SELECTION OF PROPULSION SYSTEMS FOR AUTOMOTIVE APPLICATIONS

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LTAS – Automotive Engineering
Academic Year 2021-2022

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

Outline

- Pneumatic Vehicle
- Hybrid motorization
  - Definition
  - Layout
  - Architecture
- Fuel cells
  - Definition
  - Fuel cell powered hybrid vehicles
- Comparison

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

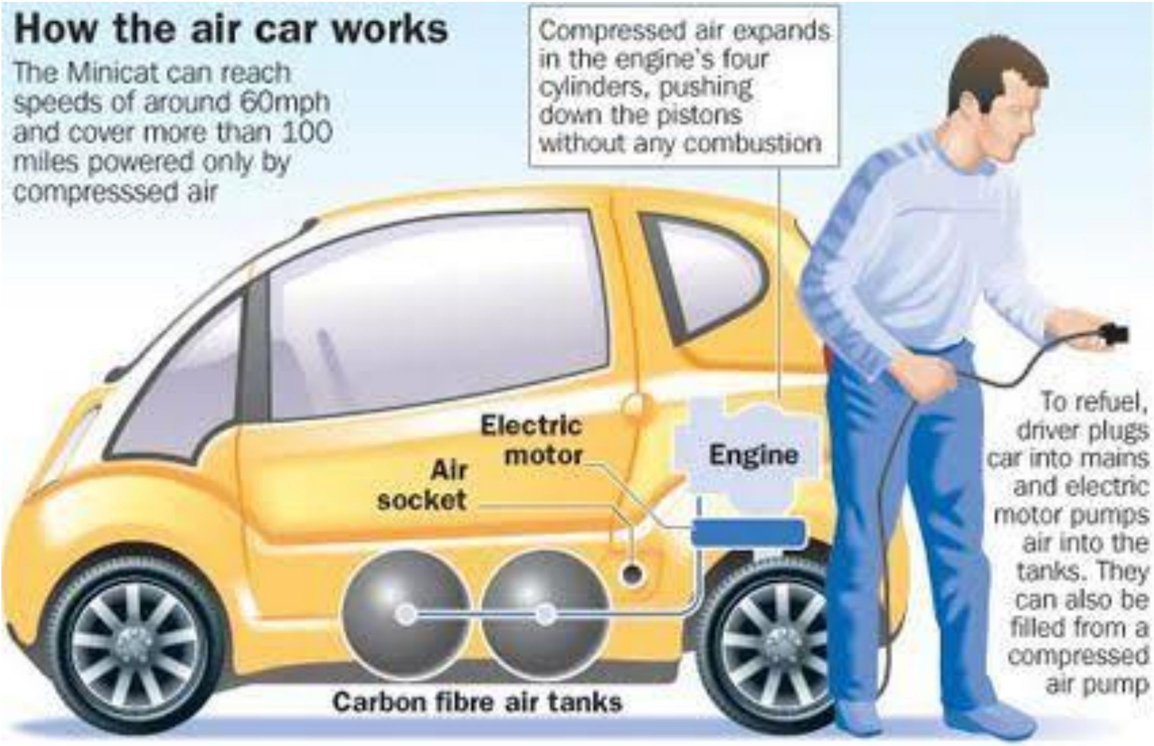
Tramway Mékarski in La Rochelle

Compressed Air Vehicle

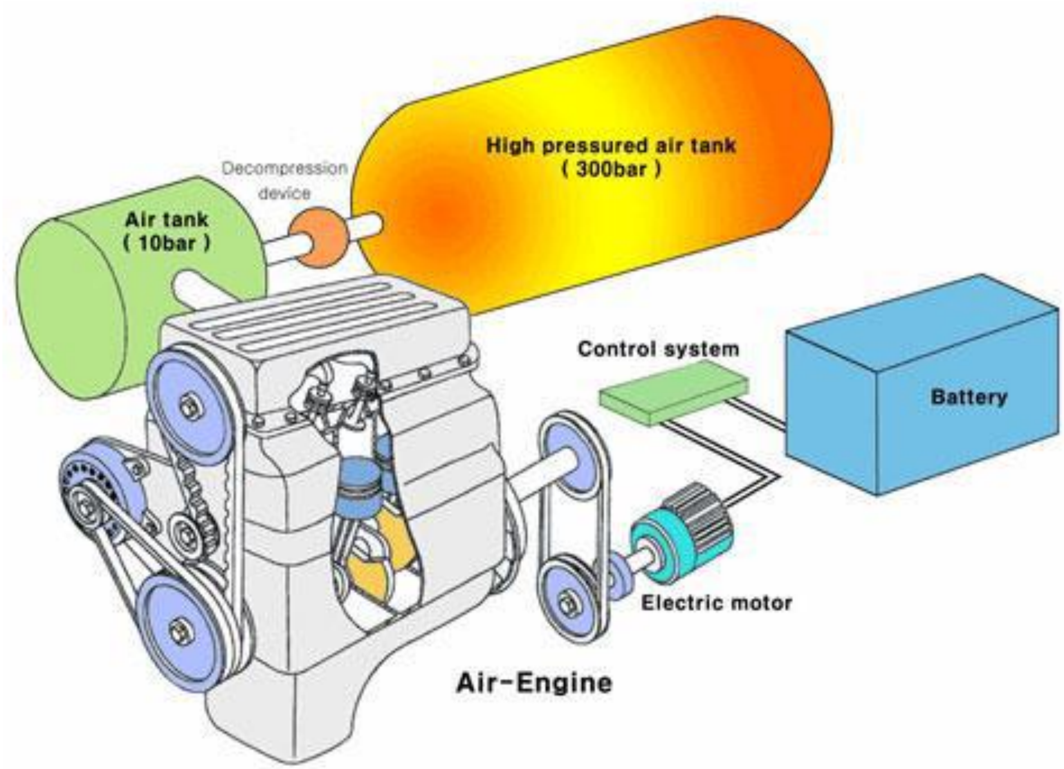
- Potential environmental advantages have generated public interest in CAV's as passenger cars, but they have not been competitive due to the low energy density of compressed air and inefficiency of the compression / expansion process.

Compressed Air Vehicle

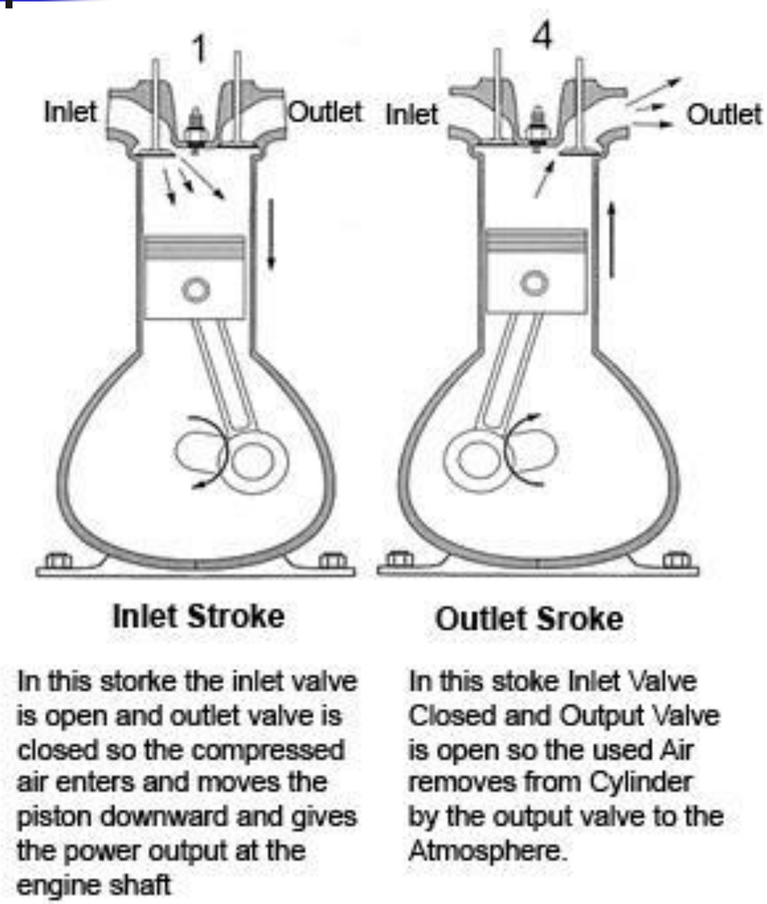
- Compressed air cars are powered by motors driven by compressed air, which is stored in a tank at high pressure such as 31 MPa (310 bar).



