# Vehicle dynamics

Lesson n.2:

Longitudinal dynamics: acceleration performance

# Outline

- Power-limited acceleration

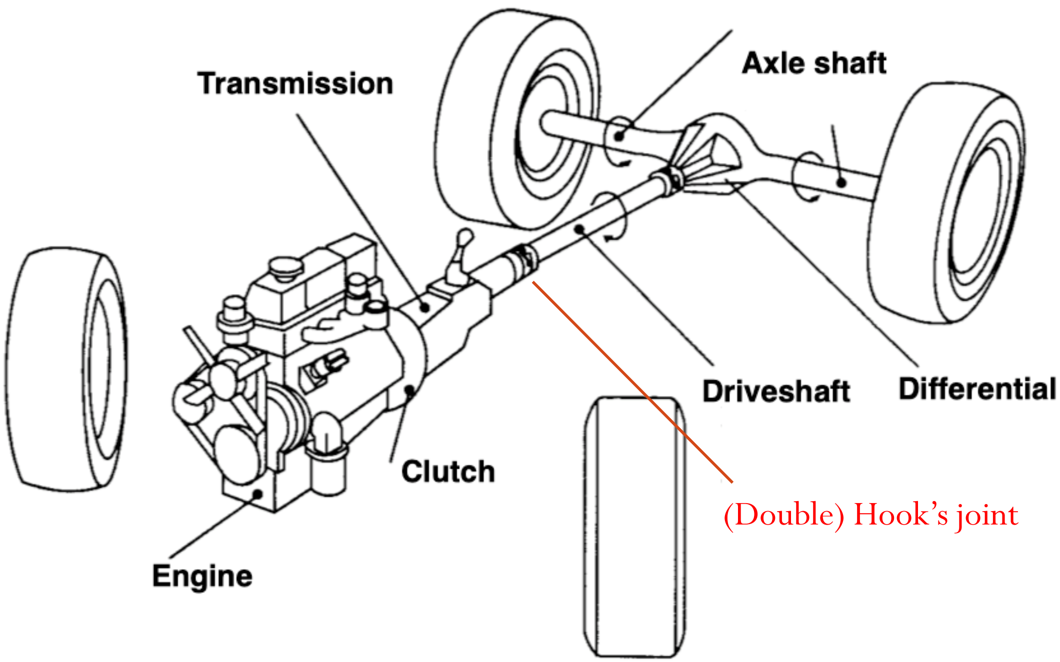
    - Powertrain: engine, clutch, transmission, driveline, differential, axle, wheel

- Traction-limited acceleration

    - Tire-road contact modelling

    - Load distribution on the wheels

# Powertrain: main components




**Engine:** provides power for traction

**Clutch:** allows to disengage engine shaft from driveshaft

**Transmission:** allows to match engine speed with vehicle speed through gearsets

**Driveshaft:** power transfer

**Differential:** turns power flow by 90° and allows speed differentiation for the traction wheels

**Axle shaft:** transmits power the the wheel (rear/front/all)

**Note:** multiple arrangements and component variants are possible

# Internal Combustion Engine (ICE)

**Spark-ignition 4-stroke engine**

Source: https://mechstuff.com

**- reciprocating engine**

- 4 cylinders, 16 valves

**Piston + connecting rod + crank:** From reciprocating motion of the piston (caused by expanding forces of gases) to rotational motion of the crankshaft

**Flywheel:** rotating disk for energy storing

**Inlet & Outlet valves:**

- Fresh air/fuel mixture in
- Exhaust gases out

**Camshaft:** synchronized valves activation

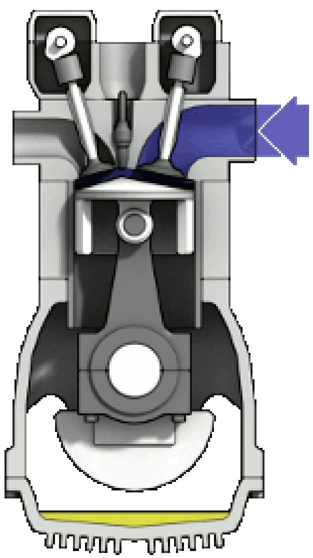
**Spark Plug*:** electric spark-induced ignition of air/fuel mixture in the combustion chamber → gas expansion

