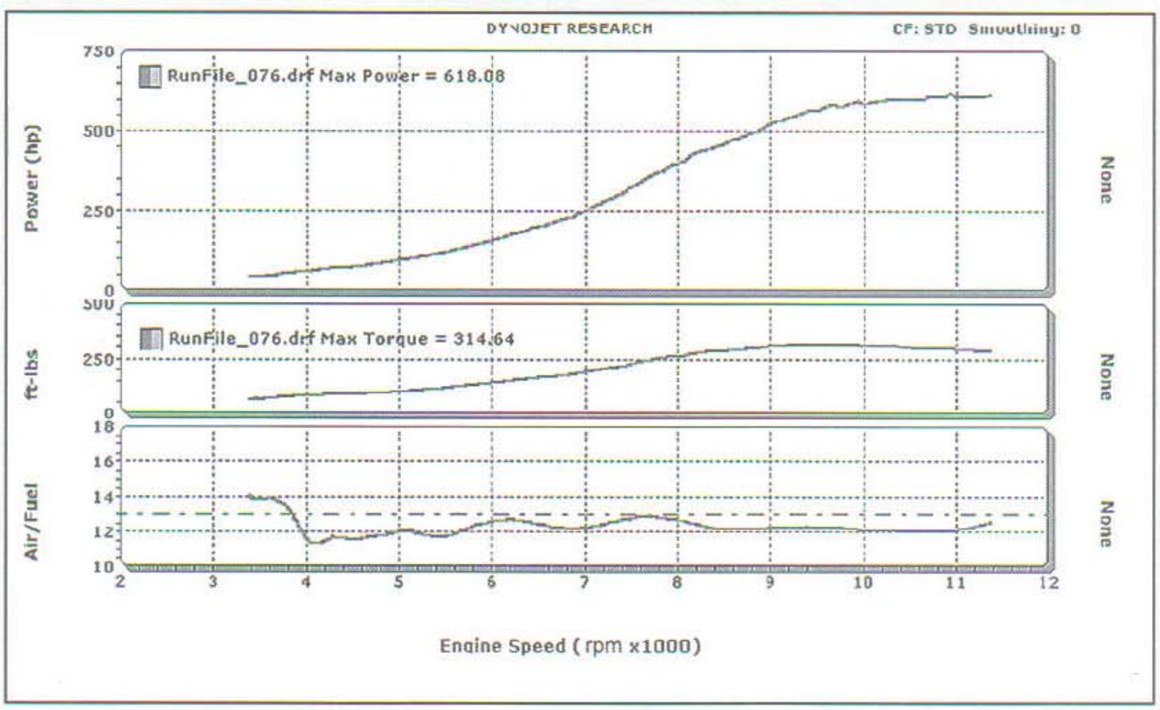
The compressor-side of the turbocharger system. The blow-off valve is mounted at the top of the up-pipe.



The airbox and air-to-liquid intercooler are fabricated as a single assembly. Half of a stock Hayabusa radiator is mounted in front of the engine radiator to supply coolant to the intercooler. An icebox has been built into the bike's swing-arm, but hasn't yet been utilized.



The Busa on a chassis dynamometer. Other than a faulty TPS sensor, which was not discovered until well into the tuning process, there wasn't much system debugging required. Build it right the first time, and this phase of a project can be very rewarding.



Many car owners would kill for rear wheel numbers like this.

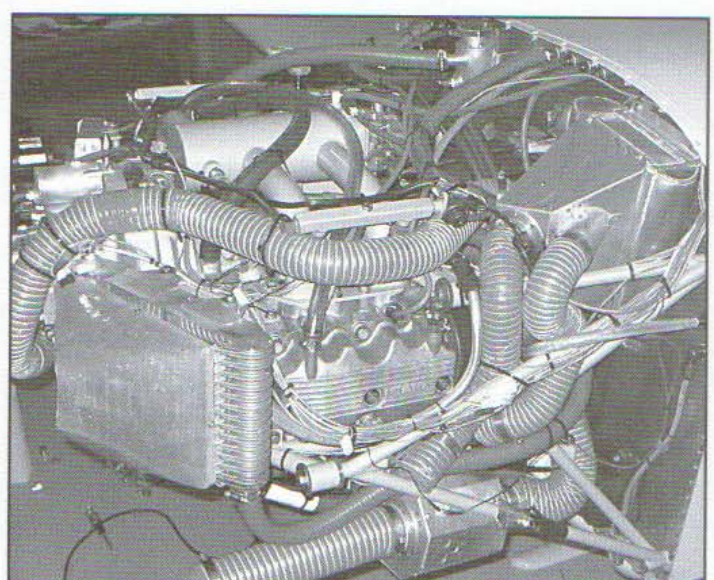
PROJECT VEHICLE 10
2003 RV6A TURBOCHARGED KIT PLANE
Turbocharging a Subaru Engine for an Aviation Application

Modern private aircraft engines are anything but state-of-the-art. Air-cooled cylinder heads, magneto-based ignition systems, and carburetors with manual mixture controls are all considered contemporary equipment for the modern pilot. While reliable, these traditional horizontally opposed Lycoming and Continental engines have changed little from their predecessors for more than 50 years. More importantly, these power plants are very expensive, and they require certified mechanics to install and work on them. An engine is one of the most expensive components of an aircraft project.

The owner of the RV6A kit plane shown here is also the president and owner of an aftermarket automotive engine management system company. When planning this kit plane project, he reasoned that a turbocharged automotive engine could be competitive with conventional aircraft engines from both price and performance standpoints. He also saw the project as an R&D test bed in which he could prove the reliability of his company's engine management system for use on homebuilt aircraft.

The engine selected for the RV6A project was a Subaru 2.2-liter, opposed-4 cylinder that was rebuilt with higher-than-stock compression forged pistons. A Garrett T3 turbocharger was selected to provide boost and was mounted via a set of custom-fabricated exhaust manifolds. The fuel, cooling, and intercooler systems were also hand-built to meet the high quality and reliability standards required for aviation duty.

The RV6A high over Canada. Approximately 2000 man-hours were required to construct the aircraft, with over 400 hours spent on the engine mounts, fuel system, cooling, and propeller alone. A turbo failure in an airplane is far more serious than one on a ground-based vehicle. Everything must be as reliable as possible.



The powerplant for the aircraft is an automotive-based Subaru EJ22. Forced induction is via a Garrett T3 turbocharger tucked up in between the block and firewall. Power at high altitude is limited by intercooler effectiveness, which varies between 50 and 60% depending on power settings and altitude.

Turbocharger System Details:

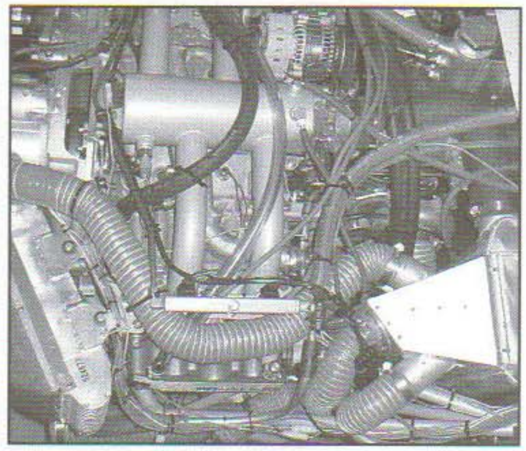
- Turbocharger: Garrett T3; Compressor: Super-60; Turbine: 0.82 AR housing with Stage III wheel; Wet center section with dynamic seals
- Exhaust Manifold: Custom 4-into-2-into-1; primary tubes are 1.75-inch diameter, 0.058 wall, 321 stainless steel tubing
- Intercooler: Spearco 6 x 9 x 3.5-inch air-to-air
- Boost Control: Integral wastegate with twin port actuator; cockpit controlled by a pneumatic regulator
- Intake Manifold: Custom plenum-type manifold, stock 60 mm Subaru throttle body
- Fuel Injection System: Bosch 390 cc/minute; twin Bosch 048 fuel pumps fed by twin Facet low-pressure pumps and surge tank; OE fuel pressure regulator; fuel is 100LL aviation gas
- Control System: Simple Digital Systems EM-4 4F programmable engine management system controls both fuel and ignition
- Exhaust System: 2.25-inch diameter 304 stainless open exhaust

Other Significant Vehicle Details:

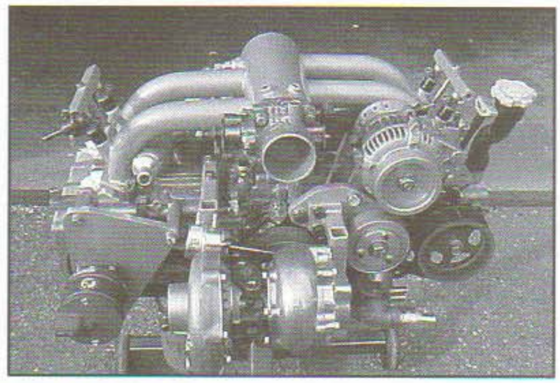
- Instrumentation: Custom 24-channel digital monitoring system that monitors numerous temperature and pressure sensors; individual cylinder probe digital EGT gauge; MAP gauge calibrated in inches of mercury, absolute; air-fuel ratio meter with exhaust oxygen sensor
- Engine Modifications: Subaru EJ22 long block disassembled, inspected, rebuilt with higher compression (9.45:1 vs. 8:1) JE forged pistons
- Propulsion: Marcotte reduction gear (2.2 to 1 ratio) installed between engine and IVO, 3 blade variable pitch composite propeller
- Cowling Modifications: Various intercooler and cooling ventilation openings added

Results:

- Max Takeoff Power: 180 hp at 4800 rpm and 40 in-Hg (20.6 psia)
- Fuel Consumption: 7.8 gal/hr economy cruise; 12.0 gal/hr climbing
- Max Air Speed: 208 mph at 15,000 feet, 5000 rpm @ 34 in-Hg (16.7psia)



Somewhere underneath all this equipment is the stout-little Subaru. The flat-four opposed-style engine means that there are two of almost everything, from cylinder heads to exhaust manifolds. Creative plumbing and custom inlet and exit ducts were required to provide adequate airflow for radiators and the intercooler.



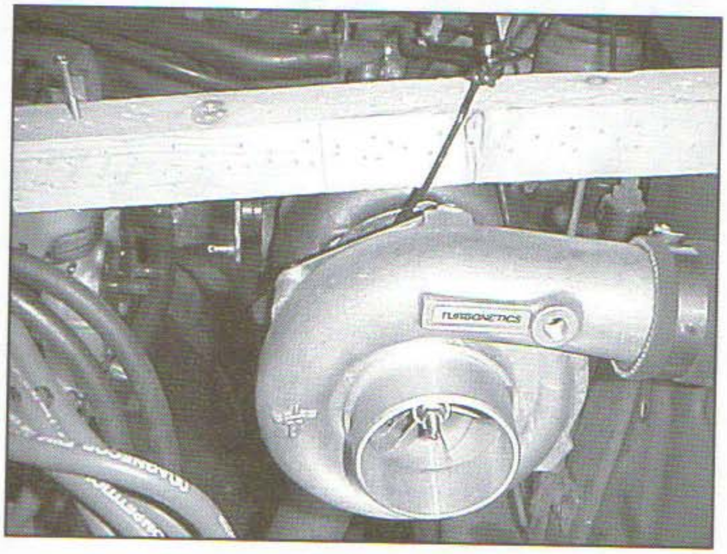
The exhaust collector flange also serves as a shelf upon which the weight of the turbocharger is carried. The flange itself is supported by two small brackets as shown. An electrically driven scavenger pump removes oil from the turbo CHRA and returns it to the pan. The turbo was sized for efficient operation between sea level and 15,000 ft. elevation. To maximize performance, the wastegate is operated in a standard turbocharged mode; i.e., turbo-normalizing was not employed.

The two exhaust headers were constructed from 1.75-inch diameter stainless steel tubing. They are joined to the collector via slip joints that allow for thermal expansion. The exhaust exiting from the turbine is an open 2.25-inch diameter tube. This open-style exhaust is nearly ideal for a turbocharged engine. Remember that it is the pressure difference between the upstream and downstream sides of the turbine that provide the bulk of the kinetic energy in the exhaust stream that powers the turbocharger.

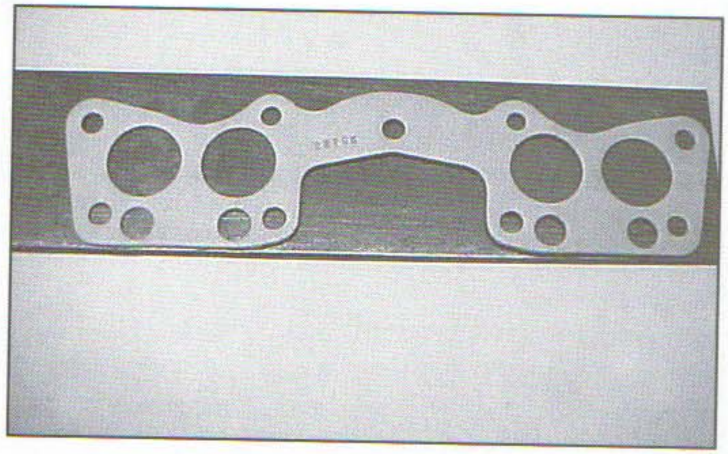
PART IV:
APPENDICES

APPENDIX A:
FABRICATING AN EXHAUST MANIFOLD

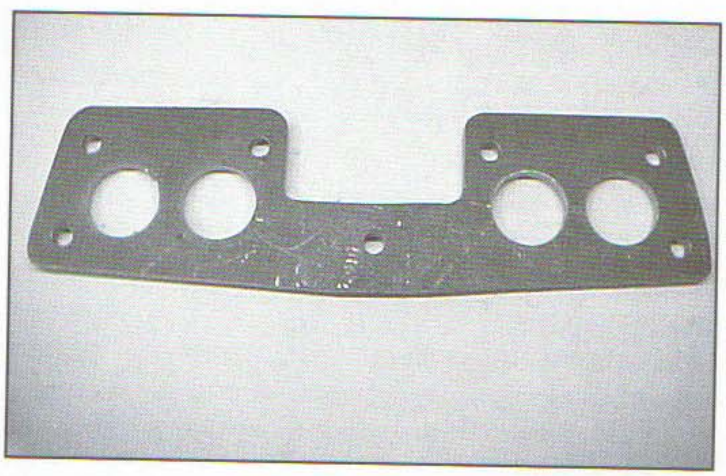
Fabricating an exhaust manifold is not overly difficult, but it does take a certain amount of persistence and welding skill. Measuring, cutting, grinding, welding, trial-fitting—and sometimes starting over—are inherent parts of the process. But the result of all this labor can be a high-performance manifold that doesn't cost a lot of money. Here, Duncan Fraser of Racetech in Calgary, Canada builds an equal-length individual-runner manifold for a Toyota 22RE engine fitted in a Celica.



The turbocharger is positioned in the engine bay. Care is taken to ensure that inlet and outlet flow paths to the turbine and compressor are smooth, with no abrupt transitions. The manifold will also have to clear a variety of pre-existing engine components under the hood. Access to the exhaust manifold bolts can't be forgotten, either.



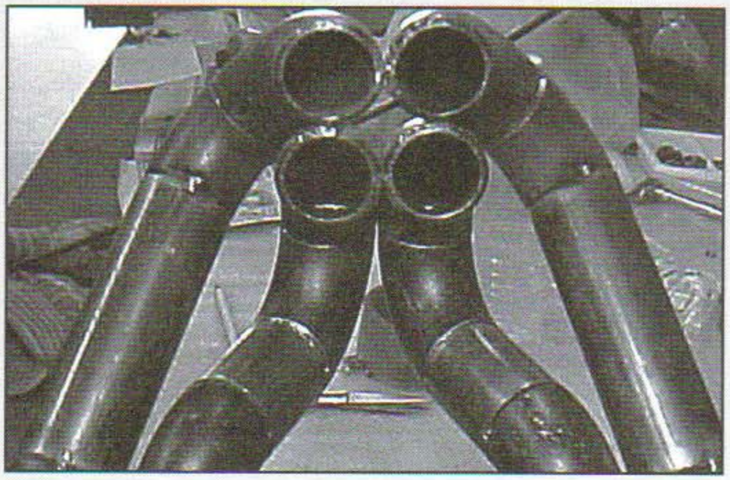
A spare exhaust gasket is used as a template to transfer the exhaust port and attachment hole patterns to 0.5-inch steel plate.



