MECA0063 : Driveline systems
Part 2: Automatic Transmission

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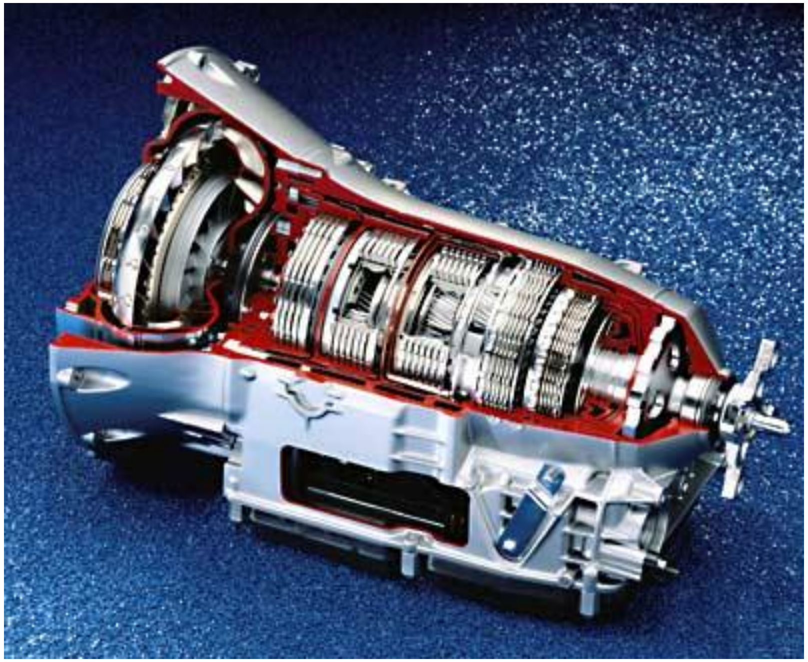
AUTOMATIC TRANSMISSIONS



Automatic transmission

- The concept of automatic transmission exhibits remarkable advantages with regards to the driver comfort, especially in urban driving and heavy traffic conditions:
  - Smooth start from standstill using hydraulic couplers/converters
  - Easy change of gear ratio taking advantage of planetary gear trains
- The mental load reduction for the driver reduces drastically the accident occurrence and improves road safety.
- There are also other advantages, for instance the average improvement of fuel economy and the reduction of pollutant emissions for a fleet of vehicles since, in average, the automatic systems have a better performance than the average driver.

Automatic transmission

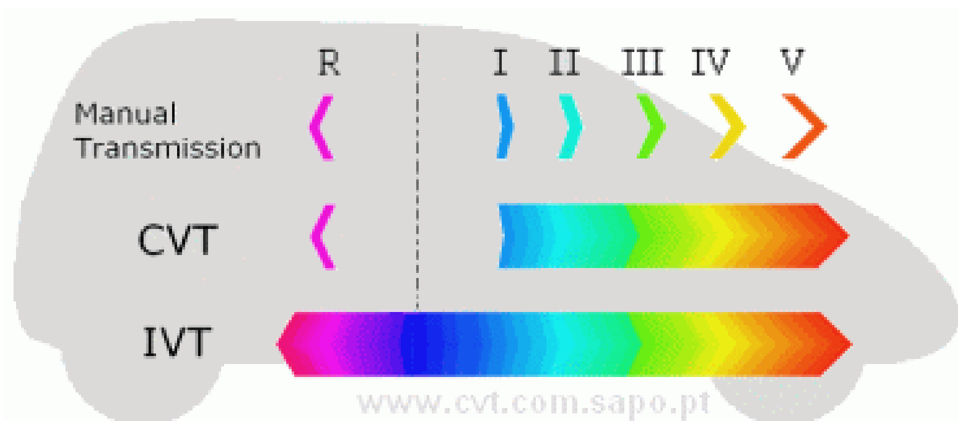
- The AT systems are appreciated on luxury and high-power vehicles. Market shares are different in Europe, USA and Japan:
  - 90% of the market in the USA
  - 20% of the market in Europe

- The AT systems are as old as the beginning of automobiles in 1920ies

- But AT has taken benefit of a continuous improvement of the technology: increasing number of gear ratios with a fixed or even reducing volume.

Automatic transmission

- Several solutions are possible for automatic transmissions:
  - Automated manual transmission
  - Conventional AT transmission using epicyclic gear trains and a hydraulic converter.
  - Continuous variable transmissions (CVT)
  - Infinite variable transmission (IVT)



Automatic transmission

Automated MT

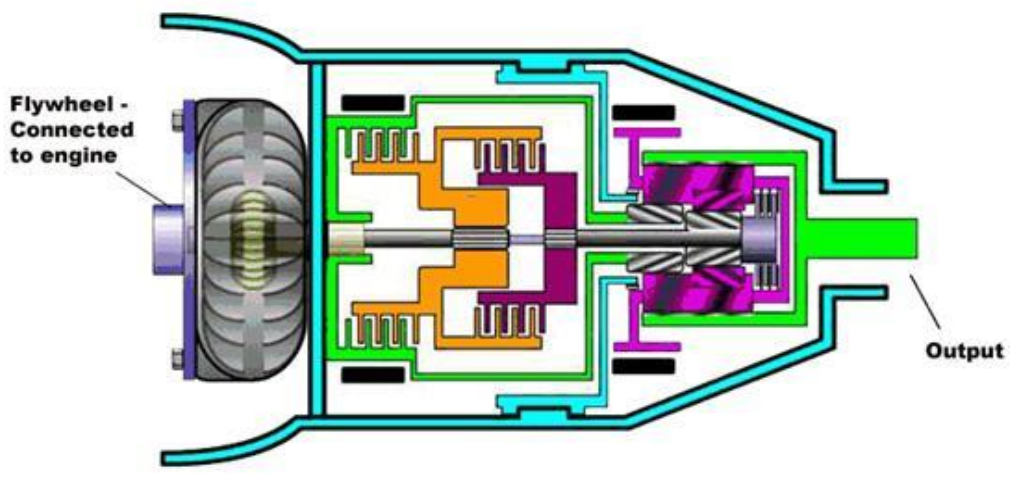
CVT

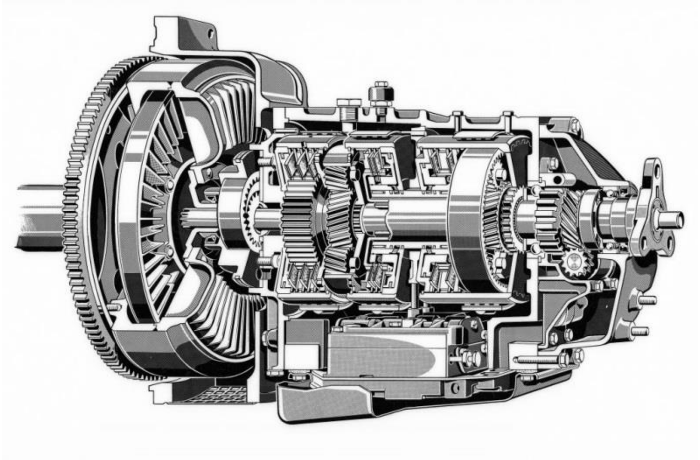
AT

IVT

Automatic transmission

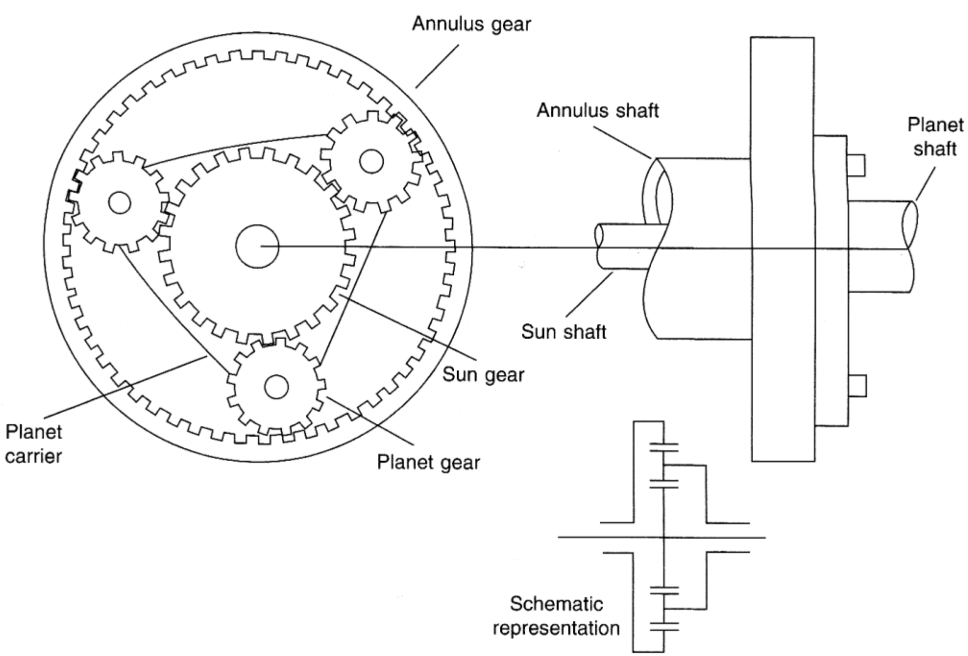
- Automatic transmissions mostly combine a hydraulic torque transmission and several epicyclical gear trains
  - A hydraulic torque converter
  - A mechanical system enabling the variable reduction ratio mostly planetary gear trains
  - A hydraulic actuation and control system including clutches and band brakes using lubricated discs to operate the gear changes

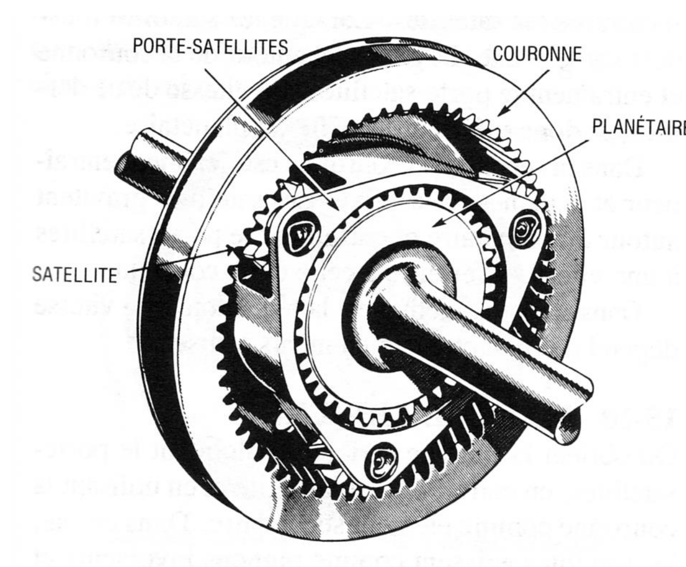




Planetary gears

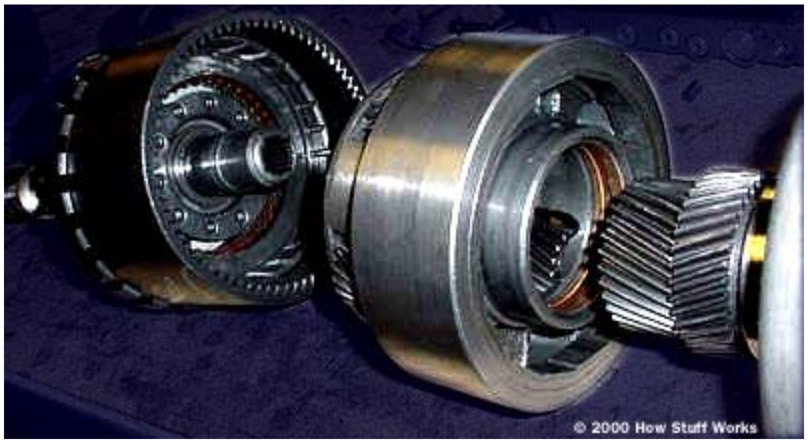
- The fundamental building bloc of AT is the planetary gear

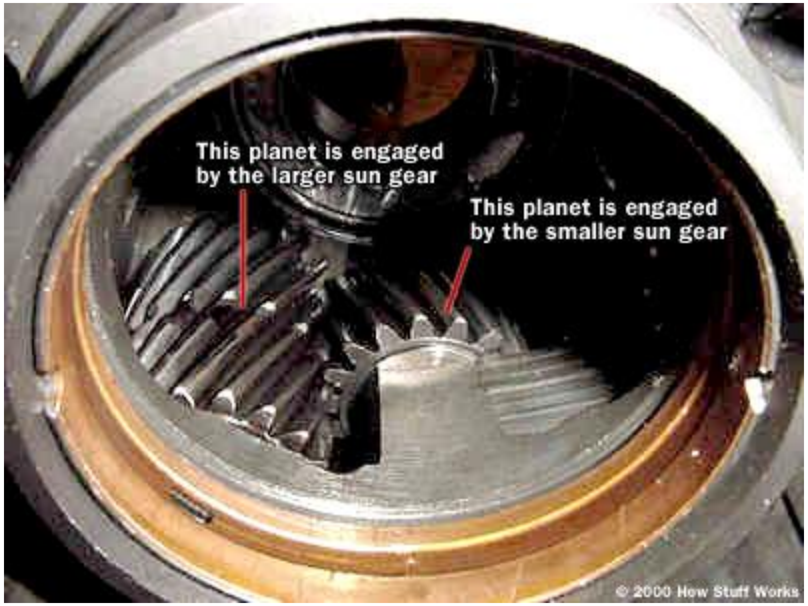




Sun = planétaire   Planet = satellite   Annulus = Couronne

Planetary gears

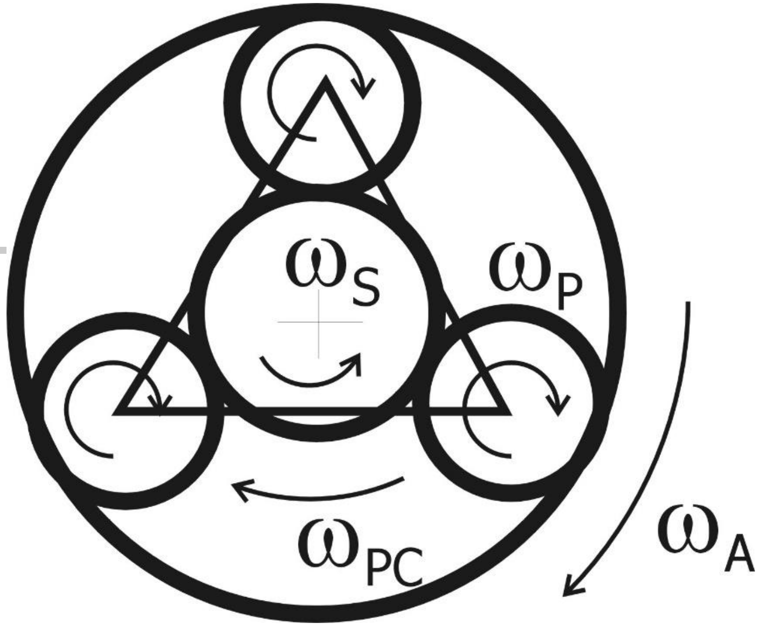




The solution is very compact

Planetary gears

- Geometrical consideration
  - S: sun
  - PC: planet carrier (or arm)
  - A: annulus (or ring)



