CPL Theory
Aircraft Systems (CSYA)

CSYA 5 – Superchargers & Turbochargers

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3. Disclaimer

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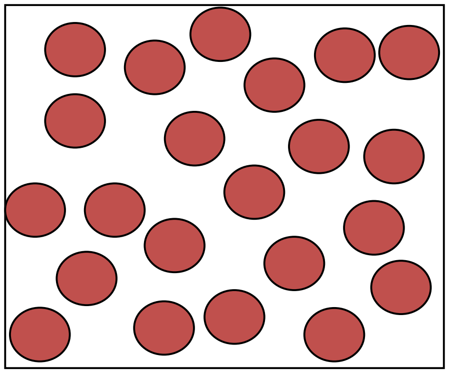
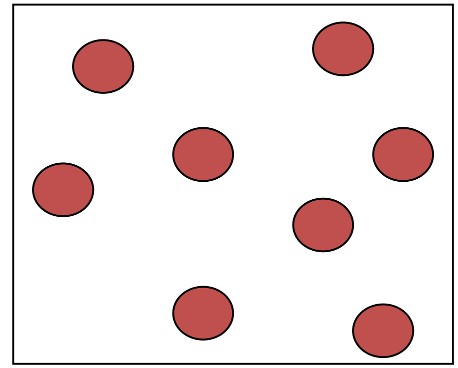
AIRCRAFT PERFORMANCE

Aircraft Performance

- As altitude increases, air pressure and air density decrease



Density at Sea Level



Density at Altitude

- This reduces the power output of **normally aspirated** piston engines because less air is being drawn into the cylinders

- For example, the air density at 30,000ft is 1/3 of that at sea level

- This means that only 1/3 of the amount of air is drawn into the cylinders – with enough oxygen to provide efficient combustion for only 1/3 as much fuel

- So, at 30,000 ft, only 1/3 of the fuel burnt at sea level can be burnt. In **normally aspirated engines**, an increase in altitude (or temperature) decreases performance

PURPOSE OF SUPERCHARGING

Purpose of Supercharging

- A supercharger artificially increases the density of the air by compressing it, forcing more air than normal into the cylinder every time the piston moves down

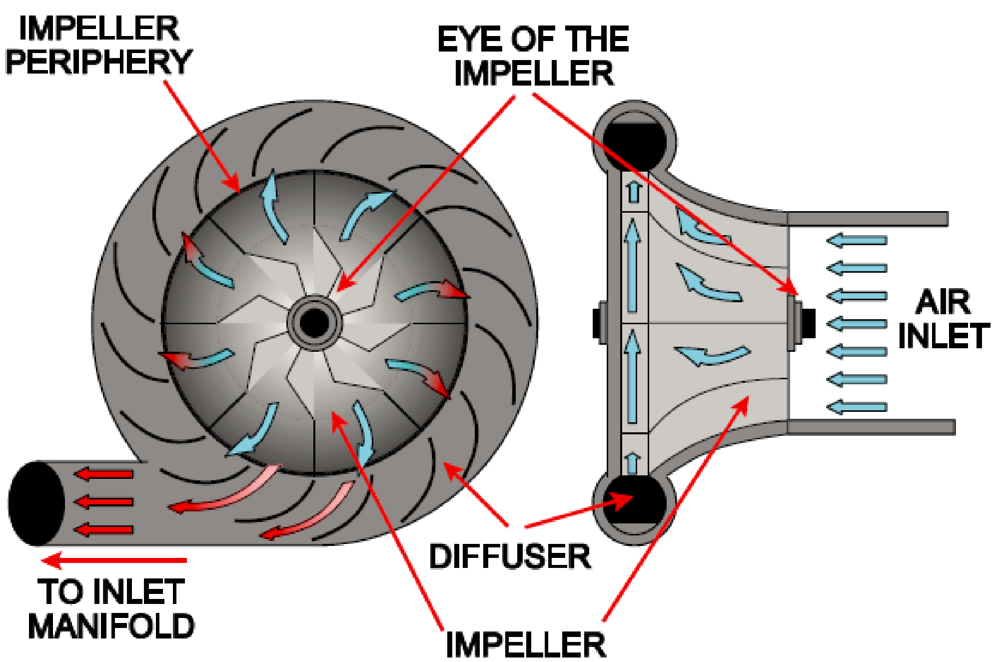
- Air will be compressed to sea-level-equivalent, or even much higher, in order to make the engine produce just as much power at cruise altitude as it does at sea level

- At high altitude, less dense air also means less drag

- So, with a supercharged engine still producing the same sea-level power, the aircraft can fly much faster at altitude than an aircraft at sea-level

Purpose of Supercharging

- Air is pumped into the inlet manifold via a compressor
- This allows power to be maintained while increasing altitude (**normalising**)



How it Works:

- Air enters at the centre of the **impeller**
- **Centrifugal force** accelerates the air outwards – an **increase in speed** means an increase in kinetic energy
- The air is then slowed by **diffuser vanes**, converting the increase in speed to an **increase in pressure**
- The **compressed air is more dense** and is then introduced to the cylinders through the induction process

Purpose of Supercharging

- As previously stated, superchargers can compress air at altitude to either:

1. The same as sea-level density

2. Higher than sea-level density

- Superchargers than maintain sea-level density up to high altitude are called **Altitude Boosted Superchargers**
- A control system is necessary to prevent overboosting at low altitude
- Superchargers that increase sea-level power rather than maintain normal power up to a high altitude are called **Ground Boosted Superchargers**
- The engine will need to be strengthened in order to resist the higher combustion pressure

COMMON METHODS OF SUPERCHARGING

Methods of Supercharging

- The centrifugal compressors used in superchargers may be:

1. Internally Driven

- Gear Driven

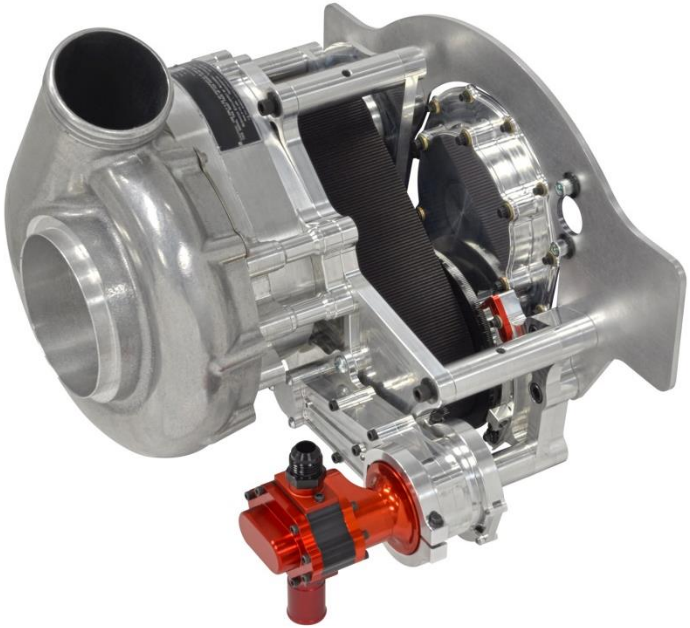
- Belt Driven

2. Externally Driven

- Exhaust Driven

- Also known as “turbosuperchargers” or simply “turbochargers”

