Powertrain architecture and transmission technologies

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Academic Year 2021-2022

Outline

- ICE Drivetrain Architecture
  - Clutches
  - MT gear boxes
  - AT gear boxes
  - CVT
  - Differential

- Architectures of electric powertrains
  - Centralized electric drivetrain
  - Distributed electric drivetrain
  - Hybrid

Outline

- Hybrid powertrain
  - Definition
  - Series, parallel and parallel-series, complex
  - Torque coupling
  - Speed coupling

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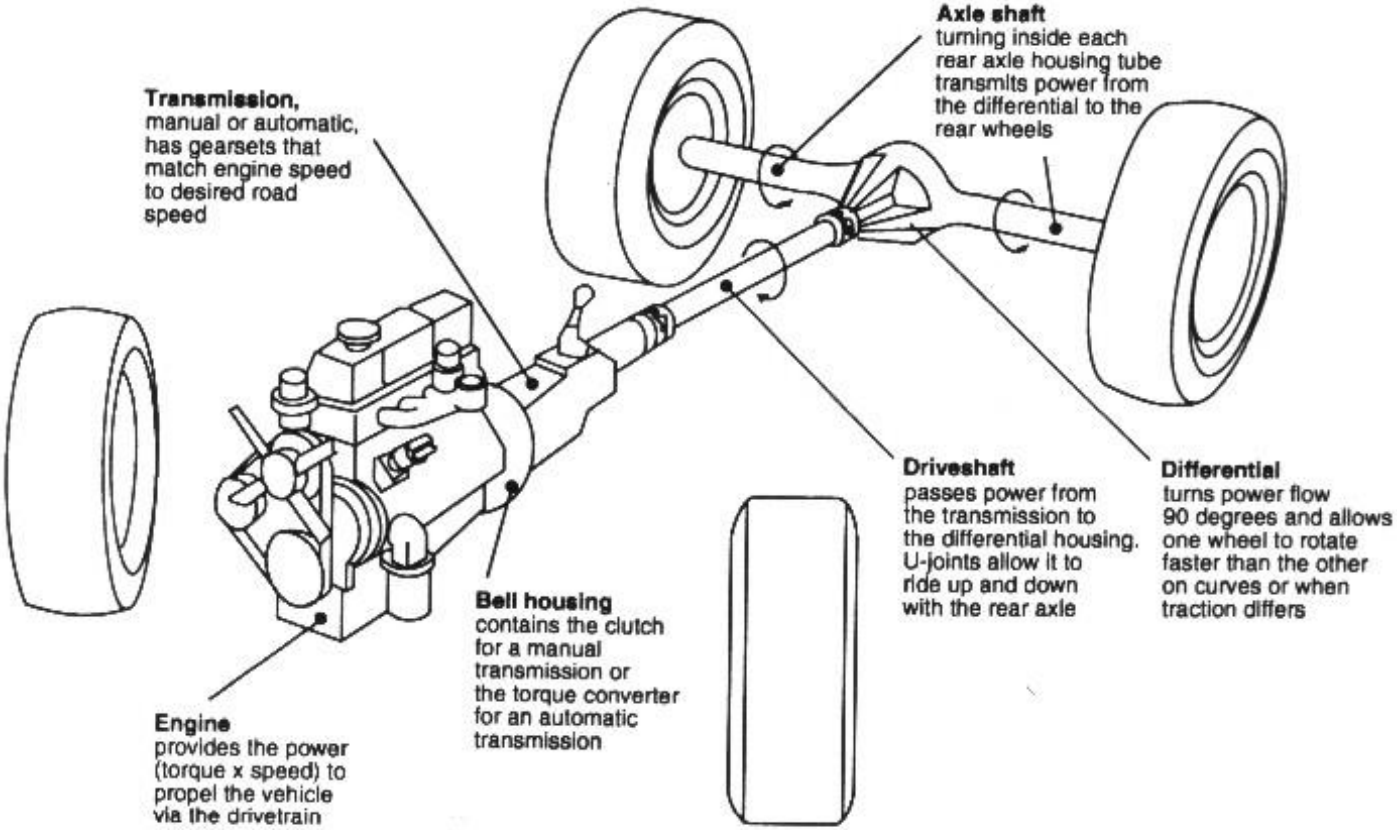
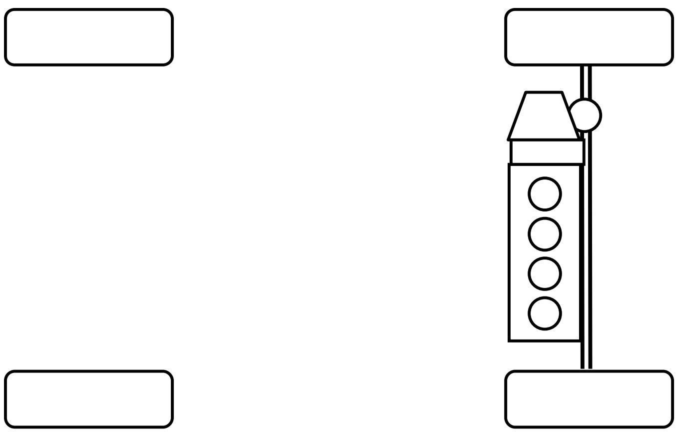
ICE Drivetrain

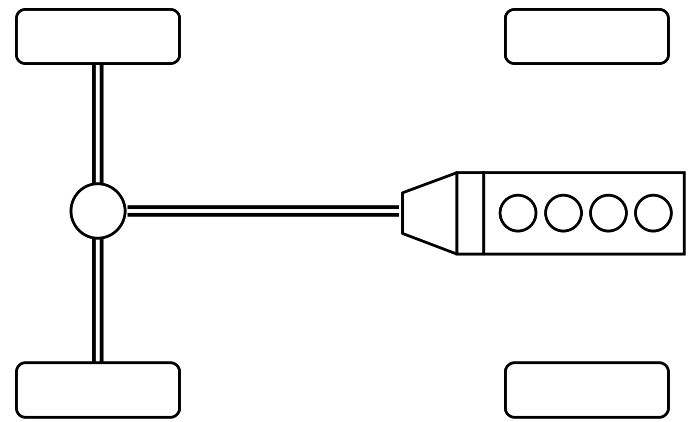
ICE Propulsion system



Gillespie, Fig 2.3

Layout of transmission

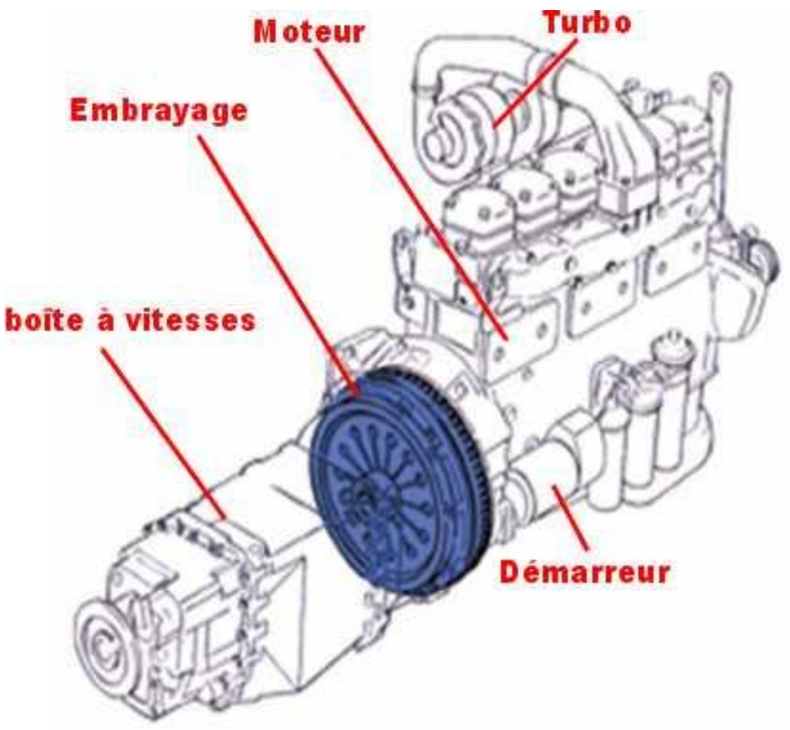


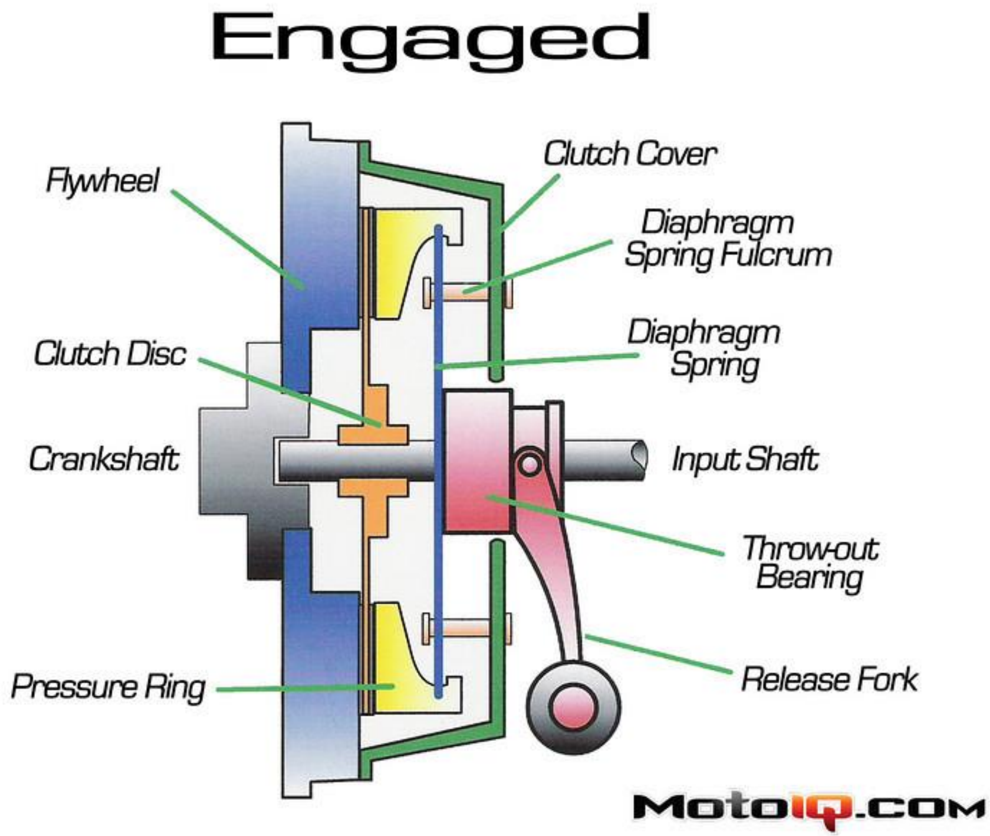


Transversal mounting

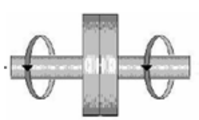
Longitudinal mounting

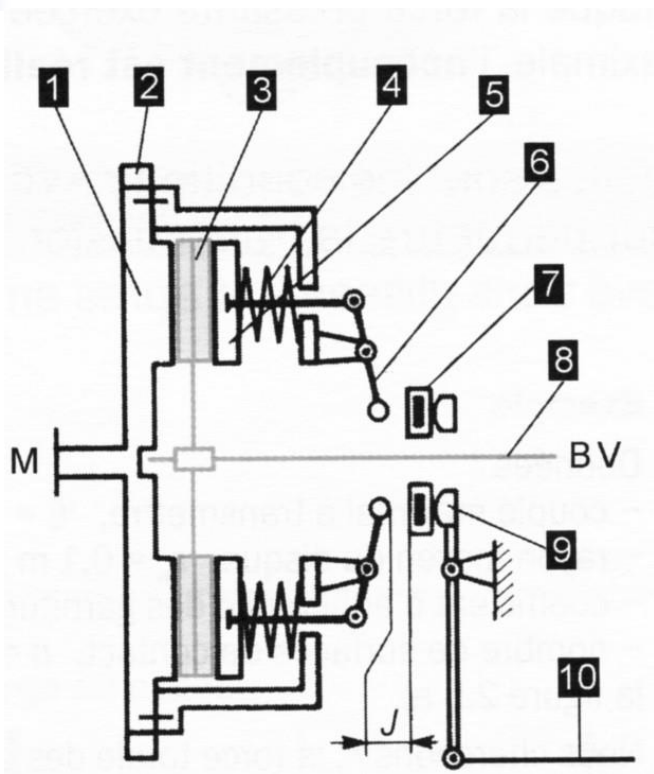
Friction Clutch



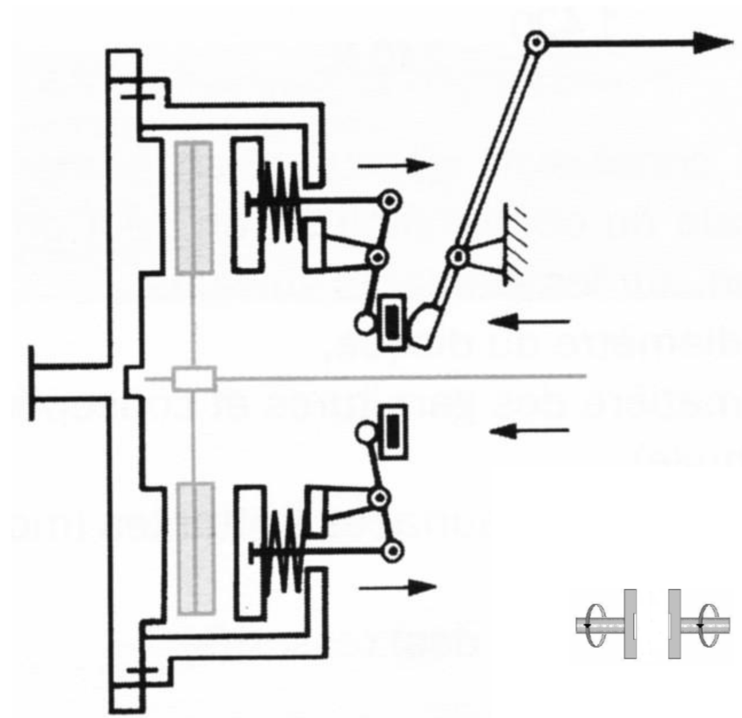


Friction Clutch



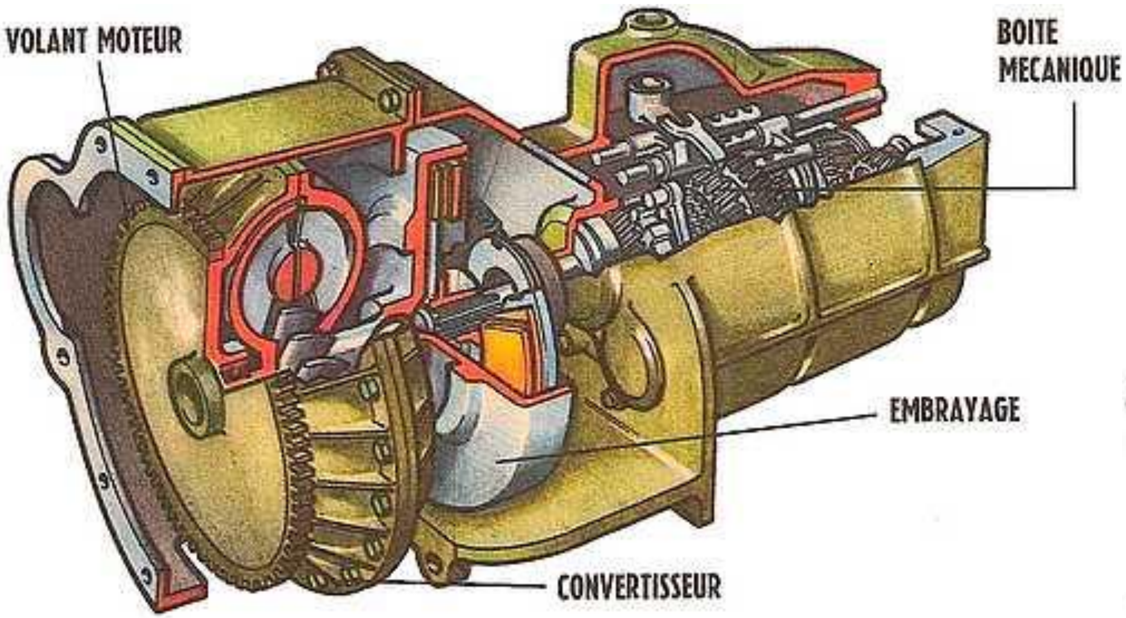


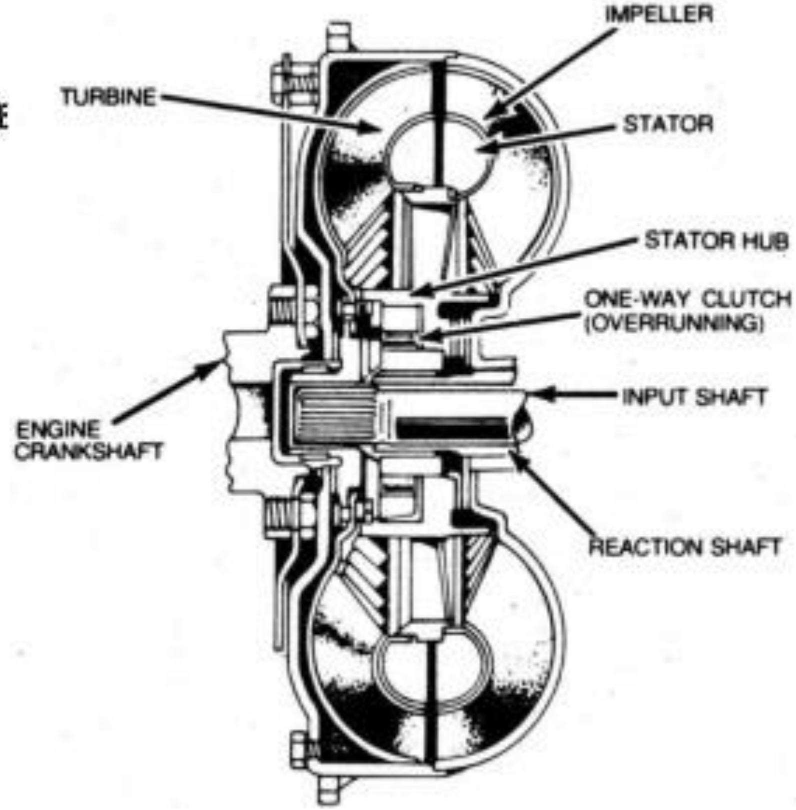
Clutch in closed position



Clutch in open position

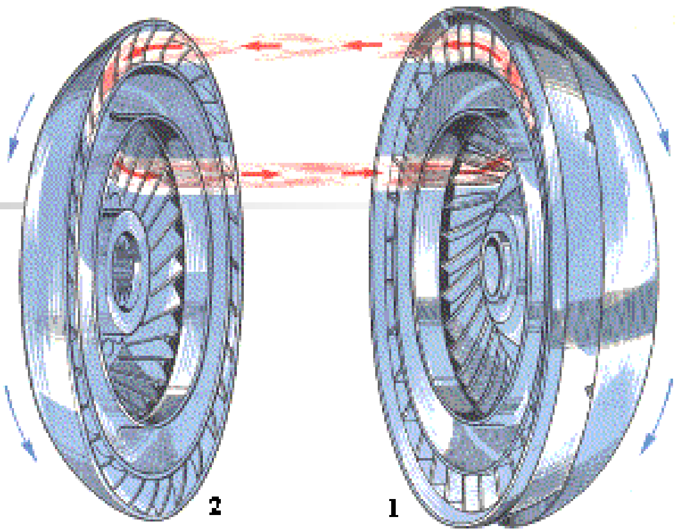
Torque converter (Hydraulic coupling)

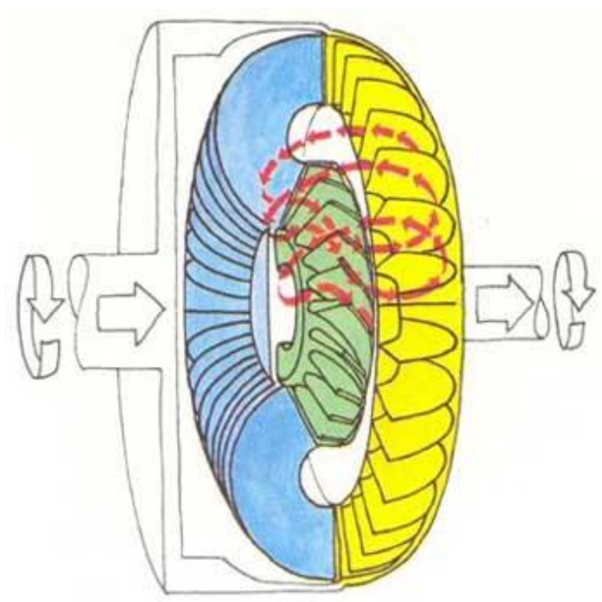




Hydraulic coupling

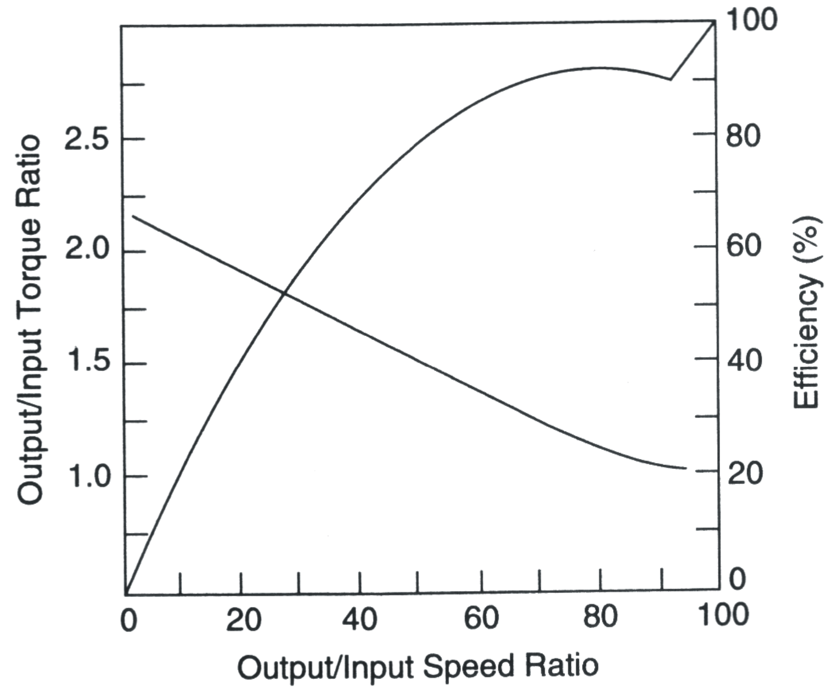
- Principle: use the hydro kinetic energy of the fluid to transfer smoothly the power from the source to the load while amplifying the output torque
- The input wheel (impeller) plays the role of a pump whereas the output wheel acts as a turbine
- One may add a fixed wheel (stator) to improve the efficiency

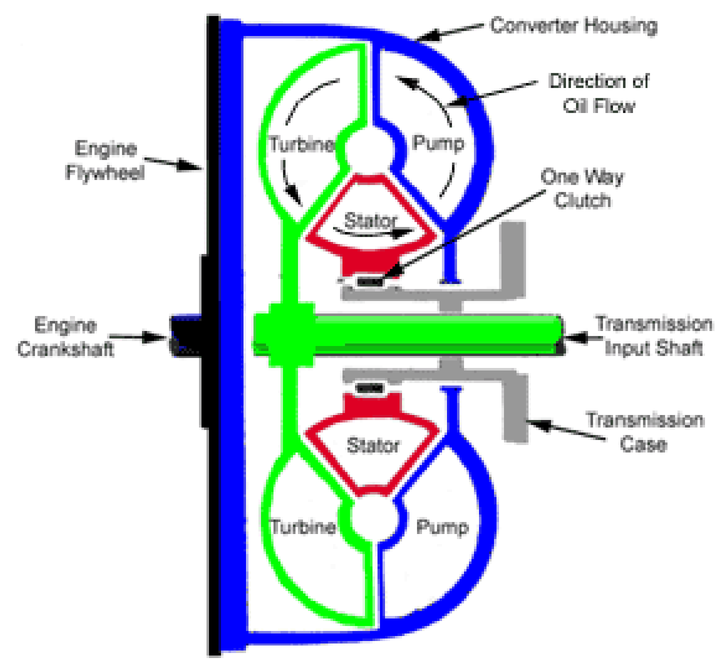




Hydraulic coupling

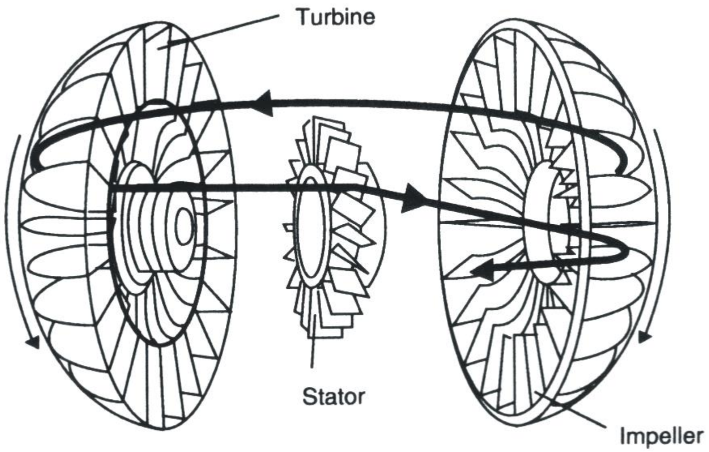
- Hydraulic torque converters exhibit a growing efficiency up to a speed ratio up to 90%.
- Max power efficiency is about 90 to 92%
- For low output rotation speeds, torque converters gives rise to magnification of the output torque.

