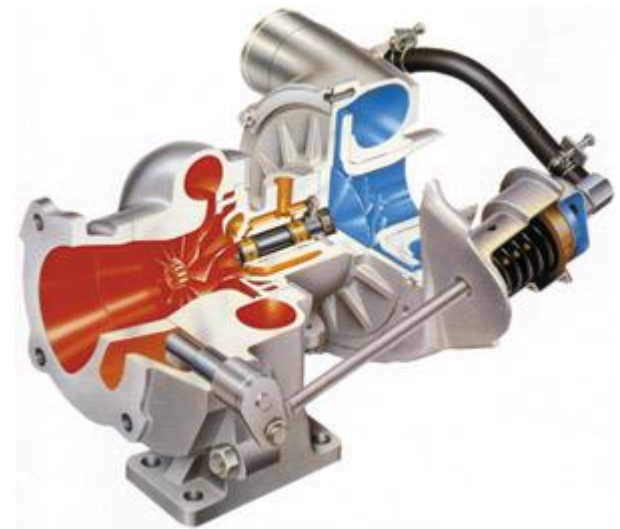


Powertrain Design and Efficiency

Turbocharger Selection

- Effect of adding a turbocharger
- Small vs Large turbo's
- Pressure and density ratios
- Compressor efficiency
- Turbine size

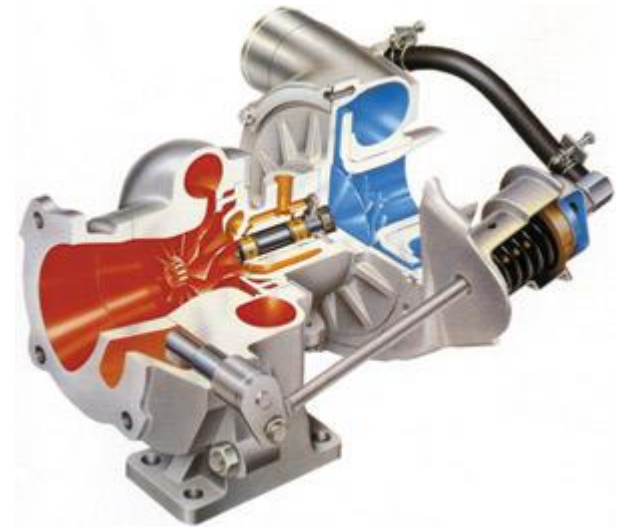
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- Effect of adding a turbocharger
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Effects of adding turbo

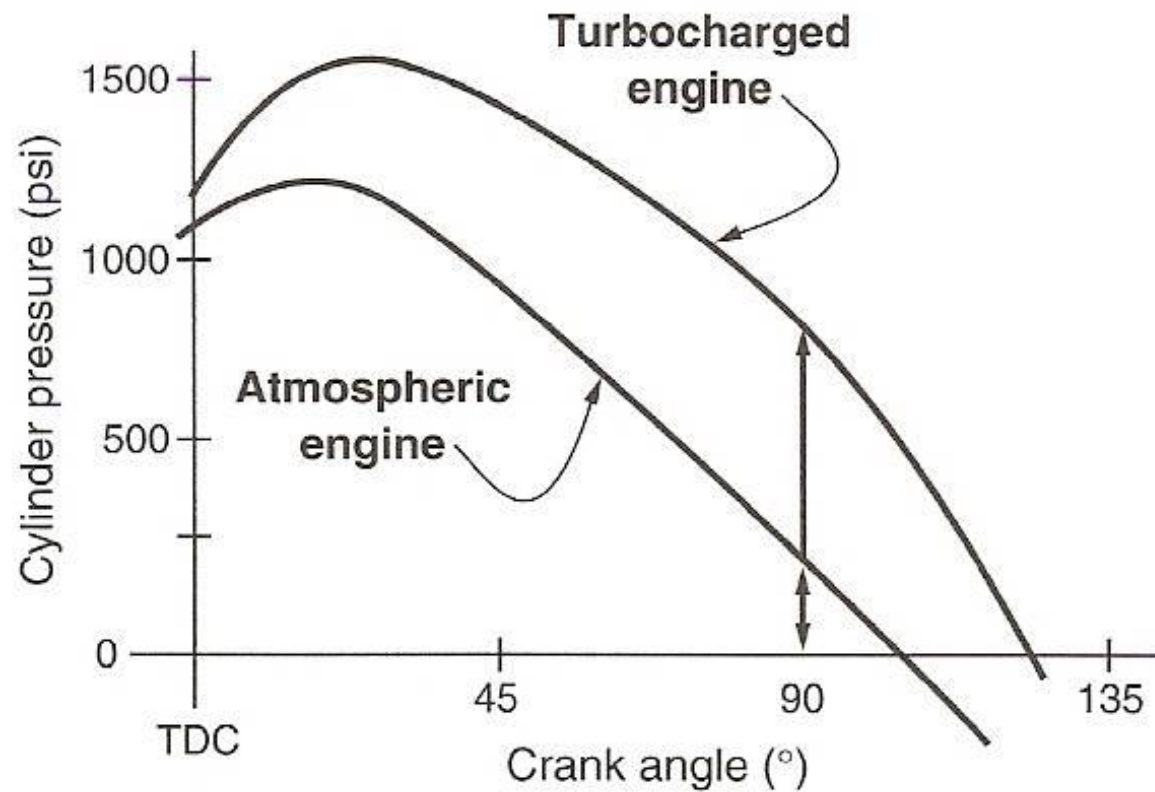


- We have shown last week that adding forced induction to an engine increases the cylinder pressures on the power stroke
- Peak pressure is increased by approximately 20% by adding a turbocharger
- Much more significant increases take place later in the power stroke when more of the mixture is burning
 - $\text{Cylinder pressure} = \text{compression pressure} + \text{combustion pressure}$
 - If a turbo effectively increases the amount of mixture burning, then its effects are less noticeable early in the stroke when less mixture has been admitted to the cylinders
- Peak loads on engine components are determined by maximum pressure

Effects of adding turbo



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Effects of adding turbo



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- Driveability
 - Often power and driveability are conflicting requirements in a naturally aspirated engine
 - This is not necessarily the case in a turbocharged engine
 - Turbocharged engines often use conservative cams and other design features which promote driveability when the turbo is off boost
- Two main factors affecting driveability when turbo is operating
 - Boost threshold
 - Lag

Effects of adding turbo



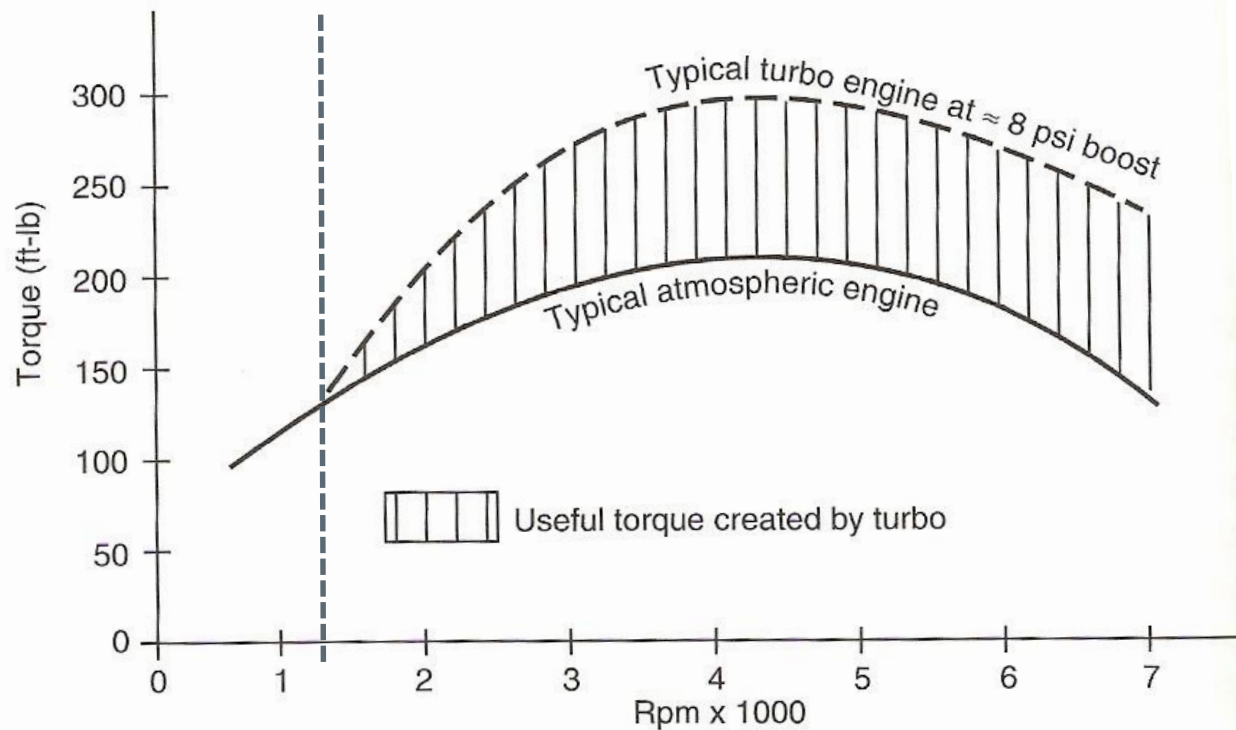
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- **Boost threshold** is the lowest engine speed at which the turbo produces boost pressure at full throttle
- Below the boost threshold, the turbo doesn't have enough exhaust gas energy to spin fast enough to produce above-atmospheric pressures in the intake manifold
- Careful system design, including use of an intercooler to reduce the need for excessively low compression ratios, is necessary to maintain adequate engine performance below the boost threshold
- At WOT, a surge in power is felt as the engine speed crosses the boost threshold

Effects of adding turbo



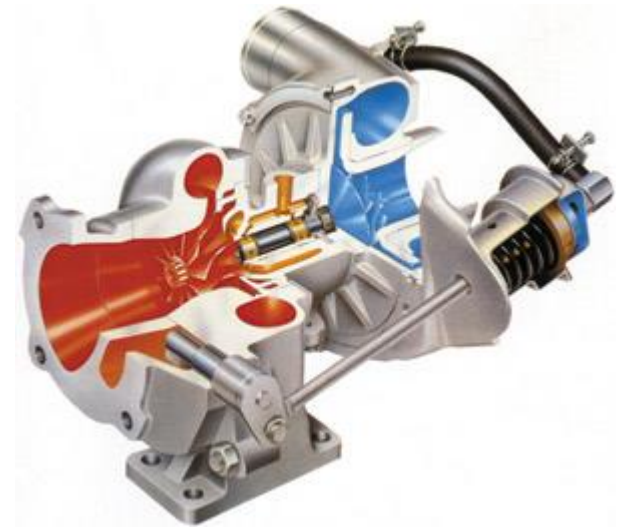
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- Effect of adding a turbocharger
- **Small vs Large turbo's**
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Small vs large turbos



