# Introduction

Internal combustion engine design for the mass market is driven by two global issues: cost of fuel and emission controls

# Price of Crude Oil

Most motor vehicle fuels are derived from crude oil which is not a renewable commodity

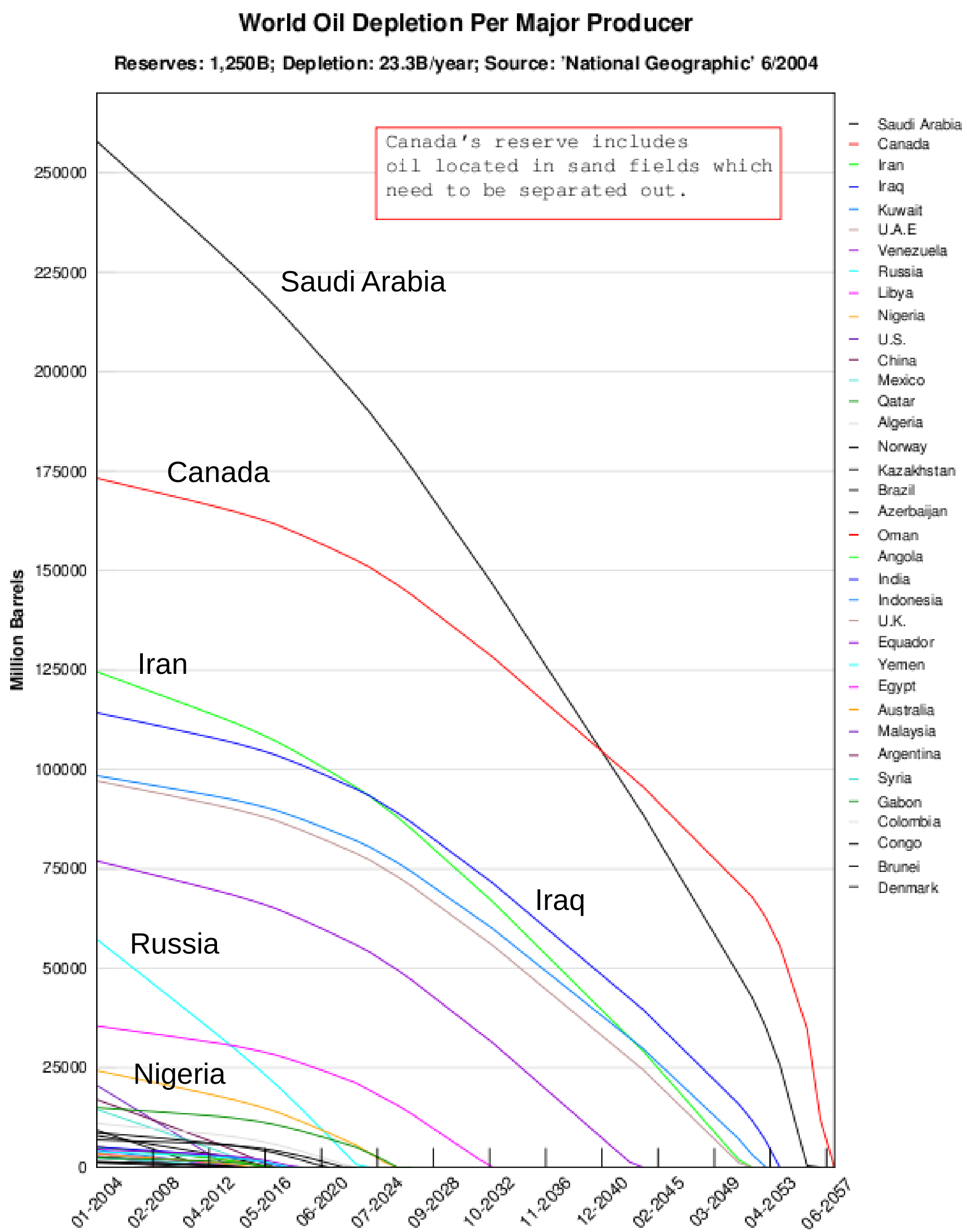
The cost of crude oil is driven by market supply and demand

**Supply** - Crude oil reserves limited to a few countries in the world, mainly the Middle East, Canada, Russia, Venezuela (U.S. ?)

Current oil reserves of roughly 1.25 trillion barrels are estimated to be depleted by 2050-2090 based on annual usage of 100 million barrels

The largest oil reserves are located in unstable countries where conflicts often affect oil production

**Demand** - expected to increase as emerging countries such as China (pop. 1.3 billion) and India (pop. 1.1 billion) prosper



World Oil Depletion Per Major Producer
Reserves: 1,250B; Depletion: 23.3B/year; Source: 'National Geographic' 6/2004
Canada's reserve includes oil located in sand fields which need to be separated out.
Million Barrels
250000
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
Saudi Arabia
Canada
Iran
Iraq
Russia
Nigeria
01-2004
02-2008
04-2012
05-2016
06-2020
07-2024
09-2028
10-2032
11-2036
12-2040
02-2045
03-2049
04-2053
06-2057
Saudi Arabia
Canada
Iran
Iraq
Kuwait
U.A.E
Venezuela
Russia
Libya
Nigeria
U.S.
China
Mexico
Qatar
Algeria
Norway
Kazakhstan
Brazil
Azerbaijan
Oman
Angola
India
Indonesia
U.K.
Equador
Yemen
Egypt
Australia
Malaysia
Argentina
Syria
Gabon
Colombia
Congo
Brunei
Denmark

# Environmental Concerns

Burning of fossil fuels in internal combustion engines produce harmful emissions that affect the health of living creatures on earth

In the developed countries the government regulates the level of harmful emissions from vehicles (UHC, NOx, SOx, CO, C)

Even the emission of chemically stable carbon dioxide (stuff we exhale) from vehicles contributes to global warming will shortly be regulated

There is a cost associated with meeting the vehicular emission standards which are becoming more and more stringent with time

## Internal Combustion Engine

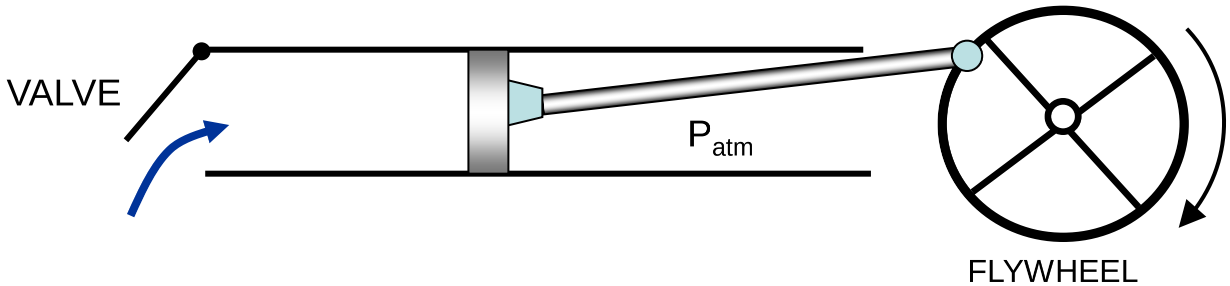
The internal combustion (IC) engine is a heat engine that converts chemical energy stored in a fuel into mechanical energy, usually made available on a rotating output shaft.

**History of IC engines:**

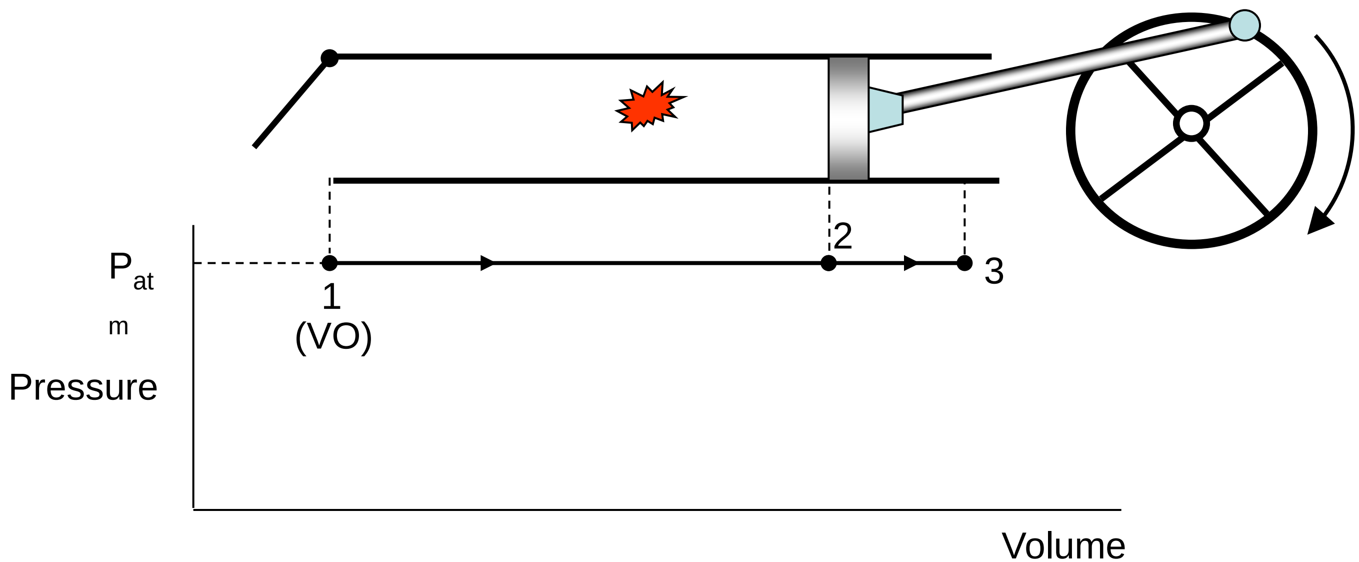
1700s - Steam engines (external combustion engines)
1860 - Lenoir engine ($\eta$ = 5%)
1867 - Otto-Langen engine ($\eta$ = 11%, 90 RPM max.)
1876 - Otto four-stroke "spark ignition" engine ($\eta$ = 14%, 160 RPM max.)
1880s - "Modern" two-stroke engine
1892 - Diesel four-stroke "compression ignition" engine
1957 - Wenkel "rotary" engine

# Atmospheric Engine

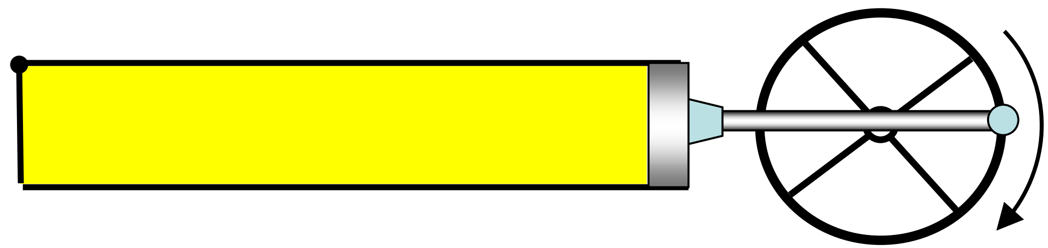
Process 1-2: Fuel air mixture introduced into cylinder at atmospheric pressure - valve open (VO)



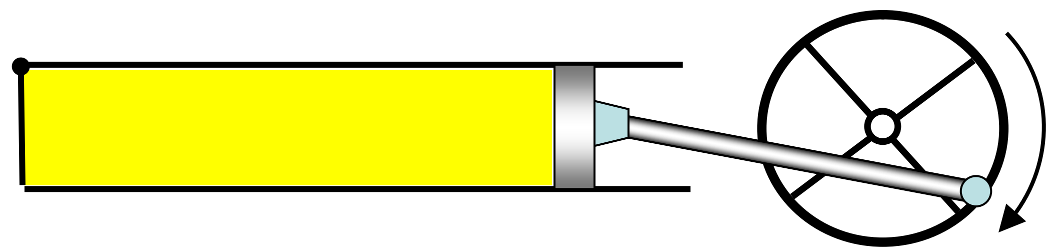

Process 2-3: Constant pressure combustion (cylinder open to atmosphere)



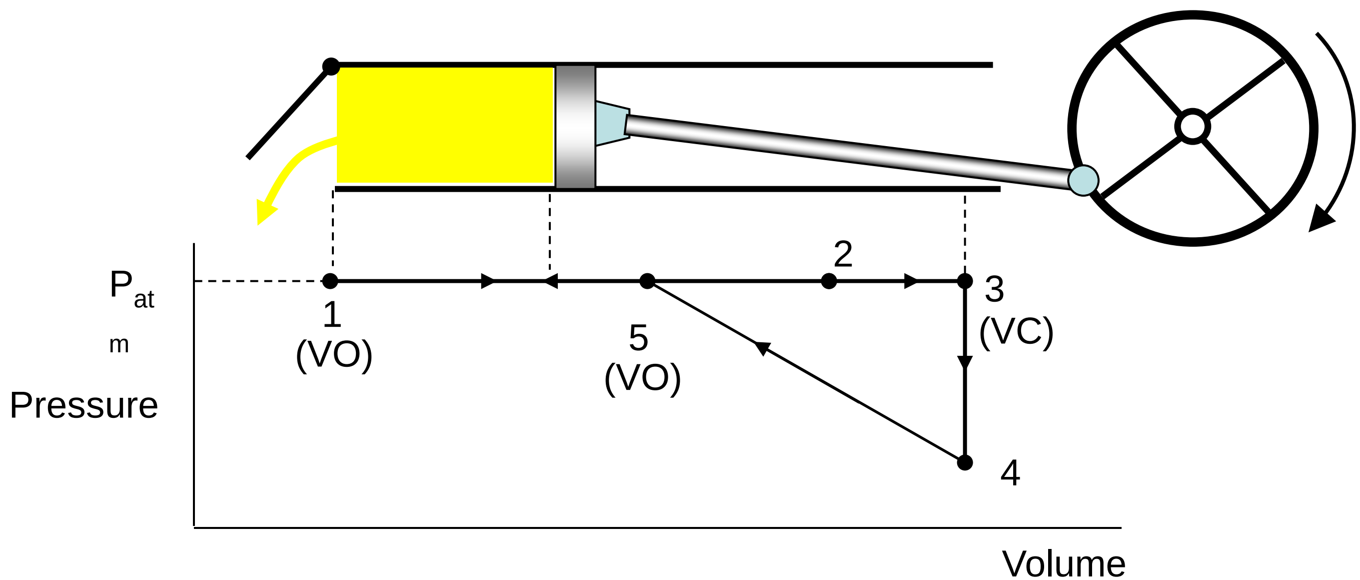
Process 3-4:  Constant volume cooling (produces vacuum)



Process 4-5:  Isentropic compression (atmosphere pushes piston)



Process 5-1:  Exhaust process



# Historical IC Engines

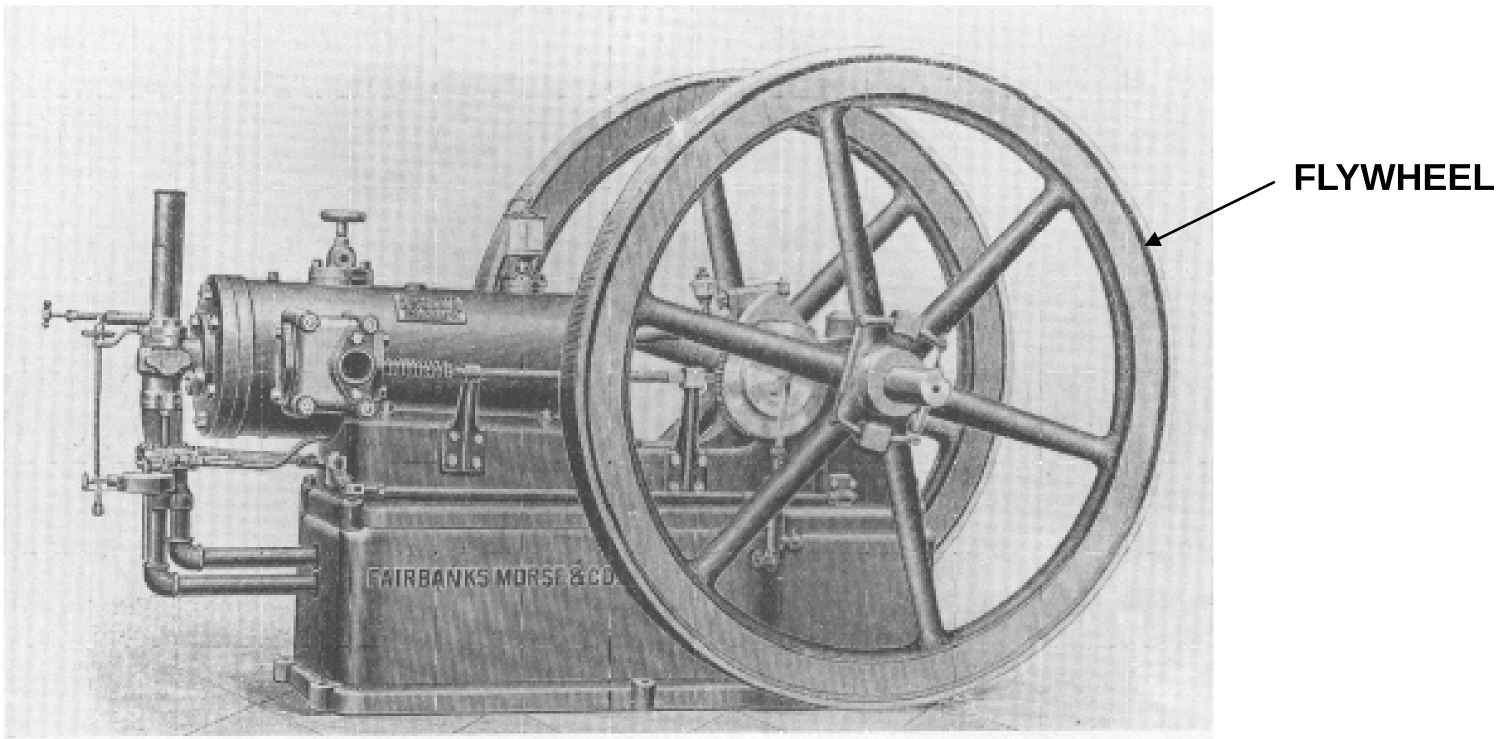
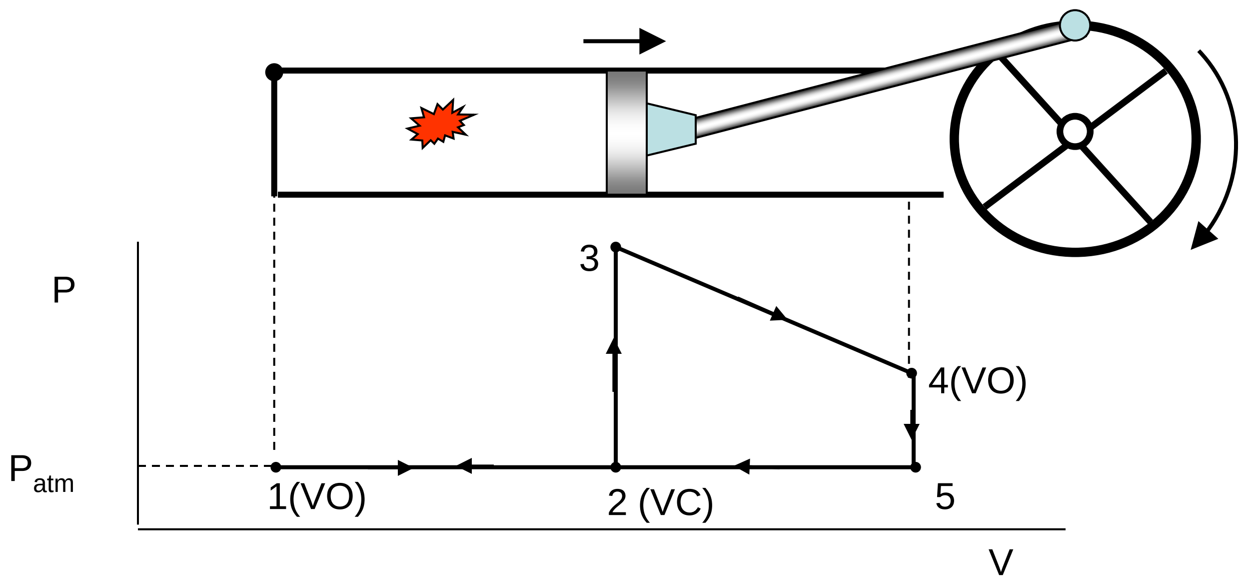



**Figure 1-1** The Charter Engine made in 1893 at the Beloit works of Fairbanks, Morse & Company was one of the first successful gasoline engine offered for sale in the United States. Printed with permission, Fairbanks Morse Engine Division, Coltec Industries.