*Different ignition principle in Diesel engines

# Internal Combustion Engine

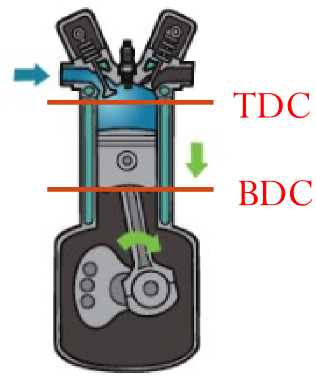
**Thermodynamic cycle**

1

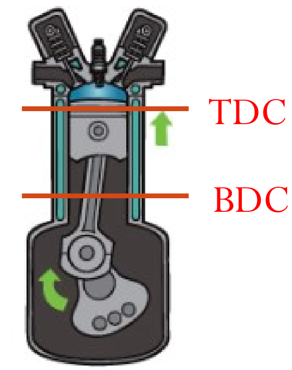


Source: https://mechstuff.com

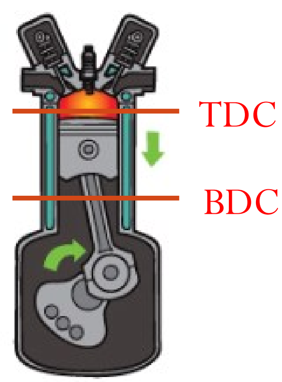
1 - Intake



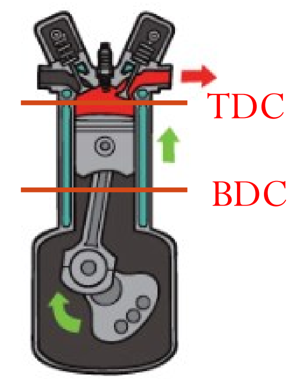

2 - Compression




3 – Combustion/Expansion



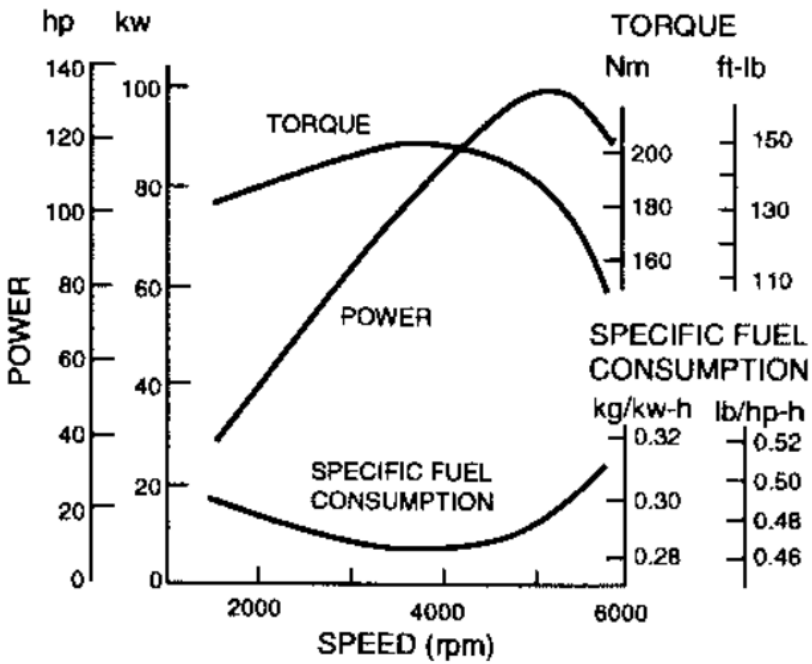

4 - Exhaust



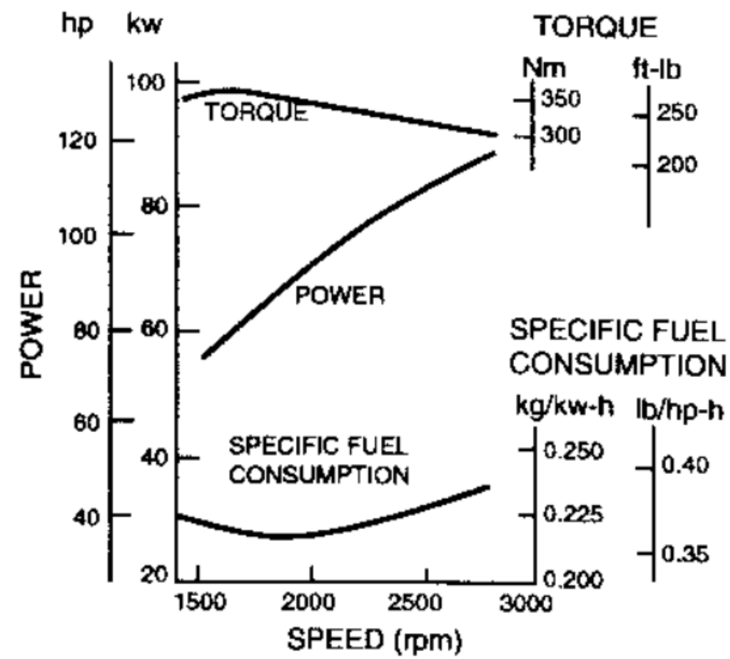

1 active stroke ➡ Multicylinder solution

# Engine characteristic curves

**Gasoline (petrol) engine**




**Diesel engine**




**Notes:**

1. Power/Torque relationship $P = T \cdot \Omega \quad \left[ W = \frac{Nm}{s} \right]$

Units Power (kW) = 0.746 HP

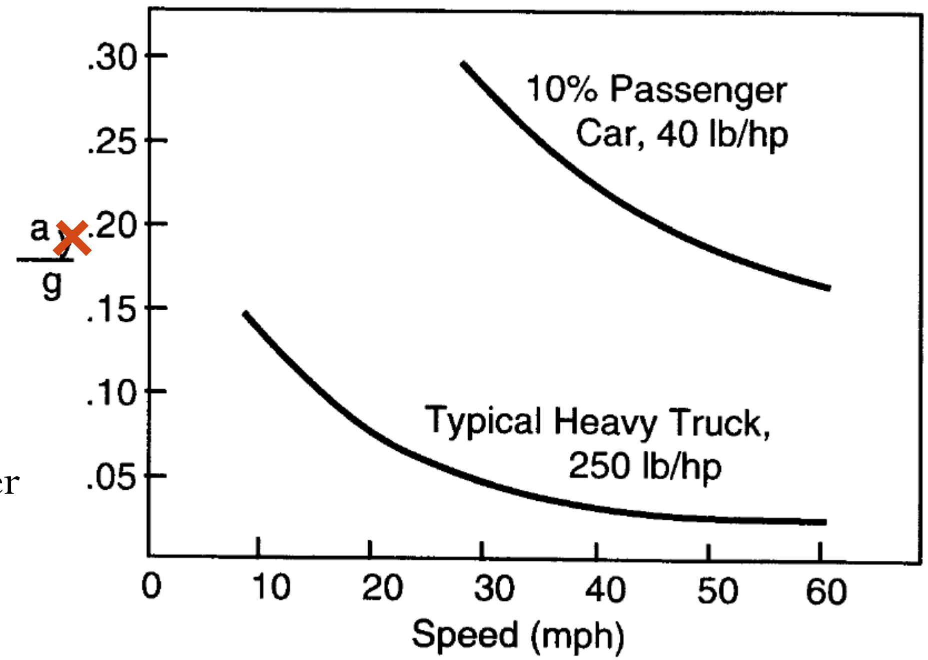
2. Limited torque and speed range → need for transmission → need for clutch (more info will follow)

# Upper limit for longitudinal acceleration

Upper limit

$$a_X = \frac{F_X}{M} = \frac{g}{V} \cdot \frac{P}{W}$$

Specific power

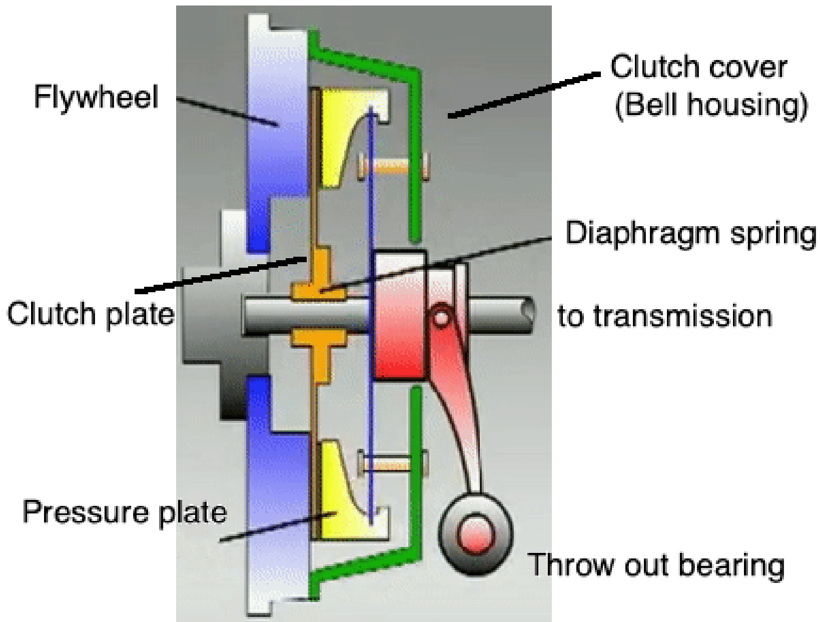



What about your car?

