1MG11:
HYBRID ELECTRIC VEHICLES

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Introduction

References

- C.C. Chan. The State of the art of Electric and Hybrid Vehicles. Proc. IEEE. vol 90 pp 24-275. 2002
- C.C. Chan and K.T. Chau. Modern Vehicle Technology. Oxford Science Publications. 2001.
- M. Ehsani, Y. Gao, S. Gay and A. Emadi. Modern Electric, Hybrid electric and, Fuel Cell Vehicles. Fundamentals, Theory and Design. CRC Press, 2005.
- Les Véhicules Electriques. Des composants au système. Sous la directionde F. Badin. Edition TECHNIP. Paris 2013

References

- R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)
- G. Genta. « The Motor Vehicle Dynamics». Levrotto & Bella di Gualini. Torino 2000.

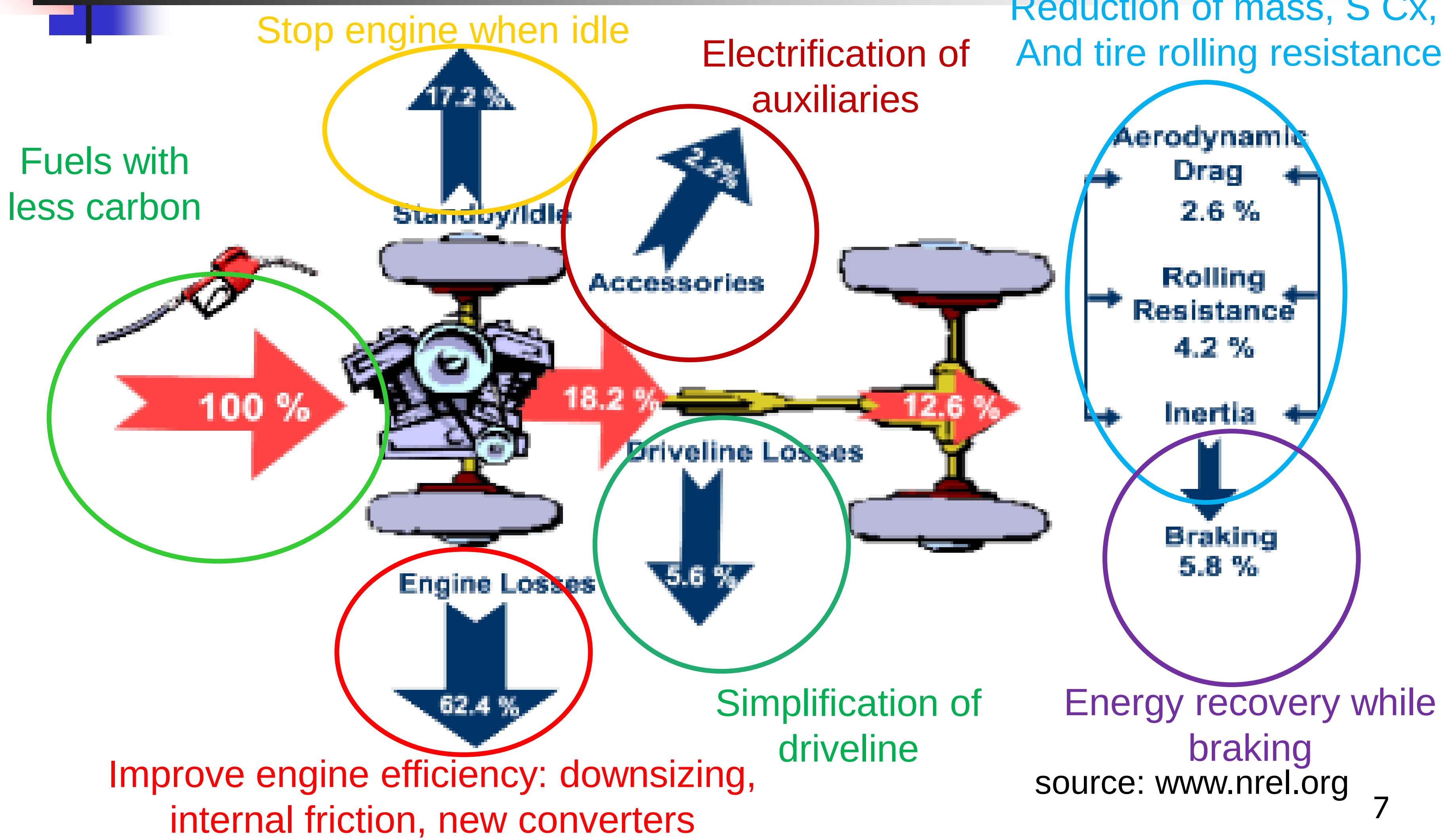
- www.hybridcars.com
- www.howstuffworks/hybrid-car.htm

Outline

- How to save fuel and reduce emissions?
- Definitions
  - Hybrid vehicle & Hybrid electric vehicle
  - Categories: Series, parallel and complex hybrids, full et mild hybrids, charge depleting, charge sustaining, plug-in hybrids
- Key components of hybrid vehicles
- Other systems for fuel efficiency improvement
- Case studies: Honda Insight and Toyota Prius

Reducing fuel consumption and emissions

Development principles of new clean propulsion systems



source: www.nrel.org

Reducing CO_2 emissions

- To reduce the emissions, several approaches
  - Substituting petrol fuels by fuels with low carbon emissions (per energy release) or fuels with a life cycle giving rise to low emissions (biofuels)
  - Improve the fuel efficiency of the converter (the most direct action)
  - Reduce the mass, which often antagonistic with the demand for greater safety, comfort, etc.
  - Internal friction and losses reduction: downsizing strategy= keep same performance with a lower cylinder displacement
  - Reduction of aerodynamic drag
  - Improve drivetrain efficiency
  - Electrification of auxiliaries and global thermal and electrical energy management

Reducing CO_2 emissions

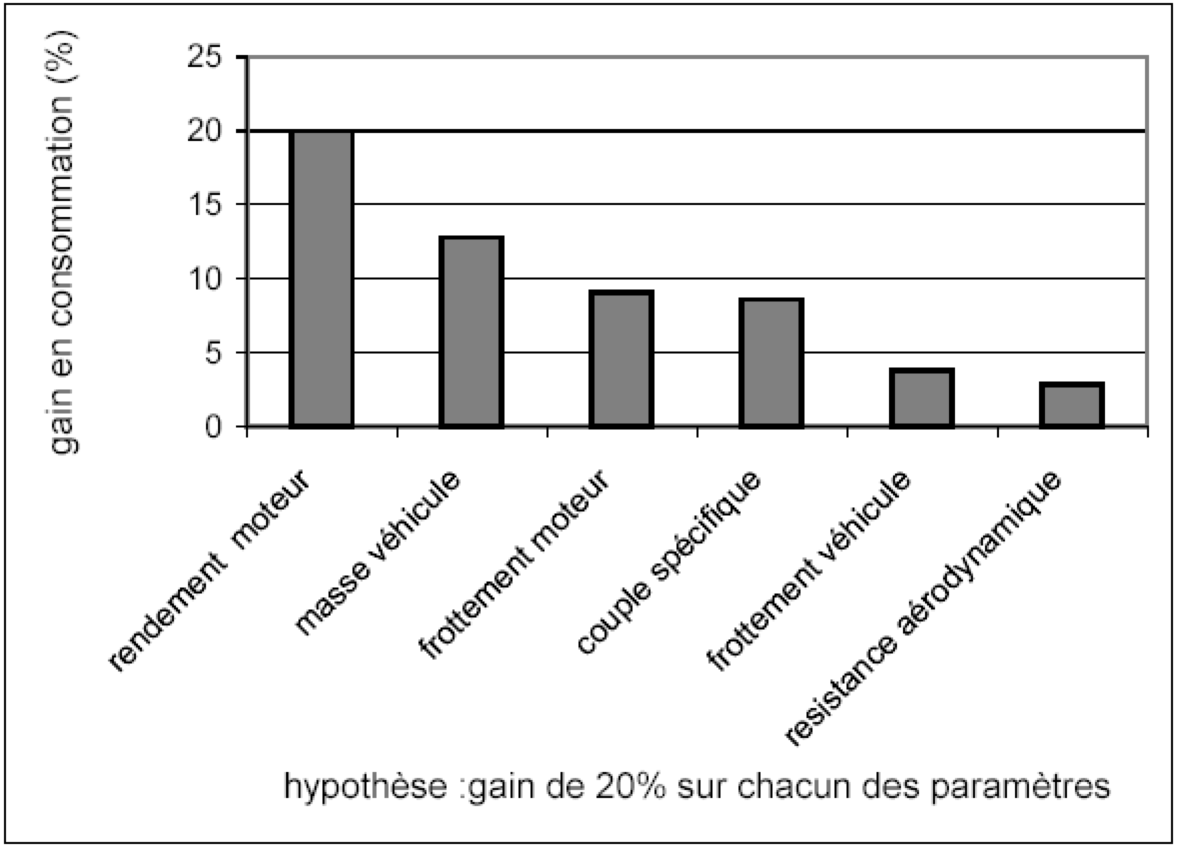
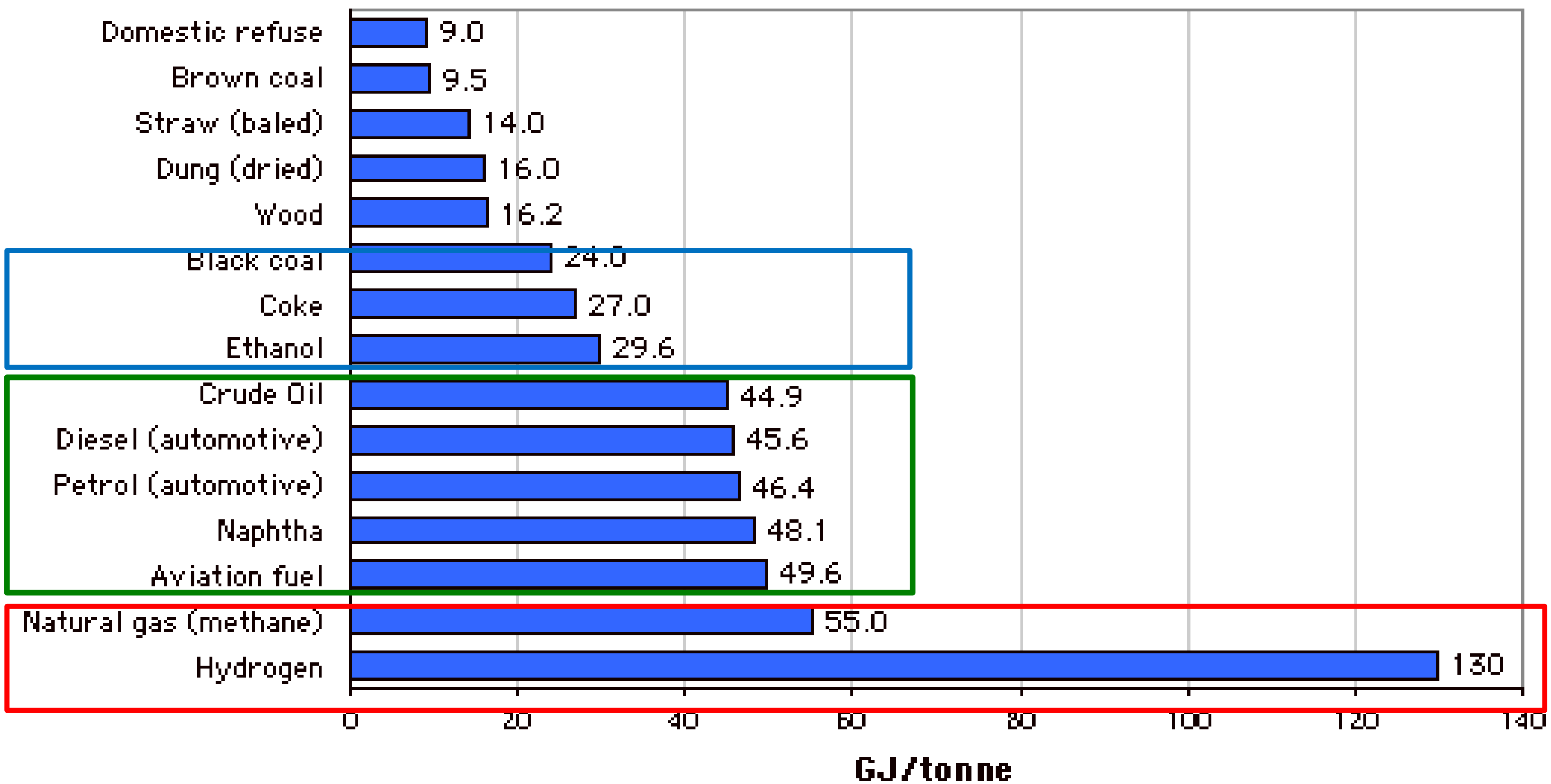


Figure 5 : Principales voies de réduction de la consommation des véhicules automobiles : impact d'une amélioration de 20% de chacun des principaux paramètres.

Selection of fuels

- Lower heat value of fuels



Substituting fuels by cleaner ones

- Substitution fuels
  - Compressed Natural Gas (CNG)
  - Liquefied Petroleum Gas (LPG)
  - Alcohols (ethanol, methanol)
  - Bio diesel (DME, etc.)
  - Hydrogen, Ammoniac
- Increasing market parts of substitution fuels
  - 2020 target : 20% of the market
  - Biofuels: 6% in 2010

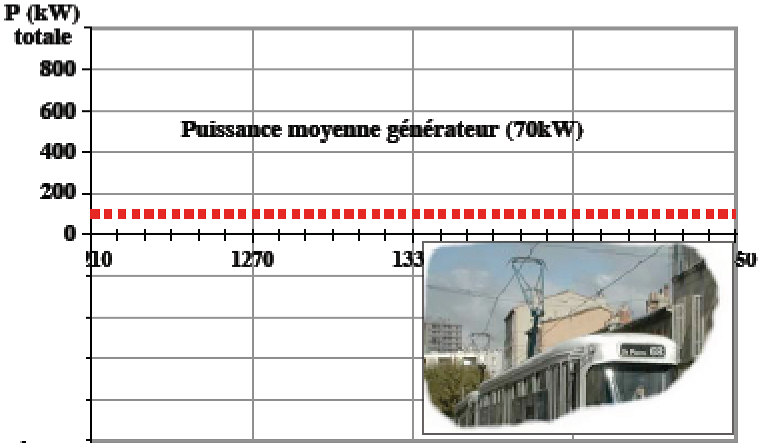
Highly variable operating conditions

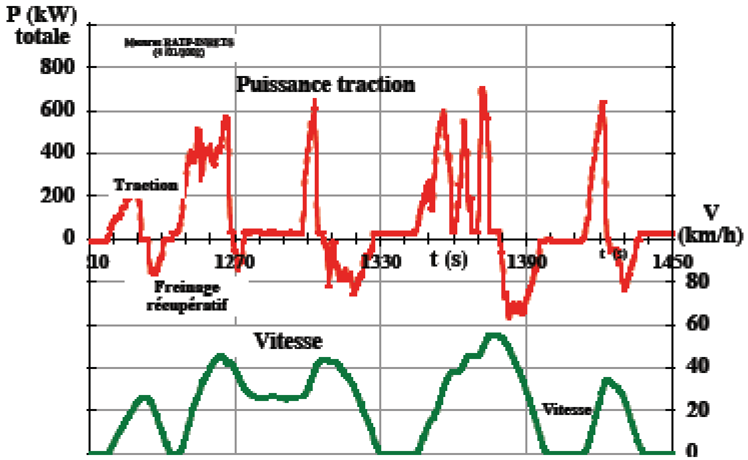
- Major difficulty of propulsion systems: the highly variable operating conditions (torque, regime)
  - Objective: sizing to average power consumption!
  - Approach: store the energy ⇨ hybrid vehicle

Average power for vehicle displacement.
Ex. Tramway 70 kW

Energy Storage

Instantaneous power for vehicle traction.
Ex. Tramway 800 kW to 1. MW

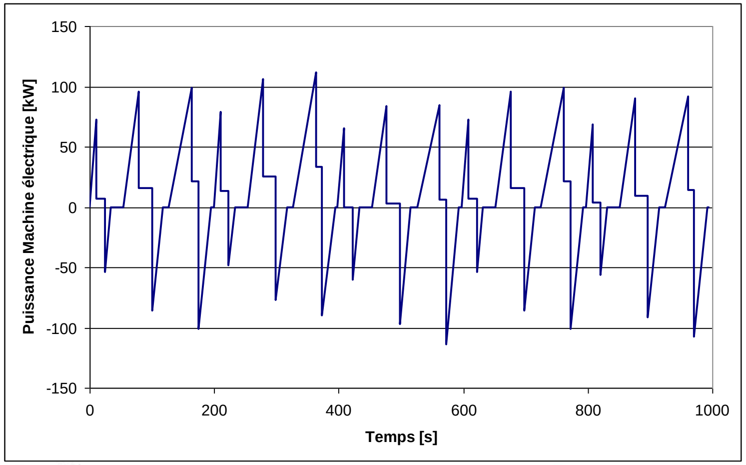


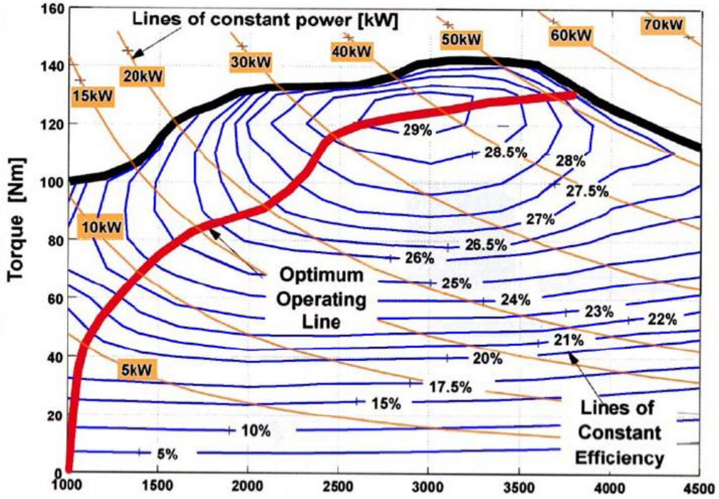


Source G. Coquery, INRETS

Improving the powertrain efficiency

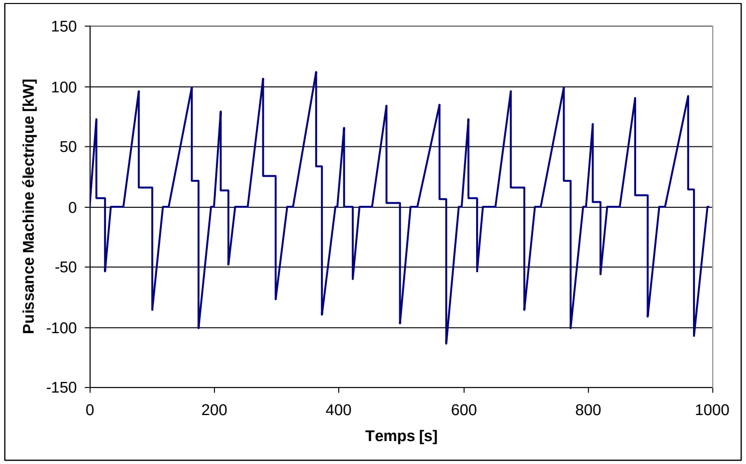
- Use main energy convertor in its most efficient range
- ➔ Battery: to shave the peak power demands
- ➔ Electric Machine to absorb the fluctuating power
- ➔ Thermal engine: sized to provide the average power demand but not the max power
  - Engine downsizing
  - Reduction of internal frictions



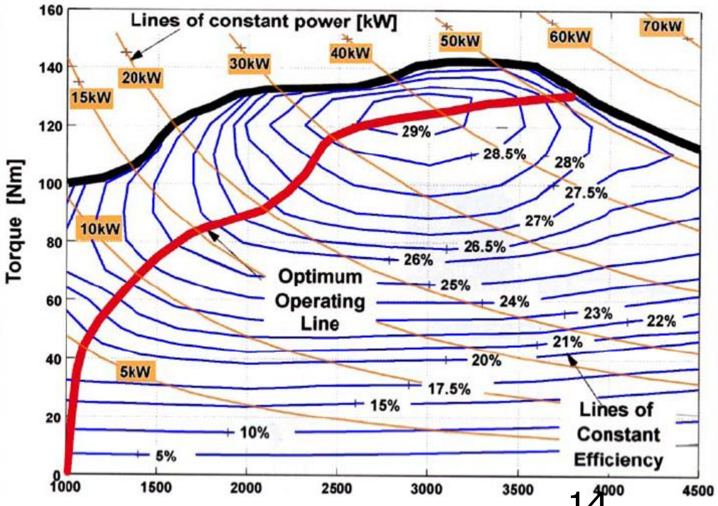


Improving the powertrain efficiency

- 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



Definitions

Definitions

- Definition of hybrid vehicle: vehicle equipped with a propulsion system that combines two or several energy sources, storages and converters.

- Possible energy sources:
  - Chemical energy: fuel converted into thermal and then mechanical energy in thermal engines for instance
  - Electrical energy: batteries, electric machines (motor / generator)
  - Kinetic energy: fly wheels
  - Elastic energy: under strain energy, compressed fluids, hydraulic or pneumatic systems)
  - Nuclear
  - Thermal: latent heat of melted salts

Definitions

- Remarks:
  - Definition is extremely flexible
  - The concept is quite old in transportation systems
    - A moped (motor bike equipped with pedals) is a hybrid vehicle inasmuch it can use engine and muscular propulsion
    - Most of diesel locos are based on a diesel engine powering a generator and electric motors but they have no electric energy storage
    - Bus and trolley bus equipped with a small diesel engine
    - Large mine vehicle are using hydrostatic (hydraulic) transmission and propulsion system
    - Submarines are mostly diesel electric or nuclear electric hybrid propulsion systems

Definitions

- For road vehicle :
  - The prime mover (principal energy source) is generally the internal combustion engine (piston engine but sometimes gas turbine)
    - Generally nonreversible energy converter
  - The auxiliary energy source (secondary source) is:
    - Electric (the most often)
    - Hydraulic
    - Pneumatic
    - Kinetic
  - In the future, the prime mover could also be a fuel cell

Definitions

- Hybrid electric vehicle: a vehicle in which the propulsion energy is available from two or more types of sources, energy storages, and converters, and at least one of them can deliver electrical energy (Chan, 2002)

  There are many kinds of HEV: petrol/diesel/CNG/H2 ICE & battery, fuel cell & battery, battery & supercaps/flywheels…

- Hybrid hydraulic vehicle: same as HEV but in this case one of the energy sources, storage and converters are hydraulic systems

Definitions

- One calls a « full hybrid » vehicle, the hybrid vehicle that can be moved at least at low speed without using its thermal engine or chemical energy converter. Another definition is that both energy sources can be used alone to move the car for a significant distance.