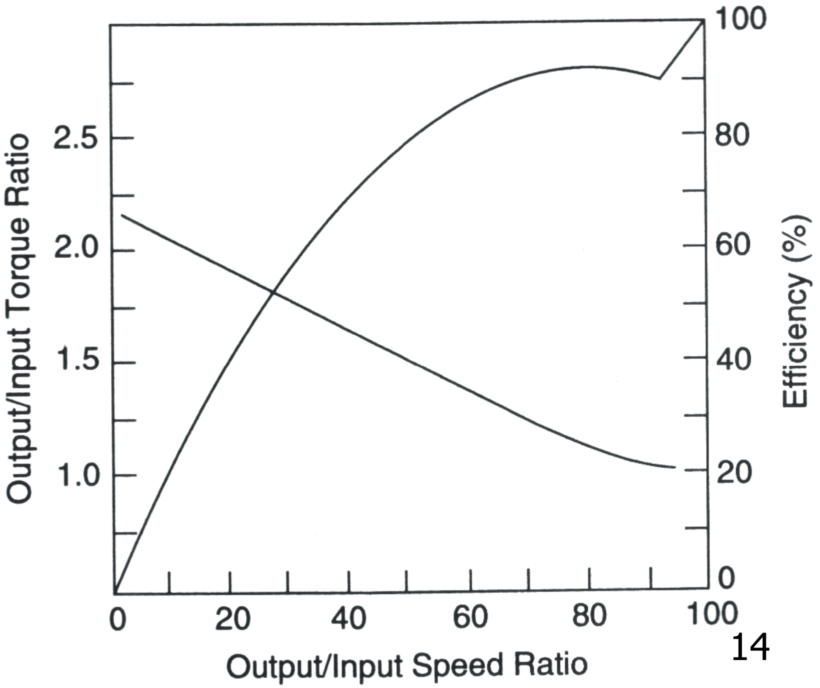




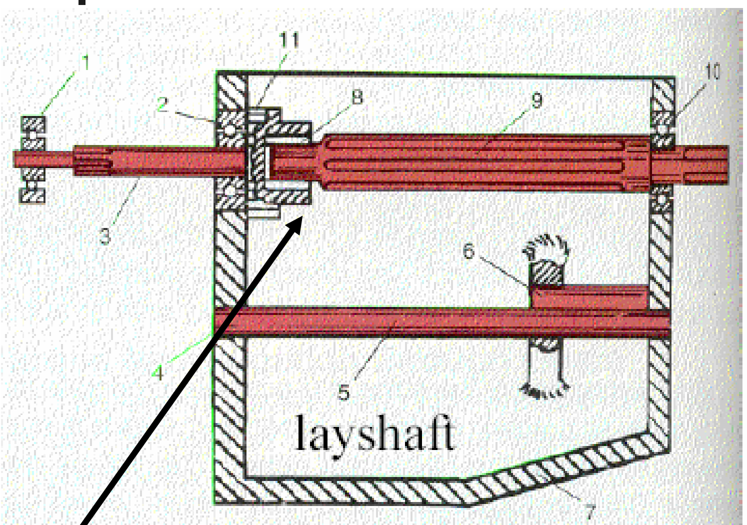
Friction and hydraulic clutches

- Clutch efficiency
  - Friction clutch $\eta=1$
  - Hydraulic coupler: $\eta \sim 0.9$



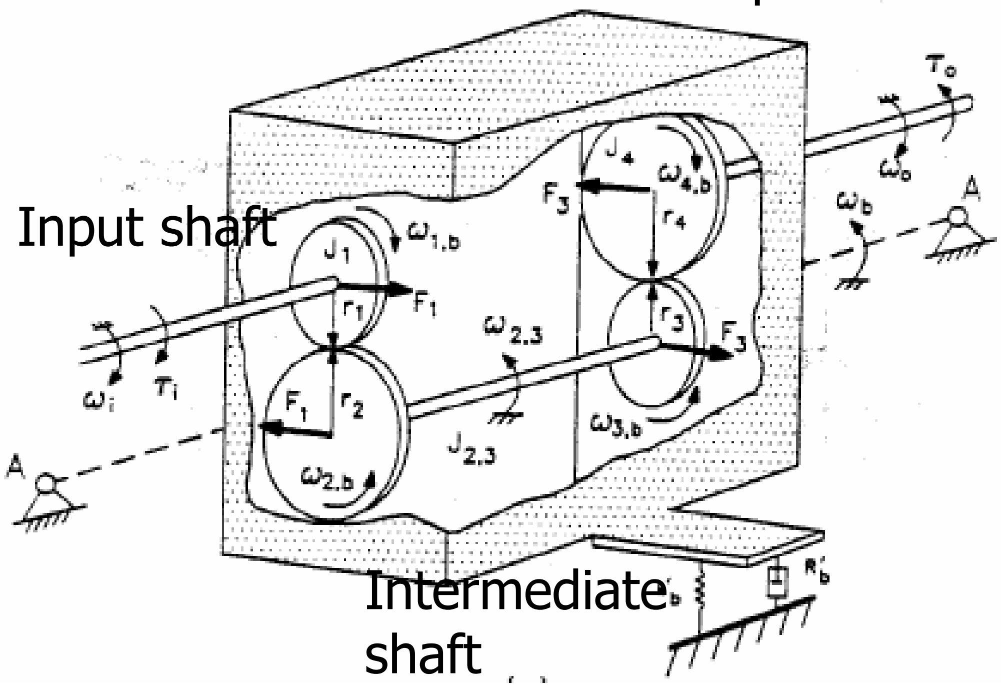


Manual gear boxes



Direct transmission

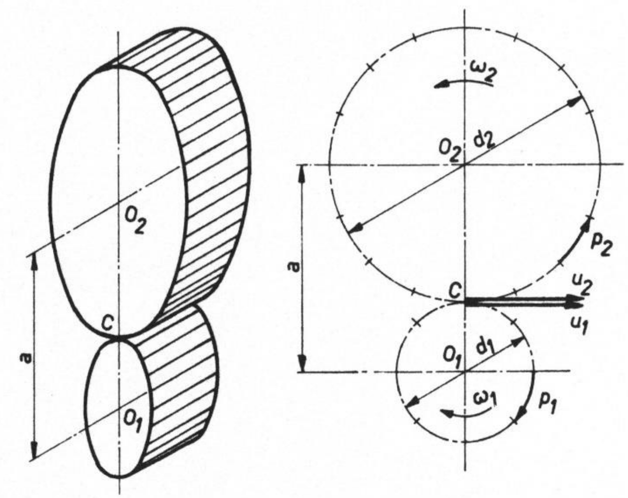
Gear box principles



The gear pairs

- Meshed gears behave like two rigid cylinders with equivalent pitch diameters d_{01} and d_{02} rolling on each other without any slippage
- If there is no slippage, on can write

$$v_1 = \frac{\omega_1 \, d_{01}}{2} = v_2 = \frac{\omega_2 \, d_{02}}{2}$$

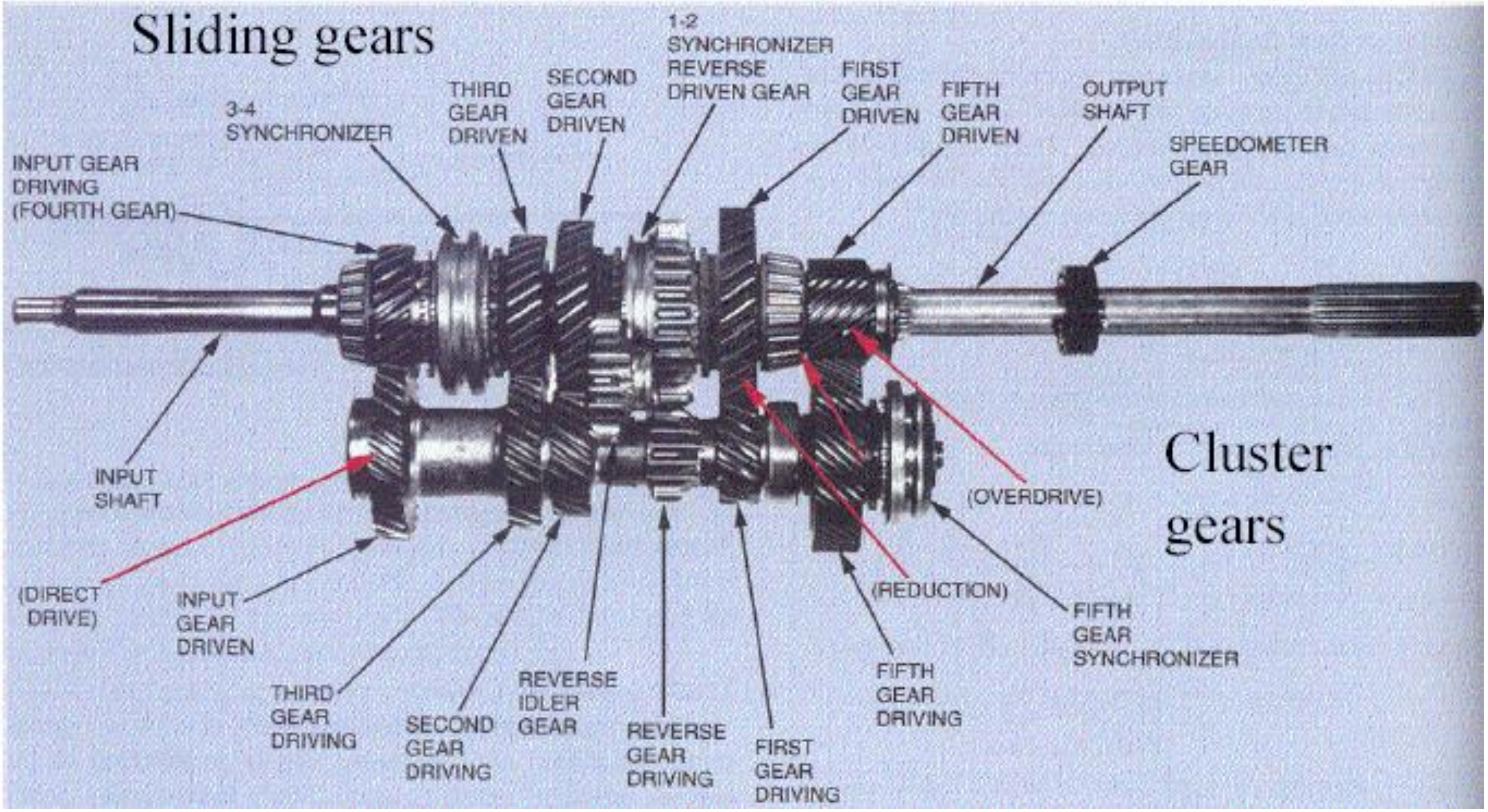


- Thus, the reduction ration i

$$\frac{d_{02}}{d_{01}} = \frac{\omega_1}{\omega_2} = i > 1$$

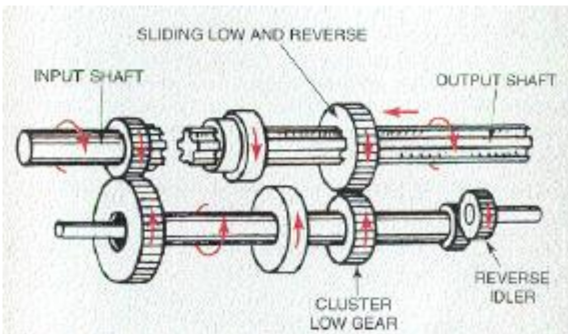
- For external meshing, there is an inversion of rotation direction while for internal gear meshes, the gear rotation direction is preserved (like belt and pulleys or chains)

