SELECTION OF PROPULSION SYSTEMS FOR AUTOMOTIVE APPLICATIONS

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Outline

- Specification of propulsion systems for automobiles
  - Ideal motorization
  - Other characteristics

- Alternative thermal motorizations
  - Steam engines
  - Stirling engines
  - Gas turbines

- Piston engines
  - Categories, working principles, torque and power curves
  - Performance
  - Depollution
  - Rotary piston engines

Outline

- Pneumatic motor
- Electric motor
  - Electric traction system
  - Types of electric machines
  - Batteries
- Hybrid motorization
  - Definition
  - Layout
  - Architecture

Outline

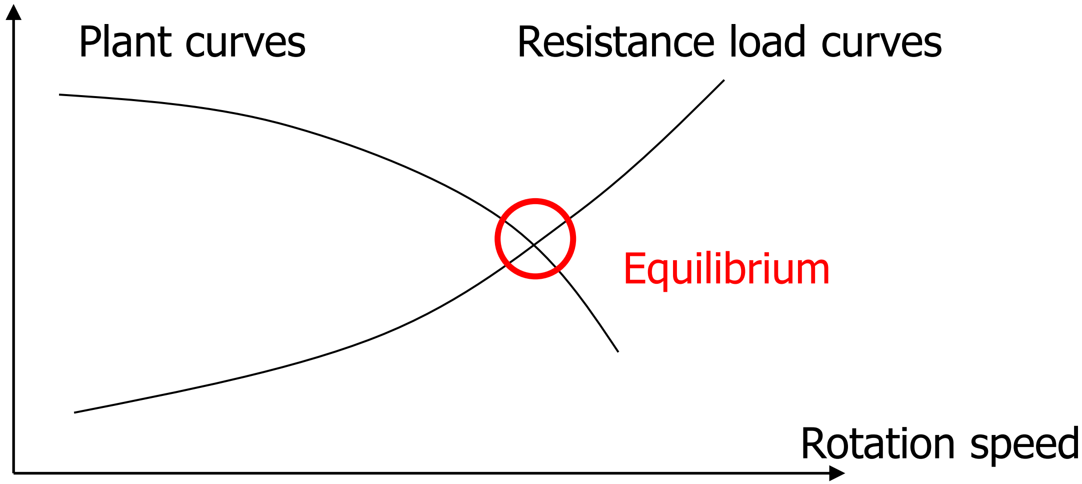
- Fuel cells
  - Definition
  - Fuel cell powered hybrid vehicles

- Comparison

Specification of propulsion systems

Ideal characteristics of a vehicle power plant

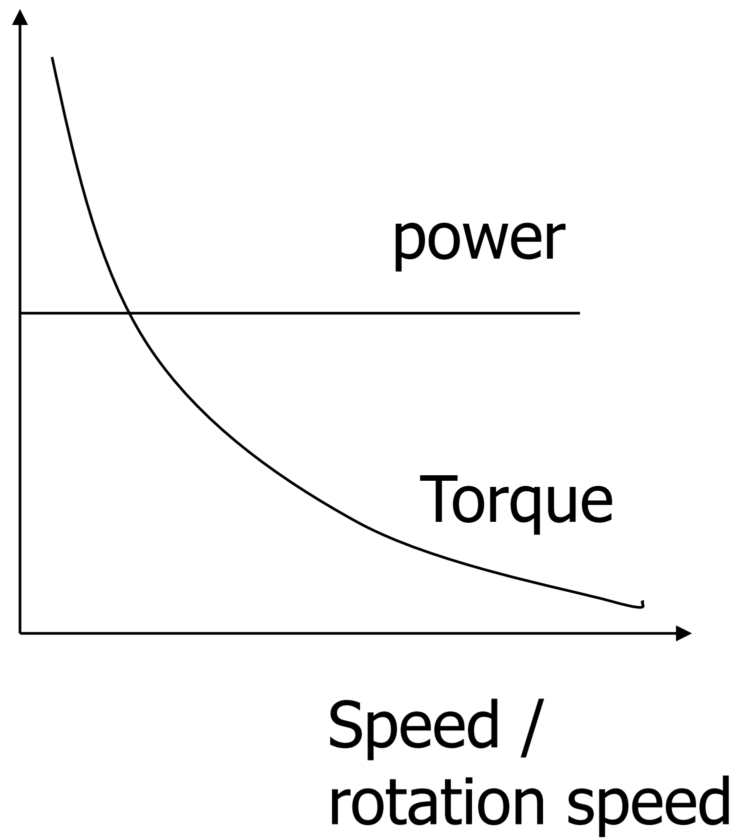
- Remind first that the operating point of a system is governed by the equilibrium between the power (forces) of the plant and the load.
- The operating point is obtained by the intersection of the power (torque) curves of the plant and of the resistance loads



Ideal characteristics of vehicle power plant

- Ideal characteristics of power plant for vehicle propulsion: the power curve should be close to constant power for any regime and so the torque curve is proportional to inverse of speed

- The constant power plant is the propulsion that maximizes the power transmitted to the vehicle for any velocity

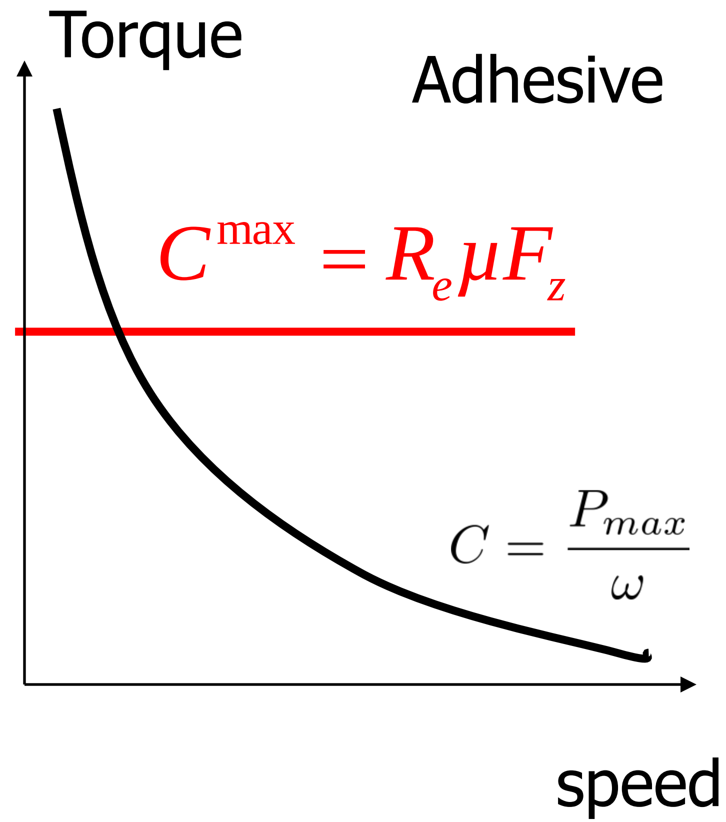


Ideal characteristics of vehicle power plant

- For low speed operation, the friction between the wheel and the road is limiting the transmitted force
- Intrinsic limitation to the maximum

$$F_x^{\max} = \mu F_z$$

$$C^{\max} = R_e F_x^{\max} = \mu F_z R_e$$



Ideal characteristics of vehicle power plant

- <u>Sensitivity of drivers</u>
  - At low speed: we are sensitive to the acceleration:
    - Large acceleration capability
    - Large drawbar pull
    - Large traction force
    - Large gradeability capability

  → High (constant) torque

  - At high speed we are sensitive to the power of the motor to be able to overcome the resistance forces (mainly aerodynamics)

  → High (constant) power

Ideal characteristics of vehicle power plant

- Motorizations that are close to ideal specification
  - Electric machines (DC motor with separately induction supply)
  - Steam engines (Rankine cycles)
- Reciprocating piston engines have less favorable characteristics:
  - Stall rotation speed
  - Non constant torque and power
  - Transmission necessary
- Why are they dominant? Because there are also other criteria to be considered!
  - Weight to power ratio
  - Reasonable energy consumption
  - Low production cost
  - Easy to start…

Ideal characteristics of vehicle power plant

- In addition, piston engines take benefit of a long history of innovation and improvements
  - Improvement of fuel consumption
    - Electronic fuel injection,
    - Lean burn techniques
    - Turbocharged engine and direct injections
    - Variable valve timing…
  - Control of emissions in reducing pollutant emission (CO, NOx, HC, PM, etc.)
    - 3 ways catalytic reduction
    - DeNox and SCR
    - DFP
    - Etc.

Ideal characteristics of vehicle power plant

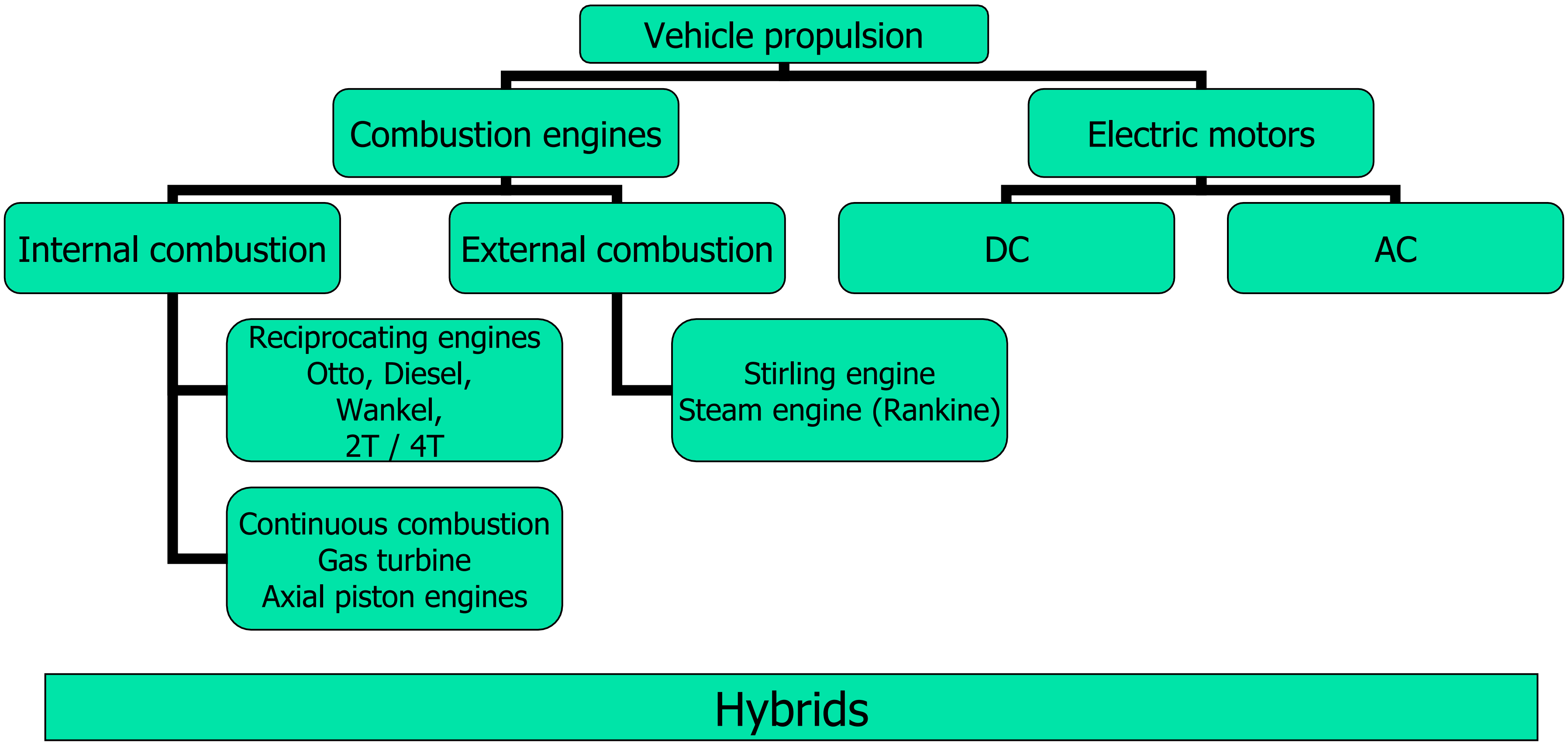
- Other criteria for vehicle power plants
  - Constant power
  - Weight to power ratio
  - Large speed operation range
  - Reasonable energy consumption
  - Control of pollutant emissions
  - Low production cost
  - Easy to start and operate
  - Serial production
  - Low maintenance
  - High reliability
  - Medium lifetime: 200.000 km about 2000 working hours

Alternative power plants

- Other combustion engines (internal / external)
  - Steam engines (Rankine cycle)
  - Gas turbines (Brayton cycle)
  - Stirling engines
  - Rotary piston engines (i.e. Wankel engine)

- Other propulsion systems
  - Electric machines
  - Hydraulic and pneumatic motors
  - Hybrid propulsion systems
  - Fuel cells and electrochemical converters

