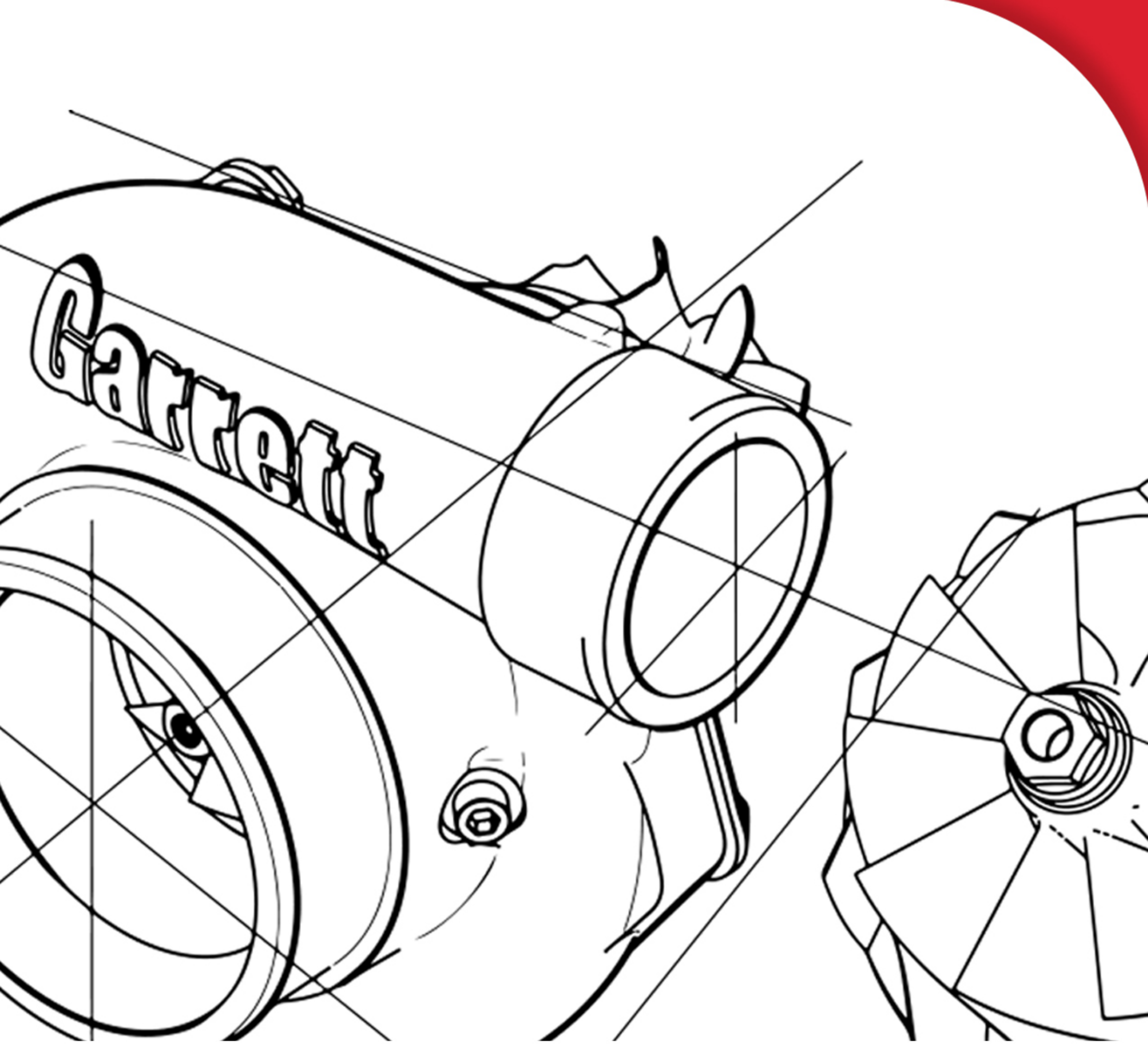

Turbo Systems 102
Advanced

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Honeywell
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Turbo Systems 102 (Advanced)

Please thoroughly review and have a good understanding of Turbo Systems 101- Basic prior to reading this section. The following areas will be covered in the Turbo System 102 - Advanced section:

1. Wheel trim topic coverage

2. Understanding turbine housing A/R and housing sizing

3. Different types of manifolds (advantages/disadvantages log style vs. equal length)

4. Compression ratio with boost

5. Air/Fuel Ratio tuning: Rich v. Lean, why lean makes more power but is more dangerous

1. Wheel trim topic coverage

Trim is a common term used when talking about or describing turbochargers. For example, you may hear someone say "I have a GT2871R ' **56 Trim** ' turbocharger. What is 'Trim?' Trim is a term to express the relationship between the inducer* and exducer* of both turbine and compressor wheels. More accurately, it is an area ratio.