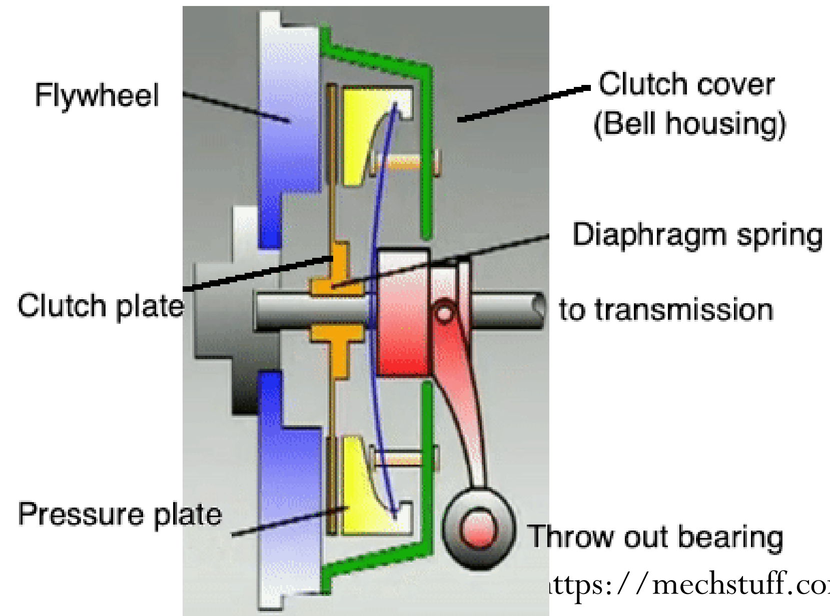
# Clutch

**Single plate clutch**

<u>Engaged mode</u>




<u>Disengaged mode</u>



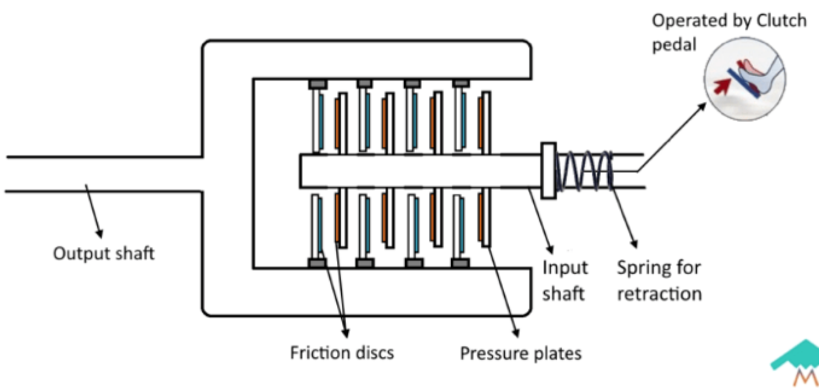

ttps://mechstuff.com

**Function: engine-to-transmission connection enabling**

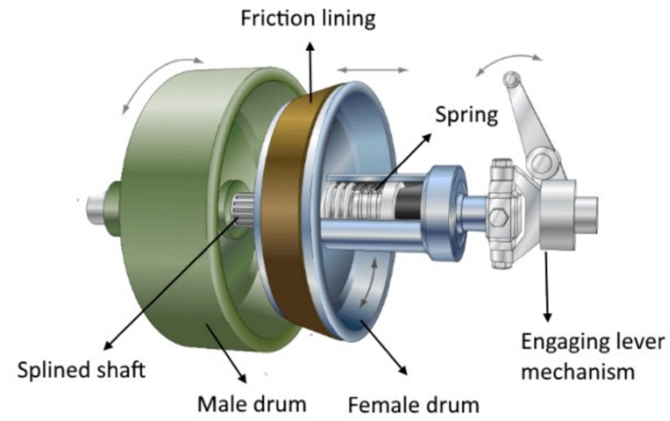
- Disengagement of a gear when the vehicle is stationary and the engine is running
- Smooth transmission of the engine power to the traction wheels at vehicle start
- Gradual loading of the engine at each gear shifting
- To permit the engaging of the gears when the vehicle is in motion

# Types of clutches used in vehicles

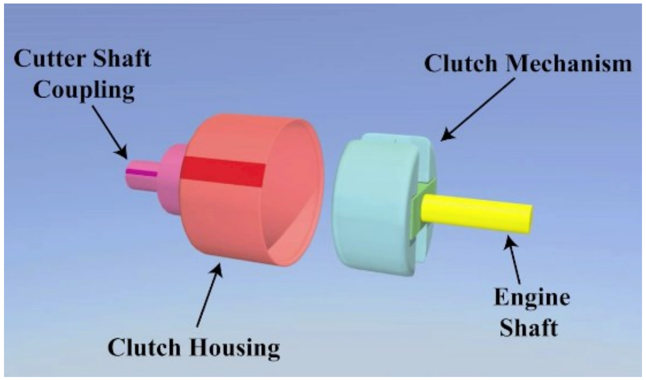
Multi-plate clutch



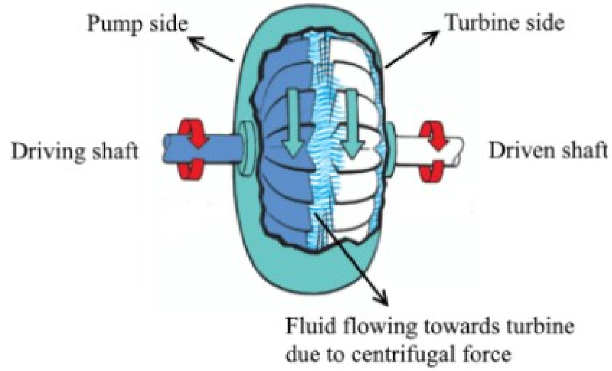

Cone clutch




Centrifugal clutch




Hydraulic clutch



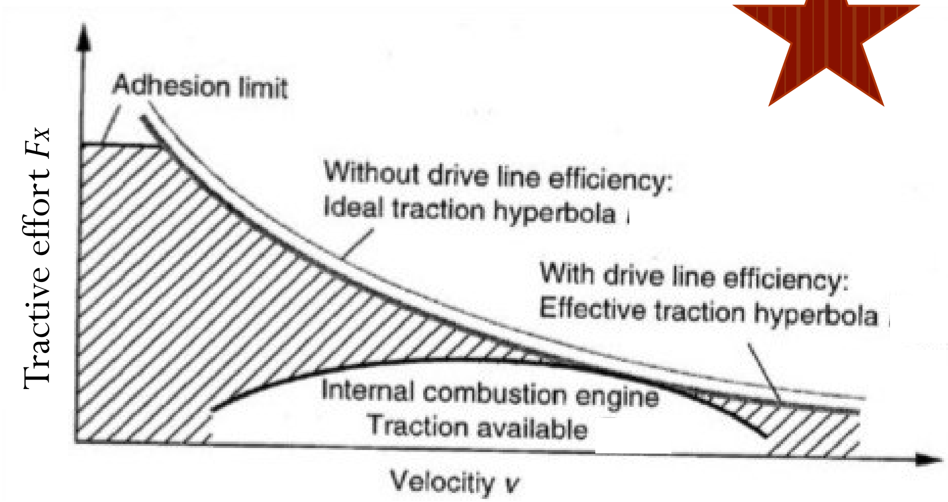



Source: https://mechstuff.com

# Transmission (or Gearbox): why do we need it?

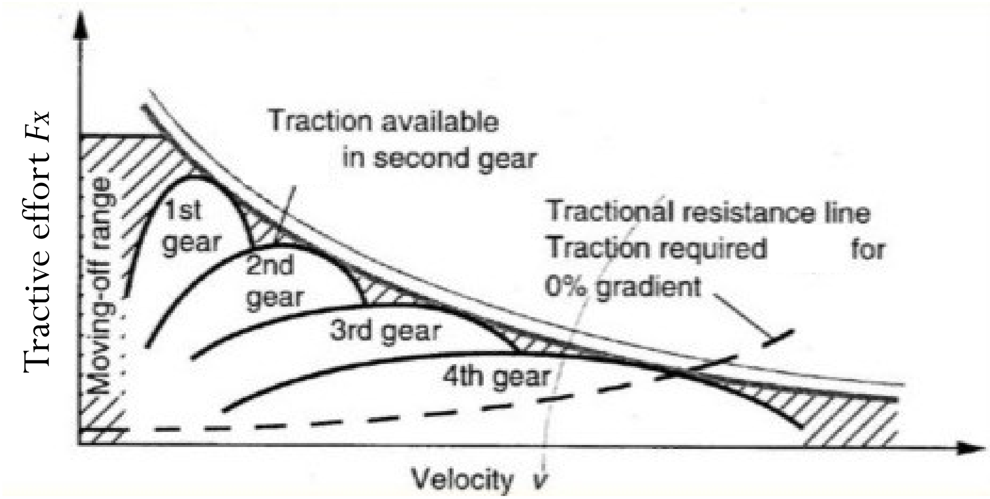
1. To keep the engine running even when the vehicle is not moving (with clutch engaged).
2. To be able to drive the car backwards by shifting to reverse gear.
3. To carry high loads OR climb steep slopes as well as achieve high speeds on straight roads.

Achieved by changing the transmission ratio between input and output shaft

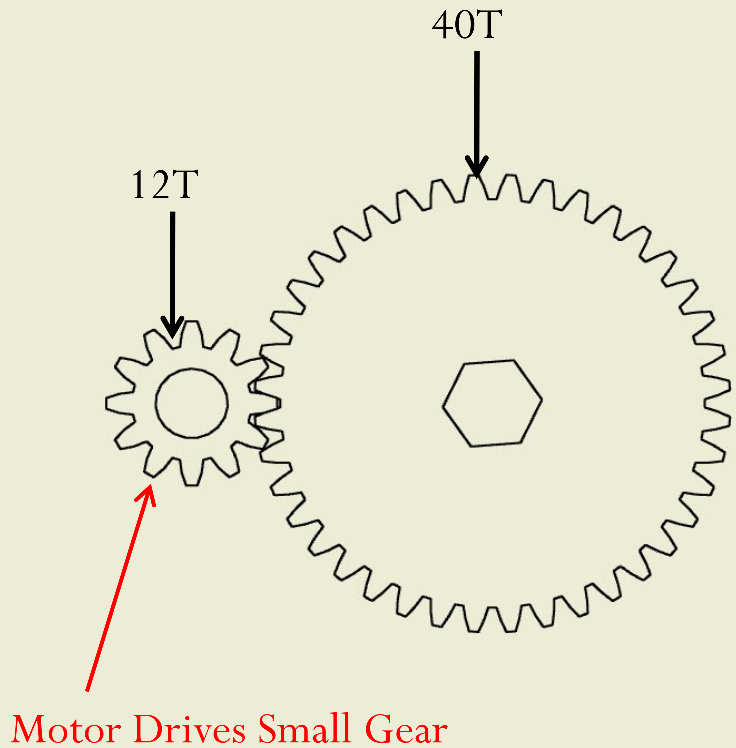



**Typical gear ratios in 5-speed gearboxes**

1st gear 3-4:1
2nd gear 2-2.5:1
3rd gear 1.4-1.6:1
4th gear 1-1.2:1
5th gear 0.7-0.8:1
Reverse gear -3.1:1