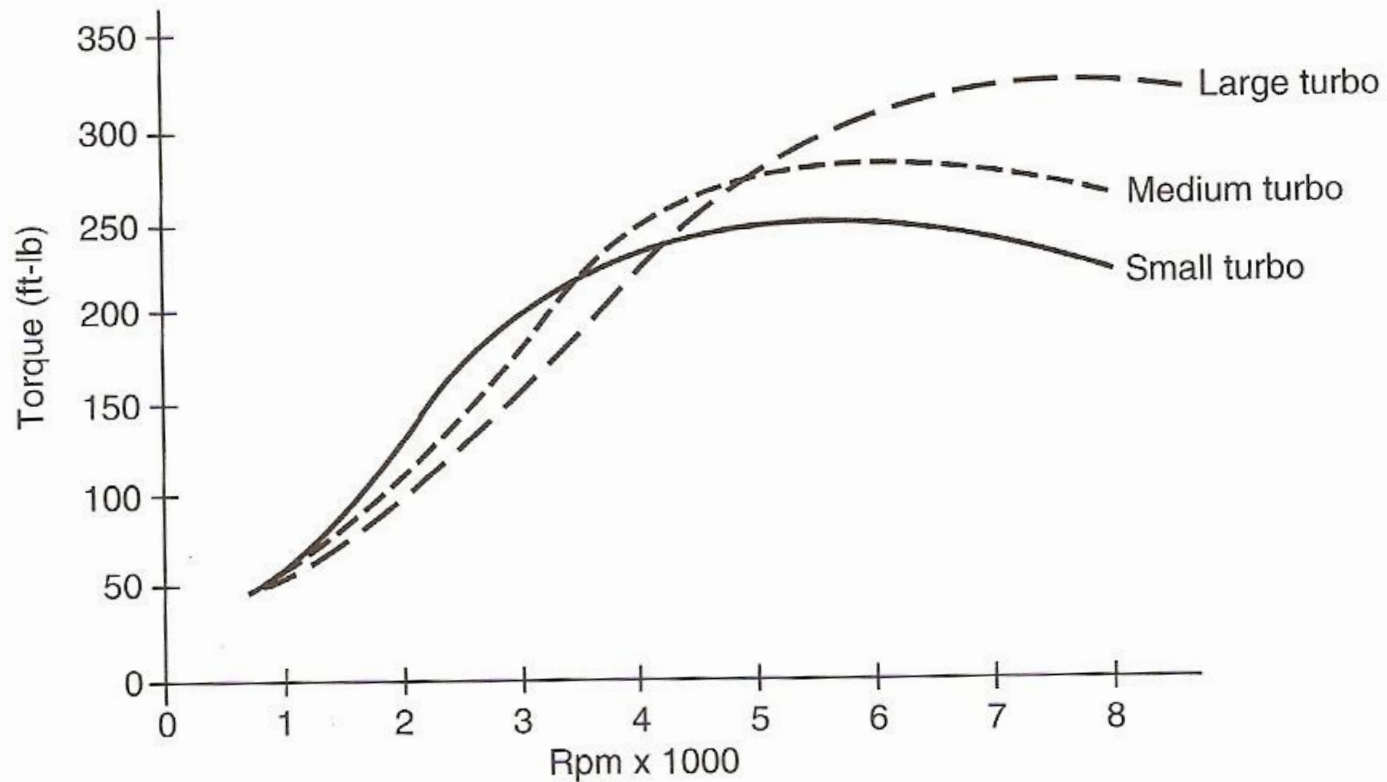
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- Turbo size is a compromise between (amongst other things):
 - Obtaining a sufficient increase in torque once the turbo is on boost
 - Lag time
- Lag time is the delay between opening the throttle and boost being developed in the inlet manifold
- Lag is more noticeable at low engine speeds

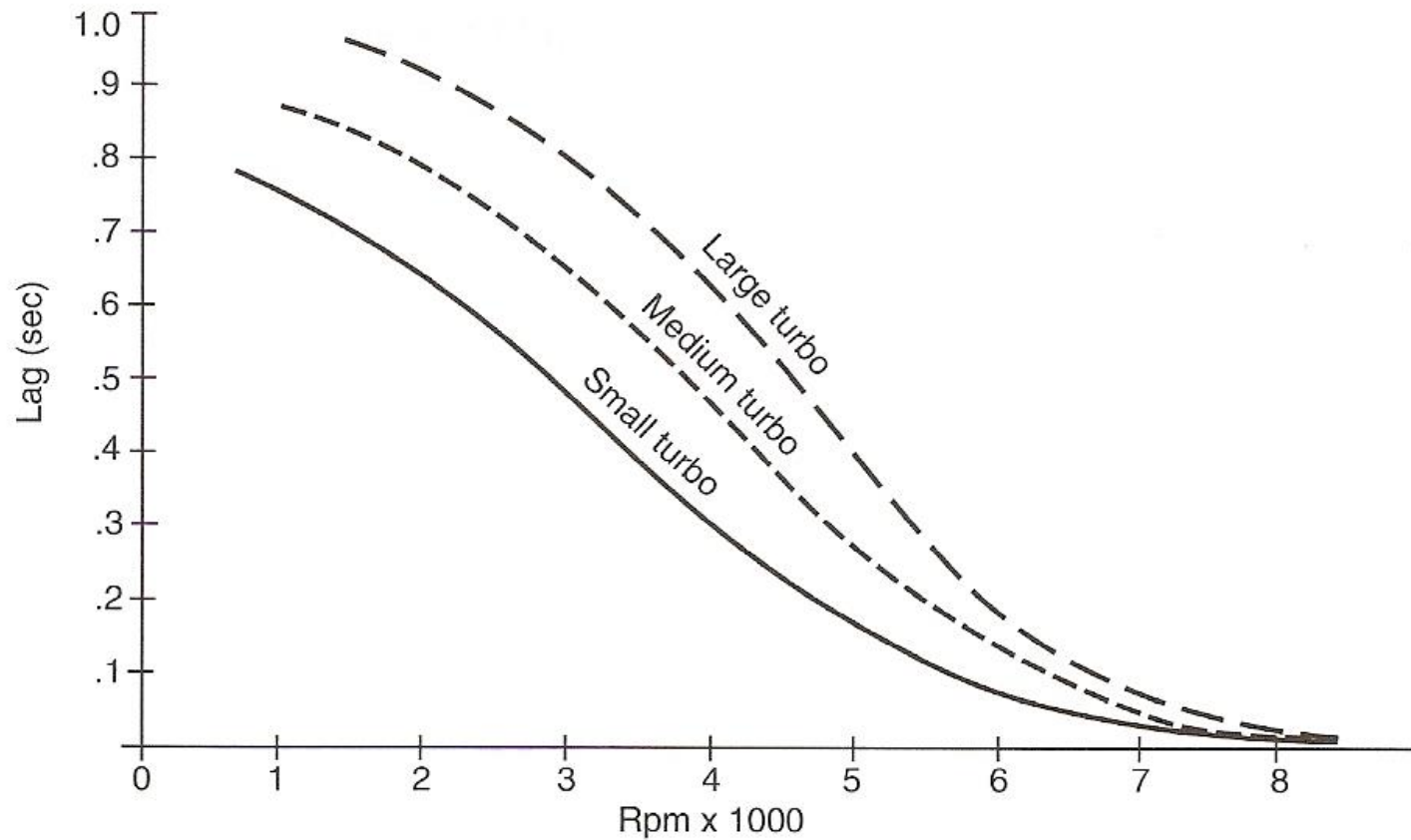
Small vs large turbos



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Small vs large turbos



Small vs large turbos



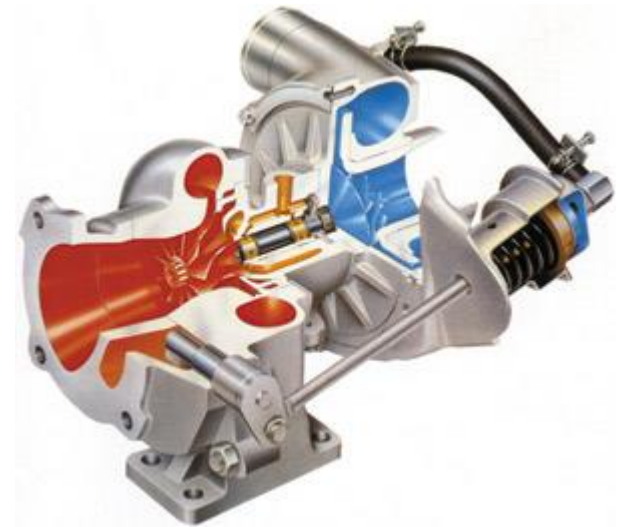
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- OEM vehicles usually have smaller turbochargers to deliver a modest torque increase but without noticeable turbo-lag
- Other vehicles have twin, differently sized turbos or variable vane technology in an attempt to avoid lag problems



- Effect of adding a turbocharger
- Small vs Large turbo's
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Pressure Ratio



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- This is the total absolute pressure produced by the turbo divided by atmospheric pressure
- i.e. It demonstrates how much the turbo increases atmospheric pressure by within a system
- It is also equivalent to the percentage improvement in power which may be expected – i.e. a 1.36 pressure ratio would be expected to give a 36% improvement in power output
- Assuming boost pressure is in psi:

$$PR = \frac{14.7 + \text{boost}}{14.7}$$

Pressure Ratio



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- For example, if an engine has 5 psi of boost:

$$PR = \frac{14.7 + \text{boost}}{14.7} = \frac{19.7}{14.7} = 1.34$$

- Approximately 34% more air (in terms of volumetric flow rate) will be flowing through the engine
- The intake pressure will be 1.34 bar (i.e. above atmospheric)