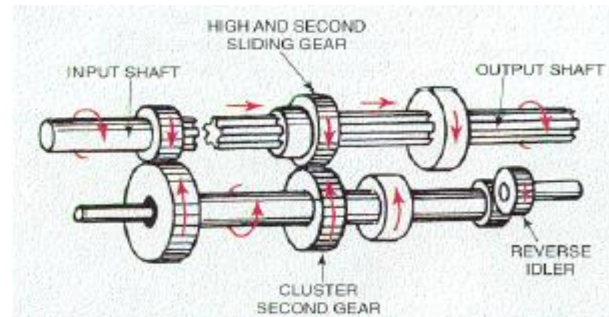
Manual gear boxes



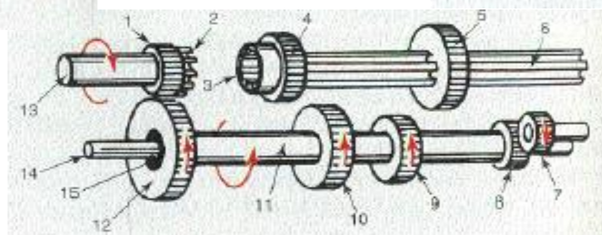
Manual gear boxes

1st



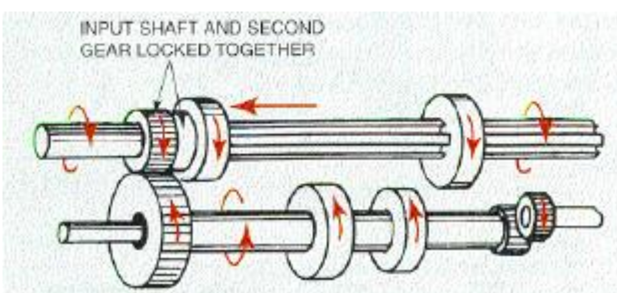


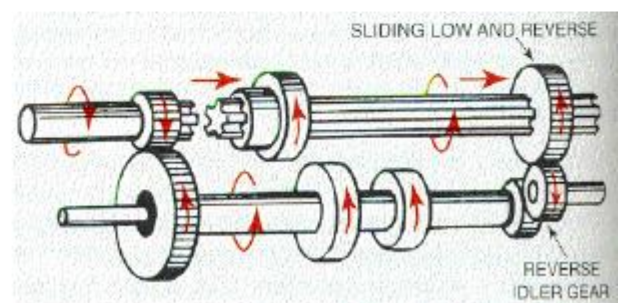
2nd



Neutral

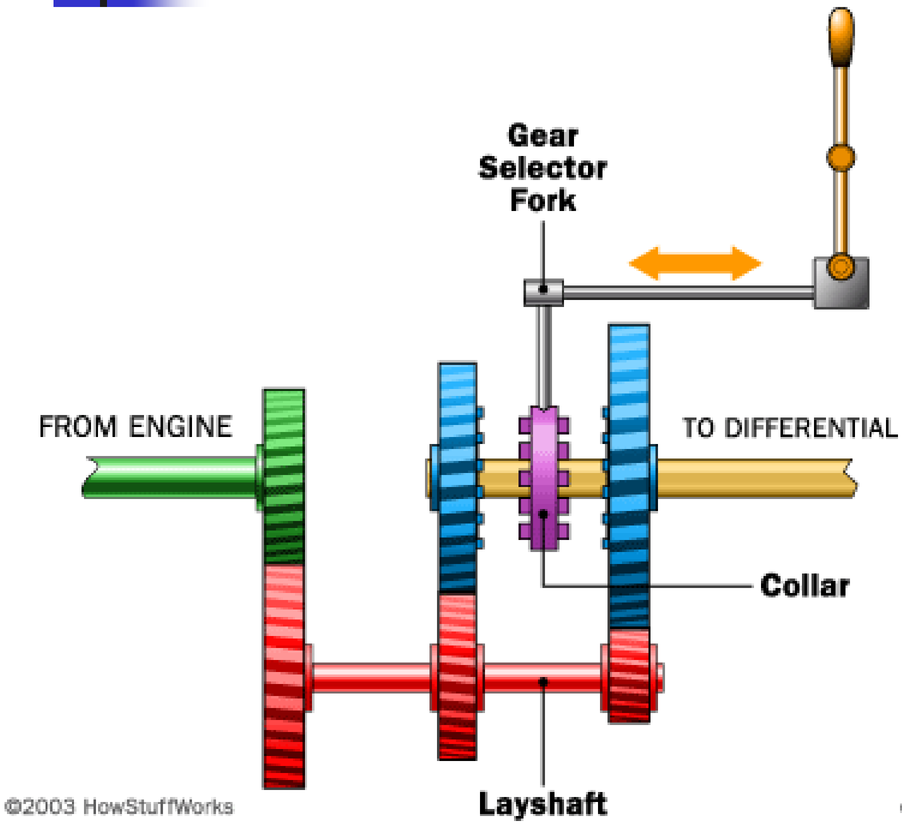
3rd

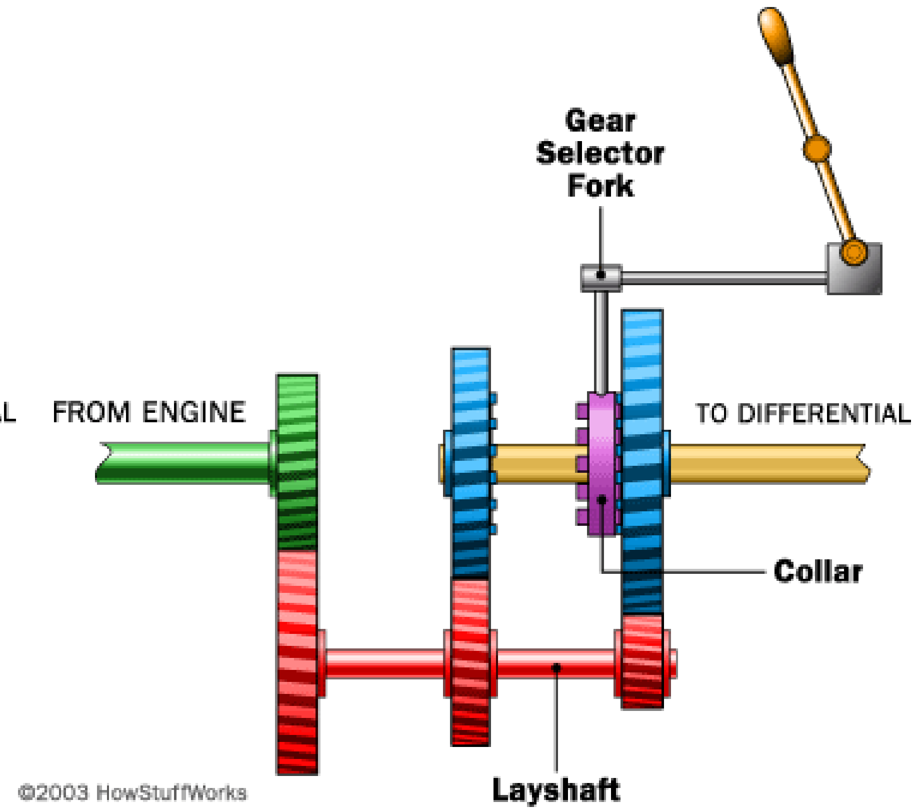




Reverse

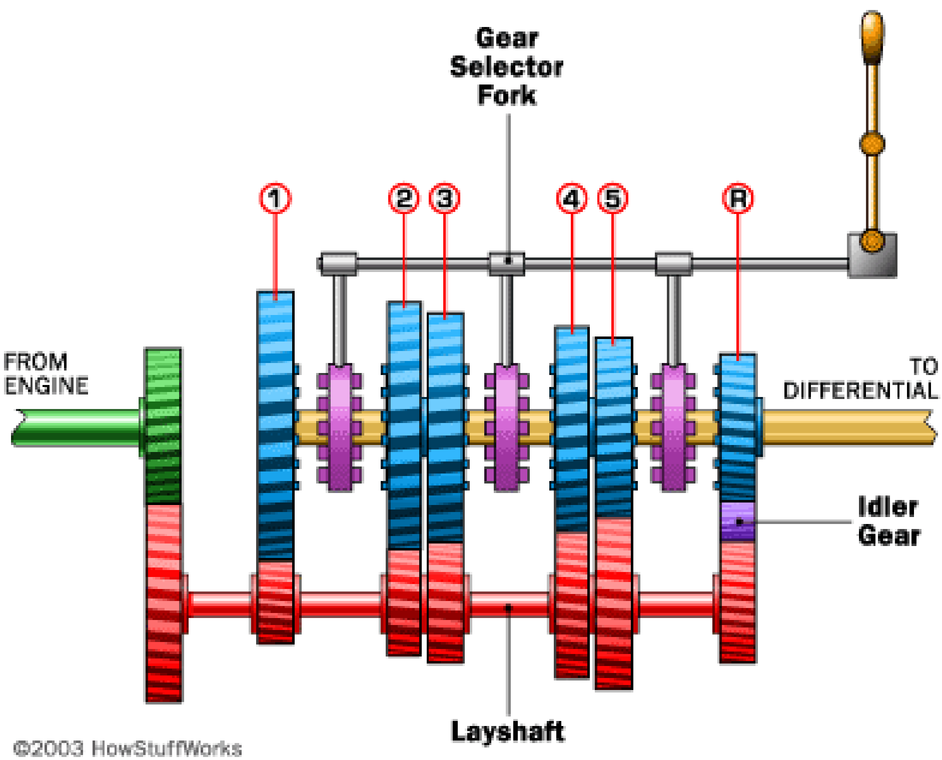
Manual gear boxes

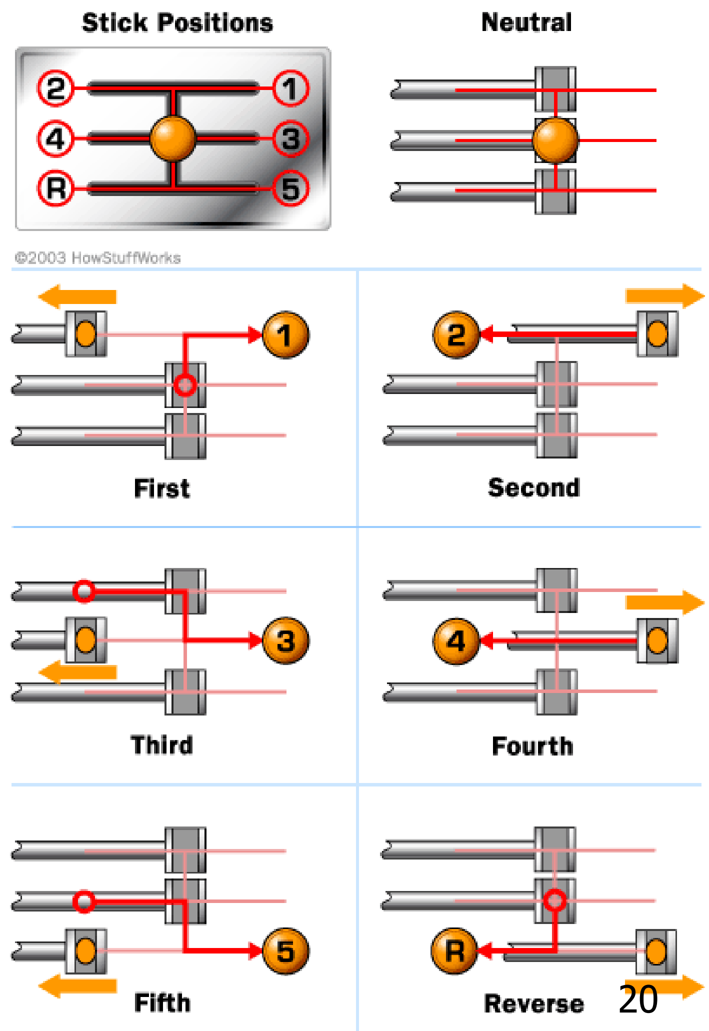




Gear selection

Manual gear boxes operations





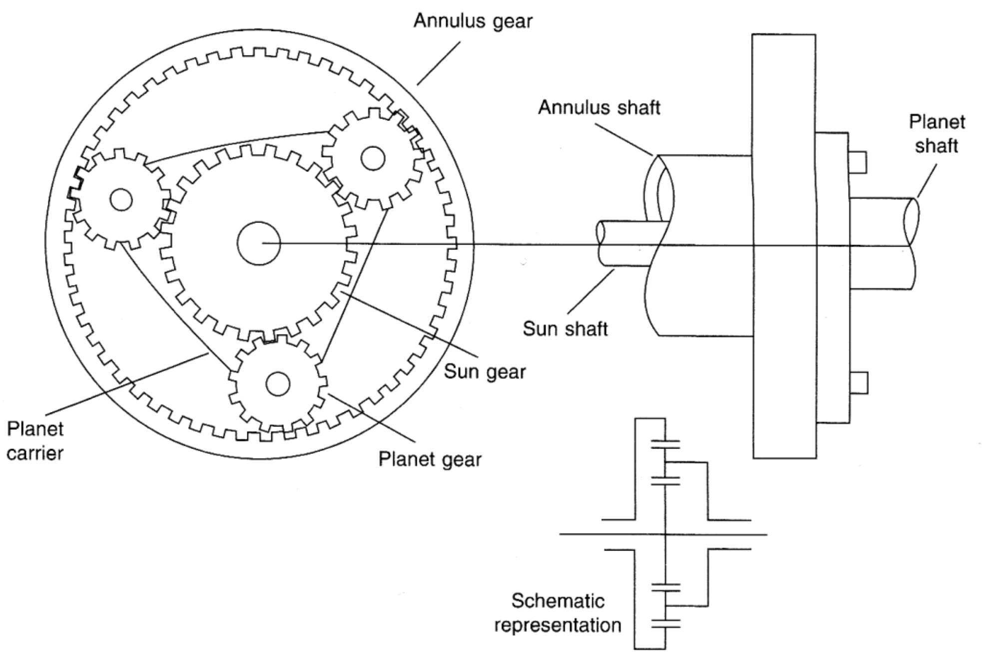
Selection of a gear ratio using rod or cable mechanism

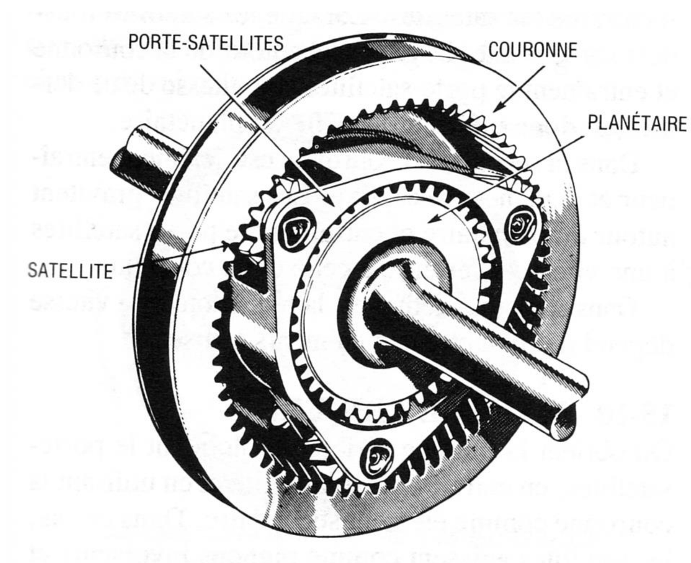
Power and tactive efforts at wheels

- Manual gearbox efficiency:
  - Efficiency of a pair of gear (good quality) η= 99% to 98.5 %
  - Gear box: double gear pairs: η = 97.5%
  - Gear box: direct drive: η = 100%

Automatic gear boxes

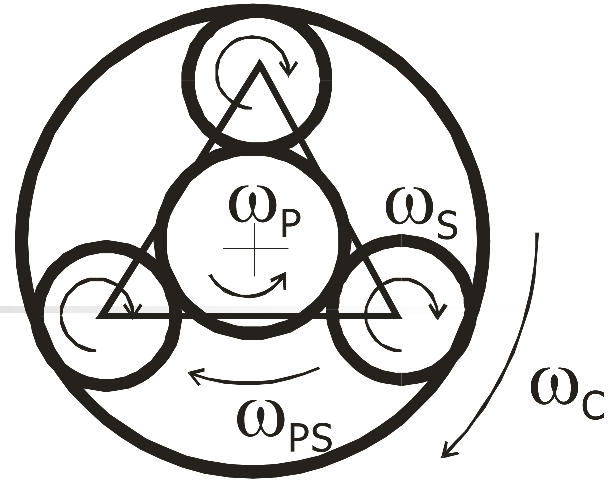
- The basic element of automatic gear boxes is the planetary gear train





Sun = planétaire   Planet = satellite   Annulus = Couronne

Planetary gear pair



- Kinematics: Willys formula

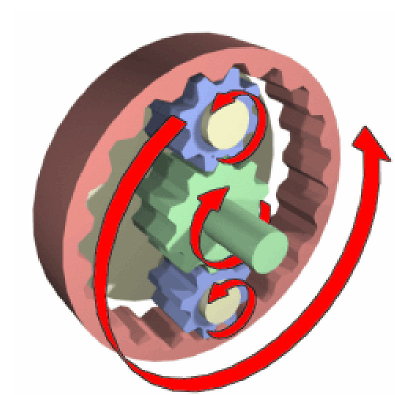
$$\omega_C Z_C + \omega_P Z_P = \omega_{PS}\,(Z_C + Z_P)$$

$$\boxed{\omega_P + i\,\omega_C = \omega_{PS}\,(1+i)} \qquad i = \frac{Z_C}{Z_P}$$

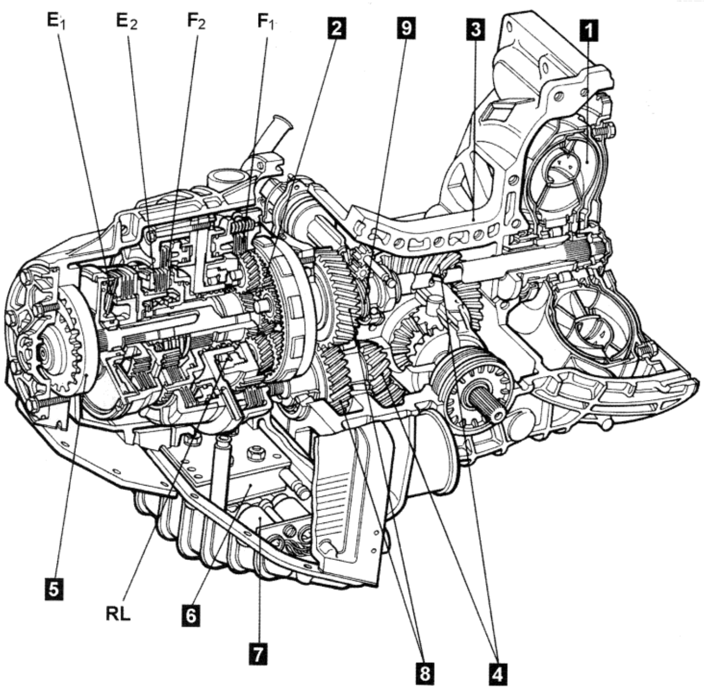
Relation between the rotation speed of the different gear trains and the ratio of teeth of the sun and the annulus

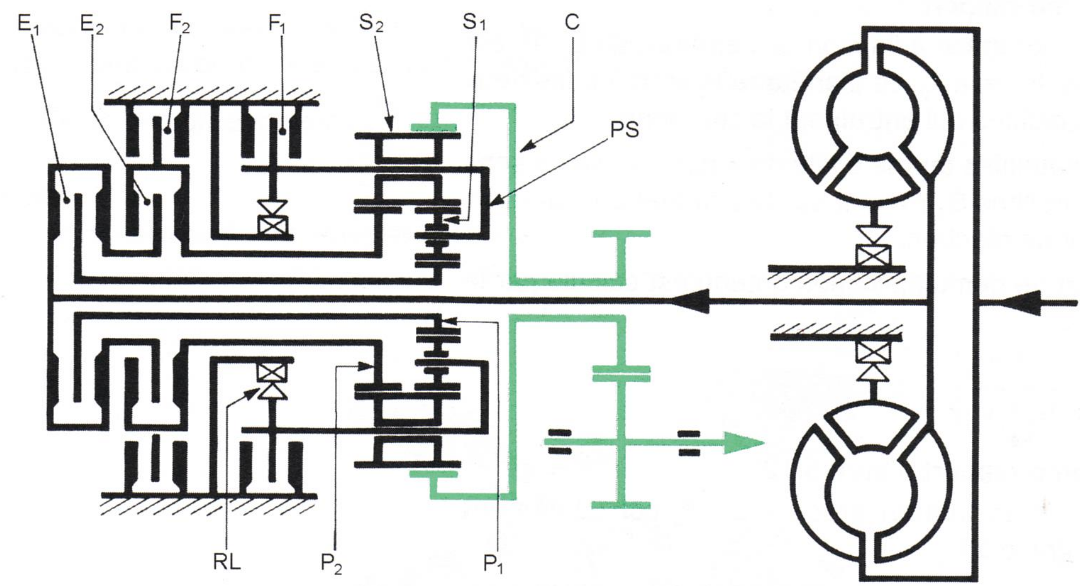
- Static: Equilibrium of torques

$$\boxed{T_{PS} = -(1+i)\,T_P = -\frac{1+i}{i}\,T_C}$$



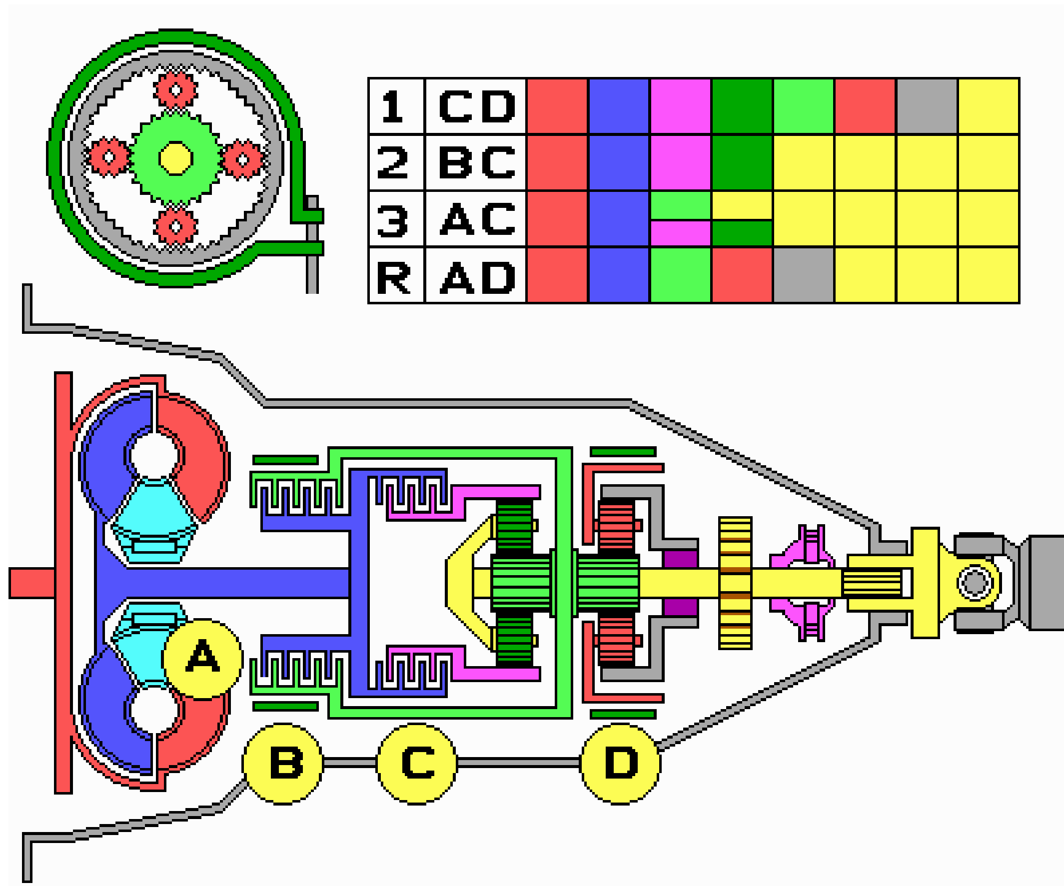
Automatic gear box





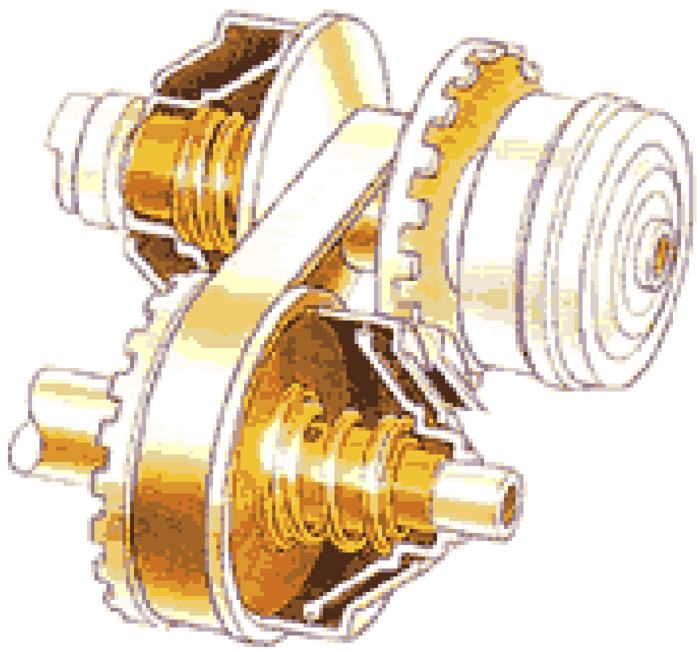
Principle of an automatic gear box based on double planetary gear trains
Mèmetaux Fig 5.9

Automatic gear box

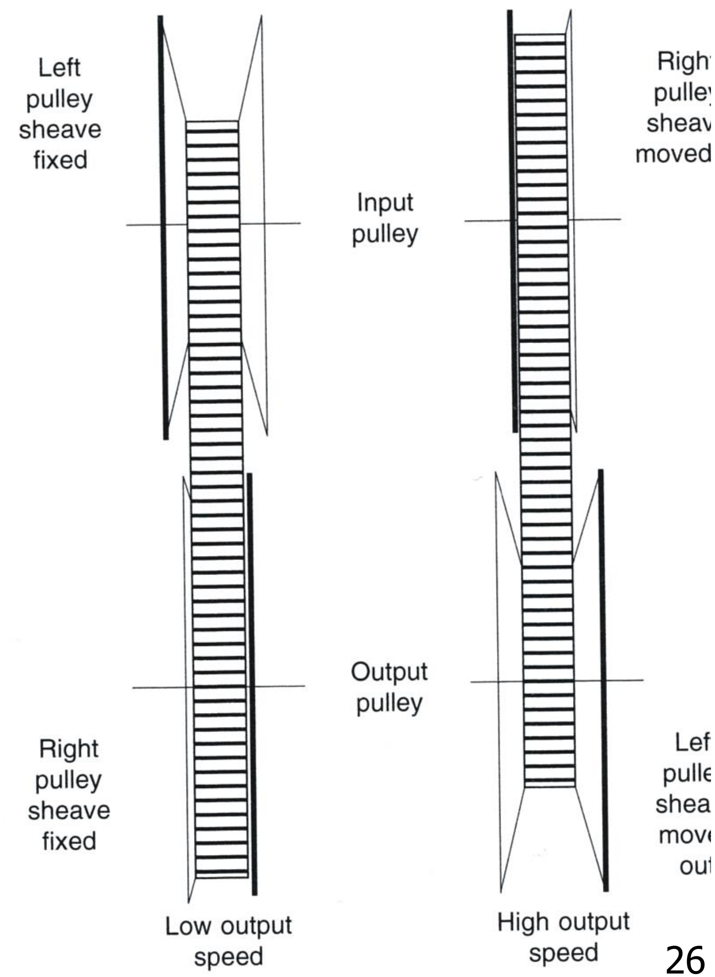


Principle of an automatic gear box based on double planetary gear trains

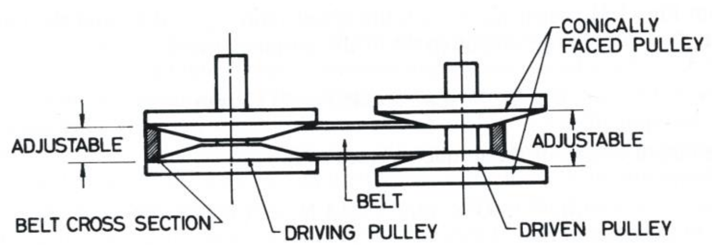
CVT : Van Doorne System

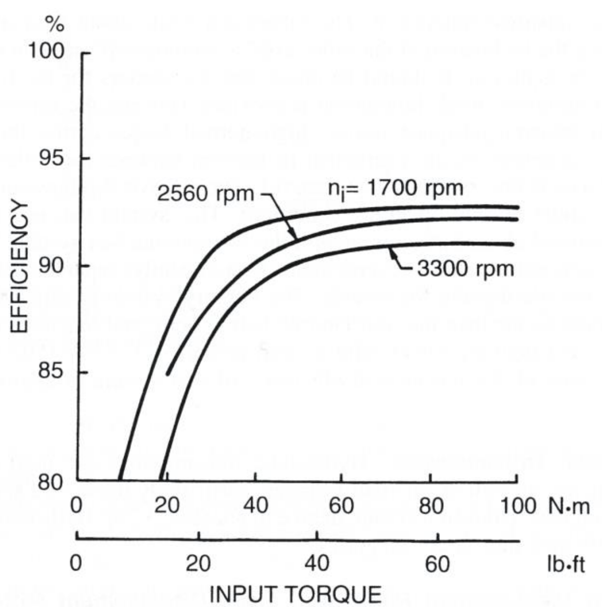


Pulleys with variable radii



CVT : Van Doorne System

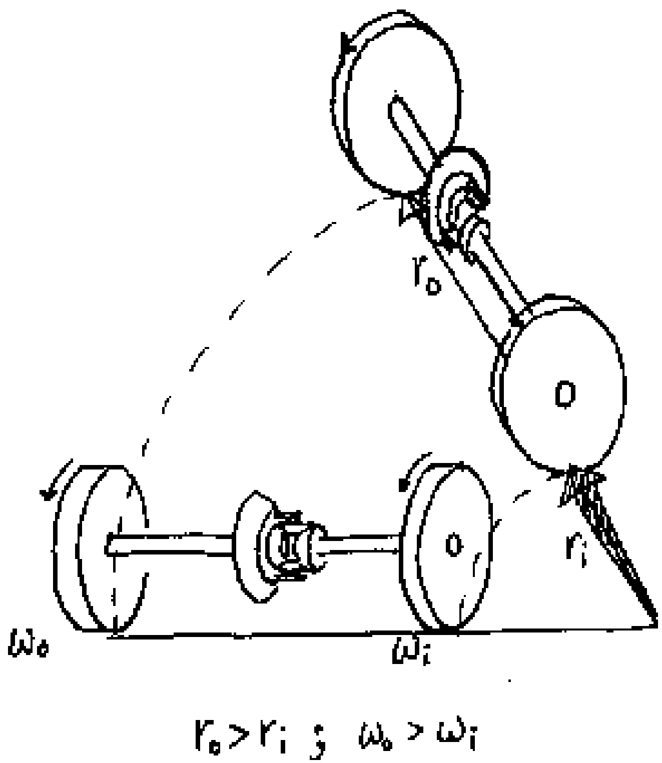




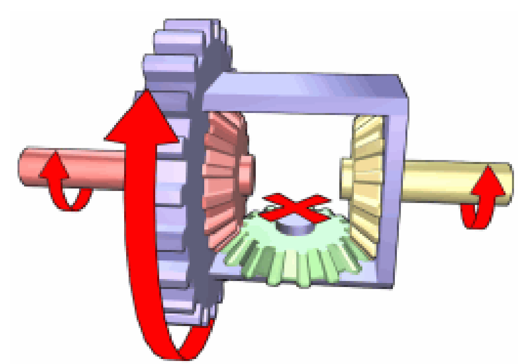
- Working principle
  - By modifying the distance between the two conical half shells, one modifies the effective radii of the pulleys and so the reduction ratio
  - Originally the system was based on the centrifugal forces, but nowadays the system is actuated by depression actuators and controlled by microprocessors