* The inducer diameter is defined as the diameter where the air enters the wheel, whereas the exducer diameter is defined as the diameter where the air exits the wheel.

Based on aerodynamics and air entry paths, the inducer for a compressor wheel is the smaller diameter. For turbine wheels, the inducer it is the larger diameter (see Figure 1.)

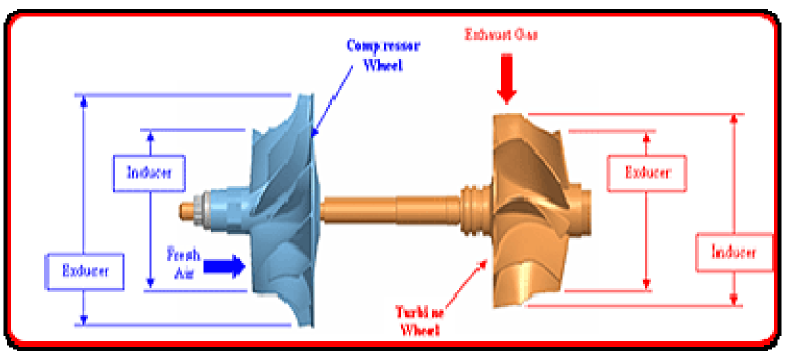


Figure 1. Illustration of the inducer and exducer diameter of compressor and turbine wheels

Example #1: GT2871R turbocharger (Garrett part number 743347-2) has a compressor wheel with the below dimensions. What is the trim of the compressor wheel?

Inducer diameter = 53.1mm
Exducer diameter = 71.0mm

$$Trim = \left(\frac{Inducer^2}{Exducer^2}\right) * 100$$

$$Trim = \left(\frac{53.1^2}{71.0^2}\right) * 100$$

$$Trim = 56$$

Example #2: GT2871R turbocharger (part # 743347-1) has a compressor wheel with an exducer diameter of 71.0mm and a trim of 48. What is the inducer diameter of the compressor wheel?

Exducer diameter = 71.0mm
Trim = 48

$$Trim = \left(\frac{Inducer^2}{Exducer^2}\right)*100$$

$$Inducer^2 = \left(\frac{Trim}{100}\right)*Exducer^2$$

$$Inducer = \sqrt{Trim/100}*Exducer$$

$$Inducer = \sqrt{48/100}*71.0$$

$$Inducer = 49.2mm$$

The trim of a wheel, whether compressor or turbine, affects performance by shifting the airflow capacity. All other factors held constant, a higher trim wheel will flow more than a smaller trim wheel.

However, it is important to note that very often all other factors are not held constant. So just because a wheel is a larger trim does not necessarily mean that it will flow more.

2. Understanding housing sizing: A/R

A/R (Area/Radius) describes a geometric characteristic of all compressor and turbine housings. Technically, it is defined as:

the inlet (or, for compressor housings, the discharge) cross-sectional area divided by the radius from the turbo centerline to the centroid of that area (see Figure 2.).

