THE STEERING SYSTEM

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Academic Year 2021-2022

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Outline

- Functions of the steering system
- Kinematic and static drawings of the steering system
  - Theory of Ackerman Jeantaud (summary)
  - Drawing of Jeantaud
  - Steering geometry
- Efforts et moments in the steering
- Steering mechanisms
  - Drawbar system
  - Bricard Mechanism (4 bars)
  - Davis mechanism
  - Rotary output mechanism
  - Linear output mechanisms
  - Rack and pinion mechanisms

Outline

- Steering assistance system
  - Hydraulic assistance
  - Electrical assistance
- The steering column

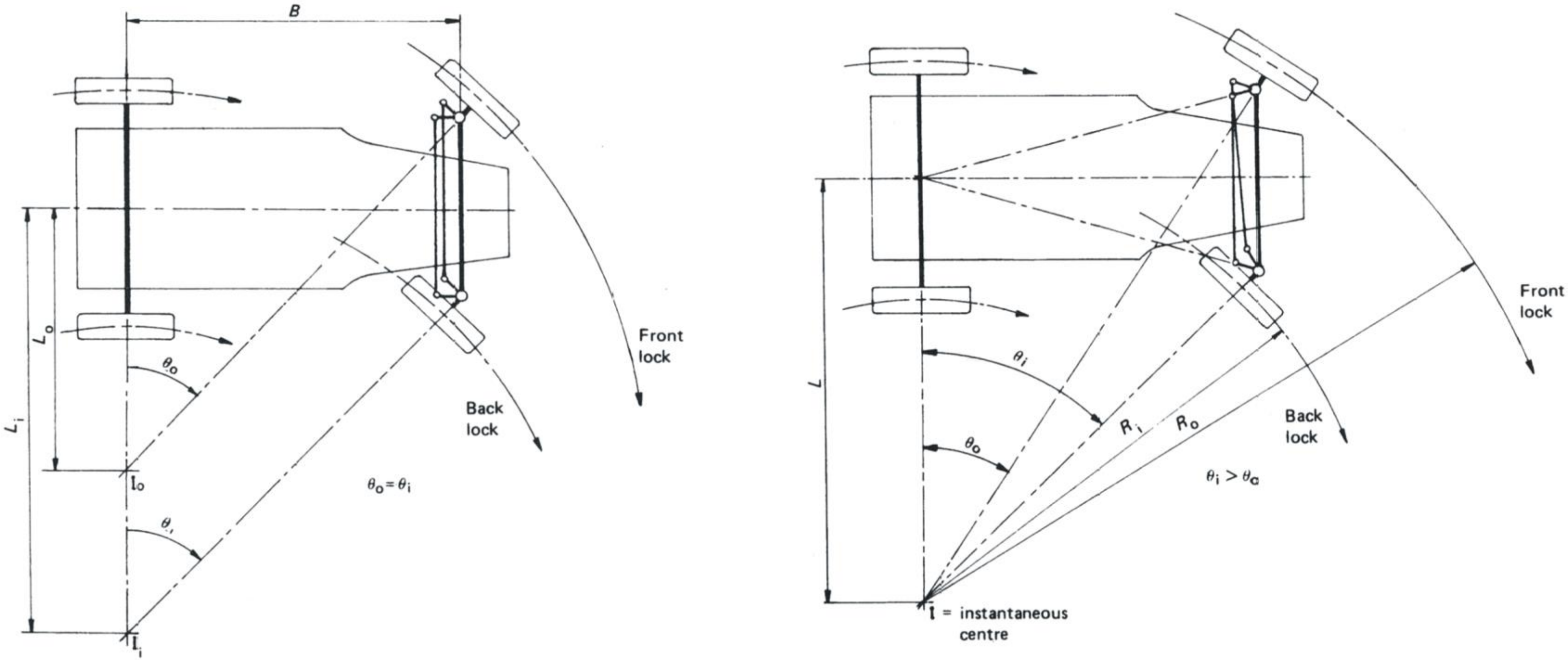
FUNCTION ANALYSIS
OF THE STEERING SYSTEM

Functions of the steering system

- The purpose of the front axle and steering system is to allow the wheels to steer in order to guide and control the vehicle.
- The front axle and its steering system have a geometry enabling:
  - A precise kinematic compatibility in cornering (Ackerman-Jeantaud conditions)
  - To limit the efforts required to perform the steering.
  - To reduce the transmission of shocks from the road to the steering wheel.
  - To avoid a loss of grip in bends and straight lines.
  - To introduce a feed back torque to keep the wheels in a straight-line position.
  - To avoid uncontrolled steering motions during suspension travel.

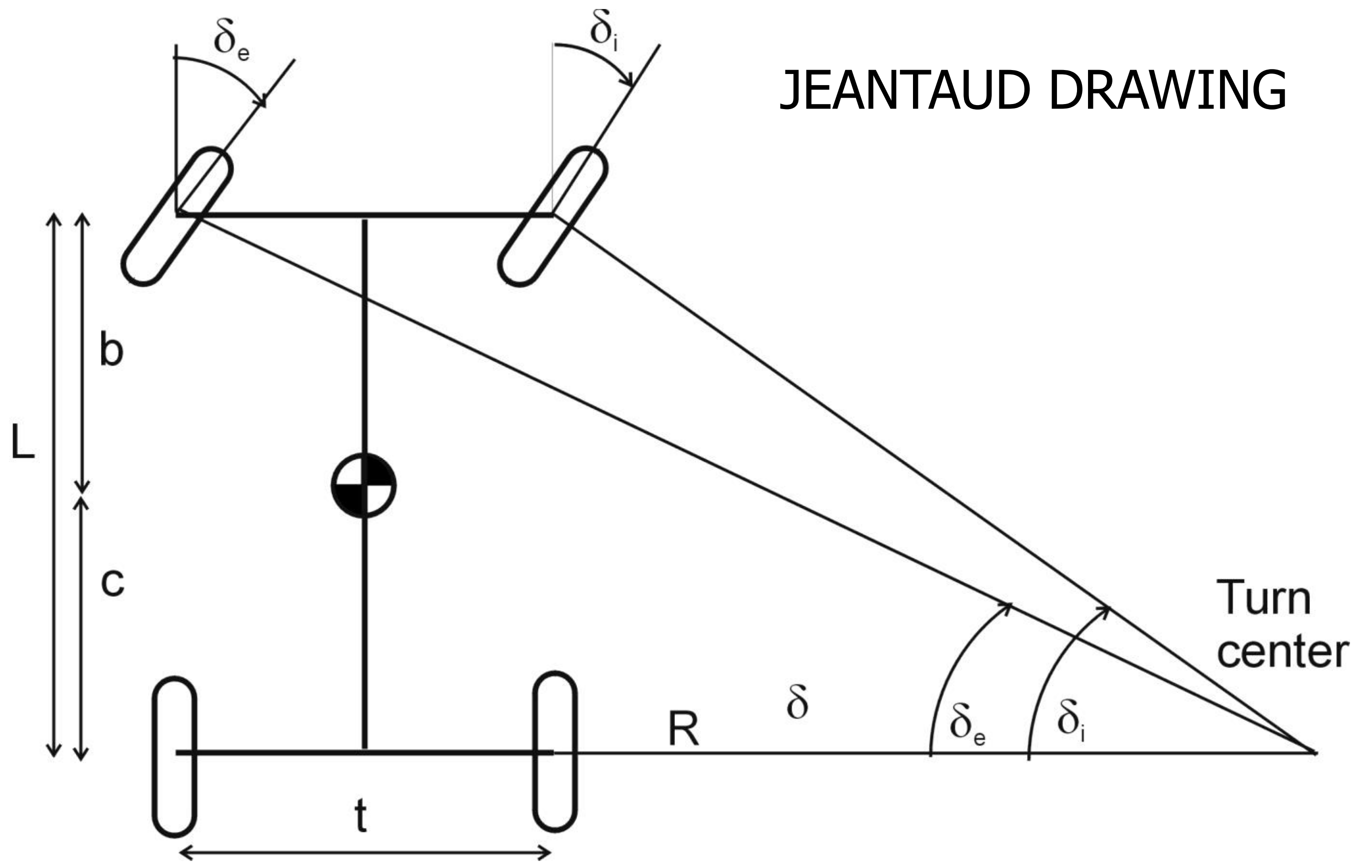
JEANTAUD GEOMETRY CONDITION

Jeantaud compatibility condition



Theory of Ackerman-Jeantaud

JEANTAUD DRAWING



Jeantaud compatibility condition

- From the sketch, it is possible to see that

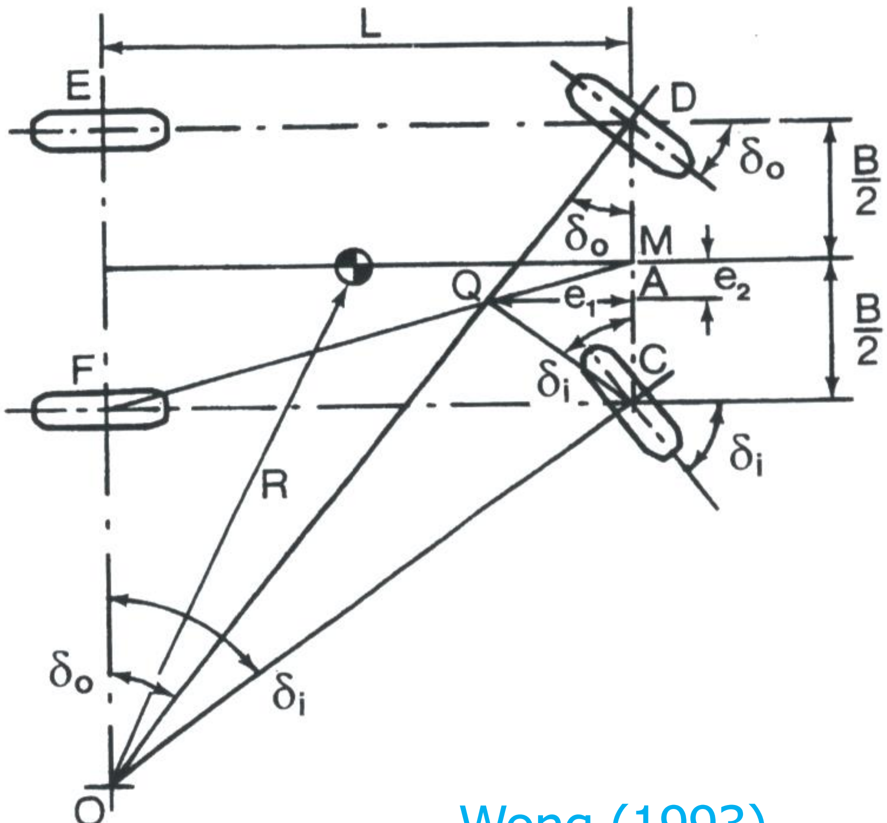
$$\begin{aligned}\tan\delta_i &= L/(R - t/2)\\ \tan\delta_e &= L/(R + t/2)\end{aligned}$$

- This gives rise to the compatibility condition of Ackerman-Jeantaud

$$\boxed{\cot\delta_e - \cot\delta_i = \frac{t}{L}}$$

- Corollary: $\delta_e \leq \delta_i$

Jeantaud drawing



Wong (1993)

- Jeantaud's drawing in its brute form is unusable in practice for calculation purposes.
- Conversely, one would prefer to resort to the following property: point Q belongs to the MF line when the Jeantaud condition is met.
- The deviation of the Q point from the line MF is a measure of the error with respect to the Jeantaud condition.

Jeantaud drawing

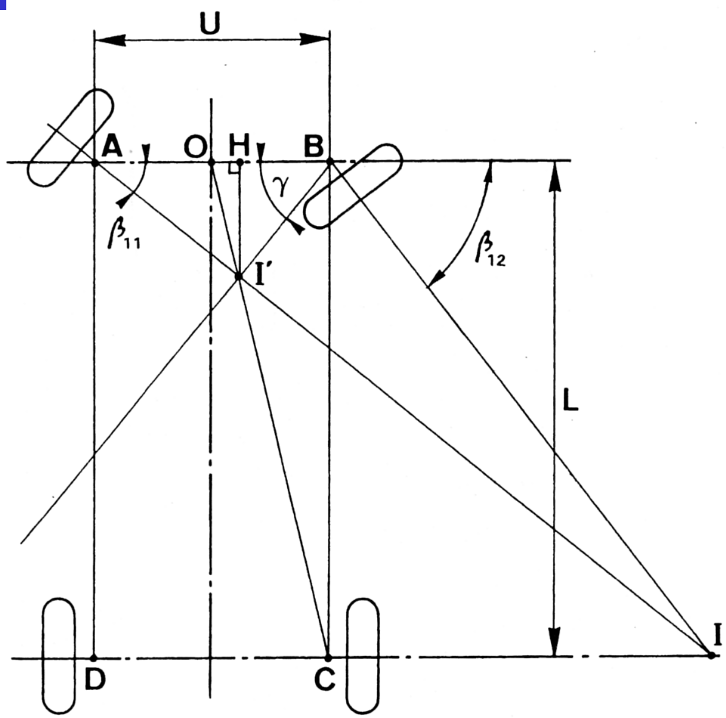


FIG. 6.2 Relation géométrique entre les angles des roues pour respecter la condition de non-ripage des pneumatiques en virage : existence d'un centre de giration I unique.

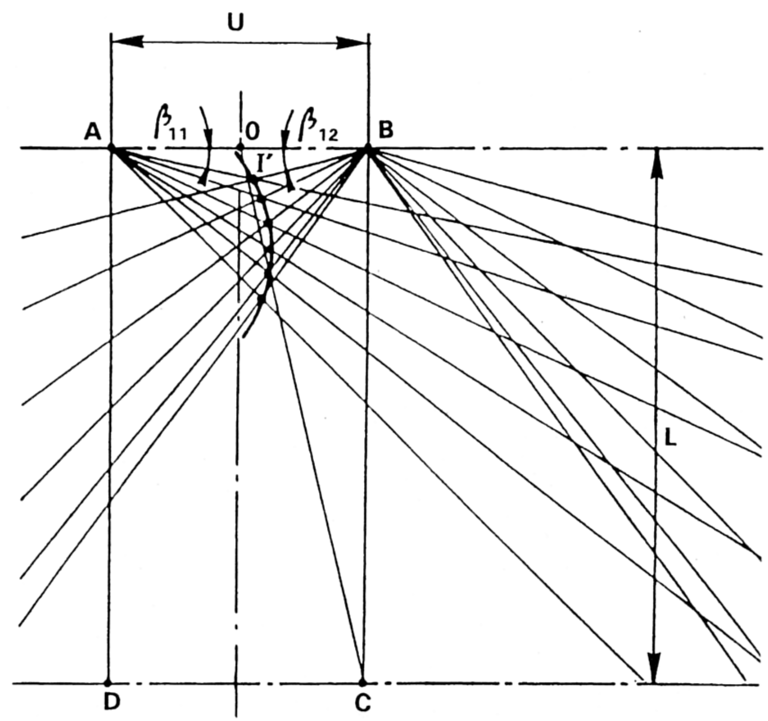
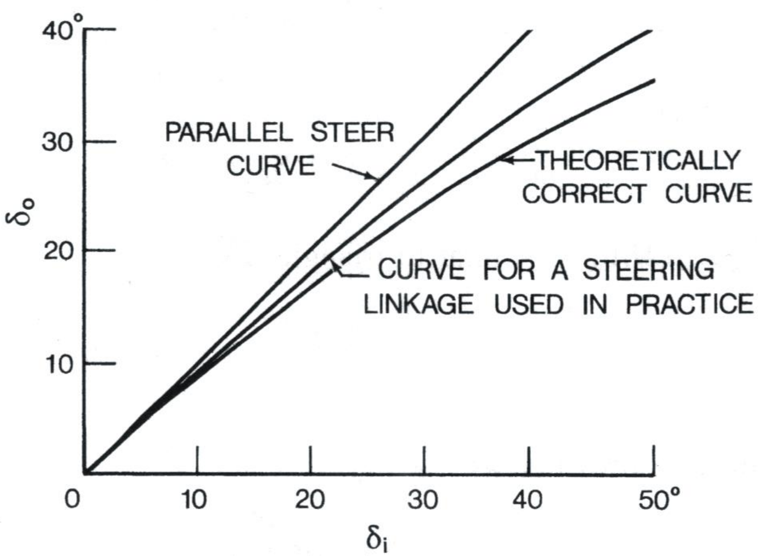


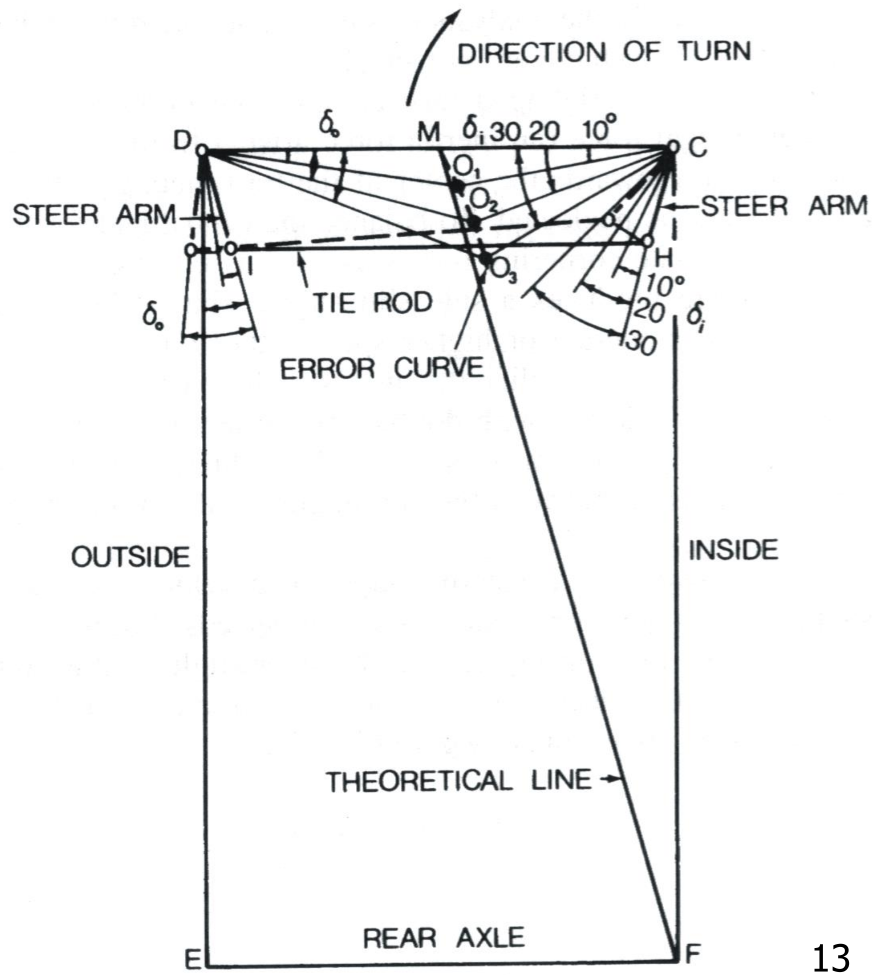
FIG. 6.3 Construction de la courbe d'erreur par rapport à l'épure de Jeantaud.