Methods of Supercharging – Internally Driven



- The compressor is located between the carburettor and the inlet valve
- Therefore, it is actually the fuel/air mixture that passes through the compressor
- A system of gears or a belt connects the engine crankshaft to the impeller, allowing it to spin about 10 times faster than the speed of the engine
- This increases the manifold pressure and as such, usually the only aircraft fitted with superchargers are aircraft with a Manifold Pressure Gauge i.e. Variable Propeller Pitch & Constant Speed Unit

Methods of Supercharging – Internally Driven

- Some systems may also have a **boost pressure gauge**

- This measures the pressure in the induction system compared to the sea level standard pressure

- Boost pressure is usually expressed in pounds per square inch **(psi) above** or **below** standard sea level atmospheric pressure

- Standard Sea Level Atmospheric Pressure is equal to:

    1. 1013.25 hPa

    2. 29.92 ''Hg

    3. 14.7 psi

- This gauge reads 0 psi, indicating that the difference between the pressure in the induction system and the MSL standard pressure is 0 – the aircraft is on the ground

Methods of Supercharging – Externally Driven

- Compressor is located before the carburettor or FCU (usually used in fuel injected only)

- The problem with Internally Driven Superchargers is that the engine has to burn extra fuel to provide the power necessary to drive the compressor

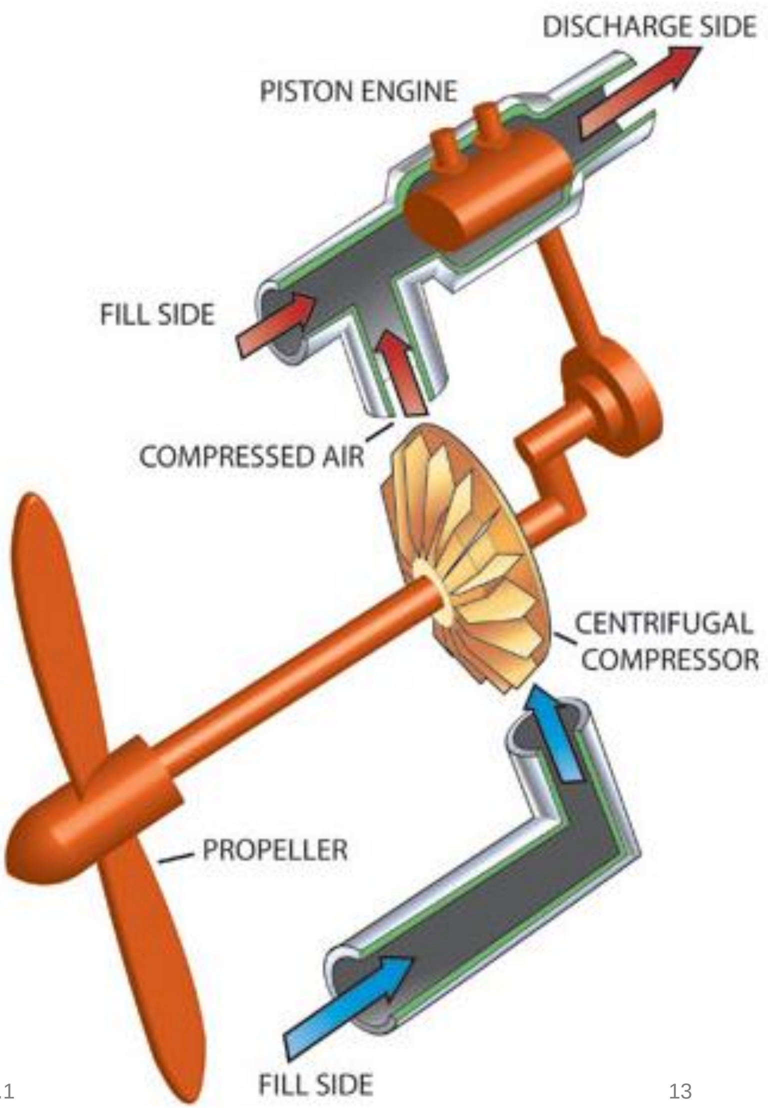
- For example, in a Rolls Royce Merlin supercharged engine (used commonly in WWII aircraft such as the Spitfire):

  - 750HP without supercharging

  - 1000HP with supercharging

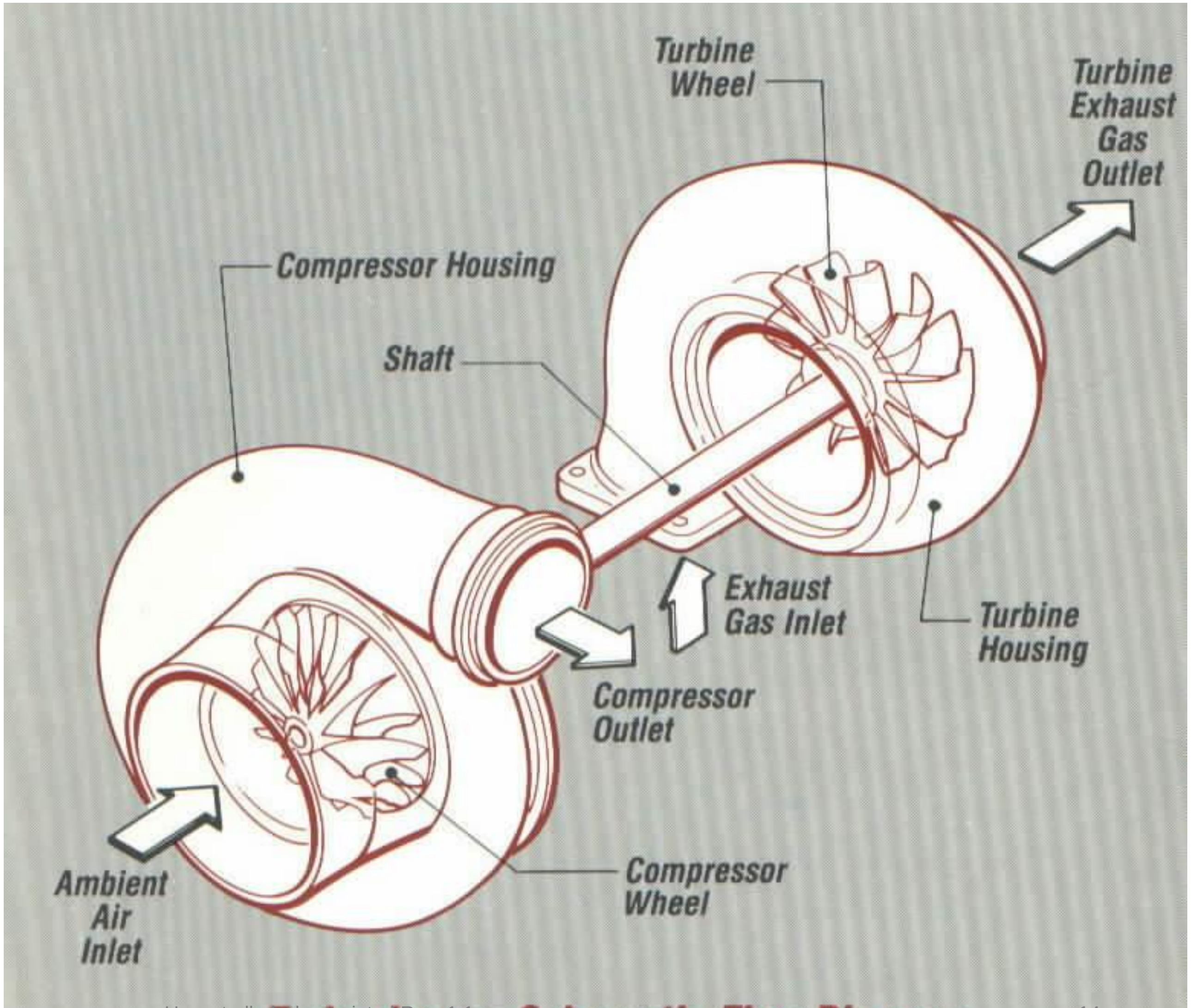
  - 150HP required to drive the supercharger

