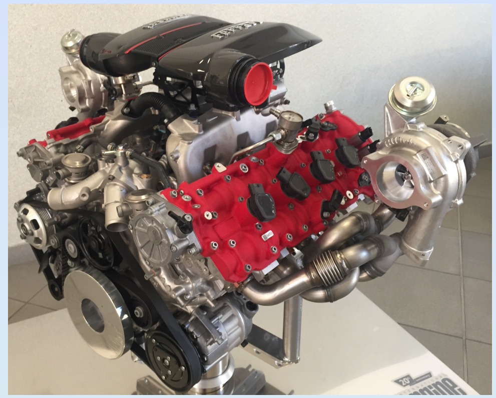
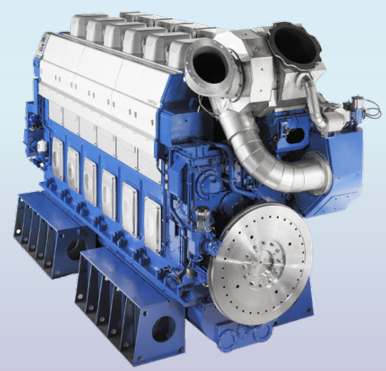
Corso di Laurea Magistrale in
Ingegneria Gestionale



Motori a Combustione Interna



Prof. Ivan Arsie

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Sistemi di Propulsione Ibrida-Elettrica

Hybrid vehicle - Definitions

- **Hybrid vehicles** are characterized by **two or more prime movers** and **power sources**.
- Usually, the term "hybrid vehicle" is used for a vehicle combining an **engine** (ICE) and an **electric motor-generator (EMG)**: **Hybrid Electric Vehicle**, HEV.
- Other "hybrid" configurations have been also proposed (mechanical, pneumatic, hydraulic).

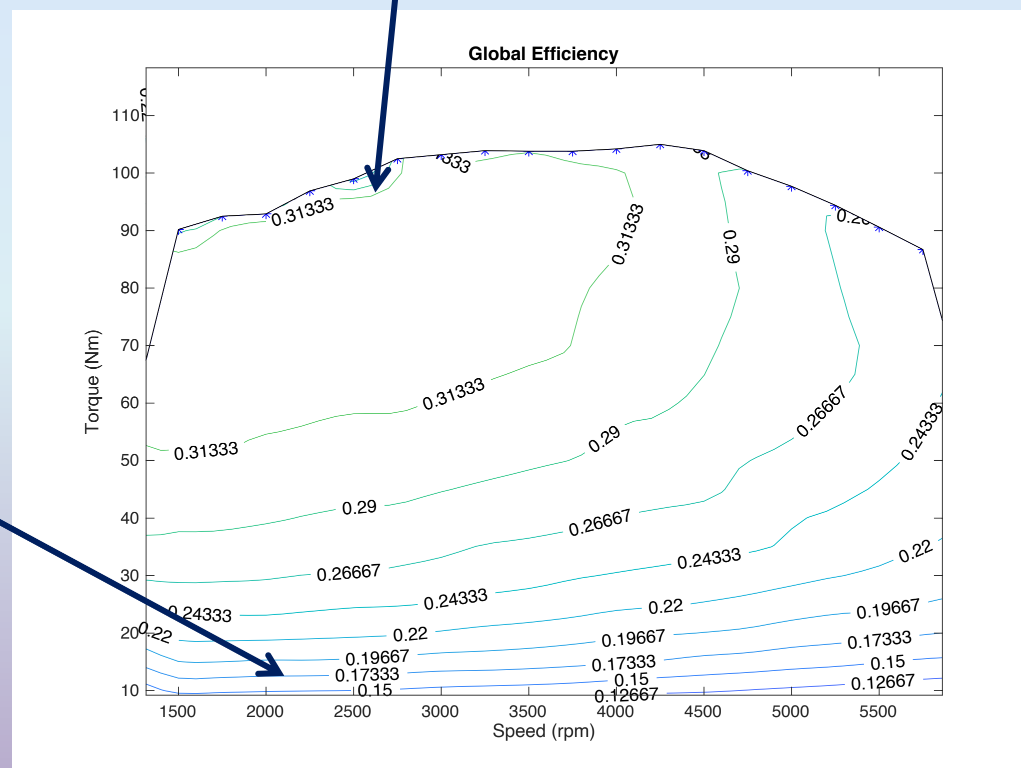
Issues of ICE

The **engine efficiency η_g** (and the specific fuel consumption ***SFC***) strongly depends on **engine operating conditions**.

Highest efficiency if achieved only in a limited part of the operating plane

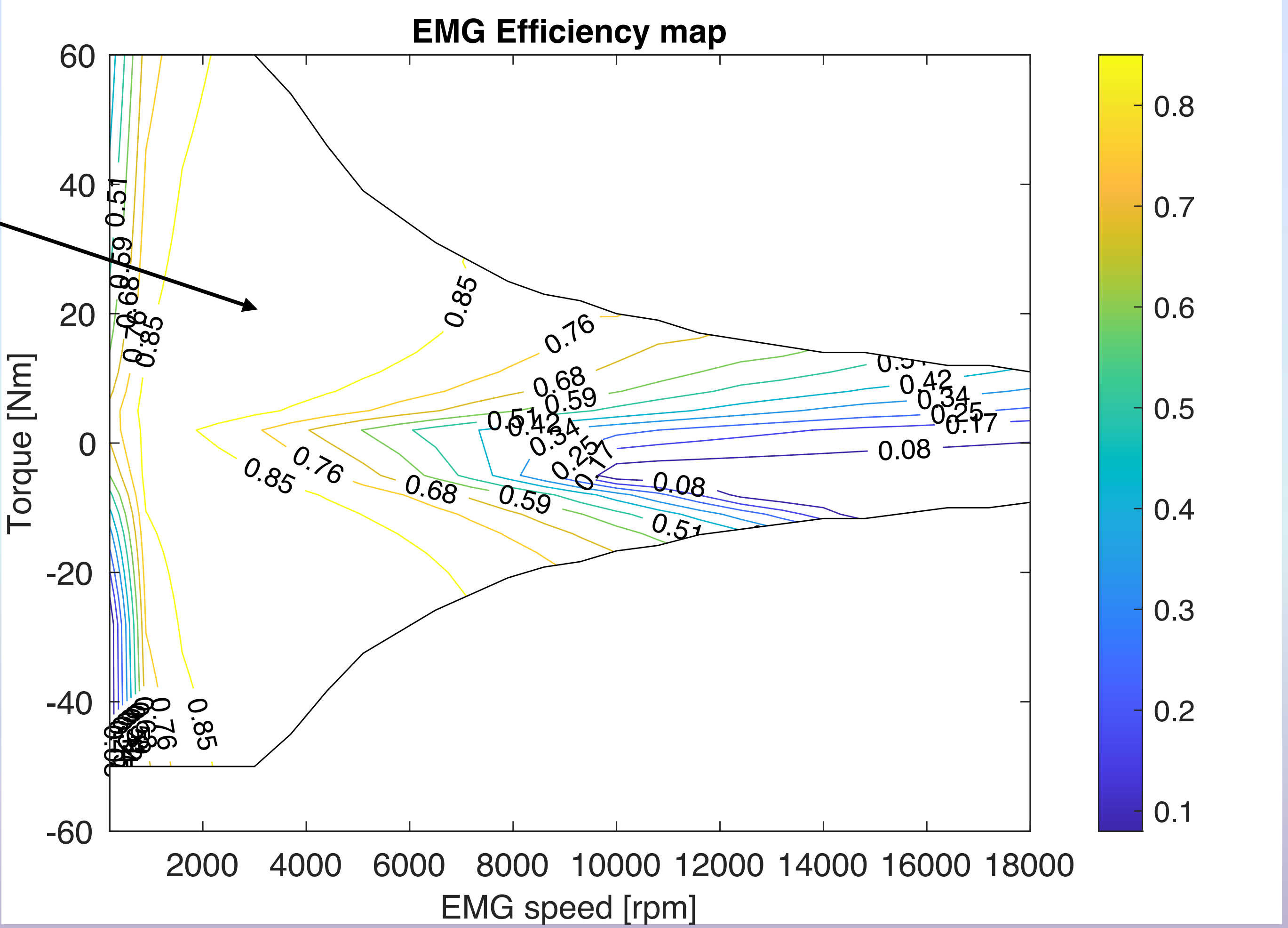
$$SFC = \frac{\dot{m}_f}{P} = \frac{1}{\eta_g LHV}$$

At part load conditions, for instance during urban driving, engine operates at low efficiency, in particular in Spark Ignition engines (due to throttle losses).



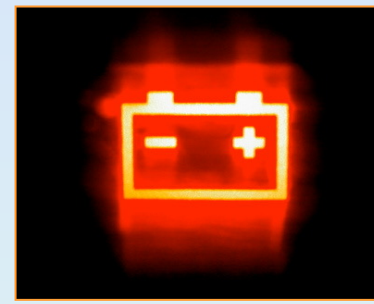
Features of EMG

High efficiency in a wide operating range



Issues of EV:
Energy density of batteries vs liquid fuels

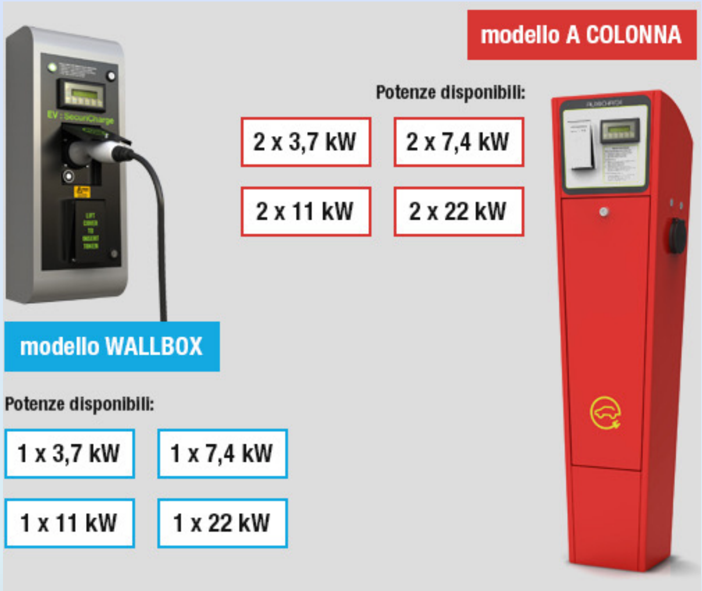
	kWh/kg	%	kWh/m3	%
Liquid Fuel	11.7	*100,00*	9.17	*100,00*
Lead-Acid	0.0297	*0,25*	0.076	*0,83*
Li-Ion	0.125	*1,07*	0.247	*2,69*



Considering that, in the average, only 25% of fuel chemical energy can be converted in mechanical energy:

	kWh/kg	%	kWh/kg	%
Liquid Fuel	2.92	*100,00*	2.29	*100,00*
Lead-Acid	0.0297	*1,00*	0.076	*3.32*
Li-Ion	0.125	*4,28*	0.247	*10.8*

Issues of EV: recharge



Power (energy per unit time) in input during «recharge»:

3.7-22 kW

Fast DC recharge:
about 100 kW

MJ/kg	42
Density kg/dm3	0,75
MJ/Liters	33,33
l/s	0,33
kg/s	0,25
MW	**10.5**

Toyota Prius

The **Toyota Prius**, first went on sale in Japan in 1997, has been the **first mass-produced hybrid vehicle**. It was introduced worldwide in 2000.