Alternative power plants



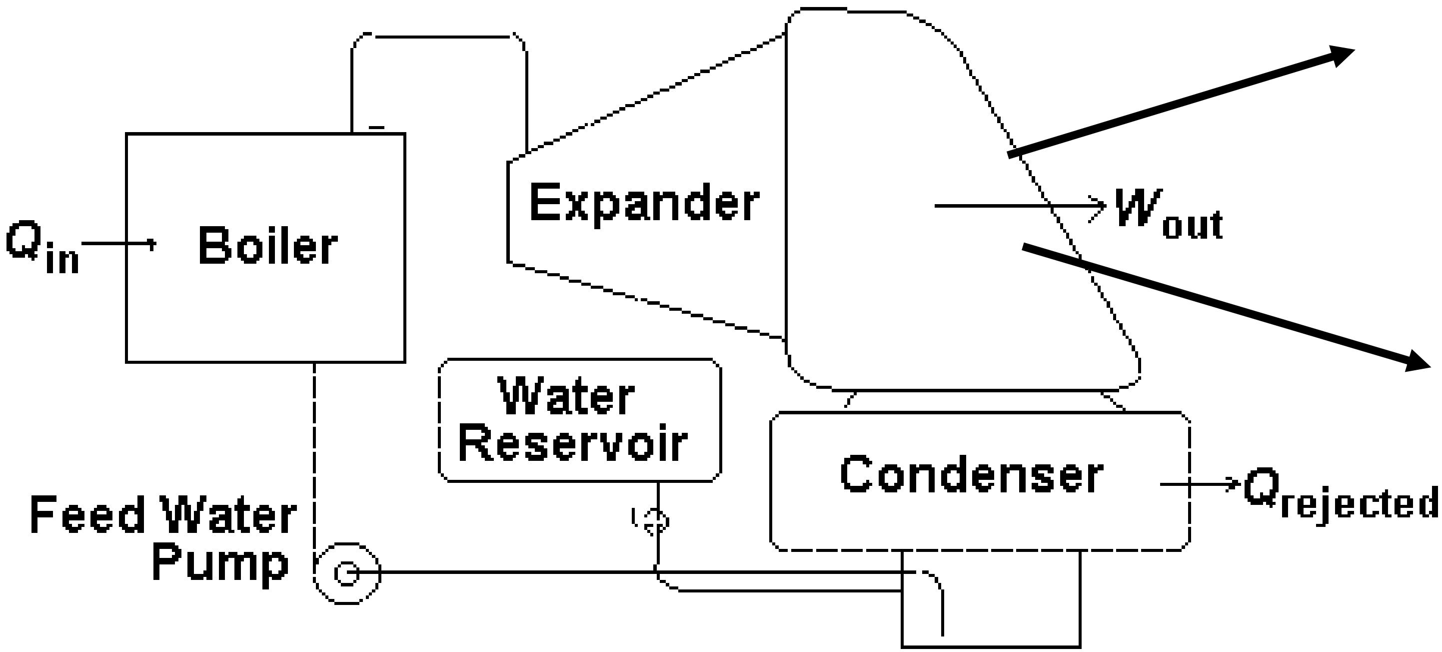
Steam engines

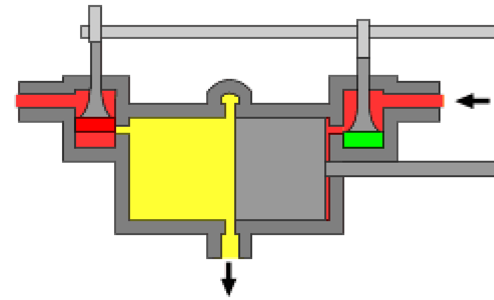
Steam engines

Cugnot's Faradier,
First automotive vehicle

Steam locomotive

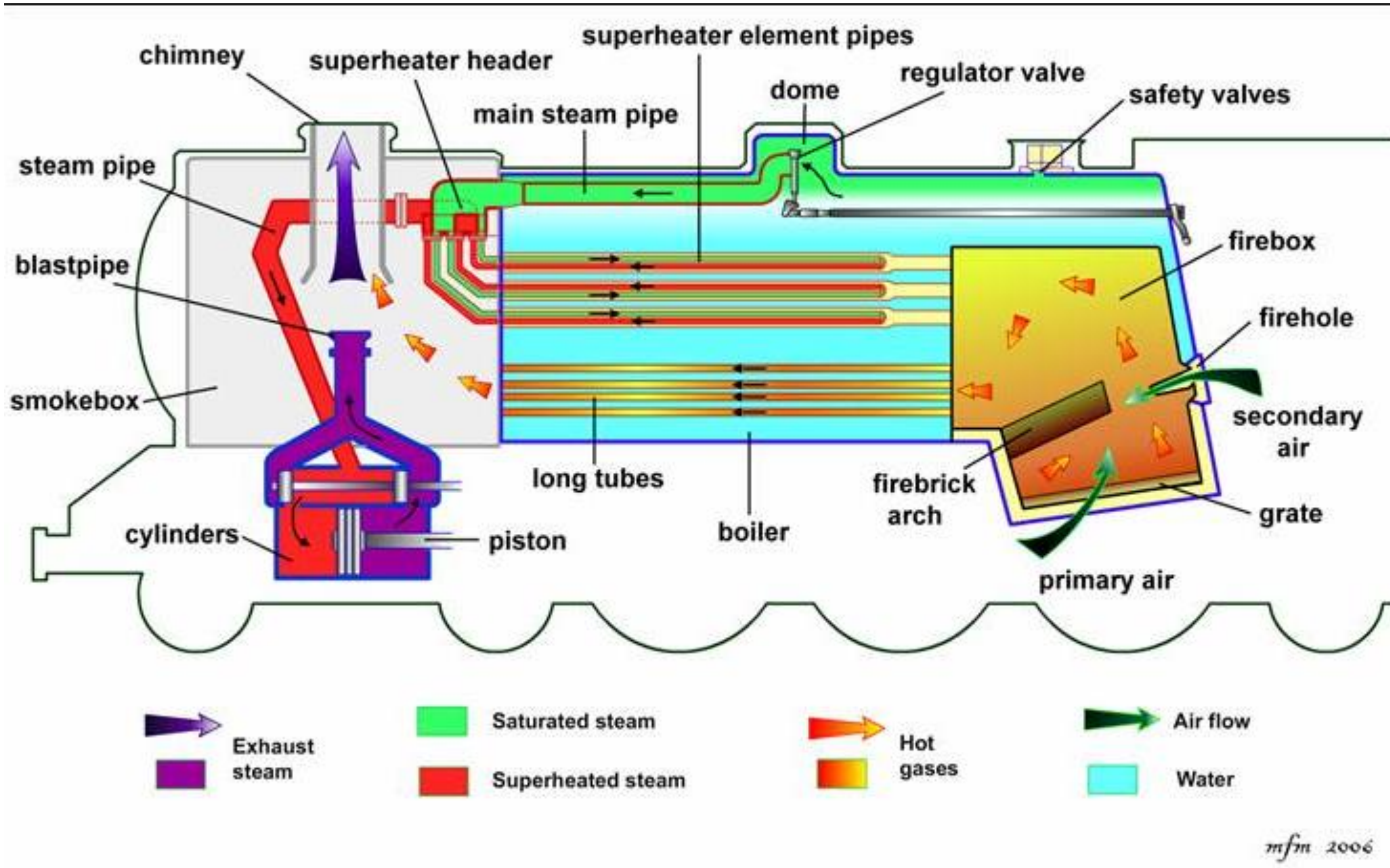
Steam engines



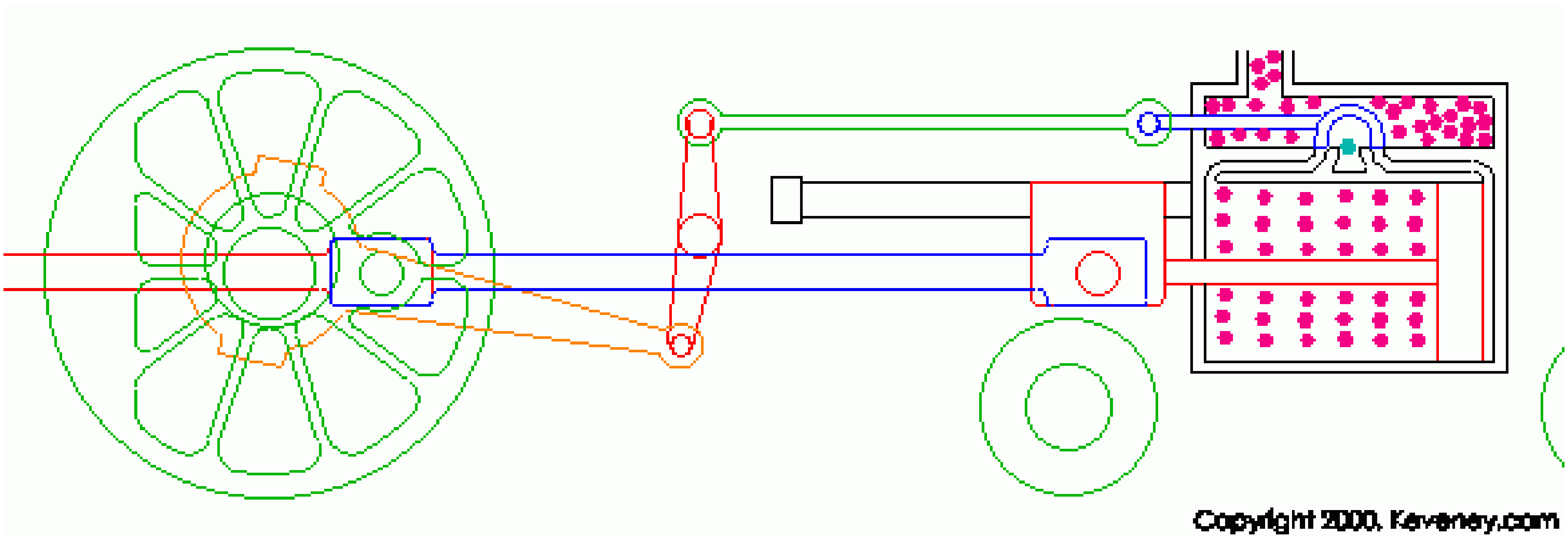


$$W_{out} = W_{in} + Q_{in} - Q_{out}$$

Steam engines



Steam engines

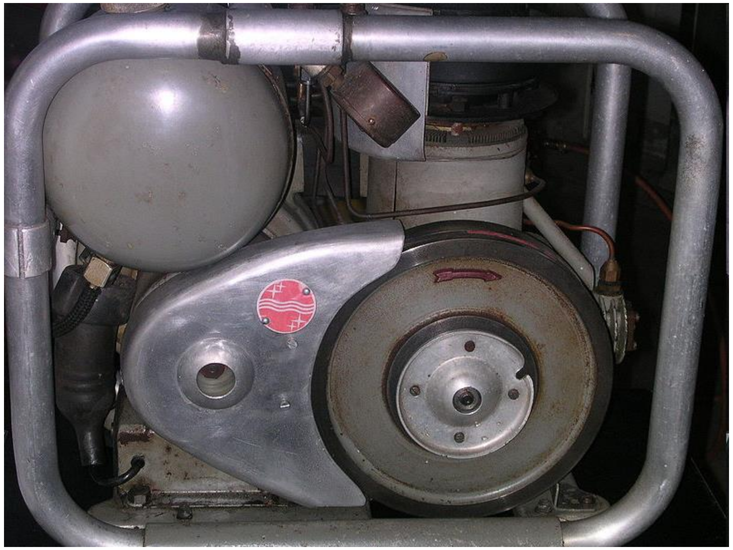


Double piston stroke: uniflow steam engine

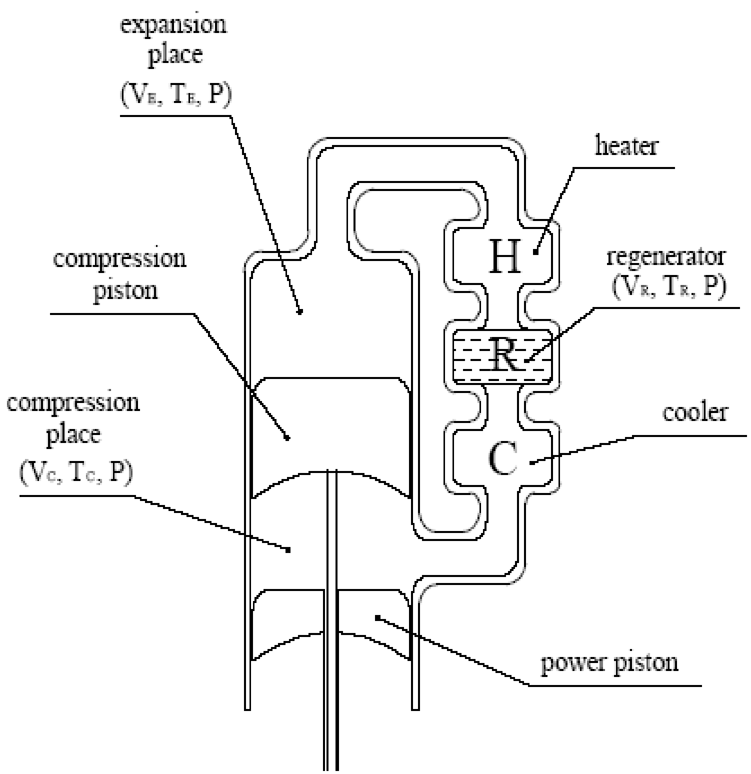
Steam engines

- Advantages:
  - Nearly ideal power / torque curves close to constant power
  - Is able to withstand temporary overcharges producing high torque at low speed, so that there is no need for transmission
  - Large range of possible fuels (external combustion)
  - Emission of pollutants could be widely minimized because of the external combustion
- Drawbacks
  - Poor weight to power ratio
  - Poor volume to power ratio
  - Set-up time is very long
  - Old solutions had a low efficiency (less than 20% in 1800ies steam locomotive with exhaust of steam)

Stirling engine

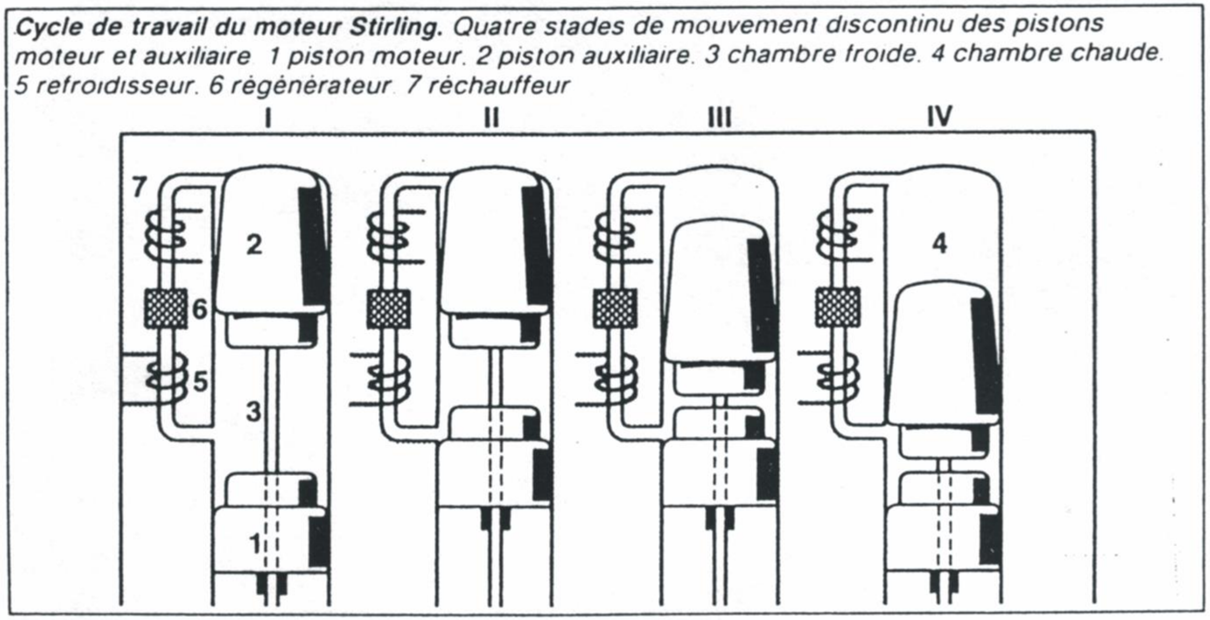


Stirling engine



- Working principle of Stirling engine is based on a closed cycle and a working fluid (helium or hydrogen) that is heated and cooled alternatively
- The Stirling engine is an external combustion engine
- It is made of two iso thermal processes and two iso volume process.
- The heat source calls for an expansion phase while the cold source is associated with the compression phase
- Both sources are separated by a <u>regenerator</u>.
- The theoretical efficiency of Stirling cycle is equal to the Carnot efficiency with the same difference of temperature.

Stirling engine



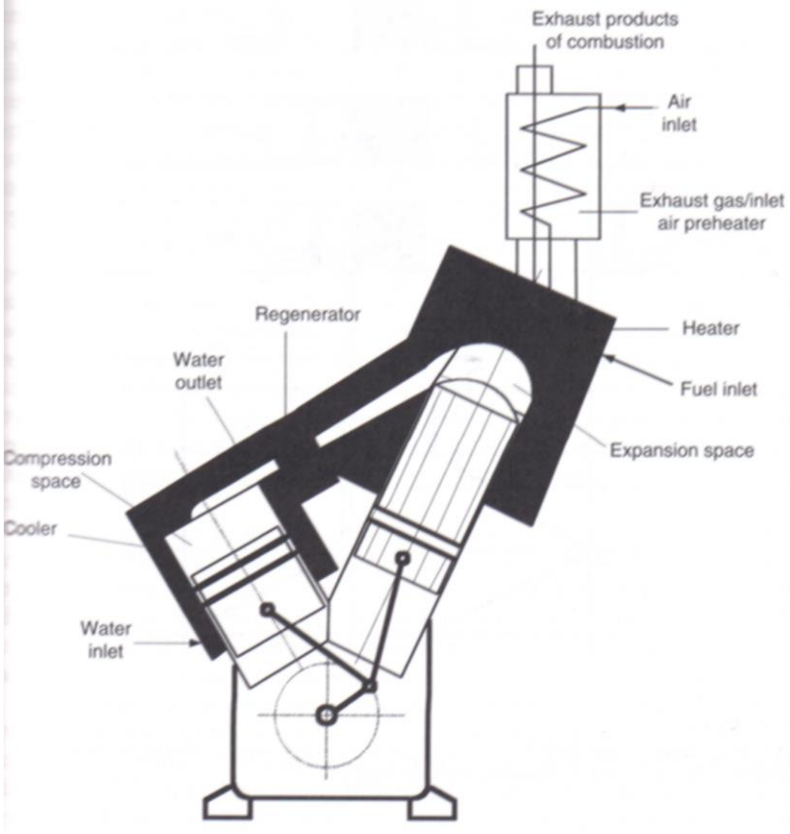
Source Bosch, Automotive handbook

Step I: The power piston (1) in lower position. The displacer piston (2) is moving in upper position. The working fluid is pushed in the cold chamber (3)
Step II: The power piston is compressing the cooled gas in isothermal process
Step III: The displacer piston moves downward and pushes the gas to the hot chamber (4) through the regenerator (6) and the heater (7)
Step IV: The hot gas is expanding and is delivering some work to the power piston. The displacer piston is moved downward

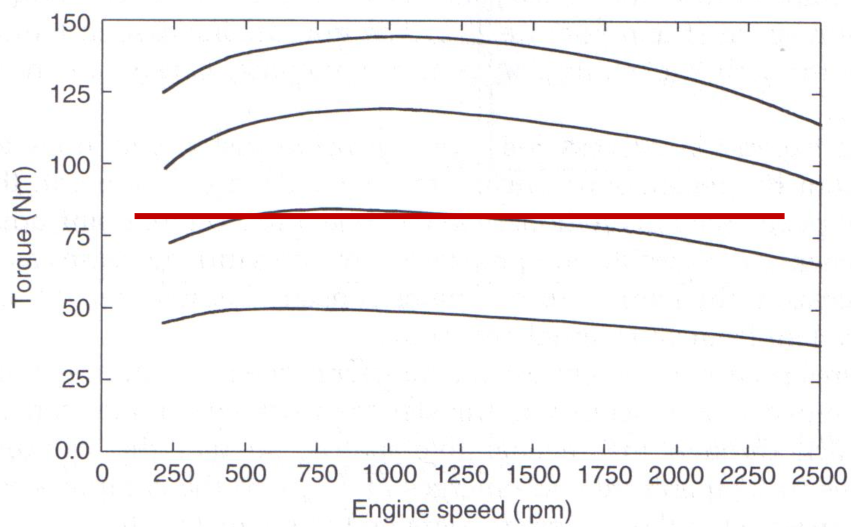
Stirling engine

- Advantages:
  - Very low specific pollutants emissions (external combustion)
  - Low noise generation
  - Several fuels can be used
  - Practical efficiency is equivalent to the best Diesel engines
- Drawbacks
  - In the state of the art: poor power to weight ratio
  - Mechanically complex
  - Low acceleration capabilities (better suited to stationary applications)
  - Too high manufacturing cost
  - Penalized by the large heat exchanger surface (air / air exchanger)

Stirling engine



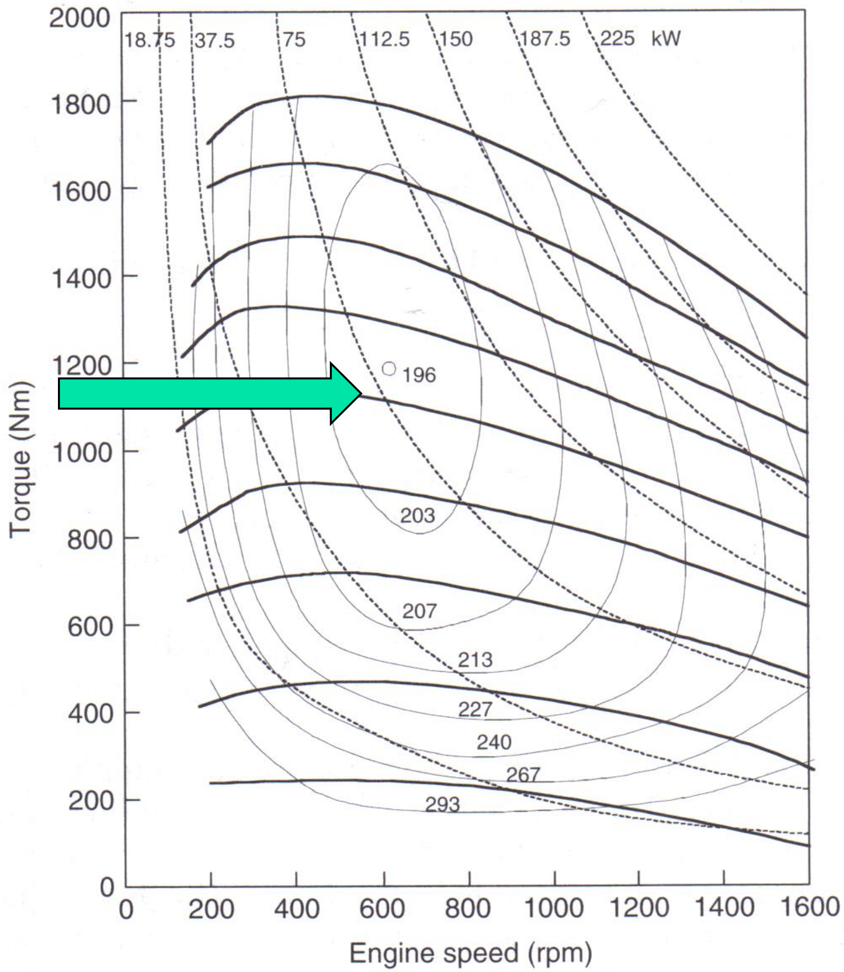
Practical layout of a Stirling engines with opposed pistons (Eshani et al. 2005)



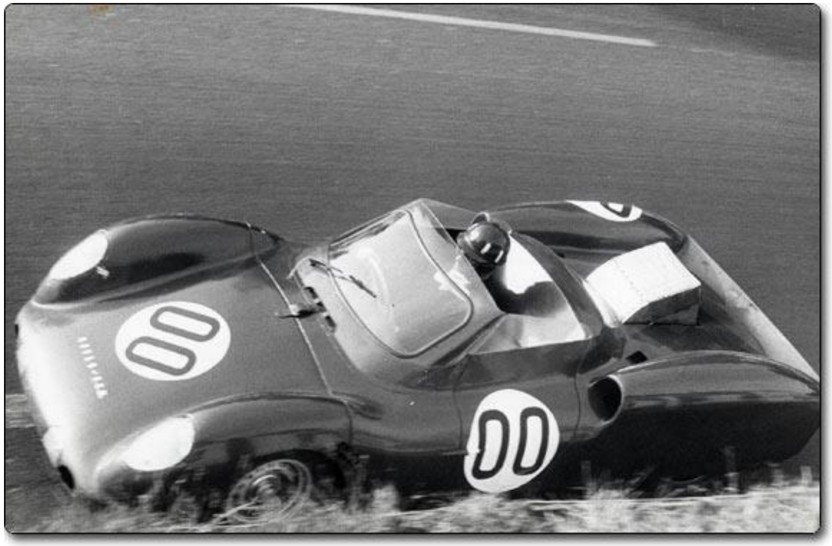
Torque / speed curves of a Stirling engine (Eshani et al. 2005)

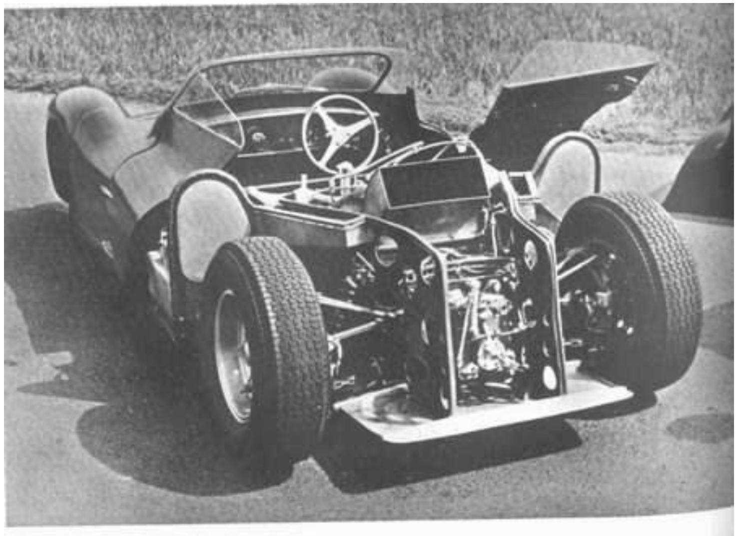
Stirling engine

Performance and fuel consumption of a Stirling engine with 4 cylinders for vehicle traction (Eshani et al. 2005)