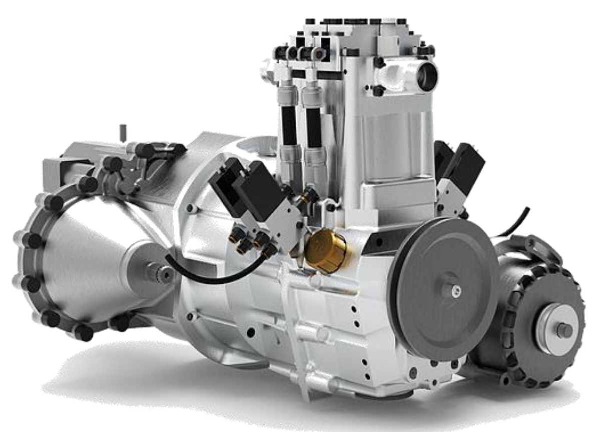
Compressed Air Vehicle



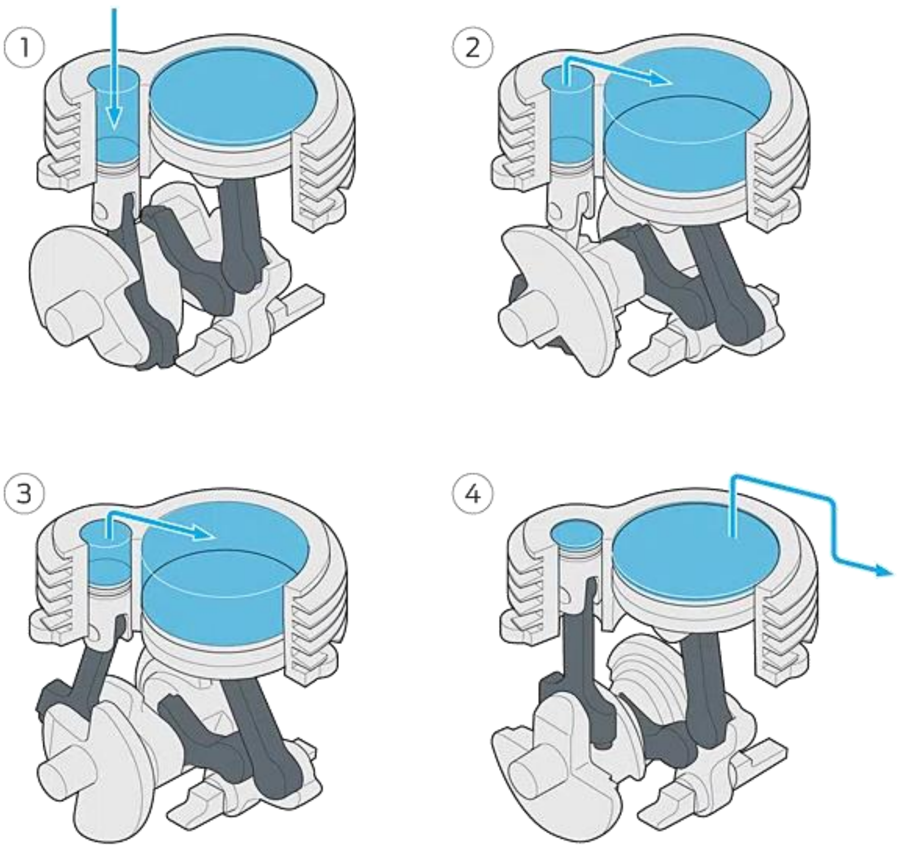
Compressed Air Vehicle

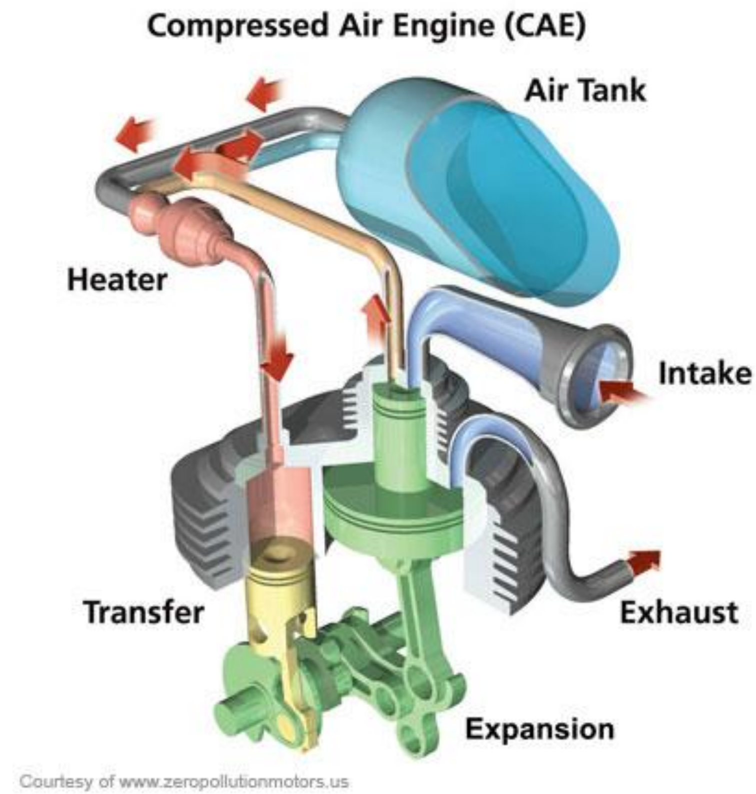


- Rather than driving engine pistons with an ignited fuel-air mixture, compressed air engines use the expansion of compressed air, in a similar manner to the expansion of steam in a steam engine.



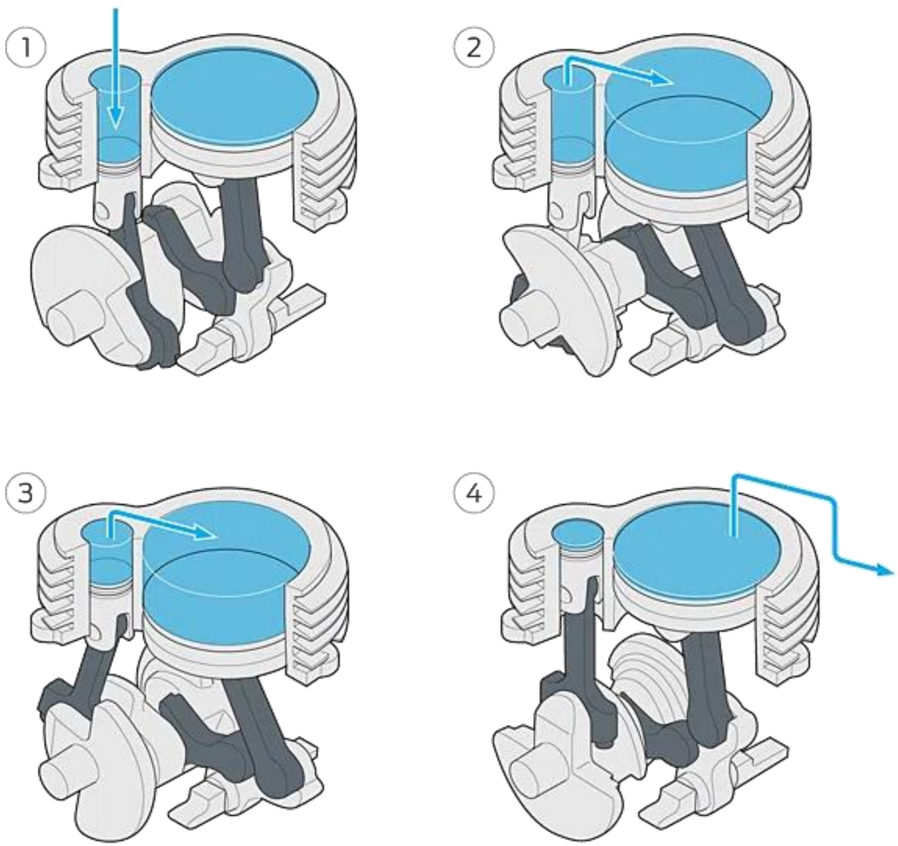
Compressed Air Vehicle





AirPod's engine uses two linked cylinders.

Compressed Air Vehicle



AirPod's engine uses two linked cylinders.

(1) Compressed air flows into the smaller cylinder first at a constant pressure of 20 bars.

(2) When the smaller piston bottoms out, the intake is closed, and the air in the small cylinder expands, flowing into the larger cylinder.

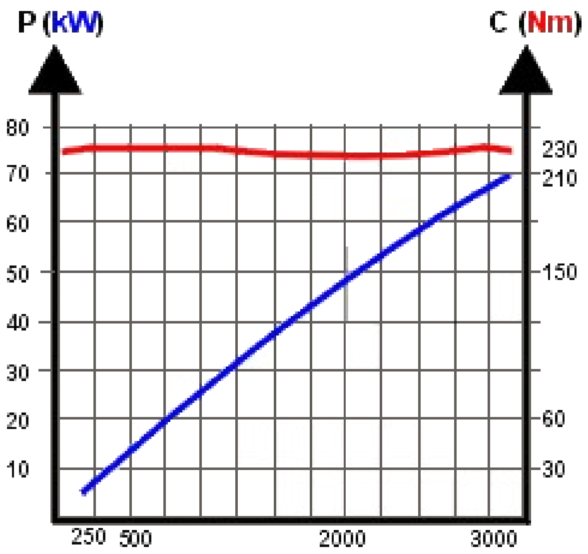
(3) (4) Both pistons then move to exhaust the expanded air, and the cycle begins again

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.

Engine power curve exemple



Torque: 230Nm (boost 285Nm)

Power: 72 kW (boost 90 kW)

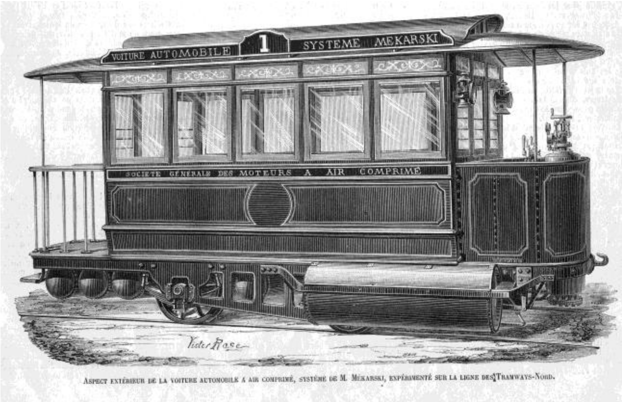
Engine speed: 3000 tr/min

Weight: 35 kg

AIR ENGINES

DISADVANTAGES

- Expansion of air in the engines leads to a large cooling. In presence of humidity the engines, <u>water freezes inside the engine</u>, 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 (4500 psi or 310 bar).
- Tanks are generally made with carbon fibers composites.
- In compressed air vehicles, tank designs tend to be isothermal; a heat exchanger 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

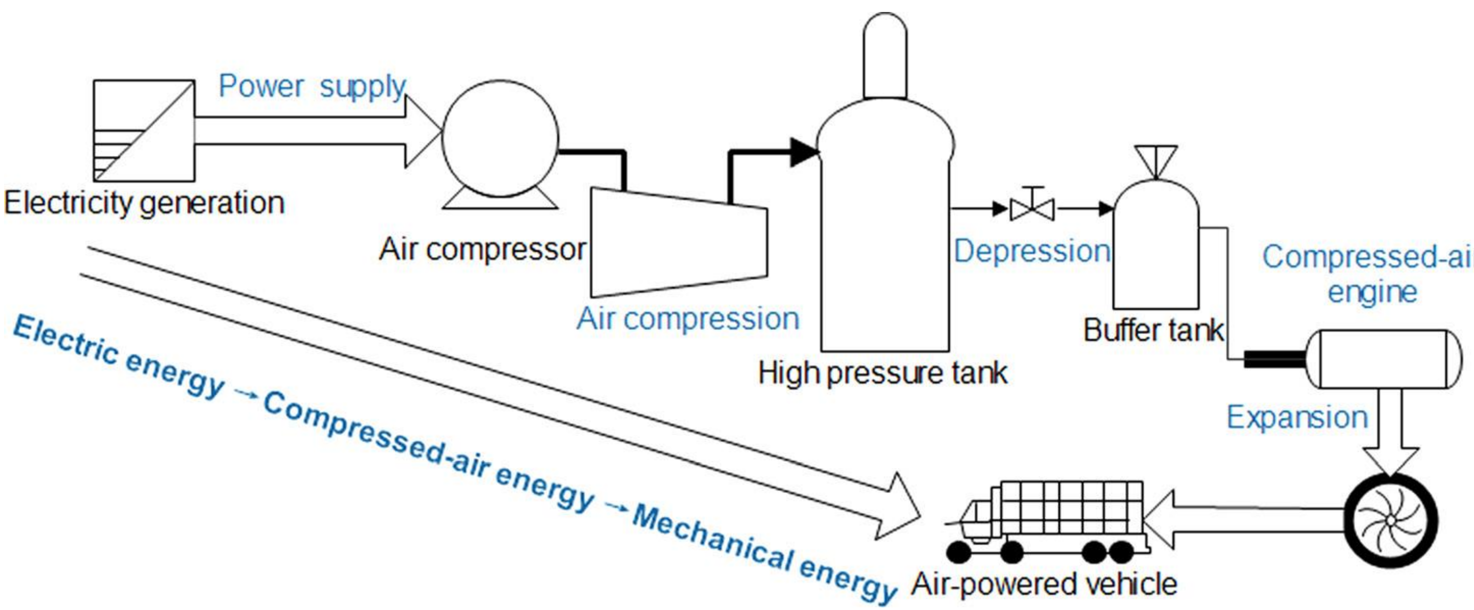
OVERALL ENERGY EFFICIENCY

- 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

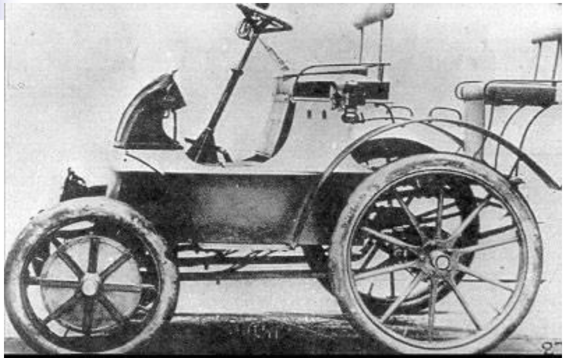
- Main advantages of Compressed Air Engine (C.A.E.) are:
  - It uses no gasoline or other bio-carbon based fuel.
  - Use of renewable fuel and energy sources
  - Zero emission.
  - Zero fuel cost (the cost is involved only in the compression of air).
  - Silent operation.
  - Expansion of the compressed 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.