Halconruy : Fig 6.2 and 6.3. Jeantaud condition and practical construction of the error curve

Jeantaud drawing

Substitute of Jeantaud drawing to avoid imprecision!



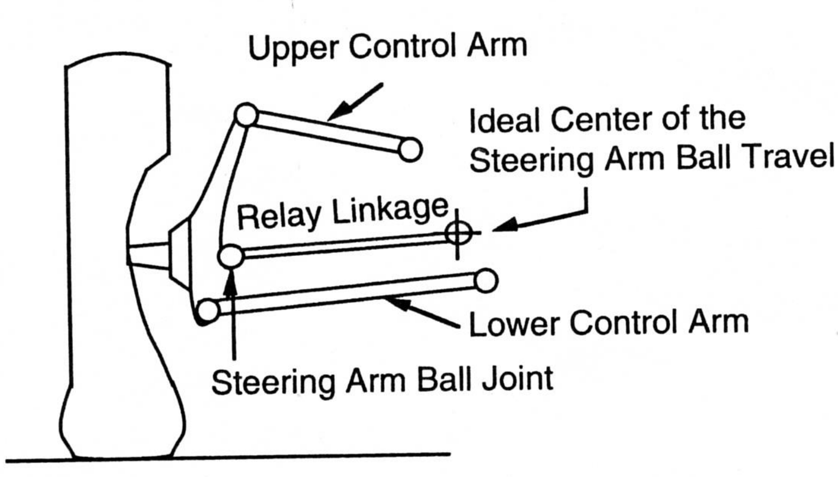


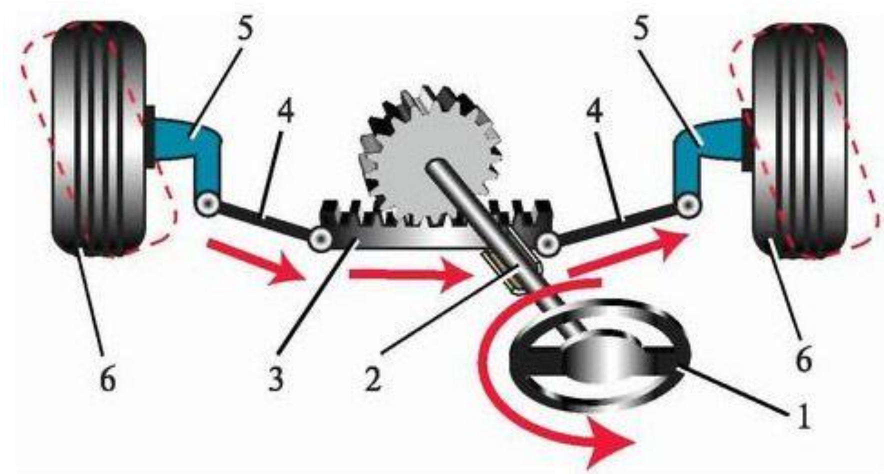
Wong (1993)

STEERING GEOMETRY

Steering Geometry

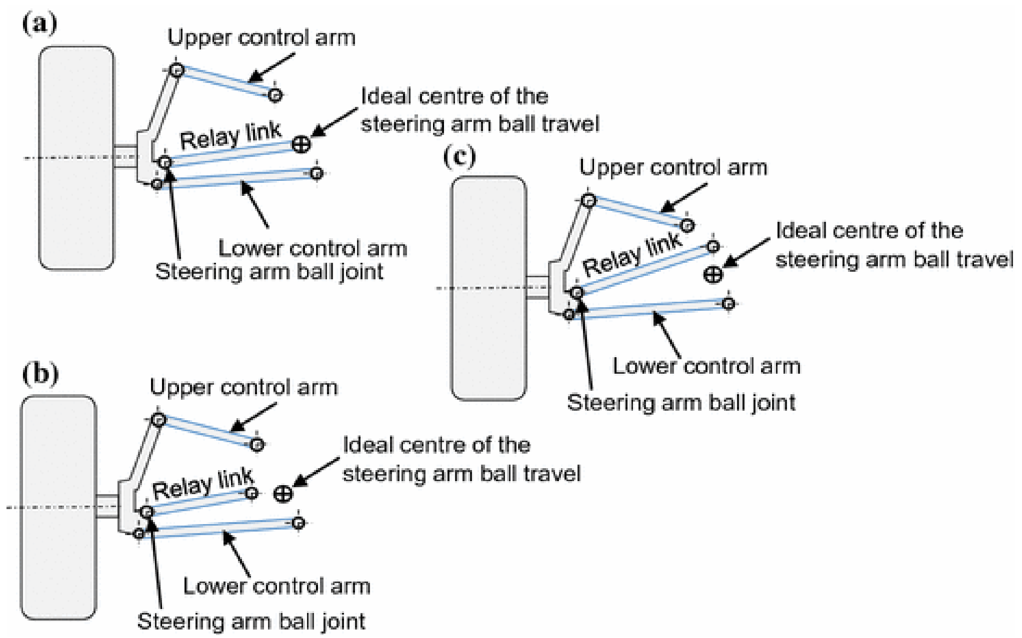
- In steering system, the relay linkage (4) transfers the steering action from gear box reduction on the vehicle to the steering arms on the wheel.





- The steering action is achieved by the translational displacement of the relay linkage despite the arbitrary suspension motion.

Steering Geometry



- Suspension travel does not result in wheel steering only if there is full compatibility between the wheel path and the linkage kinematics.
- In all other cases, wheel travel will result in toe angles and wheel steering with suspension deflections.

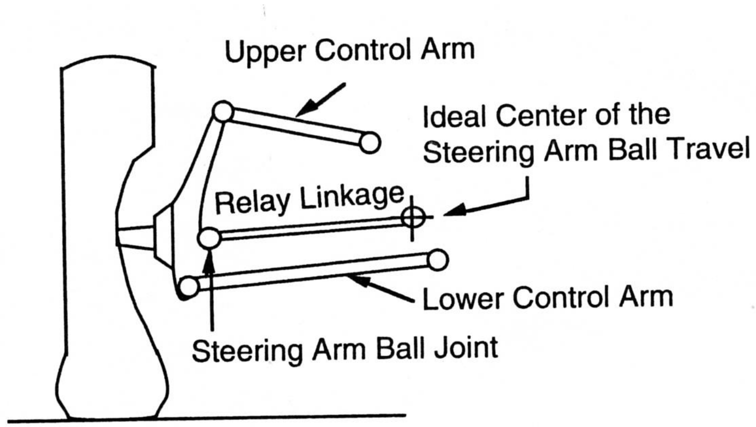
Steering Geometry

- The steering action is achieved by the translational displacement of the relay linkage despite the arbitrary suspension motion.
- Suspension travel does not result in wheel steering only if there is full compatibility between the wheel path and the linkage kinematics.
- In all other cases, wheel travel will result in toe angles and wheel steering with suspension deflections.
- In practice a perfect compatibility is not always desirable.
- Compatibility errors offer designers with the possibility to create induced steering effects resulting from wheel movements.

Steering Geometry

- Ideal geometry: the arc of the steering linkage must follow the trajectory of the ball joint on the steering knuckle during wheel travel.

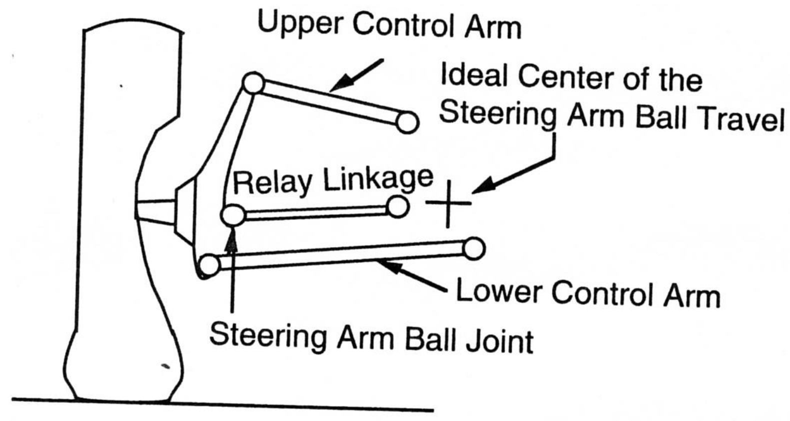
- The position of the ideal connection point of the steering linkage on the chassis can be determined either by computer-aided design or by using graphical or analytical methods.



Gillespie Fig 8.4: Ideal steering geometry for an independent front suspension

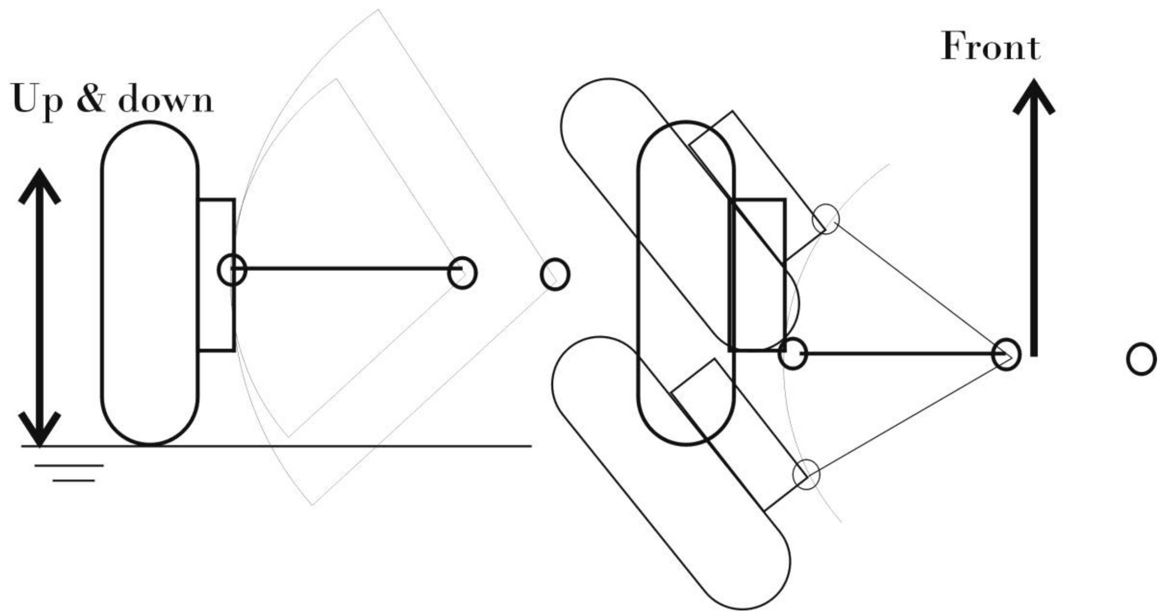
Horizontal error: toe modification

- The position of the ball joint on the chassis influences the circular trajectory described by the end of the relay linkage when it rotates about the ball joint on the chassis.
- A horizontal error in the positioning of this ball joint has the same steering effect for suspension jounce and rebound motions ➔ toe modification



Gillespie Fig 8.5: Geometry error casing toe changes

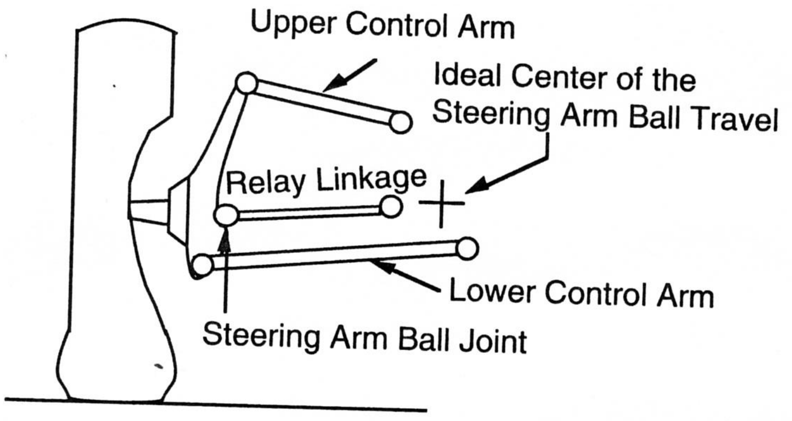
Horizontal error: toe modification



- A horizontal error in the position of this ball joint has the same steering effect in case of jounce and rebound motion of the suspension ➔ toe modification

Horizontal error: toe modification

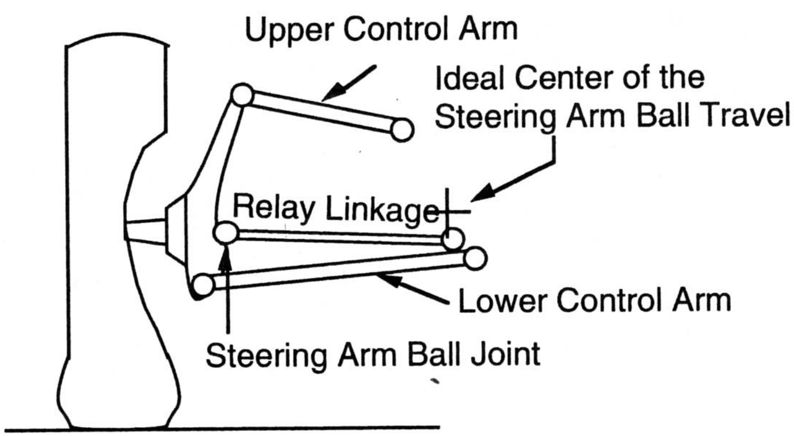
- When the joint is outboard with respect to the ideal point, an upward or downward suspension displacement forces the wheel to steer to the left if the connecting rod is assumed to be behind the axle. Both suspension deflections result in toe-out.
- If the joint is inboard, we have a toe-in creating right turn.
- It is difficult to preserve a given steering geometry during jounce and rebound.



Gillespie Fig 8.5: Horizontal error of geometry causing toe in or toe out. View front rear of left wheel.

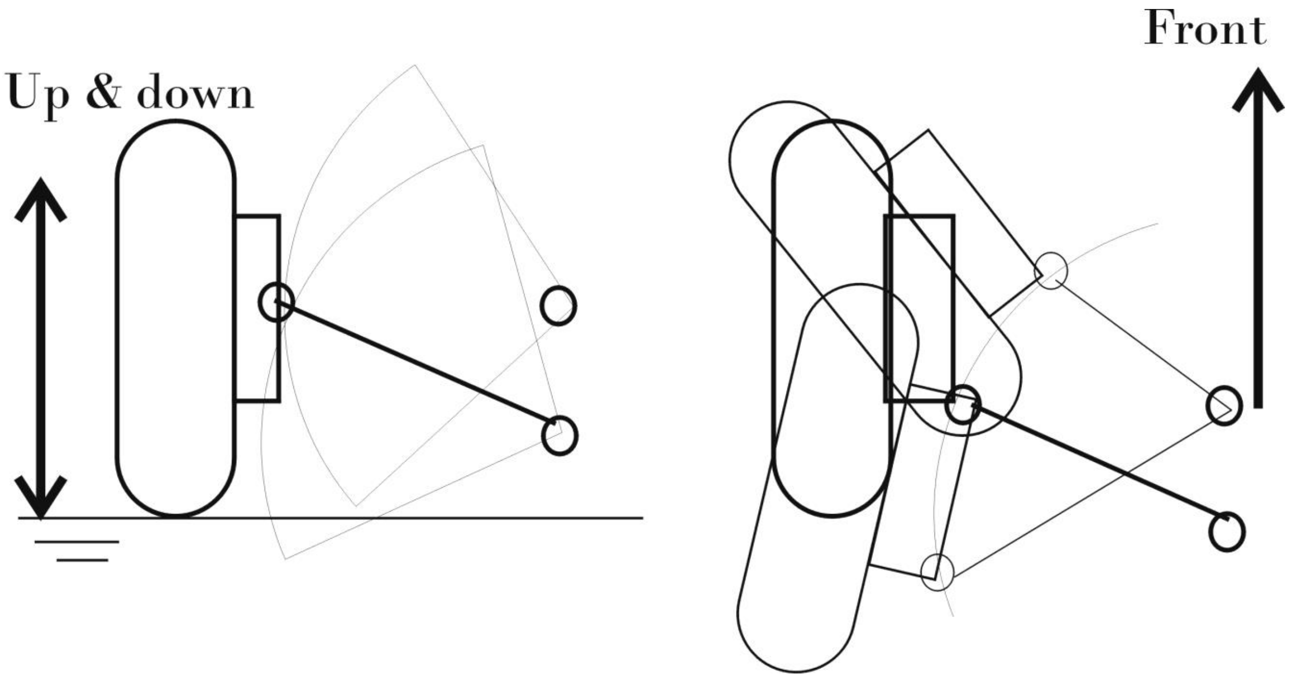
Vertical error: roll steer

- A vertical error on the positioning alters the road behavior by inducing roll-steer coupling.
- When the ball joint on the chassis is below the ideal point and the steering mechanism is behind the axle, the circular trajectory described by the steering linkage produces a left turn (toe-out) if the wheel is in compression (up) and it produces a right turn (toe-in) if the wheel is in rebound (down).
- We have alternately toe in /out with jounce and rebounds.



Gillespie Fig 8.6: Geometry error adding understeer. View front behind. Left wheel.

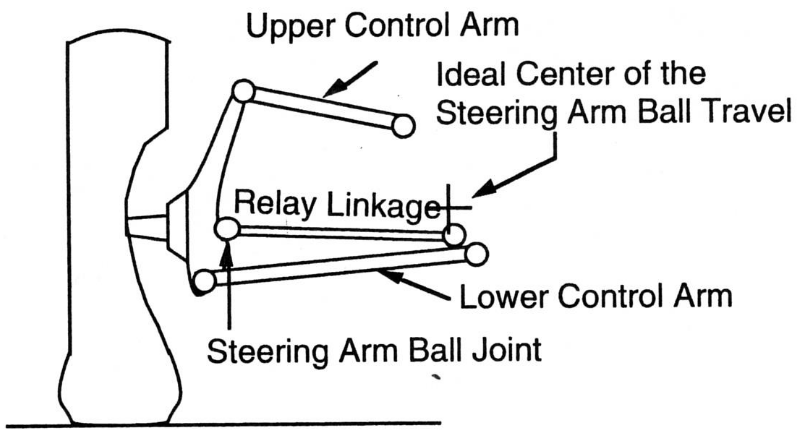
Vertical error: roll steer



- When the ball joint is below the ideal point and the steering mechanism is behind the axle, we have alternately toe in /out with jounce and rebounds.