- Externally driven superchargers overcome this by using an alternative source to drive the compressor



Methods of Supercharging – Externally Driven

- This alternative source is the exhaust gas
- The exhaust gas drives a turbine which is linked to the compressor
- This is also known as a Turbocharger
- Usually located before the carburettor or FCU (so only air is compressed, not fuel/air mixture)



Turbocharger Schematic Flow Diagram

LIMITING SUPERCHARGING

Limiting Supercharging

- The amount of boost given by a supercharger is controlled by the throttle

- At sea-level, opening the throttle fully would cause:

1. **The crankshaft to spin the impeller too fast**

2. **This would create an excessively high pressure in the cylinders**

3. **This would result in overboosting and even detonation**

- Therefore, at sea-level, the throttle must be partially choked to restrict manifold pressure to a **rated boost**

Rated Boost – MAP Red Line

- Recommended MAP limitation for supercharged engine

- Highest possible MAP that the engine can handle – above this, detonation will occur

Limiting Supercharging

- So, when operating an aircraft with a supercharged engine at or near sea-level, the throttle must be partially choked – even during take-off
- During climb, the throttle valve must be progressively opened (either manually or automatically) to maintain a desired Manifold Pressure
- Eventually, a height is reached where, to maintain that desired Manifold Pressure, the throttle is fully open – this is **Full Throttle Height**
- The aircraft may climb above this height, but that particular Manifold Pressure will no longer be available
- The height at which **rated boost** is no longer available is known as the **Critical Altitude**

Limiting Supercharging

- Don’t get confused:

  1. The aircraft can continue climbing beyond the Critical Altitude

  2. Full Throttle Height is different for different Manifold Pressures, so the aircraft can also continue climbing beyond certain Full Throttle Heights

- So how high can an aircraft climb?

Service Ceiling

- Maximum useable altitude (14,000ft in the C172)

- The Density Altitude at which an aircraft flying clean at BRoC with all engines producing maximum continuous power will produce a rate of climb of 100fpm

Absolute Ceiling

- Highest altitude at which level flight can be sustained

- Maximum thrust available equals minimum thrust required (RoC would be 0fpm)