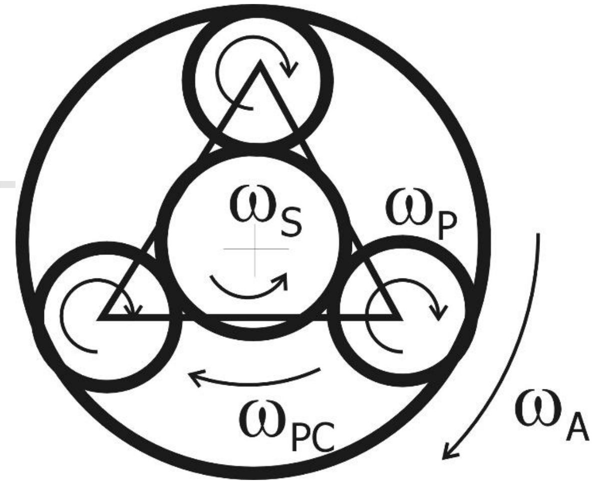
- Relations between the radii of the planet and of the planet carrier and the radii of the sun and of the annulus

$$R_{PC} = R_S + R_P \qquad R_A = R_S + 2\,R_P$$

- It comes

$$R_P = \frac{R_A - R_S}{2} \qquad R_{PC} = \frac{R_A + R_S}{2}$$

Planetary gears



- Equality of the velocities between the sun and the planet

$$\omega_S\, R_S = \omega_{PC}\, R_{PC} - \omega_P\, R_P$$

- Equality of the velocities of the annulus and the planet

$$\omega_A\, R_A = \omega_{PC}\, R_{PC} + \omega_P\, R_P$$

- It comes:

$$\omega_S\, R_S + \omega_A\, R_A = \omega_{PC}\,(R_S + R_A)$$

- In terms of the number of teeth of the sun and the annulus

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

Planetary gears

- Two factors that control the number and the spacing of the planets
- 1/ Maximum number of planets is limited by the space available: Tooth tips must not interfere
- 2/ The teeth of the planet must align simultaneously with teeth of the sun and the annulus
  - A necessary condition for the possibility of equidistant assembling

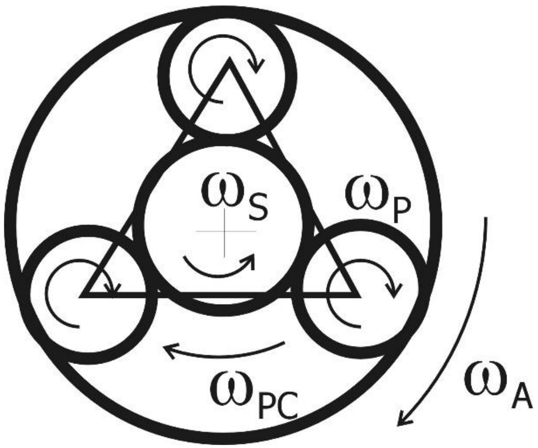
$$\frac{N_S + N_R}{n} = i$$

  - N_S and N_R the number of teeth on the sun and the ring
  - n: the number of planets
  - i: an integer

Planetary gears

- If one defines the reduction 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 under the alternative form

$$\boxed{\frac{\omega_A - \omega_{PC}}{\omega_S - \omega_{PC}} = -\frac{1}{i}}$$

- Willys formula establishes the relation between the rotation speeds of the three gear sets and the reduction ratio

Planetary gears

- If the sun is fixed

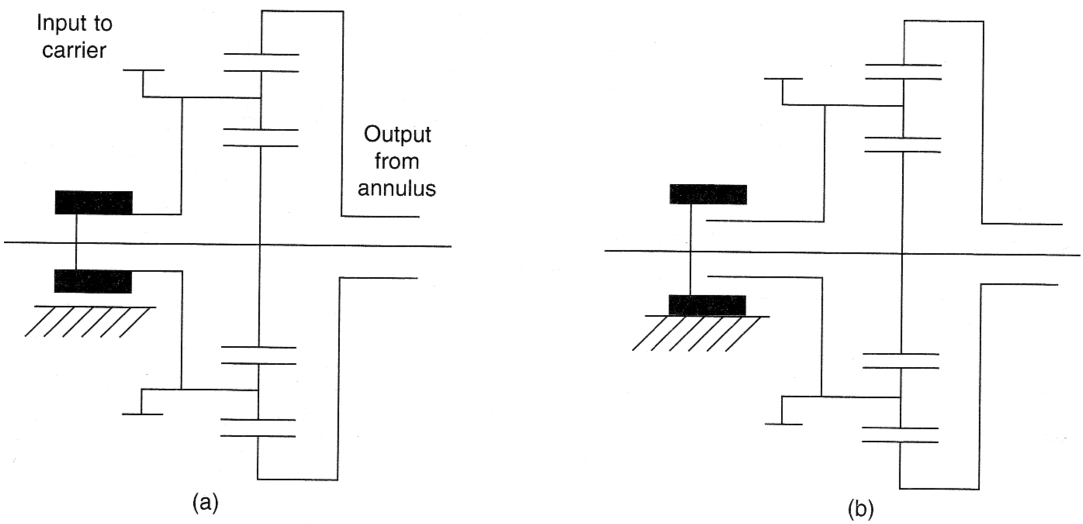
$$\omega_S = 0$$

- The Willys formula gives the reduction ratio between the planet carrier and the annulus

$$\frac{\omega_{PC}}{\omega_A} = \frac{1 + Z_A/Z_S}{Z_A/Z_S}$$

- For $Z_A/Z_s=2$

$$\frac{\omega_{PC}}{\omega_A} = 1.5$$



- If we clamp together the planet carrier and the sun

$$\omega_S = \omega_{PC}$$

- One finds

$$\frac{\omega_{PC}}{\omega_A} = 1$$

The planetary gear set

Sun	Planet Carrier	Annulus	Reduction Ratio	Remark
Fixed	Input	Output	$\frac{\omega_{PC}}{\omega_A} = \frac{1+Z_A/Z_S}{Z_A/Z_S}$	$1.12 \leq i \leq 1.67$
Fixed	Output	Input	$\frac{\omega_A}{\omega_{PC}} = \frac{Z_A/Z_S}{1+Z_S/Z_A}$	$0.6 \leq i \leq 0.8$
Input	Output	Fixed	$\frac{\omega_S}{\omega_{PC}} = 1 + Z_A/Z_S$	$2.5 \leq i \leq 5.0$
Output	Input	Fixed	$\frac{\omega_{PC}}{\omega_S} = \frac{1}{1+Z_A/Z_S}$	$0.2 \leq i \leq 0.4$
Input	Fixed	Output	$\frac{\omega_S}{\omega_A} = -Z_A/Z_S$	$-0.4 \leq i \leq -1.45$
Output	Fixed	Input	$\frac{\omega_A}{\omega_S} = \frac{-1}{Z_A/Z_S}$	$-0.25 \leq i \leq -0.67$

Planetary gear sets

- Let's define

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

- For the sake of convenience, we also note by 1, 3, 4 respectively the Sun, the Annulus and the Planet Carrier

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

- The Willys formula writes

$$\omega_1 - \lambda\,\omega_3 - (1-\lambda)\,\omega_4 = 0$$

$$-\omega_1 + \lambda\,\omega_3 + (1-\lambda)\,\omega_4 = 0$$

Planetary gear sets

- Equilibrium and conservation of power are given by

$$C_1 + C_3 + C_4 = 0$$

$$P_1 + P_3 + P_4 = 0$$

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

- We are going to show that:

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

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

Planetary gear sets

- These formulae can be established as follows.
  - Let's eliminate the velocity and the torque of the planet carrier (4)

$$\omega_4 = \frac{\omega_1 - \lambda\,\omega_3}{1-\lambda}$$

$$C_4 = -(C_1 + C_3)$$

  - Then insert into the torque equilibrium

$$C_1\,\omega_1 + C_3\,\omega_3 - (C_1 + C_3)\left(\frac{\omega_1 - \lambda\omega_3}{1-\lambda}\right) = 0$$

Planetary gear sets

- These formulae can be established as follows.
  - After some algebra, we have:

$$C_1\,\omega_1\left[1-\frac{1}{1-\lambda}\right] + C_3\,\omega_3\left[1+\frac{\lambda}{1-\lambda}\right] + C_1\,\omega_3\,\frac{\lambda}{1-\lambda} - C_3\,\omega_1\,\frac{1}{1-\lambda} = 0$$

$$C_1\,\omega_1(-\lambda) + C_3\,\omega_3 + C_1\,\omega_3\,\lambda - C_3\,\omega_1 = 0$$

$$C_1\,\lambda\,(\omega_3-\omega_1) + C_3\,(\omega_3-\omega_1) = 0$$

  - Finally, the result is:

$$\boxed{C_1 = -\frac{C_3}{\lambda}}$$

Planetary gear sets

- A similar formula can be established between the torques 1 & 4
  - Let's eliminate the annulus quantities

$$C_3 = -(C_1 + C_4) \qquad \omega_3 = \frac{\omega_1 + (\lambda - 1)\omega_4}{\lambda}$$

  - Inserting into the power conservation

$$C_1\,\omega_1 - (C_1 + C_4)\,\frac{\omega_1 + (\lambda - 1)\omega_4}{\lambda} + C_4\,\omega_4 = 0$$

$$C_1\,(\omega_1 - \omega_4)\frac{\lambda - 1}{\lambda} + C_4\,\frac{1}{\lambda}(\omega_4 - \omega_1) = 0$$

  - Finally, the result is

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

Planetary gear sets

- The relations between the torques

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

- can be reformulated to put forward the powers

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

Planetary gear sets

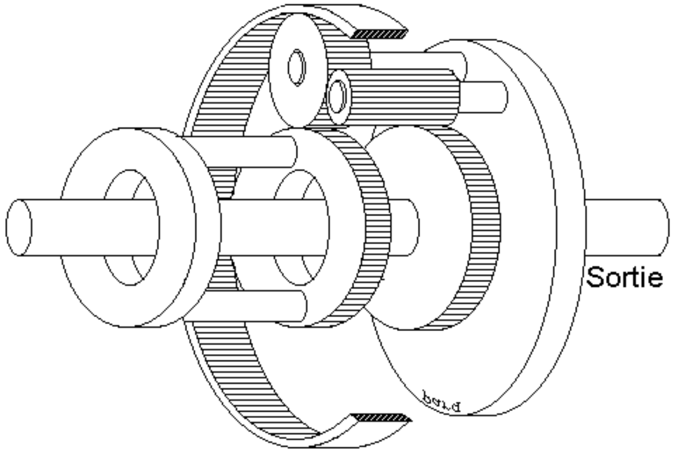
- Using the usual reduction ratio, one has the relation between the torques

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

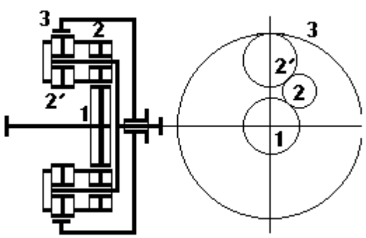
- And the powers

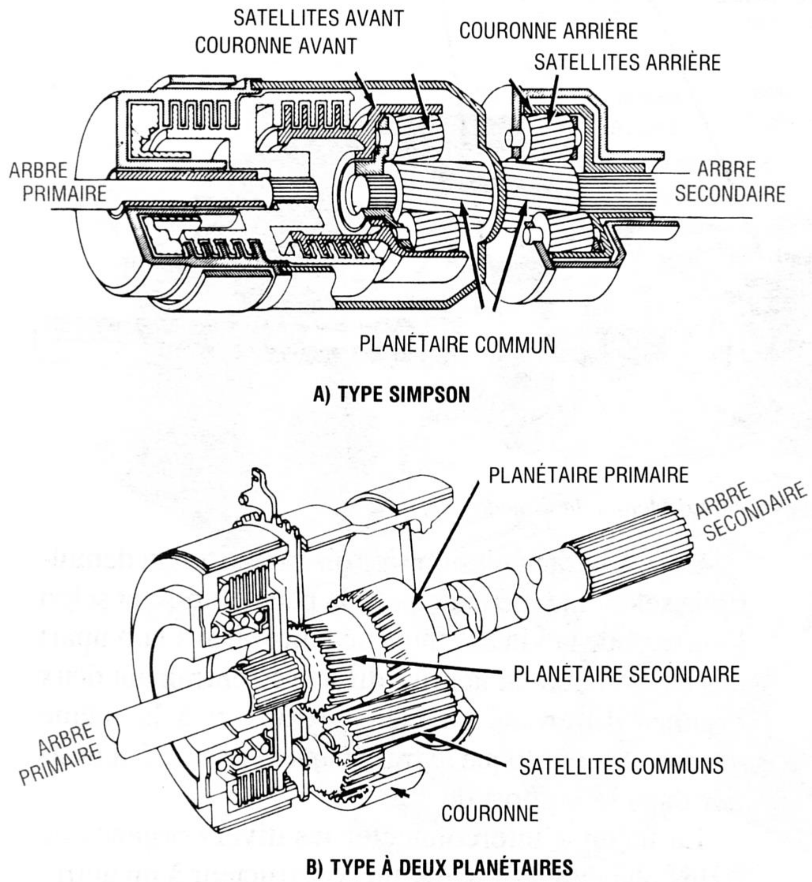
$$\boxed{\frac{P_S}{\omega_S} = \frac{P_A}{i\,\omega_A} = \frac{P_{PC}}{-(i+1)\,\omega_{PC}}}$$

Complex planetary gears



Modélisation





Ravigneaux complex gear trains

Double planetary gears by Nash Fig. 19.3

Complex planetary gears

- Working principle of basic planetary gear

https://www.youtube.com/watch?v=a1JAWoAvK-E

https://www.youtube.com/watch?v=JBB1sC7LCuQ

https://www.youtube.com/watch?v=UakeTEJlXGw

https://www.youtube.com/watch?v=SQMSSKfs4m4

- Simpson compound planetary gear

https://www.youtube.com/watch?v=r1BYOOJKyaQ

- Ravigneaux planetary gear:

https://www.youtube.com/watch?v=Y1zbE21Pzl0

AT USING PLANETARY GEAR TRAINS

- Main components of automatic transmissions using planetary gear trains:
  - Complex planetary gear trains: Simpson, Ravigneaux…

  ➔ create at least 3 or 4 gear ratios with an appropriate distribution and a rear gear
  - A set of brakes, hydraulic clutches, and free wheels

  ➔ To perform the clamping, the motion transfer or to obtain reaction forces from some gear train elements
  - A hydraulic system to actuate the brakes and the clutches: a gear pump, a pressure regulation system, servo systems, and hydraulic reservoir.
  - A command system using hydraulic or electro-hydraulic systems accounting for the vehicle speed, the engine torque, the pressure on the acceleration pedal…