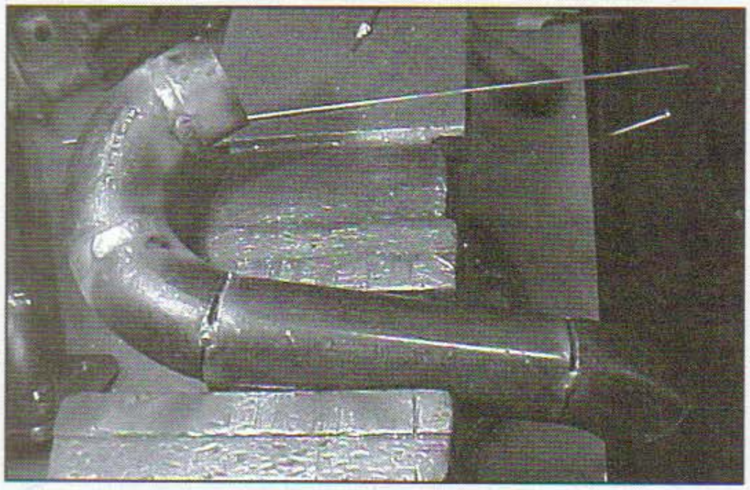
The resulting flange is both elegantly simple and strong.

The basic building block of a DIY-type exhaust manifold: a schedule-40 mild steel weld-el. These are also available in stainless steel from a variety of suppliers.

Patience is the secret to fitting up small sections of pipe and tack-welding them together. Note the junkyard cylinder head to which the exhaust flange is bolted. This keeps everything straight and flat during fit-up of the parts.

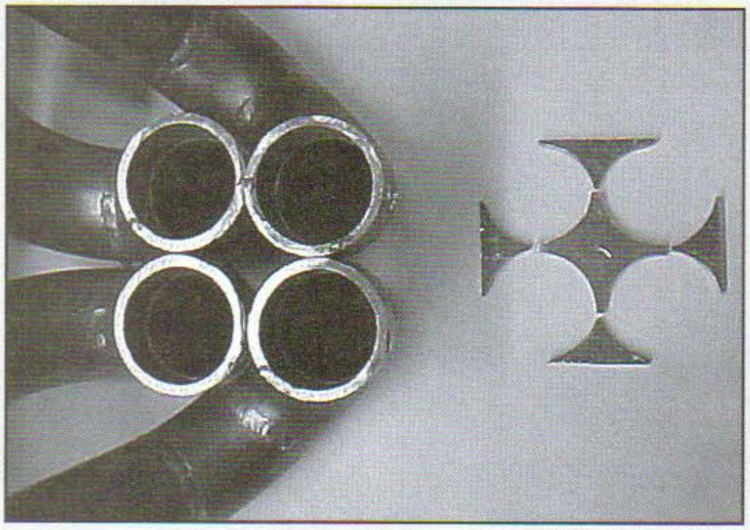


The four exhaust runners come together in a tight bundle. Don't be afraid to grind off tack welds and reposition tubes to improve the assembly fit. Once final welding is completed, there's no going back.

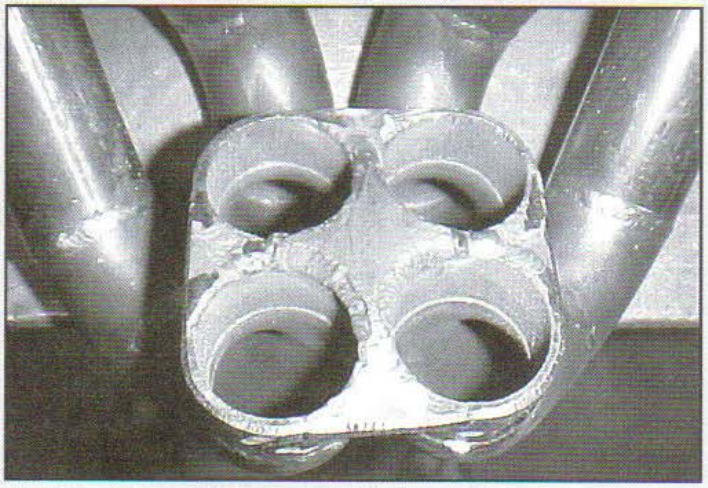


The runners are temporarily removed from the flange. This allows 360-degree access to the joint welds.

The runners are then repositioned on the flange and welded in place.

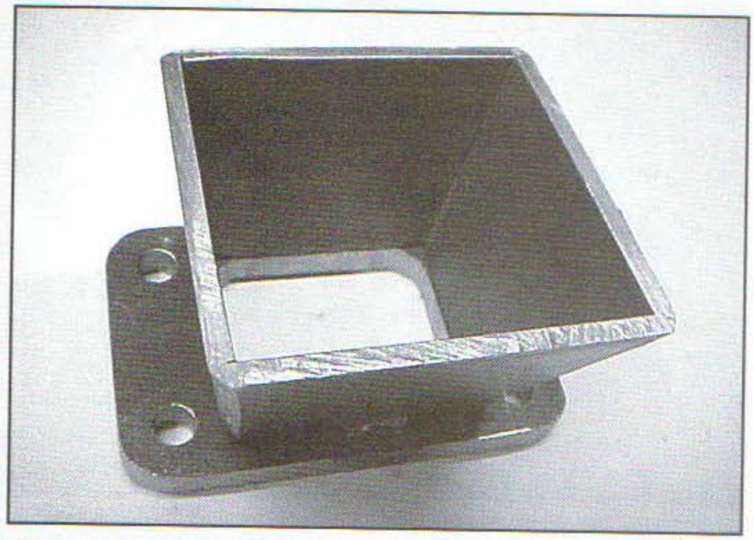


The transition to the collector is made from flat stock.

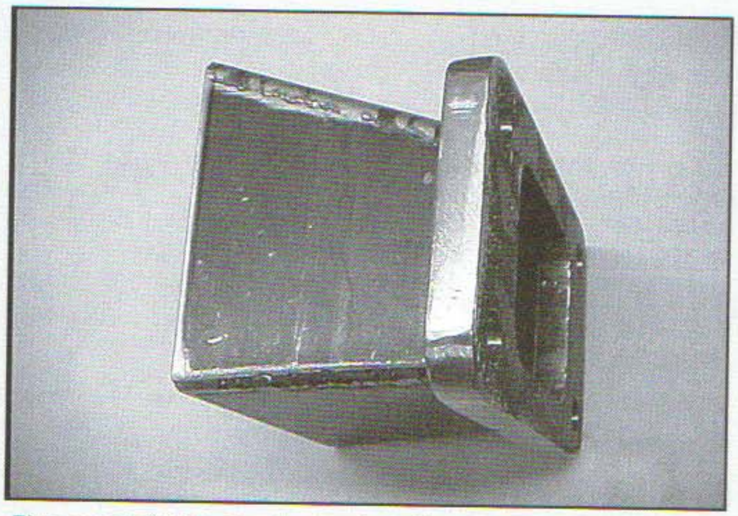


The completed runner transition. A die grinder can be used at this point to clean up the internal welds before the collector is added.

A mounting flange for the turbine is cut from 1/2-inch flat stock.



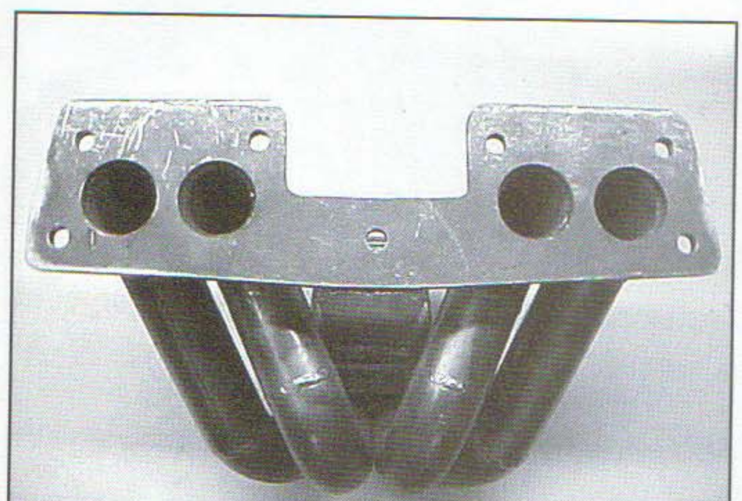
The collector is trial-fitted together with tack-welds.



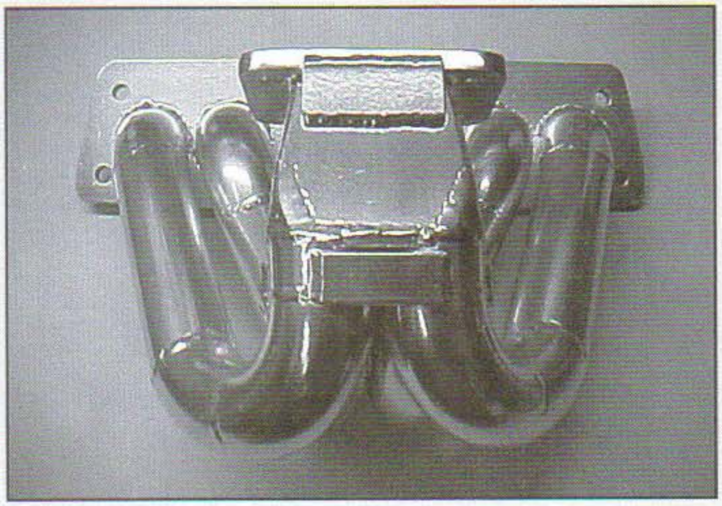
The rough-finished collector is fully seam-welded. Note the thickness of the turbine flange.

The entrance corners of the collector are then reworked to mate with the round runner tubes. This step helps ensure a less-turbulent gas flow transition from the runners to the collector.

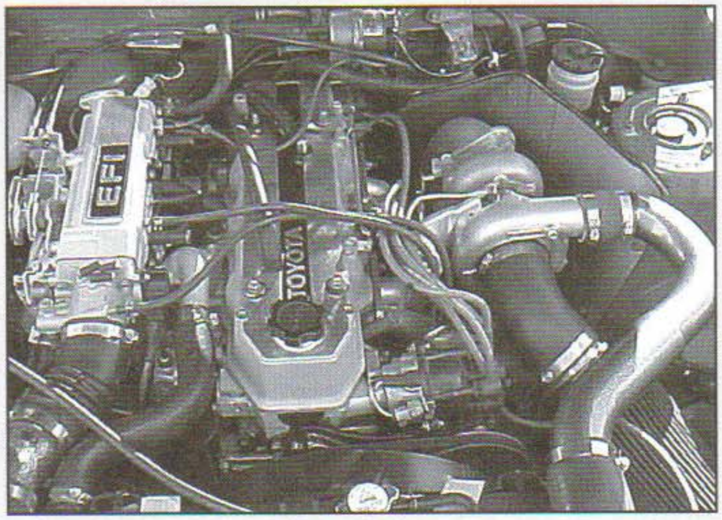
The collector is welded to the runners. Additional mounting brackets, gussets, and stiffeners are then added as required.



At this point the cylinder head and turbine flanges can be fly-cut on a milling machine to clean up and flatten their mating surfaces.



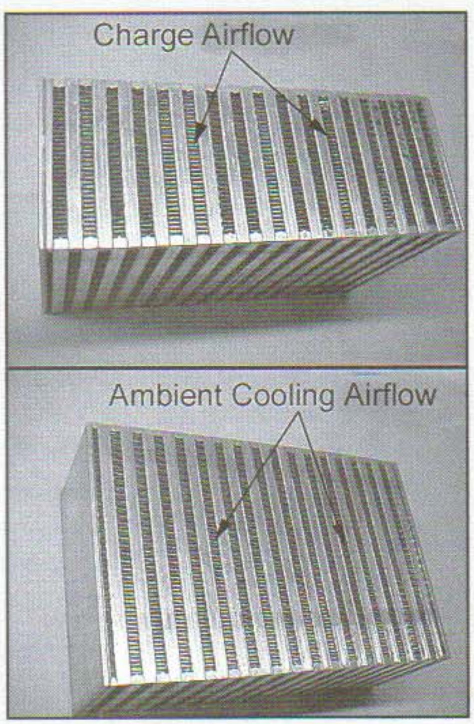
The manifold back from the coating shop. Pretty, isn't it?



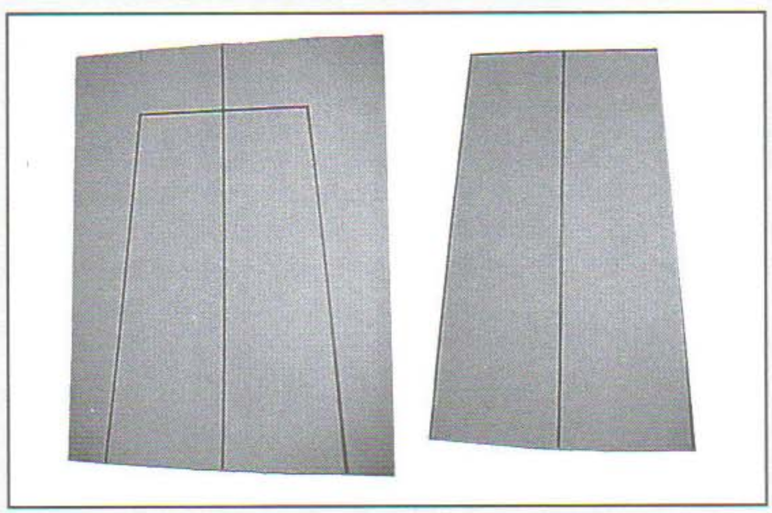
With the addition of 15 psi of boost, the 2.4-liter Toyota engine now generates an impressive 375 hp and 350 lb-ft of torque.

APPENDIX B:
FABRICATING AN INTERCOOLER

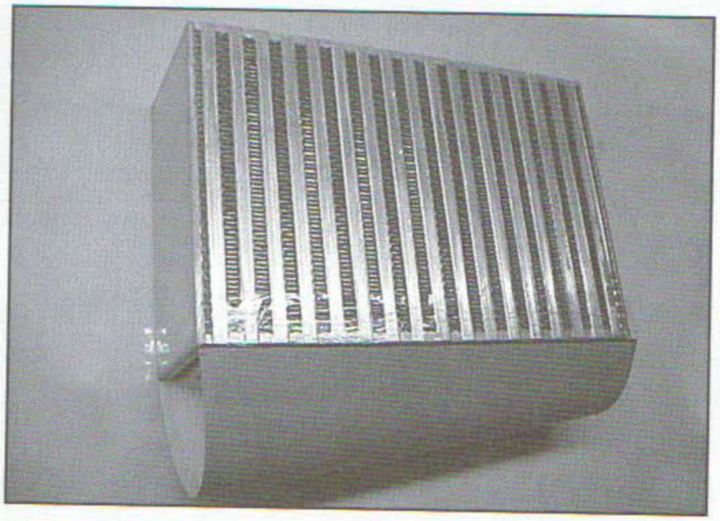
The following steps illustrate the construction of a custom air-to-air intercooler. The size and layout of the intercooler system within the vehicle, as well as the choice of individual components such as core and end tanks, is highly dependent on the application and budget. Here, Racetech in Calgary, Canada, builds a simple, but very efficient, intercooler for use in a turbocharged vehicle.