# What is the gear (transmission) ratio?

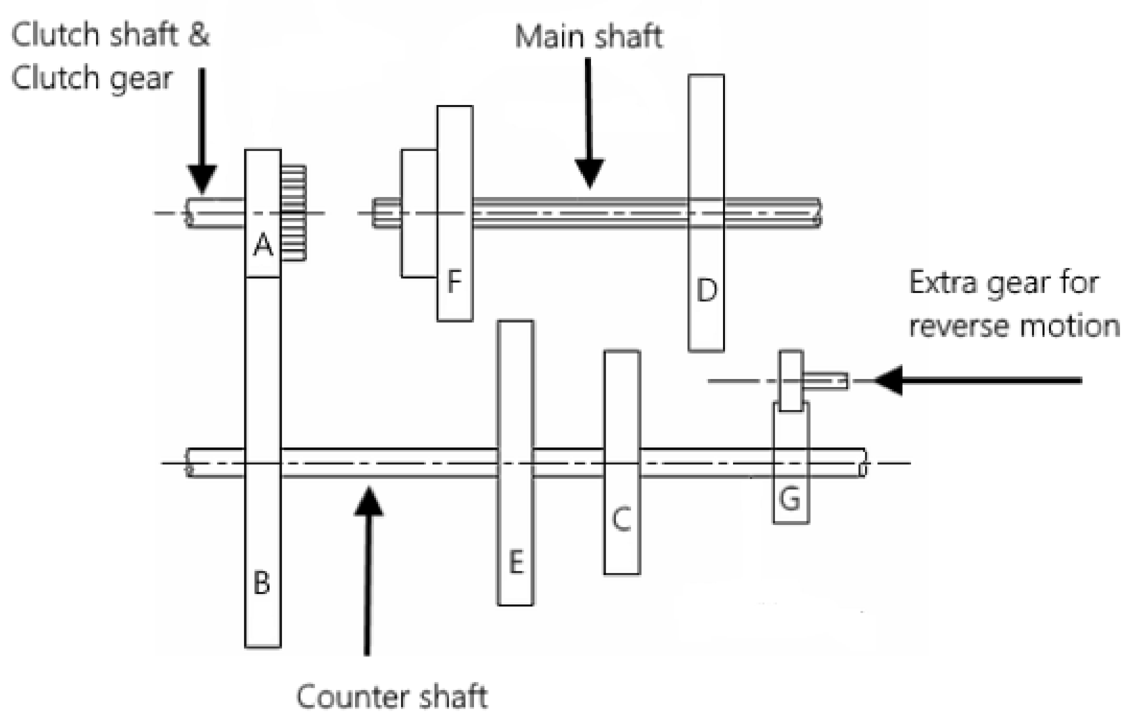



$$Reduction = \frac{40}{12} = 3.33$$

**The gearbox REDUCES speed**

**The gearbox INCREASES torque**

# Manual transmission: sliding-mesh gearbox




**3-speed gearbox**

**1st gear:** D moves on the left side, power flows through A-B-C-D

**2nd gear:** F moves on the right side, power flows through A-B-E-F

**3rd gear:** F moves to the left side, power flows through A-F

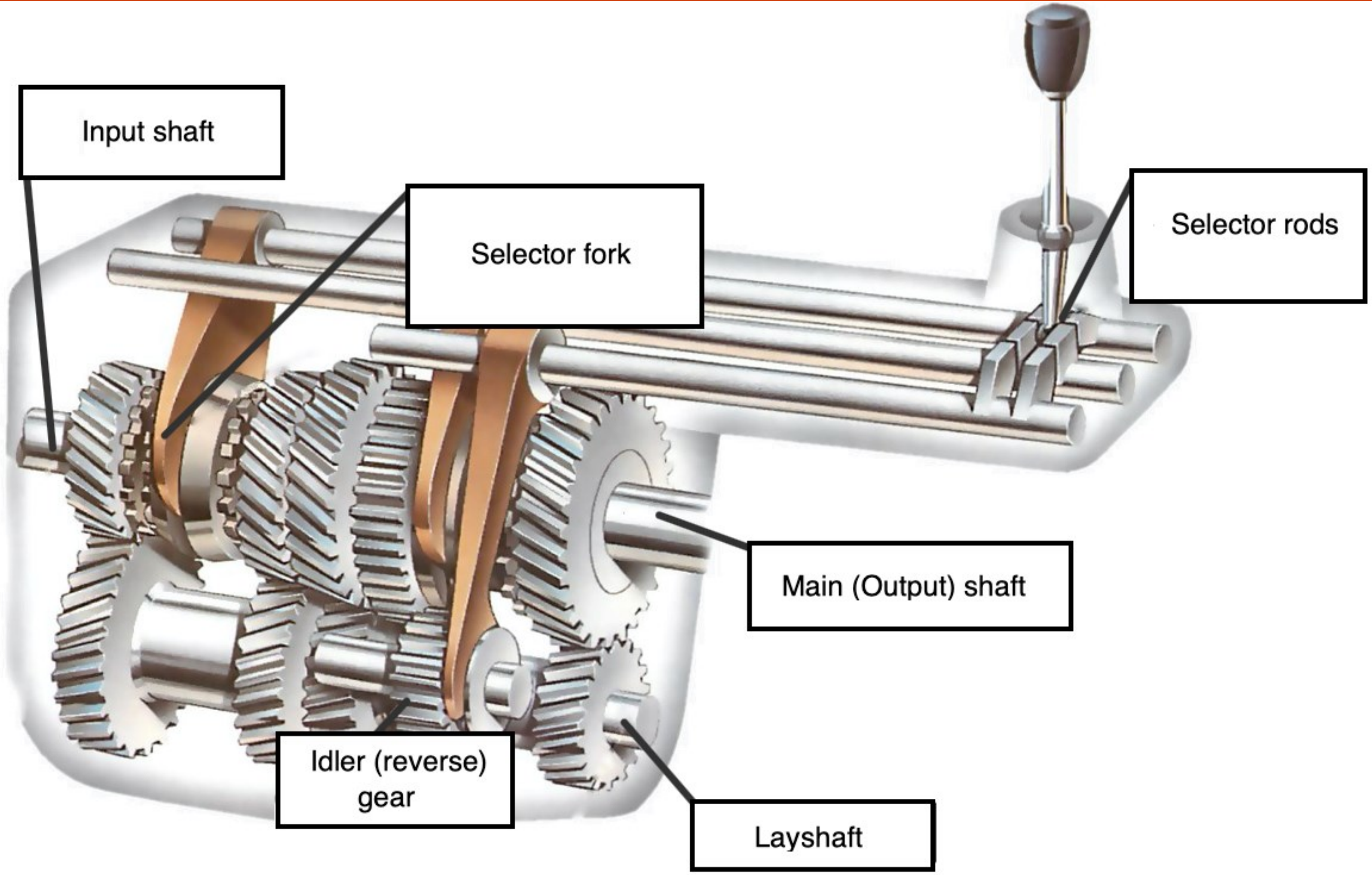
**Reverse:** D moves to the right side, power flows through A-B-G-D + idler gear

