Vehicle Performance

Pierre Duysinx

Research Center in Sustainable Automotive Technologies of University of Liege

Academic Year 2021-2022

Lesson 3:
Tractive forces

Outline

- POWER AND TRACTIVE FORCE AT WHEELS
  - Transmission efficiency
  - Gear ratio
  - Expression of power and forces at wheels
  - Power and forces diagram

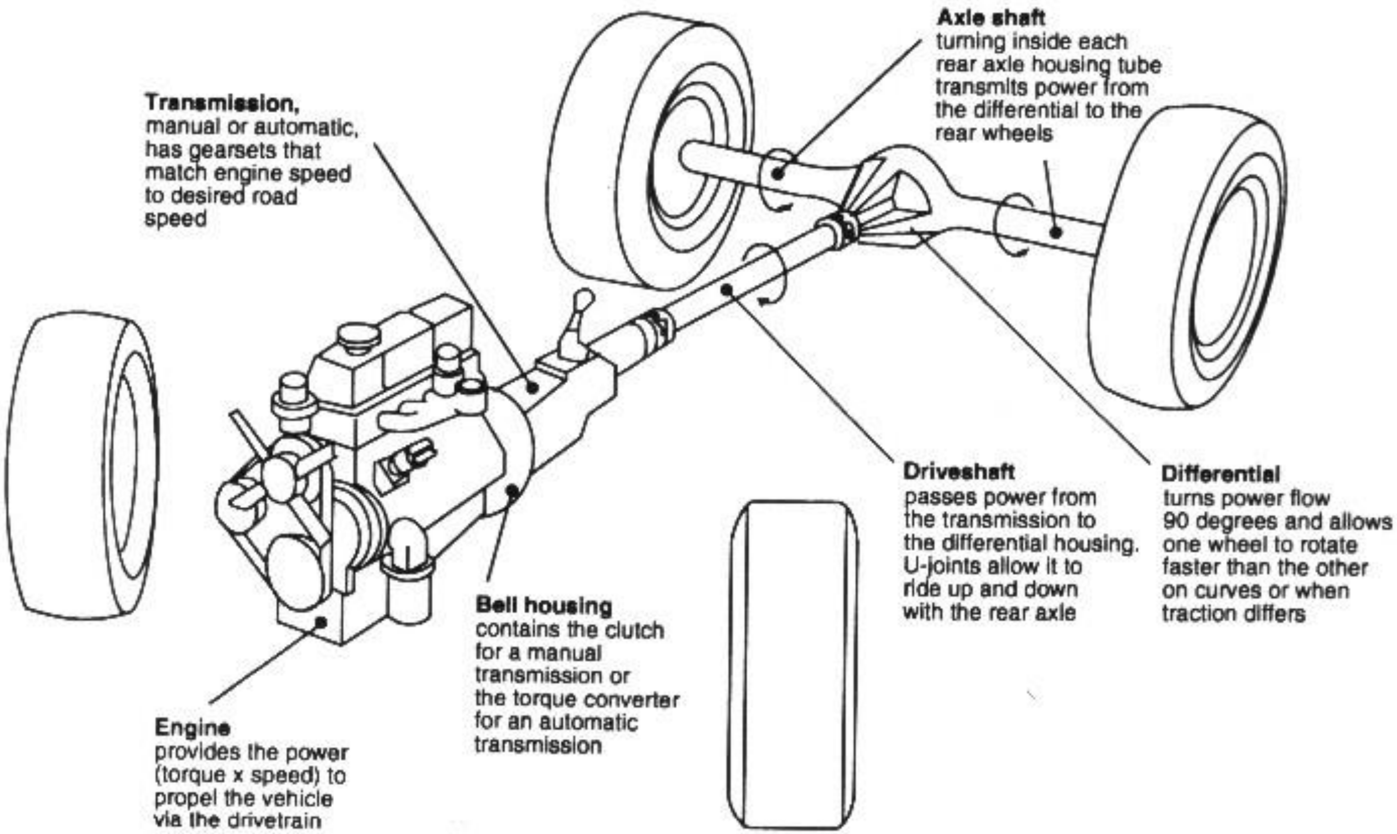
- VEHICLE ROAD RESISTANCE
  - Aerodynamic
  - Rolling resistance
  - Grading resistance
  - General expression of vehicle resistance forces

References

- T. Gillespie. « Fundamentals of vehicle Dynamics », 1992, Society of Automotive Engineers (SAE)
- R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)
- J.Y. Wong. « Theory of Ground Vehicles ». John Wiley & sons. 1993 (2nd edition) 2001 (3rd edition).
- W.H. Hucho. « Aerodynamics of Road Vehicles ». 4th edition. SAE International. 1998.
- M. Eshani, Y. Gao & A. Emadi. Modern Electric, Hybrid Electric and Fuel Cell Vehicles. Fundamentals, Theory and Design. 2nd Edition. CRC Press.