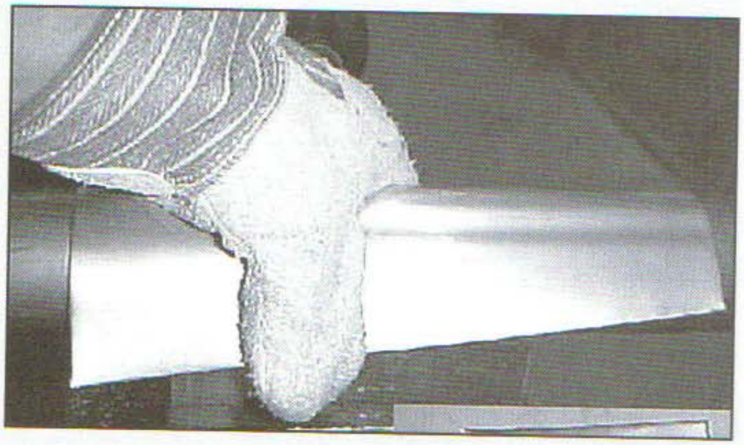
The core chosen for this build is a modern bar and plate unit from Spearco.



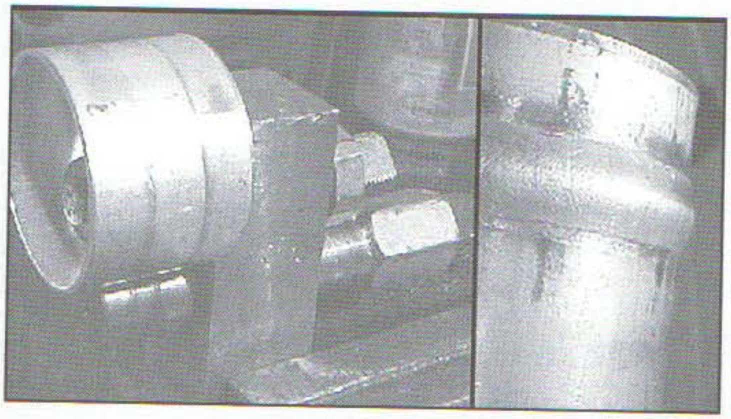
Next, the intercooler is positioned in the vehicle. This allows the designer to lay out the tubing that will supply air to and from the intercooler. End tanks are also designed at this point. A template for each tank is cut from cardboard to help mock up the design. Care should be taken to design a system with minimal tubing and as few bends as possible. Long tubes with multiple turns and bends will cause pressure drops that effectively rob horsepower.



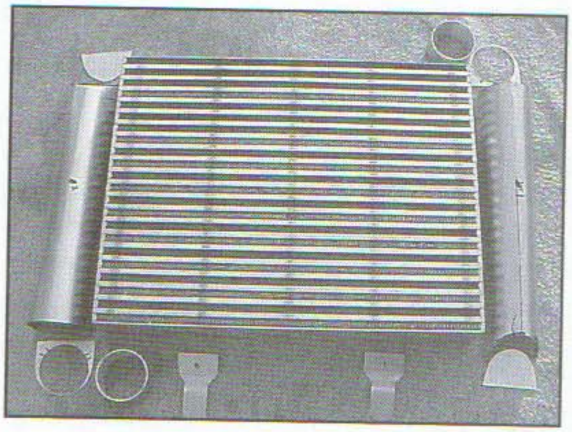
Once satisfied that the cardboard end tank layouts are correct, they can be used to trace the design onto aluminum stock.



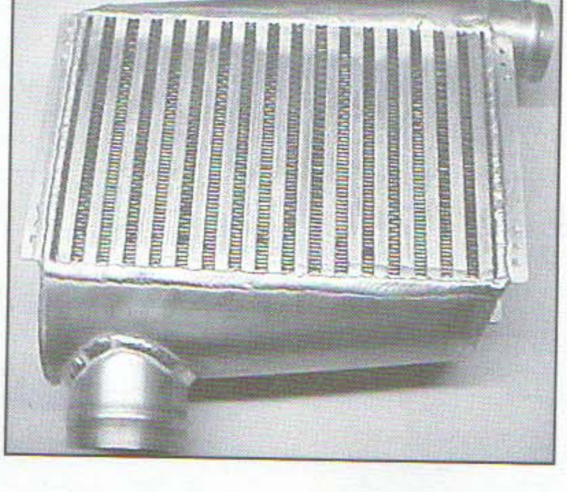
The 0.050-inch thick 6061 aluminum sheet was formed by hand around a steel tube. Care was taken to get a good fit between the final formed shape and the core edges.



Sometimes called "snouts," the tank interface tubes are constructed from 6061-T6 tubing with 0.050- to 0.060-inch wall thickness. Note the roll-formed bead that helps keep the intercooler hose from popping off under boost. Make sure the tubes are long enough for these beads, the hose clamp, and the fillet that will be formed when welding to the end tank.



End caps are cut from aluminum and trial fitted before final welding. Note that the caps have a slight slope to them, which helps guide airflow down into the final few tubes at the end of the core. Note the mount tabs, too, in the upper photograph. These are fabricated from 0.125-inch thick aluminum plate.



The complete intercooler after TIG welding.

APPENDIX C:
SINGLE VERSUS TWIN TURBOCHARGERS

Deciding between a single turbo and a twin turbo setup can be difficult. This is especially true on large displacement and V-style engines. Both single and twin setups have advantages and disadvantages that must be considered. Often, simply the allowable space under the hood will dictate the choice. So will the budget, as well as intangibles like the "wow" factor that the owner is trying to achieve when the hood is raised. But ultimately this decision should be based on the performance goals for the vehicle.

The truth is that with modern turbocharger designs, the differences between properly sized twin and single setups are relatively small. But differences do exist, and should be factored into the decision process.

If the goal is strictly to maximize the top-end horsepower output of an engine, a large single turbo setup would likely be a better choice than smaller twin turbos. Generally speaking, as turbochargers increase in size, they become somewhat more efficient. There are a number of reasons for this, including lower internal backpressure, more favorable wheel-to-housing clearances, and better flow rate to wall friction ratios. These factors are true for both the turbine and compressor sides of the turbocharger.

Plumbing and installation of a single turbo are generally easier than for twins, too. Only one set of oil and water supply and return lines are required. Similarly, only one intercooler needs to be installed and plumbed into the intake tract. V-style engines require a crossover pipe that merges one exhaust manifold with the other, but this is generally easy to accomplish.

The biggest downside of a single turbo, however, is the problem of inertia. The polar mass moment of inertia of any physical entity is a measure of how its mass is distributed geometrically throughout its body. More importantly, it's a measure of the body's resistance to rotational acceleration. A fundamental equation of physics states that the rotational acceleration of a body is proportional to the torque applied to the body, divided by its mass moment of inertia. The larger the torque, the faster the body will increase its rotational speed. Conversely, the larger the inertia, the slower the increase in speed.

A turbocharger's turbine and compressor wheels, as well as the shaft connecting them, all have inertia. Trying to express the precise amount of inertia of a complicated shape like a turbine wheel in mathematical terms is very difficult, but for a reasonable approximation we can represent a turbine or compressor wheel as a simple spinning disk.

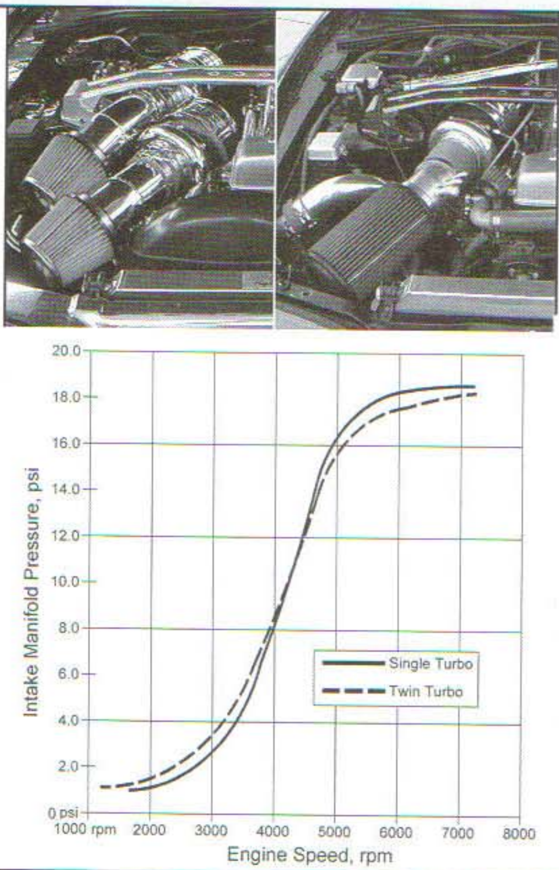
The inertia of a thin disk is equal to one half of its mass, multiplied by its radius squared. But the mass of a thin disk is also proportional to its radius squared. In other words, the polar mass moment of inertia of the disk (or turbine wheel) is a function of its size (radius) raised to the fourth power! A small increase in wheel diameter can have a large effect on inertia, which in turn means it will have a large impact on how quickly the wheel can accelerate, or spool-up.

Counteracting this to a small degree is the increase in torque applied by the exhaust gases to the turbine wheel in the larger turbine housing. But this effect only increases linearly with wheel diameter. All other things being equal, bigger turbochargers spool disproportionately more slowly than smaller turbochargers. If the primary goal is ultra-fast spool times, a twin turbocharger system would be preferable to a single.

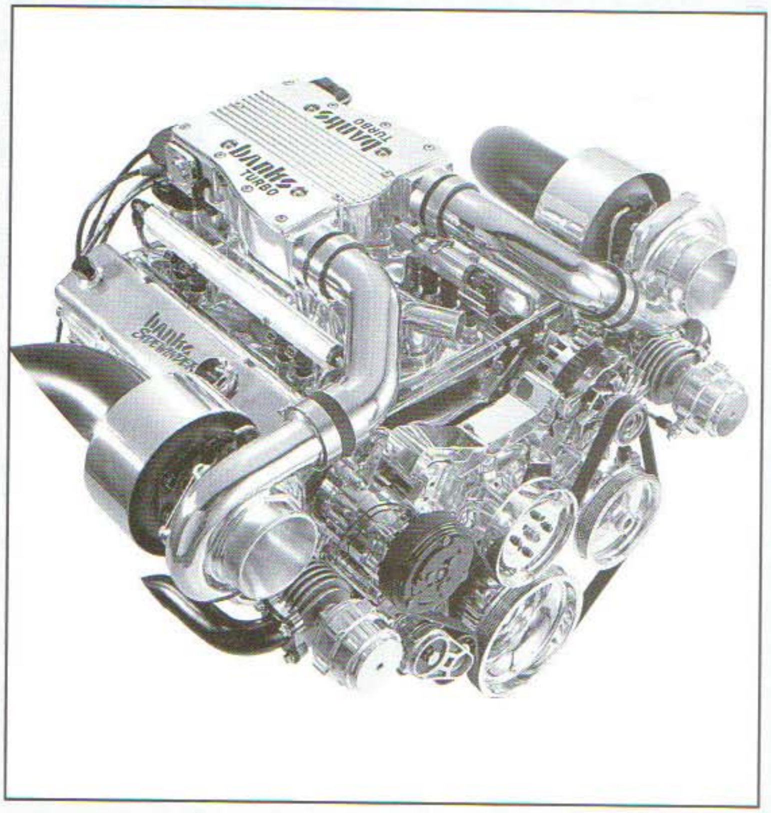
The downsides of twin turbos, however, are important to note. First and foremost, there are twice as many components to purchase and package. This includes two complete turbocharger assemblies, including their required oil and water supply and return lines, turbine outlets, and compressor inlets and outlets. You also have to consider what type of intercooler setup will be used. Will it be a single unit with dual internal paths? Or maybe twin intercoolers? Or a system that merges upstream of a single intercooler? All of these items take up significant space. This can make an already tight engine bay even more crowded, which in turn can raise under-the-hood temperatures, as well as make simple maintenance tasks harder to carry out. And don't forget reliability concerns, too. If you double the number of mechanical components in a mechanical system, by definition you increase the chance that something will break.

If you decide to go down the twin turbo path, you will need to choose between parallel and sequential plumbing. Most aftermarket and custom twin turbo setups are plumbed in a parallel arrangement. In this type of layout, the outlets of the two compressors follow identical paths through separate intercoolers and then into the intake plenum, where their flows are merged together. Each compressor generates full boost pressure, but is sized to support only half the total flow rates required by the engine.

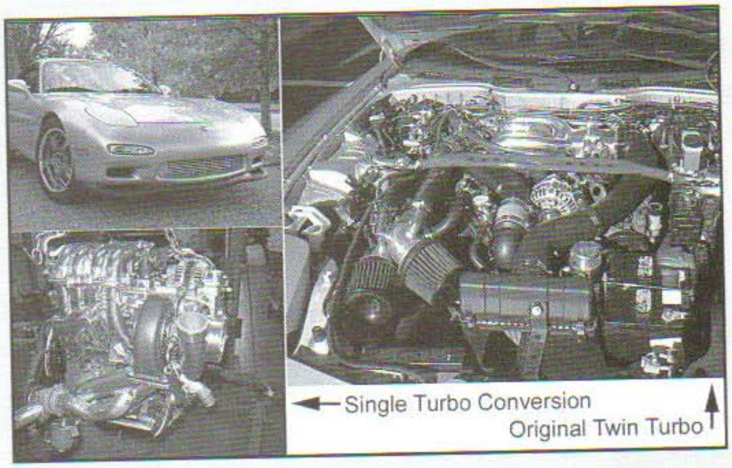
In contrast, a sequential system is one in which only one of the turbos receives exhaust gases at low engine rpm, with the second turbo being phased in gradually as engine speed increases. This allows full gas flow to accelerate a single turbo even more quickly and produce boost, with both turbos working together at higher engine speeds. Sometimes, the first turbocharger is smaller than the second unit. The downside of a sequential setup, however, is a more complicated control system to phase in and out the second turbocharger at the appropriate time.



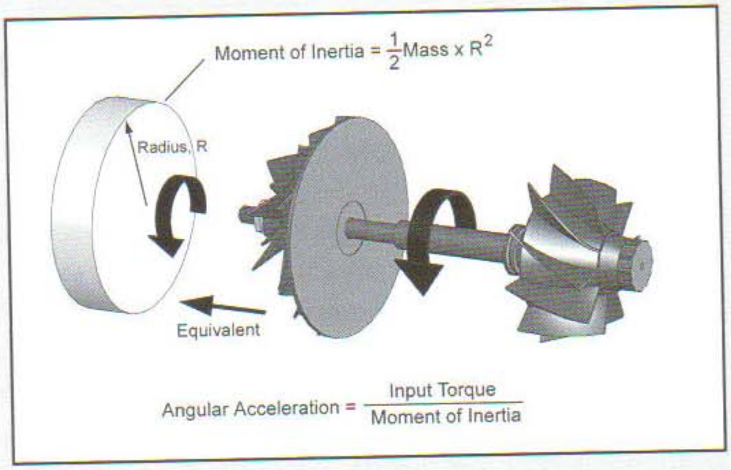
Two nearly identical Toyota Supras, one fitted with a single turbo system, the other with a twin turbo. Note the differences in boost production throughout the engine speed range. The twin turbo has a slight advantage at lower engine rpm, building boost—and consequently horsepower—earlier than the single turbo. In contrast, however, the single-turbo has a measurable advantage in the upper rpm range.