The Prius is sold in almost 80 countries and regions, with its largest markets being those of Japan and the United States.

Global cumulative Prius sales reached the milestone 1 million vehicle mark in May 2008, 2 million in September 2010, and passed the 3 million mark in June 2013.

2005 Geneva Motor Show

Toyota raises Prius 2005 European sales goal

Reuters

REUTERS

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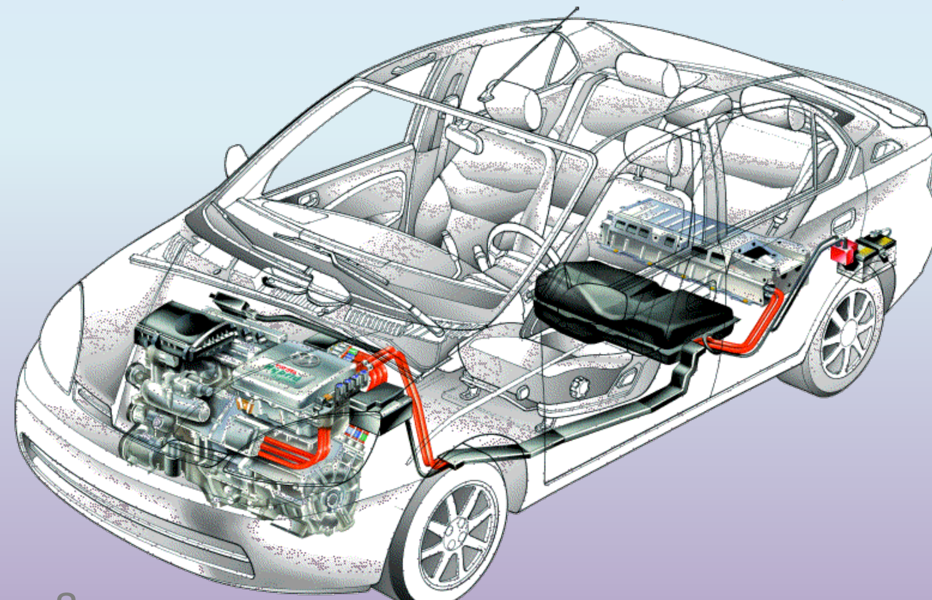
GENEVA - Toyota Motor Co.p. increased on Tuesday its 2005 European goal for sales of its Prius hybrid model to 20,000 units from the previous target of 15,000 and versus 8,200 in 2004.

"This year our target is to more than double to 20,000 hybrid vehicle sales in Europe," Takis Athanasopoulos, the



Source: Wikipedia

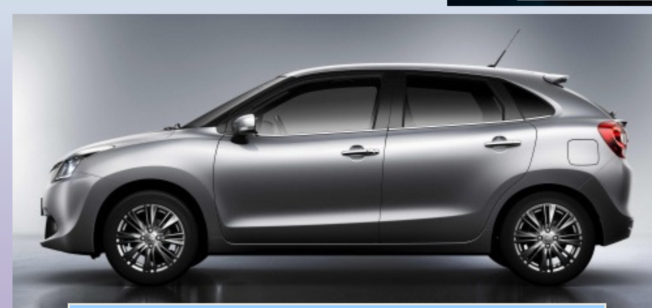
More recent HEV and PHEV

Toyota C-HR Hybrid

Toyota Auris Hybrid

Toyota RAV4 Hybrid

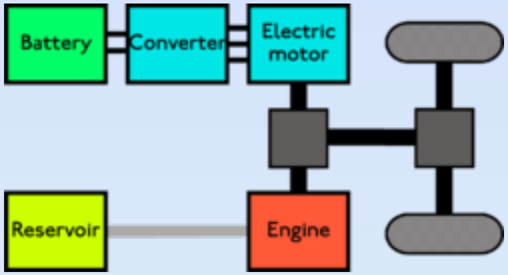
Volvo XC90 T8

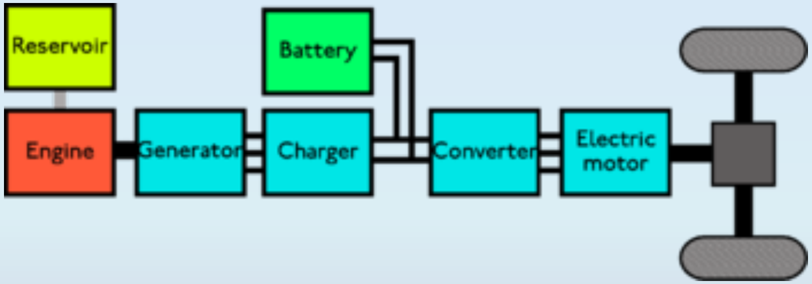


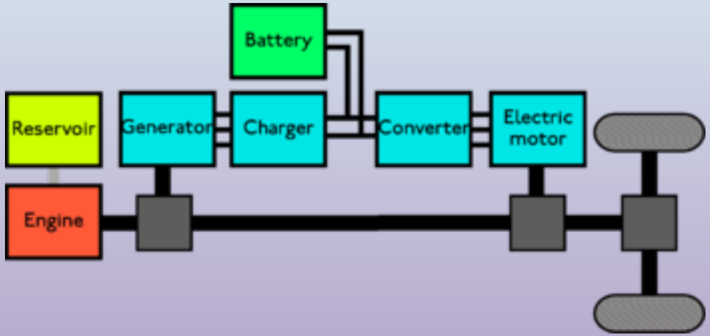
Suzuki Baleno Hybrid

HEV System Configurations

- **Parallel hybrid:** Both engine and electric motor can power the vehicle individually or simultaneously.
- **Series hybrid:** The electric motor alone drives the vehicle. The electricity can be supplied either by a battery and/or by an engine-driven generator.
- **Series-parallel, or combined hybrid:** There are both mechanical and electrical links between engine and electric motor/generator.