- On the contrary, the «mild hybrid » vehicles or part hybrid vehicles always need the prime mover to propel the car. The auxiliary power source is unable to move the car alone or solely during very short times and only for prime mover assist.

Hybridization and emission saving

- Estimation of potential CO_2 saving for a 1300 kg vehicle

	Functions	Power of e-motor	CO_2 saving on driving cycle	EV Range
1	Stop ICE at stall	2 kW	5-6%	0
2	1 + Braking energy recovery	3kW	7-10%	0
3	2+ Downsizing of ICE + Assistance during acceleration	10kW	10-15%	0,1 km
4	3 + full hybridization based on series or parallel architecture	30-50kW	15-30%	5 km
5	4 + Plug in	60-100kW	>20%	50 km

Definitions

- In the mild hybrid, one can further distinguish the different categories as micro hybrids, stop&start...
- The stop&start hybrid aims at allowing to stop engine when idling and at restarting the engine very rapidly on demand.
- Integrated Starter Alternator with Damping (ISAD) are micro hybrids characterized by small electric machines with high power density implementing features such as stop-start, regenerative braking, boost and efficiency electrical energy generation to support extended electrically operated functions.
- The hybrid with Integrated Motor Assist (IMA) system is similar to the ISAD but it has a larger electric motor and more electrical storage to move the vehicle. This means that the power of electric motor is larger and sufficiently high to move effectively the vehicle.

Stop & Start

Citroën C3 stop&start

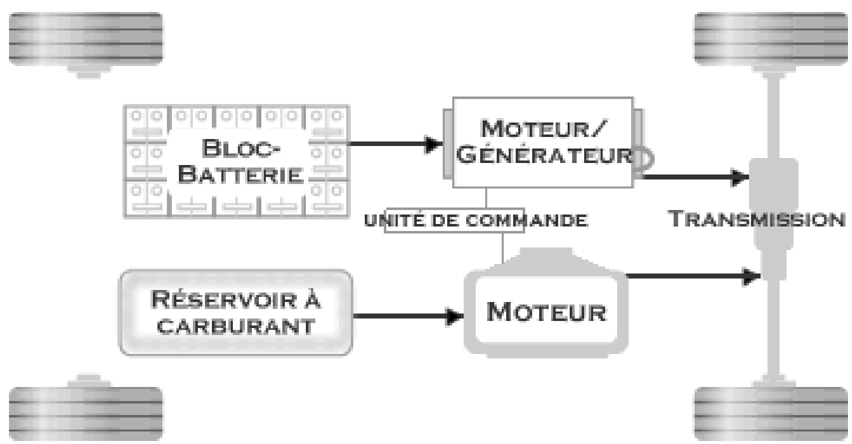
- The Stop & Start system is based on the principle of a starter alternator combined with a robotized gear box.
- When used this system is characterized by stopping the engine when being stalled at traffic jams for instance. The engine is restarted without extra fuel consumption and emissions when brake is released
- The Stop & Start system reduces fuel consumption and CO_2 emissions by about 10 %, mainly in urban driving situations without penalty on performances for intercity driving

Integrated Motor Assist

- Integrated Motor Asist implements only partly the hybridization concept because of a small e-motor: stop-start, energy recovery during braking, assistance during acceleration, and ICE downsizing.
- It does not provide only pure electric propulsion capability on significant distance, and so it is not able to propel the car alone.
- Limited fuel saving to 15%
- Example: Honda Civic IMA or Honda Insight

Definitions

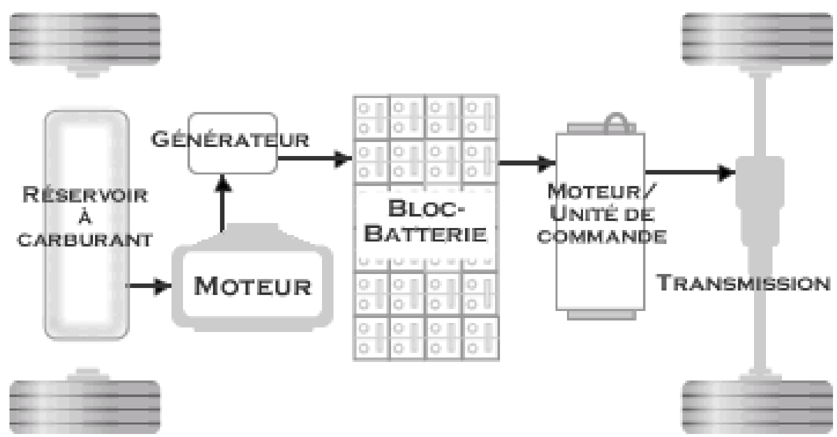
- One also distinguish series hybrid and parallel hybrid.
- In a parallel hybrid, both types of motorization are connected to the wheels and can propel the car independently or in combination.



Parallel hybrid

Definitions

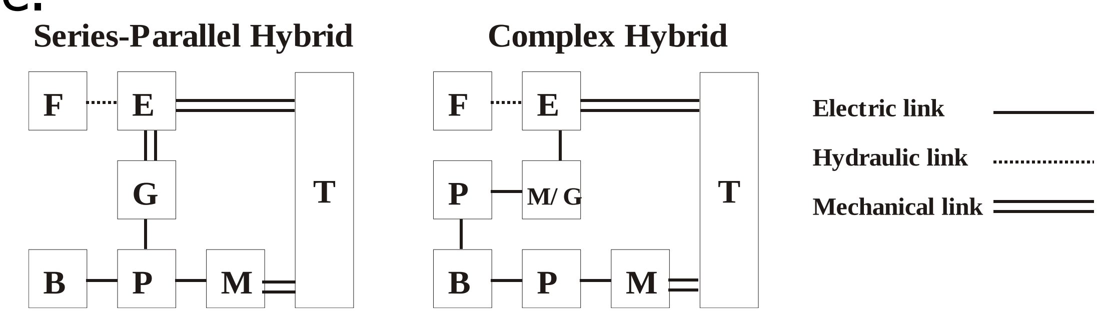
- One also distinguish series hybrid and parallel hybrid.
- In a series hybrid, the prime mover and its energy source are used to spin a generator that supplies electrical energy to either the batteries or directly the electric motor that is the only one to be geared with the wheels.



Series Hybrid

Definitions

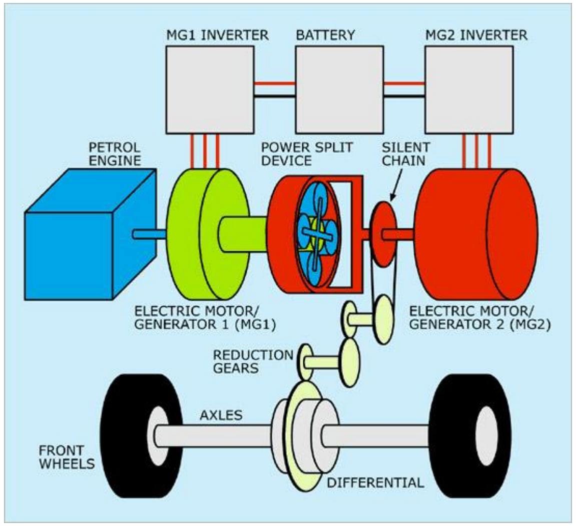
- In addition, with the increasing design complexity, on can distinguish new lay-out of hybrid traction (Chan, 2002)
- The series-parallel configuration: both energy sources can propel the vehicle. Nonetheless the system is designed to allow recovering series architecture by inserting a generator between the ICE engine and the batteries.
- The complex hybrid configuration extends also the couplings between the two kinds of propulsion chains. The more complex lay-out allows using the electric machine to receive from (generator mode) or to deliver (starter mode) energy to ICE engine.



Charge sustaining, depleting and plug-in hybrids

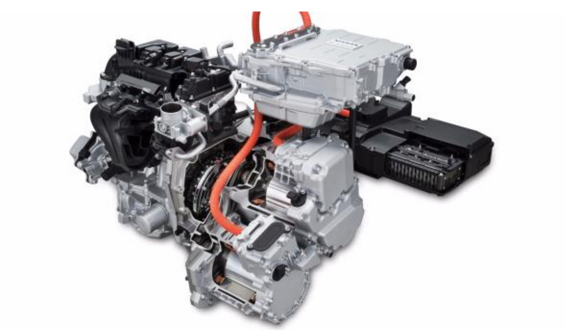
- The engineer can decide whether the batteries can be charged from the electric network or only from the prime mover (thermal engine) via the generator. This gives rise to a new distinction among hybrid vehicles.
- The « charge sustaining » hybrids are such that batteries can only be charged from the prime mover work and energy recovery from braking.
- The « charge depleting » hybrids are equipped with large batteries which have to be charged from the network for normal operation, because the prime mover is generally too small to be able to sustain the charge level during mission.
- The « plug-in » hybrids are able to sustain the charge level with the prime movers, but batteries are advantageously charged from the network for best environmental and fuel consumption performances

Charge sustaining



- The « charge sustaining » hybrids
  - They are characterized by their tail pipe emissions and the engine fuel consumption (l/100km).
  - They do not require any modifications of user behaviour to plan battery charging and skip this long operation.
  - The solution does not depend on particular infrastructure except existing ones, especially for battery charging.
  - The batteries can be kept rather small, which reduces the extra cost of hybrid system.
  - The fuel and emission savings from hybrid systems are often milder because of the necessity to charge the batteries from ICE engine and energy recovery.

Charge depleting



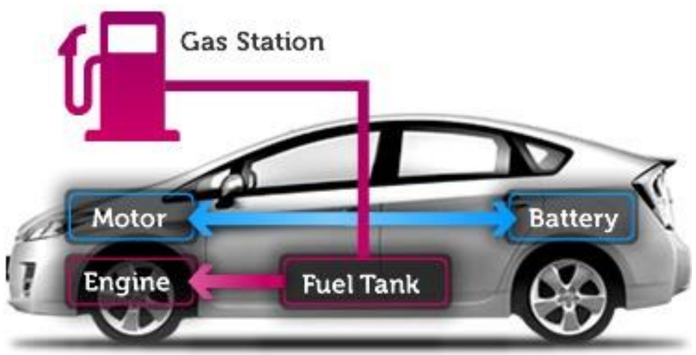
- The « charge depleting » vehicles:
  - They are characterized by the fuel consumption (l/100km) + the electricity consumption (in kWh/100km). The later are related to the (average) emissions of production of kWh on the network.
  - The sizing of the batteries requires to have usually heavy batteries, which is a penalty for the mass of the car and for the cost the vehicle.
  - Charging the batteries on the networks takes time and requires a certain self-discipline from the user.
  - The major advantage is the reduction of the CO_2 emissions and the pollutants, because of the lower environmental impact of electricity in large power plants, green electricity (renewable energy sources, nuclear plants).

Plug-in hybrid

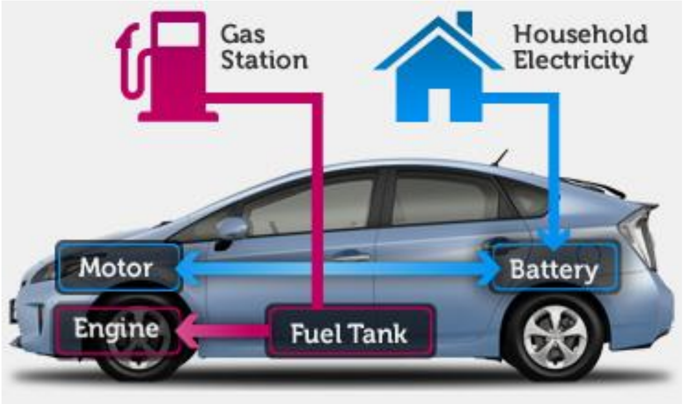
- <u>The « plug-in hybrids » vehicles:</u>
  - They are characterized by the fuel consumption (l/100km) + the electricity consumption (in kWh/100km). The later are related to the (average) emissions of production of kWh on the network.
  - The vehicle can operate in normal conditions even if the battery has not been charged at the price of a higher fuel consumption
  - Charging the batteries on the networks is a favorable option that drastically reduces the consumption of primary energy. It requires a certain discipline from the user.
  - The best efficiency is achieved when the user takes advantage of the lower environmental impact of electricity in large power plants, green electricity (renewable energy sources, nuclear plants).

Charge sustaining vs plug-in

- Charge sustaining:
  - The driving energy is produced on board by prime mover only but fuel conversion.
  - Easy adaptation for users
  - Moderate improvement of fuel efficiency
  - Still dependent on oil

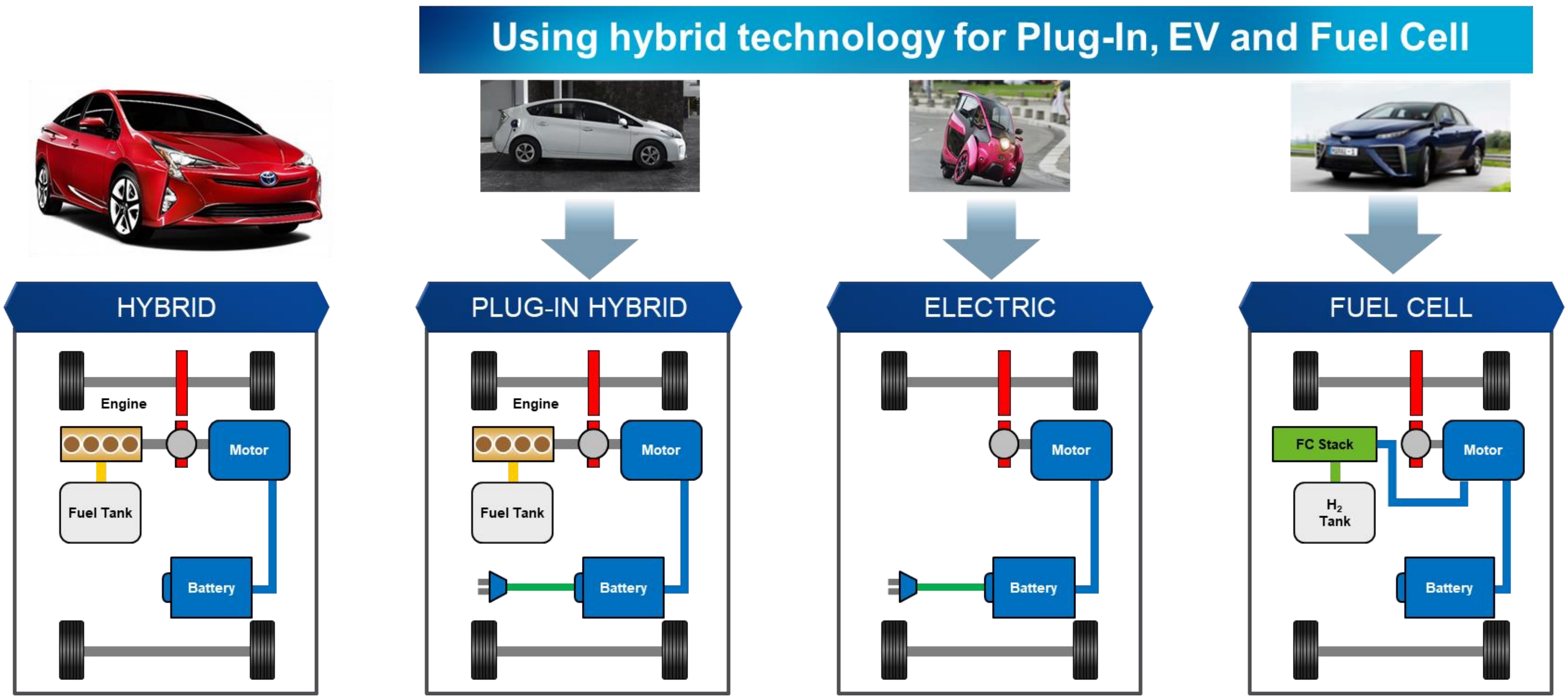


Source: Toyota



- Plug-in hybrid:
  - The energy consumed is either produced on board and by plugging-in on the grid.
  - Access to renewable energy sources
  - Range is prolongated , higher performance and low emissions
  - Energy consumption is expressed in: l/100km + kWh/100km

A FAMILY OF ELECTRIC AND HYBRID VEHICLES



HEV Architectures

Hybrid powertrains

- Hybrid electric vehicles combine two different kinds of energy storages: electricity and chemical

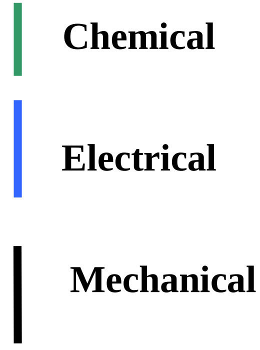
- Allows to take benefit of electric car advantages while keeping the advantages of internal combustion engines (range, easiness of refueling, etc.)

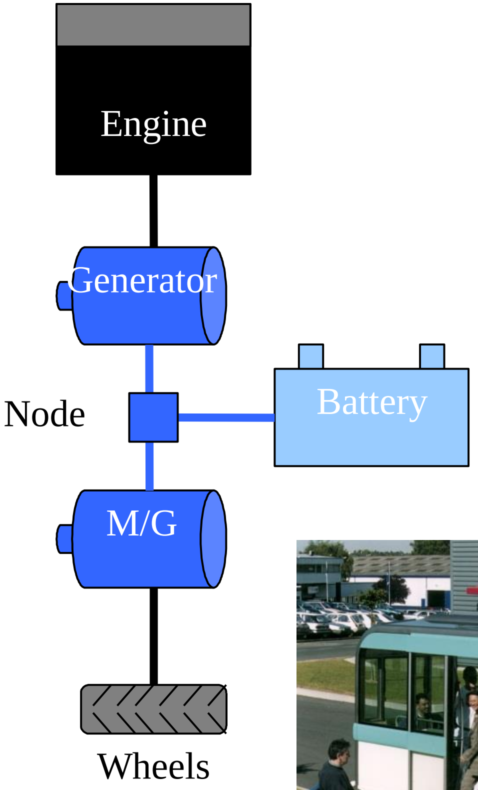
- Architectures:
  - Two basic architectures: series or parallel
  - Complex architectures

- Commercial success is beginning (e.g. Toyota Prius II, Honda Insight, etc.)

Series Hybrid Electric Vehicle

- Hybrid rate (%) : $T_s = P_{APU} / P_e$, with
  - P_{APU} : generator max power
  - P_e : electric motor max power
- ZEV (km) possible over some range
- Battery charging
  - Regenerative braking (motor ➔ generator)
  - Generator only : charge sustaining
  - Dual fuel with electric net : charge depleting / plug in hybrids
- Can be extended to fuel cell as prime mover



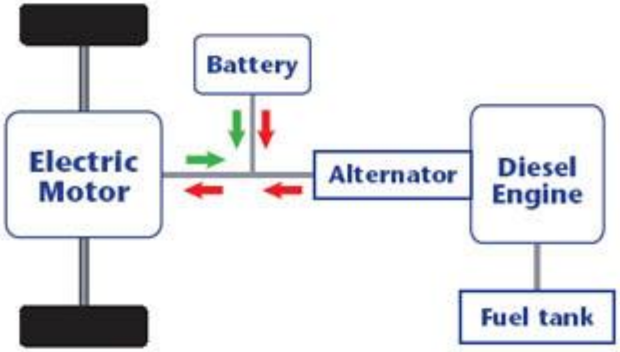


Gruau MicroBus

Series Hybrid Electric Vehicle

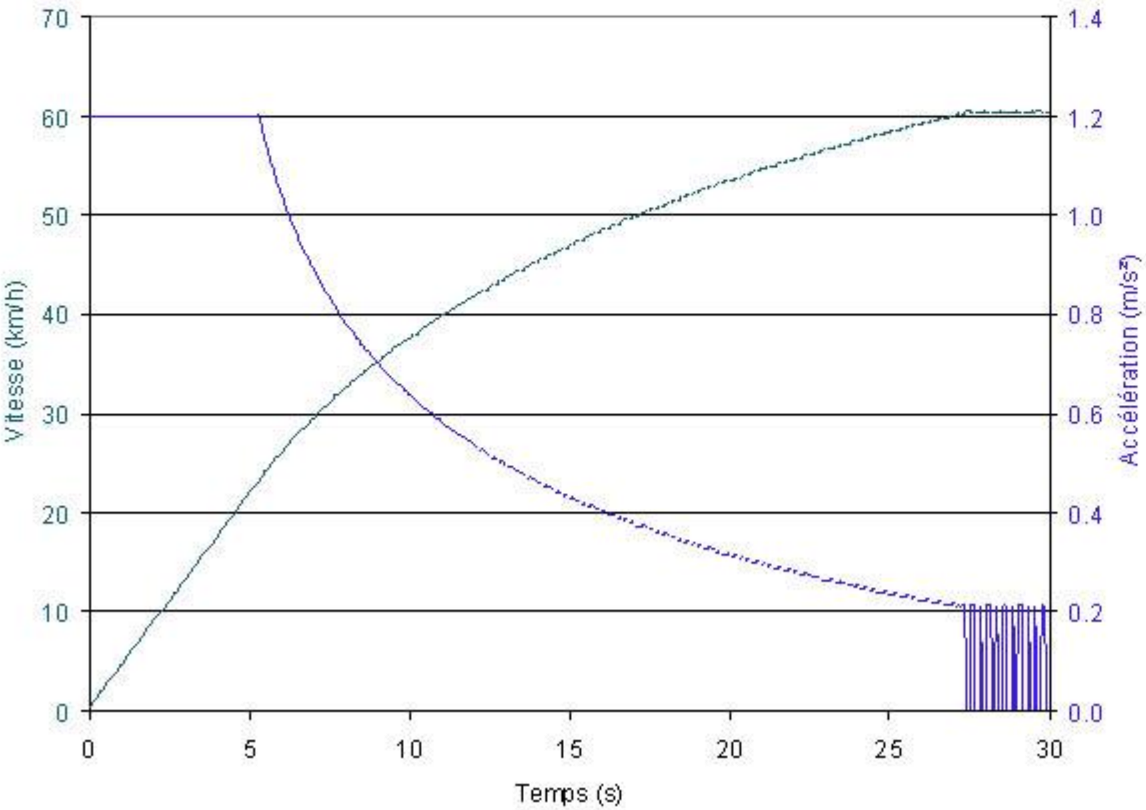
- The electric motor is the only one to be connected to the wheels. The ICE is used solely to spin a generator and to supply electricity.
- In urban situation, the batteries allow driving in pure electric mode (zero emission)
- On intercity driving, ICE is used intensively to provide the electrical energy to the batteries and the motor.
  - Efficiency is penalized by the product of all the component efficiencies!
- The hybridization rate of series : $T_s = P_{th}/P_{el}$
  (generally in the range of 40 to 80%, so come to downsizing)
- Possible extension to fuel cells as prime mover