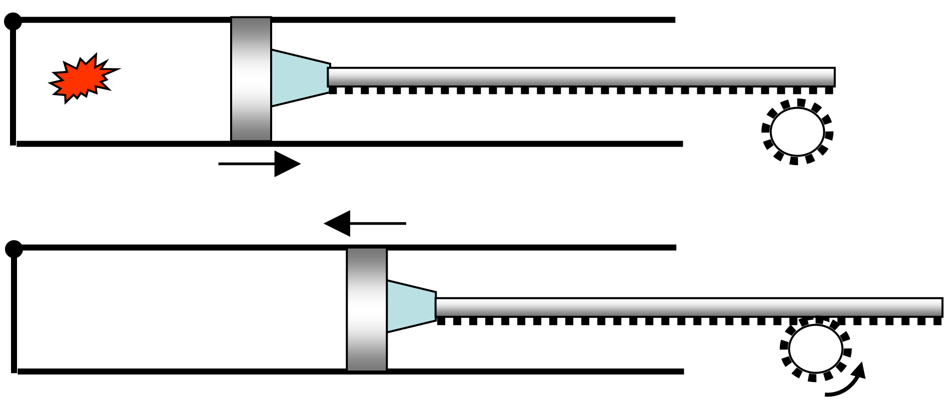
# Two-stroke Lenoir Engine

| | |
|---|---|
| Process 1-2: | Fuel air mixture introduced into cylinder at atmospheric pressure |
| Process 2-3: | At half-stroke valve closed and combustion initiated constant volume due to heavy piston producing high pressure products |
| Process 3-4: | Products expand producing work |
| Process 4-5: | At the end of the first stroke valve opens and blowdown occurs |
| Process 5-1: | Exhaust stroke |



# Two-stroke Otto-Langen Engine

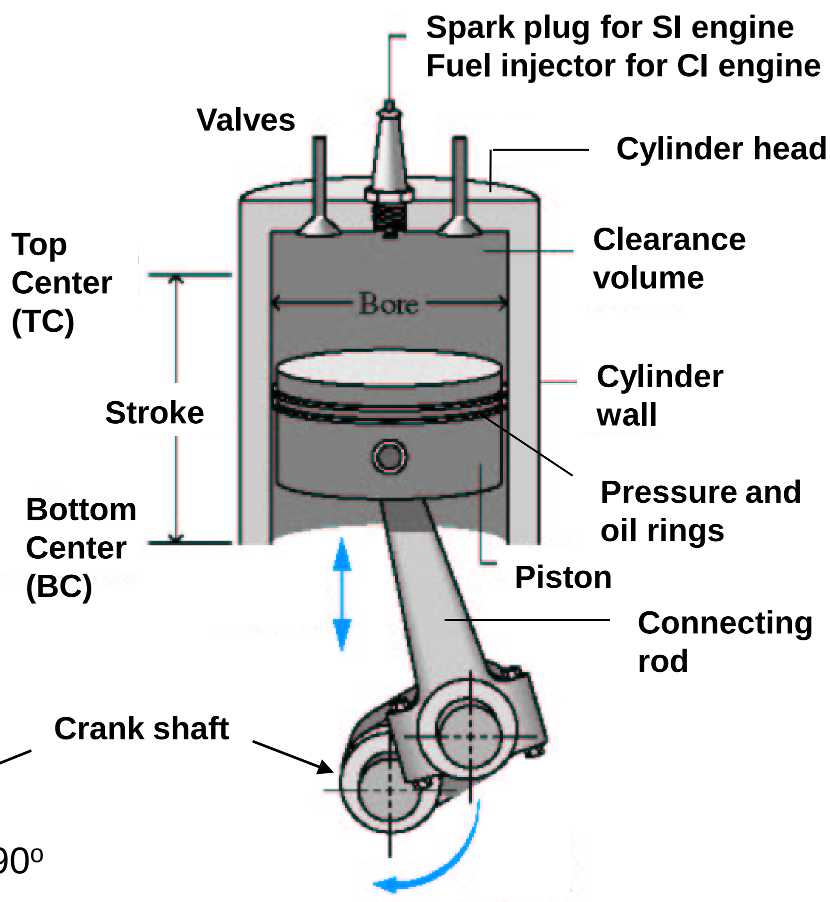
| | |
|---|---|
| Process 1-2: | Fuel air mixture introduced into cylinder at atmospheric pressure |
| Process 2-3: | Early in the stroke valve closed and combustion initiated constant volume due to heavy piston producing high pressure products |
| Process 3-4: | Products expand accelerating a free piston momentum generates a vacuum in the tube |
| Process 4-5: | Atmospheric pressure pushes piston back, piston rack engaged through clutch to output shaft |
| Process 5-1: | Valve opens gas exhausted |

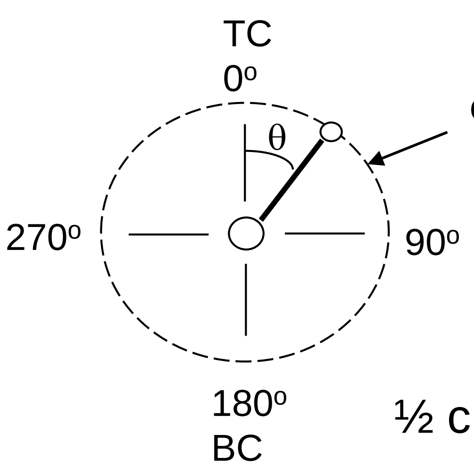


# Modern Engine Components

$$\text{time} = \frac{\text{crank angles(CA)}}{\text{crank speed}}$$

$$= CA \cdot \frac{s}{rev} \cdot \frac{1\,rev}{360\,CA}$$

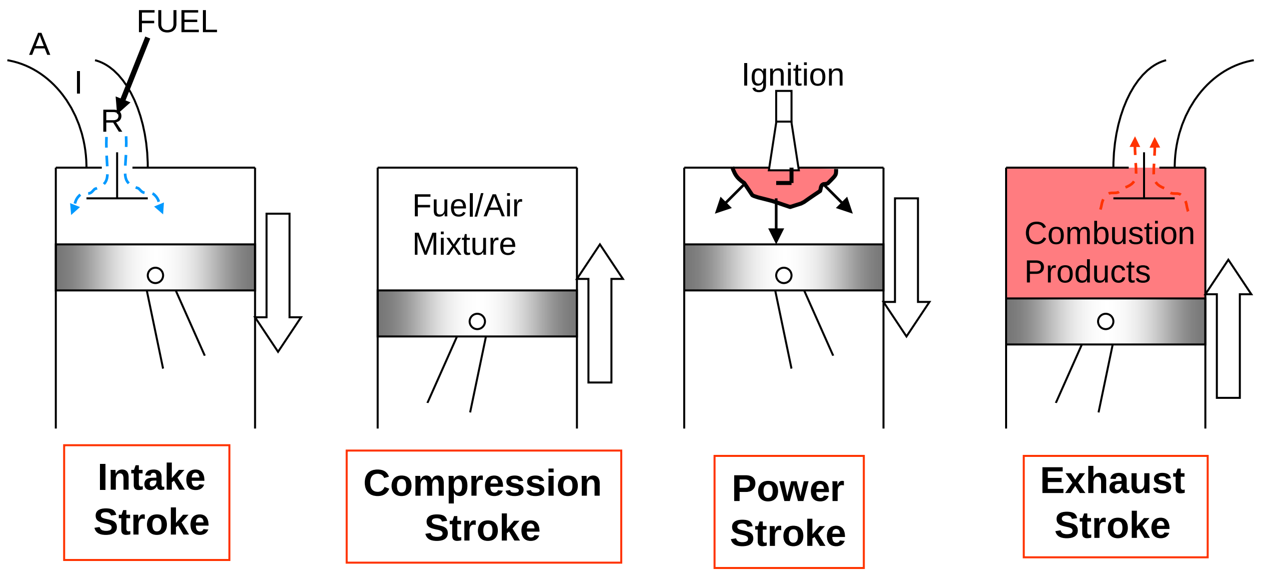



½ crank rotation = 1 piston stroke

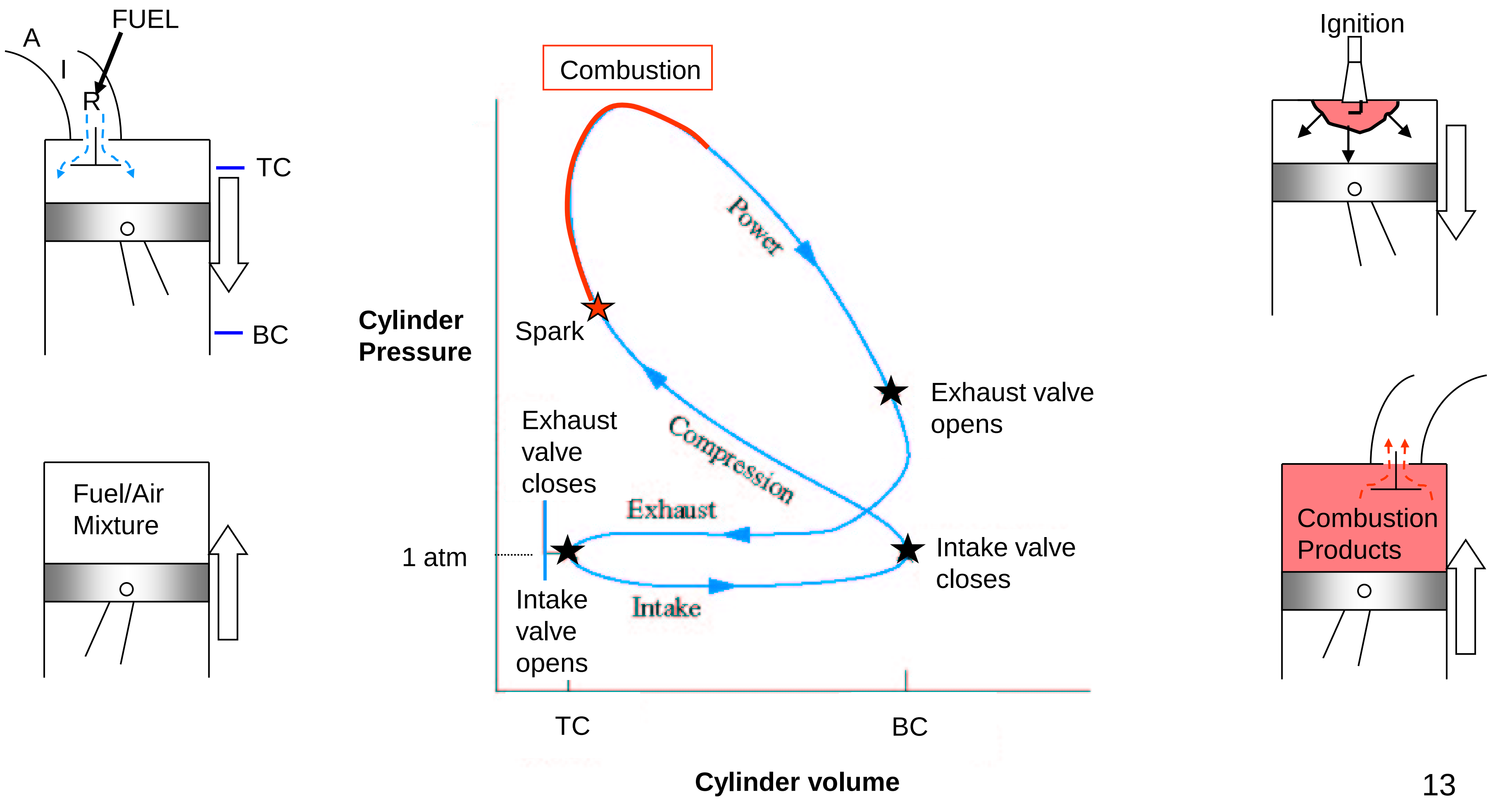
# Four-stroke Spark Ignition (SI) Engine

| | |
|---|---|
| Stroke 1: | Fuel-air mixture introduced into cylinder through intake valve |
| Stroke 2: | Fuel-air mixture compressed |
| Stroke 3: | Combustion (roughly constant volume) occurs and product gases expand doing work |
| Stroke 4: | Product gases pushed out of the cylinder through the exhaust valve |

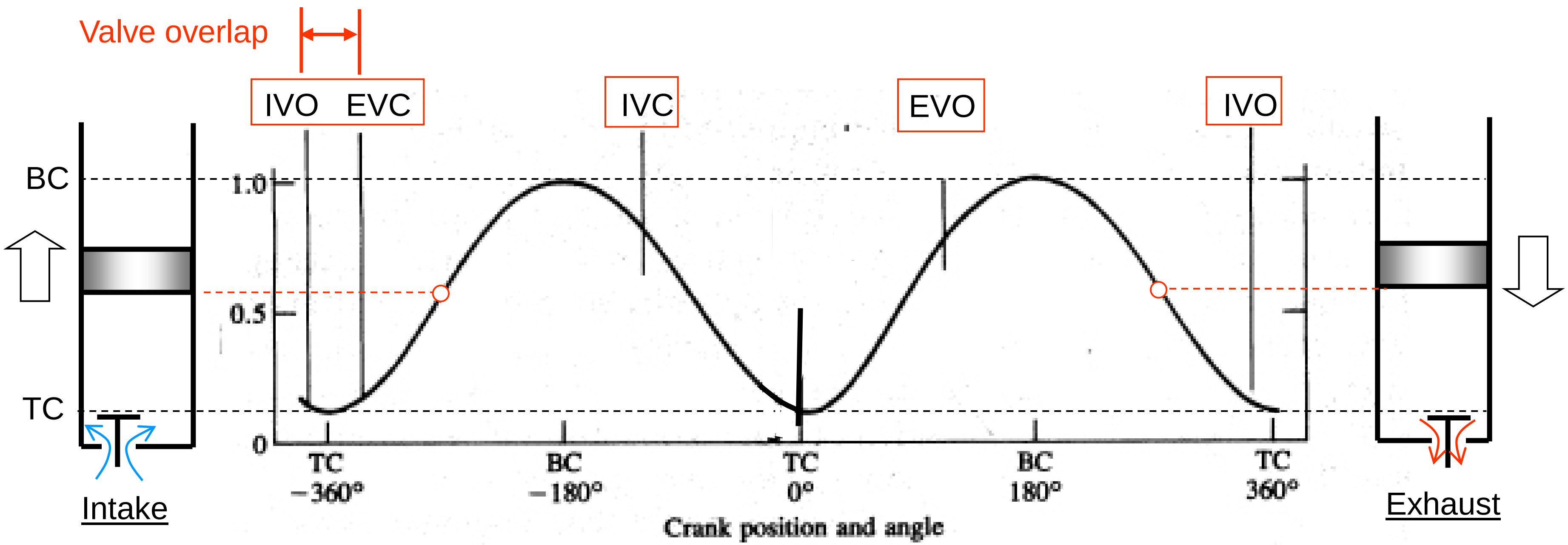


# Pressure-Volume Graph 4-stroke SI engine

One power stroke for every two crank shaft revolutions

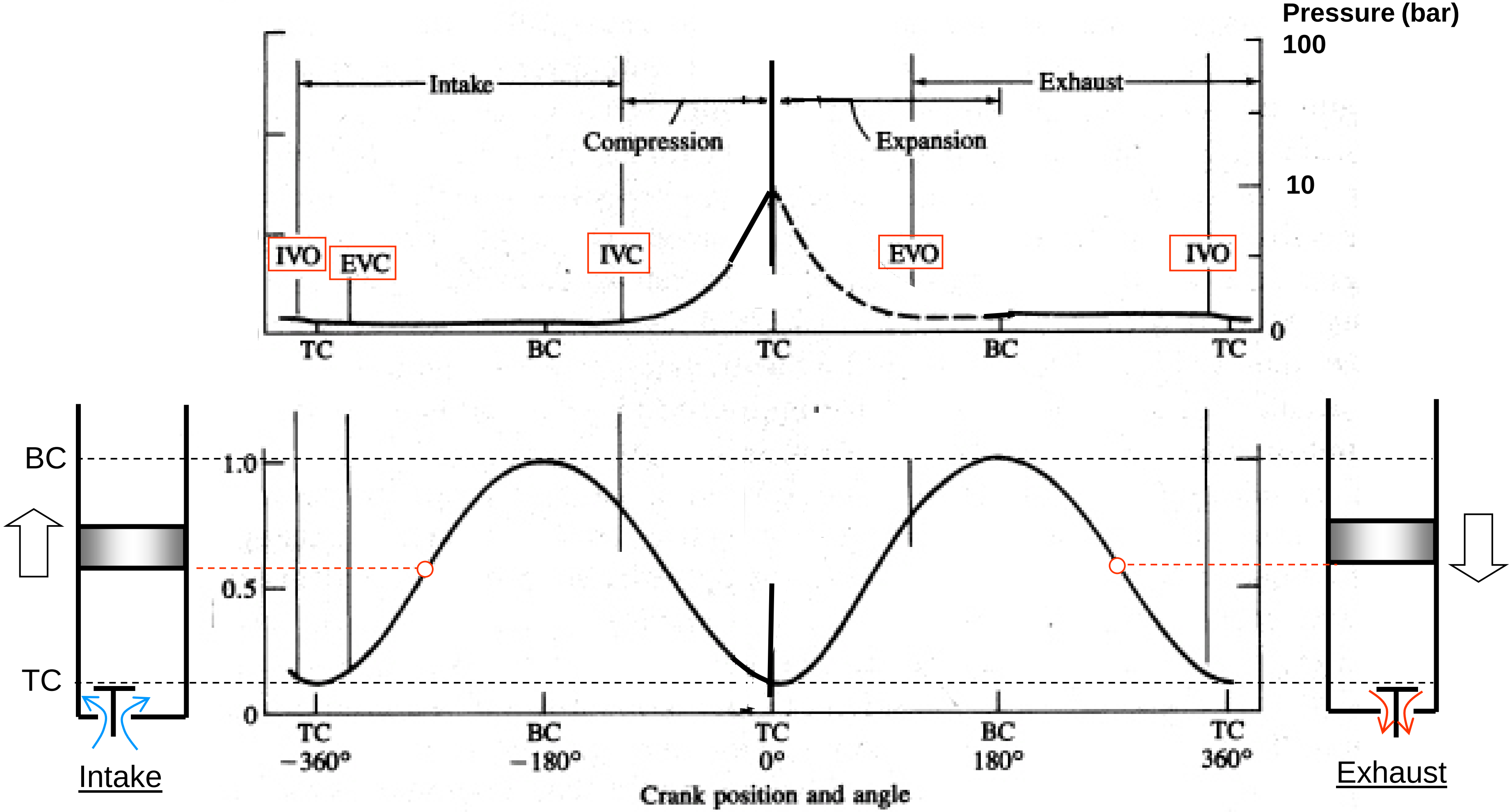


# Four-stroke engine valve timing




IVO - intake valve opens, IVC – intake valve closes
EVO – exhaust valve opens, EVC – exhaust valve opens