Vertical error: roll steer

- Because of the anti symmetry of this effect, when the body rolls, the left and right wheels steer to the same direction leading to an increase /reduction of the steering angle.
- For example, with a lower position of the ball joint on the chassis, when turning to the right, the body rolls to the left, the right wheel is in extension and the left wheel is compressed.
- Both wheels then turn to the left, which reduces the net steering angle and is therefore an understeer effect (steering reduction).

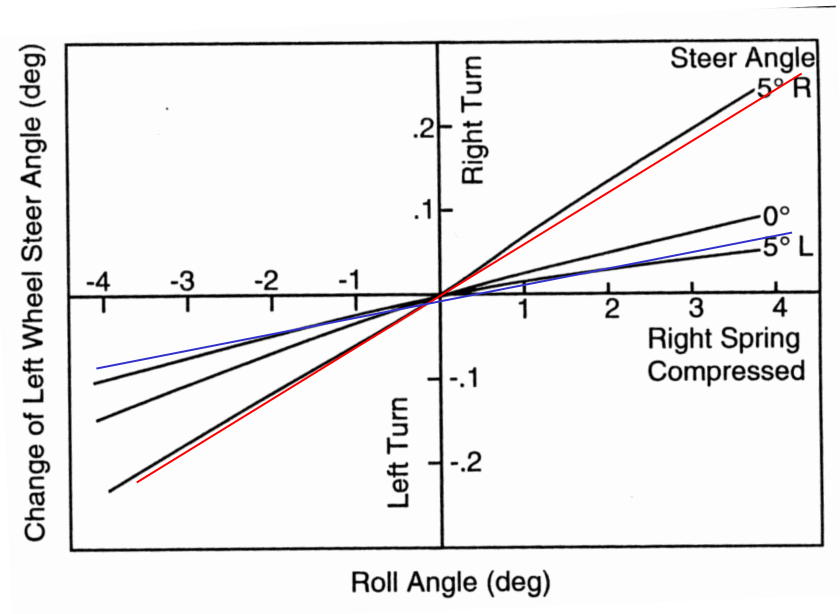


Gillespie Fig 8.6: Geometrical error leading to understeer. View from behind. Left wheel.

Vertical error: roll steer

- The figure Gillespie 8.7 shows the roll-steer coupling as measured experimentally on a vehicle.
- Rising lines to the right indicate understeer behavior.
- The slope is the roll-steer coupling coefficient ε
- The understeer gradient is then modified by the quantity:

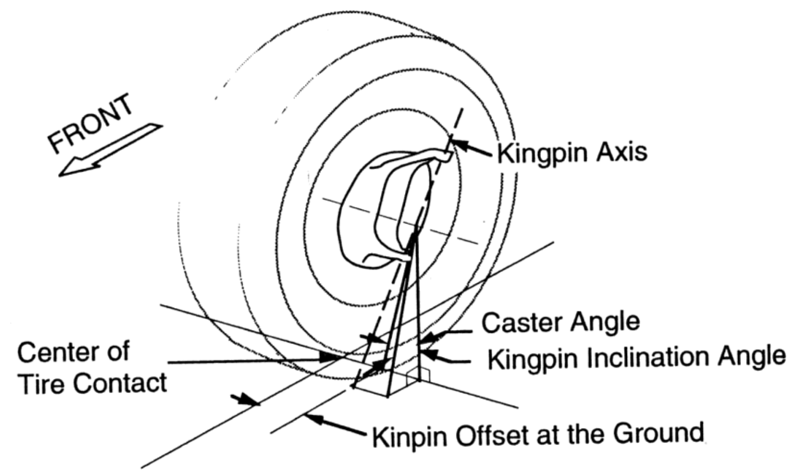
$$K_{rollsteer} = \varepsilon \frac{d\phi}{da_y}$$



Gillespie Fig 8.7: Geometrical error leading to understeer. View from behind. Left wheel.

Front wheel geometry

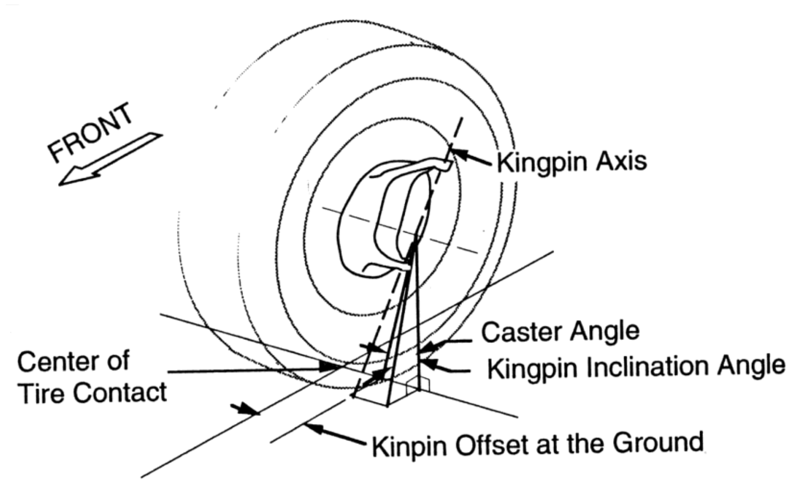
- The important thing is the geometrical position of the wheel on the ground, because it conditions the efforts that the tire can develop.
- Steering is achieved by a rotation around the kingpin axis that goes through the ball joints with the upper and lower arms.
- The pivot axis is not vertical. In the front projection plane, it makes an angle with the vertical direction called the lateral inclination angle. The pivot angle is about 10-15° in practice for passenger cars.



Gillespie Fig 8.8: Geometry of front wheels

Front wheel geometry

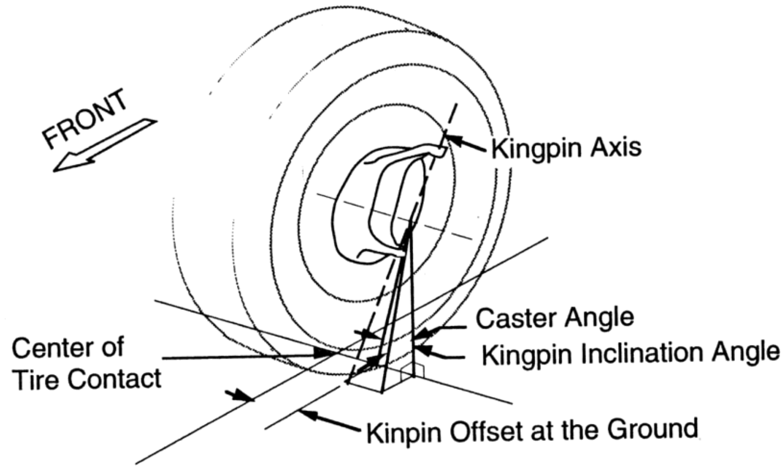
- It is common that the wheel has a lateral offset with respect to the intersection of the steering axis with the ground.
- The offset (also scrub) is defined as the distance in the ground plane between the mid plane of the wheel and the point where the kingpin axis pierces the ground plane.
- This offset can be used to create packaging space for the brakes, suspensions, steering components.
- Offset is also used to reduce the steering efforts and to improve steering feel of the road.



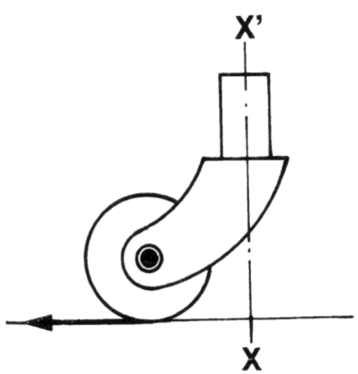
Gillespie Fig 8.8: Geometry of front wheels

Front wheel geometry

- The caster angle is the angle made by the kingpin in the side view plane. Positive caster angle places the kingpin intersection with the ground ahead of the center of tire contact.
- The distance between the contact center and the piercing point is the caster.
- A similar effect can be created by placing a longitudinal offset between the steering axis and the spin axis of the wheel (spindle), but this is very rare for cars.
- The caster angle is usually in the range of 0 to 5° but may vary with suspension deflection.

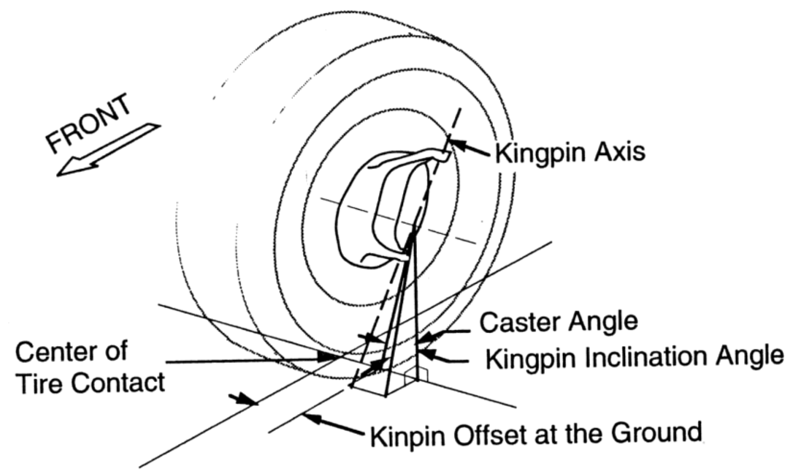


Gillespie Fig 8.8: Geometry of front wheels



Front wheel geometry

- Camber and toe-in/out are normally only secondary effects due to the steering behavior and high-speed dynamic behavior. They are not intended as such.
- The camber angle is typically set to achieve near-zero camber angles for the deflections encountered under the main dynamic load conditions.
- Non-zero static toe angles are only justified if they lead to zero toe when driving forces and rolling resistance forces are present on the road.
- Normally, the selection of camber and toe angle is dominated by attempts to reduce front tire wear rather than to improve the handling.



Gillespie Fig 8.8: Geometry of front wheels

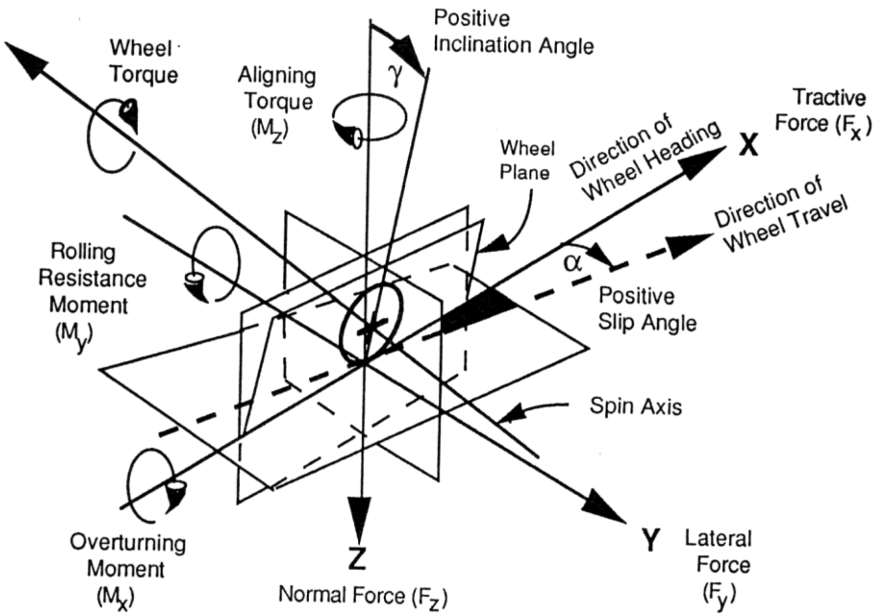
FORCES AND MOMENTS ON THE STEERING SYSTEM

Forces and moments on the steering system

- The important elements of the steering system consists not only in the visible linkage, but also in the geometry associated with the steering rotation axis at the road wheels.
- This geometry determines the reaction force and moment in the steering system affecting its overall performance.

Forces and moments on the steering system

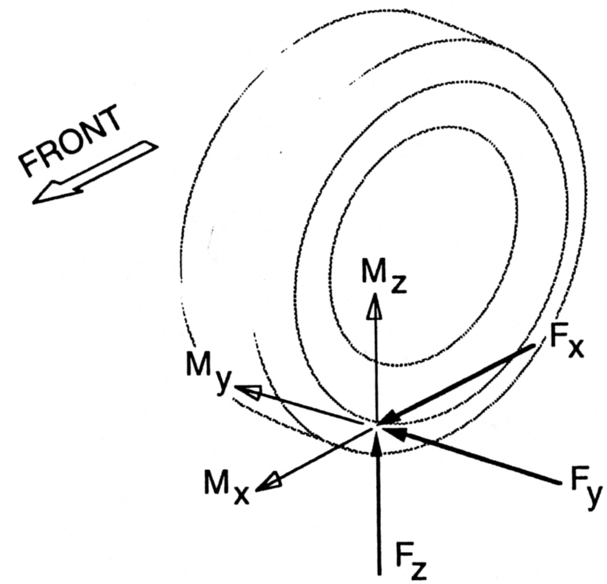
- The forces and moments in the steering system stems from those acting at the wheel-ground interface.
- Wheel contact forces are conventionally referred to the wheel contact center.
- We call them:
  - Normal force
  - Tractive force
  - Lateral force
  - Self-alignment torque
  - Rolling resistance moment
  - Overturning moment



Gillespie Fig 8.9 : SAE Definition of forces and moments

Forces and moments on the steering system

- Reactions in steering systems are described by the moment produced on the steering axis by the tire contact forces and torques, which must be resisted to control the wheel steer angle.
- The resultant of the moments acting at the right and left wheels, transmitted through the steering mechanism with their associated gear ratio gives the amount of steering–wheel torque feedback to be developed by the driver.



Gillespie Fig 8.10 : Definition of the forces et moments

Effect of the vertical force

- The vertical force F_z acting upward in the contact area induces a moment around the kingpin axis when it is tilted.
- The moment comes from either the tilt of the pivot angle or the caster angle:

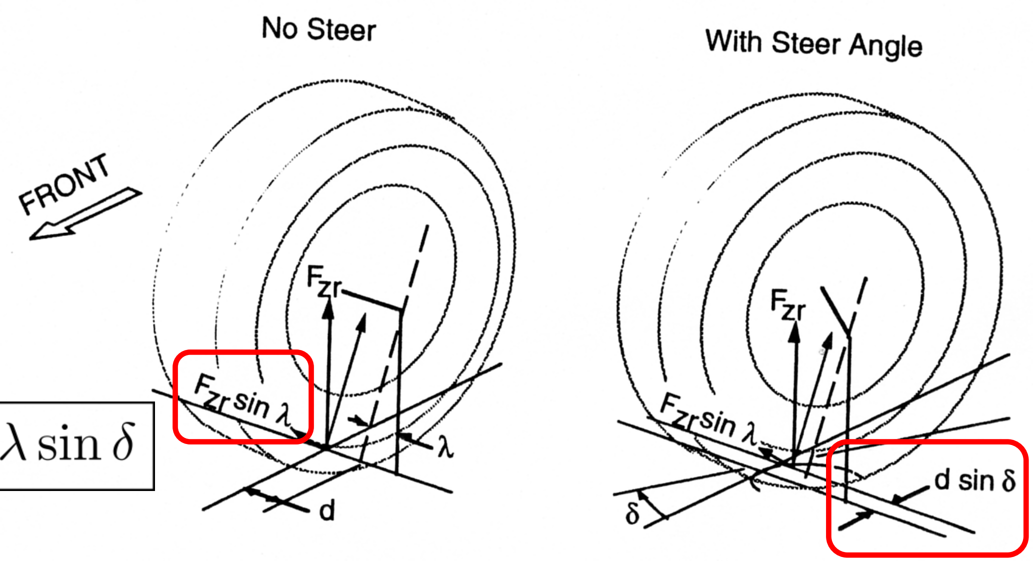
$$\boxed{M_V = -(F_{zl} + F_{zr})\ \sin\lambda\, d \sin\delta\ +\ (F_{zl} - F_{zr})\ \sin\nu\, d \cos\delta}$$

  - M_v = overall moment from left and right wheel in the steering system
  - F_{zr} and F_{zl} are the vertical loads under the left and right wheels
  - d lateral offset at the ground
  - λ lateral inclination angle
  - δ steering angle at the wheels
  - ν castor angle

Effect of the vertical force

- The effect kingpin inclination λ can be computed with the following sketch

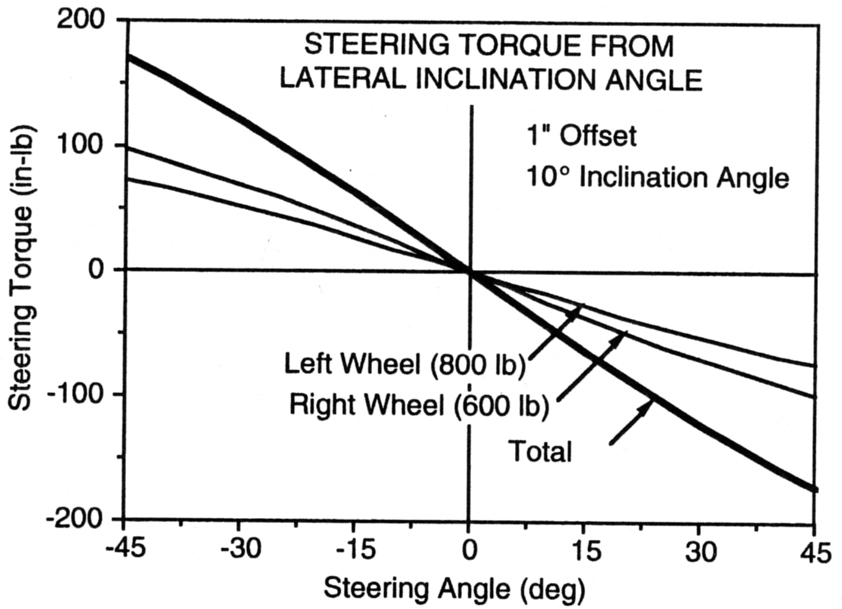
$$M_V = -(F_{zl} + F_{zr})\, d \sin\lambda \sin\delta$$



Gillespie Fig 8.11

- The force F_z generates a working component F_z sin λ
- The offset gives rise to lever arm about the kingpin axis after steering: d sin δ

Effect of the vertical force



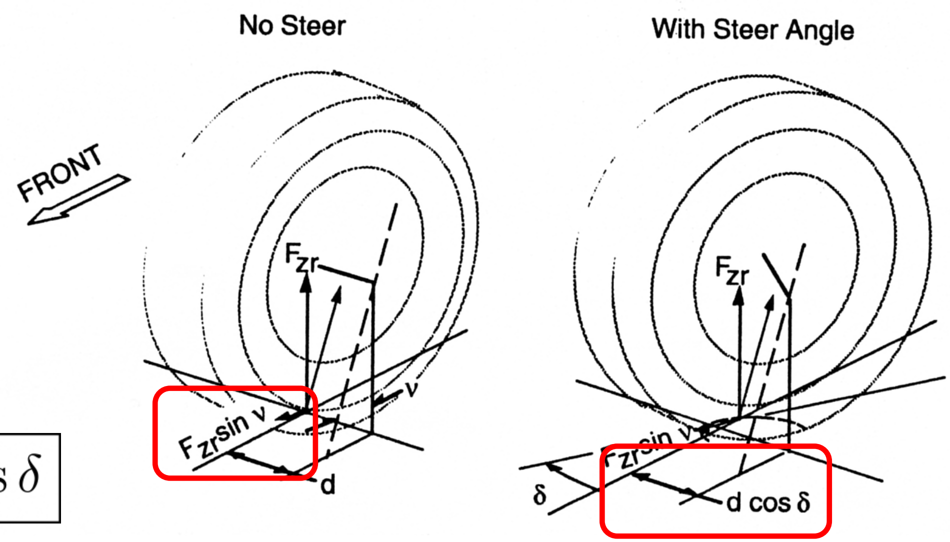
Gillespie Fig 8.12: Centering moment proportional the to weight is unaffected by left/ right load asymmetry, dependent on inclination, offset, axle load.

