SELECTION OF PROPULSION SYSTEMS FOR AUTOMOTIVE APPLICATIONS

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LTAS – Automotive Engineering

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Bibliography

- R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)
- M. Ehsani Y. Gao, S Gay & A. Emadi. Modern Electric, Hybrid Electric, and Fuel Cell vehicles. Fundamentals, Theory and Design. CRC press. 2005.
- G. Genta. Motor Vehicle Dynamics – Modeling and Simulation. World Scientific Publishing. 2003.
- T. Gillespie. « Fundamentals of vehicle Dynamics », 1992, Society of Automotive Engineers (SAE)
- W.H. Hucho. « Aerodynamics of Road Vehicles ». 4th edition. SAE International. 1998
- J.Y. Wong. « Theory of Ground Vehicles ». John Wiley & sons. 1993 (2nd edition) 2001 (3rd edition).

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
  - Rotary piston engines
- Electric motor
  - Electric traction system
  - Types of electric machines
  - Batteries

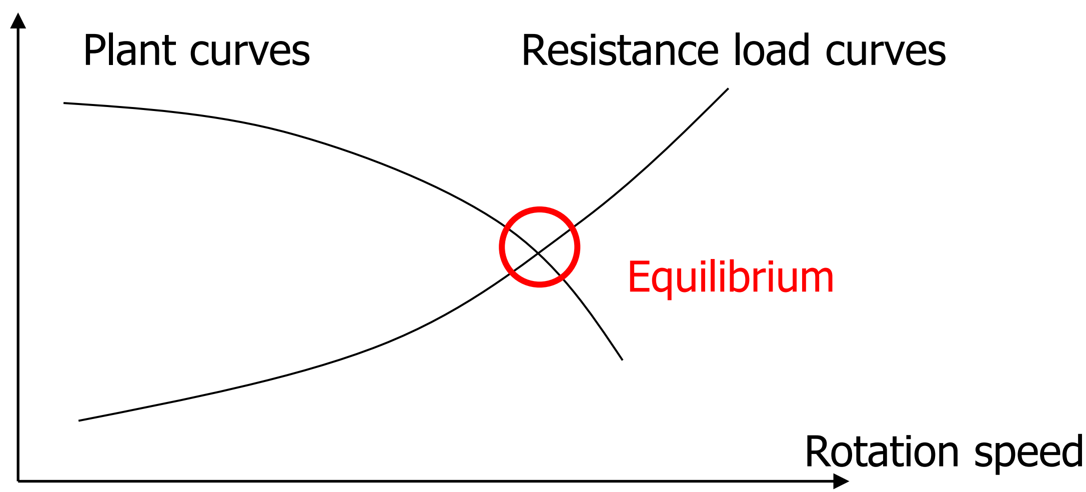
Outline

- Air compressed vehicles
- Hybrid motorization
  - Definition
  - Layout
  - Architecture
- Fuel cells
  - Definition
  - Fuel cell powered hybrid vehicles
- Comparison

Specification of propulsion systems

Ideal characteristics of vehicle power plant

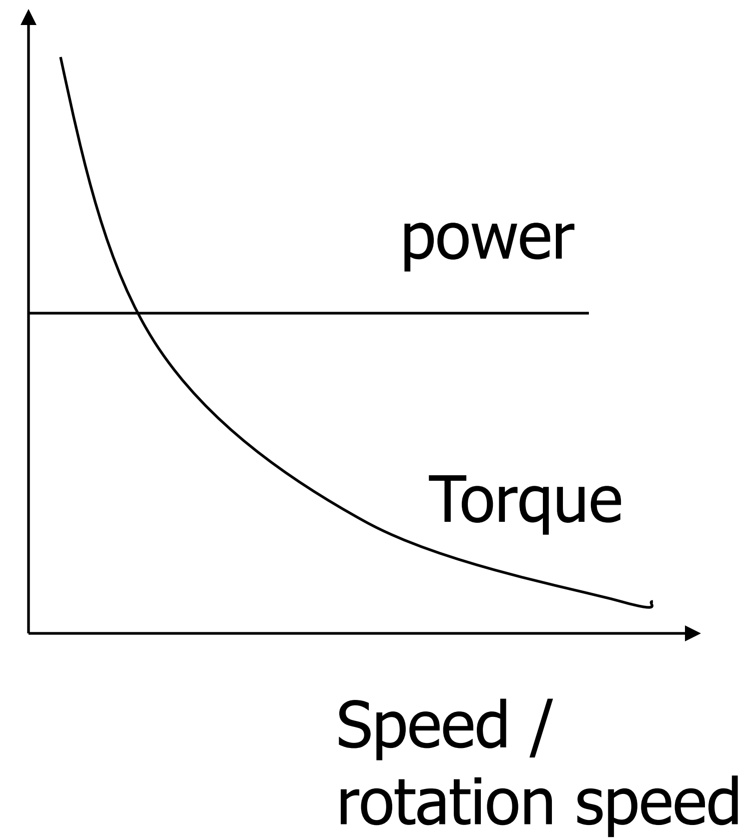
- Remind first that the operating point of a system is governed by the equilibrium between the power (forces) of the plant and the load.
- The operating point is obtained by the intersection of the power (torque) curves of the plant and of the resistance loads



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

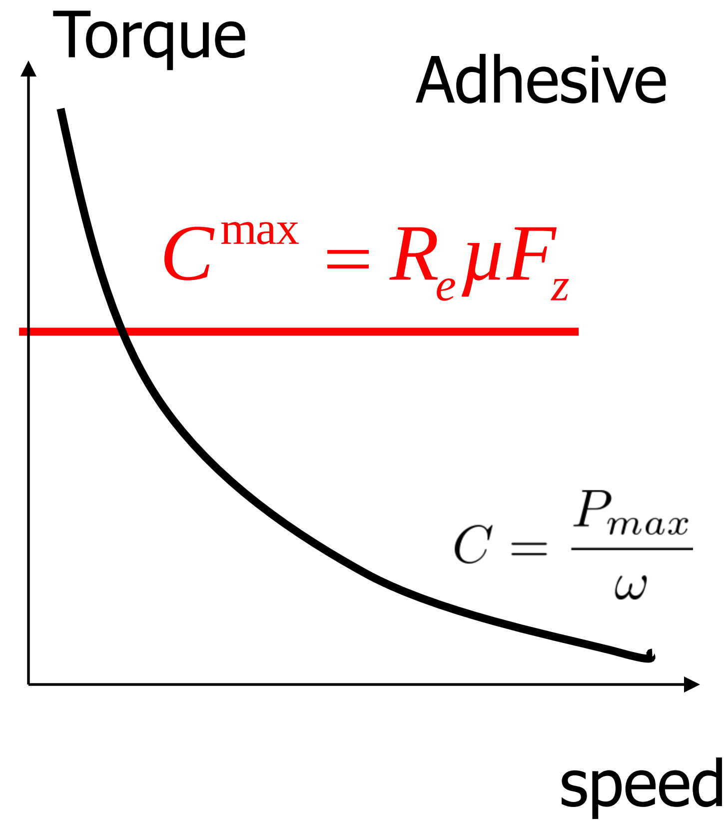


Ideal characteristics of vehicle power plant

- <u>For low speed operation,</u> 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

- Sensitivity of drivers
  - 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)
- <u>Reciprocating piston engines</u> 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

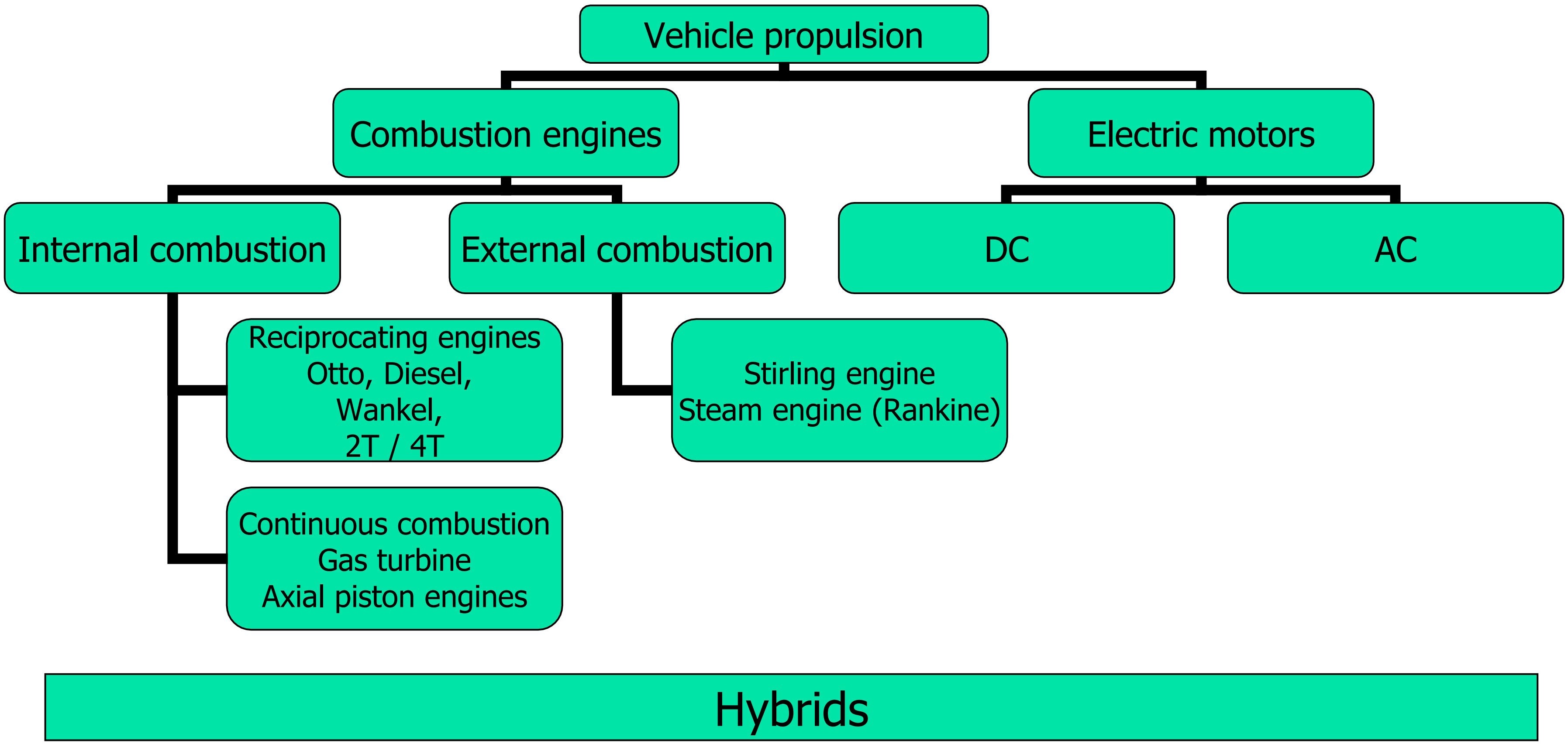
- Other criteria for vehicle power plants
  - Constant power
  - Weight to power ratio
  - Large speed operation range
  - Reasonable energy consumption
  - Control of pollutant emissions
  - Low production cost
  - Easy to start and operate
  - Serial production
  - Low maintenance
  - High reliability
  - 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 (Wankel engine)