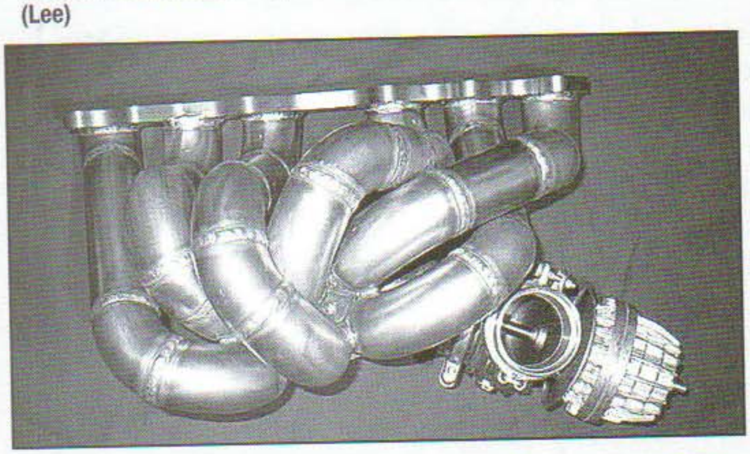
An ultra-fast–spooling twin-turbo small-block Chevy. (Gale Banks)



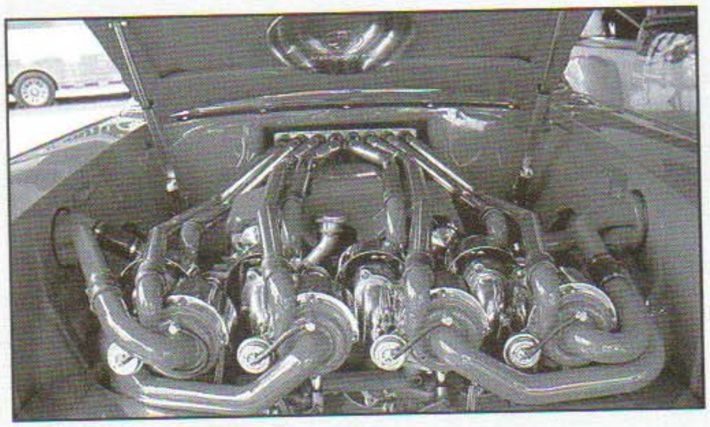
The owner of this third-generation Mazda RX-7 wanted more horsepower than his already modified sequential twin-turbo rotary engine was capable of producing. The answer was a single-turbo conversion that features a GT 35/40 turbocharger, generating 16 psi of boost. Rear-wheel output is now 412 hp and 321 lb-ft of torque. (Lee)



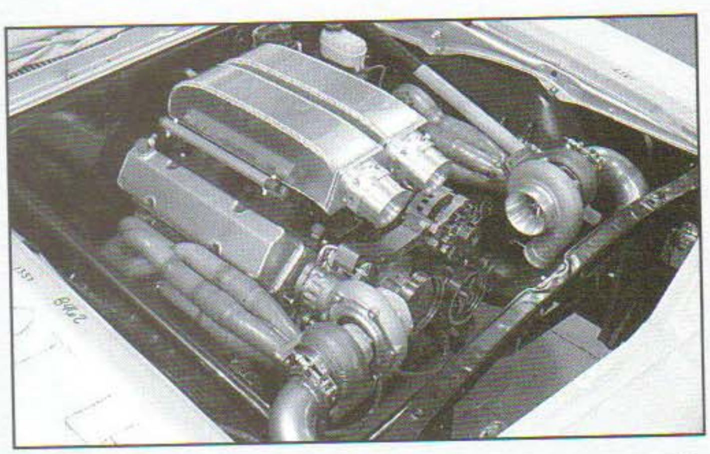
The biggest problem that has to be dealt with when considering a large single-turbo is spool-up time. Careful selection of the appropriate turbine housing A/R ratio is critical in reducing turbo lag.

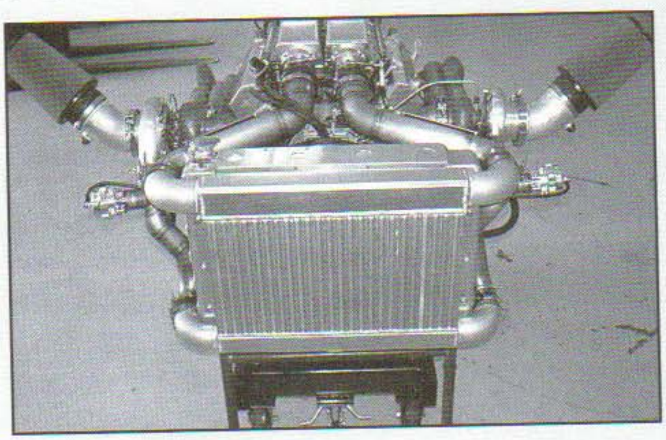


A well-engineered single-turbo conversion manifold for the 2JZ-GTE engine. Without careful design of components like this, as well as a systems-type approach to a conversion, it's easy to end up with lower performance than before the swap. (Full-Race)



Twin turbos not enough? How about eight? This 1957 Chevrolet, dubbed the Inciner8or, features an LS1 fitted with eight Borg Warner/3K turbos. Boost is set at 13.5 psi, and the vehicle generates 730 hp and 710 lb-ft of torque. (Scott Gulbranson, www.Lateral-g.net)





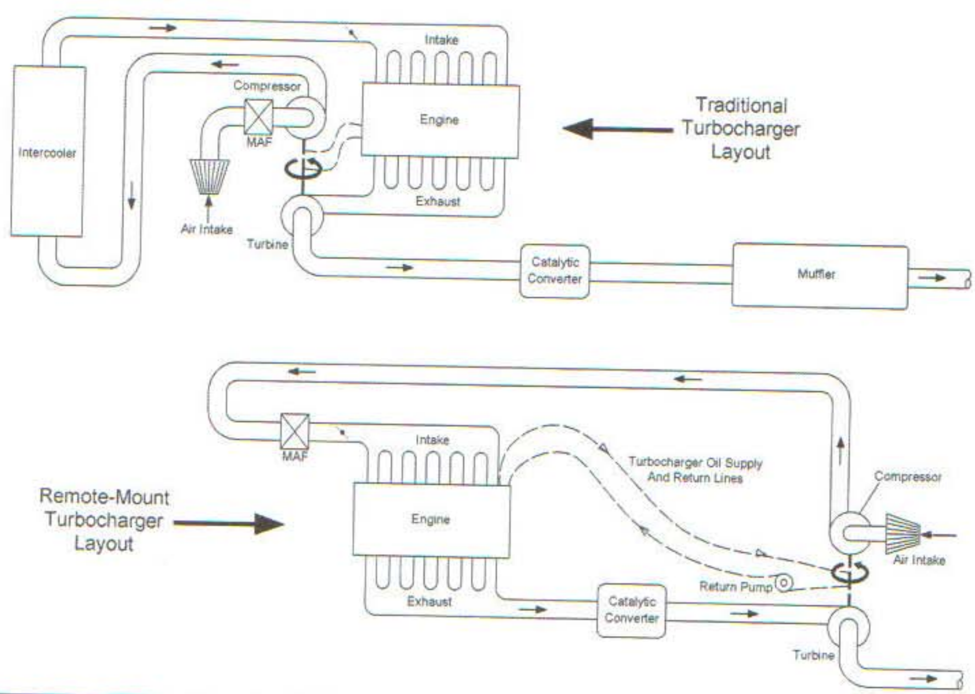
Often, the biggest hurdle when building a twin-turbocharged engine is simply packaging all the system components within the limited confines of the engine bay. The team building this Chevrolet Camaro originally located the turbines outboard and the compressors inboard (left photo). While good from an exhaust point of view, it complicated plumbing to and from the intercooler. The final configuration (right photo), swapped the positions of the hot and cold sides of the turbos. The result is a compact and efficient layout, with short, direct plumbing runs from the compressors to the intercooler, and then back to the intake plenums.

APPENDIX D:
REMOTE-MOUNT TURBOCHARGERS

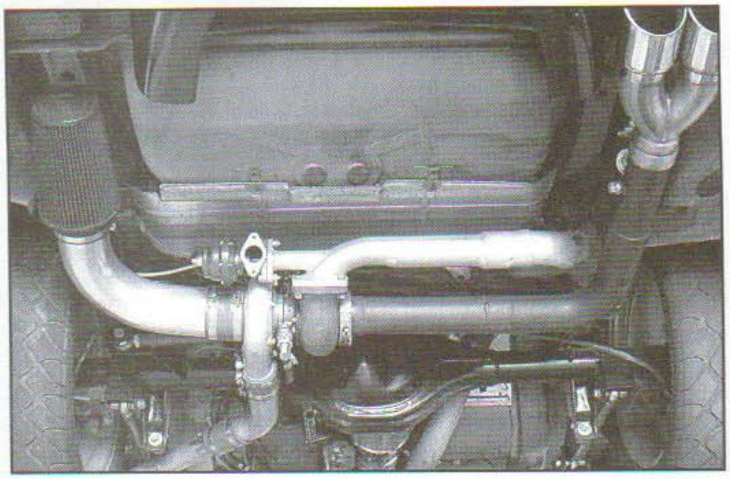
Want to turbocharge your vehicle but don't have enough space under the hood? Maybe the thought of fabricating an exhaust header and/or cutting up the front of your vehicle to mount a large intercooler has you queasy? A remote-mount, or cat-back type turbocharger system may be just the solution you're looking for.

Designed to replace the muffler and rearmost portion of a vehicle's exhaust system, a remote-mount turbocharger can provide low- to moderate-levels of boost and respectable performance gains. They can also be installed relatively easily in kit form, often taking less than six to eight hours to set up from start to finish. They can be removed just as quickly, returning the vehicle to stock noise and emissions trim with little effort. The advantages of remote-mounts also include lower temperatures under the hood, less weight on the front of the vehicle, and lower bulk oil temperatures.

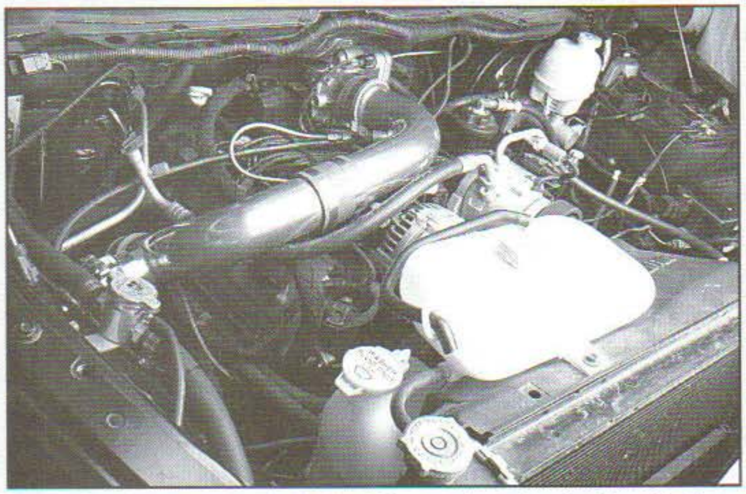
The primary downside to remote-mount turbos, however, is that they usually provide somewhat lower performance levels than a traditional turbocharger. Typically sized to generate only 5–10 psi, remote-mount turbos are applicable primarily for those seeking moderate horsepower and performance gains. Because the turbocharger is located far downstream of the engine, the exhaust gases tend to lose a fair amount of their heat energy before entering the turbine. To make up for this loss, most remote-mount turbos employ relatively small turbine housings with reduced A/R ratios. This allows the units to spool fairly quickly (turbo lag with a properly-engineered remote-mount turbo is often no worse than a traditional turbocharger system) but this ultimately limits their maximum power production ability. For most street applications, however, this effect goes unnoticed and horsepower outputs with 5–10 psi of boost is quite impressive.



A remote-mount turbocharger layout is somewhat simpler than a traditional turbocharger system. Note the absence of an intercooler; the long intake pipe between the compressor and intake manifold is designed to remove excess heat, in a sense acting like a self-contained charge-cooling device. At low levels of boost (<10 psi) this is usually adequate to prevent detonation and improve performance. Water injection is also a good choice on these types of systems. It can be injected into the intake tube right after the compressor to allow the long transit time to vaporize the water and maximize its cooling effect.

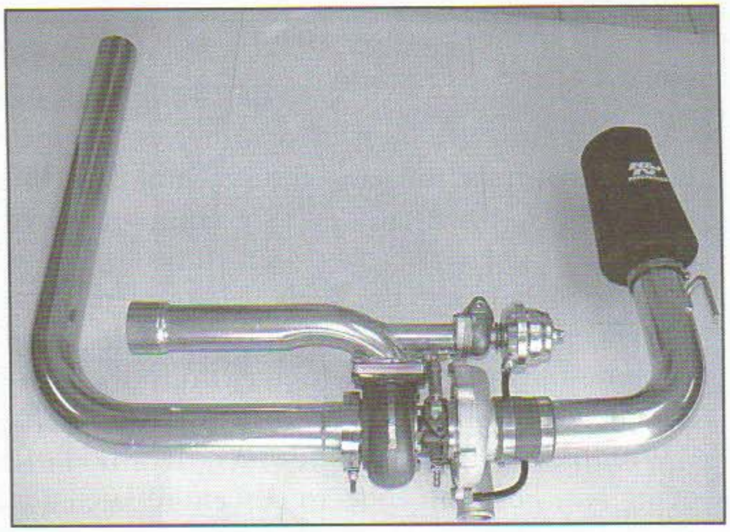


A remote-mount turbocharger replaces the muffler and exhaust system downstream of the catalytic converter. The turbine acts like a mini replacement muffler, reducing the sound level of the exhaust to acceptable levels. Note the wastegate dumping directly to the atmosphere. (Squires)

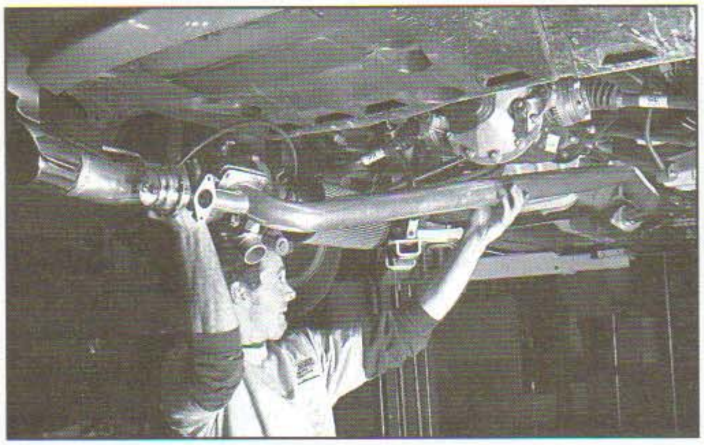


The plumbing underneath the hood is usually quite simple, with the only non-stock item visible being the intake pipe attached to the throttle body. (Squires)

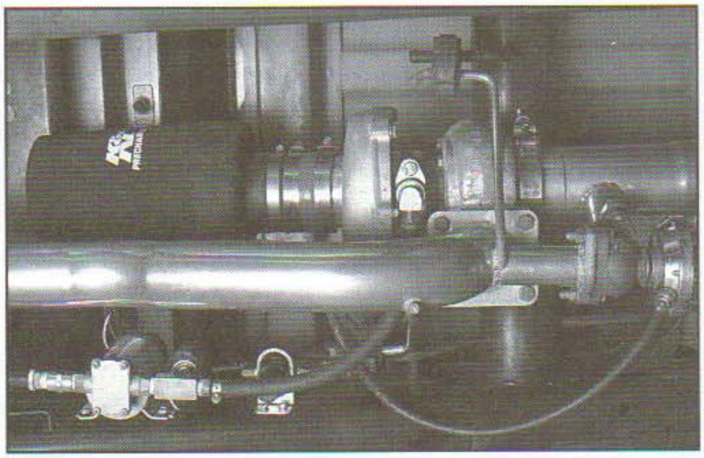
A Pontiac GTO fitted with a remote-mount turbocharger kit. (Squires)



The business end of a remote-mount turbocharger. (Squires)



Installation of a remote-mount turbocharger system often takes less than eight hours, from start to finish. Because the catalytic converter and other emissions devices can be left installed and operating on the vehicle in their stock locations, cat-back turbos are usually legal from an emissions point of view. (Squires)



Oil must be supplied to the turbocharger from the engine at the front of the vehicle. Note the scavenging/return pump in the lower left hand corner. Note also the simple muffler hanger used to support the turbocharger. A remote-mount unit replaces the stock muffler, which results in an interesting turbo whine when under boost. (Squires)

APPENDIX E: CARBURETORS AND TURBOCHARGERS

Carburetors have been used with great success on literally millions of naturally aspirated engines over the course of the past century. Until the 1980s, when electronic fuel injection (EFI) took over the marketplace, essentially every gasoline-powered vehicle sold in the world was equipped with a carburetor. There also have been turbochargers added to countless numbers of carburetor-equipped engines throughout the years. Many of these were OEM systems, such as those built by Buick, Chevrolet, Ford, Lotus, Maserati, MG, Oldsmobile, Renault, and even Rolls Royce. In addition, tens of thousands of performance enthusiasts have converted their carburetor-equipped vehicles to aftermarket forced induction with excellent results.