Series Hybrid Electric Vehicle



- Electric motor: Induction motor
  - max 48 kW
  - 57 kg
  - liquid cooled
- Batteries: Ni-Cd batteries
  - 200 V; 250 A
  - 50 kW; 21.6 kW.h
  - liquid cooled; 422 kg
- Alternator: Permanent magnets synchronous
  - Max 26 kW
- ICE: turboDiesel 900 cm^3 engine
  - direct injection
  - catalysator
  - EGR

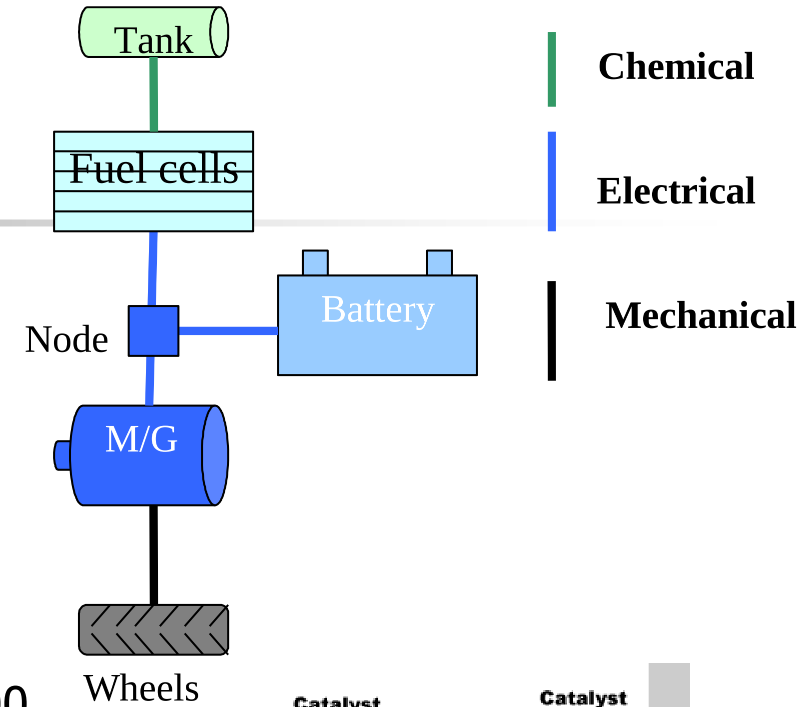
Series Hybrid Electric Vehicle



Performances:

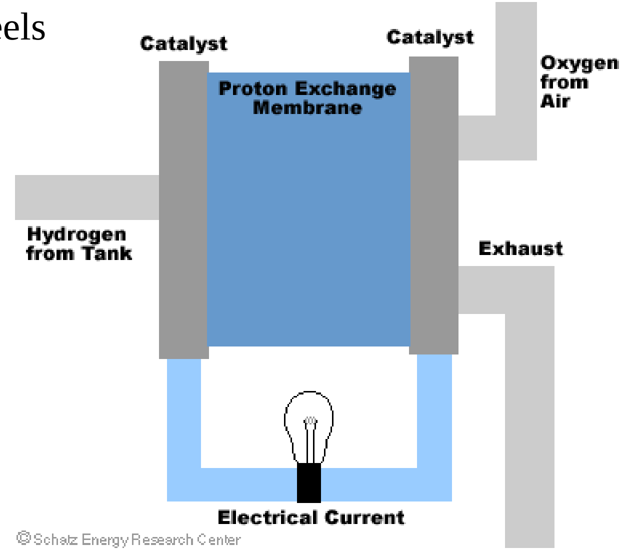
- 33%-cut in total CO2 emissions
- Euro 3 emissions compliant
- Over 25 km in electric mode
- Unlimited range in hybrid mode

Fuel Cell Powered Cars



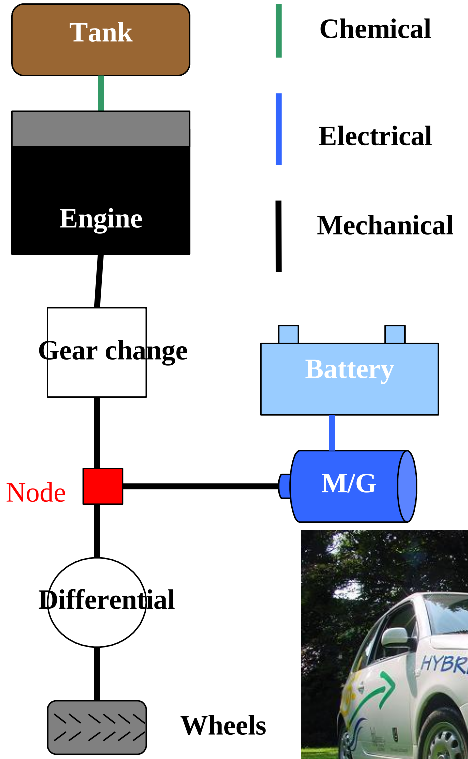
- Special case of series hybrid architecture
- Exhaust : H_2O ⇨ full ZEV
- Silent operation
- H_2 or dual fuel (electricity/H_2)
  - H_2 production, supply ?
  - H_2 storage ⇨ range limitation ~ 500 to 600 km

Toyota Mirai



Parallel Hybrid Electric Vehicle

- Hybrid rate (%) : $T_p = P_e / (P_e + P_t)$, with
  - P_t : engine max power
  - P_e : electric motor max power
  - Micro < mild < full
- ZEV mode (km) is possible in urban areas
- To deal with peak power demand, the simultaneous operation of both engines is possible (parallel mode)
- Charge sustaining / depleting

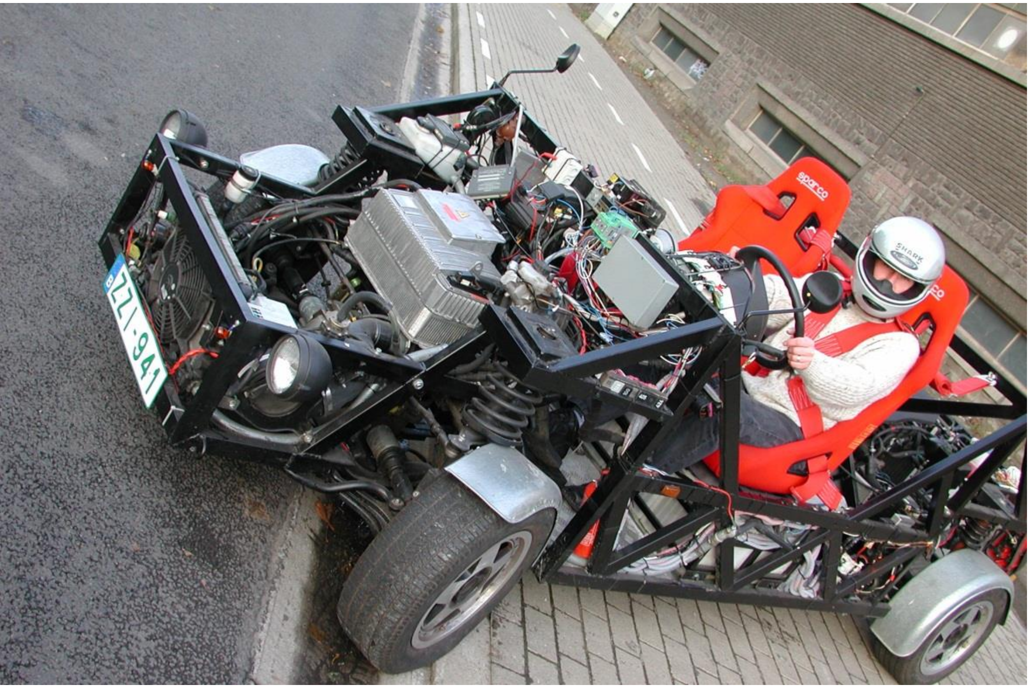


VW Lupo hybrid
Green Propulsion
60 g CO_2/km

Parallel Hybrid Electric Vehicle

- The parallel hybrid vehicle is equipped with a double propulsion system thermal + electrical powertrain both connected to the wheels
- The vehicle keeps its usual performance: autonomy, max & cruise speed…
- The electric motors may have a sufficient power to propel the car alone in pure electric mode (full hybrid) or only in combination with the IC engine (motor assist)
- For responding to peak power demand, both thermal and electrical motors work together
- There are various variants to the base configurations
- Hybridizing rate of parallel hybrid: $T_p = P_{el} / (P_{el} + P_{th})$

Parallel Hybrid Electric Vehicle



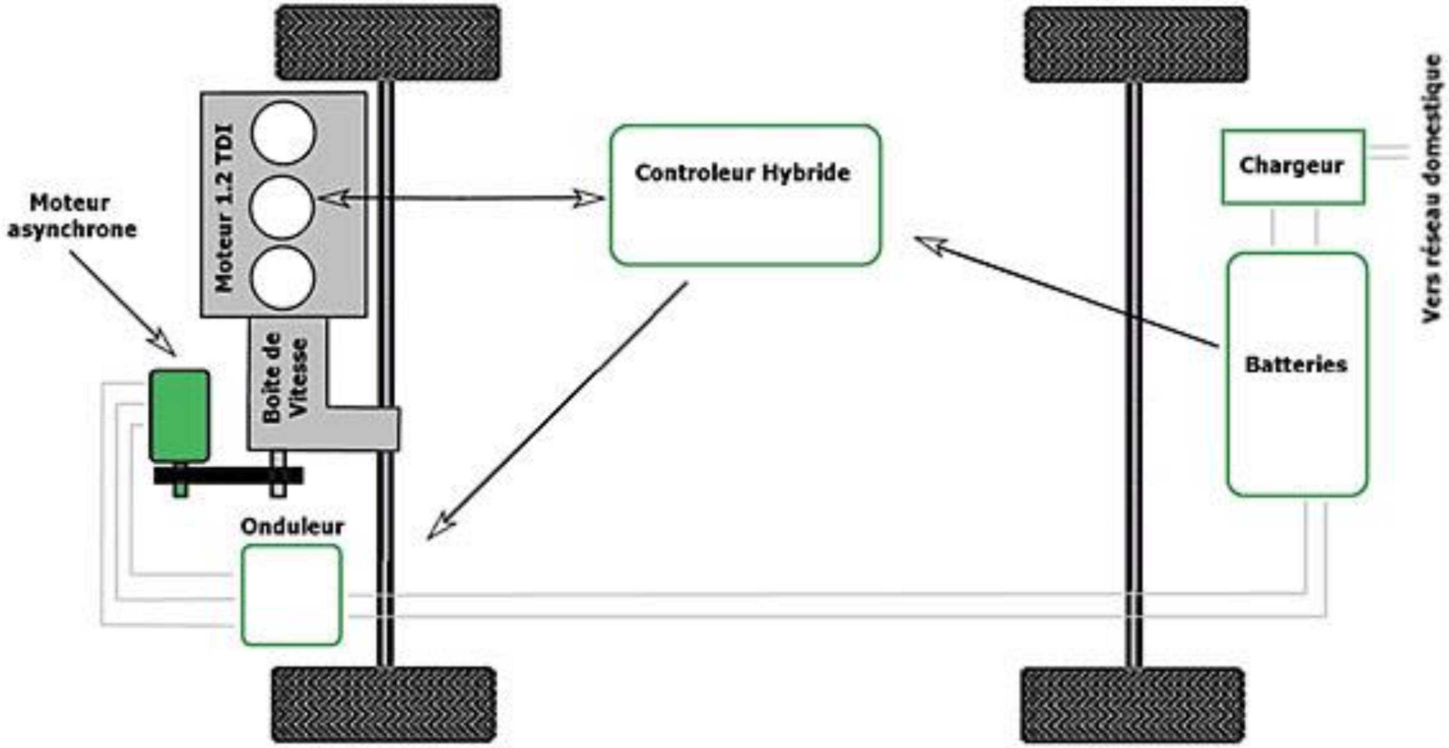
- Prototype of parallel hybrid vehicle built at ULg in 1999.
- The front drivetrain is propelled by a DC motor of 20 kW and Ni-Cd batteries.
- The rear drivetrain is driven by a small 1.4 3cylinder TDI from VW.
- Coupling of electric and internal combustion powertrain is realize through the road.

Parallel Hybrid Electric Vehicle

Lupo hybrid: BTD malmedy, Green Propulsion, Université de Liège

- Na NiCl batteries
  - 278 V; 32 A.h
  - 16 kW; 108 kg
  - 300 °C
- 14 kW induction motor
- 3 operating modes :
  - Pure electric
  - Ideal hybrid
  - Diesel Charge
- Grid-charging allowed

Parallel Hybrid Electric Vehicle

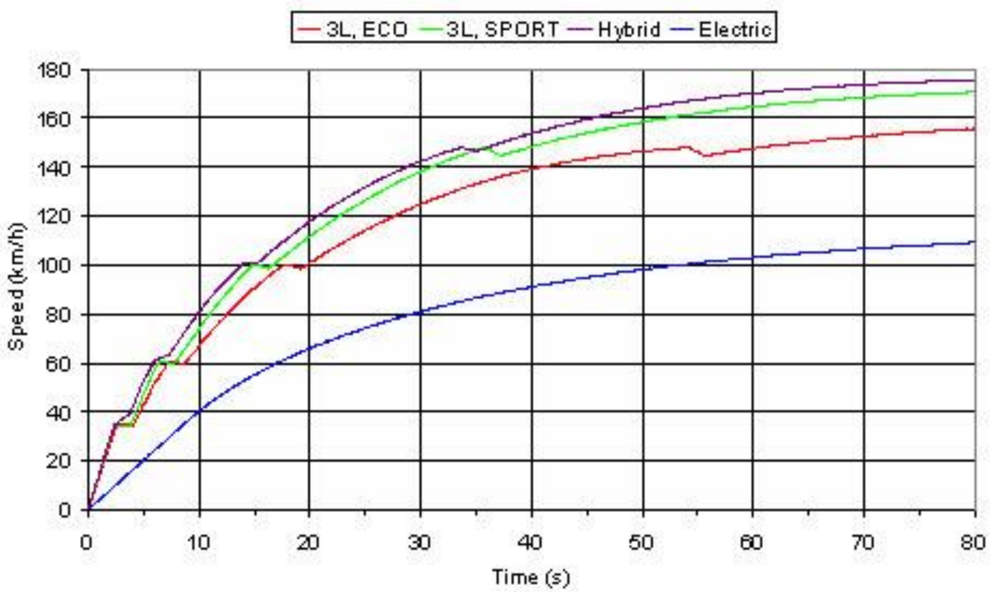


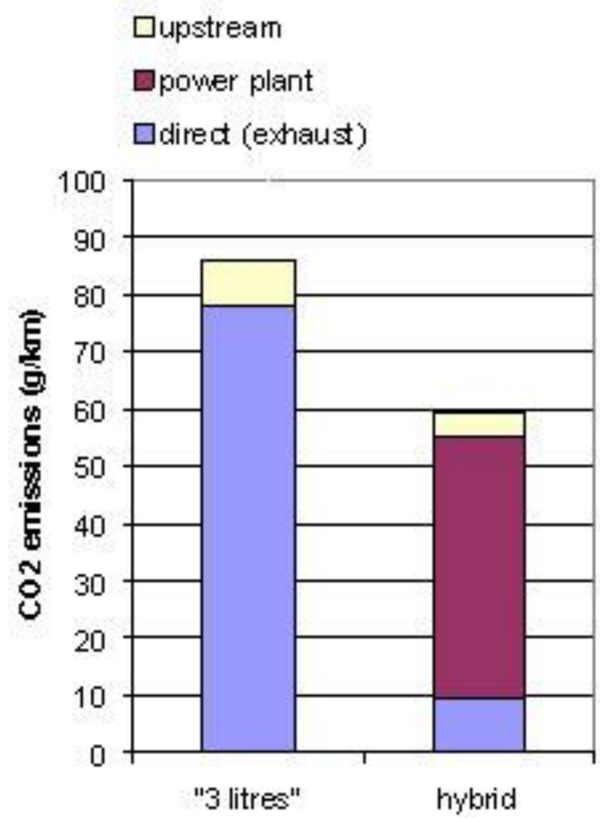
Lupo hybrid: BTD malmedy, Green Propulsion, Université de Liège

Parallel Hybrid Electric Vehicle

Performances:

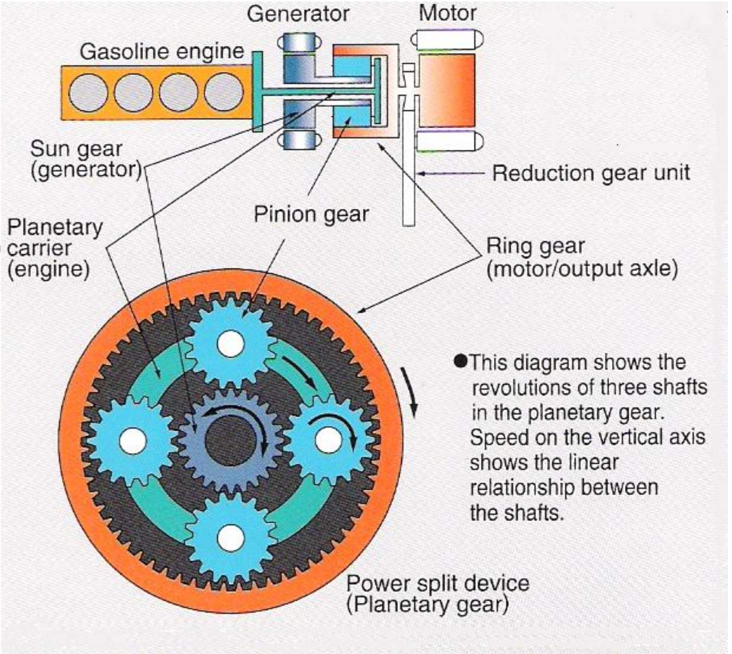
- Emissions record : 60 gr CO_2 /km !
- More than 40 km in electric mode
- Unlimited range in hybrid mode
- Improved performances





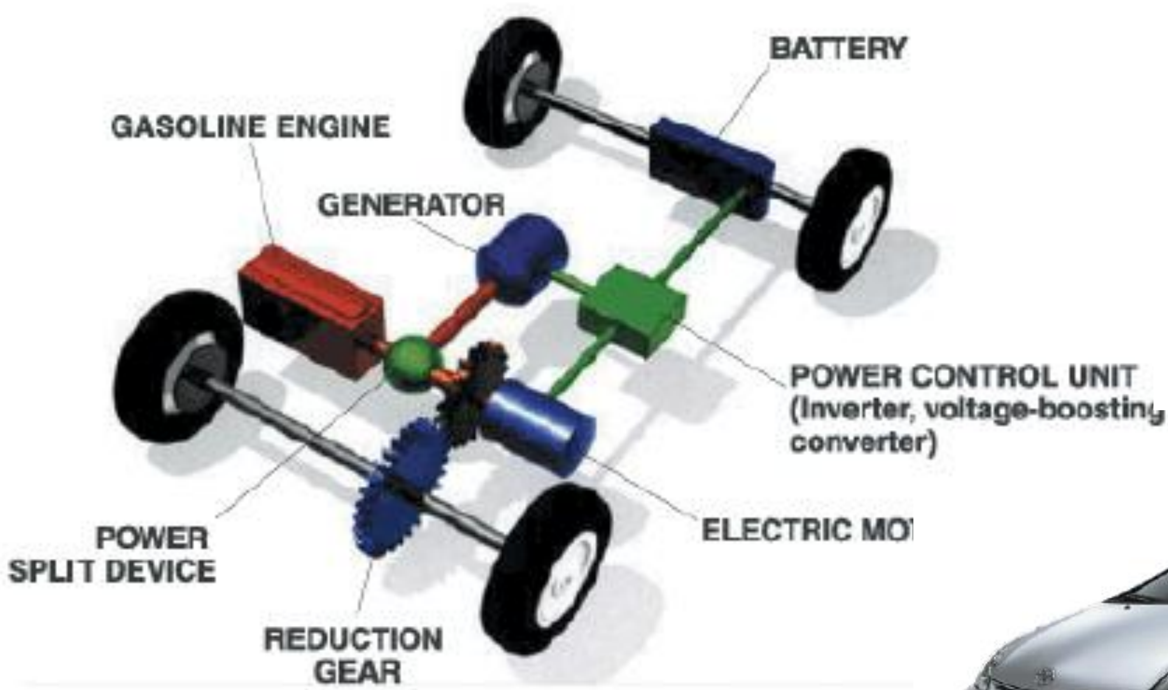
Complex Hybrid Electric Vehicle

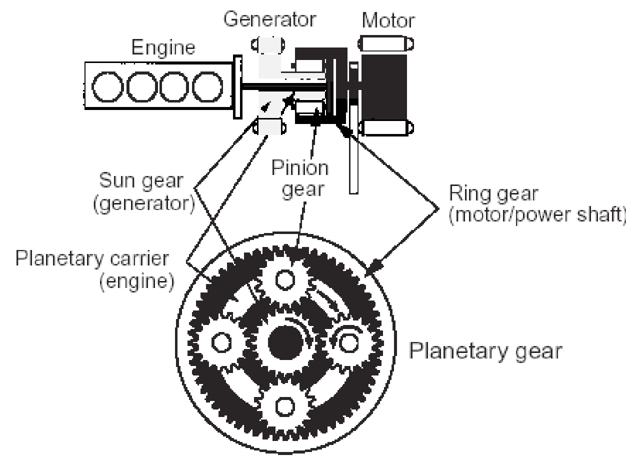
- Versus series hybrid
  - Smaller motor and generator
  - Higher transmission efficiency
- Versus parallel hybrid
  - Controlled engine speed
  - Smooth transitions
- Versus other combined
  - Planetary gear requested
  - No mechanical lock @ high load