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 → 500 km)

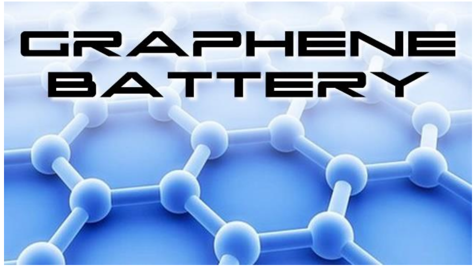
Nissan Leaf

Electric propulsion

- Nicely fitted to urban driving
  - Driving comfort and efficiency
  - Zero local emission
  - Great driving comfort
- High energy efficiency
  - Lower energy cost: 20 kWh/100 km
- Urban applications are targeted
  - Night delivery
  - Low emission zones (LEZ)

Electric propulsion: the challenges

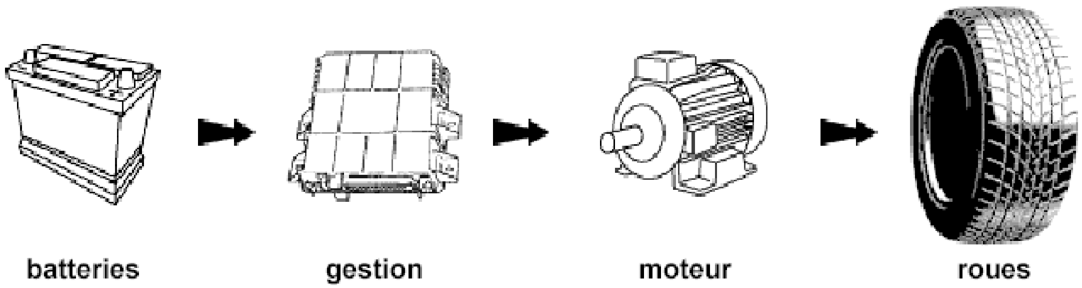
- Charging infrastructure is currently growing but still limited:
  - Public charging infrastructure v.s. company private charging stations



- Batteries: new developments
  - Temperature sensitivity
  - Recycling
  - Graphene batteries: +45% capacity / charging 12 times faster…

- Future research:
  - Fast inductive charging
  - Electrified highway by Siemens

Electric propulsion

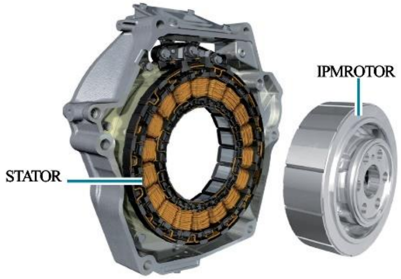


Electric drivetrains are basically composed of four components:

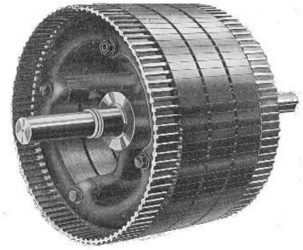
1. The electrical power source: battery if the energy is stored on board or catenaries system if connection to an external source as electric cables or rail is possible.
2. Power electronics to regulate the power, the speed, the torque.
3. The electric machine that can be operated in a reversible mode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

Electric powertrain components

- Electric machine:
  - Converting electric energy into mechanical energy (motor regime) and vice versa (generator regime)
  - Types of electric machines
    - DC shunt or series or separately excited
    - AC synchronous
    - AC induction machines; 1 phase or 3 phase machines
    - Switched Reluctance Machine

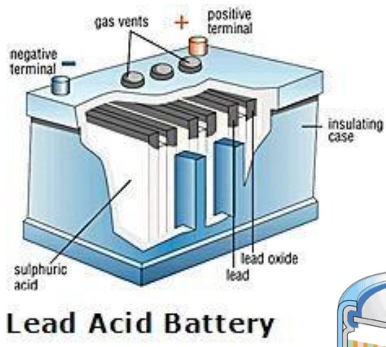


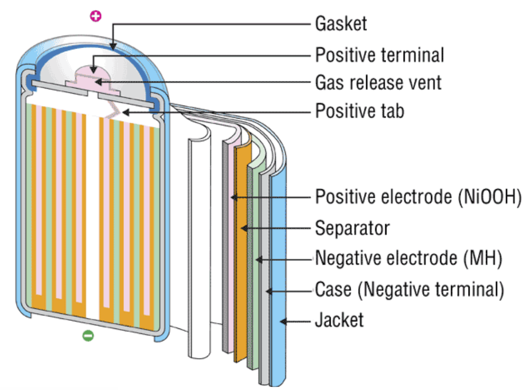
- Power electronics
  - Modulation of power, speed, torque
  - Control of machine mode (motor, generator)
  - Types
    - Chopper, DC / DC converters, etc.
    - Inverter

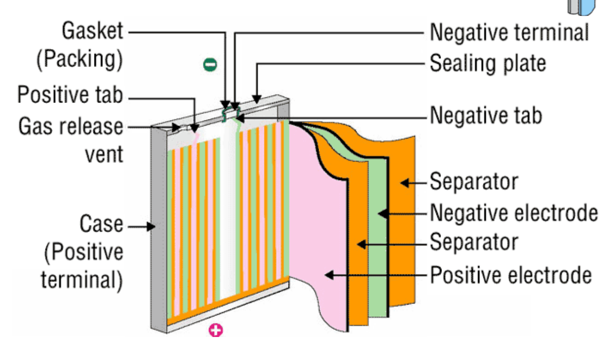


Electric powertrain components

- Batteries:
  - Storing electric energy
    - Power source
    - Peak power source
  - Types
    - Lead-acid,
    - Nickel – Cadmium,
    - Ni – MH (metal hydride),
    - Li ions
- Power storage systems
    - Super capacitors
    - Flywheels







Batteries performances

Batteries	Lead-Ac	Ni-Cd	Ni-MH	Zebra	Li-Ions
Useful specific energy [W.h/kg]	45	55	62	74	120-180
Specific power [W/kg]	90	79	118	148	294
Charge – discharge efficiency [%]	77	75	80	85	90
Life cycles [cycles]	600	1200	1200	1200	1500
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

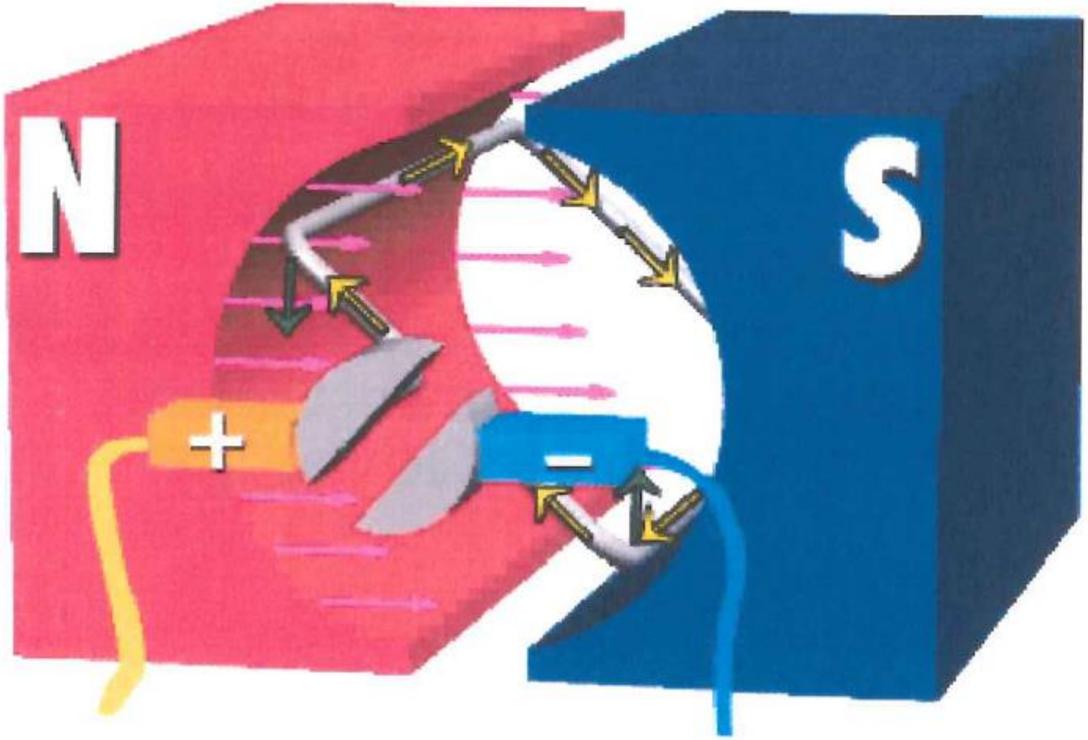
Gap 200!

DC electric motors

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

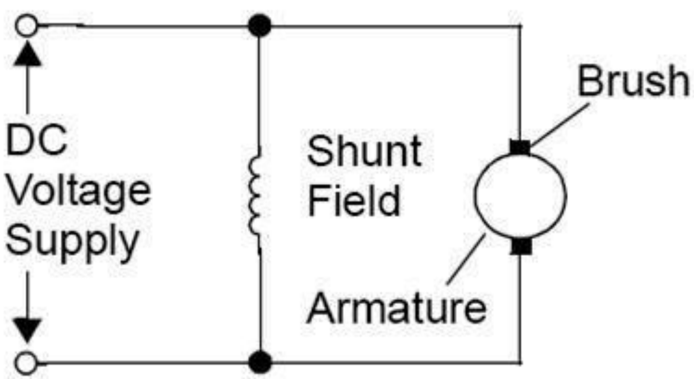
$$T = B\,i\,L\cos\alpha$$

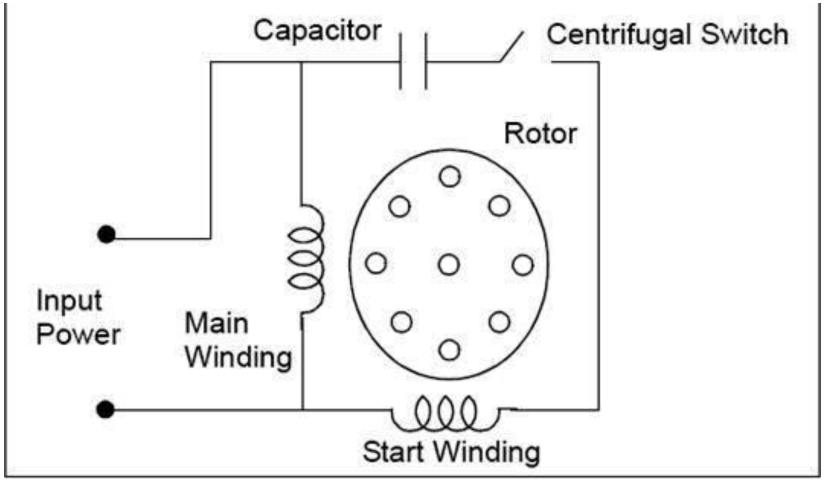
$$E = -\frac{d\Phi}{dt} = -N\,\frac{d\phi}{dt}$$