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

Alternative power plants



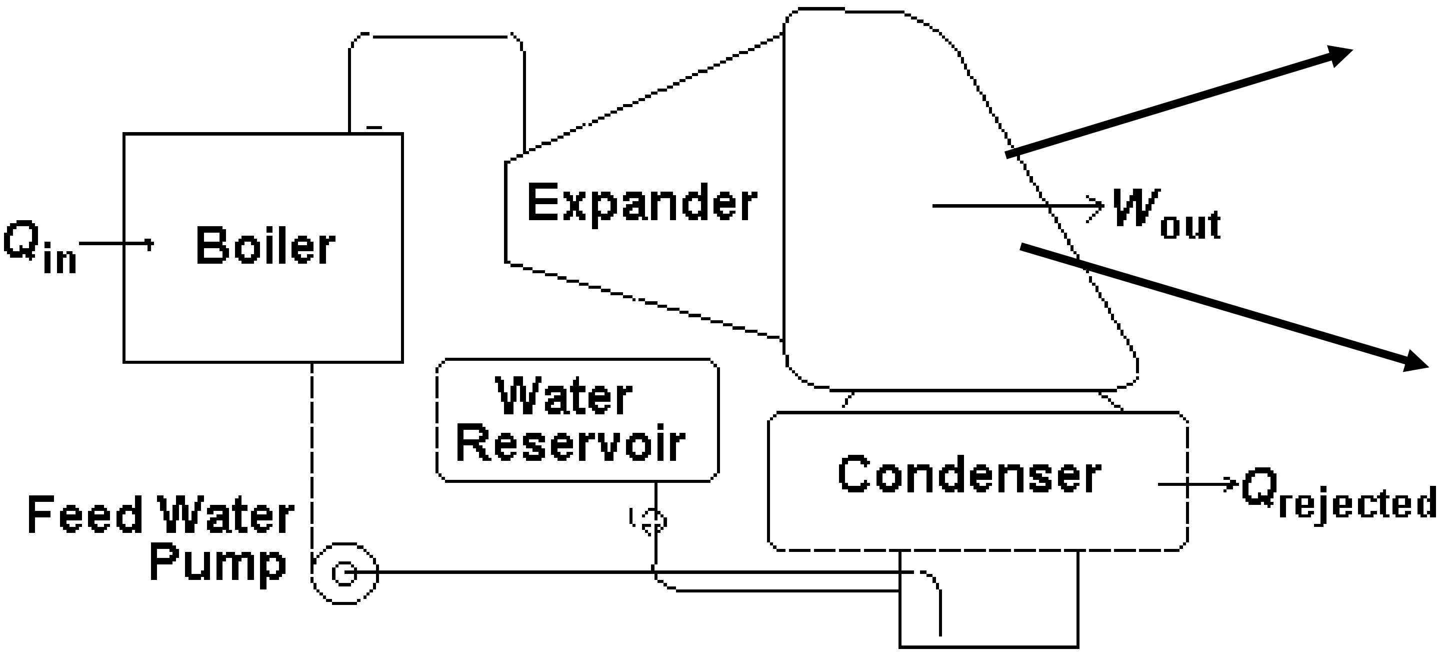
Steam engines

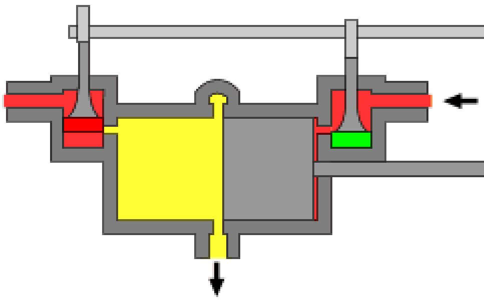
Steam engines

Cugnot's Faradier,
First automotive vehicle

Steam locomotive

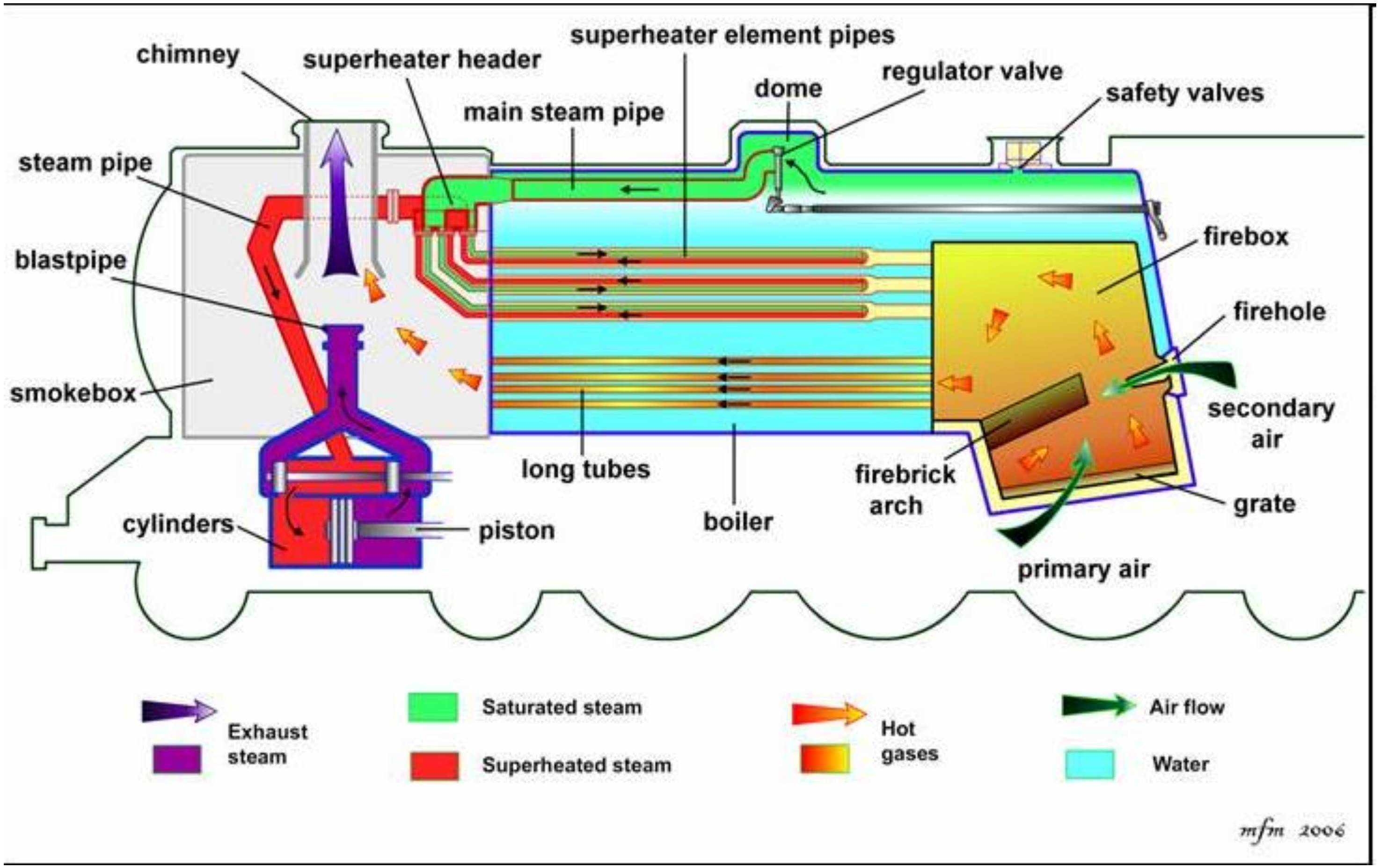
Steam engines



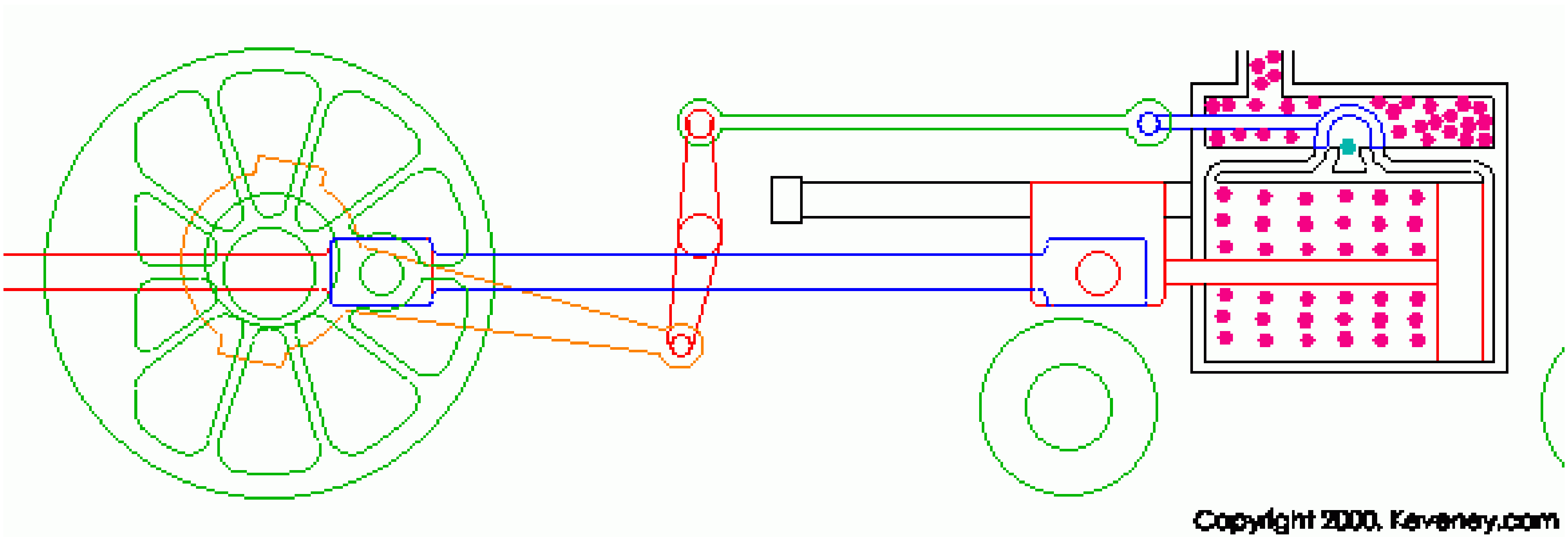


$$W_{out} = W_{in} + Q_{in} - Q_{out}$$

Steam engines



Steam engines

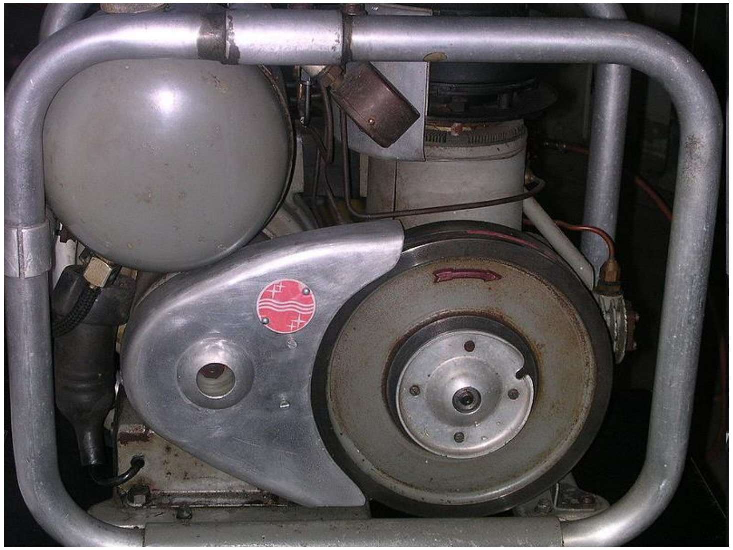


Double piston stroke: uniflow steam engine

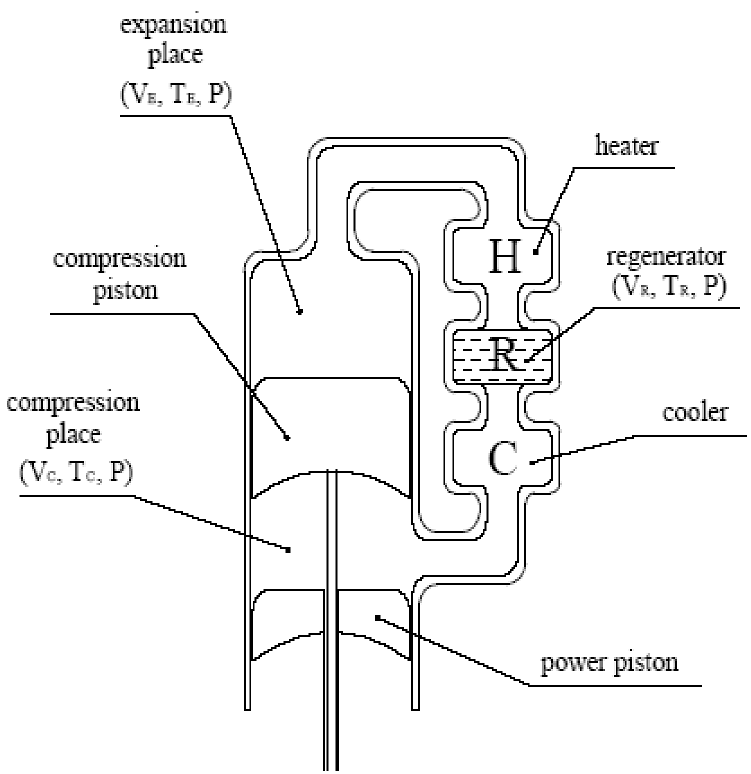
Steam engines

- 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

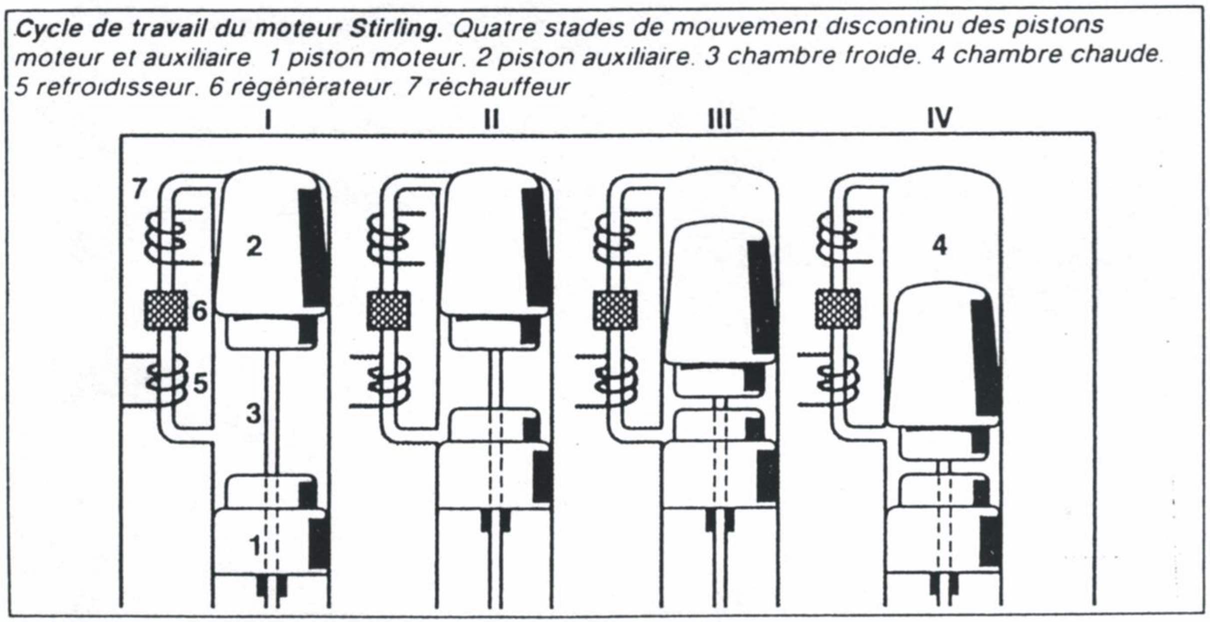


Stirling engine



- 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 regenerator.
- The theoretical efficiency of Stirling cycle is equal to the Carnot efficiency with the same difference of temperature.

Stirling engine



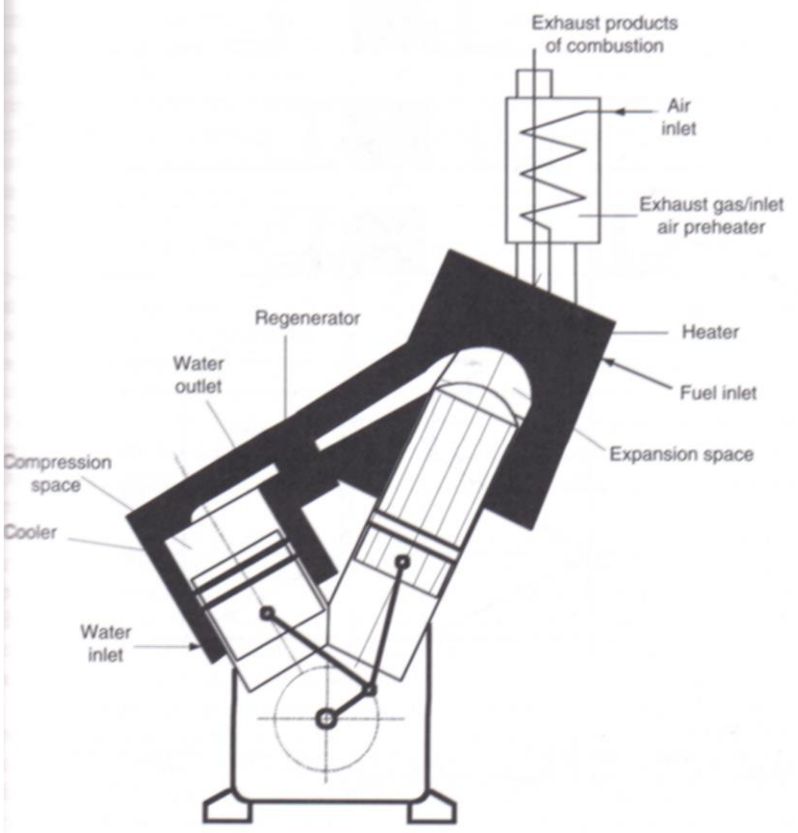
Source Bosch, Automotive handbook

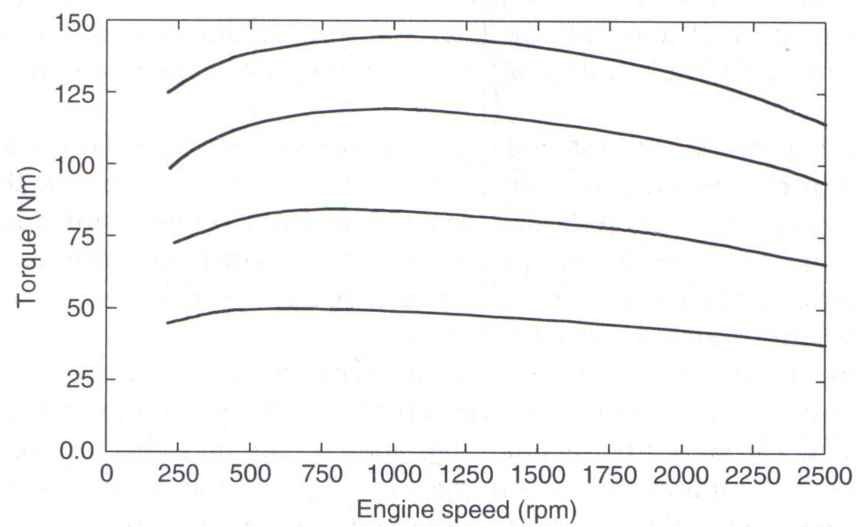
Step I: The power piston (1) in lower position. The displacer piston (2) is moving in upper position. The working fluid is pushed in the cold chamber (3)
Step II: The power piston is compressing the cooled gas in isothermal process
Step III: The displacer piston moves downward and pushes the gas to the 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



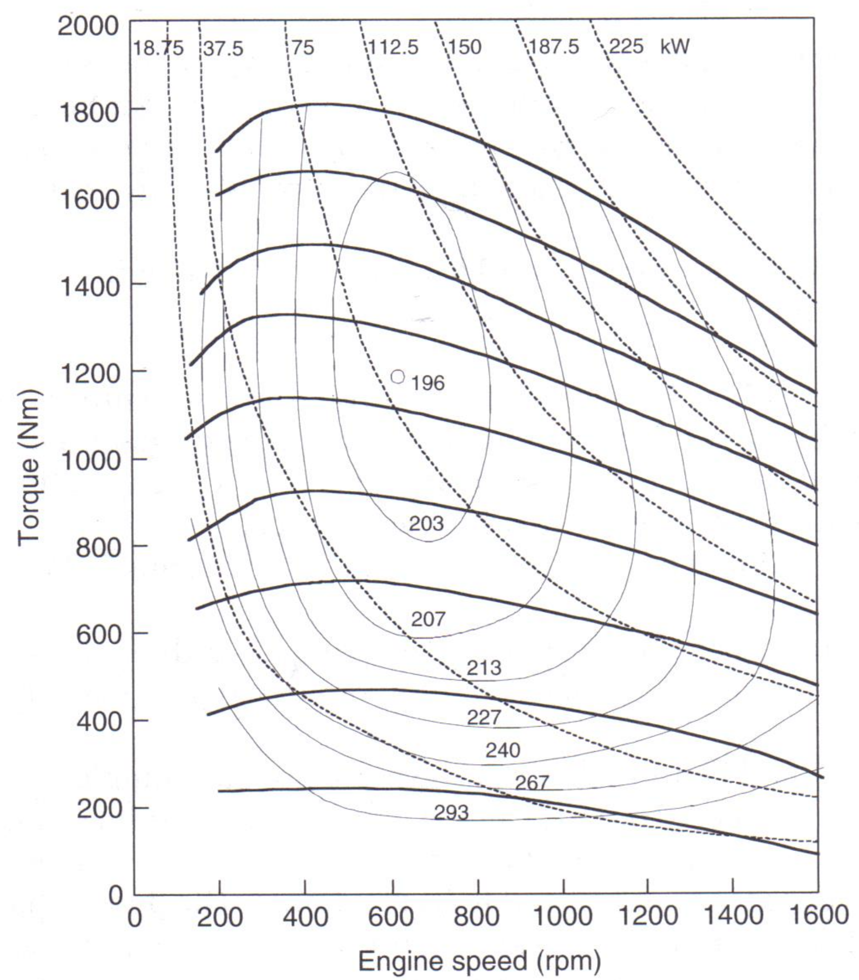


Torque / speed curves of a Stirling engine (Eshani et al. 2005)

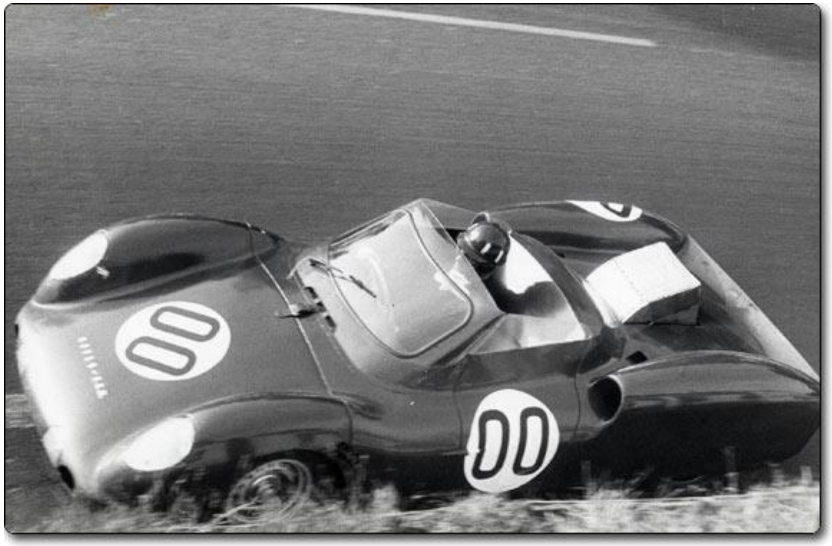
Practical layout of a Stirling engines with opposed pistons (Eshani et al. 2005)

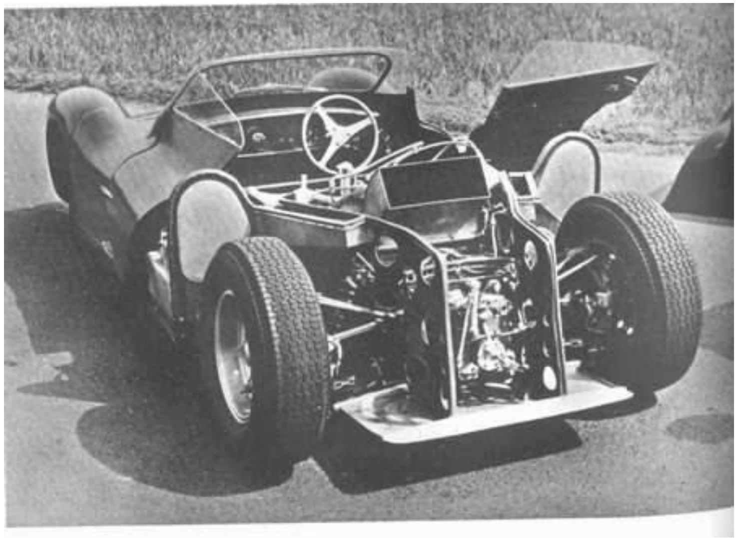
Stirling engine

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



Gas turbine

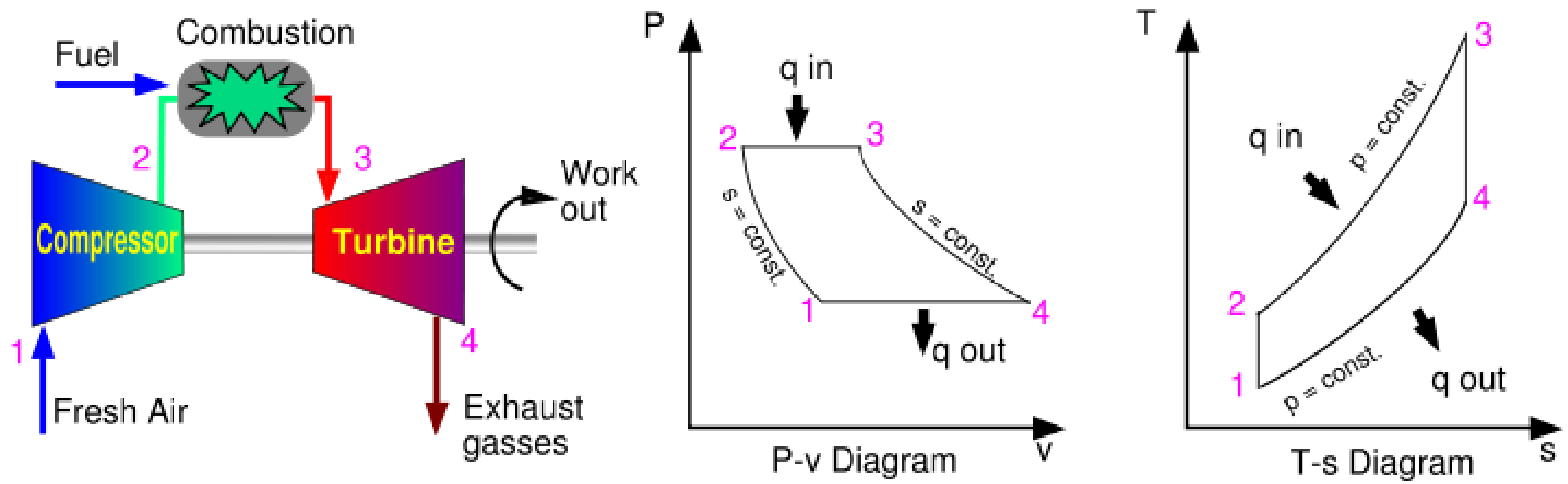




Gas Turbine

- 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…

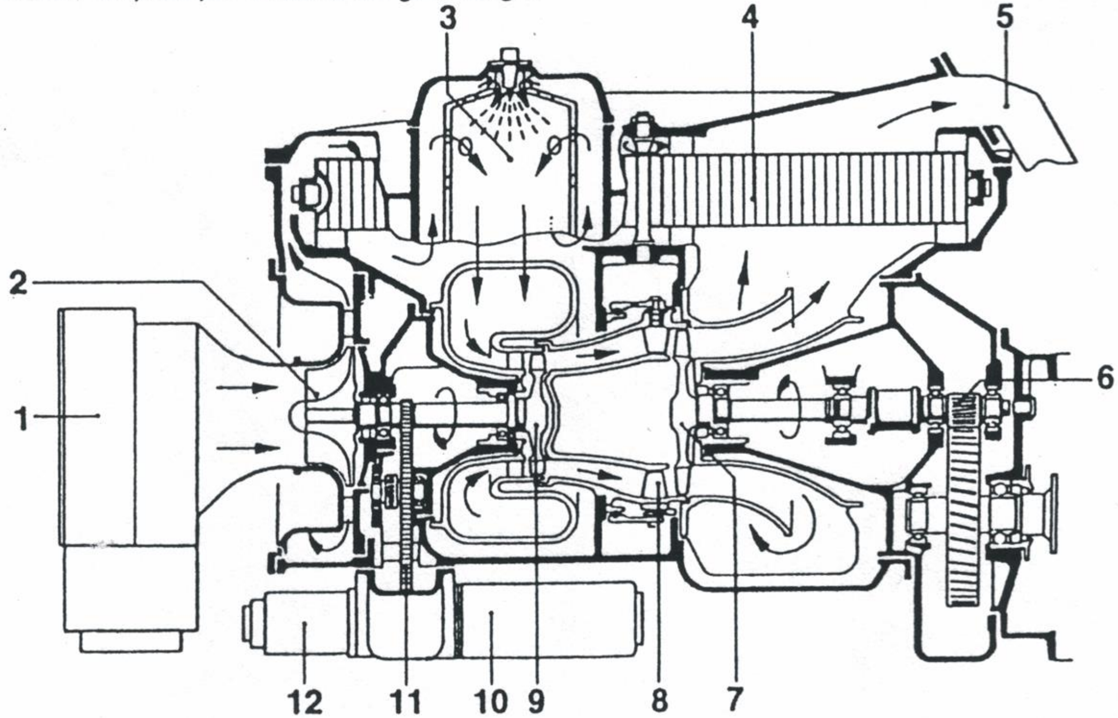
Gas Turbine



Idealized Brayton Cycle

Gas Turbine

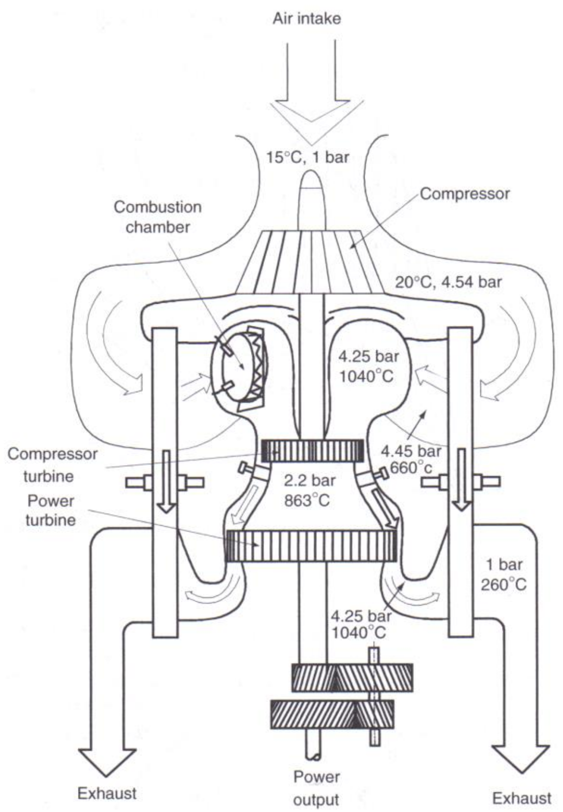
Turbine à gaz. *1 filtre et silencieux, 2 compresseur radial, 3 chambre de combustion, 4 échangeur de chaleur, 5 conduit des gaz d'échappement, 6 réducteur, 7 turbine de travail, 8 aubes fixes réglables, 9 turbine du compresseur, 10 démarreur, 11 entraînement de l'équipement auxiliaire, 12 pompe à huile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



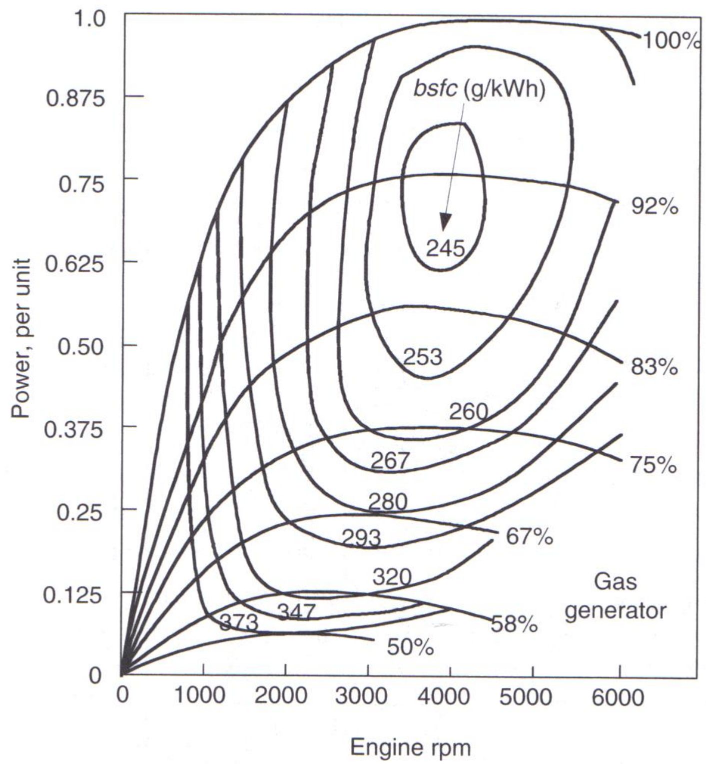
Gas Turbine

- 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 gear box to connect to the wheels (and so a weight penalty)

Gas Turbine



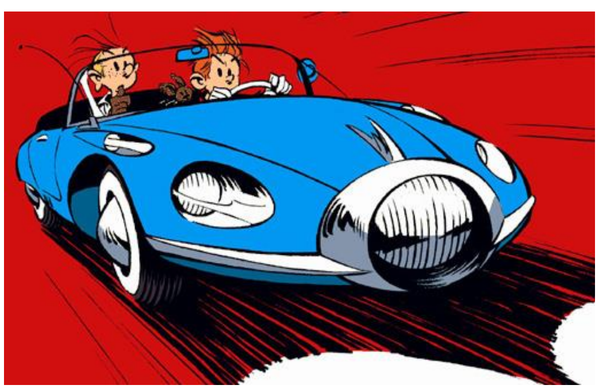
Gas turbine with exchanger
Eshani et al. 2005