Density Ratio



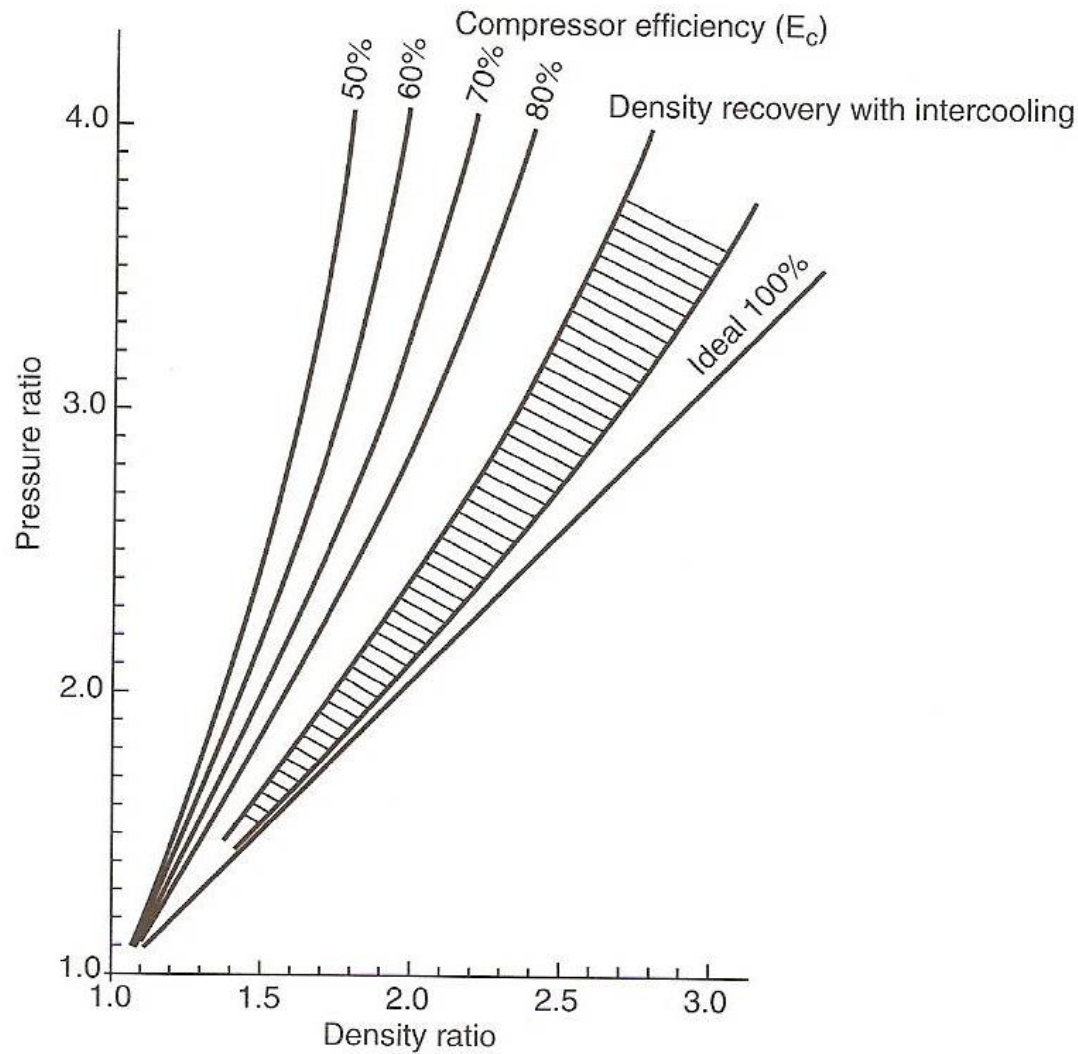
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- Compressing the air heats it up
- Thus, the air expands slightly
- Therefore, the mass flow rate of air never increases by quite as much as the volumetric flow rate
- Thus the density ratio is less than the pressure ratio
- Intercooling can reduce the charge temperature and allows the density ratio to approach the pressure ratio
- Because turbocharger systems are not thermodynamically ideal, the density ratio will never equal the pressure ratio

Density Ratio



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Airflow requirements



- For a naturally aspirated engine, the volumetric flow rate of air through the engine is given by:

$$V = \frac{v \times \eta_v \times N}{2 \times 60}$$

where:

V	=	volumetric flow rate (m ³ /s)
v	=	total engine displacement (m ³)
η_v	=	volumetric efficiency (say 0.85)
N	=	engine speed (rpm)

Airflow requirements



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- For a turbocharged engine, this flow rate must be increased according to the pressure ratio in order to deliver the desired increase in performance, e.g.:

$$V_t = PR \times \frac{v \times \eta_v \times N}{2 \times 60}$$

- Many turbocharger datasheets are in imperial units, where volumetric flow rate is in cubic feet per minute (cfm)
- $1 \text{ m}^3/\text{s} = 2119 \text{ cfm}$

Airflow requirements



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- **Example:** A 4 cylinder engine has a bore of 75mm and a stroke of 90mm. Its volumetric efficiency (in n.a. configuration) is 85%. What is the flow rate through the engine at 5500rpm? If the engine is fitted with a turbocharger giving a 7psi boost, what is the flow rate that the turbocharger must deliver when the engine is running at 5500rpm?

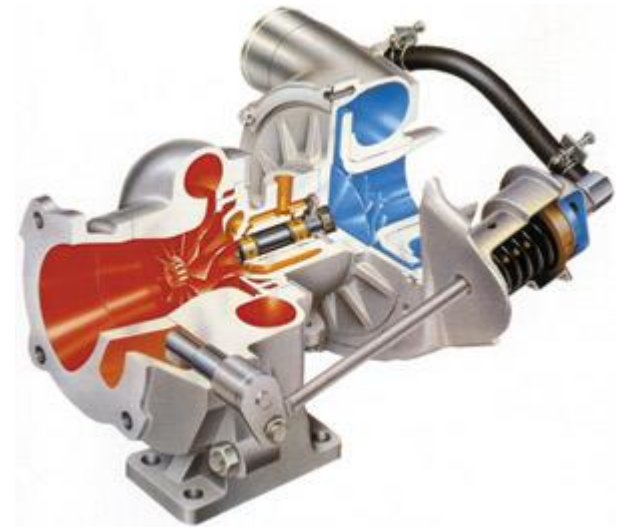
$$PR = \frac{14.7 + \text{boost}}{14.7}$$

$$V_t = PR \times \frac{v \times \eta_v \times N}{2 \times 60}$$



- Effect of adding a turbocharger
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Compressor Efficiency



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- This is a measure of how well the compressor can pump air without increasing its temperature above that given by the laws of thermodynamics
- We know that if we compress air, it gets hotter
- This temperature rise can be calculated using thermodynamics
- Measured temperatures are always higher than these theoretical temperatures
- **The ratio of calculated to actual temperature rise is the compressor efficiency**

Compressor Efficiency



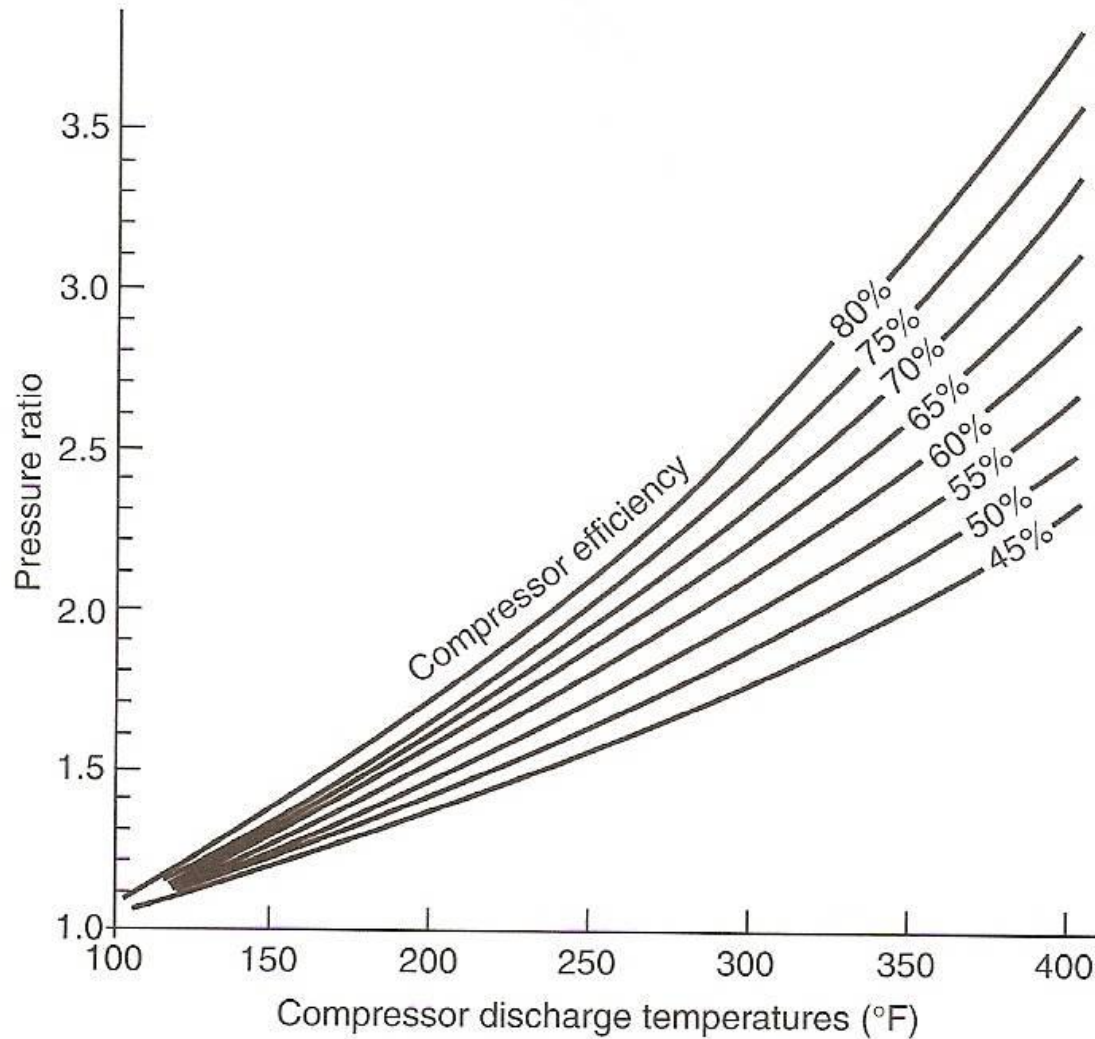
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- We wish to keep this temperature rise as low as possible to preserve the air density
- At a given pressure ratio, the more efficient the compressor, the lower the charge temperature
- Compressor efficiency varies with operating conditions (i.e. pressure ratio and air flow rate)
- Peak efficiencies are usually between 70 and 80%