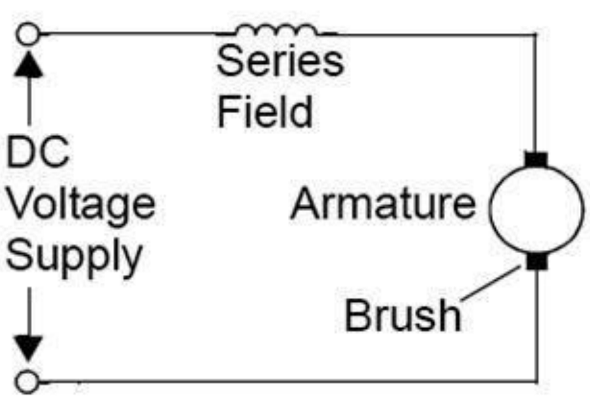


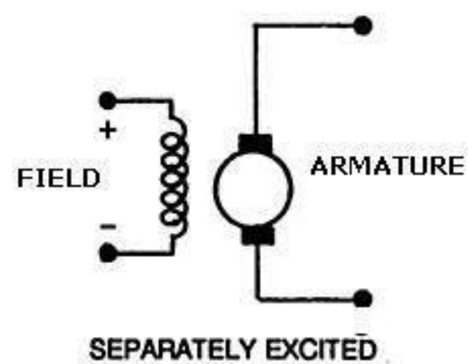
Working principal of a DC motor

Performance curves of electric machines

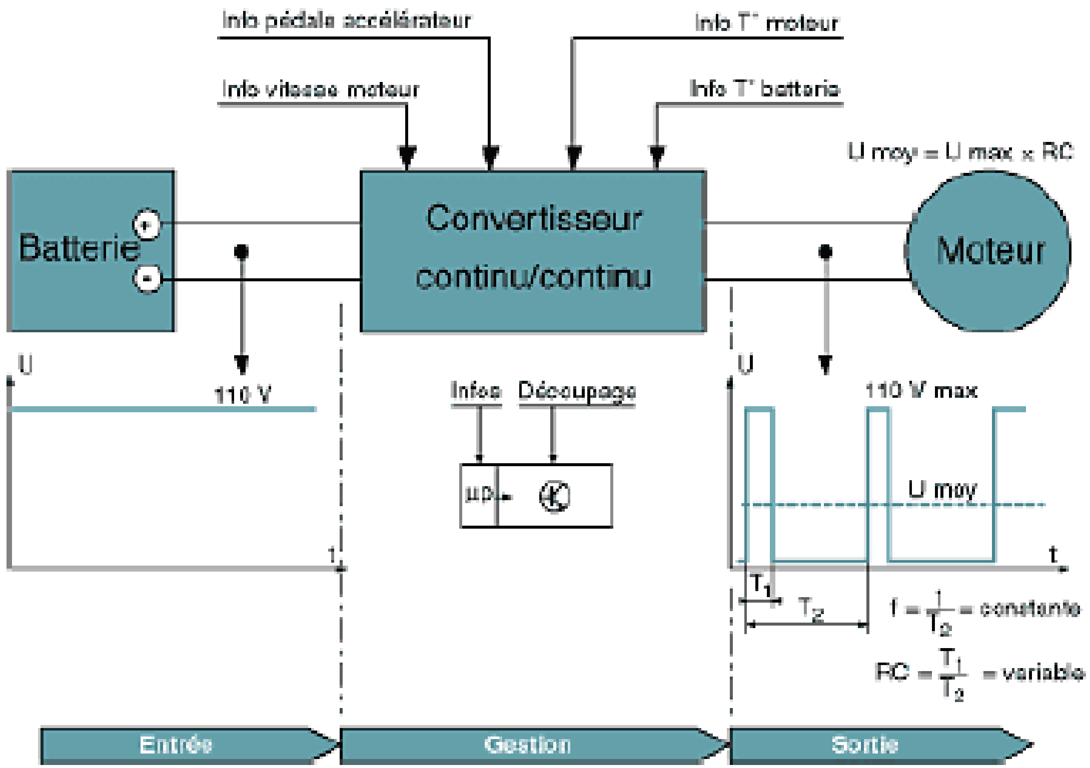






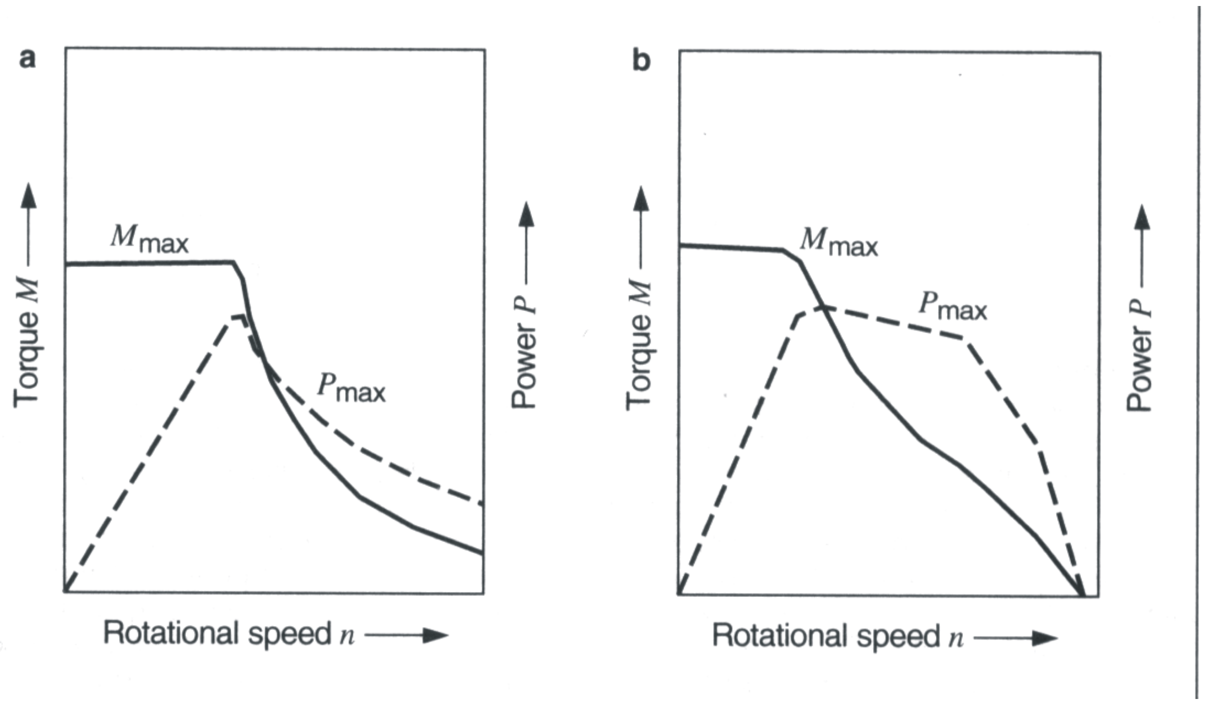


Power electronic and control of DC machines



Working principle of a chopper

DC motor: series and separated excitation



DC series motor

DC motor with separated excitation

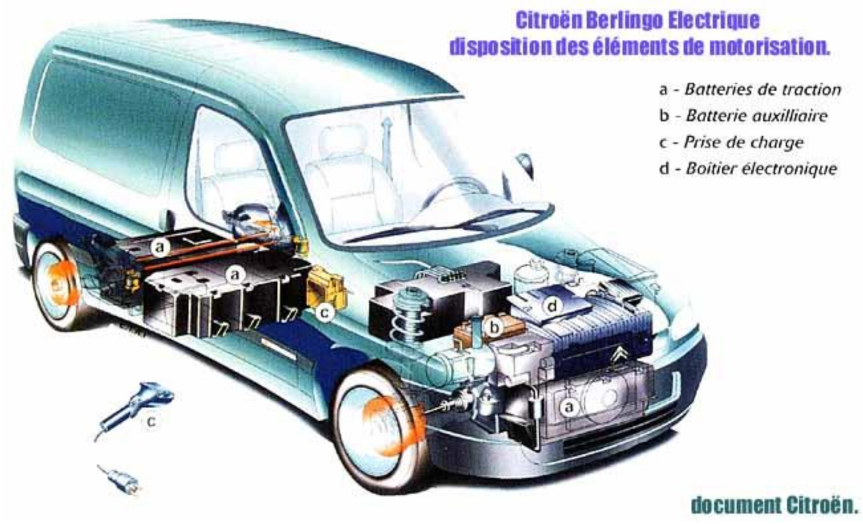
DC tractions motors

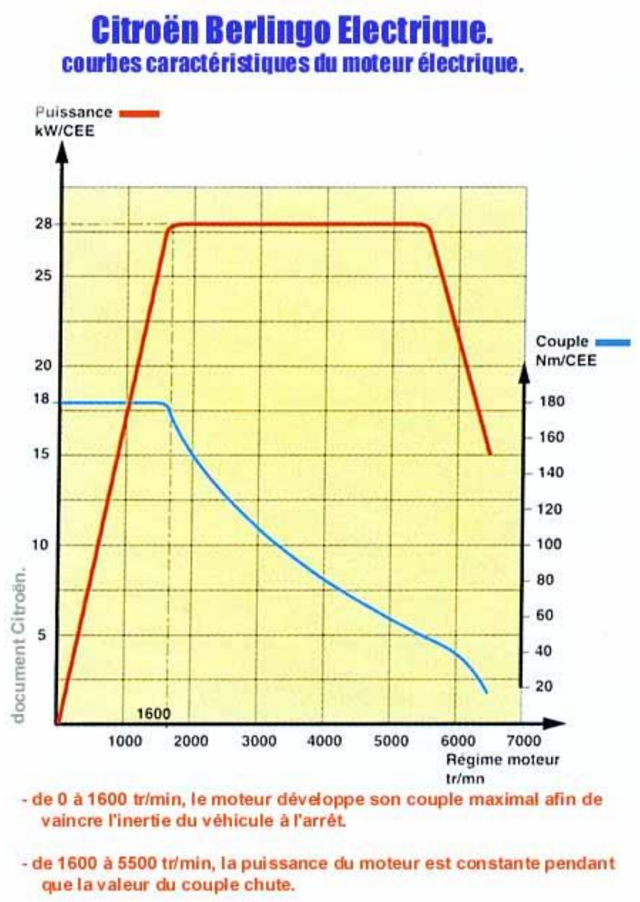
Peugeot 106 Electrique - EDF-GDF du Var
détail du raccordement véhicule - borne de recharge

- 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.