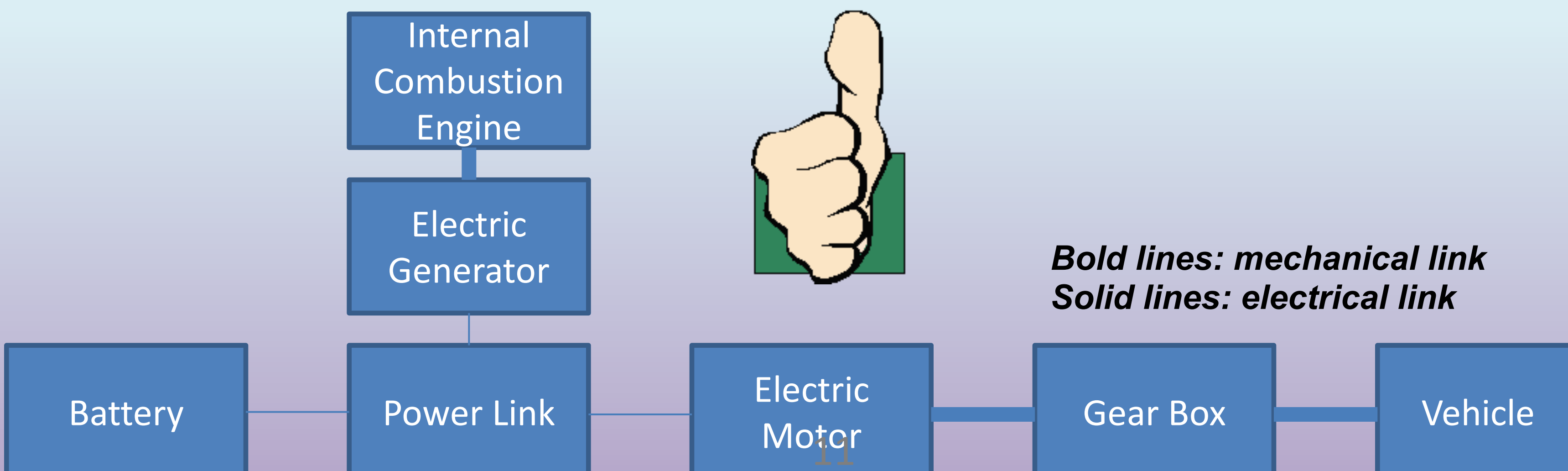






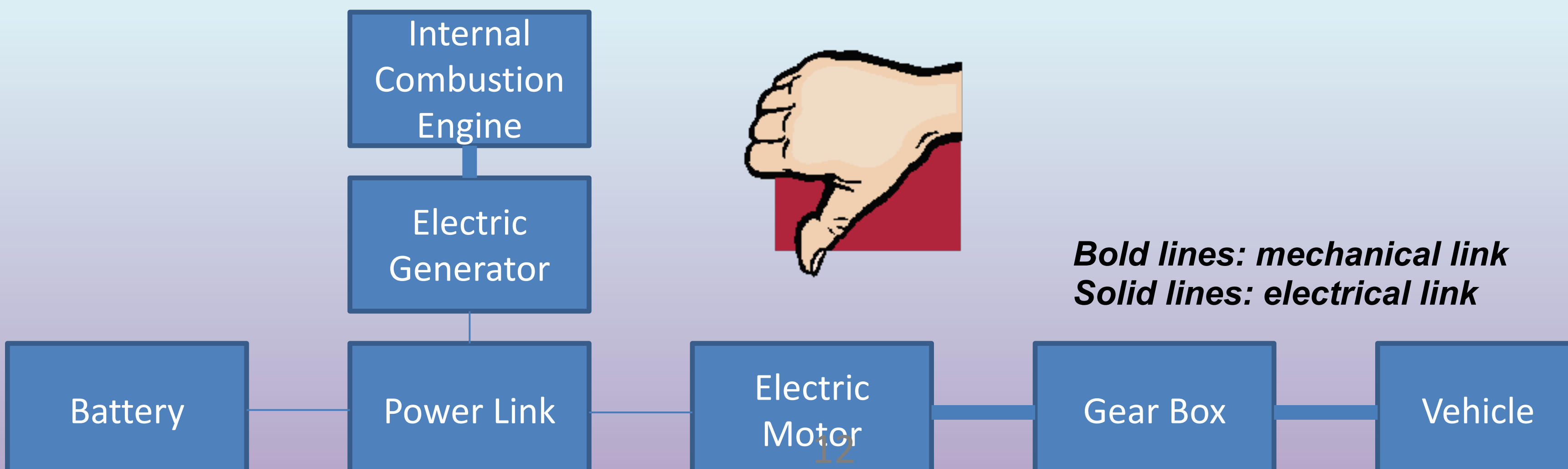
Series HEV - Advantages

- The engine operation is not related to the power requirements of the vehicle, thus the engine can be operated at a point with **optimal efficiency and emissions**.
- The engine is mechanically decoupled from the drive axle:
  - the transmission **does not require a clutch;**
  - **lay-out** can be optimized;
  - good **insulation** for **vibrations and noise** can be achieved, since the engine is not mechanically connected to the transmission.



Series HEV - Disadvantages

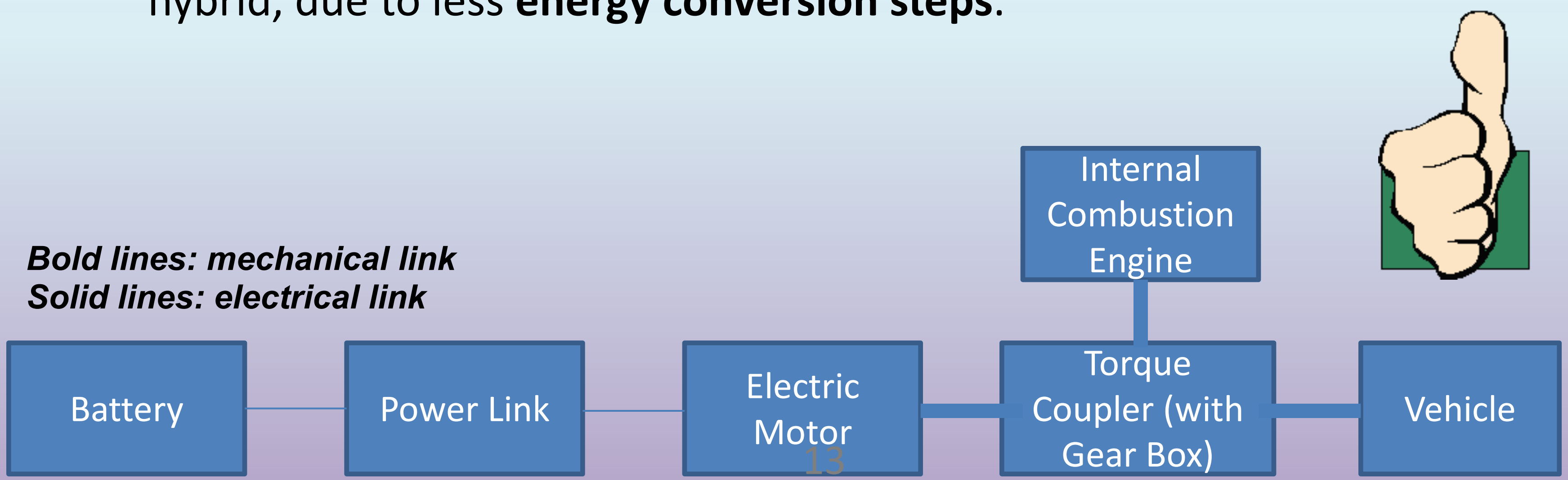
- **3 machines** are needed: one engine, one electric generator, and one electric traction motor. This cause **additional weight and cost**.
- At least the traction motor has to be sized for the **maximum power requirements** of the vehicle.
- The overall tank-to-wheel efficiency is reduced due to **multiple energy conversions**.



Parallel hybrid - Advantages

- Power could be **optimally distributed** between electrical and thermal mover.
- Both machines can be sized for a **fraction of the vehicle maximum power →** Less weight and cost with respect to series hybrid.
- Engine can be **downsized**, with increased efficiency.
- The overall **tank-to-wheel efficiency** is higher with respect to series hybrid, due to less **energy conversion steps**.

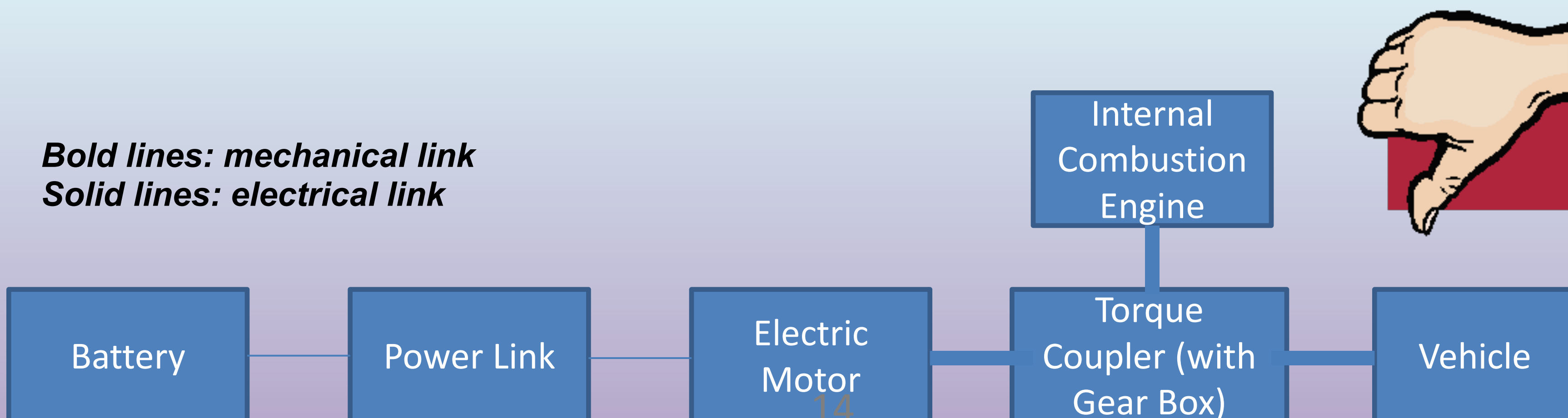
Bold lines: mechanical link
Solid lines: electrical link



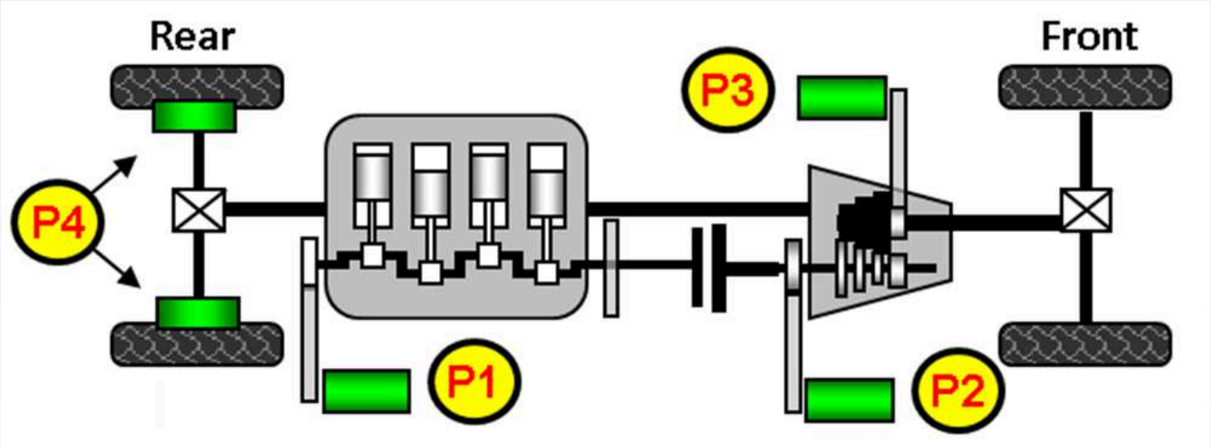
Parallel hybrid - Disadvantages

- A **clutch** is needed, since the engine is mechanically linked to the drive train.
- The electric generator is smaller, and this may **limit the recoverable braking energy**.
- Engine operation can be somewhat optimized thanks to motor assistance, but not so effectively as in a series hybrid.