At using complex gear trains

- 1: Torque converter
- 2: Planetary gears
- 3: Housing
- 4: Differential
- 5: Oil pump
- 6: Hydraulic distribution
- 7: Electrohydraulic servo
- Clutches E1 and E2
- Brake F1 and F2 clamping the planet carrier PS
- Free wheel RL

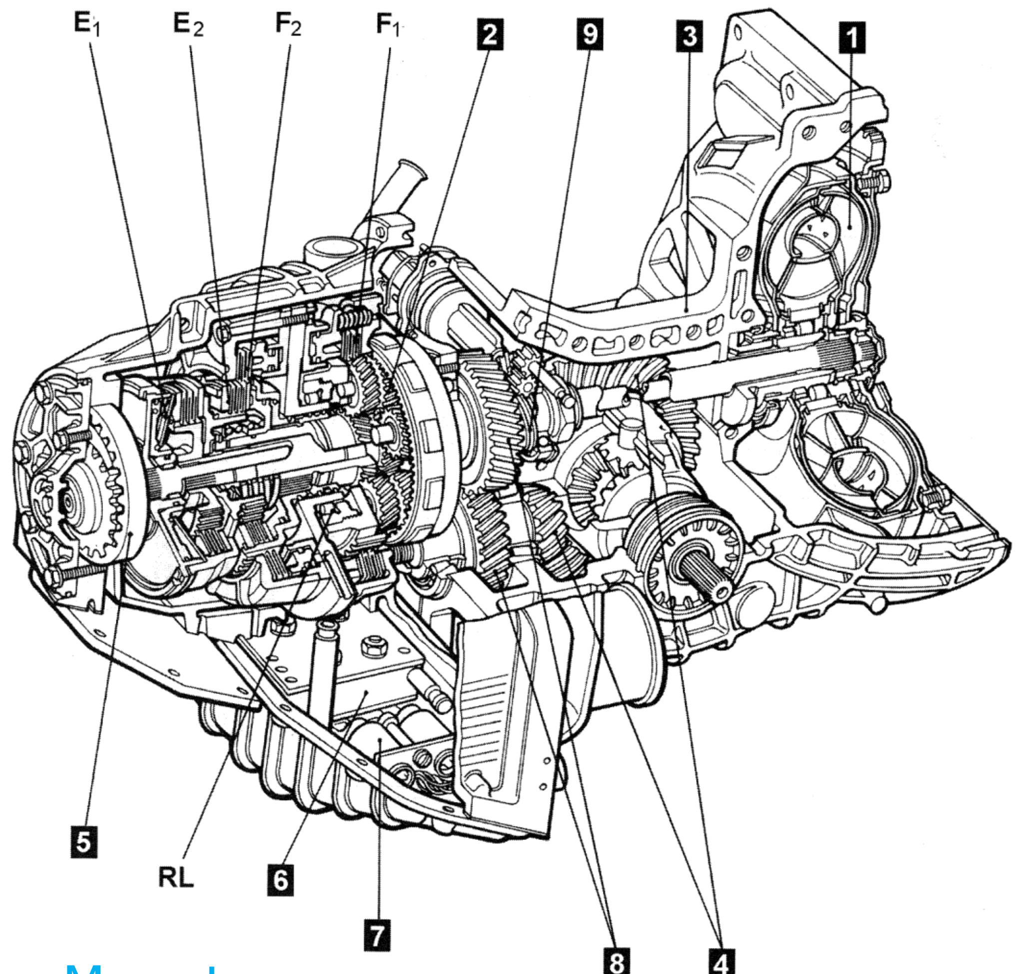


Fig. Memeteau

At using complex gear trains

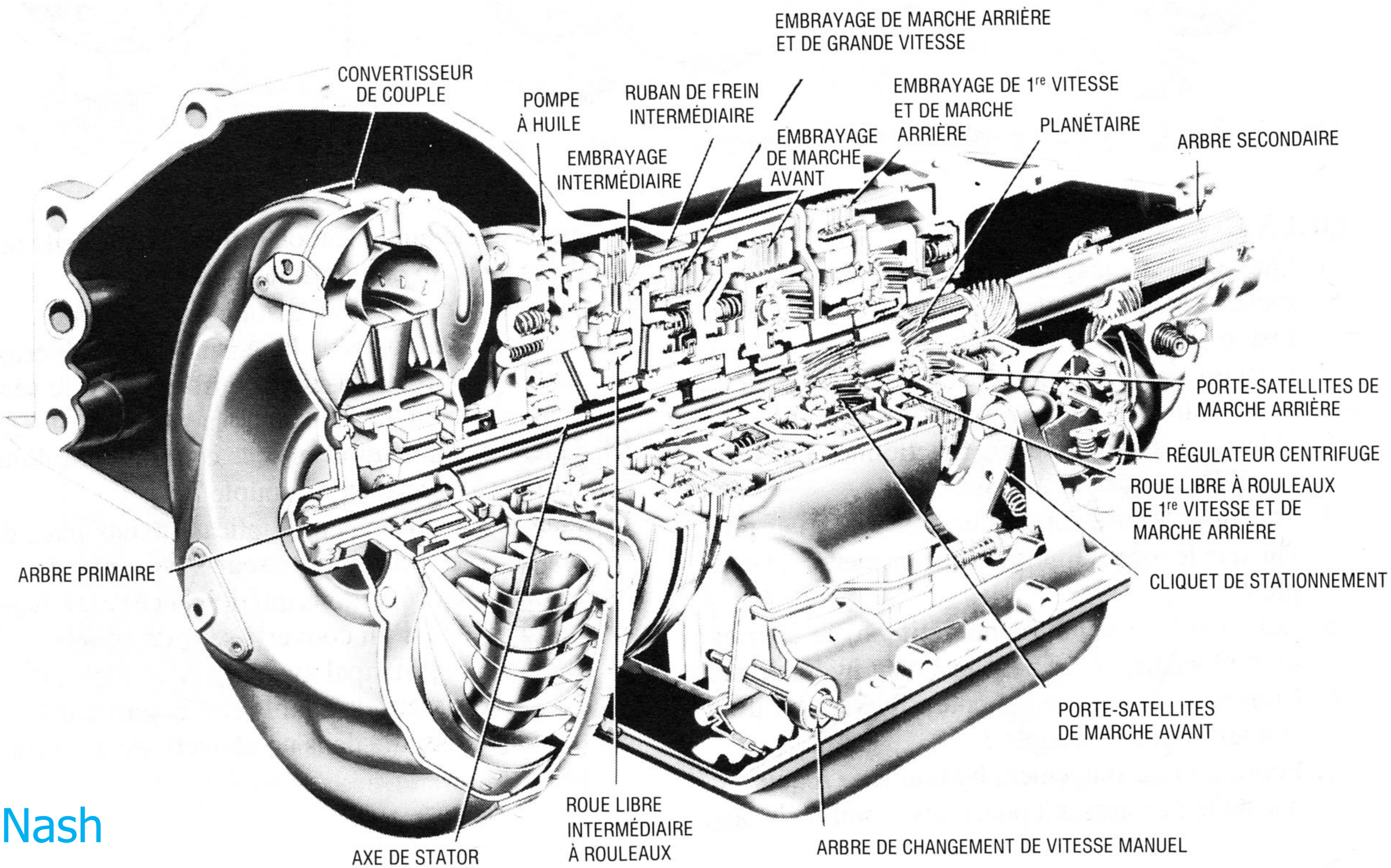


Fig. Nash

AT USING COMPLEX GEAR TRAINS

- Gear trains implemented in AT gear boxes are usually:
  - Gear trains with double planetary gear trains and two planet sets e.g. SIMPSON
  - Gear trains with double sun and two sets of planetary gears e.g. RAVIGNEAUX

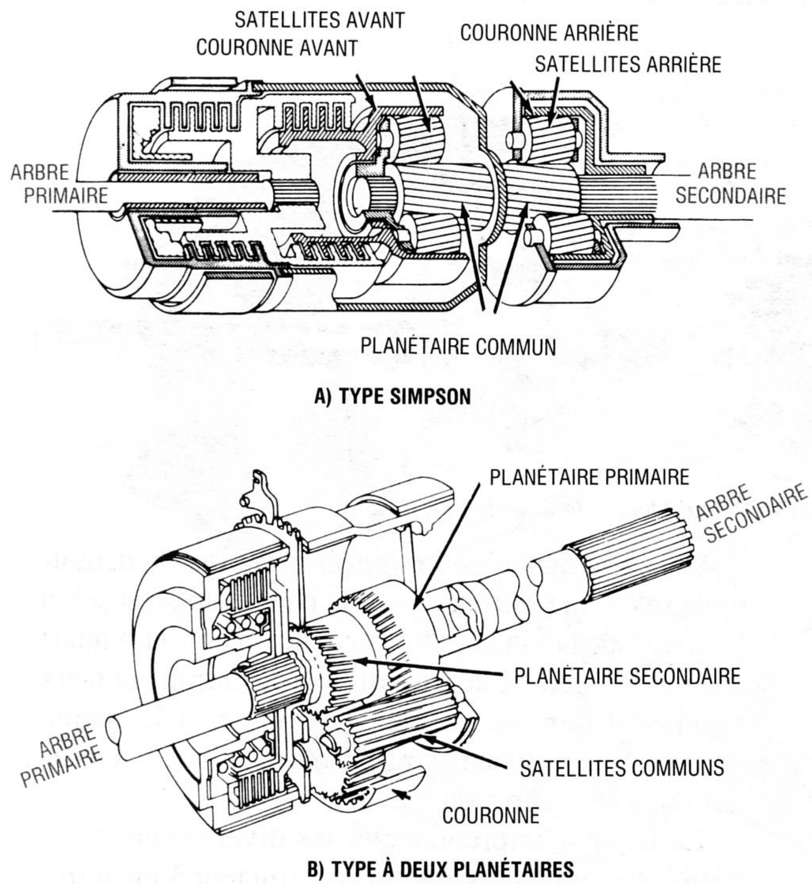
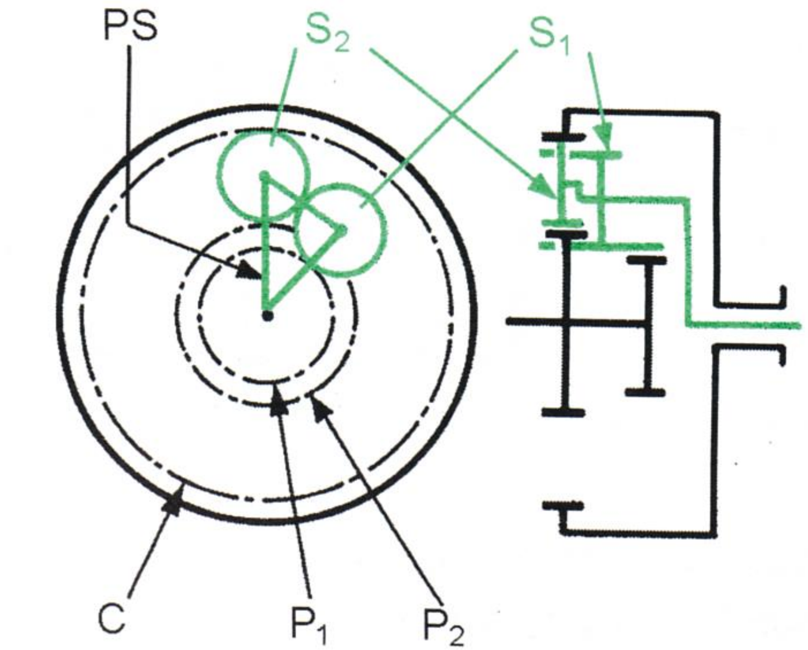


Fig. Nash

Complex gear trains

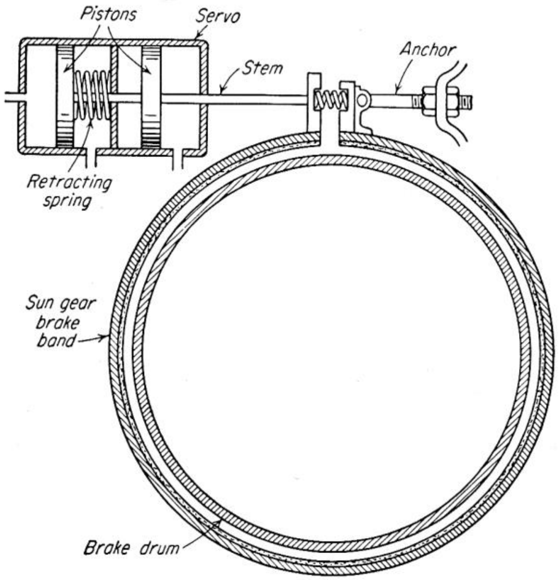
- Small sun gears P1
- Large sun gears P2
- Planet gears S1
- Planet gears S2 mounted on a planet carrier PS free to spin in one way due to free rolling RL device
- Annulus C