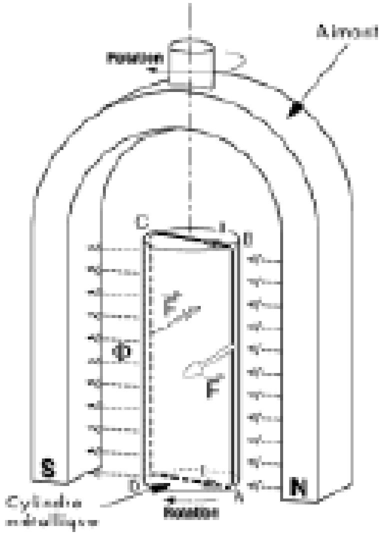
- Disadvantages:
  - Brushes (carbon) must be replaced periodically: replacement after 3000 h of operation
  - Range of supply voltage is limited
  - Lower specific power
  - Medium energy efficiency (80-85%)
  - Rotor losses : very difficult to eliminate

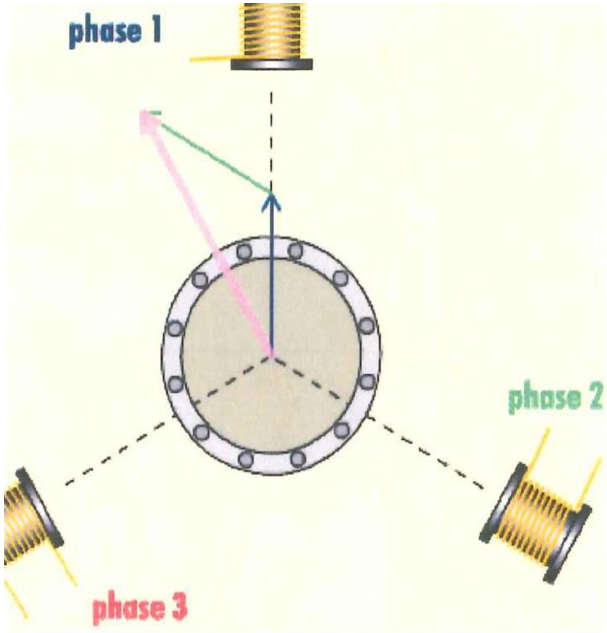
DC electric machines





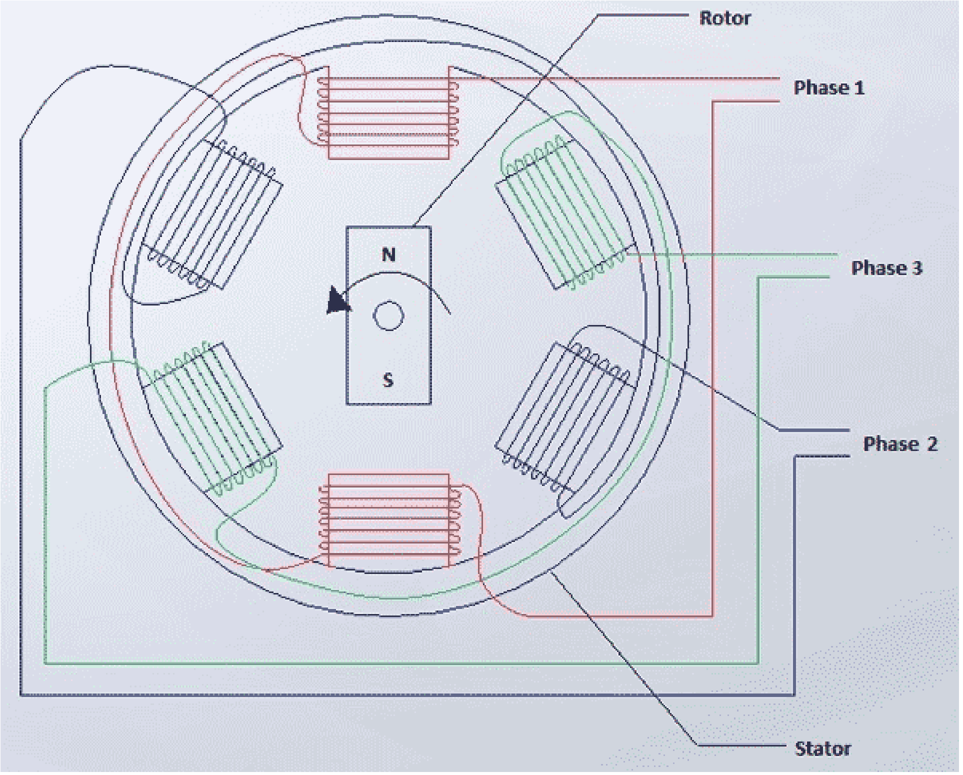
AC asynchronous electric motors



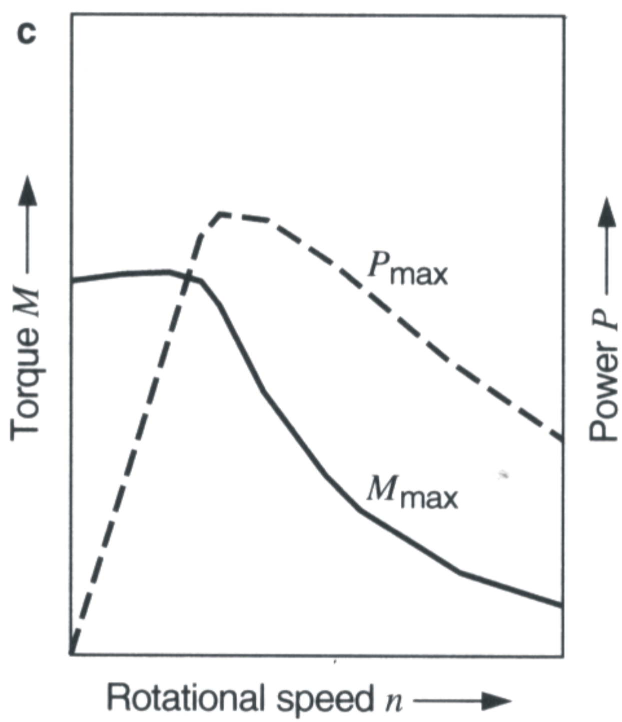


Working principle of AC asynchronous motors

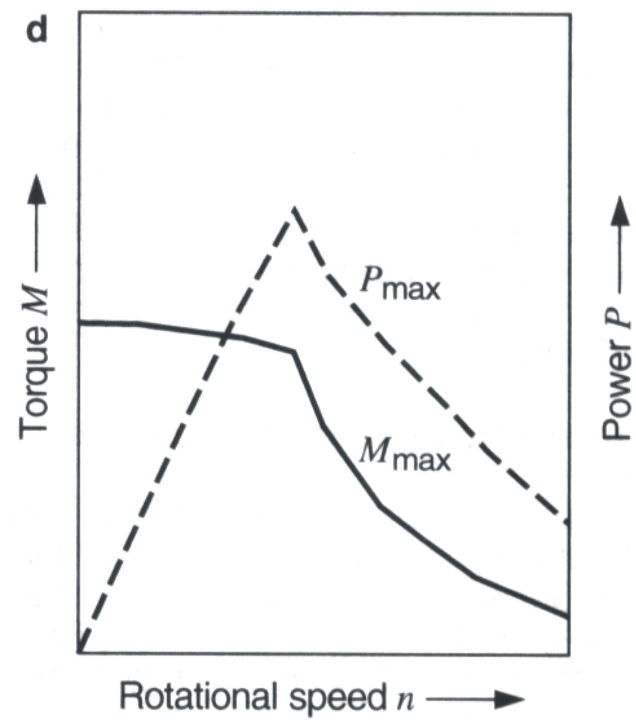
AC Synchronous motors



AC motors: induction vs synchronous



AC induction motor



AC synchronous motor

Traction electric machines

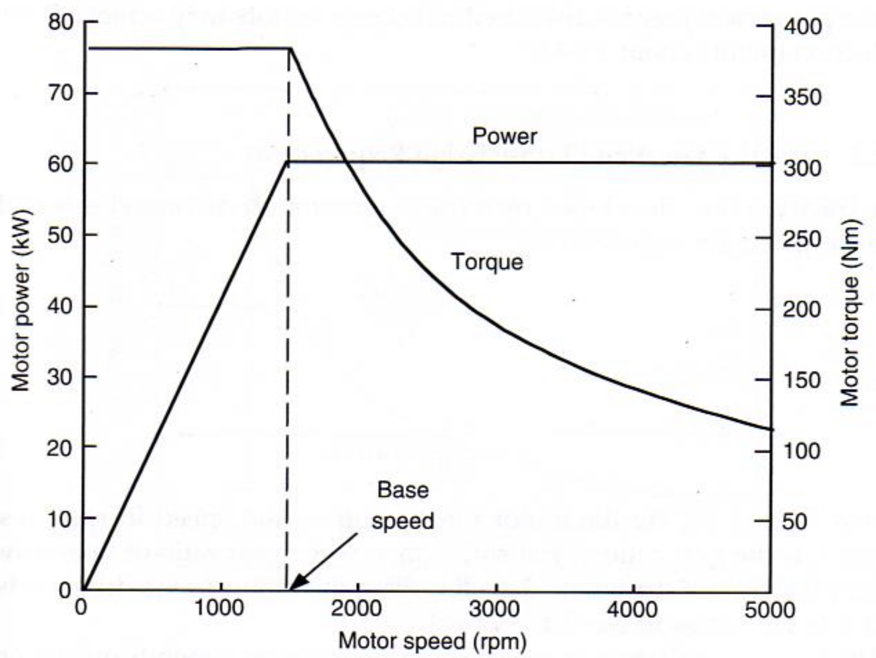
DC MOTORS

- 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)

Traction motor characteristics



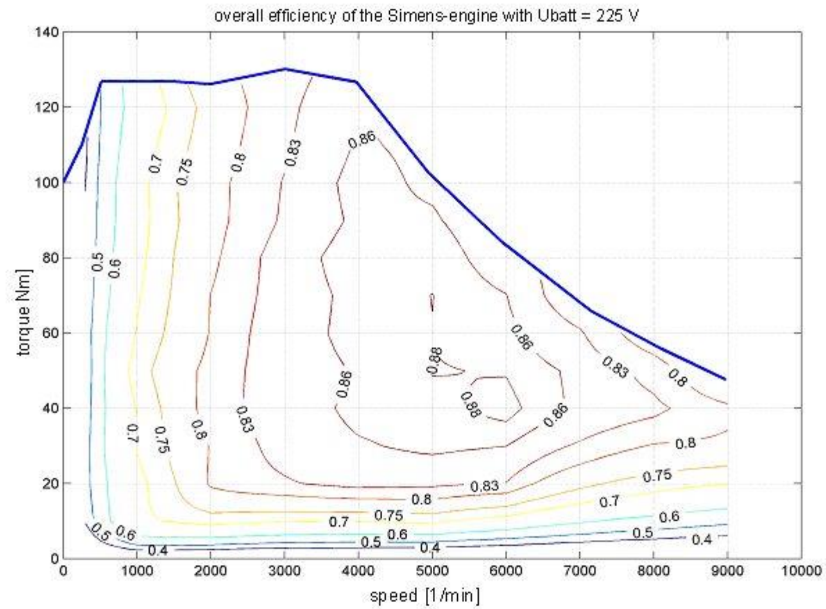
- At low speed: constant torque
  - Voltage supply increases with rotation speed through electronic converter while flux is kept constant
- At high speed: constant power
  - Motor voltage is kept constant while flux is weakened, reduced hyperbolically with the rotation speed
- Base speed: transition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



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: series and parallel

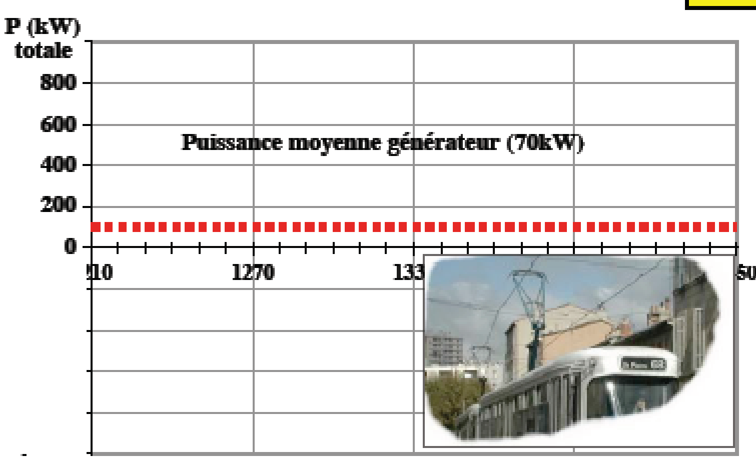
Highly variable operating conditions

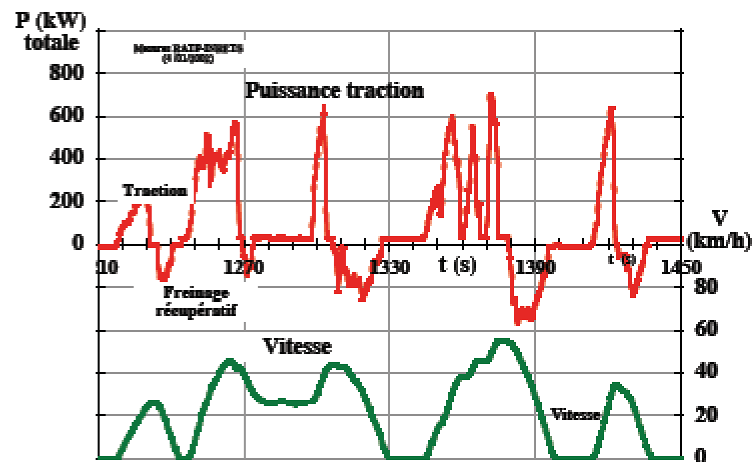
- Major difficulty of propulsion systems: the highly variable operating conditions (torque, regime)
  - Objective: sizing to average power consumption!
  - Approach: store the energy ⇨ hybrid vehicle