Gas turbine

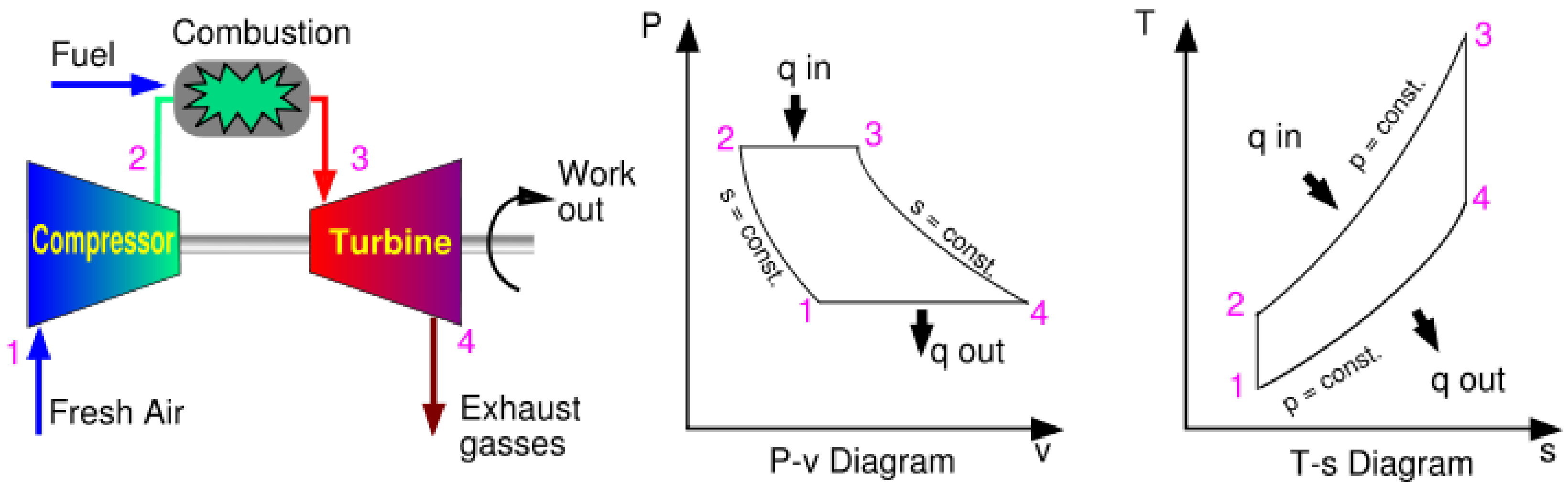




Gas Turbine

- Gas turbines are ones of the oldest types of internal combustion engines
- Gas turbines are based on the Brayton cycle, which is an open cycle
- They include an air compressor, a combustion chamber and an expansion turbine
- Turbine is actuated by the working fluid and converts the heat energy of the fluid into mechanical power. The shaft can be connected to a generator or connected to the wheels (generally via a mechanical gear box)
- The combustion chamber of the gas turbine can burn a wide variety of fuels: kerosene, gasoline, natural gas…

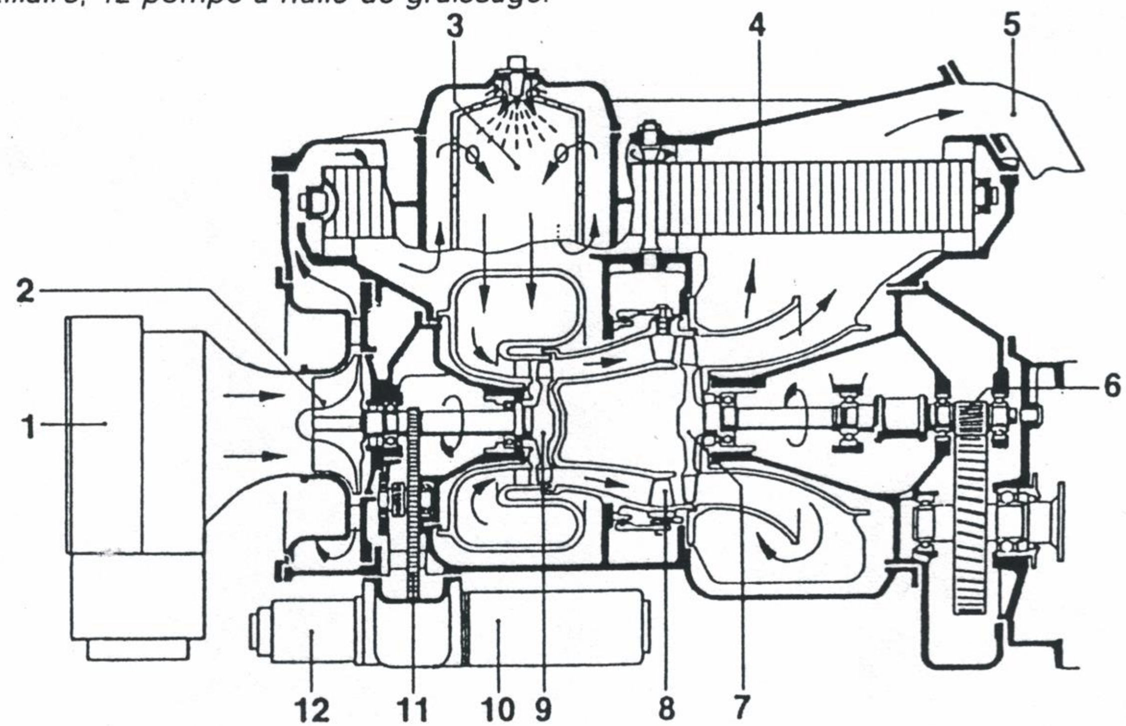
Gas Turbine



Idealized Brayton Cycle

Gas Turbine

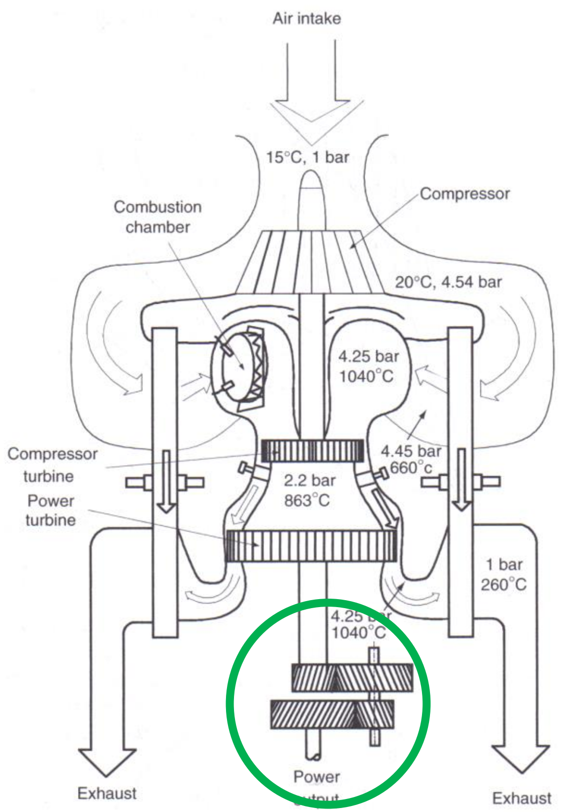
Turbine à gaz. 1 filtre et silencieux, 2 compresseur radial, 3 chambre de combustion, 4 échangeur de chaleur, 5 conduit des gaz d'échappement, 6 réducteur, 7 turbine de travail, 8 aubes fixes réglables, 9 turbine du compresseur, 10 démarreur, 11 entraînement de l'équipement auxiliaire, 12 pompe à huile de graissage.



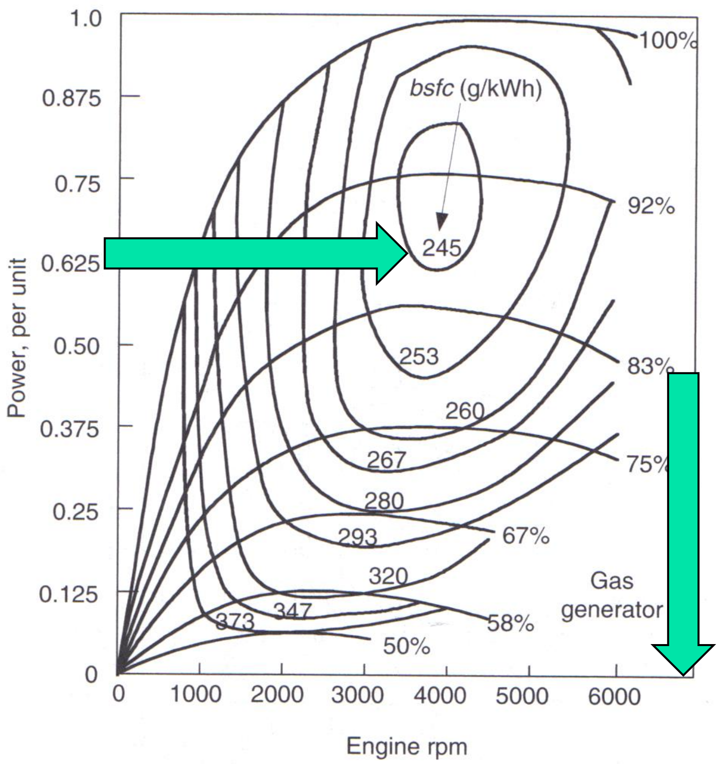
Gas Turbine

- Advantages:
  - High power to weight ratio
  - Ability to use a wide range of fuels
  - Low emissions of pollutants CO et HC
  - Good mechanical balancing and low vibrations because of the rotary motion
  - Flat torque curves for double shaft solutions
  - Long periods between two maintenances
- Disadvantages
  - Low efficiency away from the design point
  - Bad fuel efficiency away from the nominal design point
  - High cost (high temperature materials, heat exchangers)
  - Bad dynamic responses (slow rotation acceleration)
  - High rotation speed ➔ need for a large reduction ratio gear box to connect to the wheels (and so a weight penalty)

Gas Turbine



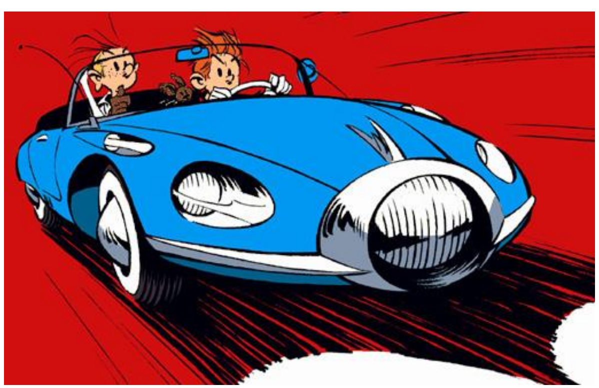
Gas turbine with heat exchanger
Eshani et al. 2005



Performance and fuel consumption of a gas turbine Konograd KKT. Eshani et al. 2005

Gas Turbine

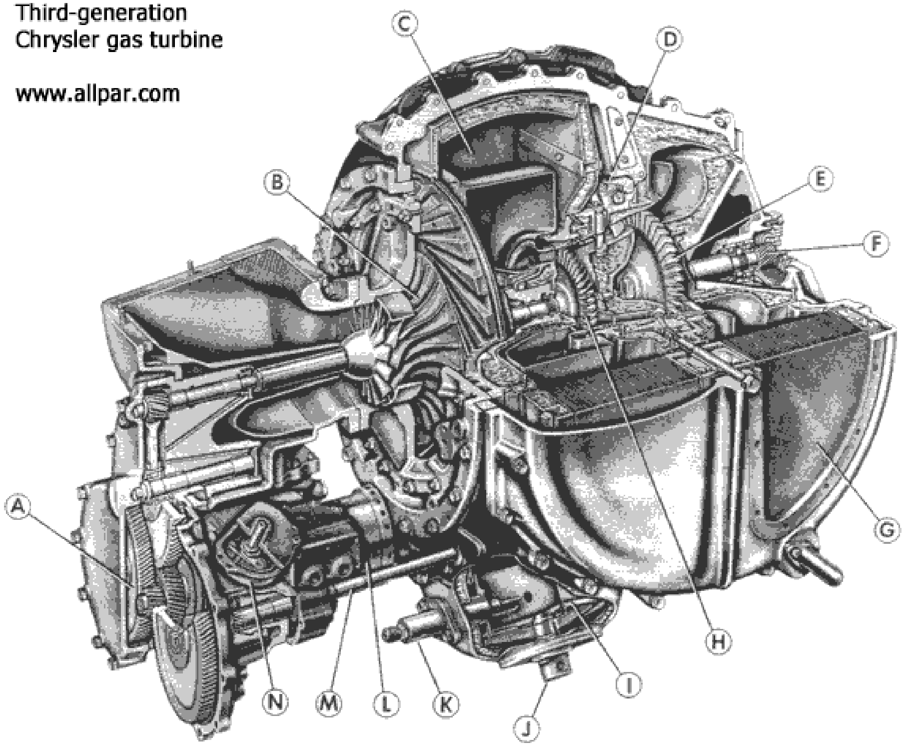
- One reports several tentative applications of gas turbines to automobile
  - As soon as the WWII, Rover has been interested in gas turbines and has realized prototypes between 1950 and 1961.
  - In 1963, the Rover BRM 00 has participated to the 24 hours of Le Mans with Graham Hill et Richie Gunther and has finished in 8th position.
  - Later, gas turbines have been applied in heavy vehicles such as M1 Abraham armored vehicles.



Gas Turbine

Third-generation
Chrysler gas turbine

www.allpar.com



MAIN COMPONENTS OF THE TWIN-REGENERATOR GAS TURBINE: (A) accessory drive; (B) compressor; (C) right regenerator rotor; (D) variable nozzle unit; (E) power turbine; (F) reduction gear; (G) left regenerator rotor; (H) gas generator turbine; (I) burner; (J) fuel nozzle; (K) igniter; (L) starter-generator; (M) regenerator drive shaft; (N) ignition unit.

Turbine Car by Chrysler (1963)

Piston engines

History of ICE

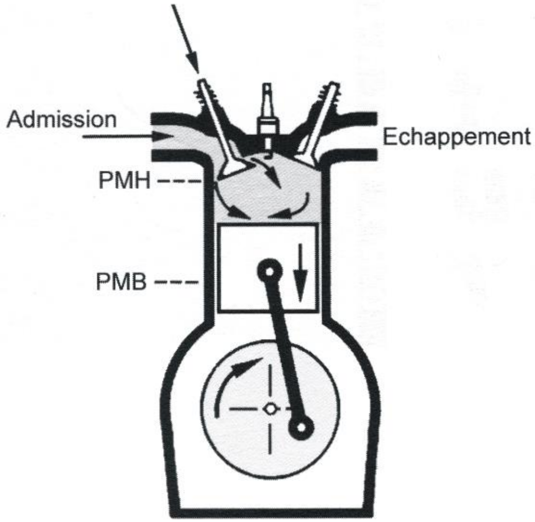
- 1700: Steam engine
- 1860: Lenoir motor (efficiency η~5%)
- 1862: Beau de Rochas defines the working principles of internal combustion engines
- 1867: Motor of Otto & Langen (η~11% and rotation <90 rpm)
- 1876: Otto invents the 4-stroke engine with spark ignition (η~14% and rotation < 160 rpm)
- 1880: Two-stroke engine by Dugan
- 1892: Diesel invents the 4-stroke diesel engine with compression ignition
- 1957: Wankel invents the rotary piston engine

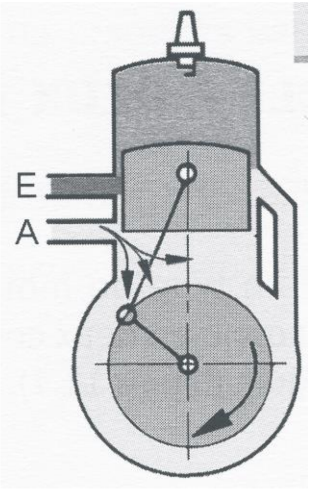
Piston engines (Gasoline and Diesel)

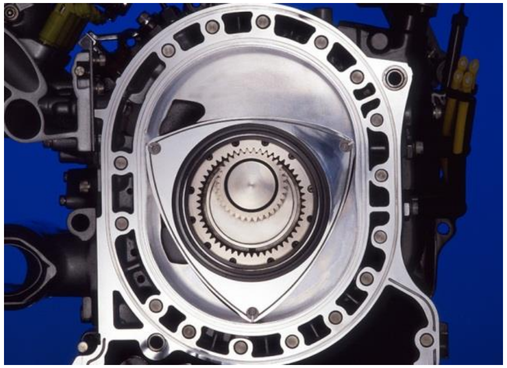
One distinguishes several variants

- Fuels:
  - Gasoline, diesel, LPG, Natural Gas, H_2, bio-fuels…
- Thermodynamic cycles:
  - Otto : spark ignition engine
  - Diesel : compression ignition engine
- Fuel injection
  - Direct or indirect
  - Turbocharged or atmospheric
- Cycles
  - 2 strokes
  - 4 strokes

Classification

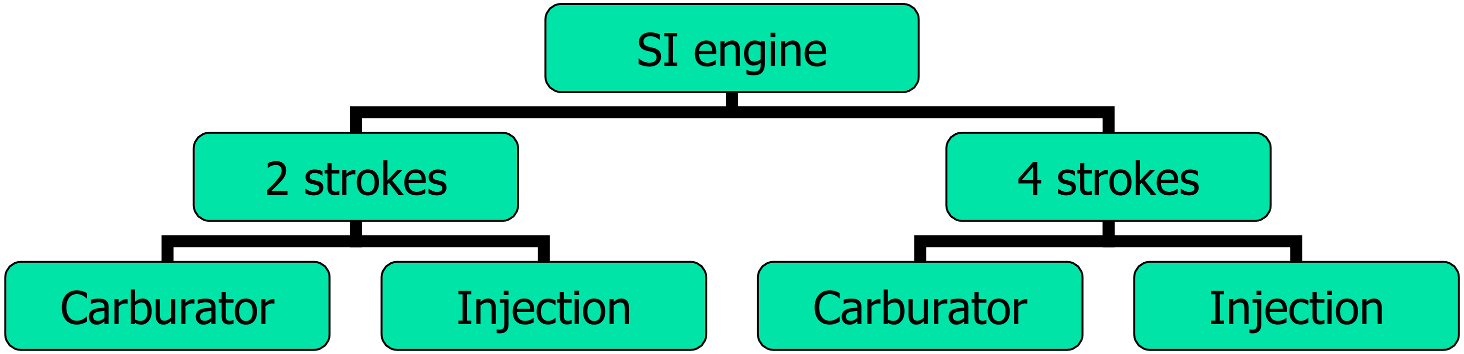


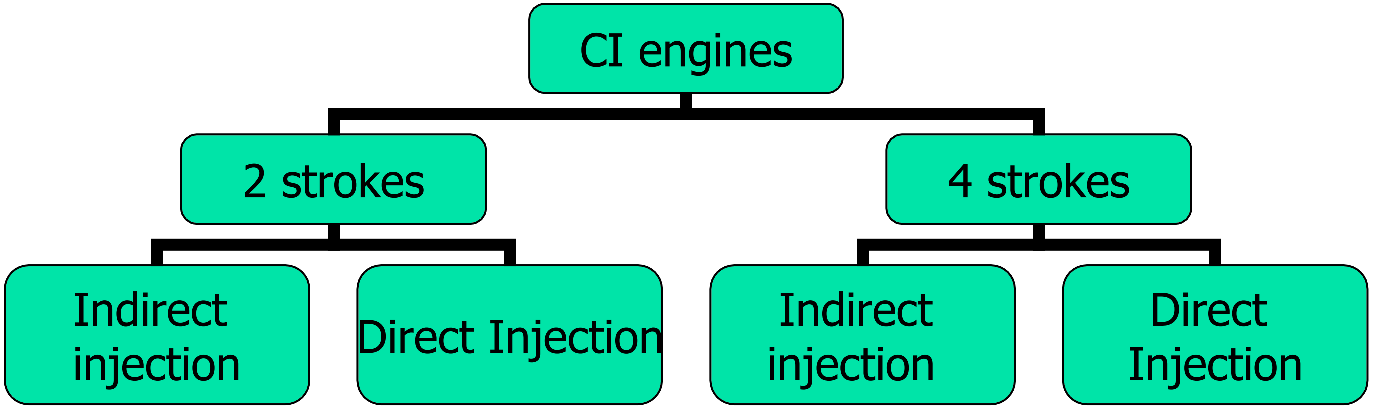




- The 4-stroke engine performs the 4 steps in 4 strokes, that is, in two crankshaft rotations.
- The 2-stroke engine carries out the four steps in two strokes, that is, in one crankshaft rotation.
- The rotary engine: the rotating motion is replacing the alternating motion. The rotor rotation realizes the four steps in one rotation