With the advent of EFI, however, the world of turbocharged carburetor-equipped vehicles is slowly dying out. For most modern day enthusiasts, a carburetor is an interesting, yet antiquated device. If you are starting a turbocharged engine project from scratch, EFI is clearly the better choice for most projects. But if you are planning to turbocharge a vehicle that has a pre-existing carburetor system, it may make financial sense to keep this factory fuel system intact and simply add a turbo to it. For simplicity, it's hard to beat a carburetor. As stated back in Chapter 11, the power output potential of a properly set up carburetor-based turbo system can be equal to that of an EFI-equipped vehicle.

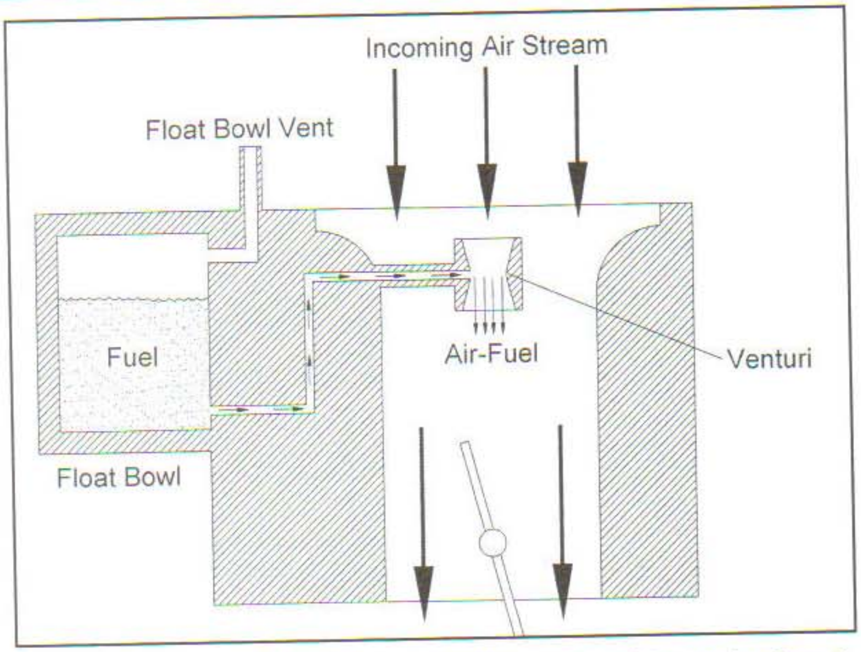
Carburetor Basics

The carburetor is a simple device. Think of it as just a tube through which air flows on its way into the engine. At one end of the tube is a throttle plate that controls the amount of airflow. At another location within the tube, there is a section called the venturi. The venturi is simply a narrowed down portion of the tube. Air speeds up as it passes through the venturi, much like the water in a wide river accelerates as it travels through a narrow canyon. In the carburetor, the fast moving air passing through the venturi results in a local pressure drop.

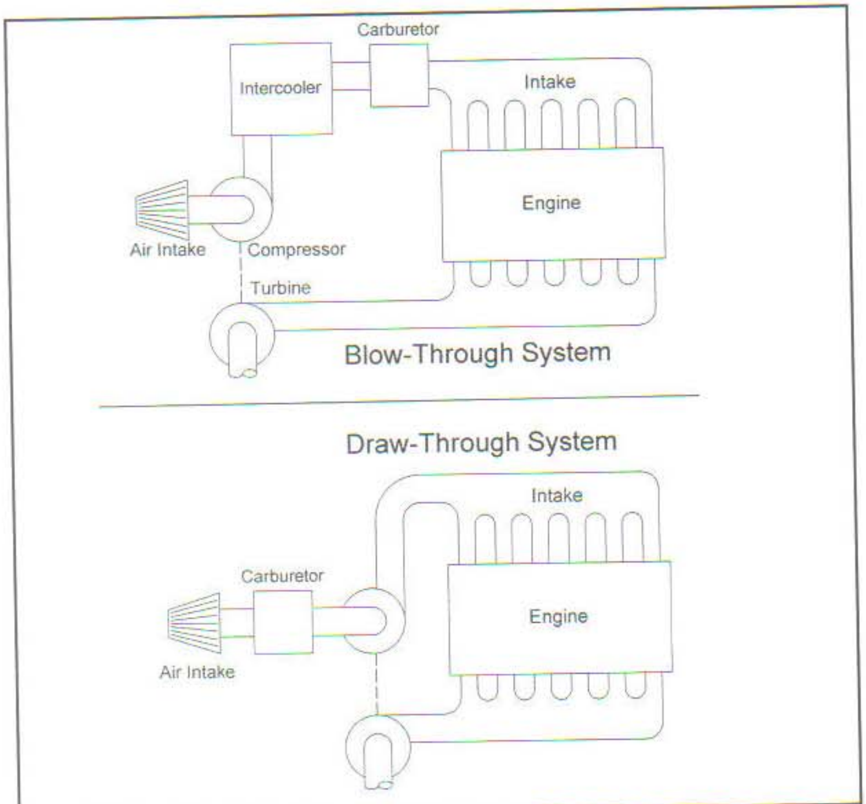
Physicists like to describe this pressure drop phenomena with something called Bernoulli's equation. Of all the formulas a first-year engineering student faces in college, the one he most likely remembers from fluid mechanics class is Bernoulli's. This ubiquitous equation is based on the principle of energy conservation and is integral to such concepts as why airplanes fly and why carburetors work the way they do.

In simple terms, Bernoulli's equation states that the total energy contained in a fluid flow (gas or liquid) is constant. Further, this total energy quantity is comprised of three basic parts: pressure, kinetic, and potential energy. Potential energy is the energy associated with height and gravity and isn't really germane to the discussion of carburetors. This leaves just pressure and kinetic energy. If a flow of air accelerates through a carburetor venturi, its kinetic energy increases. But because the total energy contained within the flow has to remain constant, something else has to decrease. In other words, the pressure energy of the flow drops. Put another way, pressure decreases with increased flow speed.

The secret to how a carburetor works lies in the utilization of this local pressure drop. At the center of the venturi is a small hole, or jet. By connecting this hole to a reservoir of fuel (i.e., the float bowl), the gasoline in the bowl is subjected to a pressure gradient. Because of this, the venturi siphons fuel out of the bowl, through the jet, and mixes it with the air stream. The faster the air flows through the carburetor, the larger the pressure gradient acting on the fuel and, consequently, the more fuel that gets added to the air. The actual amount of gasoline flow can be adjusted by changing the jet size. In a sense, a carburetor is a self-governing fuel delivery system. As the throttle plate is opened and more air



A carburetor is a simple device. Low pressure is created by accelerating air through a venturi. This draws fuel from a float bowl to an intake jet located in the venturi. The result is a self-regulating air-fuel mixture delivery system. Even better, carburetors can be combined with forced induction to create reliable horsepower with simple modifications.



Turbo-carburetor systems are constructed in one of two ways: blow-through or draw-through. A blow-through system locates the carburetor downstream of the compressor. A draw-through system positions the carburetor upstream of the compressor.

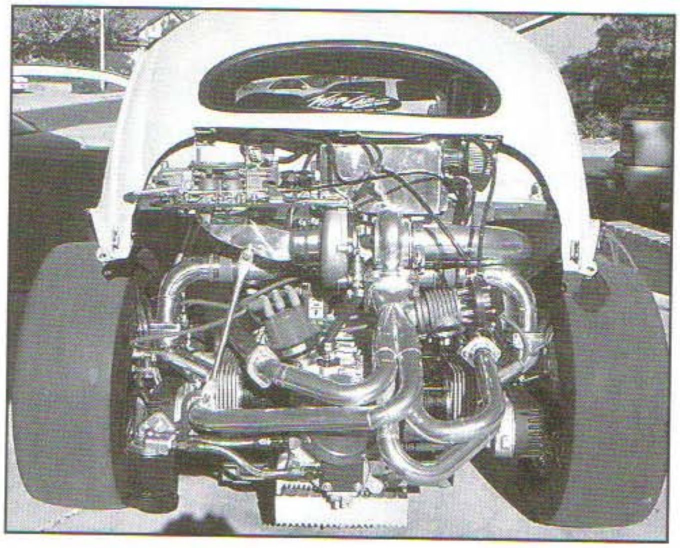
is drawn into the engine, an increased amount of fuel is added, thereby maintaining the correct air-fuel mixture ratio.

Because of this intrinsic self-adjusting ability, a carburetor can provide excellent results when used in conjunction with the increased flow rate of air supplied by a turbocharger. There are, however, some possible modifications and special care required for the carburetor. These changes depend on the basic layout of the fuel delivery system, including the carburetor position relative to the turbocharger compressor. There are two locations in which to mount the carburetor, either upstream or downstream of the turbo. These are respectively known as draw-through and blow-through layouts. Both have advantages and disadvantages. Let's take a closer look.

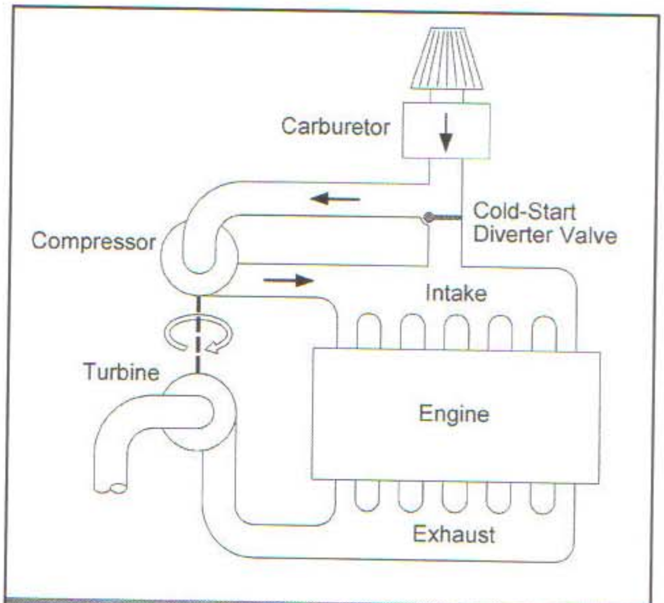
Draw-Through Systems

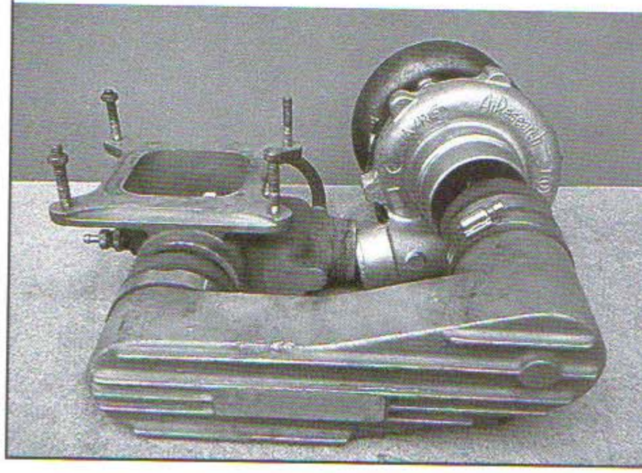
Perhaps the simplest method of turbocharging a carbureted engine is via a draw-through layout. A draw-through turbocharger system is one in which the carburetor is mounted *upstream* of the turbo-charger compressor. As the turbocharger spools, the suction created at the inlet of the compressor pulls air through the carburetor.

At first glance, a draw-through layout would appear to be an ideal choice for a carbureted engine. Because the carburetor sees only increased airflow under boost, it behaves the same way a normal carburetor does; i.e., the more air that passes through the venturi, the



A well-packaged draw-through carburetor system installed on a Volkswagen. (Turbosmart)





Some draw-through systems incorporate a diverter valve that aids start-up when the engine is cold. This is necessary due to the long and inefficient flow path from the carburetor to the intake valves. Because of the number of sharp bends, abrupt flow transitions, and the overall length of the intake path, fuel can fall out of suspension from the air stream, especially when the system is cold.

more fuel that gets drawn out of the bowl and into the air stream. No special seals, floats, or other high-pressure modifications to the carburetor are required, and tuning is relatively straightforward. Blow-off valves are also not required with draw-through systems. This is because the throttle is upstream of the compressor. (This is a good thing, too, as a BOV venting a "wet" air-fuel mixture from a draw-through system into the engine bay would be a dangerous thing.) The only changes required to a carburetor used in a draw-through system are things like the addition of a reference signal supplied to the carburetor's power valve, larger fuel inlet control needles, and a fuel pump sized to match the desired horsepower goal. This makes for a simple to implement system. Tuning with a wide-band air-fuel meter can also be used with excellent results.

There are some problems with a draw-through arrangement, however. First and foremost is the fact that an intercooler cannot—and should not—be used on a street-driven draw-through turbo system. The atomized fuel passing through the intercooler tends to fall out of suspension from the air, puddling and pooling inside the device. This can lead to dangerously lean air/fuel mixtures and/or an intercooler that is waiting to explode.

Counteracting this to some extent is the inherent latent heat of vaporization ability of the atomized fuel flowing through the intake tract. In much the same way water injection works to lower intake temperatures, the suspended fuel droplets in the intake charge absorb a large amount of heat. Water injection can also be used to help further control detonation and keep temperatures down.

Another concern with draw-through systems includes sluggish throttle response, especially on poorly designed systems with long intake tracts. Good system design will minimize inlet plumbing length, and reduce the number of sharp bends and abrupt flow transitions.

Often, a draw-through system will provide some type of warm air stove from the exhaust, or a heated waterjacket to prevent carburetor icing. At first glance it seems counterintuitive to heat the carburetor or inlet tract. Such thinking is correct in a naturally aspirated vehicle, but in a draw-through system, heating aids part-throttle drivability. And when properly executed, it has a relatively minor effect on vehicle performance during high-speed operation.

Finally, a draw-through system should employ a mechanical carbon face seal on the turbocharger compressor side to withstand vacuum during closed throttle events—otherwise, oil will be pulled from the turbocharger into the intake tract. Most modern turbochargers do not include this type of carbon face seal unless specifically requested during purchase.

Blow-Through Systems

The majority of carburetor systems built today by enthusiasts are configured in a blow-through arrangement. A blow-through turbo system is one in which, logically enough, the carburetor is placed after, or downstream of the compressor. The turbocharger draws in air and then directs it through the carburetor.

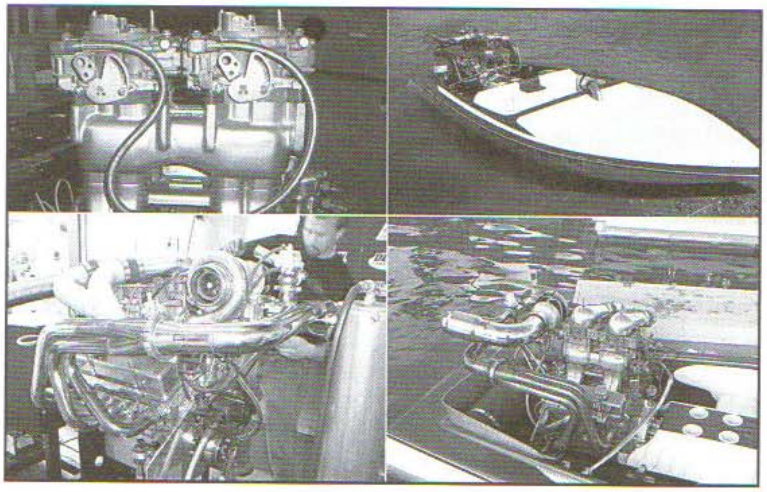
The biggest advantage of blow-through systems is that an intercooler can be used between the compressor and the carburetor. Throttle response is improved, too, as the carburetor is farther downstream in the intake track. Cold starts also benefit from a blow-through arrangement, because of the reduced tendency for the fuel to fall out of suspension.