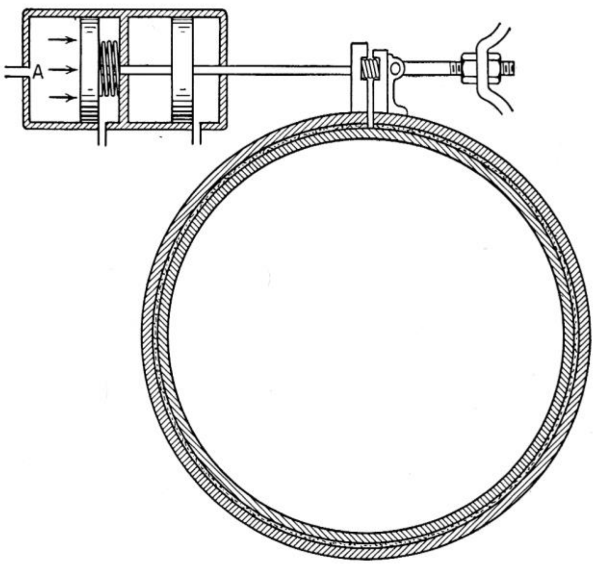


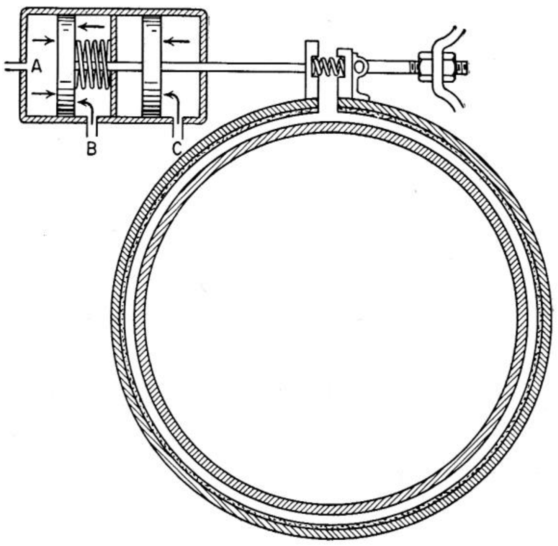
Mèmetaux Fig 5.9

Band brakes in AT

- Band brakes can be easily adapted in AT



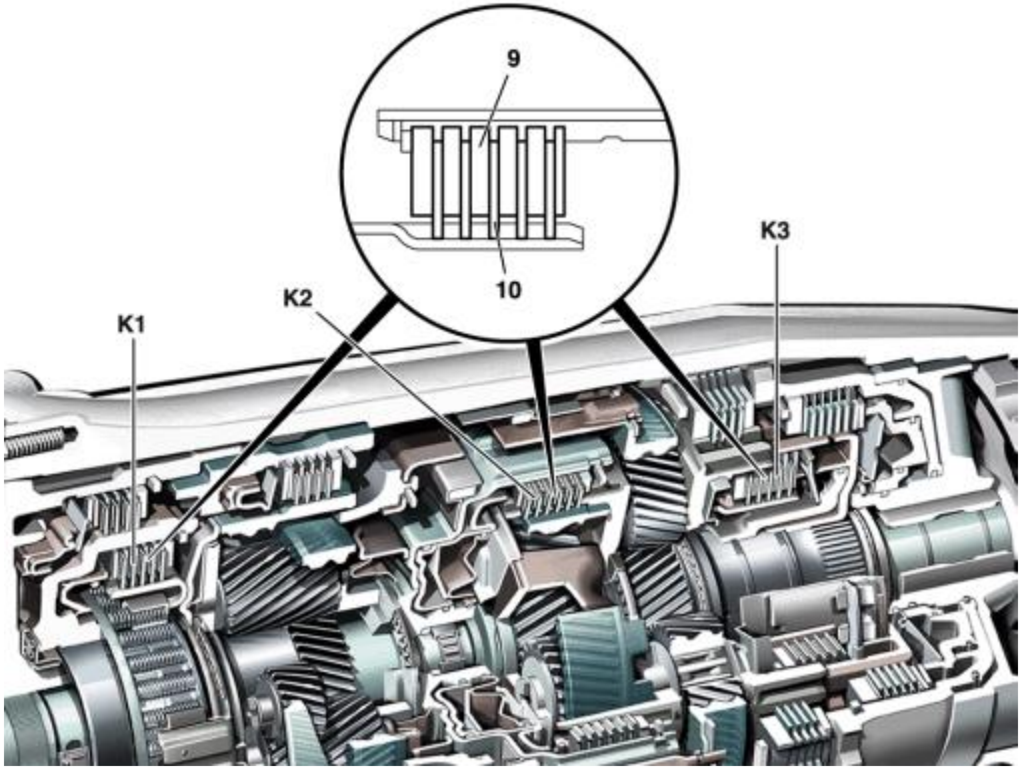




Multiple disk clutch in AT

- Hydraulic multiple disk clutches are well appropriate in AT

S 450 Series clutch with splined bore and lube port for increased lubrication.



Multiple disk clutch in AT

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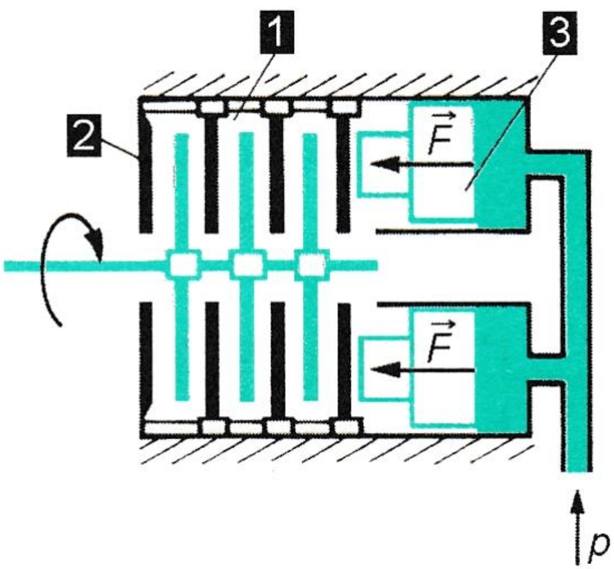
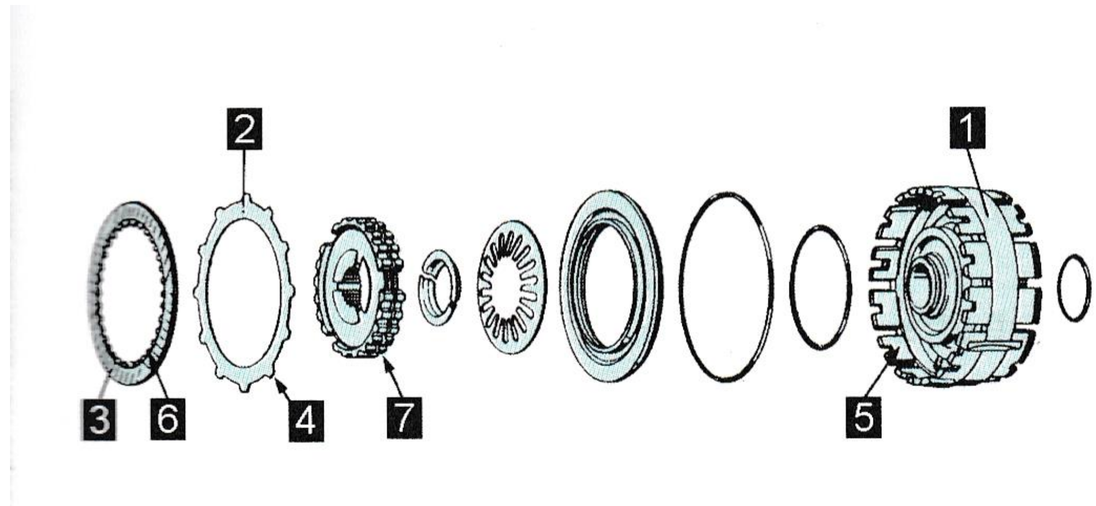


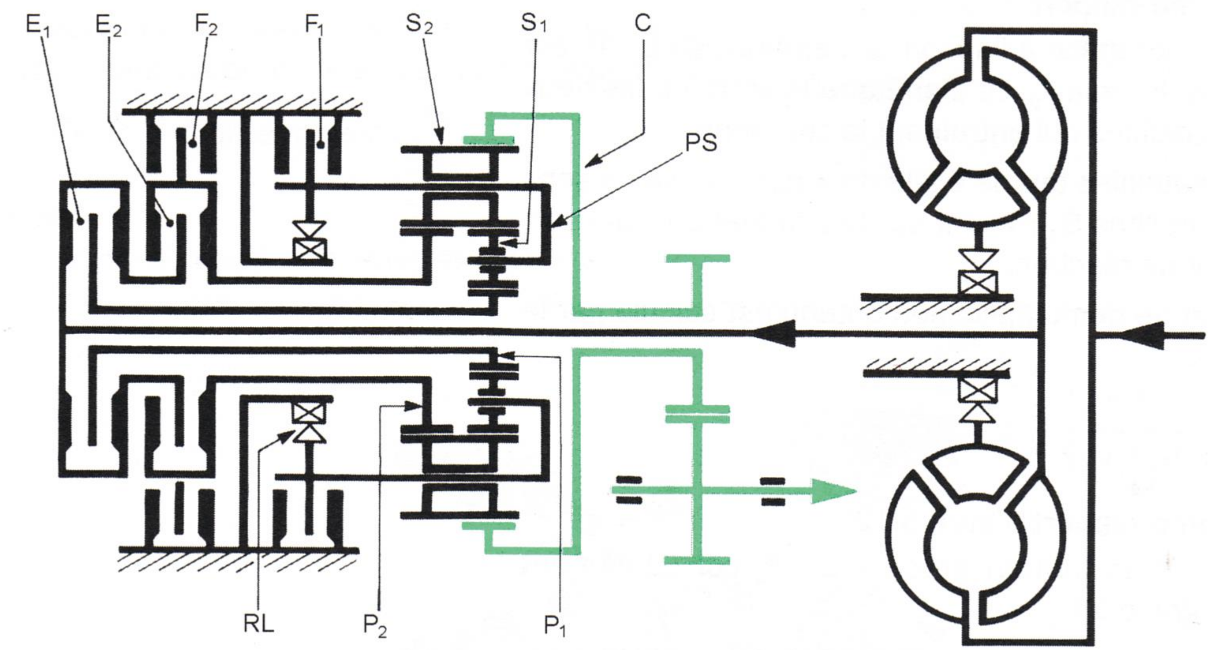
Mèmetaux Fig 6.1



Mèmetaux Fig 6.2

At using complex gear trains

- Clutch E1: connecting sun P1 to engine
- Clutch E2: connecting sun P2 to engine
- Brake F1 blocking the rotation of the planet carrier PS
- Brake F2 blocking the rotation of the sun P2
- A free wheel RL is blocking the rotation of PS in a reverse direction with respect to the rotation of the annulus C

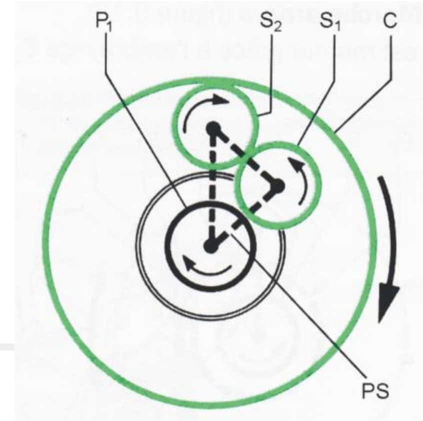


Working principle of an AT gear box with a complex double planetary gear train.
Mèmetaux Fig 5.9

At using complex gear trains

- For all gear ratio, one can identify
  - An input component that is connected to the power source
  - An output component, connected to the driveline and the wheels
  - A reaction element whose rotation is blocked because of a brake or a one-way rotation wheel

At using complex gear trains



Gear ratio 1

- P_1 is connected to the engine by clutch E_1
- Planet gears S_1 are spinning, and
- Rotation of S_1 is transferred to pinion S_2
- Rotation of S_2 is transmitting the motion to the annulus C
- The large sun P_2 spins freely
- Annulus is connected to the wheels.

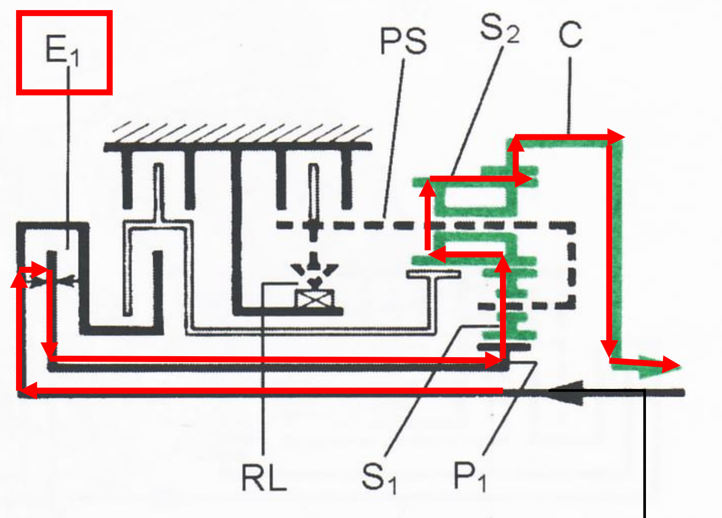


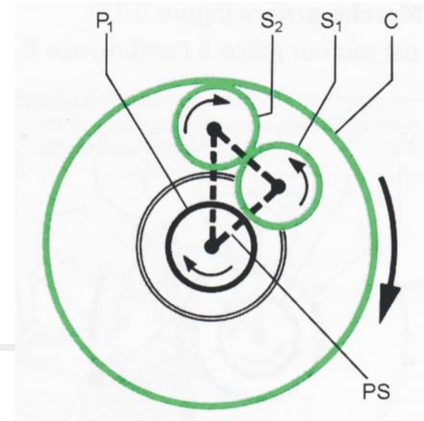
Fig. 5.10 b – Premier rapport.

- élément moteur P_1 par E_1.
- élément de réaction : porte-satellites par RL.
- transmission du mouvement par S_1, S_2 et C.
- éléments non sollicités.

At using complex gear trains

- The reactive torque developed by the annulus C blocks the rotation of the planet carrier PS because of the freewheel device RL
- PS is playing the role of reaction element
- The overall reduction ratio is governed by

$$i = \frac{\omega_C}{\omega_{P1}}$$



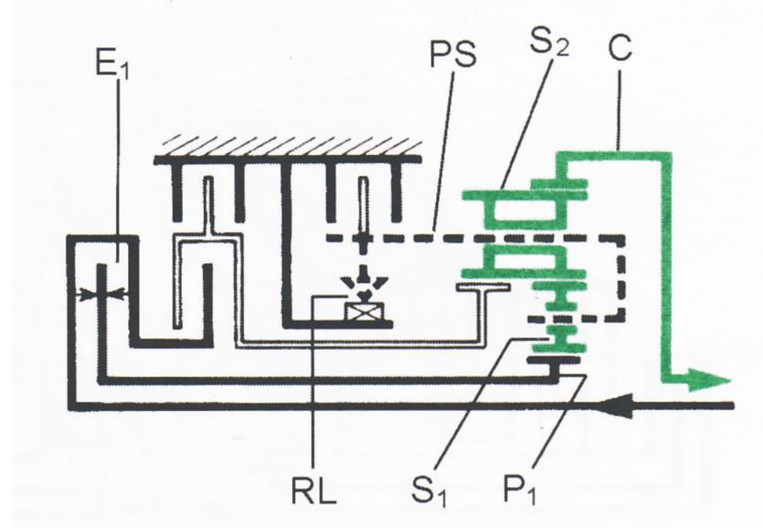


Fig. 5.10 b – Premier rapport.

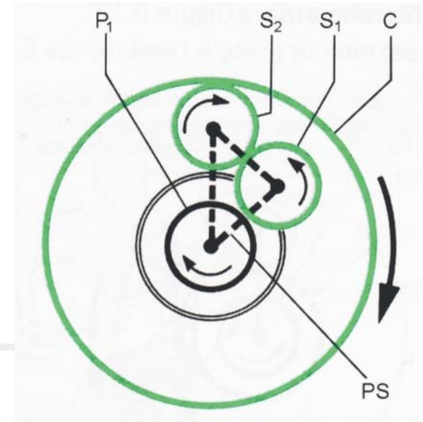
——— élément moteur P_1 par E_1.

-------- élément de réaction : porte-satellites par RL.

——— transmission du mouvement par S_1, S_2 et C.

═══ éléments non sollicités.

