



## Introduction

Testing is absolutely essential to the product development process, and the need to test supercharger products is no different. On the technical side, the development engineer must know if his design and product execution meets specifications. For example, were his initial assumptions correct? What about modeling and simulations conducted during the design process – were these calculations correct, and does the actual performance, in fact, validate them? From the consumer's perspective, he wants to know what level of performance he can expect from his hard-earned dollars. Will this supercharger perform as advertised? What power levels can I expect to gain? How does one manufacturer's products stack up against another's? The bulk of these very legitimate questions can be answered through testing. Further, the efficiency of a supercharger (compressor) can **only** be determined through appropriate bench testing, conducted in accordance with an adopted standard. Fortunately, the science behind testing of turbomachinery products, like centrifugal superchargers, is mature and has benefited from many years of development. It is through the correct and consistent application of test discipline that both engineers and consumers alike can be presented with trustworthy data to assess supercharger performance.

## Purpose and Intent

The purpose of this paper is to review, discuss, and educate readers on the subject of supercharger testing and the importance of compressor efficiency. Although there is a need to delve into some rather advanced engineering topics such as thermodynamics, we will make all attempts to restrict the use of intimidating terms and nomenclature. Hopefully, you, the reader will come away from this paper with a more detailed understanding of supercharger testing, why it is important, how to interpret test data and how you may benefit from having good test data. We believe this can only help you to meet your performance goals and make a better choice when evaluating products.

## Fundamentals

Before discussing the finer points of supercharger testing, it might be prudent to first review a few fundamental topics of supercharging, effects on engines, and perhaps more importantly, what specific supercharger performance parameters should be evaluated during a test. This, then, establishes the primary criteria against which one can evaluate and compare products.

### ***Supercharging 101***

First, the fundamental purpose of supercharging: ***A supercharger increases the gas (air) density at the inlet to the engine.*** That's it in a nutshell. Now, we have all heard about how a supercharger "forces" air into an engine, or "pumps" more air in, etc. The engine, of course consumes more air and, *with the proportionally correct amount of additional fuel*, will make more power. Although the distinction may be subtle, embracing this fundamental principle is important. Here's why:

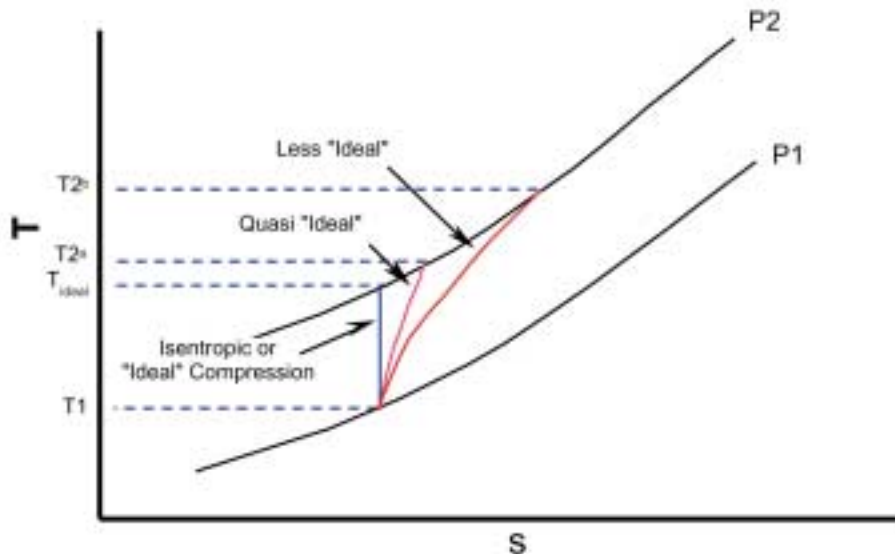
- ***An engine will "pump" a fixed volume of air, at a given speed, assuming WOT operation.*** This volumetric flowrate, of course, is entirely dependent on the engine size, speed, and volumetric efficiency. Items such as tuned intake and exhaust systems, ported cylinder heads, modified camshaft profiles and the like are all designed to improve volumetric efficiency, which increases power.