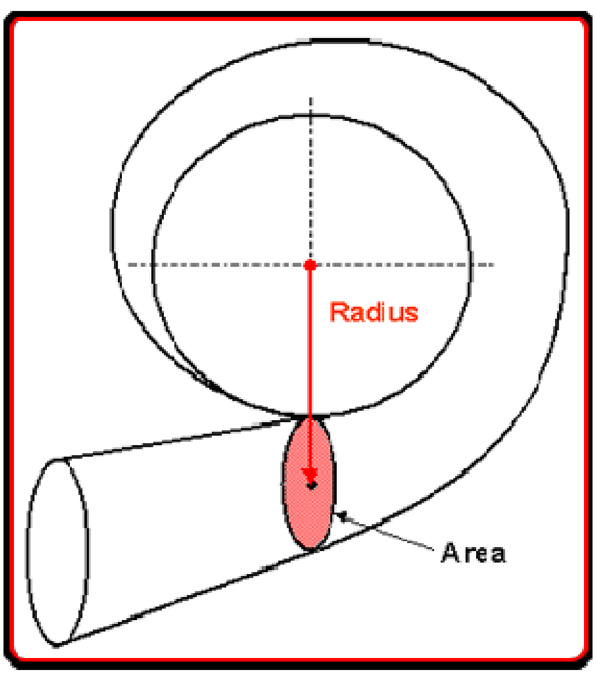


Figure 2. Illustration of compressor housing showing A/R characteristic

The A/R parameter has different effects on the compressor and turbine performance, as outlined below.

Compressor A/R - Compressor performance is comparatively insensitive to changes in A/R. Larger A/R housings are sometimes used to optimize performance of low boost applications, and smaller A/R are used for high boost applications. However, as this influence of A/R on compressor performance is minor, there are not A/R options available for compressor housings.

Turbine A/R - Turbine performance is greatly affected by changing the A/R of the housing, as it is used to adjust the flow capacity of the turbine. Using a smaller A/R will increase the exhaust gas velocity into the turbine wheel. This provides increased turbine power at lower engine speeds, resulting in a quicker boost rise. However, a small A/R also causes the flow to enter the wheel more tangentially, which reduces the ultimate flow capacity of the turbine wheel. This will tend to increase exhaust backpressure and hence reduce the engine's ability to "breathe" effectively at high RPM, adversely affecting peak engine power.

Conversely, using a larger A/R will lower exhaust gas velocity, and delay boost rise. The flow in a larger A/R housing enters the wheel in a more radial fashion, increasing the wheel's effective flow capacity, resulting in lower backpressure and better power at higher engine speeds.

When deciding between A/R options, be realistic with the intended vehicle use and use the A/R to bias the performance toward the desired powerband characteristic.

Here's a simplistic look at comparing turbine housing geometry with different applications. By comparing different turbine housing A/R, it is often possible to determine the intended use of the system.

Imagine two 3.5L engines both using GT30R turbochargers. The only difference between the two engines is a different turbine housing A/R; otherwise the two engines are identical:
1. Engine #1 has turbine housing with an A/R of 0.63
2. Engine #2 has a turbine housing with an A/R of 1.06.

What can we infer about the intended use and the turbocharger matching for each engine?

Engine#1: This engine is using a smaller A/R turbine housing (0.63) thus biased more towards low-end torque and optimal boost response. Many would describe this as being more "fun" to drive on the street, as normal daily driving habits tend to favor transient response. However, at higher engine speeds, this smaller A/R housing will result in high backpressure, which can result in a loss of top end power. This type of engine performance is desirable for street applications where the low speed boost response and transient conditions are more important than top end power.

Engine #2: This engine is using a larger A/R turbine housing (1.06) and is biased towards peak horsepower, while sacrificing transient response and torque at very low engine speeds. The larger A/R turbine housing will continue to minimize backpressure at high rpm, to the benefit of engine peak power. On the other hand, this will also raise the engine speed at which the turbo can provide boost, increasing time to boost. The performance of Engine #2 is more desirable for racing applications than Engine #1 where the engine will be operating at high engine speeds most of the time.

3. Different types of manifolds (advantages/disadvantages log style vs. equal length)

There are two different types of turbocharger manifolds; cast log style (see Figure 3.) and welded tubular style (see Figure 4.).