To make a blow-through system work correctly, however, the carburetor has to be modified to handle the higher density airflow passing through it. Recall that a carburetor adds fuel to the air stream based on a pressure gradient, or difference, between the venturi and the fuel bowl. In a naturally-aspirated engine, the bowl is at ambient pressure, and the air stream passing through the carburetor experiences a drop in pressure below ambient. The difference between the pressure inside the bowl and that in the air stream pulls the fuel out through the jets.

The problem with this arises in a forced-induction application because the air passing through the carburetor is at a higher pressure than in the bowl. Fuel is pushed backward through the jets *toward* the bowl because of the boost pressure. To counteract this effect, the float bowl (or entire carburetor) must be pressurized to the same level as the air stream exiting the compressor/intercooler. Older applications often enclosed the entire carburetor within a large pressurized "box" to solve this problem. Most modern applications, however, utilize some type of bonnet or "hat" that is attached to the top of the carburetor. This pressurizes both the venturi and the float bowls on carburetors such as Holley's double-pumpers.

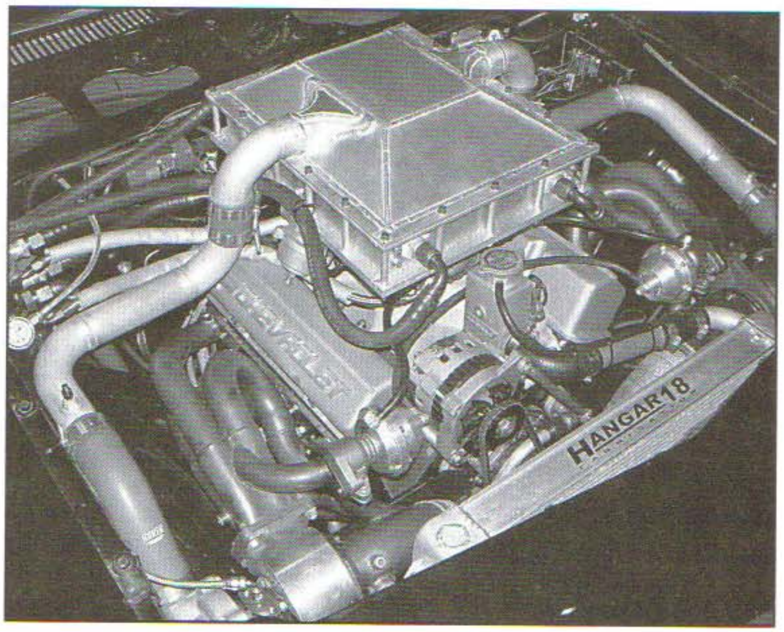
Even with the float bowls pressurized, however, carburetors cannot entirely compensate for the increased air density and pressure provided by a turbocharger. Careful jetting and air bleed modifications will be required to bring a blow-through system into proper tune. Best all-around performance is frequently obtained with carburetors sized somewhat "too small" by the naturally aspirated hot rod crowd. Again, a wide-band air-fuel meter is highly recommended for tuning.

Other common carburetor modifications required on blow-through systems include the replacement of hollow brass and plastic floats with Nitrophyl foam-type units that aren't susceptible to collapsing under boost pressure, larger fuel inlet control needles, and a blow-off valve to prevent pressure spikes from dislocating internal seals and gaskets. It is also recommended that all carburetor orifices that could vent an air/fuel mixture under boost be blocked or air sealed. This typically includes the throttle shafts.

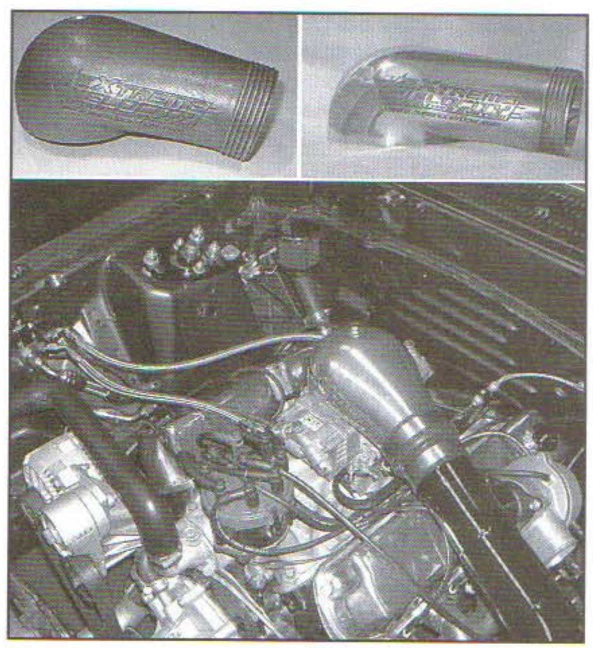


There are many excellent examples of carbureted projects built every year by old-school enthusiasts. This Sanger flat-bottom V-drive is powered by a built 355 cid Chevrolet, and features dual 660 cfm Holley carburetors. The turbocharger is a 75 mm GT42, configured in a blow-through layout. The combination creates a dyno-proven 632 hp and 569 lb-ft of torque at 6300 rpm and 10 psi of boost. If you're going to build a blow-through turbo-carburetor project, this is an excellent example to study. (Macy)

Finally, a pressure reference line from the carburetor to the mechanical fuel pump is necessary to "boost reference" the pump diaphragm. Alternatively, an electric fuel pump system can be used with a boost-referenced fuel pressure regulator that maintains at least 4 psi of pressure above the desired boost pressure, along with sufficient rated flow capacity at this higher fuel pressure. Many failed attempts at blow-through carbureted turbo systems can be traced back to the inability of the fuel pump, fuel delivery piping system, and/or regulator to supply the required fuel pressure and flow rate.



Another nice example of a blow-through turbo-carburetor system. This Chevrolet features twin turbochargers and an air-to-water intercooler mounted directly above (upstream) of the carburetor. (Slater)



Carburetor hats are designed to pressurize the venturi section of the carburetor, as well as the float bowls. (Sharer)

A

A2A: (slang) an acronym for an air-to-air intercooler.

A2W: (slang) an acronym for an air-to-water intercooler.

Absolute Pressure: the measurement of pressure that includes the effect of ambient atmospheric pressure. At sea level, the atmospheric pressure is approximately 14.7 pounds per square inch. See also *Psig, Psia*.

Absolute Temperature: the measurement of temperature on a scale that extends upward from 0 degrees on the Rankine scale. To convert from degrees Rankine to degrees Fahrenheit, subtract 460. For example, 650° R = 190° F.

Adiabatic: a process that occurs without heat loss or gain from the surrounding environment. Another way of stating this is to say an adiabatic process is one that is completely "insulated," with no additional energy gained or lost. In the case of a turbocharger compressor one often hears such things as "operating at 75% adiabatic efficiency." See also *Compressor Efficiency*.

Advance: see *Ignition Advance*.

AFC: an acronym for air fuel controller or air fuel computer.

AFM: an acronym for airflow meter. See *Mass Airflow*.

Aftercooler: an alternative term for a charge air cooler. An intercooler is also a charge air cooler.

Air/Fuel Ratio: the ratio of air mass to fuel mass in the combustion chamber. For pump gasoline, the air/fuel ratio in an engine is typically between 11:1 and 17:1. Values above 14.7:1 are consider lean; values below 14.7:1 are considered rich. See also *Stoichiometry*.

All Motor: (slang) a naturally-aspirated engine.

Alpha-N: an electronic fuel injection system that chiefly uses two variables (alpha and N) to estimate airflow into the engine. Alpha is the angle of the throttle position sensor, and N is the engine speed, measured in rpm. A lookup table is then used to convert to airflow.

Ambient: the weather conditions outside of the engine bay. Ambient pressure, for example is the local air pressure.

Anti-Lag System: a system used on some specialty race vehicles (e.g., World Rally Championship cars) to reduce boost lag at low rpm and when lifting the throttle during gear changes. An anti-lag system is usually ECU-controlled and employs drastic ignition retardation and fuel enrichment to create afterburning of unburned air-fuel mixture in the exhaust manifold. The resulting high exhaust temperature and pressure help maintain the turbo spool. This technique is also sometimes used by drag racers to create boost on the starting line prior to a race. See also *Boost Lag*.

Anti-Surge Valve: see *Bypass Valve*.

A/R Ratio: a geometric property of compressor and turbine housings. For most common discussions, however, it refers only to the turbine housing. For a turbine, the A/R ratio is equal to the ratio of the exhaust inducer nozzle area, divided by the exhaust inducer radius (measured from the center of the turbine shaft to the center of the inducer nozzle area. Typical turbine values range from 0.4 to 2.0.

Atomization: the process of converting a volume of liquid into very small droplets. This typically refers to fuel atomization that occurs through a fuel injector. Note that atomization is not the same thing as vaporization.

B

B-Pipe: a portion of the exhaust system, usually ascribed to the piping that exists between the downpipe (or sometimes catalytic converter) and the muffler.

Backplate: the metallic disk or plate that forms the inboard portion of the compressor housing when it is assembled. It is attached to the center, or bearing housing.

Bar: a unit of measurement of pressure. One bar approximately equals the air pressure at sea level, i.e., 14.7 psi.

Batch Fire: a type of fuel injection system in which all fuel injectors fire simultaneously. Because of its simplicity, batch fire is often used by aftermarket EFI systems.

BDC: see *Bottom Dead Center*.

Bearings: the mechanical device(s) located inside the center housing that provide for free rotation of the turbocharger shaft. Most turbochargers have one or two journal-type bearings that are fabricated of sintered bronze. Some aftermarket turbos use rolling element (ball) bearings.

Bearing Housing: a component of the center housing and rotating assembly that mounts and supports the bearings.

Biturbo: the marketing name given to Maserati's parallel twin turbo system.

Blow-Through: a forced-induction system that uses a carburetor located downstream of the compressor. The carburetor is fed pressurized air that literally "blows through" it.

Blow-Off Valve: a relief device used to vent air in the intake tract out to the atmosphere. Blow-off valves often operate (i.e., vent) during gear changes or other times when the throttle plate is suddenly closed under high boost conditions. This keeps the compressor spooled and prevents compressor surge.

BMEP: see *Brake Mean Effective Pressure.*

Bonnet: see *Carburetor Hat.*

Boost: the amount of pressure produced by a compressor, normally measured in psig or Bar.

Boost Creep: the uncontrolled rise of boost from a turbocharger beyond normal operating pressure limits. Boost creep is often due to a faulty or undersized wastegate. Boost creep can also be caused by a poorly designed exhaust manifold and/or incorrect placement of the wastegate relative to the exhaust flow.

Boost Controller: a device that controls the amount of boost produced by a turbocharger by adjusting the position of wastegate. Boost controllers can be either manually or electronically operated.

Boost Lag: the delay, when the engine is in an rpm range where boost can be created, between the time the throttle plate is fully opened and noticeable (greater than 1 psig) boost is measured. Lag is affected by the rotational inertia of the spinning turbocharger components, and also by the A/R ratio of the turbine housing.

Boost Map: an internal data table used by certain types of electronic boost controllers to adjust boost as a function of engine rpm and other variables.

Boost Point: see *Boost Threshold.*

Boost Spike: (slang) a term used to describe compressor surge that causes rapid, sometimes violent pressure rises in the intake tract.

Boost Threshold: the engine speed, measured in rpm, above which boost pressure from the compressor is greater than ambient pressure. Only when the boost pressure exceeds ambient is the engine power increased over an equivalent naturally-aspirated engine. Not to be confused with lag.

Bottom Dead Center: the crankshaft position in which the piston is at its lowest point in the bore, and the combustion chamber volume is maximized. Unless specified otherwise, BDC normally refers to the crankshaft position for the number one cylinder in an engine.

BOV: see *Blow -Off Valve.*

BPV: see *Bypass Valve.*

Brake Mean Effective Pressure: the average cylinder pressure during a piston's power stroke that is required to achieve a specified level of power. The BMEP is often indirectly calculated by measuring the output of an engine on a brake dynamometer. Typical forced-induction BMEP values range from 200–400 psig.

Brake Specific Fuel Consumption: the measured rate of fuel consumed by an engine on a brake dynamometer while producing a given amount of horsepower. BSFC is typically expressed in units of pounds of fuel consumed per hour per horsepower. Typical values range from 0.4 to 0.7 lb/hr-hp.

BSFC: see *Brake Specific Fuel Consumption.*

Bump Hose: see *Hump Hose.*

Butt Dyno: (slang) a term used to express a driver's subjective perception of the amount of power or torque that a vehicle produces.

Butterfly: (slang) the throttle plate inside a throttle body.

B-Width: the height of a compressor or turbine wheel blade tip. Generally speaking, the larger the B-width, the more flow a wheel is capable of supporting.

Bypass Valve: a pressure relief device that diverts pressurized air from the downstream side of a compressor back to the upstream side. Much like blow-off valves, bypass valves operate (i.e., vent) during gear changes or other times when the throttle plate is suddenly closed under high-boost conditions.

C

CARB: an acronym for the California Air Resources Board. The CARB is known for setting relatively stringent standards for air quality. A CARB-approved turbocharger component will have passed the emissions requirements set forth by the resources board and is legal for use on public highways and roadways.

cartridge does not include the rotating shaft or wheels.

Carburetor Hat: a manifold attached to the top of a carburetor used in forced-induction applications. The hat supplies pressured air to both the carburetor venturi and the float bowls.

Cartridge: see *Center Housing and Rotating Assembly.*

Cat: (slang) see *Catalytic Converter.*

Cat-Back Exhaust: the portion of the exhaust system that extends from the rear of the catalytic converter to the tail pipe tip. A cat-back system usually includes the muffler(s), connecting pipes, and exhaust tip(s).

Cat-Back Turbo: see *Remote-Mount Turbocharger.*

Catalytic Converter: an emissions-control device in the exhaust system, usually upstream of the muffler. A catalytic converter typically contains a precious metal, such as palladium or platinum. The metal acts as a catalyst for chemical reactions that convert unburned hydrocarbons and carbon monoxide fumes into less-harmful gases in the exhaust stream.

CDT: an acronym for compressor discharge temperature.

Center Housing and Rotating Assembly: a turbocharger assembly without compressor or turbine housings installed, or any wastegate mechanism. Also known as a CHRA. The CHRA includes the central bearing housing, the bearings, the cooling and lubrication systems, the turbine shaft, and both the compressor and turbine wheels. Also known as a cartridge by some turbo manufacturers, but technically speaking a cartridge does not include the rotating shaft or wheels.

Center Section: see *Bearing Housing.*

Centrifugal Compressor: see *Compressor.*

CFD: an acronym for computational fluid dynamics, which is a numerical analysis technique used to predict gas and liquid flow characteristics through mechanical equipment, such as turbochargers, intercoolers, and intake manifolds.

Charge Air Cooler: see *Intercooler.*

Charge Cooling: the cooling of intake air (charge air) via an intercooler or a water injection system. Charge cooling typically does two things: (a) increases the density ratio of the intake air; and (b) reduces combustion chamber temperatures, which result in increased knock resistance.

CHRA: see *Center Housing and Rotating Assembly.*

CHT: an acronym for cylinder head temperature. Often refers to the electrical signal created by a temperature sensor mounted on an engine cylinder head.

CID: an acronym for cubic inches of displacement.

Clearance Volume: the volume of the combustion chamber when the piston is at top dead center.

Clip: see *Clipped Turbine Wheel.*

Clipped Turbine Wheel: a turbine wheel that has had the trailing edges of its blade at the exducer (exit) side machined down, often at a slight angle (5–15 degrees). A clipped turbine wheel frequently spools more slowly than an equivalent non-clipped wheel. It is sometimes used to alleviate choked flow.

Closed Loop: an electronic fuel injection system is said to operate in "closed loop" when it uses exhaust-gas information (e.g., feedback from an oxygen sensor) to adjust the amount of fuel injected.

CNC: an acronym for computer numerical control. CNC refers to the computer control of machine tools, such as mills and lathes, for the purpose of repetitive manufacturing of complex parts. The advantage of CNC is the high degree of repeatable precision and accuracy that can be achieved over hand-controlled machining.

Cold Side: (slang) the compressor portion of a turbocharger.