Compressor Efficiency



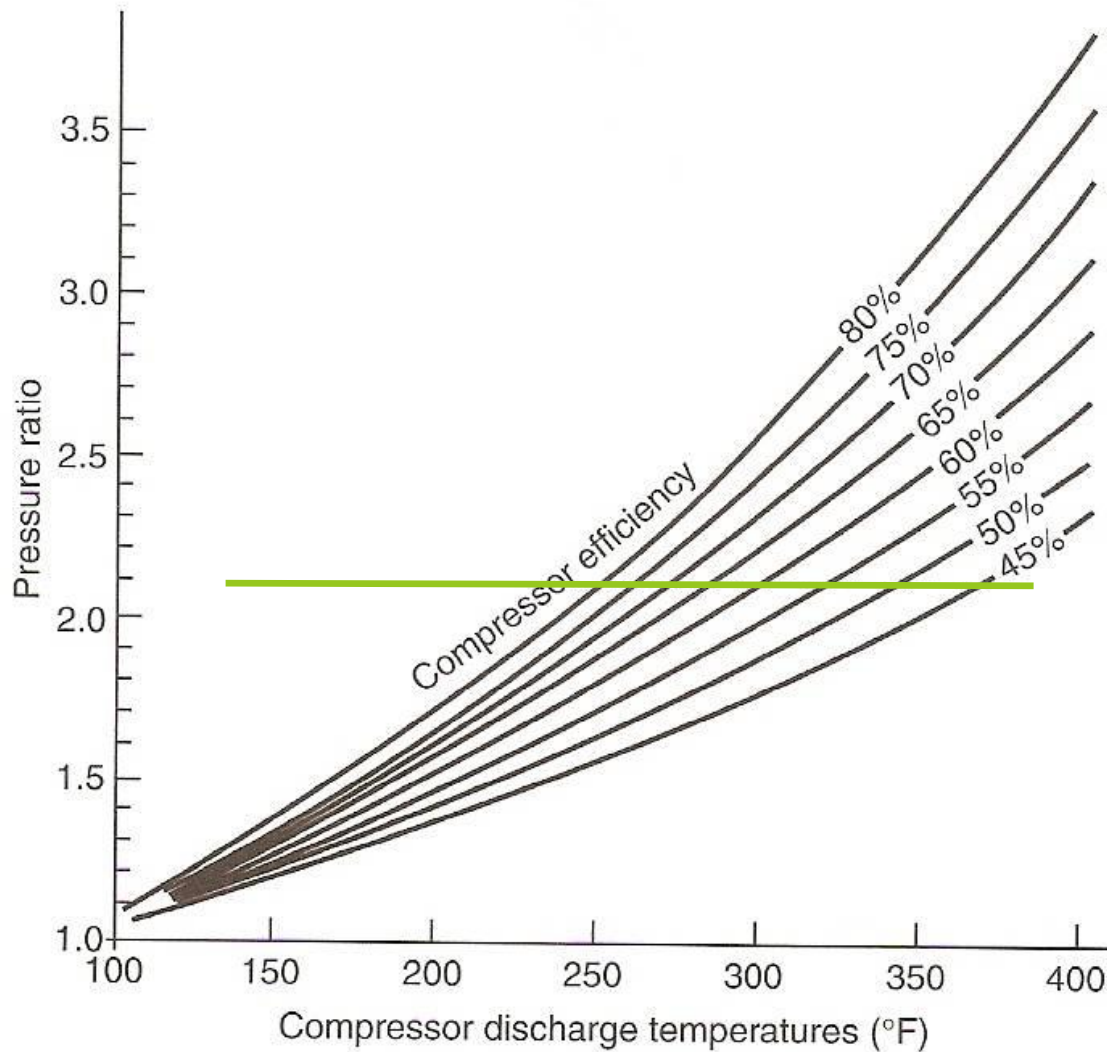
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Compressor Efficiency



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Compressor Efficiency



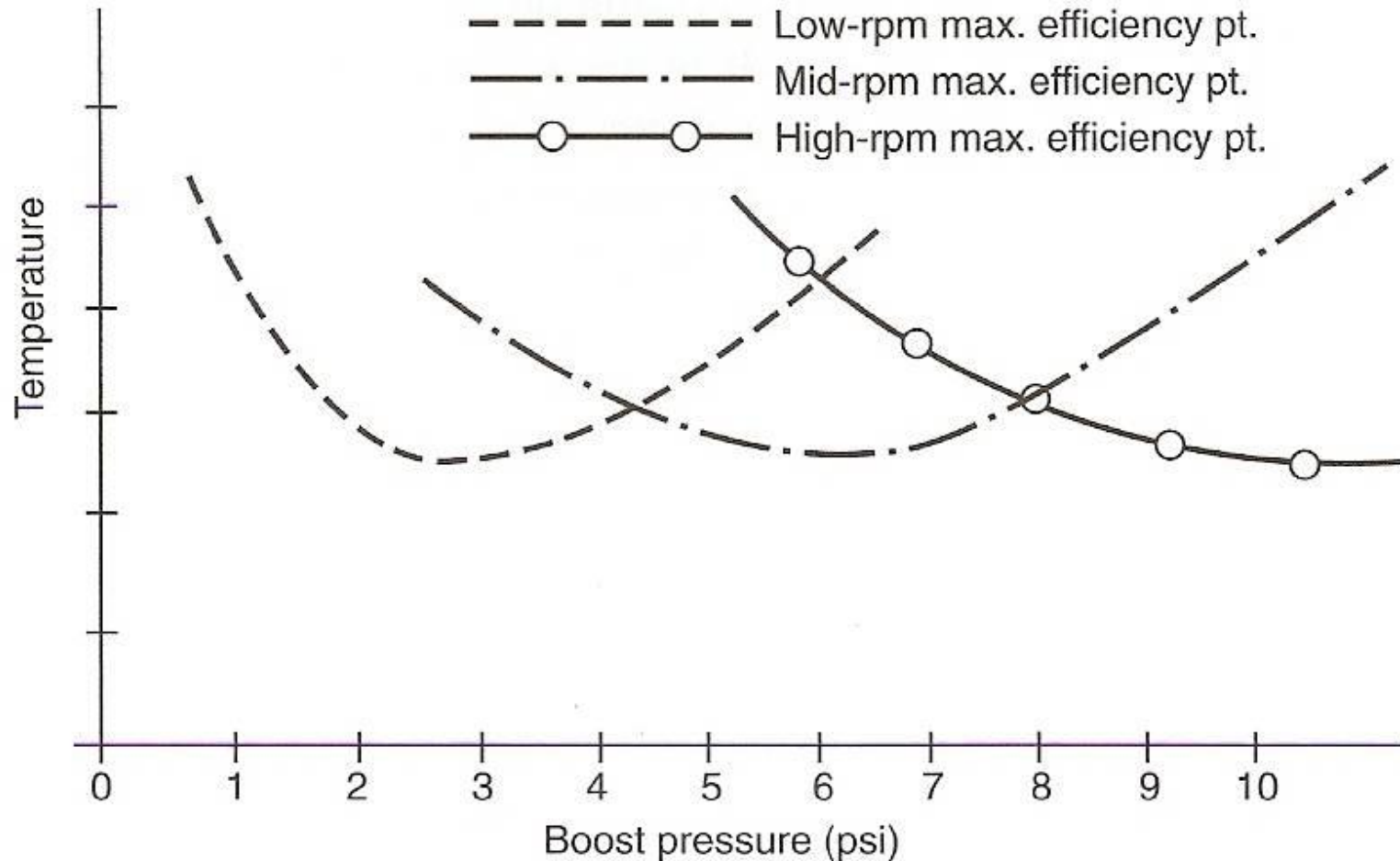
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- Each compressor will have a particular pressure ratio and airflow at which it is most efficient
- Thus we can choose our compressor size to position this point of maximum efficiency at the most useful part of the engine speed range
- Some judgement is needed here
 - Too low a speed for maximum efficiency can lead to excessive charge temperatures and reduced power at maximum rpm
 - Too high a speed for maximum efficiency can affect mid-range performance

Compressor Efficiency



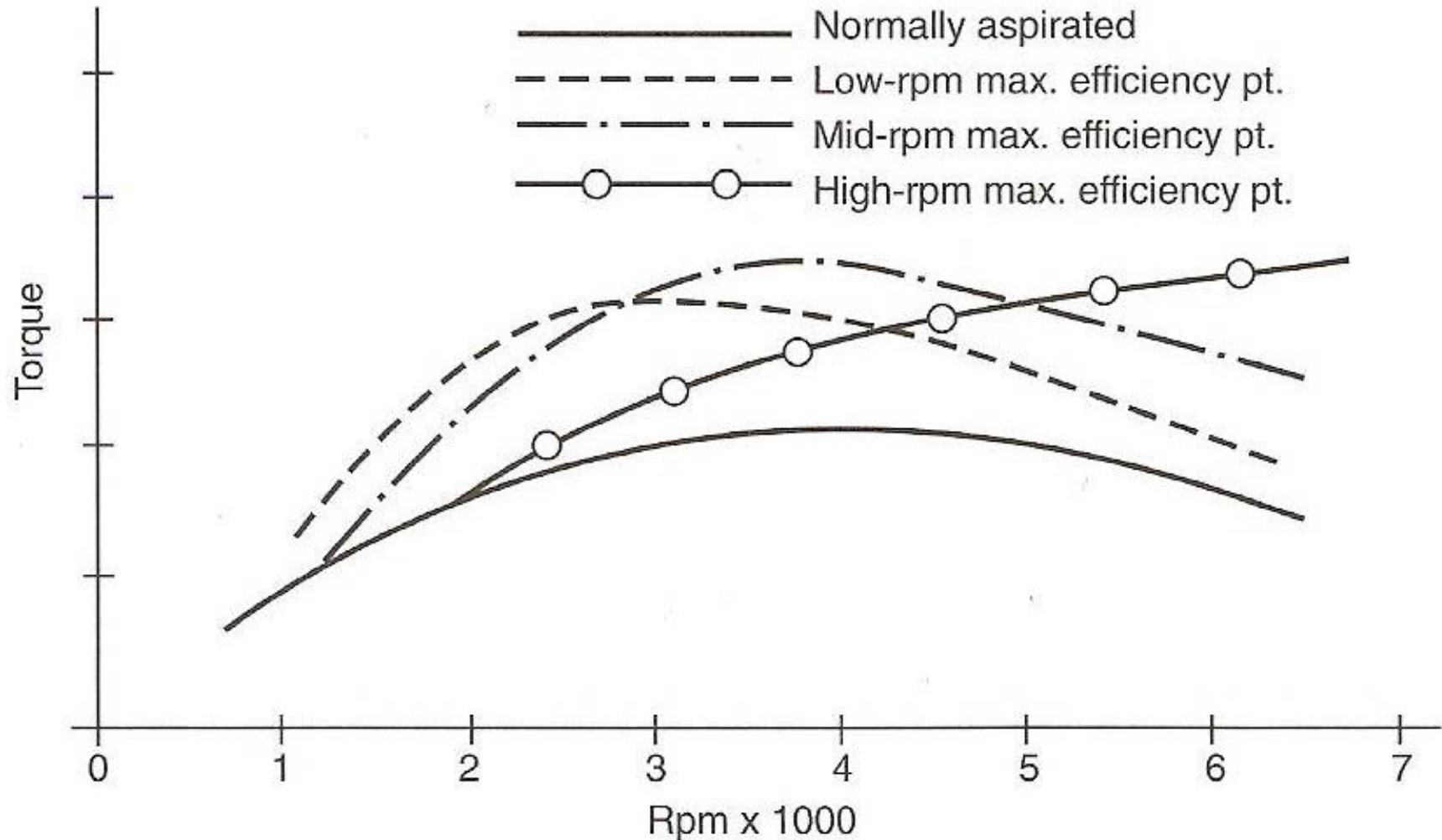
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Compressor Efficiency