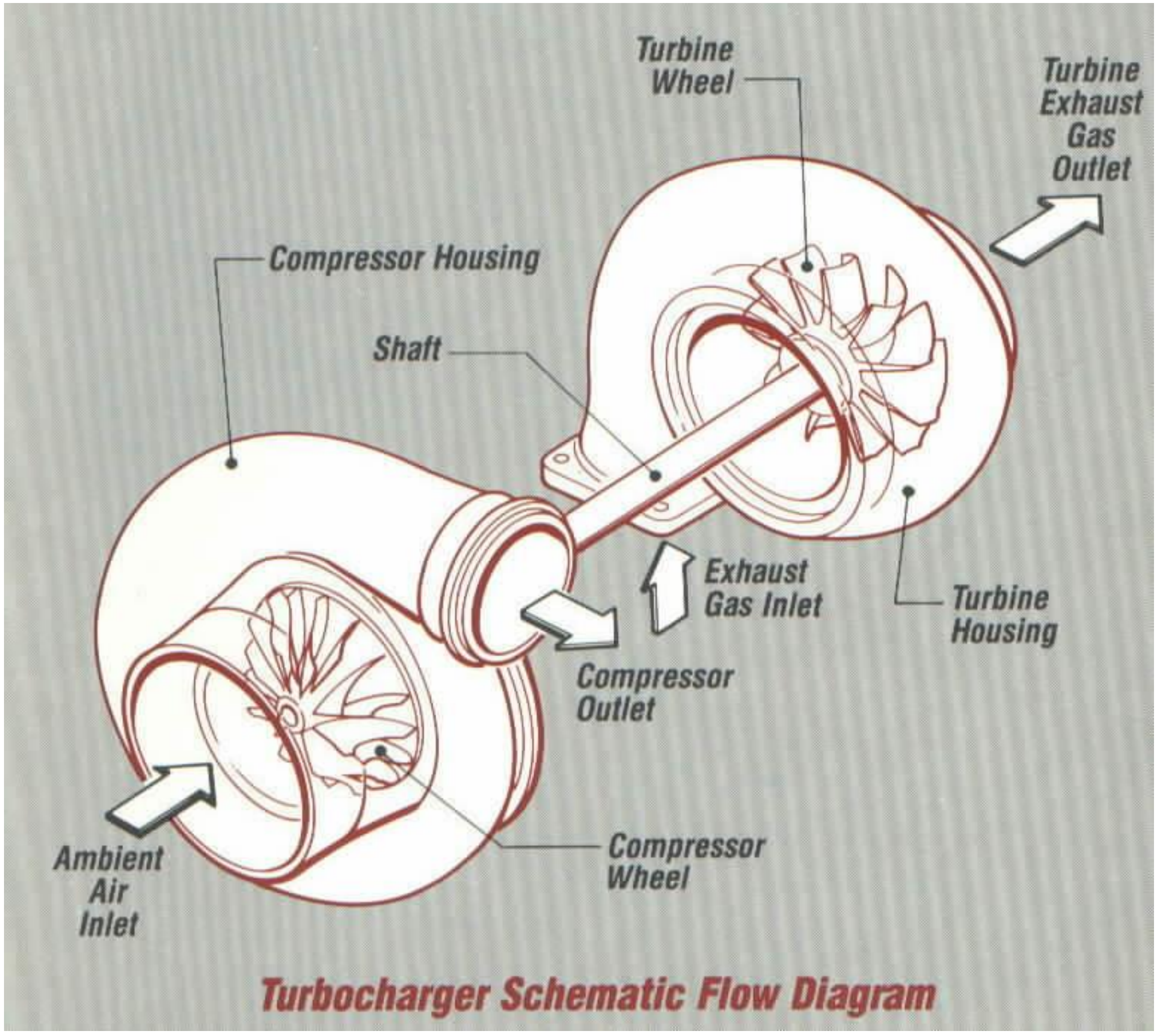
TURBOCHARGER SYSTEMS

Turbocharger Systems

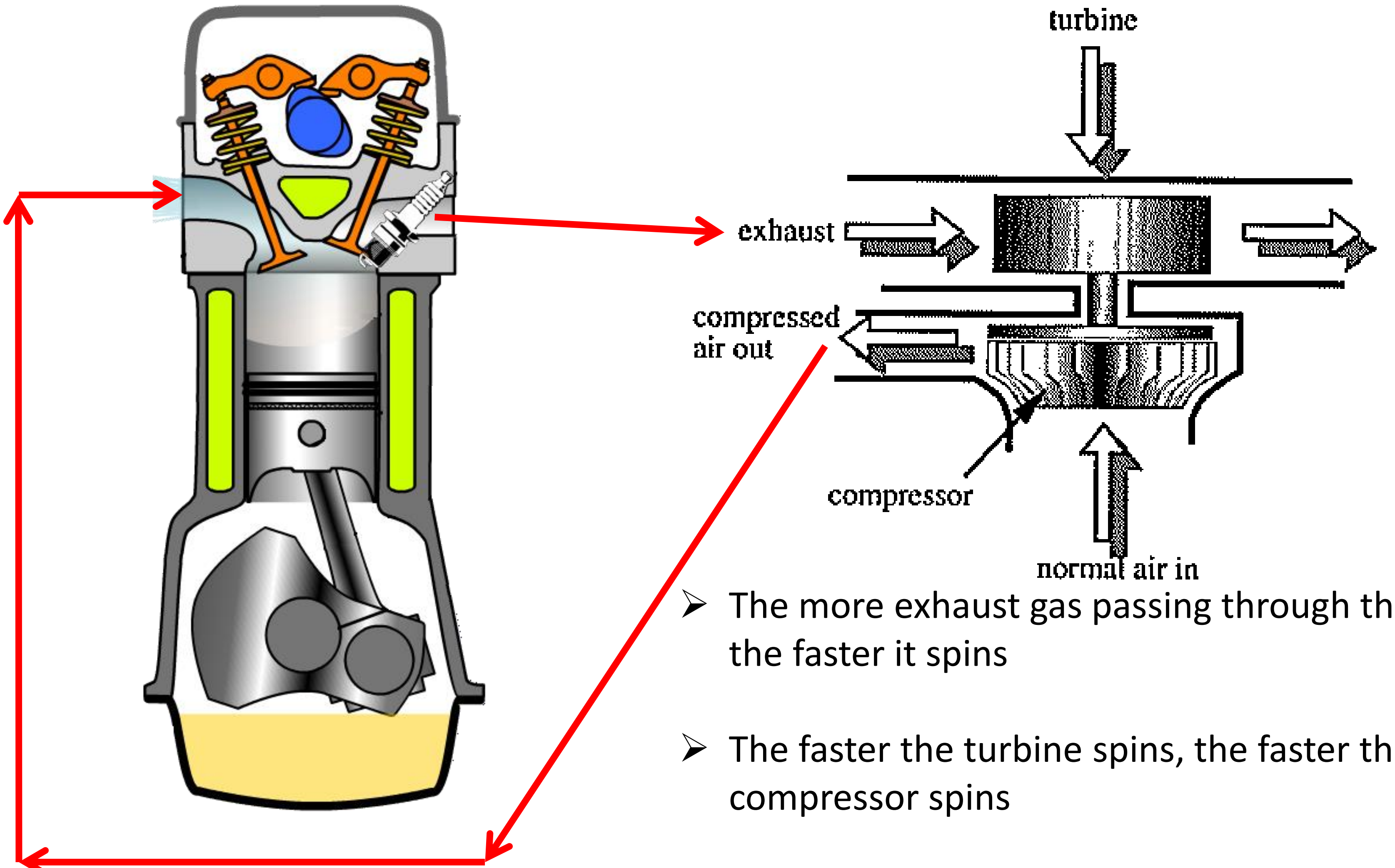
- Turbochargers are more efficient than superchargers as they utilise exhaust gas to power the compressor rather than engine power

- The basic function is:

1. The exhaust gas from combustion drives a turbine
2. This turbine is linked to the compressor
3. The compressor increases the density of air entering the cylinders