At using complex gear trains



- In this configuration, the vehicle braking can not generate any engine brake because of the one-way constraint of the free-wheeler RL.
- To develop an engine brake behavior in gear 1, it is necessary to actuate brake F1 that stop the rotation of the planet carrier of S2

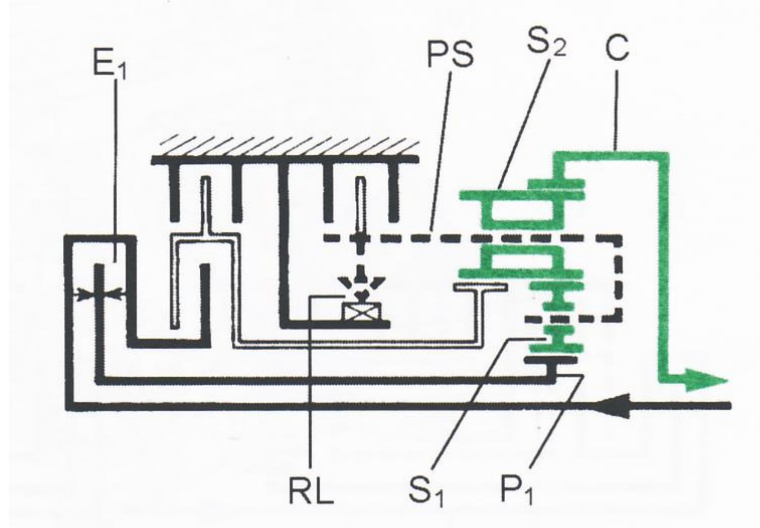


Fig. 5.10 b – Premier rapport.

——— élément moteur P_1 par E_1.

-------- élément de réaction : porte-satellites par RL.

——— transmission du mouvement par S_1, S_2 et C.

═══ éléments non sollicités.

At using complex gear trains

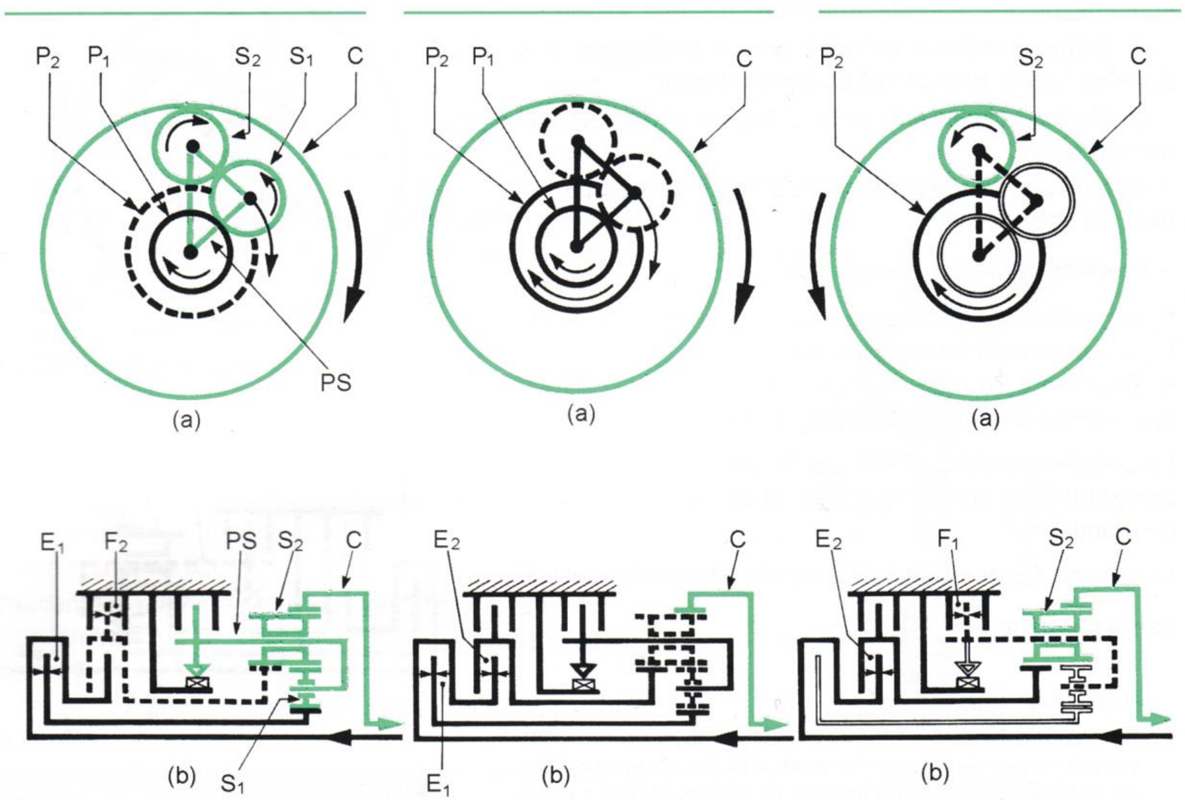


Fig. 5.11 – Deuxième rapport.

P_1. Moteur.
P_2. Élément de réaction.
PS tourne.
S_1, S_2, C. Éléments récepteurs.

Fig. 5.12 – Troisième rapport.

P_1, P_2. Moteurs.
Les pignons étant de diamètres différents, le train se trouve bloqué.

Fig. 5.13 – Marche arrière.

P_2. Moteur.
PS bloqué (élément de réaction).
S_2, C. Récepteurs.

At using complex gear trains

Gear ratio 2

- The small sun P_1 is connected to the engine via clutch E_1
- The large sun P_2 rotation is blocked by brake F_2
- The rotation of the sun P_1 creates a spin of the short pinion S_1 and thus the spin of long pinion S_2, and finally of the annulus C.
- The planet carrier PS also rotates because the pinion S_2 rolls on sun gear P_2 that works as a reaction element.

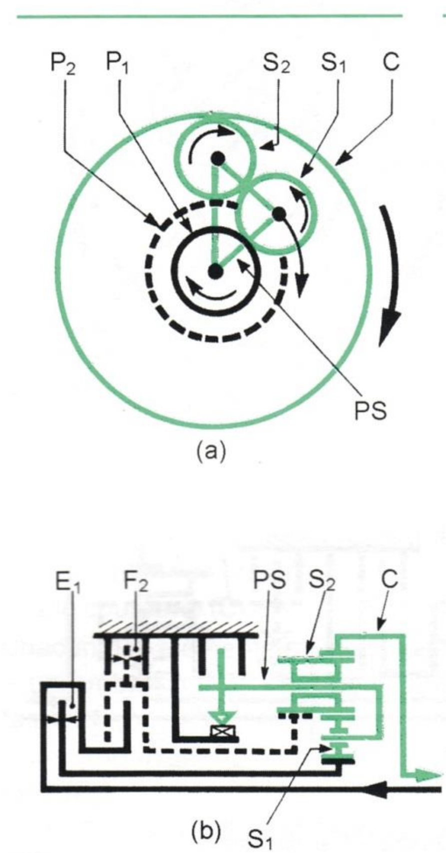


Fig. 5.11 – Deuxième rapport.

P_1. Moteur.
P_2. Élément de réaction.
PS tourne.
S_1, S_2, C. Éléments récepteurs.

At using complex gear trains

Gear ratio 2

- The final gear ratio is governed by the equation

$$\frac{\omega_C\,(\omega_{P1}+\omega_{P2})}{\omega_{P2}(\omega_{P2}+\omega_C)}$$

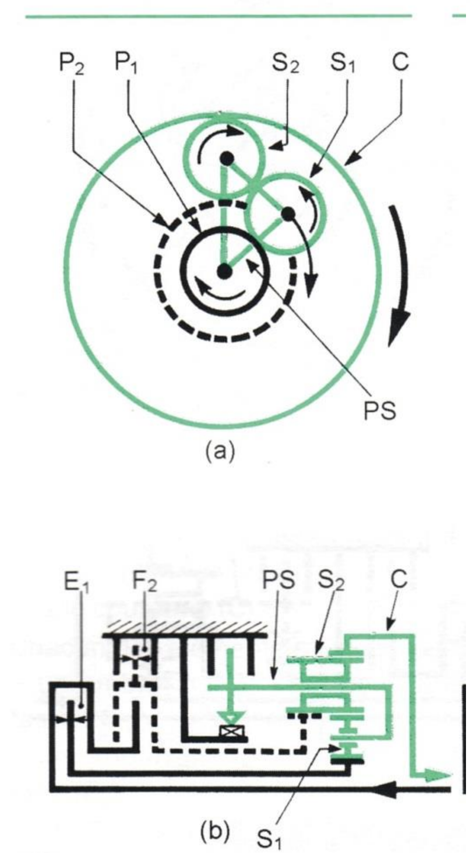


Fig. 5.11 – Deuxième rapport.

P_1. Moteur.
P_2. Élément de réaction.
PS tourne.
S_1, S_2, C. Éléments récepteurs.

At using complex gear trains

Gear ratio 3

- P_1 is always the input because it is connected to the engine via clutch E_1
- P_2 is also connected to the input (engine) through clutch E2
- Both suns P_1 and P_2 having different diameters but rotating at the same speed, they block the rotation of the planet carrier motion and the pinions S_1 and S_2 spins as a solid element.
- The annulus spins at the same rotation speed as well
- Gear ratio = 1

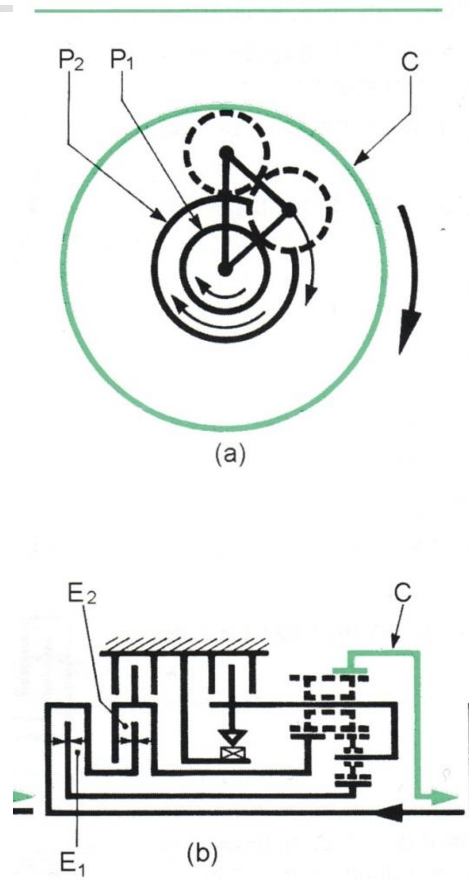


Fig. 5.12 – Troisième rapport.

P_1, P_2. Moteurs.
Les pignons étant de diamètres différents, le train se trouve bloqué.

At using complex gear trains

Reverse Gear ration

- P_2 is the input, and it is connected to the engine through E_2
- The planet carrier PS is clamped by brake F_1 and serves as reaction element.
- Sun P_2 rotation is transferred to pinion S_2
- Rotation of pinions S_2 drives the annulus C in reverse direction compared to the sun P_2
- Reduction ratio is

$$-\frac{\omega_C}{\omega_{P2}}$$

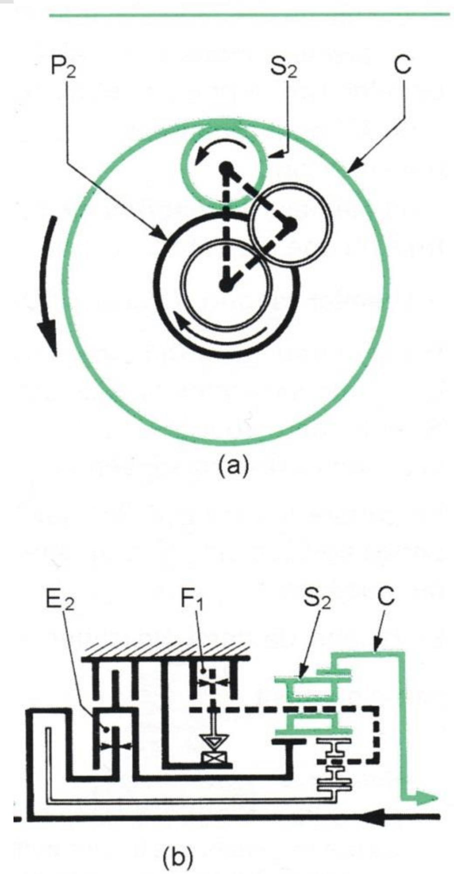
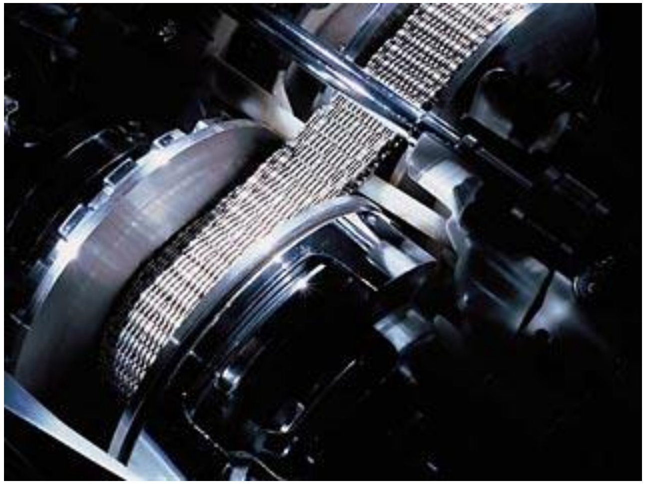


Fig. 5.13 – Marche arrière.

P_2. Moteur.
PS bloqué (élément de réaction).
S_2, C. Récepteurs.

Continuous Variable Transmission - CVT



Continuous Variable Transmissions

- Growing interest for fuel economy and reduction of pollutant emissions
- A continuous variable reduction ratio allows the engine working at its optimal fuel conditions within a large range of wheel rotation speeds and vehicle ground speed.
- Two important technological implementations
  - Van Doorme system: the most famous variable pulley variator system
  - Perburry system: system using two toroidal rollers connecting two input and output discs.