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- **The AIR MASS flowrate through the engine is a product of inlet air density and the volumetric flowrate.** So, this means that for any given engine, one very effective way to get more air through it is to increase the density of the air available at the inlet.
- **With increased AIR MASS flowrate, we can now add the correct amount of additional fuel and produce more power.** The important distinction is that power strongly depends on air density, i.e., the amount of oxygen available in a given volume to combine with fuel.
- Since superchargers increase the inlet air density to the engine, **they are also and often referred to as “compressors”**.

### Thermodynamics of Compression

Let's turn things up a notch and introduce a little more science. Figure 1 is called a temperature-entropy or “T-s” diagram, and is useful for mapping the thermodynamics involved during a compression process. Let's say that “P1” is some low pressure, approximately 15 psia (standard sea-level pressure is 14.69 psia). “P2” is a higher pressure, and we'll assume it to be 30 psia. So, the “compression” is from P1 to P2. If this compression occurs along a vertical line on the T-s diagram, it is termed “isentropic”, which means that it is “ideal” or perfect. In other words, it occurs with no losses. We can also see that the temperature of the air (gas) also rises with compression, and that even an isentropic or ideal compression process results in a temperature rise. Note also that some refer to this as the “heat of compression”. This behavior follows the “ideal gas law” relationship, which relates the pressure [P] temperature [T] and volume [V] of a gas with a constant of proportionality, called the gas constant [R]<sup>1</sup>. Further, there are many possible processes that can occur, but all result in greater temperature rise than the “ideal” process as it is impossible to construct a machine to produce a completely loss-less, or perfect compression.



**Figure 1** – T-s diagram of compression process. Even “ideal” compression results in temperature rise, according to the ideal gas law. As process becomes less ideal, i.e., less “efficient”, temperature rise becomes greater. All processes, however, result in the same pressure, P2.

<sup>1</sup> This, by the way, is not Boyle's Law. Robert Boyle, in 1662, studied the effects of pressure and volume *at constant temperature* on gases. The more generalized ideal gas law results from a combination of Boyle's relationship ( $PV_{T=const} = constant$ ), and others. See [www.chm.davidson.edu/ChemistryApplets/GasLaws/index.html](http://www.chm.davidson.edu/ChemistryApplets/GasLaws/index.html) for more info.

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### ***The Importance of Compressor Efficiency***

As the “gold standard” would be the (impossible to achieve) ideal compression process, we can now consider more realistic compression processes that involve actual compressors or superchargers to accomplish the compression work. In this sense, we consider the “efficiency” of the actual compression process relative to the ideal process, and call this the “isentropic efficiency”. Now, an isentropic or ideal process would also be 100% efficient. Actual compressors, therefore operate at efficiencies below this level. Also, the further a process deviates from the ideal, the less efficient it becomes, and, the greater the temperature rise. So as depicted in Figure 1, the process resulting in T2b is less efficient than T2a. Now here’s the rub;

- A less efficient compressor produces less density rise, at the same pressure. This follows from the ideal gas law relationship:

$$\rho = P/RT$$

- A less efficient compressor absorbs more crankshaft drive power, at the same pressure and flowrate.
- Therefore, and given these two properties, ***the most efficient compressor will produce the greatest net-power gain potential on the engine.***

### ***The Essentials***

From the foregoing discussion, we can see that compressor or supercharger efficiency must be at the top of the list of tested parameters – the engineer must be able to test the efficiency of his compressor design in order to assess how well he accomplished his job. The consumer, on the other hand, wants the greatest potential net-power gain for his money. Thus, he will want to compare the tested efficiencies of various competing products and decide accordingly – choosing the most efficient product will deliver the greatest potential net-power gain. Other important performance parameters, which can only be determined from controlled tests include:

- **Range** – This refers to the stable or useable flow range, when operating at a constant speed. Typically, the lowest flow point of a centrifugal compressor is the “surge” line, where operating instabilities occur. At the high-flow end is the “choke” region, where the compressor can no longer maintain pressure. At either of these extremes, efficiency drops-off rapidly and overall performance suffers.
- **Pressure** – Clearly an important property as the fundamental purpose of the compressor is to develop increased pressure. So, testing for pressure performance would entail operating at various impeller speeds from minimum to the safe maximum, and measuring pressure performance and the corresponding efficiency levels. It should be noted that some compressors by design cannot develop high pressure while also maintaining good efficiency; the temperature rise combined with the increased drive power, in fact, may be so excessive that a net loss in engine power may result.
- **The Pressure versus Flow Behavior** – Relevant to more advanced studies, this refers to the shape of the individual pressure vs. flow curves. In many cases, a flat performance curve may be preferred as this offers improved flexibility for matching the compressor to various engines. Again, testing is required in order to accurately characterize.

## **SAE J1723 Test Standard**

The SAE has published a Surface Vehicle Standard for testing automotive supercharger products entitled "J1723 Supercharger Testing Standard", issued August, 1995. J1723 has also been submitted for recognition as an American National Standard, per the American National Standards Institute (ANSI).

### ***Why a Standard?***

The most fundamental reasons behind not only adopting a test standard but also adhering very closely to it is so that products may be evaluated in a consistent and repeatable manner, against a common set of criteria, so that the results may be compared directly. For example, the automotive OE community uses the SAE J1349 test standard to obtain, correct, and publish engine net horsepower ratings. This means that engine power claims may be compared across all manufacturers. Further, if an adopted standard is used at one test facility, then the same results will be obtained at a different facility, when using the same standard while testing the same product. This means that tests will produce results that are repeatable, when adhering to the standard. Lastly, the consumer benefits when he has available performance data on competing products, obtained through tests conducted in accordance with a standard. This way, he knows for certain that he can, without bias, compare product performance across all manufacturers that use the standard and publish the data.

### ***J1723 – An Overview***

J1723 applies to the various types of available superchargers, including roots, screw/lysholm, and centrifugal-type products. It applies to bench testing and has been adopted by the SAE to specify, among others:

- A standard basis for supercharger efficiency rating
- Reference inlet air supply test conditions
- A method for correcting observed efficiency to standard conditions
- A method for presenting test results in an accurate and usable way
- A method to compare superchargers without the effects of engine dynamics and intercooling

Strict requirements are set forth regarding the necessary laboratory equipment, test measurement and accuracy, installation of the test article(s), test conditions, and presentation of results. Some of the important instrumentation requirements include:

- **Test Sections** – Appropriately matched inlet and discharge test sections, of specified diameter and length, must be used. Each of these shall be equipped with multiple temperature and pressure probes installed at precise locations. Pressure measurements shall be +/- 0.5 kPa (generally 0.1%) accuracy or better. It is further required that the discharge test section be insulated between the supercharger and at least 1 diameter beyond the outlet temperature measurement location.
- **Inlet Flow** – A flow measurement device, with 1% or better accuracy is required.
- **Torque Meter** – +/- 0.5% or better accuracy required. This is for measuring mechanical drive power to the supercharger and determining mechanical efficiency.

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- **Speed/Tachometer** – +/- 0.2% or better accuracy. During tests, input test speed shall not deviate more than +/- 0.2%, or +/- 10 revs/min, whichever is greater.