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

➡ **Stockage d'énergie tampon** ➡

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

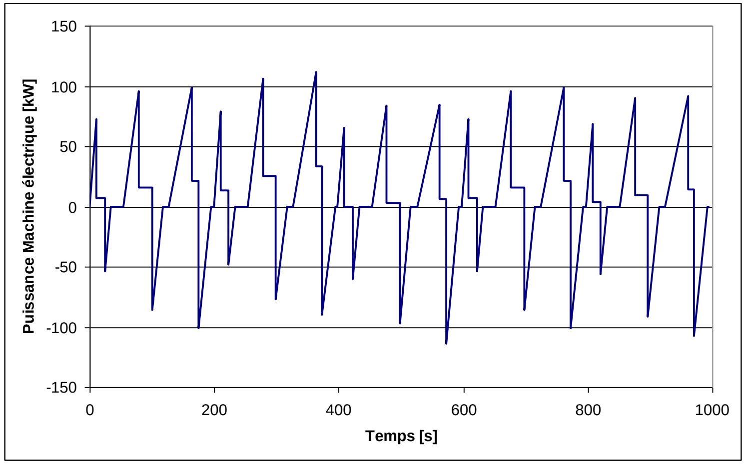




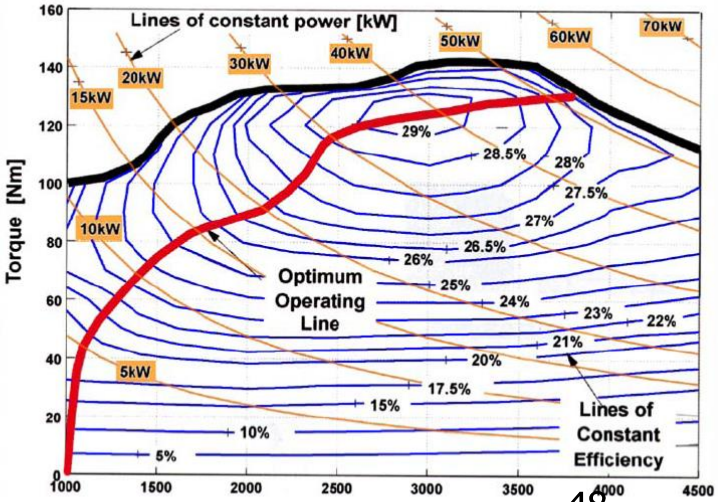
Source G. Coquery, INRETS

Improve powertrain efficiency

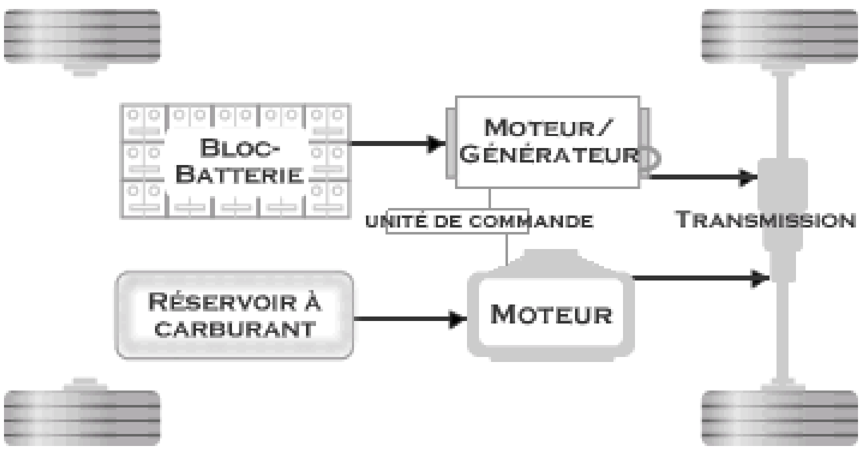
- Use energy storage to level energy flow
  - Recover braking energy
  - Smooth out the peak powers
  - Reduce the size of the prime mover as close as possible to the average power



- 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

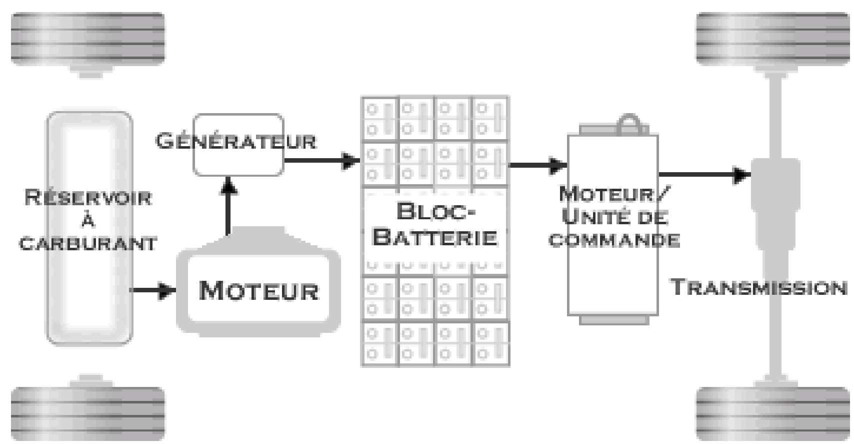


Hybrid propulsion powertrains



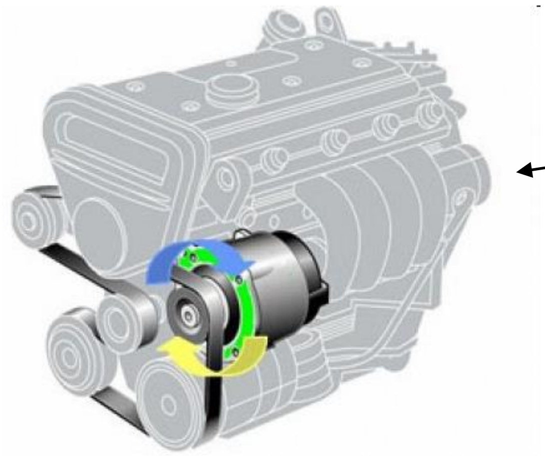
Parallel hybrid

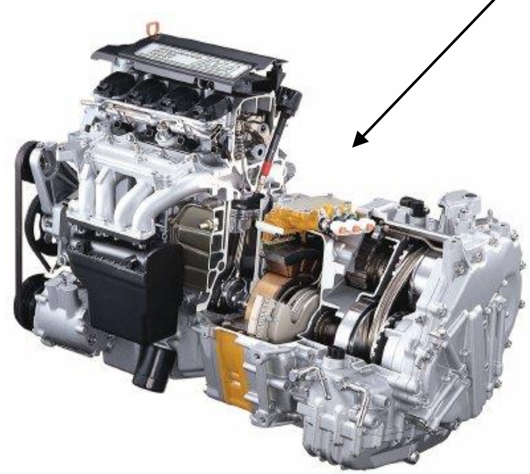
Serial hybrid

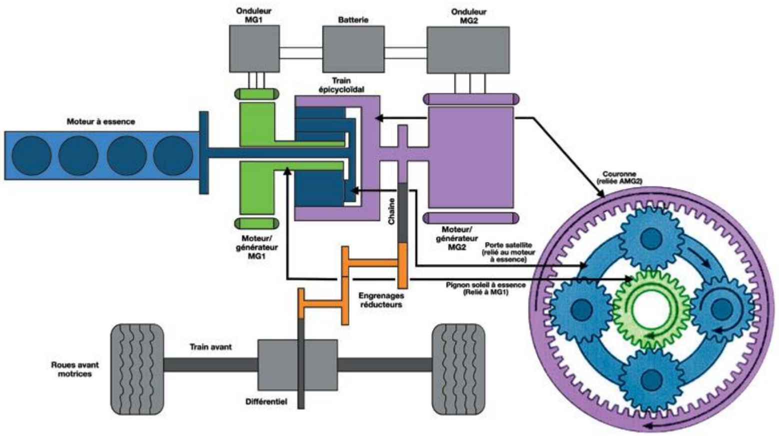


Various levels of hybridization

- Different levels 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







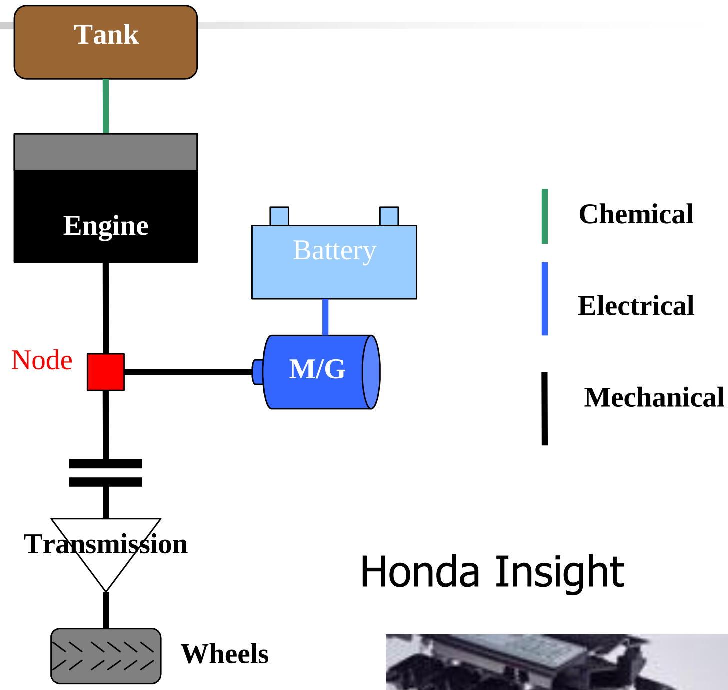
Various levels of hybridization

	Functions	Power of e-motor	CO_2 reduction
1.	Stop engine at idle	2 -3 kW	-8%
2.	1.+Braking energy recovery	3 kW	-10%
3.	1.+2.+engine downsizing	10 kW	-15%
4.	1.+2.+3.+full hybrid	>30kW kW	-30%