Bold lines: mechanical link
Solid lines: electrical link

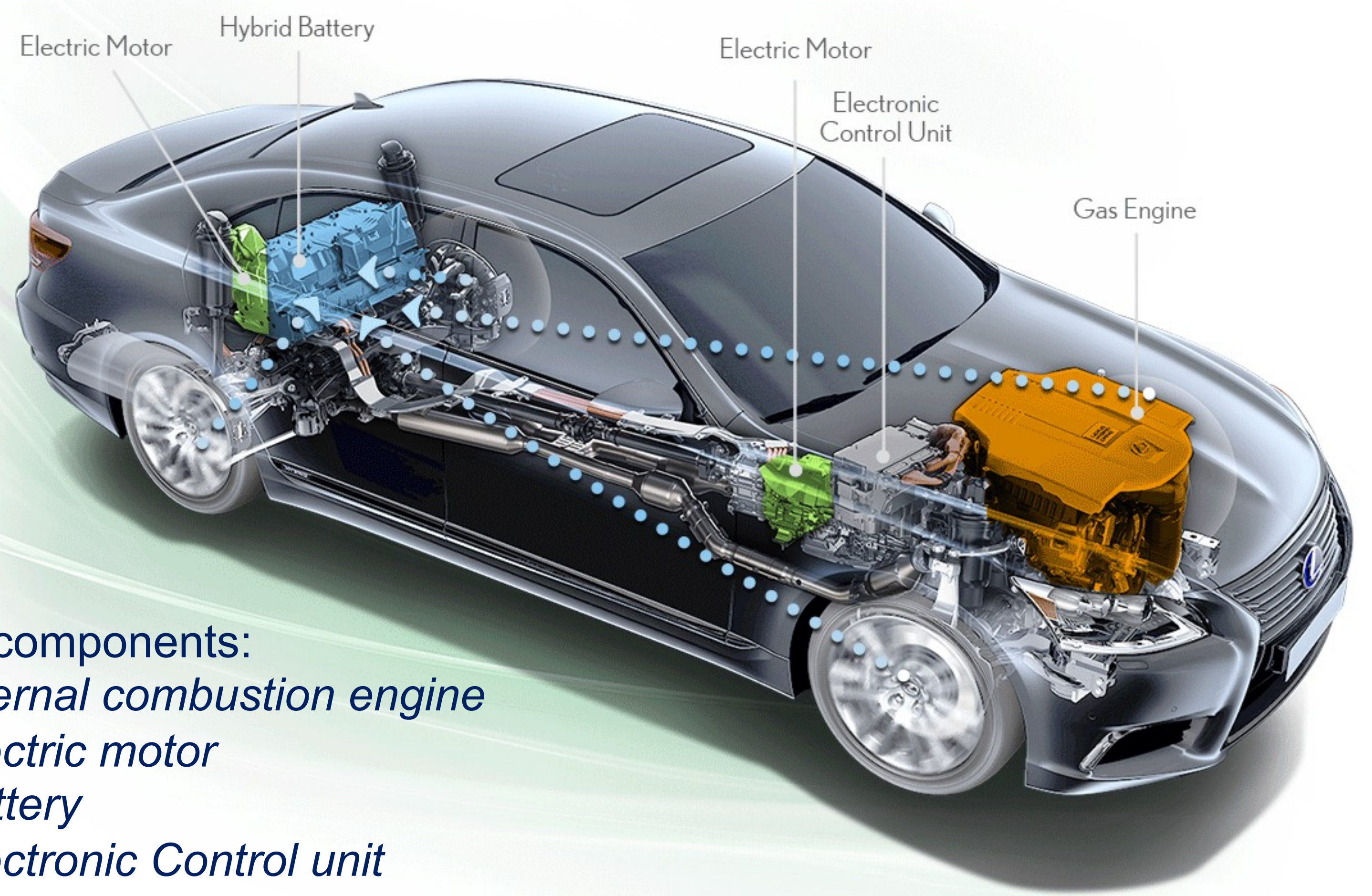


Parallel Hybrid Powertrain Lay-out



- P0/P1: Belt Starter Generator/Integrated Starter Generator
- P2: EM located between clutch and gearbox (upstream)
- P3: EM located between gearbox (downstream) and final drive
- P4: EM located between final drive and wheel (e.g. in-wheel e-motors)

Parallel Hybrid Powertrain Lay-out



Main components:

- *Internal combustion engine*
- *Electric motor*
- *Battery*
- *Electronic Control unit*

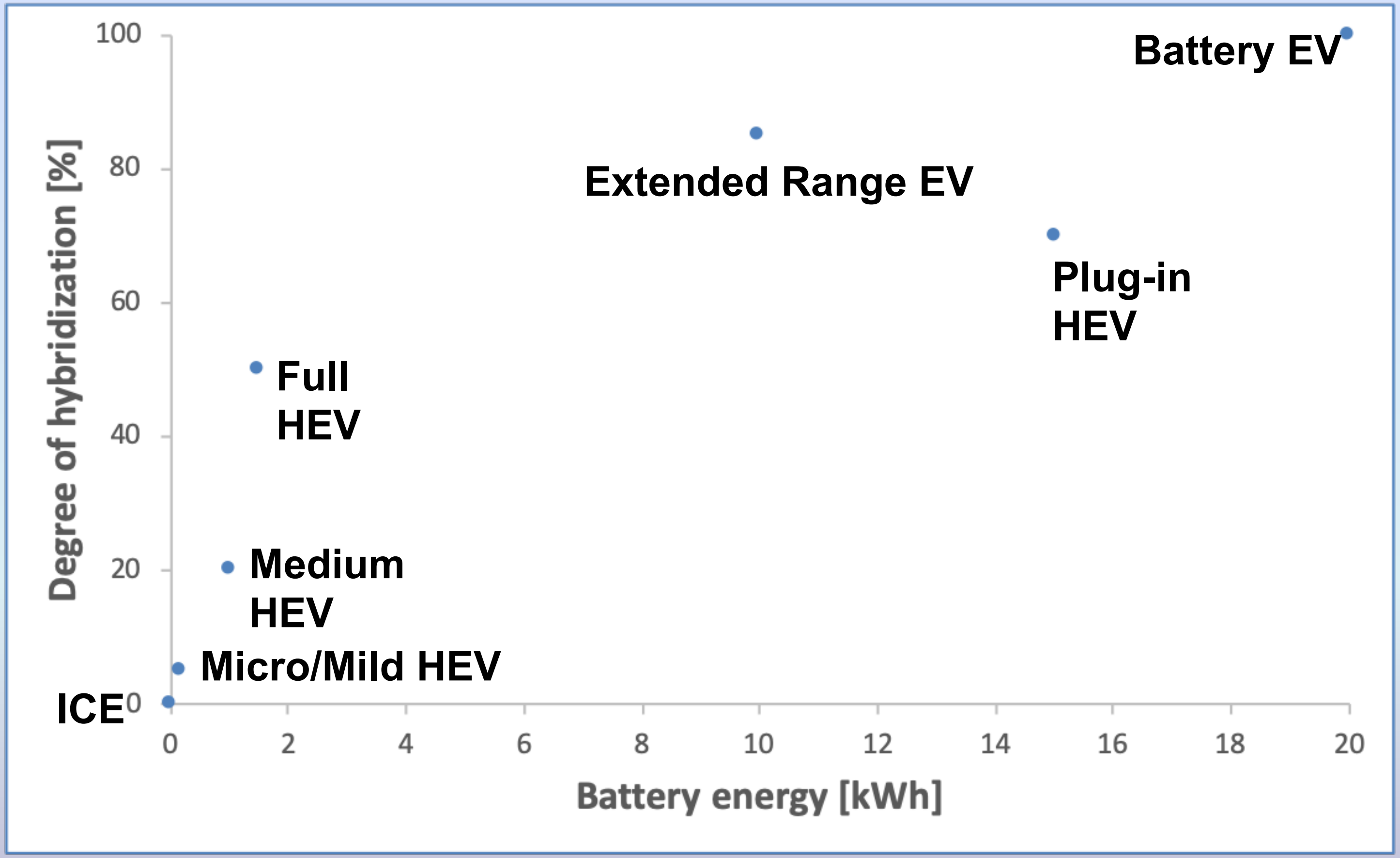
Degree of Hybridization

- A fundamental parameter in a Hybrid Electric Vehicle is the **Degree of Hybridization** (*DoH*).
- It is defined as the ratio of the **maximum power of electric motor** (EM), over the **sum** of the **maximum power of the (thermal) internal combustion engine** (ICE) and of the **electric motor**.

$$DoH = \frac{P_{EM,max}}{P_{ICE,max} + P_{EM,max}}$$

- DoH may range from **zero** (pure ICE) to **one** (pure EV). Its value characterizes the **different kinds of hybrid vehicles**.

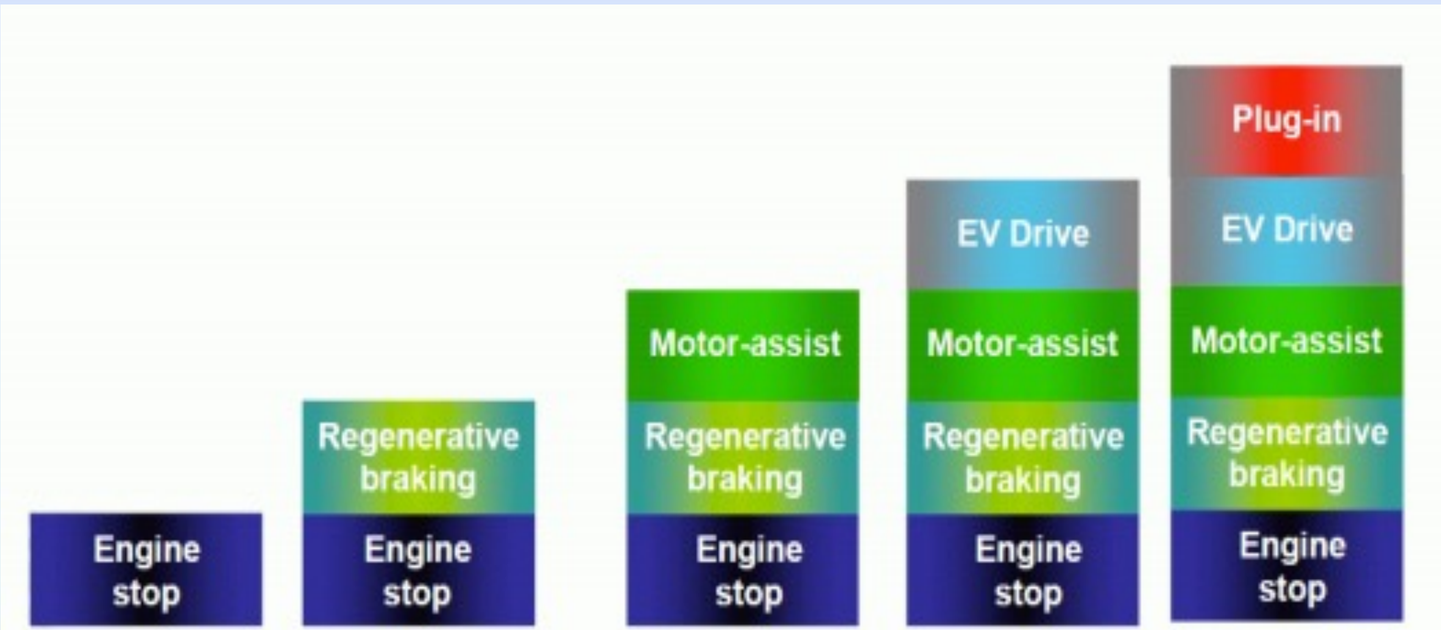
Degree of hybridization vs. battery capacity



Functional classification of EV/HEVs in terms of degree of hybridization and battery capacity (typical values).