- The moment on the steering system due to the kingpin inclination λ and the vertical load is null for at zero steer angle.
- For a given steering angle, left and right wheels act together producing a centering moment and tending to reduce the steer angle.
- The moment is proportional to the weight on the axle and is independent of left / right load imbalance.

Effect of the vertical force

- The effect of the caster angle ν can be evaluated from the following sketch:

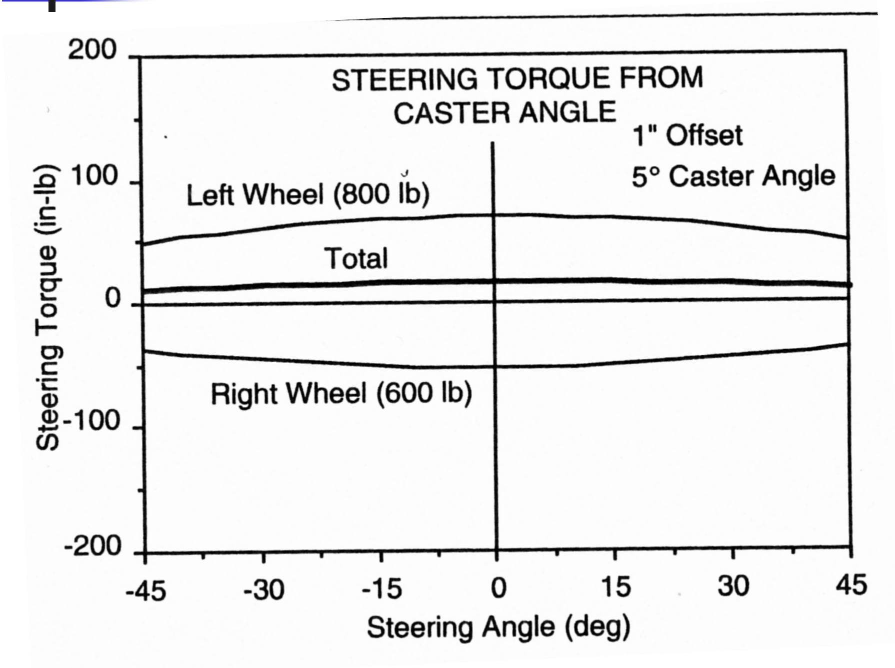
Gillespie Fig 8.13: Moment produced by the vertical force acting on the caster angle



$$M_V = (F_{zl} - F_{zr})\, d \sin\nu \cos\delta$$

- The component perpendicular of the vertical force to the kingpin axis is $F_z \sin\nu$
- The lever arm is d cos δ .

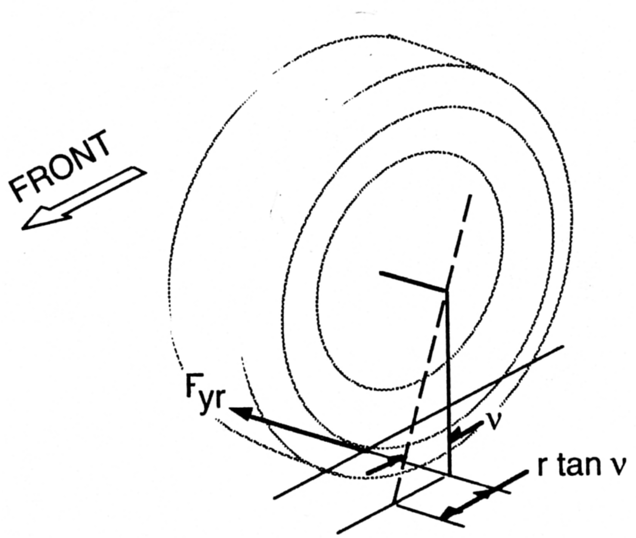
Effect of the vertical force



Gillespie Fig 8.14: The axle rolls when there is a turn. The moment is sensitive to the left / right asymmetry. The moment depends on the offset, the caster, the difference in vertical load under the wheels.

- The moment on the left and right wheels have opposite sign moments.
- If they are symmetrical, they cancel each other out.
- The vertical load and the caster angle can affect the toe if the steering is flexible.
- Left - right asymmetries can lead to moments in the steering.
- When one wheel goes up and the other goes down, the moment can also depend on the roll stiffness.

Effect of the lateral force



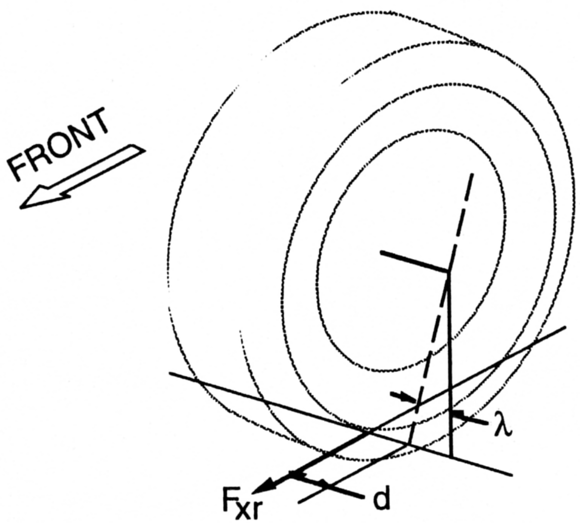
Gillespie Fig 8.15 : Moment produced by a lateral force in the presence of a caster

- The lateral force F_y acting at the wheel contact center yields a moment through the longitudinal offset resulting from the caster angle:

$$\boxed{M_L = -(F_{yl} + F_{yr})\, R_e \tan\nu}$$

  - F_{yr} and F_{yl} are the lateral forces developed under the left and right tires
  - R_e the radius of the tire
  - ν the caster angle
- The lateral forces create a moment tending to reduce the wheel steering for a positive caster (understeer effect)

Effect of the tractive force



Gillespie Fig 8.16 : Moment produced by a tractive force

- The traction force F_x acting at the wheel contact center acts on the kingpin axis to produce a moment which is function of the lateral offset d:

$$\boxed{M_T = (F_{xl} - F_{xr})\, d \cos\delta \cos\lambda \cos\nu}$$

  - F_{xr} and F_{xl} the tractive forces developed under the left and right tires
  - d the lateral offset
- The left and right wheels yield moments with opposite signs. They cancel each other out through the steering system
- Load imbalance due to μ-slip for instance produces a steering moment which is dependent on the lateral offset d.

Effect of the aligning moment

- The self-aligning moment of the tire acts vertically and can result in a component parallel to the pivot axis. The alignment moment is therefore transmitted to the steering system as:

$$\boxed{M_{AT} = (M_{zl} + M_{zr})\ \cos\lambda\ \cos\nu}$$

  - M_{zl} and M_{zr} the aligning moment acting on left and right tires
  - λ the kingpin angle
  - ν the caster angle

- In normal conditions, aligning torques always tend to reduce the steering angle so that they have an understeer contribution. Only in high side slip angles and important braking condition, the aligning torque can become unstable and they have an oversteer contribution.

Effects of the rolling resistance and overturning moments

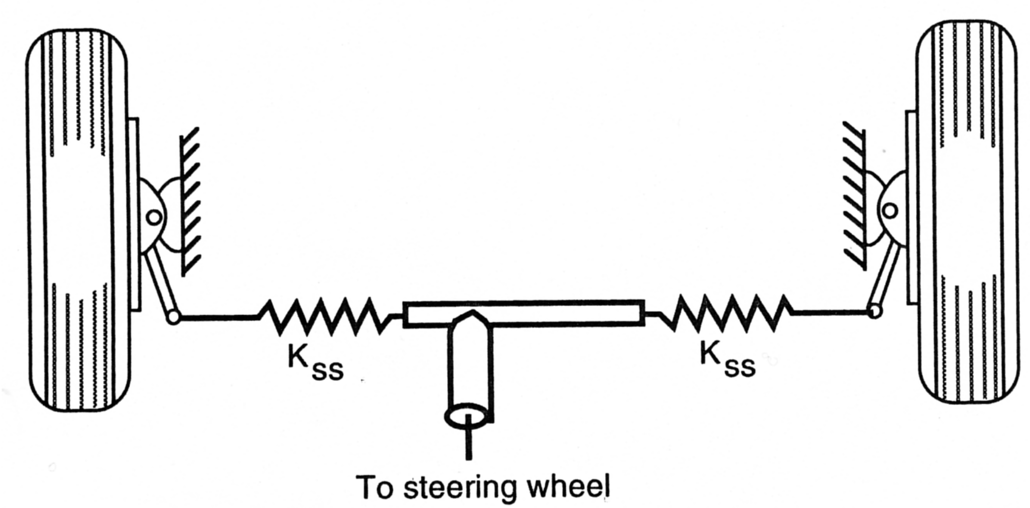
- The rolling resistance and the overturning moments have only sine contributions around the pivot axis.
- They induce only second-order effects and are generally neglected in steering system analysis.

EFFECT OF STEERING SYSTEM COMPLIANCE
&
STEERING SYSTEM MODELLING

Modelling of steering system

- The moments and forces about the kingpin axis are applied load acting on the steering mechanism.
- The applied moments produce moments on the steering systems can be used to determine the feedback torque to be developed at the steering wheel.
- In order to quantify the influence of the forces and moments in open loop control, it is necessary to take into account the behavior of the steering mechanism: flexibility, backlash, etc.
- A very simple model can be adopted for low frequencies, provided that the stiffness of the steering rods, the equivalent stiffness of the gearboxes, the lateral suspension flexibility, the transfer functions of the assistance systems, etc. are introduced.
- For more advanced calculations, it is necessary to resort to numerical models based multi-body dynamics (MECANO, ADAMS).

Modelling of steering system



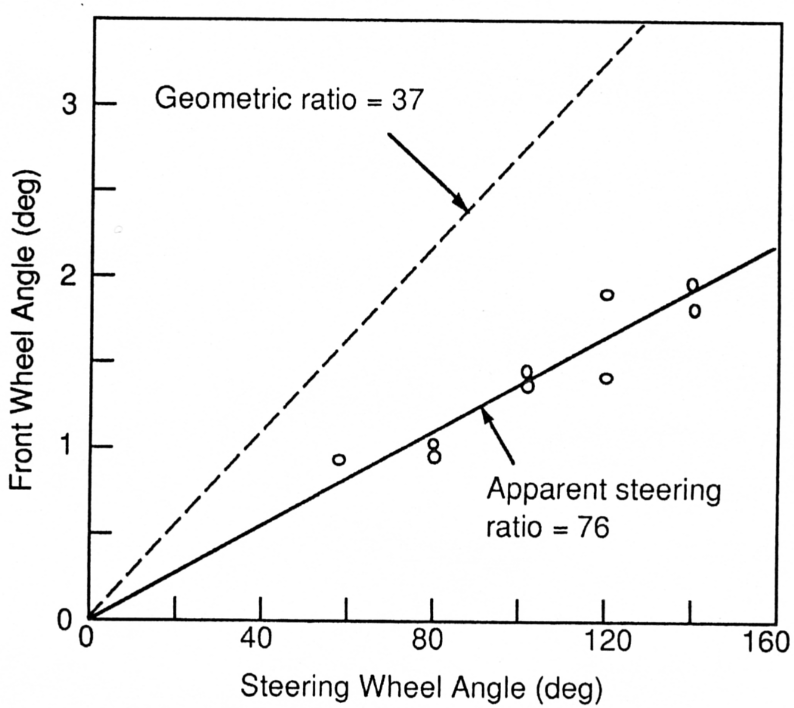
Gillespie: Fig 8.17: Simplified model of a steering system

SOME INVESTIGATIONS OF THE INFLUENCE OF THE STEERING SYSTEMS

Influences of the steering system

- The design of the steering system has an influence on the steering performance measures:
  - The feeling of the centering
  - Returnability, i.e. ability to return to neutral point
  - Steering efforts to be developed by the driver
  - …
- In addition, the system also has an impact on the vehicle dynamic behavior and the directional response:
  - Transient response
  - Cornering behavior
  - Braking stability
  - …

Reduction ratio of the steering system

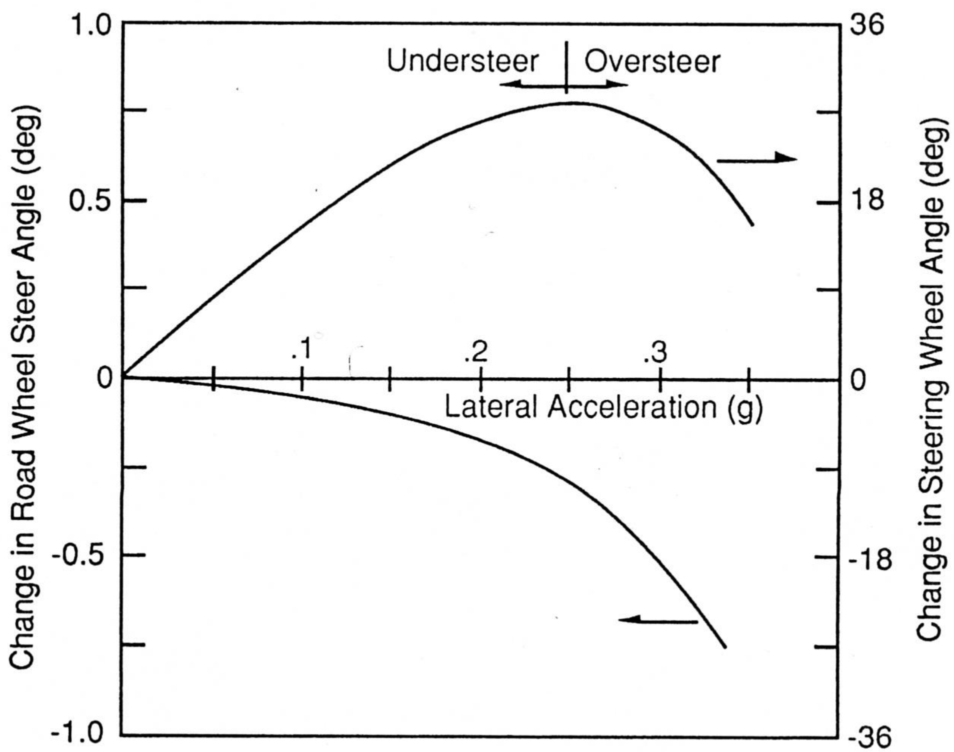


Gillespie. Fig 8.18: Experimental measurement of the reduction ratio of a truck's steering ratio

- The reduction ratio of the steering system is the ratio between the angle of rotation of the steering wheel and the actual steering angle at the road wheels.
- Typically:
  - For passenger cars: 15-20 : 1
  - For trucks: 20-36: 1
- Because of the flexibility of the system, this apparent ratio can be multiplied by a factor of 2!
- The torque gradient will also vary with the load on the tires, the tire pressure, the friction coefficient…

Understeer effects of the steering system

Understeer effects of the steering system



Gillespie Fig 8.19: Understeer gradient measured at the steering wheel and at the road wheel of a truck

- Cornering behavior is often assessed using understeer gradient.
- The flexibility of the steering system results in a deviation of the wheel steer compared to the steering wheel angle.
- The caster angle and the self-aligning moment also add their understeer contributions to those present due to the compliance in the steering mechanism.

Understeer effects of the steering system

- The magnitude of the compliance steering system contribution depends on front-wheel loads and caster angle.
- The dominant effects are the torque of lateral forces M_L and the self aligning moment M_{AT}.
- A simple analysis shows that they provide the following :

$$\boxed{K_{STRG} = \frac{W_f\,(R_e\,\nu + p)}{K_{SS}}}$$

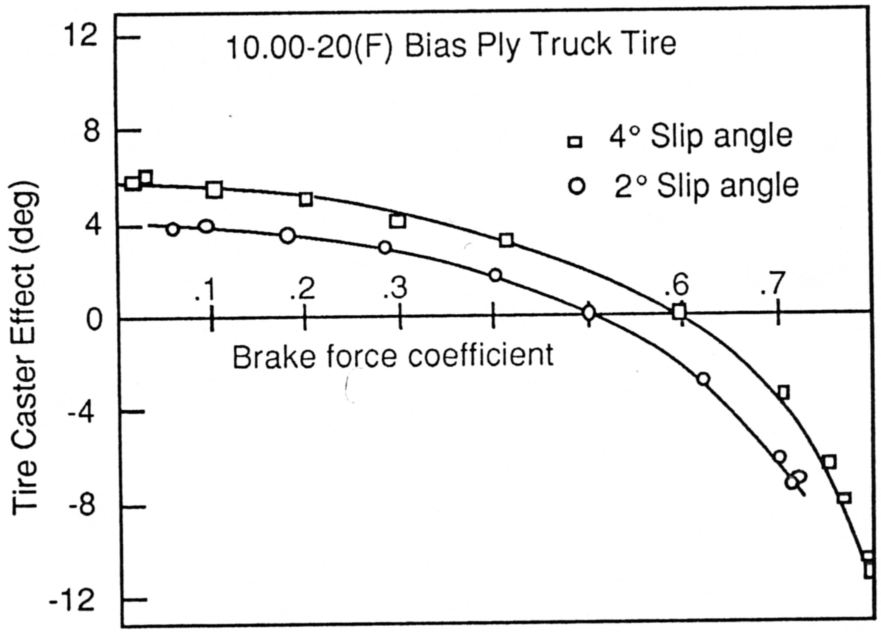
  - K_{strg} Understeer increment (deg/g) due to the steering system compliance
  - W_f the weight under the front axle
  - R_e the tire radius
  - p the pneumatic trail
  - ν the caster angle
  - K_{ss} the apparent (effective) stiffness of the steering system Nm/deg

Braking stability

Braking stability

- Braking is a striking illustration in which the steering system plays a crucial role in directional response.
- In particular, its design has a direct influence on the stability and the resistance to asymmetrical braking effects.
- The caster angle is a key parameter for the stability to resist deviations caused by the front brake imbalance, but its effectiveness is highly vulnerable during braking conditions.
- Pitching, diving and squat tend to absorb the few degrees of initial mechanical caster preset in normal trim conditions.
- During severe braking conditions, the tire aligning torque and the pneumatic trail (which is equivalent to 4-8 degrees of caster in free rolling) can reverse and disappear to give rise to unstable feedback torque.