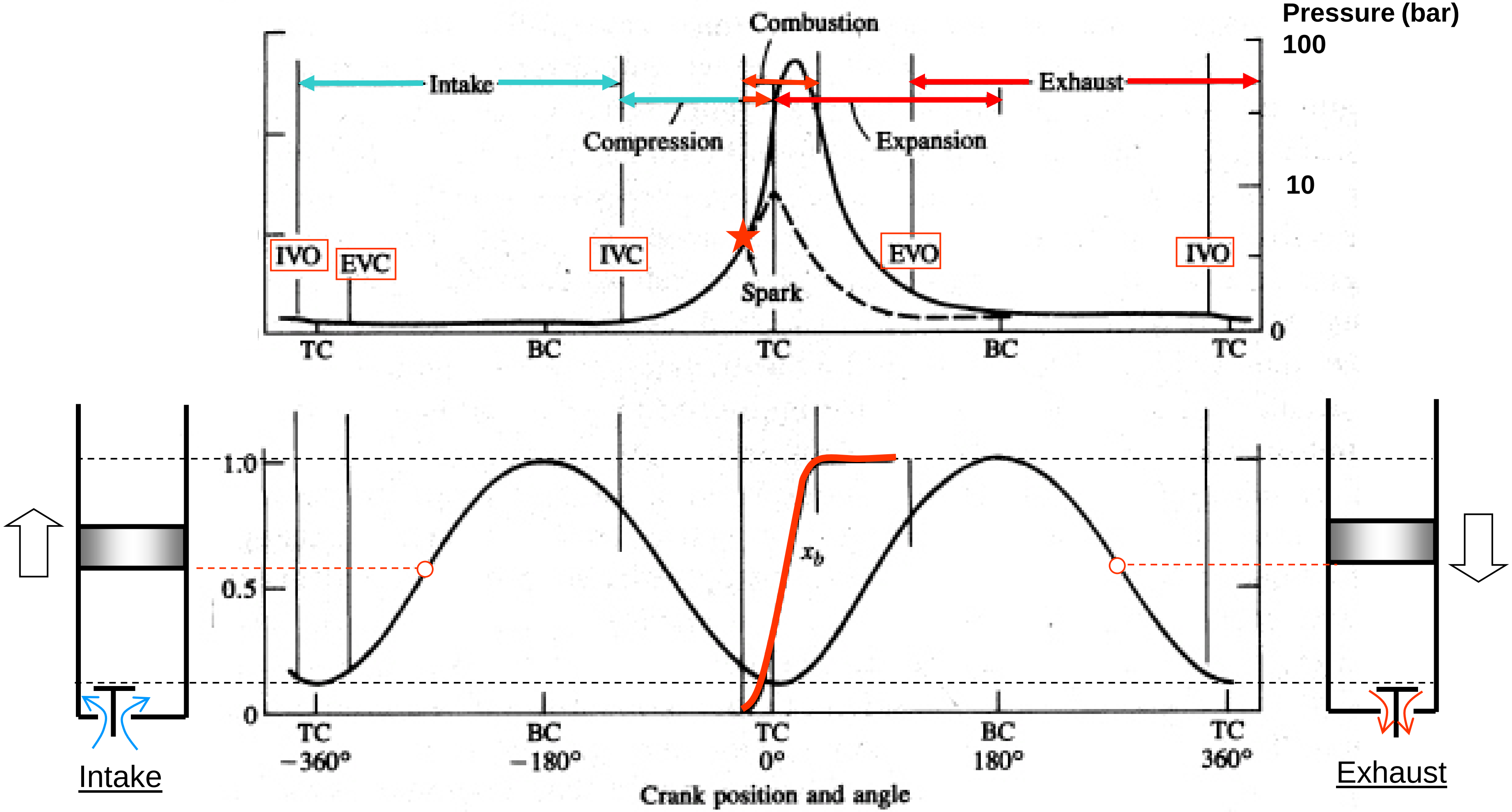
## Cylinder pressure for motored four-stroke engine




IVO - intake valve opens, IVC – intake valve closes

EVO – exhaust valve opens, EVC – exhaust valve opens

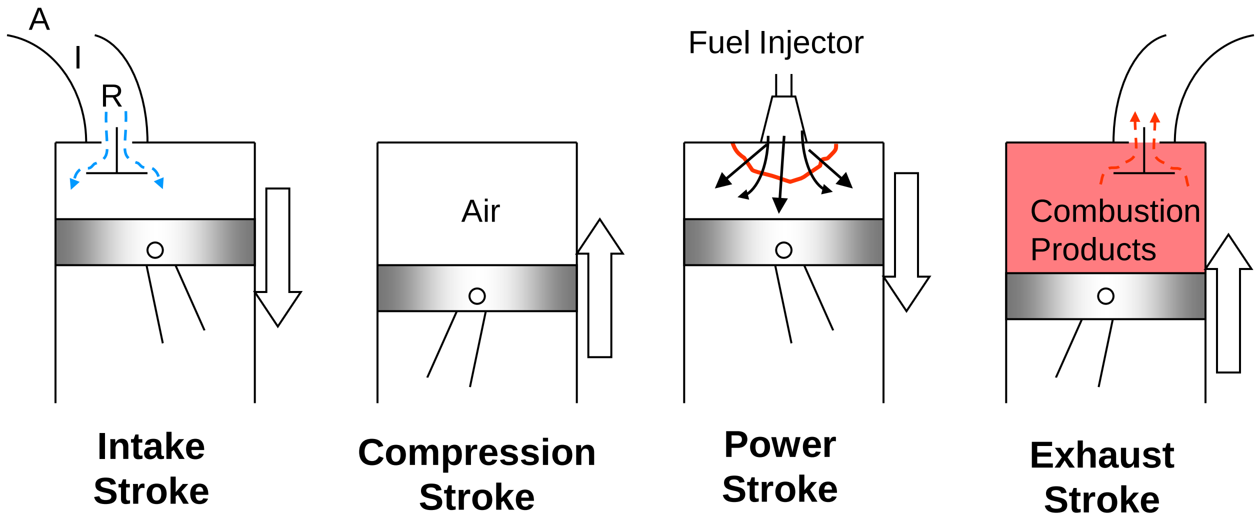
# Four-Stroke SI Engine



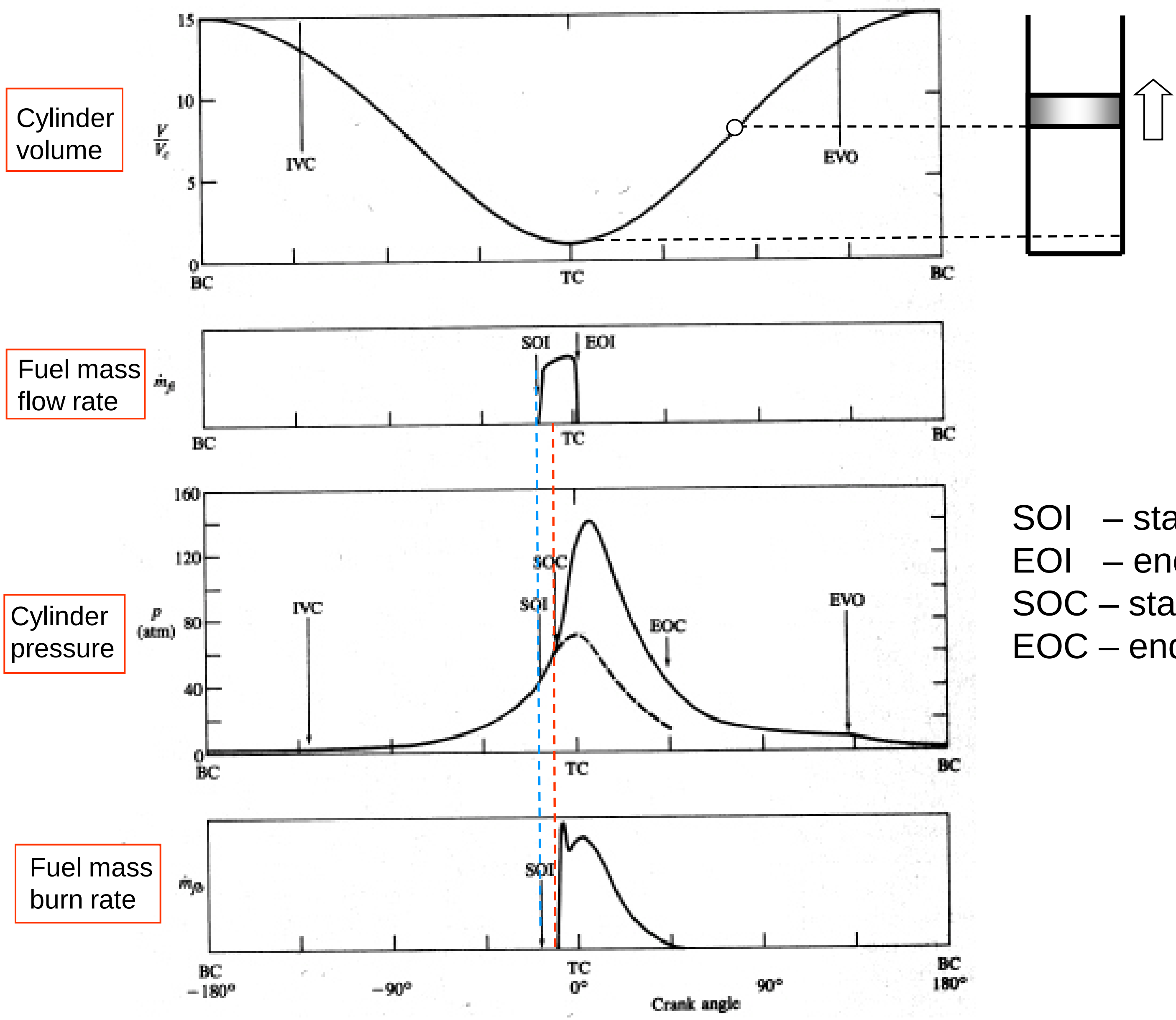

IVO - intake valve opens, IVC – intake valve closes
EVO – exhaust valve opens, EVC – exhaust valve opens
$X_b$ – burned gas mole fraction

# Four stroke Compression Ignition (CI) Engine

Stroke 1: Air is introduced into cylinder through intake valve
Stroke 2: Air is compressed
Stroke 3: Combustion (roughly constant pressure) occurs and product gases expand doing work
Stroke 4: Product gases pushed out of the cylinder through the exhaust valve

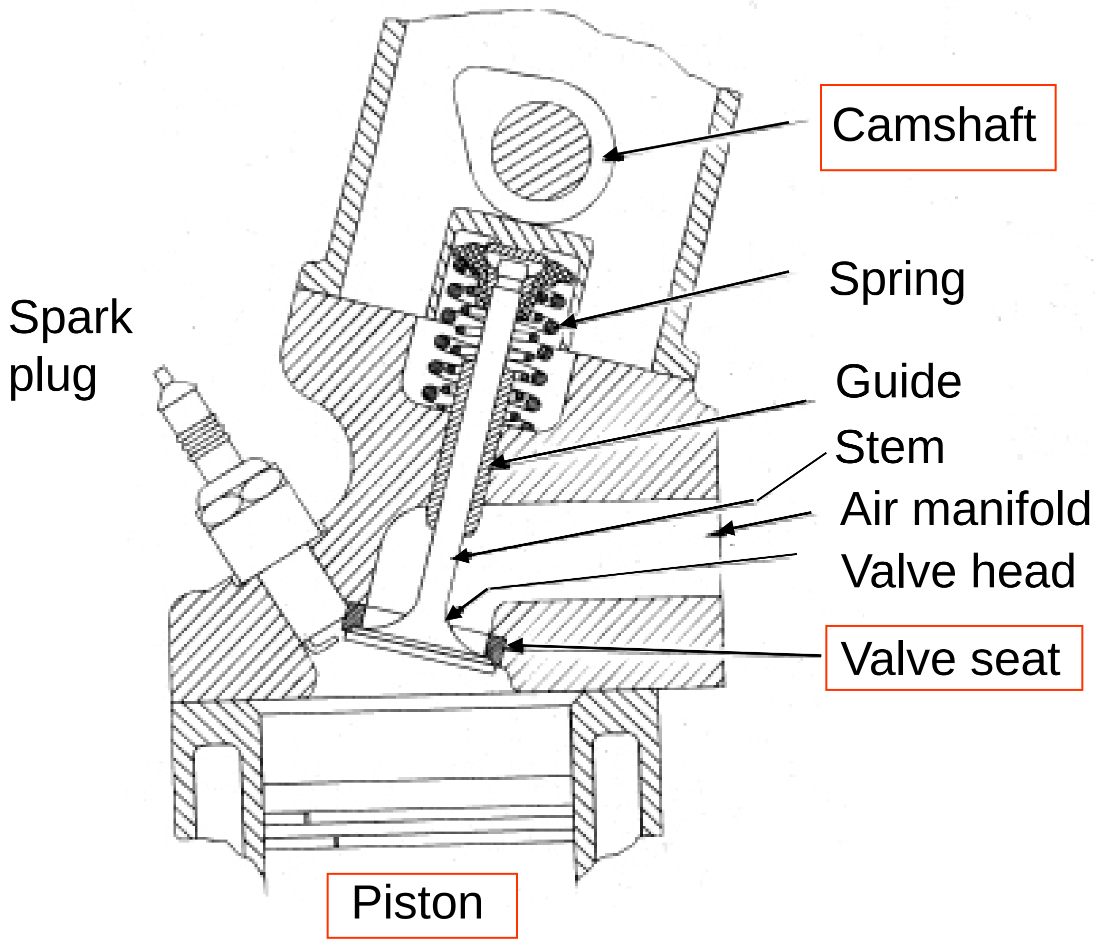


# Four-Stroke CI Engine

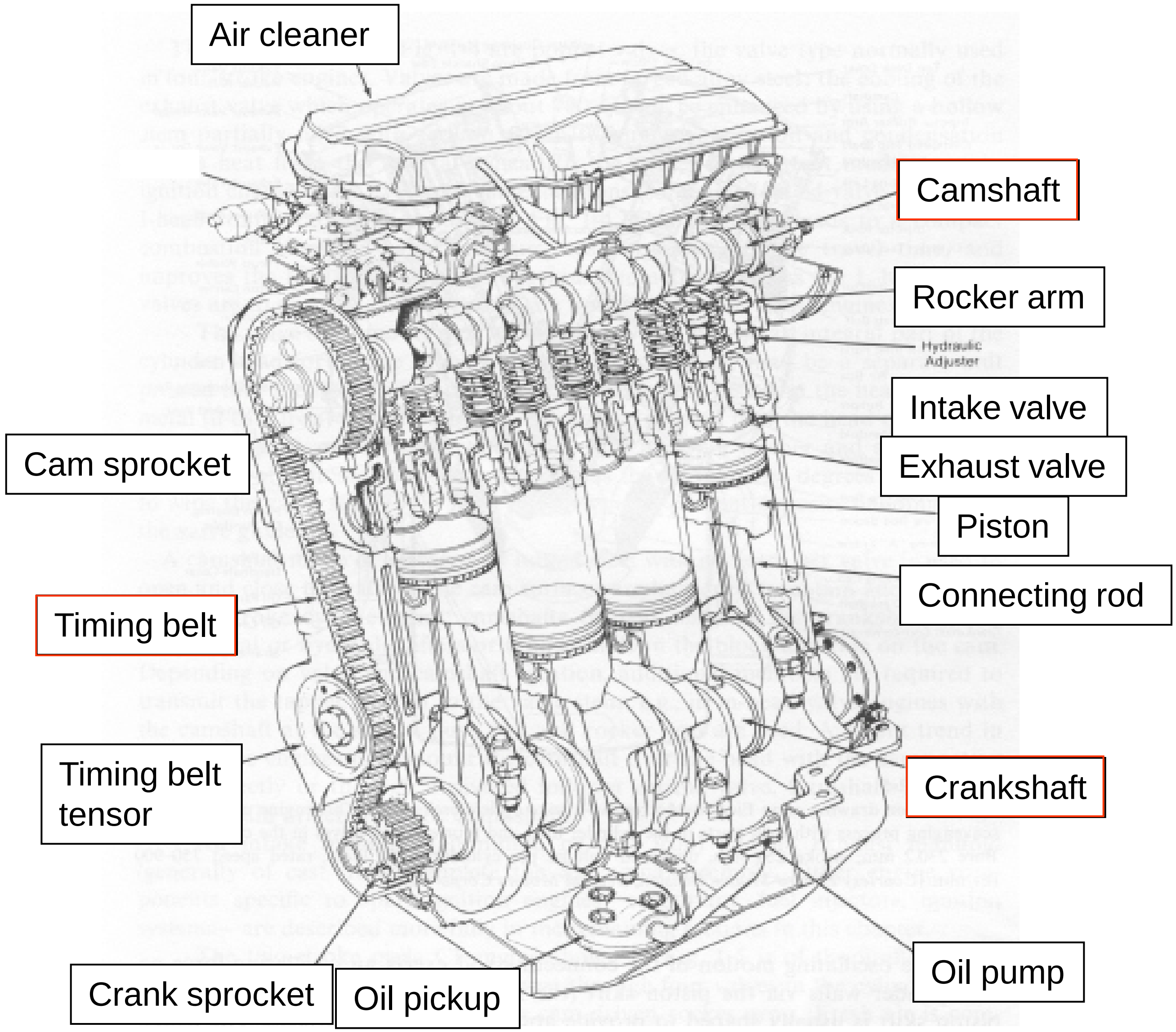


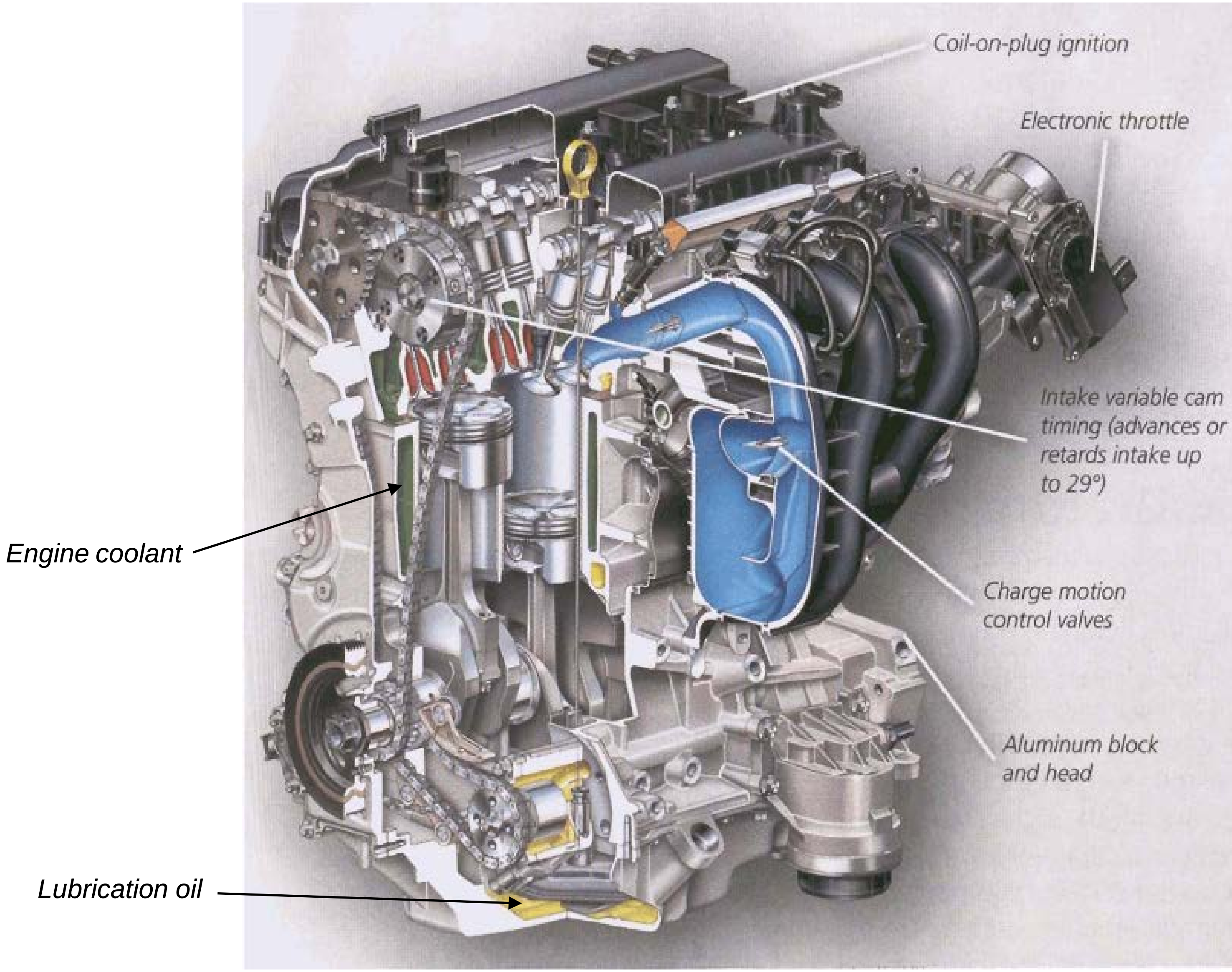

SOI – start of injection
EOI – end of injection
SOC – start of combustion
EOC – end of combustion