Source: L.Guzzella and A.Sciarretta (2012), Vehicle Propulsion Systems, Introduction to Modeling and Optimization, Springer.

Degree of Hybridization



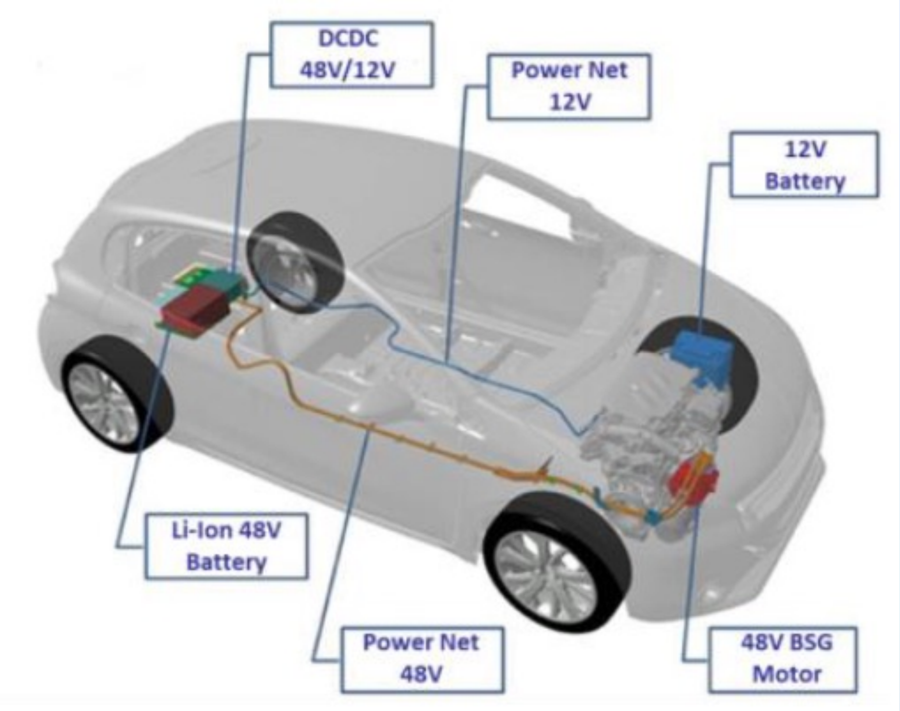
Hybrid features

micro/mild medium full plug-in

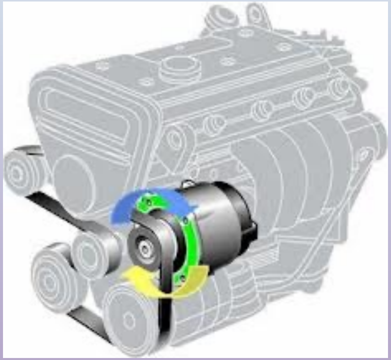
DoH

- Different levels of hybridization and of hybrid features can be achieved, at increasing values of the Degree of Hybridization *DoH*.

Micro Hybrids with BSG



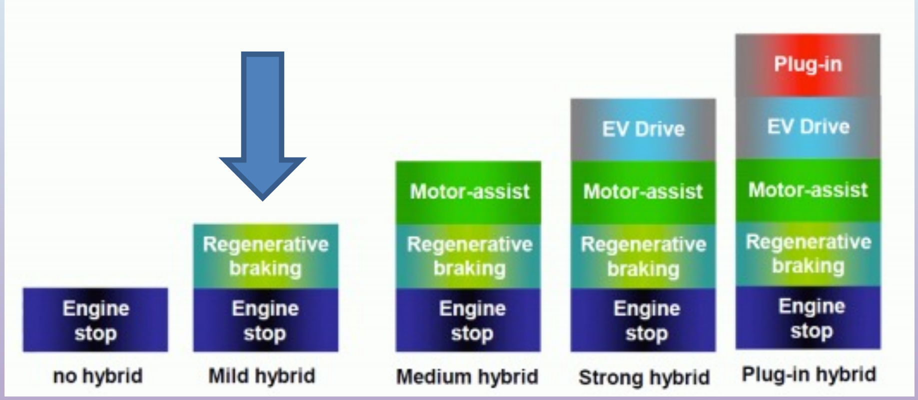
- The most advanced Micro Hybrid work at higher voltage (i.e. 48 V) with a **Belt Starter Generator** (BSG), up to about 15 kW.
- They use two **different voltage levels** (12V and 48V), a Lithium-Ion battery of about 300-500 Wh, and a DC/DC converter for recharging the 12V battery.
- A **reinforced belt** is adopted to allow adequate torque transfer.
- A limited support to the engine during **acceleration** and some recuperation of **braking energy** can be achieved with such systems.



Belt Starter Generator

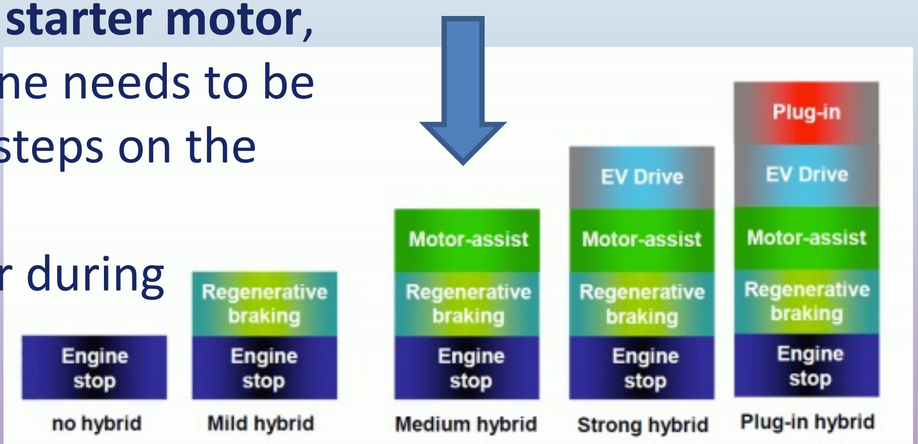
Mild Hybrids

- **Mild hybrids** are essentially conventional vehicles with oversized starter motors, **allowing the engine to be turned off whenever the car is coasting, braking, or stopped**, yet restart quickly and cleanly.
- As in other hybrid designs**, the motor is used for regenerative braking to recapture energy**.
- But there is **no motor-assist**, and **no EV mode at all**. Therefore, many people do not consider these to be hybrids, since there is no electric motor to drive the vehicle, and these vehicles do not achieve the fuel economy of real hybrid models.



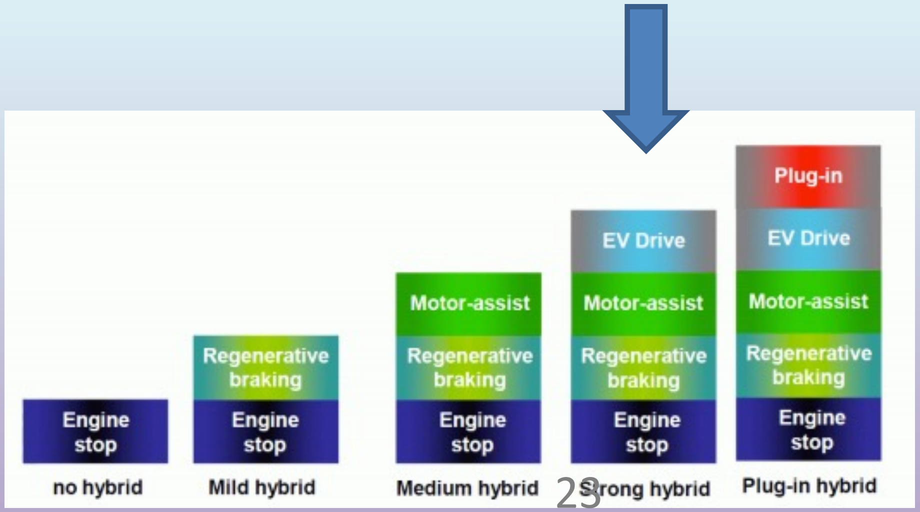
Medium Hybrid

- **Motor assist hybrids** use the engine for primary power, with a torque-boosting electric motor connected in parallel to a largely conventional powertrain.
- **EV mode is only possible for a very limited period of time**, and this is not a standard mode. Compared to full hybrids, the amount of electrical power needed is smaller, thus the **size of the battery system can be reduced**.
- The electric motor, mounted between the engine and transmission, is essentially a **very large starter motor**, which operates not only when the engine needs to be turned over, but also when the driver "steps on the gas" and **requires extra power**.
- The electric motor works as a generator during **regenerative braking**.