Braking stability



Gillespie. Fig 8.20: Change in tire aligning torque when braking

Braking stability

- In the case of asymmetrical braking forces (due to a brake malfunction or a μ-slip condition), the moment around the kingpin acts on the compliant steering mechanism axis and tends to steer the vehicle back to the initial trajectory.
- For example, a differential friction coefficient creates a yaw moment that pulls the car to the side with the greater friction coefficient.
- With a positive lateral offset (inboard offset), the steering moment also tends to turn the vehicle in the same direction.
- This argues for a negative offset (outboard offset) to compensate for both effects, for instance when diagonal split brake failure modes are employed.

Braking stability

- A negative lateral offset is beneficial for braking stability. When braking on a surface with low slip conditions, the <u>negative offset</u> creates a torque about the kingpin yielding a steering rotation that <u>tends to reduce the yaw moment coming from the differential braking forces in the two wheels</u>.

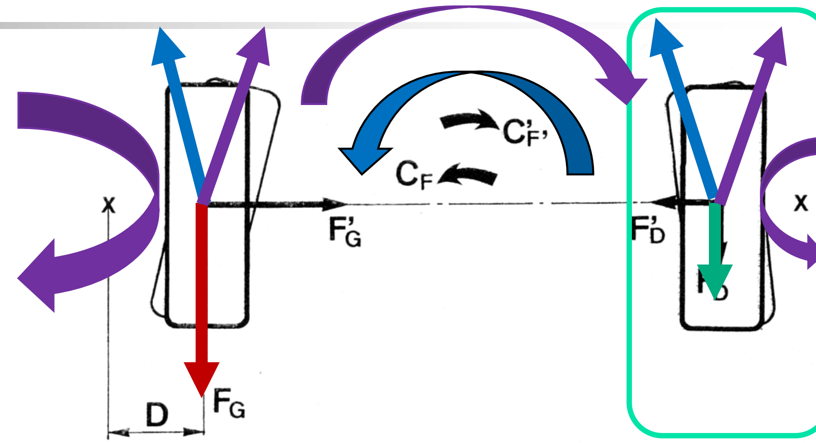


FIG. 3.12 Effet stabilisant du déport négatif.

.a figure représente une vue de dessus d'un essieu avant avec ın déport (D) négatif. L'adhérence est supposée plus importan-e côté gauche que côté droit. Les forces de freinage transmis-ibles sont proportionnelles à l'adhérence disponible (FG et FD). La présence d'un déport négatif tend à faire tourner les oues vers la droite (F'G "l'emporte" sur F'D) ce qui crée un :ouple C'F' qui stabilise le véhicule, s'opposant au couple CF ıénéré par la dissymétrie d'adhérence.

Halconruy Fig. 3.12

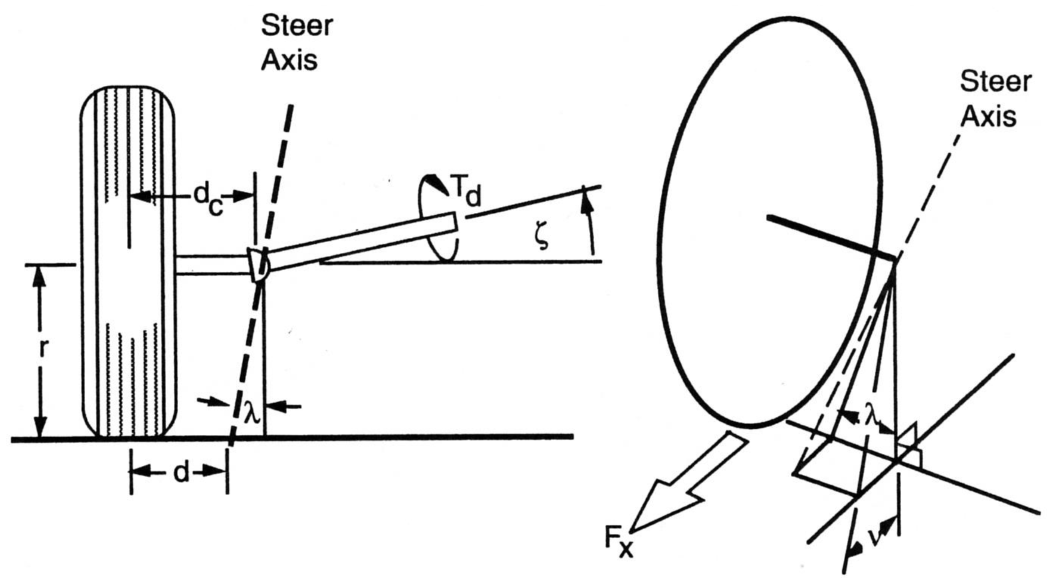
Influence of front-wheel drive

Effect of front-wheel drive

- It is well known that front-wheel drive (FWD) vehicles are subject to variations in their cornering behavior with the application of an engine power to the wheels.
- In most cases, the application of traction force results in understeer.
- While throttle on produces understeer, throttle off yields oversteer.
- Four effects explain this observation:
  - The engine torque component about the steer axis
  - The influence of tractive forces on the cornering properties of tires
  - The influence of tractive forces on aligning torques
  - The longitudinal weight transfer (Front to rear load transfer)

Driveline torque about the steer axis

- Even in a straight ahead driving, the engine torque produces a moment around the pivot axis.
- A constant velocity joint connects the half-drive shaft to the wheel spindle



Gillespie Fig 8.21: Drive forces and torque acting on a front wheel.

Driveline torque about the steer axis

- If we neglect the rolling resistance and the moments deriving from the normal force between the tire and the road, it comes:

$$M_{SA} = F_x \, d \cos\nu \cos\lambda \; + \; T_d \sin(\lambda + \zeta)$$

- As we have

$$T_d = F_x \, R_e$$

- One can write

$$\boxed{M_{SA} = F_x \; [d \cos\nu \cos\lambda \; + \; R_e \; \sin(\lambda + \zeta)]}$$

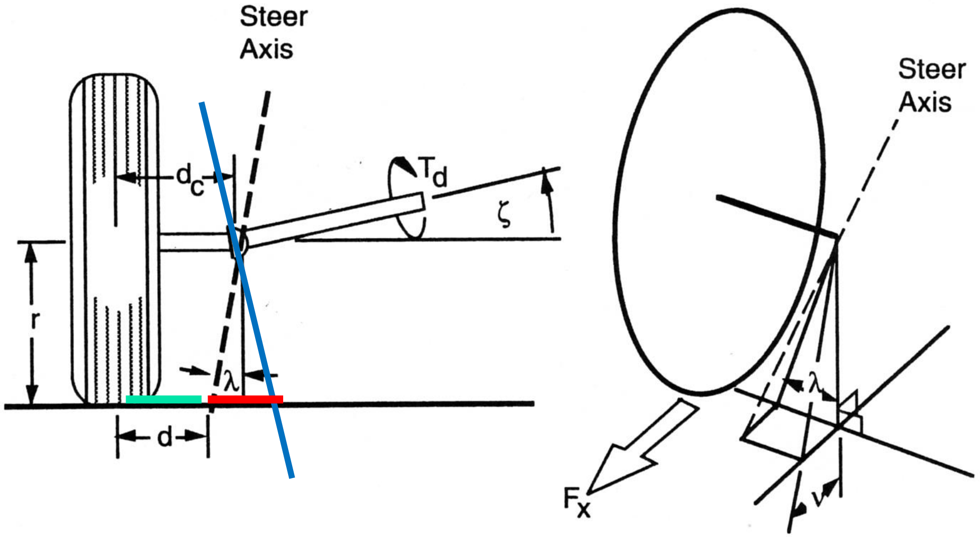
- Usually, the caster angle and inclination angles are small so that their cosines is close to 1:

$$\boxed{M_{SA} \simeq F_x \; [d \; + \; R_e \; \sin(\lambda + \zeta)]}$$

Driveline torque about the steer axis

$$\boxed{M_{SA} \simeq F_x \; [\underline{d} \; + \; \underline{R_e \; \sin(\lambda + \zeta)}]}$$

- The propulsive force gives a moment whose lever arm is the offset increased by the distance to the perpendicular to the constant velocity joint.



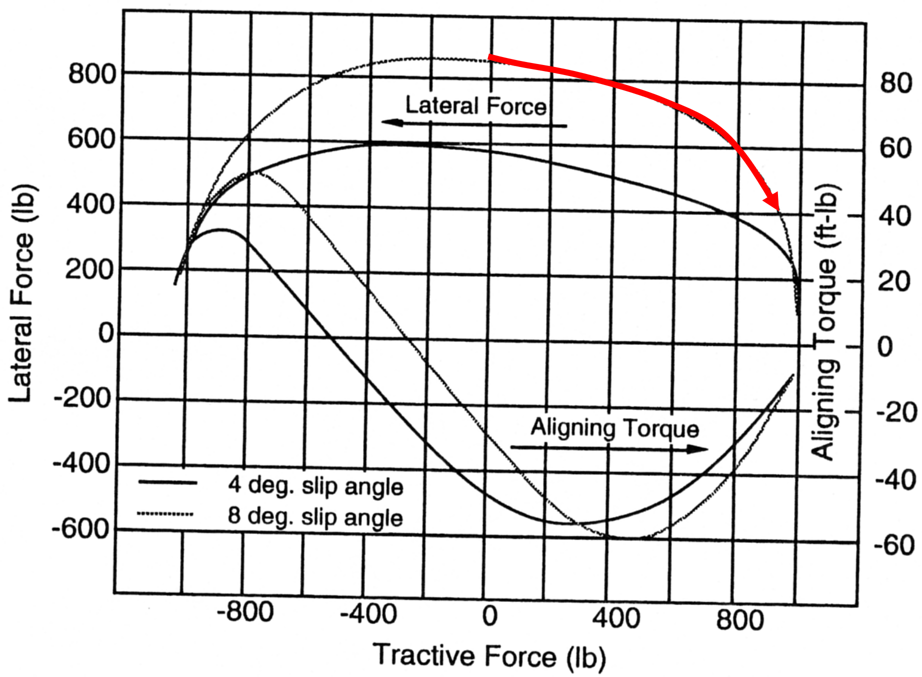
Gillespie Fig 8.21: Drive forces and torque acting on a front Wheel.

Driveline torque about the steer axis

$$\boxed{M_{SA} \simeq F_x \left[d + R_e \sin(\lambda + \zeta) \right]}$$

- As the vehicle turns, roll increases the inclination angle on the inside wheel (lifting up) and decreases the inclination angle on the outside wheel. As a result, the lever arm becomes smaller on the outer side and becomes larger on the inner side. This results in a moment that is directed toward the outside of the turn.
- The engine torque component therefore leads to an increment of the understeer gradient for front wheel driven cars.
- The increase coming from the front drive torque on the understeer gradient is of the order of 1 deg/g.

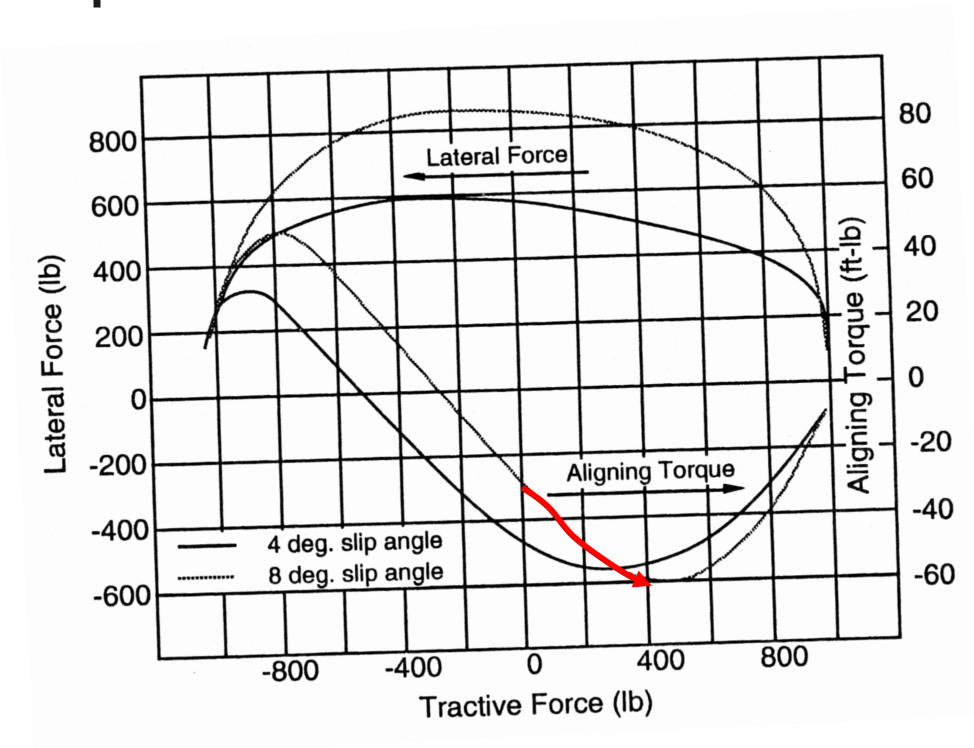
Influence of the tractive forces on the tire cornering forces



$$K_{us} = \frac{m\ c}{C_{\alpha f}\ L} - \frac{m\ b}{C_{\alpha r}\ L}$$

- As the tire develops a tractive force, its ability to generate a lateral force decreases (longitudinal/ lateral forces interaction).
- This reduces the steering power of the front axle.
- The application of an engine torque therefore leads to an increment of understeer gradient.
- It is estimated that this increment is of the order of 0 to 2 deg/g for an engine torque going from 0.2 g (traction) to -.05 g (braking).

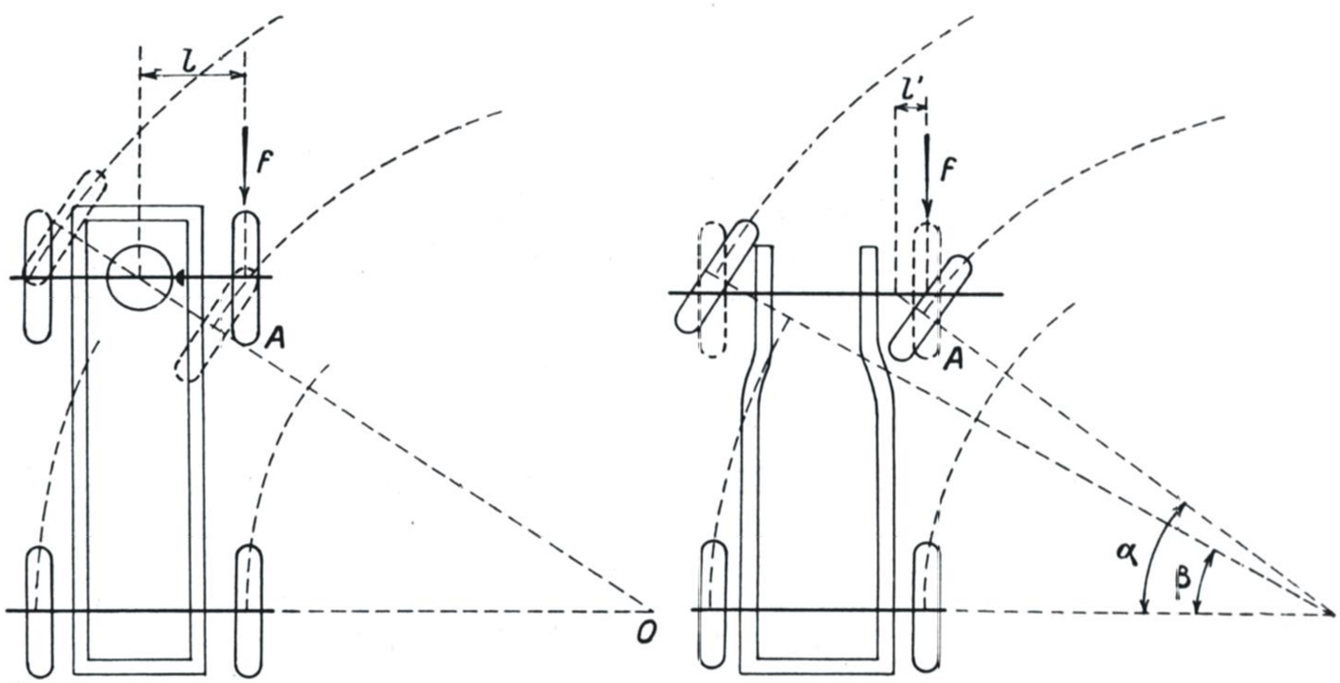
Influence of the tractive forces on the tire aligning torque



- As the tire develops a tractive force, its self-aligning torque increases.
- This increases the tendency of the tire to reduce its side slip angle.
- The application of an engine torque therefore leads to an increment of understeer gradient.
- This increment is estimated to be in the range of 0.5 to 1 deg/g of understeer gradient.

TECHNOLOGY OF STEERING MECHANISMS

Steering mechanisms



① Direction avec cheville ouvrière ② Direction avec essieu brisé

Because of packaging reasons, the broken axle steering system has replaced the turntable steering with a central pivot.