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

Gas Turbine

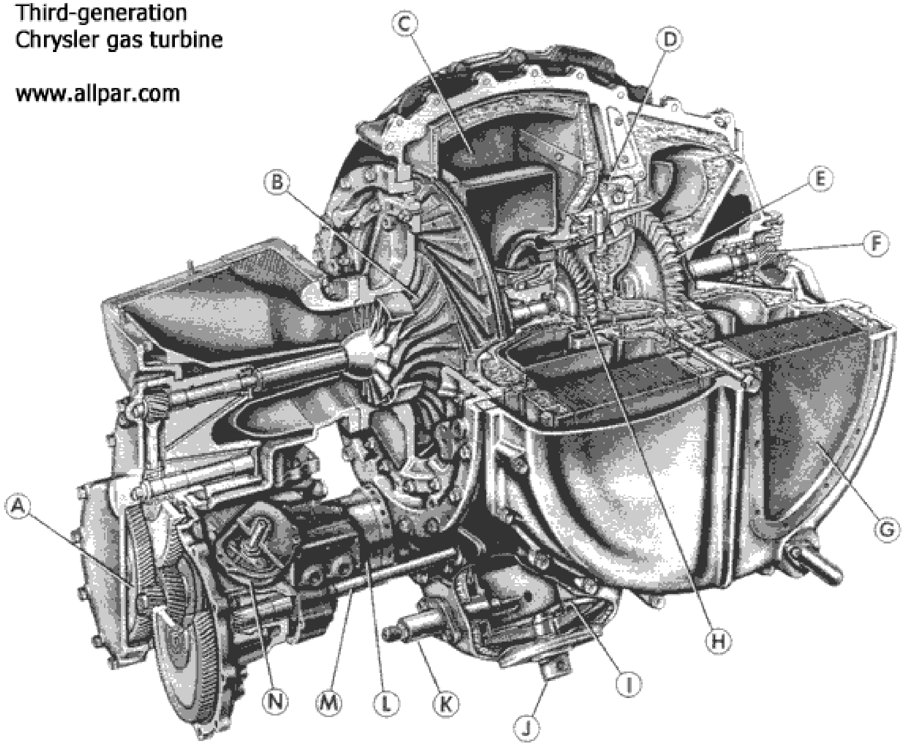
- One reports several tentative applications of gas turbines to automobile
  - As soon as the WWII, Rover has been interested in gas turbines and has realized prototypes between 1950 and 1961.
  - In 1963, the Rover BRM 00 has participated to the 24 hours of Le Mans with Graham Hill et Richie Gunther 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

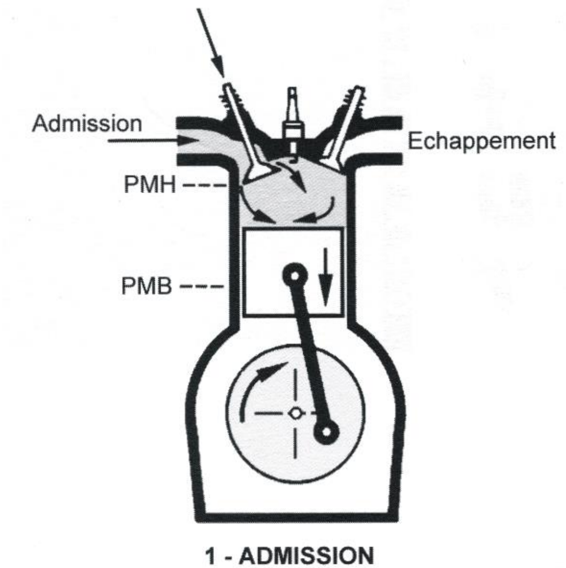
- 1700: Steam engine
- 1860: Lenoir motor (efficiency η~5%)
- 1862: Beau de Rochas defines the working principles of internal combustion engines
- 1867: Motor of Otto & Langen (η~11% and rotation <90 rpm)
- 1876: Otto invents the 4-stroke engine with spark ignition (η~14% and rotation < 160 rpm)
- 1880: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

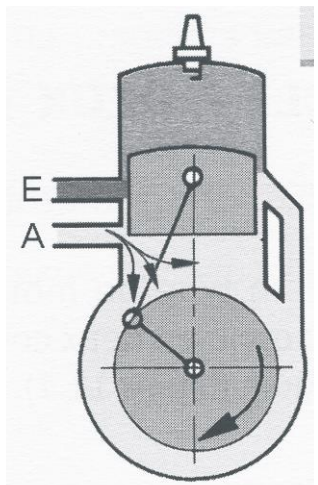
Piston engines (Gasoline and Diesel)

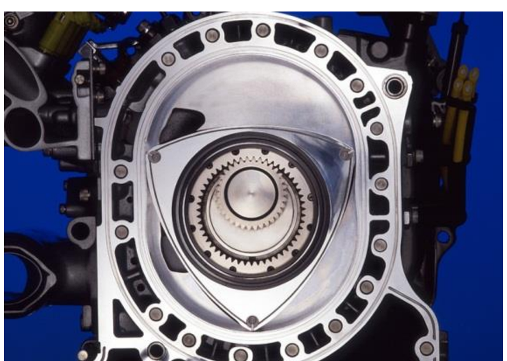
One distinguishes several variants

- 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

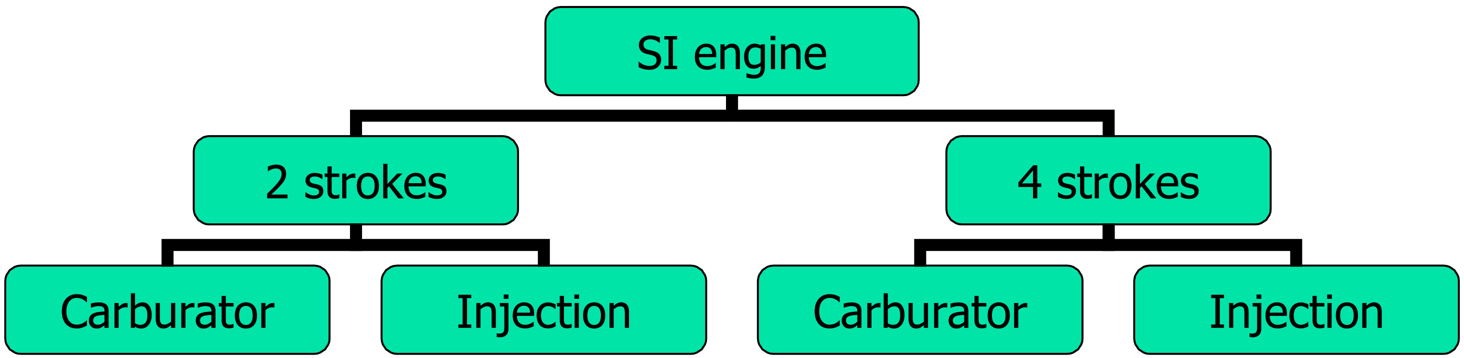


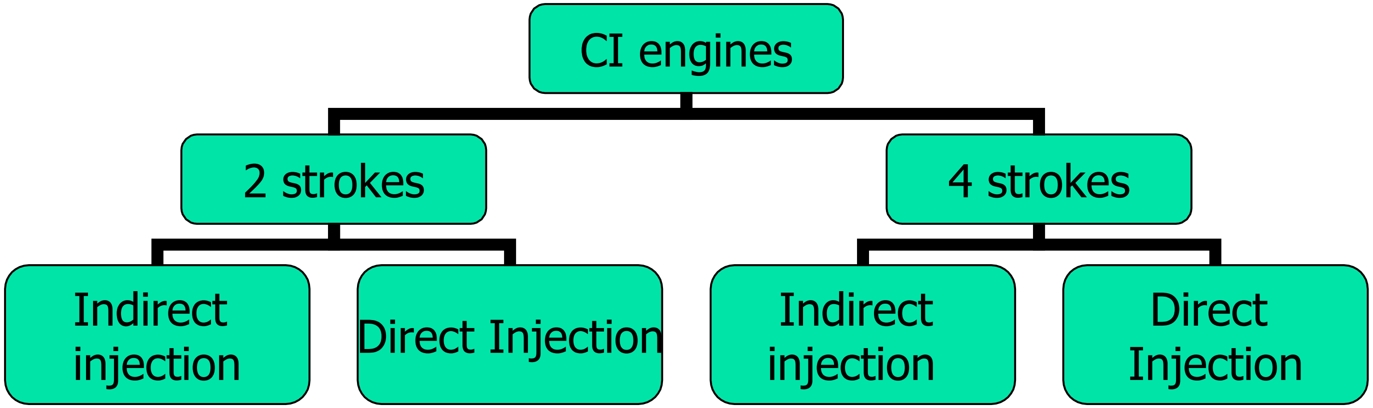




- The 4-stroke engine performs the 4 steps in 4 strokes, that is, in two crankshaft rotations.
- The 2-stroke engine carries out the four steps in two strokes, that is, in one crankshaft rotation.
- The rotary engine: the rotating motion is replacing the alternating motion. The rotor rotation realizes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

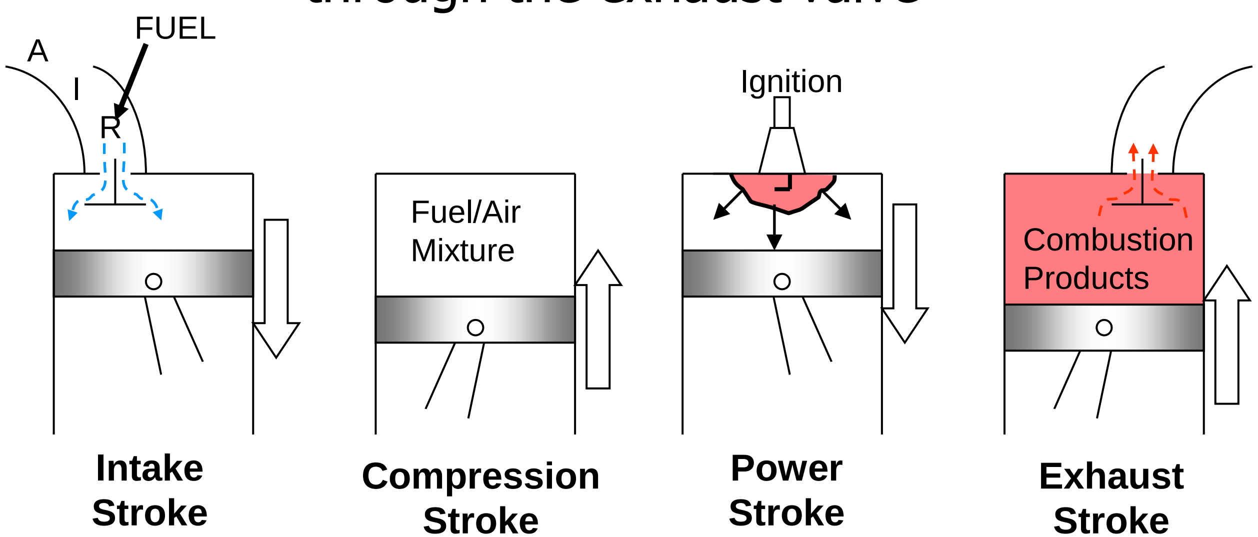
Classification





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 amount of technological developments to control the emissions of pollutants

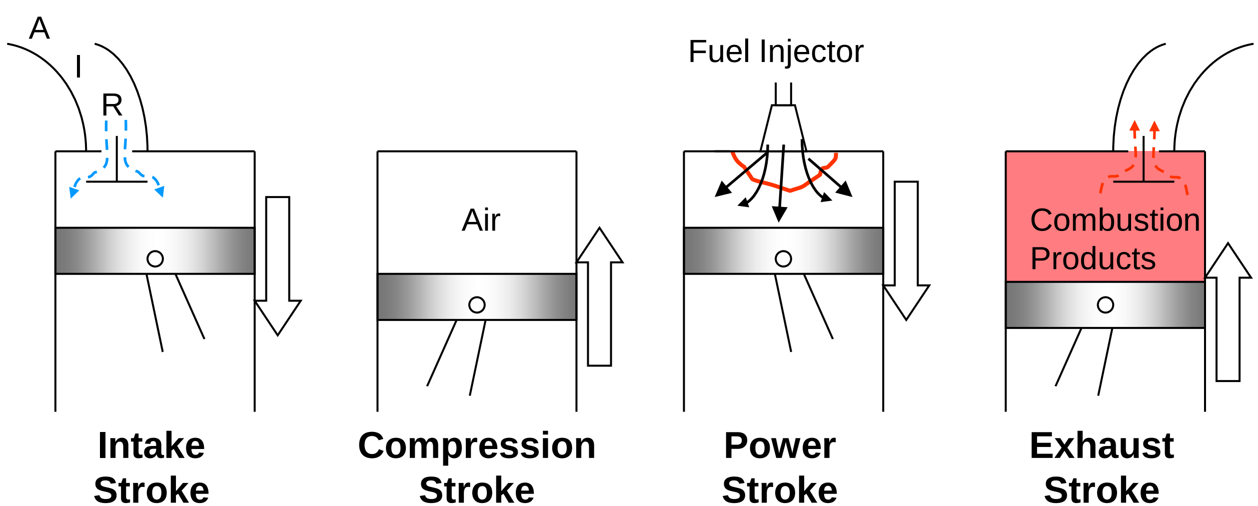
- Disadvantages:
  - Bad fuel economy and tedious emission control (HC, CO et NOx) when operated at <u>part load</u> and <u>cold temperature conditions</u>

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

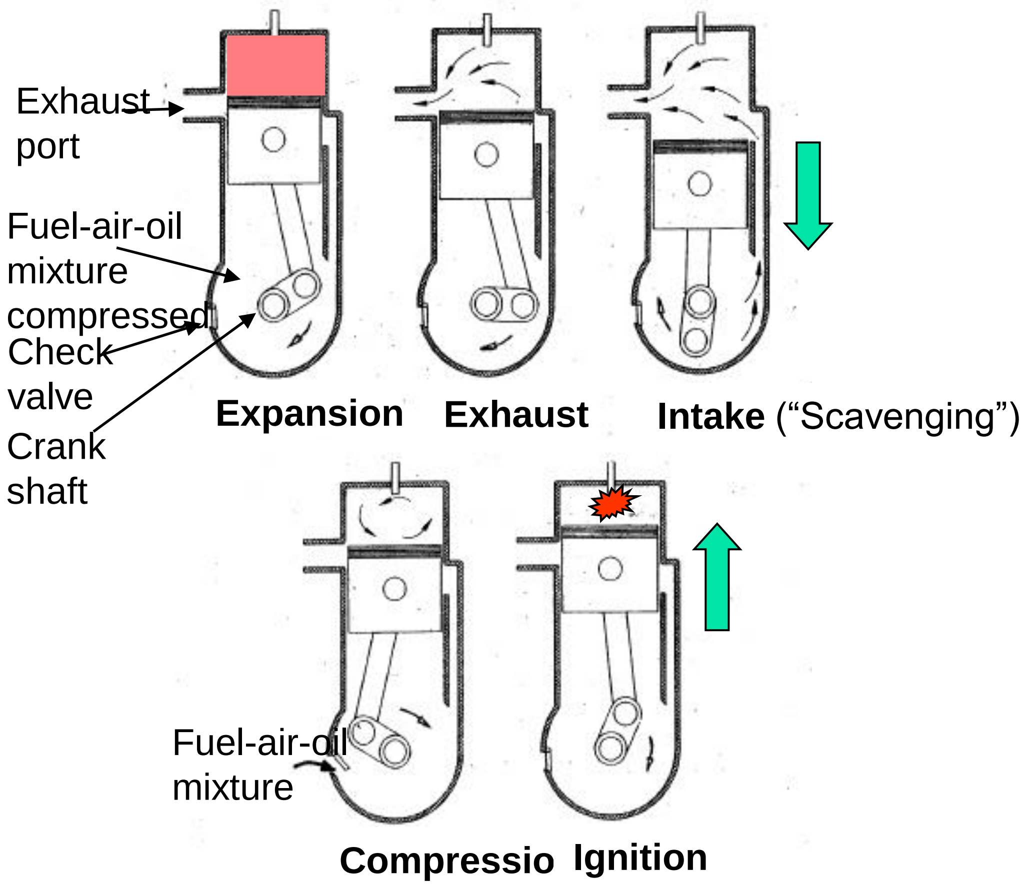
- Advantages:
  - Higher efficiency because of the higher compression ratio
  - Largely developed and technological availability
  - Low CO and HC emissions

- 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

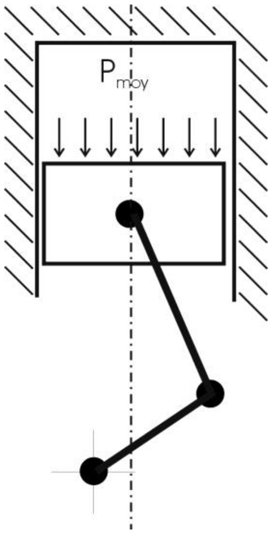
- Compared to 4-stroke engines, 2-stroke engines have
  - A higher power to weight ratio since there is one power stroke per crank shaft revolution.
  - Simple valve design.
  - A lower fabrication cost.
  - A lower weight.
- However, several drawbacks:
  - Incomplete scavenging or too much scavenging.
  - 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….

Indicated mean effective pressure

- The brake mean effective pressure bmep is a fictitious *constant* pressure that would produce the same output work per cycle as if it were acting on the piston during the power stroke

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

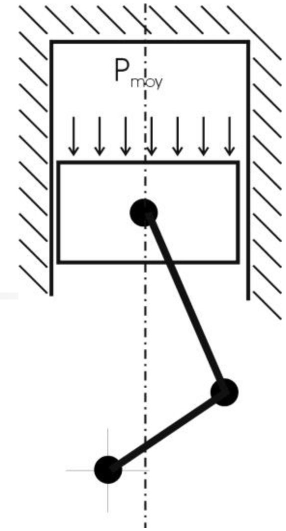
$$W_{1stroke}^{1cyl} = \mathrm{bmep}.\frac{\pi B^2}{4}.l = \mathrm{bmep}.V_{1cyl}$$



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

$$W_{1stroke}^{ncyl} = \mathrm{bmep}.V_{1cyl}.n_{cyl} = \mathrm{bmep}.V_d$$

Indicated mean effective pressure



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

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

- 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

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

- And the torque writes

$$C = \frac{\dot{W}}{\omega} = \text{bmep}\frac{V_d}{2.n_R.\pi}$$

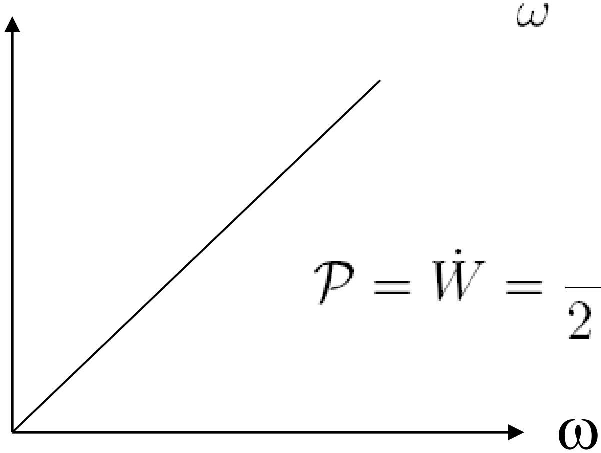
Torque speed curves of ICE

- The power curves is proportional to the rotation speed:

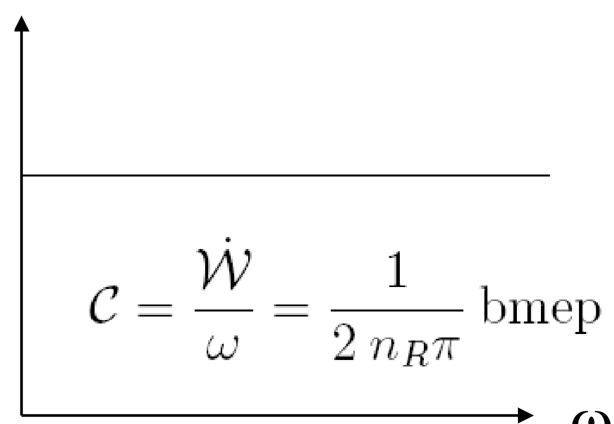
$$\mathcal{P} = \dot{W} = \frac{\omega}{2\, n_R \pi}\, \mathrm{bmep}\, V_d$$

- The torque speed curve is constant

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

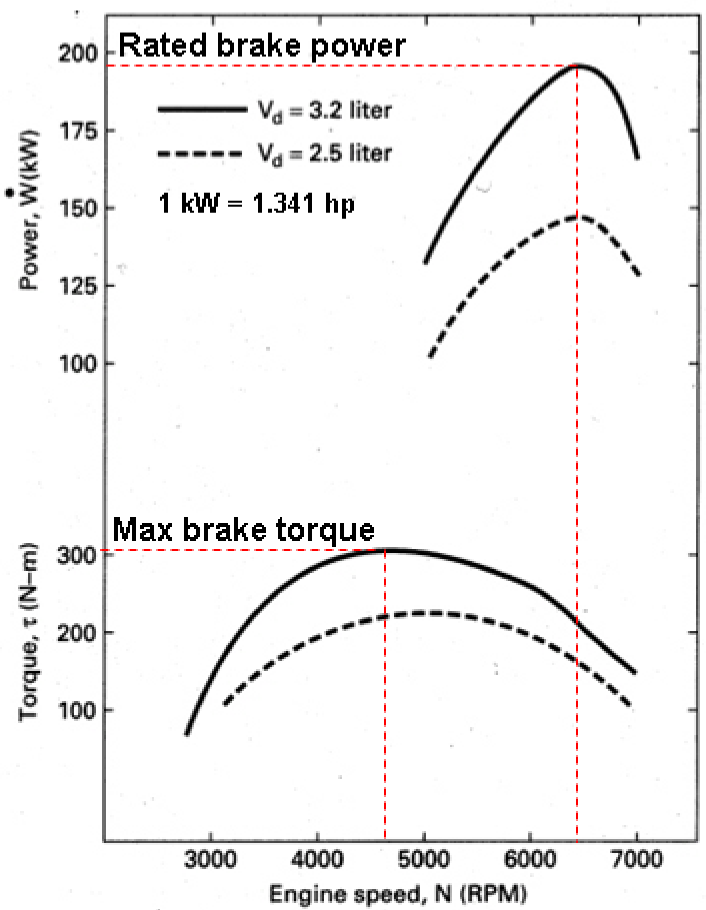


$$\mathcal{P} = \dot{W} = \frac{\omega}{2\, n_R \pi}\, \mathrm{bmep}\, V_d$$



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

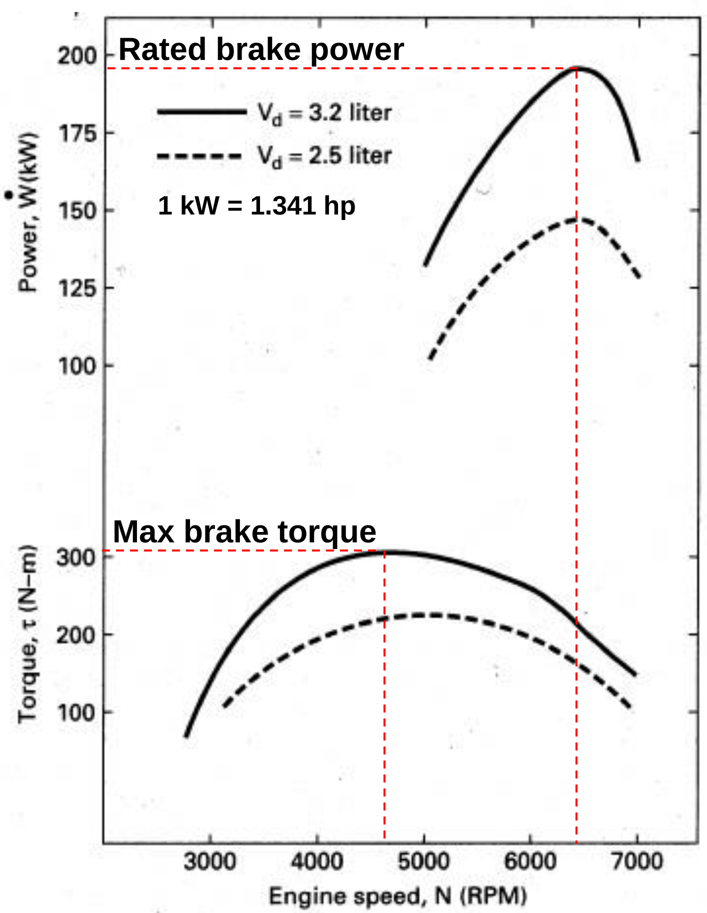
Power and torque as function of the rotation speed