**Neutral:** no gear of the counter shaft meshes with the output one



Source: https://mechstuff.com

# Manual transmission: constant-mesh gearbox




**Input shaft:** receives engine power/torque

**Output shaft:** transmits power/torque to the driveshaft

**Layshaft:** connects the input shaft and the output shaft

**Selector rods and forks:** enable gear selection

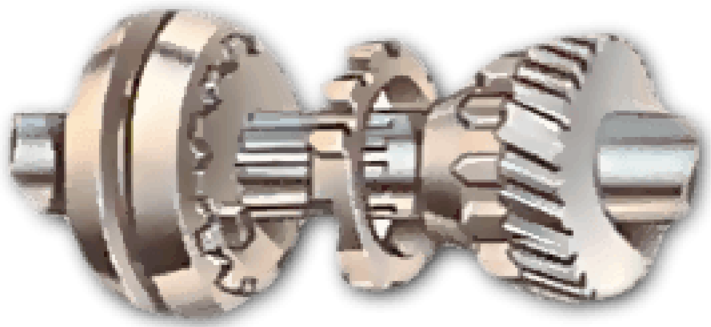
**Idler gear:** engages to provide reverse motion

**Synchronizer:** enables smooth gear shifting

https://www.howacarworks.com

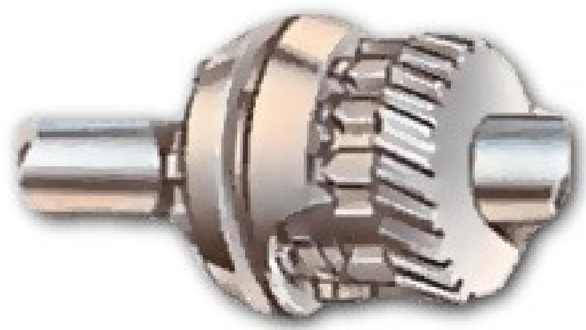
# Syncronizer

**Syncronizer disengaged**



The gear on the output shaft turns freely on a bush, rotated by a meshing gear on the layshaft. The synchronizer unit, splined the the output shaft, is close but disconnected from the gear.

**Syncronizer engaged**



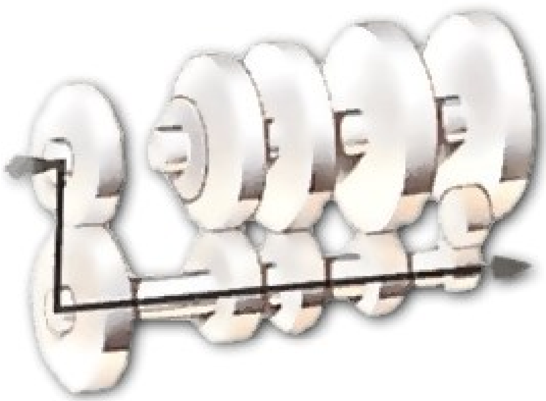
The fork moves the synchromesh towards the selected gear. Friction surfaces synchronise the shaft speeds, and synchronizer and gear lock together.



https://www.howacarworks.com

# 4-speed manual transmission

Neutral



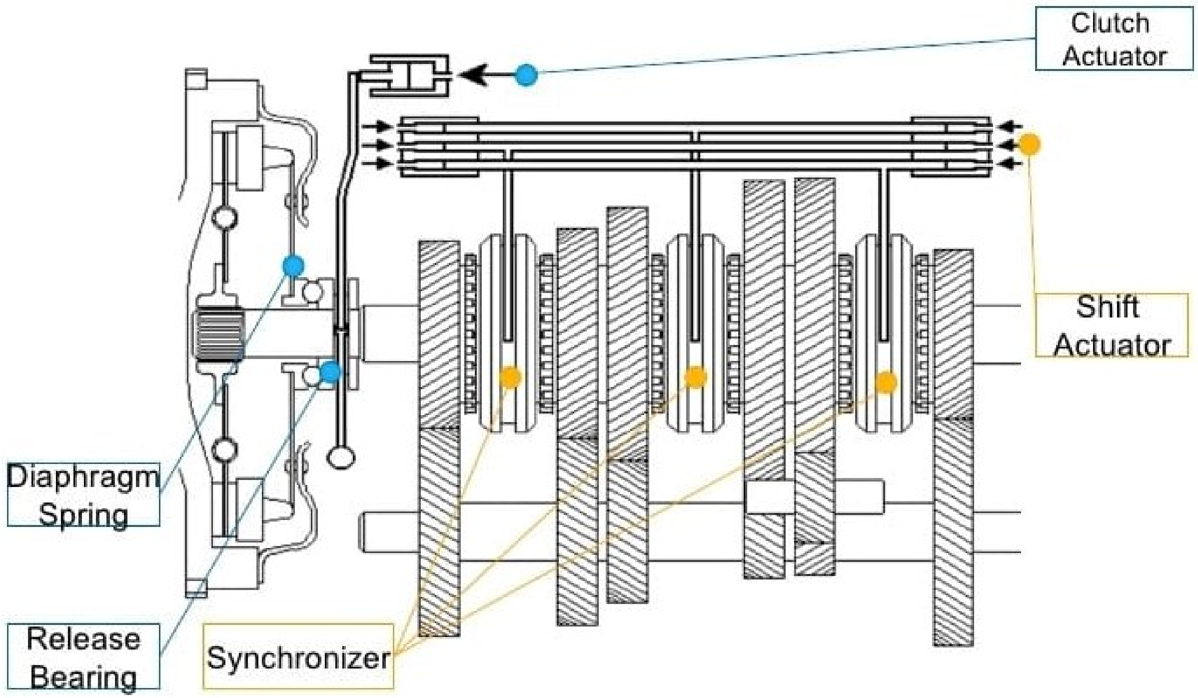
1st gear

4th gear

Reverse

https://www.howacarworks.com

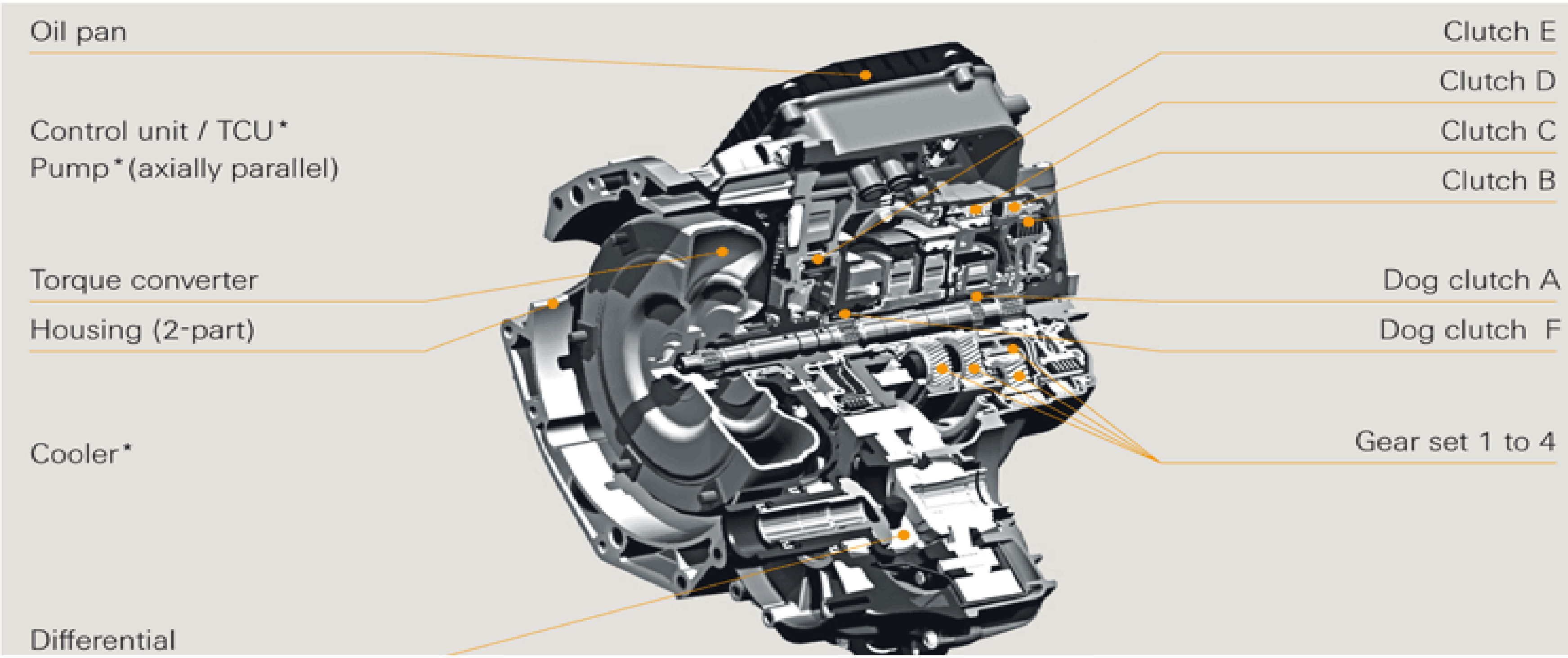
# Automated manual transmissions (AMT)