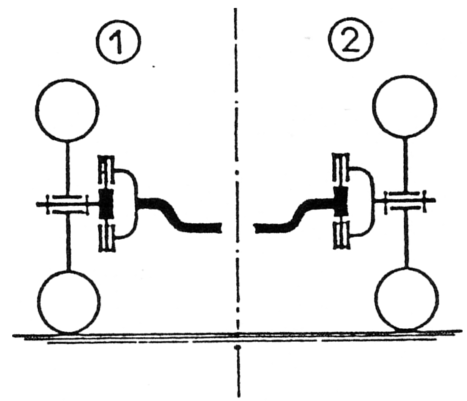
Steering mechanisms

- Turntable steering and the swing axle is abandoned on vehicles except trailers:
  - High drawbar forces on the pivot in case of force on one wheel
  - Too much swept space
  - Architecture "above" the axle

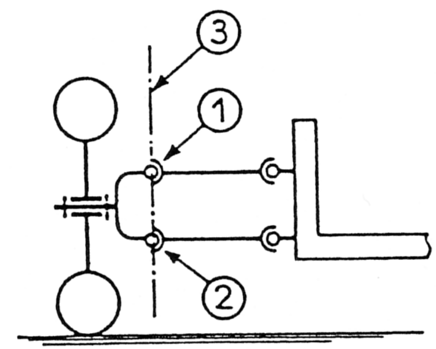
Steering mechanisms

- Case of the rigid axle:
  - The system (1) with kingpin and a swivel axle
  - System (2) with fixed axis
  - Use of bronze rings or bearings for joints

- Case of the axle with independent suspensions
  - The ball joints allows for perpendicular movements of direction and suspension.
  - The pivot axis is materialized by the line passing through the center of the two ball joints.

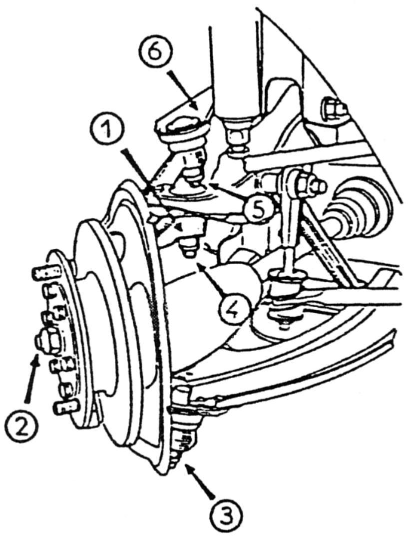


Pivot pour essieux rigides :
(1) à chape ouverte ;
(2) à chape fermée.



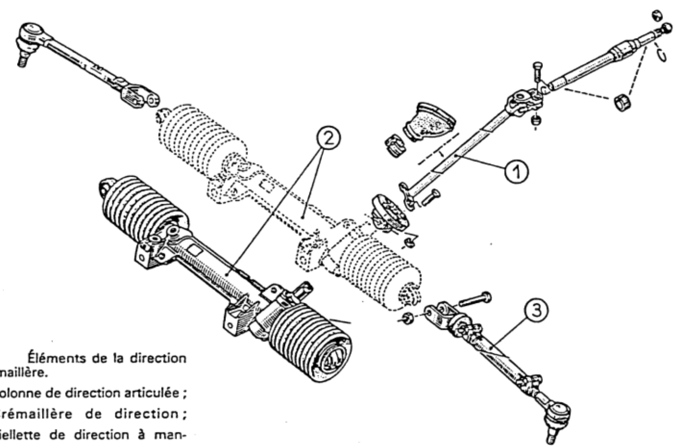
Pivot pour train à roues indépendantes. Rotule de direction-suspension.
(1) Rotule supérieure ;
(2) Rotule inférieure ;
(3) axe de pivotement.

Steering mechanisms

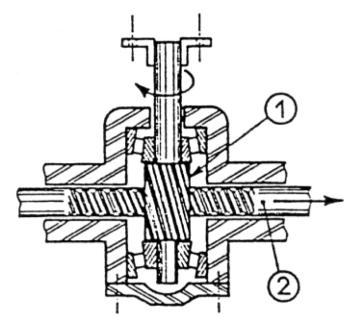


Éléments de direction d'un train à roues indépendantes : (1) Porte-fusée ; (2) Fusée. Rotules de direction et de suspension ; (3) Rotule inférieure ; (4) Rotule supérieure ; (5) Rotule de commande de direction ; (6) Biellette de direction.

- The steering control is carried out by an arm solidly attached to the spindle carrier and connected to the steering linkage via a steering control ball joint (5).
- In rack and pinion systems, the steering linkages are connected to a rack, the linear movement of which is achieved by the movement of a steering wheel via the pinion (1) which ensures the gear reduction ratio of the steering mechanism.

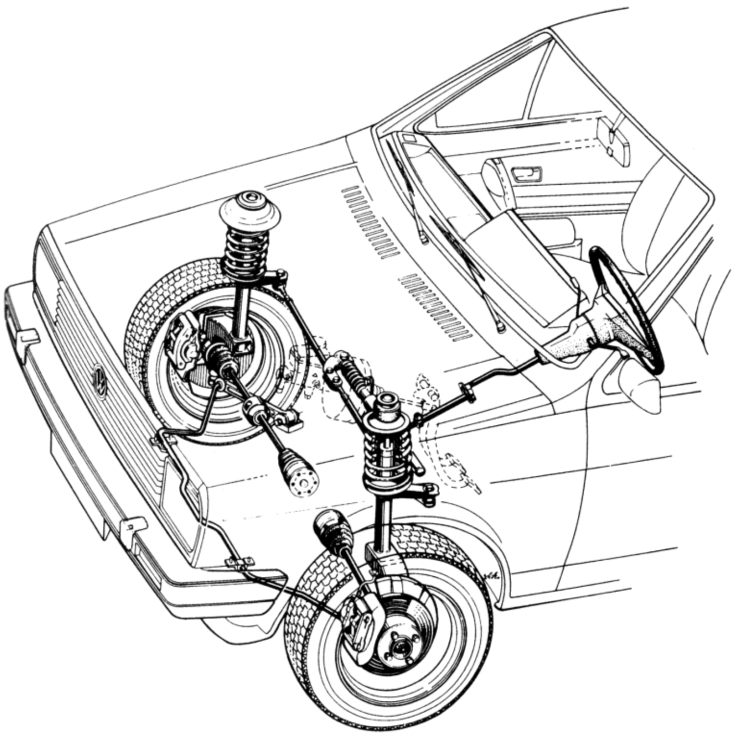


Éléments de la direction à crémaillère.
(1) Colonne de direction articulée ;
(2) Crémaillère de direction ;
(3) Biellette de direction à manchon réglable.



Crémaillère de direction : (1) Pignon ; (2) Crémaillère.

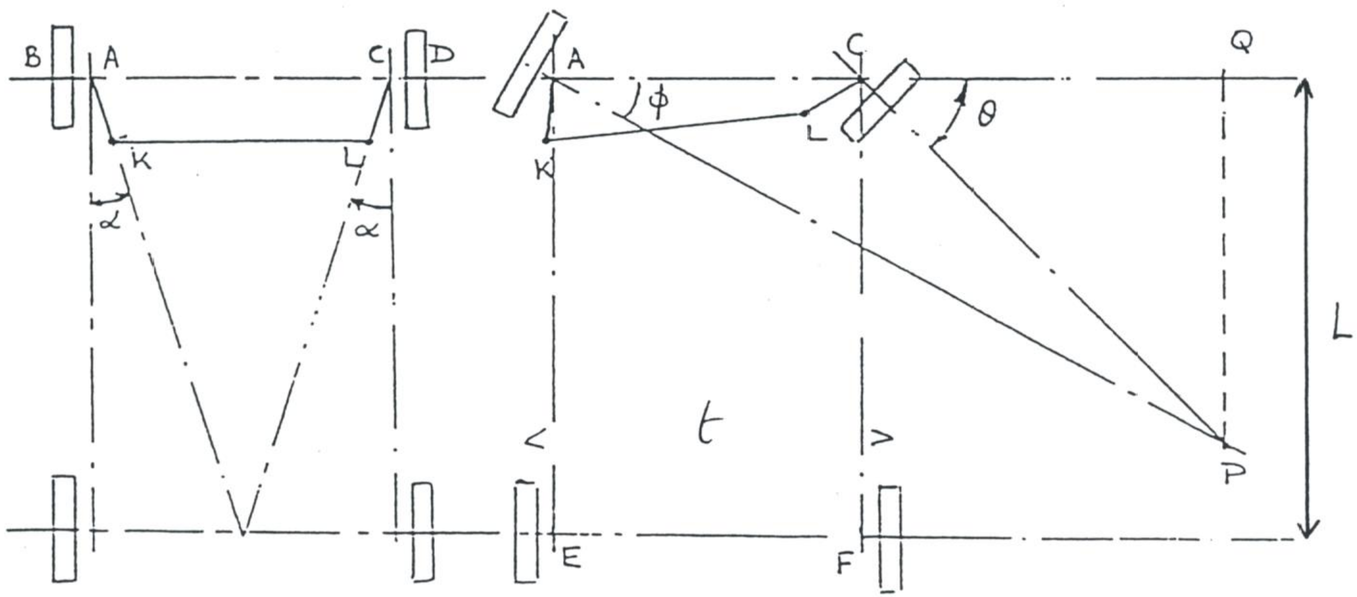
Steering mechanisms



Reimpel. Fig 4.1: Front axle with McPherson strut system of the VW Polo (until 1994) with its steering system.

- In Mc Pherson suspension, the steering linkage is directly attached to the guiding tube of the MacPherson strut.

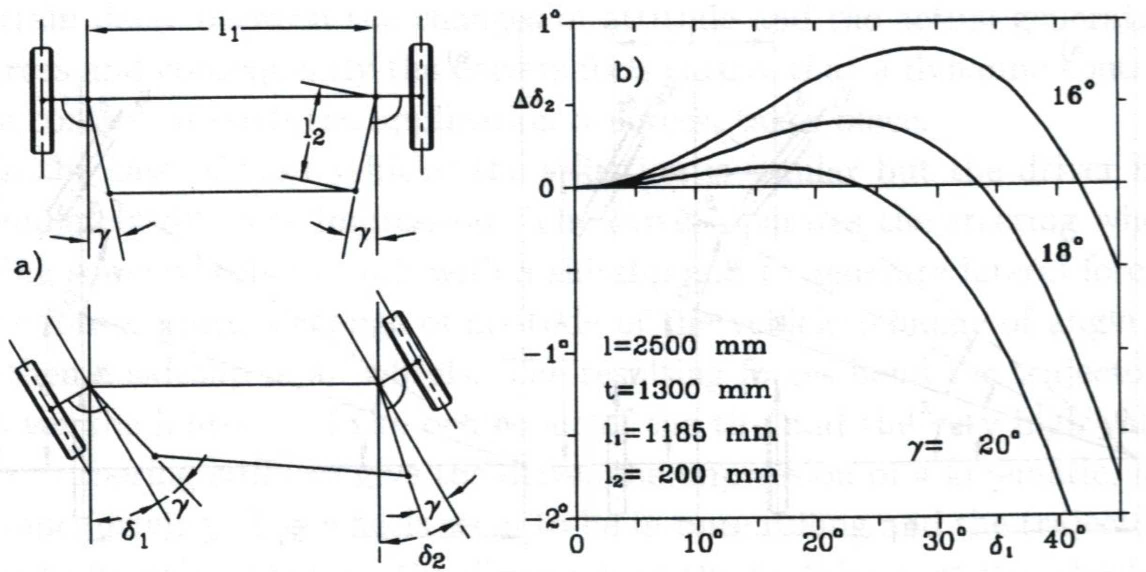
Four-bar mechanism



- The four-bar mechanism (also called as Bricard mechanism) is the most famous steering mechanism and is often used in modern vehicles.
- The four-bar mechanism does not respect the Jeantaud kinematic condition for any steering angles.

Four-bar mechanism

- The Jeantaud kinematic condition is not satisfied for four-link mechanism. Error can be reduced but not canceled

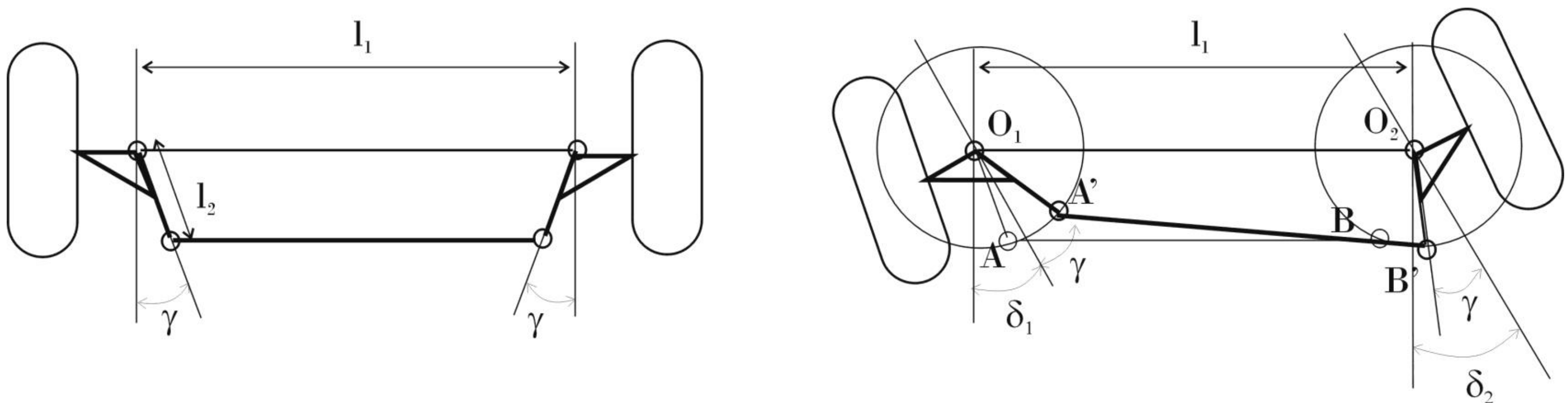


$$\sin(\gamma - \delta_e) + \sin(\gamma + \delta_i) =$$

$$\frac{l_1}{l_2} - \sqrt{\left[\frac{l_1}{l_2} - 2\sin\gamma\right]^2 - [\cos(\gamma - \delta_e) - \cos(\gamma + \delta_i)]^2}$$

Four-bar mechanism

- The error of the four-bar mechanism compared to Jeantaud kinematic condition can be calculated as follows

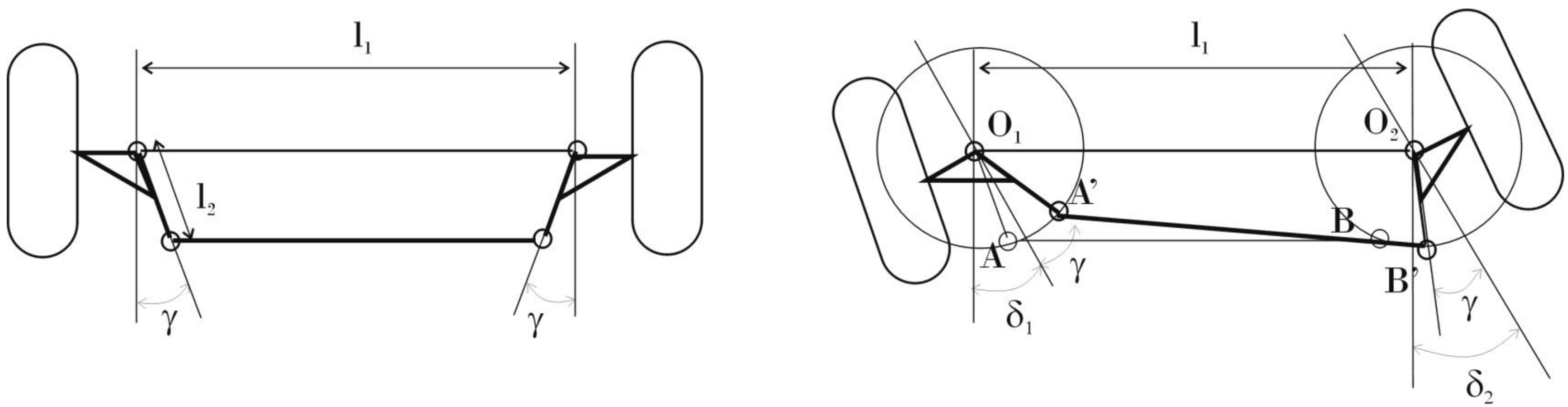


- Track rod length remains unchanged. In the initial configuration it is given by

$$\overline{AB} = l_1 - 2\, l_2 \sin \gamma$$

Four-bar mechanism

- The error of the four-bar mechanism compared to Jeantaud kinematic condition can be calculated as follows



- When the steering wheel is turned, the new positions of A and B becomes A′ and B′. In the local reference frame centered in O_1:

$$\overrightarrow{O_1A'} = \begin{bmatrix} l_2 \sin(\gamma + \delta_1) \\ -l_2 \cos(\gamma + \delta_1) \end{bmatrix} \qquad \overrightarrow{O_1B'} = \begin{bmatrix} l_1 - l_2 \sin(\gamma - \delta_2) \\ -l_2 \cos(\gamma - \delta_2) \end{bmatrix}$$

Four-bar mechanism

- The distance A'B' is

$$\overline{A'B'}^2 = [l_2 \sin(\gamma + \delta_1) + l_2 \sin(\gamma - \delta_2) - l_1]^2 + [l_2 \cos(\gamma + \delta_1) - l_2 \cos(\gamma - \delta_2)]^2$$

- The distance A'B' must remain equal to AB. It comes

$$\overline{A'B'}^2 = (l_1 - 2\, l_2 \sin\gamma)^2 = \overline{AB}^2$$

- If γ, l_1, l_2, δ_1 are given, one can get the relation

$$\sin(\gamma + \delta_1) + \sin(\gamma - \delta_2) = l_1/l_2 - \sqrt{[l_1/l_2 - 2\sin\gamma]^2 - [\cos(\gamma - \delta_2) - \cos(\gamma + \delta_1)]^2}$$

Four-bar mechanism

- After some algebraic manipulations, it comes

$$1 + \sin(\gamma - \delta_2)\sin(\gamma + \delta_1) - \lambda \sin(\gamma - \delta_2) - \lambda \sin(\gamma + \delta_1)$$
$$+ [\lambda - 2\sin\gamma]\ \sin\gamma - \cos(\gamma - \delta_2)\cos(\gamma + \delta_1) = 0$$