- 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:

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

- Under variable operating conditions

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

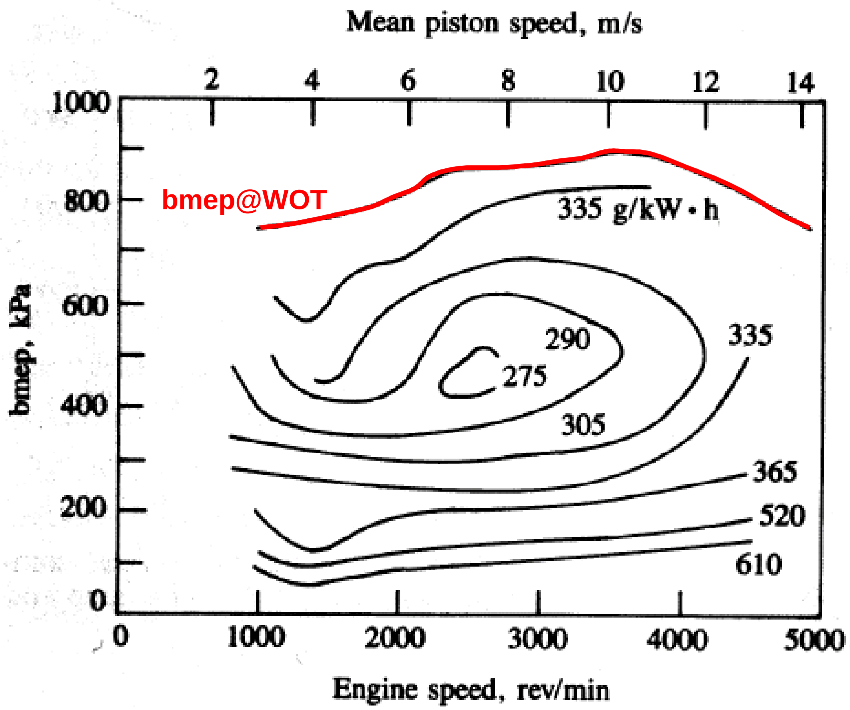
$$dm_f = \dot{m}_f\, dt$$

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

- 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

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.

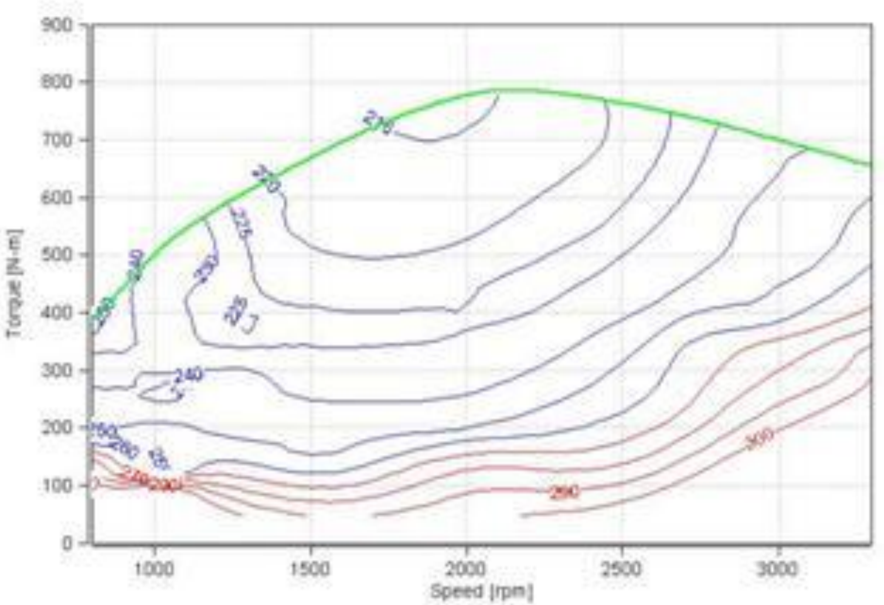


$$bmep = \frac{2\pi \cdot C \cdot n_R}{V_d}$$

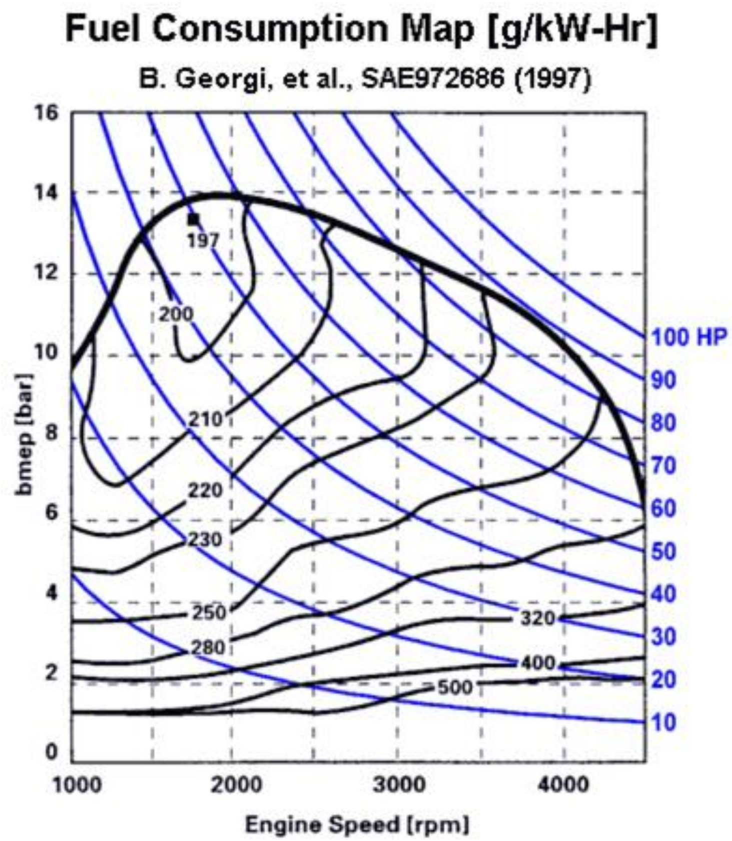
$$\dot{W}_b = (2\pi \cdot N) \cdot C$$

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

Piston engines characteristics: fuel consumption

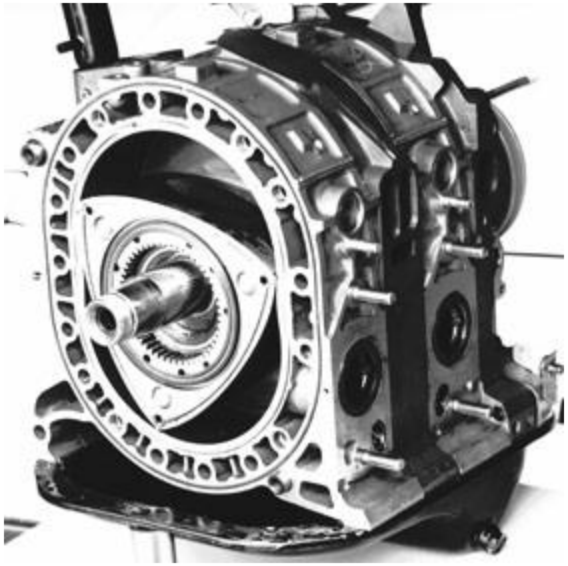


Gasoline engine



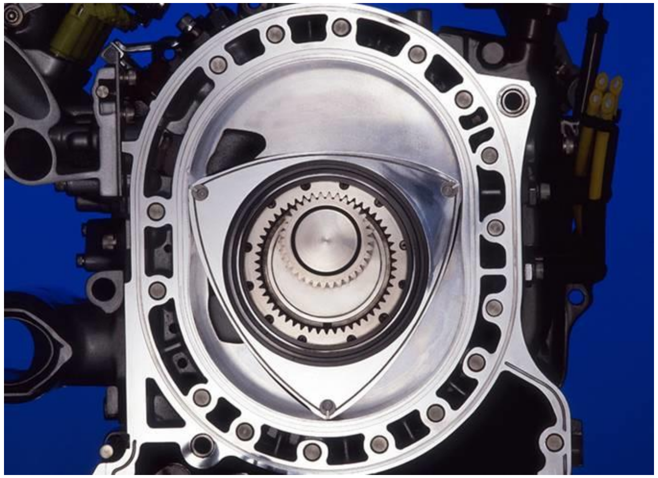
Diesel engine

Wankel Rotary Engines



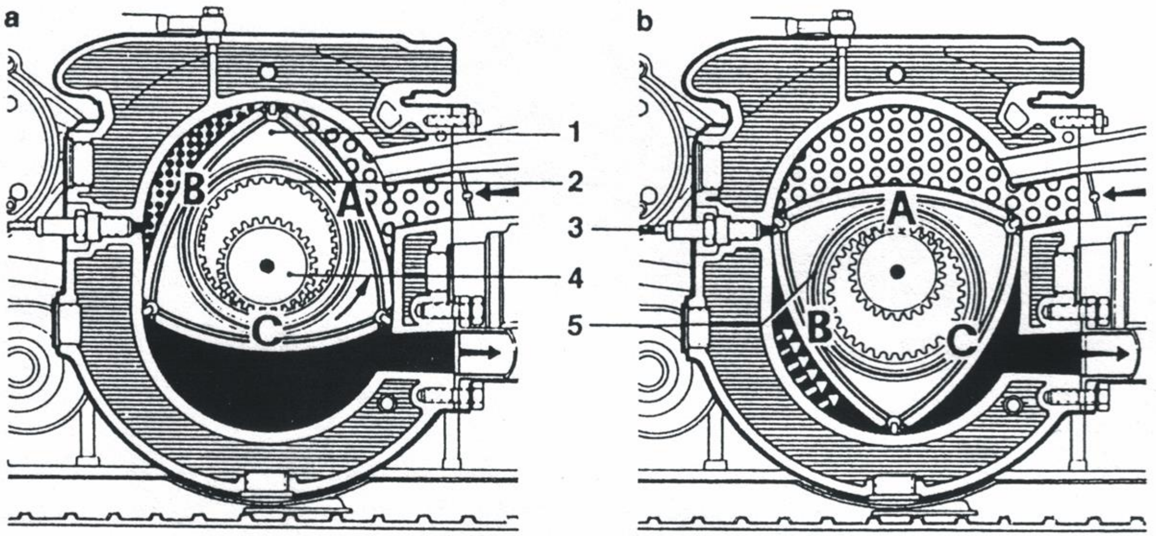
Wankel rotary engines

- 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.



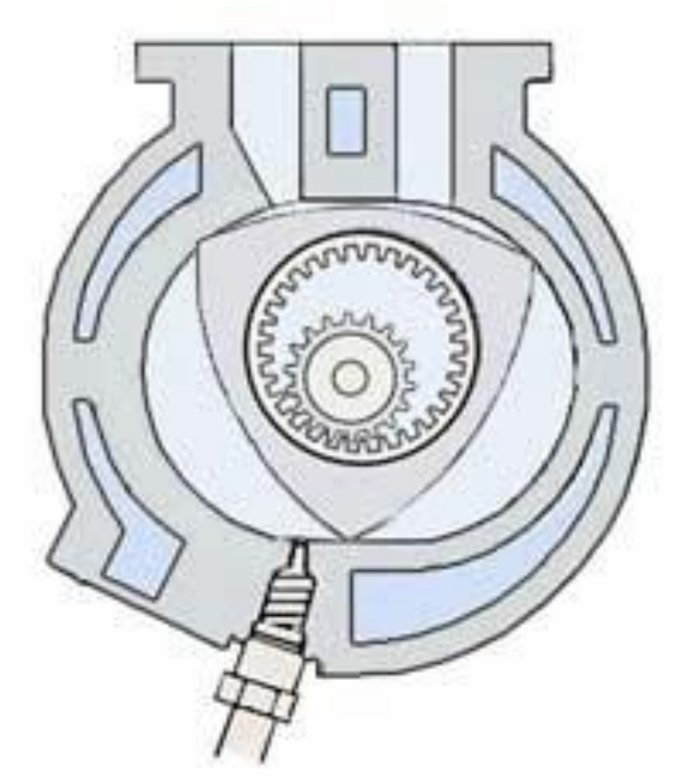
Wankel rotary engines

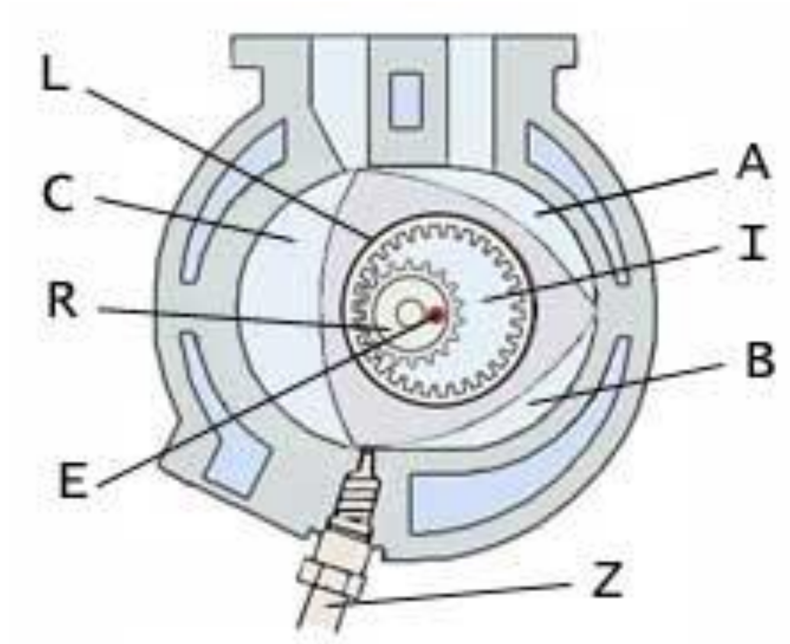
Conception et mode de fonctionnement du moteur à piston rotatif Wankel.
1 piston, 2 denture intérieure dans le piston, 3 bougie d'allumage, 4 pignon fixe, 5 bande de roulement de l'excentrique.
a: la chambre A aspire, la chambre B comprime, les gaz brûlés sont expulsés de la chambre C. (Le passage des 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

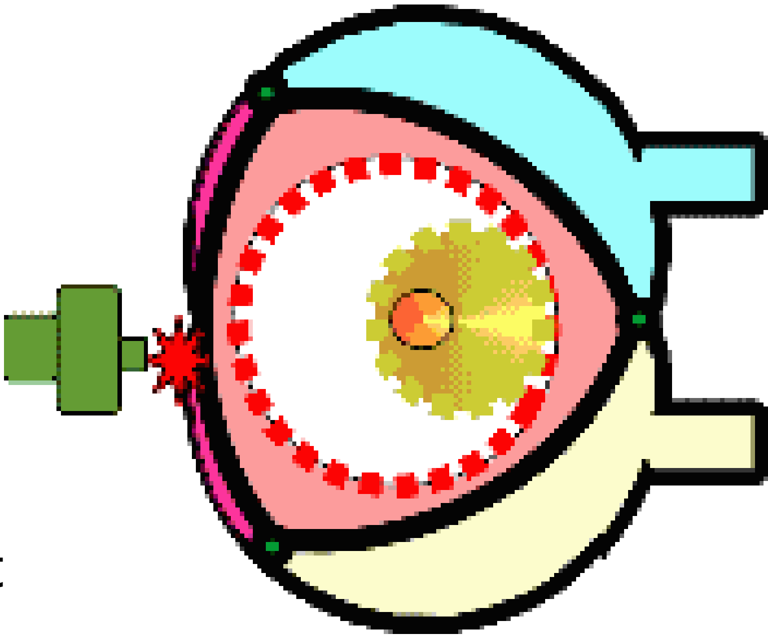




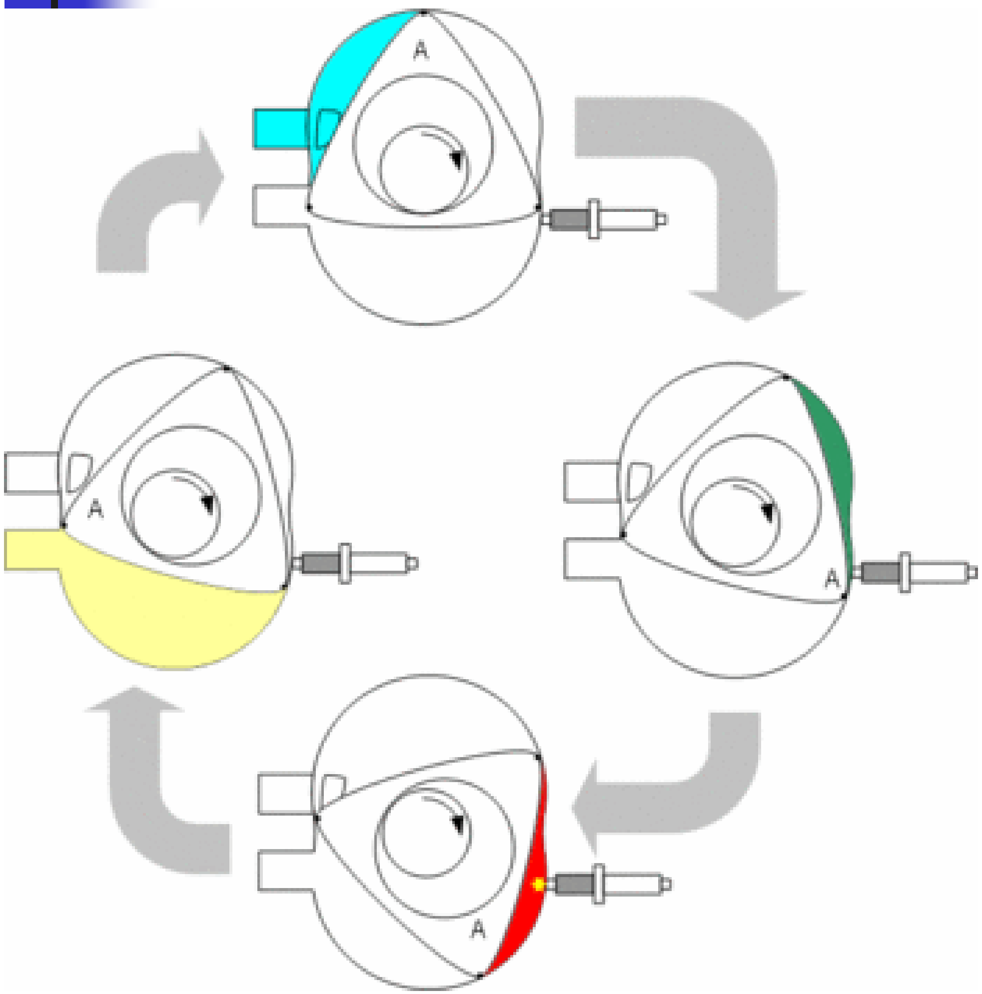
E: Pinion – L: Eccentric

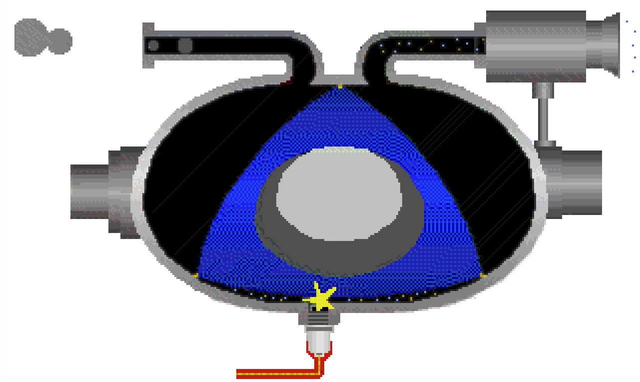
Wankel rotary engines

- Combining a suitable layout of the inlet, outlet and ignition devices, the volume variation of each chamber works out the 4 strokes of the Otto cycle in one revolution of rotor.
- As the rotor has 3 chambers, one observes a full cycle every 1/3 of the rotor revolution
- The gear ratio between the crankshaft pinion and the interior gears of the eccentric provides a 1:3 reduction ratio so that one can see a cycle at each revolution of the crankshaft



Wankel rotary engines



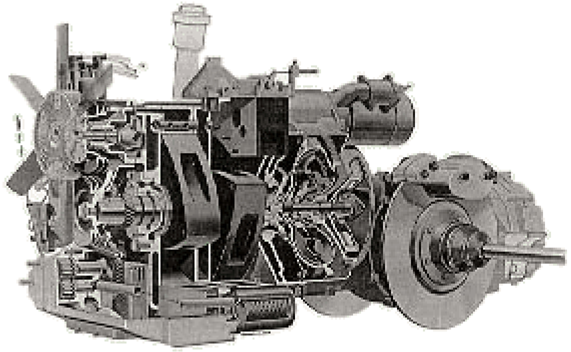


Wankel rotary engines

- 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

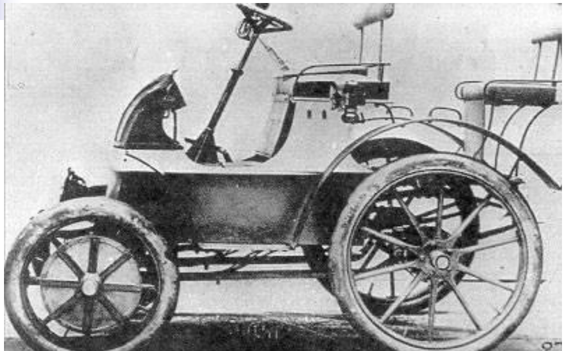
Wankel rotary engines

- 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



Electric traction

Electric cars


The early 1900's Lohner-Porsche, originally electric-powered, then with an internal combustion engine powering hub-mounted electric motors.