Possible reduction in consumption for a 1300 kg vehicle

Mild hybrid vehicle

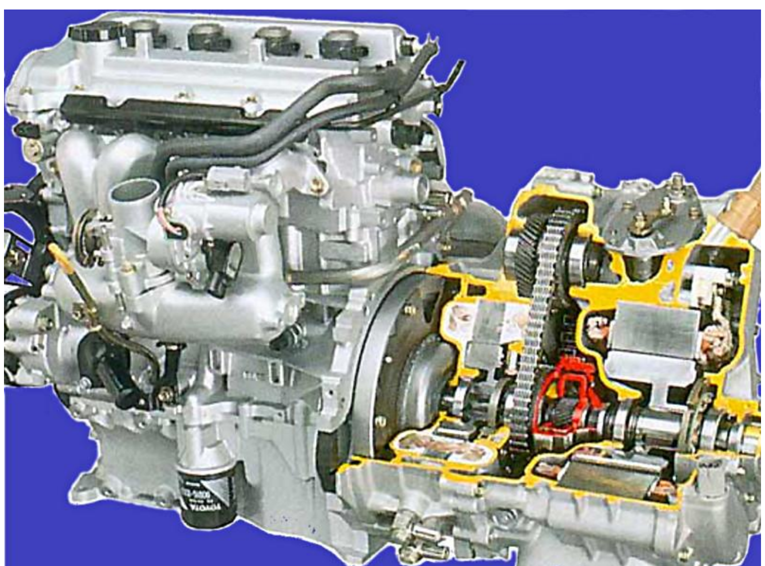
- Mild architecture
  - Small electric machines (~10 kW)
  - Fonction Stop & start
  - Low braking energy recovery capability
  - Power / torque assist of the main engine
- Substitute the flywheel, the starter and the alternator
- No pure electric mode

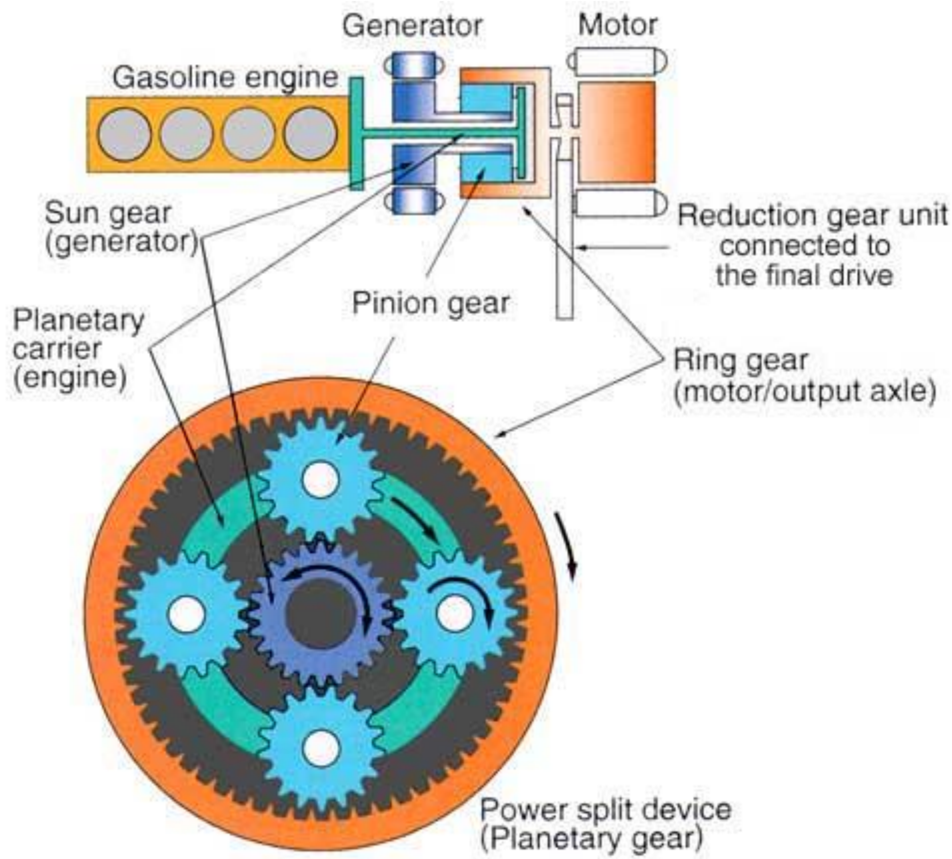


Honda Insight

Full hybrid: Toyota Prius transmission

Transmission of
Toyota Prius II

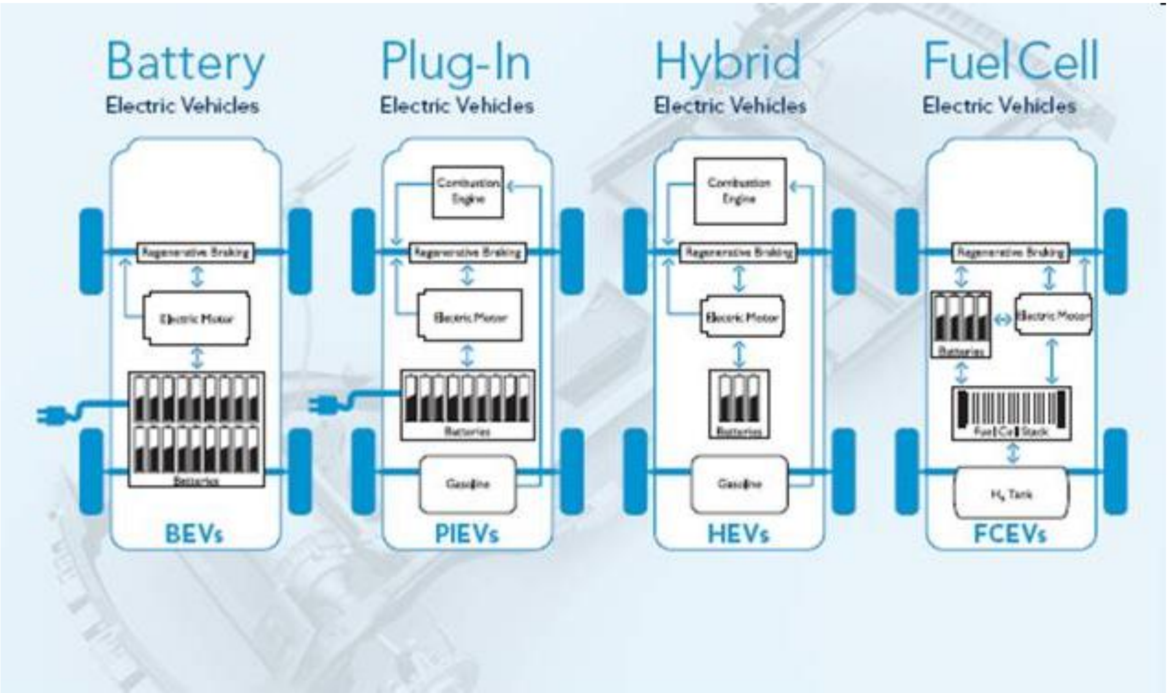




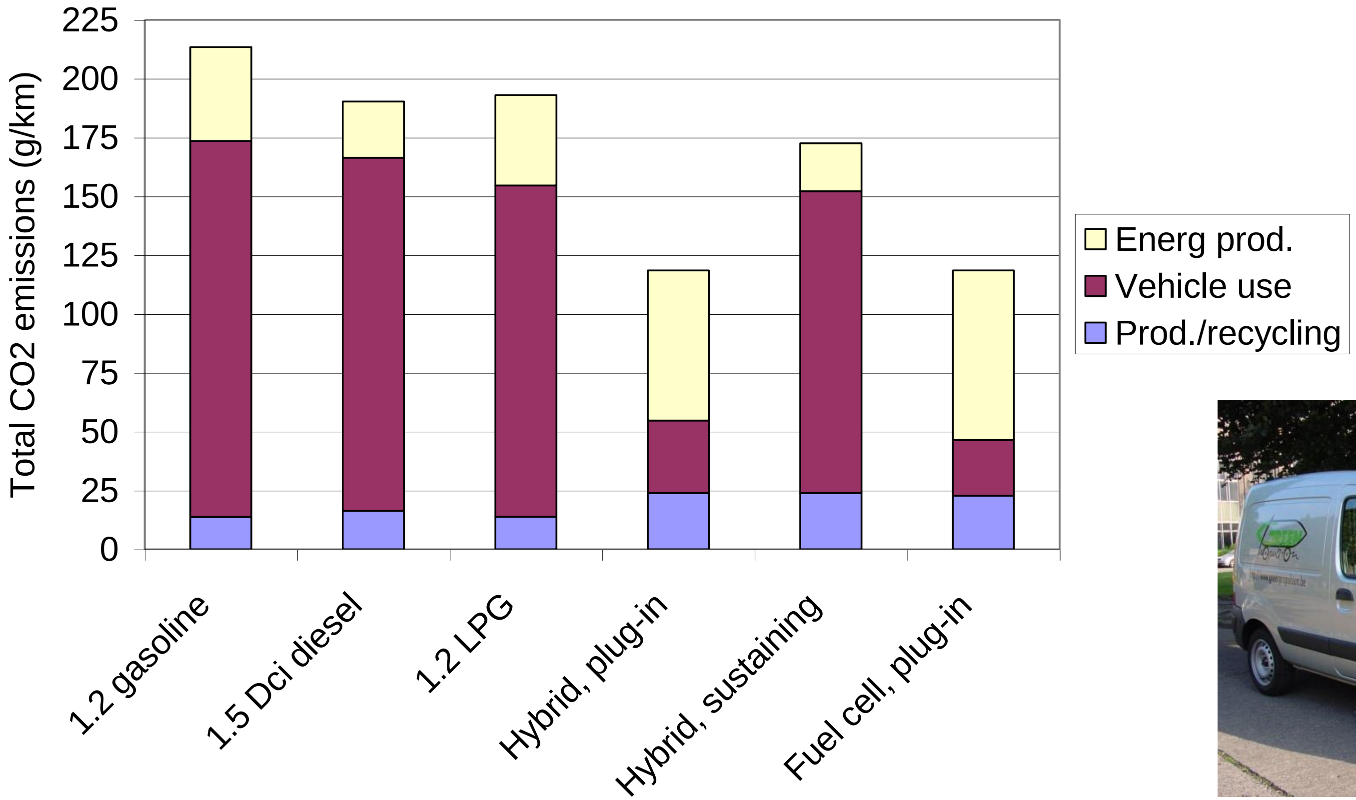
Courtesy: Toyota Motor Corporation

Various level of hybridization

- Different charging scenarios
  - Charge sustaining (no external charging)
  - Charge depleting (mostly external charging)
  - Plug in (daily range on external charging)
  - Range extender using a fuel cell