  - Where $\lambda = l_1/l_2$
- This equation can be solved to obtain δ_2 as a function δ_1. After some manipulations, the following relation can be derived

$$A\sin^2(\gamma - \delta_2) + B\sin(\gamma - \delta_2) + C = 0$$

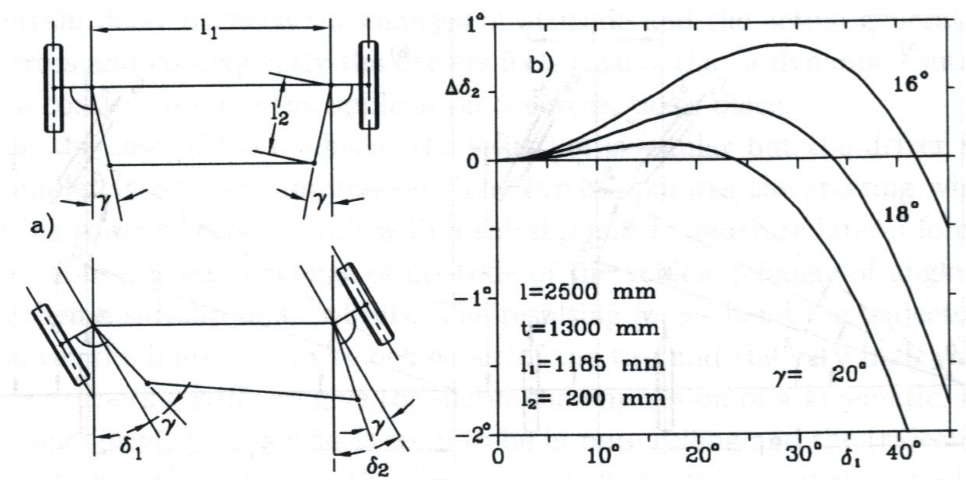
$$A = 1 + \lambda^2 - 2\sin(\gamma + \delta_1) \qquad B = 2D[\sin(\gamma + \delta_1) - \alpha]$$
$$C = D^2 - \cos^2(\gamma - \delta_1) \qquad D = 1 - \lambda\sin(\gamma + \delta_1) + [\alpha - 2\sin\gamma]\sin\gamma$$

Four-bar mechanism

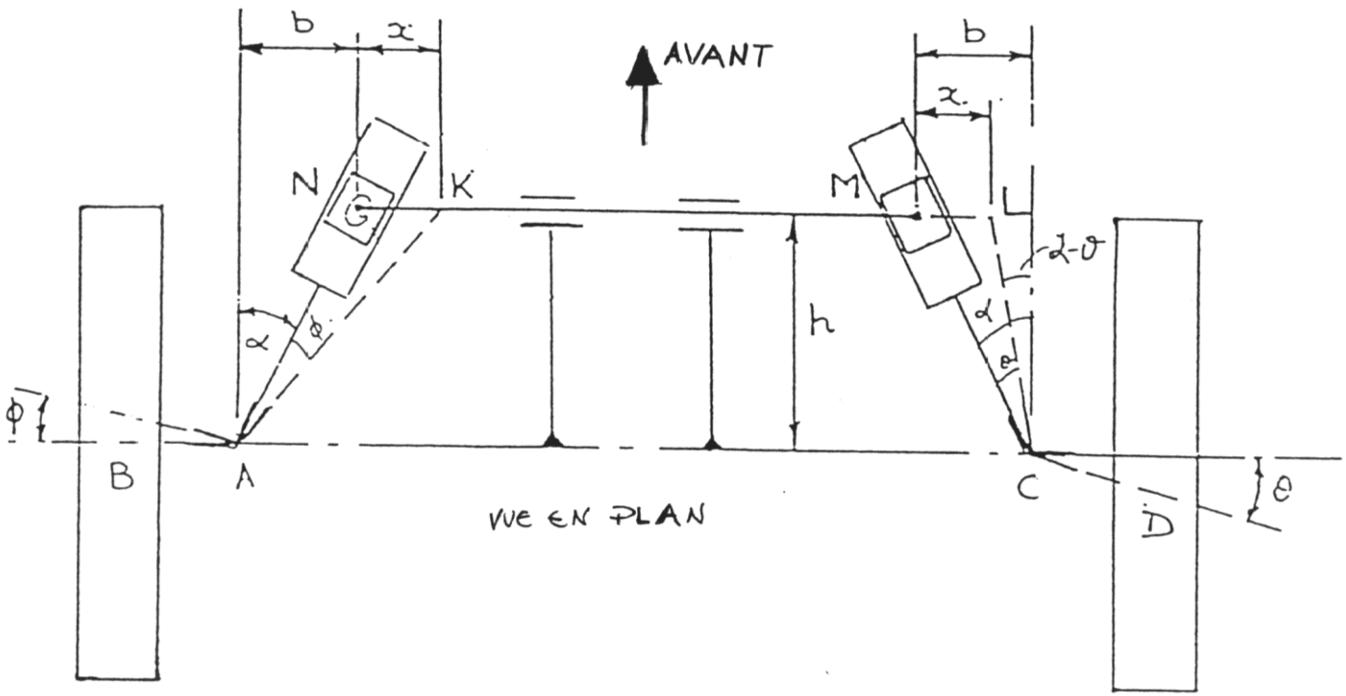
- If the two steering converge on the mid point of the rear axle as initially suggested by Jeantaud

$$\gamma = \arctan(\frac{t}{2L}) = \arctan(\frac{l_1}{2L})$$

- The relation $\delta_2=\delta_2(\delta_1)$ is compared with the obtained value using the correct Jeantaud kinematic relationship.
- It is calculated here for γ=16°, 18° and 20°



Mechanism of Davies



There is a known mechanism that respect the Jeantaud kinematic condition whatever be the steering angle. It is the Davies mechanism.

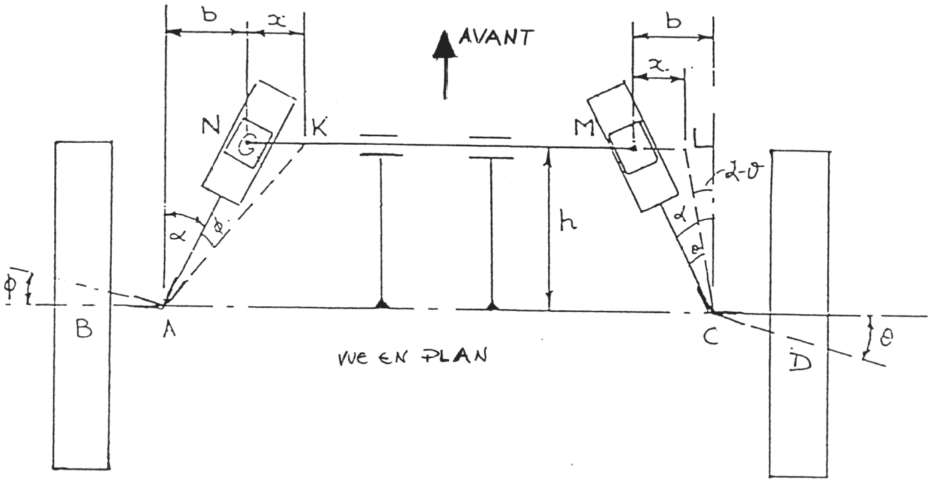
Mechanism of Davies

- It comes from the figure that

$$\tan\alpha = \frac{b}{h}$$

$$\tan(\alpha+\phi) = \frac{b+x}{h}$$

$$\tan(\alpha-\theta) = \frac{b-x}{h}$$



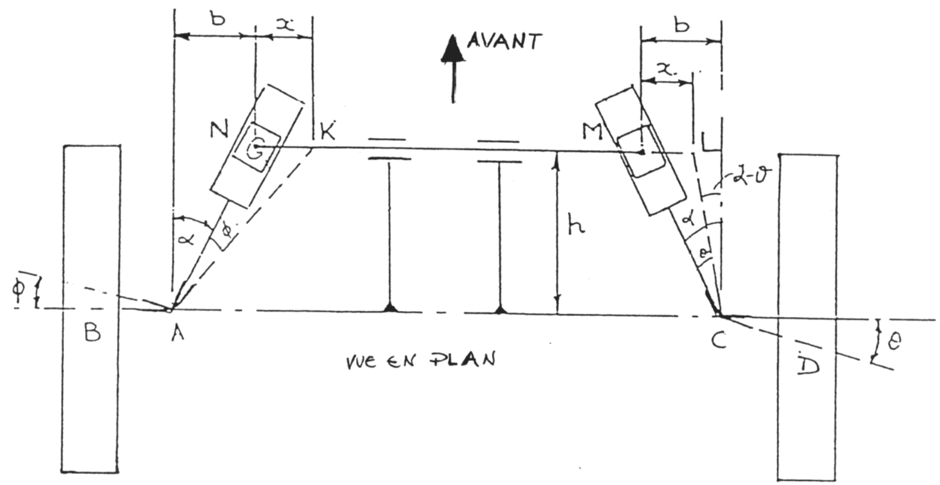
- Reminding that

$$\tan(\alpha+\phi) = \frac{\tan\alpha + \tan\phi}{1 - \tan\alpha\tan\phi}$$

Mechanism of Davies

- If we substitute the values of tan α and tan($\alpha+\phi$), it comes

$$\frac{\frac{b}{h}+\tan\phi}{1-\frac{b}{h}\tan\phi}=\frac{b+x}{h}$$



$$\Rightarrow \tan\phi=\frac{h\,x}{h^2+b^2+bx}$$

- In a similar way

$$\tan(\alpha-\theta)=\frac{\tan\alpha-\tan\theta}{1+\tan\alpha\tan\theta} \Rightarrow \tan\theta=\frac{h\,x}{h^2+b^2-bx}$$

Mechanism of Davies

- If we combine the two previous results, one gets

$$\begin{aligned}\cot\phi - \cot\theta &= \frac{h^2 + b^2 + bx}{hx} - \frac{h^2 + b^2 - bx}{hx} \\ &= \frac{2b}{h} = 2\,\tan\alpha\end{aligned}$$

- If we want to satisfy Jeantaud conditions,

$$\cot\phi - \cot\theta = \frac{t}{L}$$

- we have the geometrical condition

$$\boxed{\tan\alpha = \frac{t}{2\,L}}$$

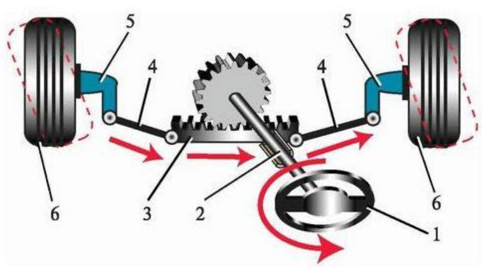
- This means that the steering linkage CM and AM must be such their line would intersect at the mid point of the rear axle

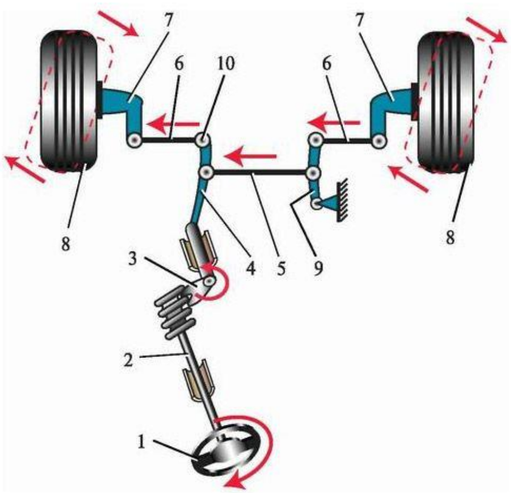
Mechanism of Davies

- In practice, the Davies mechanism is not used for at last two main reasons:
  - It is complex because of the presence of the three slider joints
  - It is quite sensitive to the assembly tolerances.
- One generally prefers four-bar mechanisms or equivalent because they are more robust

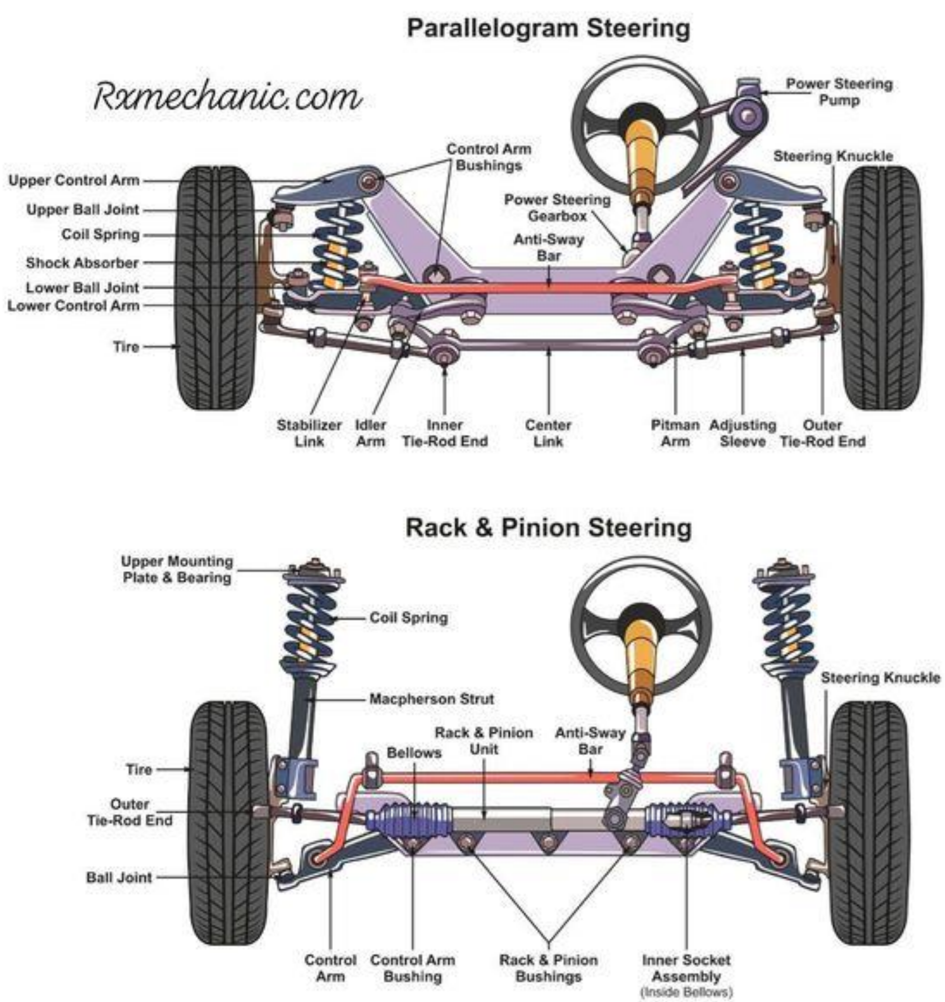
Other steering mechanisms

- The role of the steering mechanism:
  - To be interposed between the end of the steering column and the steering wheel
- It is a box, fixed to the chassis with
  - At the input, a coupling shaft with the steering column
  - At the exit, a steering linkage actuating the spindle
- Depending on the implementation, one distinguishes:
  - Rotary output mechanism
  - Linear output mechanism



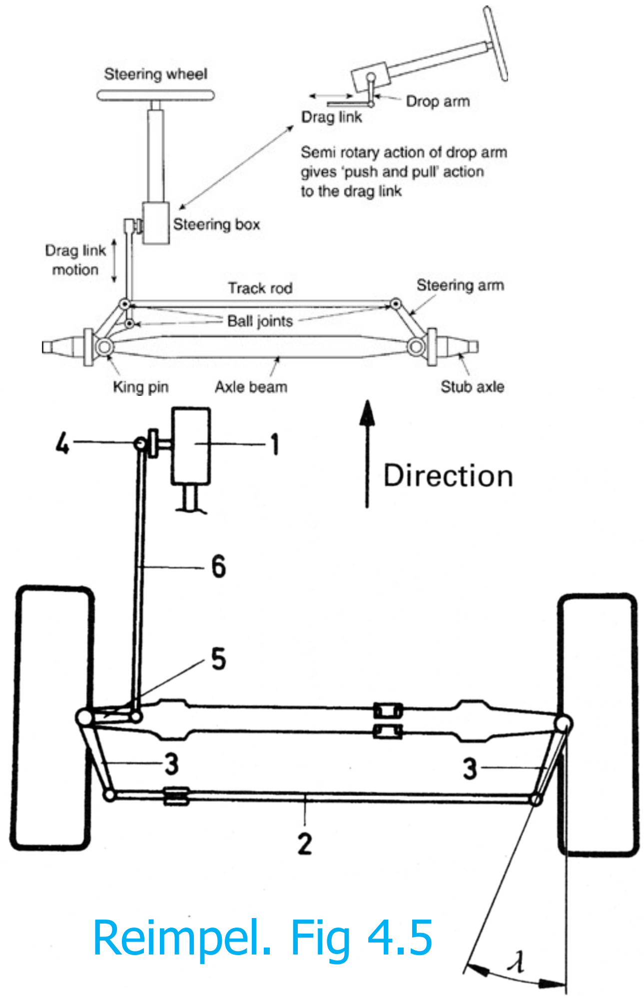


Other steering mechanisms



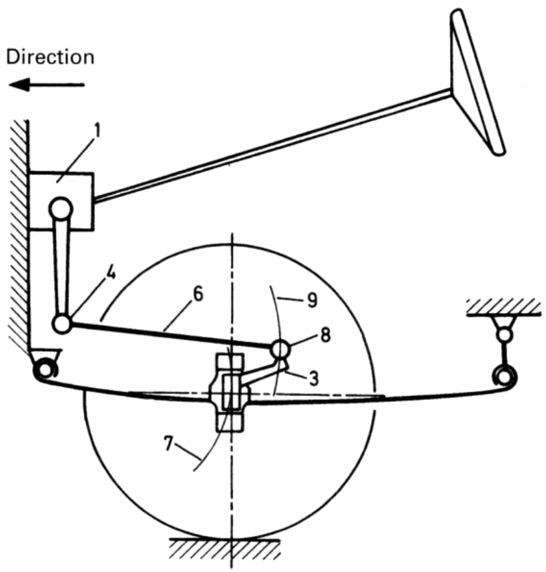
Rotary output mechanisms

- On rigid axles, apart from the two coupling levers (3) which are solidly attached to the wheel carrier, we have only one tie rod (2), the idler bar (5) attached to one of the wheels, and one control rod (6) to steer the wheels.
- The steering wheel and the steering tube are connected to the steering box (1), which includes gearbox.
- The output of the steering gearbox is connected to the control rod via a steering leverage (4).