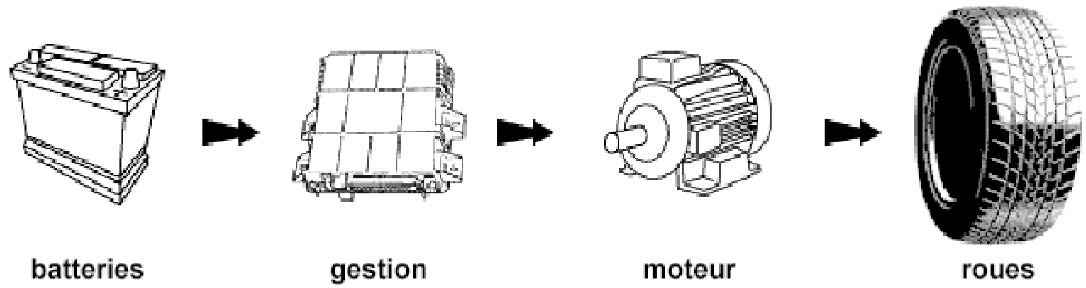
- Electric cars were very dominant at the turn of the 20th century but they were substituted by ICE engines in the period from 1905 to 1915
- Revival interest for electric cars at every petrol or energy crisis
- But up to now, electric cars have always experienced a commercial failure
- At the turn of the 21th century, electric propulsion systems are coming back at the front stage

Electric propulsion

- Advantages:
  - Zero direct emission
  - Low noise emissions
  - Regenerative braking
  - High torque at low speed
  - Good driving comfort → urban application
  - Simple mechanical transmission (generally no gear box, no clutch), speed and torque regulation,
  - Perfect solution if external power supply (catenaries)
- Disadvantages:
  - Batteries: cost, extra-weight, life time
  - Charging time (~2 hours → 6 hours)
  - Limitation of range (200 km → 450 km?)

Nissan Leaf

Electric propulsion



Electric drivetrains are basically composed of four components:

1. The electrical power source: battery if the energy is stored on board or catenaries system if connection to an external source as electric cables or rail is possible.
2. Power electronics to regulate the power, the speed, the torque.
3. The electric machine that can be operated in a reversible mode (motor or generator).
4. A simple mechanical transmission to communicate the mechanical power to the wheels

Batteries performances

Batteries	Lead-Ac	Ni-Cd	Ni-MH	Zebra	Li-Ions
Useful specific energy [W.h/kg]	17	38	62	74	105
Specific power [W/kg]	90	79	118	148	294
Charge – discharge efficiency [%]	60	65	80	85	85
Life cycles [cycles]	600	1200	1200	1200	1000
Specific cost [€/kW.h]	0,339	0,508	1,159	0,781	0,734

Batteries challenge

Fuel / energy systems	Gasoline	Diesel	Li-Ions
Specific energy [W.h/kg]	11.833	11.667	105
Average efficiency while driving [%]	12	18	80
Specific energy at wheel [W.h/kg]	1420	2100	84

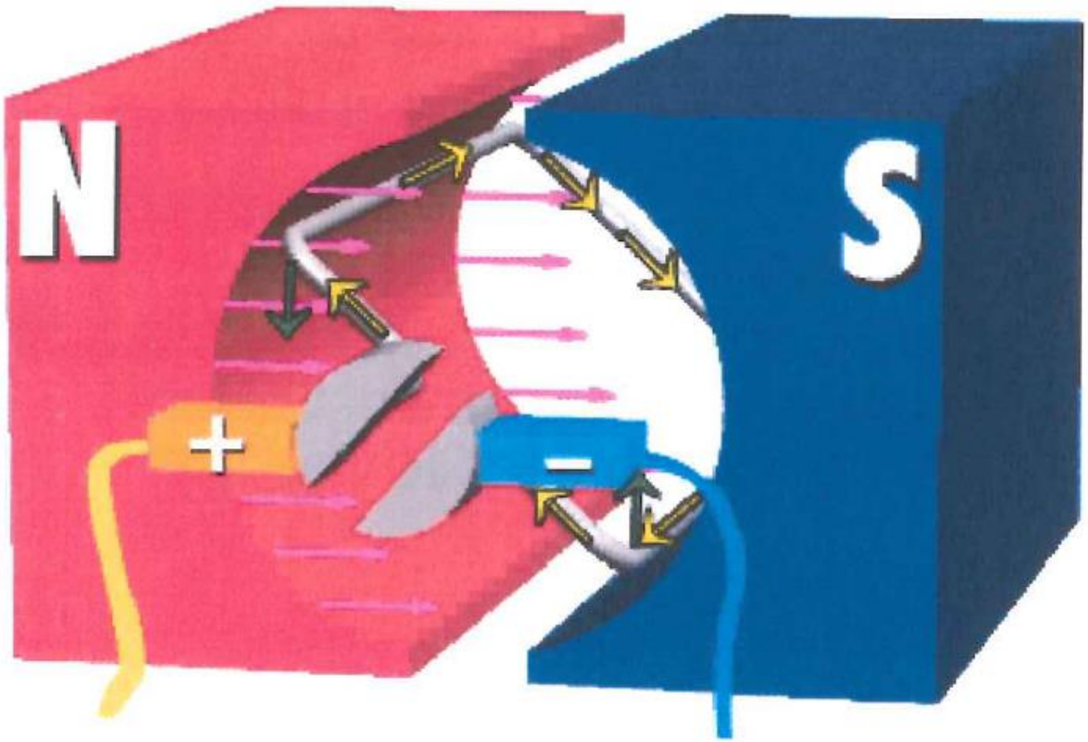
Gap 200!

DC electric motors

$$\vec{F} = i\,\vec{l} \times \vec{B}$$

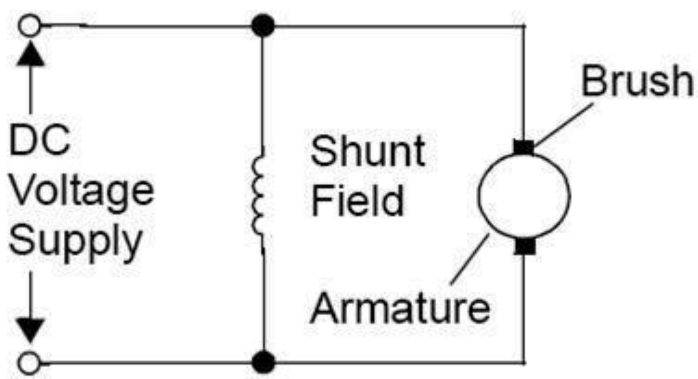
$$T = B\,i\,L\cos\alpha$$

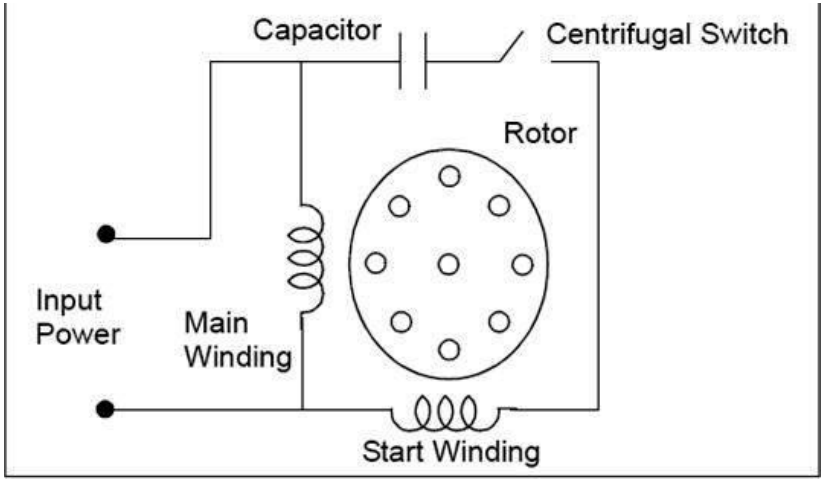
$$E = -\frac{d\Phi}{dt} = -N\,\frac{d\phi}{dt}$$

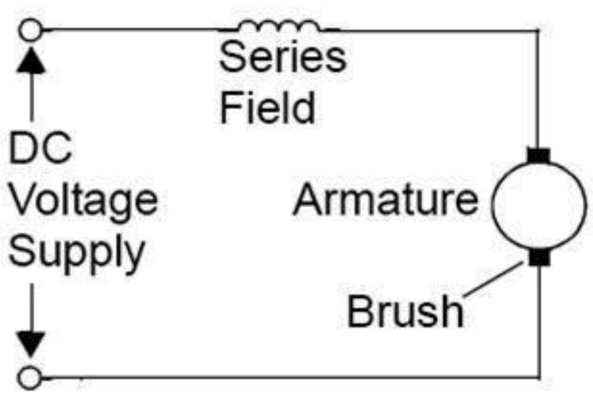


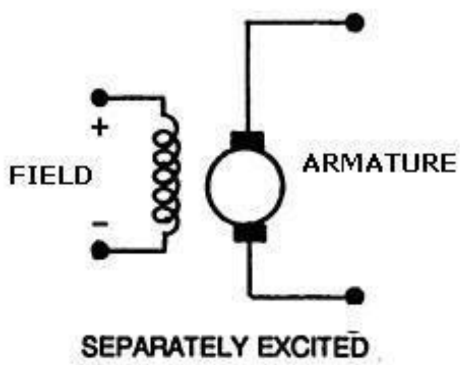
Working principal of a DC motor

Performance curves of electric machines

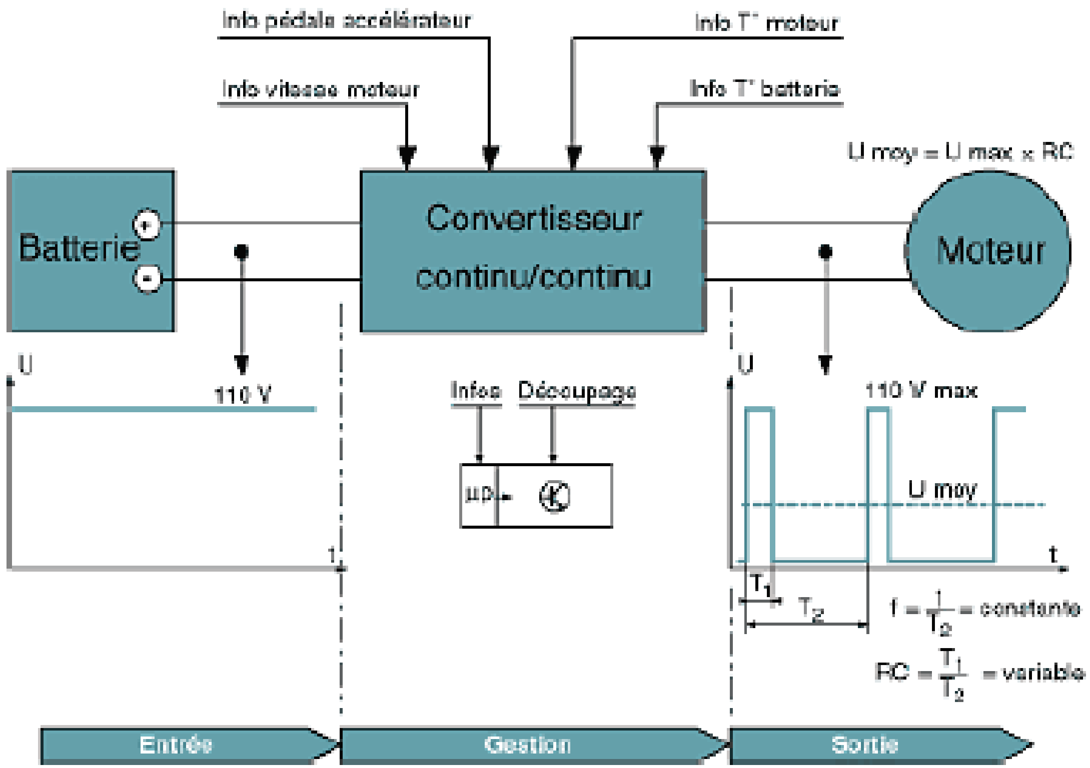






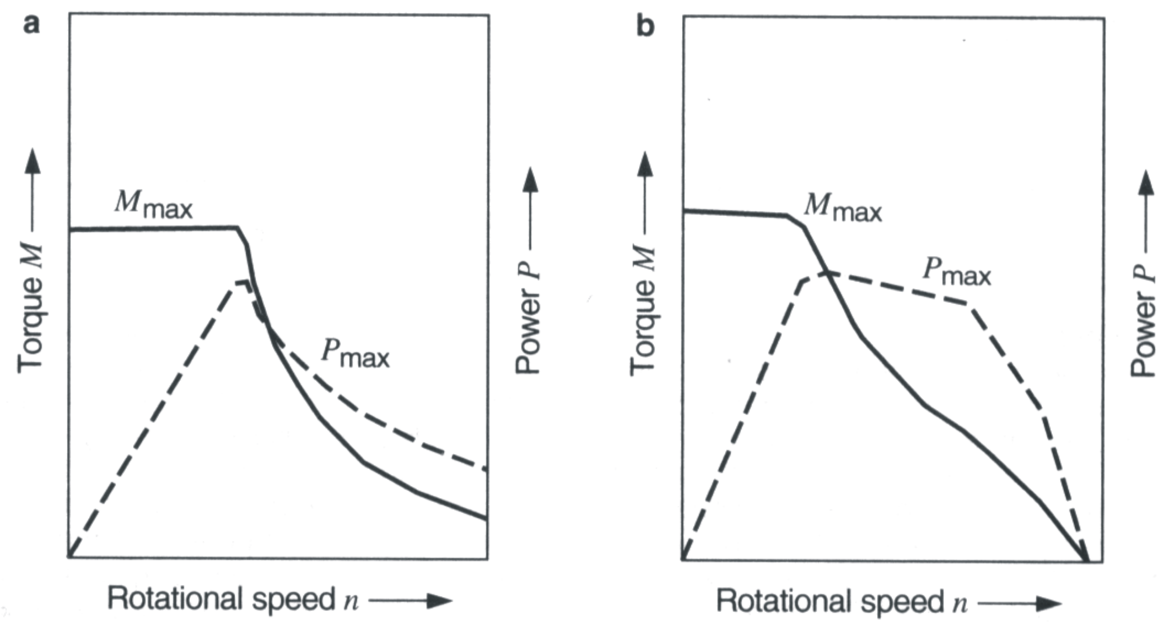


Power electronic and control of DC machines



Working principle of a chopper

DC motor: series and separated excitation



DC series motor

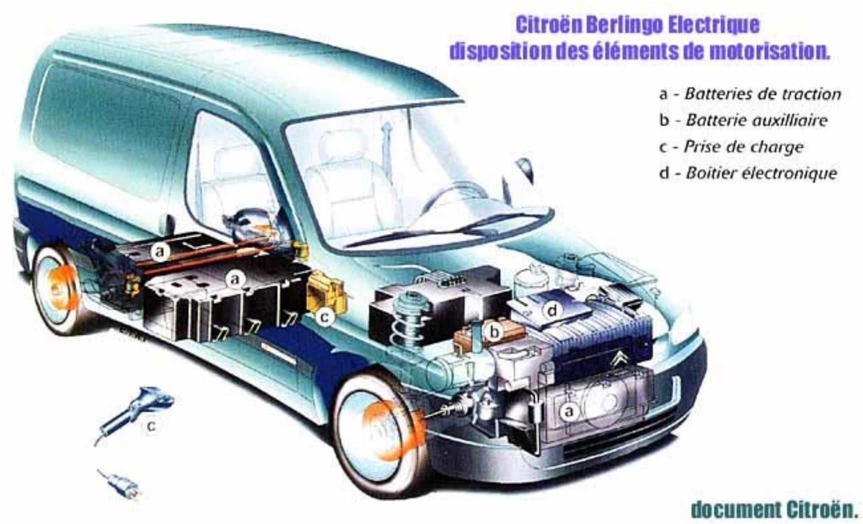
DC motor with separated excitation

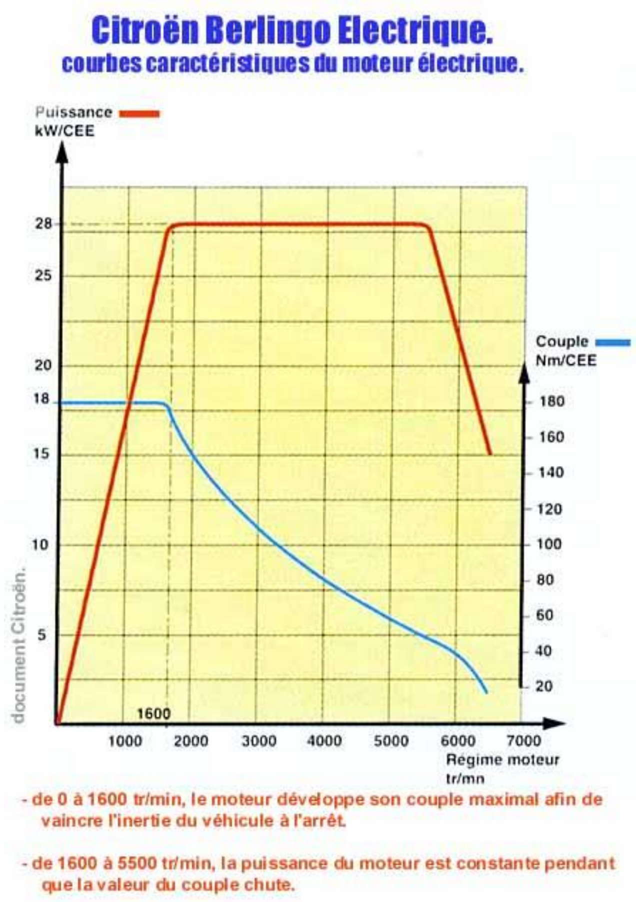
DC tractions motors

Peugeot 106 Electrique - EDF-GDF du Var
détail du raccordement véhicule - borne de recharge

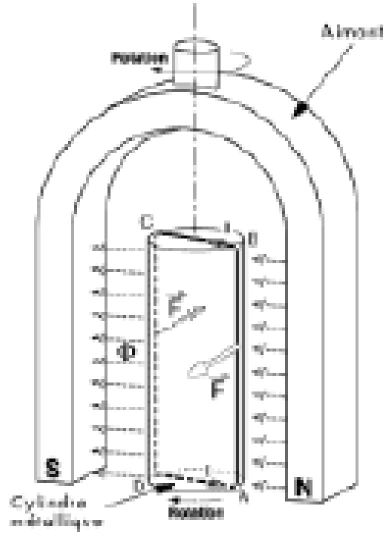
- Advantages of DC motors
  - Mature technology
  - Control of DC motor is well known: speed control from DC energy sources
    - Variable resistor → chopper (PWM)
  - Early usage of DC motors in vehicles based on DC series architecture: electric vehicles, tramways, etc.
- Disadvantages:
  - Brushes (carbon) must be replaced periodically: replacement after 3000 h of operation
  - Range of supply voltage is limited
  - Lower specific power
  - Medium energy efficiency (80-85%)
  - Rotor losses : very difficult to eliminate