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Compressor Efficiency



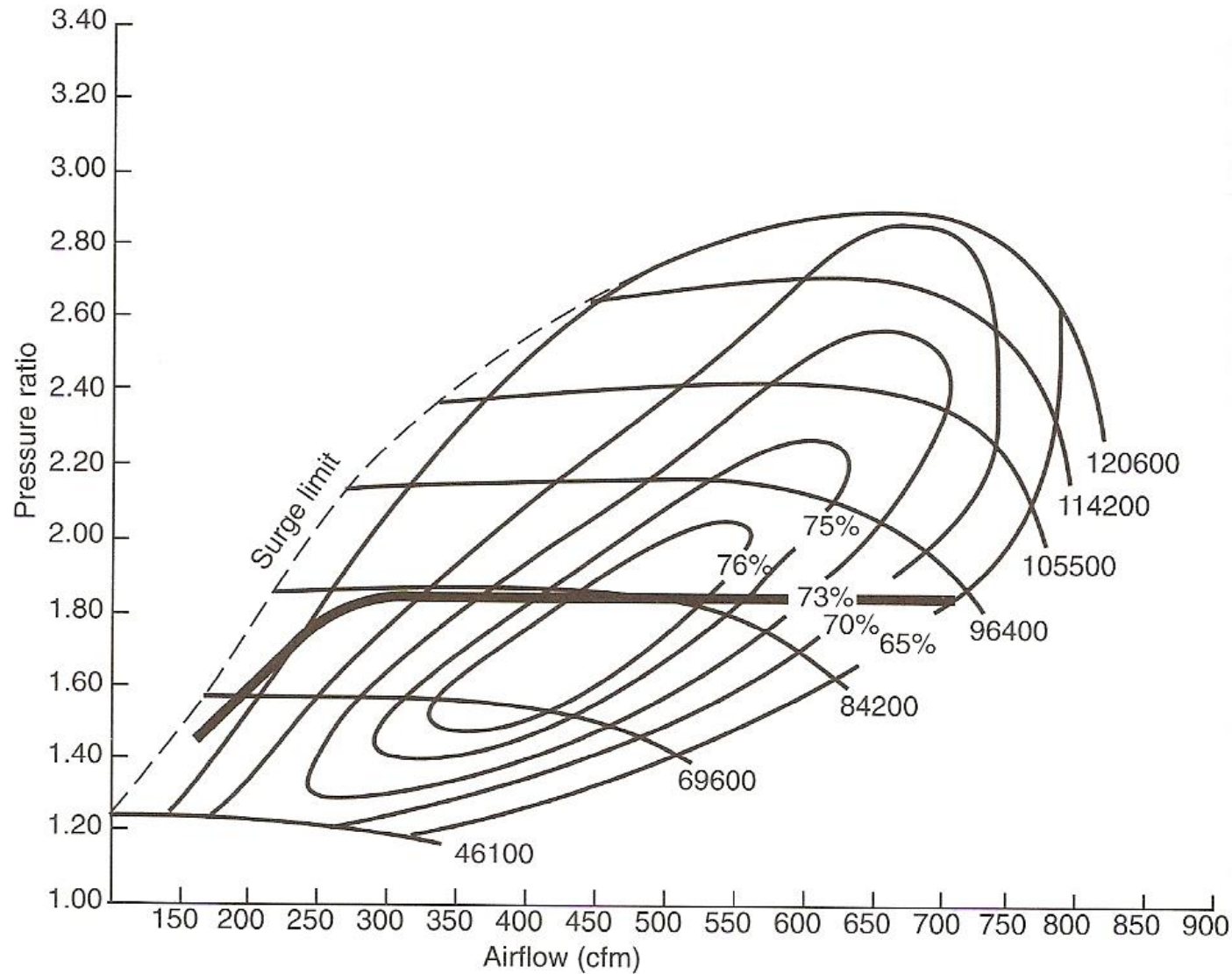
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- Earlier, we have seen how the required pressure ratio and air flow may be calculated when an engine is fitted with a turbocharger
- A turbocharger map shows how airflow, pressure ratio, compressor speed and efficiency are linked

Compressor Efficiency



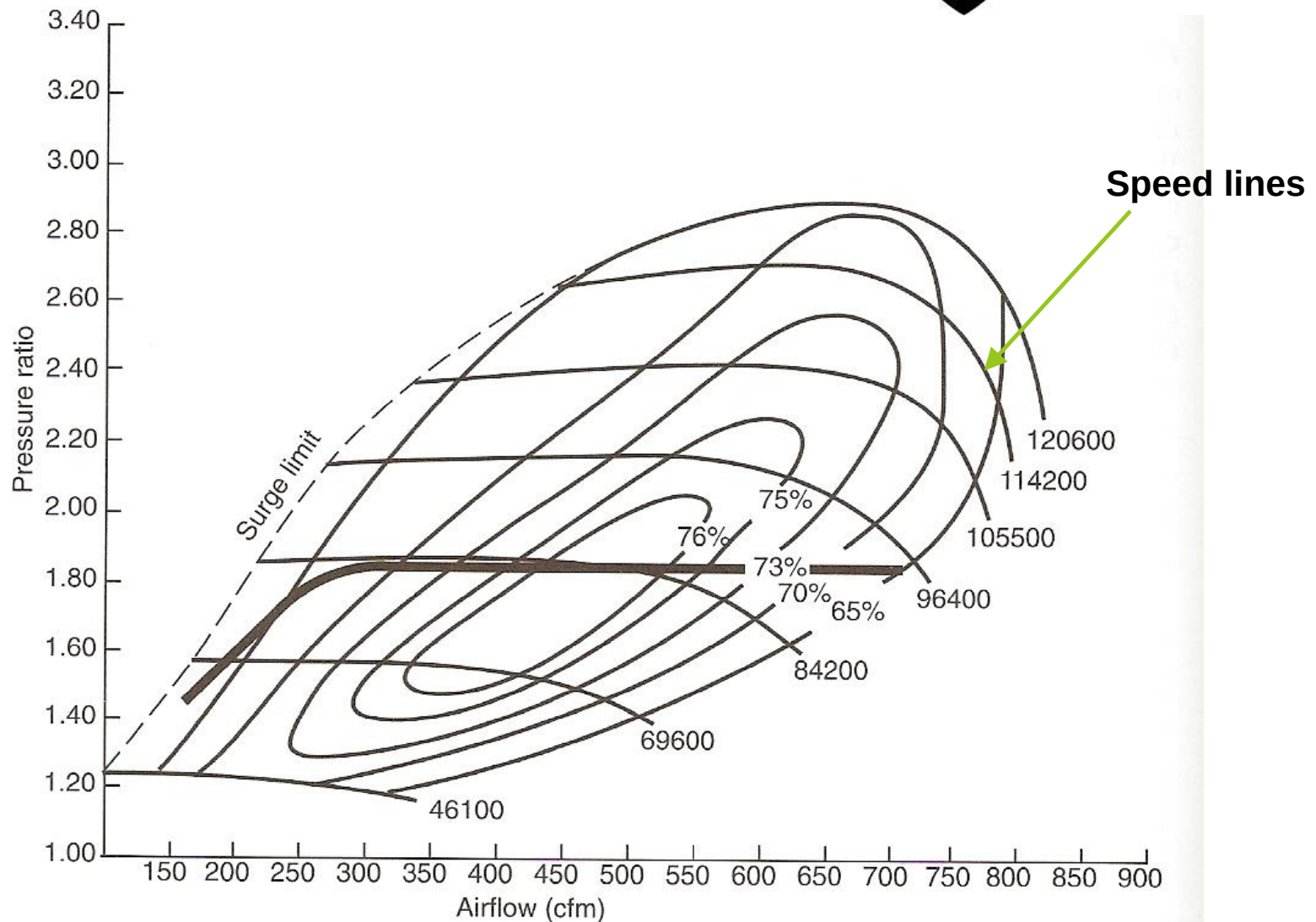
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Compressor Efficiency



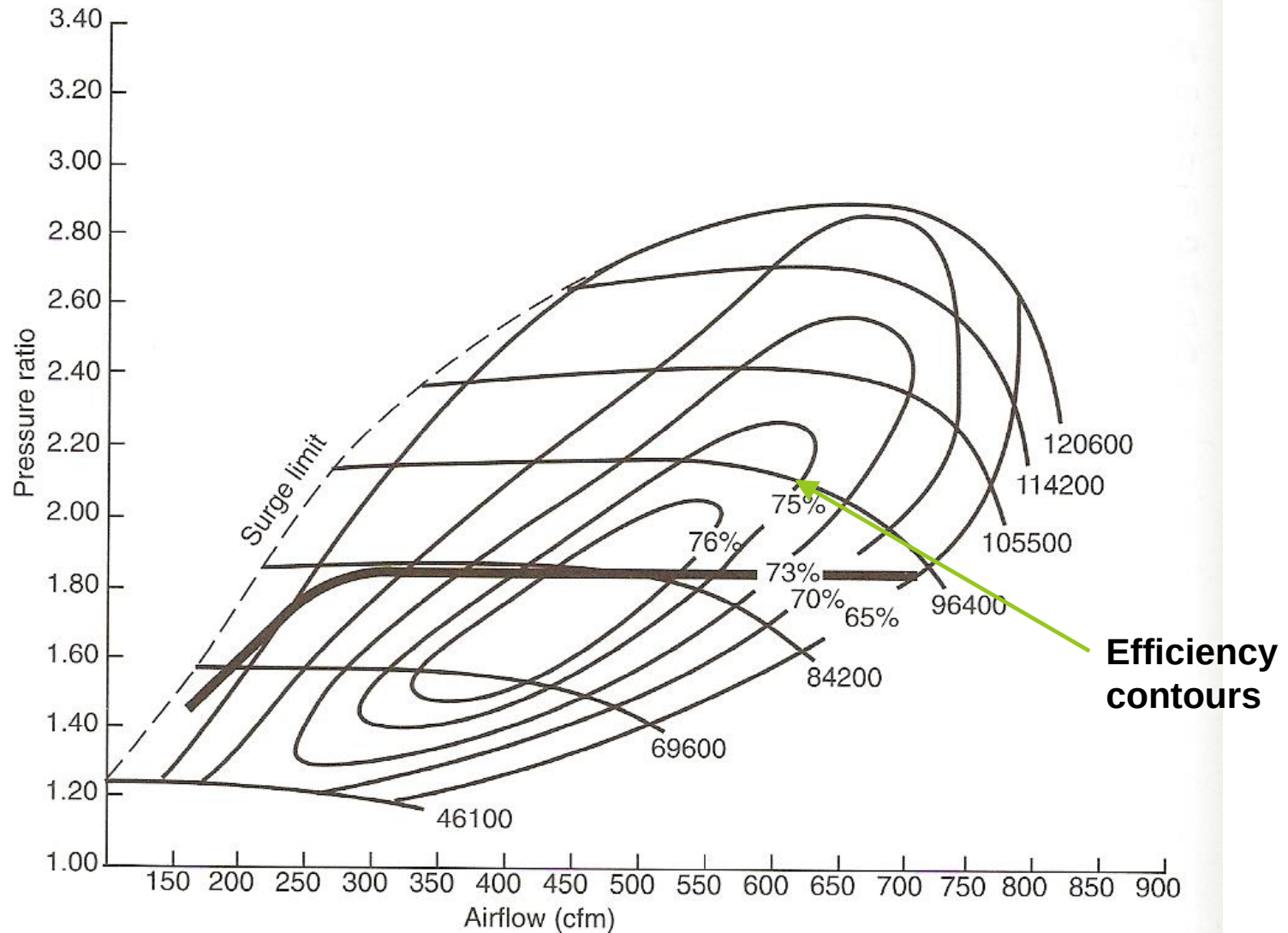
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Compressor Efficiency