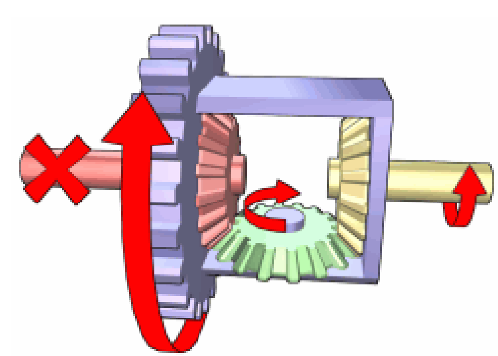
- PERFORMANCES
  - Variable reduction ratios varying between 4 to 6 (1:0,5→ 2:1) are achieved
  - Variable efficiency depends on the input torque and the rotation speed

Differential system

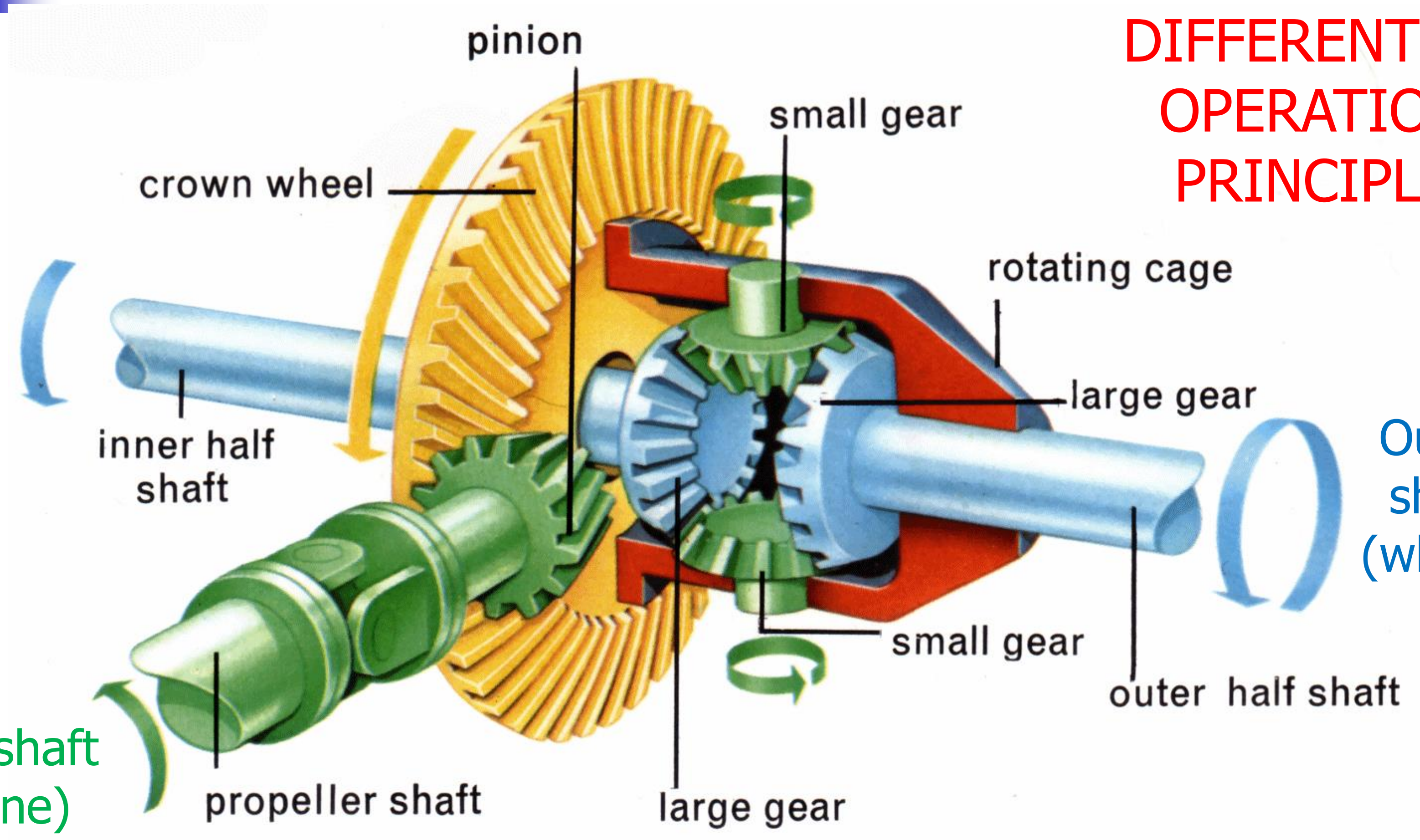


- During turn, the inner and outer wheels have different rotation speeds because of different radii.
- Differential allows to have different speeds in left / right wheels with one single input torque
- The differential allows to split the input power between the two output shafts.





Differential system

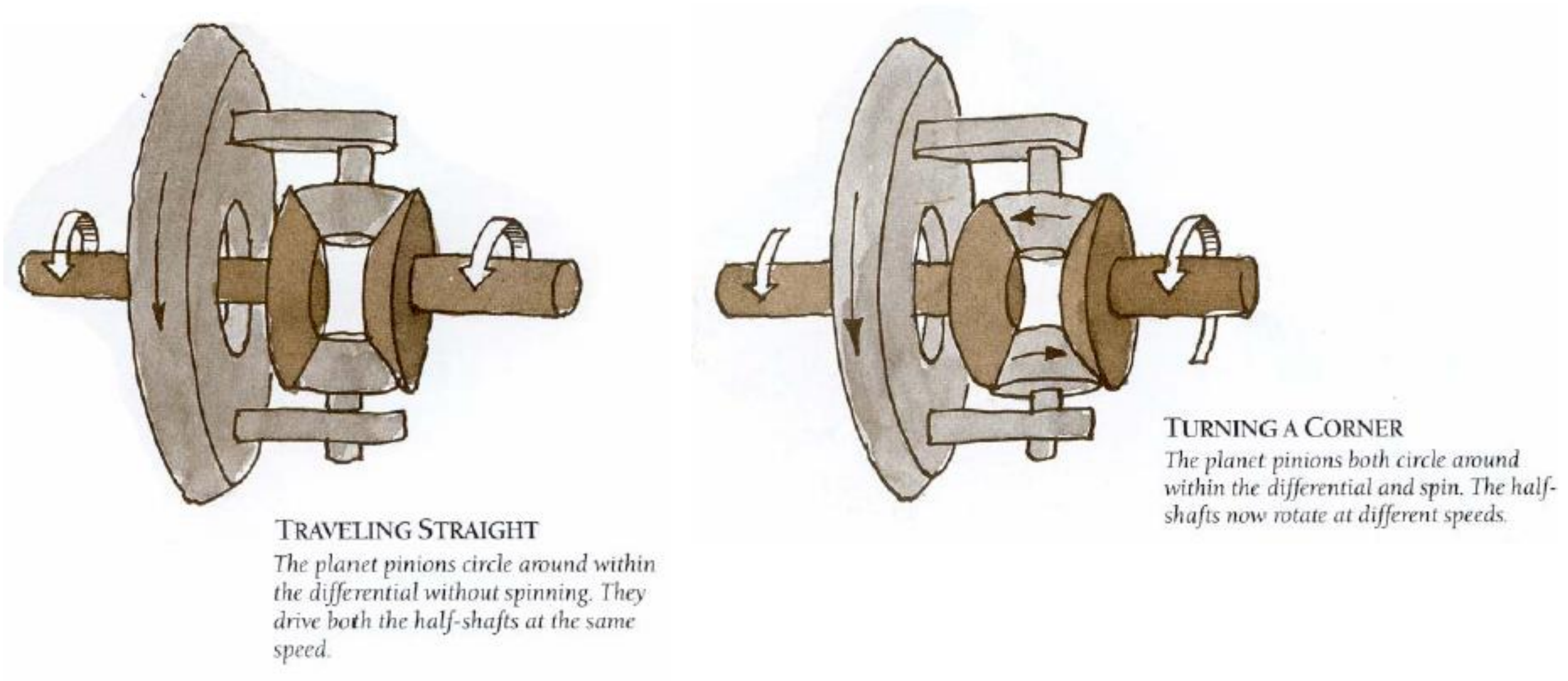


DIFFERENTIAL OPERATION PRINCIPLE

Output shafts (wheel)s

Input shaft (engine)

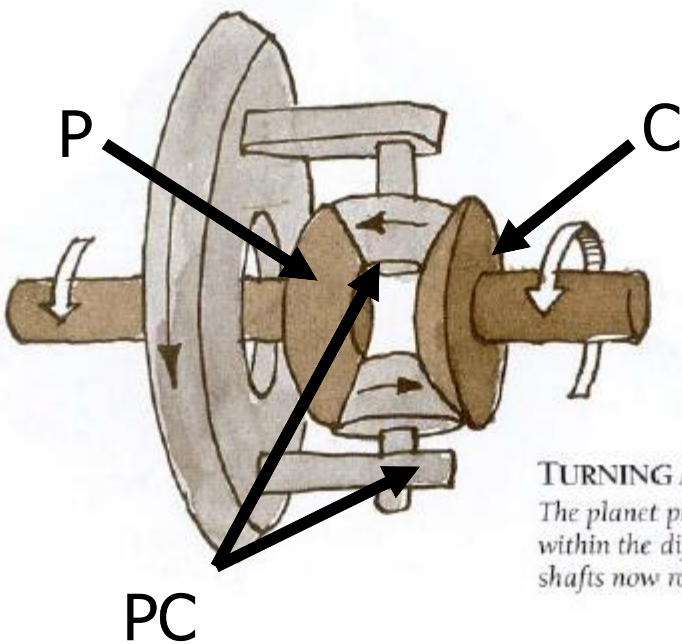
Differential system



Working principle of differential system

Differential system

$$\omega_P = \omega_L \quad \omega_C = \omega_R \quad \omega_{PS} = \omega_{in}$$



TURNING A CORNER
The planet pinions both circle around within the differential and spin. The half-shafts now rotate at different speeds.

$$Z_P = Z_C$$

$$i = \frac{Z_C}{Z_P} = 1$$

- Differential systems can be studied as planetary gears with equal number of teeth for sun and annulus.

$$\omega_P + i\,\omega_C = \omega_{PS}\,(1+i)$$

$$\iff \omega_L + \omega_R = 2\,\omega_{in}$$

$$\iff \frac{\omega_L + \omega_R}{2} = \omega_{in}$$

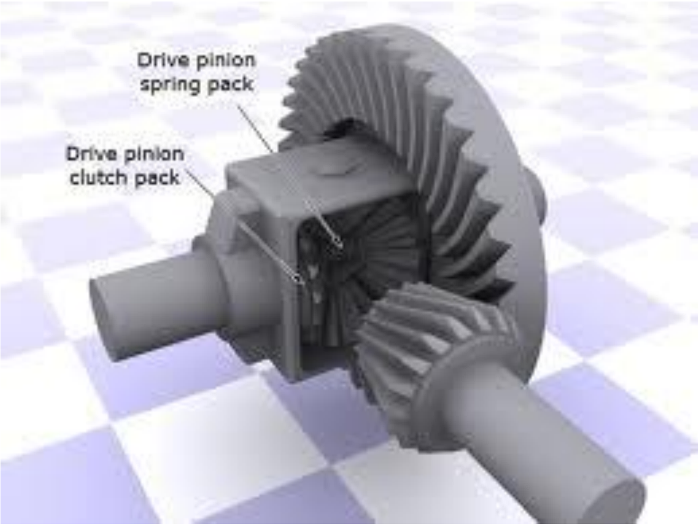
$$T_{PS} = -(1+i)\,T_P = -\frac{1+i}{i}\,T_C$$

$$\iff T_{in} = -2\,T_L = -2/1\,T_R$$

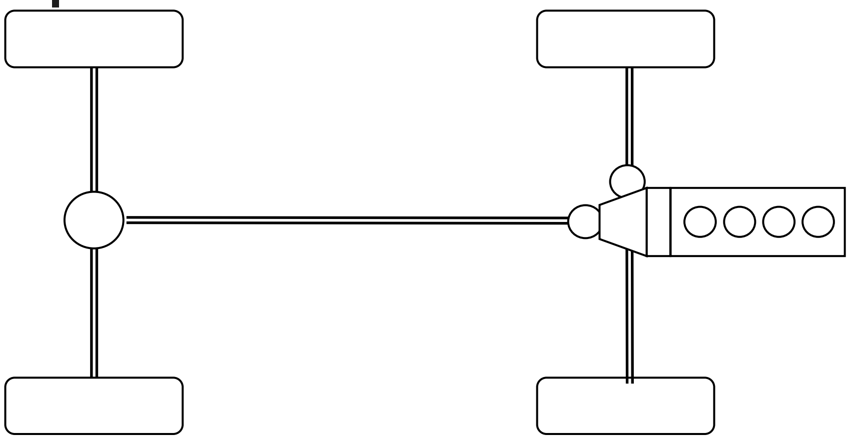
$$\iff T_L = T_R = -T_{in}/2$$

Differential system

- Efficiency of differential
  - Longitudinal layout: 90° change of direction (bevel pair) + offset of the shaft (hypoid gear): η = 97,5 %
  - Transversal layout: no bevel → good quality gear pair: η = 98,75%



Transfer box

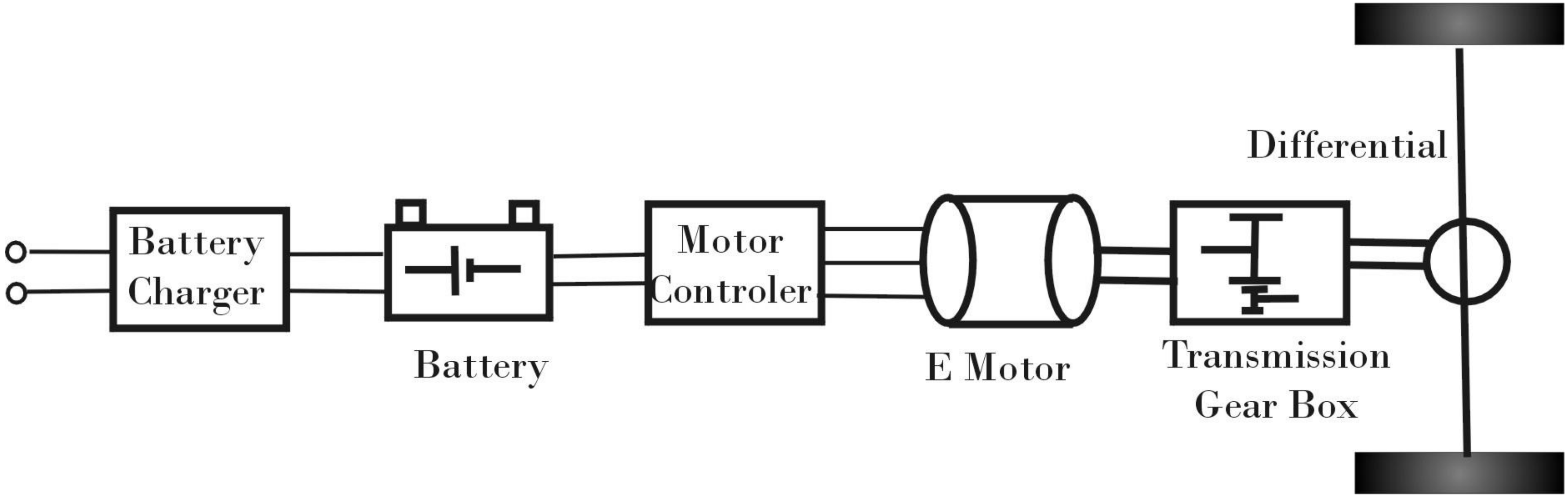


- Special differential system for 4-wheel drive vehicle
- The transfer box splits the torque between the front and rear axles.

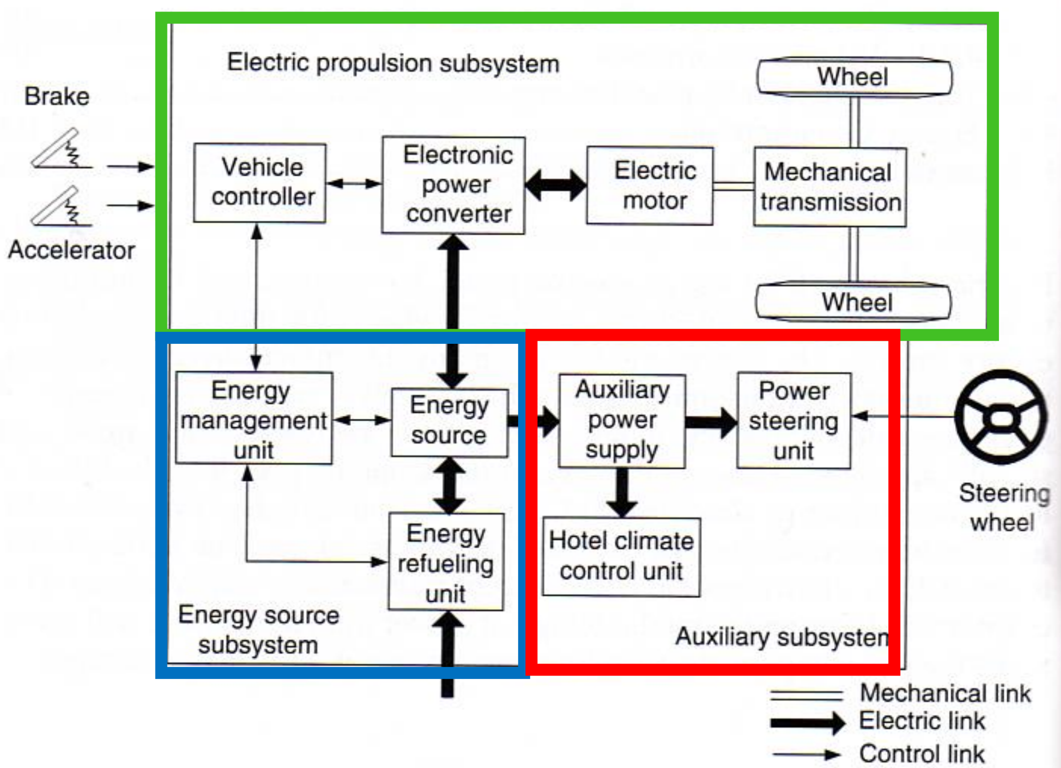
Electric Powertrain Architecture

Electric powertrain

- Basic electric traction architecture usually mounted on light and heavy vehicles, as well as industrial vehicles (fork lifters, airfield vehicles…) and two wheelers



Electric powertrain



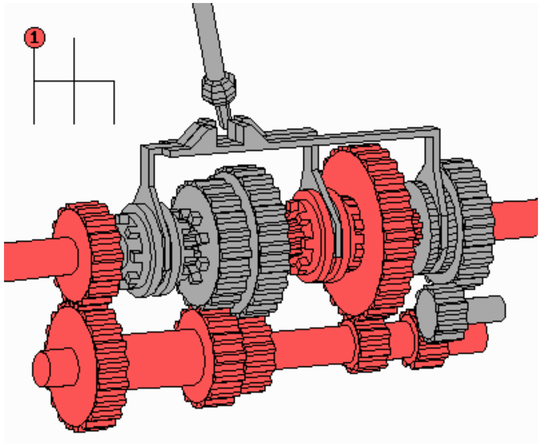
- A modern electric drive is conceptually more complicated.
- It is made of 3 subsystems
  - Electric motor propulsion
  - Energy source
  - Auxiliary

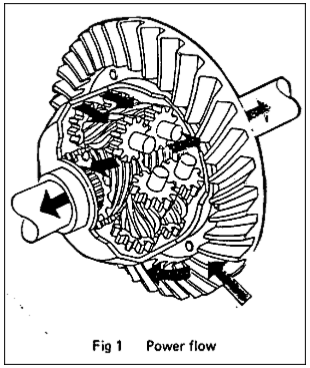
Electric powertrain

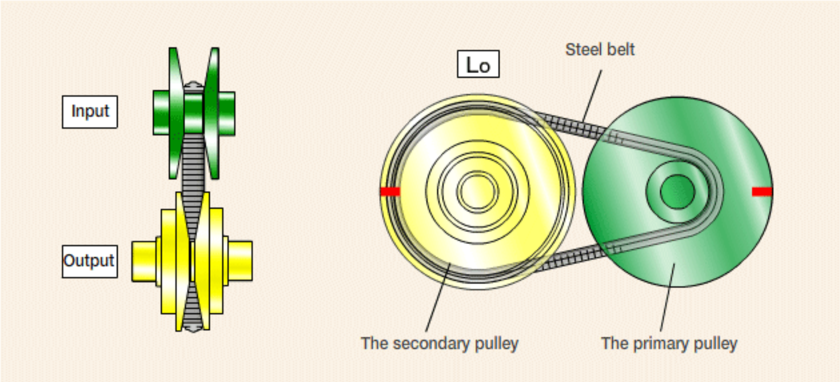
- Electric propulsion system
  - Vehicle controller
  - Power electronic converter
  - Electric motor
  - Mechanical Transmission
  - Driving wheels
- Energy source subsystem
  - Energy source or storage
  - Energy management unit
  - Energy refueling unit
- Auxiliary
  - Power steering
  - Hotel climate control
  - Auxiliary supply unit

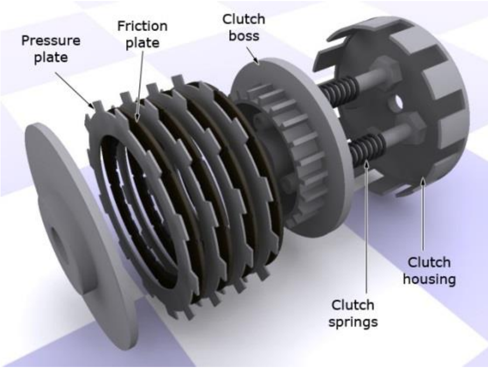
Electric powertrain components

- E-Transmission (mechanical)
  - Gear box
  - Differential
  - Wheels

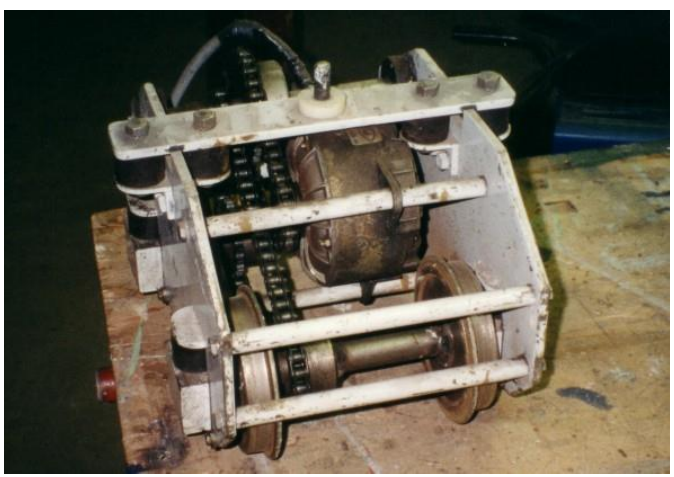








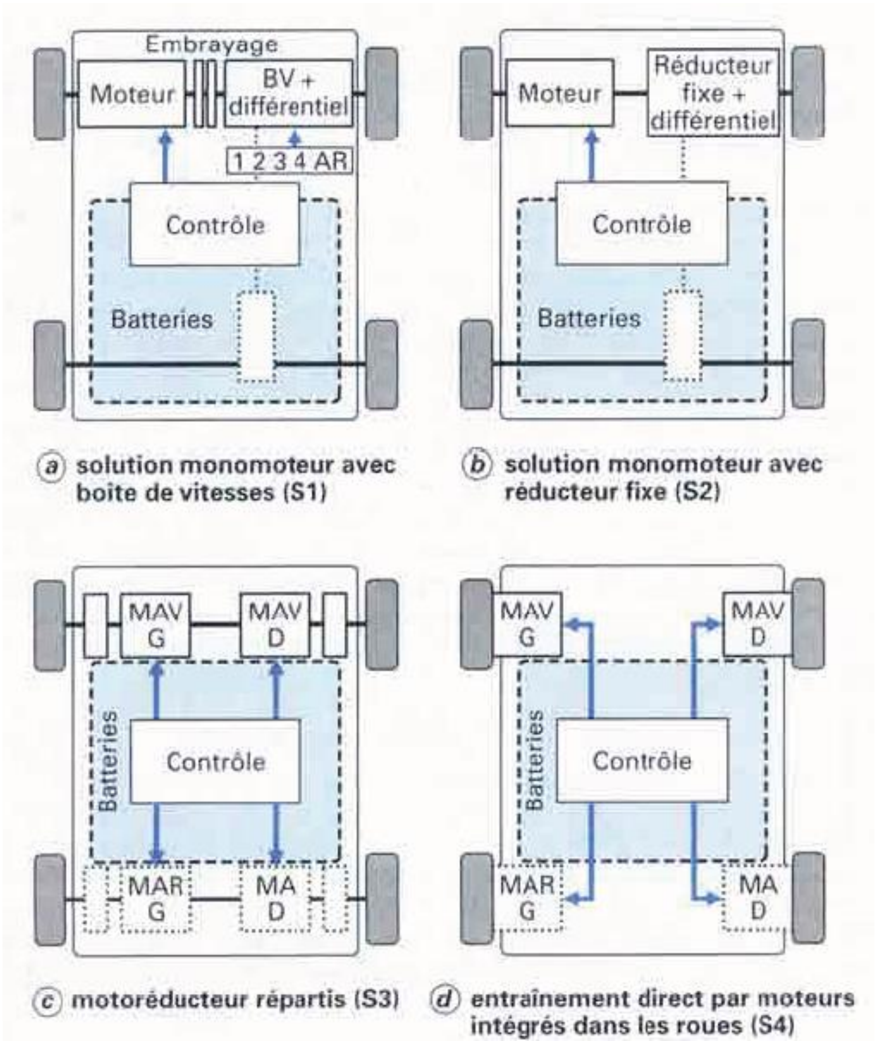
Electric powertrain architrectures



One can distinguish 2 different solutions:

- Centralized motorization: similar to ICE configuration = one single motor and the power is transmitted to the wheels via a transmission line including a gear box, a transfer box, axle differentials, axle and shafts.
- Decentralized motorization: electric motors are located on each wheels or against each wheel sets (boogie).
  - On can further distinguish motors actuating the wheel shaft or using direct drive technique

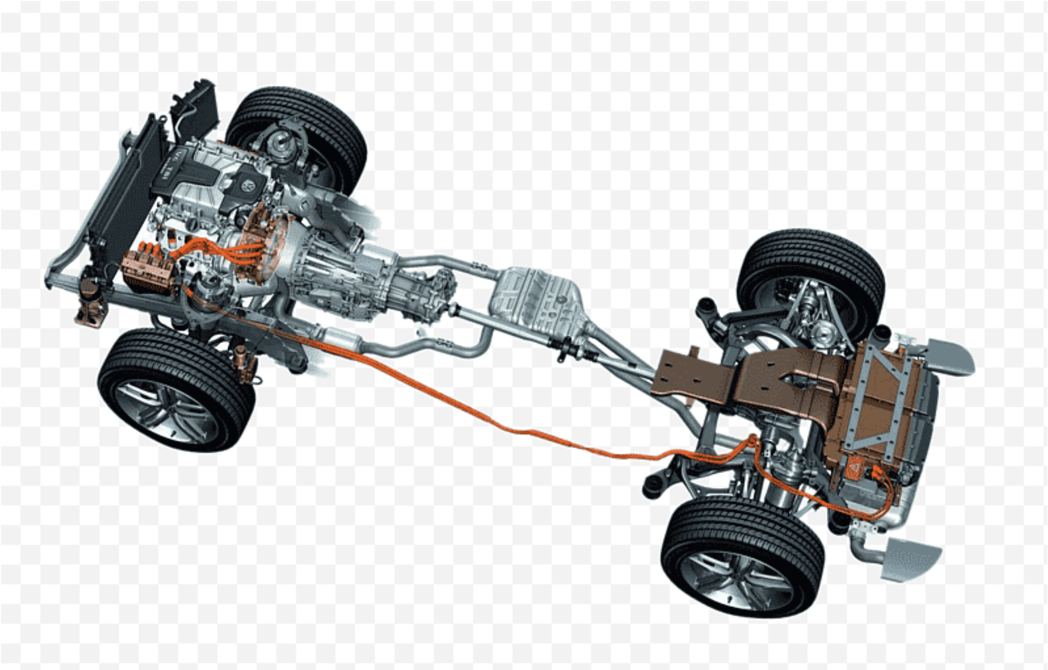
Electric powertrain architectures



Multon (2001)

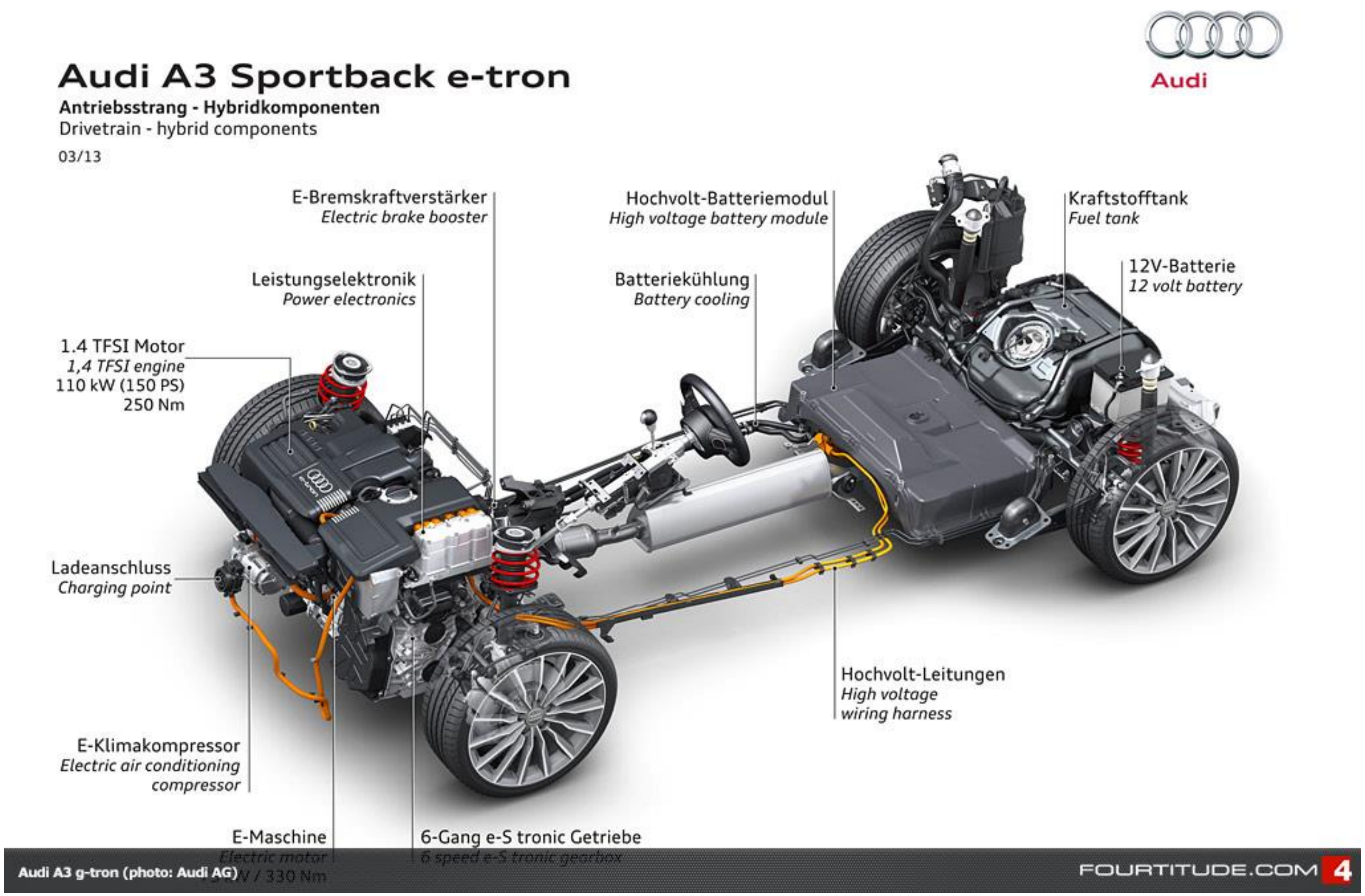
Centralized motorization

Electric vehicle Car Volkswagen Touareg Powertrain

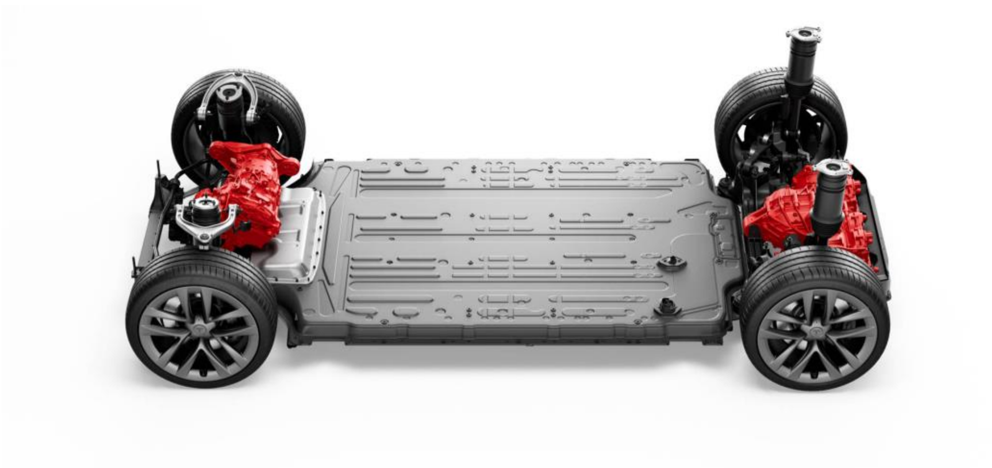


- Similar concept to ICE engine
- May be not adapted to modern electric motorization

Centralized motorization

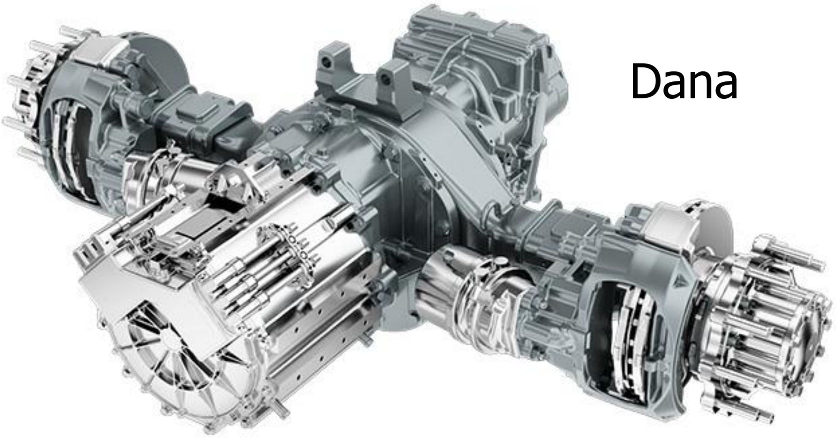


Decentralized motorization

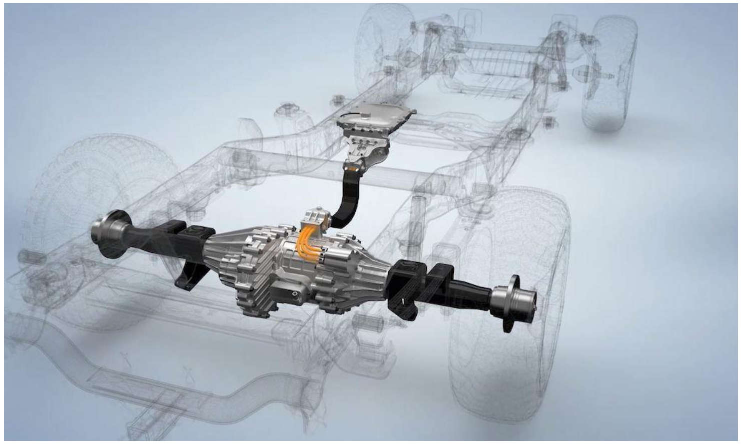


- Dual motor of Tesla 3
- All wheel drive solutions
- Based on e-axle concept

Decentralized motorization: e-axle



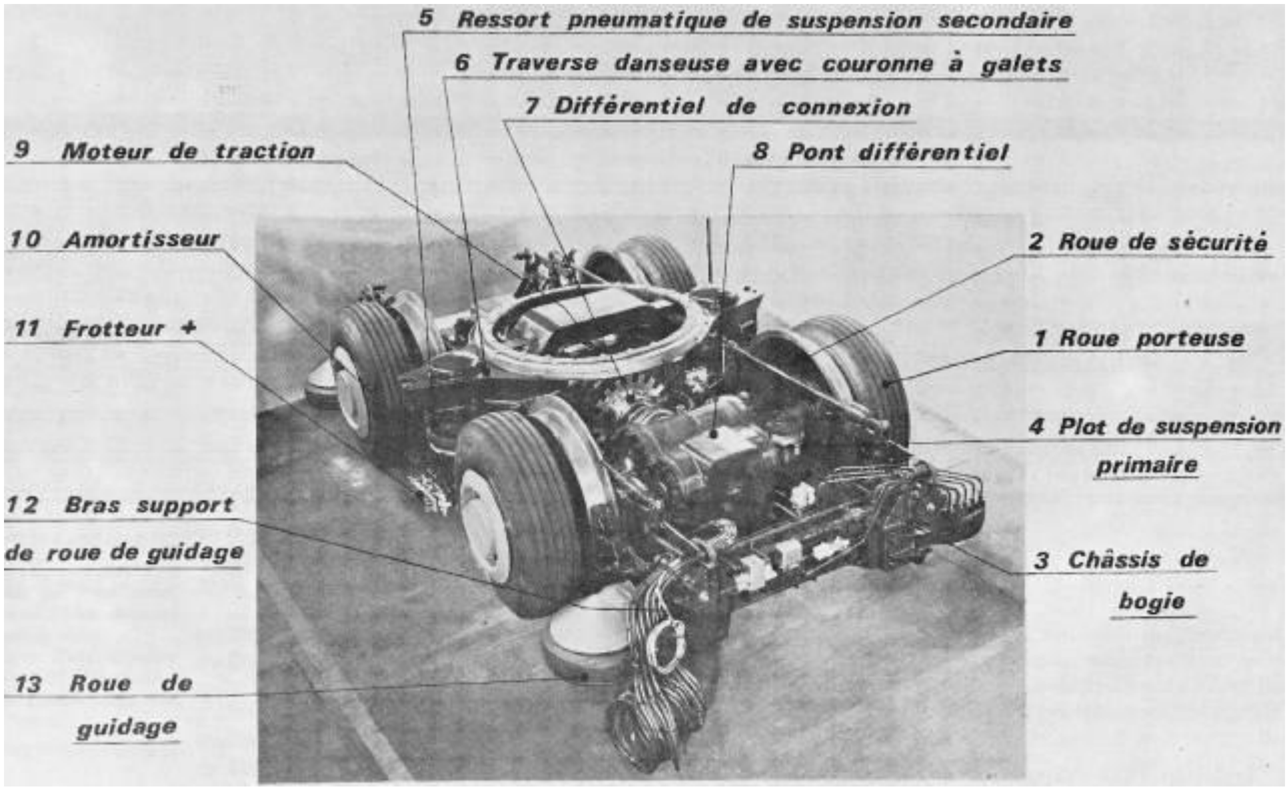
Dana



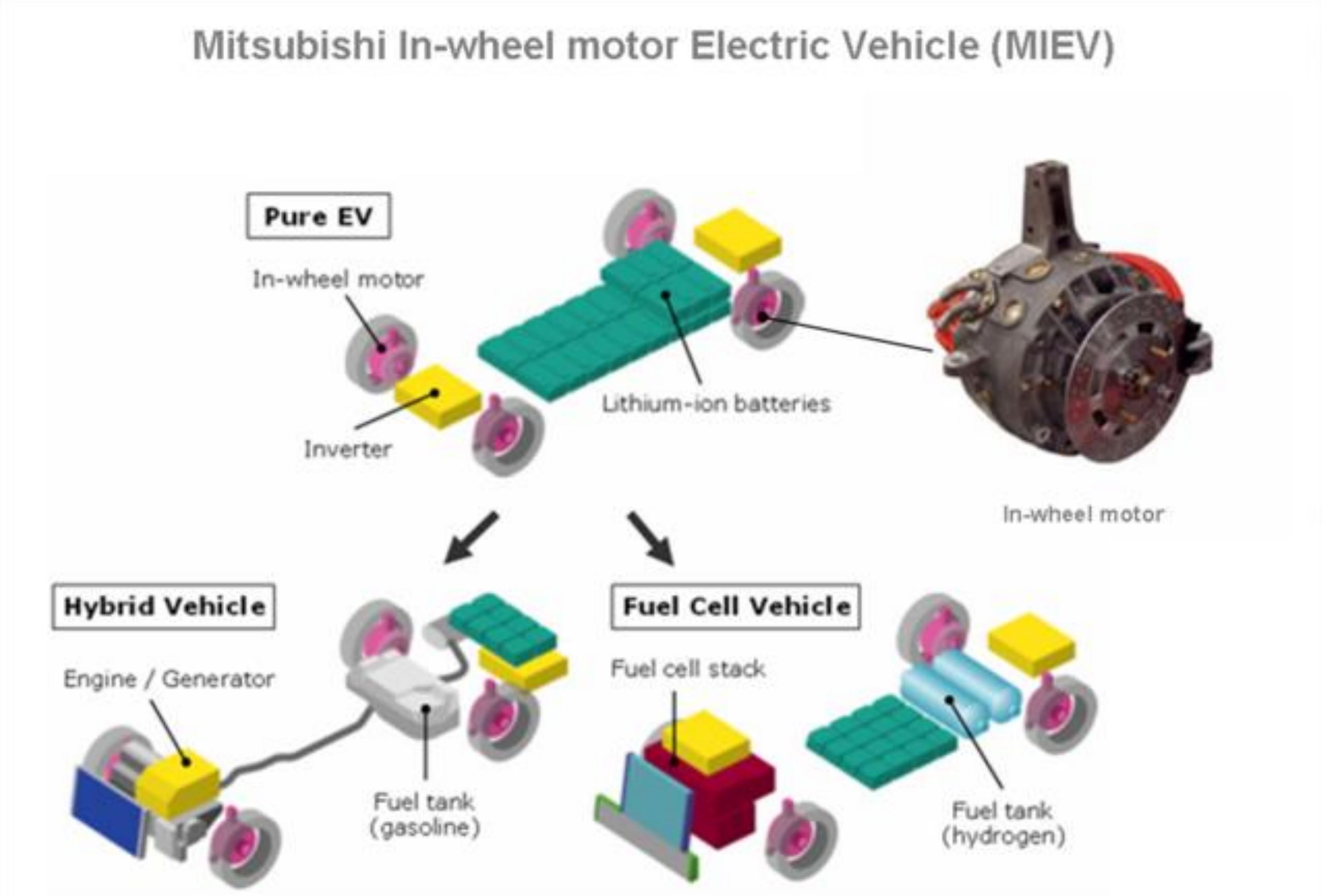
Magna

- Concept of e-axle.
- One electric drivetrain per axle: e-motor + gear box
- Directly operated on the axle

Decentralized motorization

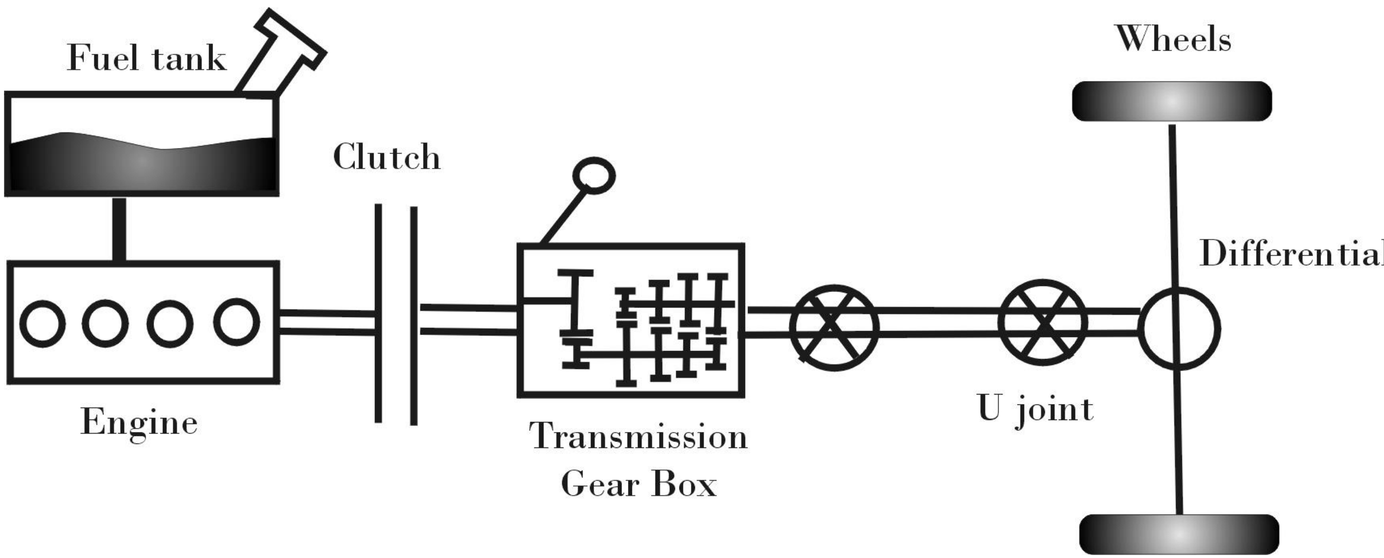


Decentralized motorization



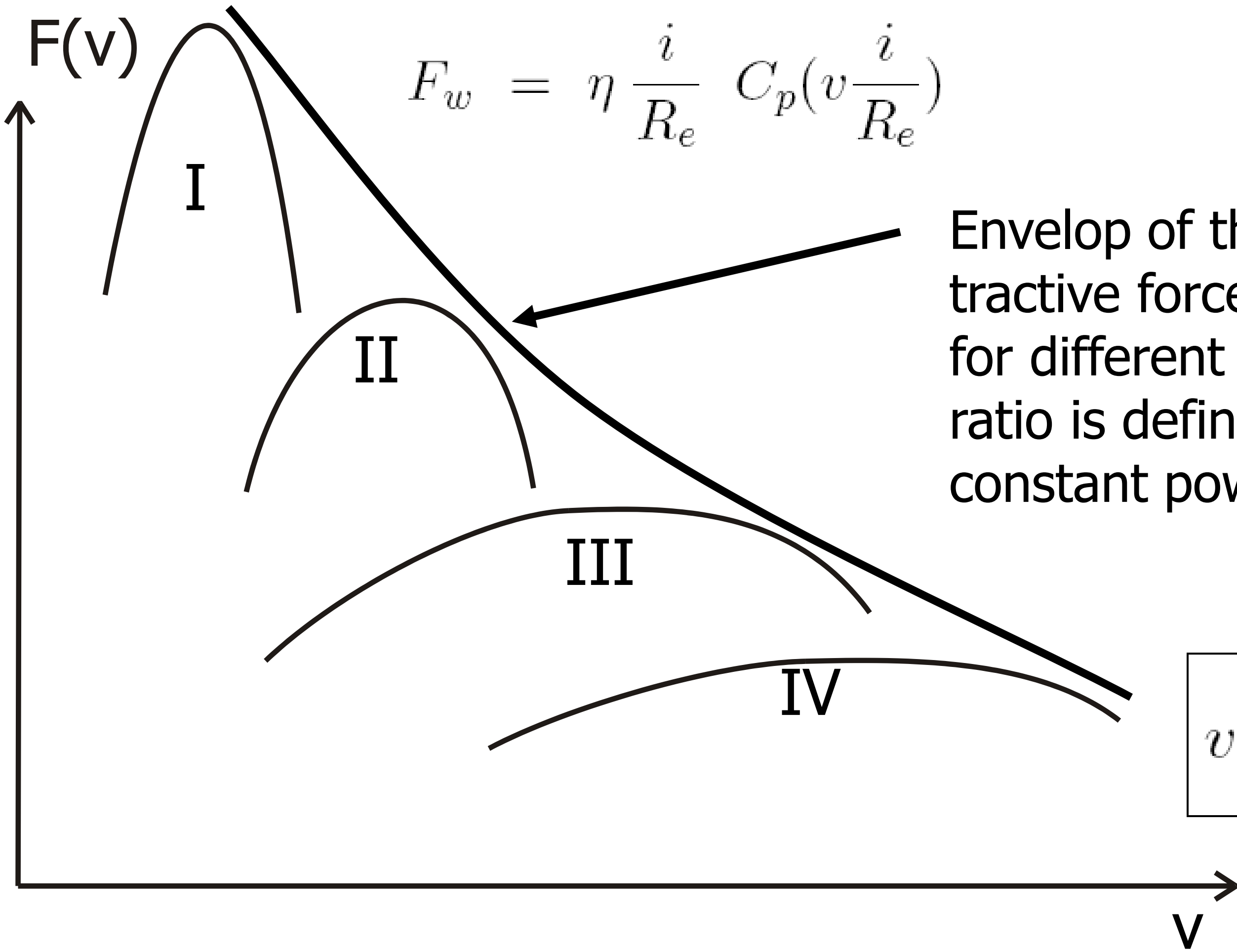
Need for a gear box and a clutch?