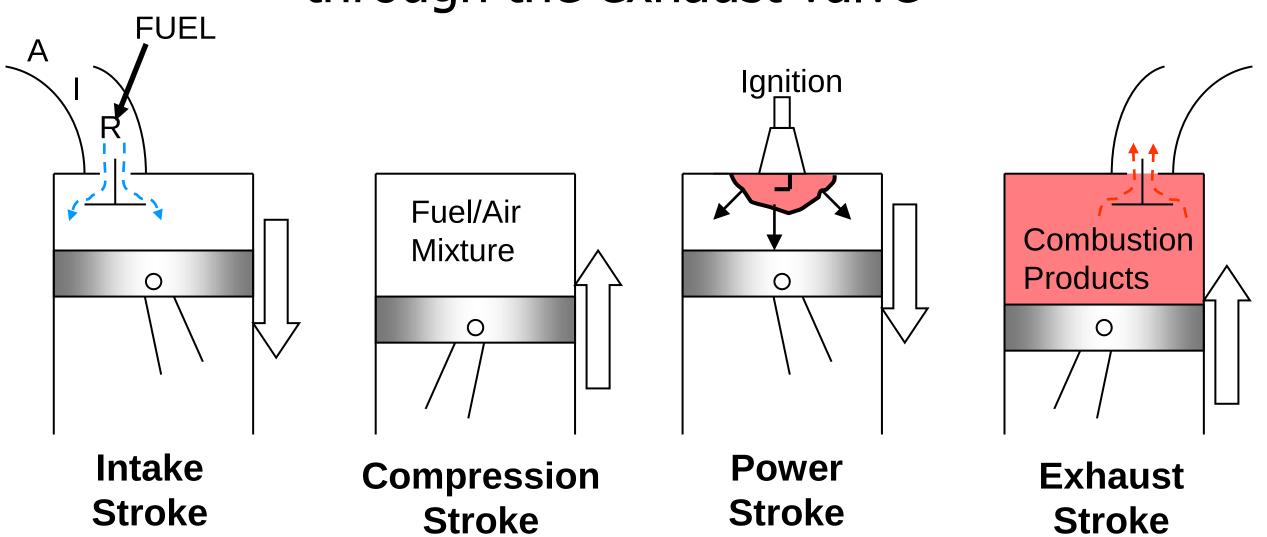
Classification





4 stroke engines: gasoline

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



4 stroke engines: gasoline

- Advantages:
  - The spark ignition engine relies on a well-known principle, on mature and well mastered technologies,
  - Good weight to power ratio
  - It is able to work while burning different fuels: gasoline, diesel, methanol, ethanol, natural gas, LPG, hydrogen…
  - It takes benefit of a large number of technological developments to control the emissions of pollutants

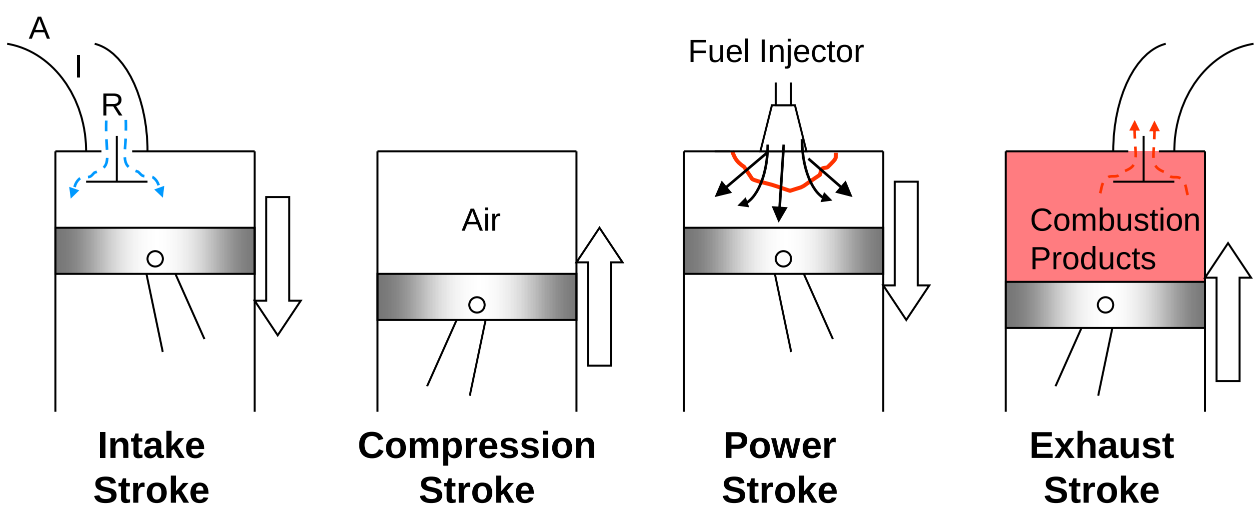
- Disadvantages:
  - Bad fuel economy and tedious emission control (HC, CO et NOx) when operated at part load and cold temperature conditions

4 stroke engines: diesel

- The Four stroke Compression Ignition (CI) Engine is generally denoted as the Diesel engine
- The cycle is similar to the Otto cycle albeit that it requires a high compression ratio and a low dilution (air fuel) ratio.
- The air is admitted in the chamber and then compressed. The temperature rises the ignition point and then the fuel is injected at high pressure. It can inflame spontaneously.
- There is no need for a spark and so keeping a stoichiometric air fuel ratio is not necessary.

4 stroke engines: diesel

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



4 stroke engines: Diesel

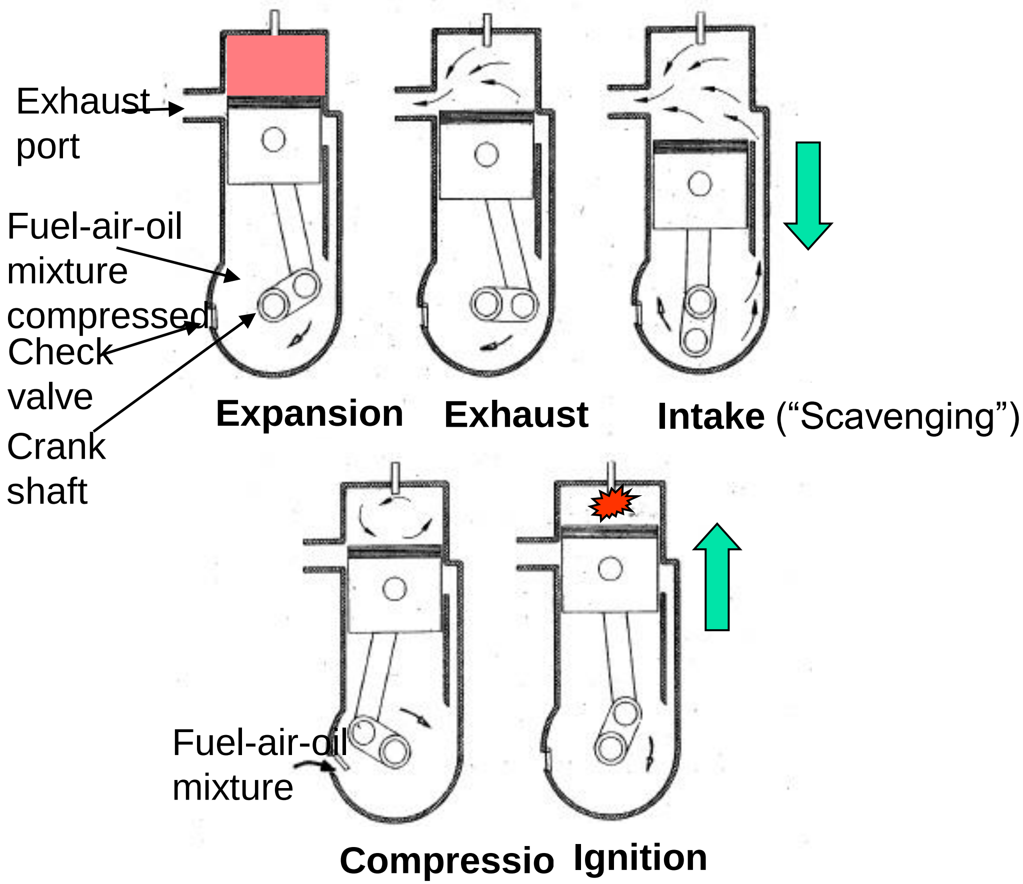
- Advantages:
  - Higher efficiency because of the higher compression ratio
  - Largely developed and technological availability
  - Low CO and HC emissions

- Disadvantages:
  - Larger PM and NOx emissions ratios
  - Heavier and larger than gasoline engines, but still good compared to other technologies

2-stroke engines

- Dugald Clerk has invented the 2-stroke engine in 1878 in order to increase the power to weight ratio for an equal volume.
- The 2-stroke engines is also simpler with regards to the valve system
- The 2-stroke principle is applicable to both spark ignition engine and to compression ignition engine. It is however more usual with spark ignition engines (small engines for tools).
- The 2-stroke engine involves two strokes, and the cycle is carried out during a single crankshaft revolution.

2-stroke engines



Stroke 1: Combustion products expand doing work. Gas are sent to exhaust line.
Fresh air (and fuel) replaces the exhaust gas.

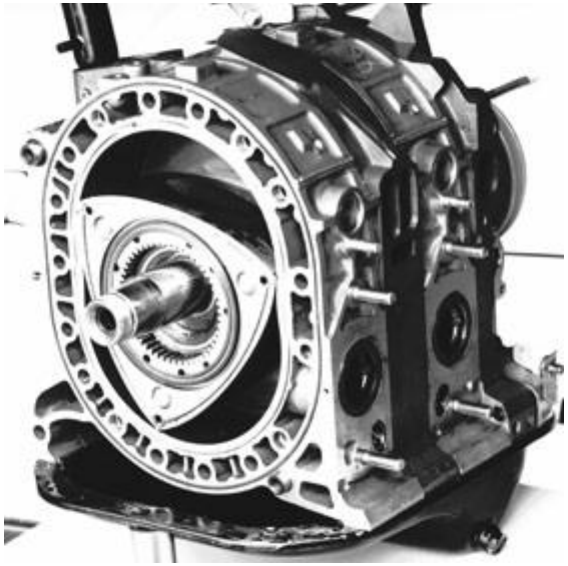
Stroke 2: Fuel-air mixture is introduced into the cylinder and is then compressed. Combustion is initiated at the end of the stroke.

* Power delivered to the crankshaft on every revolution

2-stroke engines

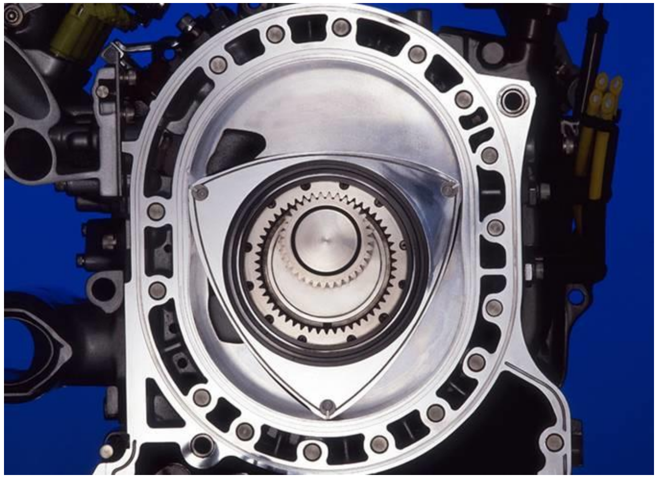
- Compared to 4-stroke engines, 2-stroke engines have
  - A higher power to weight ratio since there is one power stroke per crank shaft revolution.
  - Simple valve design.
  - A lower fabrication cost.
  - A lower weight.
- However, several drawbacks:
  - Incomplete scavenging or too much scavenging.
  - Higher emission rates: emissions of HC, PM, CO are quite badly controlled (even though mitigated for CI 2-stroke engine)
  - Burns oil mixed in with the fuel
  - Exhaust gas treatment is less developed than for the 4-stroke engines
- Most often used for small engine applications such as lawn mowers, marine outboard engines, motorcycles….

Wankel Rotary Engines



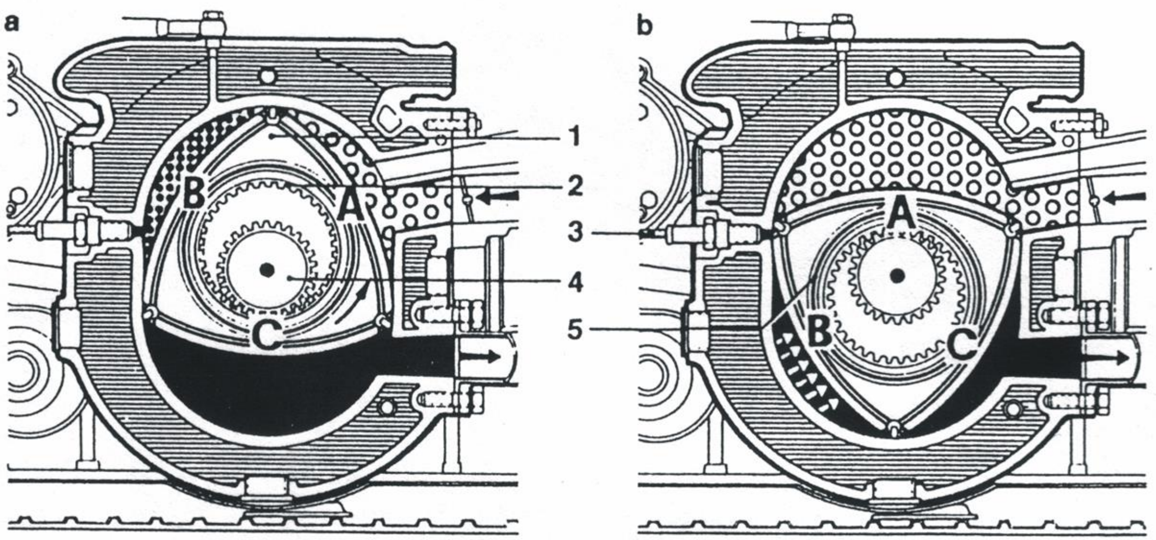
Wankel rotary engines

- In 1951, Felix Wankel began to develop the rotary piston engine at NSU.
- Instead of the reciprocating mechanism, the rotary engine uses a rotary mechanism to convert the gas pressure into a rotating motion instead of using reciprocating pistons.
- The four-stroke cycle takes place in a variable volume pocket located between the interior of an oval-like epitrochoid-shaped housing and the rotor that is similar in shape to a Reuleaux triangle.



Wankel rotary engines

Conception et mode de fonctionnement du moteur à piston rotatif Wankel.
1 piston, 2 denture intérieure dans le piston, 3 bougie d'allumage, 4 pignon fixe, 5 bande de roulement de l'excentrique.
a: la chambre A aspire, la chambre B comprime, les gaz brûlés sont expulsés de la chambre C. (Le passage des gaz dans l'étranglement de la trochoïde est possible grâce à des cavités ménagées dans les flancs du piston).
b: la chambre A est remplie de gaz frais, les gaz en cours de combustion se détendent dans la chambre B et font tourner l'arbre à excentrique par l'intermédiaire du piston; les gaz brûlés sont ensuite expulsés de la chambre C. La phase suivante correspond à nouveau à la partie a de la figure, si ce n'est que la chambre C a pris la place de la chambre A. En un tiers de rotation (120°), le piston a ainsi exécuté le cycle complet du procédé à quatre temps sur ses trois flancs, pendant ce temps, l'arbre à excentrique a effectué une rotation complète.



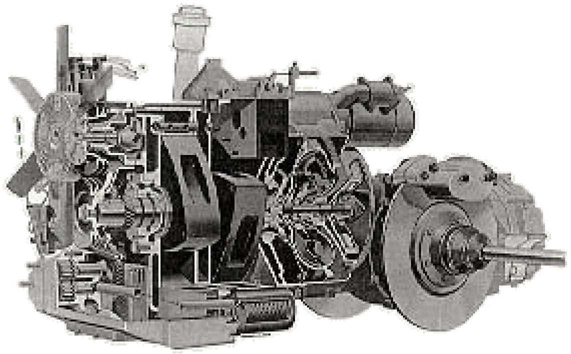
Bosch (2002)

Wankel rotary engines

- Advantages
  - Perfect balancing of the rotating mass that allows high rotation speeds
  - Favorable (linear) torque curve
  - Compact and simple design
  - Lightweight
  - Can be operated with various fuels such as H_2
- Disadvantages
  - Lower efficiency than piston engines (lower compression ratio)
  - Slightly higher specific emissions (HC, NOx, CO)
  - The combustion chamber does not allow the compression ignition (Diesel) cycles
  - Manufacturing cost is more important

Wankel rotary engines

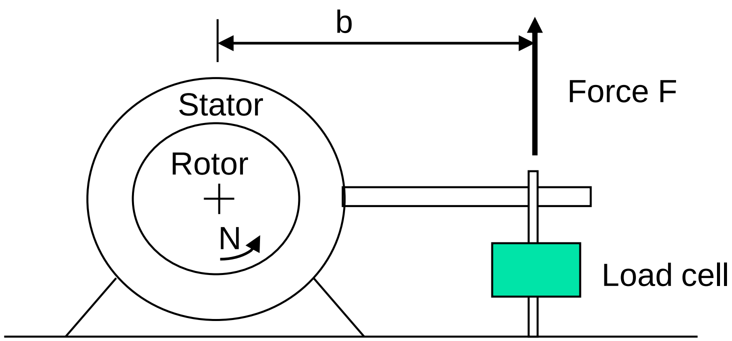
- Wankel rotary engines were first used in NSU vehicles
- After the NSU bankruptcy, Mazda bought the rights for the patents of the rotary engines
- In use for a limited number of models, especially sport cars (e.g. Mazda RX8)
- Future applications of rotary engines may be related to its ability to be operated with alternative gaseous fuels such as H_2



Piston engine performance

Measure of torque and power developed by the engine

- The torque is measured on the output shaft mounted on the crankshaft using a dynamometer



- The torque C developed by the engine is given by

$$\mathcal{C} = F \cdot b \quad [\mathrm{J} = \mathrm{N.m}]$$

- The power absorbed by the brake is the product of the torque times the rotation speed N [tr/s]

$$\dot{W} = \mathcal{C} \cdot \omega = \mathcal{C} \cdot 2\pi \cdot N \quad [\mathrm{Watt} = \mathrm{N.m.rad/s}]$$

Measure of torque and power developed by the engine

- Torque is the ability of the engine to produce a work while power describes the rate at which it is able to develop that work.

- The term effective power, developed at the brake, is used to describe the power measured at the output shaft, which is the usable and transferable power to the load: $\dot{W}_b$

- The brake power is lower than the (indicated) power generated by the gas in the cylinders because of friction losses and parasitic loads of the auxiliaries (water and oil pumps, compressor...).