### ***Stabilization Requirement***

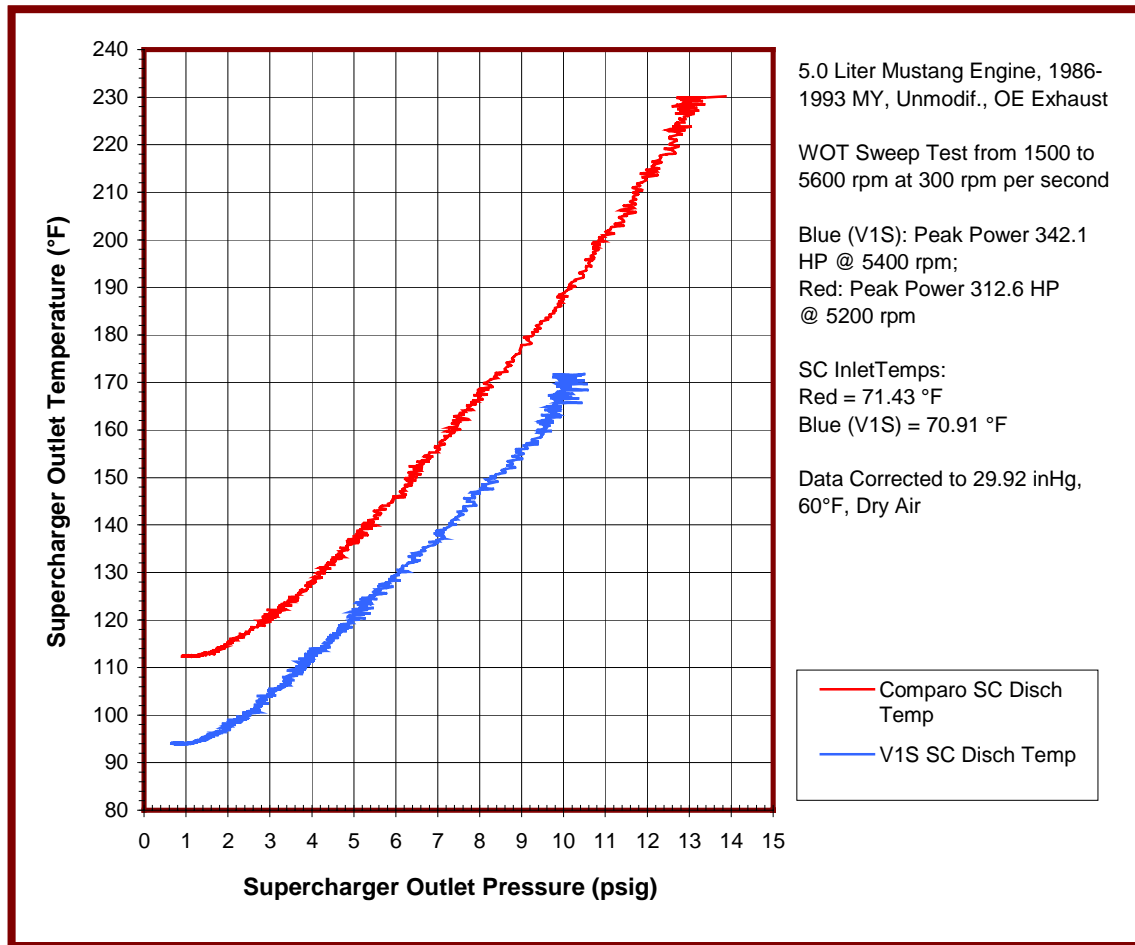
In order to obtain accurate and repeatable results, the supercharger must be operated at a fixed speed and flow setting, and all temperature readings must completely stabilize before a data point can be logged. Stabilization is essential in order to obtain accurate and repeatable measurements. Further, and in the case of testing centrifugal compressors, thermal stabilization means minimum heat transfer from the compressed air occurs, and the adiabatic assumption is supported. Given these, ***and only these conditions***, an accurate and repeatable efficiency measurement can be made.