- For piston engines (ICE), the gear box + clutch is necessary because of the unfavorable speed-torque of the engine



Typical drivetrain architecture with an ICE propulsion system

Do EV need a gear box and a clutch?



$$F_w = \eta \frac{i}{R_e} C_p(v \frac{i}{R_e})$$

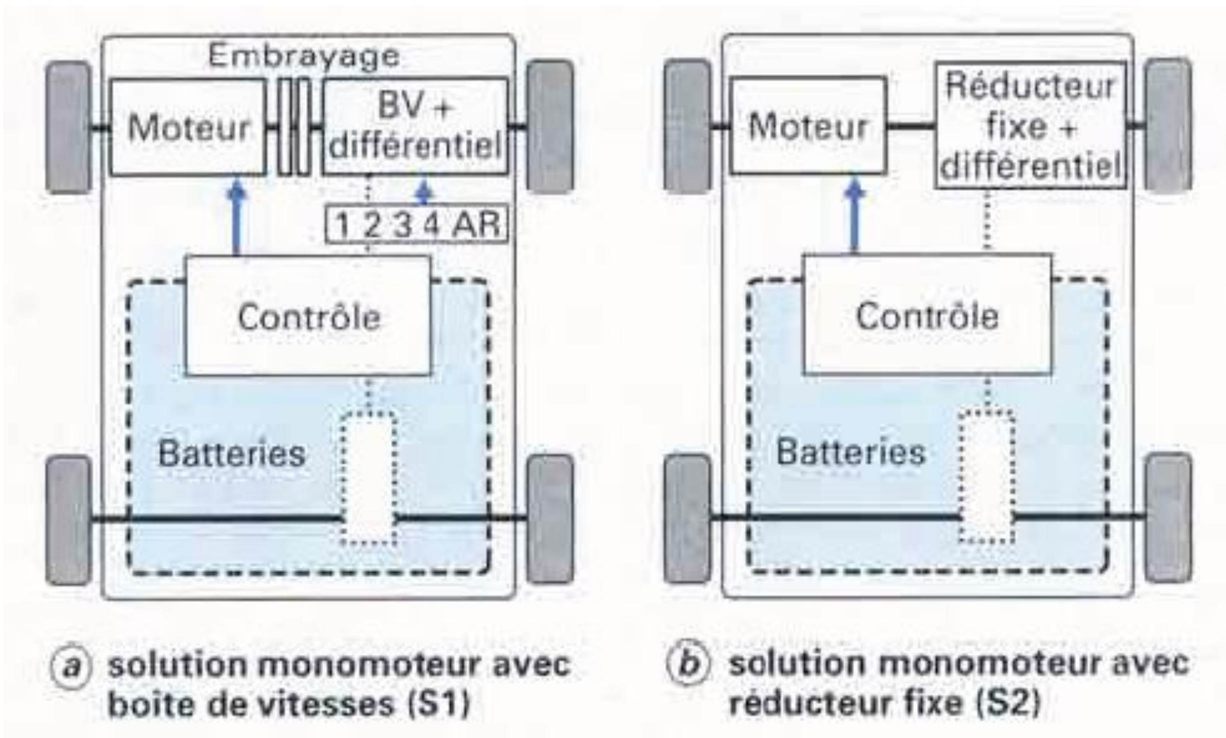
Envelop of the tractive force curves for different gear ratio is defining a constant power (1/v)

$$\boxed{v = \frac{R_e}{i} \omega_p}$$

Do EV need a gear box and a clutch?

- In a naïve conversion of ICE cars to electric, one keeps the gear box and may be the clutch.
- However electric machines have
  - No idle speed
  - Large range of operating speed (0 to 3.000 rpm - 12.000 rpm)
  - Electronic controllers can regulate torque and speed easily
  - Power curve of e-motor close (ideal) constant power
- Electric drivetrain can be equipped with a simple gear box: one or two gear ratios

Do EV need a gear box and a clutch?



Multon (2001)

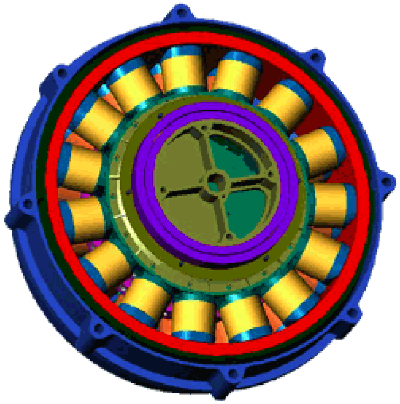
Do EV need a gear box and a clutch?

- Advantages of gear box with a fixed reduction ratio :
  - No shock during operations. Smooth driving.
  - Planetary gear boxes can achieve important reduction ratios in a single stage with a good efficiency

- Cost of electric motor strongly depends on the maximum torque:
  - Using a high-speed motor is favorable to reduce the cost
  - But the acceleration factor is affected by a high gear ratio

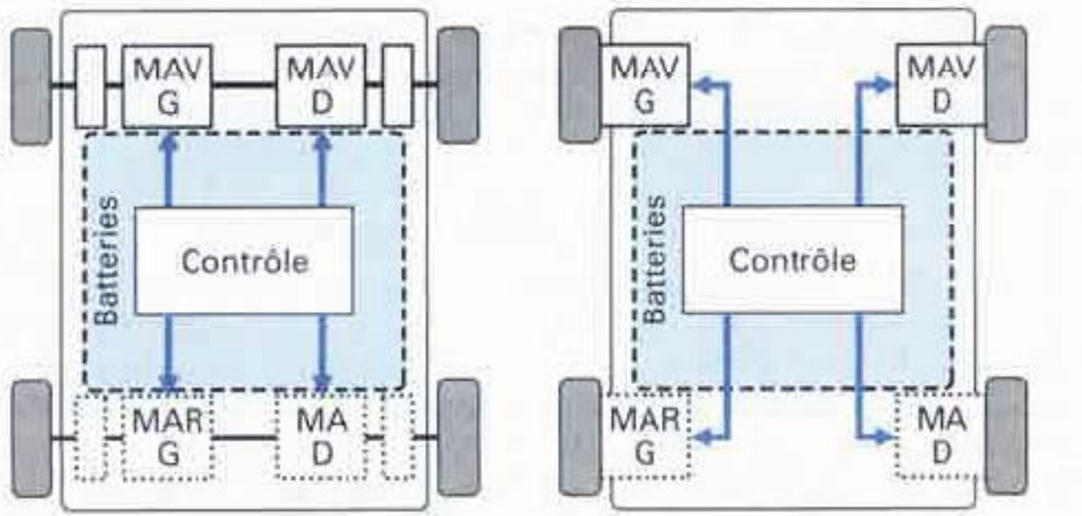
- Selection of a single or multiple gear ratios depends on:
  - Acceleration requirements
  - Max slope and max drawbar pull requirements
  - Speed range of the motor

Unique or multiple motors configuration?

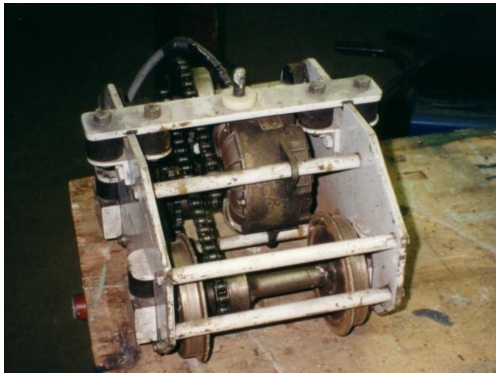


- The single motor configuration is typical from ICE.
- With electric motors, on can imagine more innovative designs and it is possible to actuate each degrees of freedom independently as in robots and mechatronic systems.
- With distributed motorizations using multiple motors, one can even abandon the concept of differential and replace it by 2 or 4 motors, one per each wheel.
- The mechanical differential is replaced by an electronic differential device with control loop.

Multiple motors configurations



(c) motoréducteur répartis (S3)
(d) entraînement direct par moteurs intégrés dans les roues (S4)



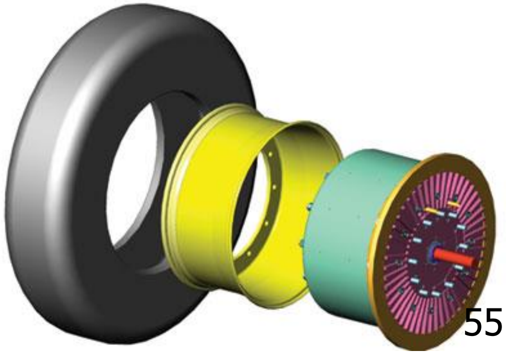
Multon (2001)

Unique or multiple motor configuration?

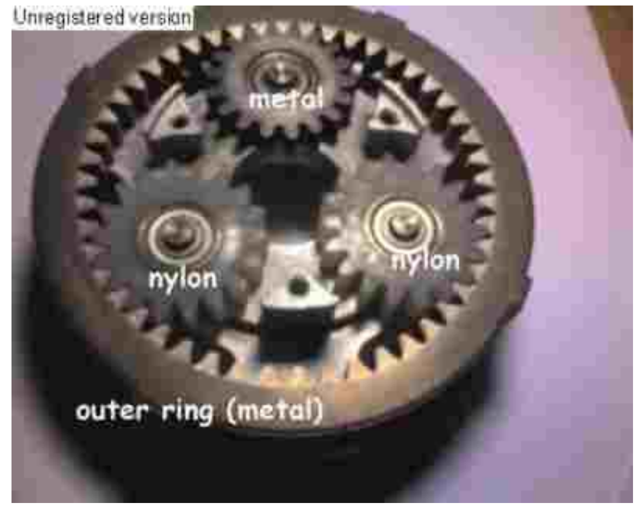
- Advantages of multiple motor configurations
  - Reduction of the weight and volume constraints
  - Electronic differential opens new possibilities to control the torque and speed differences at each individual wheel
  - New possibilities in controlling the vehicle dynamics:
    - Longitudinal dynamics: anti skid and anti lock braking (ABS) systems
    - Lateral dynamics: extended electronic stability program
- Inconvenient
  - Using additional electronic systems
  - Reliability of the overall system?
  - Functional safety should be considered carefully
  - Additional cost
  - Increasing system complexity

In-wheel motor concept

- The concept of in-wheel motors minimizes or avoids completely the mechanical transmission by placing directly the motors inside the wheels
- One distinguishes :
  - Inner in-wheel motors whose rotation speed is rather high and is reduced using a fixed gear ratio
  - Outer in-wheel motors whose rotation speed is low and that are connected in direct-drive
- Both approaches generally use permanent magnet (PM) motors because of their high specific power.



Inner in-wheel motor



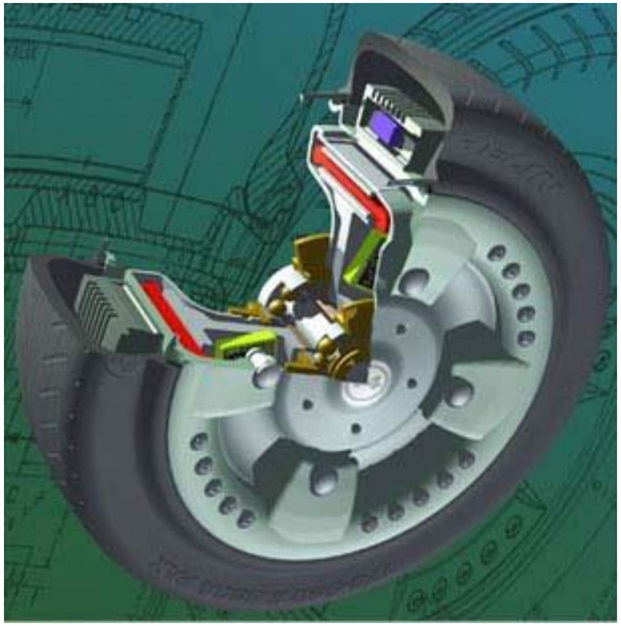
In-wheel motor concept

- Bike applications:

www.acclivity.ca

www.smart-bike.net

Outer in-wheel motor



TM4 in-wheel motor

Mitsubishi in-wheel motor

Read more at: http://www.electricvehiclesresearch.com/articles/3108/in-wheel-electric-motors-gain-market-share

In-wheel motor concept

- The inner in-wheel motor
  - The max rotation speed is rather high (for instance 10 000 rpm)
  - Requires an embedded gear box (about 10:1) for instance a planetary gear mounted on the wheel hub
  - Smaller size and smaller weight
  - Smaller cost

- The outer in-wheel motors
  - Simplicity of the concept
  - No reduction of speed nor gear box
  - Larger size and higher weight: might have some impact on comfort and road holding
  - High cost

In-wheel motor concept

In-wheel motor from TM4

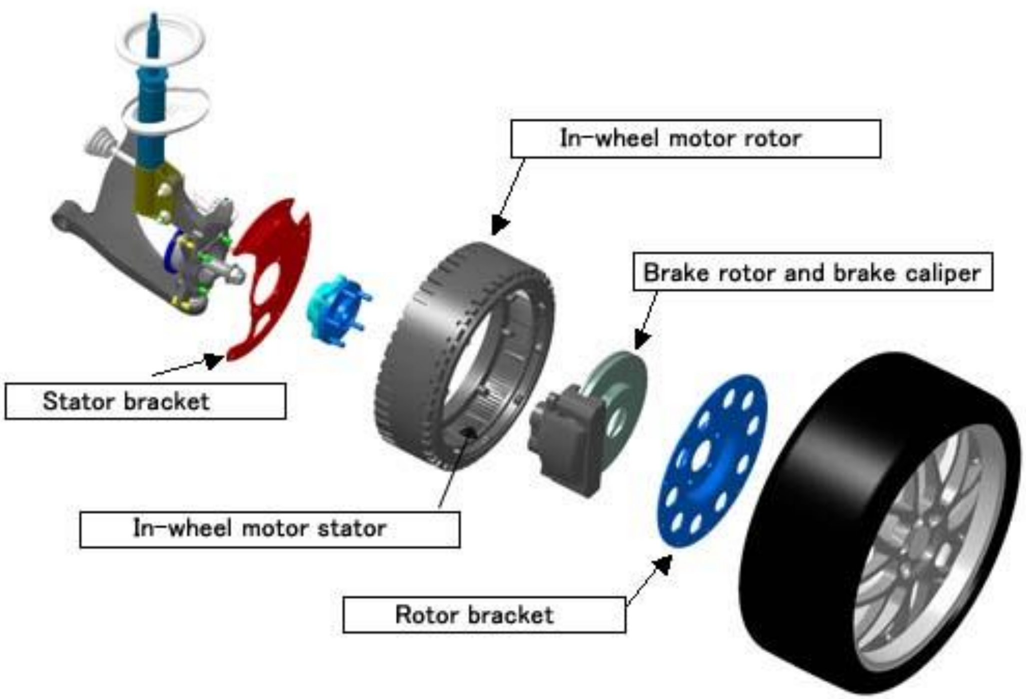
Motor wheel specifications in brief
(other versions are available)

Peak Power 80 kW 107 hp
Nominal Power: @950rpm 18.5kW (25hp)
Peak torque 670 Nm 494 lb ft
Nominal torque @ 950 rpm 180 Nm (133lbft)
Peak speed: 1385 rpm
Max continuous speed: 1235 rpm
Efficiency under continuous load @ 950rpm η=96.3 %
Maximum supply voltage 500 VDC

In-wheel motor concept

MIEV Lancer Evolution equipped by 4 in-wheel motors

In-wheel motor concept

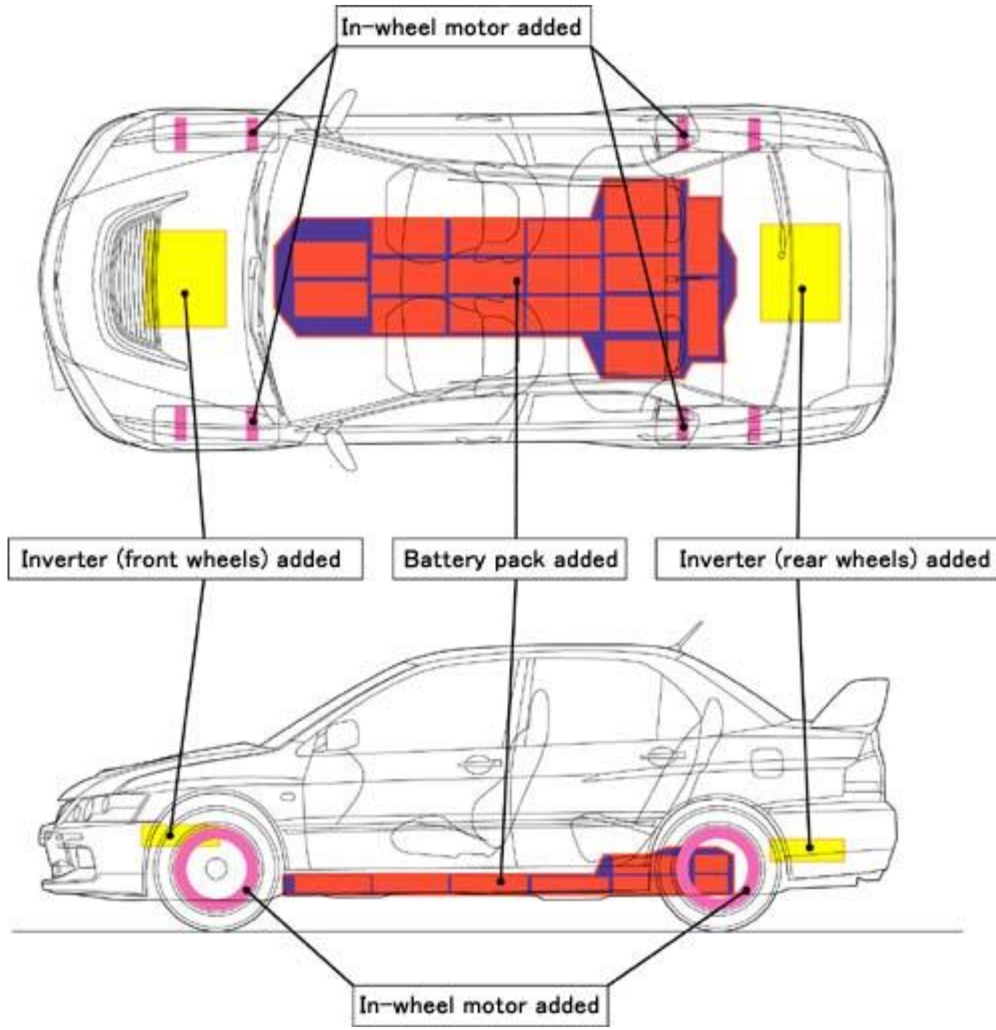


Motor (outer-rotor type)	Type	Permanent magnetic synchronous
	Maker	Toyo Denki Seizo K.K.
	Max. output	50 kW
	Max. torque	518 Nm
	Max. speed	1500 rpm
	Dimensions	445 mm (dia.) x 134 mm
	No. fitted	4

MIEV Lancer Evolution equipped by 4 in-wheel motors

In-wheel motor concept

MIEV Lancer Evolution equipped by 4 in-wheel motors



Hybrid Electric Powertrain Architecture

Definitions

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

- Hybrid electric vehicle: a vehicle in which the propulsion energy is available from two or more types of energy storages, sources 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…

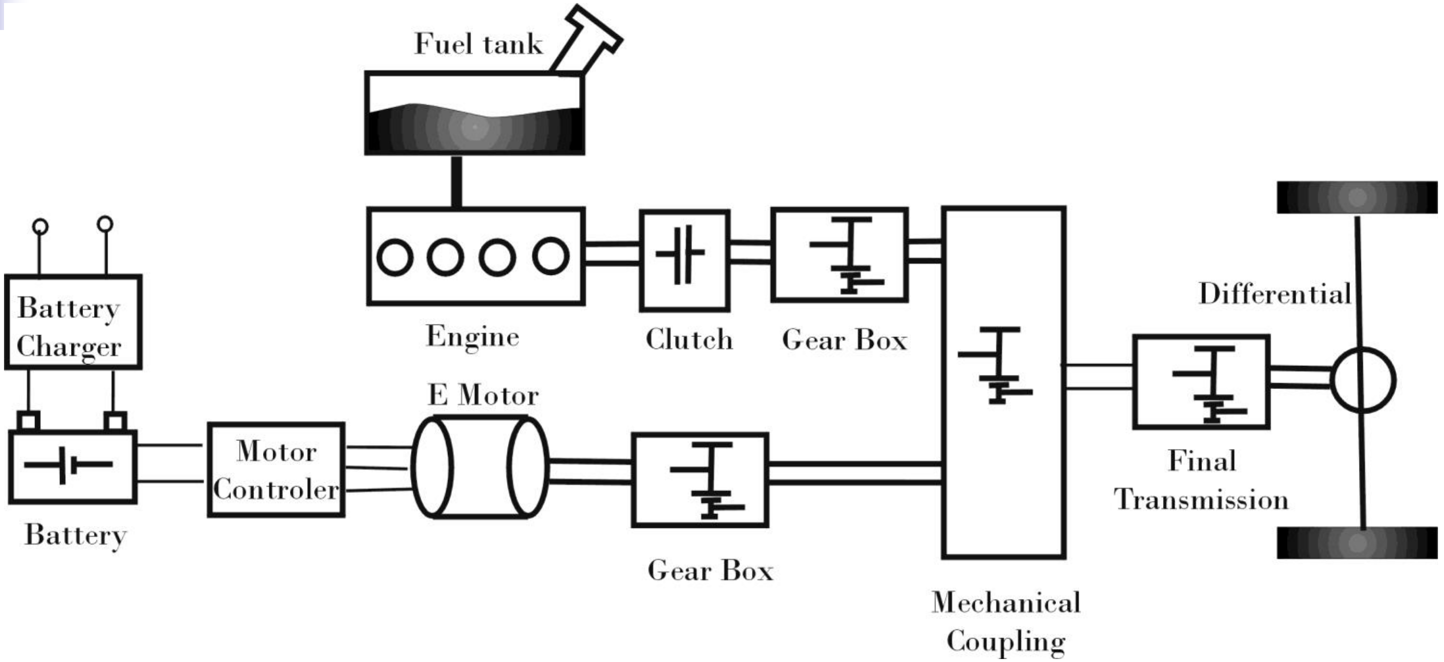
- Hybrid hydraulic vehicle: same as HEV but in this case one of the energy sources, storage and converters is a hydraulic system

Definitions

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

  Typically the fuel tank supplies the ICE while the batteries are the energy source for the electric motor.
- 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.