# Poppet Valve Actuation with Overhead Camshaft



# Engine Anatomy






Ford's inline 4-cylinder Duratec 2.3 Liter (SAE Automotive Engineering, Oct. 2005)

## Modern Two-Stroke Spark Ignition Engine

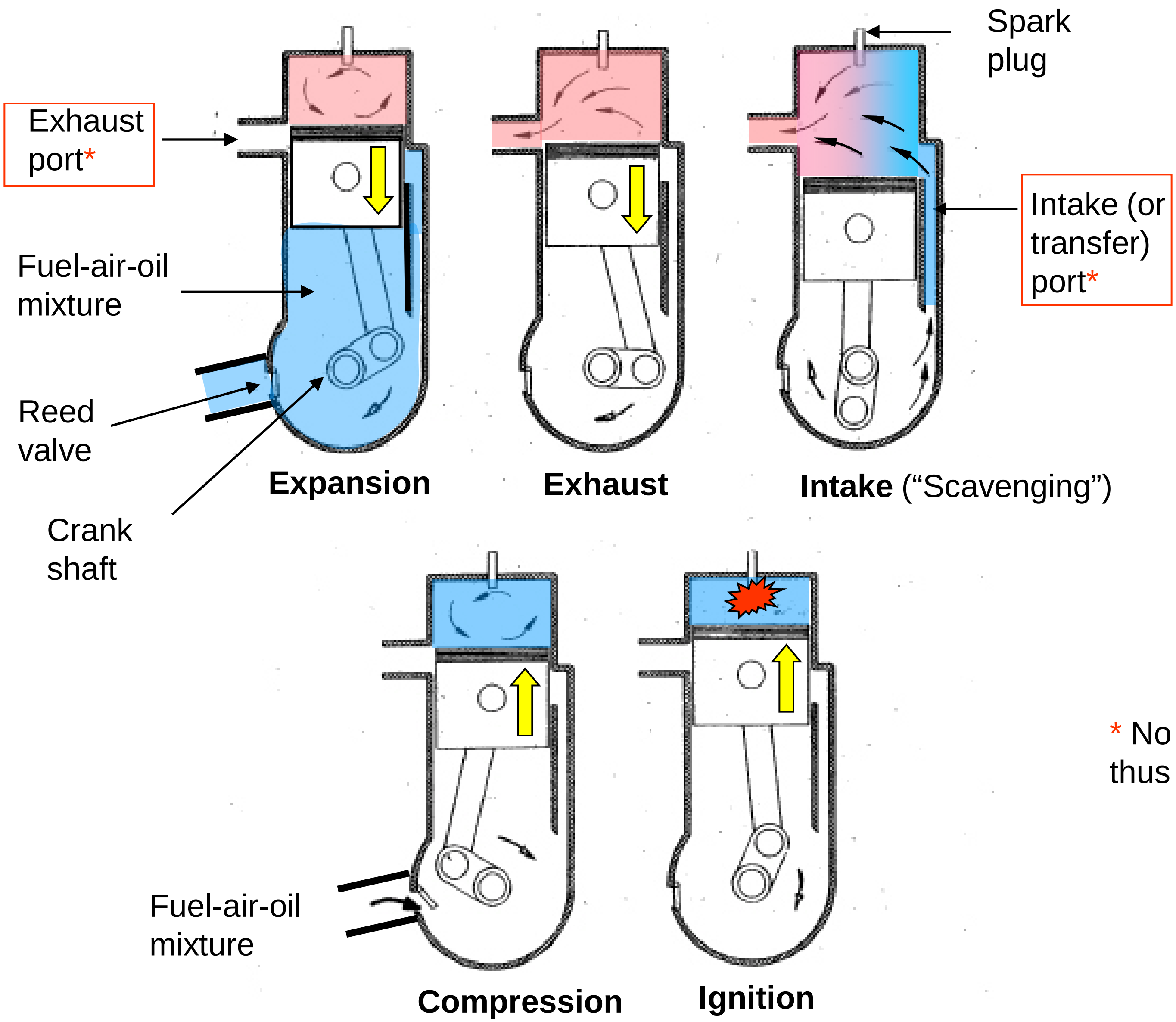
Stroke 1: Fuel-air mixture is introduced into the cylinder and is then compressed

*combustion initiated at the end of the first stroke

Stroke 2: Combustion products expand doing work and then exhausted from the cylinder

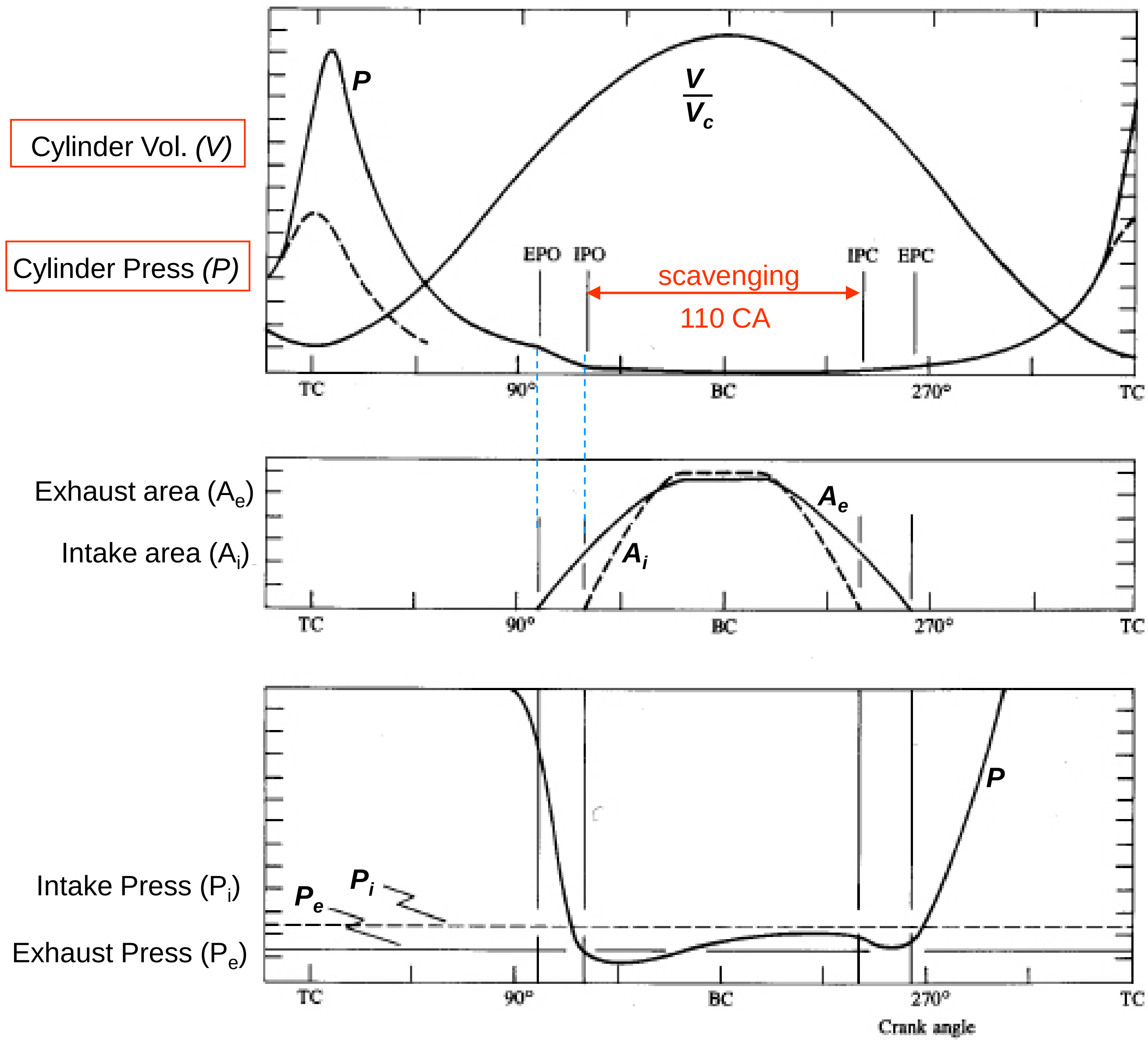
* Power delivered to the crankshaft every revolution

# Traditional two-stroke SI engine



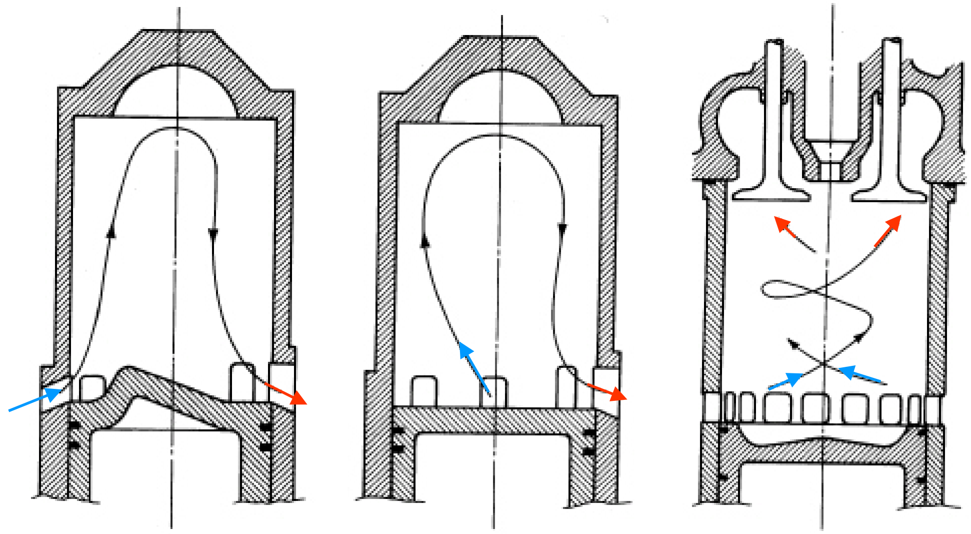

* No valves and thus no camshaft

# Two-Stroke CI Engine

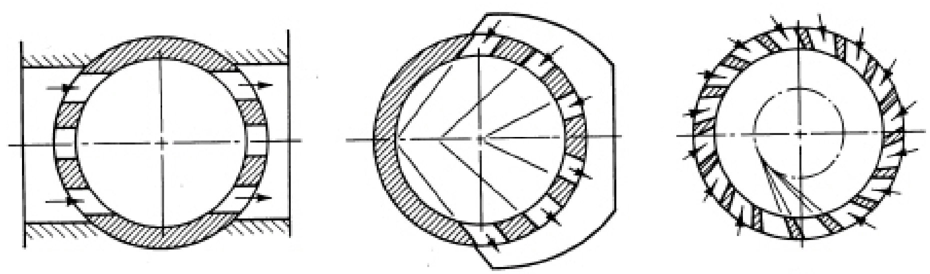



EPO – exhaust port open
EPC – exhaust port closed
IPO – intake port open
IPC – intake port closed

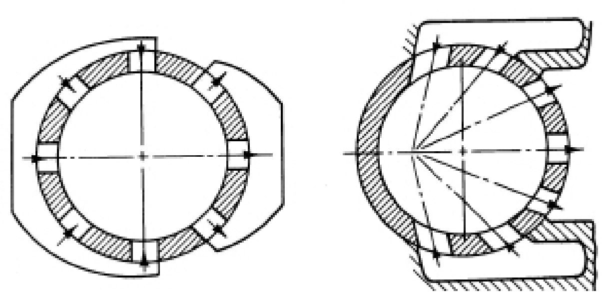
# Scavenging in Two-Stroke Engine



**Cross** **Loop** **Uniflow**



(a) (b) (c)



**Advantages of the two stroke engine:**

Power to weight ratio is higher than the four stroke engine since there is one power stroke per crank shaft revolution.

No valves or camshaft, just ports

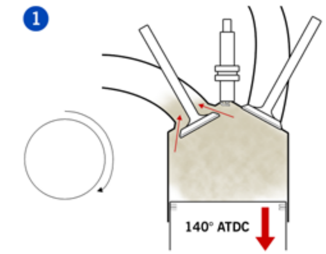
Most often used for low cost, small engine applications such as lawn mowers, marine outboard  engines, motorcycles….

**Disadvantages of the two-stroke engine:**

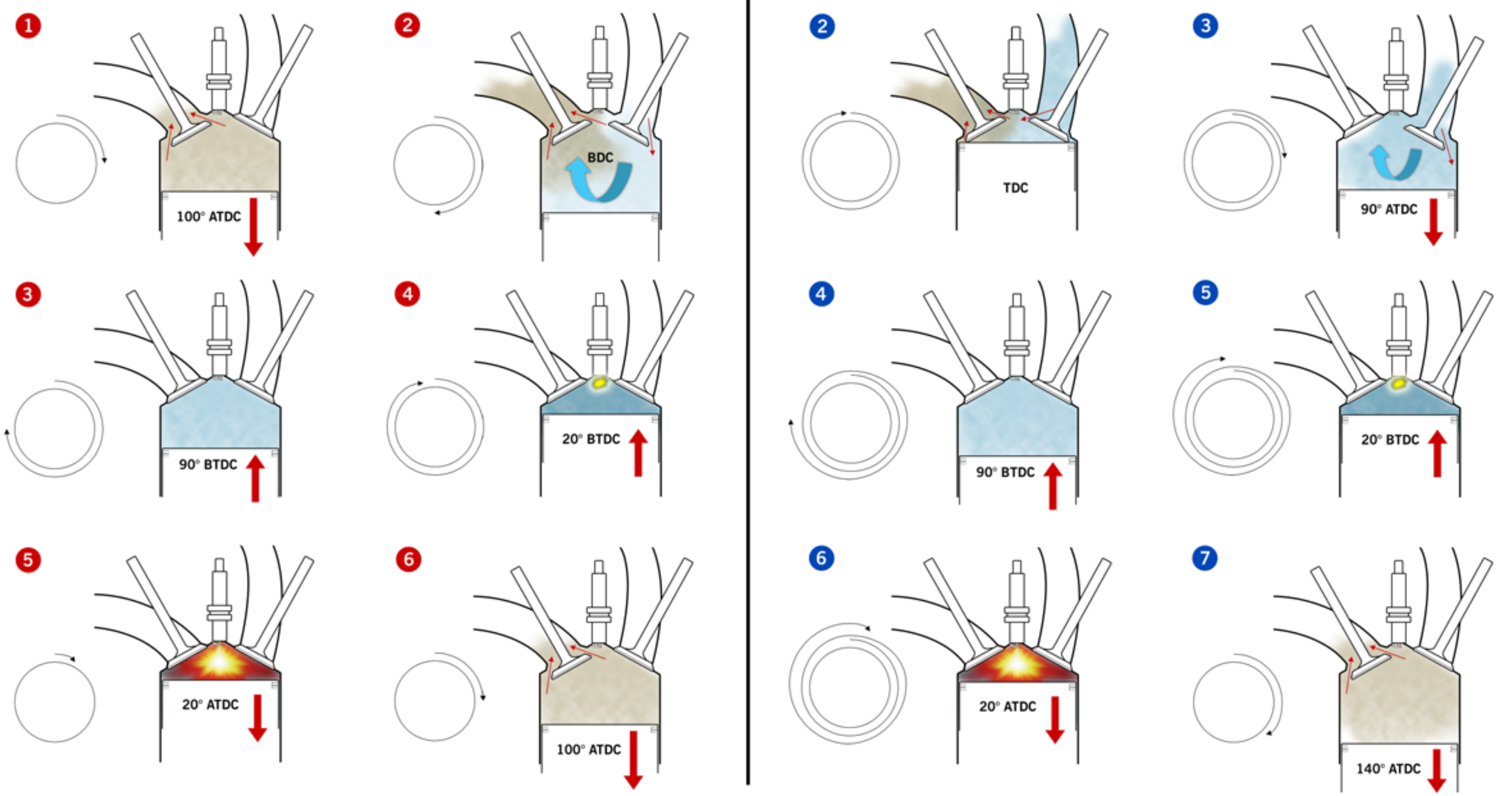
Incomplete scavenging – limits power
Fuel-air “short circuiting” – low fuel efficiency, high HC emission
Burns oil mixed in with the fuel – high HC emission

# THE 2/4SIGHT ENGINE CONCEPT

The 2/4SIGHT engine concept is based on an innovative design of combustion system combined with advanced valve train and control technologies, enabling automatic switching between two- and four- stroke operation (2005)



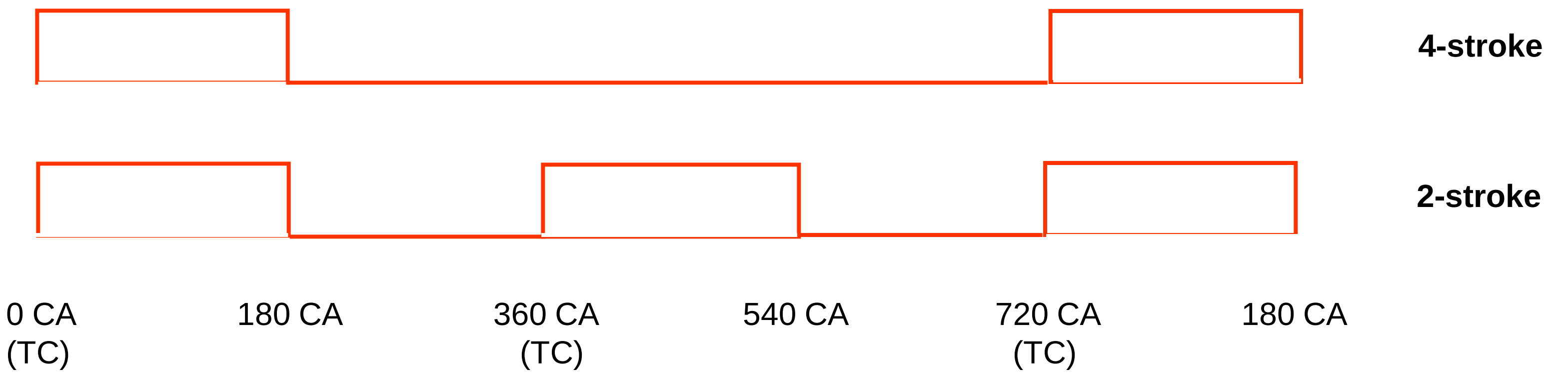

**2/4SIGHT engine in 2-stroke mode** | **2/4SIGHT engine in 4-stroke mode**



# Single Cylinder Engine

Single-cylinder engine gives one power stroke per crank revolution (360 CA) for 2 stroke, or every two revolutions for 4 stroke.

The torque pulses on the crank shaft are widely spaced, and engine vibration and smoothness are significant problems.