- The power produced in the cylinder by the working fluid is called the indicated power: $\dot{W}_i$

Engine mechanical efficiency

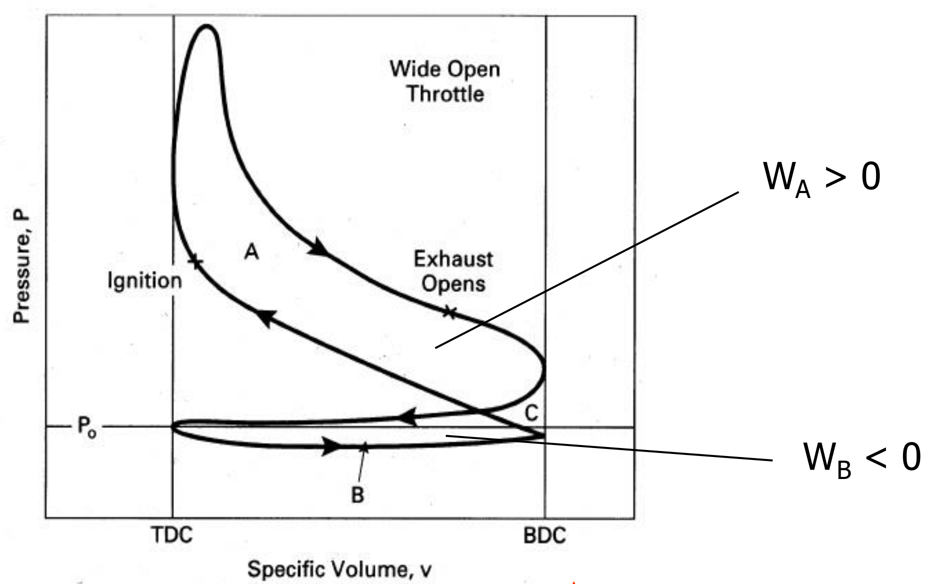
- A part of the thermodynamic work produced by the fluid is lost to overcome the engine frictions, the heat losses as well as the work to pump the gas in and out of the engine
- The friction power $\dot{W}_f$ is used to estimate as a whole the power dissipated by these losses:

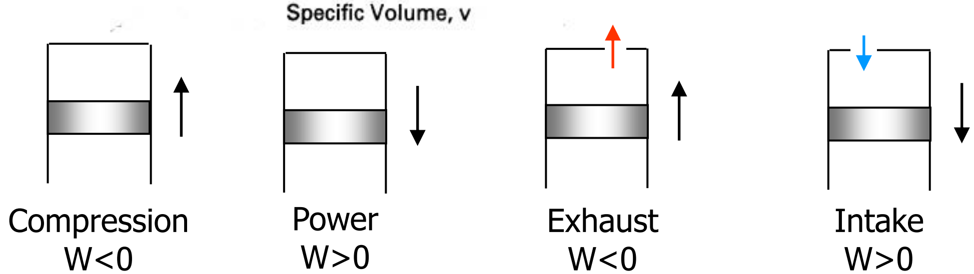
$$\dot{W}_f = \dot{W}_{i,g} - \dot{W}_b$$

- The mechanical efficiency of the engine is defined accordingly as:

$$\eta_m = \frac{\dot{W}_b}{\dot{W}_{i,g}} = 1 - \frac{\dot{W}_f}{\dot{W}_{i,g}}$$

Measure of indicated torque and power





- Given the cylinder pressure data over the operating cycle of the engine one can compute the work done by the gas on the piston.
- This data is typically given as p vs V
- The indicated work per cycle is given by

$$W_i = \oint p \, dV$$

Measure of torque and power developed by the engine

- Indicated power is given by

$$\dot{W}_i = \frac{W_i \cdot N}{n_R}$$

- where
  - N – crankshaft speed in rev/s
  - n_R – number of crank revolutions per cycle
    - = 2 for 4-stroke
    - = 1 for 2-stroke

- Power can be increased by increasing:
  - the engine size, V_d
  - compression ratio, r_c
  - engine speed, N

Mean effective pressure

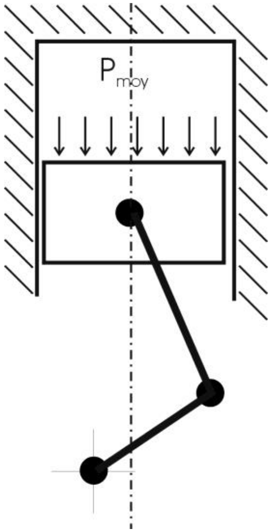
- The indicated mean effective pressure imep is a fictitious *constant* pressure that would produce the same work per cycle as if it acted on the piston during the power stroke

- The expression of the work done during the working stroke by one piston

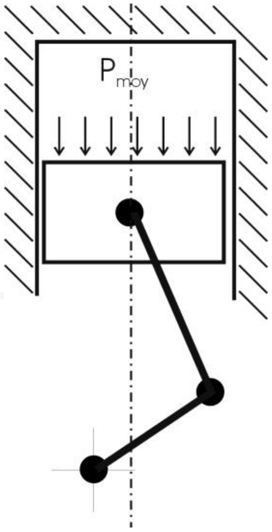
$$W_{1stroke}^{1cyl} = \text{imep}.\frac{\pi B^2}{4}.l = \text{imep}.V_{1cyl}$$

- The work of the n_{cyl} pistons over the cycle is:

$$W_{1stroke}^{ncyl} = \text{imep}.V_{1cyl}.n_{cyl} = \text{imep}.V_d$$



Mean effective pressure



- The work of the n_{cyl} pistons over the cycle is:

$$W_{1stroke}^{ncyl} = \text{imep}.V_{1cyl}.n_{cyl} = \text{imep}.V_d$$

- For a $2*n_R$-stroke engine the duration of the cycle is given by

$$t_{1stroke} = n_R.t_{1turn} = 2.n_R.\pi/\omega = n_R/N$$

N [turn/s] or w in [rad/s]

- Then power is given by

$$\dot{W}_i = \text{imep}.V_d.\frac{\omega}{2.n_R\pi} = \text{imep}.V_d.\frac{N}{n_R}$$

- And the torque writes

$$C_i = \frac{\dot{W}_i}{\omega} = \text{imep}\frac{V_d}{2.n_R.\pi}$$

Mean effective pressure

- The indicated mean effective pressure imep is a fictitious *constant* pressure that would produce the same work per cycle as if it acted on the piston during the power stroke

$$\text{imep} = \frac{W_i}{V_d} = \frac{\dot{W}_i . n_R}{V_d . N} \quad \rightarrow \quad \dot{W}_i = \frac{\text{imep}.V_d.N}{n_R} = \frac{\text{imep}.A_p.\bar{U}_p}{2.n_R}$$

- *imep* does not strongly depend on engine speed.

- *imep* is a better parameter than torque to compare engines for design and output because it is weakly dependent of engine speed, N, and of engine size, V_d.

Brake mean effective pressure

- The brake mean effective pressure (bmep) is defined similarly to the indicated mean effective pressure as a fictitious *constant* pressure that would produce the same brake work per cycle as if it acted on the piston during the power stroke

$$\text{bmep} = \frac{W_b}{V_d} = \frac{\dot{W}_b . n_R}{V_d . N} \quad \rightarrow \quad C_b = \frac{\dot{W}_b}{\omega} = \text{bmep}\frac{V_d}{2.n_R.\pi}$$

- If the power is strongly dependent on the rotation speed, the torque remains less sensitive to the rotation since bmep is weakly dependent on the rotation speed.

Brake and indicated mean effective pressure

- Order of magnitude of the brake mean effective pressure of modern engines:
  - Four-stroke engines:
    - Atmospheric
      - SI engine: 850 – 1050 kPa
      - CI engine: 700 – 900 kPa
    - Turbocharged
      - SI engine: 1250 - 1700 kPa
      - CI engine: 1000 - 1200 kPa
  - Two-stroke engines
    - SI engine : idem 4 stroke
    - Large 2-stroke diesel engines (e.g. boat) ~1600 kPa
  - Remark
    - Bmep is maximum at maximum torque and wide open throttle
    - At nominal power, the bmep is lower by 10 to 15%

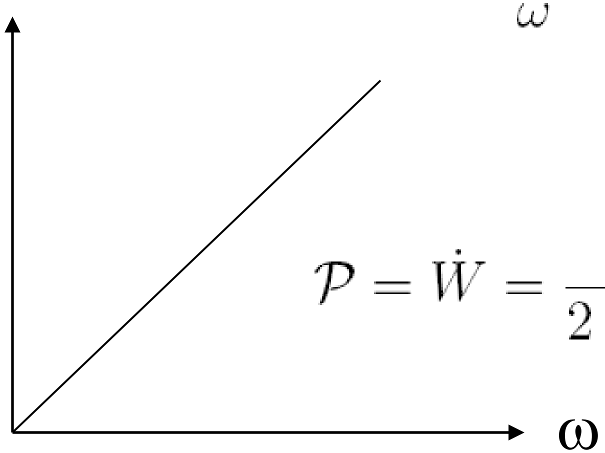
Torque speed curves of ICE

- The power curves is proportional to the rotation speed:

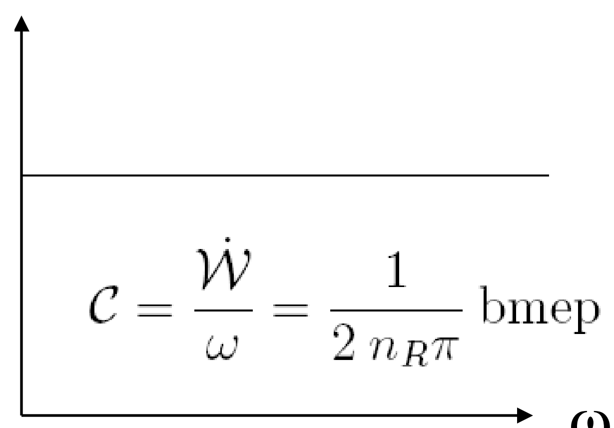
$$\mathcal{P} = \dot{W} = \frac{\omega}{2\, n_R \pi}\, \mathrm{bmep}\, V_d$$

- The torque speed curve is constant

$$\mathcal{C} = \frac{\dot{\mathcal{W}}}{\omega} = \frac{1}{2\, n_R \pi}\, \mathrm{bmep}\, V_d$$

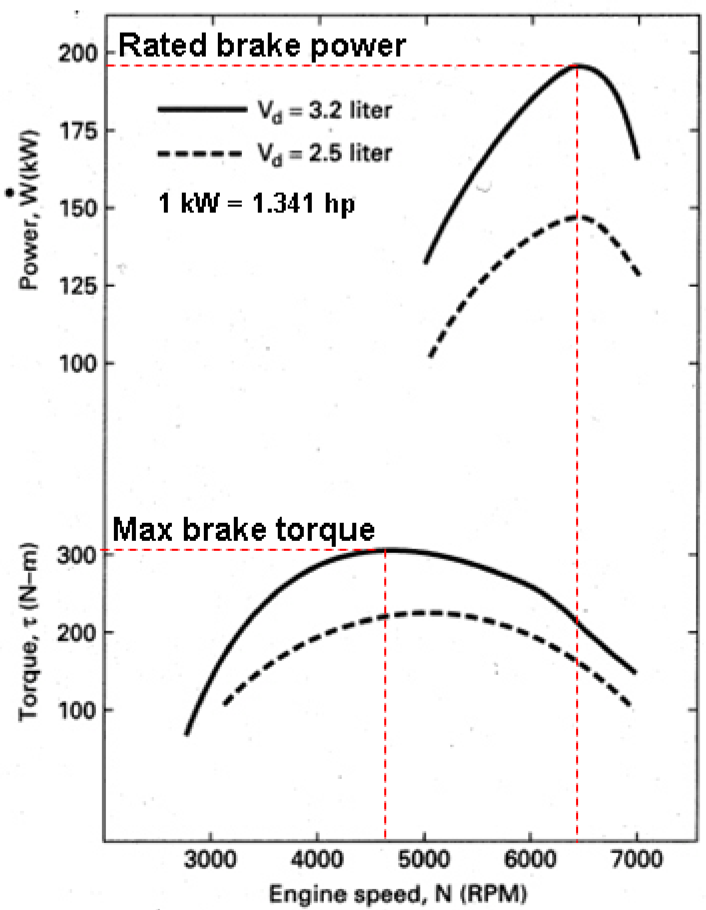


$$\mathcal{P} = \dot{W} = \frac{\omega}{2\, n_R \pi}\, \mathrm{bmep}\, V_d$$



$$\mathcal{C} = \frac{\dot{\mathcal{W}}}{\omega} = \frac{1}{2\, n_R \pi}\, \mathrm{bmep}\, V_d$$

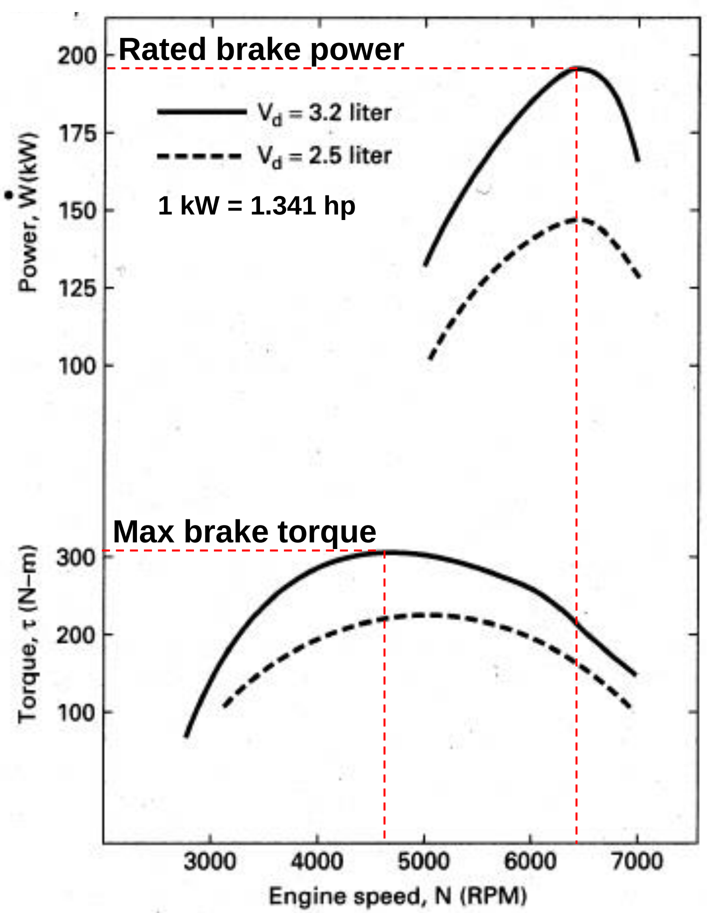
Power and torque as function of the rotation speed



- One observes that the power curve exhibits a maximum when engine rotation speed increases. This maximum power is called nominal power or rated power.
- The brake power increases as long as the torque does not drop too drastically.
- At high regimes, after nominal regime, the friction power increases a lot, and the brake power is finally decreasing

$$\dot{W}_b = \dot{W}_{i,g} - \dot{W}_f$$

Power and torque as function of the rotation speed



- At low regimes, the torque is reduced compared to maximum torque, because of heat losses increases between the gas and the piston or the cylinder sides since the time spent in the chamber becomes longer.

Fuel consumption of thermal engines

- The brake specific fuel consumption of the engine is the mass of fuel that is used to develop a given work *W* at the brake:

$$\text{bsfc} = \frac{m_f}{W_{mot}}$$

- Under variable operating conditions

$$dW_{mot} = \dot{W}_{mot}\, dt$$

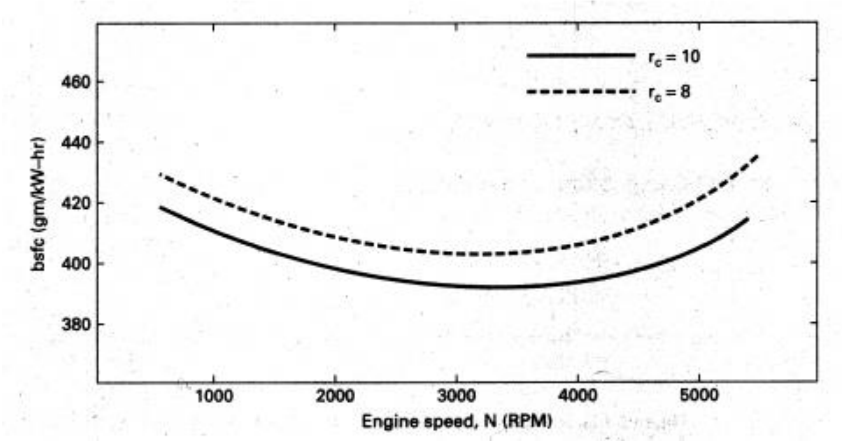
$$dm_f = \dot{m}_f\, dt$$

$$\text{bsfc} = \frac{\dot{m}_f}{\dot{W}_{mot}}$$

- The fuel consumption depends on the operation point (power/torque/rotation speed)
- The fuel consumption is mapped on the power / torque / bmep curve diagram wrt rotation speed

Brake Specific Fuel Consumption vs Engine Speed

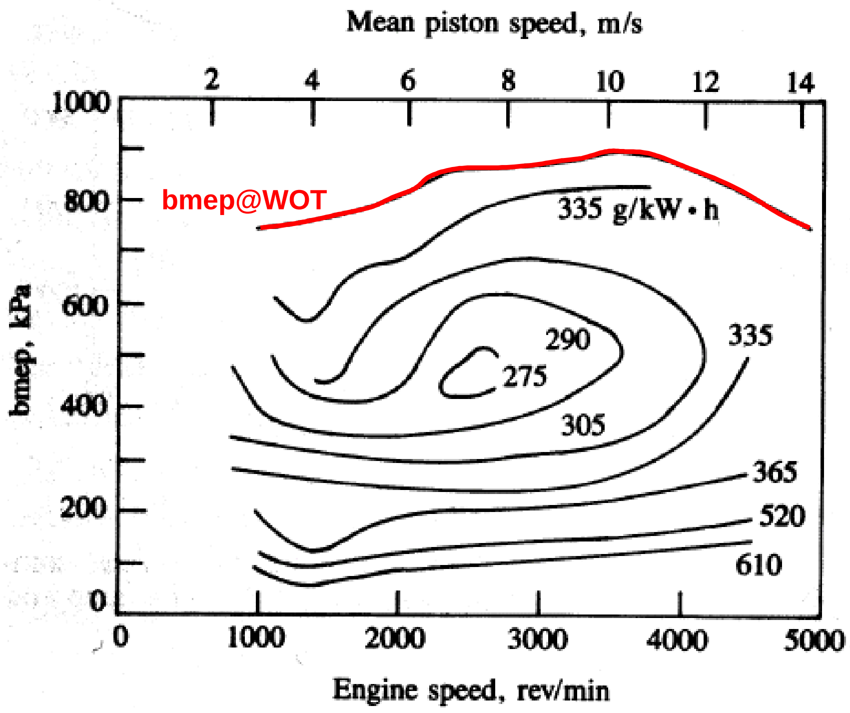
- There is a minimum in the bsfc versus engine speed curve



- At high rotation speeds, the bsfc increases due to increased friction i.e. smaller $\dot{W}_b$
- At lower speeds the bsfc increases due to the increasing time available for heat losses from the gas to the cylinder and piston wall, and thus a smaller $\dot{W}_i$
- Bsfc decreases with compression ratio due to higher thermal efficiency

Fuel consumption of thermal engines

- One often uses the fuel consumption mapping to illustrate the variability of the fuel consumption with the torque and the rotation speed.