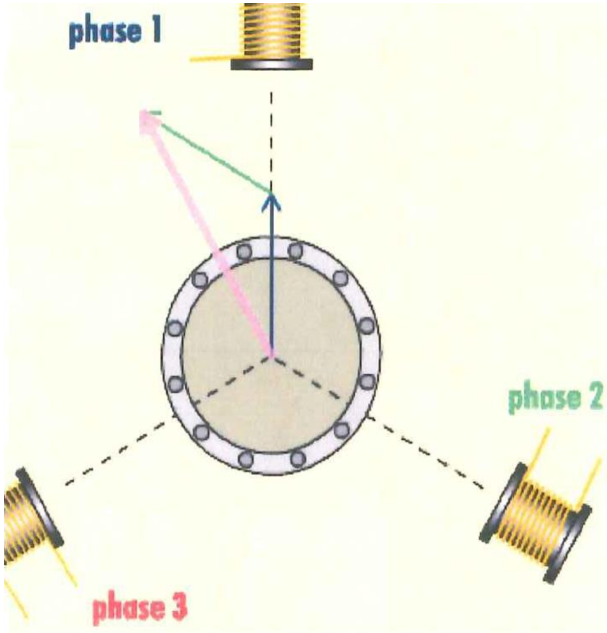
DC electric machines





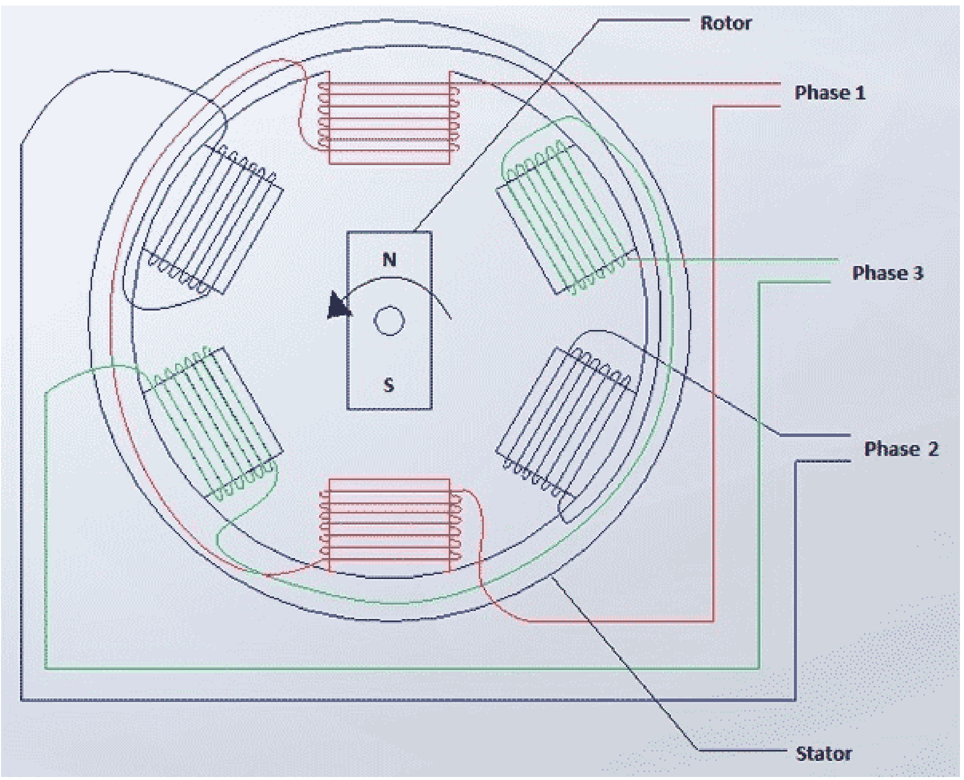
AC asynchronous electric motors



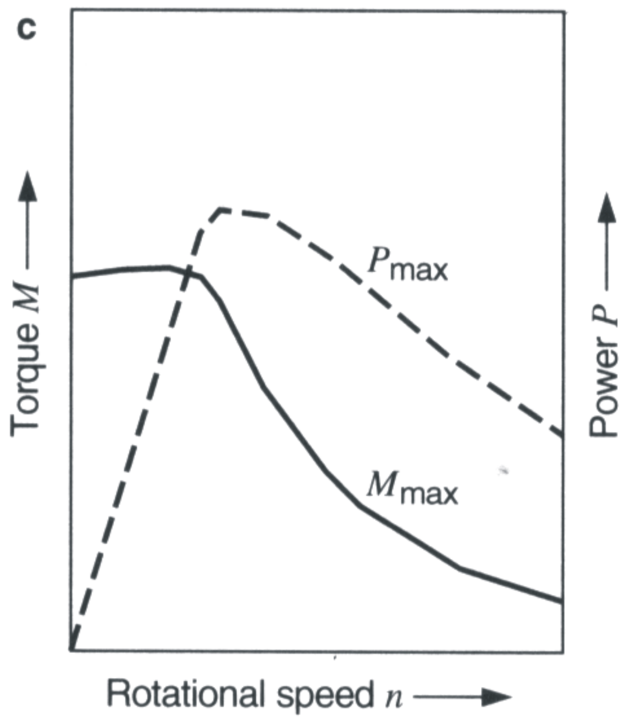


Working principle of AC asynchronous motors

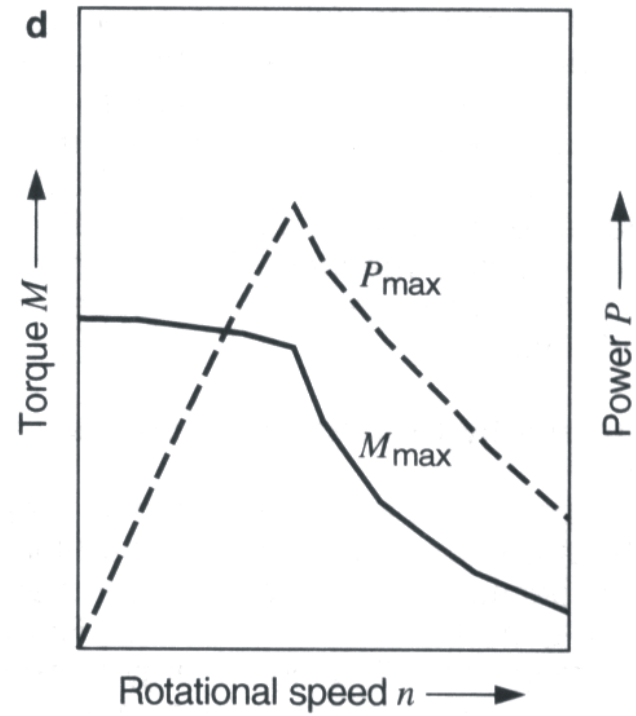
AC Synchronous motors



AC motors: induction vs synchronous

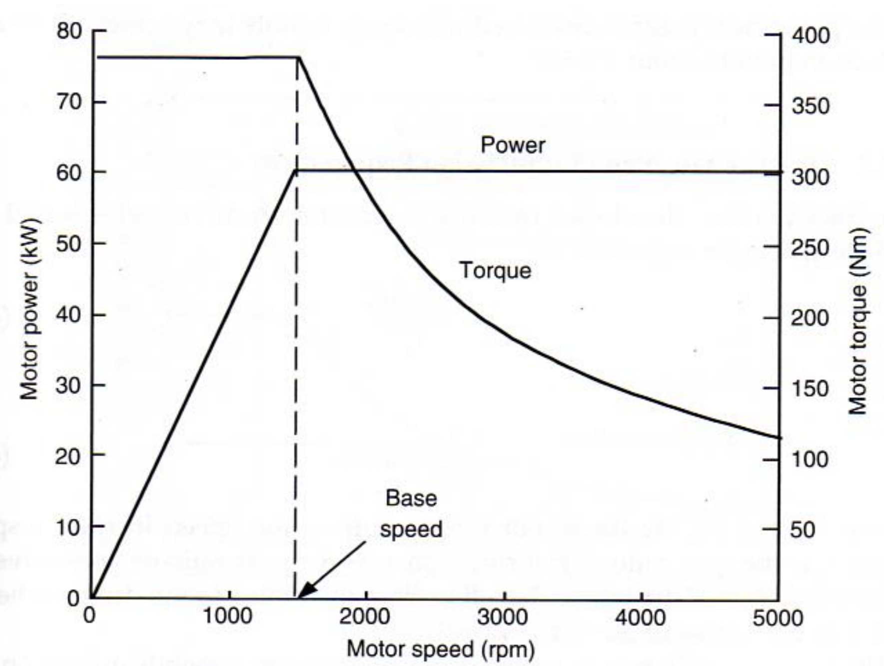


AC induction motor



AC synchronous motor

Traction motor characteristics

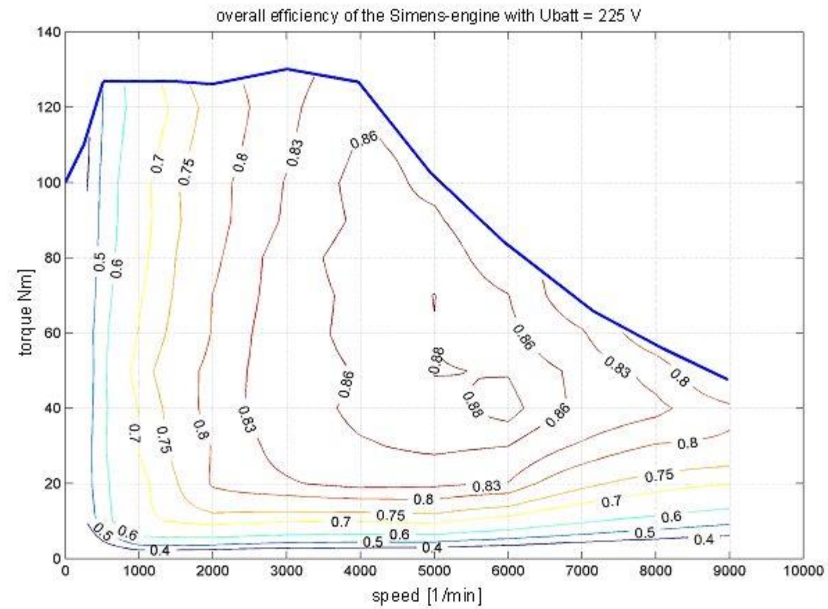


- At low speed: constant torque
  - Voltage supply increases with rotation speed through electronic converter while flux is kept constant
- At high speed: constant power
  - Motor voltage is kept constant while flux is weakened, reduced hyperbolically with the rotation speed
- Base speed: transition speed from constant torque to constant power regime

Traction motor efficiency map

- Electric machine efficiency in transformation of the electric power to mechanical power is dependent on the operating conditions

$$\eta = \frac{\mathcal{P}_{meca}}{\mathcal{P}_{elec}}$$



- It can be mapped on the torque/power-speed space
- The efficiency mapping can be different when working as a motor (generally lower) than as a generator (often better)

Traction electric machines

DC MOTORS

- Serial or separated excitation
  - Price still high (-)
  - Reliability and control (+)
  - Maintenance (brush) (-),
  - Weight (-)
  - Max speed (-)
  - Efficiency ~80% (-)
- Control by chopper with PWM command

AC MOTORS

- Asynchronous machines
  - High maximum speed
  - Low maintenance, high reliability
  - Weight
  - Good efficiency (~95%)
- Synchronous machines
  - Maintenance, efficiency , reliability (+)
  - Expensive (-), max speed lower than AC async (-)
- Inverter with vector command (f,I,V)

Compressed Air Vehicles

Compressed Air Vehicle

- A compressed-air vehicle (CAV) is a transport mechanism fueled by tanks of pressurized atmospheric gas and propelled by the release and expansion of the gas within a pneumatic motor.

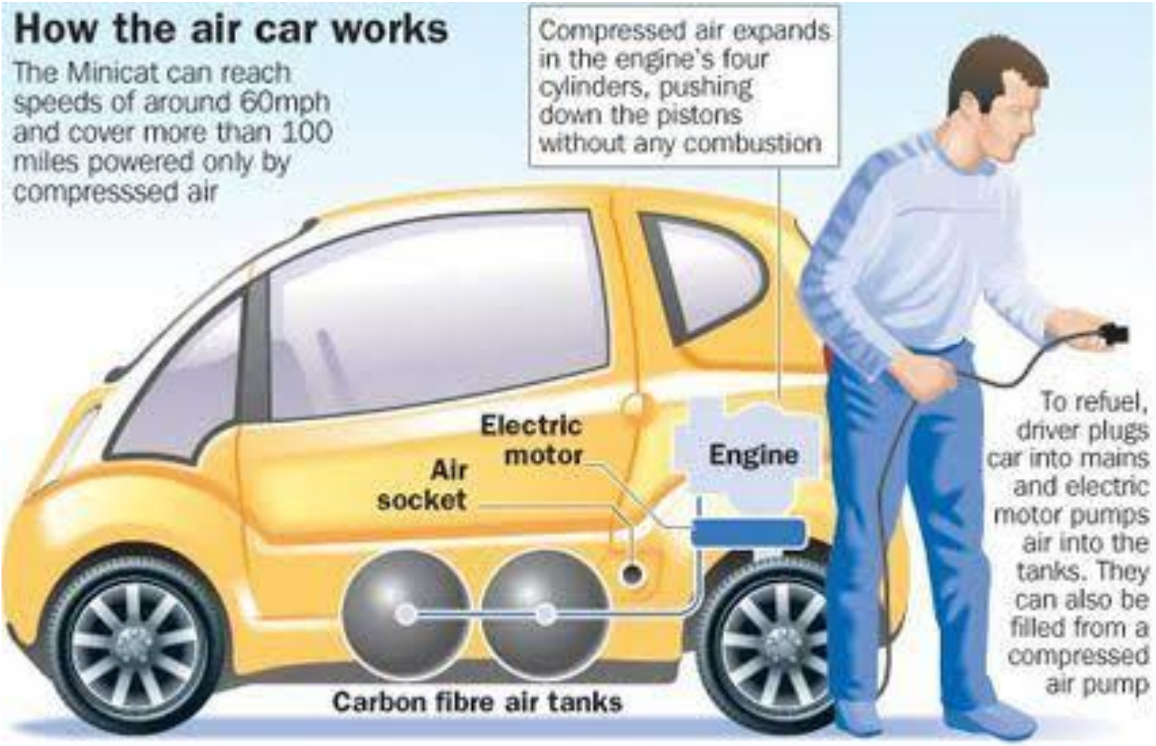
- The technology of Compressed Air Vehicle was used as soon as the mid 19th century in locos for mine and tramway applications. The main advantage was the absence of production of smoke and the low risk of ignition in presence of potentially dangerous gases.

Pneumatic locomotives, during the construction of the Gotthardbahn from 1872 to 1882

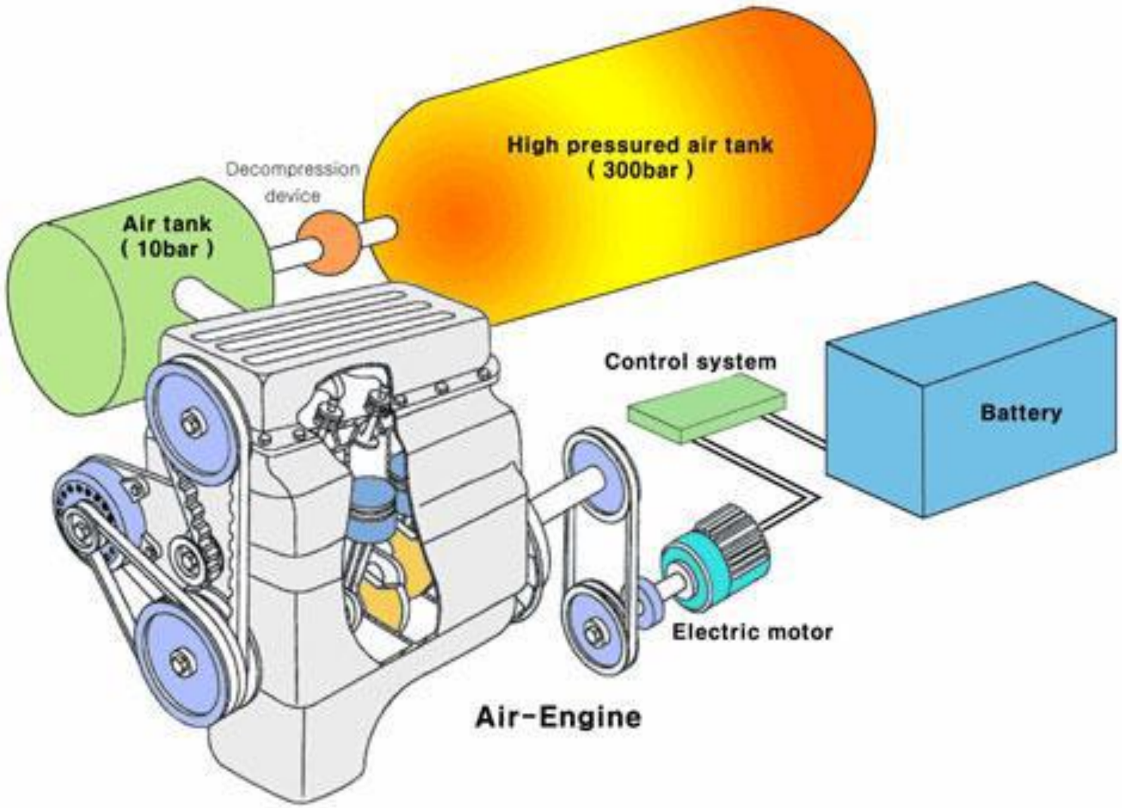
Tramway Mékarski at La Rochelle

Compressed Air Vehicle

- Compressed air cars are powered by motors driven by compressed air, which is stored in a tank at high pressure such as 31 MPa (4500 psi or 310 bar).



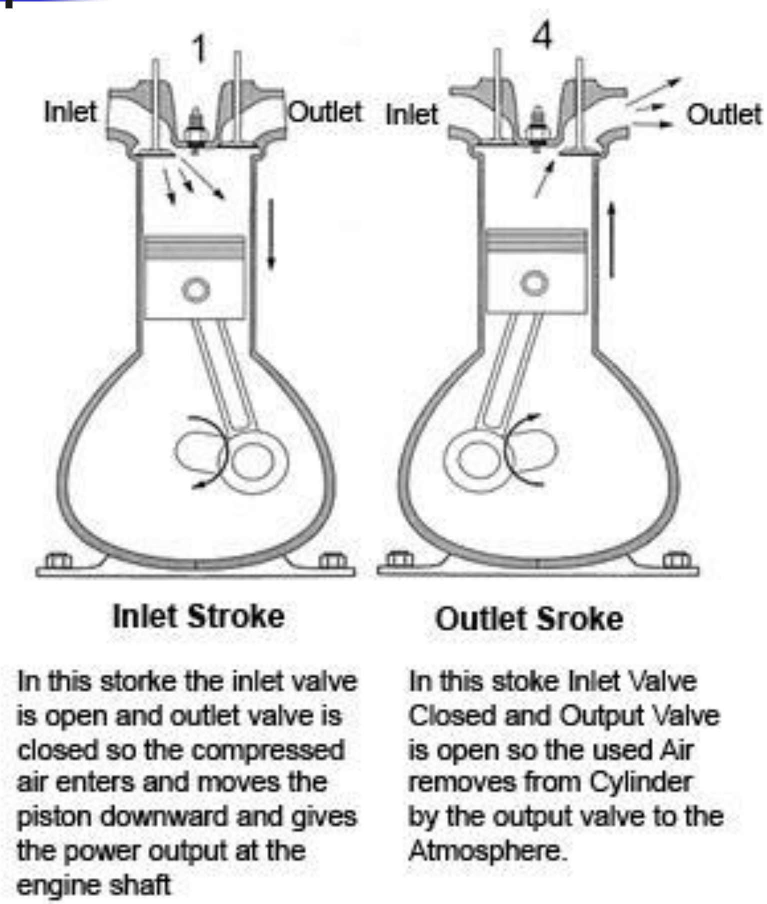
Compressed Air Vehicle



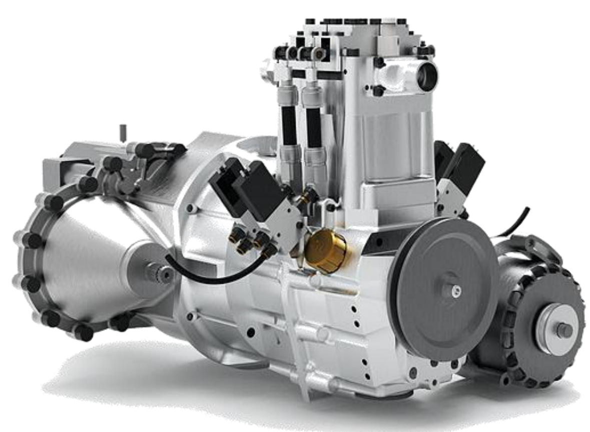
Compressed Air Vehicle

- Rather than driving engine pistons with an ignited fuel-air mixture, compressed air cars use the expansion of compressed air, in a similar manner to the expansion of steam in a steam engine.
- Potential environmental advantages have generated public interest in CAV's as passenger cars, but they have not been competitive due to the low energy density of compressed air and inefficiency of the compression / expansion process.

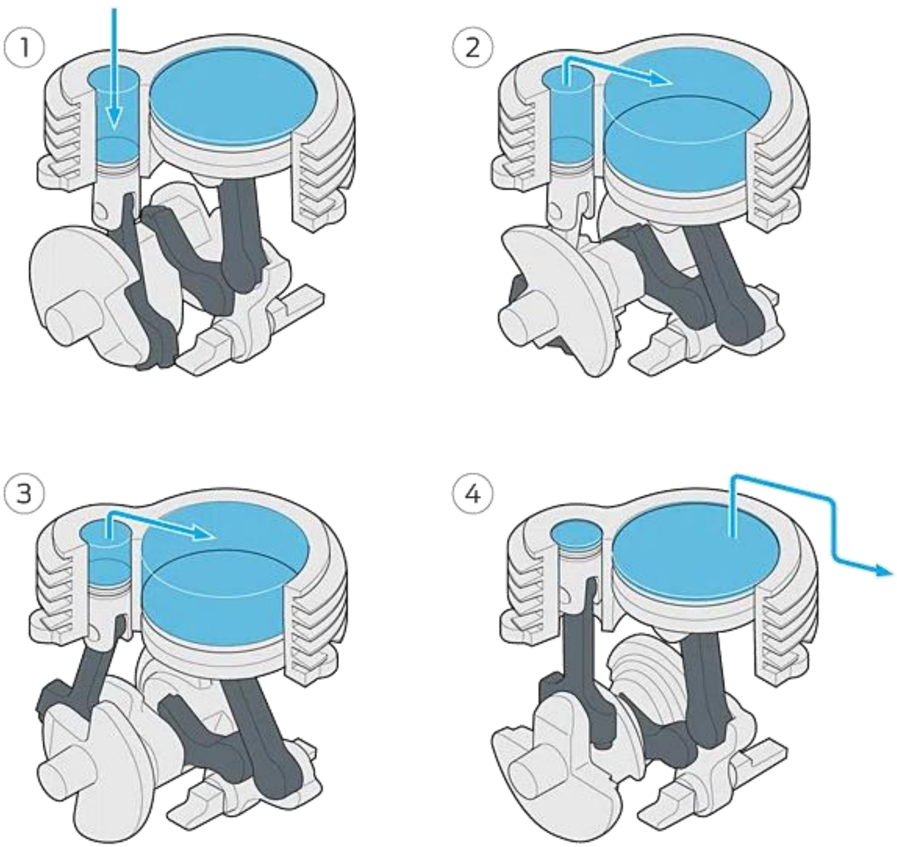
Compressed Air Vehicle

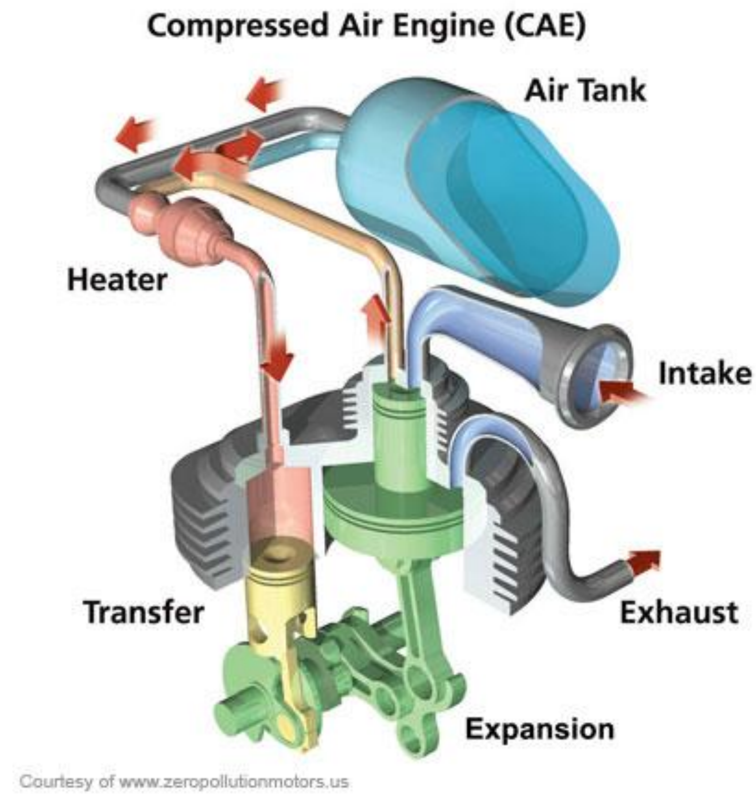


- Rather than driving engine pistons with an ignited fuel-air mixture, compressed air engines use the expansion of compressed air, in a similar manner to the expansion of steam in a steam engine.