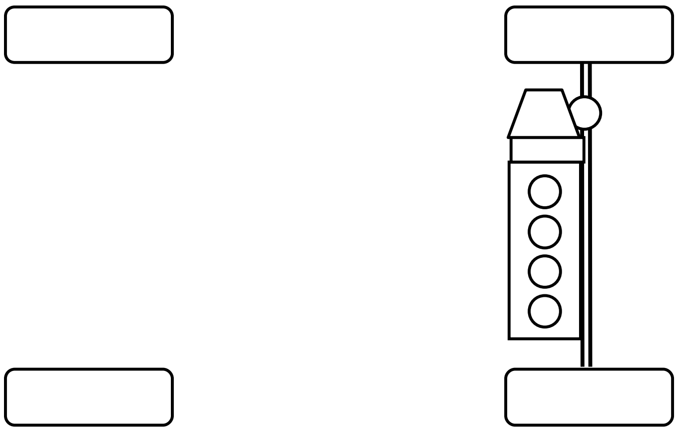
Propulsion system architecture

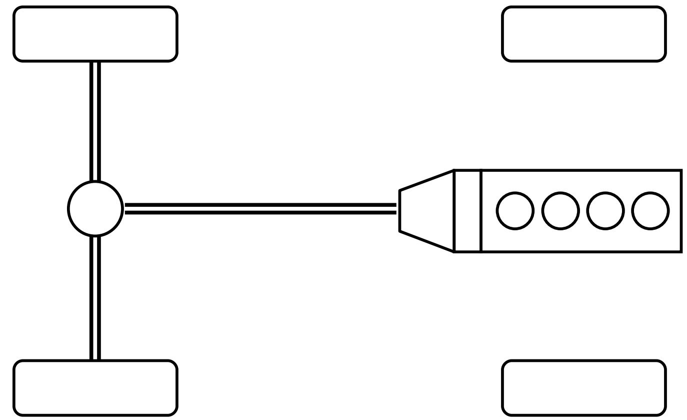
Propulsion system



Gillespie, Fig 2.3

Layout of transmission

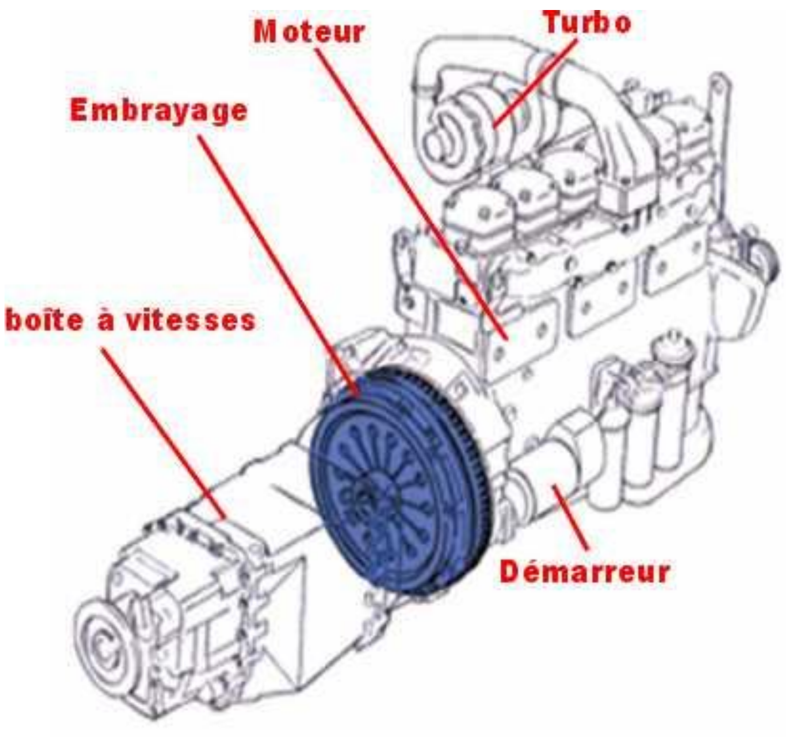


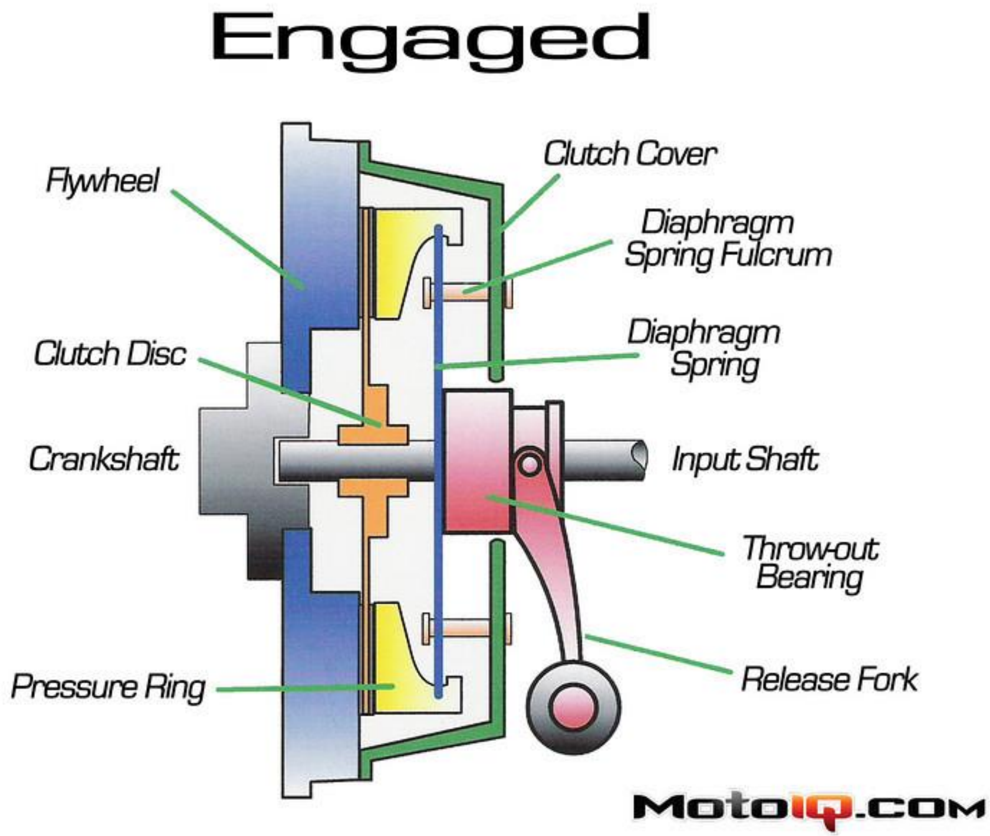


Transversal mounting

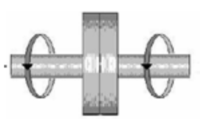
Longitudinal mounting

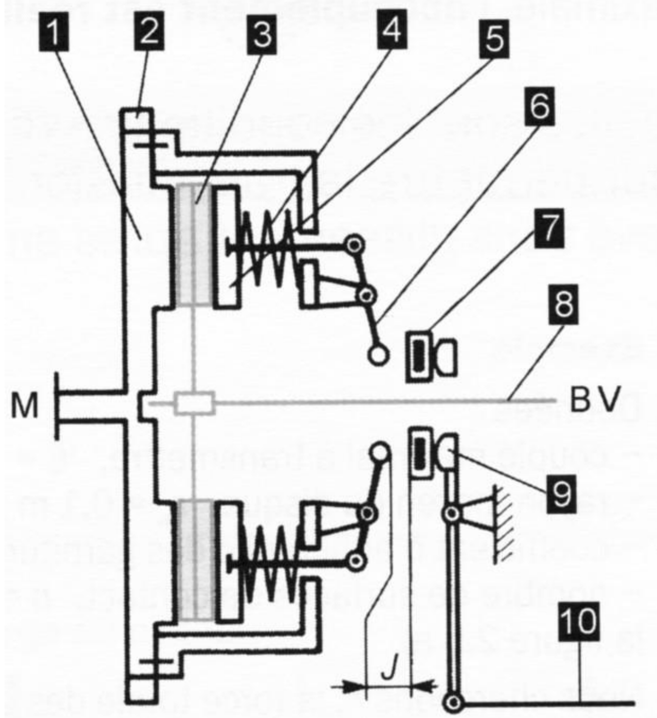
Friction Clutch

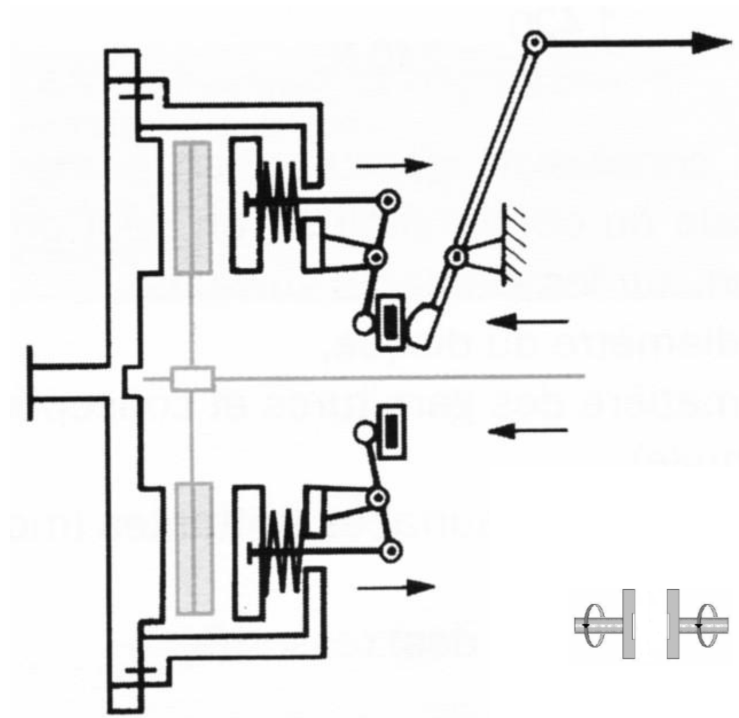




Friction Clutch



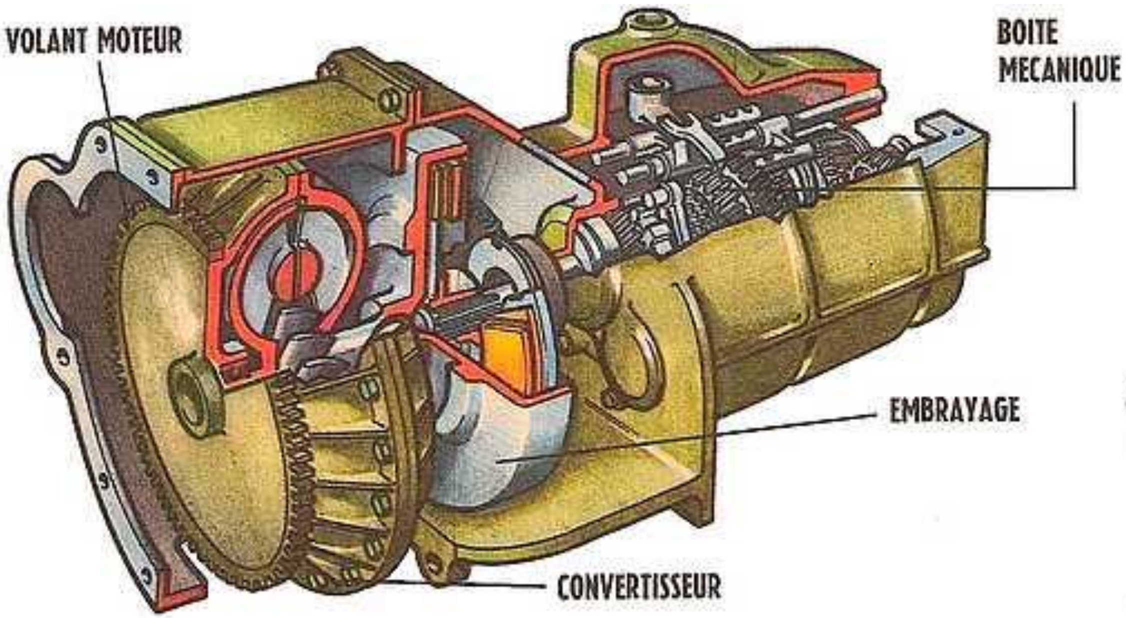


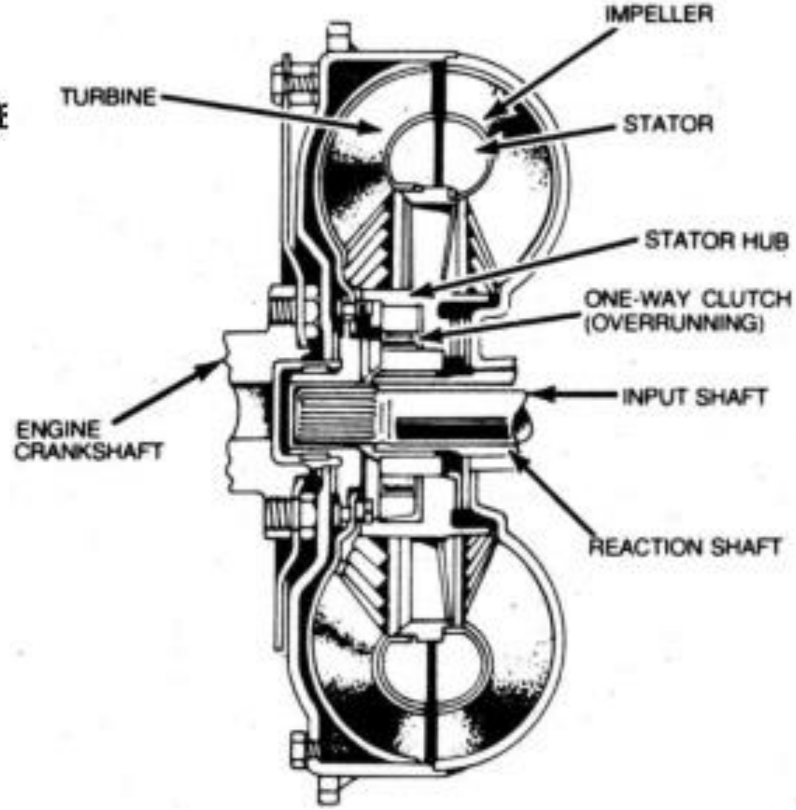


Clutch in closed position

Clutch in open position

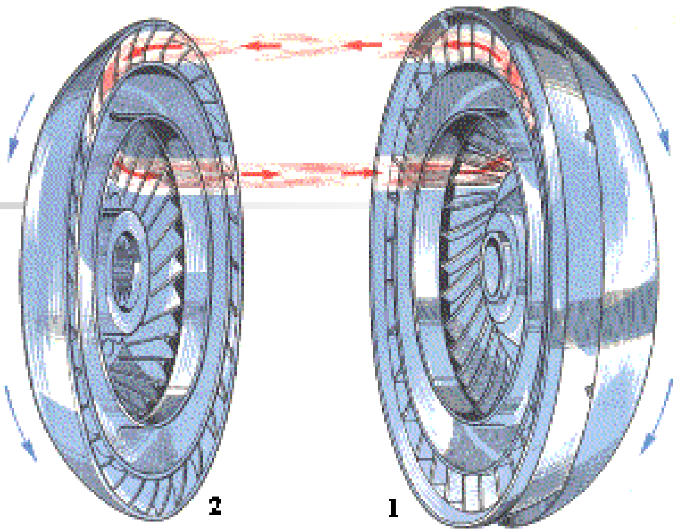
Torque converter (Hydraulic coupling)

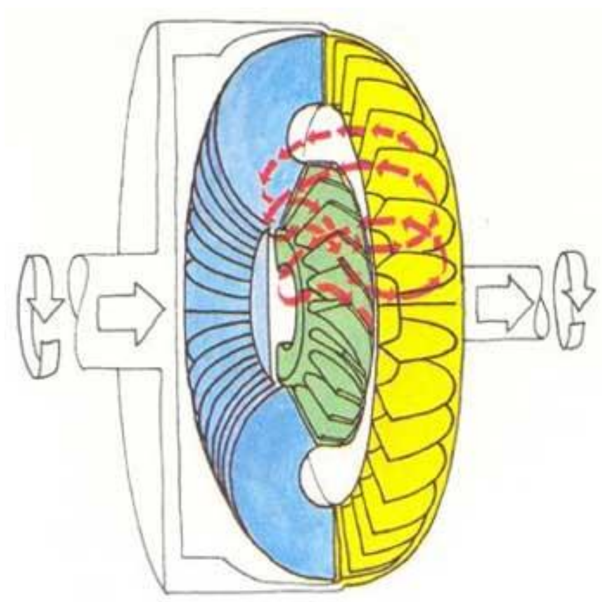




Hydraulic coupling

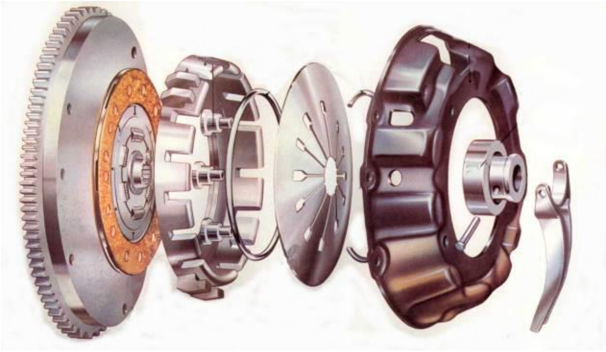
- Principle: use the hydro kinetic energy of the fluid to transfer smoothly the power from the source to the load while amplifying the output torque
- The input wheel plays the role of a pump whereas the output wheel acts as a turbine
- One may add a fixed wheel (stator) to improve the efficiency