Full Hybrid

- A **full hybrid** can run on just the engine **(thermal mode)**, just the batteries **(electrical mode)**, or a combination of both **(hybrid mode)**.
- A large, **high-capacity battery pack** is needed for battery-only operation



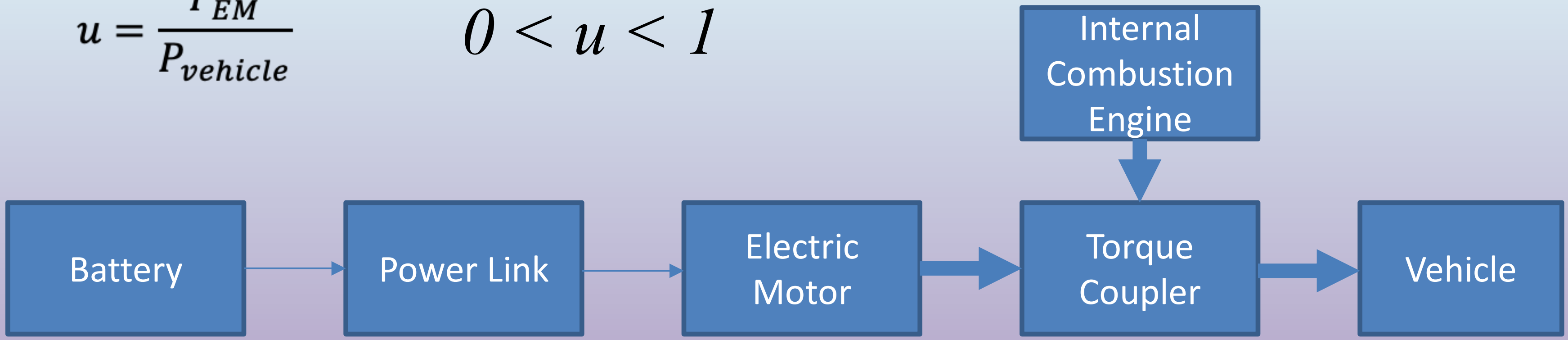
Plug-In HEV

- A **plug-in hybrid electric vehicle (PHEV) is a full hybrid**, able to run in electric-only mode, with larger batteries and the ability to **recharge from the electric power grid**.
- Their main benefit is that they **can be gasoline-independent for daily commuting, but also have the extended range of a hybrid for long trips.**
- Fuel efficiency is calculated based on actual **fuel consumed by the ICE and its gasoline equivalent of the kWh of energy delivered by the utility during recharge**.
- The **"well-to-wheel" efficiency and emissions** of PHEVs compared to gasoline hybrids **depends on the energy sources used for the grid utility** (coal, oil, natural gas, hydroelectric power, solar power, wind power, nuclear power).

Modes of operation of parallel hybrid vehicles: Power Assist

- During **startup** or **acceleration**, the engine provides only a fraction of the total power at the wheels, while the remaining part is delivered by the motor. This operating mode is often referred to as ***power assist*** mode.

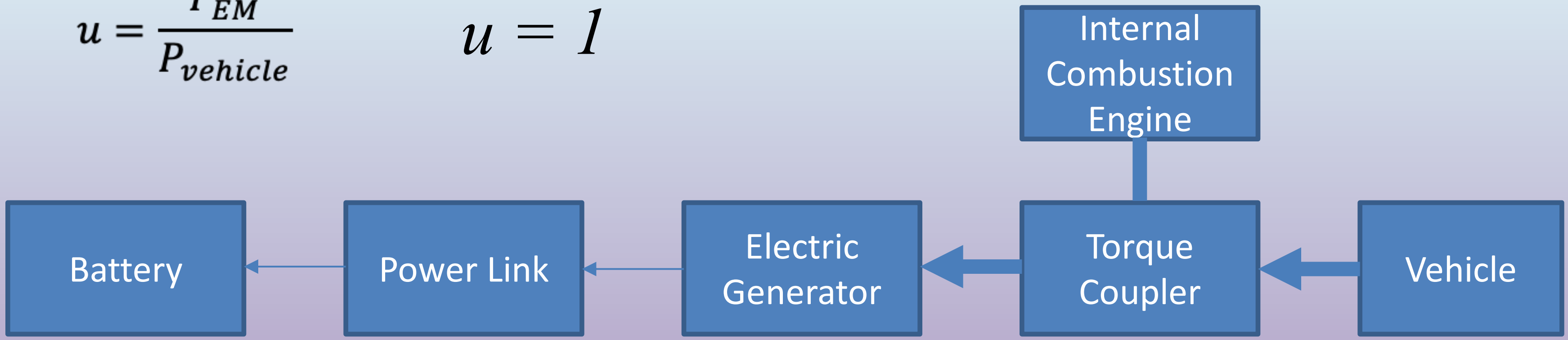
$$u = \frac{P_{EM}}{P_{vehicle}} \qquad 0 < u < 1$$



Modes of operation of parallel hybrid vehicles: Regenerative Braking

- During **braking** or **deceleration**, the motor acts as generator and recuperates energy into the battery.

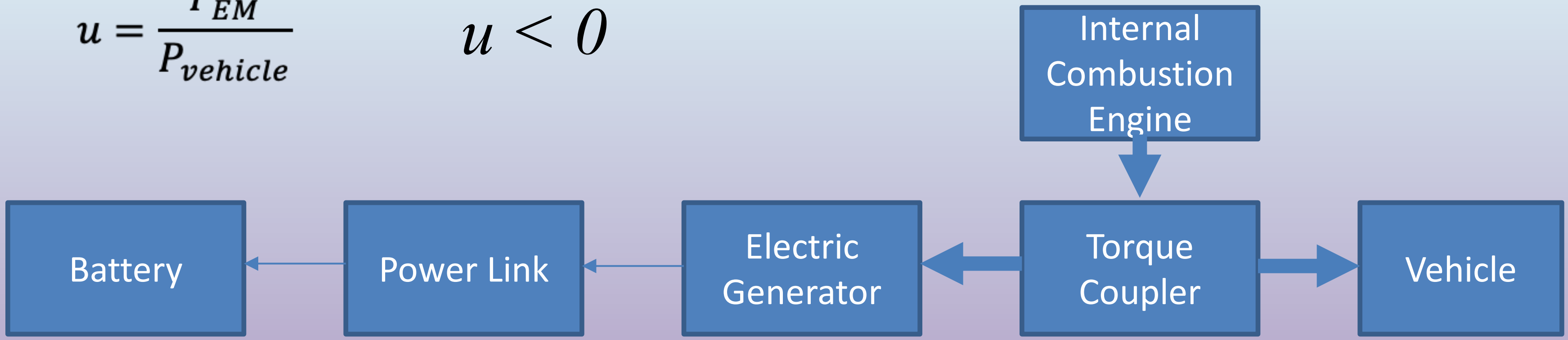
$$u = \frac{P_{EM}}{P_{vehicle}} \qquad u = 1$$



Modes of operation of parallel hybrid vehicles: Battery Recharging

- It is also possible to shift the **operating point of the engine** towards **higher efficiency**.
- At light load, the engine would then provide more power than strictly demanded and the extra power would be used to charge the battery via the electric machine.

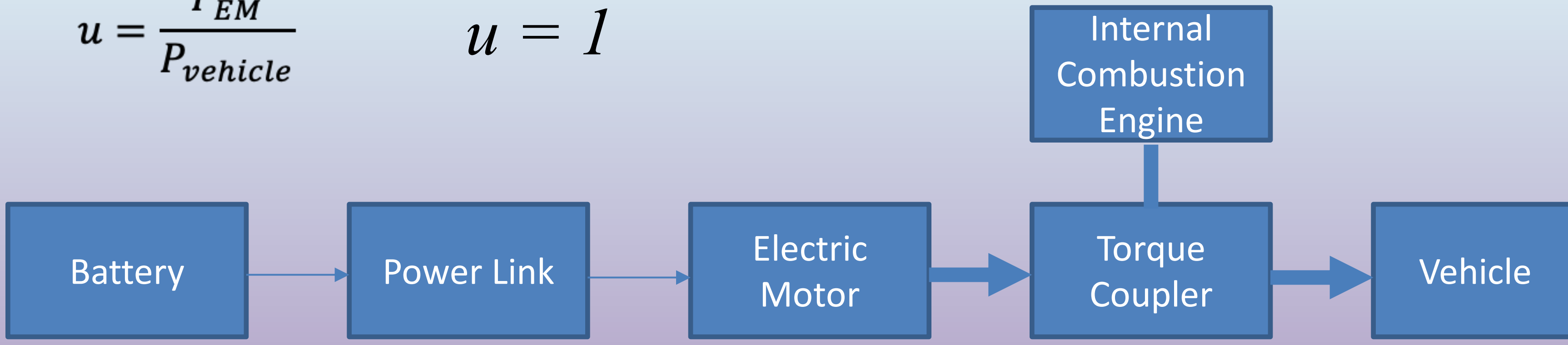
$$u = \frac{P_{EM}}{P_{vehicle}} \qquad u < 0$$



Modes of operation of parallel hybrid vehicles: Pure Electric

- In pure electric mode, engine is off and **only the electric motor drivers the vehicle**.
- In such way, **Zero Emission Vehicle** mode can be achieved. This is particularly useful in urban driving, when battery is enough charged.

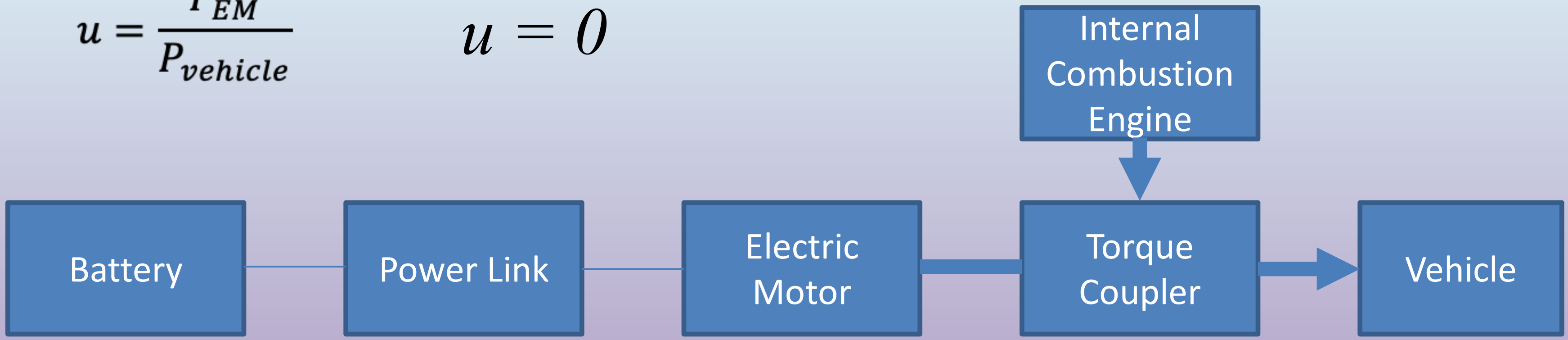
$$u = \frac{P_{EM}}{P_{vehicle}} \qquad u = 1$$



Modes of operation of parallel hybrid vehicles: Thermal Mode

- In **thermal mode**, the vehicle is powered **only by the engine**, as in a conventional vehicle.
- This mode may be used in extra-urban driving. Electric assistance would be necessary to reach the maximum vehicle power.