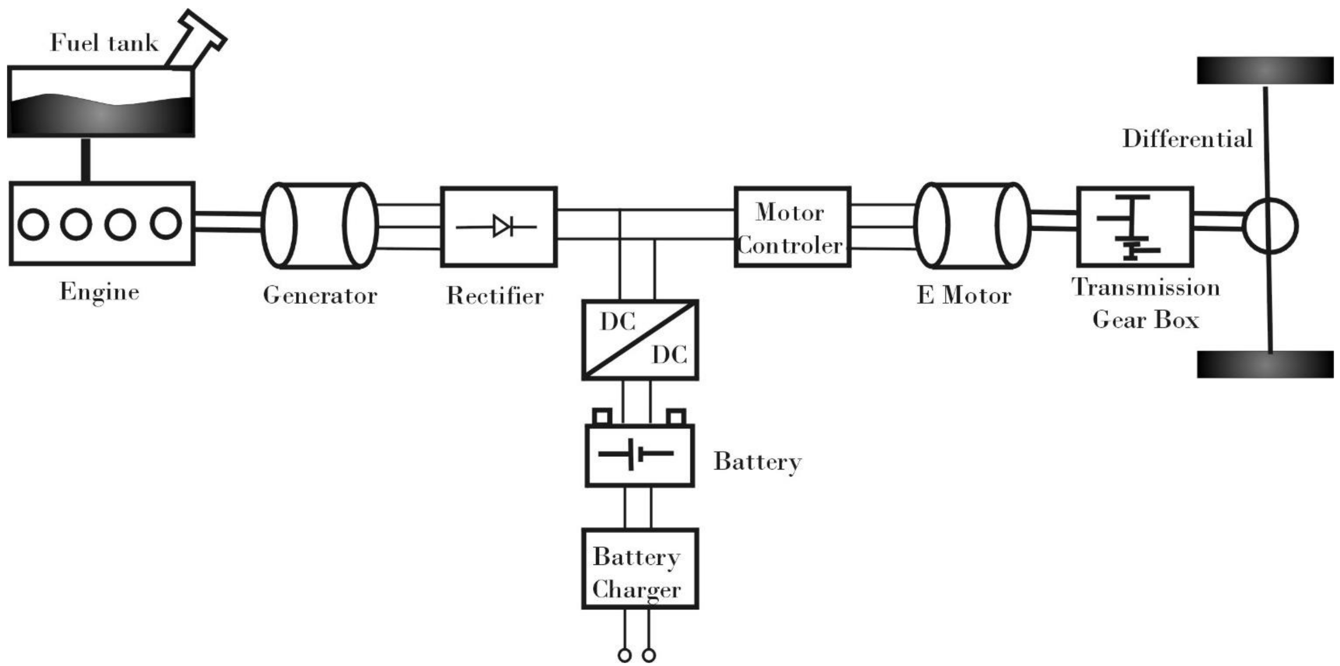
Parallel hybrid electric powertrains



- TWO MODE TRACTION or PARALLEL HYBRID
  - The ICE powertrain is used outside of the cities while electric powertrain is more efficient for urban driving

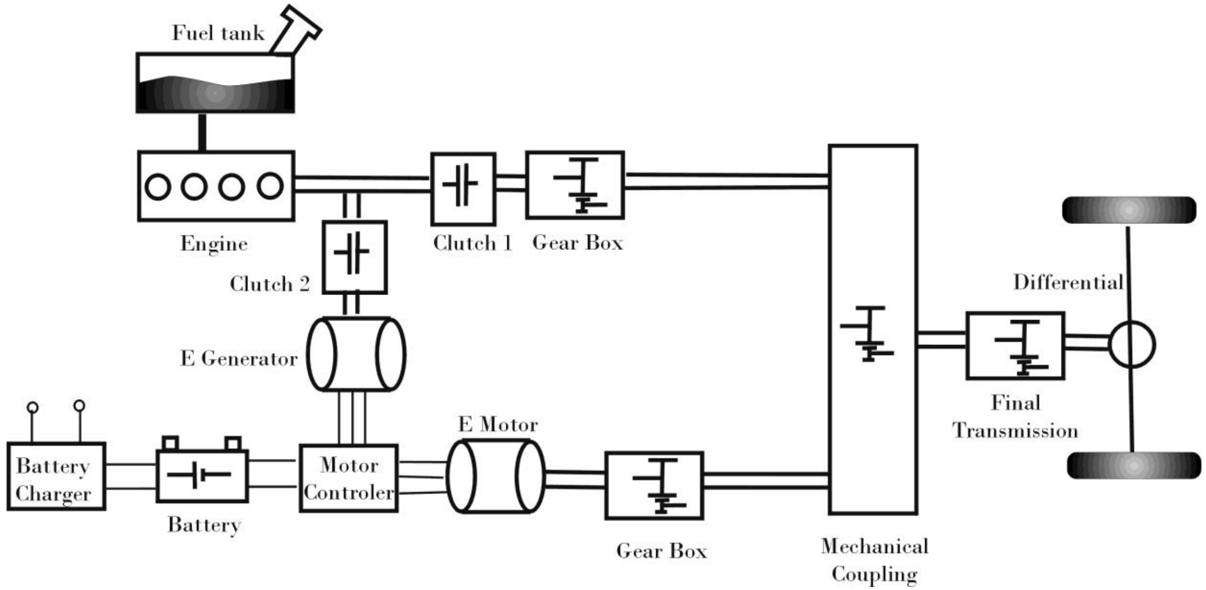
Series hybrid electric powertrains

- SERIE ELECTRIC POWERTRAIN
  - The ICE (piston engine or gas turbine) is used to power a generator that continuously feeds in batteries
  - The battery supplies the electric motor that is the only drive to be connected to the wheels



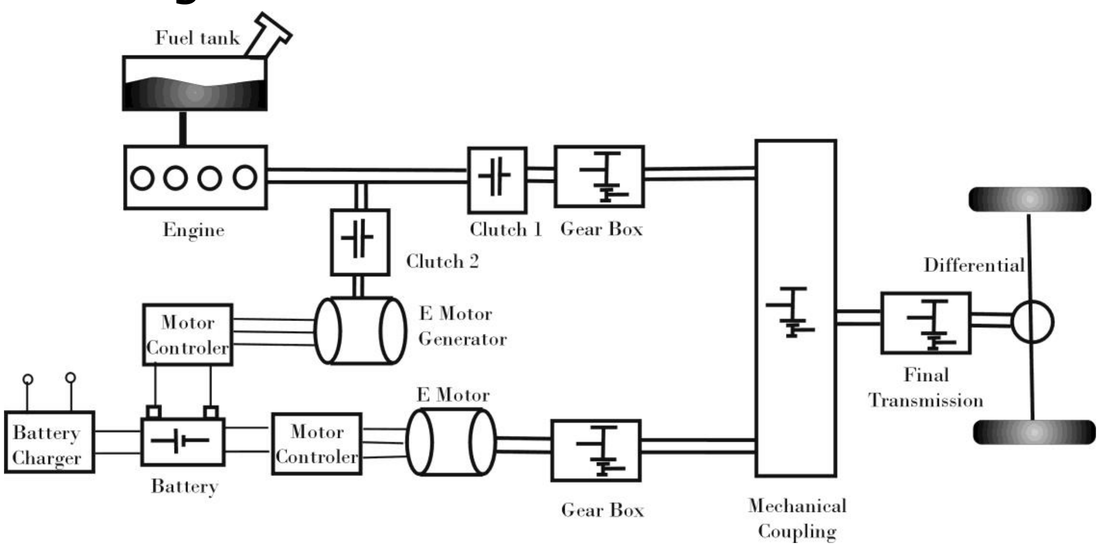
Definitions

- Other more complex configurations are possible (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.



Definitions

- Other more complex configurations are possible (Chan, 2002)
  - 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.



Torque coupling: Two shaft configuration

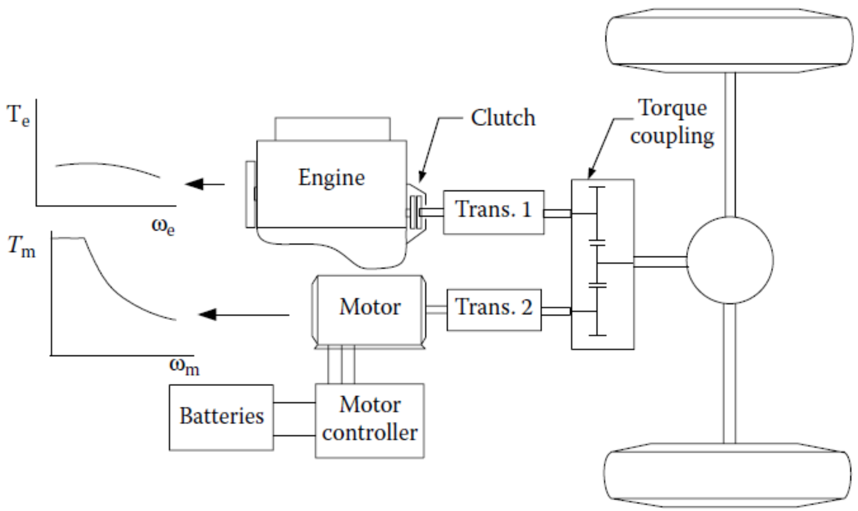


Fig. 5.8 Eshani et al. (2010)

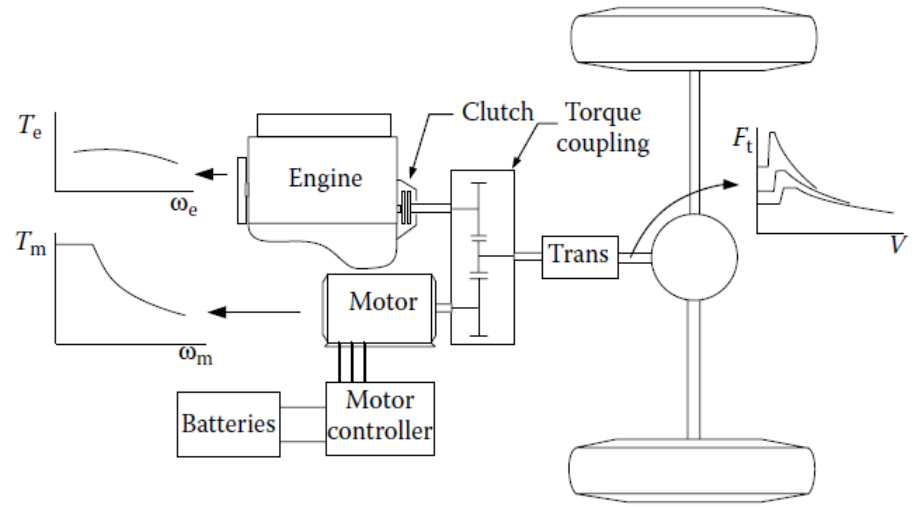


Fig. 5.10 Eshani et al. (2010)

- In the parallel hybrid configuration, a classical option is to use two separate shafts, one for the e-motor and one for the engine.
- The transmission and mechanical reduction components can be placed before or after the torque coupling device

Torque coupling: single shaft configuration

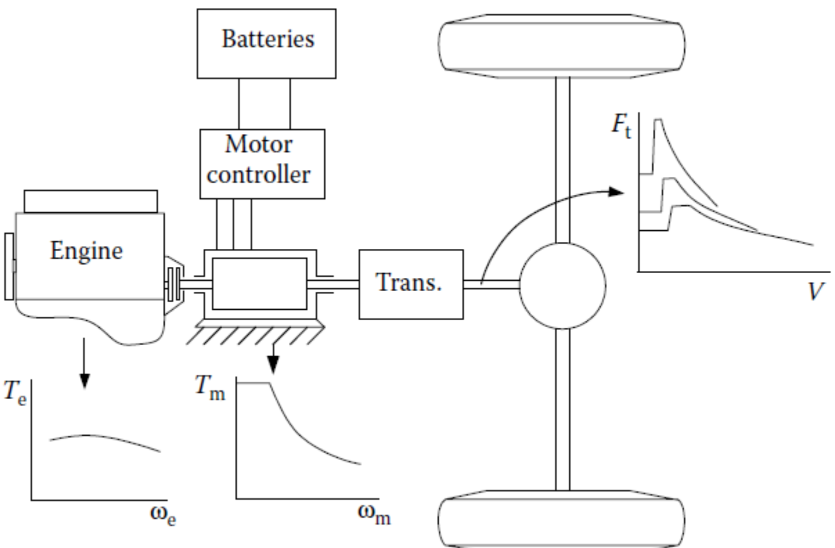


Fig. 5.11 Eshani et al. (2010)

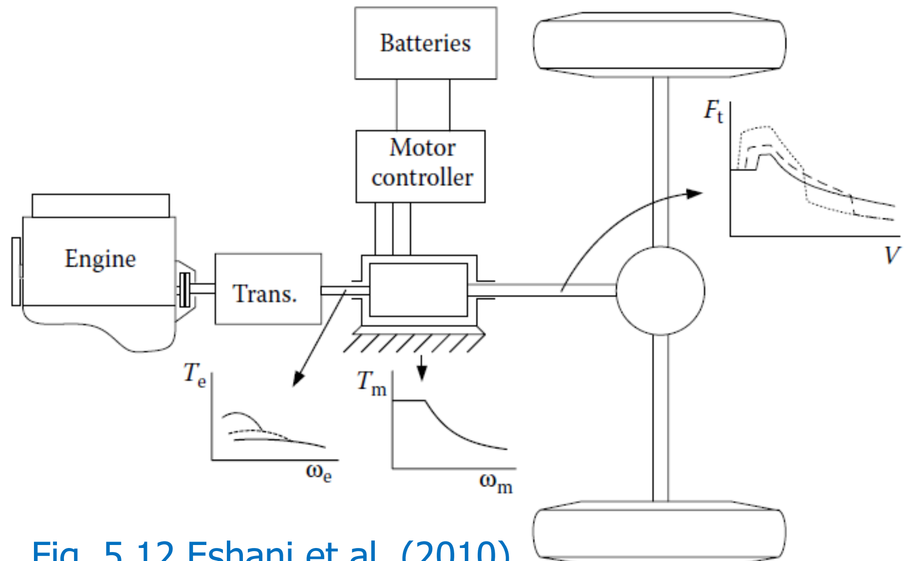


Fig. 5.12 Eshani et al. (2010)

- In the parallel hybrid configuration, the alternative option is to have a single shaft mounting.
- The drawback is that the e-motor and the engine rotation speeds are linked.
- Decoupling the engine and e-motor rotation speeds requires clutches

Torque coupling devices

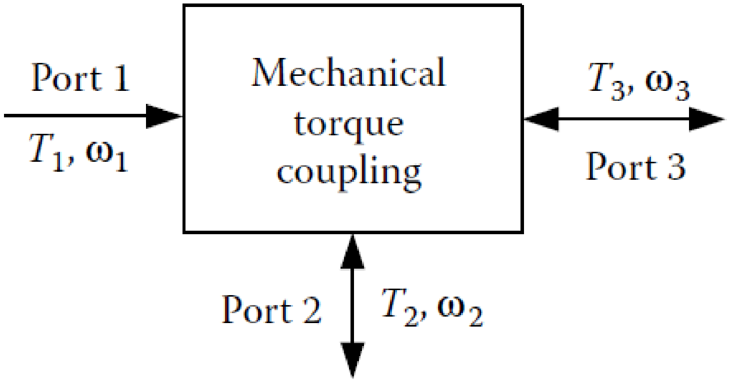
- Torque coupling devices realize the sum of the input torques and transmit the result to wheel shafts

$$T_3\omega_3 = T_1\omega_1 + T_2\omega_2$$

$$T_3 = k_1T_1 \ + \ k_2T_2$$

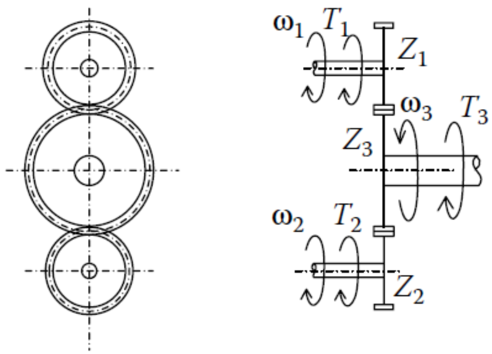
- With the reduction ratios

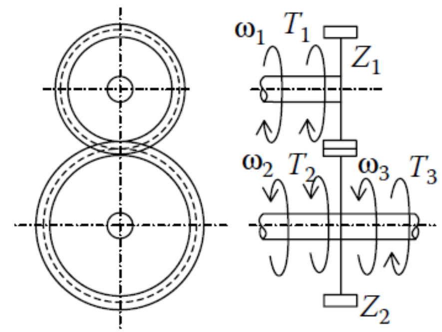
$$\omega_3 = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2}$$



Torque coupling devices

Gear Box





$k_1 = \frac{z_3}{z_1}, \quad k_2 = \frac{z_3}{z_2}$

Z_1, Z_2, Z_3---Tooth numbers of the gears

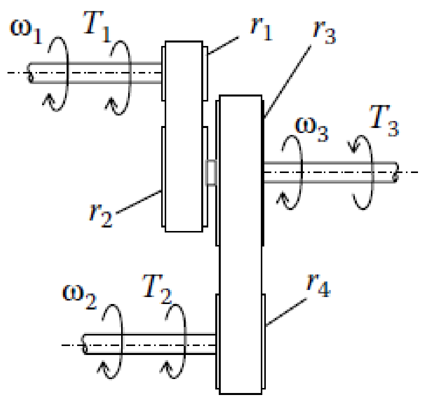
$k_1 = \frac{z_2}{z_1}, \quad k_2 = 1$

Z_1, Z_2---Tooth numbers of the gears

- Torque coupling can be carried out by two gear trains meshing to the final shaft or by single gear train.

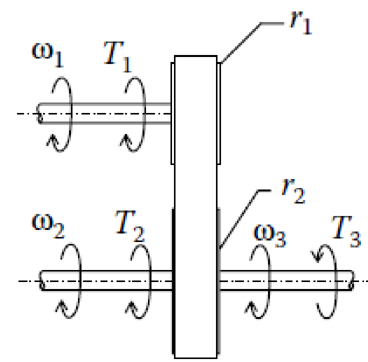
Torque coupling devices

Pulley or chain assembly



$k_1 = \frac{r_2}{r_1}, \quad k_2 = \frac{r_3}{r_4}$

r_1, r_2, r_3 and r_4 ---Radii of the pulleys



$k_1 = \frac{r_2}{r_1}, \quad k_2 = 1$

r_1, and r_2 ---Radii of the pulleys

- Torque coupling can be realized also using chains or pulleys

Torque coupling: separated axles

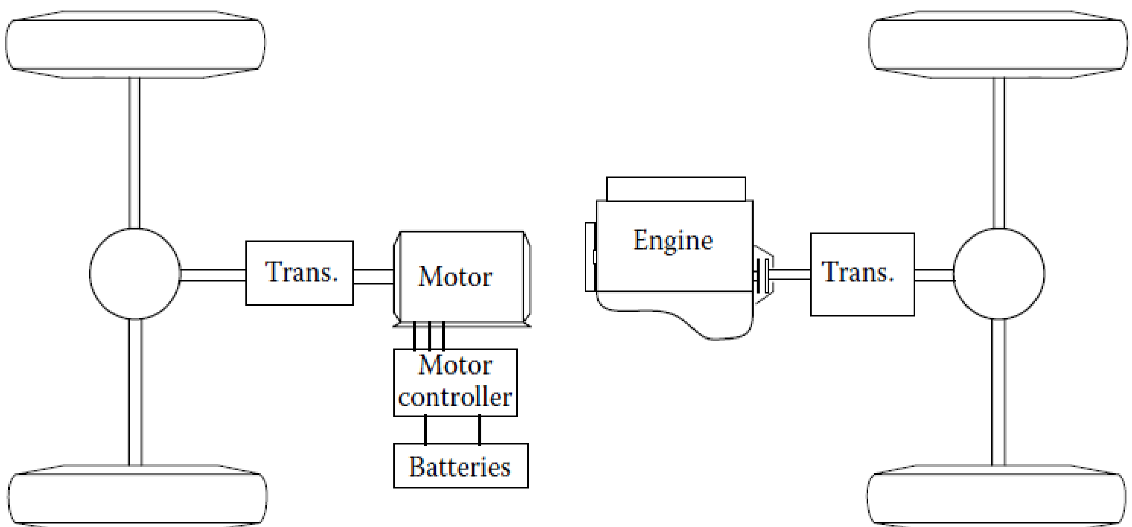


Fig. 5.13 Eshani et al. (2010)

- A third alternative option is to use the road as the mechanical coupling. Each motor is placed on a different axle.
- The drawback if that coupling efficiency is impacted by the road tire efficiency.
- The advantage is that one gets an all-wheel drive vehicle for free…