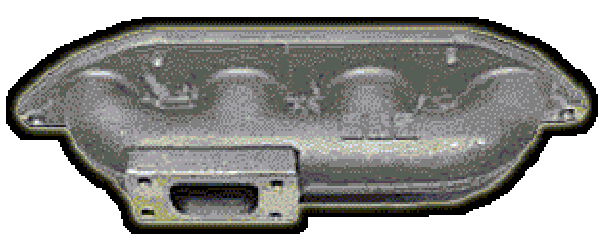


Figure 3. Cast log style turbocharger manifold

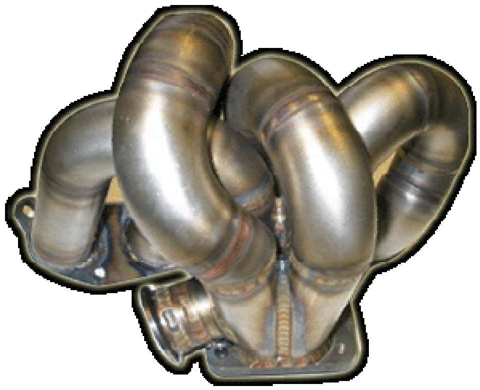


Figure 4. Welded tubular turbocharger manifold

Manifold design on turbocharged applications is deceptively complex as there many factors to take into account and trade off

General design tips for best overall performance are to:

- Maximize the radius of the bends that make up the exhaust primaries to maintain pulse energy
- Make the exhaust primaries equal length to balance exhaust reversion across all cylinders
- Avoid rapid area changes to maintain pulse energy to the turbine
- At the collector, introduce flow from all runners at a narrow angle to minimize "turning" of the flow in the collector
- For better boost response, minimize the exhaust volume between the exhaust ports and the turbine inlet
- For best power, tuned primary lengths can be used

Cast manifolds are commonly found on OEM applications, whereas welded tubular manifolds are found almost exclusively on aftermarket and race applications. Both manifold types have their advantages and disadvantages. Cast manifolds are generally very durable and are usually dedicated to one application. They require special tooling for the casting and machining of specific features on the manifold. This tooling can be expensive.

On the other hand, welded tubular manifolds can be custom-made for a specific application without special tooling requirements. The manufacturer typically cuts pre-bent steel U-bends into the desired geometry and then welds all of the components together. Welded tubular manifolds are a very effective solution. One item of note is durability of this design. Because of the welded joints, thinner wall sections, and reduced stiffness, these types of manifolds are often susceptible to cracking due to thermal expansion/contraction and vibration. Properly constructed tubular manifolds can last a long time, however. In addition, tubular manifolds can offer a substantial performance advantage over a log-type manifold.

A design feature that can be common to both manifold types is a " **DIVIDED MANIFOLD"** , typically employed with " **DIVIDED** " or "twin-scroll" turbine housings. Divided exhaust manifolds can be incorporated into either a cast or welded tubular manifolds (see Figure 5. and Figure 6.).

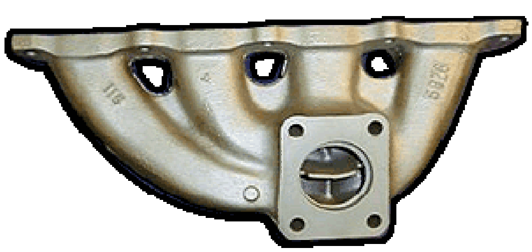


Figure 5. Cast manifold with a divided turbine inlet design feature

Figure 6. Welded tubular manifold with a divided turbine inlet design feature

The concept is to DIVIDE or separate the cylinders whose cycles interfere with one another to best utilize the engine's exhaust pulse energy.

For example, on a four-cylinder engine with firing order 1-3-4-2, cylinder #1 is ending its expansion stroke and opening its exhaust valve while cylinder #2 still has its exhaust valve open (cylinder #2 is in its overlap period). In an undivided exhaust manifold, this pressure pulse from cylinder #1's exhaust blowdown event is much more likely to contaminate cylinder #2 with high pressure exhaust gas. Not only does this hurt cylinder #2's ability to breathe properly, but this pulse energy would have been better utilized in the turbine.

The proper grouping for this engine is to keep complementary cylinders grouped together-- #1 and #4 are complementary; as are cylinders #2 and #3.