Cold Side Housing: see *Compressor Housing.*

Cold Side Scroll: see *Compressor Housing.*

Compression Ratio: the displacement of an engine plus the clearance volume, divided by the clearance volume. Compression ratios for turbocharged engines typically range from 7.5:1 to 9:1. Naturally aspirated engines usually have compression ratios greater than 9:1.

Compressor: the part of a turbocharger that draws air in and accelerates it to a high velocity by the rotation of an impeller wheel. A typical compressor is comprised of a backing plate, an outer housing called the volute or scroll, and an impeller wheel. The compressor housing and diffuser slow down the fast moving airflow, converting kinetic energy of the airflow into pressure energy.

Compressor Efficiency: a measure of how much of the energy consumed by a compressor ends up as useful boost pressure. This is usually measured by comparing the actual measured temperature rise with the temperature rise that would have occurred if the air had been perfectly compressed (adiabatic).

Compressor Efficiency Map: a graph of compressor efficiency as a function of flow rate and pressure ratio. Used to select and size a compressor for a specific application.

Compressor Housing: the aluminum housing that encloses the compressor impeller. The shape and size of the compressor housing, along with the impeller shape and size, dictate how efficient a compressor is.

Compressor Impeller: see *Compressor Wheel.*

Compressor Trim: see *Trim.*

Compressor Wheel: the bladed wheel that spins, thereby accelerating the air passing through a compressor.

CPS: an acronym for crankshaft position sensor.

CR: see *Compression Ratio.*

Crankshaft Horsepower: the amount of horsepower an engine produces, as measured at its flywheel on an engine dynamometer. Due to drivetrain loss effects, the crankshaft horsepower is always greater than the amount of power that reaches the driven wheels. See also *Wheel Horsepower, Front Wheel Horsepower, Rear Wheel Horsepower.*

D

Dashpot: (slang) a term used to describe a wastegate actuator.

Density: the mass of an object, divided by its volume. The density of air, for example, at 60° F and at sea level pressure is equal to 0.077 lb/cubic foot.

Density Ratio: the increase in air density after compression and intercooling. The density ratio is computed from the pressure ratio, the compressor efficiency, and the intercooler efficiency. This density ratio is always lower than the pressure ratio.

Detonation: a spontaneous auto-ignition and combustion of the air-fuel mixture inside the combustion chamber that occurs apart from the normal flame front. Detonation occurs after regular ignition has been initiated. The result of detonation is very high local temperature and pressure spikes that can cause damage to the piston and cylinder head. Detonation is often heard as a characteristic "pinging," "tinking," or "knocking" sound.

Diamond Star Motors: a popular line of turbocharged vehicles from a Chrysler-Mitsubishi partnership formed in the 1980's. Models include the Eclipse, Galant, Talon, and Laser vehicles.

Diffuser: the part of the compressor that slows and redirects the impeller-accelerated airflow, trading velocity for pressure rise.

Disco Potato: (slang) the popular Garrett GT28RS turbocharger. This turbocharger features a ball bearing CHRA, and is well suited for high-performance 1.8- to 2.7-liter engines, such as the 2.0-liter Nissan SR20DET.

Diverter Valve: see *Bypass Valve.*

DIY: an acronym for do it yourself. Commonly refers to turbocharger systems that are built from scratch or from components sourced from a junkyard.

Downpipe: the part of the exhaust system that attaches to and extends downstream from the outlet of the turbocharger turbine.

DR: see *Density Ratio.*

Draw-Through: a forced-induction system that uses a carburetor located upstream of the compressor. Ambient air is pulled, or "drawn-through" the carburetor before being pressurized by the compressor.

Drivetrain Efficiency: the ratio of wheel horsepower to crankshaft horsepower, expressed as a percentage.

Dry Housing: a turbocharger bearing housing (CHRA) that relies only on lubricating oil for cooling. See also *Wet Housing.*

DSM: an acronym for Diamond Star Motors.

Dual-Scroll: see *Twin Scroll Turbine*

Dump Valve: see *Bypass Valve.*

Duty Cycle: the time that a fuel injector is open, divided by the time it theoretically could be open during two complete engine revolutions (for a four-stroke engine). Usually expressed as a percentage.

Dyno: see *Dynamometer.*

Dynamometer: a device used to measure force, torque, or power output from an engine.

E

EBC: see *Electronic Boost Controller*

ECM: an acronym for Engine Control Module.

ECU: see *Electronic Control Unit.*

EDIS: an acronym for Ford's Electronic Distributorless Ignition System. Often used on aftermarket- and DIY-type fuel and spark-control systems.

Effectiveness: a term used to describe the performance of a heat exchanger, such as a charge air cooler, or intercooler.

Efficiency: a term used to describe the performance of a mechanical device that converts energy from one form to another. For example, a compressor converts kinetic energy of its spinning wheel to kinetic energy of the air stream. See *Compressor Efficiency.*

Efficiency Island: an area of relatively constant compressor efficiency, as displayed on a compressor efficiency map.

EFI: see *Electronic Fuel Injection.*

EGO: an acronym for exhaust gas oxygen sensor. See *Oxygen Sensor.*

EGR: see *Exhaust Gas Recirculation.*

EGT: see *Exhaust Gas Temperature.*

Electronic Boost Controller: an electronic device used to measure and adjust boost pressure via the wastegate. See also *Manual Boost Controller.*

Electronic Fuel Injection: a computer-controlled system used to measure the airflow into an engine and then regulate the amount of fuel that is injected along with that airflow. There are a number of different type of EFI systems, including alpha-N, mass airflow, and speed density. See also *Closed Loop, Open Loop.*

Electronic Control Unit: an electronic device (i.e., computer) connected to various sensors and mechanical items on an engine, and responsible for a number of functions, including the monitoring and control of fuel delivery and ignition timing. The ECU serves as the fundamental electronic unit for control of the EFI system. Also known as Engine Control Unit, Engine Control Module, Engine Management System, ECU, EMS.

EMS: an acronym for engine management system. See *Electronic Control Unit.*

Energy: the capacity of a physical system to do useful work. Energy can take a wide variety of forms, including chemical (e.g., fuel), heat, and kinetic (i.e., motion).

Engine Management System: see *Electronic Control Unit.*

Enrichment: the addition of extra fuel to lower the air/fuel ratio.

EVC: an acronym for electronic valve controller. Some manufacturers, such as HKS, use this term for their electronic boost control devices.

Exducer: a gas flow outlet. On turbochargers, exducer is most often used to describe the exhaust gas exit portion of the turbine. A less common (but also correct) usage of the term is to describe the compressed air outlet of the compressor wheel. Also known as exducer bore on the turbine side of a turbocharger. See also *Trim.*

Exhaust Dump Valve: see *Wastegate.*

Exhaust Gas Recirculation: an anti-pollution device that directs some engine exhaust back into the intake manifold. It is used primarily to reduce oxides of nitrogen in the exhaust stream.

Exhaust Gas Temperature: the bulk gas flow temperature, measured in the exhaust stream. The EGT is sometimes used to determine an engine's thermal efficiency.

Exhaust Manifold: the steel manifold connected to a cylinder head that is used to collect and direct the hot exhaust gases to the turbocharger turbine.

F

Fast Idle Control: see *Idle Air Control.*

Fat: (slang) see *Rich.*

Flash Programmable: an ECU that can be repeatedly reprogrammed.

Flex Section: the flexible portion of a downpipe that allows for some minor differential movement between the engine/turbo assembly and the remainder of the exhaust system.

Flywheel Horsepower: the horsepower measured on an engine dynamometer at the output of the crankshaft.

FMIC: an acronym for a front-mounted intercooler.

FMU: an acronym for fuel management unit. See also *Fuel Pressure Regulator.*

Forced Induction: a system that pushes, or "forces," air into the cylinders of an engine at pressures greater than atmospheric. Turbocharged and supercharged engines are both examples of forced induction.

FPR: see *Fuel Pressure Regulator.*

Free-Float: a turbocharger is said to be "free-floating" if it has no wastegate device to control boost. This is common on diesel engines that can withstand high boost without detonation.

Front Wheel Horsepower: the horsepower measured on a dynamometer at the driven wheels of a front-wheel drive automobile. This will always be less than the horsepower measured at the crankshaft. See also *Wheel Horsepower.*

Fuel Cut: a safety system that many OEM electronic control units (ECUs) used to temporarily reduce power production. When an ECU determines that an engine is in an unsafe condition (e.g., revving too high, or inducting too much air), a "fuel cut" command is generated that turns off fuel flow to the engine. Fuel is restored after the ECU determines that the engine has reverted to a safe operating condition.

Fuel Cut Defencer (or Defenser): an aftermarket device used to disable an OEM fuel cut system. See *Fuel Cut.*

Fuel Injector: the solenoid-operated valve used to spray, or inject, fuel into an intake runner. The flow through an injector is determined by the size of the injector, the line pressure of the fuel, and the time that the injector remains open. In most applications, one injector per engine cylinder is fitted, but more can be employed in high power applications. Alternatively, larger injectors can often be substituted for smaller OEM units.

Fuel Pressure Regulator: the inline device used to restrict, or regulate, the fuel pressure acting on the upstream side of the fuel injectors.

FWHP: an acronym for flywheel horsepower or front wheel horsepower. Note that these are two very different quantities. Flywheel horsepower refers to the horsepower an engine produces at its crankshaft, as measured on an engine dynamometer. Front wheel horsepower refers to horsepower delivered to the drive wheels on a front-wheel drive vehicle, as measured on a chassis dynamometer. The horsepower created at the drive wheels will always be less than the flywheel horsepower.

G

Gamma: a term often used to express the ratio of the calculated (or measured) air-fuel ratio to the stoichiometric value. A gamma equal to 1 is the same as stoichiometry.

Garrett: a popular manufacturer of turbochargers and turbocharger components. Also known as AiResearch, TurboGarrett, AlliedSignal, Honeywell International, and Honeywell Turbo Technologies.

Gauge Pressure: the measurement of pressure including only the pressure above that of the local ambient atmospheric pressure. Also called psig.

GReddy: an aftermarket supplier of turbocharger equipment.

GT: a popular series of modern turbochargers produced by Garrett.

H

Hair Dryer: (slang) a turbocharger.

Heat Shield: a metallic or composite barrier used to separate a hot device from a heat-sensitive area of the vehicle. For example, a heat shield is often employed to isolate the high-temperature energy radiating from the turbine.

Heat Soak: (slang) a situation where a device has reached thermal equilibrium with its surroundings. For example, an intercooler is said to be "heat soaked" when its bulk temperature has risen to a point where it cannot effectively remove thermal energy from the compressed air stream flowing through it. Heat soak is more likely to occur on warm days than cool.

High-Impedance Injector: fuel injectors designed to operate with a simple 12-volt circuit. The resistance of high-impedance injectors is commonly 10–15 ohms.

HKS: an aftermarket supplier of turbocharger equipment.

Holset: a UK-based manufacturer of turbochargers and turbocharger components for mid-sized diesel engines. Holset is owned by Cummins Engine Company and supplies turbos for almost all Cummins diesel engines as well as many European diesel applications.

Home Brew: (slang) a turbocharger system that is built using inexpensive components, such as those found at a junkyard or from a collection of different OEM vehicles.

Horsepower: the rate at which work is performed in a physical system. One horsepower is equal to 550 ft-lb of work performed in one second, or roughly 0.75 kilowatts. Horsepower can also be calculated if the torque (lb-ft) and rpm are known; i.e., horsepower = (rpm x torque)/5252.

Hot Side: the turbine portion of a turbocharger.

Hot Spot: (slang) localized areas inside the combustion chamber that retain heat. Hot spots can cause pre-ignition or detonation.

Hump Hose: (slang) a hose with a local increase in diameter somewhere along its length. This "hump" allows the hose to flex or bend. Hump hoses are often used to connect an intercooler to a throttle body.

Hybrid: a turbocharger that uses parts from two different families of turbochargers to create a completely new turbo. An example is the popular T3/T4 turbocharger. This unit uses T3 turbine components combined with T4 compressor.

I

IAC: see *Idle Air Control.*

IAT: an acronym for intake air temperature, or induction air temperature. Often used to refer to the intake air temperature sensor that is mounted to the intake plenum.

Idle Air Control: a stepper motor, valve, or other device mounted on the throttle body that makes fine adjustments to the airflow into an engine when it is at idle. Used to maintain a specific idle rpm under changing idle loads and conditions (e.g., when the air conditioning is switched on).

Ignition Advance: the angle a crankshaft rotates between the time the ignition spark is initiated and the piston reaches top dead center. Too much ignition advance results in high cylinder pressures and, potentially, detonation and engine damage. Too little ignition advance typically results in poor thermal efficiency and torque production.

Ignition Retard: the act of reducing ignition advance.

IHI: a Japan-based manufacturer of turbochargers and turbocharger components.

Impeller: see *Compressor Wheel.* The term "impeller" has largely been replaced by the term "wheel" since the SAE adopted it as a standard in the 1980s.

Inches of Mercury: a measure of pressure, using the height of a column of mercury, measured in inches. Inches of mercury are abbreviated as: in-Hg. One inch of mercury approximately equals 0.5 psi.

Inches of Water: a measure of pressure, using the height of a column of water, measured in inches. Inches of water are abbreviated in-H_2O. One inch of water approximately equals 0.036 psi.

Inducer: a gas flow inlet. On turbochargers, the term inducer is most often used to describe the air inlet portion of the compressor. A less common (but also correct) usage of the term is to describe the hot gas inlet to the turbine.

Inertia: see *Polar Moment of Inertia.*

In-Hg: see *Inches of Mercury.*

In-H_2O: see *Inches of Water.*

Injector: see *Fuel Injector.*

Intercooler: a heat exchanger located in the intake tract, normally between the compressor outlet and the throttle body. Intercoolers are used to remove some of the heat energy in the air stream that was added by the compressor. Also known as aftercoolers (primarily in diesel terminology) and called charge air coolers by engineers and turbo manufacturers.

J

Japanese Domestic Market: a term for automotive parts and components that are only sold in Japan. Because of less restrictive emissions controls and the availability of higher octane fuel in Japan, Japanese Domestic Market engines and engine components often produce more power than their US equivalents. Also known as JDM and J-Spec.

JDM: an acronym for Japanese Domestic Market.

J-Spec: see *Japanese Domestic Market.*

K

KiloPascal: a measure of pressure. One hundred kiloPascals (kPa) approximately equals the atmospheric air pressure at sea level.

KKK: a European-based manufacturer of turbochargers and turbocharger components. KKK was renamed 3K and combined with Schwitzer to form BorgWarner Turbocharger Division, headquartered in Germany.

Knock: (slang) see *Detonation.*

Knock Sensor: a sensor that detects detonation in the combustion chamber. Usually knock sensors are mounted on the engine block or cylinder head and detect detonation and pre-ignition by means of acoustic sensing.

Knock Threshold: the point at which detonation begins inside a combustion chamber. Most modern engines that employ knock sensors constantly adjust ignition advance to operate just below the knock threshold.

kPA: see *kiloPascal.*

L

Lag: see *Boost Lag.*

Lambda: a value used to express the ratio of air to fuel in a mixture as a function of stoichiometry. A stoichiometric ratio of 14.7 parts of air to 1 part of fuel is equal to a lambda value of 1. Leaner mixtures than this will have correspondingly higher lambda values, while richer mixtures will have lower lambda values. An air-to-fuel ratio of 12.5:1, for example, is approximately equivalent to a lambda of 0.85.

Lean: an air/fuel ratio greater than 14.6:1 (i.e., a ratio greater than stoichiometry).

Look-Up Table: (slang) a term used to describe the internal data and/or transfer functions stored inside an electronic control unit. Alpha-N control systems, for example, use a simple relationship between engine speed, throttle position, and airflow. A look-up table is used to quantify this relationship and determine the appropriate amount of fuel required for combustion.

Low-Impedance Injectors: a type of fuel injector that is designed to operate at a much lower current than that supplied by a direct 12-volt connection. The resistance of a low-impedance injector is *commonly 1–3 ohms.*

M

MAF: see *Mass Airflow.*

Manual Boost Controller: a non-electronically-operated device that is used to adjust the amount of pressure that a wastegate actuator see. This affects the point at which the wastegate opens, thereby changing the amount of boost produced by the compressor.