Van Doorne systems

DAF Variomatic

HISTORICAL PERSPECTIVE

- Variomatic System was invented and applied in DAF (DAF = Van Dorne Automobile Fabrik)
- Nowadays, it is famous for its application in many midsize cars such as FIAT or FORD.
- It is adopted in many modern vehicles

APPLICATIONS

- Mainly for small vehicles with low power engines (< 1.6 L)
- Small passenger cars, motorscooters, and snow mobile

Van Doorne systems

Focus C-max

Toyota Yaris

Honda Insight

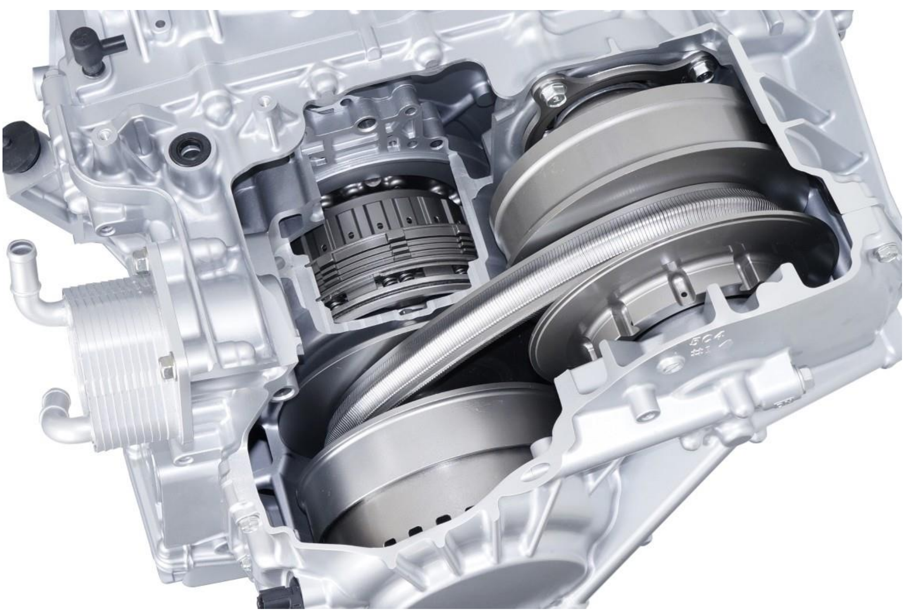
Opel Vectra

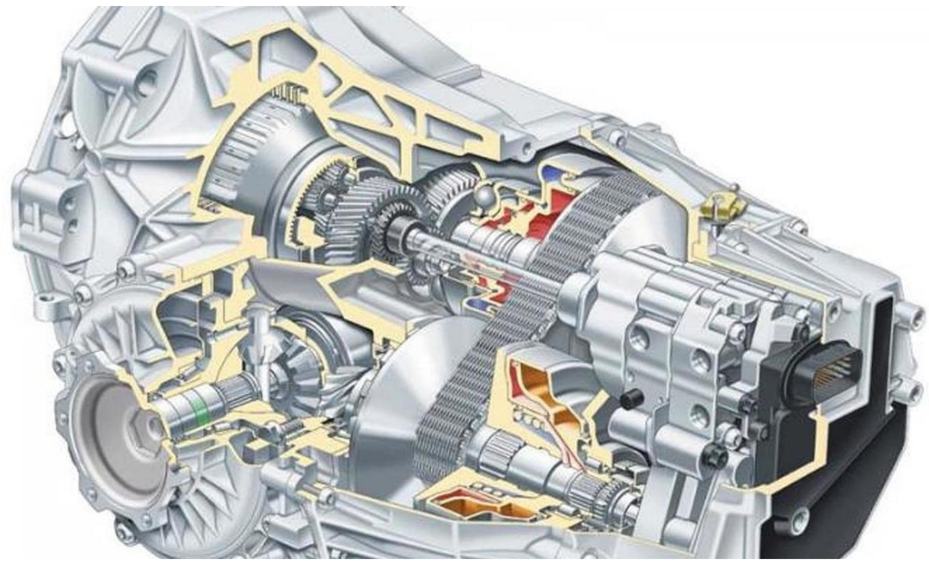
Fiat Punto 1.2L

Toyota Estima Hybrid

Van Doorne systems

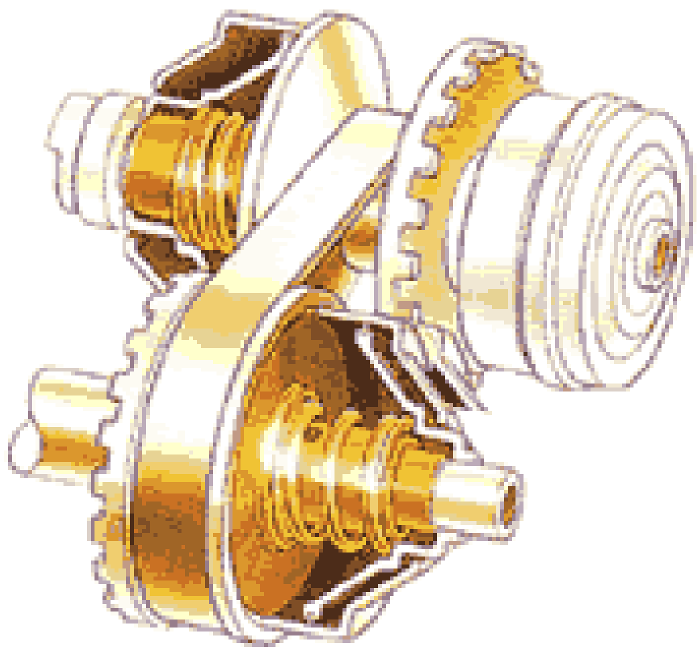
CVT implemented in the Honda Civic

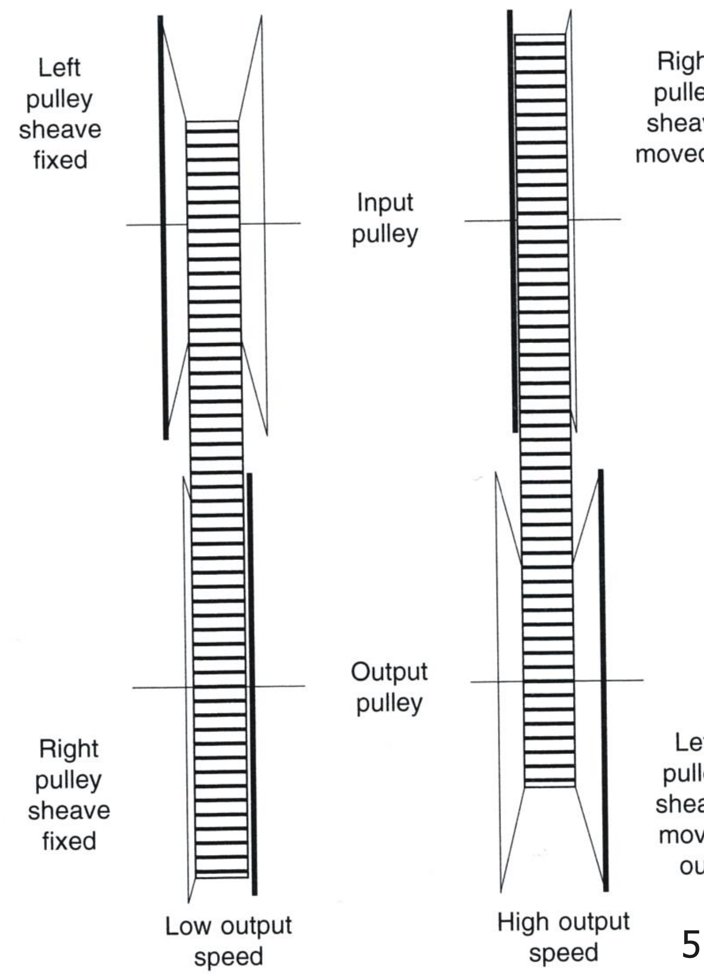




CVT in Audi multitronic

Van Doorne systems

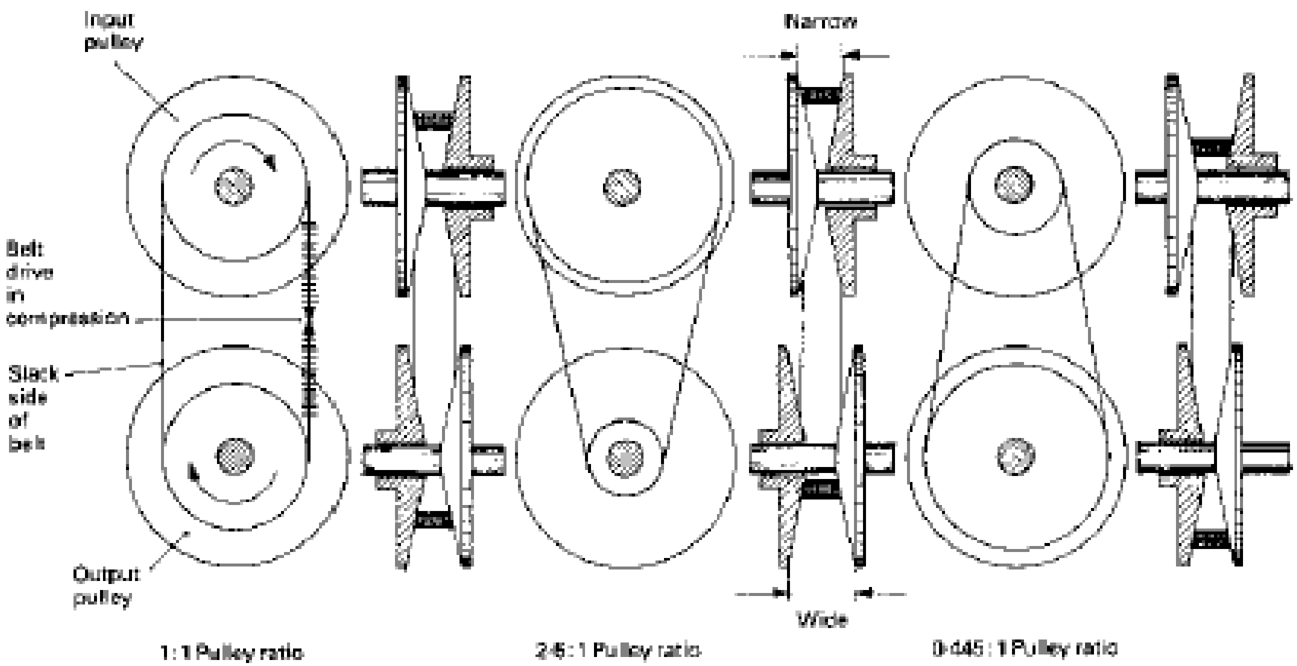




Van Doorne systems

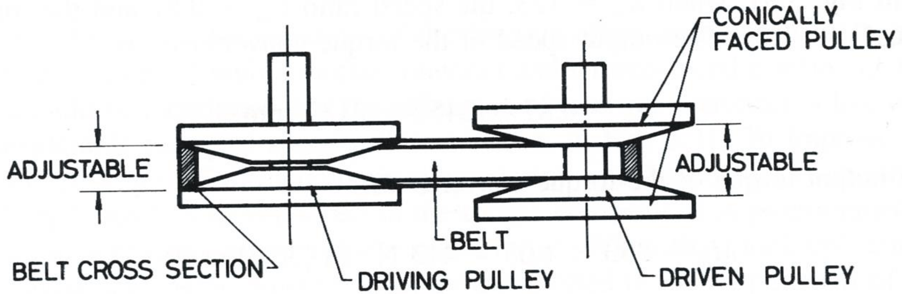
- OPERATION PRINCIPLE
  - The system includes two pairs of conical pulley sheaves and a fixed length V metal belt.
  - By modifying the distance between the pulleys, the belt rolling radius is changed and so the rotation speed of the pulleys.
  - When the radii are modified in a synchronized manner, the reduction ratio can be changed continuously.
  - As in V-belts, the no slip condition between the pulleys and the belt depends on a sufficient normal force. The pressure control between the pulley sheaves produce a tension load in the belt.
  - Initially the modification of the pulley distances was realized using a pure mechanical system based on centrifugal forces and an actuator working with depression.
  - Modern systems include an actuator controlled by a microprocessor.

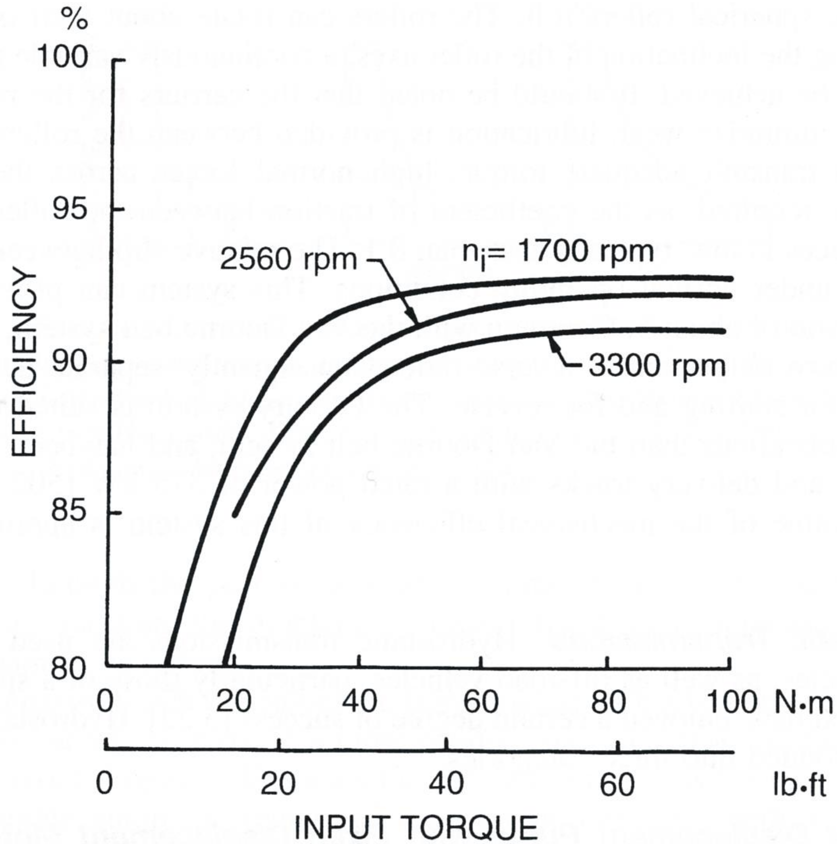
Van Doorne systems



- PERFORMANCE
  - The reduction ratio can be modified with a range of 4 to 6.
  - The transmission efficiency is function of the input torque and rotation

Van Doorne systems



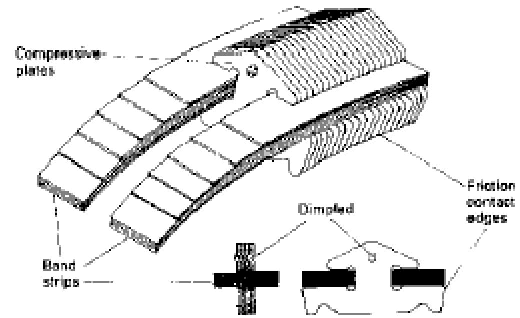


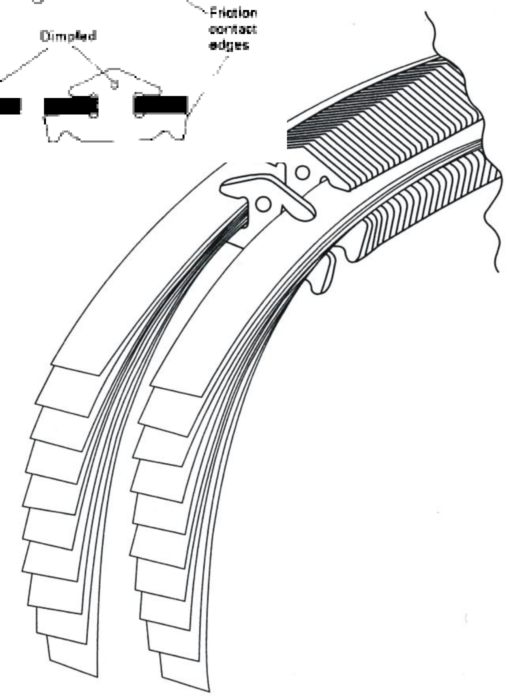
- Variation of the transmission efficiency is a function of the input torque . See figure Wong Fig 3.34 and 3.35 given for a reduction ratio fixed to 1

Van Doorne systems

- THE BELT
  - The belt is assembled from two packs of flexible high strength steel bands with a set of individual trapezoidal segment blocks (2 mm thick) retained by these bands.
  - The design improves the efficiency and reduces the noise.
  - The belt is able to work only under compression so the name of « compression belt ».