Toyota Prius II

Complex Hybrid Electric Vehicle

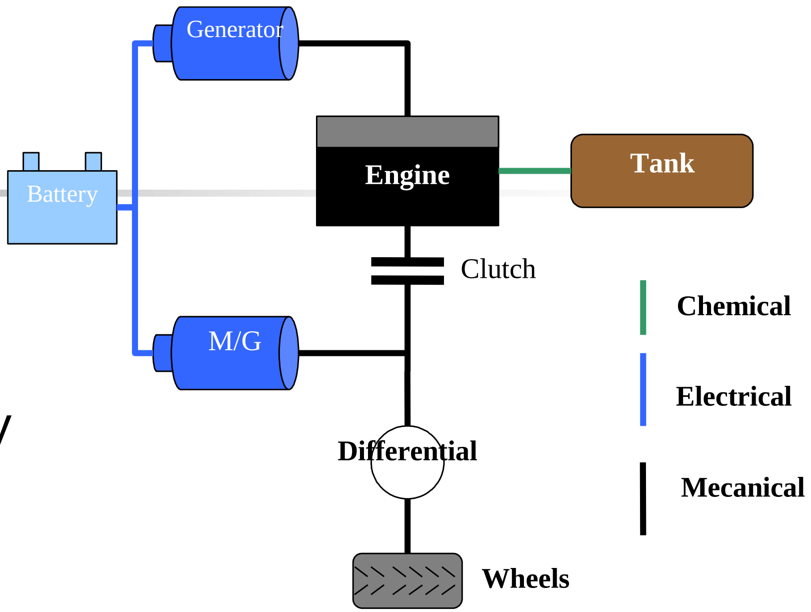




Toyota Prius II

Combined Hybrid Electric Vehicle

- Versus series hybrid
  - Smaller motor and generator
  - Higher transmission efficiency
- Versus parallel hybrid
  - No gearbox requested
  - Smooth transitions
- Versus other combined
  - Uncontrolled engine speed when clutch is closed
  - Mechanical lock at high load/speed



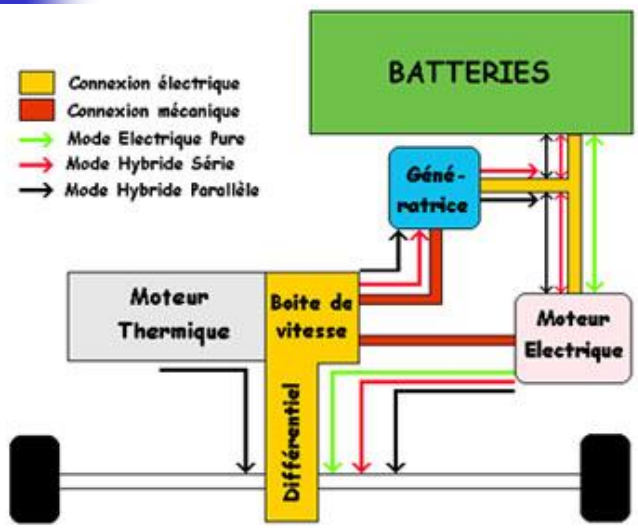
Renault Kangoo Hybrid
Green Propulsion

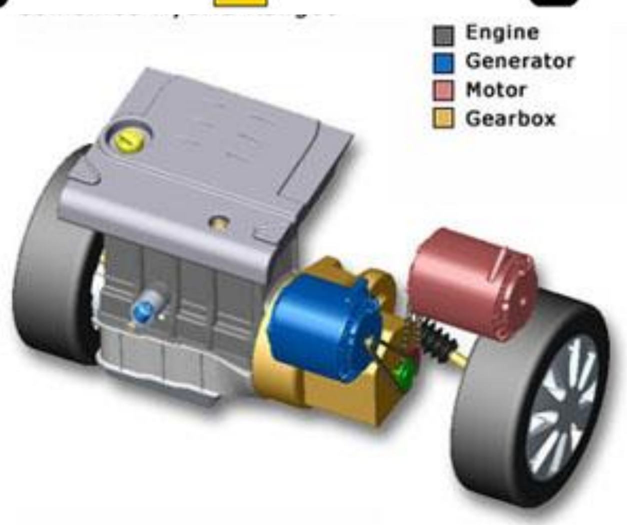
Combined Hybrid Electric Vehicle

The project:

- City center parcel delivery
- Transformation of a production vehicle
- Ultra low CO_2 emissions
- The technology of tomorrow, available today

Combined Hybrid Electric Vehicle

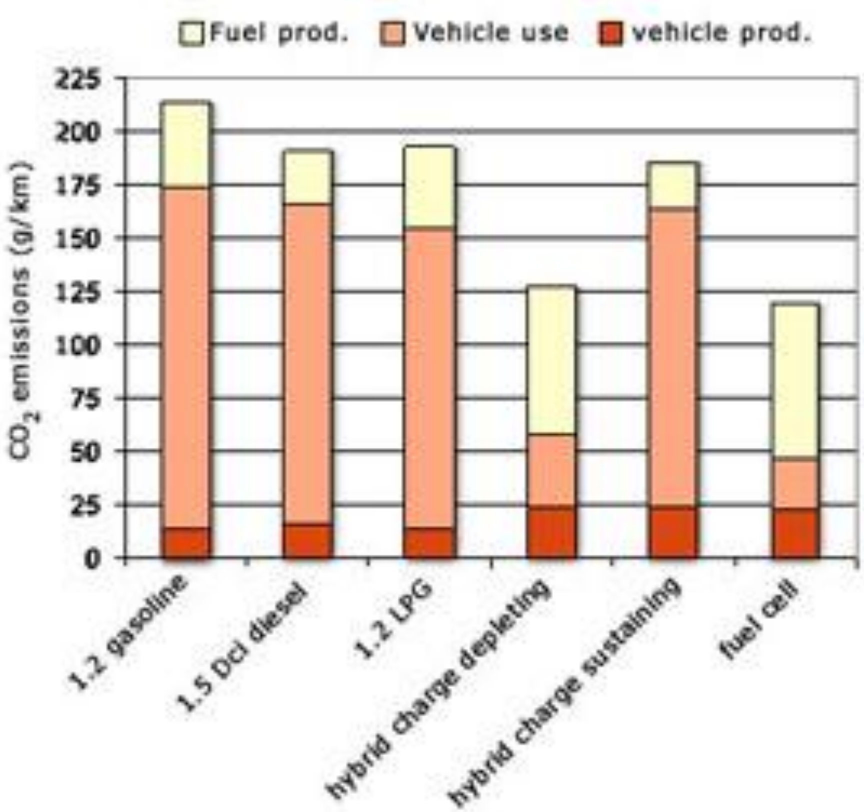




Combined series/parallel hybrid

- Li-ions batteries
  - 260 V; 200 A
  - 50 kW; 9,4 kW.h
  - liquid cooled; 100 kg
- Induction motor 48 kW
- Asynchronous generator 12 kW

Combined Hybrid Electric Vehicle

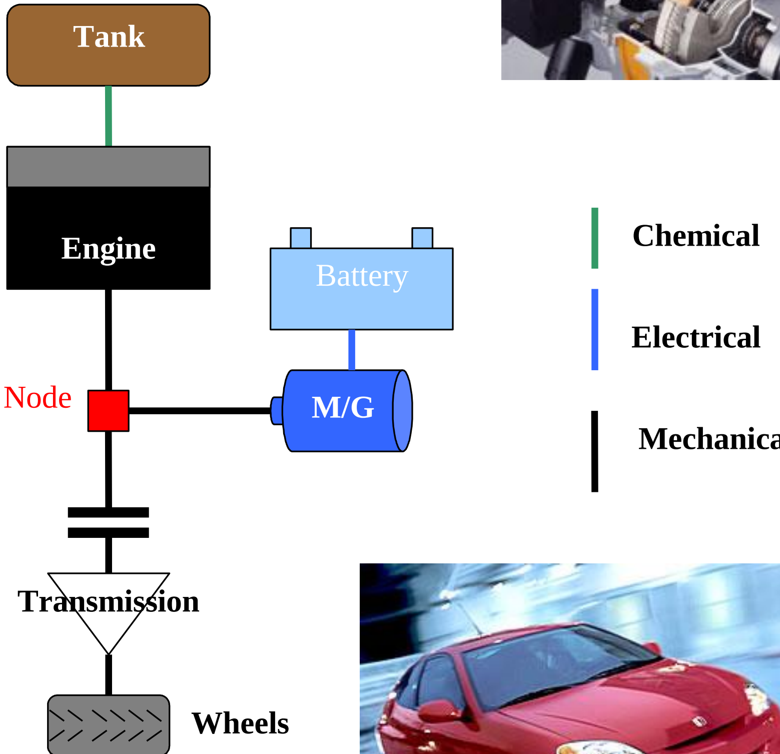


Performances:

- 33%-cut in total CO_2 emissions (vehicle from cradle to grave)
- More than 40 km in electric mode
- Unlimited range in hybrid mode
- Improved performances

Parallel Mild Hybrid Electric Vehicle

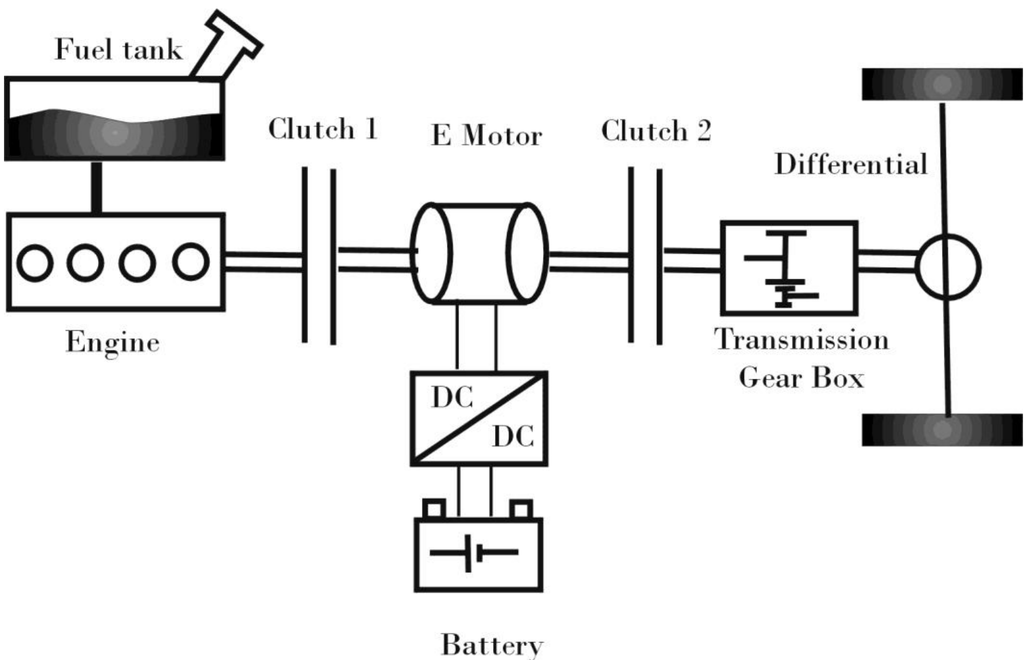
- Mild architecture
  - Small electric machines
  - Stop & start function
  - Small capacity regenerative braking
  - Additional power to prime mover
- Replaces flywheel, starter and alternator
- NO pure electric mode



Honda Insight

Mild Hybrid Electric Vehicle

- Mild hybrids sound to be a promising way for many European Car Manufacturers
- Generally the mild hybrid is built on a parallel configuration with a single shaft.



Mild Hybrid Electric Vehicle

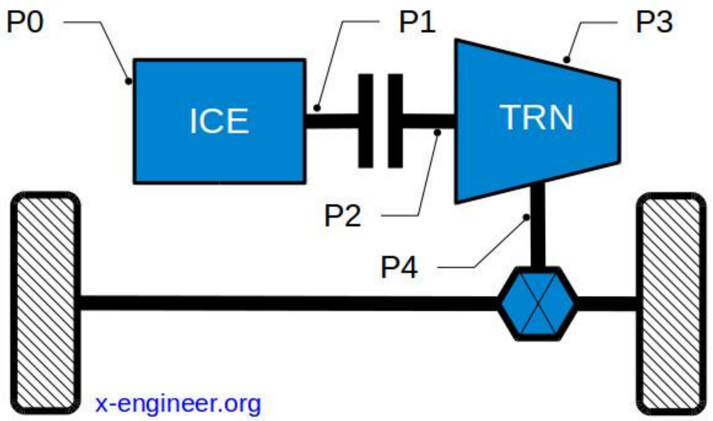
- In mild hybrid, a clutch (1) is inserted between the engine and the electric machine in order to disconnect the IC engine from the transmission line to use the car in pure electric mode (full hybrid mode) if it is possible
- Several solutions to connect the electric machine to the engine shaft (crankshaft) :
  - Belt link
  - Direct meshing using a gear box
  - Mounting directly the electric machine onto the flywheel and the crankshaft
- The later (direct mounting onto the flywheel) is often retained for mild hybrid

Mild Hybrid Electric Vehicle

- Mild hybrid uses generally small electric machines with power range from 5 to 25 kW.
- Main purpose of IMA: assisting the engine by providing an extra torque to the transmission when strong accelerations.
- The motor assist is able to reduce the peak power demands from the engine. Thus the engine can be downsized to provide a sufficient power for normal operating conditions
- Integrating the electrical machine and the engine leads to a compact solution.
- The integrated motor assist also allows using a usual gear box and a clutch.

Mild Hybrid Electric Vehicle architecture

- The electric machine can be positioned, relative to the other powertrain components, in five major points:
  - P0 The electric machine is connected with the internal combustion engine through a **belt**, on the front-end accessory drive (FEAD)
  - P1 The electric machine is connected **directly** with the crankshaft of the internal combustion engine

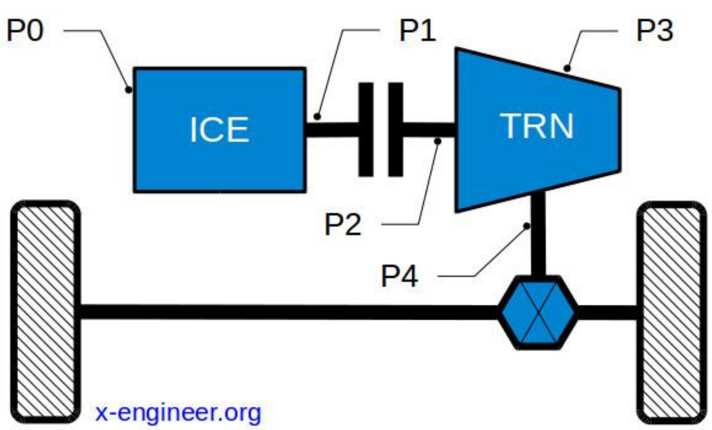


- P0 and P1 architectures do not allow the mechanical disconnection of the electric machine from the engine.

Mild Hybrid Electric Vehicle architecture

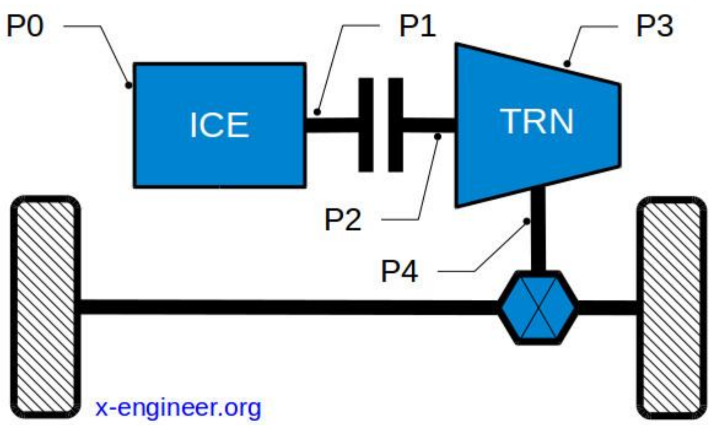
- P2: The electric machine is side-attached (through a **belt**) or **integrated** between the internal combustion engine and the transmission; the electric machine is decoupled from the ICE and it has the same speed of the ICE (or a multiple of it)

- P3: The electric machine is connected through a **gear mesh** with the transmission; the electric machine is decoupled from the ICE and its speed is a multiple of the wheel speed



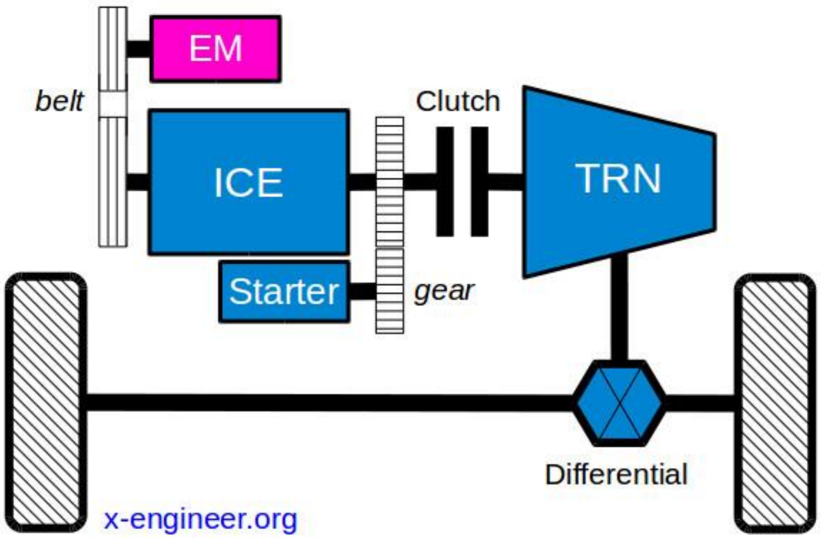
Mild Hybrid Electric Vehicle architecture

- P4: The electric machine is connected through a **gear mesh** on the rear axle of the vehicle; the electric machine is decoupled form the ICE and it's located in the rear axle drive or in the wheel's hub

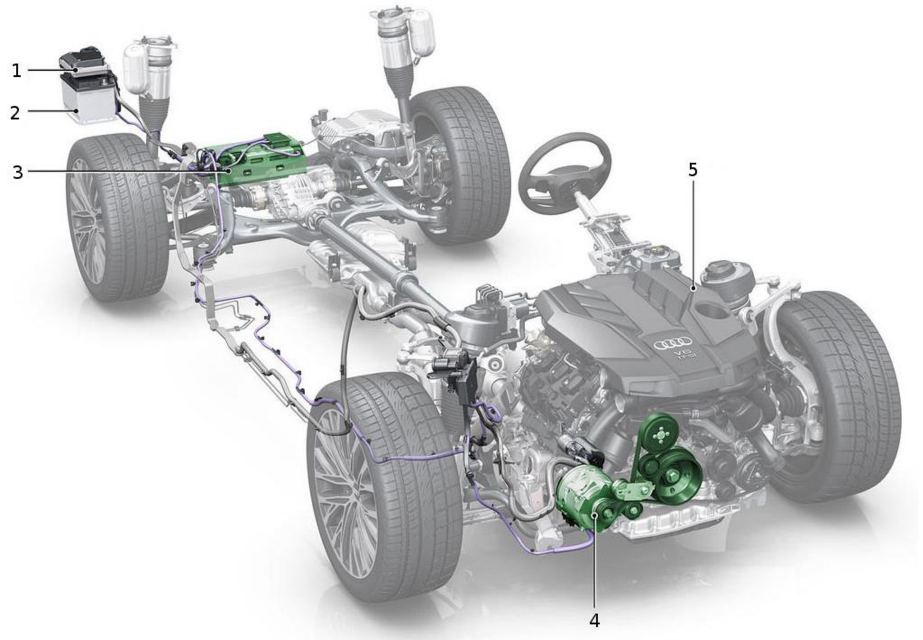


- P2, P3 or P4 configurations disconnects the electric machine from the engine through a **clutch**..

Mild Hybrid Electric Vehicle

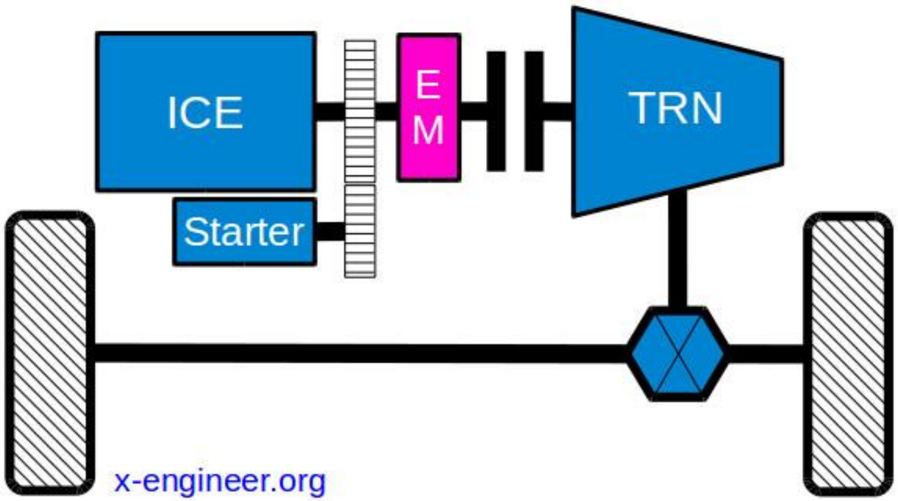


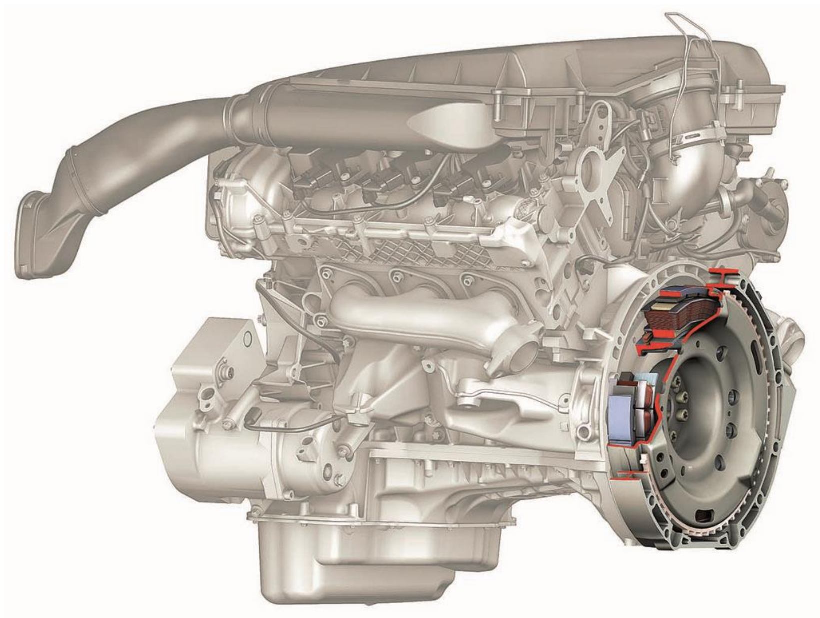
Belt Starter Generator Architecture (P0)