Mandrel Bend: a fabrication technique in which metal tubing is bent such that the cross-sectional shape or diameter throughout the arc of the bend is not reduced or changed. Mandrel bent tubes typically produce smaller pressure drops than other types of bends. High performance exhausts are often fabricated with mandrel bent.

Manifold Absolute Pressure Sensor: a sensor attached to the intake manifold that measures pressure inside the plenum. Often used in speed-density type EFI systems.

MAP: see *Manifold Absolute Pressure Sensor.*

MAS: an acronym for mass air sensor. See *Mass Airflow.*

Mass Airflow: an electronic fuel injection system that measures the amount of airflow into an engine by means of an airflow meter.

MAT: an acronym for manifold air temperature. Often refers to the sensor mounted on the intake manifold that detects the air temperature inside the plenum.

MBC: see *Manual Boost Controller.*

MBT: an acronym for maximum best torque.

MEP: see *Brake Mean Effective Pressure.*

MIG: an acronym for metal inert gas welding. This is a type of welding that utilizes a welding gun through which a continuous wire electrode and an inert shielding gas are fed.

Minimum Best Torque: the smallest ignition advance setting that results in maximum torque output from the engine.

MPI: an acronym for multi-port (fuel) injection.

N

Narrow-Band Sensor: an oxygen sensor whose output is optimized around the stoichiometric ratio of 14.7 parts air to 1 part fuel. A narrow-band sensor is extremely sensitive to variations in exhaust gas oxygen content and will not provide accurate measurements of air-fuel ratios much above or below stoichiometry.

Naturally Aspirated: an engine that draws in air for combustion without the aid of any forced-induction devices or chemical means (e.g., nitrous oxide). Also known as normally-aspirated.

Nitrous Oxide: an oxygen-rich gas, which can be injected into the intake charge air to increase engine performance.

NLA: an acronym for no longer available.

NOS: see *Nitrous Oxide.*

Normally Aspirated: see *Naturally Aspirated.*

O

O_2 Sensor: see *Oxygen Sensor.*

OBD: an acronym for on-board diagnostics, which is a computer-based system built into all 1996 and newer light-duty cars and trucks. OBD monitors the performance of some of the engines' major components, including individual emission controls.

OEM: see *Original Equipment Manufacturer.*

Offset Delay: the delay, usually measured in milliseconds, between the time an ECU sends an open signal to an injector, and the time that the injector actually opens and full fuel flow is achieved.

Open Loop: an electronic fuel injection system is said to operate in "open loop" mode when it does not use any exhaust gas information (e.g., feedback from an O_2 sensor) to adjust the amount of fuel injected.

Original Equipment Manufacturer: the company or corporation that manufactured the original part for the auto supplier.

Otto Cycle: a four-stroke engine cycle, used by most internal combustion automotive engines. Named after Nikolaus Otto, who patented the four-stroke engine in 1876.

Over Boost: the condition when a turbocharger creates more boost than intended.

Oxygen Sensor: a sensor in the exhaust pipe, usually located immediately downstream of the turbocharger or upstream of the catalytic converter. The O_2 sensor measures the amount of unconsumed oxygen remaining in the exhaust stream following combustion. This information is used by the ECU to adjust the air-fuel ratio when running under closed-loop conditions. There are two common types of oxygen sensors: narrow-band and wide-band.

P

PCV: see *Positive Crankcase Ventilation.*

Piggyback Electronics: an electronic device that is added to an OEM control system. For example, an aftermarket air-fuel controller that modifies the signals into or out of the ECU is considered a piggyback device.

Ping: (slang) see *Detonation.*

Plumb Back Valve: see *Bypass Valve.*

PMI: see *Polar Moment of Inertia.*

Polar Moment of Inertia: a measure of a body's resistance to rotation. Inertial-type chassis dynamometers employ steel drive rollers with large polar moments of inertia to simulate load. Also known as polar mass moment of inertia.

Porting: the act of grinding or machining away material inside of a flow device. On naturally aspirated engines, porting usually entails reshaping and/or enlarging intake and exhaust pathways in the cylinder head and manifolds. On turbocharged engines, porting can be performed on items such as the turbine housing, wastegate aperture, and O_2 housing to increase performance.

Port Injection: an electronic fuel injection system in which individual fuel injectors are located at or near the intake valves of each cylinder.

Positive Crankcase Ventilation: an anti-pollution system that is used to direct engine crankcase fumes into the intake manifold, from where they are inducted into the combustion chamber.

PR: see *Pressure Ratio.*

Pre-Ignition: the premature ignition of the air-fuel mixture in the combustion chamber before the regular ignition spark occurs. Often caused by excessively high pressure and/or hot surfaces inside the combustion chamber.

Pressure Drop: a reduction in fluid pressure. With flow through a pipe, pressure drop is usually attributed to long flow lengths, in-line restrictions, bends, and/or tubing diameter changes.

Pressure Ratio: the outlet pressure of a compressor, divided by the inlet pressure. Note that the two pressure values are in absolute pressure units.

PRofec: a line of popular electronic boost controllers manufactured by GReddy.

PS: an acronym for Pferdestärke, which is a measurement of engine power used in some foreign markets, notably Europe. Sometimes called "continental" horsepower. One horsepower is approximately equivalent to 1.014 PS.

Psia: an acronym for pounds of force per square inch absolute, which includes the effect of ambient pressure. At sea level, a measurement in units of psia equals that of psig plus 14.7.

Psig: an acronym for pounds of force per square inch gauge, which does not include the effect of ambient pressure. Most common automotive gauges read in psig (boost, oil pressure, tire pressure, etc.). Ambient air pressure in units of psig equals zero. To convert to psia add the local ambient air pressure.

Pulse Width: the amount of time that a fuel injector remains open, thereby affecting the amount of fuel sprayed into the intake tract. Pulse width is typically measured in milliseconds.

Pump Gas: a gasoline having an octane rating between 88 and 93.

R

Race Gas: a high-octane gasoline, typically greater than 100-octane. Race gas is used to improve the resistance to detonation inside the combustion chamber, thereby allowing higher compression ratios, increased boost, and/or advanced ignition timing.

Rattle: (slang) see *Detonation.*

Rear Wheel Horsepower: the horsepower measured by a dynamometer at the driven wheels of a rear-wheel drive automobile. This will always be less than the horsepower measured at the crankshaft. Also known informally as RWHP. See also *Wheel Horsepower.*

Re-Circulating Valve: see *Bypass Valve.*

Remote-Mount Turbocharger: a turbocharger that is installed far downstream of a conventional turbocharger, often replacing the muffler at the rear of the car.

Retard: see *Ignition Retard.*

Reversion: the backward flow of gas. For example, exhaust reversion is the flow of spent gases in the exhaust manifold back into the combustion chamber during valve overlap.

Rich: an air/fuel ratio less than 14.7:1 (i.e., less than stoichiometric).

Rising Rate Fuel Pressure Regulator: a regulator that increases delivered fuel pressure as a function of boost pressure; the higher the boost pressure, the higher the fuel pressure.

Roots: a type of supercharger often found on older V8 engines and in some drag racing vehicles.

RPM: an acronym for rotations per minute or revolutions per minute.

RRFPR: see *Rising Rate Fuel Pressure Regulator.*

RWHP: see *Rear Wheel Horsepower.*

S

S-AFC: an air-fuel computer manufactured by APEXi.

Schwitzer: a manufacturer of turbochargers and turbocharger components. Now part of BorgWarner Turbocharger Systems.

Scramble: a feature on some electronic boost controllers that allows additional boost for a preset amount of time. Also known as over-take boost.

Scroll: a compressor or turbine housing volute.

Sequential Fire: a fuel injection system in which individual fuel injectors are activated separately and in a sequence that is timed to correspond to the opening of each cylinder's intake valve(s). Many OEM EFI systems are sequential fire.

Sequential Turbocharger: a system that employs two turbochargers in series with valves to operate one at low speed, and either the larger, or both turbos at higher speeds.

SFC: an acronym for specific fuel consumption. See *Brake Specific Fuel Consumption.*

SMT-6: a commercial brand for a piggy-back engine management device.

Snail: (slang) a turbocharger.

Snout: an alternative name for the tube connection that is part of an intercooler end tank.

Spearco: a performance aftermarket supplier, best known for their intercoolers. Owned by Turbonetics.

Specific Fuel Consumption: see *Brake Specific Fuel Consumption.*

Speed Density: an electronic fuel injection system that uses manifold absolute pressure and engine rpm information to estimate the amount of airflow into an engine. This information is then used to determine the fuel injection requirements.

Spin-Up Time: see *Lag.*

Split-Inlet Turbocharger: see *Twin Scroll Turbine.*

Spooled: a turbocharger that is spinning at a rotational velocity sufficient to produce noticeable boost; i.e., above its boost threshold.

Stand-alone: an engine management system that entirely replaces the OEM control system (e.g., ECU).

Stoichiometry: a chemically balanced air-fuel ratio. For normal pump gasoline, stoichiometry occurs at an air-fuel ratio of 14.7 parts air to 1 part fuel, by weight.

Supercharger: a forced-induction system that uses an engine-driven compressor to create a flow of pressurized air.

Surge: an unstable flow through a compressor.

Surge Limit: a near-vertical line on a compressor efficiency map. To the left of the line, the compressor is surging and unstable. For any given pressure ratio, there is a minimum threshold airflow rate below which the compressor surges.

Swing Valve: an internal wastegate.

T

T3/T4: a designation for a popular hybrid turbocharger that combines the large output of a T4 compressor with the fast spooling T3 turbine. See *Hybrid*.

TBI: see *Throttle Body Injection*.

TD: a designation for several popular Mitsubishi-made turbochargers.

TDC: see *Top Dead Center*.

Test Pipe: (slang) a section of straight pipe used to replace a catalytic converter.

Thermal Efficiency: the amount of useful work derived from an engine divided by the amount of chemical energy released during combustion. Expressed as a percentage. Typical 4-stroke gasoline-powered engines have thermal efficiencies around 30%.

Thin: (slang) see *Lean*.

Three-Way Catalyst: a combination of the rare elements palladium, platinum, and rhodium, typically used in modern catalytic converters for reducing harmful emissions.

Throttle Body: the valve used to meter, or adjust, the amount of air entering an engine.

Throttle Body Injection: an electronic fuel injection system in which one or more large fuel injectors are located at or near the throttle plate in the throttle body.

Throttle Position Sensor: a sensor attached to the throttle body that measures throttle position. Most throttle position sensors are potentiometers, where throttle position is proportional to the electrical resistance across the unit.

TIG: an acronym for tungsten inert gas welding. In this process, an electric arc is formed between a non-consumable tungsten electrode (that is part of welding gun) and the metal being joined. An inert gas is fed through the gun tip to improve the quality of the weld. An optional external filler rod is often employed to form the weld bead.

TMIC: an acronym for a top-mounted intercooler.

Top Dead Center: the crankshaft position in which a piston is at its highest point in the bore, and the combustion chamber volume is minimized. Unless specified otherwise, TDC normally refers to the appropriate crankshaft position for the number one cylinder in an engine.

Torque: the product of a force and its lever arm. Informally referred to as a "twisting force."

TPS: see *Throttle Position Sensor*.

Trim: a numeric value used to describe the size of either a turbine or compressor wheel. Many turbo manufacturers use letters or words to designate the trim-size of their wheels; a chart is required to convert these letters or words into meaningful numeric values.

Turbine: the turbine is the part of the turbocharger that converts kinetic and heat energy of the exhaust gas stream into rotational kinetic energy. A typical turbine is comprised of a steel housing, a turbine wheel, and an internal wastegate.

Turbine Housing: the steel housing that encloses the turbine wheel. The shape and size of the turbine housing, along with the turbine trim, dictate how quickly the turbine accelerates and to what maximum speed it can rotate.

Turbine Trim: see *Trim*.

Turbine Wheel: the bladed wheel mounted inside the turbine housing that captures the kinetic energy of the exhaust stream and powers the compressor of a turbocharger.

Turbocharger: a forced-induction device that is powered by kinetic and heat energy contained in the exhaust stream flowing from an engine. A turbocharger is comprised of three major components: the turbine assembly, the compressor assembly, and the center housing and rotating assembly.

Turbo Lag: see *Lag*.

Turbonetics: a California-based supplier of turbochargers, components, and kits.

TWC: an acronym for a three-way catalyst.

Twin Charged: an engine that has both a supercharger and a turbocharger installed.

Twin Entry: see *Twin Scroll Turbine*.

Twin Scroll Turbine: a turbine that has two separate volutes built into its housing. This arrangement allows for more optimal engine performance, particularly on smaller four- and six-cylinder engines.

Twin Turbo: a system employing two turbochargers to supply pressurized air to the engine. These turbochargers are arranged either in parallel or sequential mode.

U

UEGO: an acronym for universal exhaust gas oxygen sensor. Also known as a wide-band oxygen sensor.

Up-Pipe: (slang) an unobstructed tube section sometimes used to replace a pre-turbocharger catalytic converter on some vehicles (notably, the Subaru WRX).

V

Vaporization: a process whereby a liquid changes state into a gas.

Variable Area Turbine Nozzle: a type of turbine that has a movable set of internal vanes that can change with rotation speed. This results in an effective change in the A/R ratio of the turbine; i.e., the turbine behaves like a small A/R unit at low speed to improve lag, and like a large A/R unit at high speed to improve upper rpm horsepower.

Variable Nozzle Turbine: a type of turbine that is adjustable. Garrett and others use a VNT or variable nozzle turbine that has a movable set of internal vanes that can change with flow or speed. This results in an effective change in the A/R ratio of the turbine; i.e., the turbine behaves like a small A/R unit at low speed to improve lag, and like a large A/R unit at high speed to improve upper rpm horsepower. These systems require a controller to set the nozzle to the correct position based on engine conditions.

VGT: a trade name for a Holset-designed Variable Geometry Turbine with a single sliding wall that changes the effective nozzle size.

VNT: see *Variable Nozzle Turbine.*

VBC: an acronym for variable boost controller, which is HKS' term for a remotely adjustable manual boost controller.

Volumetric Efficiency (VE): a numeric value (usually expressed as a percentage) that is equal to the volume of air physically drawn into a cylinder, divided by the theoretical displacement of that cylinder. Also referred to (informally) as the "breathing capacity" of an engine. Volumetric efficiency varies with engine design and rpm. Typical VE values for naturally-aspirated engines range from 75–90%. VE values for specialty race cars can exceed 100%.

Volute: the correct technical term for Scroll.

VPC: an acronym for vein pressure converter. A VPC is an aftermarket fuel management device that serves to replace an OEM air metering device, such as a MAF unit.

W

Wasted Spark: an ignition system in which the spark plugs in separate cylinders are fired together, whether or not any or all of those cylinders are in the ignition phases of their cycles. The extra spark has very little if any effect and is thus "wasted."

Wastegate: a valve that is used to divert exhaust gas flow around a turbine, thereby limiting the boost produced by the turbocharger. A wastegate can be internal (inside the turbine housing) or external (separate from the turbocharger).

Wastegate Creep: the premature movement (opening and leaking) of a wastegate actuator, thereby causing a delay in the time required for a turbocharger to make full boost. See also *Boost Creep.*

Water Injection: a charge-cooling system that relies on the injection of a small quantity of water (or a mixture of water and methanol) into the air-fuel mixture. The water vaporizes (evaporates), thereby cooling the airflow. This in turn increases the density ratio of the airflow and also tends to reduce the combustion chamber temperatures.

Wet Housing: a turbocharger bearing housing (CHRA) that receives both engine coolant and lubricating oil for cooling. See also *Dry Housing.*

Wheel Horsepower: the amount of horsepower an engine produces, as measured at the vehicle's driven wheels on a chassis dynamometer. See also *Crankshaft Horsepower.*

Wide-Band Oxygen Sensor: an oxygen sensor that is capable of accurately measuring air-fuel ratios over a wide range, centered nominally around 15:1. Typical ranges are 10:1 to 20:1.

WOT: an acronym for Wide-Open Throttle; i.e., a throttle plate that is open to a position that allows maximum airflow; i.e., "pedal to the metal."

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