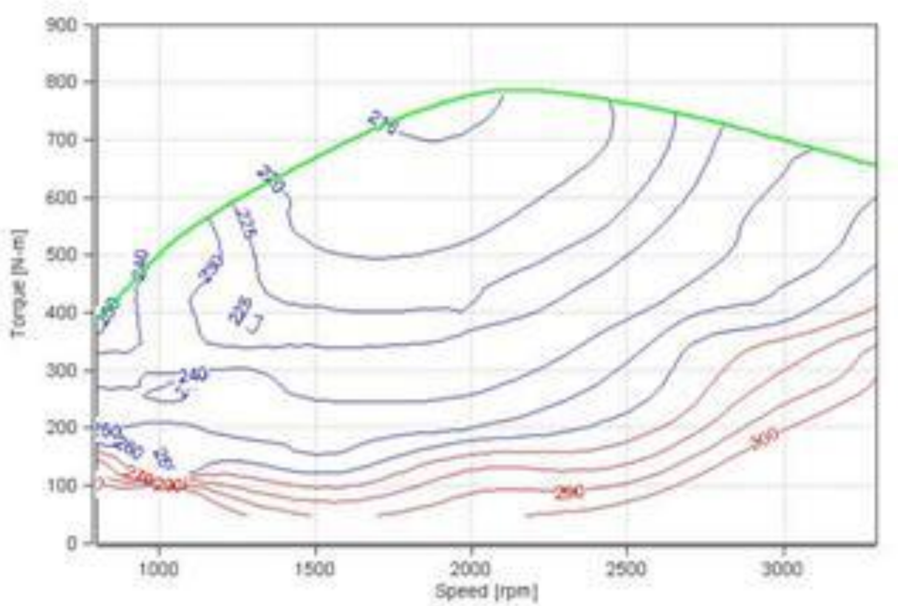


$$bmep = \frac{2\pi \cdot C \cdot n_R}{V_d}$$

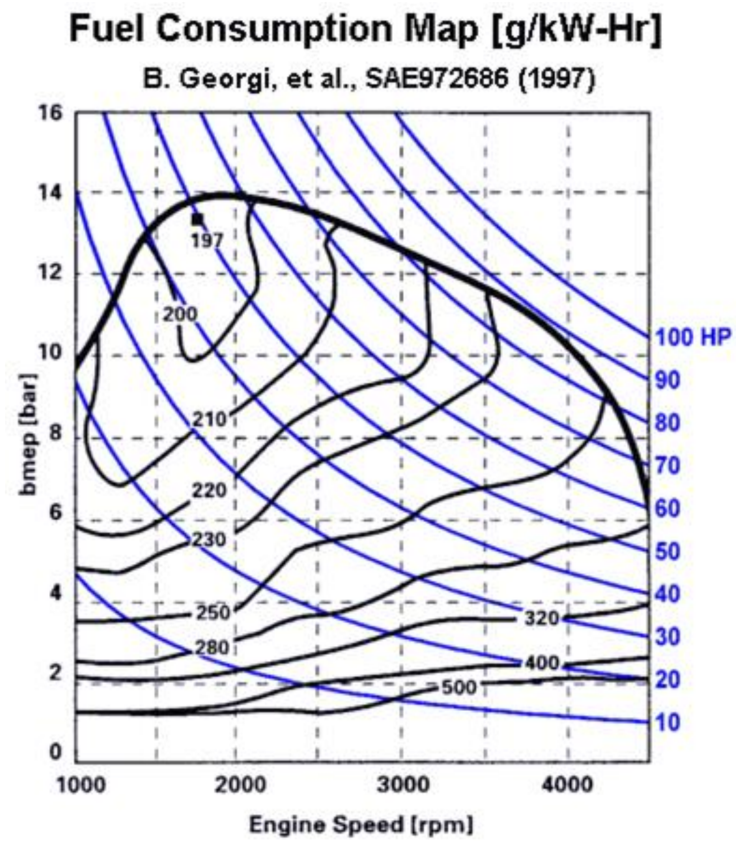
$$\dot{W}_b = (2\pi \cdot N) \cdot C$$

$$bsfc = \frac{\dot{m}_f}{\dot{W}_b}$$

Piston engines characteristics: fuel consumption

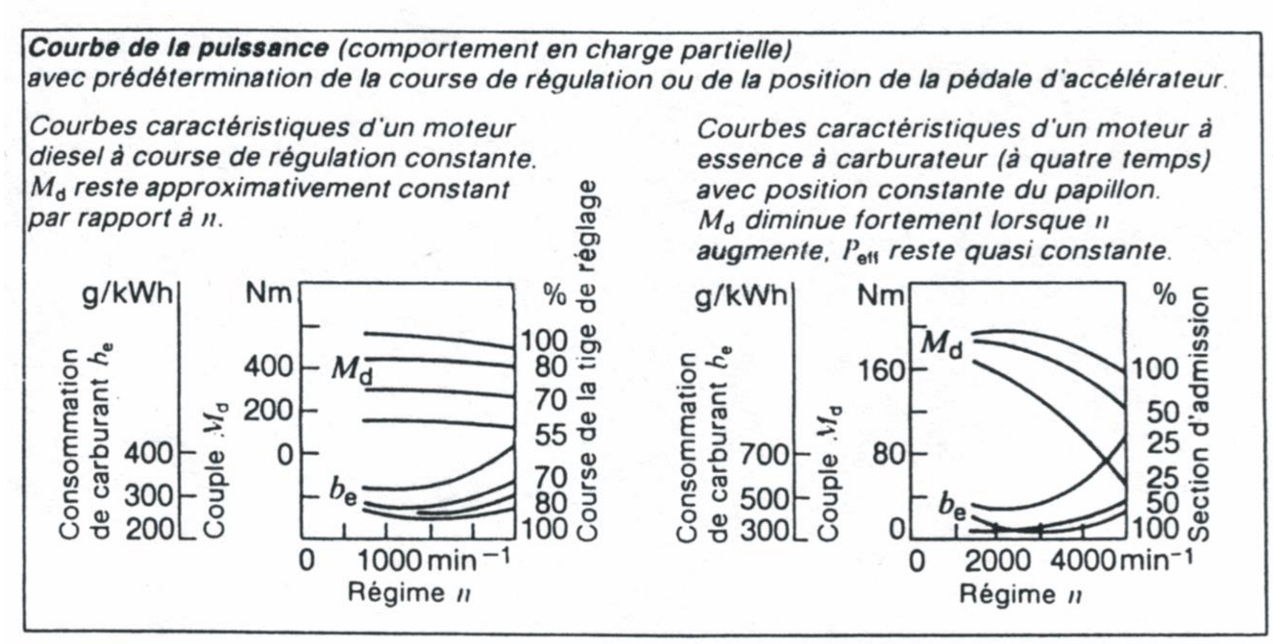


Gasoline engine



Diesel engine

Fuel consumption of thermal engines



ENERGY CONSUMPTION AT PART LOAD:

Faster increase of fuel consumption at part laod for gasoline engines

- Increase at high speed (but also at very low rotation speeds)
- A part load

Emissions of pollutants

- With the growing importance of regulation of emissions, there is a great interest in assessing the four main pollutants emissions :
  - Nitrogen oxides (NOx),
  - Carbone monoxide (CO)
  - Unburnt hydrocarbons (HC),
  - Particulate matters (PM).

- Two kinds of measures are generally used to characterize the emission of pollutants:
  - Specific emissions (SE)
  - Emission Index (EI)

Emission rates

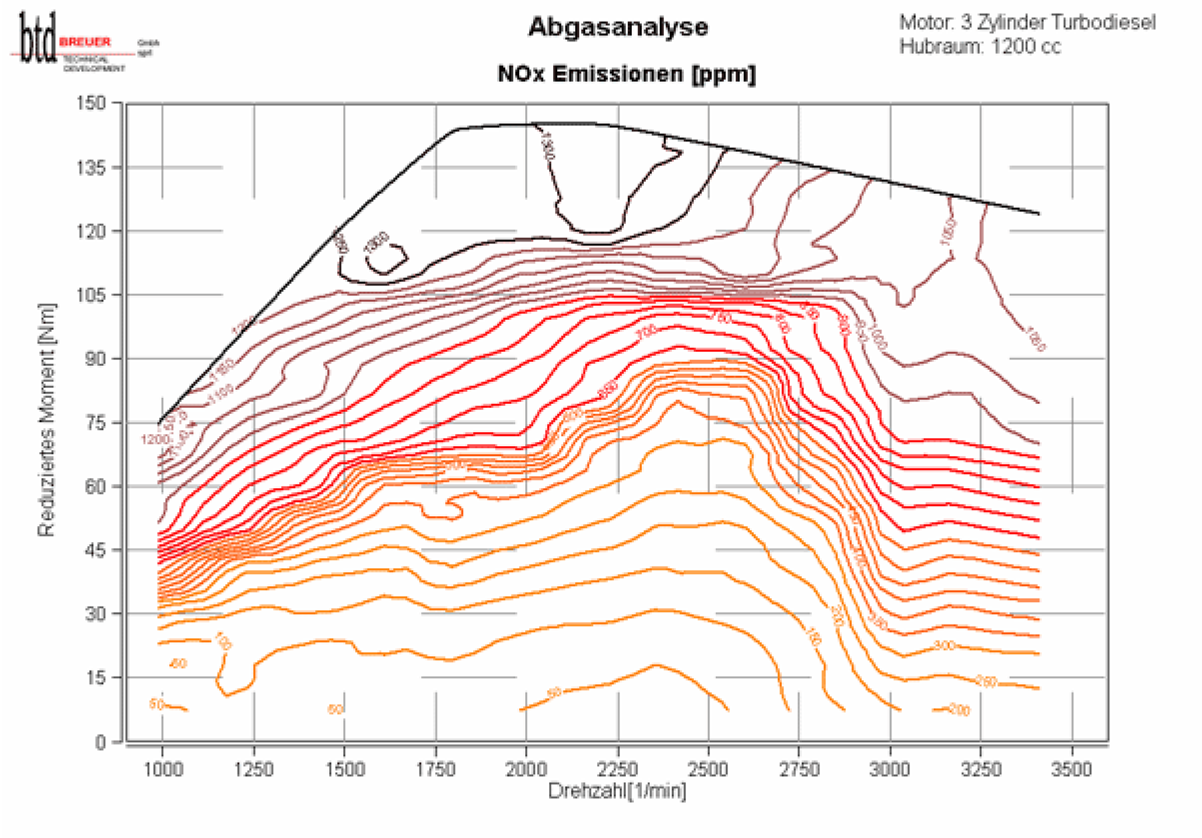
- Specific emissions

$$
\begin{aligned}
(SE)_{NOx} &= \dot{m}_{NOx}/\dot{W}_b \\
(SE)_{CO} &= \dot{m}_{CO}/\dot{W}_b \\
(SE)_{HC} &= \dot{m}_{HC}/\dot{W}_b \\
(SE)_{PM} &= \dot{m}_{PM}/\dot{W}_b
\end{aligned}
$$

- Emission index

$$
\begin{aligned}
(EI)_{NOx} &= \dot{m}_{NOx}/\dot{m}_f \\
(EI)_{CO} &= \dot{m}_{CO}/\dot{m}_f \\
(EI)_{HC} &= \dot{m}_{HC}/\dot{m}_f \\
(EI)_{PM} &= \dot{m}_{PM}/\dot{m}_f
\end{aligned}
$$

Piston engines characteristics: emission rates



Volumetric efficiency

- Due to the very short cycle time and the pressure losses in the air flow during intake and exhaust, the amount of intake air is far from ideal.
- The volumetric efficiency of the engine to admit air is defined by:

$$\eta_v = \frac{\text{Air admitted}}{\text{Theoretical air quantity}} = \frac{m_a}{\rho_a V_d} = \frac{n_R \dot{m}_a}{\rho_a V_d N}$$

  - Where ρ_a is the density of the air at atmospheric conditions p_0, T_0, i.e. for a perfect gas: $\rho_a = p_0 / r_a T_0$, with r_a= 0.287 kJ/kg*K

- Typical values for fully open throttle valves are in the order of 75-90% and drop when closed.

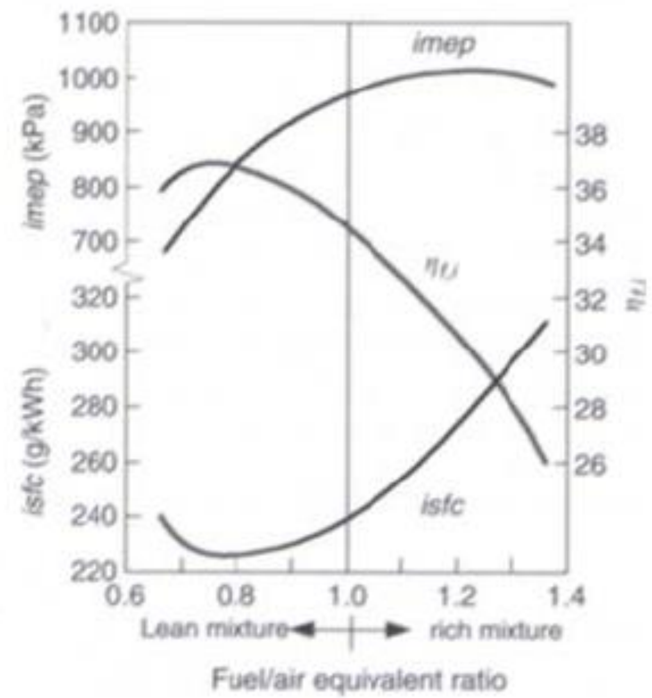
Air fuel ratio

- For combustion to take place, an appropriate amount of air (21% oxygen) and fuel must be introduced into the cylinder.
- The air-fuel ratio of the mixture (or fuel-air ratio) is defined.

$$\mathrm{AF} = \frac{m_a}{m_f} = \frac{\dot{m}_a}{\dot{m}_f} \qquad \mathrm{FA} = \frac{m_f}{m_a} = \frac{\dot{m}_f}{\dot{m}_a}$$

- Taking into account the proportion of oxygen in the air, the stoichiometric ratio for petrol and diesel is about 14.8, with combustion possible in the range of 6 to 19.
- For petrol engines, the AF is between 12 (rich) and 18 (lean) depending on the operating conditions.
- For diesel engines, the mixture can be very inhomogeneous, and combustion can take place with an AF of between 18 and 70%.

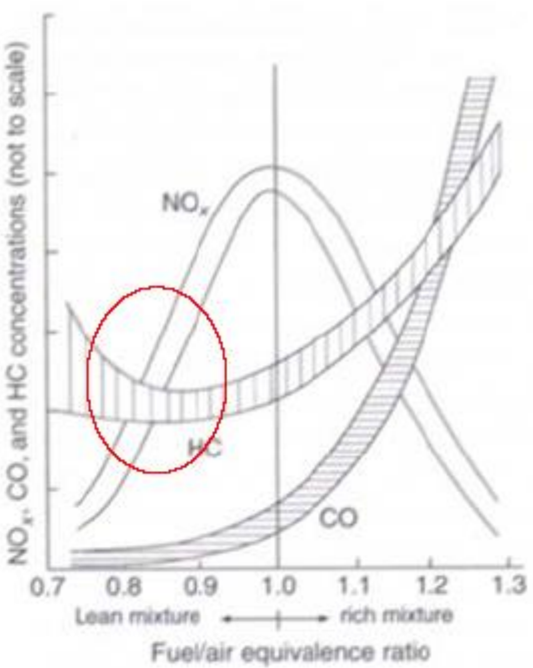
Air fuel ratio



$$\phi = \frac{(\mathrm{FA})_{actual}}{(\mathrm{FA})_s}$$

- Fuel richness is a crucial element for engine performance, efficiency and emission control
- The imep is maximum for a slightly rich mixture (ϕ~1,2)
- Efficiency η decreases with increasing ϕ because of unburnt fuel.
- For very lean mixtures, however, spark ignition engines may not be able to cause ignition and secondly the gas combustion temperature drops leading to a lower mean effective pressure

Air fuel ratio



$$\phi = \frac{(\mathrm{FA})_{actual}}{(\mathrm{FA})_s}$$

- Fuel richness has an important effect on the emission control of spark ignition engines
- Lean mixtures produce less NOx, HC and CO until the mixture becomes too lean and produces unburnt fuel due to poor combustion.
- Very different picture for the NOx curve that tends to form at stoichiometric mixtures, because of the presence of hot spots and high pressures. So lean or rich mixture reduce the NOx emissions.
- Emissions control is a complex problem.

Emission control

- Three techniques:
  - Fuel treatment
  - Engine improvement
  - Exhaust after-treatment

- Fuel treatment:
  - Composition modified by additives or via the refining process to remove pollutants or facilitate the exhaust after-treatment process
  - Lead used to increase octane rating is replaced by Methyl Tertiary Butyl Ether (MTBE), less aggressive to the environment
  - Sulphur: desulphurization of fuels to avoid H_2S and damage to catalytic converters

Emission control

- Improve engine design to reduce pollutant formation
  - Intake: fresh air intake to lower cylinder temperature and reduce NOx formation.
  - Improved the air fuel mixture homogeneity through electronic injection and turbulent intake flow.
  - Aluminum engine block to allow engine operation at lower temperatures
  - Liquid sodium filled exhaust valves for improved cooling
  - Piston head covered with resistant coatings to reduce heat transfer to the piston
  - Use of a lambda sensor to monitor the oxygen level in the exhaust gases....

Emission control

- Exhaust gas after-treatment
  - Still the most effective way to reduce pollutants
  - The catalytic converter is a common device (mandatory in the EU and USA) for reducing exhaust pollutants
  - The catalytic converter is made of catalytic materials (Pt, Rh) which facilitte the reduction of CO, HC and NOx to less aggressive compounds:
    - $2\ NO_x \rightarrow N_2 + O_2$
    - $HC + O_2 \rightarrow CO_2 + H_2O$
    - $2\ CO + O_2 \rightarrow 2\ CO_2$
  - The three-way catalyst converter does all three reactions simultaneously.
  - The catalyst only acts at high temperature, so that most of the emissions come from the first minute of operation after the cold start.

Emission control

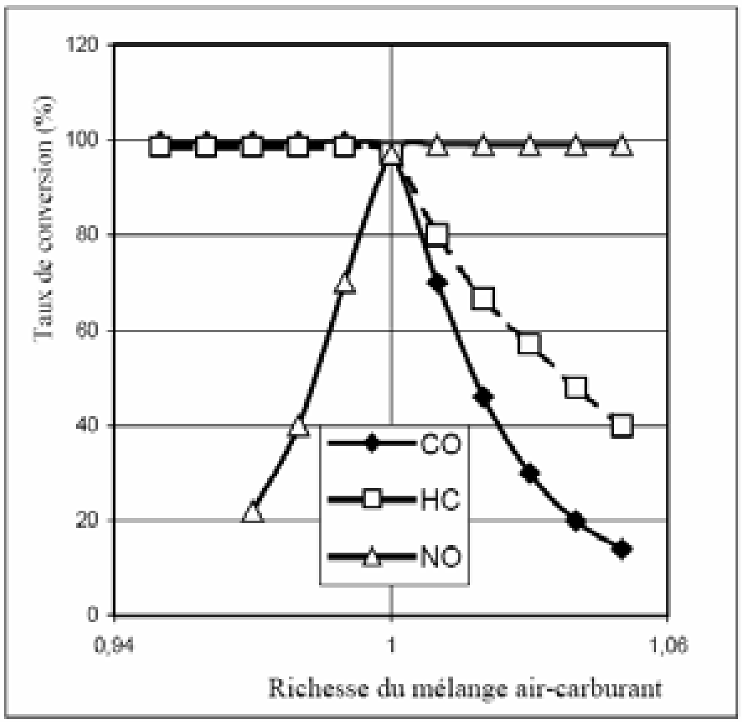


Figure 3 : Principe de fonctionnement d'un catalyseur 3 voies

- Exhaust after treatment
  - The three-way catalyst requires the presence of oxygen in the exhaust (thus a slight excess of oxygen in the intake) and a fairly precise adjustment of the mixture richness.
  - This regulation is possible thanks to the measurement of the oxygen level (lambda probe) and an electronic injection.

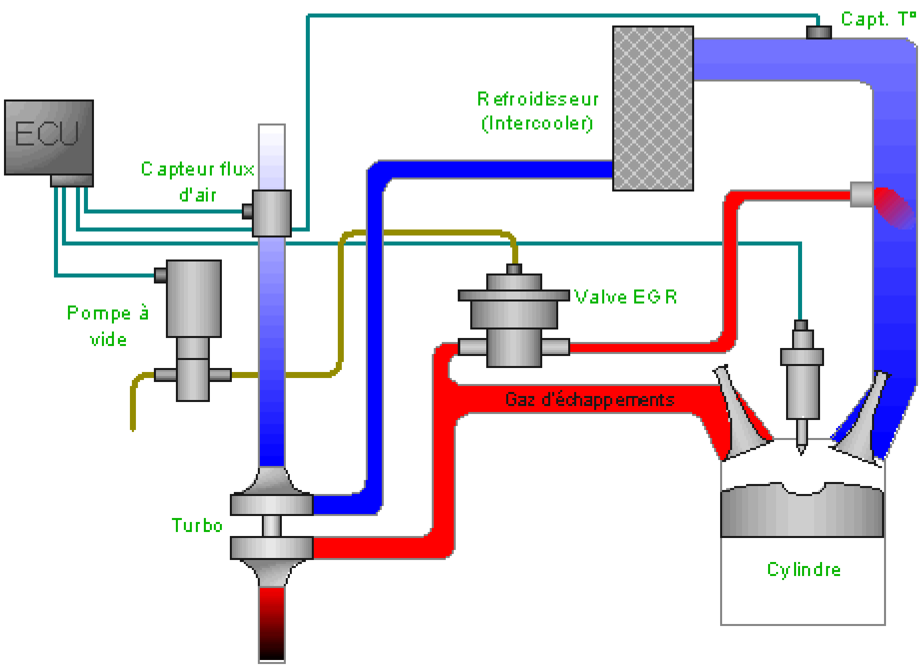
Diesel engines

- Efficiency of direct injection diesel engine is 30% higher than petrol engine in practice
  - High downsizing potential: 1.2 to 1.5 litre engines with high specific performance (specific torque of 150 Nm/l and specific power of 50 kW/l)
  - 5 to 10% reduction with high pressure direct injection and variable geometry turbocharging
- The real challenge for diesel is the ability to meet future pollutant emission standards
  - 3-way catalysis impossible due to excess air
  - NOx reduction is impossible to reduce with the combustion optimization
  - Post treatment of particulate matters and NOx removal

Improving Diesel engines

- Improvement routes:
  - Injection system:
    - Number of injections per cycle: 5 to 7
  - Optimization of the combustion chamber
  - Depollution systems
    - Reduction of NOx using selective catalytic reduction (SCR) or NOx traps
    - Particulate filters
    - Continuous regeneration systems
    - 4-way catalytic converter
  - New combustion processes
    - Homogeneous combustion in lean conditions (HCCI)

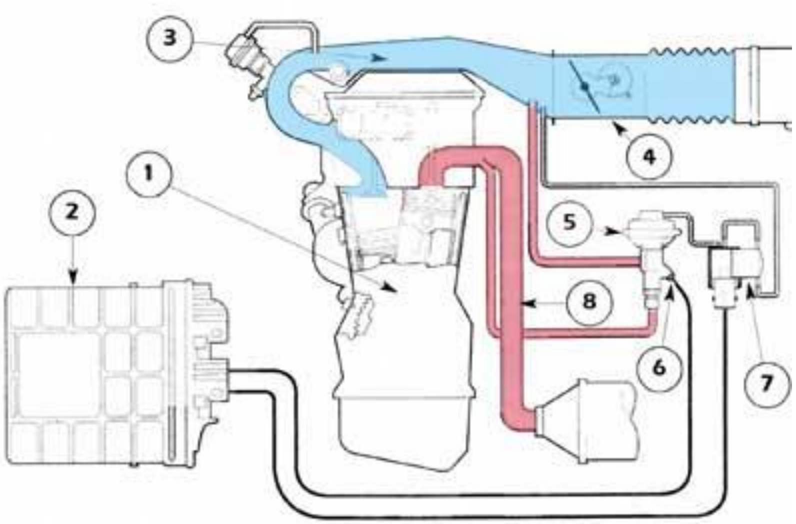
Exhaust Gaz Recirculation (EGR)



- The EGR valve first appeared in the 1970s in the United States. It was first tested by General Motors to reduce nitrogen oxide (NOx) emissions from vehicles.