Ex: Audi A8 48V MHEV

Mild Hybrid Electric Vehicle

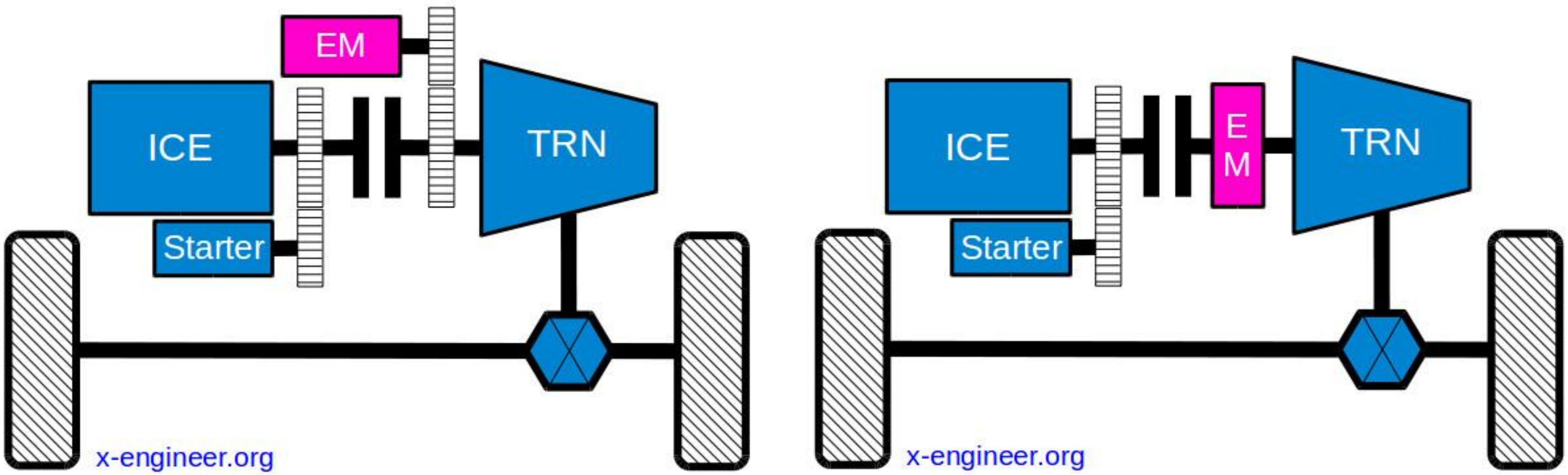




Crankshaft mounted electric machine (P1)

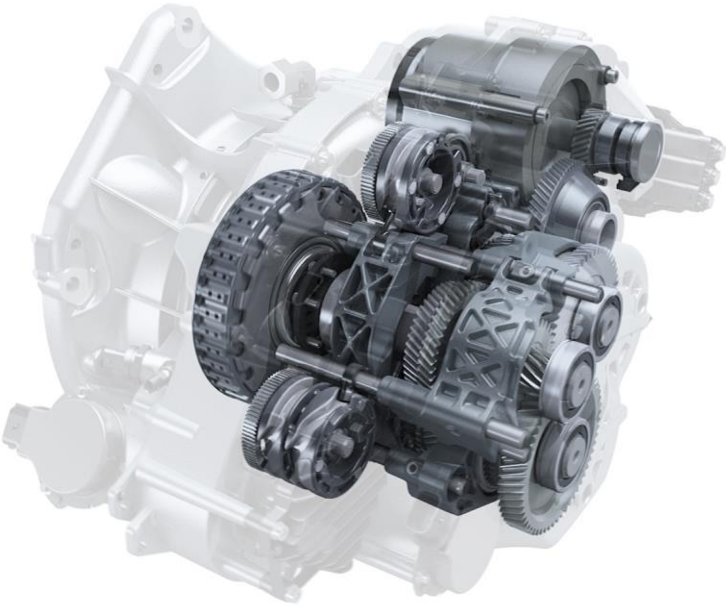
Ex: Honda IMA or Mercedes S400

Mild Hybrid Electric Vehicle



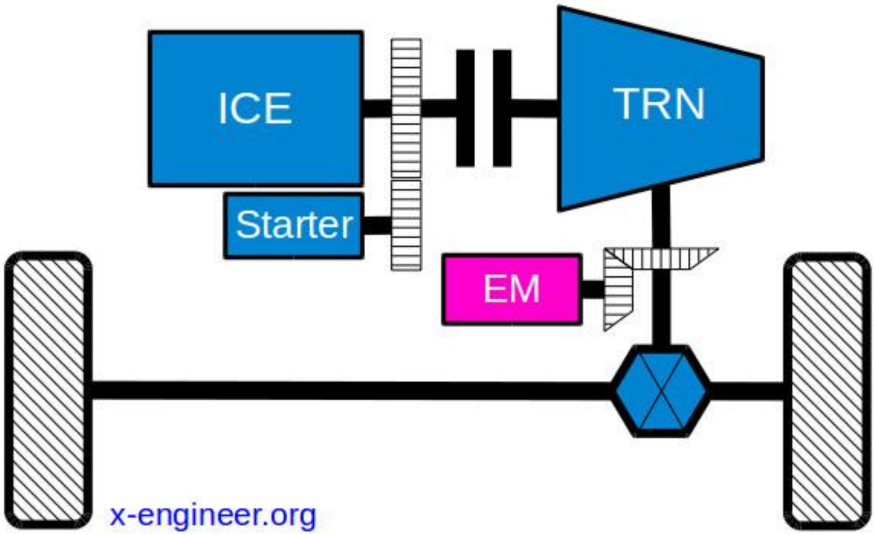
Driveline side electric machine MHEV architectures (P2)
Side EM (left) and integrated EM (right)

Mild Hybrid Electric Vehicle



Driveline side electric machine MHEV architectures (P2)
Ex: Getrag Hybrid Double Clutch Transmission

Mild Hybrid Electric Vehicle



Driveline side electric machine MHEV architectures (P3)

Ex: Valeo 48V Electric Rear Axle Drive (ERAD)

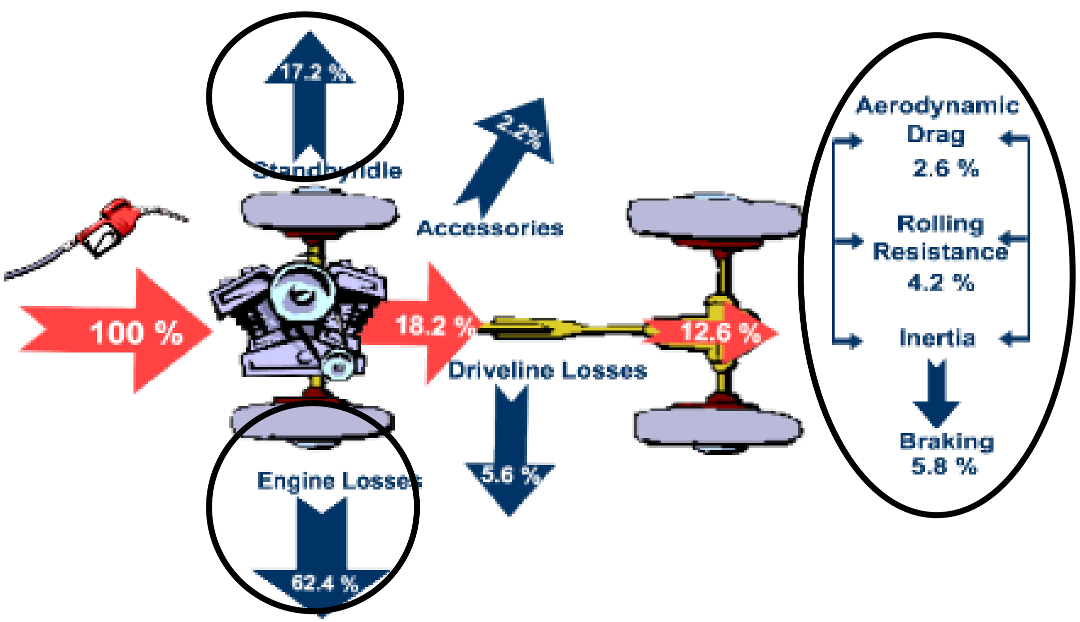
Mild Hybrid Electric Vehicle

- By preserving usual transmission systems, mild hybrids can carry out high efficiency
- They also achieve low production costs.
- However they provide some of the advantages of full hybrids:
  - Regenerative braking (up to a certain limit because of small size of electric motor and limited capacity of batteries)
  - Stop and start system
  - Leveling peak power by assisting the engine during acceleration, hill climbing, etc.
- The major drawback of this solution is the fact that all components are connected to a single shaft and that the electric machine and the engine must always work at the same rotation speed, which reduces strongly the flexibility of the system

HEV strategies to save energy and emissions

HEV energy saving strategies

- In order to reduce the fuel consumption and emissions, the hybrid electric vehicles use several mechanisms
  - Improve the engine performances
  - Reduce the losses
  - Optimize energy management



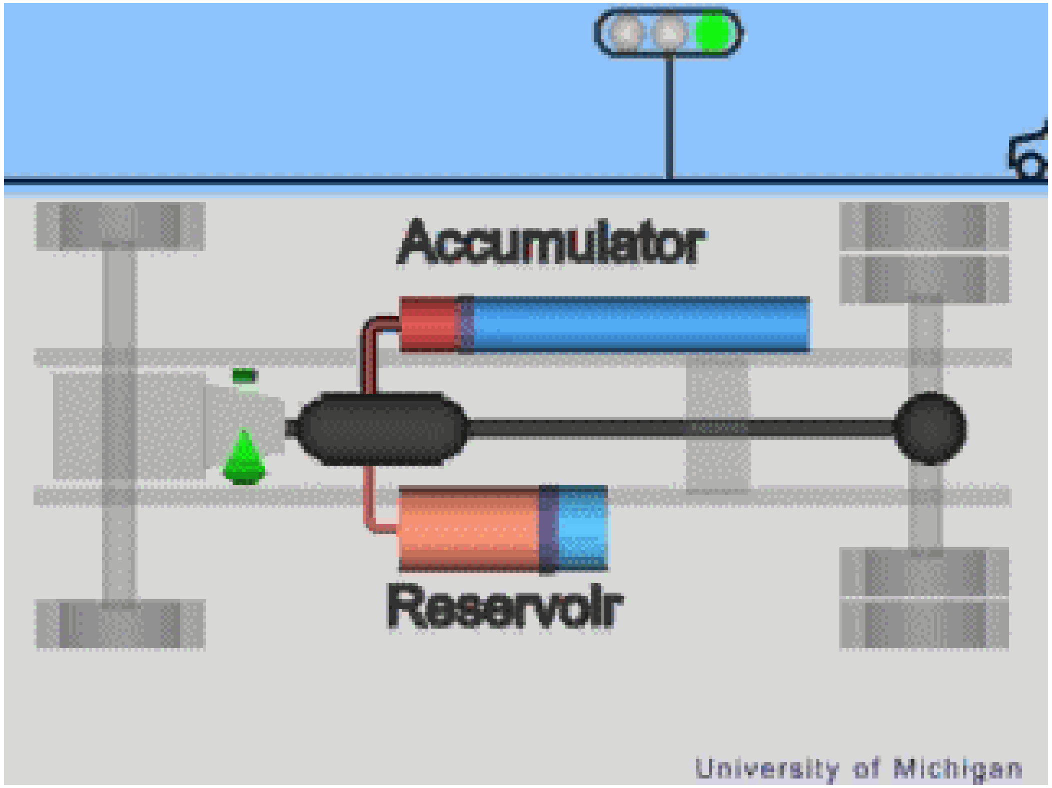
HEV energy saving strategies

- Improving engine performance
  - Reducing the size of the Internal Combustion Engine (downsizing)
  - Operate the ICE in its most efficient working conditions
  - Stop the engine when idling
  - Substitute petrol by fuel with low CO_2 emissions
  - Implement energy recovery during braking
- Reduction of losses
  - Reduce the vehicle mass
  - Reduce the aerodynamic drag
  - Use low rolling resistance tires
- Optimize the energy management
  - Automate some of driving decisions such as gear box management

Energy recovery during braking

- Braking is one of the most important energy loss
  - The car kinetic energy is lost by heating the brakes
- Use reversibility of electric/hydraulic machines and energy storage capabilities to recover at least part of this energy
- Efficiency of energy recovery during braking depends on:
  - The more or less important capacity of the batteries, the efficiency of the converters
  - The topology of the energy recovery system: mostly dependent on the braking system
  - The number of driven wheels in the transmission: most of the time only one axle is driven which restricts braking for safety reasons

Energy recovery during braking



Principle of energy recovery during braking with a hydraulic system

Energy recovery during braking

- Energy recovery capability depends on:
  - The size of the alternator / generator of the electric machine (~10 kW)
  - The energy capacity of the battery, that is sensitive to charge current for instance
  - The max power of the battery (function of the maximum admissible current)
- But also
  - Safety conditions for braking: stability of braking, 2- or 4-wheels braking?
- Practically, energy braking is activated during downhill for mild slopes. The mechanical brakes are still used when a guaranteed deceleration is required.

Energy recovery during braking

To understand the braking problem, one investigates the following situation. Car (m=1200 kg) braking from 60 km/h to 0 on a dry road (μ=0,8)

- Kinematics
$$v = -a\ t\ +\ v_0$$
- Dynamics
$$ma = F = \eta\ \mu\ m\ g$$
$$a = \eta\ \mu\ g = 7{,}8 m/s^2$$
- Stopping time
$$t_{stop} = v_0 / |a| = 2{,}12 s$$
- Dissipated energy:
$$\Delta E = \frac{1}{2} m v_0^2 - \frac{1}{2} m v_f^2 = 166{,}66 kJ$$

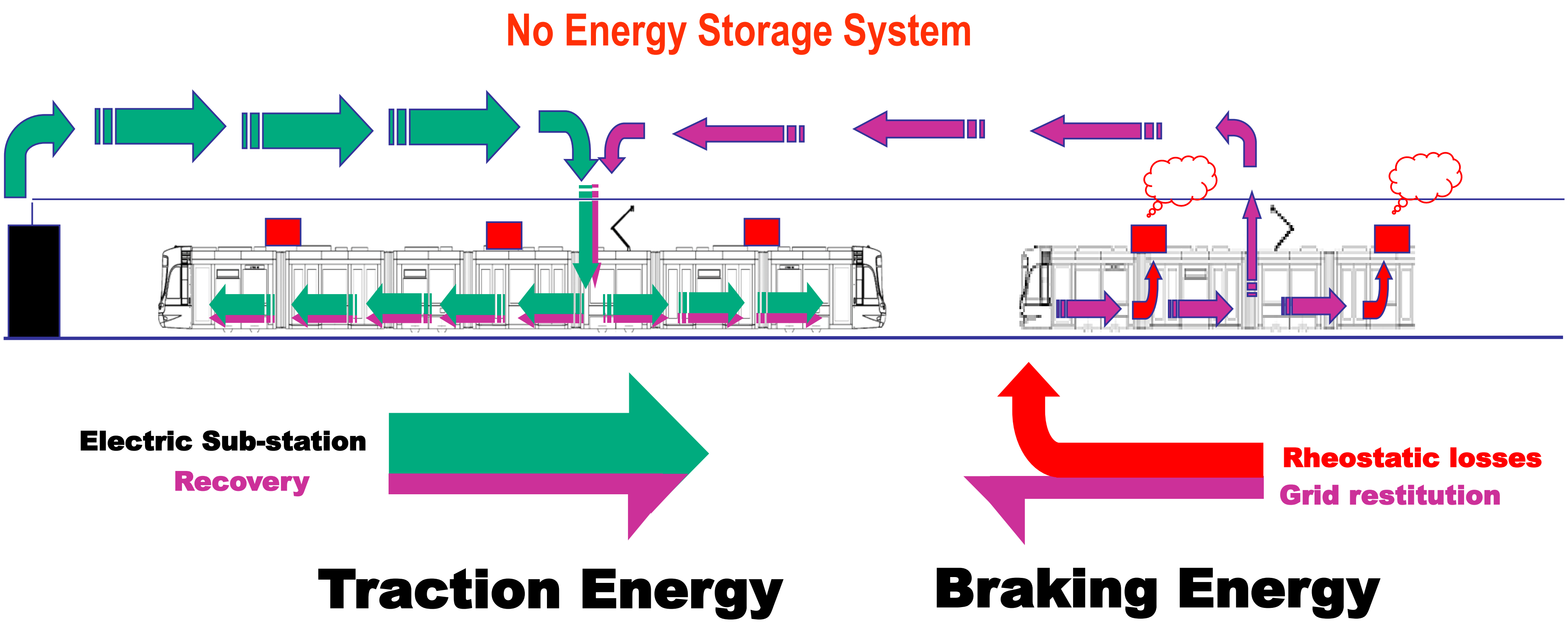
Energy recovery during braking

- Dissipated power:

$$P_{average} = \frac{\Delta E}{t_{stop}} = 78,480 kW$$

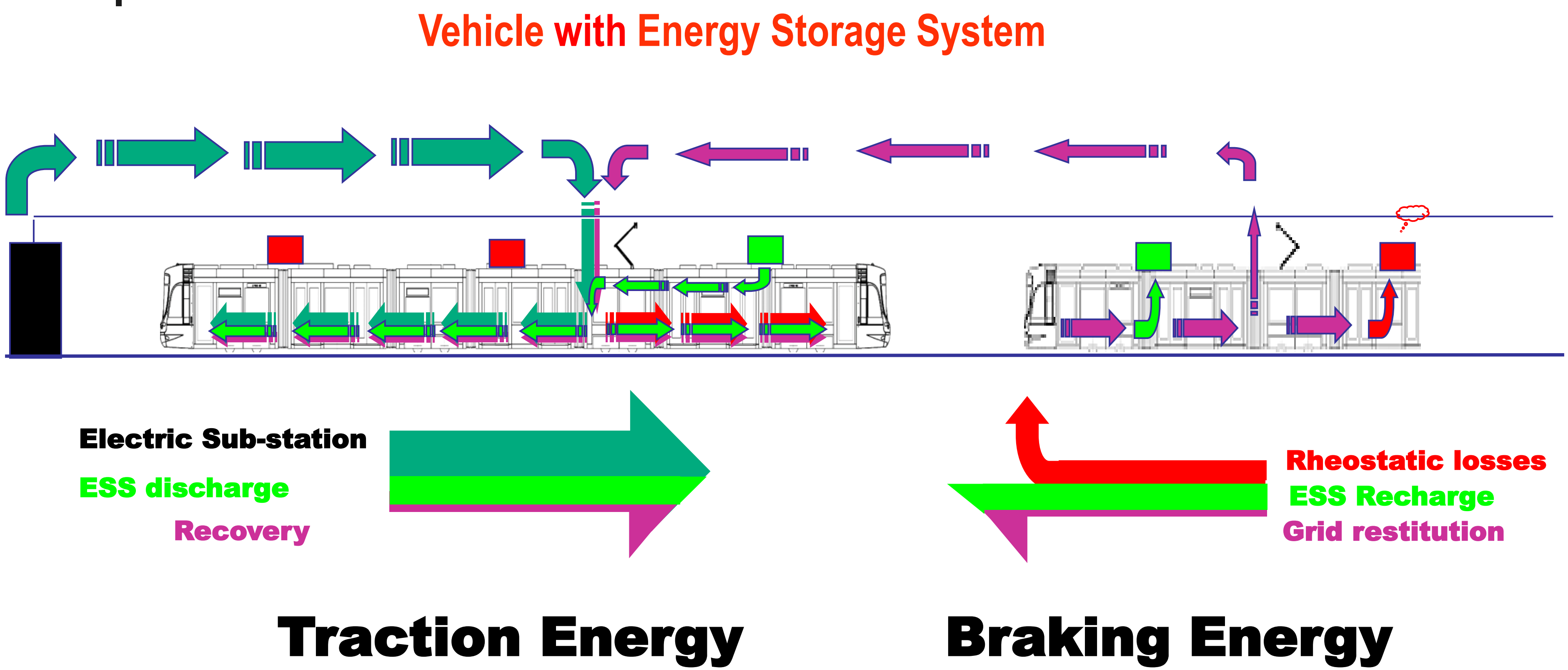
$$P_{\max} = \frac{2\Delta E}{t_{stop}} = 156,960 kW$$