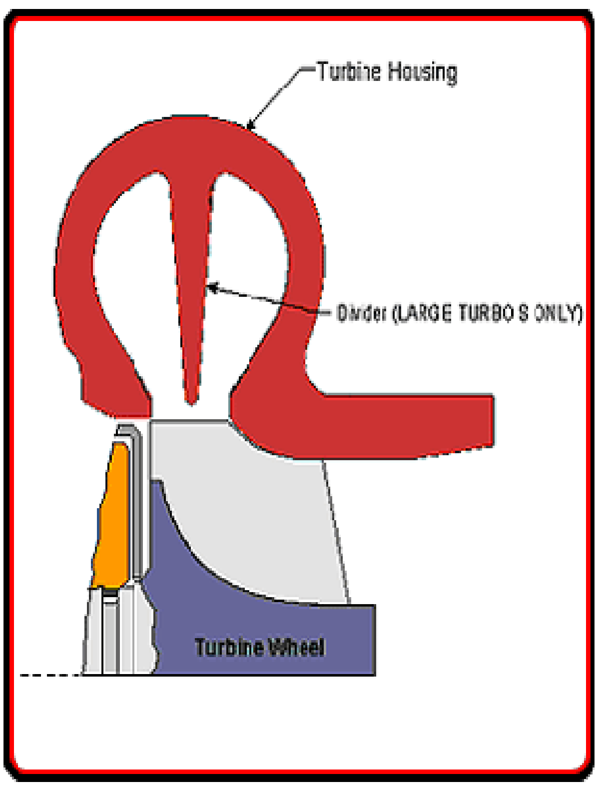


Figure 7. Illustration of divided turbine housing

Because of the better utilization of the exhaust pulse energy, the turbine's performance is improved and boost increases more quickly.

4. Compression ratio with boost

Before discussing compression ratio and boost, it is important to understand engine knock, also known as detonation. Knock is a dangerous condition caused by uncontrolled combustion of the air/fuel mixture. This abnormal combustion causes rapid spikes in cylinder pressure which can result in engine damage.

Three primary factors that influence engine knock are:

1. **Knock resistance characteristics (knock limit) of the engine:** Since every engine is vastly different when it comes to knock resistance, there is no single answer to "how much." Design features such as combustion chamber geometry, spark plug location, bore size and compression ratio all affect the knock characteristics of an engine.
2. **Ambient air conditions:** For the turbocharger application, both ambient air conditions and engine inlet conditions affect maximum boost. Hot air and high cylinder pressure increases the tendency of an engine to knock. When an engine is boosted, the intake air temperature increases, thus increasing the tendency to knock. Charge air cooling (e.g. an intercooler) addresses this concern by cooling the compressed air produced by the turbocharger
3. **Octane rating of the fuel being used:** octane is a measure of a fuel's ability to resist knock. The octane rating for pump gas ranges from 85 to 94, while racing fuel would be well above 100. The higher the octane rating of the fuel, the more resistant to knock. Since knock can be damaging to an engine, it is important to use fuel of sufficient octane for the application. Generally speaking, the more boost run, the higher the octane requirement.

This cannot be overstated: engine calibration of fuel and spark plays an enormous role in dictating knock behavior of an engine. See Section 5 below for more details.

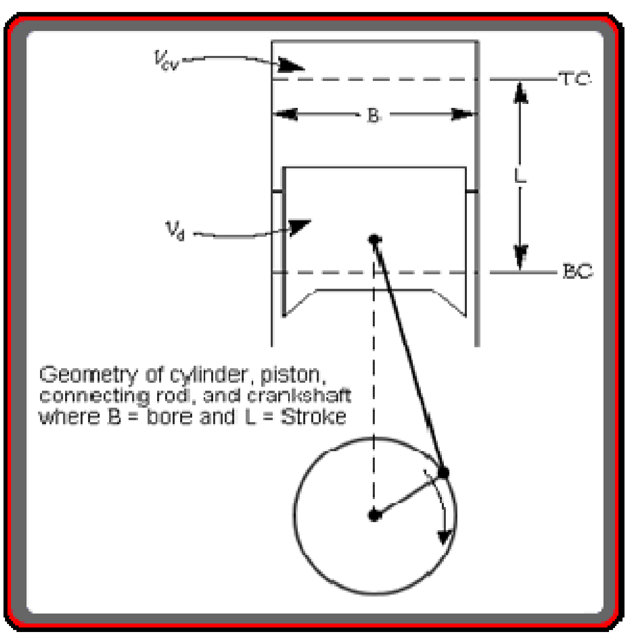
Now that we have introduced knock/detonation, contributing factors and ways to decrease the likelihood of detonation, let's talk about compression ratio. Compression ratio is defined as:

$$Compression\_Ratio = \frac{displacement\_volume + clearance\_volume}{clearance\_volume}$$

or

$$CR = \frac{V_d + V_{cv}}{V_{cv}}$$

where
CR = compression ratio
V_d = displacement volume
V_{cv} = clearance volume



Geometry of cylinder, piston, connecting rod, and crankshaft where B = bore and L = Stroke