### ***Some Misconceptions***

Believe it or not, there are some in the supercharger industry who contend that the J1723 standard is flawed and inappropriate for evaluating automotive supercharger products because it "...does not account for the dynamic operation of a supercharger in actual use." This is further compounded by the belief that a supercharger may conversely run cooler, i.e., somehow become more efficient when operating on the vehicle, even though it tests poorly in the test cell. This erroneous thinking is apparently due to the requirement that the supercharger be operated at fixed speed, flow, and pressure until fully stabilized, before a data point can be logged, per the standard. This is quite unlike the normal, dynamic operation when installed on a vehicle. Interestingly, other test codes such as the ASME PTC-10 also require stabilization; this particular test code has been a mainstay of industrial compressor testing for decades. Nonetheless, such arguments readily collapse given the following realizations:

- Efficiency performance is entirely dependent on the design of the compressor – poorly designed compressors perform poorly, whether operation is continuous and stabilized, or dynamic.
- Given the same input drive speed and air-flow rate, a compressor will not consume any less drive power when installed under the hood, than it does in the test cell.
- A more efficient compressor, on the other hand, will always deliver cooler charge air and consume less engine power than an inefficient compressor, at the same (flow and pressure) operating point. This fact holds whether the compressor is running continuously at the operating point, or rapidly "sweeps" through it.
- More insight is afforded upon examining dynamometer test data. Figure 2 depicts the discharge temperature versus boost performance for two supercharger products, a Vortech V1S Trim with curved discharge, and a comparison centrifugal supercharger product. The data for both compressors was obtained from an engine dynamometer sweep test, with each supercharger mounted on the same engine. The V1S attains a peak efficiency of 71% when tested per the J1723 standard. The competing product, 61%. Inlet temperatures were within 0.5°F for the dyno test. From the plot it is clear that the V1S exhibits cooler discharge temperatures than the competing product, even under these dynamic operating conditions. This is because it is a more efficient compressor, as the J1723 test indicates. This also means that a hotter running compressor on the test stand will also run hotter [than a more efficient compressor] on the engine.

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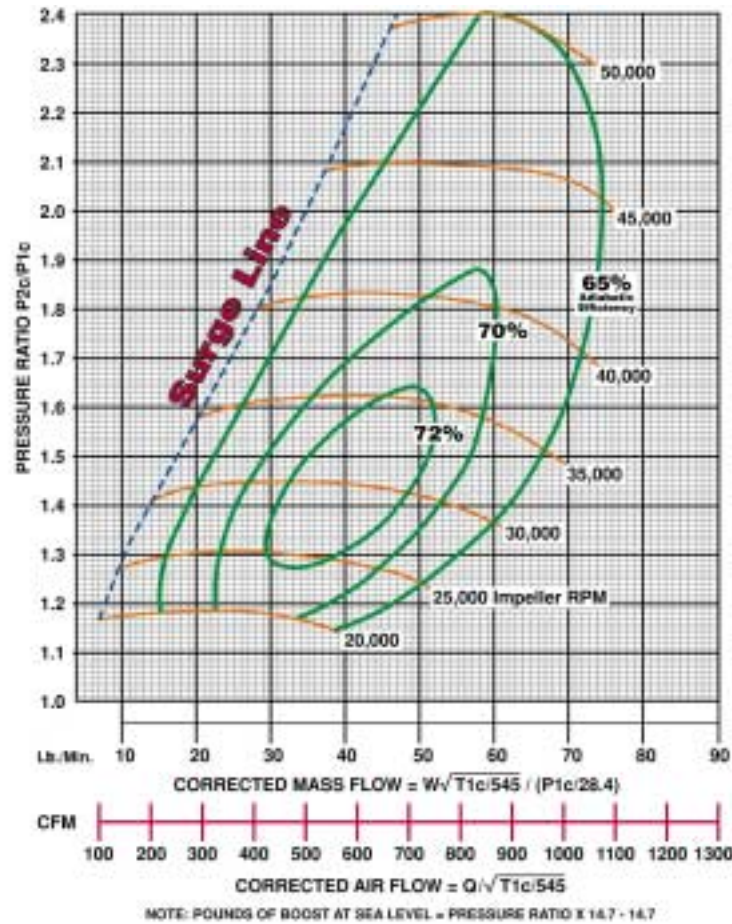


**Figure 2** – Discharge temperatures of Vortech V1S Trim with curved discharge (71% efficiency) and a comparison centrifugal supercharger (61% efficiency) when operating on engine dynamometer sweep test. 5.0 Liter Mustang engine; 1500 RPM to 5800 RPM in ~ 15 secs. Inlet air temperatures are within 0.5 °F. Vortech V1S delivers cooler charge air at a given boost level than competing product.