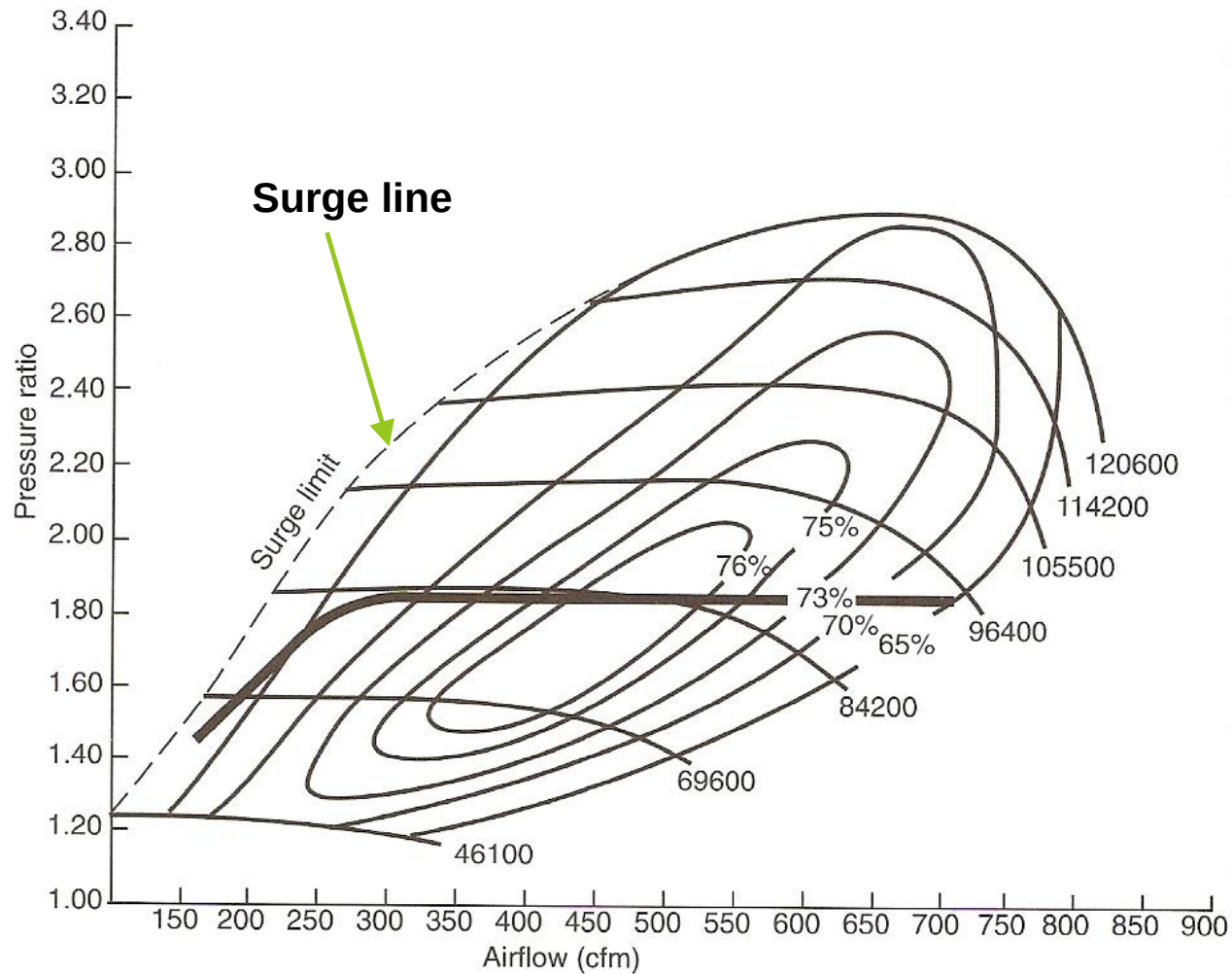
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Compressor Efficiency



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Compressor Efficiency



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- At a particular pressure ratio, the surge line represents the minimum flow rate conditions under which the compressor can operate
- At flow rates below the surge limit, the flow becomes unstable, and there are large fluctuations in pressure and flow rate
- Thus, for a given flow rate and pressure ratio, the operating efficiency of the compressor can be found from the flow map

Compressor Efficiency



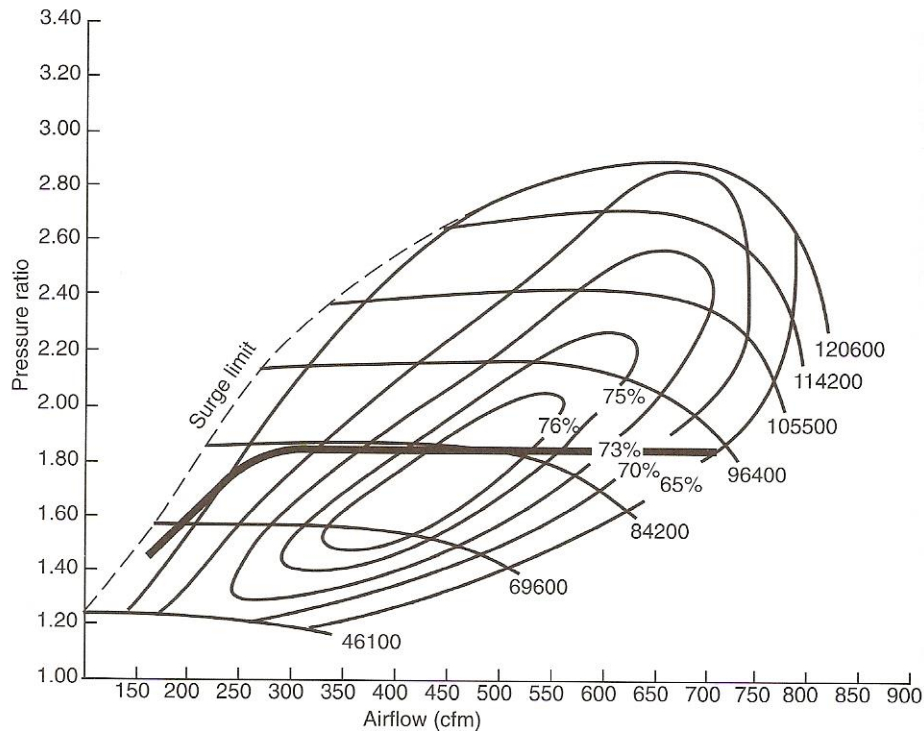
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- As an example, we will consider an engine which, when turbocharged requires 700 cfm at a pressure ratio of 1.82, at 5500rpm redline.
- Two compressor maps are considered, for two different Turbonetics compressors (60-1 and the H3)
- On each map, we plot 700cfm and $PR=1.82$ to determine the operating efficiency

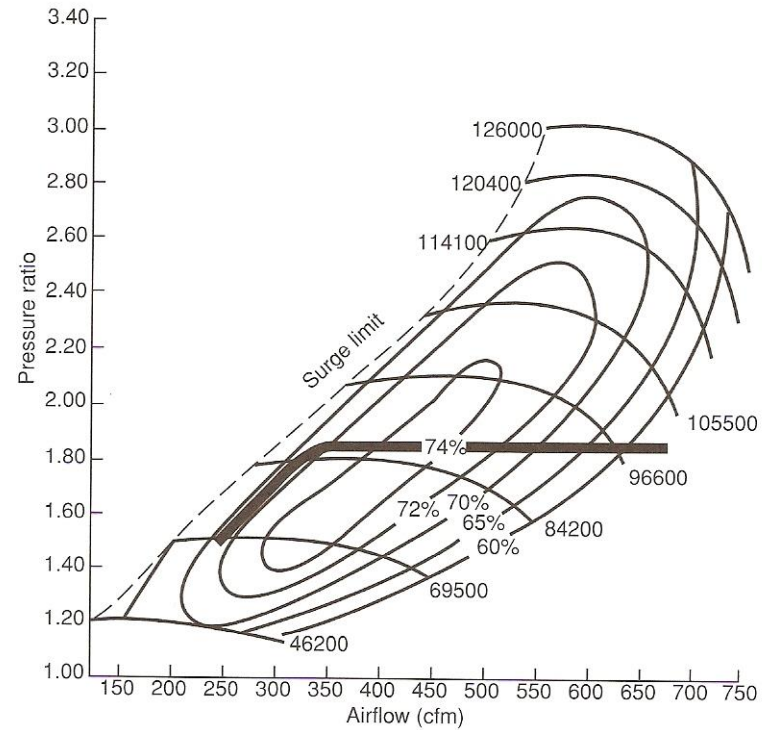
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Turbonetics 60:1