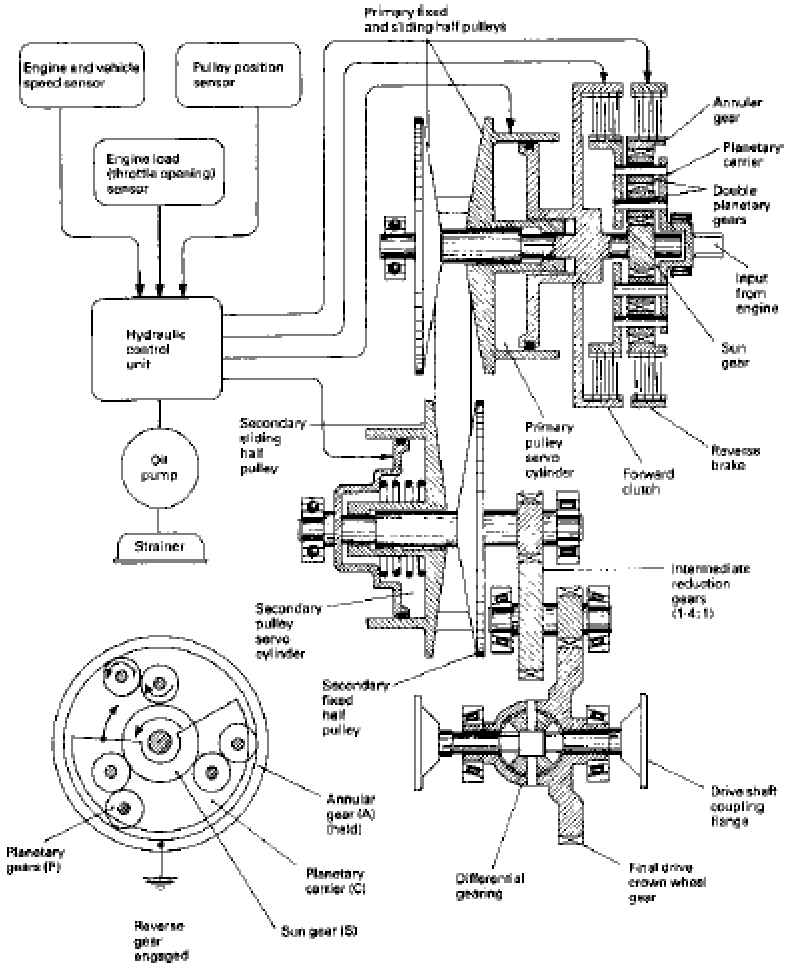
    The working principle is contrary to that of rubber belt.

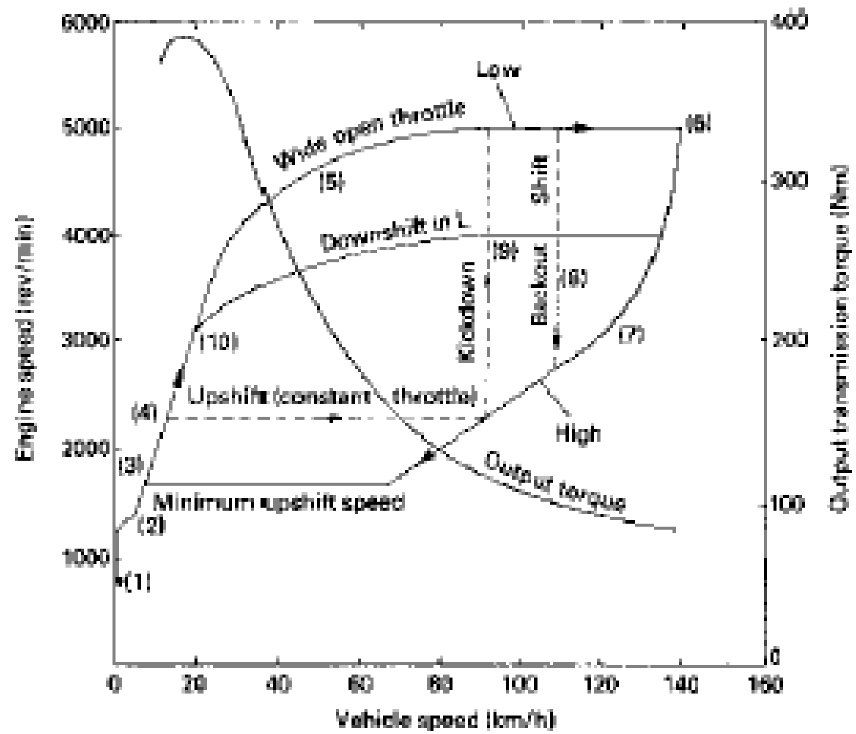




Happian Smith Fig 13.28

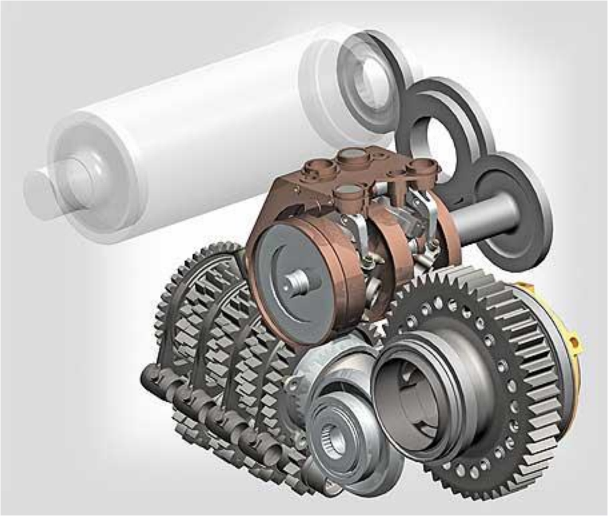
Van Doorne systems



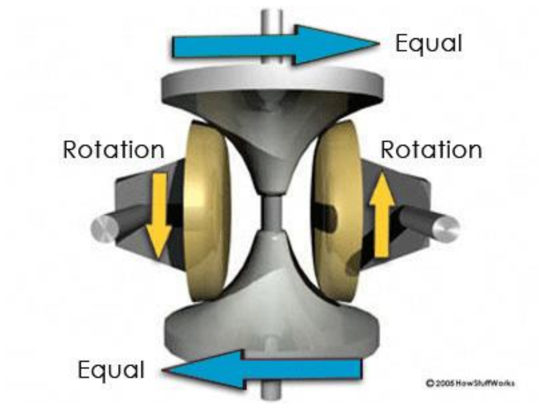


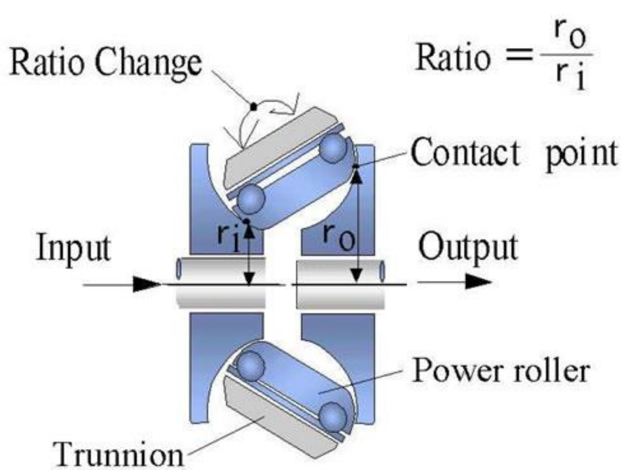
Heisler: Advanced Vehicle Technology
Fig 5.28 & 5.29

Infinite Variable Transmission - IVT



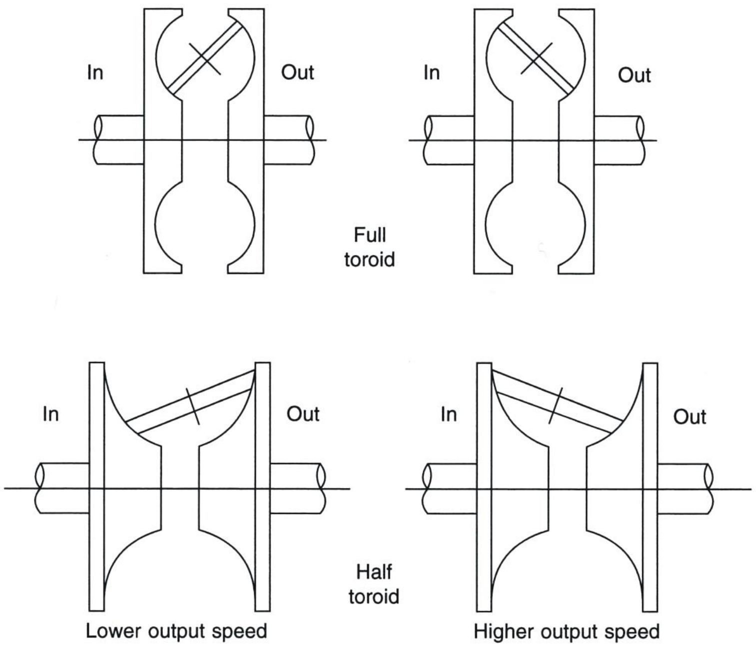
Traction drive designs





- The alternative mechanical alternative to pulley-belt systems are based on the idea of transmitting the rotation via a rotating element between an input and an output discs.
- The ratio of the radii of the contact points between the rotating elements and the input/output discs determines the reduction ratio.
- One modifies the reduction ratio by changing the axis of a rotating element (the roller) between input and output discs.

Perbury systems



Happian Smith Fig 13.31

- In the variation device of the Perburry system, the input and output discs have a toroid profile.
- The rotation motion is transmitted via the rotation of the intermediate disc, i.e. the roller, whose inclination is variable.
- Generally there are several rollers which are distributed over the circumferences and spins about their axis.
- The inclination of the roller is controlled by an actuation mechanism.

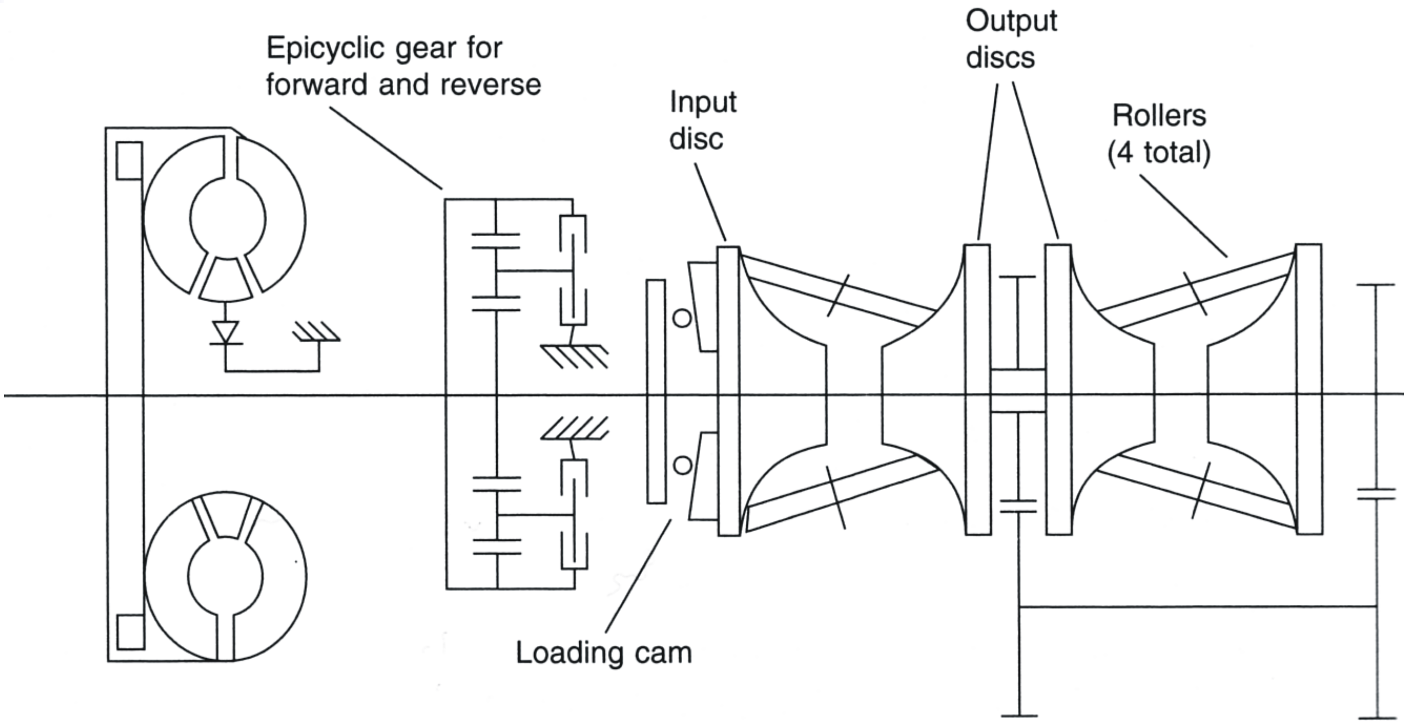
Perbury system

- Please notice that the roller carrier remains fixed with respect to the chassis.
- The torque transmission is assured by the friction force between the input/output discs and the roller. To avoid a gross slip, one requires:
  - The application of a high compressive force between the discs and the roller since the dry friction coefficient is about $\mu=0{,}1$
  - The lubrication problem is a crucial issue to reduce the wear. The elasto-hydrodynamic film is typically 0,5 μm thick.
- The material selection and the lubricant choice are key issues to ensure the reliability and the durability of the system.
- Typically a small angular slip of 1 - 2% between input and output speed is accepted

Perbury system

- The Perburry system provides reduction ratios within the range of 1 to 5.
- The transmission drive is not able to deliver a zero-output power, so that to interrupt the power it is necessary to couple it with a hydraulic torque converter to implement start from rest.
- The device is not able to invert the rotation speed so that it is generally coupled with a planetary gear set to provide a reverse speed.
- The Perburry Systems were developed for small and large powertrain systems: Bus with 375 kW engine or Nissan Gloria 3L engine with 370 Nm
- The energy efficiency of the system is about 90%, which is generally a better transmission efficiency than equivalent AT