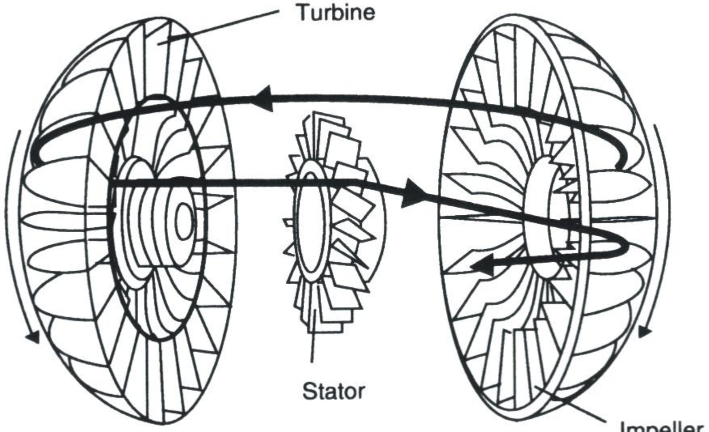


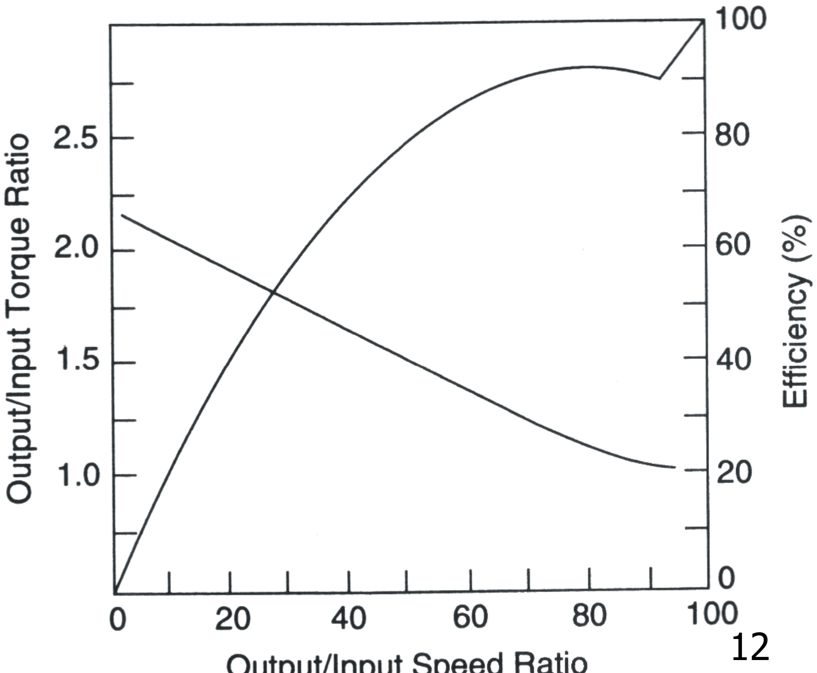


Friction and hydraulic clutches

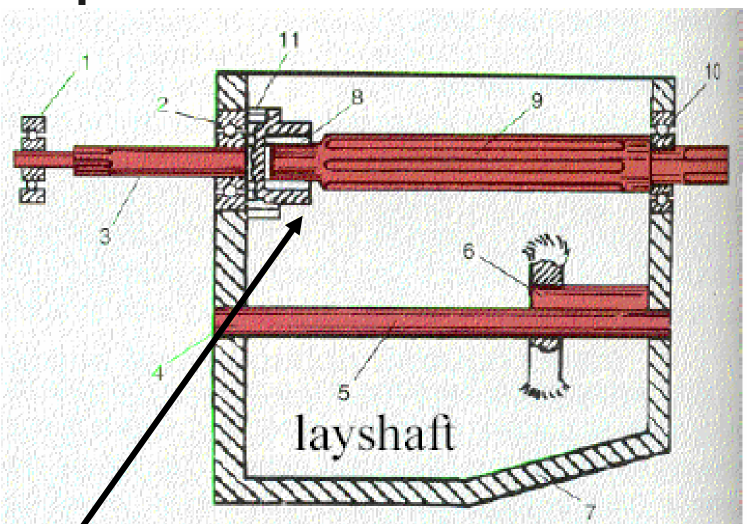
- Clutch efficiency
  - Friction clutch $\eta=1$
  - Hydraulic coupler: $\eta \sim 0.9$







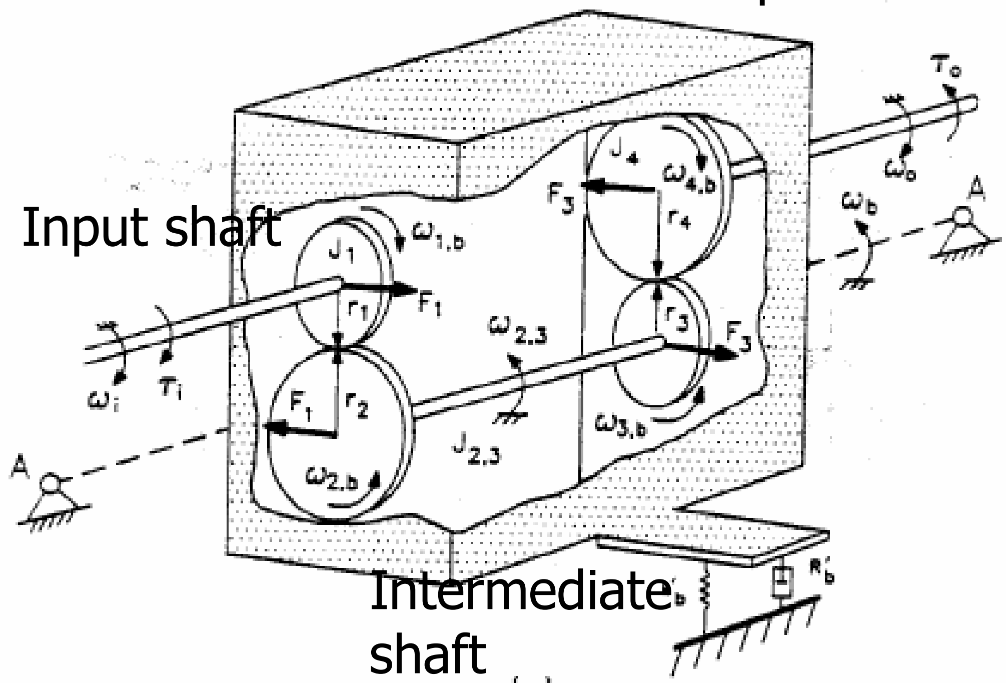
Manual gear boxes



Direct transmission

Gear box principles

Output shaft



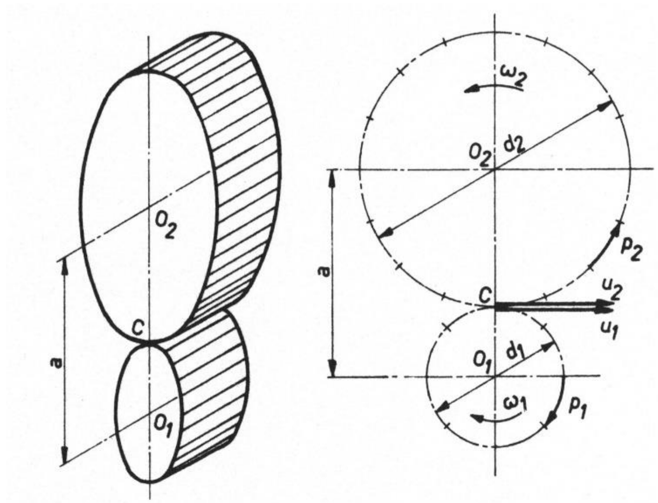
Input shaft

Intermediate shaft

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

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

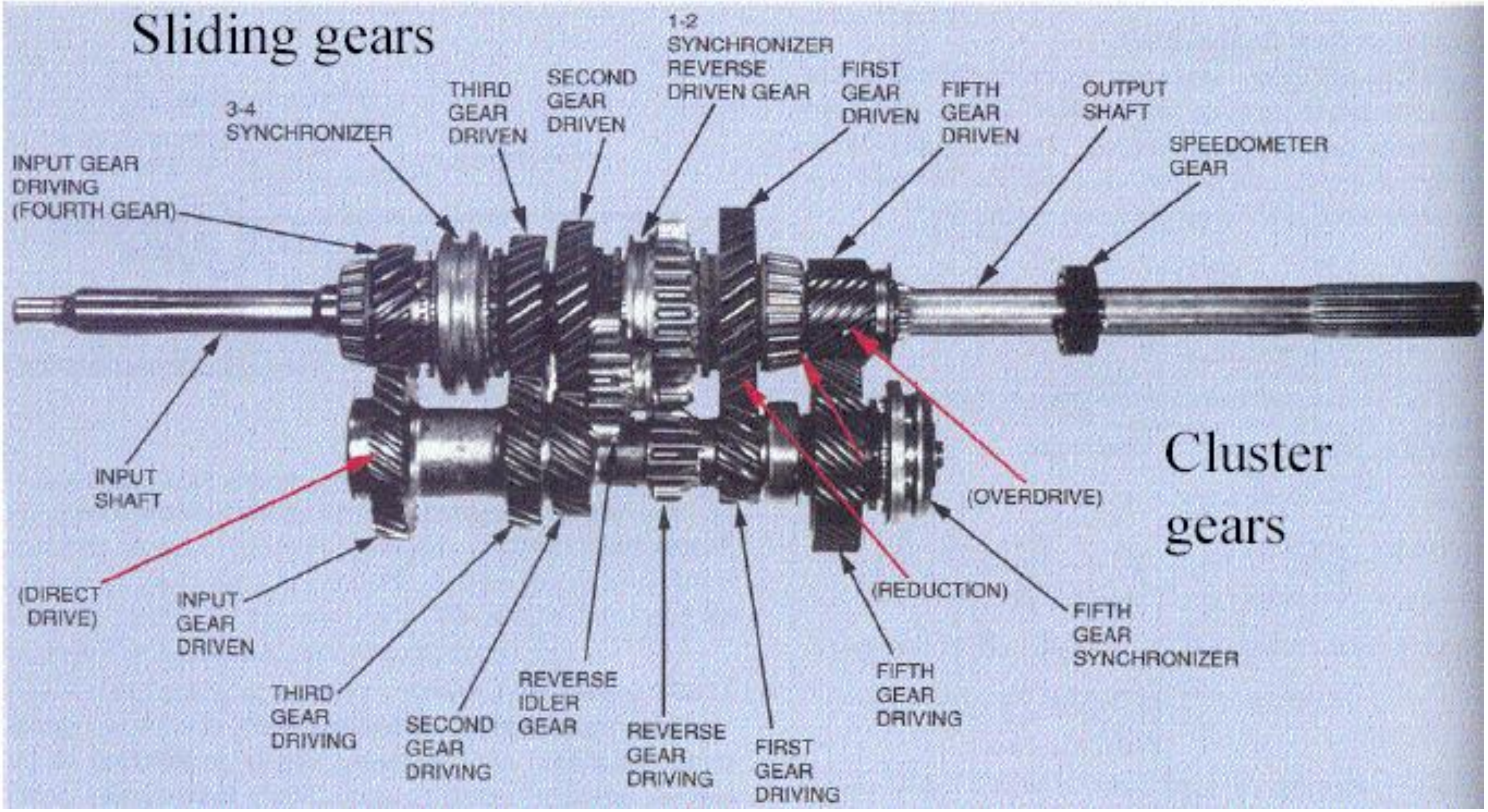


- Thus, the reduction ratio i

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

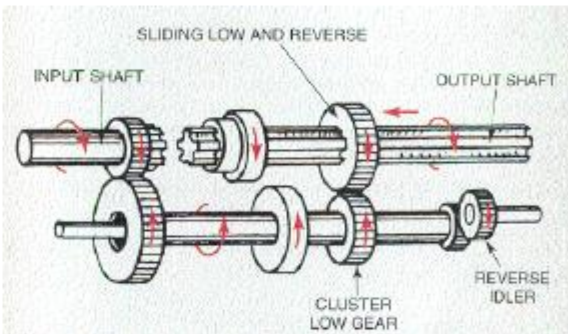
- For external meshing, there is an inversion of rotation direction while for internal gear meshes, the gear rotation direction is preserved (like belt and pulleys or chains)