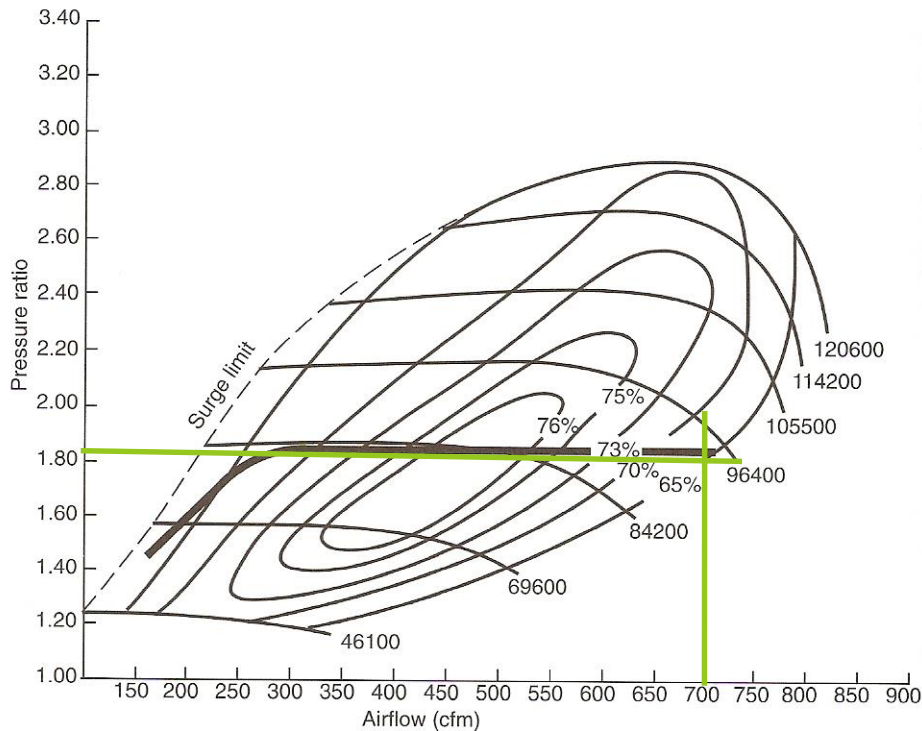


Turbonetics H3

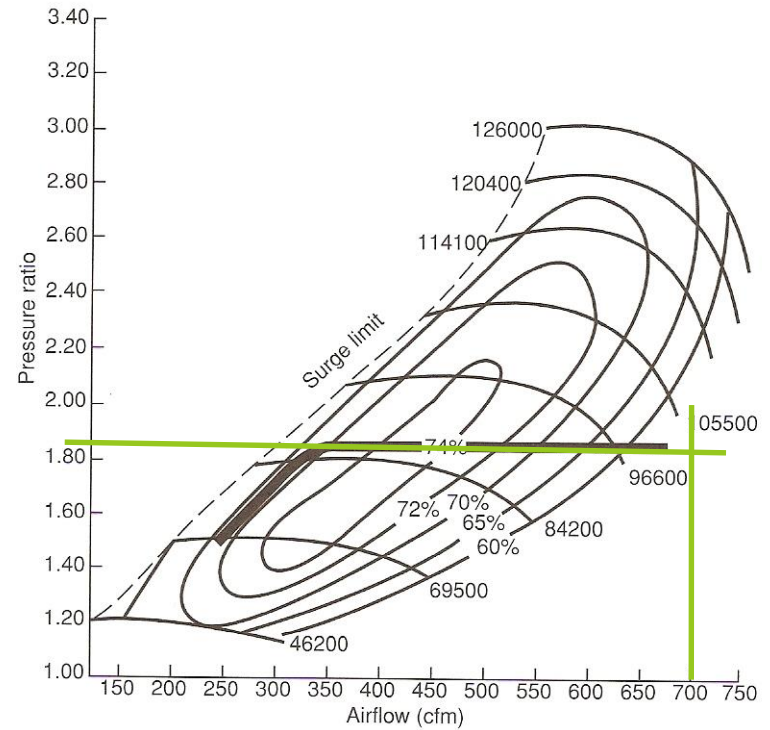
Compressor Efficiency



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Turbonetics 60-1



Turbonetics H3

Compressor Efficiency



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- With the 60-1 compressor, the intersection is at an efficiency of approximately 65%, and a compressor speed of around 92000 rpm
- For the H3, the intersection is to the right of the 60% line, with probably around 50% actual efficiency, with a speed of around 105000rpm
- The 60-1 compressor is a better selection
- Finally, the characteristics of the compressor at lower engine speeds must be checked

Compressor Efficiency



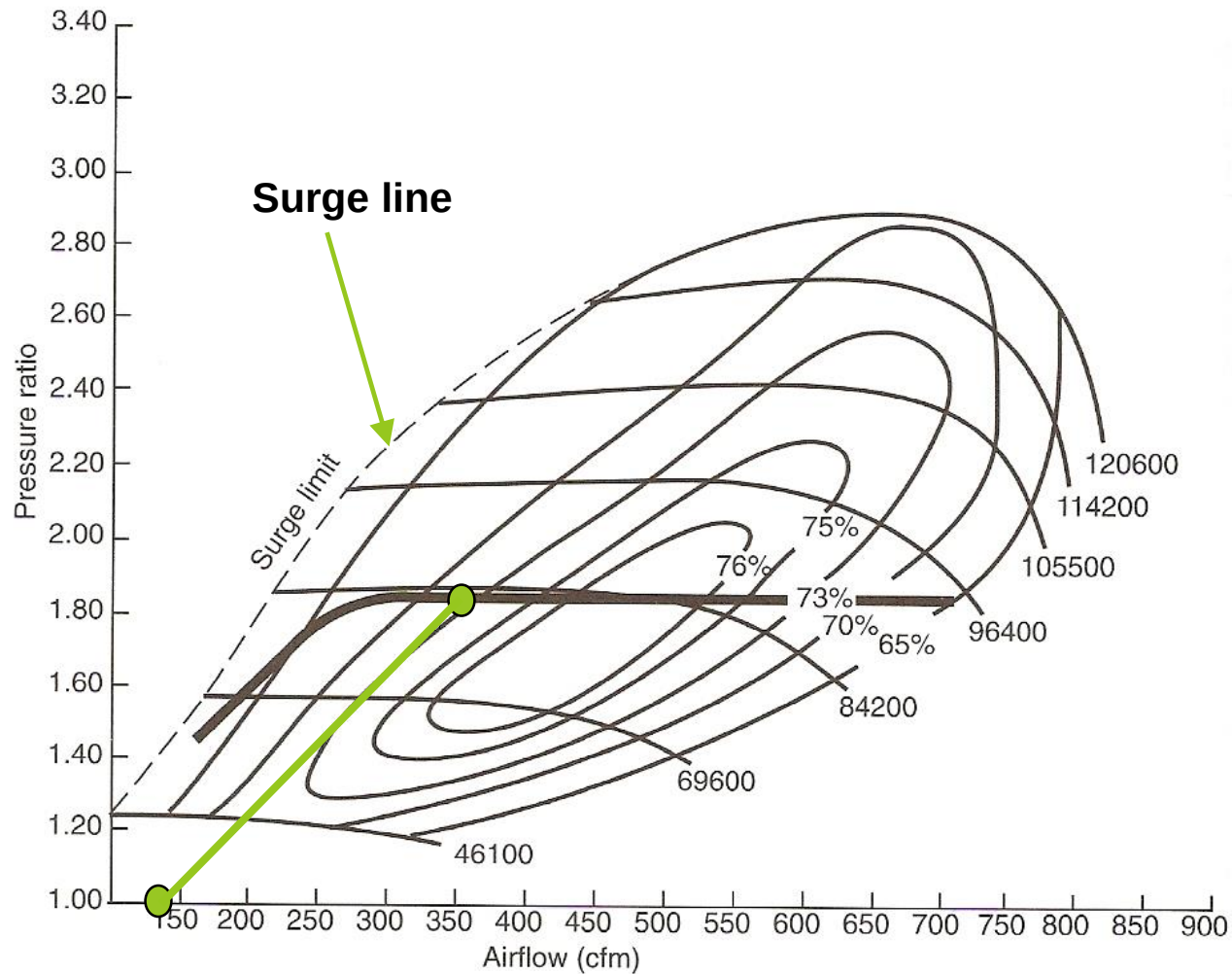
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- Firstly, consider that you more than likely wish the full pressure ratio of 1.82 to be reached at half the maximum engine speed (i.e. $5500/2 = 2750\text{rpm}$)
- At 2750rpm, the air flow is 350 cfm, so plot a point with $PR=1.82$, air flow = 350 cfm on the compressor map
- Next, draw a line from this point to a point with $PR=1$, cfm = 20% of the maximum (i.e. 140 cfm in this example)
- **This line must lie completely to the right of the surge limit line**

Compressor Efficiency



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Compressor Efficiency

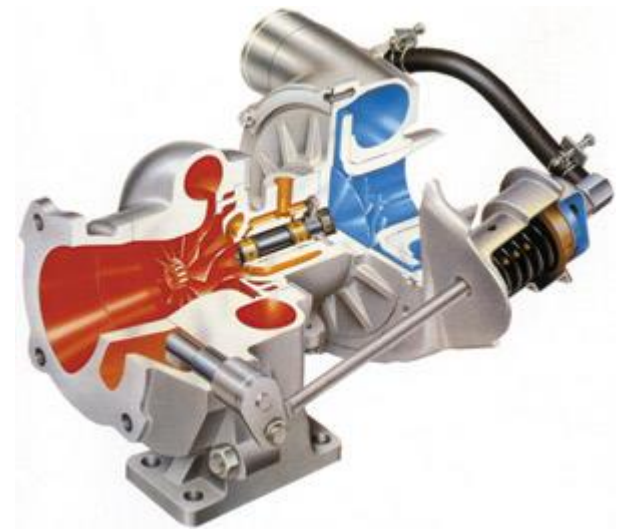


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- This approach is a slight simplification
- It's really air **mass** flow rate which dictates power.
- Some compressor maps are plotted against mass flow rate (often in lb/min)
- Here, the maps are corrected to standard temperature and pressure conditions
- In this case, multiply CFM by 0.07 to give lb/min
- More complex approaches to compressor selection use simulation software
- Talk to the turbo supplier

- Effect of adding a turbocharger
- Small vs Large turbo's
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- Turbine size

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Turbine Size



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- i.e. Selecting the other half of a turbocharger
- This is quite a complex field – often it is best to select a compressor and then speak to the manufacturer or supplier to select a turbine
- However, some approximate sizing calculations can be carried out to give some “ball park” turbine sizes
- Smaller turbines will spin faster for a given exhaust gas energy
- Smaller turbines will, however, generate more exhaust back pressure