Turbocharger Systems

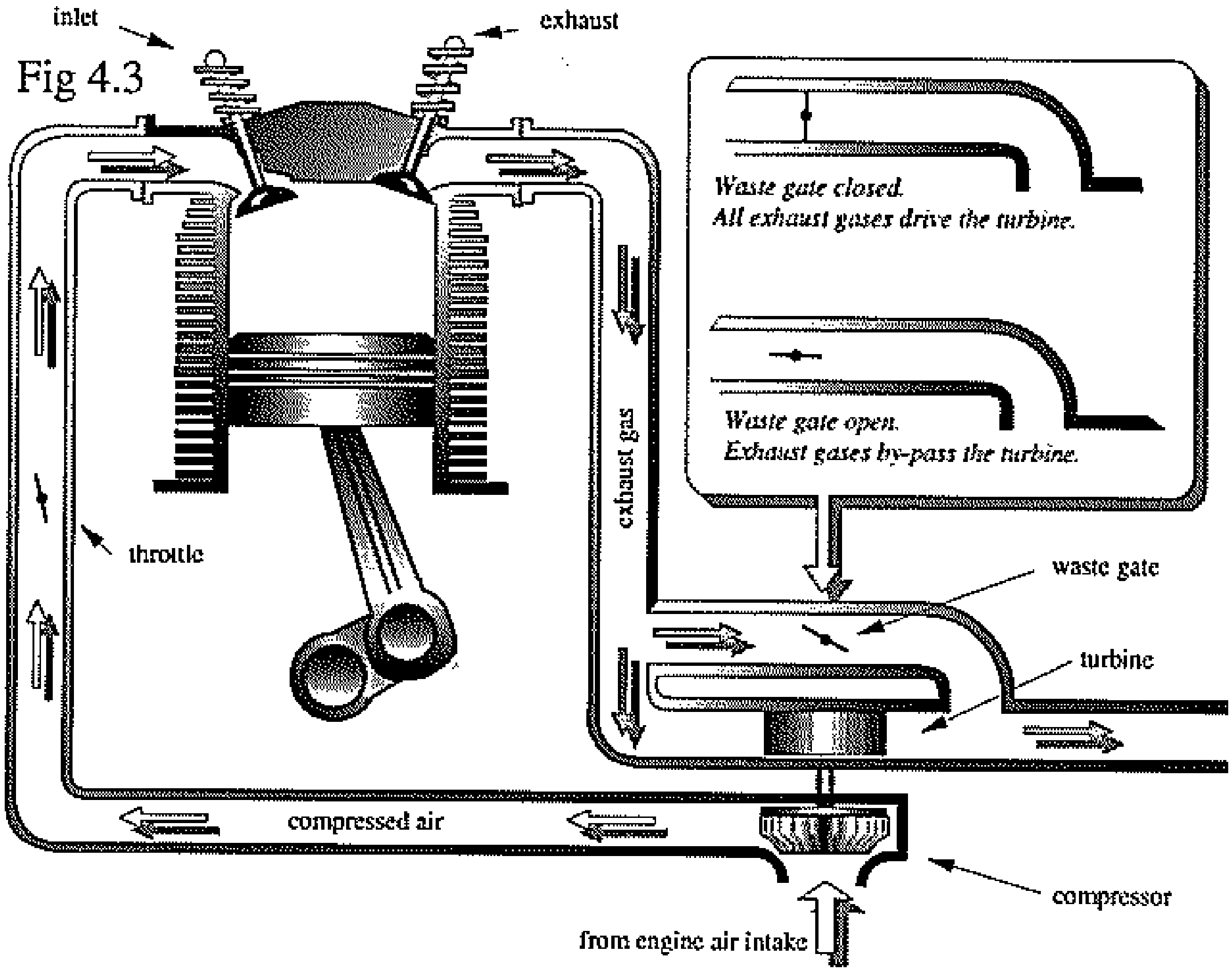


- The more exhaust gas passing through the turbine, the faster it spins
- The faster the turbine spins, the faster the compressor spins
- The faster the compressor spins, the greater the compression of air entering the engine

Turbocharger Systems

- The amount of exhaust gas passing through the turbine is controlled by a **waste gate**
- If the waste gate is open, exhaust gas will bypass the turbine and exit the system through the exhaust port
- If the waste gate is closed, the exhaust gas will drive the turbine

Fig 4.3



Turbocharger Systems – Waste Gate Control

- There are several different methods of waste gate control:

  1. **Fixed Waste Gate**
  2. **Cockpit Adjustable Waste Gate (Manual)**
  3. **Throttle Operated Waste Gate**
  4. **Automatic Waste Gate**

- For methods 2-4:

  1. **A spring force opens the waste gate**
  2. **Oil pressure from the engine is used to close the waste gate**

Turbocharger Systems – Waste Gate Control

Fixed Waste Gate

- The waste gate is fixed in a pre-selected position by an engineer on the ground
- It cannot be adjusted (opened or closed) by the pilot in flight
- A fixed amount of exhaust gas is always directed to the turbine
- This means that overboosting is likely if the throttle is opened too far at low altitudes

Cockpit Adjustable Waste Gate (Manual)

- A separate control is provided in the cockpit for adjusting the waste gate position
- The waste gate will initially be left open during start, taxi and climb
- Once the required MAP can no longer be maintained at full throttle, the pilot will use the control to progressively close the waste gate

Turbocharger Systems – Waste Gate Control

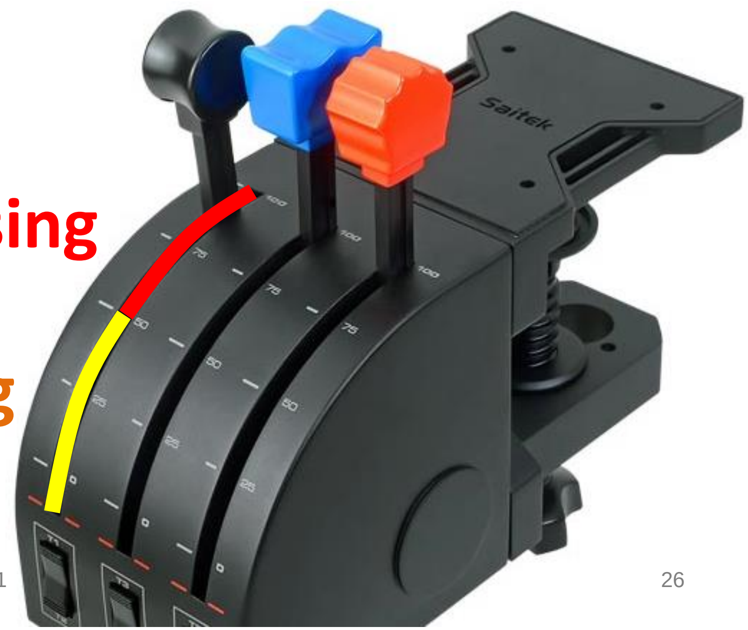
Turbocharger Systems – Waste Gate Control

Throttle Operated Waste Gate

- The first portion of throttle advance from idle opens the throttle butterfly and leaves the waste gate fully open

- Once the throttle butterfly reaches the fully open position, any further advance in throttle position begins to close the waste gate and power the turbine

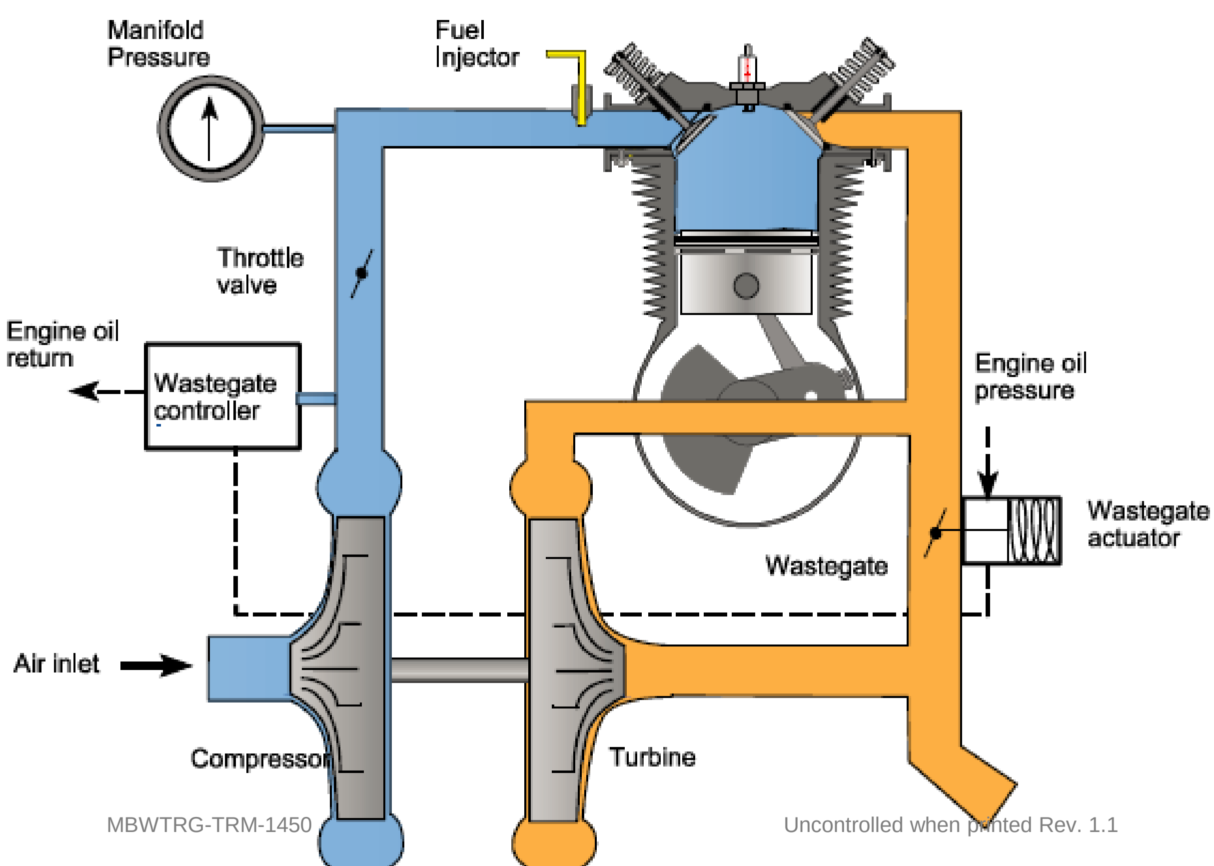
- Care must be taken not to push the throttle all the way forwards on take-off like you would for a normally aspirated engine – this will overboost!