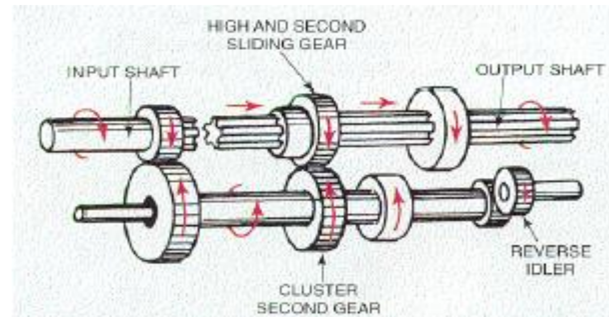
Manual gear boxes



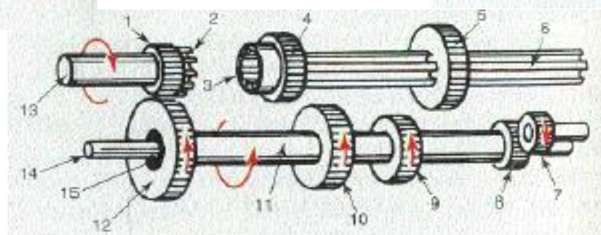
Manual gear boxes

1st

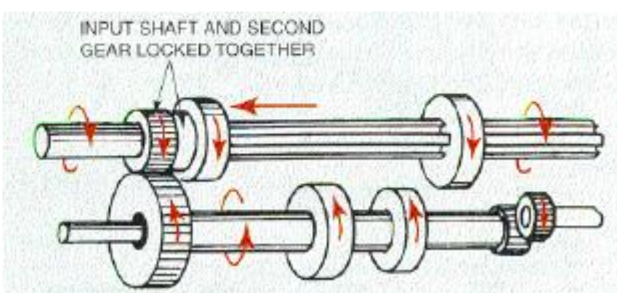




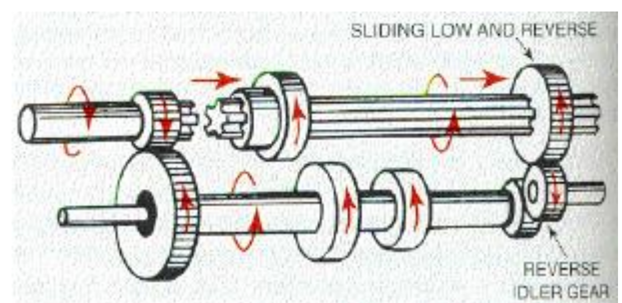
2nd



Neutral

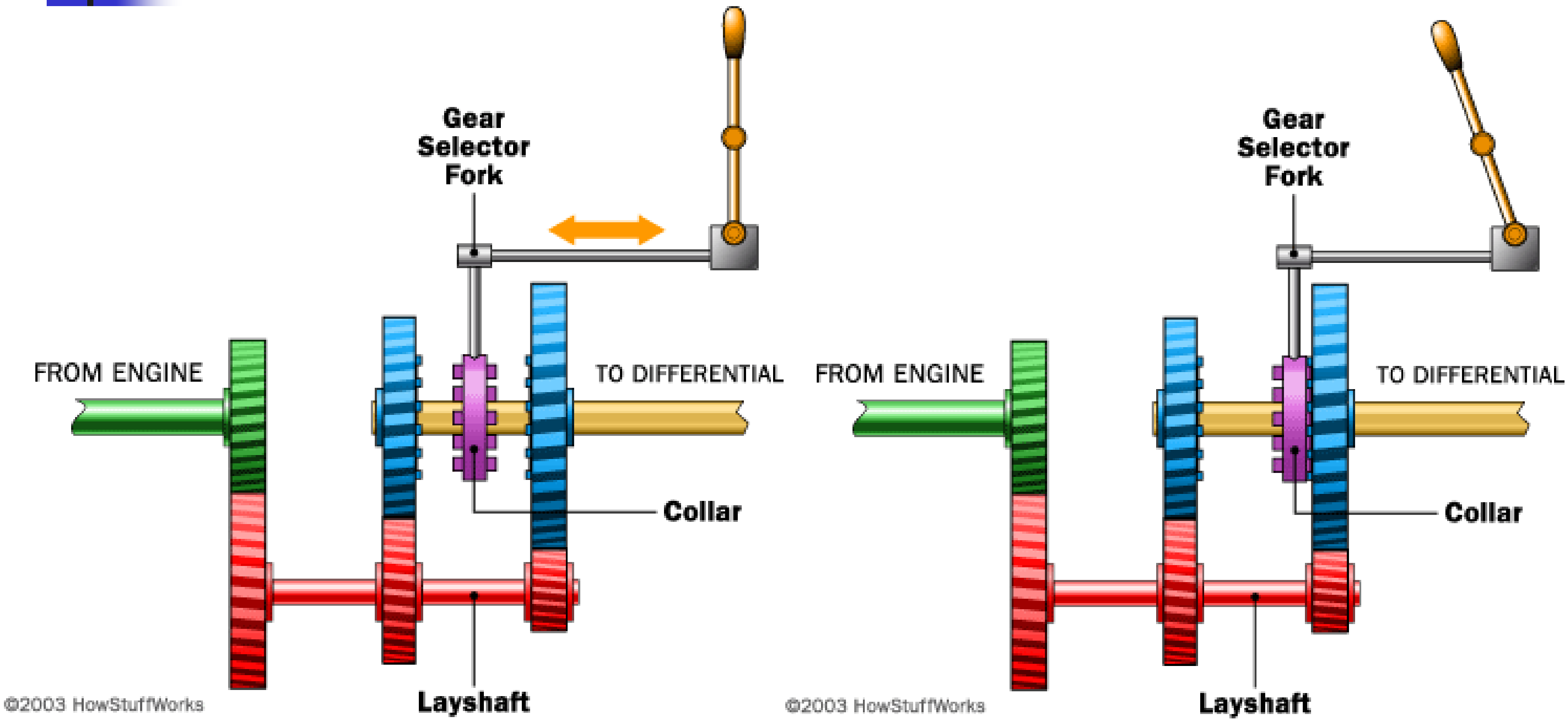


3rd



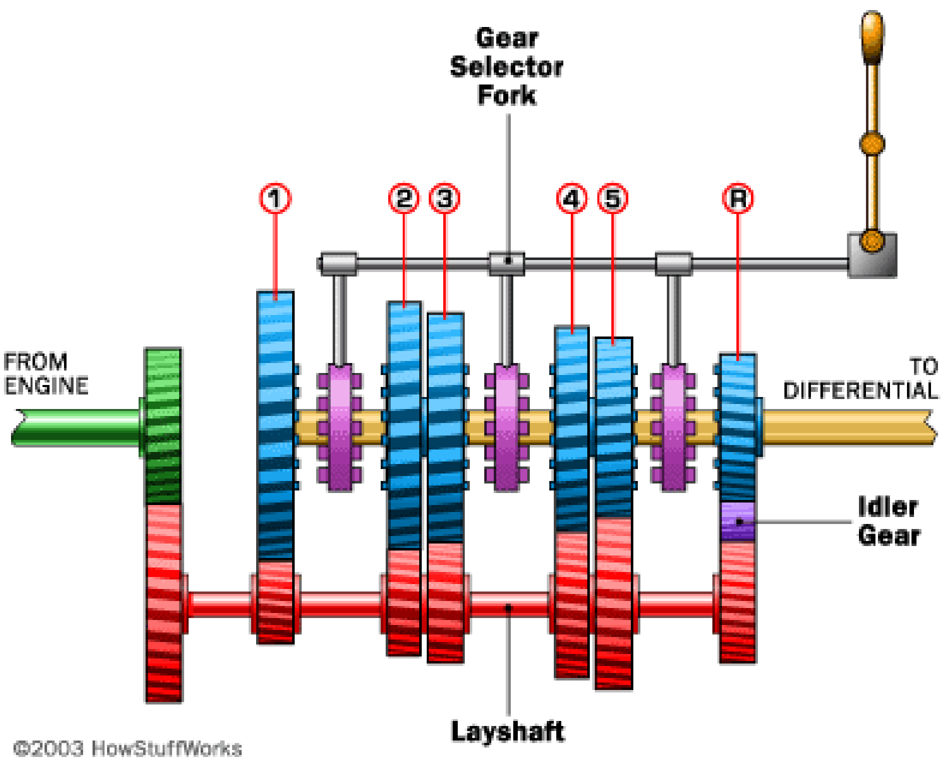
Reverse

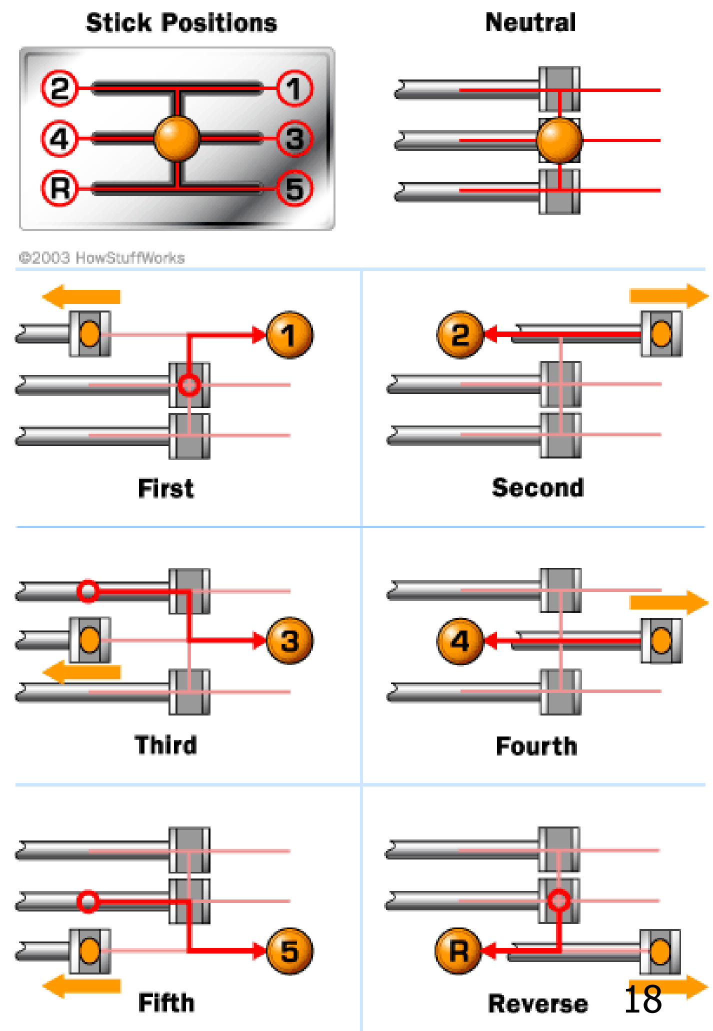
Manual gear boxes



Gear selection

Manual gear boxes operations





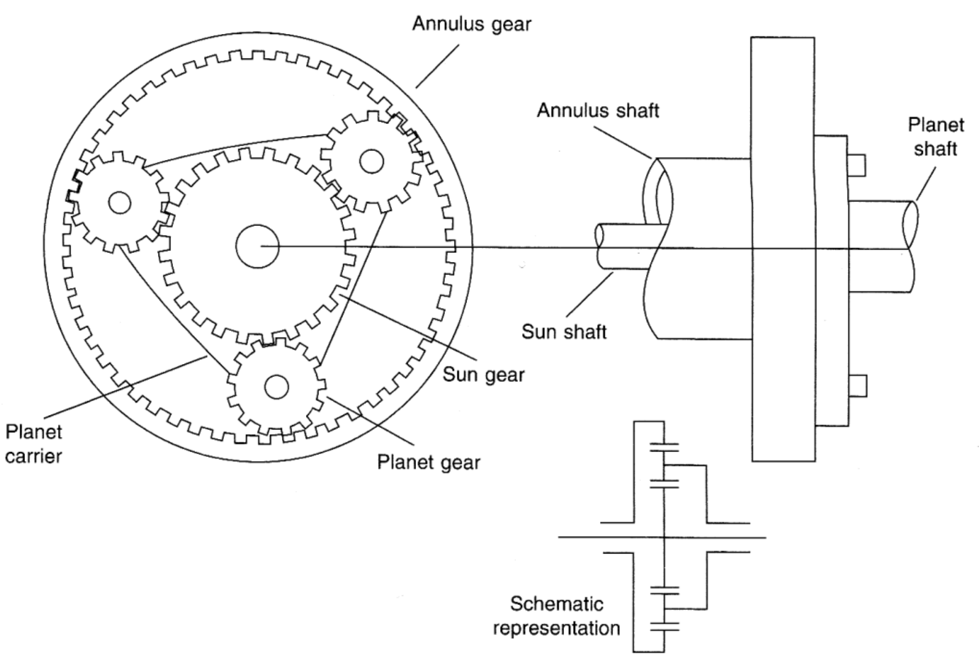
Selection of a gear ratio using rod or cable mechanism