Speed coupling: planetary gear

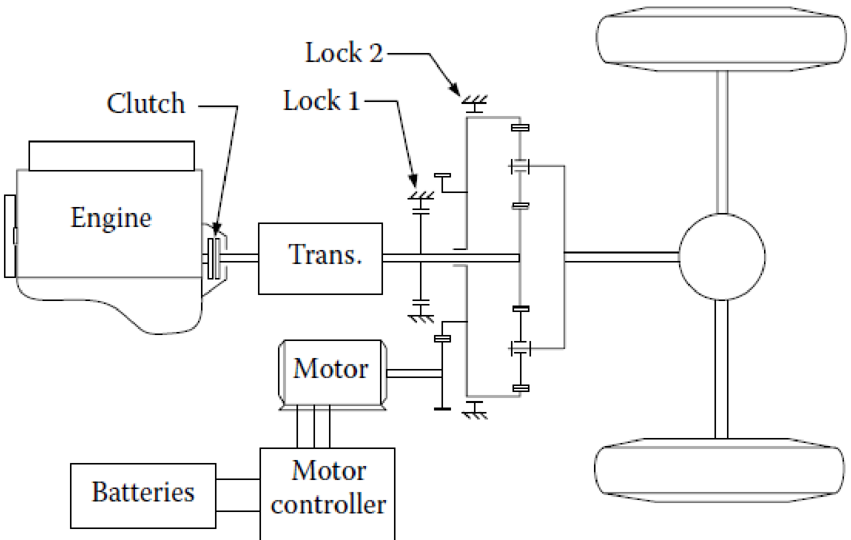
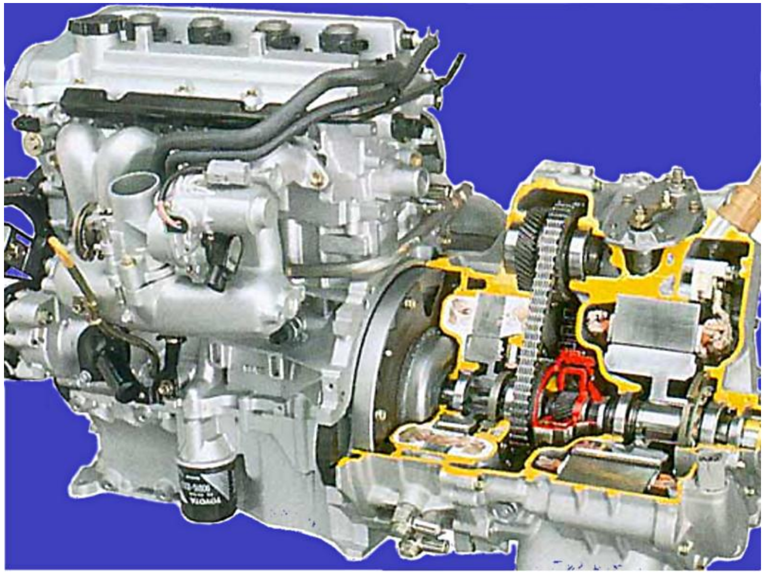


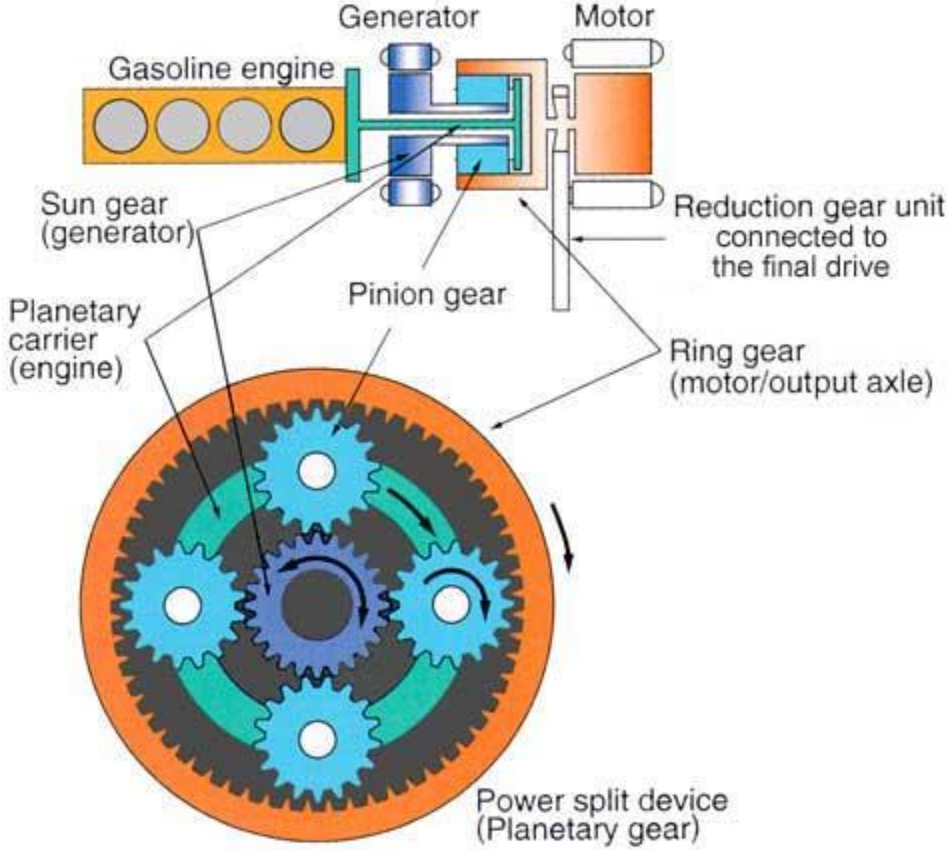
Fig. 5.18 Eshani et al. (2010)

- Among the complex coupling architectures, the torque coupling using a planetary gear train is the most famous one.
- The difficulty lies in the complex algorithm necessary to deal with the rotation speed constraint between the three input / output velocities

Toyota Prius transmission

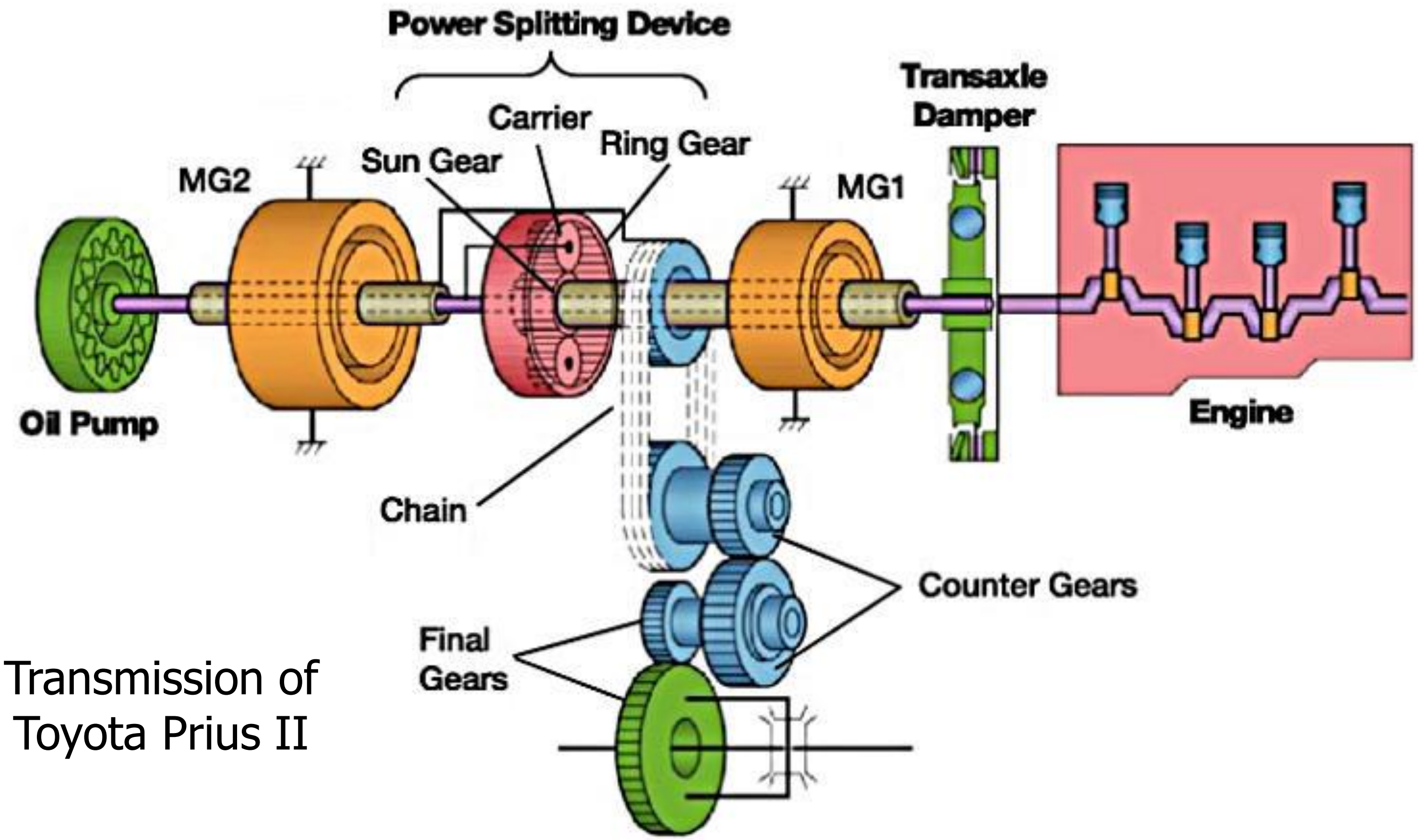
Transmission of
Toyota Prius II





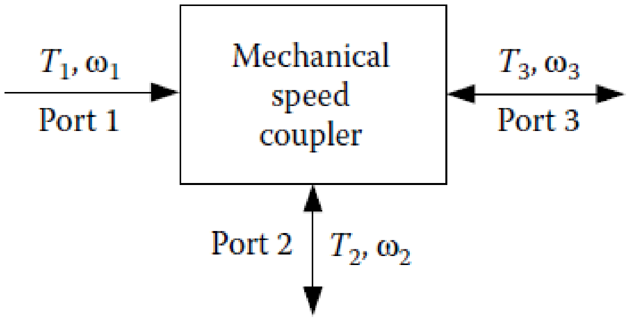
Courtesy: Toyota Motor Corporation

Toyota Prius transmission



Transmission of Toyota Prius II

Planetary gear

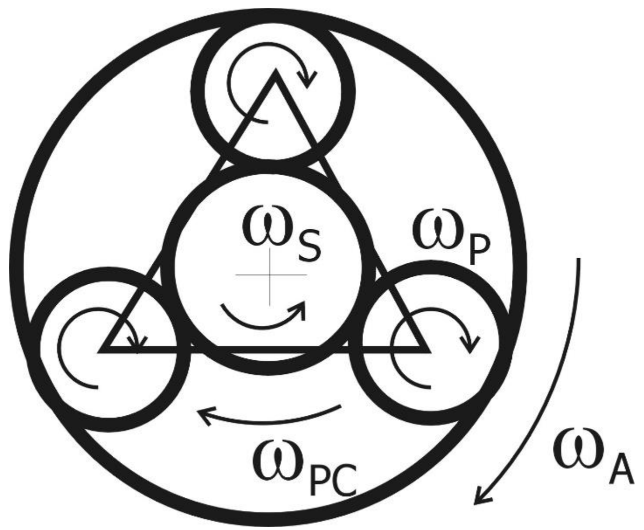


- Speed coupling ➔ Kinematic relation between the sun, the planet carrier and the annulus

$$\boxed{\omega_S\, Z_S + \omega_A\, Z_A - \omega_{PC}(Z_S + Z_A) = 0}$$

- With the gear ratio

$$i = \frac{Z_A}{Z_S} = \frac{R_A}{R_S}$$

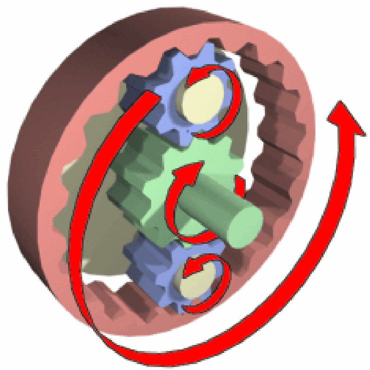


- One finds the Willys formula

$$\boxed{\omega_S + \omega_A\, i \;=\; \omega_{PC}(1 + i)}$$

- Or alternatively

$$\boxed{\frac{\omega_S - \omega_{PC}}{\omega_A - \omega_{PC}} = -i}$$



Planetary gear sets

- Equilibrium and conservation of power are given by

$$C_1 + C_3 + C_4 = 0$$

$$P_1 + P_3 + P_4 = 0$$

$$C_1\,\omega_1 + C_3\,\omega_3 + C_4\,\omega_4 = 0$$

$$\lambda = -i = -\frac{Z_A}{Z_S}$$

$$\begin{aligned} \omega_1 &= \omega_S \\ \omega_3 &= \omega_A \\ \omega_4 &= \omega_{PC} \end{aligned}$$

- After some algebra one finds

$$\frac{C_1}{1} = \frac{C_3}{-\lambda} = \frac{C_4}{\lambda - 1}$$

$$\boxed{\frac{C_S}{1} = \frac{C_A}{i} = \frac{C_{PC}}{-(i+1)}}$$

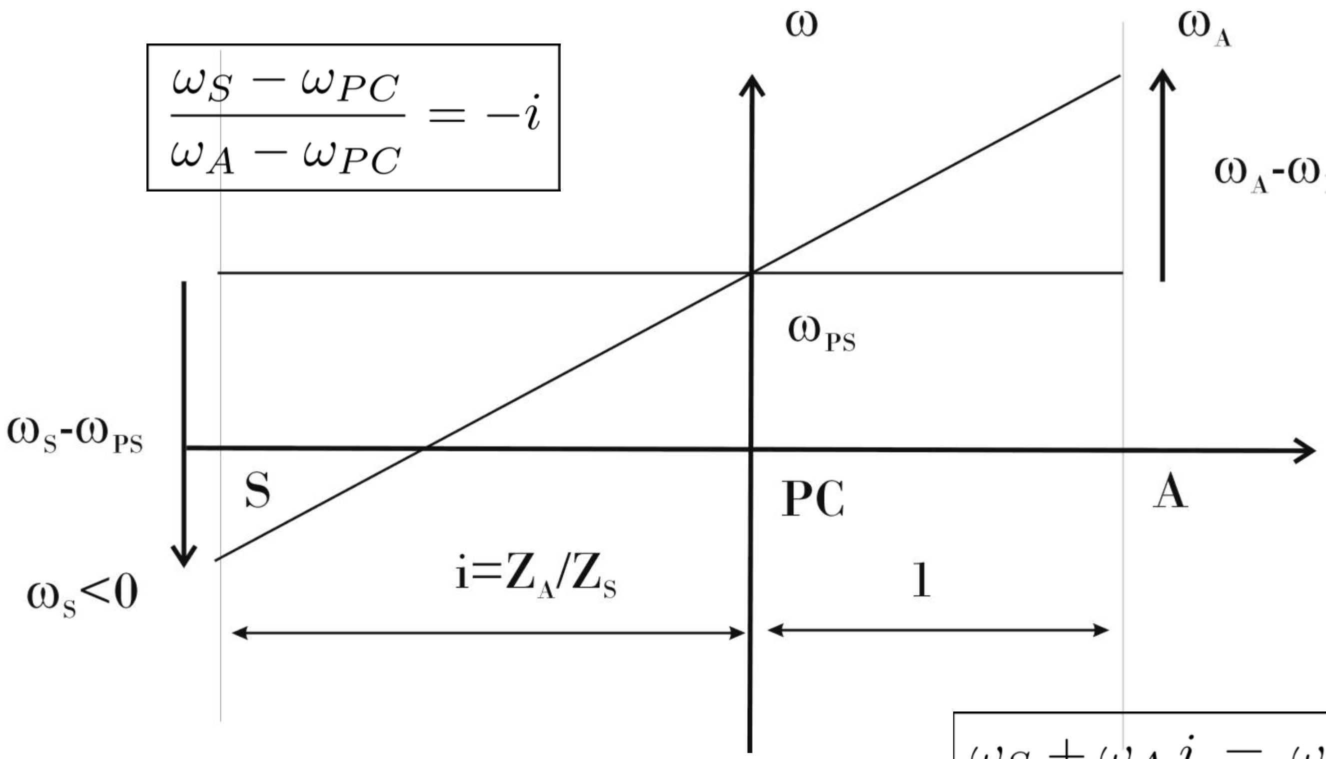
$$\frac{P_1}{\omega_1} = \frac{P_3}{-\lambda\omega_3} = \frac{P_4}{(\lambda - 1)\omega_4}$$

$$\frac{P_S}{\omega_S} = \frac{P_A}{i\,\omega_A} = \frac{P_{PC}}{-(i+1)\,\omega_{PC}}$$

Planetary gear sets

- The linear relation can be represented graphically

$$\boxed{\frac{\omega_S - \omega_{PC}}{\omega_A - \omega_{PC}} = -i}$$



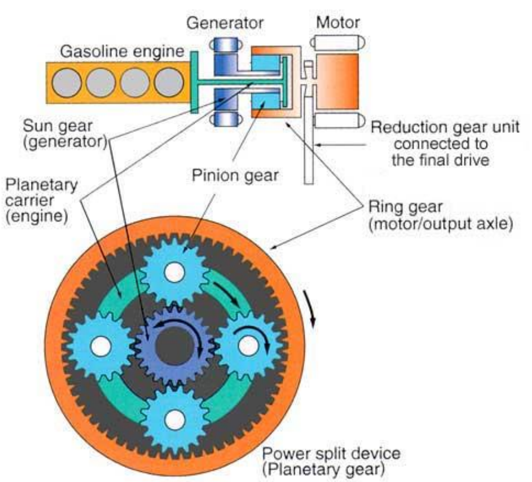
$$\boxed{\omega_S + \omega_A\, i \;=\; \omega_{PC}(1+i)}$$

Planetary gear sets

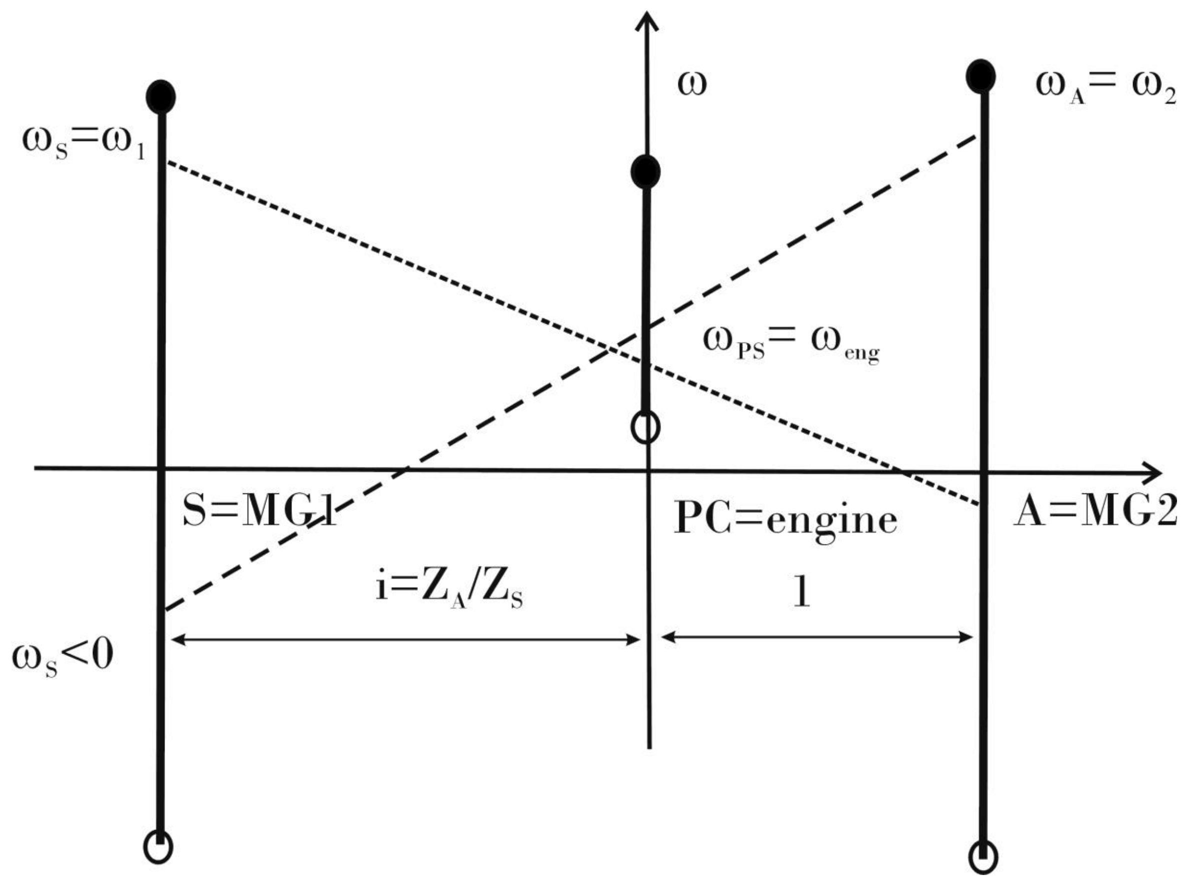
- Power split regimes

$$\boxed{\omega_{MG1} + \omega_{MG2}\, i \;=\; \omega_{ENG}(1+i)}$$

$$\begin{aligned} \omega_{MG1} &= \omega_S \\ \omega_{MG2} &= \omega_A \\ \omega_{Eng} &= \omega_{PC} \end{aligned}$$



Courtesy: Toyota Motor Corporation



Speed coupling: transmotor configuration

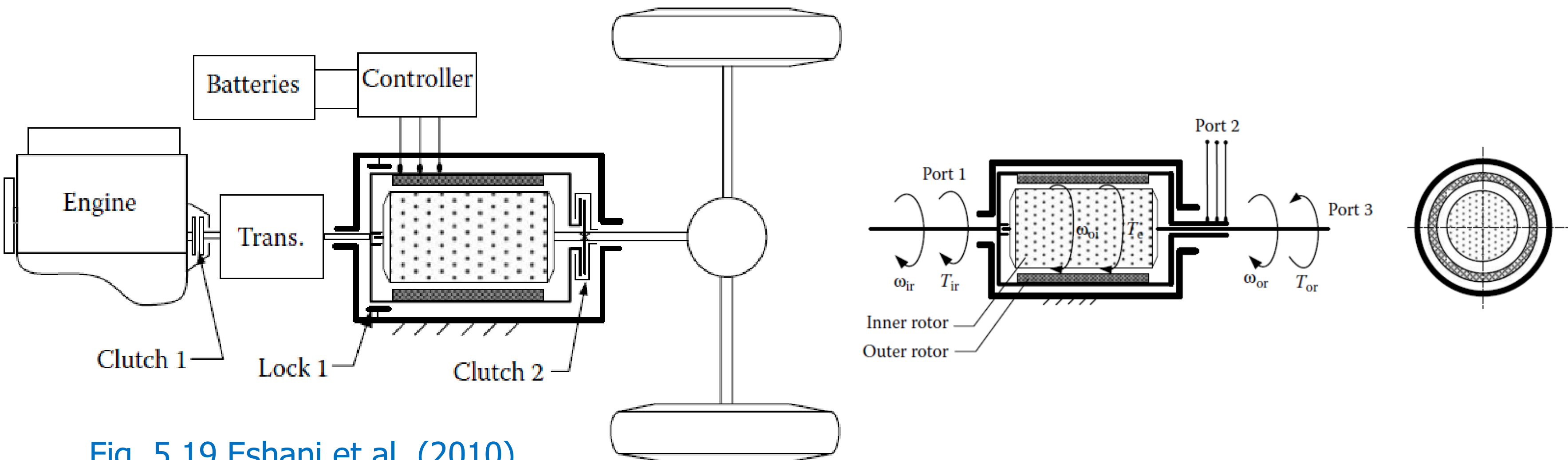


Fig. 5.19 Eshani et al. (2010)

- Finally, it is also possible to use non mechanical devices to realize the speed coupling.
- Transmotors are typically used to perform this task.