Compressed Air Vehicle



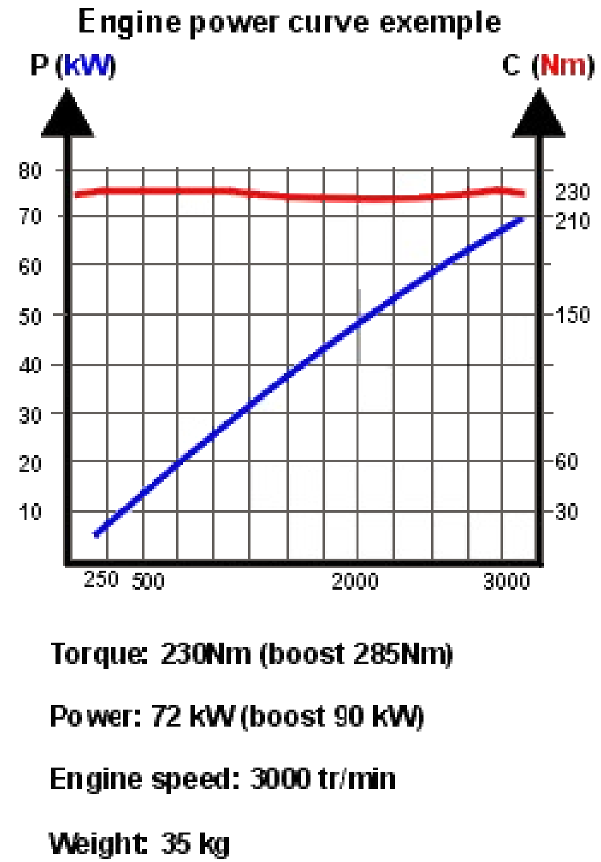


AirPod's engine (MDI) uses two linked cylinders.

AIR ENGINES

ADVANTAGES

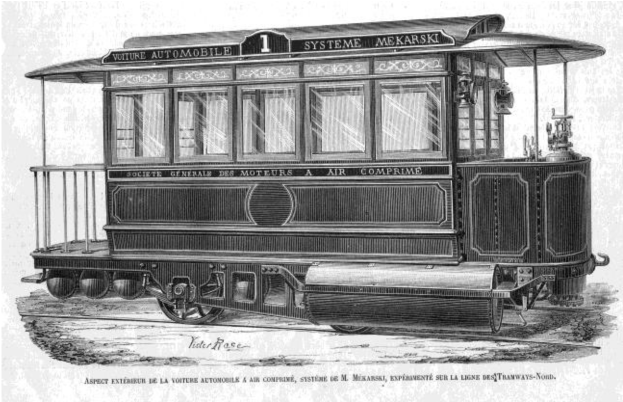
- Air engines can work at <u>low rotation speed</u>. That is 100 to 200 rpm depending on the displacement volume
- Air engines have a <u>high torque</u> and nearly independent of the rotation speed in the whole operating range of the engine.
- Air engines could provide cold to <u>cool down the vehicle</u>, but it is not able to provide heat as ICE.
- Compared to an ICE with the same nominal power (7kW), air engines have same weights and volumes.



AIR ENGINES

DISADVANTAGES

- Expansion of air in the engine leads to a large cooling of the gas. In presence of humidity the engines, water freezes inside the engine, and the engine is blocked.
- Solution proposed by Louis Mékarski (1876) consists in heating the compressed air with overheating water under pressure. But this requires a large amount of energy.
- Other solution is to used completely dried air.



AIR STORAGE TANKS

- Compressed air is stored in a tank at high pressure such as 31 MPa (310 bar).
- Tanks are generally made with carbon fibers composites.
- In compressed air vehicles tank designs tend to be isothermal; a heat exchanger of some kind is used to maintain the temperature (and pressure) of the tank as the air is extracted.
- Compressed air has relatively low energy density. Air@30 MPa contains about 50 Wh of energy per liter (and normally weighs 372 g per liter). For comparison, a lead–acid battery contains 60-75 Wh/l.
- <u>A tank of 300 l at 300 bars</u> can contain a maximum of 14,3 kWh. In practice, this reduces to <u>7 kWh</u> for adiabatic expansion.

AIR STORAGE TANKS

- Refueling the compressed air container using a home or low-end conventional air compressor may take as long as 4 hours, though specialized equipment at service stations may fill the tanks in only 3 minutes.
- To store 2.5 kWh @300 bar in 300-liter reservoirs (90 m^3 of air @ 1 bar), requires about 30 kWh of compressor energy with a single-stage adiabatic compressor.
- However, intercooling and isothermal compression is far more efficient and more practical than adiabatic compression, if sufficiently large heat exchangers are fitted. Efficiencies of up to 65% might perhaps be achieved, (whereas current efficiency for large industrial compressors is max. 50%) however this is lower than the Coulomb's efficiency with lead acid batteries.

AIR STORAGE TANKS

- The storage tank may be made of steel, aluminum, carbon fiber, and Kevlar.
- The system can be operated over 100.000 cycles so that its life can be considered as nearly unlimited.
- The rate of self-discharge is very low opposed to batteries that deplete their charge slowly over time.

Compressed Air Vehicle

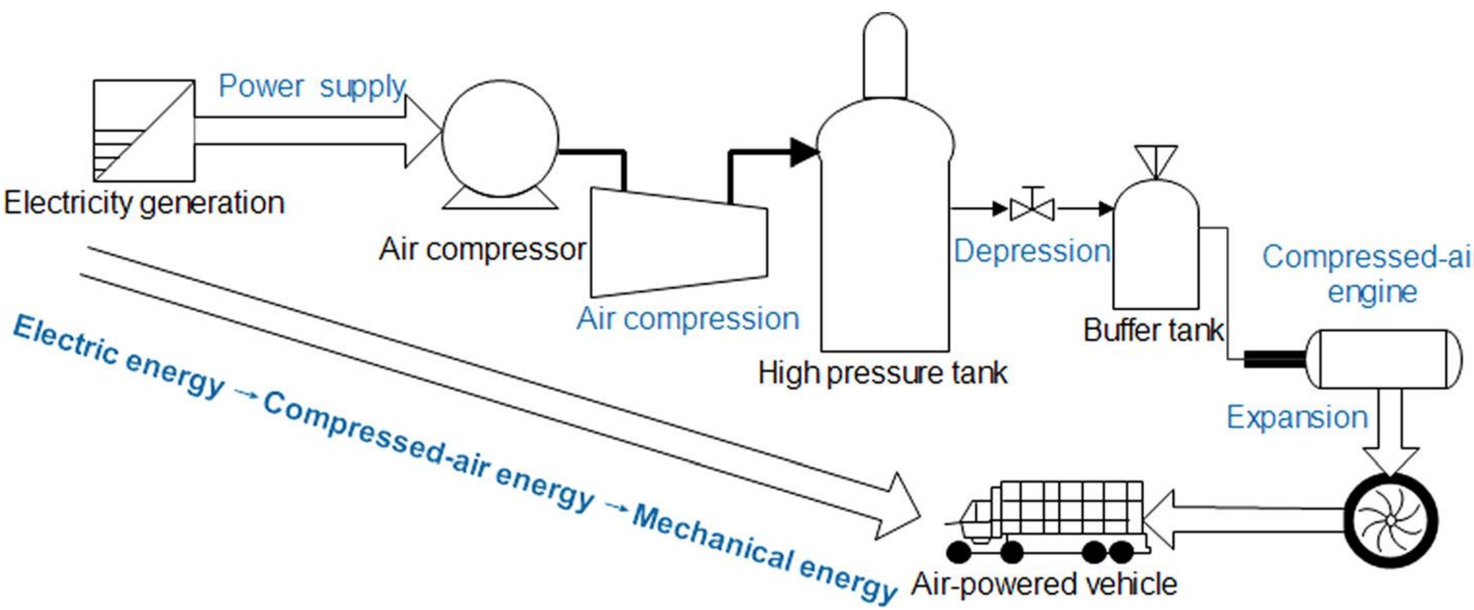
OVERALL ENERGY EFFICIENCY

- The principal disadvantages are the steps of energy conversion and transmission, because each inherently has loss.
- For compressed-air cars, the power plant's electricity is transmitted to a compressor, which mechanically compresses the air into the car's tank. The car's engine then converts the compressed air to mechanical energy. This means that the overall energy efficiency of Compressed Air Vehicle is small.
- Using isothermal compression with intercooling, the overall efficiency of a vehicle using compressed air energy storage might be around 5-7%. For comparison, well to wheel efficiency of a conventional internal-combustion drivetrain is about 14%

Compressed Air Vehicle

OVERALL ENERGY EFFICIENCY

- Using isothermal compression with intercooling, the overall efficiency of a vehicle using compressed air energy storage might be around 5-7%. For comparison, well to wheel efficiency of a conventional internal-combustion drivetrain is about 14%



Compressed Air Vehicle

RANGE

- Early tests have demonstrated the limited storage capacity of the tanks; the only published test of a vehicle running on compressed air alone was limited to a range of 7.22 km. MDI claimed in 2007 that an air car will be able to travel 140 km in urban driving and have a range of 80 km with a top speed of 110 km/h (68 mph) on highways, when operating on compressed air alone but as of August 2017 have yet to produce a vehicle that matches this performance.

Compressed Air Vehicle

- Main advantages of Compressed Air Engine (C.A.E.) are:
  - It uses no gasoline or other bio-carbon based fuel.
  - Use of renewable fuel and energy sources
  - Zero emission.
  - Zero fuel cost (the cost is involved only in the compression of air).
  - Silent operation.
  - Expansion of the compressed air lowers its temperature; this may be exploited for use as air conditioning.
  - Reduction or elimination of hazardous chemicals such as gasoline or battery acids/metals
  - Some mechanical configurations may allow energy recovery during braking by compressing and storing air.

Compressed Air Vehicle

- Disadvantages of Compressed Air Engine (C.A.E.) are:
  - Low overall efficiency (<10%)
  - Limited range (around 100km)
  - Less power output
  - High pressure of compressed air may lead to bursting of storage tank.
  - Probability of air leakage.

Hybrid propulsion systems

Hybrid propulsion powertrains

- The hybrid powertrains combines two kinds of propulsion systems and their related energy storages.
- Generally the hybrid electric powertrains are the most famous ones. They combine typically an ICE engine, an electric motor and an electric energy storage system
- The goal of hybridization is to combine the advantages of the two basic systems (e.g. zero emission of EV and range of ICE) and to mitigate their drawbacks.
- There are two major families of powertrain layout combining the two types of propulsion systems.

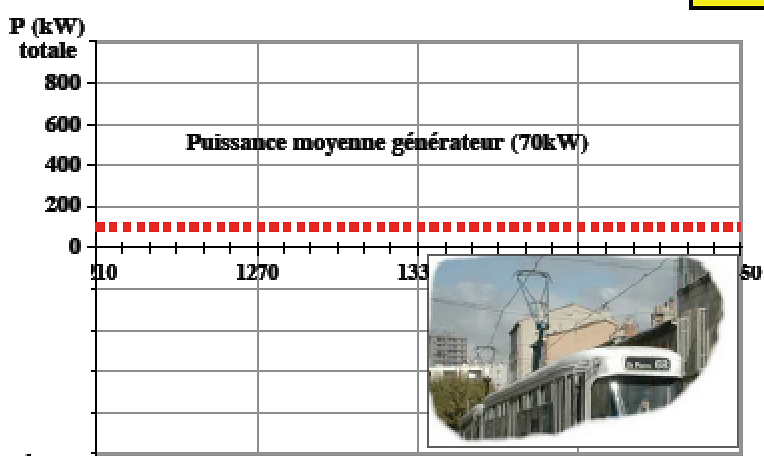
Highly variable operating conditions

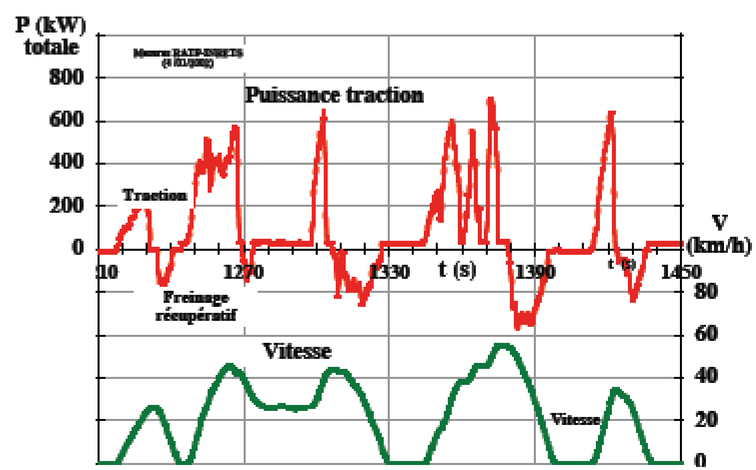
- Major difficulty of propulsion systems: the highly variable operating conditions (torque, regime)
  - Objective: sizing to average power consumption!
  - Approach: store the energy ⇨ hybrid vehicle

Puissance moyenne
utile au déplacement
(ex. tramway : 70kW)

⇨ **Stockage d'énergie tampon** ⇨

Puissance instantanée
Absorbée pour la traction
(ex. tramway: 800kW à 1MW)

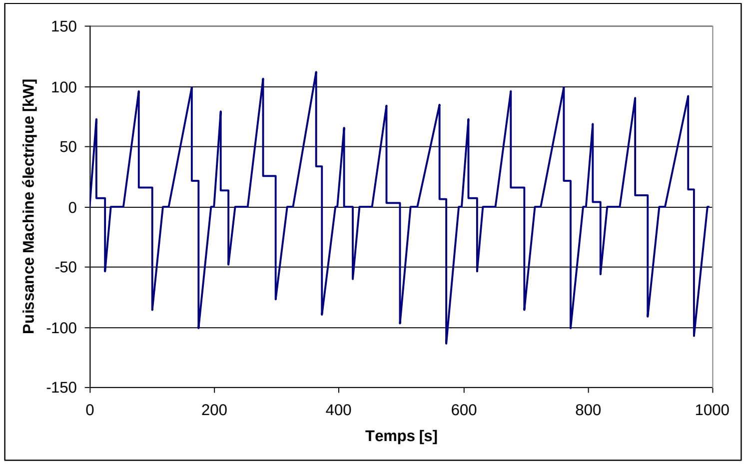




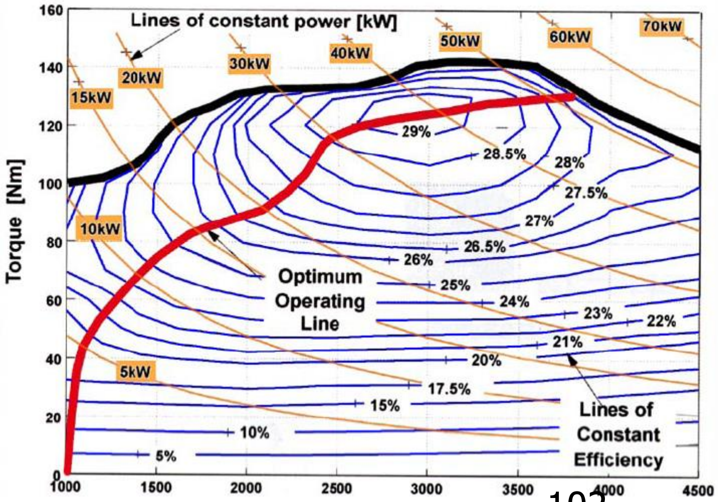
Source G. Coquery, INRETS

Improve powertrain efficiency

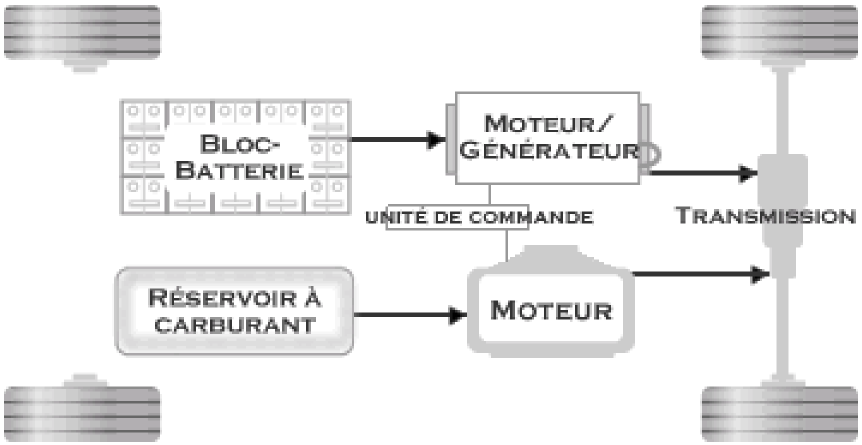
- Use energy storage to level energy flow
  - Recover braking energy
  - Smooth out the peak powers
  - Reduce the size of the prime mover as close as possible to the average power



- Improve the energy efficiency of the engine
  - Reduce the engine size while preserving the torque
  - Reduce the internal engine frictions
  - Place the operating points of the engines in its most favourable regimes

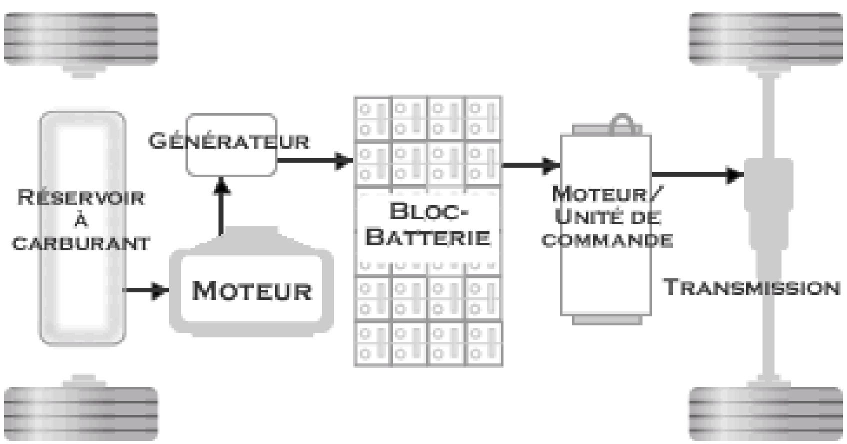


Hybrid propulsion powertrains

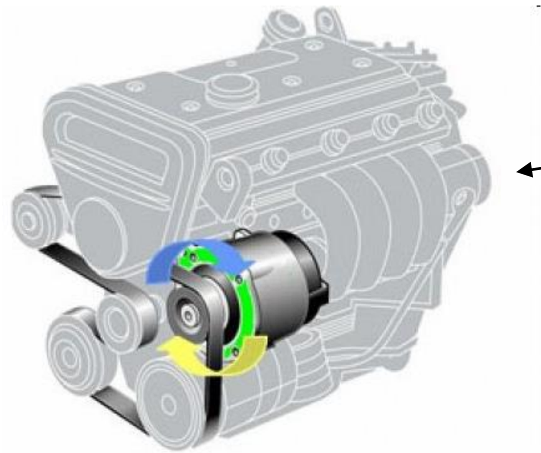


Parallel hybrid

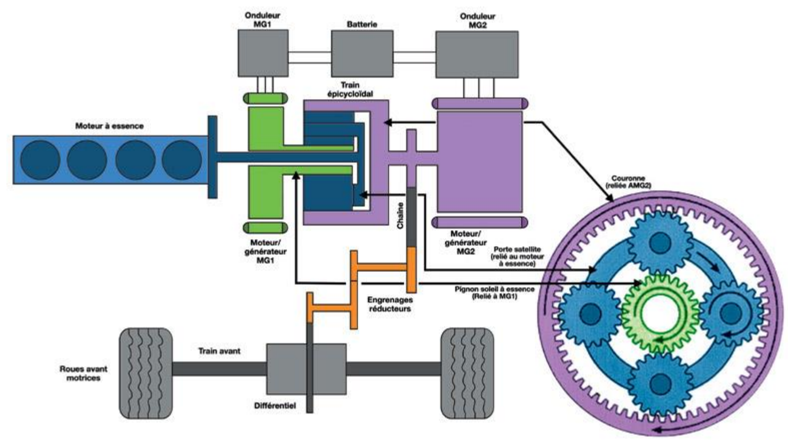
Serial hybrid



Various levels of hybridization

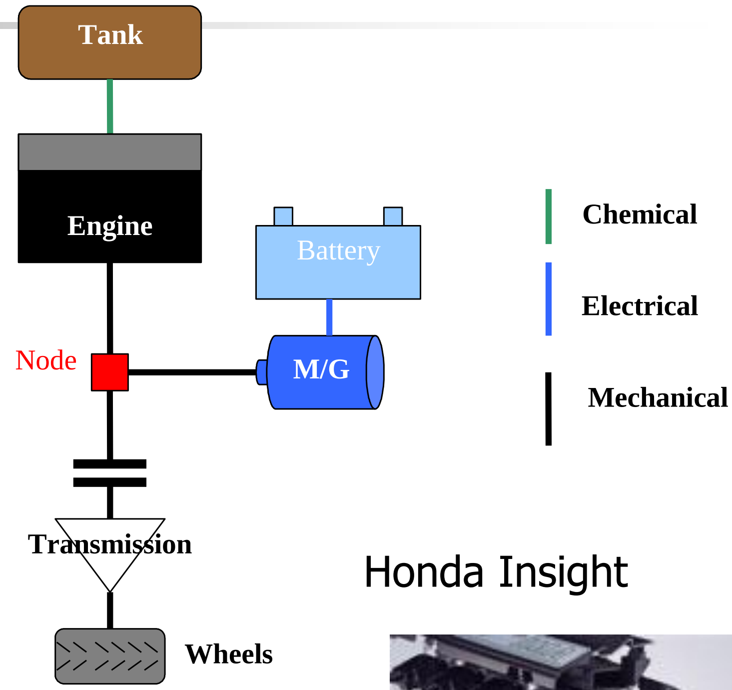


- Different level of hybridization:
  - Stop engine at stall operation (Start & Stop)
  - Motor assist using e-motor
    - Ex Integrated Motor Assist by Honda
  - Full hybrid
    - Ex Toyota Prius



Mild hybrid vehicle

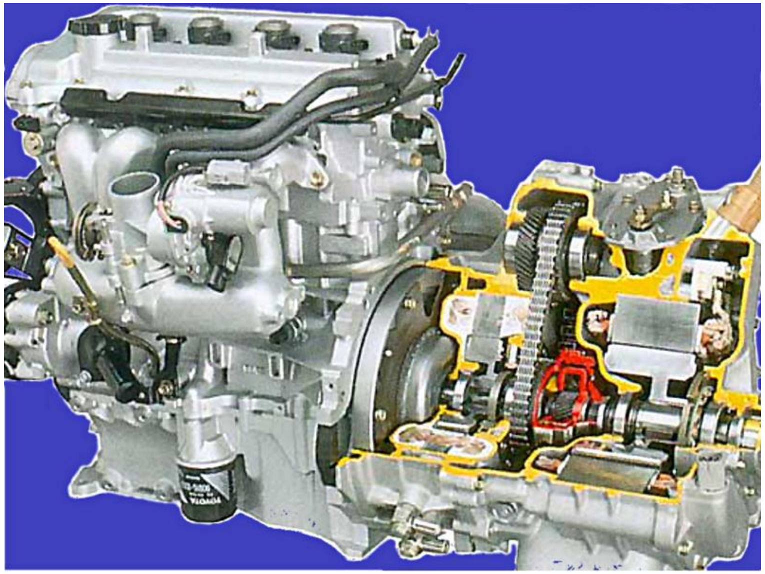
- Mild architecture
  - Small electric machines (~10 kW)
  - Fonction Stop & start
  - Low braking energy recovery capability
  - Power / torque assist of the main engine
- Substitute the flywheel, the starter and the alternator
- No pure electric mode