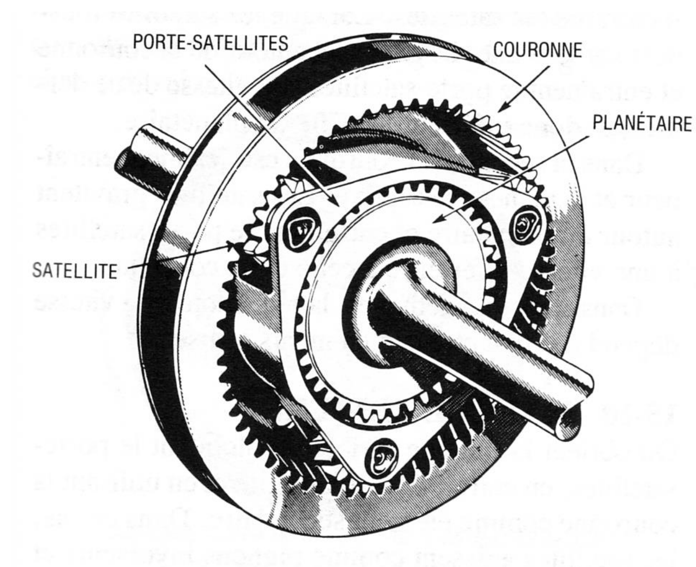
Power and tractive efforts at wheels

- 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

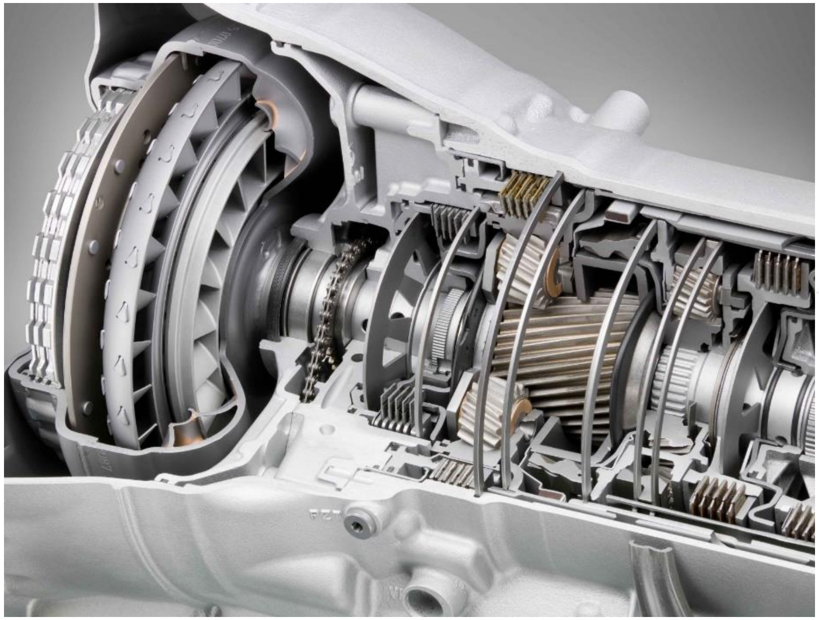
- The basic element of automatic gear boxes is the planetary gear train