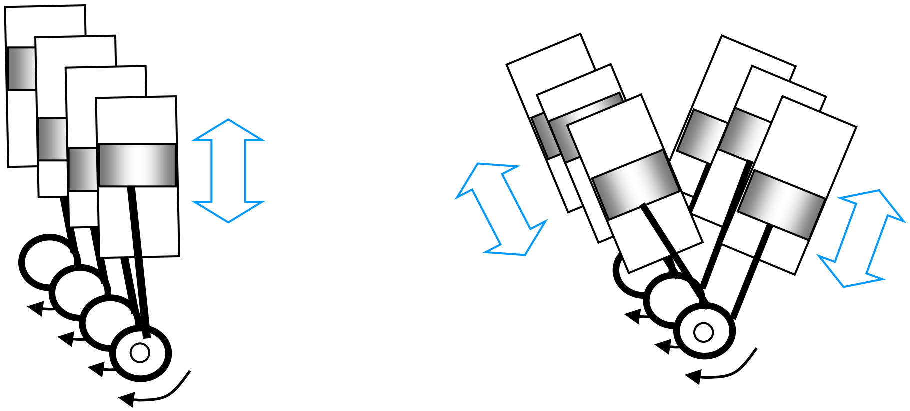



Single cylinder engine used in applications where engine weight and size is important (garden equipment)

# Multi-cylinder Engines

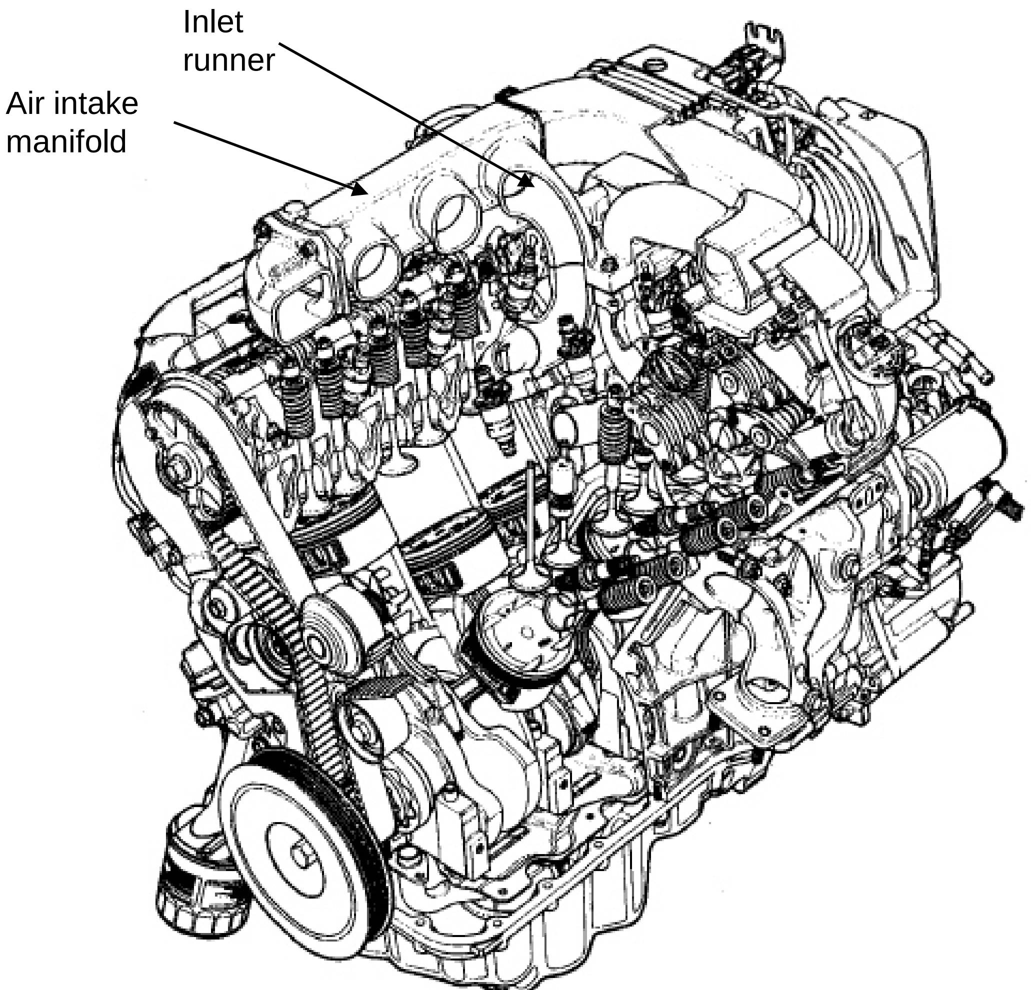
Multi-cylinder engines spread out the displacement volume amongst multiple smaller cylinders. Increased frequency of power strokes produces smoother torque characteristics.

Most common cylinder arrangements are in-line 4, 6 and V-6,-8:



Engine balance (inertia forces associated with accelerating and decelerating piston) better for in-line versus V configuration.

# V-6 Engine

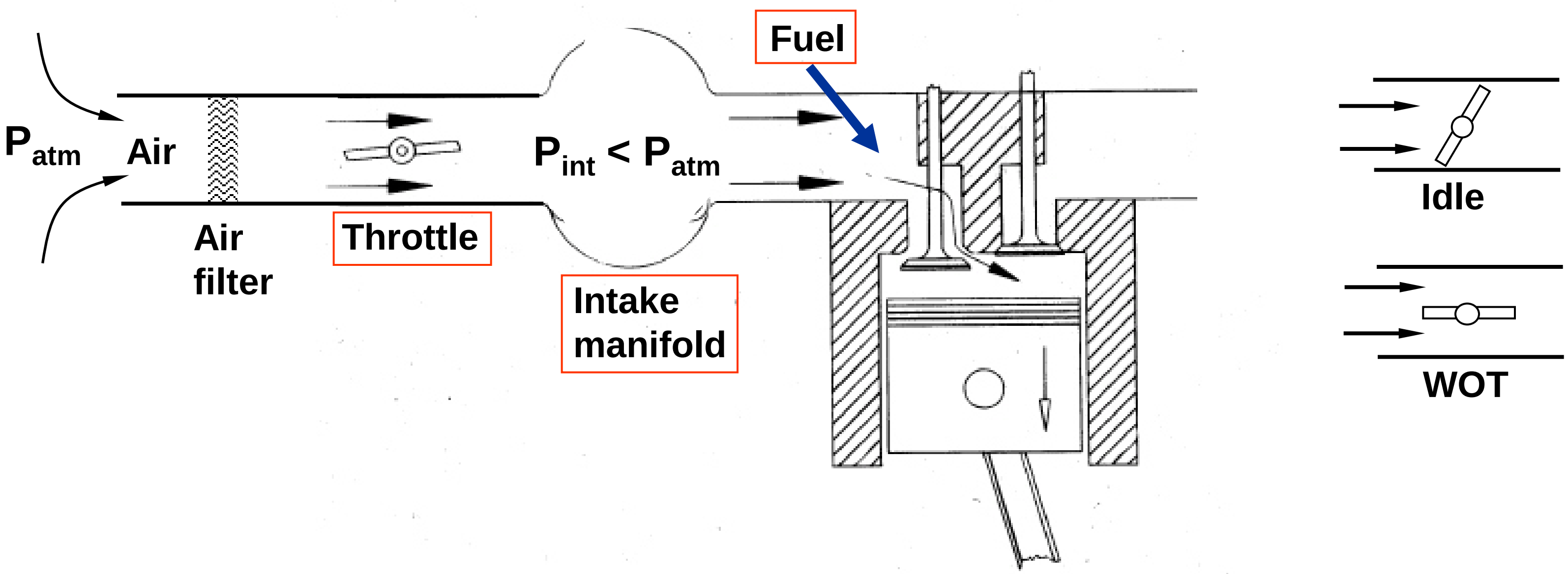


# SI Engine Power Regulation

For proper combustion the ratio of the mass of air to the mass of fuel in the cylinder must be roughly 15.

An IC engine is basically an air engine, the more air that enters the cylinder, the more fuel can be burned, the more energy (power) output.

Vary throttle position - Maximum intake pressure (and power) achieved at wide-open-throttle (WOT) and minimum at idle

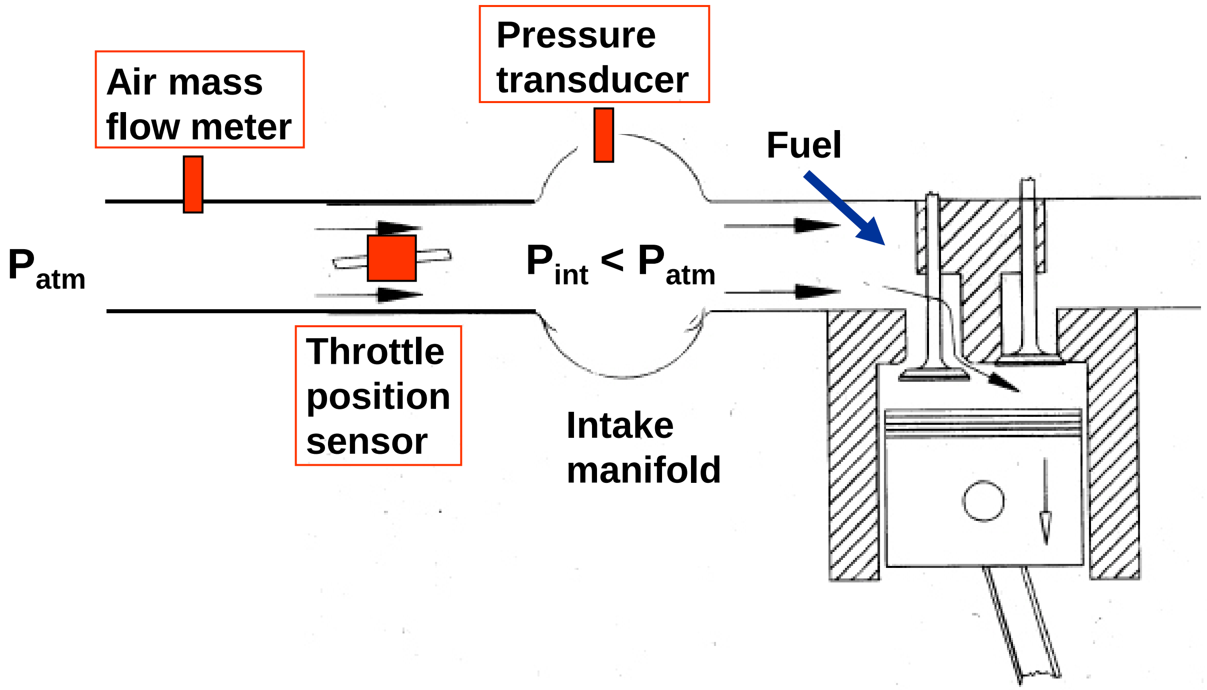


# Power Regulation Methods

Basic methods:

1) Manifold pressure
2) Air mass flow rate
3) Throttle position

Engine Control Unit (ECU) activates the fuel injector solenoid for a duration corresponding to measurement of air flow or pressure



# Fuel-Air Mixing

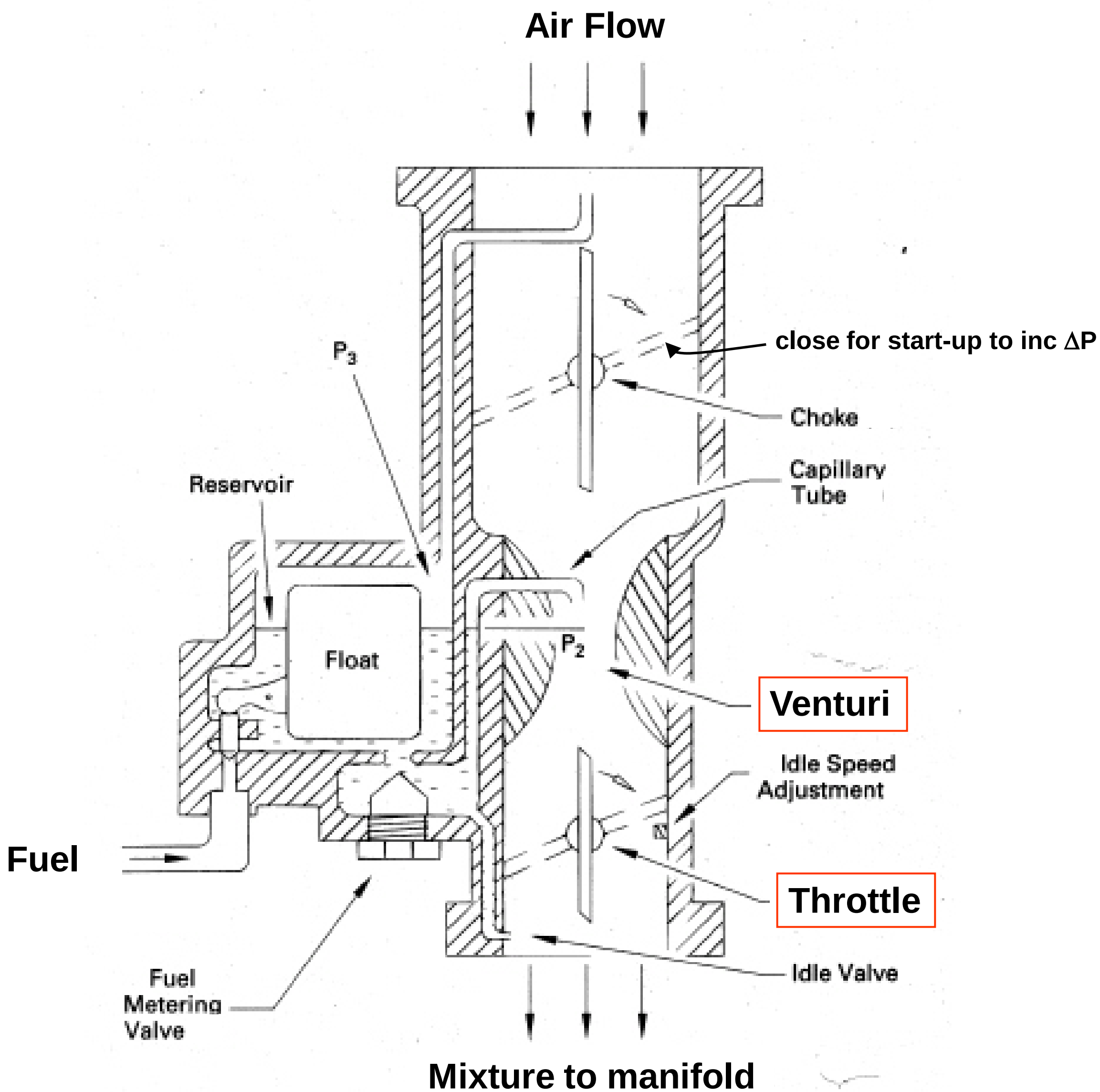
In spark ignition engines the air and fuel are usually mixed prior to entry into the cylinder.

Initially a purely mechanical device known as a carburetor was used to mix the fuel and the air

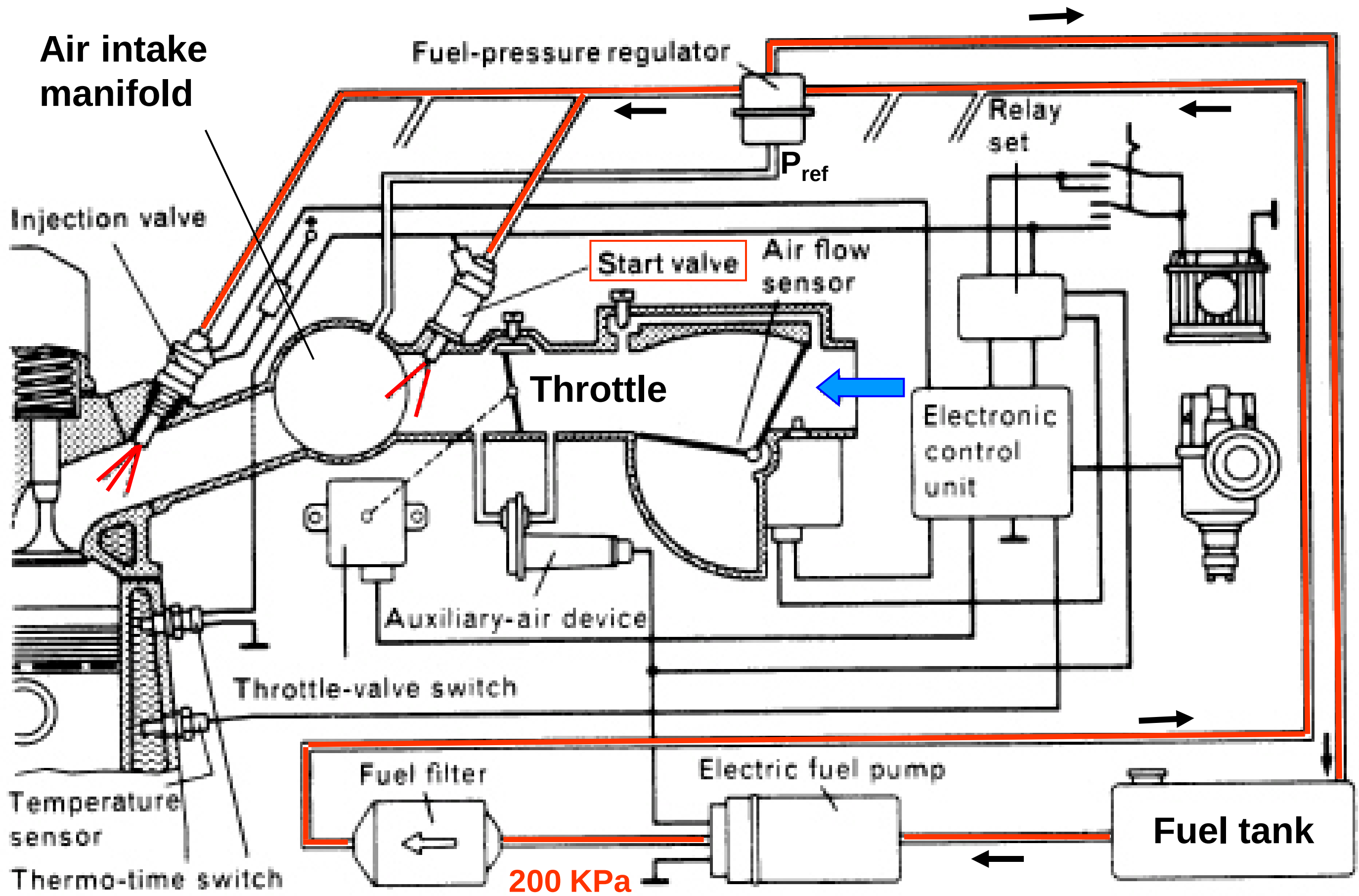
Most modern cars use electronic fuel-injection systems:

- 1980s single injector used to spray fuel continuously into the air manifold
- 1990s one injector per cylinder used to spray fuel intermittently into the intake port

# Basic Carburetor



# SI Engine Fuel Injection System



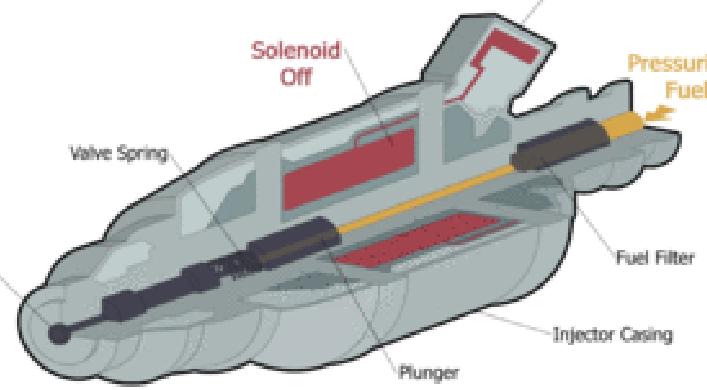

Injector fuel pressure varied relative to manifold pressure (engine load).
During start-up additional fuel is added through a second injector.

# Port fuel injector

Fuel line

Battery and
ECU

Intake port



## Diesel Fuel Injection System

With diesel engines fuel is sprayed directly into the cylinder, power is varied by metering the amount of fuel added (no throttle)

Diesel fuel injection systems operate at high-pressure, > 100 MPa
• fuel pressure must be greater than the compression pressure
• need high fuel jet speed (high injector pressure difference) to atomize droplets small enough for rapid evaporation

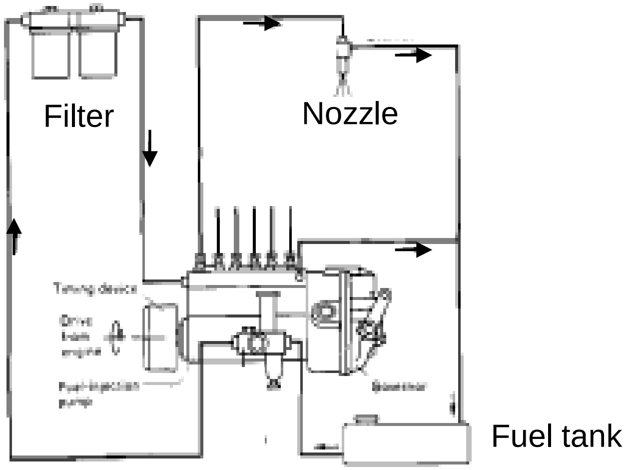
Fuel system includes fuel pump, lines and nozzles

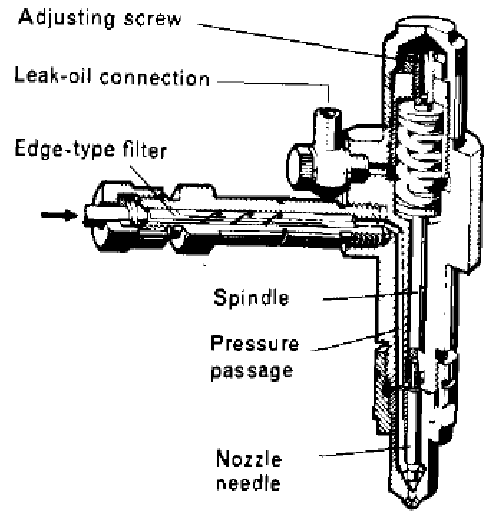
In traditional systems the pump is used to raise the pressure of the fuel, meter the fuel and control injection timing

The pressure is raised by individual barrel-plunger for each nozzle (in-line type) or a single barrel plunger (distributor type).