- Similar layout as manual transmission
- Automated (ECU controlled) activation of shift and clutch (hydraulic, electromechanical,… )
- Several commercial variants
- Pros: cost-efficient (wrt AT), driver comfort, semi-automatic option (to accommodate different driving styles), tunable shifting programs, reduced fuel consumption (based on optimized shifting)
- Cons: fuel-efficient settings and overtaking maneouvers, jerky shifting (mitigated in recent gearboxes)

# Automatic transmissions (AT)

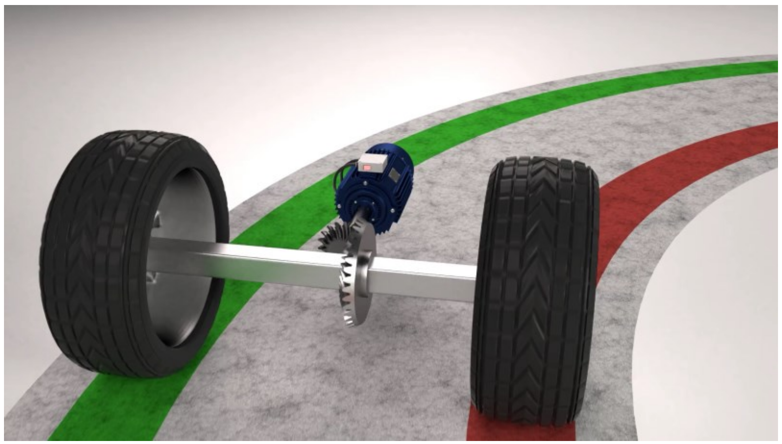
9 speed ZF AT



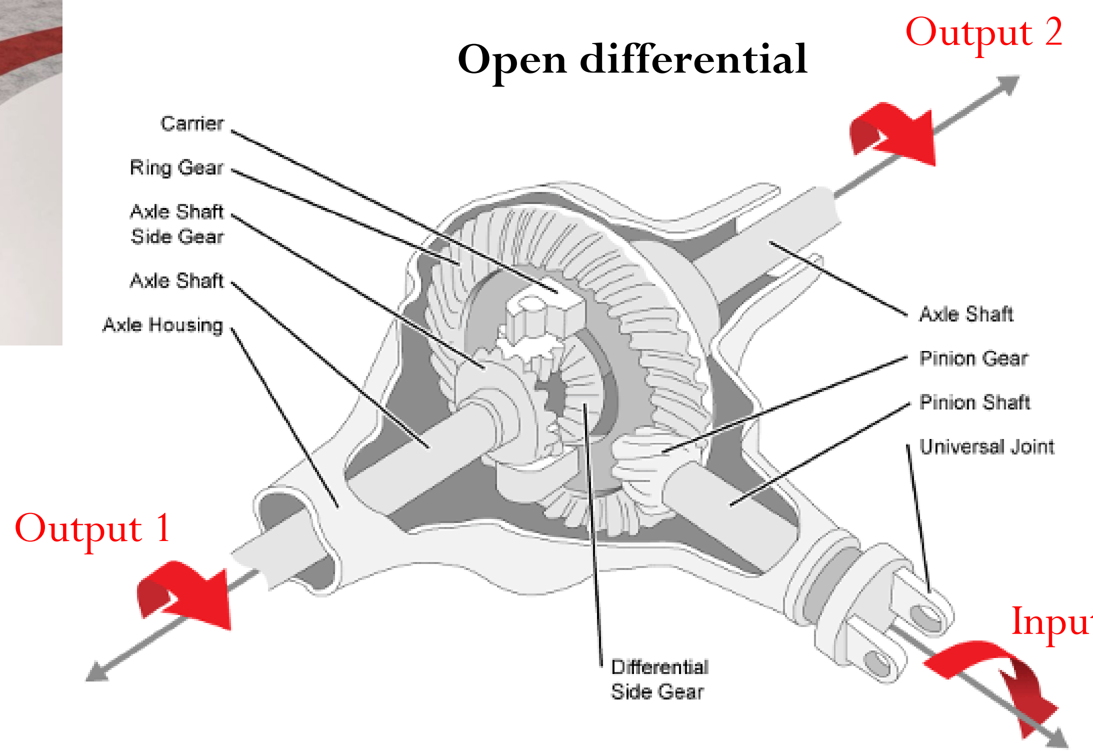

- Different layouts and wide variety of commercial variants
- Automatic (ECU controlled) activation by multiple mechanical systems (clutches, brakes)
- Pros: wide-spread range of gear ratio (almost 10, from 4.7 in 1$^{st}$ gear to 0.48 in 9$^{th}$ gear), driver comfort, tunable shifting programs, reduced fuel consumption (based on optimized shifting), smooth shifting
- Cons: cost and complexity, size and weight (mitigated in recent gearboxes)

# Differential: why do we need it?

Driving a car along a turn



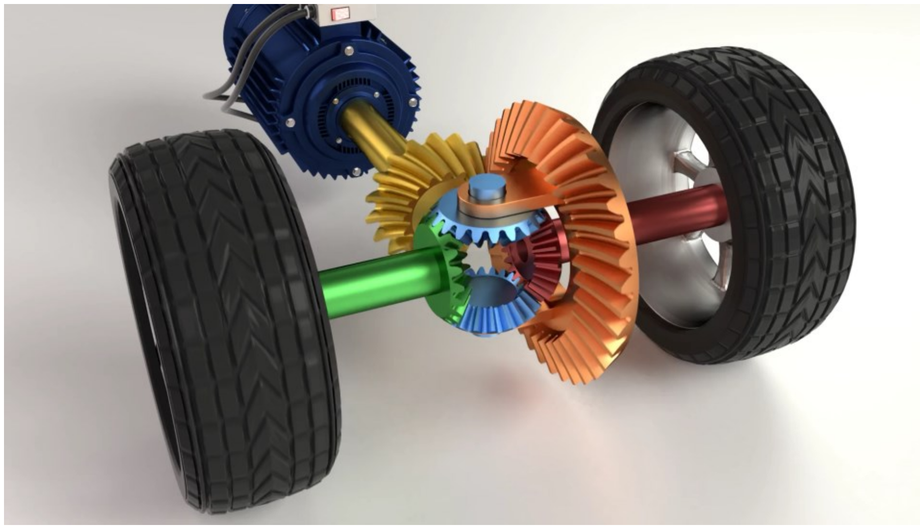
Source: https://www.tec-science.com




Kinematic relationship: $\boxed{\omega_{out1} + \omega_{out2} = 2 * \tau_0 * \omega_{in}}$