Perbury system

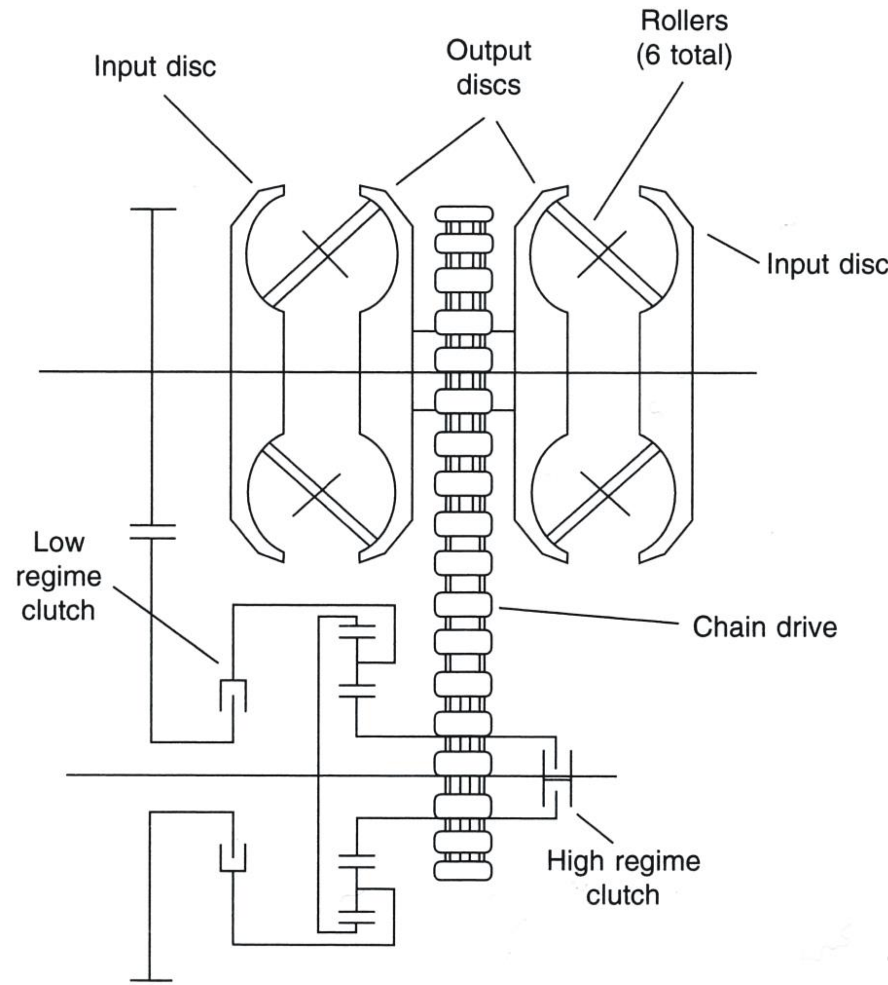


A dual-cavity half-toroidal transmission system

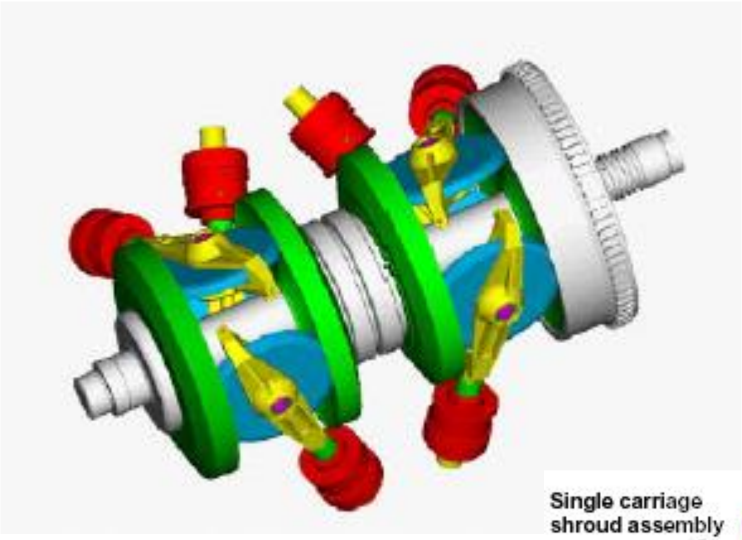
Happian Smith Fig 13.32

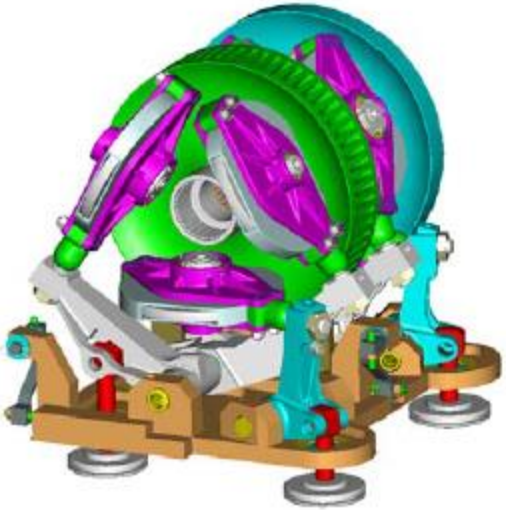
Perbury system

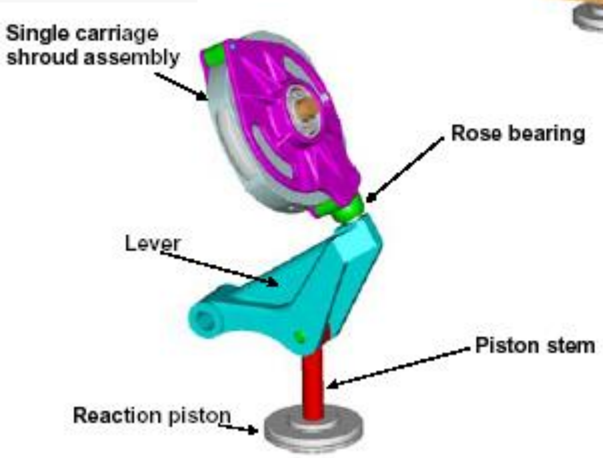
Working principle of Torotrak transmission from *Happian Smith Fig 13.33*



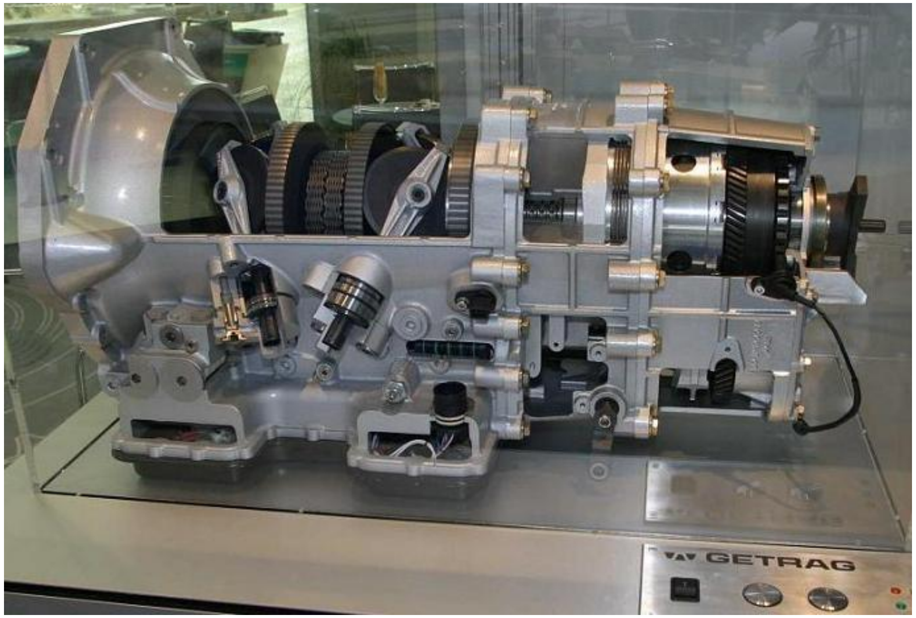
Torotrak system

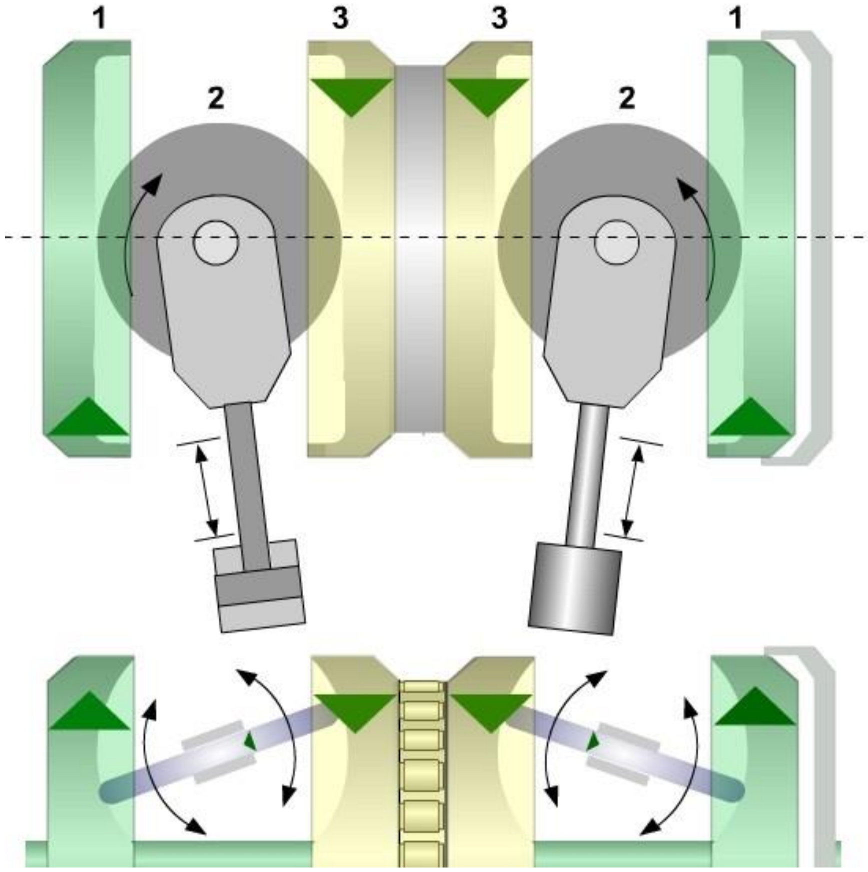




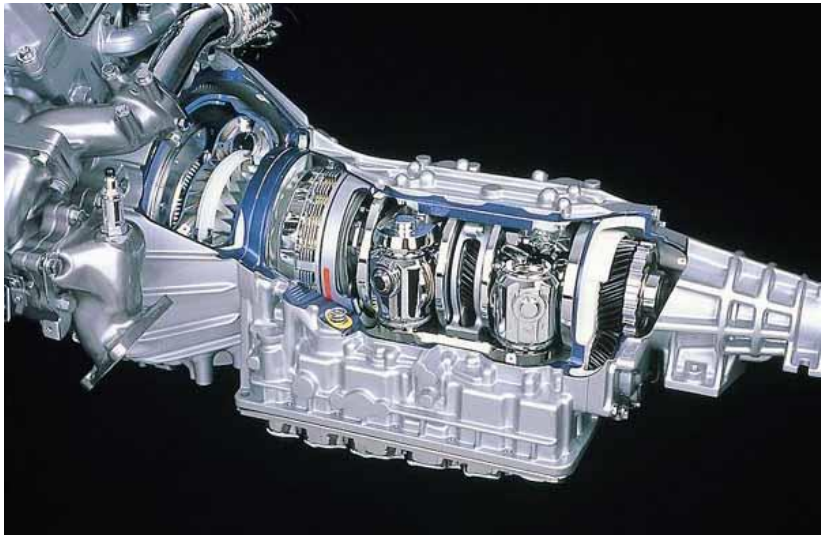


Torotrak system

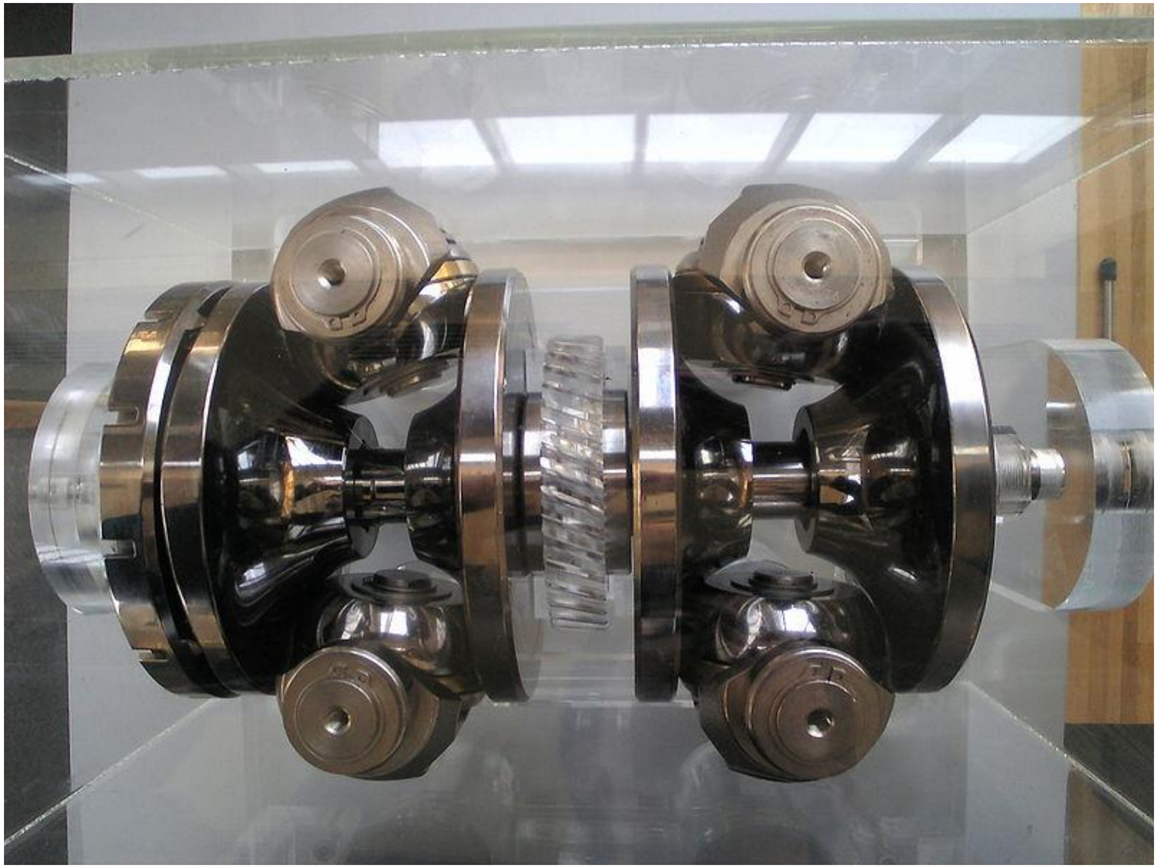




Extroïd system



Extroïd system



NuVinci system