Turbocharger Systems – Waste Gate Control

Automatic Waste Gate

- **Air density controllers (used at full throttle settings)** and **differential pressure controllers (used at settings other than full throttle)** monitor the system and adjust the waste gate to achieve and maintain a desired MAP



- The controller shown here is a **density controller**
- When the “upper deck pressure” (MAP) drops, the diaphragm expands, preventing engine oil from returning to the sump
- This oil instead is directed to a piston – the waste gate actuator
- The piston closes the waste gate

TROUBLESHOOTING TURBOCHARGER PROBLEMS

Bootstrapping

- **Bootstrapping** is an unstable condition that occurs with turbochargers fitted with automatic waste gate control
- Any change in temperature inside the system or even an RPM fluctuation will cause a slight change in power
- This will be noticeable as a changing pressure on the MAP gauge
- This change in power will alter the position of the waste gate through the automatic controller – once again changing pressure on the MAP gauge
- The result is bootstrapping – **a drifting MAP** without any throttle movement
- This can be reduced by the fitting of **additional density controllers**
- These additional controllers contain capsules fitted with **dry nitrogen,** which are capable of sensing any small temperature deviation and adjusting the system to maintain the desired MAP

Leak in the Induction System

- If a leak occurred in the induction system in-flight, the result would depend on the type of waste gate:

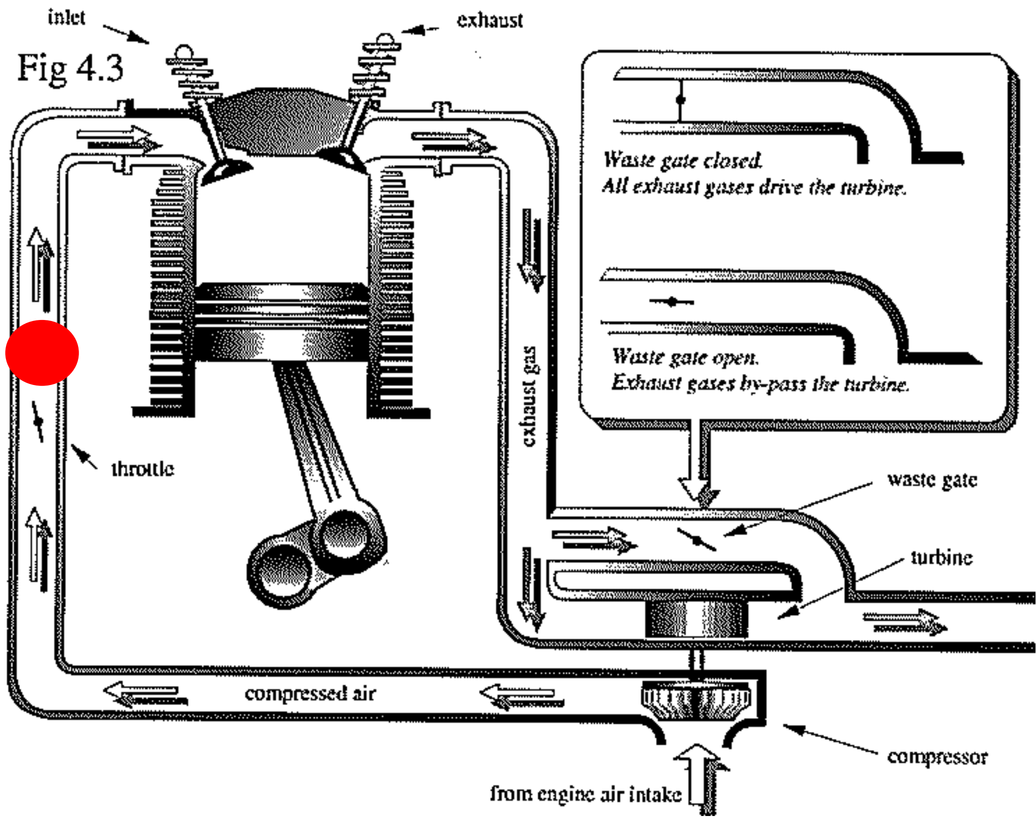
Cockpit/Throttle Operated:

- Pilot would notice a reducing MAP

- Waste gate would have to be closed more than normal to maintain MAP

Automatic:

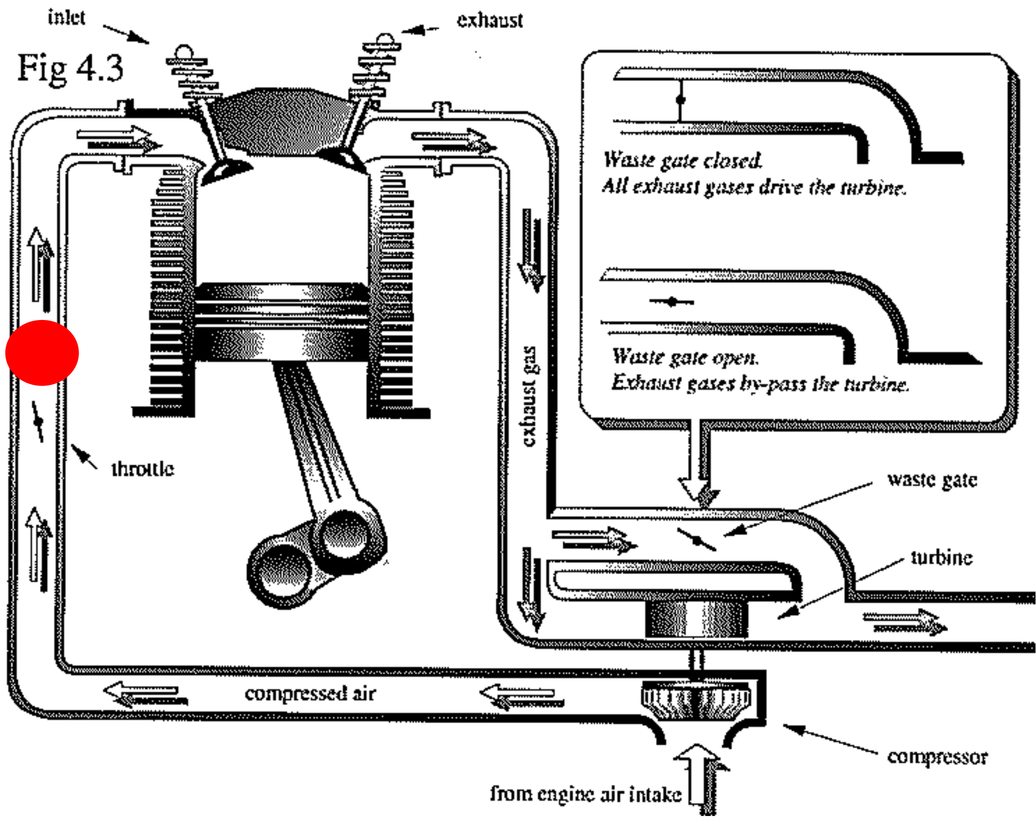
- The waste gate would automatically close to keep the upper deck pressure (MAP) at the required level



- The pilot would not be aware that the leak is occurring as there is no indication in the cockpit for an automatic waste gate

Leak in the Induction System

- If a leak occurred in the induction system but this time on the ground, the MAP may actually be **higher than normal**



- If the engine is idling on the ground, the MAP should be just below the ambient pressure as the movement of the pistons creates suction inside the cylinders

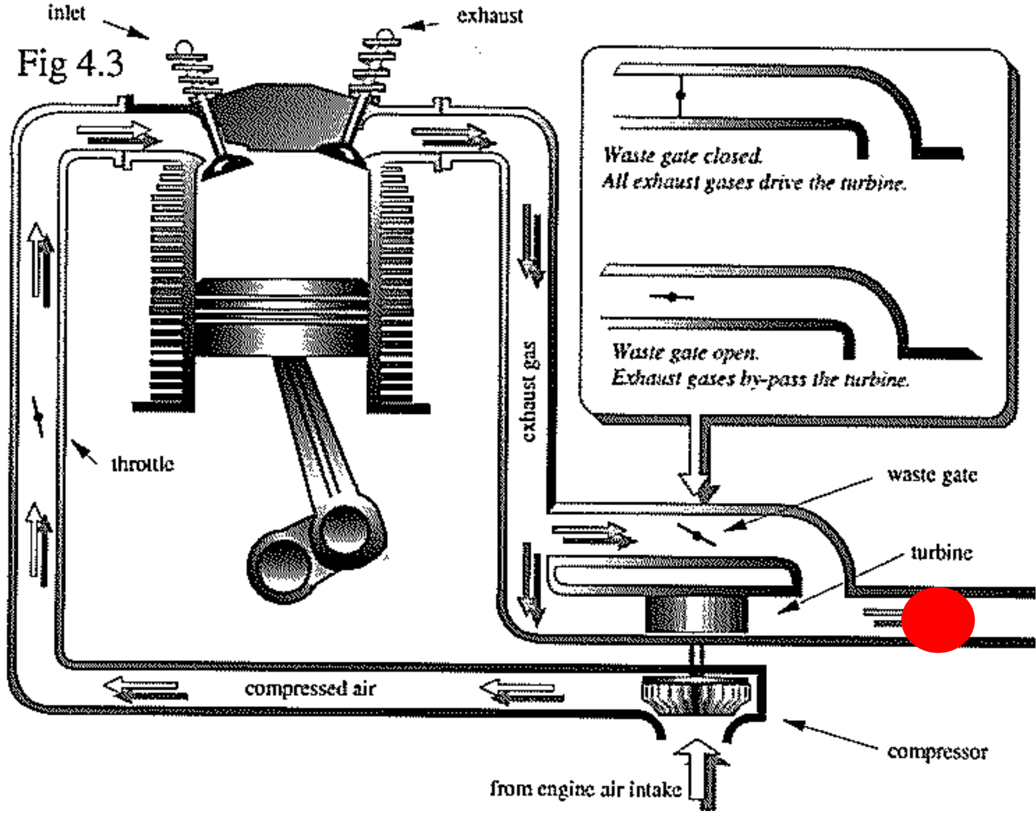
- A leak would cause a greater flow of ambient air **into** the system, therefore increasing the MAP

- Note that because more air is now flowing into the induction system, the mixture has become more lean

- This could possibly cause misfiring once the power is increased for taxi/take-off

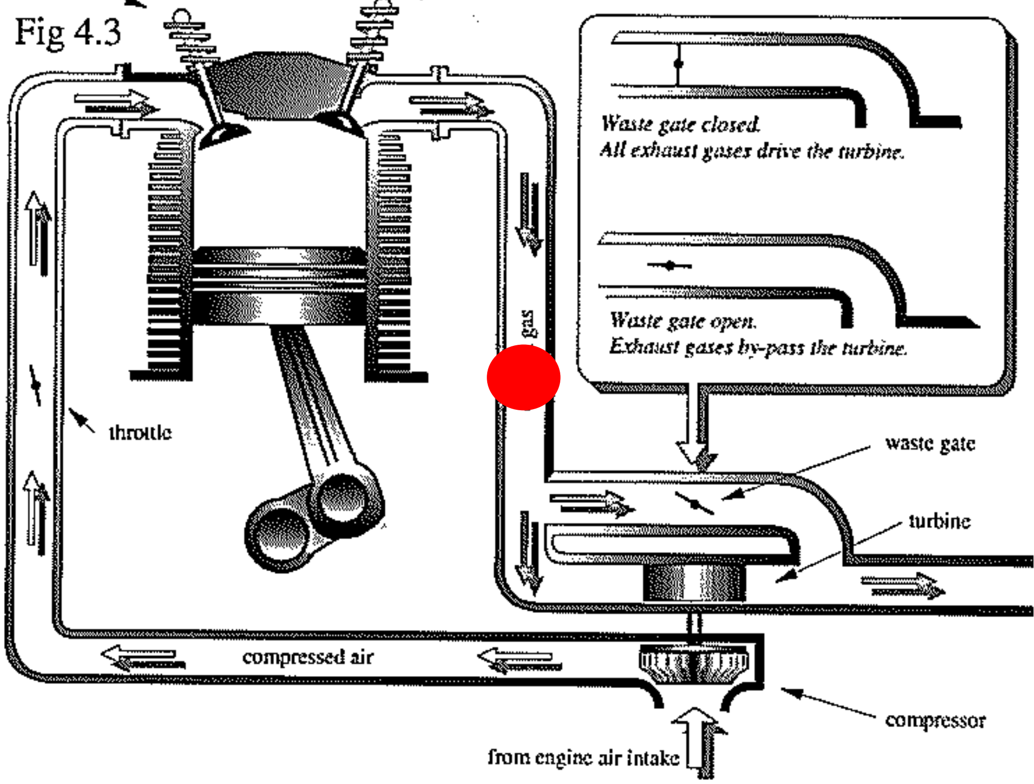
Leak in the Exhaust System: Downstream of Waste Gate