# Differential: why do we need it?

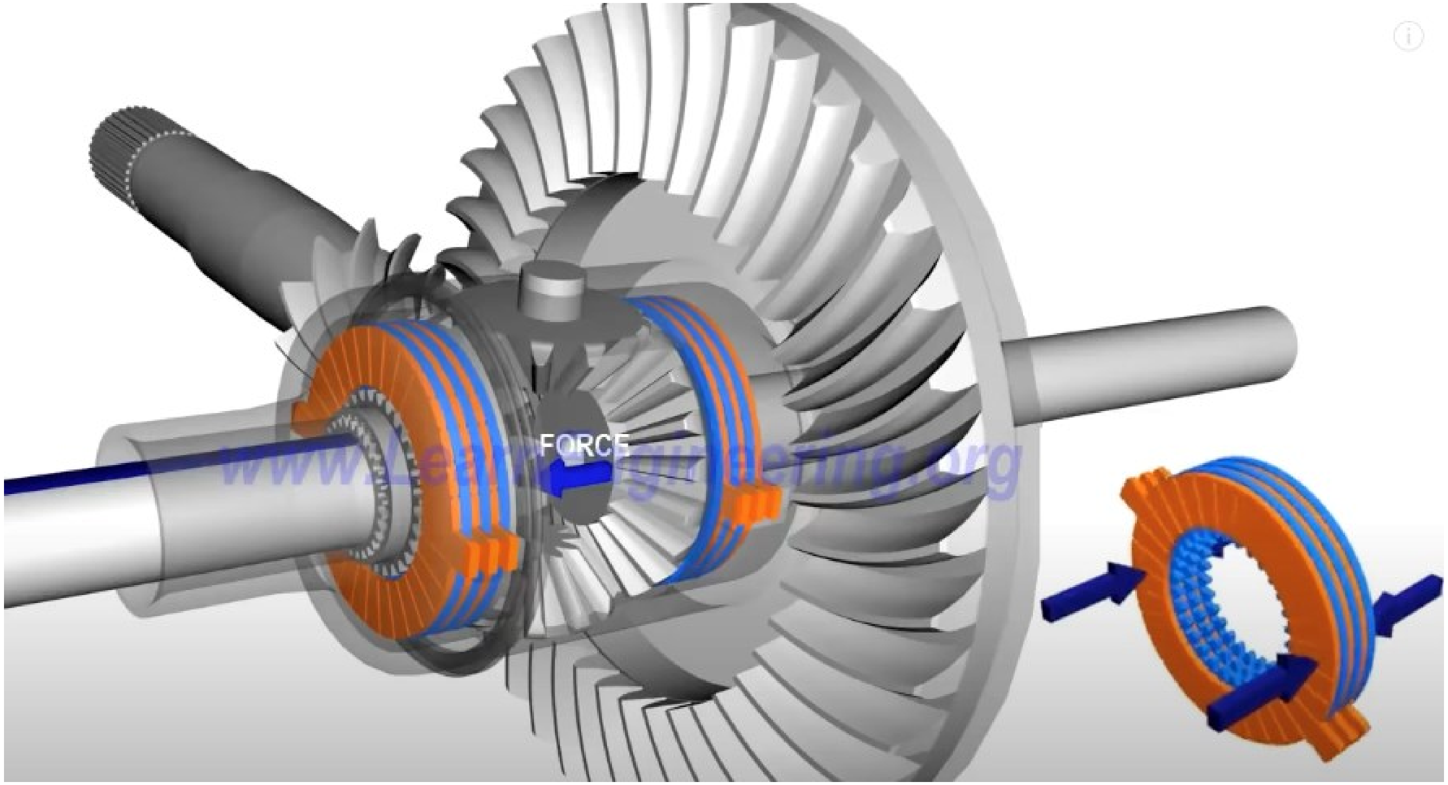
Driving a car along a turn



Driving a car along a straight-line

Source: https://www.tec-science.com

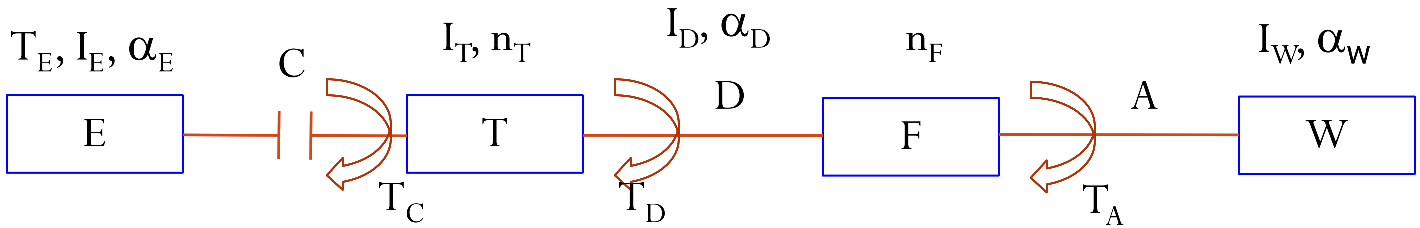
# Limited slip differentials (LSD)




- Clutch type
- Cone differential
- Hydraulic locking type
- Torsen (worm gears)

# Power-limited acceleration

Dynamics of the powertrain:




Engine:

$$T_c = T_e - I_e\,\alpha_e$$

Transmission:

$$T_d = (T_c - I_t\,\alpha_e)\,N_t$$

Differential + axle:

$$F_x\,r + I_w\,\alpha_w = \underbrace{(T_d - I_d\,\alpha_d)\,N_f}_{T_A}$$

Kinematic relationships

$$a_x = \alpha_w\,r$$

$$\alpha_d = N_f\,\alpha_w$$

$$\alpha_e = N_t\,\alpha_d = N_t\,N_f\,\alpha_w$$

$$\boxed{F_x = \frac{T_e N_{tf}}{r}\,\eta_{TF} - \{(I_e + I_t)\,N_{tf}^2 + I_d N_f^2 + I_w\}\,\frac{a_x}{r^2}}$$

# Power-limited acceleration

Rotational equilibrium of the powertrain:

$$F_x = \frac{T_e N_{tf}}{r} \quad \eta_{TF} \{(I_e + I_t) N_{tf}^2 + I_d N_f^2 + I_w\} \frac{a_x}{r^2}$$

Translational equilibrium of the vehicle

$$M a_x = \frac{W}{g} a_x = F_x - R_x - D_A - R_{hx} - W \sin \Theta$$

$$\boxed{(M + M_r)\, a_x = \frac{T_e N_{tf} \eta_{tf}}{r} - R_x - D_A - R_{hx} - W \sin \Theta}$$

PS:- $T_E$ input data

- $M_r$ equivalent mass for rotating bodies →
- $\eta_{TF}$ efficiency typically in the range 80% - 90%
- $N_{TF}$ variable based on the gear shift

Mass factor:

$(M+M_r)/M=1+0.04+0.0025\, N_{tf}2$

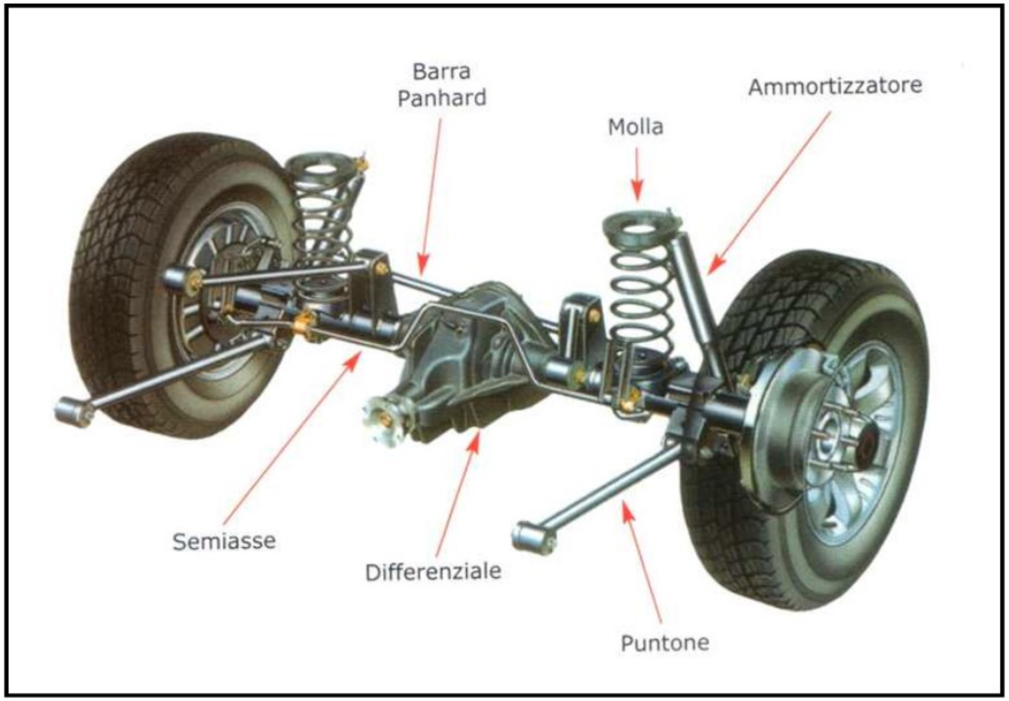
# Traction-limited acceleration

$$F_{X,max} = \mu W$$

Let's compute Fx under the following assumptions:

- Solid axle suspension
- Rear driving axle
- Open differential

Sospensione ad assale (ponte) rigido



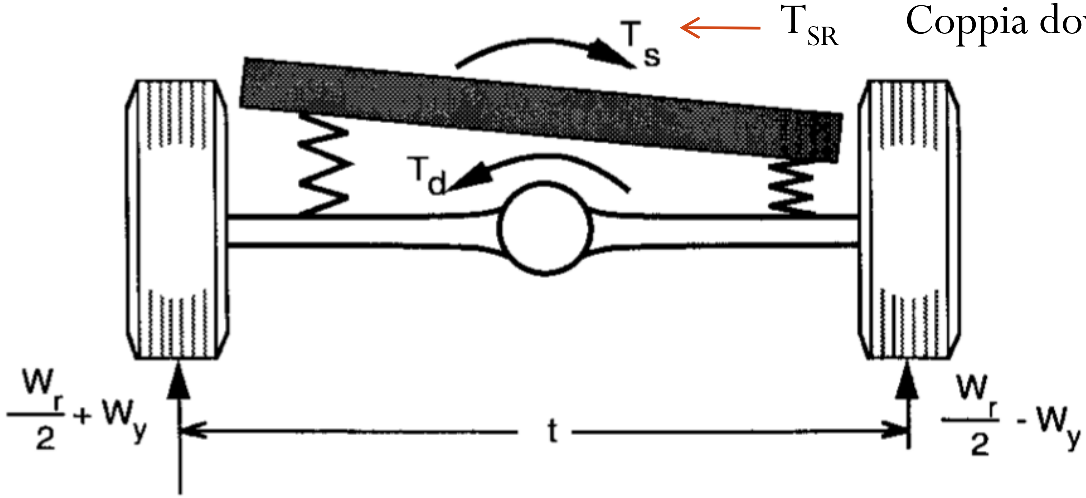

Vantaggi: semplicità costruttiva

Svantaggi: potere autosterzante, masse non sospese considerevoli (differenziale)

# Trasferimento di carico trasversale

Schemi per l'analisi dei carichi

$T_{SR}$ Coppia dovuta al rollio




$$\Sigma T_o = (W_r/2 + W_y - W_r/2 + W_y)\, t/2 + T_s - T_d = 0$$

$$W_y = \frac{T_D - T_{SR}}{t}$$

$$T_d = F_x\, r/N_f$$

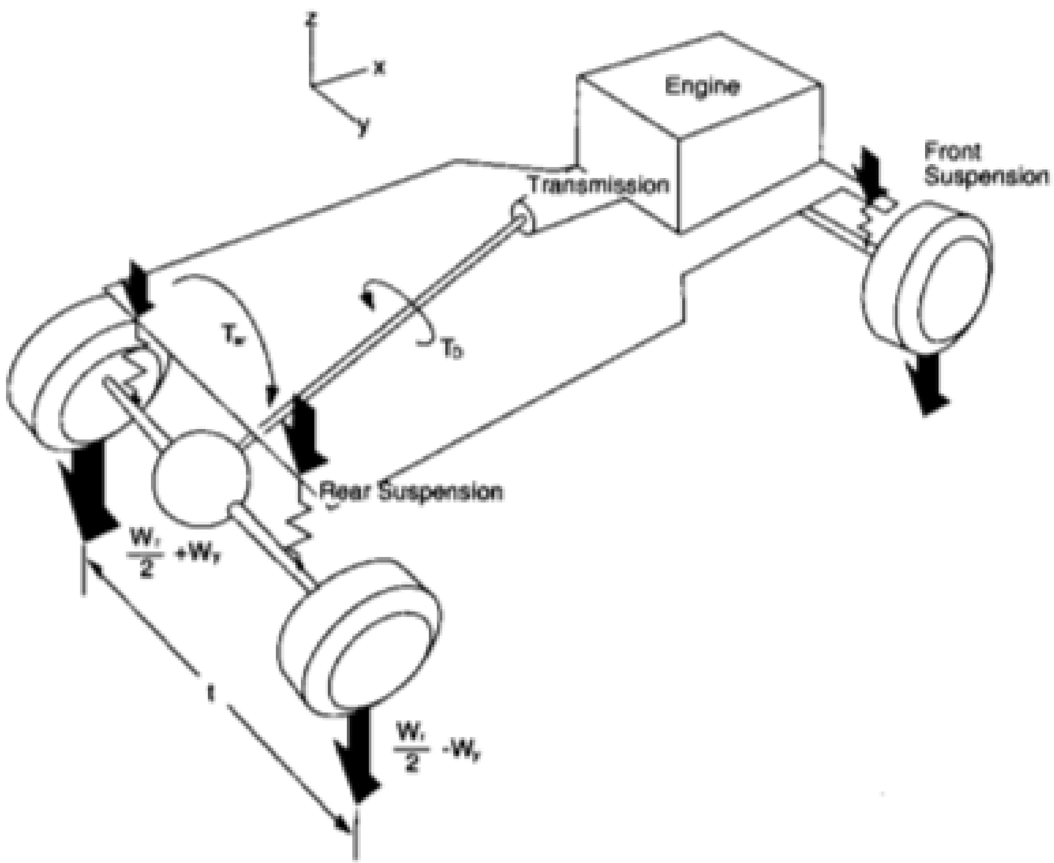
$$T_{SR} = k_{\Phi_R}\, \Phi$$

Rigidezza a rollio

Angolo di rollio

# Trasferimento di carico trasversale

Schemi per l'analisi dei carichi




$$\phi = T_d / K_\phi = T_d / (K_{\phi f} + K_{\phi r})$$

$$T_{sr} = K_{\phi r} T_d / (K_{\phi f} + K_{\phi r})$$

# Trasferimento di carico trasversale

Hp: - resistenza aerodinamica e al rotolamento trascurabile
- moto in pianura

$$W_r = W\left(\frac{b}{L} + \frac{F_x}{M\,g}\,\frac{h}{L}\right)$$

$$\boxed{F_{X,max} = 2\mu\,(W_r/2 - W_y)}$$

$$W_y = \frac{T_D - T_{SR}}{t}$$

$$T_d = F_x\, r/N_f$$

$$T_{sr} = K_{\phi r}\, T_d /(K_{\phi f} + K_{\phi r})$$

$$\boxed{F_{xmax} = \frac{\mu \frac{W b}{L}}{1 - \frac{h}{L}\mu + \frac{2\mu r}{N_f t}\frac{K_{\phi f}}{K_\phi}}}$$

$$\boxed{a_{X,max} = F_{X,max}/M}$$

Sistema con differenziale autobloccante

$$\boxed{F_{xmax} = \frac{\mu \frac{W b}{L}}{1 - \frac{h}{L}\mu}}$$

# Traction-limited acceleration

$$\boxed{F_{X,max} = \mu W}$$

Let's compute Fx under the following assumptions:

- Rear driving wheel
- Independent suspensions

$$W_r = W\left(\frac{b}{L} + \frac{F_x}{Mg}\frac{h}{L}\right)$$

$$F_{X,max} = \mu W_r$$

$$\boxed{F_{xmax} = \frac{\mu \frac{W b}{L}}{1 - \frac{h}{L}\mu}}$$

$$\boxed{a_{X,max} = F_{X,max} / M}$$