- To reduce NOx emissions, the maximum combustion temperature must be reduced. This can be done by diluting the gases admitted by the engine with an inert gas, which, by interposing itself between the fuel and the oxidant, slows down the speed of combustion and absorbs calories.

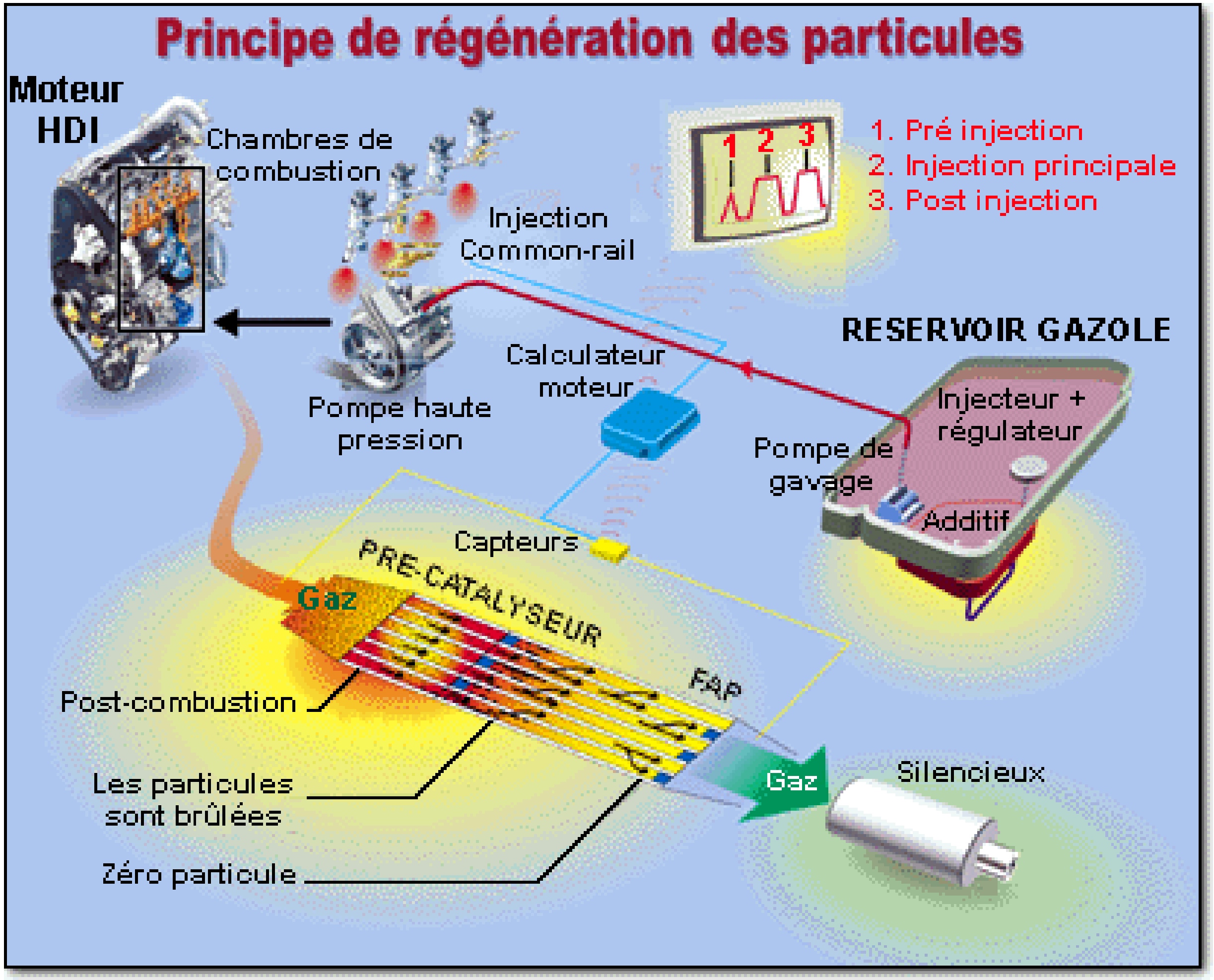
Exhaust Gaz Recirculation (EGR)



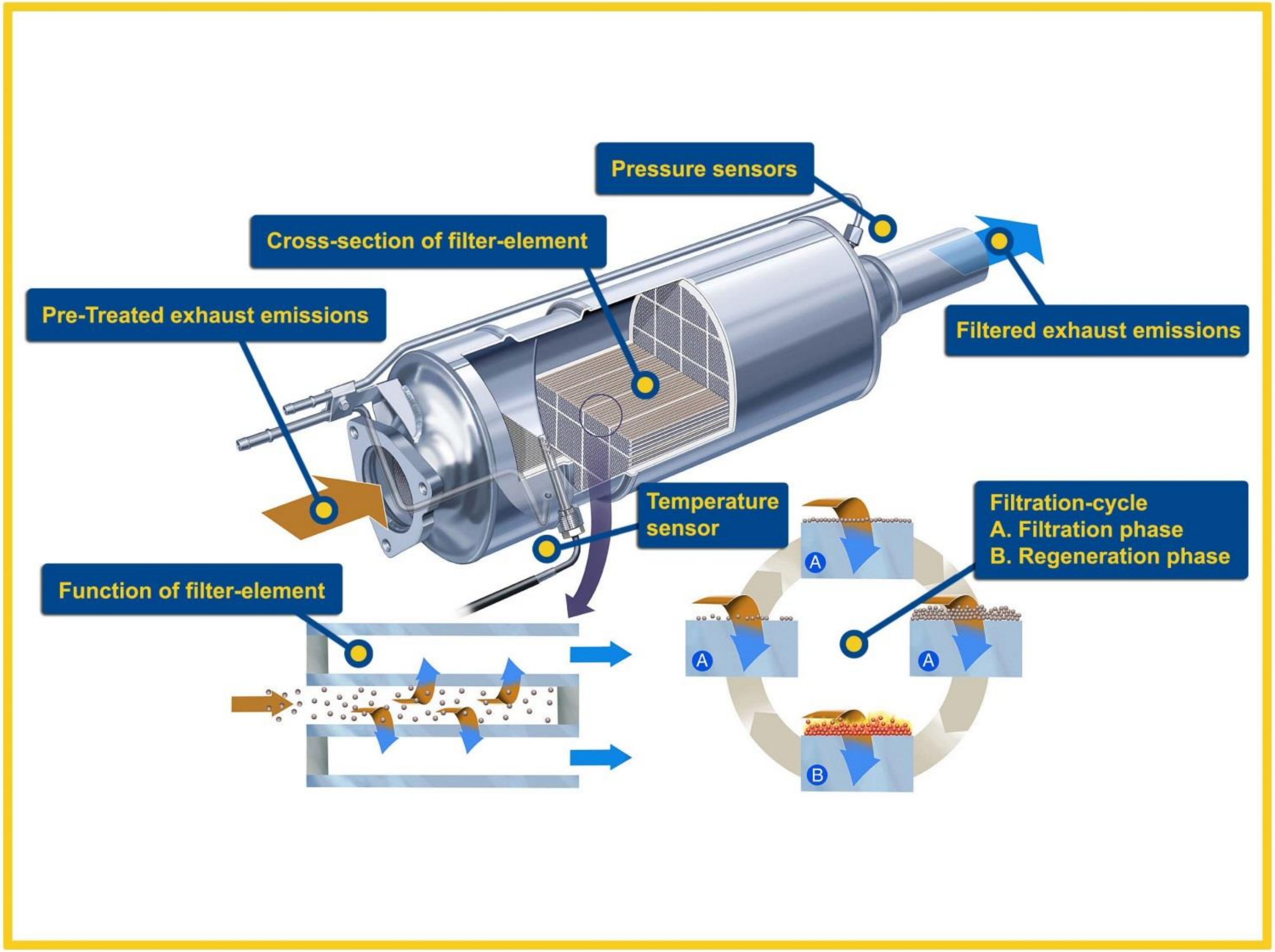
1/ Engine 2/ Computer (ECU) 3/ Admission pipes 4/ Control of throttle valve 5/ EGR waste gate 6/ Temperature sensor 7/ EGR solenoid 8/ Exhaust manifold

- As the exhaust gases contains inert gases, it is a question of recirculating part of these gases into the intake manifold.
- The ECU controls the EGR via a solenoid valve or an electric motor according to several parameters (water temperature, air temperature, full load idle information....)

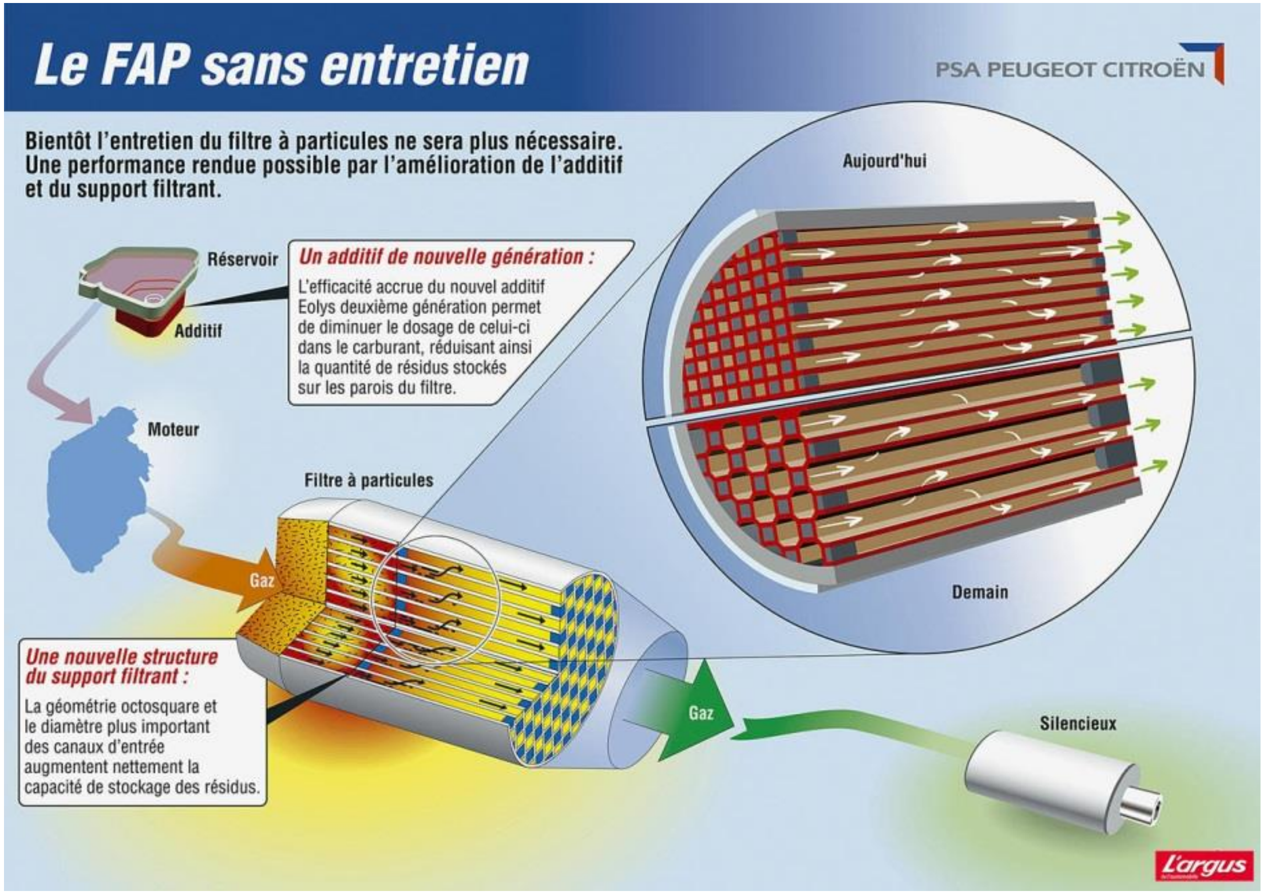
Diesel engine: Particulate filters



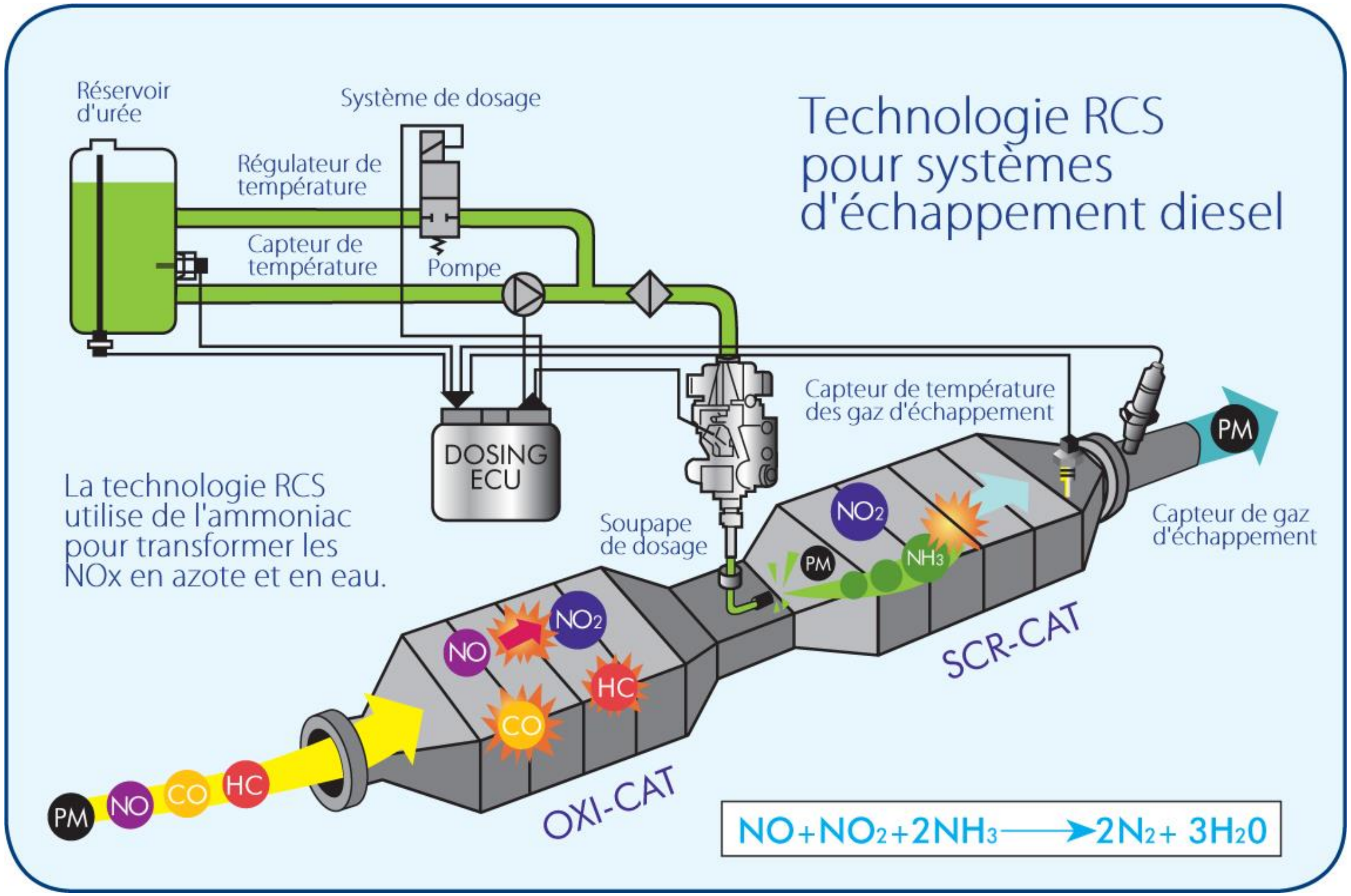
Diesel engine: Particulate filters



Diesel engine: Particulate filters



Diesel engine: DeNOx



Diesel engine: DeNOx

La SCR (Selective Catalytic Reduction)
Le système d'élimination des NOx le plus performant

❶ **Transformation de l'Adblue®** (urée) **en ammoniac** (NH_3) dans la ligne d'échappement

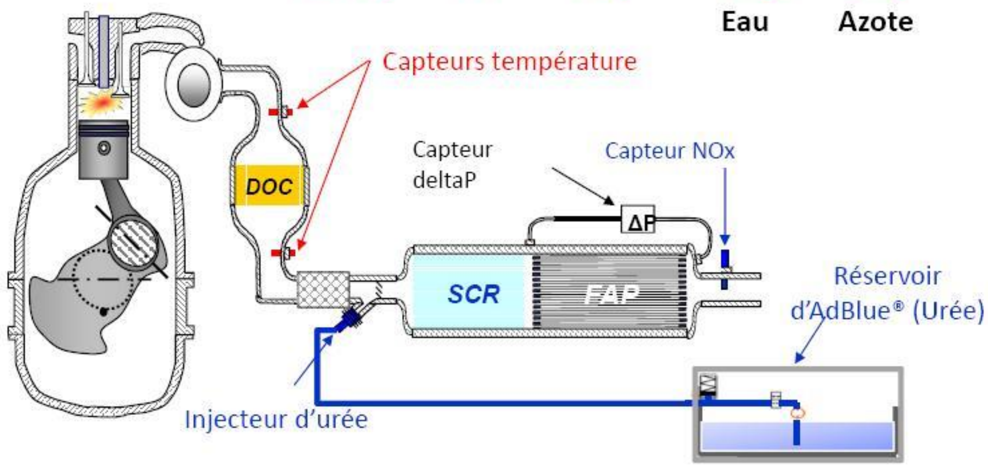
$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$$