Energy recovery during braking

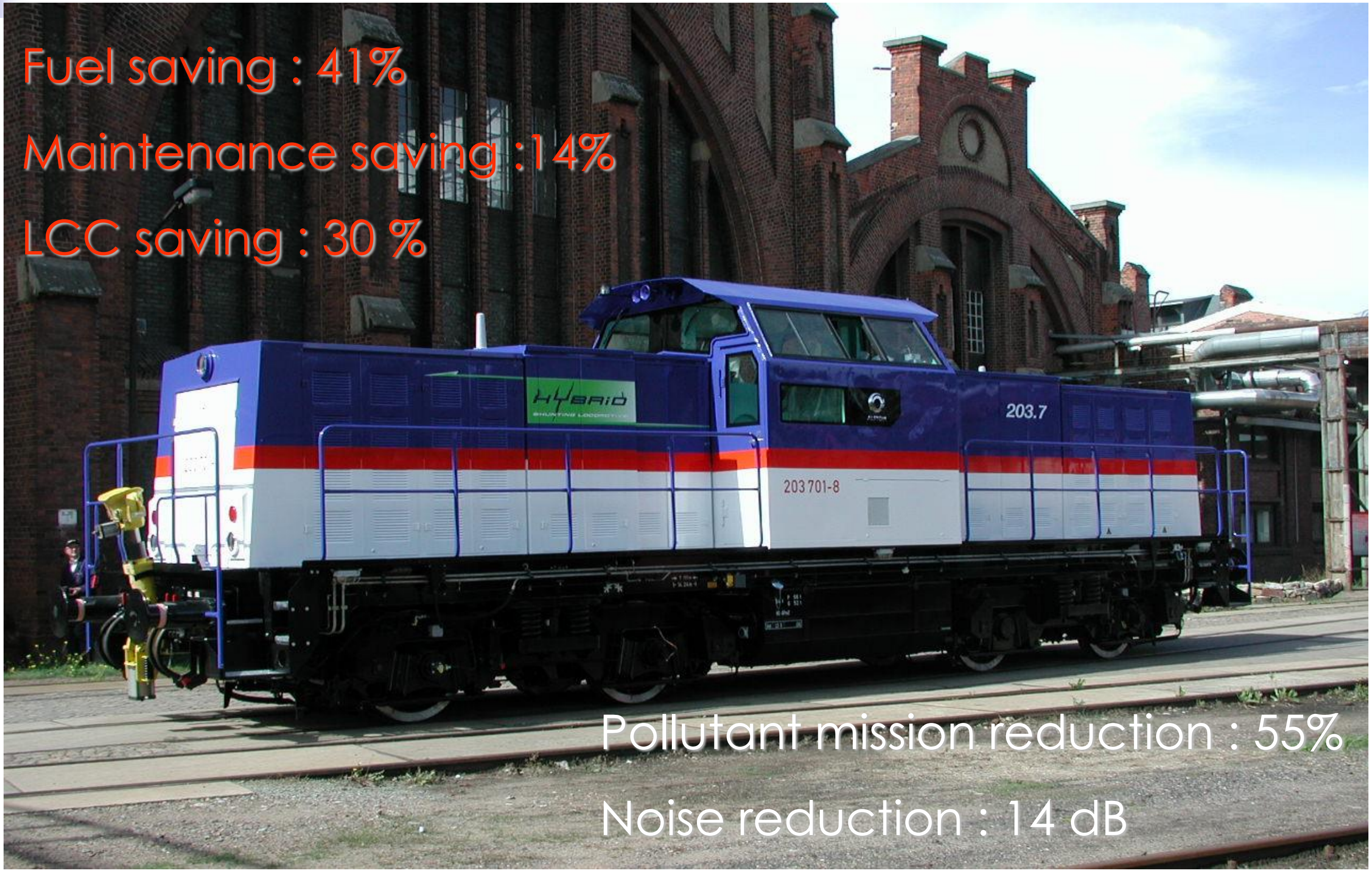


Headway (s)	240	420	600
Line receptivity	83%	72%	63%

Energy recovery during braking

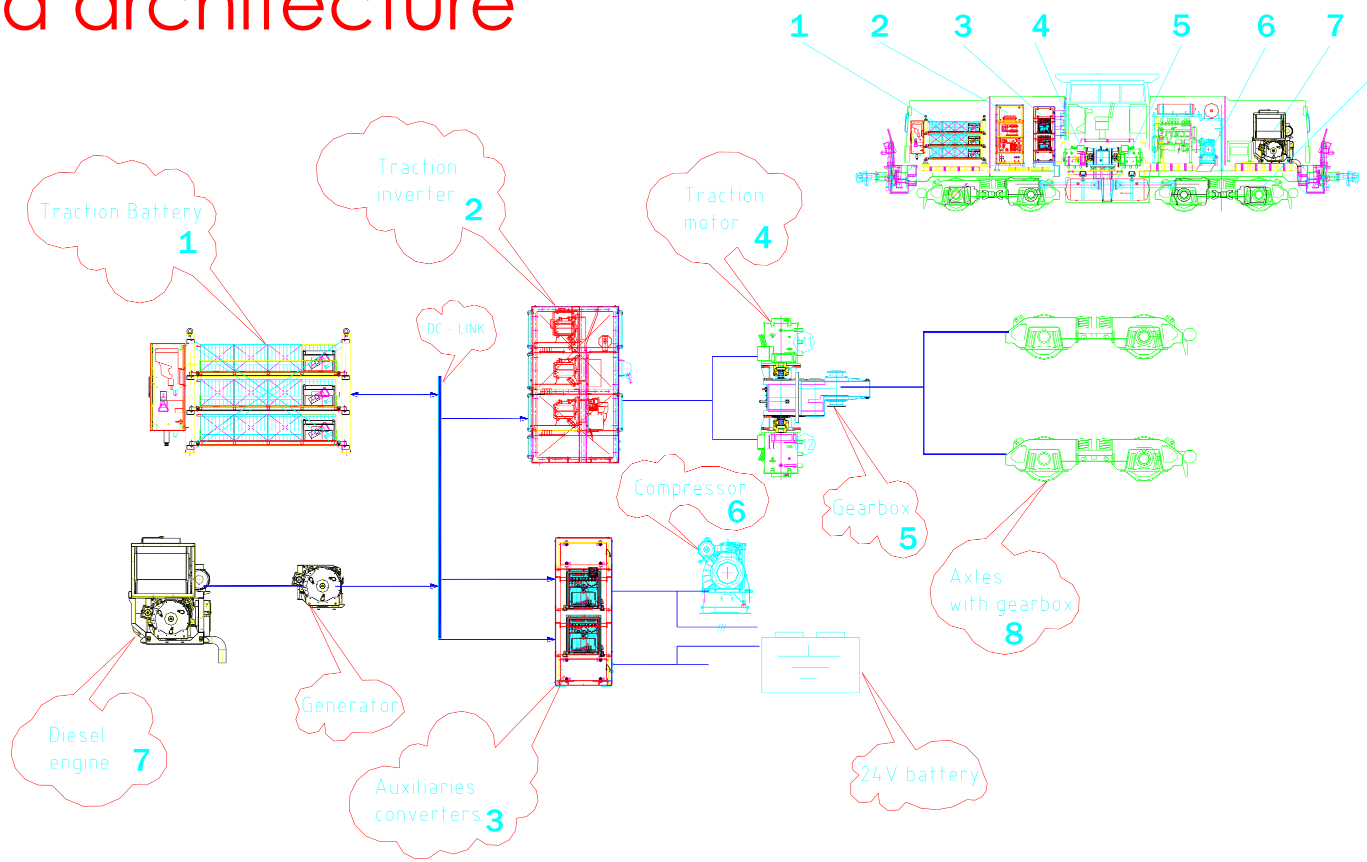


Hybrid locomotive : Low Environmental Impact Locos



Hybrid locomotive: Traction System

Hybrid architecture



Lightweight structures

- Using lightweight materials:
  - Aluminum
  - Magnesium alloys
  - Composite materials
- New and innovative manufacturing and forming processes
  - Tailored blanks
  - Hydro forming
  - Thixo forming…
- Optimizing shapes, geometries, topologies and materials

Advanced aerodynamics

- Reduction of drag forces has a great impact on fuel consumption on highway and peri urban driving
- Depends on
  - C_x: drag coefficient (C_x usually around 0,30-0,35 for modern cars)
  - S: frontal surface
- C_x depends on
  - The external shape: front design, rear design, floor
  - The wheels
  - The details
  - Internal aerodynamics

Drag source in road vehicles

DRAG COEFFICIENT COMPONENT	TYPICAL VALUE
Forebody	0.05
Afterbody	0.14
Underbody	0.06
Skin Friction	0.025
Total Body Drag	0.275
Wheels and wheel wells	0.09
Drip rails	0.01
Window recesses	0.01
External mirrors	0.01
Total Protuberance Drag	0.12
Cooling system	0.025
Total Internal Drag	0.025
Overall Total Drag	0.42[1]
VEHICLE OF THE 1980s	
Cars	0.30 - 0.35
Vans	0.33 - 0.35
Pickup trucks	0.42 - 0.46

[1] Based on cars of 1970s vintage.

Gillespie Fig 4.11

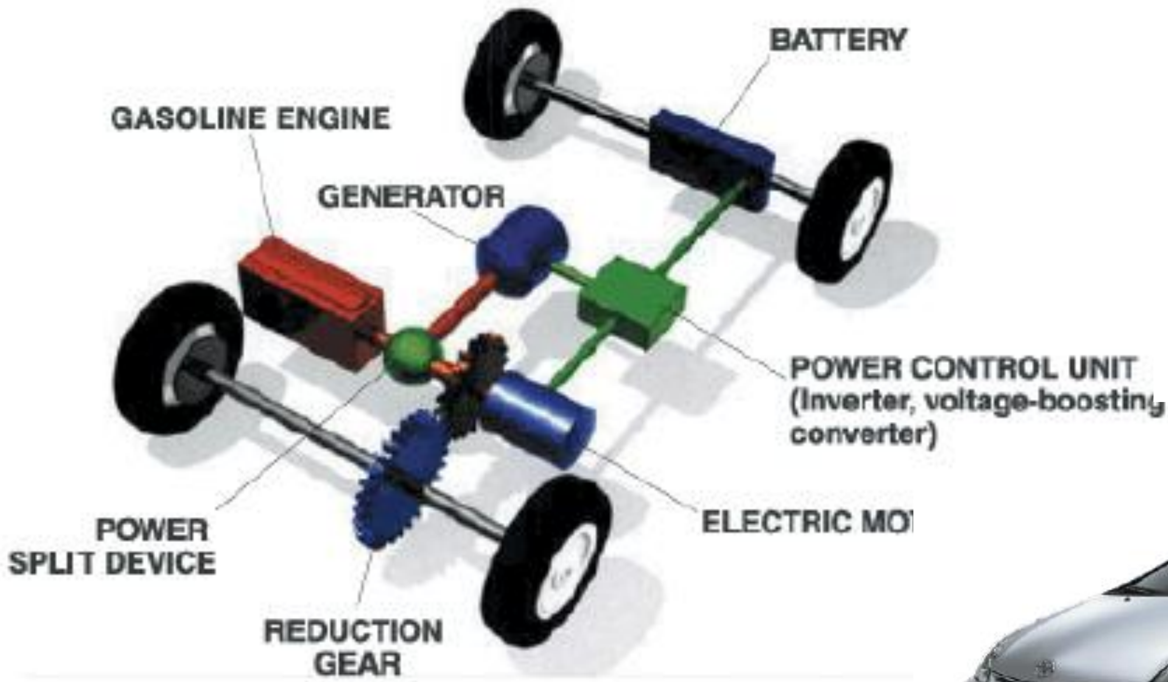
- 65% of the drag is coming from the body shape (front body, after body, underbody, skin friction)
  - Large field of improvement, especially for the after body in which most of the turbulence occurs, but restrictions due to aesthetic!
- Sensitivity also
  - Wheels (21%)
  - Details (7%)
  - Internal drag (6%)

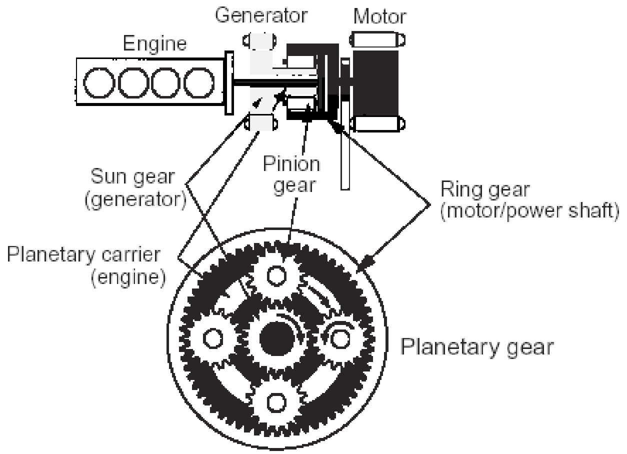
Low rolling resistance tires

- Usual tires are optimized for comfort, friction properties in various conditions and noise reduction.
- New generation of tires are designed for reducing the rolling resistance (LRR low rolling resistance tires)
  - Inflation pressure is very important!
  - Rubber quality
- Examples:
  - Michelin Energy
  - Bridgestone Potenza RE92
  - Continental Eco Tires

Case study: Toyota Prius

TOYOTA PRIUS II





Toyota Prius II

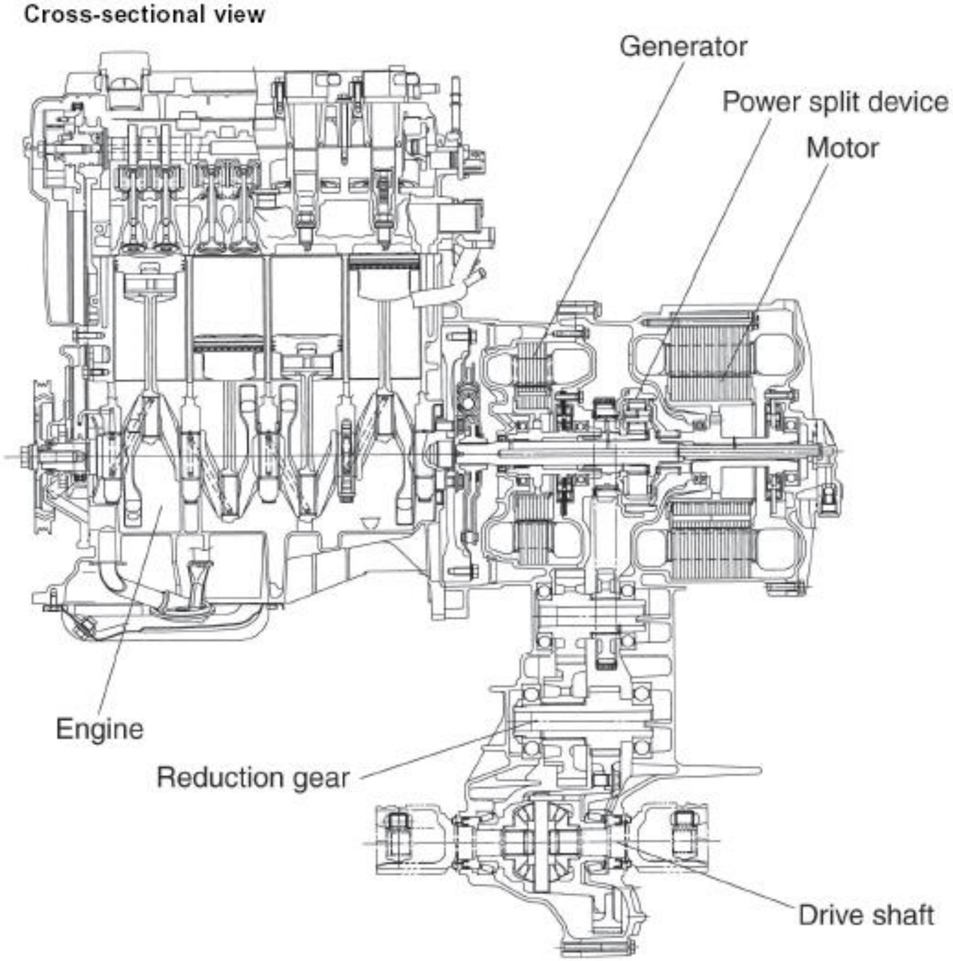
Toyota Prius II

Specifications of new hybrid system

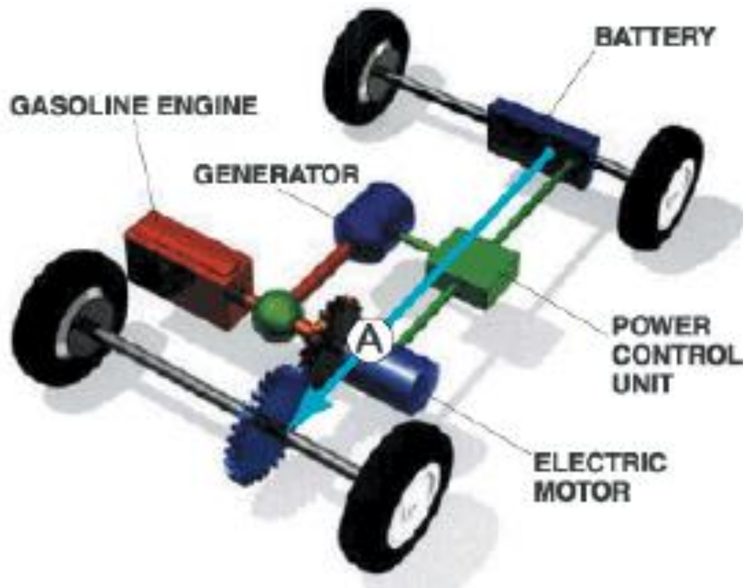
	Item	THS II	THS
Engine	Type	1.5 L gasoline (high-expansion ratio cycle)	←
	Maximum output in kw (Ps)/rpm	57 (78)/5,000	53 (72)/4,500
	Maximum torque in N-m (kg m)/rpm	115 (11.7)/4,200	115 (11.7)/4,200
Motor	Type	Synchronous AC motor	←
	Maximum output in kw (Ps)/rpm	50 (68)/1,200-1,540	33 (45)/1,040-5,600
	Maximum torque in N-m (kg m)/rpm	400(40.8)/0-1,200	350(35.7)/0-400
System*	Maximum output in kW (Ps)/vehicle speed km/h	82(113)/85 or higher	74 (101)/120 or higher
	Output at 85km/h in kW (PS)	82 (113)	65 (88)
	Maximum torque in N-m (kg m)/vehicle speed km/h	478(48.7)/22 or lower	421 (42.9)/11 or lower
	Torque at 22km/h in N-m (kg m)	478 (48.7)	378 (38.5)
Battery	Type	Nickel-metal hydride	←

*Maximum combined engine and hybrid battery output and torque constantly available within a specified vehicle speed range (Toyota in-house testing)

Toyota Prius II

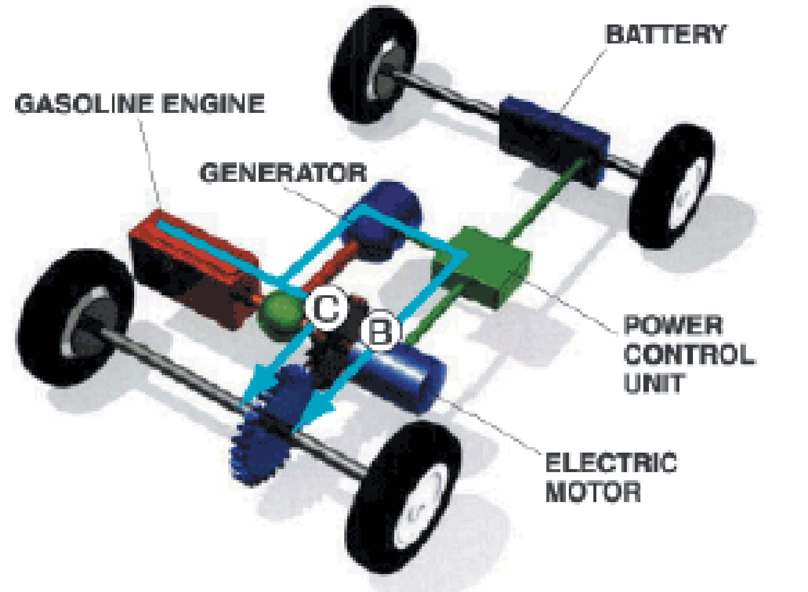


Toyota Prius II



1 Start and low to mid-range speeds

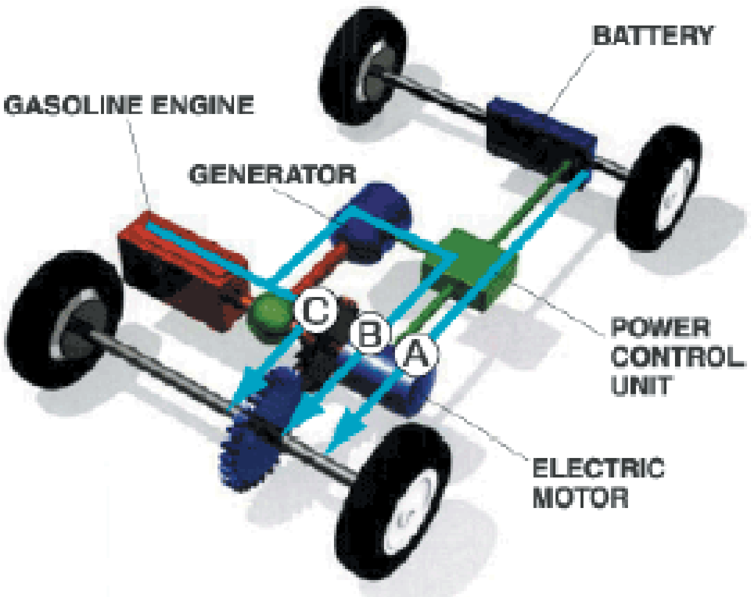
The engine stops when in an inefficient range, such as at start-up and in low to mid-range speeds. The vehicle runs on the motor alone. (A)



2 Driving under normal conditions

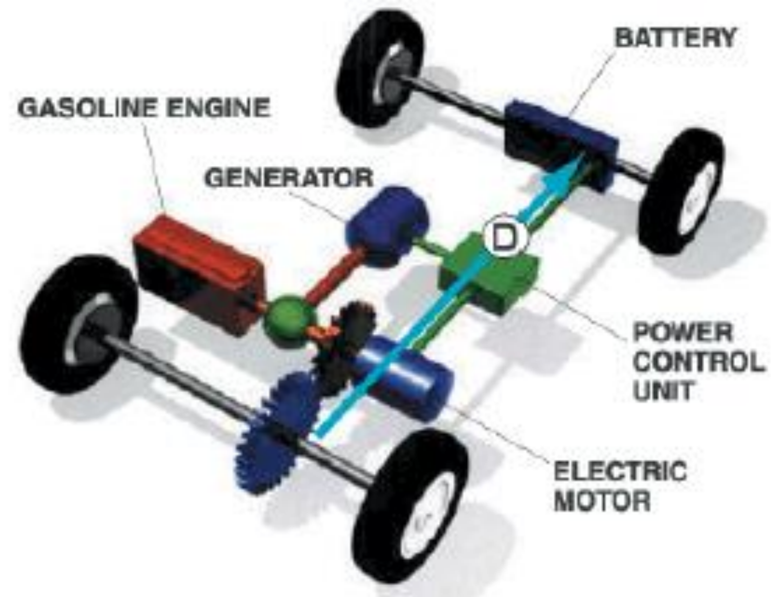
Engine power is divided by the power split device. Some of the power turns the generator, which in turn drives the motor. (B)
The rest of the power drives the wheels directly. (C)
Power allocation is controlled to maximize efficiency.

Toyota Prius II



3 Sudden acceleration

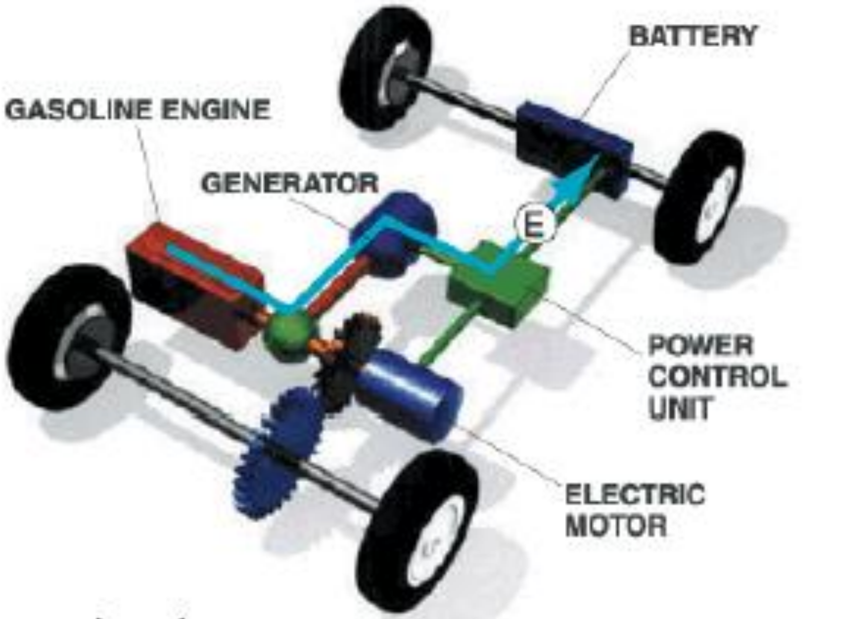
Extra power is supplied from the battery (A), while the engine and high-output motor provide smooth response (B+C) for improved acceleration characteristics.