Hybrid plug-in

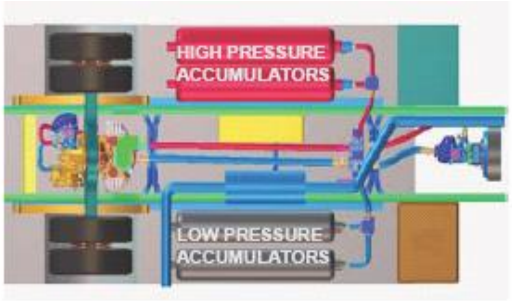


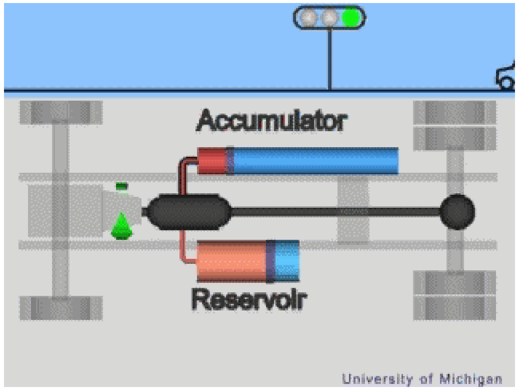
Source: www.green propulsion.be

Renault Kangoo Hybrid
Green Propulsion

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





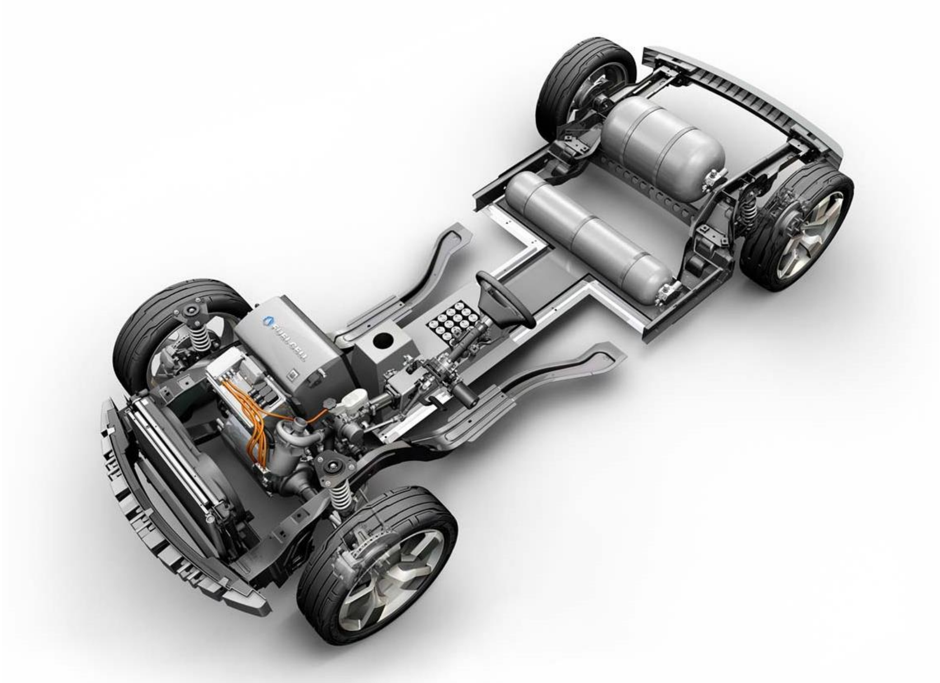
Smart Truck

Hybrid Pneumatic Vehicle

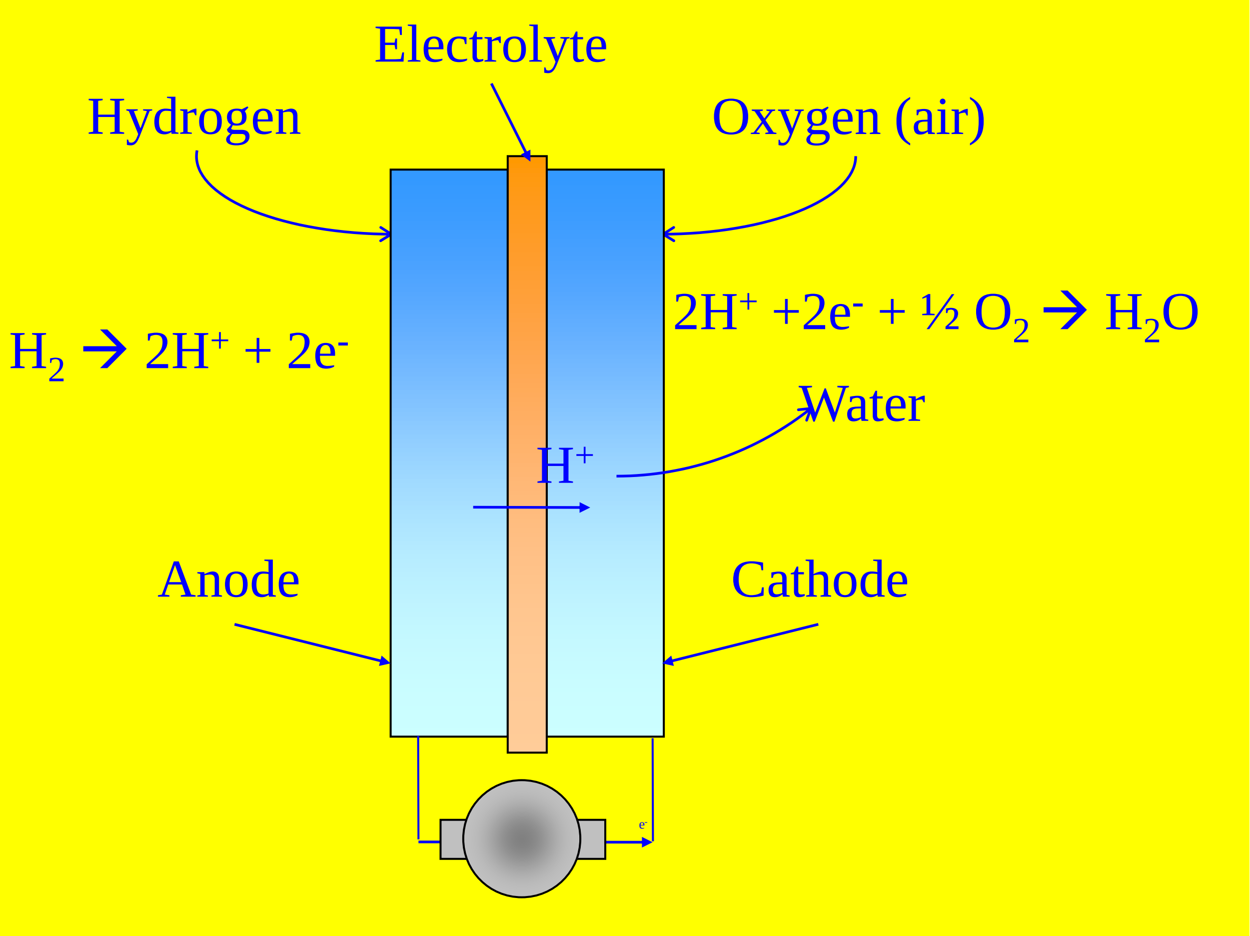
- While the air storage system offers a relatively low power density and vehicle range, its high efficiency is attractive for hybrid vehicles that use a conventional internal combustion engine as a main power source. The air storage can be used for regenerative braking and to optimize the cycle of the 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



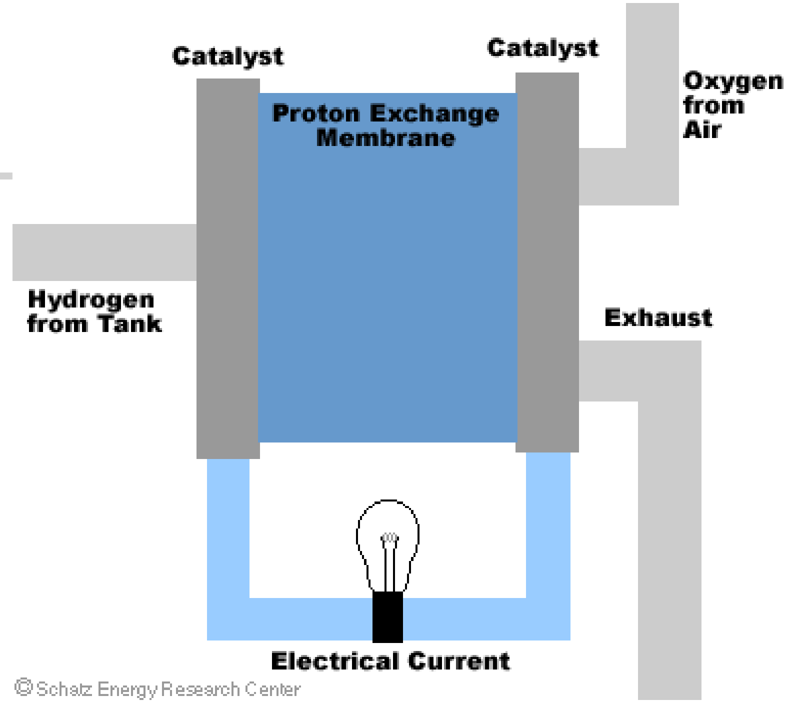
Fuel cell



Electrolyte
Hydrogen
Oxygen (air)
$2H^+ + 2e^- + ½ O_2 \rightarrow H_2O$
$H_2 \rightarrow 2H^+ + 2e^-$
Water
H^+
Anode
Cathode

Fuel cell

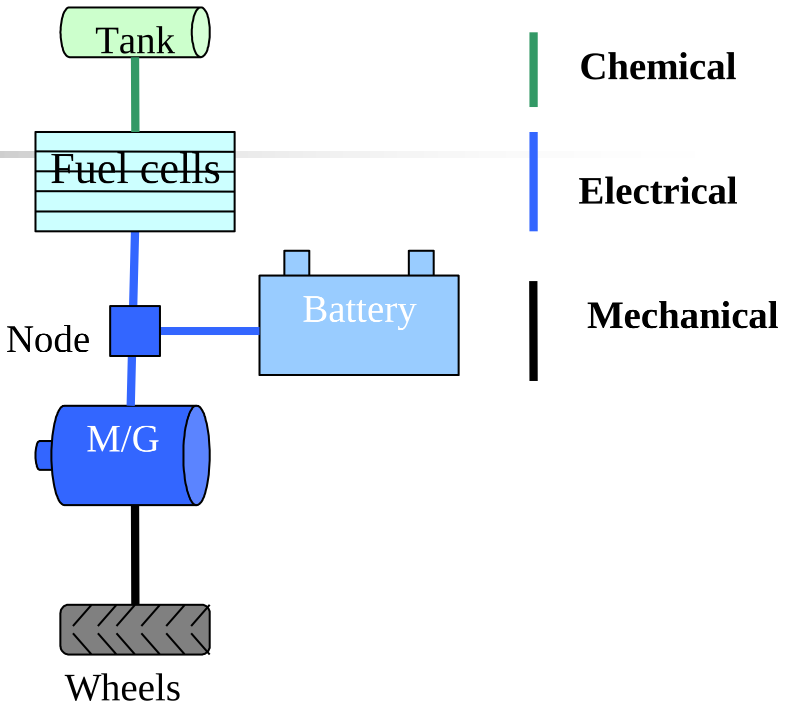
- Fuel Cell carries out a direct conversion of the fuel chemical energy into electrical energy
- Electrochemical reaction (oxide-reduction) without flame
- The hydrogen $H_2 - O_2$ fuel cell: inverse reaction of water electrolysis
- High fuel efficiency (>50%)
- Major issues:
  - Cost related of electrodes 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

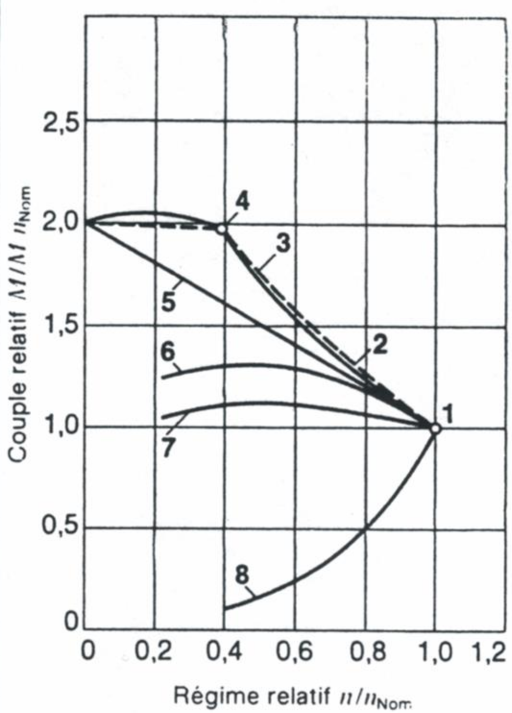
Comparison of propulsion systems

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
Motocycles 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
Voitures avec 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
Voitures 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
Camions Moteur suralimenté	2000 ... 3200	15 ... 17	10 ... 13	15 ... 20	8 ... 3	230 ... 205	15 ... 30
Camions 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)