Turbine Size



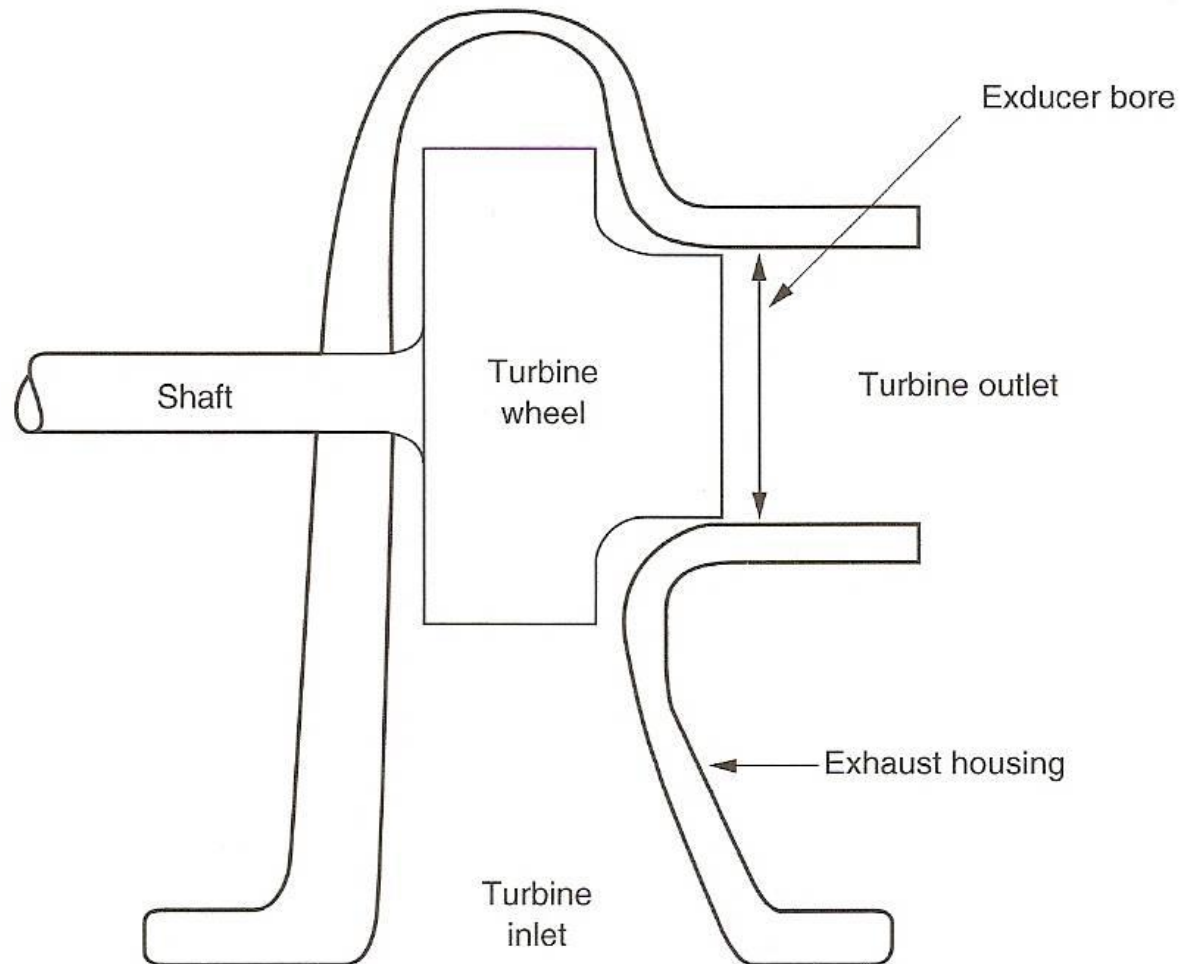
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- Basic turbine size is a measure of the turbine's ability to generate enough power to drive the compressor at the flow rates necessary
- Larger turbines generally offer higher power outputs than smaller turbines
- Turbine size is usually specified on exducer bore (i.e. the diameter of the outlet of the turbine housing)

Turbine Size



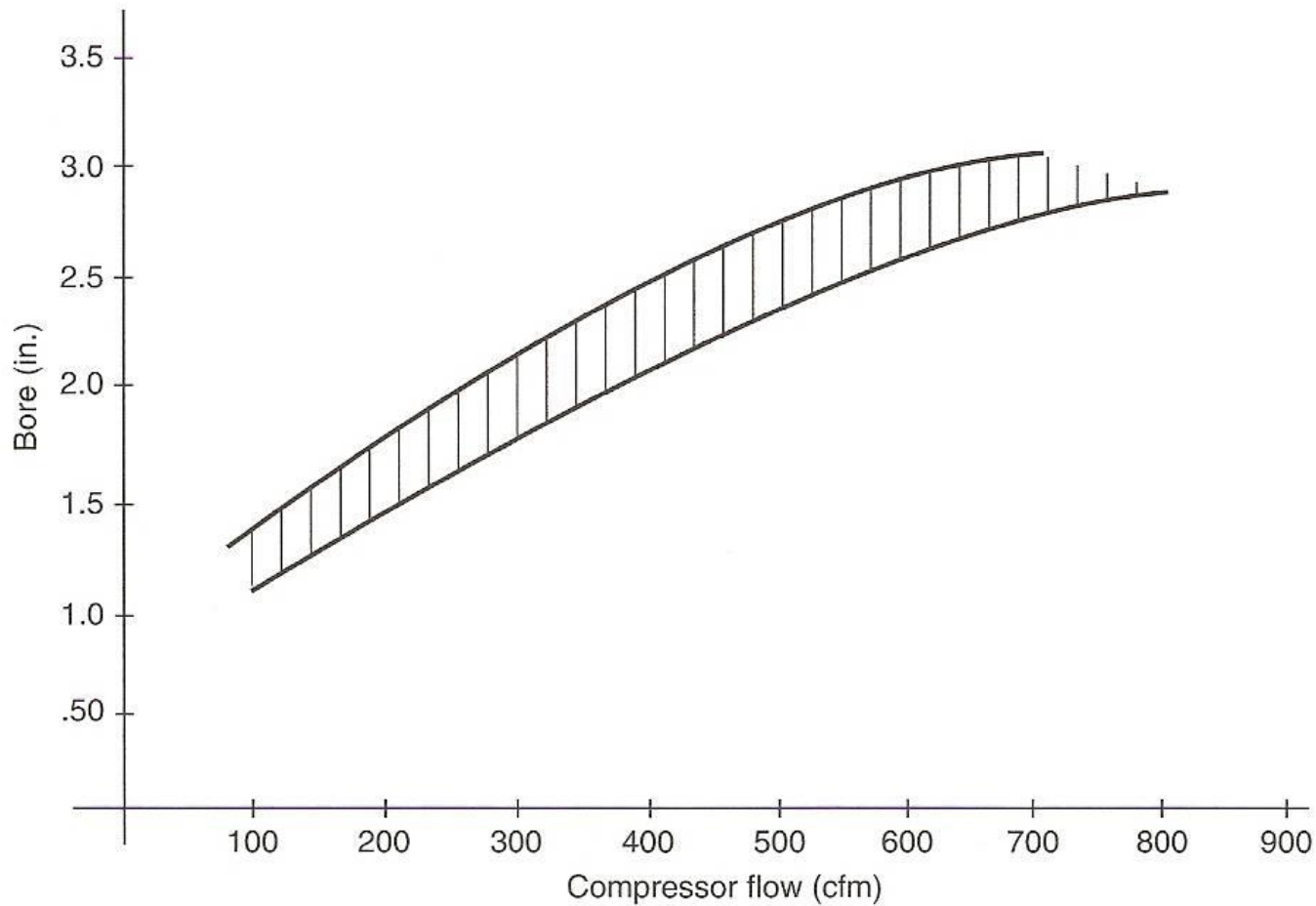
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Turbine Size



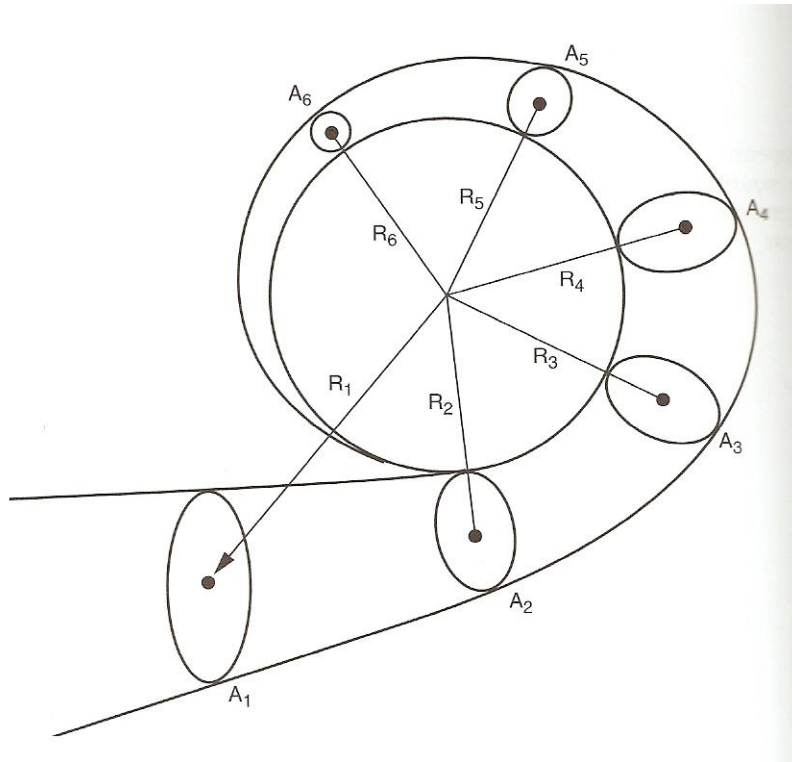
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Turbine Size



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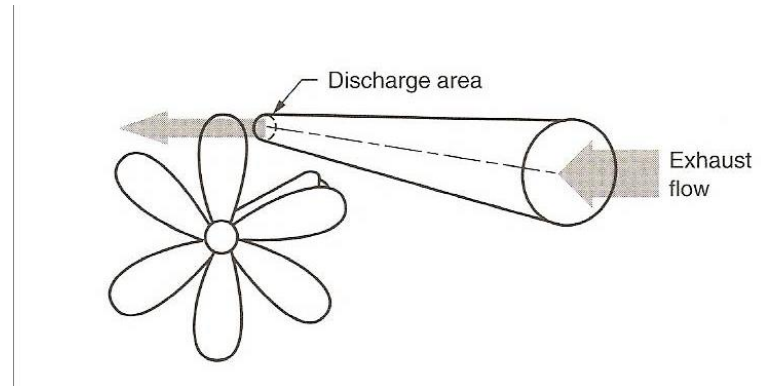
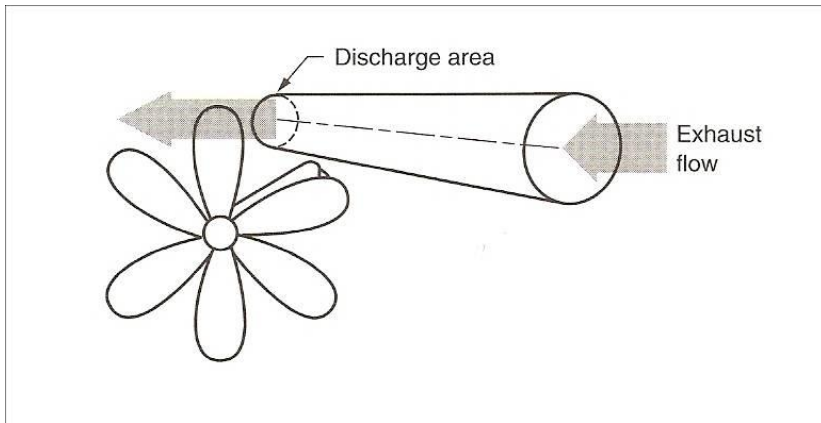
- The turbine size parameter is the Area to Radius ratio (A/R)
- This is the ratio of the bore area to radius of the turbine housing, and is **constant** as the volute “unwinds” itself

Turbine Size



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- As the exhaust gases enter the turbine, they make the turbine spin with a peripheral blade speed approximately equal to the gas speed
- Reducing the A (whilst keeping R constant) will result in higher exhaust gas speeds and hence a higher turbine speed (and more boost from the compressor)



Turbine Size



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- A higher A/R ratio will generate more power (i.e. Higher boost) but can prevent the turbine spinning fast enough
- A lower A/R ratio will result in a very rapid turbine response, but can give fading power in the upper rev range