The compression ratio from the factory will be different for naturally aspirated engines and boosted engines. For example, a stock Honda S2000 has a compression ratio of 11.1:1, whereas a turbocharged Subaru Impreza WRX has a compression ratio of 8.0:1.

There are numerous factors that affect the maximum allowable compression ratio. There is no single correct answer for every application. Generally, compression ratio should be set as high as feasible without encountering detonation at the maximum load condition. Compression ratio that is too low will result in an engine that is a bit sluggish in off-boost operation. However, if it is too high this can lead to serious knock-related engine problems.

Factors that influence the compression ratio include: fuel anti-knock properties (octane rating), boost pressure, intake air temperature, combustion chamber design, ignition timing, valve events, and exhaust backpressure. Many modern normally-aspirated engines have well-designed combustion chambers that, with appropriate tuning, will allow modest boost levels with no change to compression ratio. For higher power targets with more boost , compression ratio should be adjusted to compensate.

There are a handful of ways to reduce compression ratio, some better than others. Least desirable is adding a spacer between the block and the head. These spacers reduce the amount a "quench" designed into an engine's combustion chambers, and can alter cam timing as well. Spacers are, however, relatively simple and inexpensive.

A better option, if more expensive and time-consuming to install, is to use lower-compression pistons. These will have no adverse effects on cam timing or the head's ability to seal, and allow proper quench regions in the combustion chambers.

5. Air/Fuel Ratio tuning: Rich v. Lean, why lean makes more power but is more dangerous

When discussing engine tuning the **'Air/Fuel Ratio'** (AFR) is one of the main topics. Proper AFR calibration is critical to performance and durability of the engine and it's components. The AFR defines the ratio of the amount of air consumed by the engine compared to the amount of fuel.

A **'Stoichiometric'** AFR has the correct amount of air and fuel to produce a chemically complete combustion event. For gasoline engines, the stoichiometric , A/F ratio is 14.7:1, which means 14.7 parts of air to one part of fuel. The stoichiometric AFR depends on fuel type-- for alcohol it is 6.4:1 and 14.5:1 for diesel.

So what is meant by a rich or lean AFR? A lower AFR number contains less air than the 14.7:1 stoichiometric AFR, therefore it is a richer mixture. Conversely, a higher AFR number contains more air and therefore it is a leaner mixture.

For Example:
15.0:1 = Lean
14.7:1 = Stoichiometric
13.0:1 = Rich

Leaner AFR results in higher temperatures as the mixture is combusted. Generally, normally-aspirated spark-ignition (SI) gasoline engines produce maximum power just slightly rich of stoichiometric. However, in practice it is kept between 12:1 and 13:1 in order to keep exhaust gas temperatures in check and to account for variances in fuel quality. This is a realistic full-load AFR on a normally-aspirated engine but can be dangerously lean with a highly-boosted engine.

Let's take a closer look. As the air-fuel mixture is ignited by the spark plug, a flame front propagates from the spark plug. The now-burning mixture raises the cylinder pressure and temperature, peaking at some point in the combustion process.

The turbocharger increases the density of the air resulting in a denser mixture. The denser mixture raises the peak cylinder pressure, therefore increasing the probability of knock. As the AFR is leaned out, the temperature of the burning gases increases, which also increases the probability of knock. This is why it is imperative to run richer AFR on a boosted engine at full load. Doing so will reduce the likelihood of knock, and will also keep temperatures under control.

There are actually three ways to reduce the probability of knock at full load on a turbocharged engine: reduce boost, adjust the AFR to richer mixture, and retard ignition timing. These three parameters need to be optimized together to yield the highest reliable power.

For further in-depth calculations of pressure ratio, mass flow, and turbocharger selection, please read Turbo Systems 103 Expert tutorial.