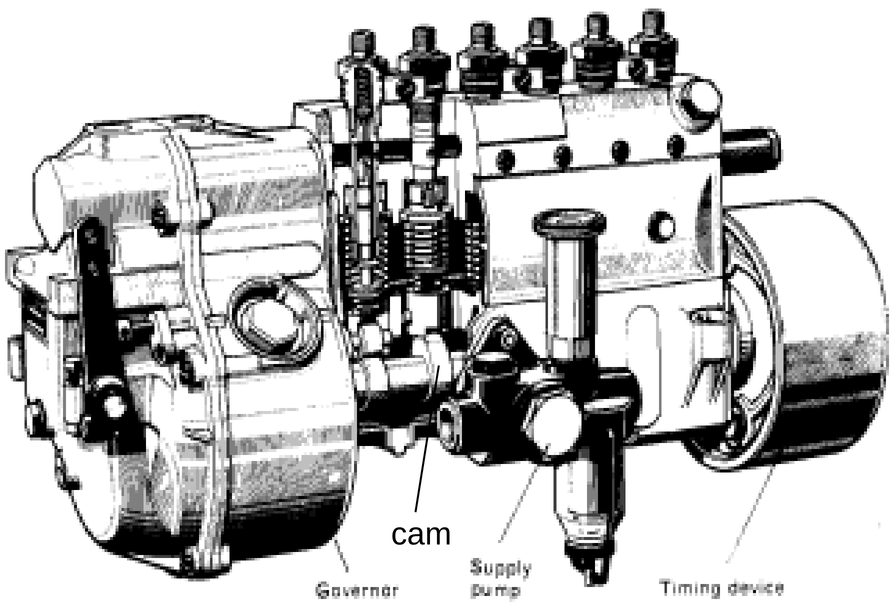
Nozzle is a passive device that actuates (spindle rises) when the fuel pressure increases. The spindle is normally held closed by a spring.

# In-line Diesel Fuel Injection System

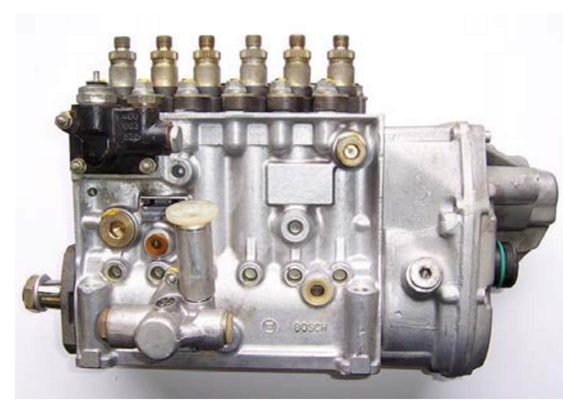



Fuel injector nozzle




In-line fuel-injection pump (compresses and meters)



Bosch in-line injector pump

## Electronic Unit injector

Pump (cam actuated) and nozzle incorporated into single unit
(used in Jetta 2004-2006 TDI engine: VW called unit injector Pumpe Düse )
- doesn't meet 2009 emission regulations

Low pressure (500 kPa) fuel pump delivers filtered fuel to injector port

Delphi E-1

Plunger up stroke - pump element fills with fuel

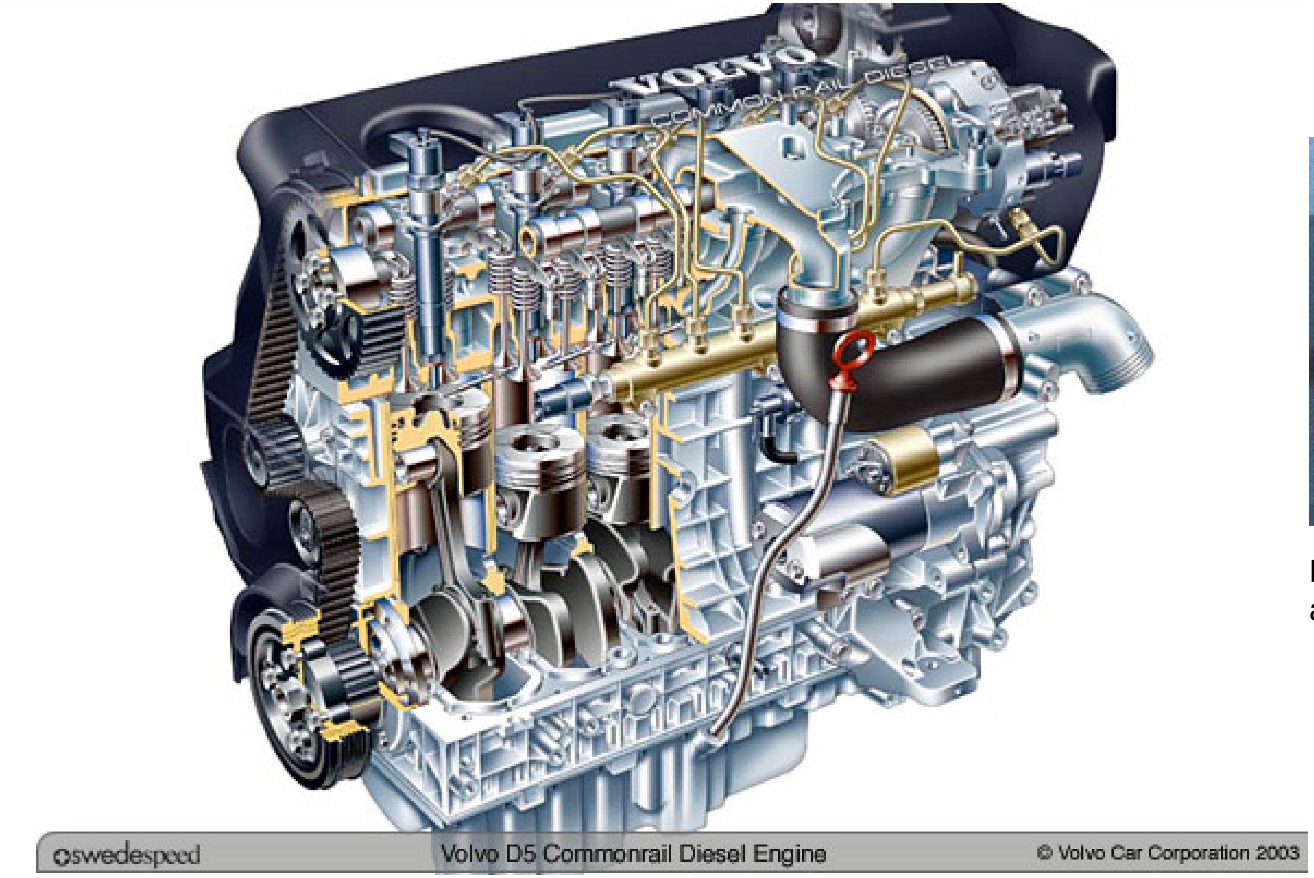
Plunger down stroke:

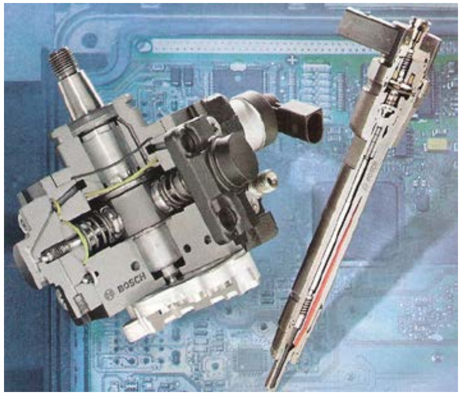
- solenoid de-energized fuel spills into return duct
- solenoid is energized fuel is compressed (2000 bar) injector needle valve opens
- solenoid de-energized fuel valve opens pressure drops needle valve opens

# Common Rail Diesel Fuel Injection System

Latest Diesels use high pressure (2000 bar) common rail with solenoid or piezoelectric actuated injectors (used in 2009 VW Jetta, 2009 M-Benz ).

Multiple injections per stroke possible.



Bosch diesel pump (2000 bar) and piezoelectric injector

## Gasoline Direct Injection (GDI) Engine

GDI engine combines the best features of SI and CI engines:

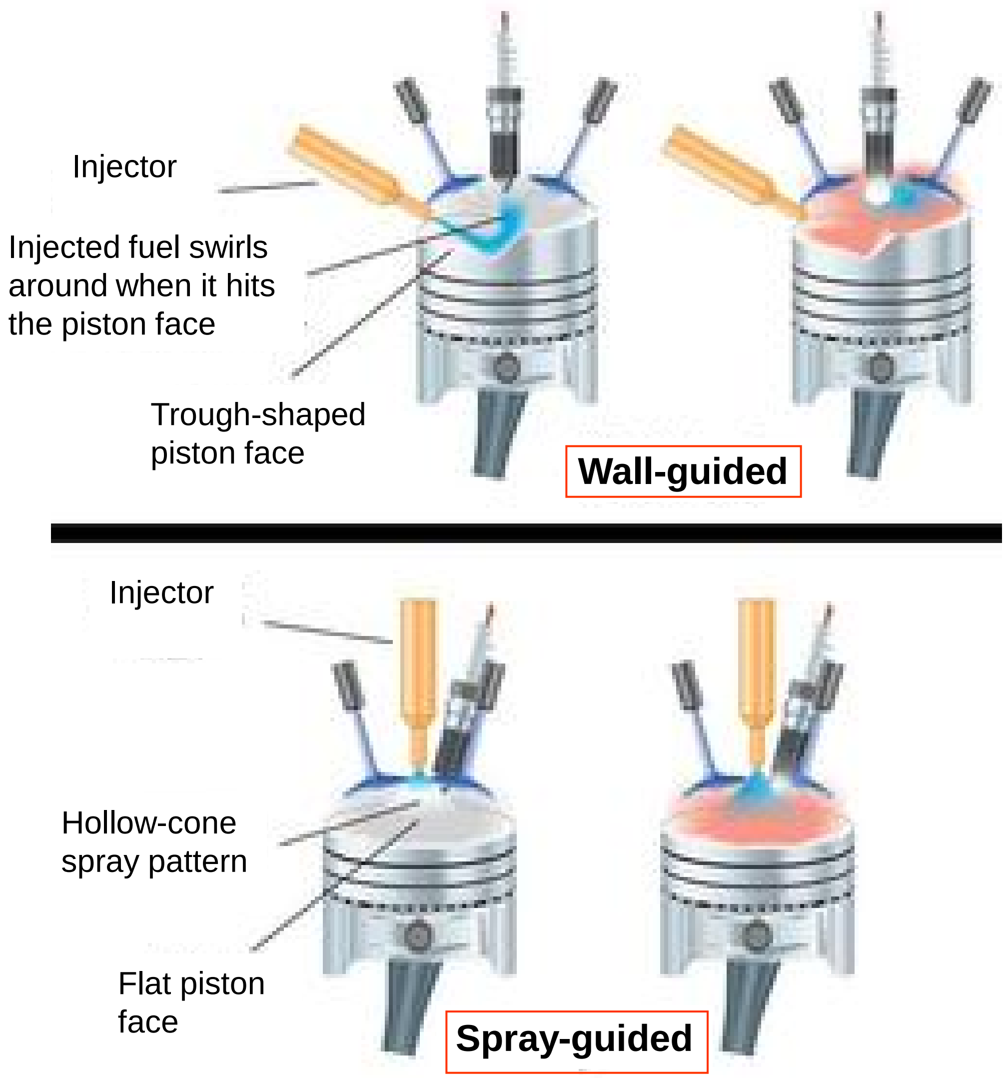
Fuel is injected directly into the cylinder during the intake stroke or the compression stroke (high pressure injector)

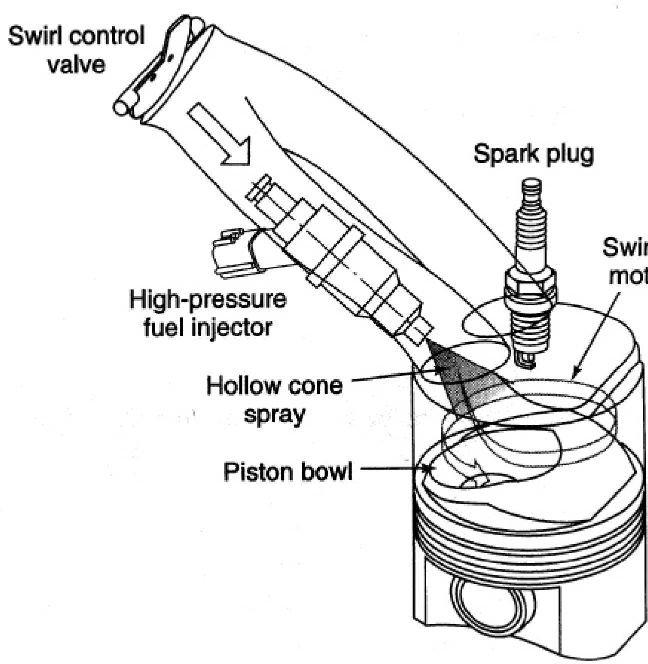
Operate at optimum compression ratio (12-15) for efficiency by injecting fuel directly into engine during compression (avoiding knock associated with SI engines with premixed charge)

Control engine power by fuel added (no throttle → no pumping work)

During intake stroke fuel cools the cylinder wall allowing more air into the cylinder due to higher density

# Two types of GDI Engines






Wall-guided GDI

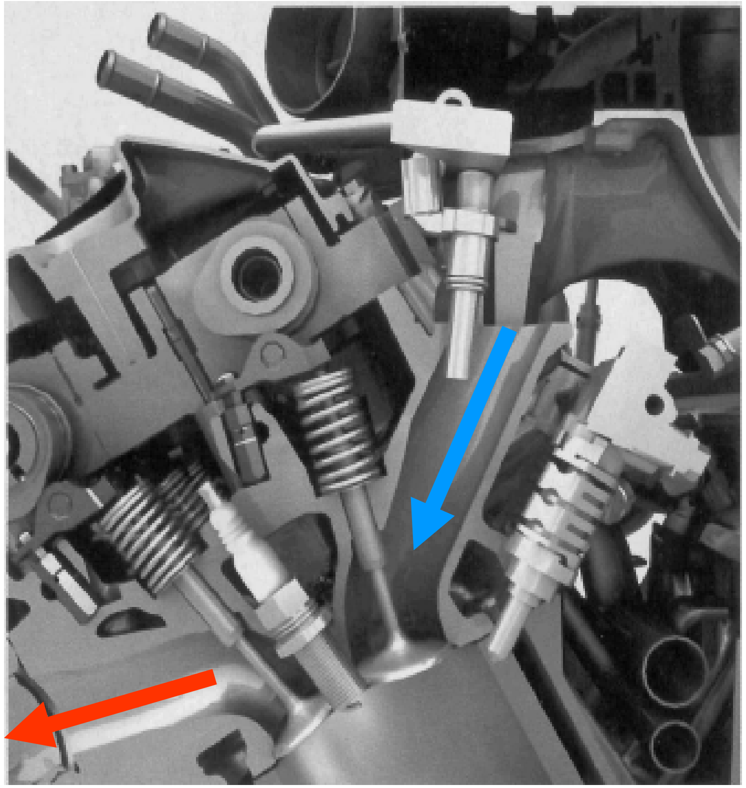
BMW spray-guided GDI

# Dual Port and Direct Fuel Injection

Stoichiometric mixture created by combination of fuel port and direct fuel injection

- Low rpm use 30-40% DI to produce extra in-cylinder turbulence

- High RPM and load use 100% DI to reduce air temp (increase density)



2006 Lexus 3.5 L V6 engine (SAE Automotive Engineering Dec 2005)

# GDI $\boxed{\text{stratified-charge mode}}$

Create easily ignitable fuel-air mixture at the spark plug and a leaner fuel-air mixture in the rest of the cylinder.

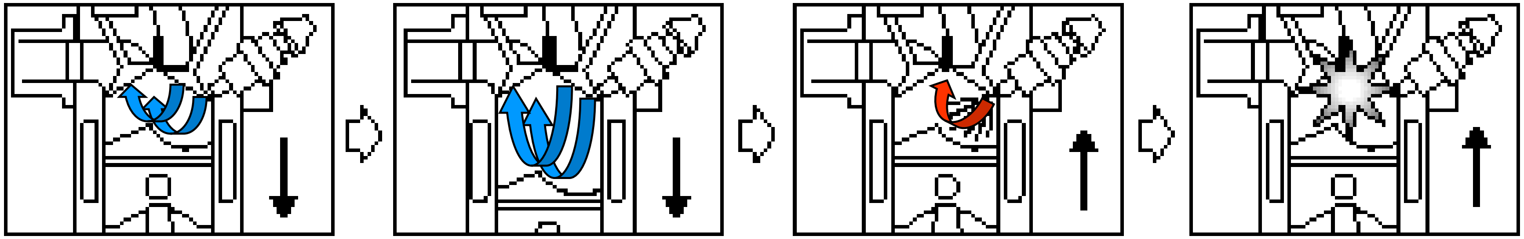
Lean burn results in lower emissions and higher energy efficiency

Example:

Mitsubishi GDI engine achieves complete combustion with an air-fuel ratio of 40:1 compared to 15:1 for conventional engines

This results in a 20% improvement in overall fuel efficiency and CO2 production (greenhouse gas), and reduces NOx emissions (responsible for ozone production - smog) by 95% with special catalyst

## Stratified Charge Engine



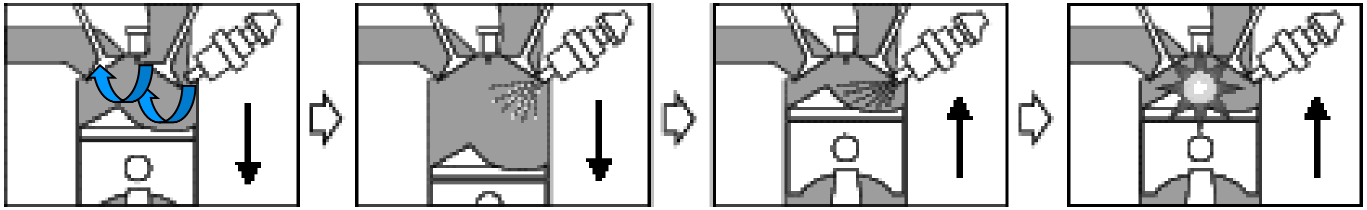
During intake stroke air enters the cylinder

Near the end of the compression stroke fuel is injected and directed by the piston head bowl towards the spark plug

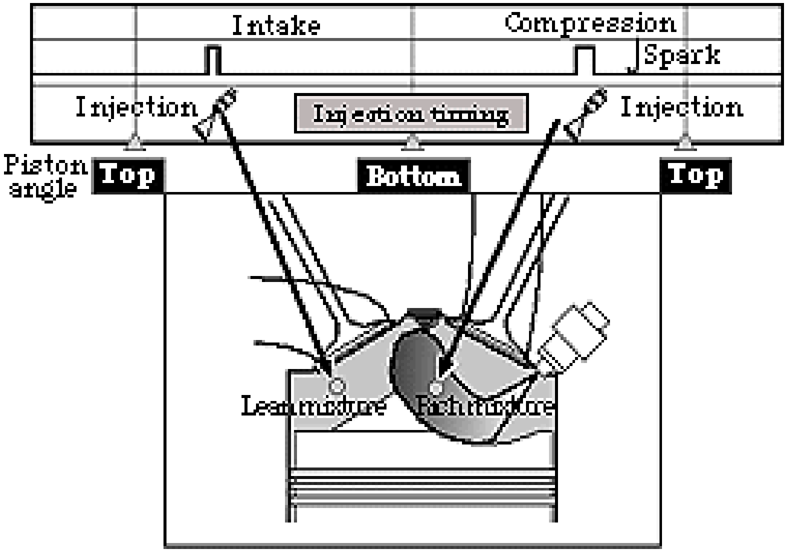
The mixture at the spark plug is “rich” in fuel thus easy to ignite but the amount of fuel injected results in an overall “lean” fuel-air mixture