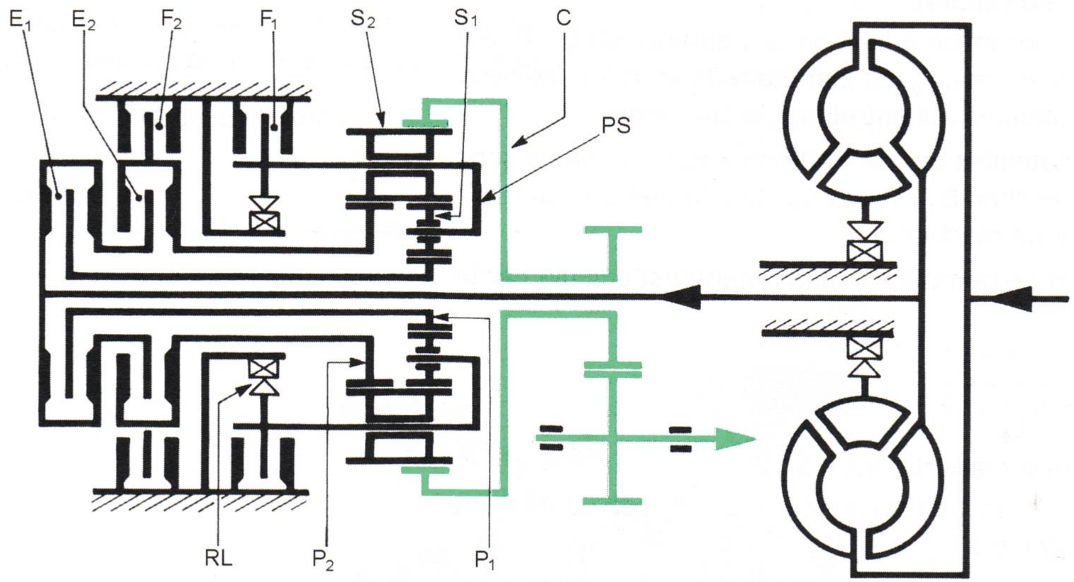




Sun = planétaire Planet = satellite Annulus = Couronne

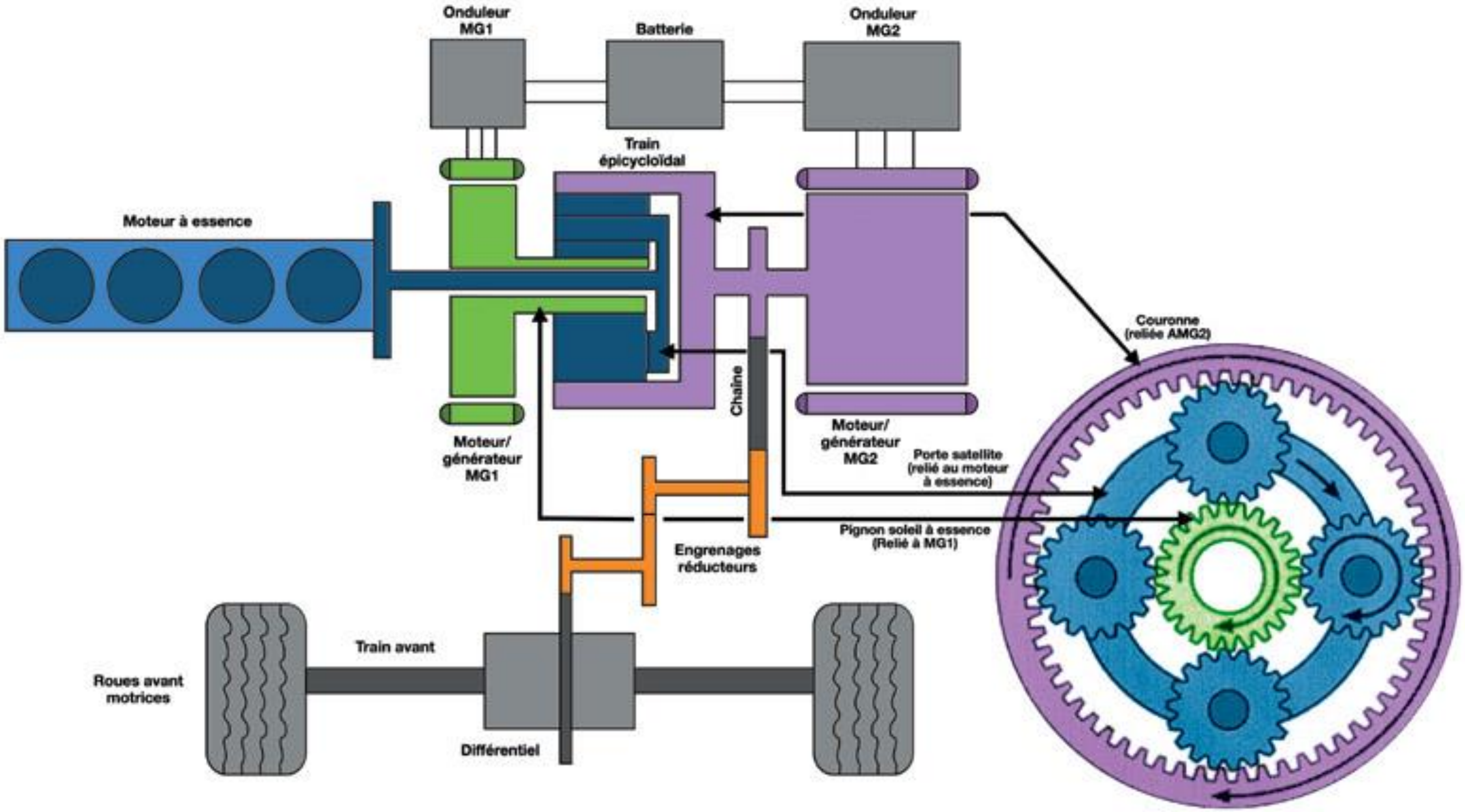
Automatic gear box



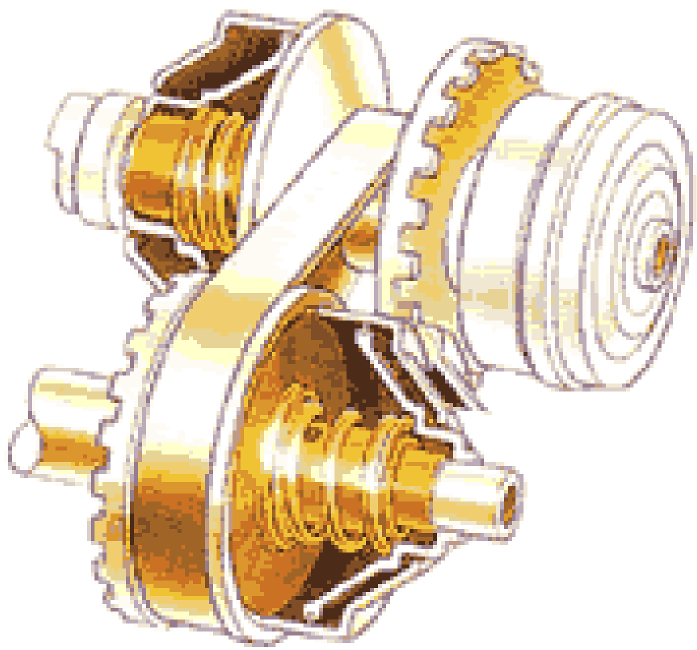


Principle of an automatic gear box based on double planetary gear trains

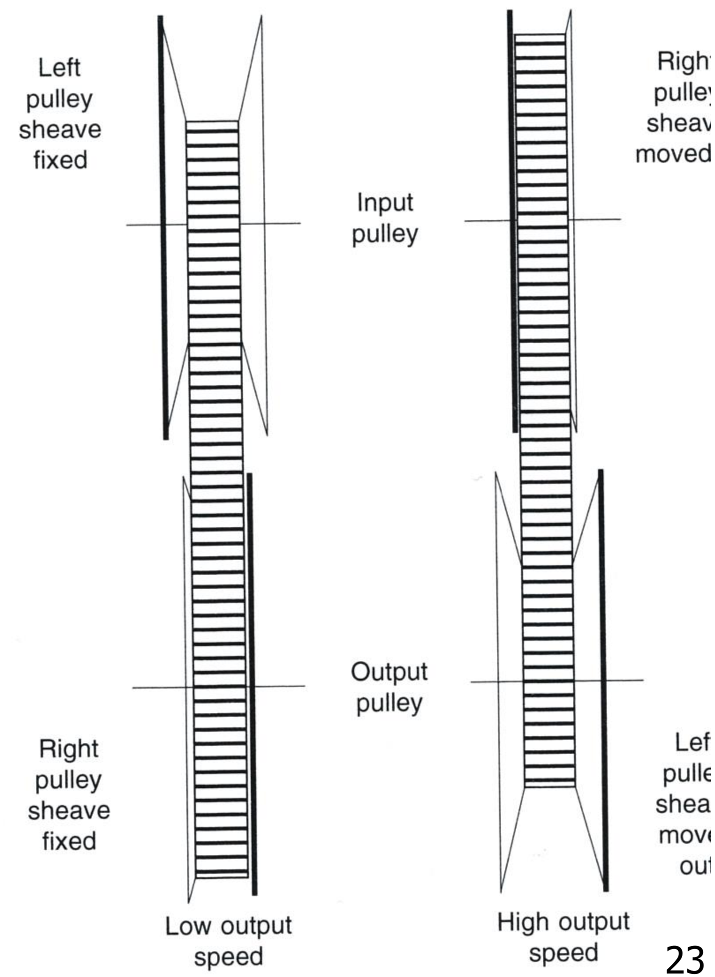
Planetary gear in HEV



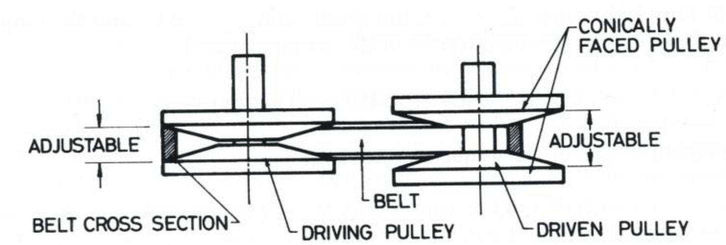
CVT : Van Doorne System

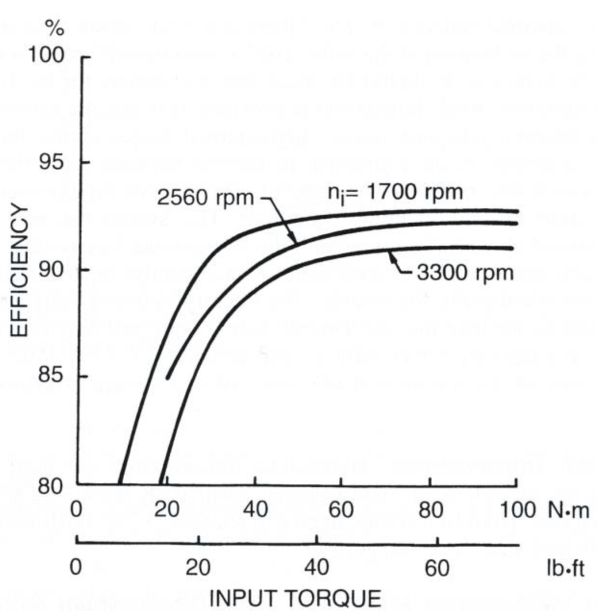


Pulleys with variable radii



CVT : Van Doorne System

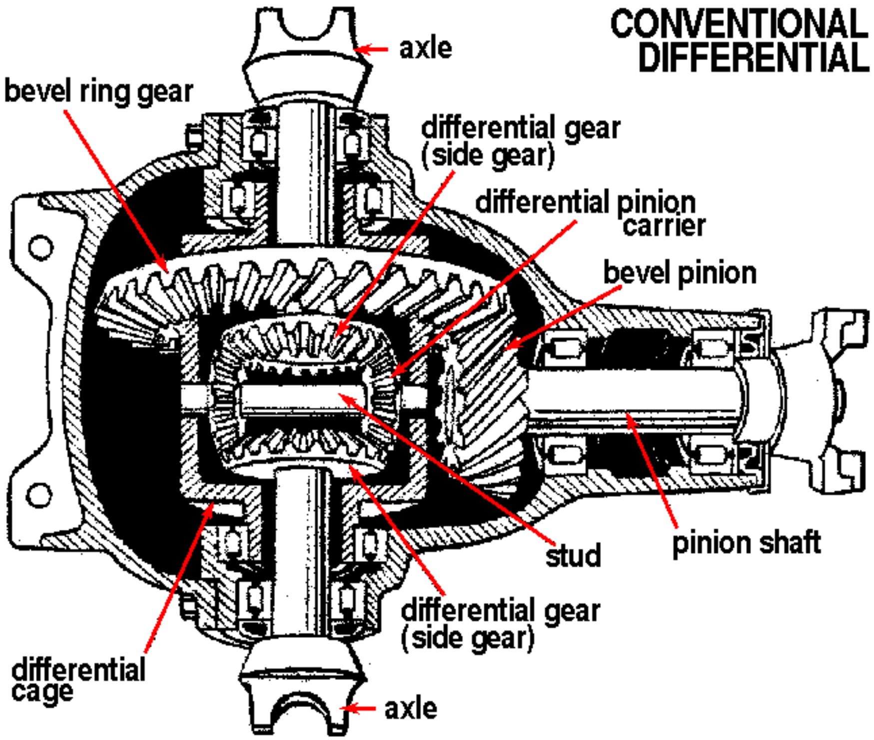




- Working principle
  - By modifying the distance between the two conical half shells, one modifies the effective radii of the pulleys and so the reduction ratio
  - Originally the system was based on the centrifugal forces, but nowadays the system is actuated by depression actuators and controlled by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

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

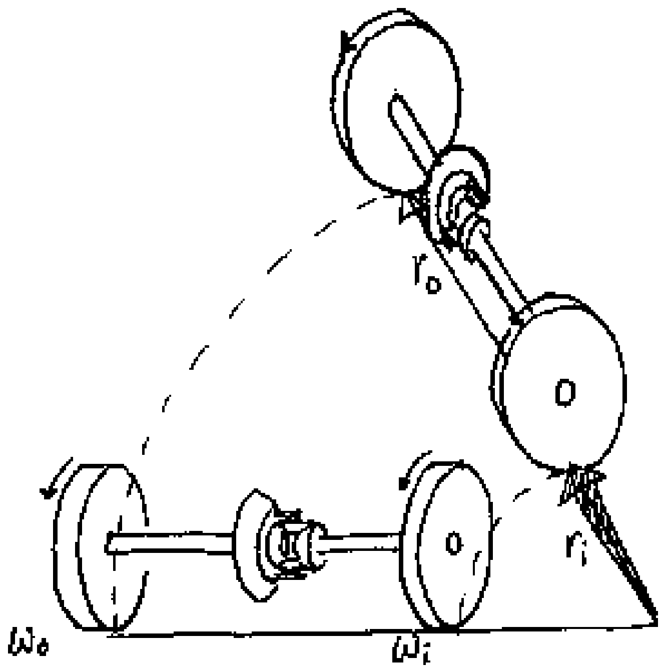
Differential system



Output shafts (wheels)

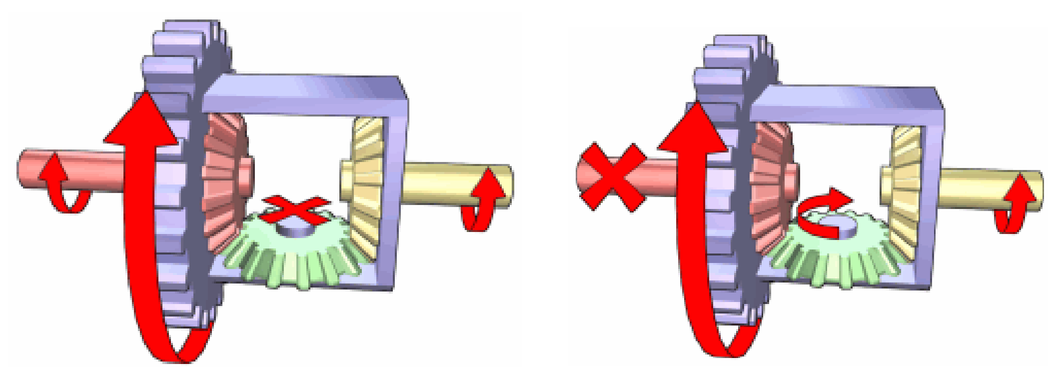
- During turn, the inner and outer wheels have different rotation speeds because of different radii.
- Differential systems allow a different speed in left / right wheels with one single input torque
- Differential systems can be studied as planetary gears with equal number of teeth for sun and annulus.

Differential

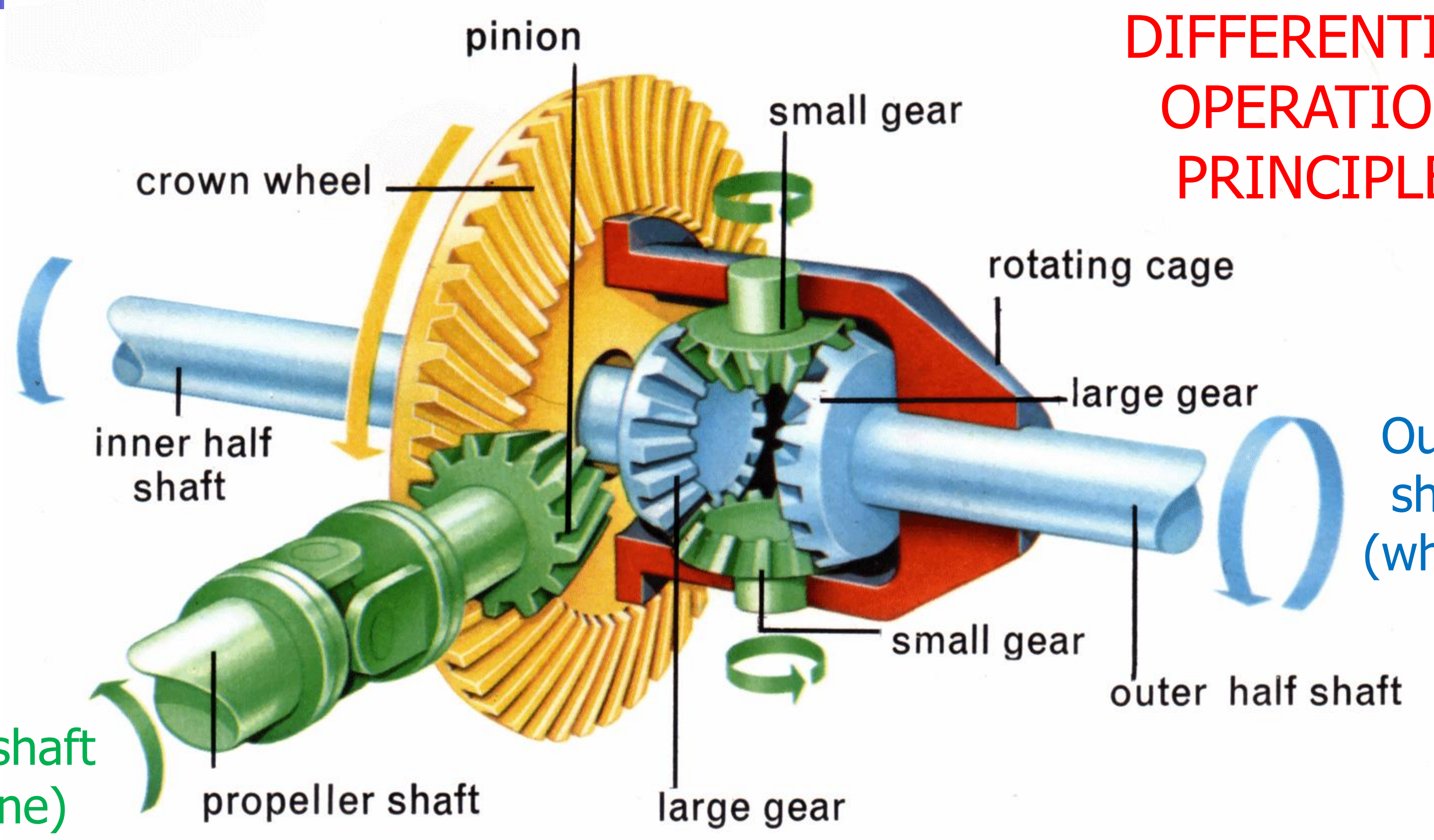


$r_o > r_i$; $\omega_o > \omega_i$

- Differential is a device that allows to split the engine power to the two wheel shafts while allowing them to spin at different rotation speeds.
- For straight line motion, both wheel spins at the same speed.
- In turn, the inner wheel spins at a lower speed than the outer wheel.