4 Deceleration, braking

The high-output motor acts as a high-output generator, driven by the vehicle's wheels. This regenerative braking system recovers kinetic energy as electrical energy, which is stored in the high-performance battery. (D)

Toyota Prius II



5 Battery recharging

Battery level is managed to maintain sufficient reserves. The engine drives the generator to recharge the battery when necessary. (E)

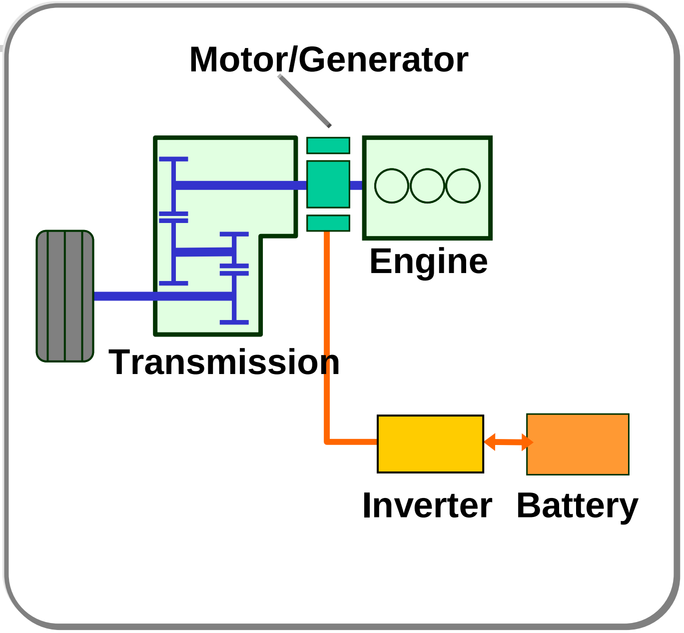
6 At rest

The engine stops automatically.

Case study: Honda Insight

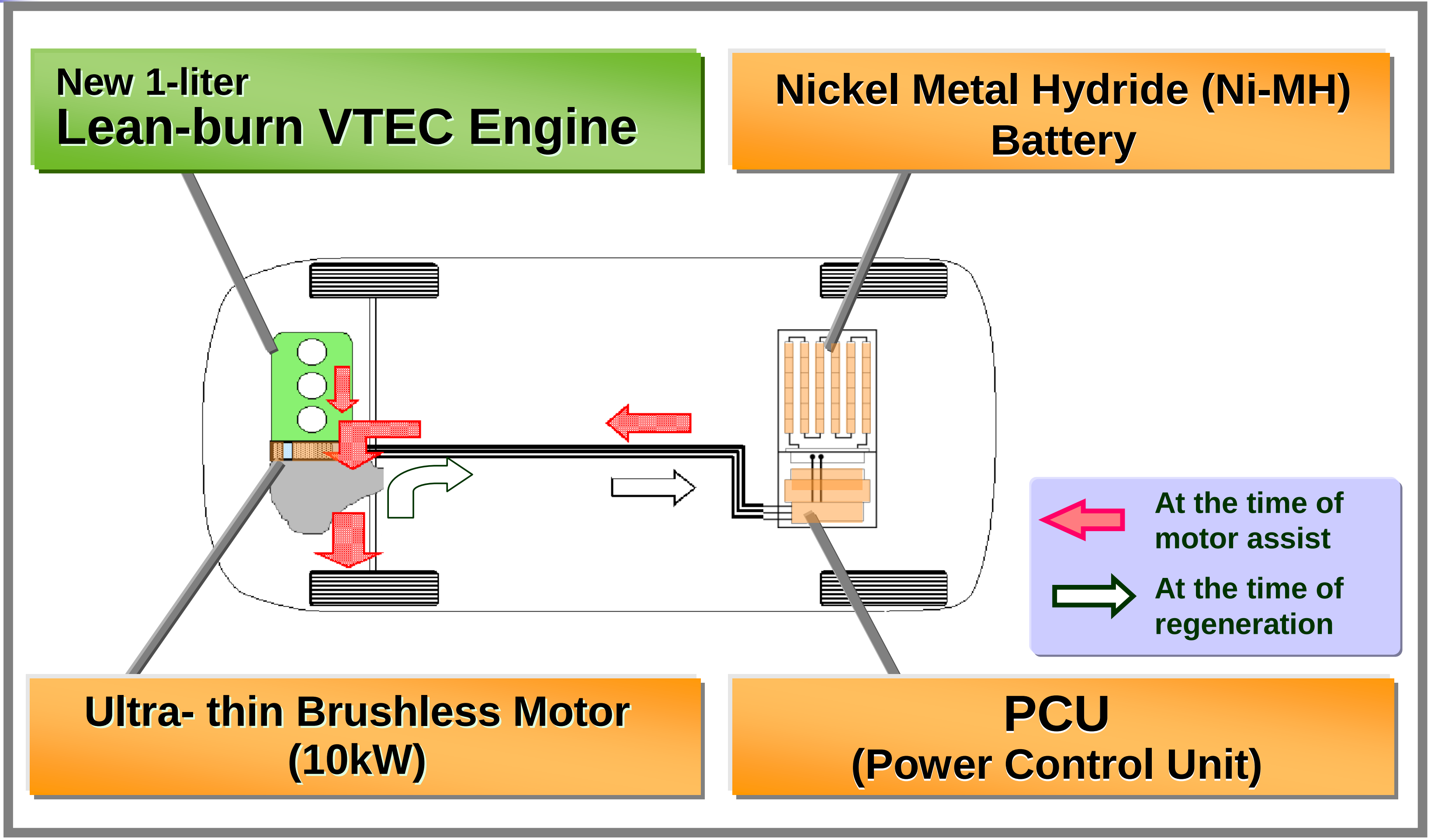
Honda Insight

- Mild hybrid architecture
  - Small electric machine (~10 kW)
  - Function « Stop & start»
  - Small capability of energy recovery during braking
  - Motor assist of main power source
- Replace the flywheel by an integrated starter alternator



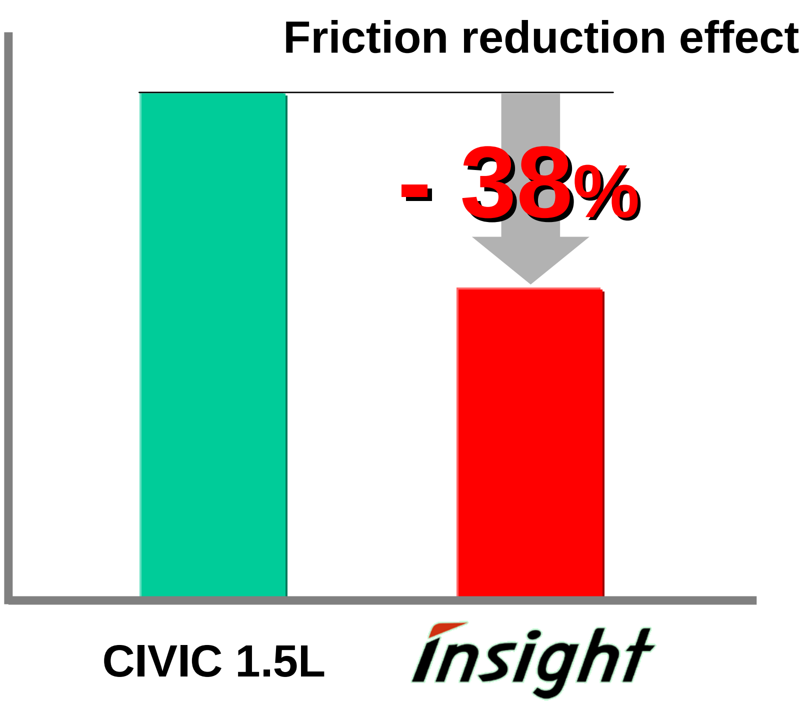
Honda Insight

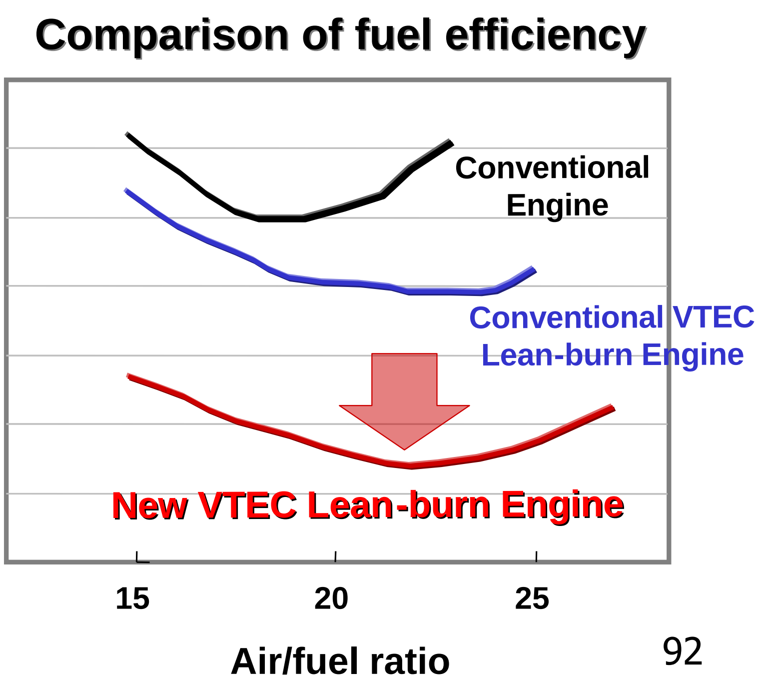
Honda Insight



Honda Insight

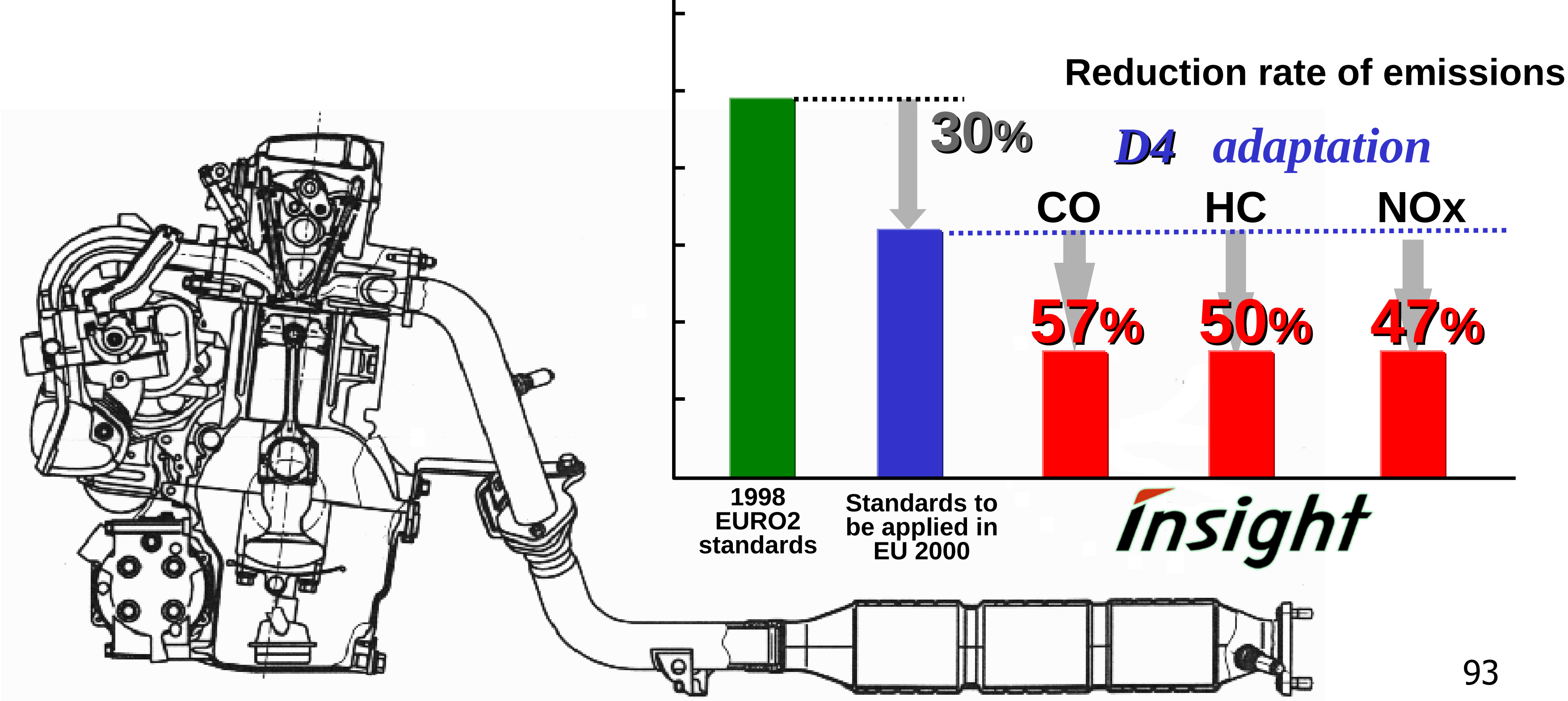
- Downsizing: motorization 1 L
  - Reduction of internal friction
  - Reduction of fuel consumption
  - Improving the exhaust gas treatment



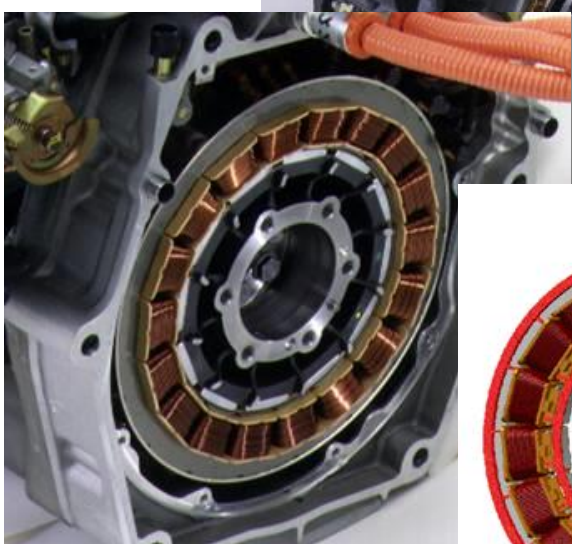


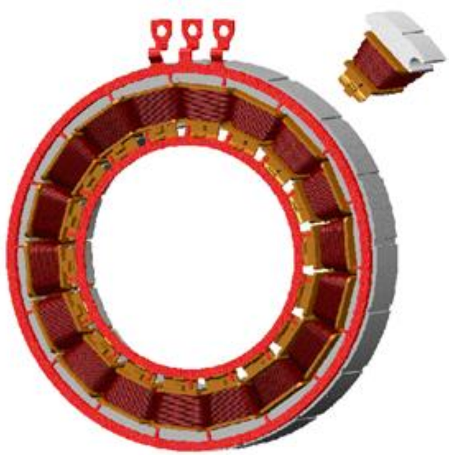
Honda Insight

- Downsizing: example of Honda Insight
  - Improving the exhaust gas treatment: new catalytic converter for NOx able to work in lean burn



Honda Insight

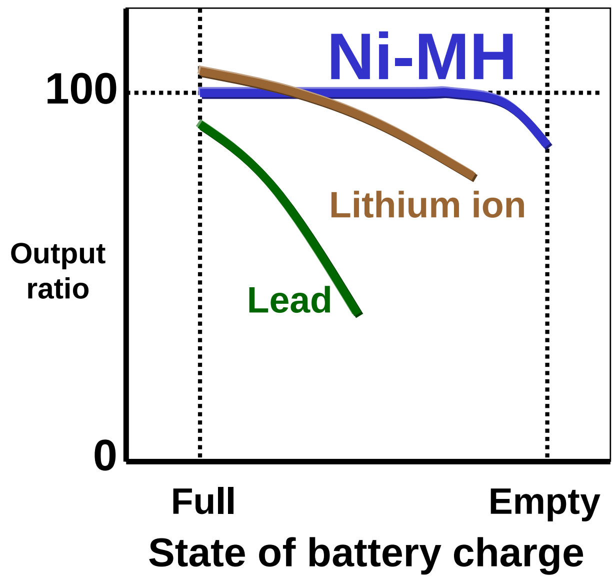




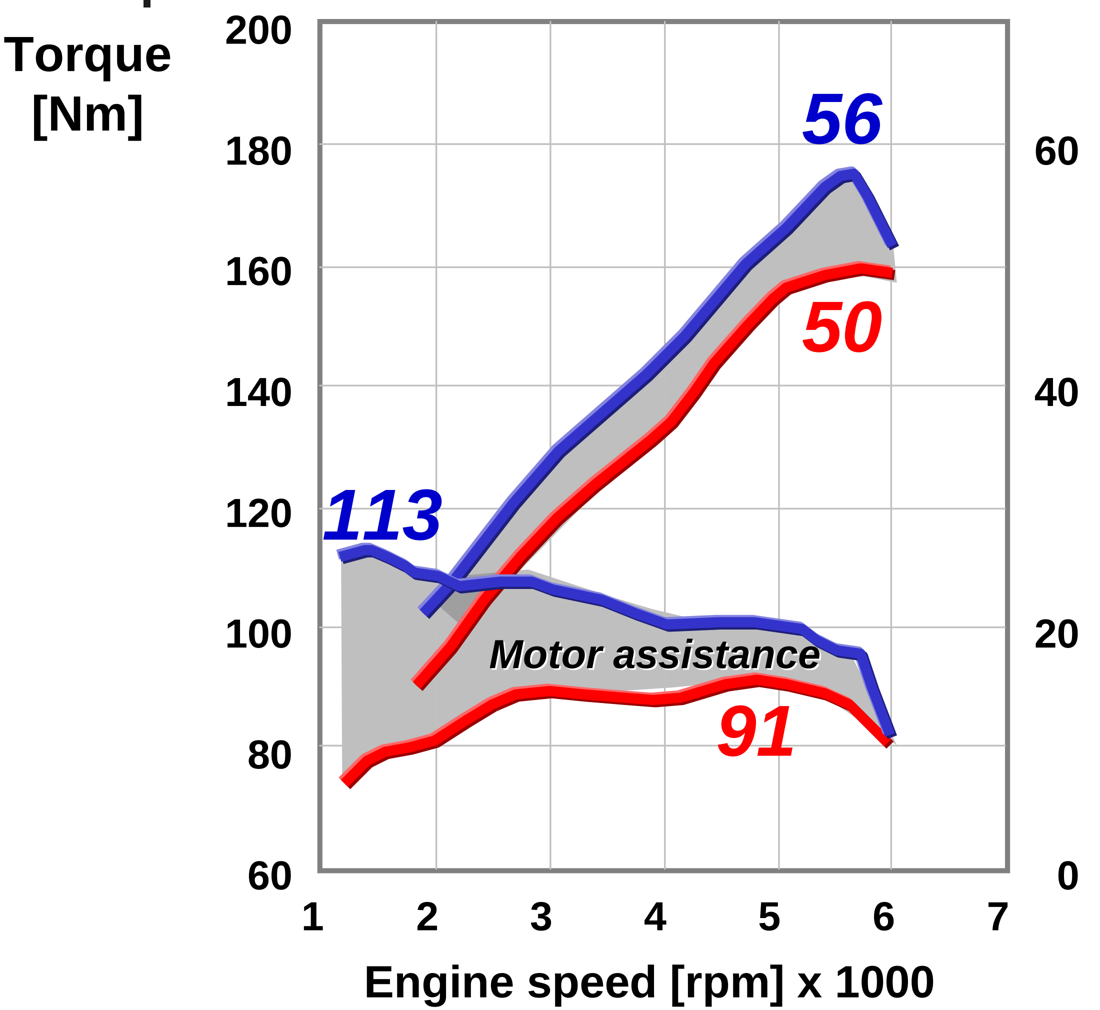
- A brushless permanent magnet motor with a high efficiency and lightweight with a power of 10kW
- Lightweight motor with a high torque
  - Large diameter, multipole
- Ultra thin motor
  - Stator split with salient poles
  - Centralized distribution

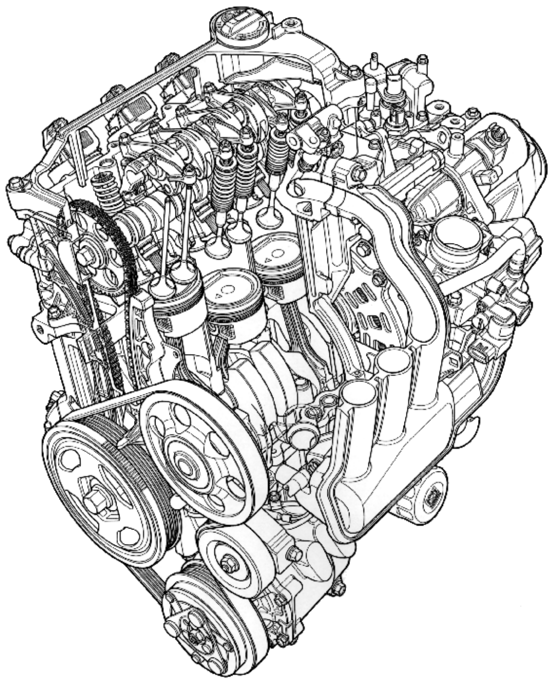
Honda Insight

- Ni-MH batteries
- Battery pack of 144 V
  - 20 modules = 120 cellules
- Characteristics are stable and high, and stable in time