Lowers heat transfer to the walls but increases thermal cyclic load on the spark plug, and standard catalytic converter doesn’t work

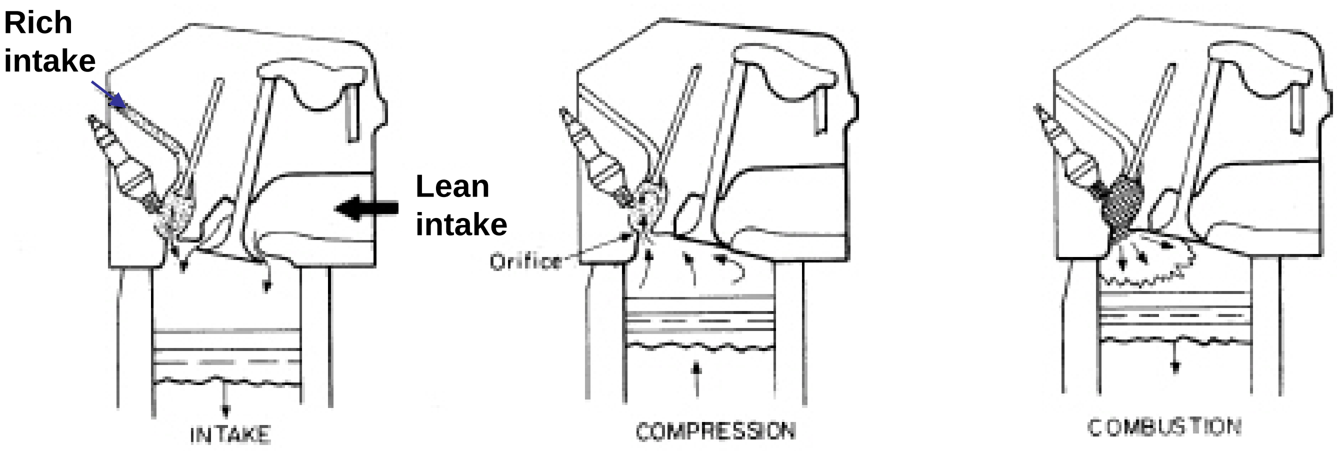
# Mitsubishi Two-Stage Ignition GDI Engine



Two-Stage Mixing injection timing



# Two-Chamber Torch or Jet Ignition Engine



# Homogeneous Charge Compression Ignition (HCCI)

Premixed lean fuel-air mixture is created in the cylinder like a SI engine but ignition occurs spontaneously at the end of compression like a Diesel engine

Get the efficiency of a Diesel with low temperature, flameless release of energy throughout the cylinder → no need for expensive low-NOx emission after-treatment

Can use multiple fuel types: gasoline, diesel, ethanol, etc.

Fuel-air mixture is preheated by either heating the air or mixing with combustion products from previous cycle

Challenge: control the ignition timing for different load and engine speeds, need spark ignition for cold start up

## Homogeneous Charge Compression Ignition (HCCI)

GM demonstrated the first HCCI engine in a 2007 Saturn Aura

Vehicle gets 15% better fuel economy compared to port injected engine while meeting current emission standards

Engine uses direct injection, variable valve timing and lift

## Plug-in Electric Vehicles

Electric motor driven from battery pack that is recharged via electric outlet

In 1996, 800 GM EV-1 were made available for lease in California

All the leased vehicles were crushed at the end of the 3 year lease, chronicled in the movie Who Killed the Electric Car?

GM re-entry into electric vehicle is the Chevy Volt plug-in out in 2010, a small IC engine powers a generator that runs motor once the batteries are depleted after 50 mile range ($40k, less subsidies)

Others due in 2011 are Toyota Prius, Nissan Leaf, Tesla Roadster

Used for US government vehicles

## Electric Motor Powered Vehicles

Biggest asset: no emissions, low end torque, no gears

Problems:
- vehicle range dictated by battery storage
- batteries need to be recharged which takes several hours
- cost of batteries
- weight of batteries

Alternative is **gas-electric** hybrid:
-Toyota Prius (1997), Honda Insight (2000)

N.A. Prius sales:

| 2001 | 2002 | 2004 | 2005 | 2007 |
|---|---|---|---|---|
| 15,556 | 20,119 | 53,991 | 107,897 | 183,800 |

## Gasoline-Electric Hybrid Vehicles

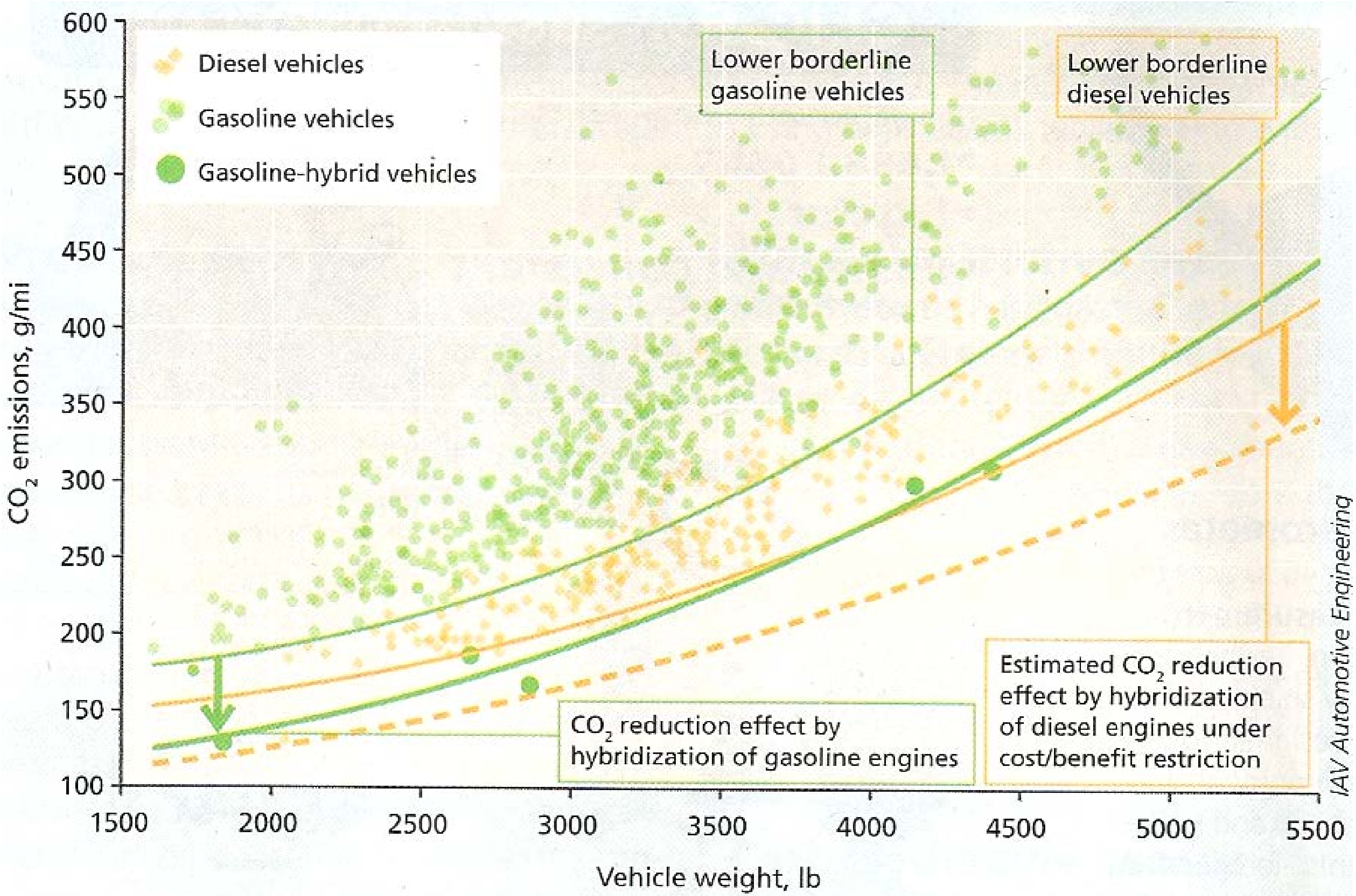
Parallel hybrid uses a combination of a small IC engine (1-1.5 L) and an electric motor driven off batteries, in a series hybrid IC engine only charges the batteries (GM Volt).

Electric motor is used exclusively during cruise and idle when the vehicle is stationary.

IC engine kicks in when additional power is needed during acceleration and up hills.

Vehicles use regenerative braking - during braking the electric motor acts like a generator recharging the batteries, so never need to recharge.

Disadvantage: premium price (initially subsidized) and cost to replace batteries after 8 year 160,000 km warranty period is expensive



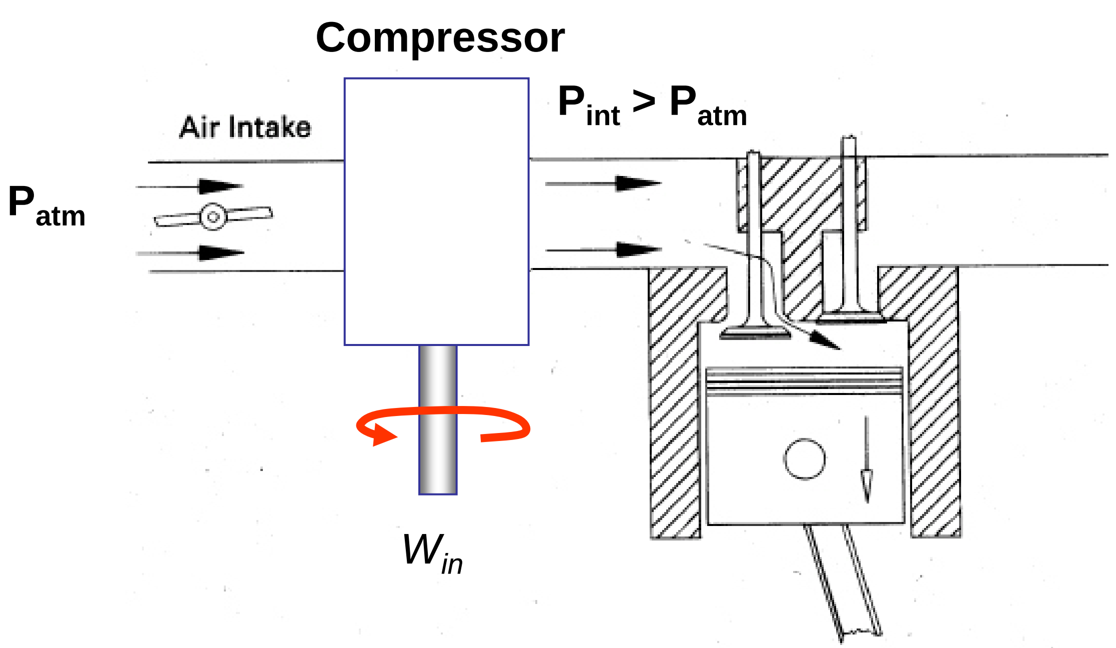
Diesel vehicles
Gasoline vehicles
Gasoline-hybrid vehicles
Lower borderline gasoline vehicles
Lower borderline diesel vehicles
Estimated $CO_2$ reduction effect by hybridization of diesel engines under cost/benefit restriction
$CO_2$ reduction effect by hybridization of gasoline engines
$CO_2$ emissions, g/mi
Vehicle weight, lb
IAV Automotive Engineering

## Supercharger and Turbocharger

These devices are used to increase the power of an IC engine by raising the intake pressure and thus allowing more fuel to be burned per cycle.

Allows the use of a 4 cyl instead of 6 cyl engines → cost effective

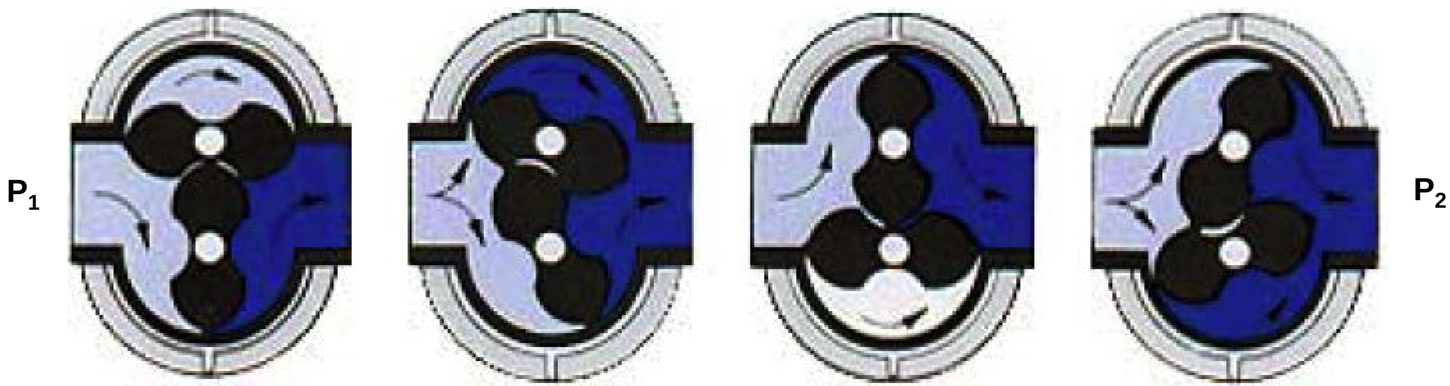
**Superchargers** are compressors that are mechanically driven by the engine crankshaft and thus represents a parasitic load.



# Positive Displacement Compressors

Positive displacement compressors: piston, Roots, and screw

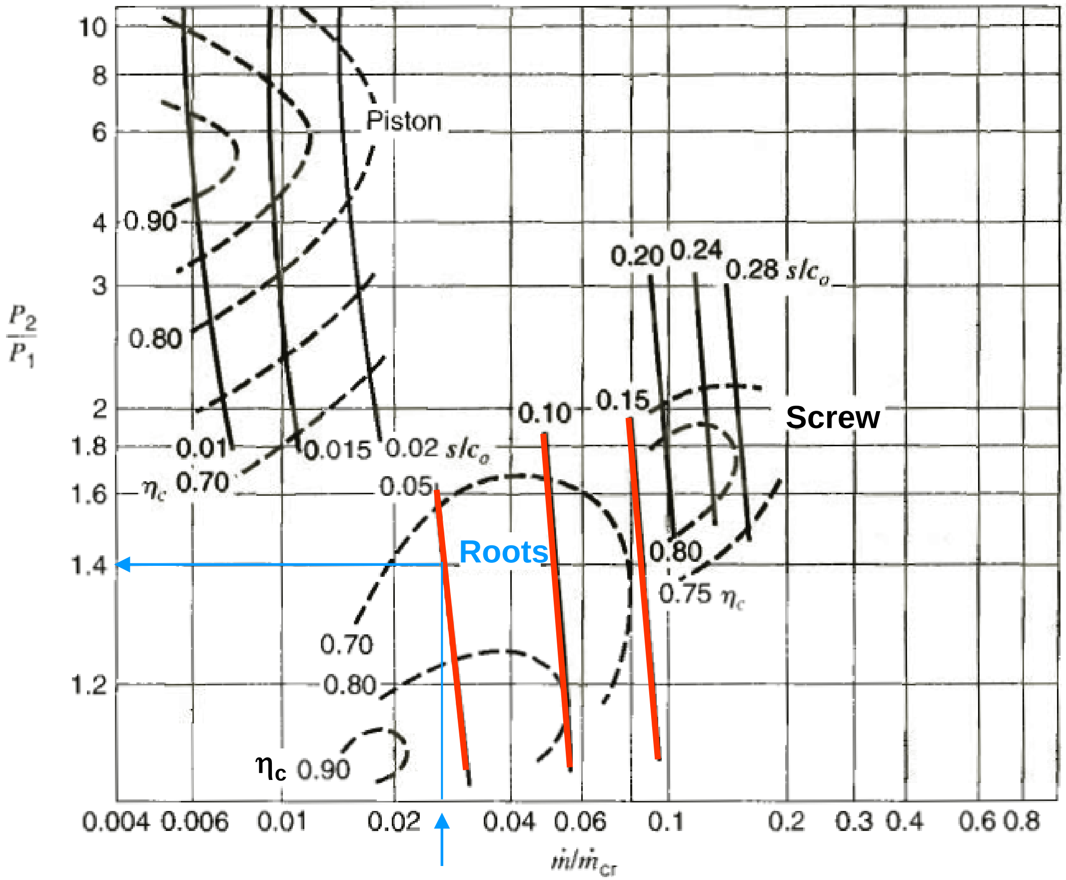
Most common is the Roots compressor – pushes air forward without pressurizing it internally.




Pressurization occurs in the manifold when the air flow rate supplied is larger than that ingested by the cylinders.

Produces constant flow rate independent of boost pressure ($P_2$)

# Performance of Positive Displacement Compressors




$s/c_o$ = rotor tip Mach#
~ pump speed

$\eta_c$ = compressor efficiency: isentropic work/actual work

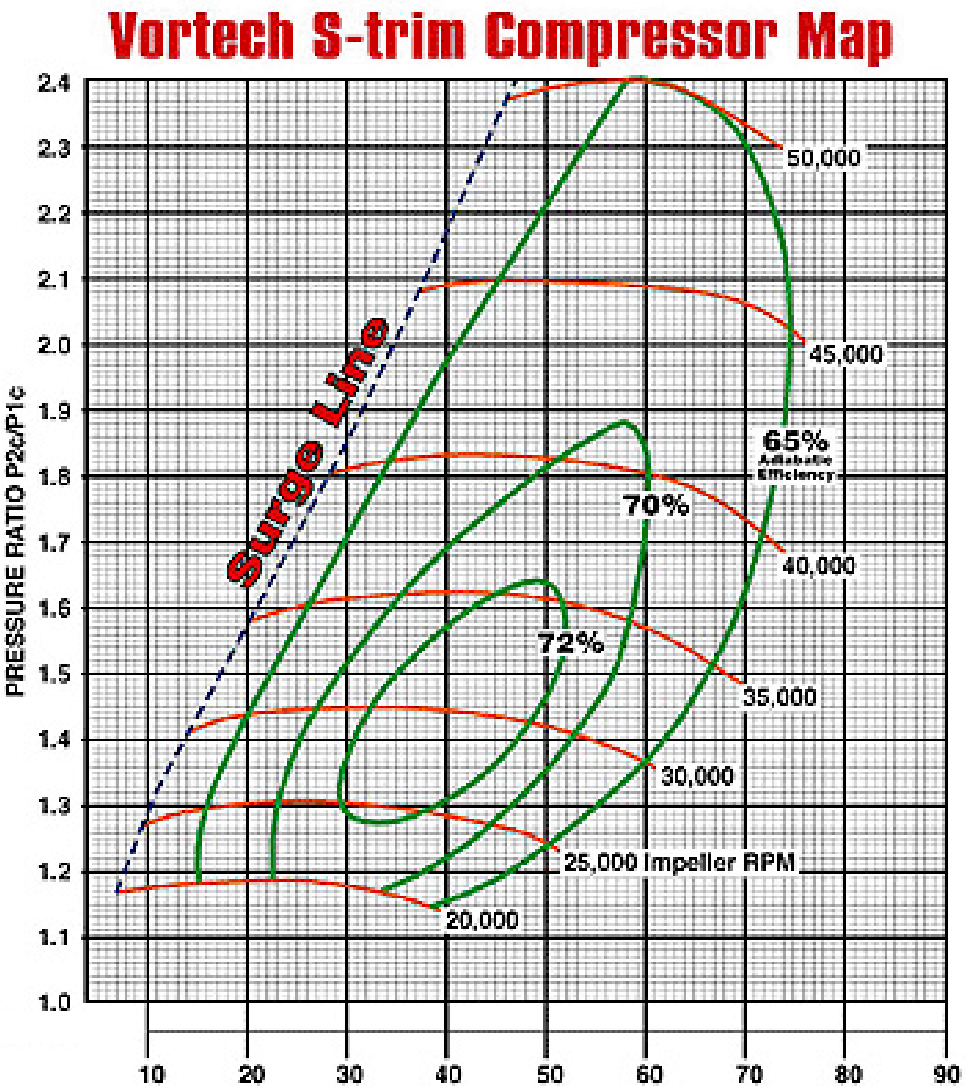
Extra energy goes to heat up air leading to a reduction in density

## Dynamic Compressors

Dynamic compressor has a rotating element that adds tangential velocity to the flow which is converted to pressure in a diffuser.