Urée **Ammoniac**

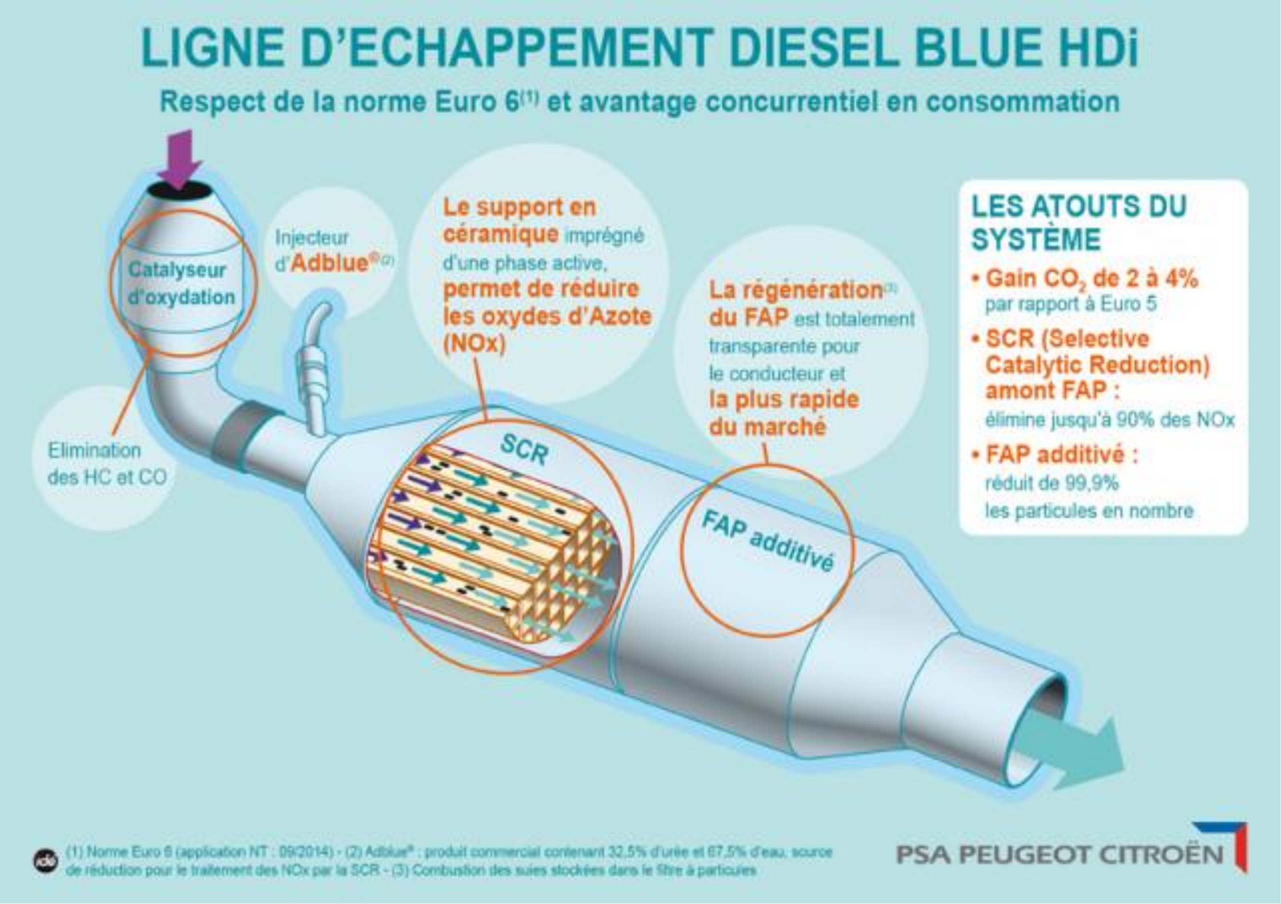
❷ **Réaction de l'ammoniac** (NH_3) **sur les NOx** pour donner de l'eau et de l'azote

$$2NH_3 + NO + NO_2 \rightarrow 3H_2O + 2N_2$$

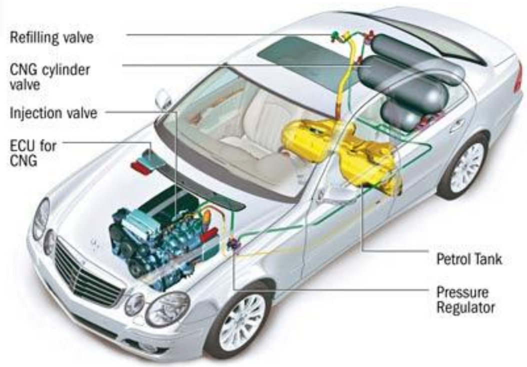
Eau **Azote**

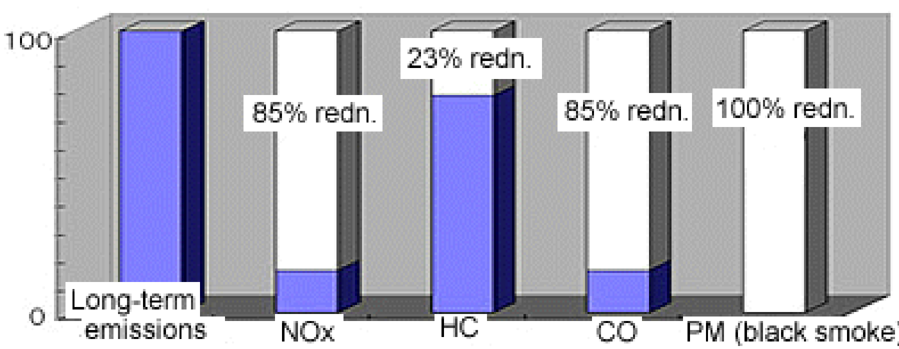


Diesel engine: DeNOx

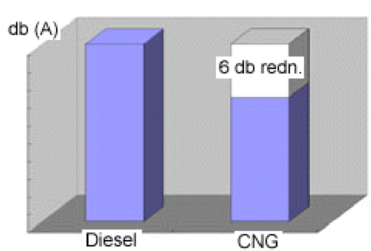


CNG engines





IVECO Stralis Cursor 11



- Natural Gas is an excellent alternative fuel:
  - Easy adaption of classic internal combustion engines
  - Large reserves of natural gas are available
  - Reduction of CO_2 emissions (-10%) and air pollution (PM: -95%)
- Target: optimization of engine efficiency → allows a reduction of 5 to 10% of CO_2 emissions compared to Diesel engine
- Target by EU: substitution: 10% in 2020

Natural Gas (Gazeous or Liquified)

Energy per storage volume for common fuel

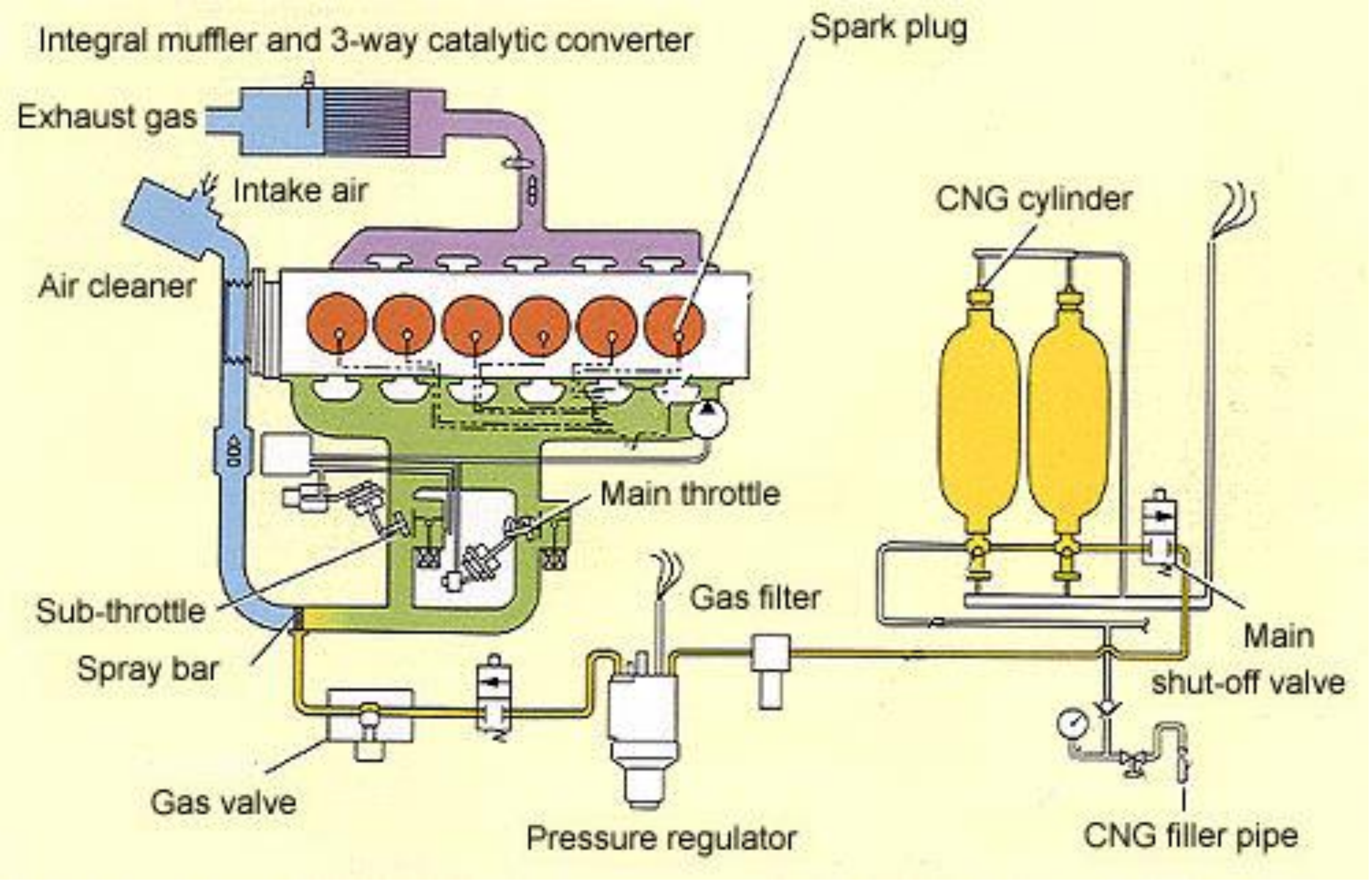
	Density kg/m^3	LHV kJ/kg	Energy MJ/m^3		Volume (for same energy)
Gasoline	750	42 690	32 020		
Diesel fuel	835	42 770	35 710	+11%	× 0.9
Gaseous methane 1013 hPa, 273 K	0.716	50 010	36	− 100%	× 889
Gaseous methane 20 Mpa, 293 K	173 (AGA8)	50010	8 652	− 73%	× 3.7

(1 MPa = 10 bars)

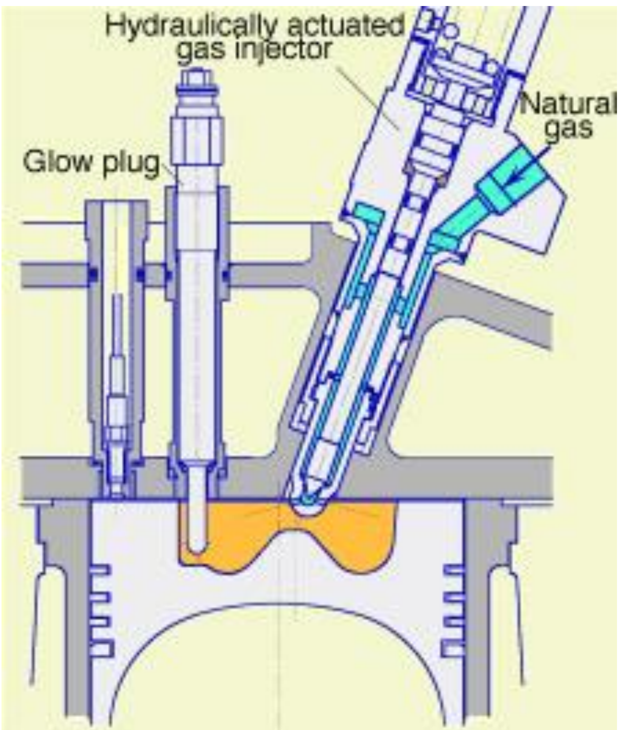
Questions to be solved

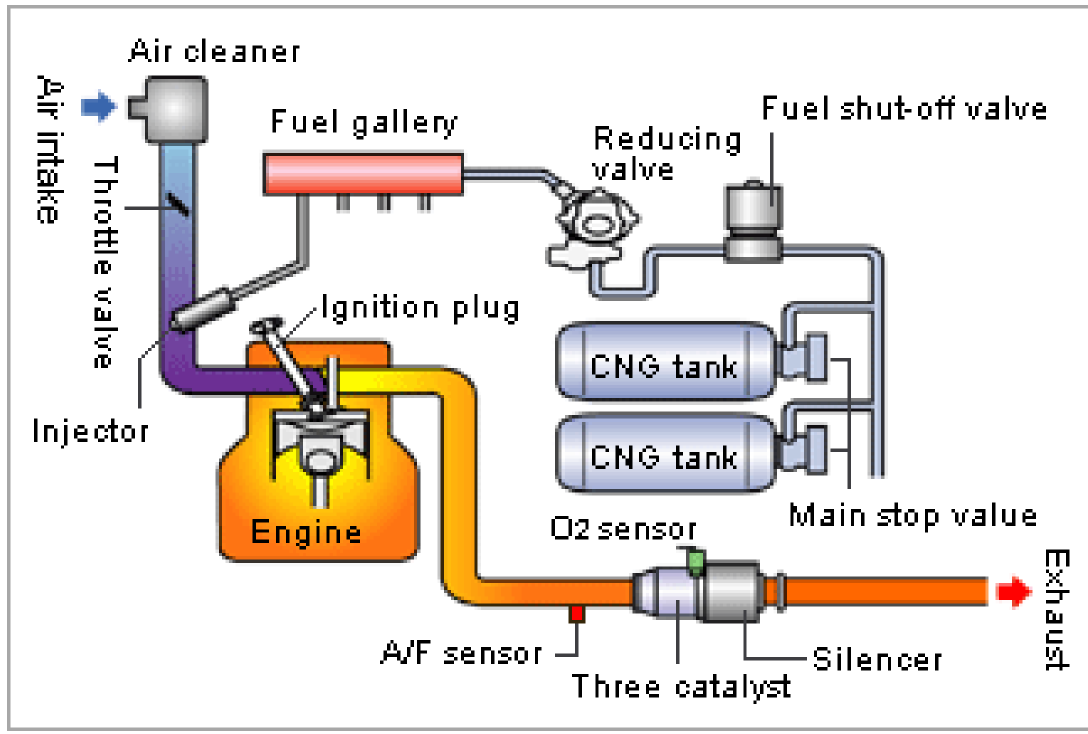
- Emissions of CH_4 and development of specific after treatment to be developed
- Refueling station network still under construction: 68 stations in Belgium mostly in Flanders
- CNG (200/350/800 bar) Volume per unit of energy content still high ➔ Limited autonomy: 300 to 400 km
- LNG (3 bars @ -143°C / 8 bars @-130°C): Volume reduced by 2.4 ➔ Extension of autonomy to 700 to 800 km and over

Engines dedicated the CNG

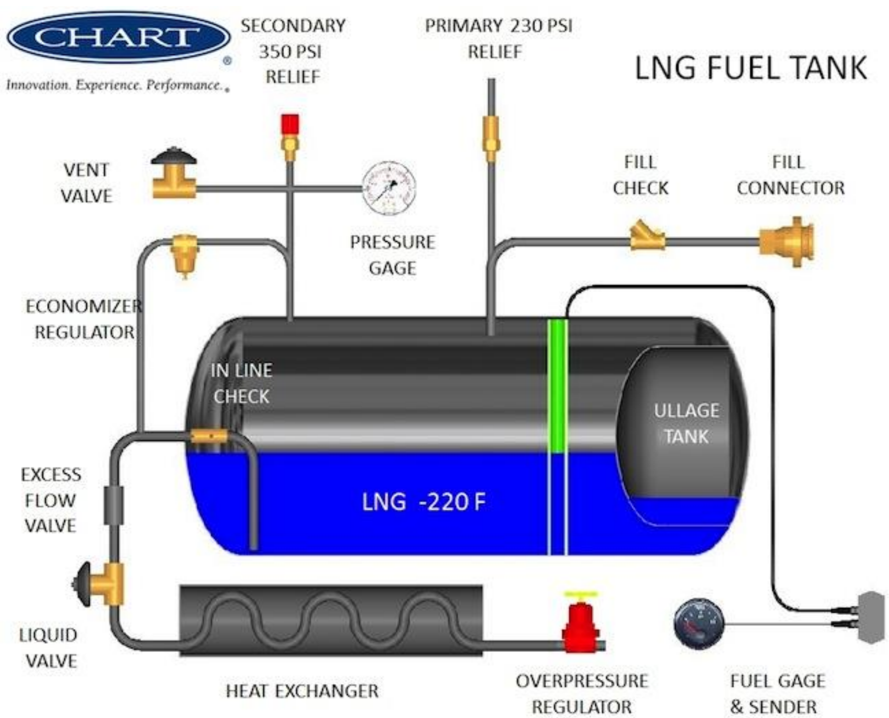


CNG: injection system



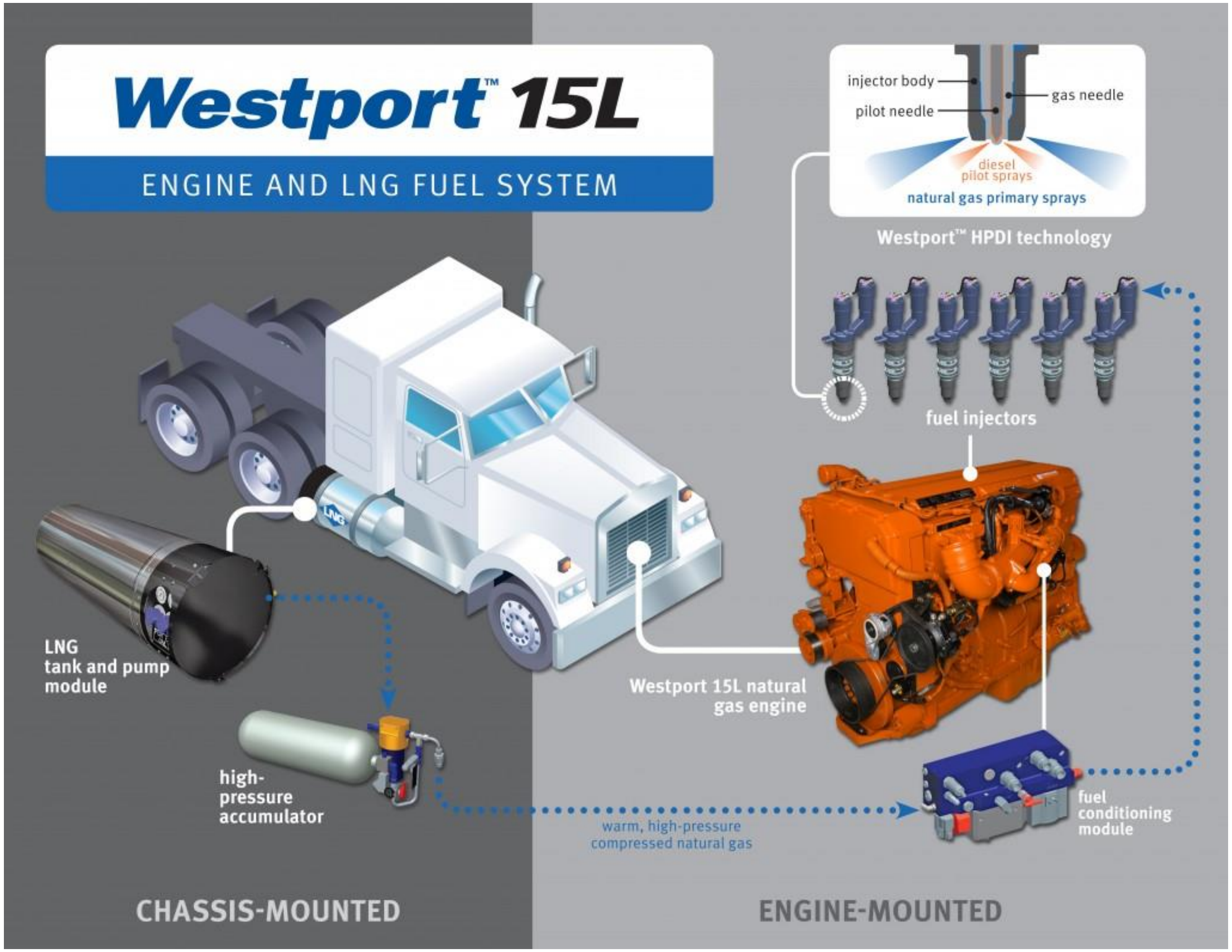


LNG: tank


LNG FUEL TANK
SECONDARY 350 PSI RELIEF
PRIMARY 230 PSI RELIEF
VENT VALVE
PRESSURE GAGE
FILL CHECK
FILL CONNECTOR
ECONOMIZER REGULATOR
IN LINE CHECK
ULLAGE TANK
LNG -220 F
EXCESS FLOW VALVE
LIQUID VALVE
HEAT EXCHANGER
OVERPRESSURE REGULATOR
FUEL GAGE & SENDER


ups
USDOT 021800
Liquid Natural Gas Vehicle
LNG

LNG: injection system



MOTEUR CI + GAZ NATUREL

CNG

- ADVANTAGES
  - Easy adaptation of piston engine technology
  - High lower heat value
  - Refueling network is feasible
  - Particulate matter
  - High performance

- INCONVENIENTS
  - Storage system: large volume
  - Gas station in progress
  - Control of CH4 emission becomes critical

Energy per storage volume for common fuel

	Density kg/m^3	LHV kJ/kg	Energy MJ/m^3		Volume (for same energy)
Gasoline	750	42 690	32 020		
Diesel fuel	835	42 770	35 710	+11%	× 0.9
Gaseous methane 1013 hPa, 273 K	0.716	50 010	36	– 100%	× 889
Gaseous methane 20 Mpa, 293 K	173 (AGA8)	50010	8 652	– 73%	× 3.7

	Mileage km	CO g/km	UHC g/km	NOx g/km	CO_2 g/km
Euro IV – 2005		1.00	0.10	0.08	
Utac results	3150	0.26	0.08	0.04	140.5
IFP results	3270	0.30	0.09	0.04	136.4
IFP results	52 220	0.38	0.06	0.05	131.7

CNG study by IFP (Tilagone & Venturi, 2004)