Honda Insight

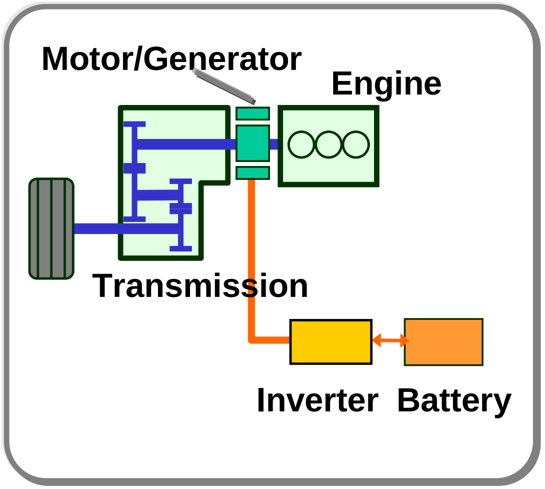




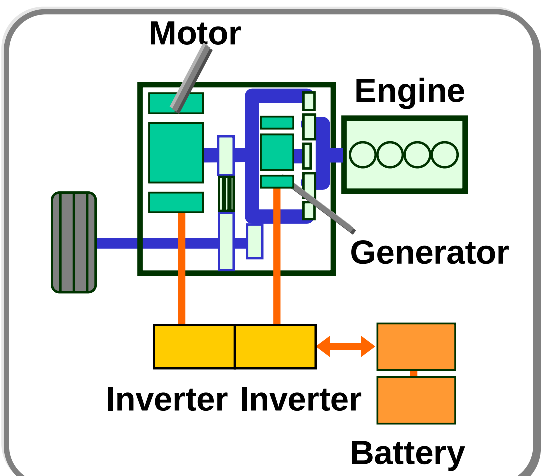
- Motor assist for the Honda Insight

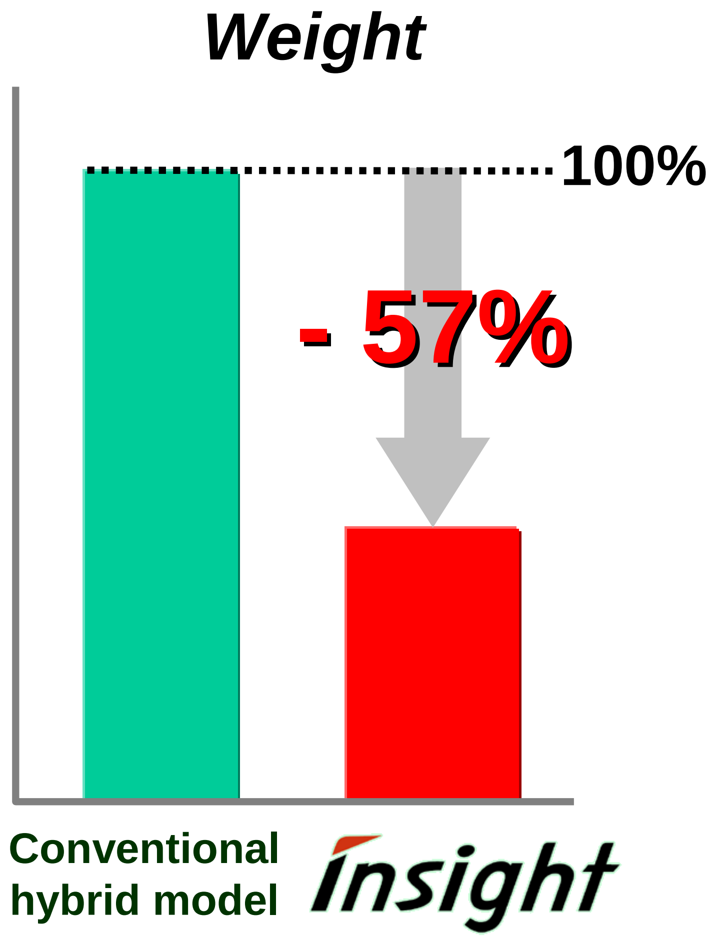
Honda Insight

Insight



Conventional hybrid model



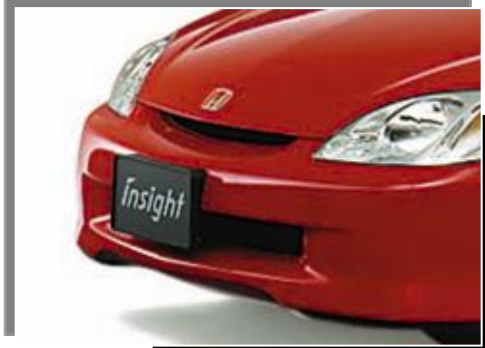


Honda Insight

- Lightweight vehicle
  - Using aluminum
  - New manufacturing technologies for production and recycling of aluminum
    - Extrusion, Thixo forming
    - High properties for crashworthiness and high stiffness
  - -47 % for mass saving
- Vehicle aerodynamic
  - -30 % saving on S Cx ~ 5% on consumption
- Low rolling resistance tires
  - -40% saving on rolling resistance ~ -6 % on fuel consumption
- Selection of accessories with low energy consumption
  - Electric steering assistance…

Honda Insight

Aerodynamics



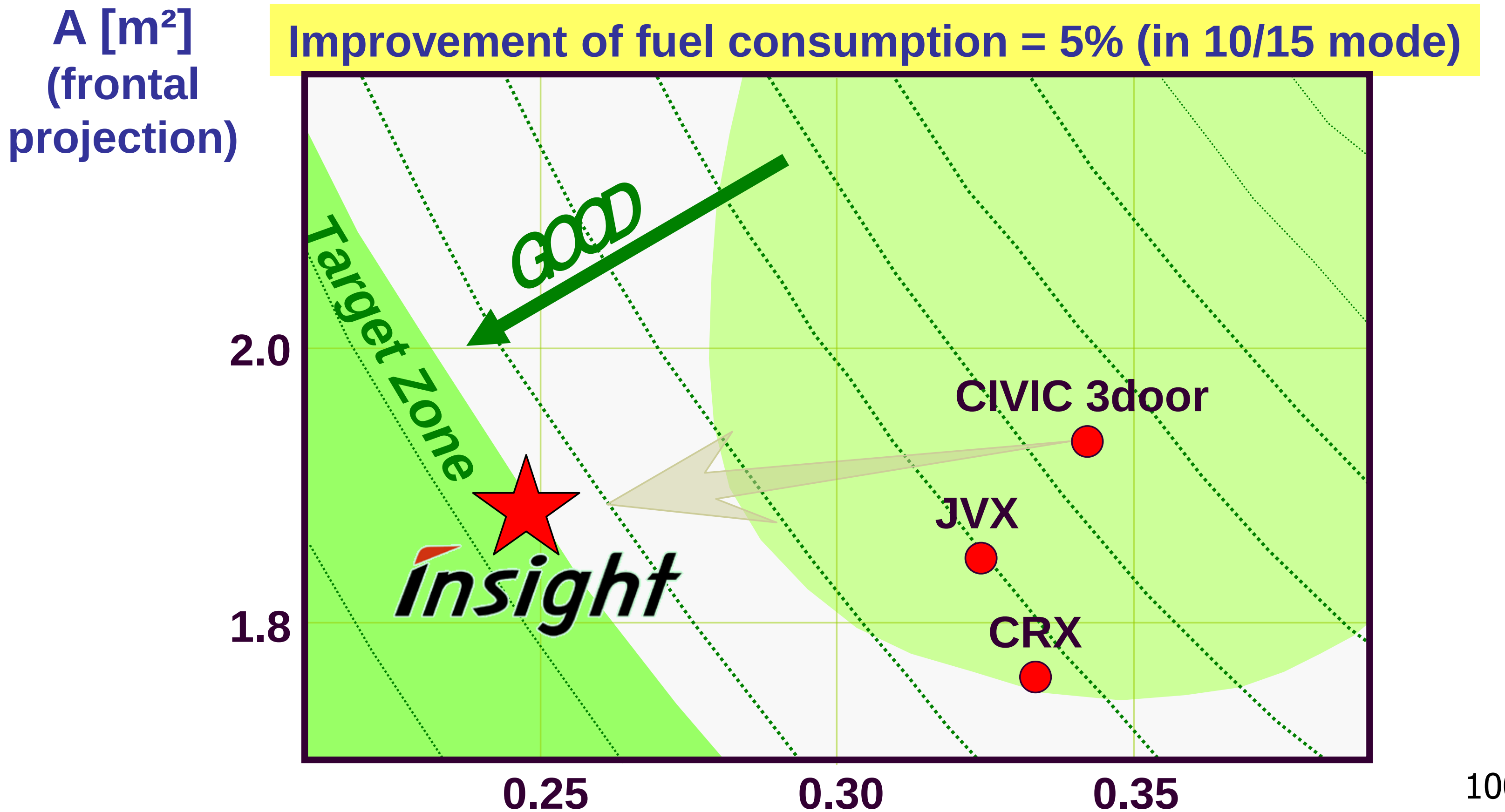
Front grill

Door mirrors

Rear wheel skirt

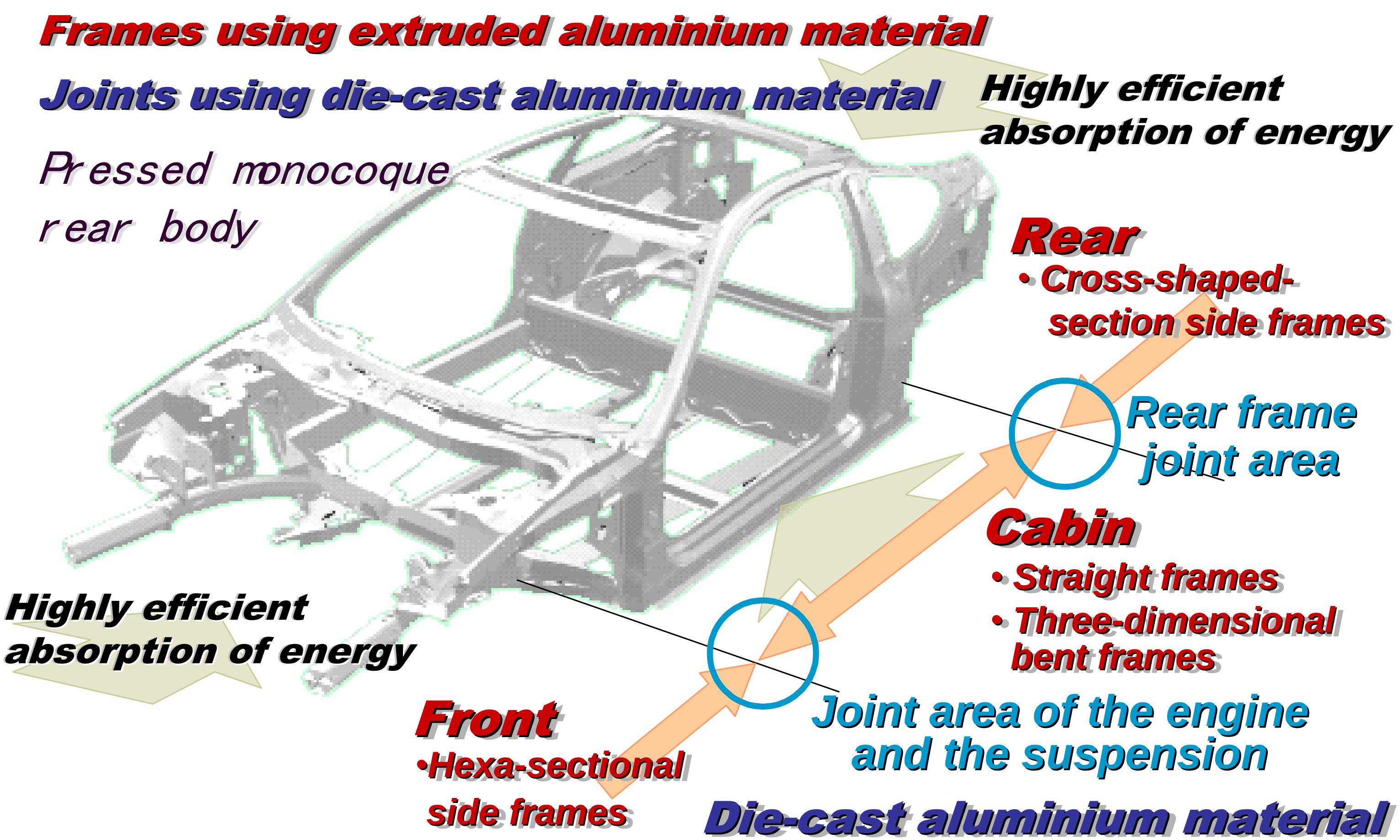
Honda Insight

Cd × A of Insight is 30 % lower than Civic model



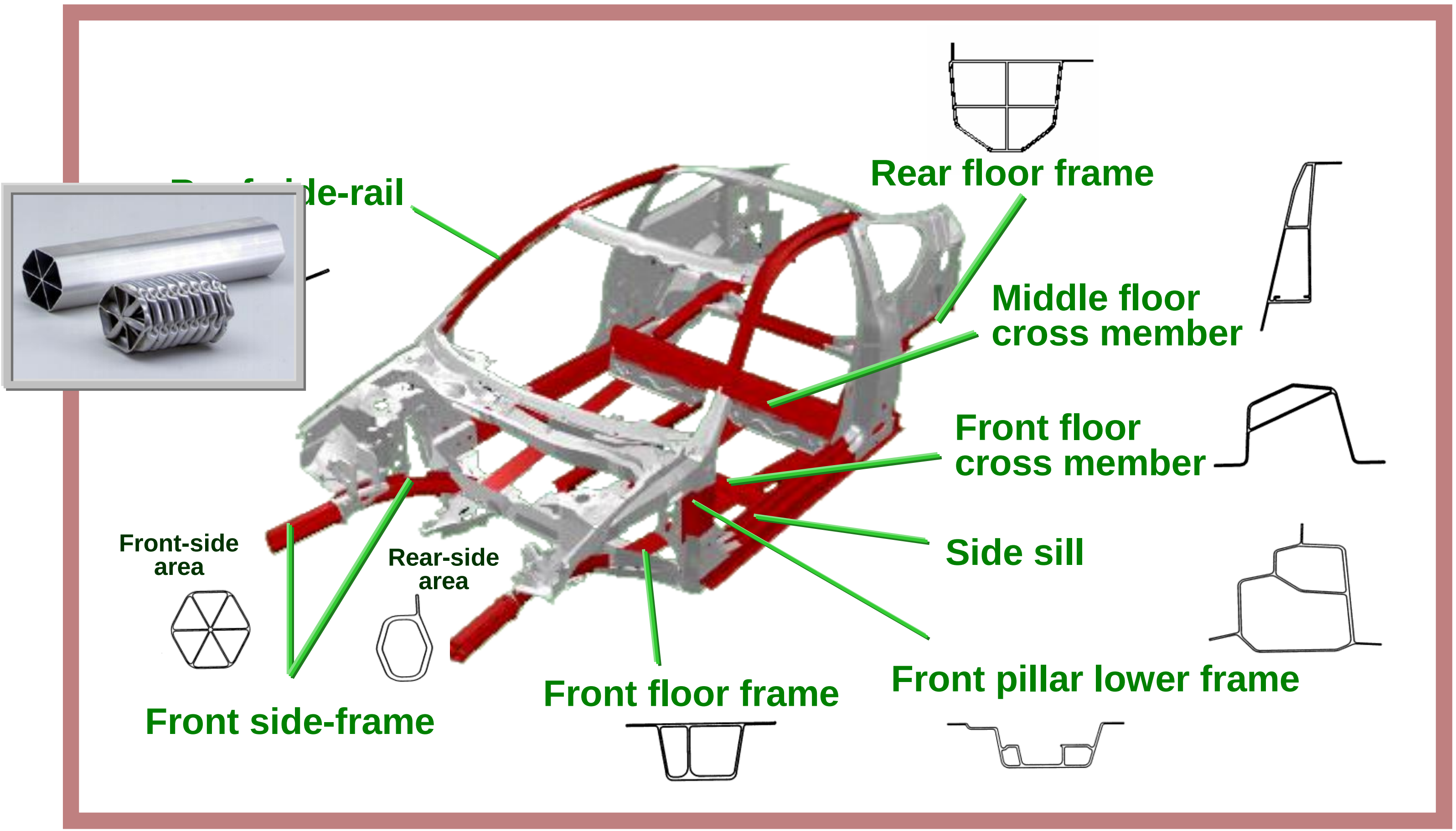
Honda Insight

Aluminum structure of the Honda Insight



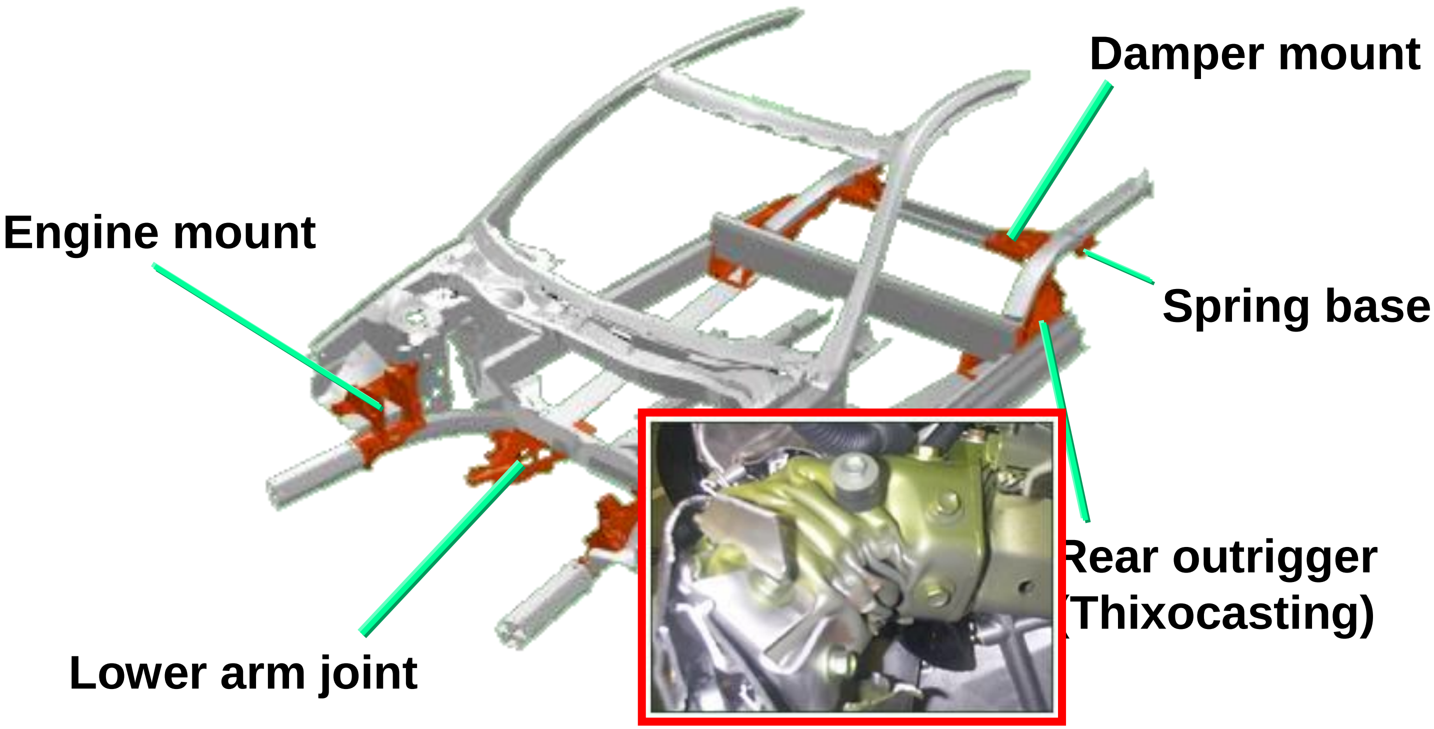
Honda Insight

Aluminum structure of the Honda Insight



Honda Insight

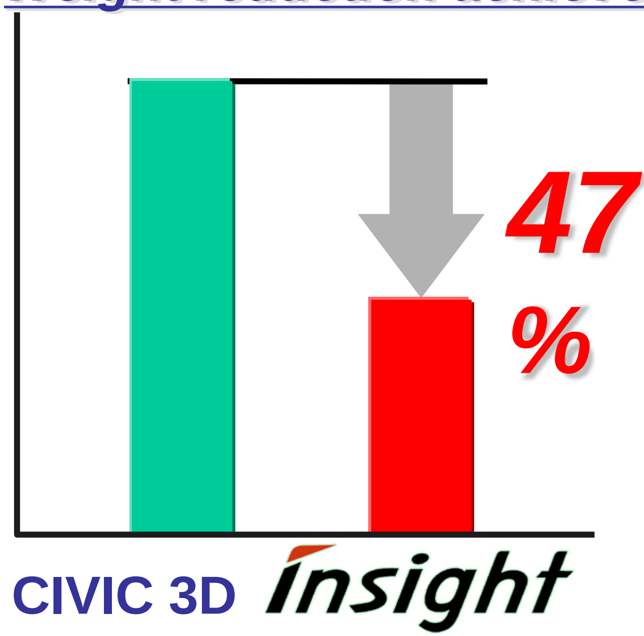
Aluminum structure of the Honda Insight



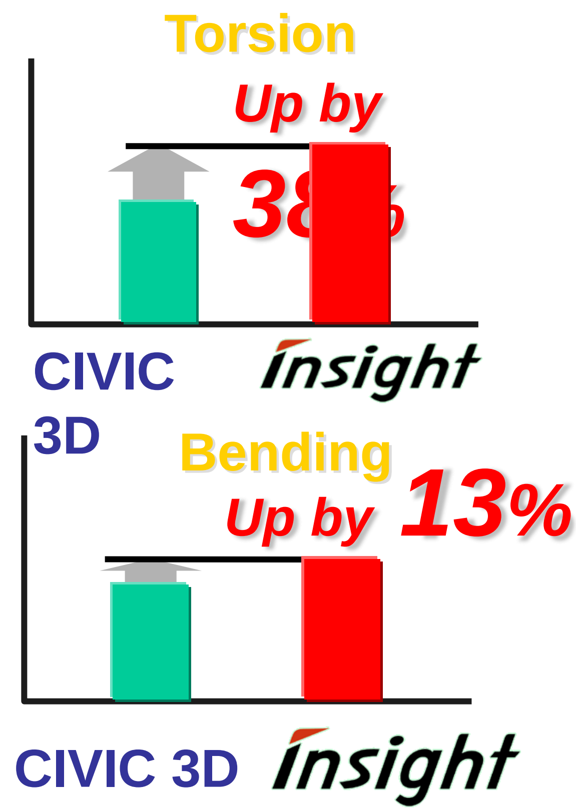
Honda Insight

Aluminum structure of the Honda Insight

Weight reduction achieved



Body rigidity



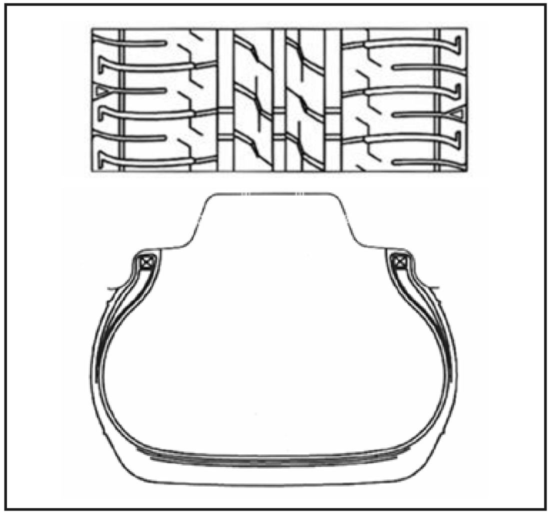
Honda Insight

Low rolling resistance tires of the Honda Insight

Compound
Lowering rolling resistance without sacrificing braking-performance on wet roads

Profile
Improving control stability and ride comfort by adopting improvements in the side wall

Tread pattern
Improving braking performance by adopting the newly developed pattern (wet/dry)



165/65R14

Rolling resistance coefficient
- 40% (compared with Civic)

Fuel efficiency (93/116/EC)
6 % up

Honda Insight

Selection of components with low energy consumption: steering system

Pinion-shaft-driven EPS

- Small, light, and compact
- EPS with less power loss

Fuel efficiency (93/116/EC)

3 % up

Motor-driven pinion shaft