Most common is the radial (or centrifugal) type

Produces a constant boost pressure independent of the mass flow rate




Mass flow rate (Pounds of air per minute)

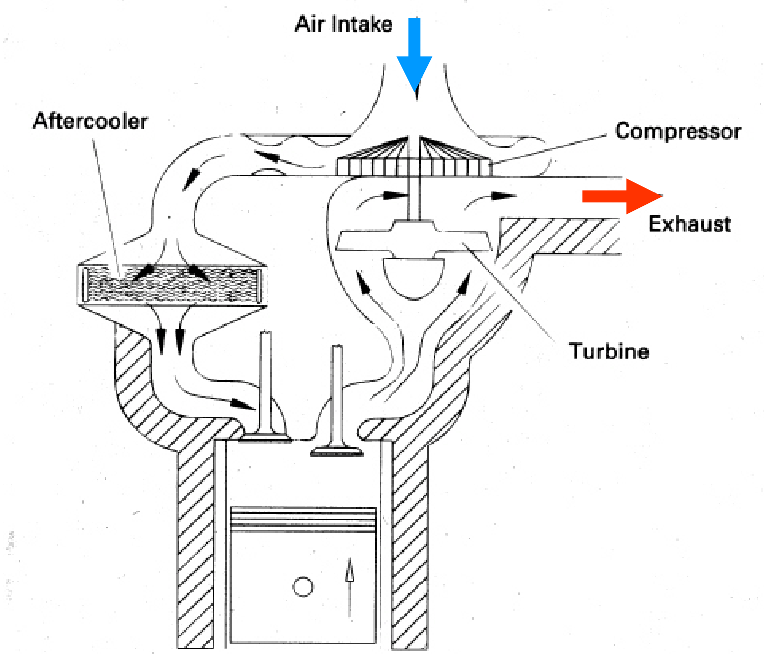
To the left of surge line the flow is unstable (boundary layer separation and flow reversal)

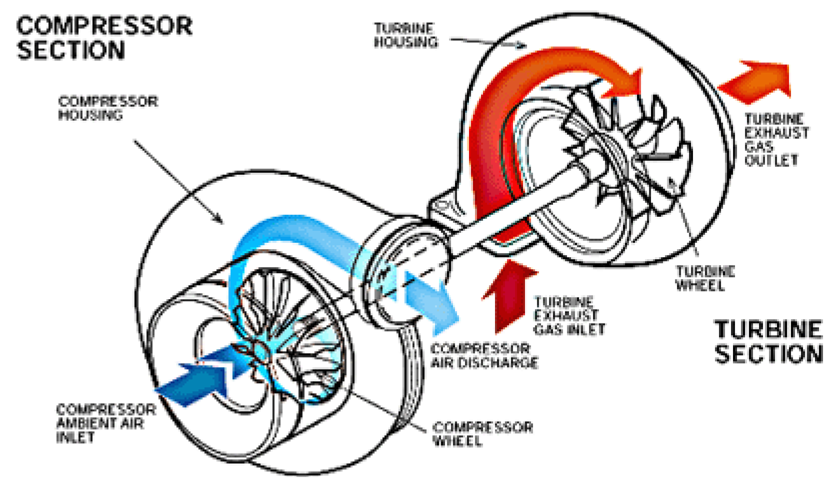
To the right of 65% line the compressor becomes very inefficient:

a) air is heated excessively

b) takes excess power from the crank shaft

**Turbochargers** couple a compressor with a turbine driven by the exhaust gas. The compressor pressure is proportional to the engine speed



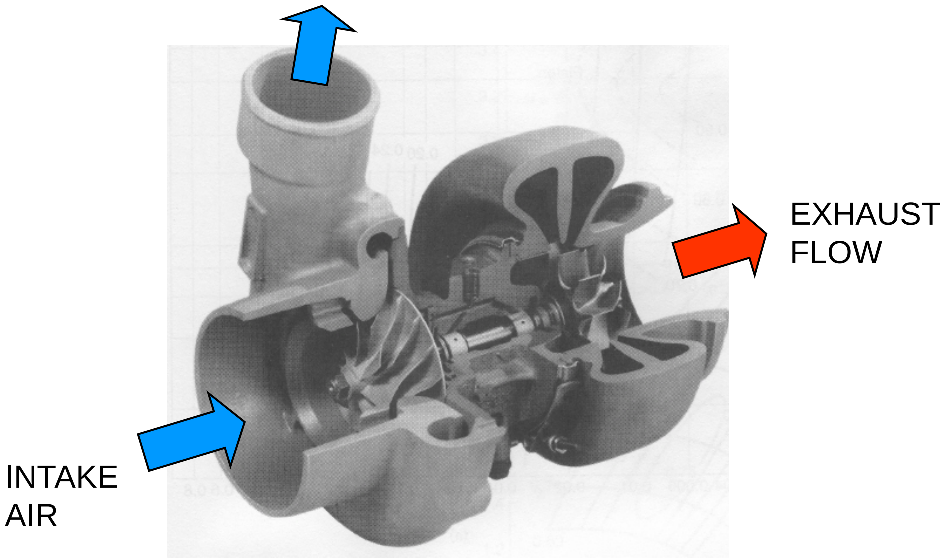




Compressor also raises the gas temperature, so after-coolers are used after the compressor to drop the temperature and thus increase the air density.

The peak pressure in the exhaust system is only slightly greater than atmospheric – small $\Delta P$ across turbine

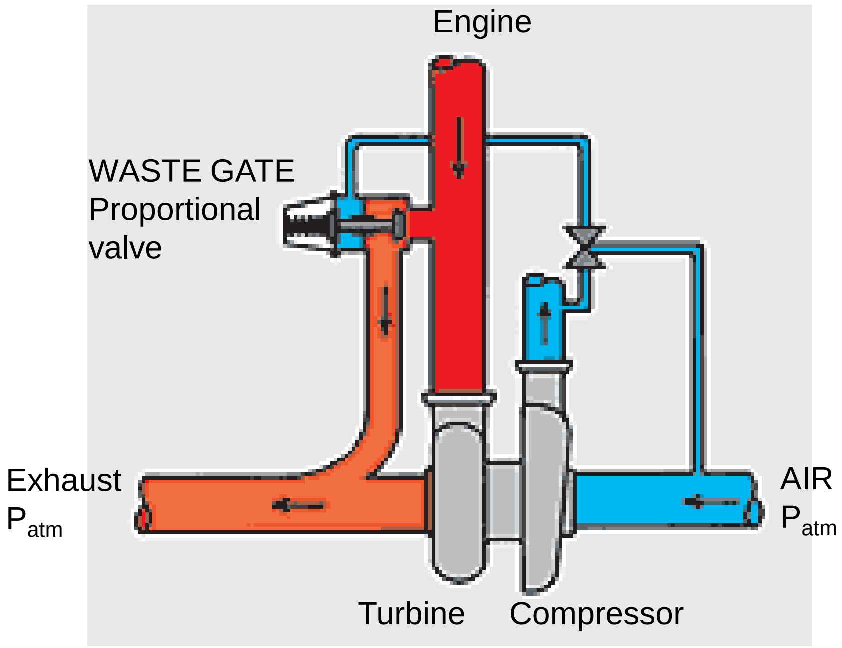
In order to produce enough power to run compressor the turbine speed must be very fast (100k-200k rev/min) – long term reliability an issue

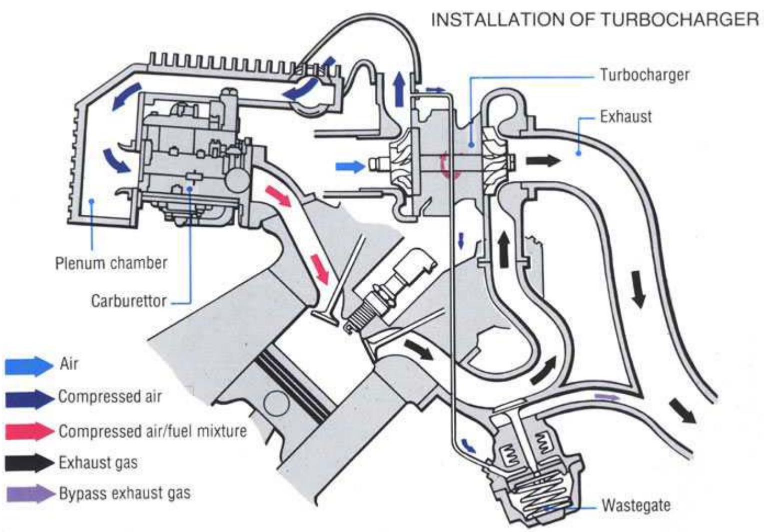
Takes time for turbine to spool up to speed, so when the throttle is opened suddenly there is a delay in achieving peak power - turbo lag



Waste gate valve used to bypass exhaust gas flow from the turbine

It is used as a full-load boost limiter and in new engines used to control the boost level by controlling the amount of bypass using proportional control to improve drivability



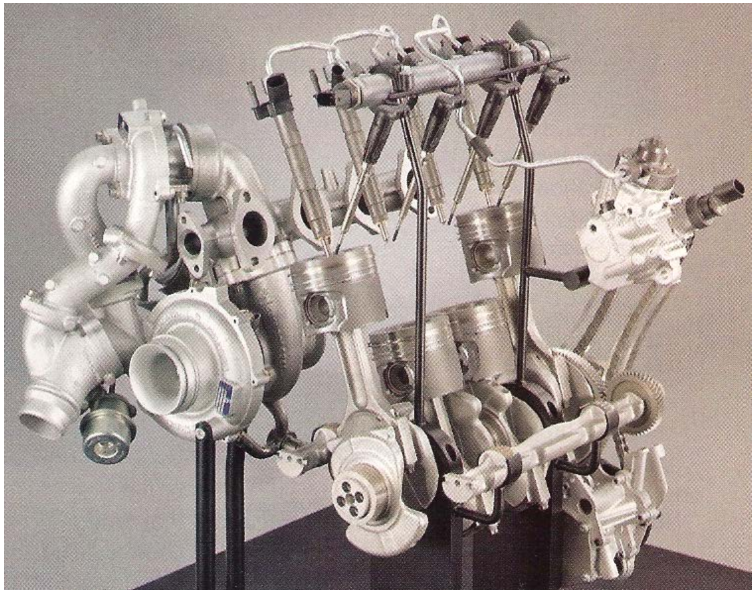
# Turbo Lag Reduction: Twin Turbo

Two turbochargers:
• Smaller turbo for low rpm low load and a larger one for high load
• Smaller turbo gets up to speed faster so reduction in turbo lag

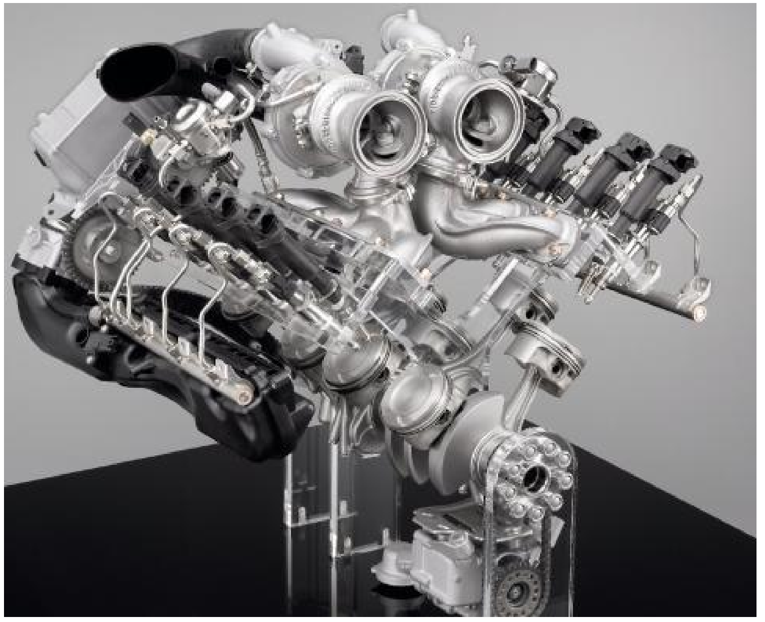
Supercharger/turbo:
• Supercharger used at low speed to eliminate turbo lag
• At higher rpm turbo charger used exclusively to eliminate parasitic load

2006 Volkswagen Golf GT 1.4 L GDI uses twin turbo:

| | |
|---|---|
| 0-2400 rpm | roots blower |
| >3500 rpm | turbo charger |



BMW 2.0L I4 turbo diesel surpasses 100 hp/L (75 kW/L)



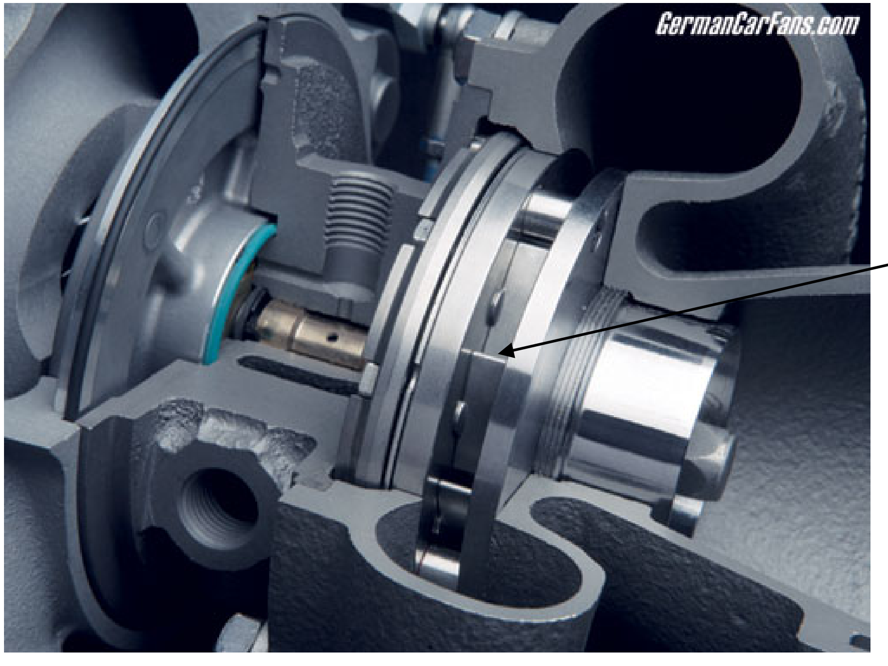
2008 BMW 4.4L V8 valley mounted twin turbo

# Turbo Lag Reduction: Variable Geometry Turbo (VGT)

Variable guide vanes direct the flow of exhaust gas from the engine in exactly the direction required on to the turbine wheel of the turbocharger.

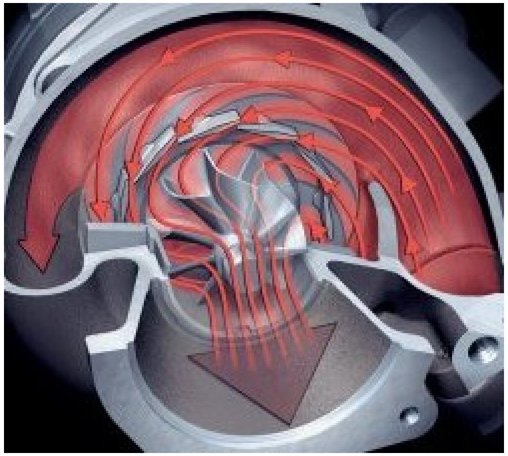
Good response and high torque at low engine speeds as well as superior output and high performance at high engine speeds

VGT used on diesel engines with exhaust temps (700-800 C) not normally used in SI engine due to high exhaust temp (950 C)

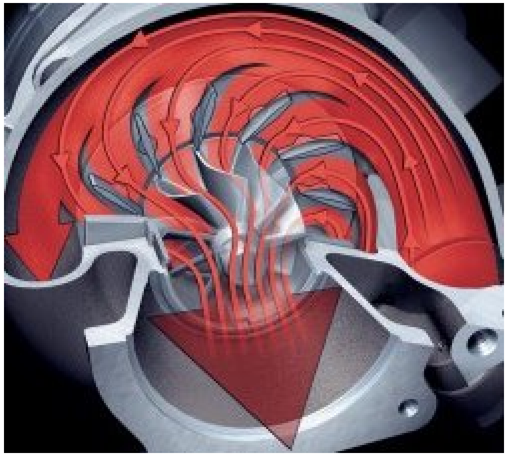





2006 Porche 911  Variable Turbine Geometry uses temperature-resistant materials

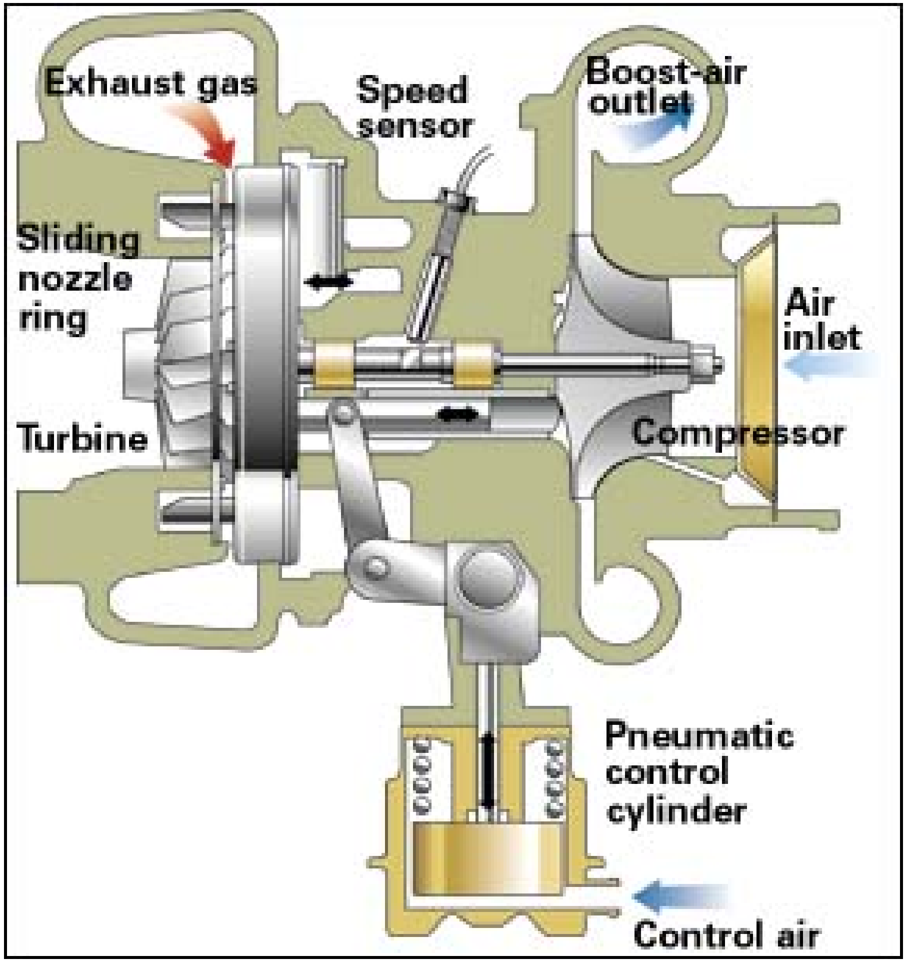


**Low rpm:**
Vanes are partially closed accelerating the exhaust gas flow. The exhaust flow hits the turbine blades at right angle. Both make the turbine spin faster



**High rpm:**
The vanes are fully opened to take advantage of the high exhaust flow. This also releases  the exhaust pressure in the turbocharger, saving the need for waste gate.

# Variable Geometry Turbo




Holset VGT