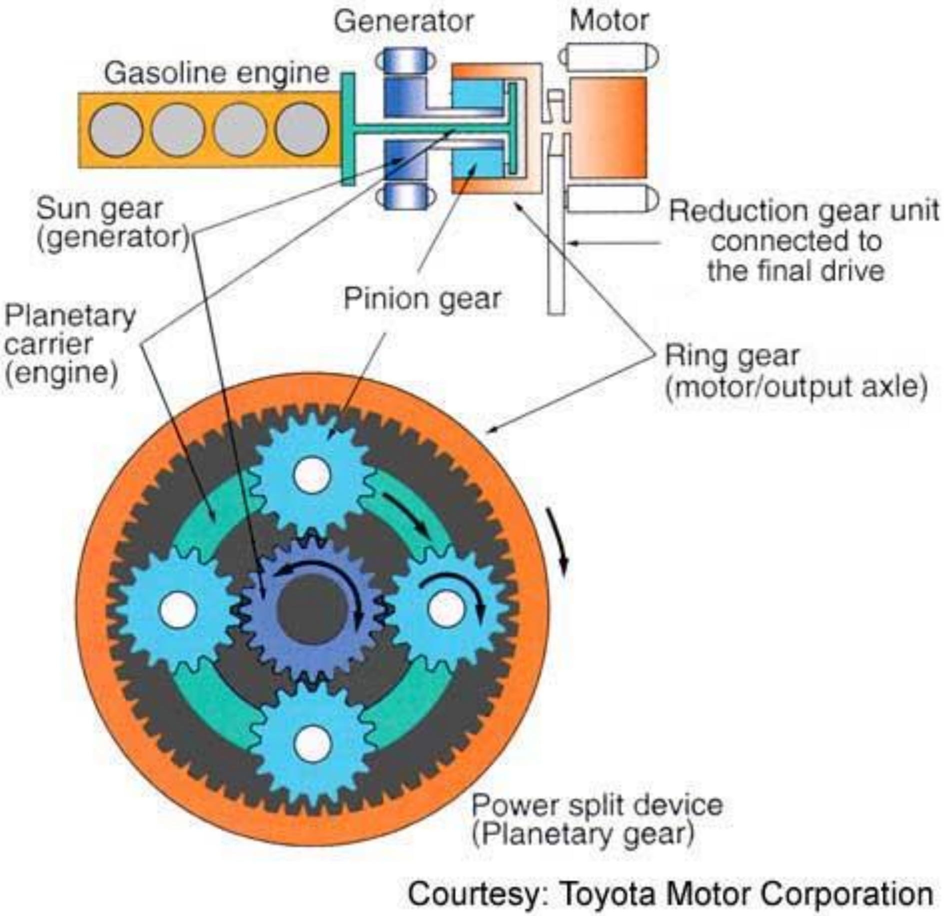


Honda Insight

Full hybrid: Toyota Prius transmission

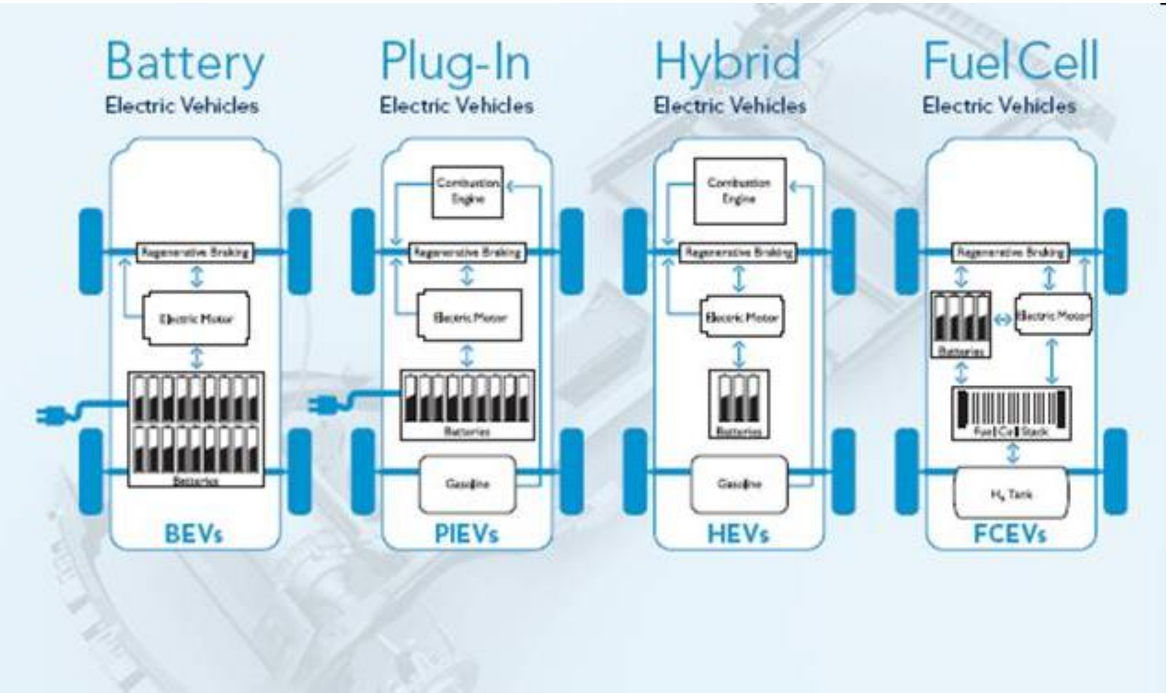
Transmission of Toyota Prius II





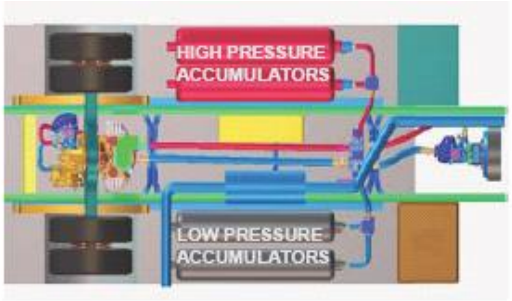
Various levels of hybridization

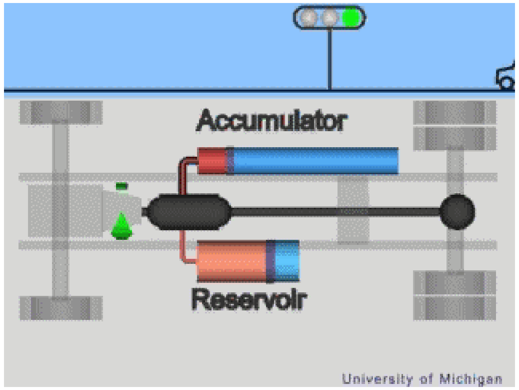
- Different charging scenarios
  - Charge sustaining
  - Charge depleting
  - Plug in
  - Range extender using a fuel cell



Hybrid hydraulic vehicle

- Alternative energy storage: hydraulic accumulator
- Low specific energy density:
  - Mild hybrid
  - Motor assist
- High power density
  - Well adapted to heavy vehicles
  - And to urban vehicles with frequent stop and start with high acceleration / decelerations
- Development linked to the emergence of novel class of reversible motor pump with a low cost





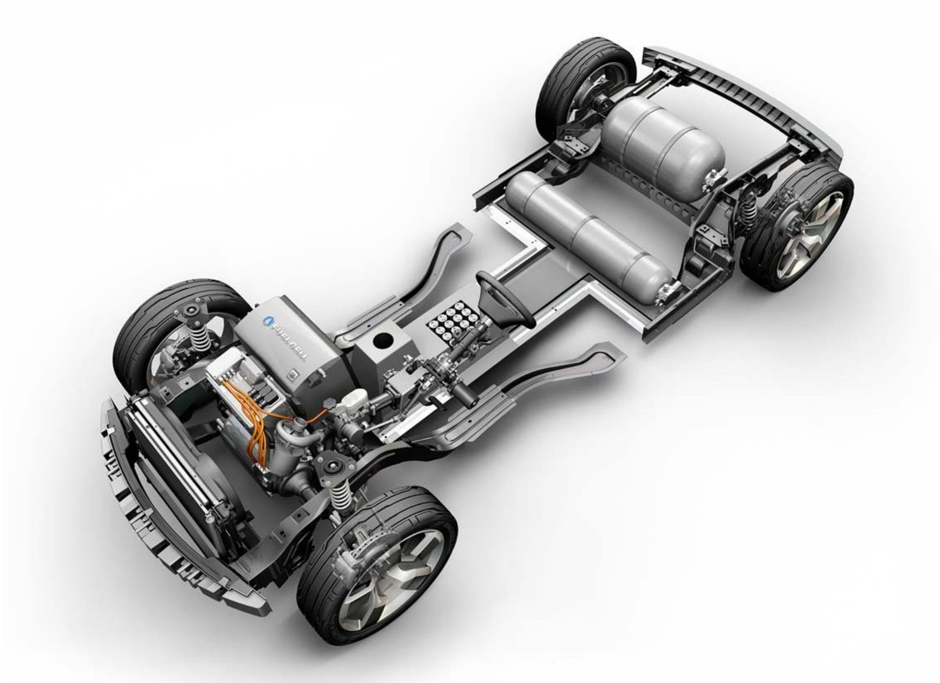
Smart Truck

Hybrid Pneumatic Vehicle

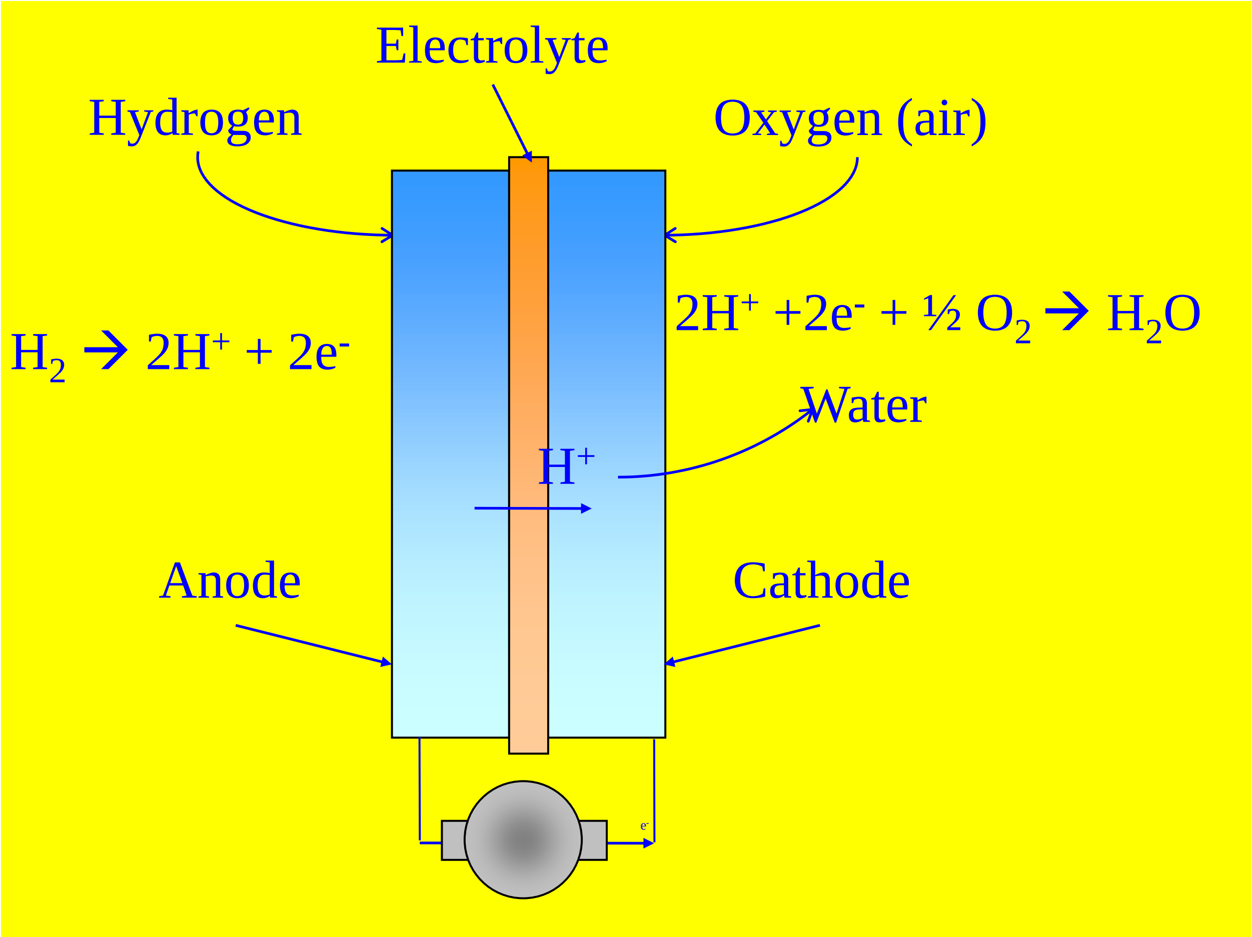
- While the air storage system offers a relatively low power density and vehicle range, its high efficiency is attractive for hybrid vehicles that use a conventional internal combustion engine as a main power source. The air storage can be used for regenerative braking and to optimize the cycle of the piston engine which is not equally efficient at all power/RPM levels.

PSA Peugeot Citroën Hybrid Air concept exhibited at the 2013 Geneva Motor Show.

Fuel cells



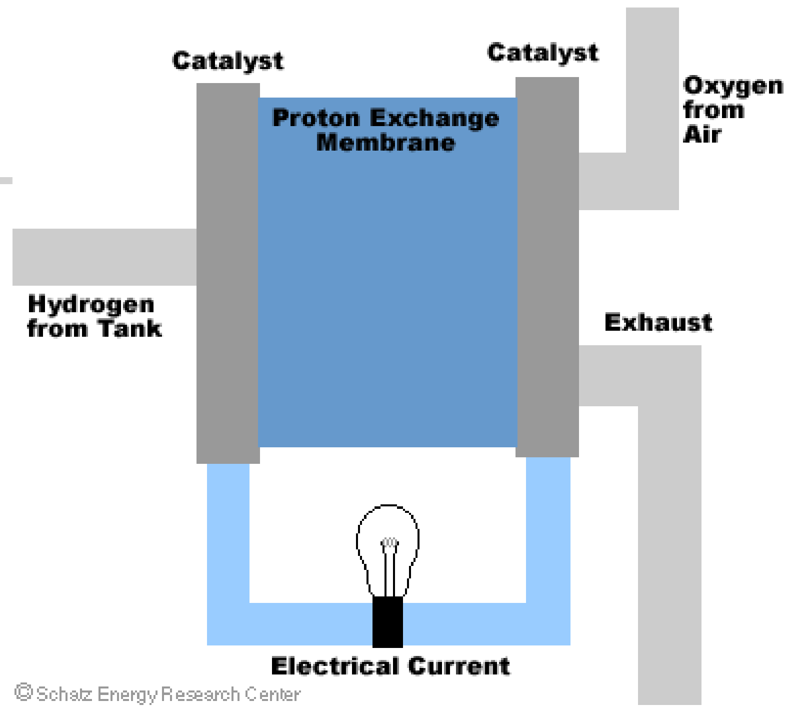
Fuel cell



Electrolyte
Hydrogen
Oxygen (air)
$2H^+ + 2e^- + \frac{1}{2} O_2 \rightarrow H_2O$
$H_2 \rightarrow 2H^+ + 2e^-$
Water
H^+
Anode
Cathode
e^-

Fuel cell

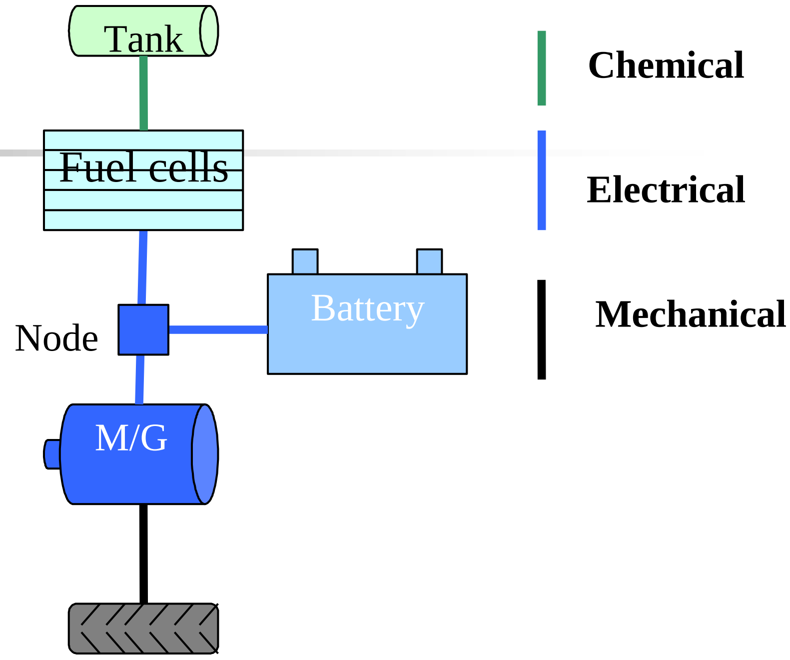
- Fuel Cell carries out a direct conversion of the fuel chemical energy into electrical energy
- Electrochemical reaction (oxide-reduction) without flame
- The hydrogen $H_2 - O_2$ fuel cell: inverse reaction of water electrolysis
- High fuel efficiency (>50%)
- Major issues:
  - Cost related of electrodes made of precious metal, membranes
  - Reliability
- Hydrogen technology: a real start?



Viessmann-Panasonic domestic FC

Fuel Cell Powered Vehicles

- Zero emission vehicle:
  - No pollutant emission except H_2O
  - Nearly silent operation
- Powertrain layout based on series hybrid architecture
  - Energy storage based on batteries or supercaps
  - Recovery of braking energy
  - Increased autonomy > 400km
- Hydrogen production & distribution
  - H_2 or plug-in hybrid on electrical network
  - H_2 production and distribution?



Toyota Mirai

Fuel cell

- Fuel Cell principle: direct electrochemical (oxydo-reduction) converter of Hydrogen fuel into electricity

- Advantages:
  - No direct emission of pollutants
  - Using other fuels (ex methanol) is possible via reforming process
  - High conversion efficiency (theoretical 90% - practical 55%)
- Drawbacks
  - Not a fully mature technology, but rapidly gaining confidence
  - Thermal control is still partly an open challenge
  - Lower power to weight ratio compared to ICE

Comparison of propulsion systems

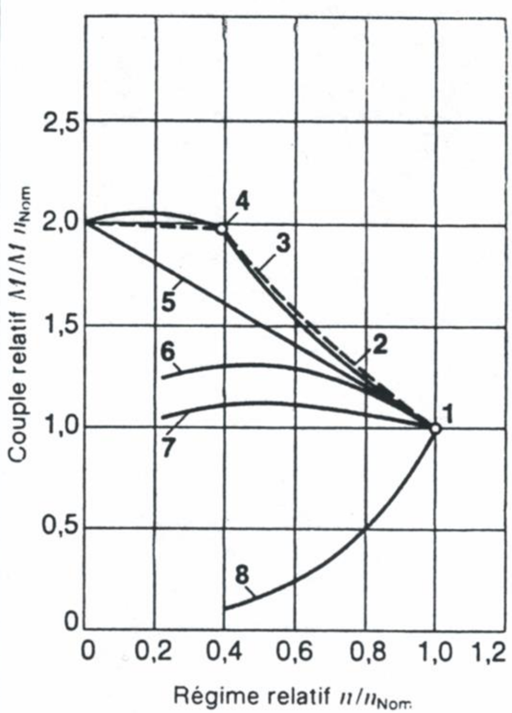
Comparison of propulsion systems

Type de moteur		Régime min^{-1}	Taux de compression	Pression moyenne bar	Puissance spécifique kW/l	Rapport poids/puissance kg/kW	Consommation de carburant g/kWh	Augmentation du couple %
Moteur à essence pour								
Motocycles	2 temps	4500 ... 8000	7 ... 9	4 ... 6	30 ... 50	5 ... 2,5	600 ... 400	5 ... 10
	4 temps	5000 ... 9000	8 ... 11	7 ... 10	30 ... 70	4 ... 1	350 ... 270	5 ... 25
Voitures avec	Moteur atmosphérique	4500 ... 7500	8 ... 12	8 ... 11	35 ... 65	3 ... 1	350 ... 250	15 ... 25
	Moteur suralimenté	5000 ... 7000	7 ... 9	11 ... 15	50 ... 100	3 ... 1	380 ... 280	10 ... 30
Camions		2500 ... 5000	7 ... 9	8 ... 10	20 ... 30	6 ... 3	380 ... 270	15 ... 25
Moteur diesel pour								
Voitures	Moteur atmosphérique	3500 ... 5000	20 ... 24	6 ... 8	20 ... 30	5 ... 3	320 ... 240	10 ... 15
	Moteur suralimenté	3500 ... 4500	20 ... 24	9 ... 12	30 ... 40	4 ... 2	290 ... 240	15 ... 25
Camions	Moteur atmosphérique	2000 ... 4000	16 ... 18	7 ... 10	10 ... 15	9 ... 4	240 ... 210	10 ... 15
	Moteur suralimenté	2000 ... 3200	15 ... 17	10 ... 13	15 ... 20	8 ... 3	230 ... 205	15 ... 30
	Avec RAS[1])	1800 ... 2600	14 ... 16	13 ... 18	20 ... 25	5 ... 3	225 ... 195	30 ... 60
Modèles spéciaux								
Moteur à pistons rotatifs		6000 ... 8000	7 ... 9	8 ... 11	35 ... 45	1,5 ... 1	380 ... 300	5 ... 15
Moteur Stirling		2000 ... 4500	4 ... 6	–	–	10 ... 7	300 ... 240	20 ... 40
Turbine à gaz		8000...70 000	4 ... 6	–	–	3 ... 1	1000 ... 300	50 ... 100

Bosch (2002)

Comparison of propulsion systems

Couple relatif pour différents systèmes d'entraînement.
1 point de référence: point de conception de la turbine à gaz, moteur à pistons n_{max}. 2 moteur à vapeur, 3 moteur électrique. 4 limitation de la pression maximale ou du courant maximum, 5 turbine à gaz à double corps. 6 moteur à explosion, 7 moteur diesel. 8 turbine à gaz fixe.



- Torque curve is favourable to electric motors and steam engines
- Torque curve of gas turbines is very bad with regards to the application

Bosch (2002)