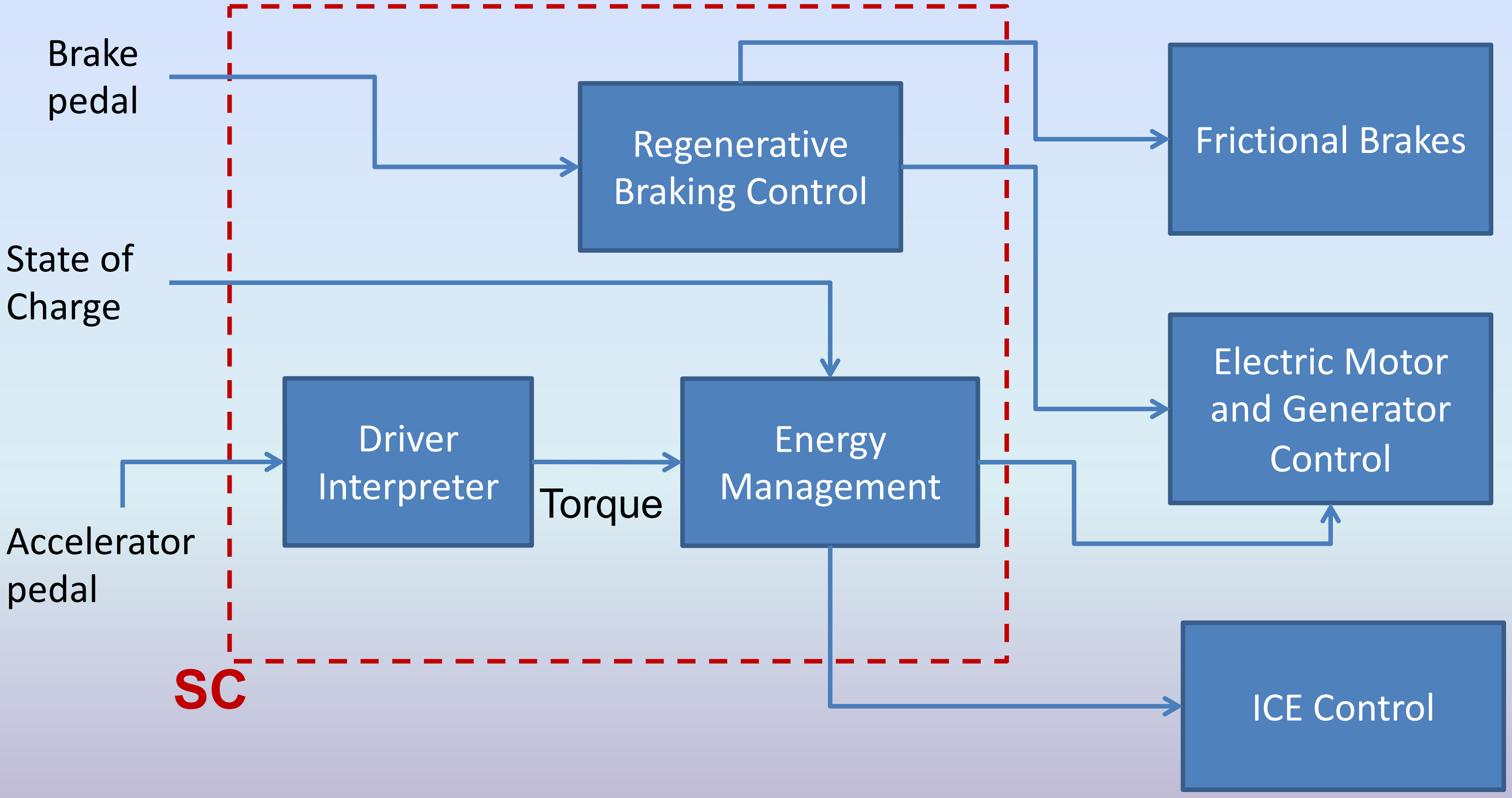
$$u = \frac{P_{EM}}{P_{vehicle}} \qquad u = 0$$



Energy Management

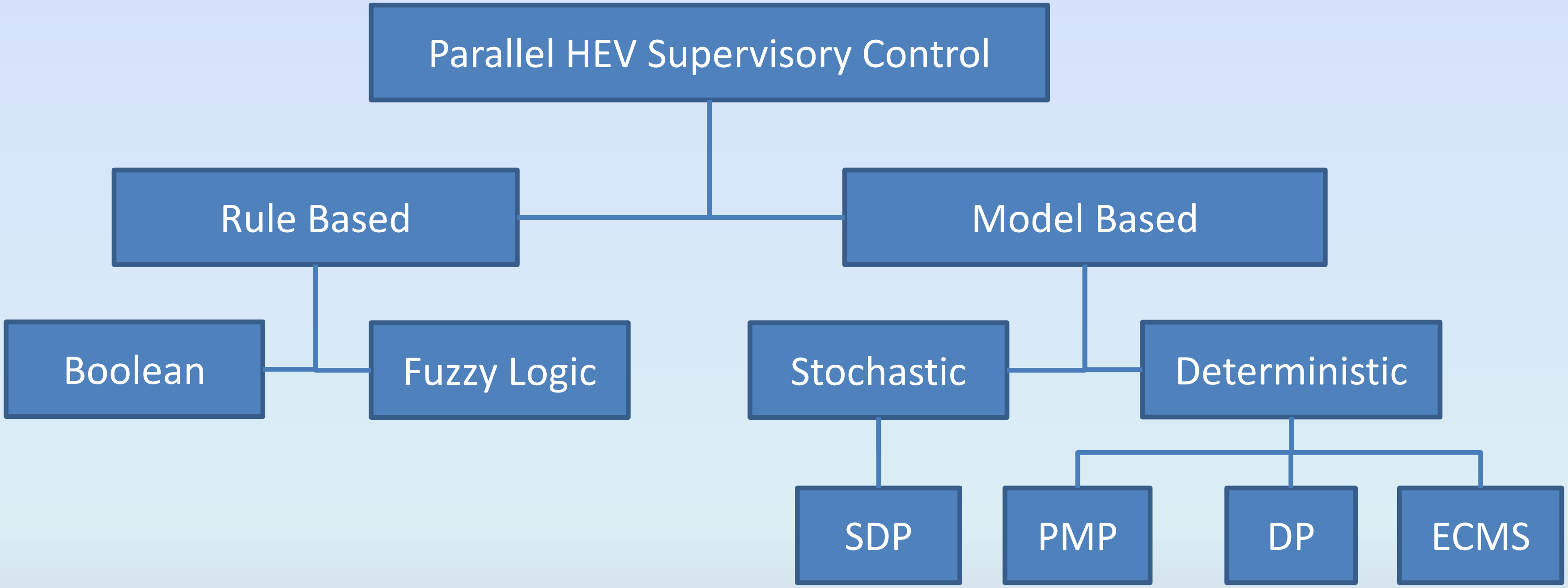
- In all types of hybrid vehicles, a **supervisory controller** (SC) must determine how the powertrain components should operate, in order to satisfy the **power demand** of the drive line in the best way.
- The main objective of the SC is **reducing the overall energy use**, typically in the presence of various **constraints** due to **emissions**, **driveability** requirements and the characteristics of the components.
- Different classification approaches can be adopted for the SC:
  - Off-line vs real-time
  - Causal vs non-causal (i.e. vehicle mission known in advance)
  - Heuristic vs optimal
  - Rule based vs model based

Supervisory Control Schematics



The scheme shows the main functions and components of a **Supervisory Control** SC (also Vehicle Management Unit, VMU) for a HEV.

Supervisory Control Classification



Acronyms:
DP: Dynamic Programming
ECMS: Equivalent Consumption Management Systems
MPC: Model Predictive Control
PMP: Pontryagin's Minimum Principle
SDP: Stochastic Dynamic Programming
T-ECMS: Telemetry ECMS

Adapted from: Tae Soo Kim, Optimal Control of a Parallel Hybrid Electric Vehicle with Traffic Preview, PhD Thesis, The University of Melbourne, November 2011

Rule based approach

In map based approach, the decisions about power split (u) for a Parallel HEV may be expressed as a function of vehicle torque and speed.

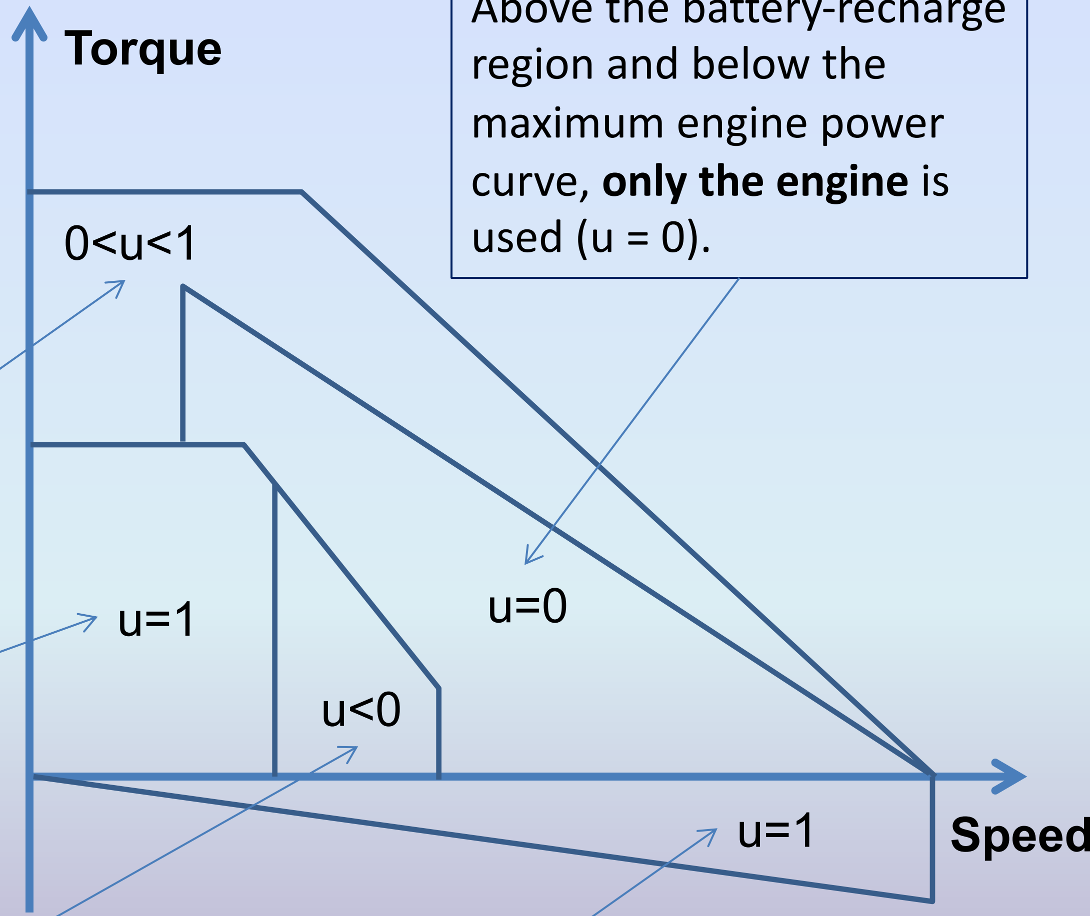
Above the maximum power of the engine, the motor is used to **assist the engine** (0 < u < 1).