- If the leak is downstream of the waste gate, then exhaust gas will still be capable of reaching the turbine
- Therefore, the leak will have no effect on engine performance
- However, the leak may cause exhaust gas to spill into the engine cowling
- This would increase the risk of engine fire



Leak in the Exhaust System: Upstream of Waste Gate

- If the leak is upstream of the waste gate, then not as much exhaust gas will reach the turbine
- This will reduce engine performance in much the same way as a leak in the induction system
- The engine will simply behave like a normally aspirated engine
- Note that once again, exhaust gas may be leaking into the engine bay and pose a risk of fire



Turbine Damage

- The turbine is located in a very hostile environment
- It is subject to hot exhaust as high as 800° - 900° C
- The turbine also spins at high RPM – usually between 50,000 and 80,000 RPM
- The combination of high centrifugal forces and high temperatures can cause the blades of the turbine to **stretch** and deform
- If they stretch too far, they may scrape against the inside of the turbine housing, causing increased friction and even further heat
- Failure of the turbine would produce:

1. Significant power loss as the engine becomes normally aspirated
2. Smoke trailing from the engine as oil from the failed turbine is pumped into and burnt by the hot exhaust gas

Sticky Waste Gate

- In addition to the extremely high temperatures, the exhaust system also contains various bi-products of combustion, including:

    1. **Lead**
    2. **Carbon**
    3. **Sulphur**

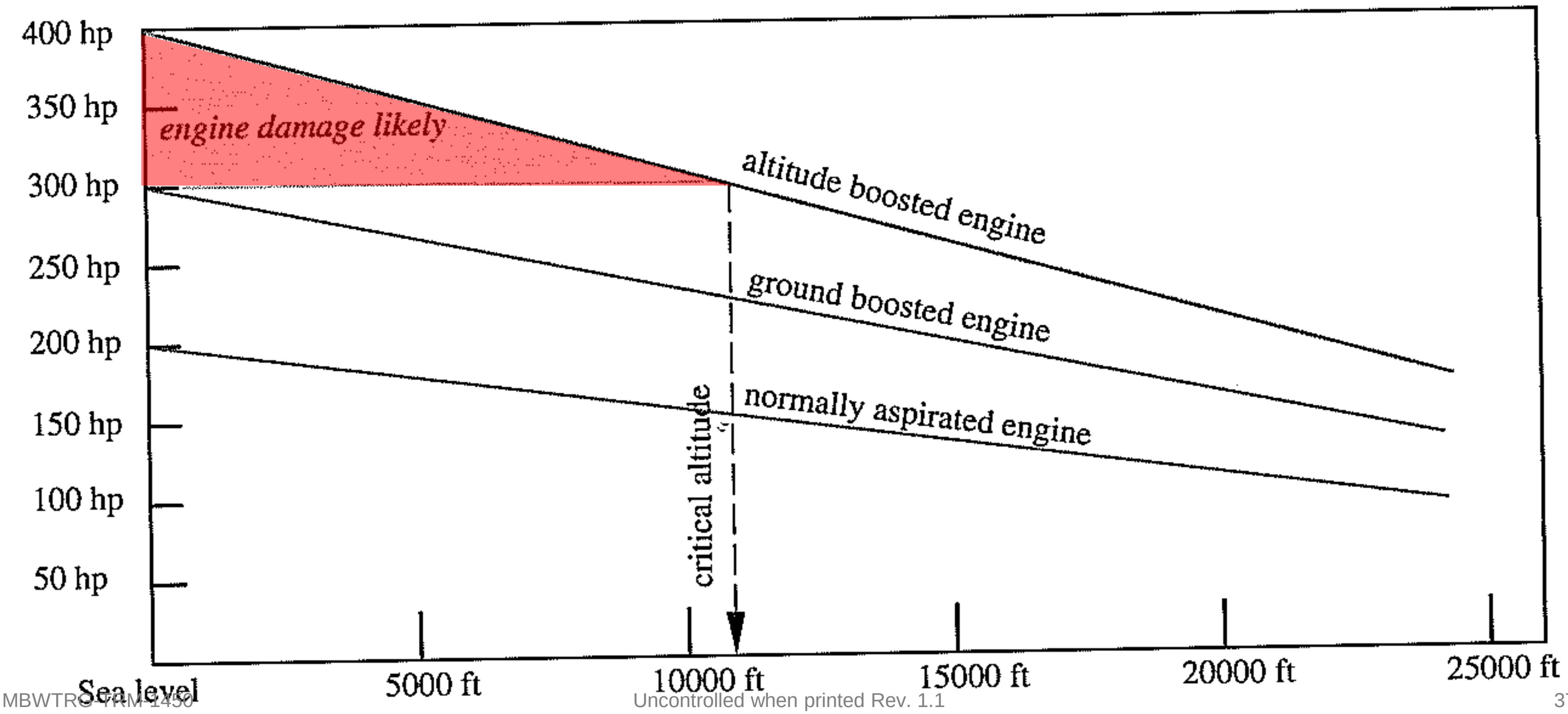
- These can cause the waste gate to “stick” i.e. it will not open and close smoothly
- The waste gate will now move in a jerky and erratic motion
- This will be seen in the cockpit on the **MAP Gauge as abnormal fluctuations**

PREVENTING ENGINE DAMAGE

Preventing Engine Damage

- Below we can see that ground boosting and altitude boosting using a super or turbocharger can increase engine horsepower

- However, remember that below the critical altitude, over boosting and detonation are possible if we do not operate the throttle partly closed



Preventing Engine Damage

Below are some pieces of advice to avoid damaging a turbo or supercharger engine:

Do not exceed rated boost

- Rated Boost is indicated by the red line on the MAP Gauge
- If this is exceeded, overboosting and detonation can occur
- Only use the recommended RPM and MAP combinations

Avoid sudden throttle movements

- The turbine and compressor are spinning at high RPM and any sudden change can cause excessive loads on engine components – particularly bearings

Avoid sudden shutdowns

- Before shutdown, the engine should be allowed to cool and stabilise at low RPM

Preventing Engine Damage

The turbo/supercharger system may also have specific design features incorporated:

Two-Speed Supercharger Drive Arrangement

- The supercharger uses a clutch mechanism or spring drive to separate the system into two speeds – high speed and low speed
- At low altitudes, low rotation of the impeller is used to prevent overboost
- At high altitudes, high speed rotation of the impeller can be tolerated

Intercooler

- An intercooler is placed before the cylinders
- This cools the air and **reduces risk of detonation**