## Compressor Maps

A compressor map is the product of a completed J1723 test. This map presents the most significant performance results from testing in a very clear and useful manner. Multivariate data are displayed and include the pressure versus flow curves, each obtained at a fixed operating speed, and the all-important iso-efficiency contours, which are often referred to as efficiency “islands”. The term “map” is quite appropriate as, usually, the useful operating range of the compressor is displayed in its entirety and full knowledge of compressor performance can be obtained at any specific operating point. With a compressor map, one can also over-plot an engine air demand curve and determine whether the compressor is suitably matched to the engine. An example of a compressor map is shown in Figure 3.

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**Figure 3** – Compressor map for Vortech V1S-Trim supercharger. Peak operating efficiency (island) of 72% is attained. Compressor can attain at least 65% efficiency up to a Pressure Ratio (PR) of 2.4; with flow up to 75 lbm/min. Compressor can operate outside of this range, but at reduced efficiency.

### Speedlines

These are lines of constant speed operation on the map, and indicate pressure rise vs. flow, at the indicated impeller speed. The lines are constructed by taking 5 to 7 data points, at various flows from surge to choke, and fitting a curve to these data to form the line. To develop a complete map, multiple speed lines are constructed to cover to the operating speed range of the supercharger. This also minimizes inaccuracies arising from interpolating the data. Thus, many stabilized operating points (perhaps 50 or more) must be logged in order to construct a complete map. This may consume several days in the test cell.

### Pressure Ratio (PR)

The term “pressure ratio” is simply the absolute discharge pressure divided by the absolute inlet pressure. By plotting pressure rise as a ratio, one can quickly and conveniently determine the discharge pressure of the compressor, when the inlet pressure is known. Further, and according to J1723, the PR is to be computed using the stagnation or “total” pressure measurements. The total measurements differ from static

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measurements in that the kinetic energy of the high velocity air is accounted for and incorporated. In essence, then, this computes the complete change in air energy state from the compressor inlet to the outlet.

### ***Efficiency “Islands”***

For each data point logged, there is also a corresponding efficiency. The efficiency “islands” are lines of constant efficiency, which are over-plotted on the pressure vs. flow map. They are obtained through a graphical construction process from the efficiency vs. flow curves.

### ***Data Correction***

Data correction is extremely important if the data and/or performance maps are to be useful. Correction is required so that results of different tests, on different products can be compared directly and in meaningful ways. Basically, correction means: “...this is how the compressor would perform with inlet air at 29.23 in-Hg abs. pressure, and 537 °R” the J1723 standard conditions. Of course, one can correct data to other “standard” conditions; this is yet another rationale supporting use of the J1723 standard.

## **Closure**

Supercharger testing is vital to the design and development process, and affords the consumer meaningful ways to evaluate product performance. The SAE J1723 test standard establishes procedures, requirements, and data presentation methods so that supercharger products can be accurately and consistently evaluated. The resulting corrected compressor map allows both engineer and consumer alike to compare products from various manufacturers, without bias or need for more complex interpretations.

Efficiency is perhaps the most important performance parameter of all, and the J1723 standard provides for it's accurate quantification. Increased compressor efficiency provides greater air density rise per pound of boost, at reduced input power absorbed from the engine crankshaft – a double benefit. As the most efficient compressor affords the consumer the greatest potential net-power gain on his engine, the savvy customer would be well advised to request efficiency test data, or better, a certified J1723 compressor map from a manufacturer before making a purchase choice.