Below a certain vehicle speed and a certain wheel power, **pure electric driving** is selected ($u = 1$).

For intermediate power levels, the engine is forced to deliver excess torque to **recharge the battery** (u < 0).

Above the battery-recharge region and below the maximum engine power curve, **only the engine** is used (u = 0).

At negative torque values, **regenerative braking** is adopted



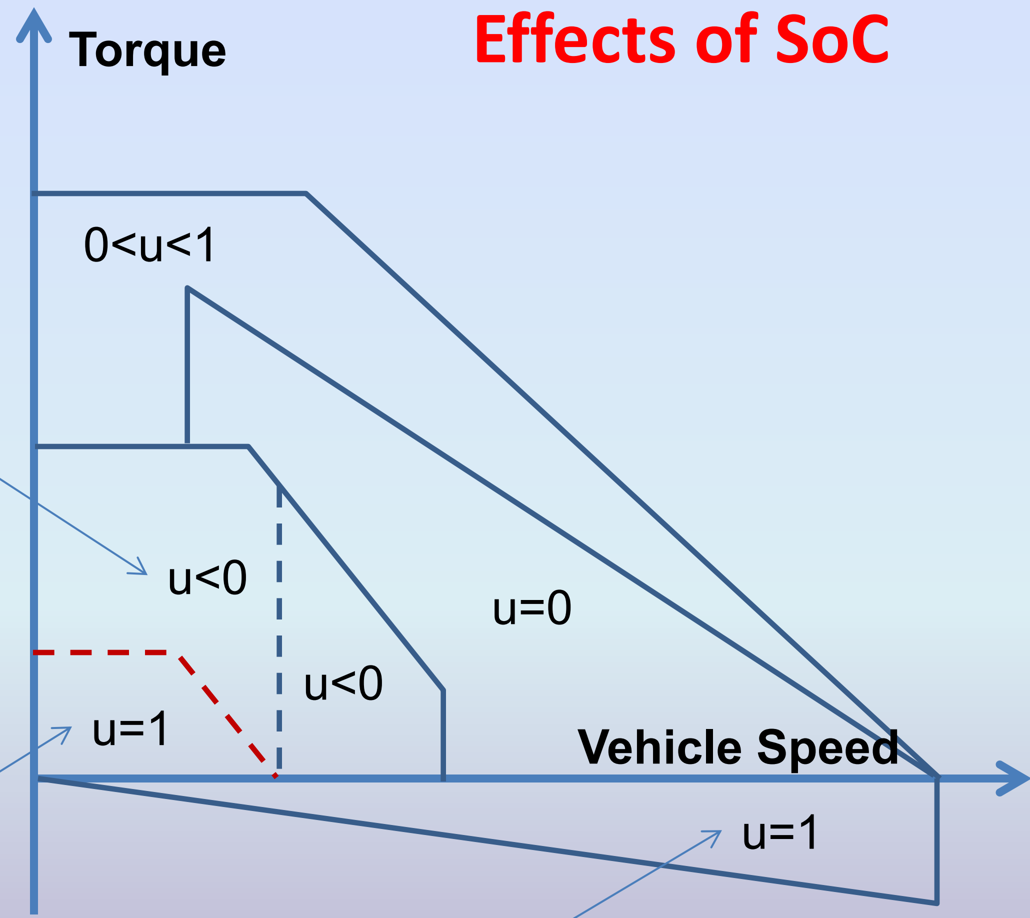
Rule based approach

Effects of SoC

The extensions of certain areas depend also by the actual state of charge (SoC) of the battery.

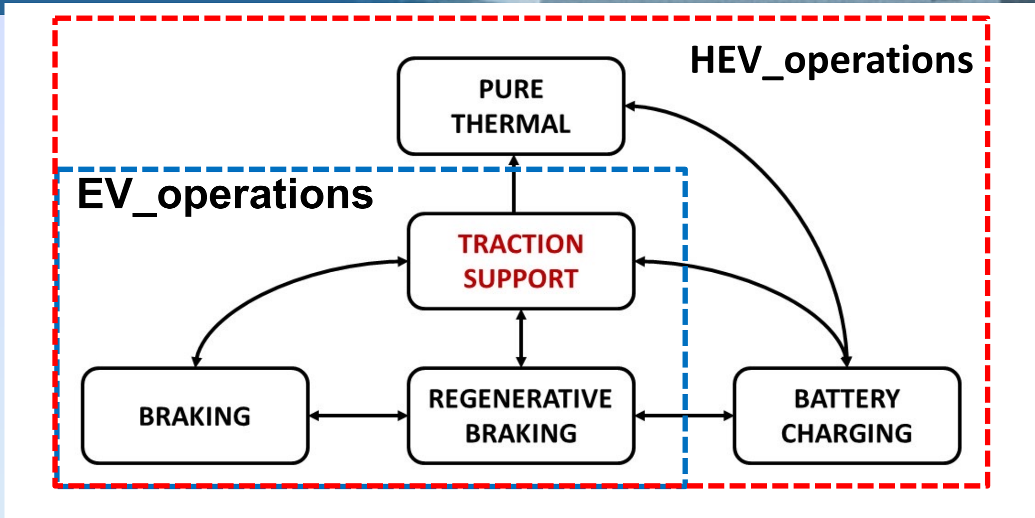
The operating region where the engine is forced to deliver excess torque to **recharge the battery** (u < 0) is enlarged as the SoC decreases (**red line**), while it is reduced or eliminated when battery is full charged.

When SoC decreases, the area of **pure electric driving** (u = 1) is reduced too.



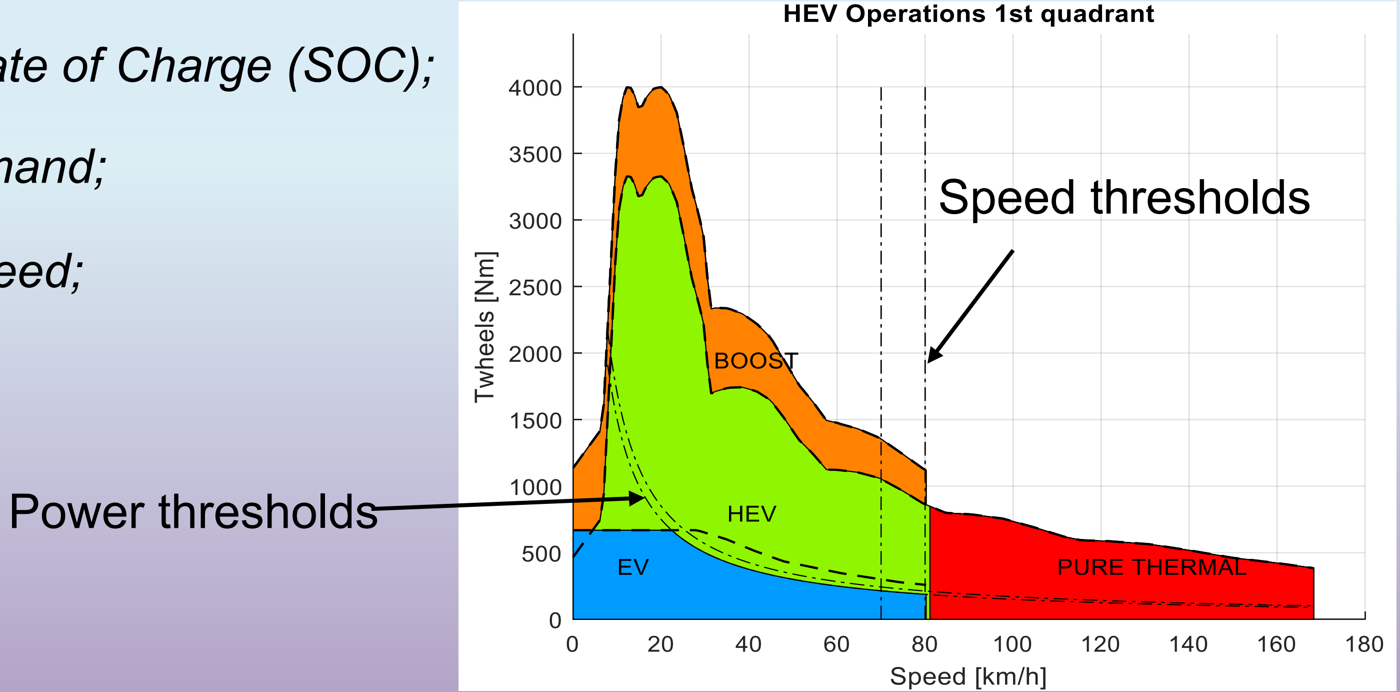
When battery is **fully charged**, the current coming from electric brakes **cannot be delivered to the battery**.

Rule based approach



Transition between Pure EV and HEV depends on following main conditions:

- *Battery State of Charge (SOC);*
- *Power demand;*
- *Vehicle speed;*



Optimal Energy Management
Off-line vs real-time strategies

- Two basically different approaches can be adopted to design optimal control strategies in a HEV:
  - **Off-line strategies**. The **driving mission is assumed to be known a priori (Non-causal)**. No constraints of computational power and time are given. This strategy is **not implementable**, but is useful for the components design/sizing, to determine **benchmarks**, to assess the quality of implementable sub-optimal strategies.
  - **On-line strategies**. In general, **driving mission is not known**, except in particular conditions. There are also limitations in terms of computational time and power, and on reliability. **Sub-optimal strategies** are therefore often implemented.

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