Differential system

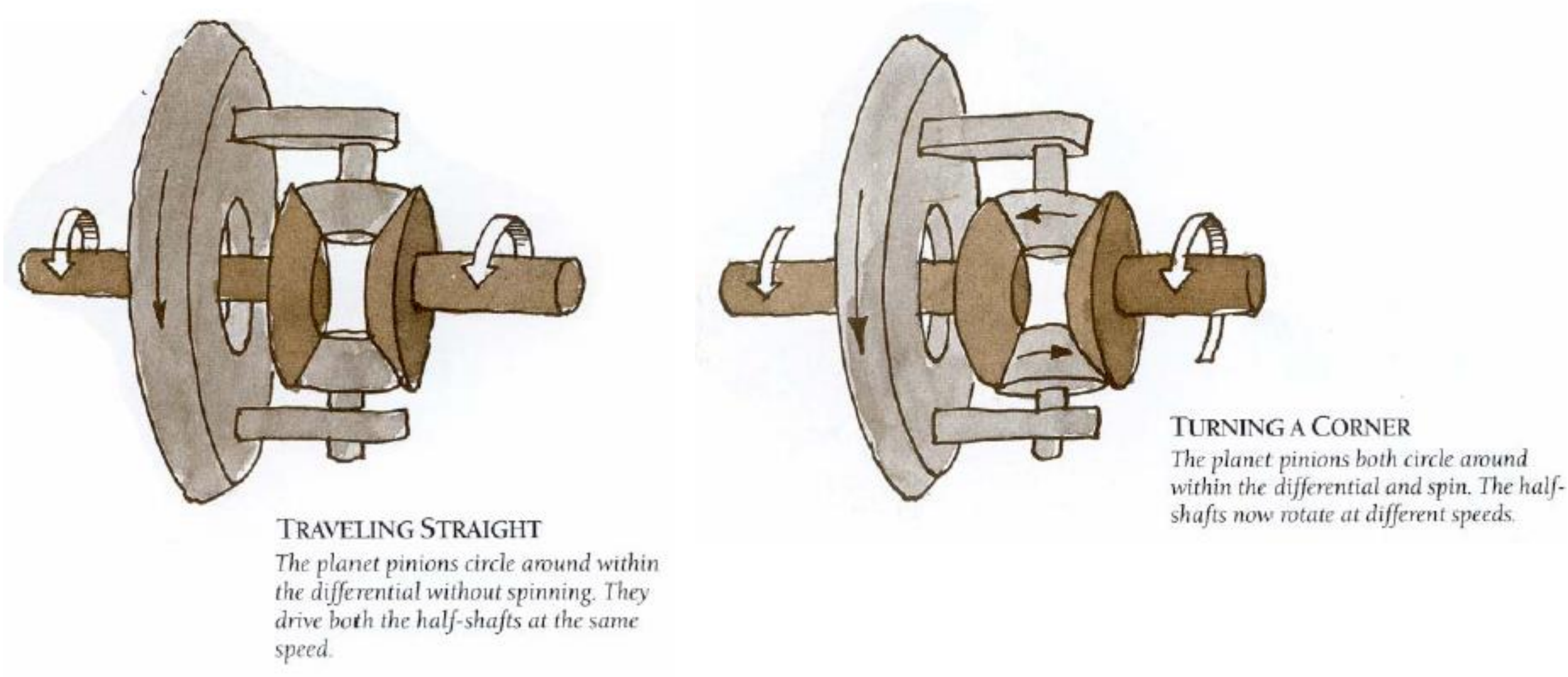


DIFFERENTIAL OPERATION PRINCIPLE

Output shafts (wheels)

Input shaft (engine)

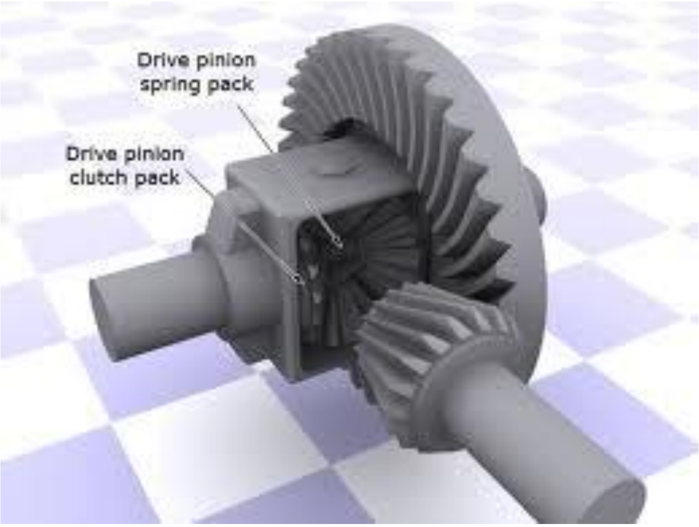
Differential system



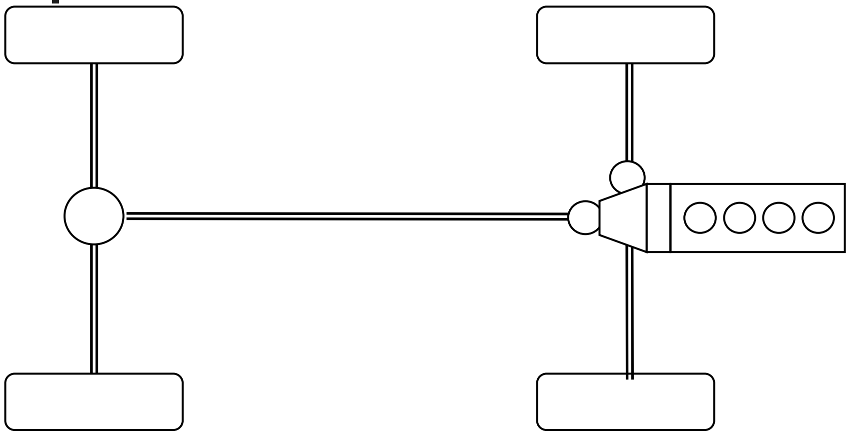
Working principle of differential system

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.

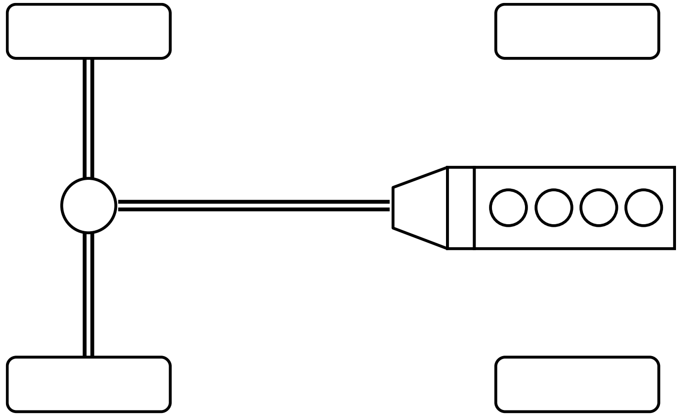
Power train tractive effort

Power and tractive effort

POWER AT WHEELS

- The power that comes to the wheels is the engine power multiplied by the efficiency of the transmission efficiency η

$$\mathcal{P}_w = \eta_t \, \mathcal{P}_p$$



- The driveline efficiency η_t :
  - Clutch
  - Gear box
  - Differential and transfer box
  - Kinematic joints

$$\eta_t = \eta_{clutch} \, \eta_{box} \, \eta_{dif} \, \eta_{joints}$$

Power and tractive effort

Global efficiency in various situations

	Gear ratio	Longitudinal layout	Transversal layout
Friction clutch	Normal	1. 0,975. 0,975 = 0,95	1. 0,975 . 0,985 = 0,96
	Direct	1. 1. 0,975 = 0,975	X
Hydraulic coupling	Normal	0,88 . 0,975 . 0,975 = 0,86	0,88 . 0,975 0,985 = 0,865
	Direct	0,88 . 1 . 0,975 = 0,88	x

Power and tractive effort

WHEEL TRACTIVE EFFORT

- Power at wheels and power at the plant

$$\mathcal{P}_w = F_w \, v \qquad\qquad \mathcal{P}_p = C_p \, \omega_p$$

- Gear ratio i>1

$$\omega_p = i \, \omega_w \qquad\qquad i = i_{box} \, i_{dif} \qquad\qquad i = \frac{\omega_{in}}{\omega_{out}}$$

- Displacement speed and rotation speed of the wheels

$$v = \omega_w \, R_e$$

  - Re: effective rolling radius of the tire

Power and tractive effort

TRACTIVE FORCE

- Relation between plant rotation speed and traveling speed

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

- Transmission length R/i
  - Indicates the travelling speed for a given plant rotation speed.
  - Generally given in km/h per rpm of the plant
  - Example 30 km/h per 1000 tr/min

$$\frac{R_e}{i} = \frac{30/3,6}{1000\;2\,\pi/60} = 0,07958\,m$$

Power and tractive effort

TRACTIVE FORCES

- It follows

$$F_w \, v \;=\; \eta_t \;\; C_p \, \omega_p$$

$$F_w \;=\; \eta_t \;\; C_p \, \frac{\omega_p}{v}$$

- Then the tractive force writes

$$\boxed{F_w \;=\; \eta_t \;\; C_p \, \frac{\omega_p}{\omega_w R_e} \;=\; \eta_t \;\; C_p \, \frac{i}{R_e}}$$

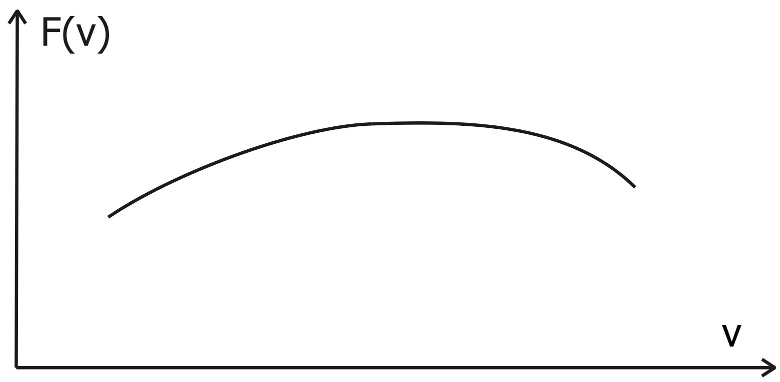
Tractive force vs vehicle speed

- For a given speed v and a transmission ratio, one has the engine rotation speed:

$$\omega_p = i\,\omega_w = v\frac{i}{R_e} \qquad C_p(\omega_p) = C_p(v\frac{i}{R_e})$$

- So for a given transmission ratio, one gets the tractive force in terms of the vehicle speed

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

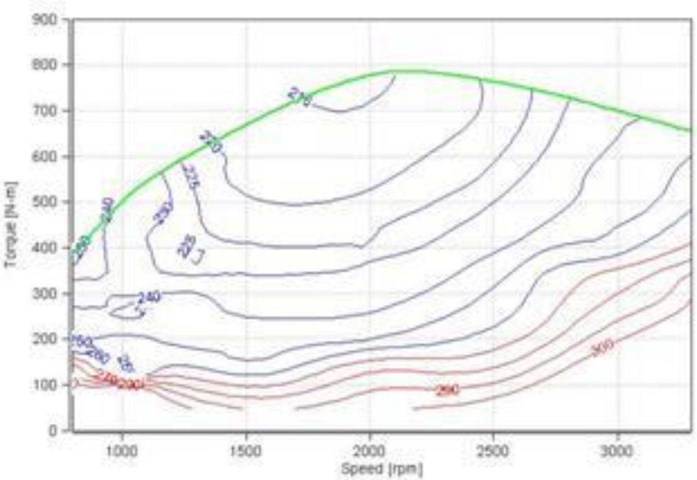


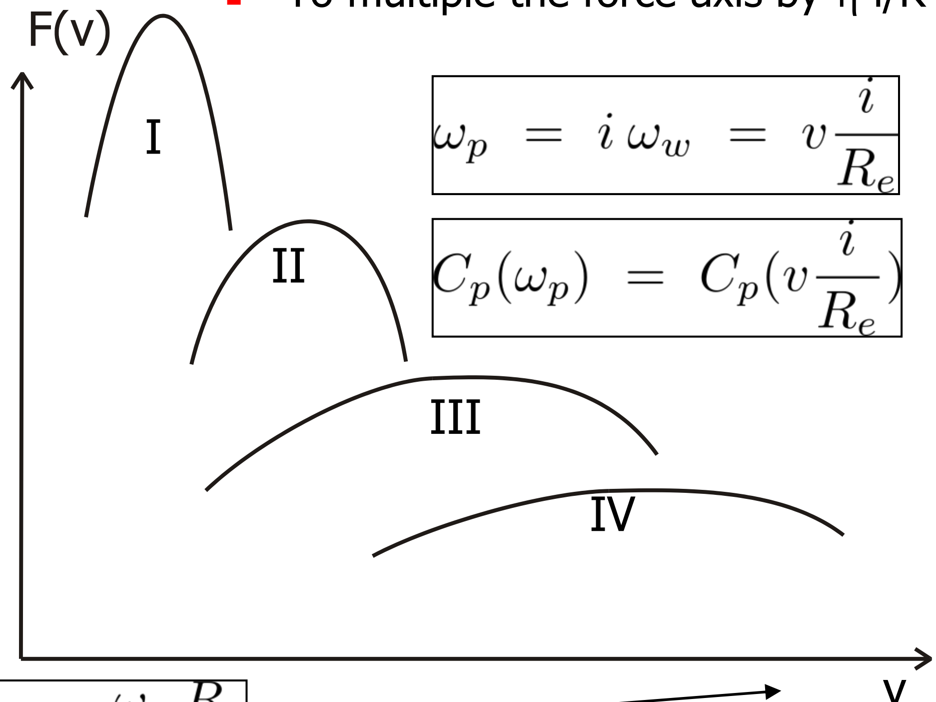
- Plotting the curves requires
  - Multiplying the speed curve by R/i
  - Multiplying the tractive force by η i/R

Tractive force vs vehicle speed

- To draw the tractive force curve, you have to:
  - To multiply the speed axis by R/i
  - To multiple the force axis by η i/R

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



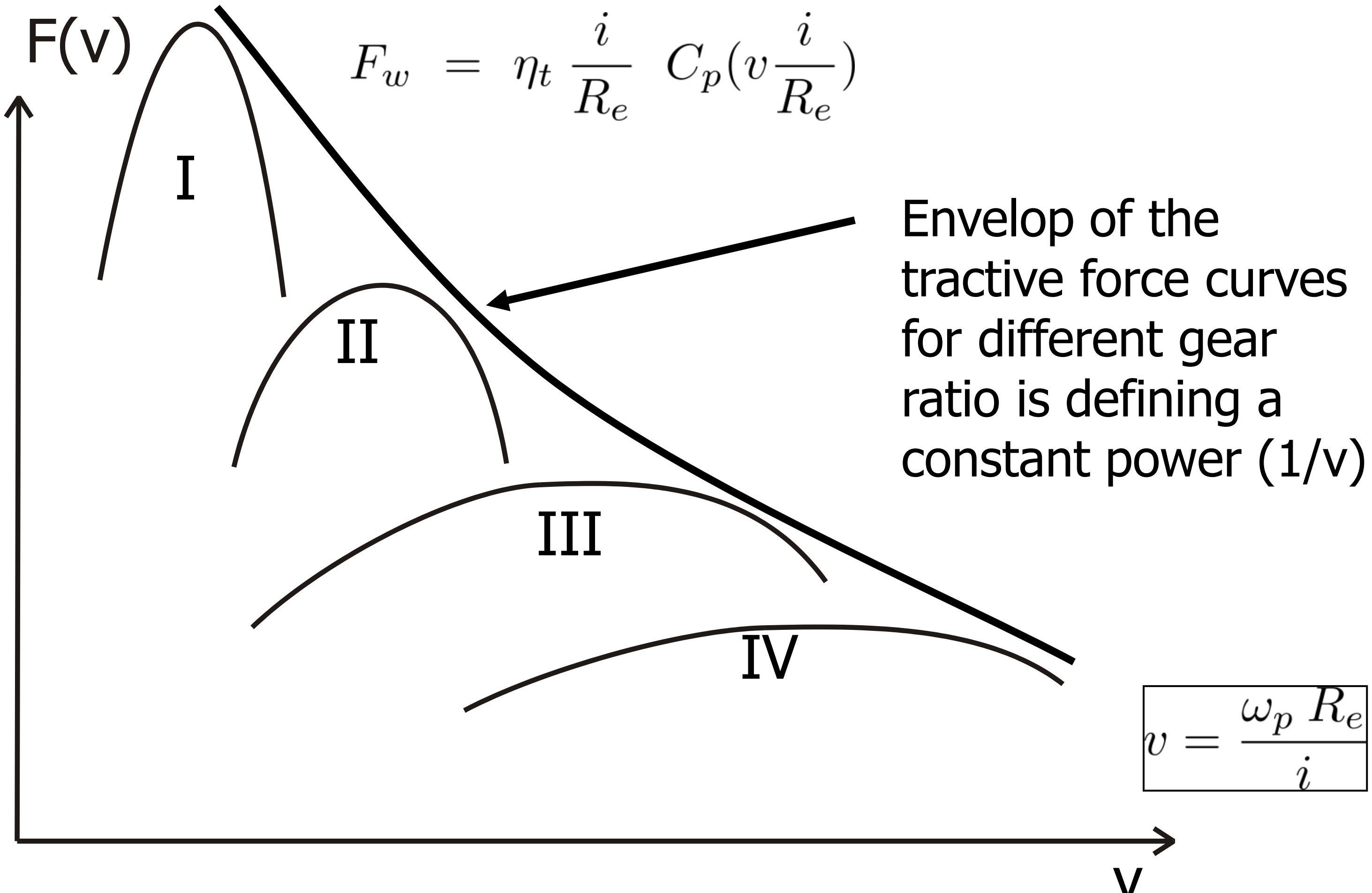


$$\omega_p = i\,\omega_w = v\frac{i}{R_e}$$

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

$$v = \omega_w\,R_e = \frac{\omega_p\,R_e}{i}$$

Tractive force vs vehicle speed

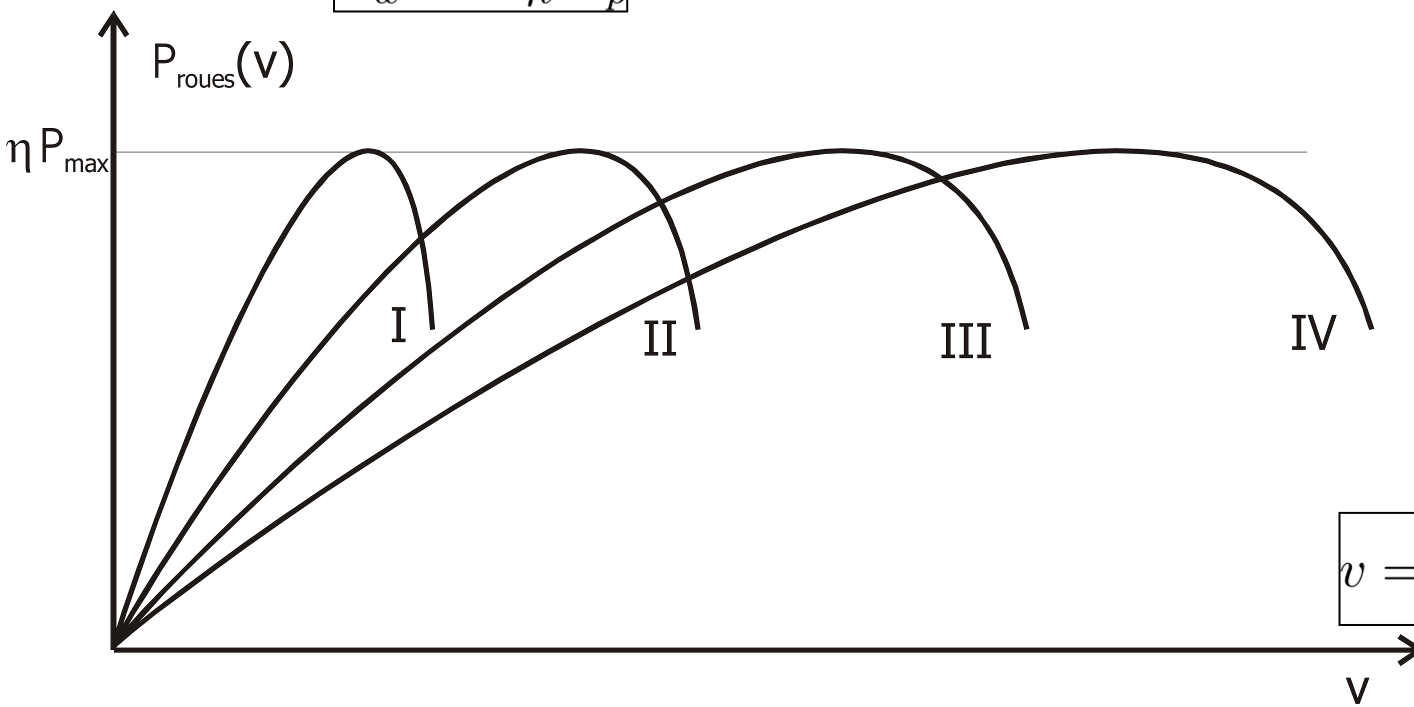


$$F_w = \eta_t \frac{i}{R_e} \; C_p(v \frac{i}{R_e})$$

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

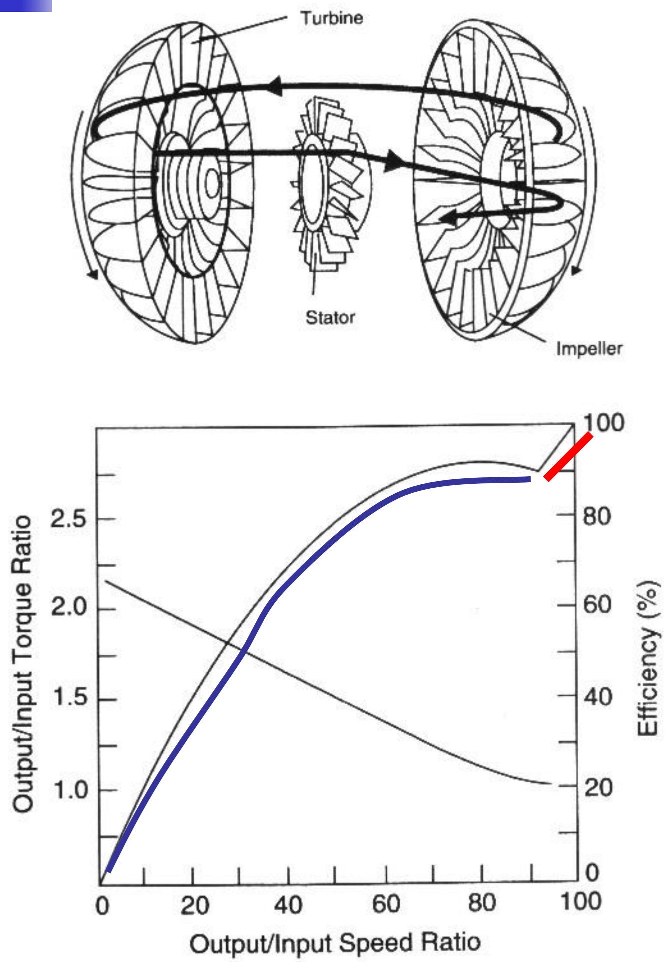
Tractive power vs vehicle speed

$$\boxed{\mathcal{P}_w = \eta_t \, \mathcal{P}_p}$$

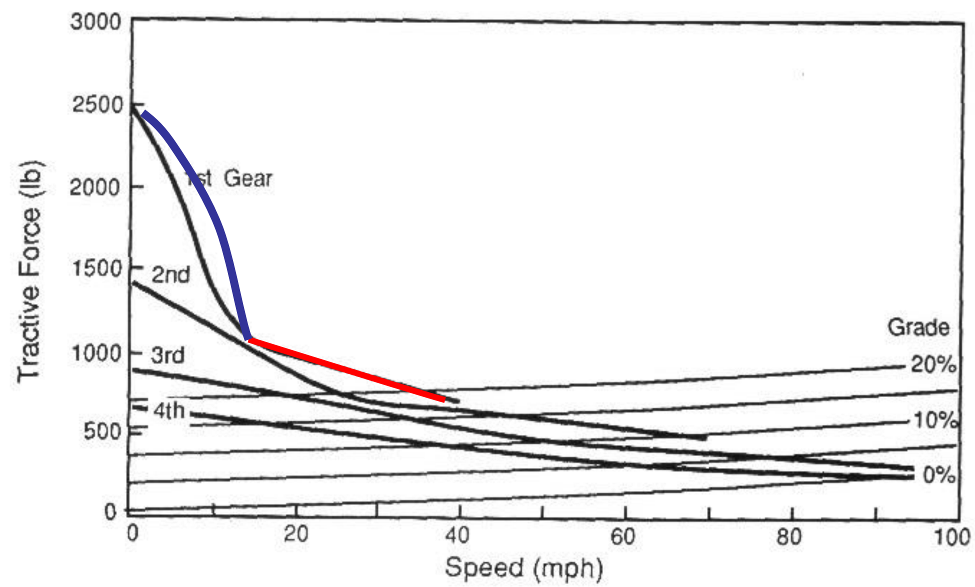


$$\boxed{v = \frac{\omega_p \, R_e}{i}}$$

Tractive force vs vehicle speed



Effect of automatic transmission and hydraulic clutch



Gillespie, Fig 2.5, 2.6