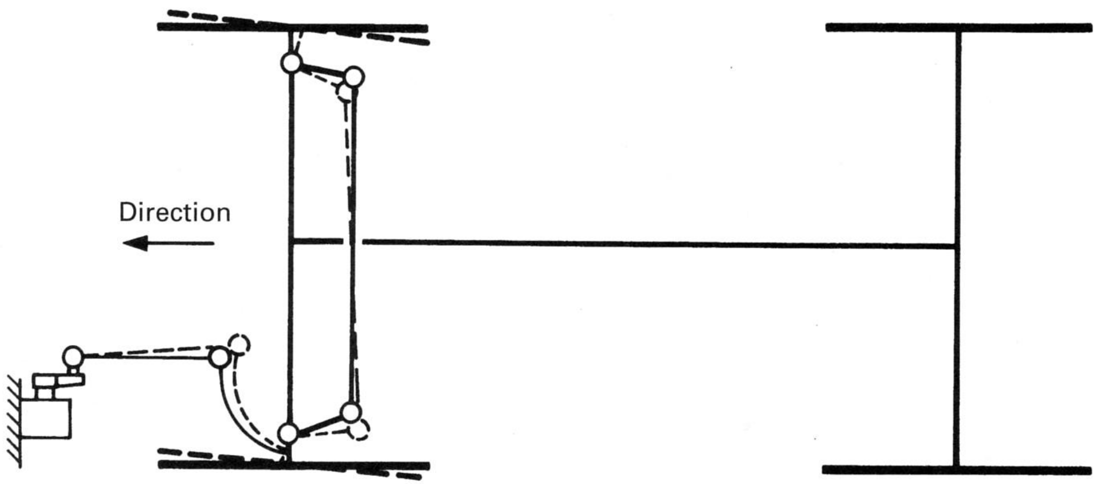


Reimpel. Fig 4.5

Rotary output mechanisms



Reimpel et al. Fig 4.6



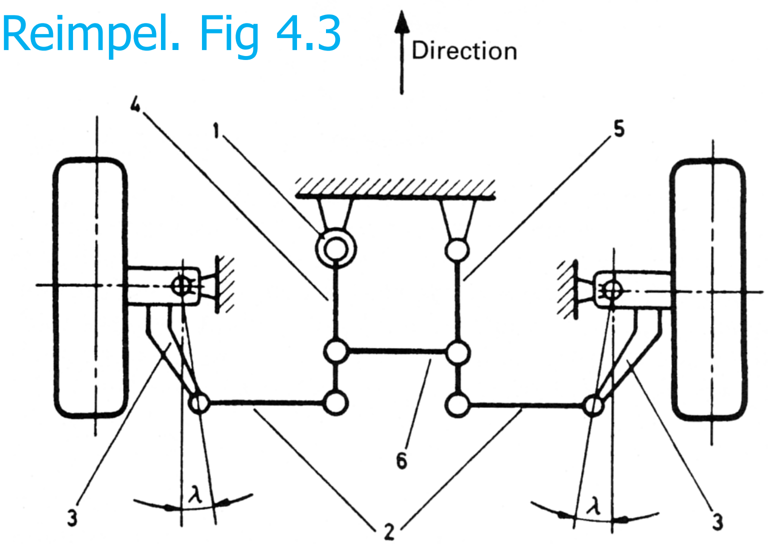
Reimpel et al. Fig 4.7

The following figures show the phenomenon of induced steering during a bounce and rebound travel for a rigid axle

Rotary output mechanisms

- A-shaped synchronous steering system for independent wheels suspension
- Front suspension of a left-hand drive car.
- The guide bar (3) and the coupling lever (4) and auxiliary lever (5) turn in the same direction.
- The auxiliary lever (5) forms a deflection.
- The steering rods (2) are attached to these two bars.

Reimpel. Fig 4.3



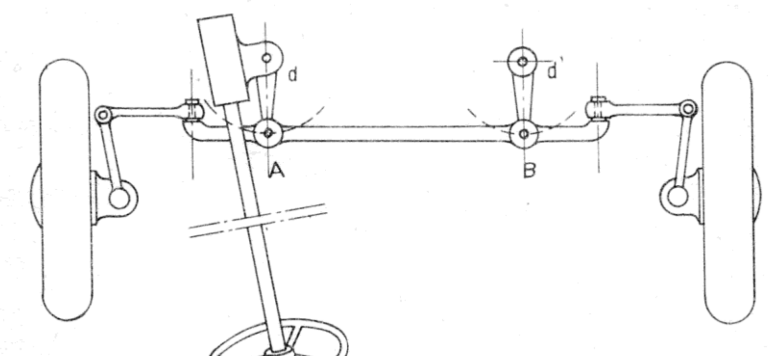
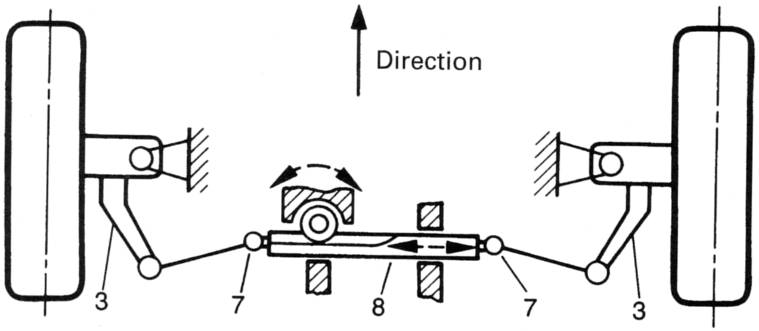


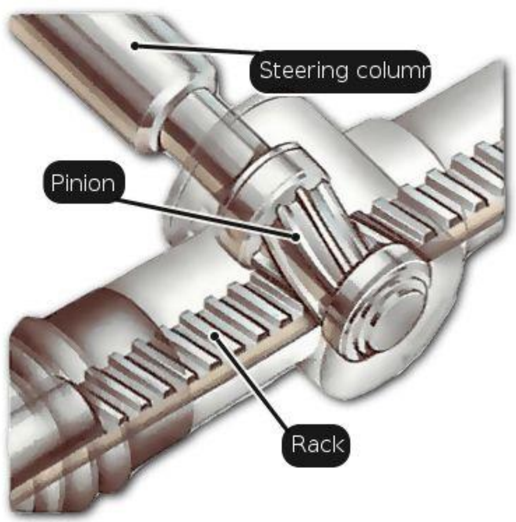
FIG. 148.

Linear output mechanism

- A steering system that is currently widely used for axles with independent wheels is the rack-and-pinion system.
- The system makes a triangle behind the front axle.
- The middle section of the tie rod (8) is used as the steering control lever. A rack and pinion is machined-tooled on this part, which meshes with a pinion fixed to the end of either the steering column or of a shaft connected to it by a bevel gear.
- The inner ends (7) of the steering tie-rod are attached to the end of the rack while the outer ends are connected to the levers (3) on the wheel carrier.

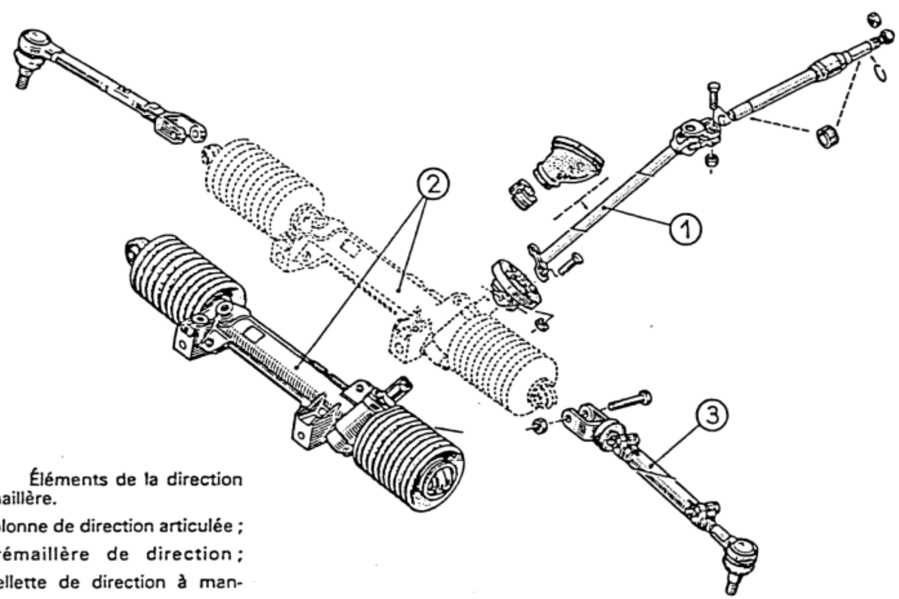


Reimpel. Fig 4.4



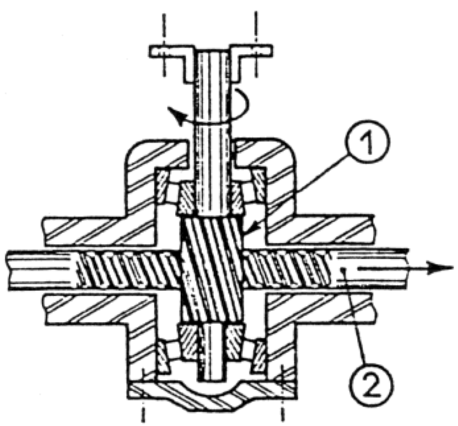
Steering boxes

Rack and pinion steering box



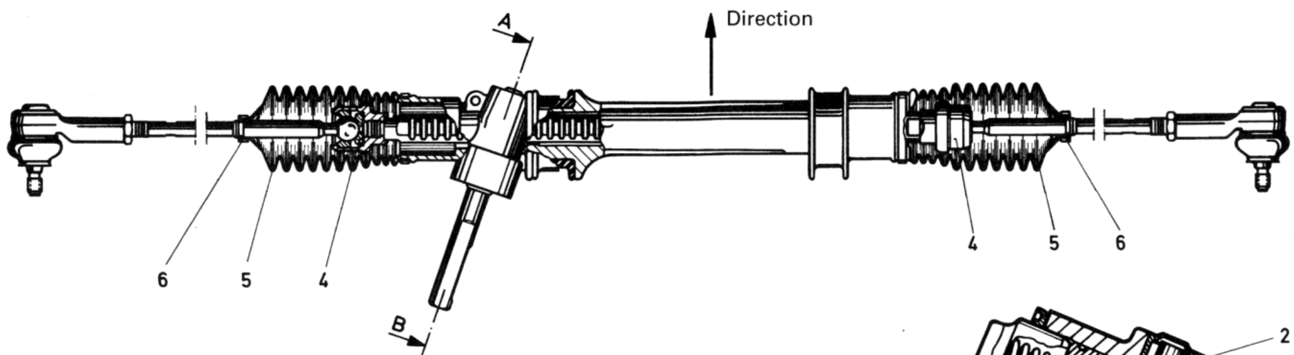
Éléments de la direction à crémaillère.
(1) Colonne de direction articulée ;
(2) Crémaillère de direction ;
(3) Biellette de direction à manchon réglable.

- The steering rods are connected to a rack and pinion (1), which is moved by the movement of a steering wheel via the pinion (1), which provides the transmission.

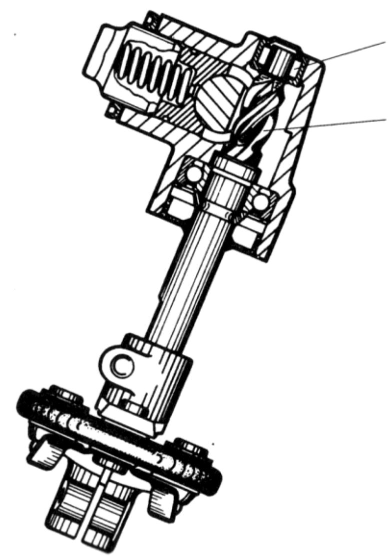


Crémaillère de direction : (1) Pignon ; (2) Crémaillère.

Rack and pinion steering box

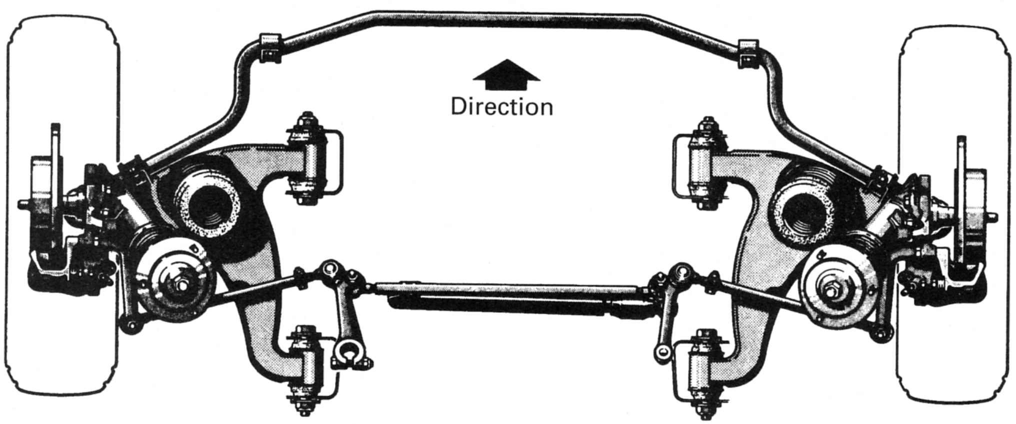


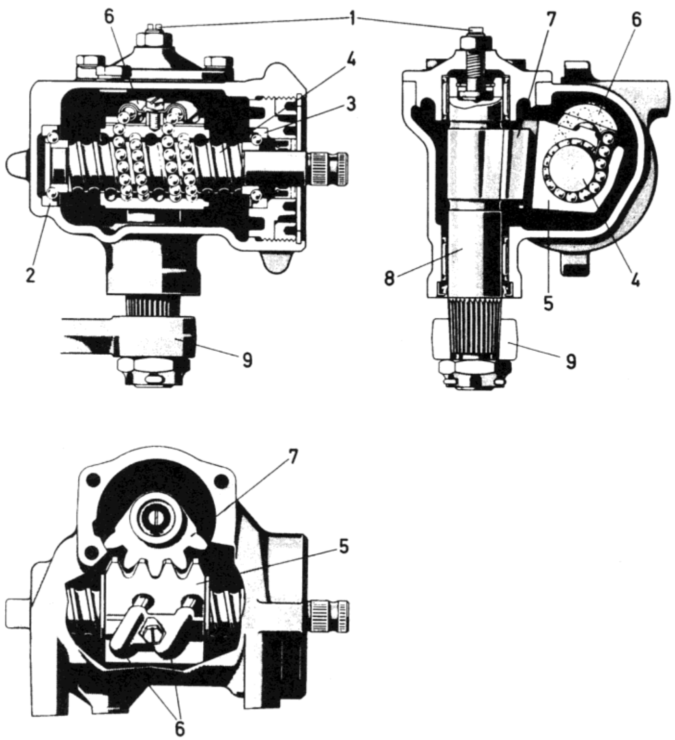
Section A–B



Reimpel et al. Fig 4.9: Rack and pinion on a Vauxhall-Opel Corsa. The pinion 1 has a helical cut due to the high ratio. It is carried from below by the needle bearing 2. The bearing housing has a cover plate to facilitate assembly and prevent dirt ingress.

Screw and sector steering box with recirculating balls

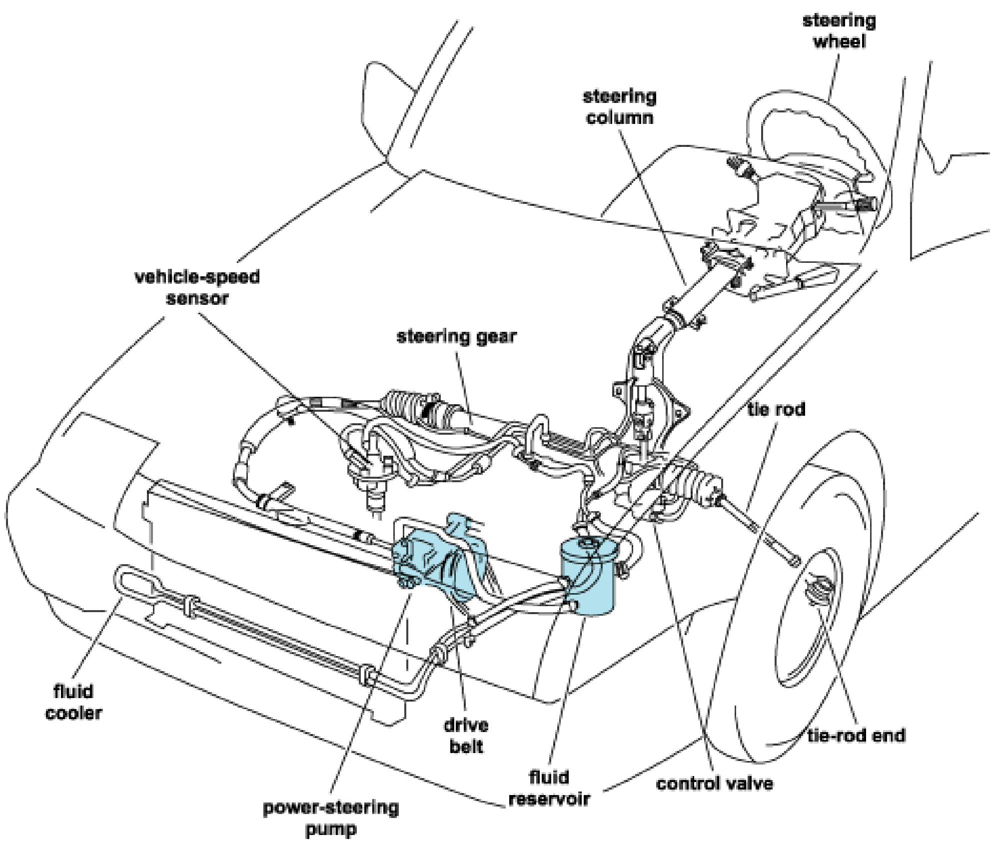




Reimpel et al. Fig 4.12 & 4.15: Strut damper of a Mercedes front axle. Mercedes Benz recirculating ball steering suitable for passenger cars and light vans. Today this is generally fitted as a hydraulic power-assisted versions

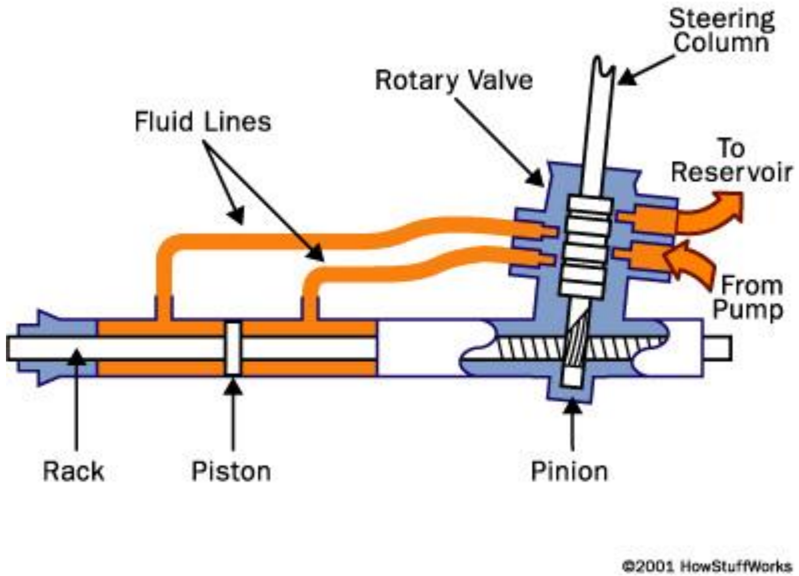
Power steering

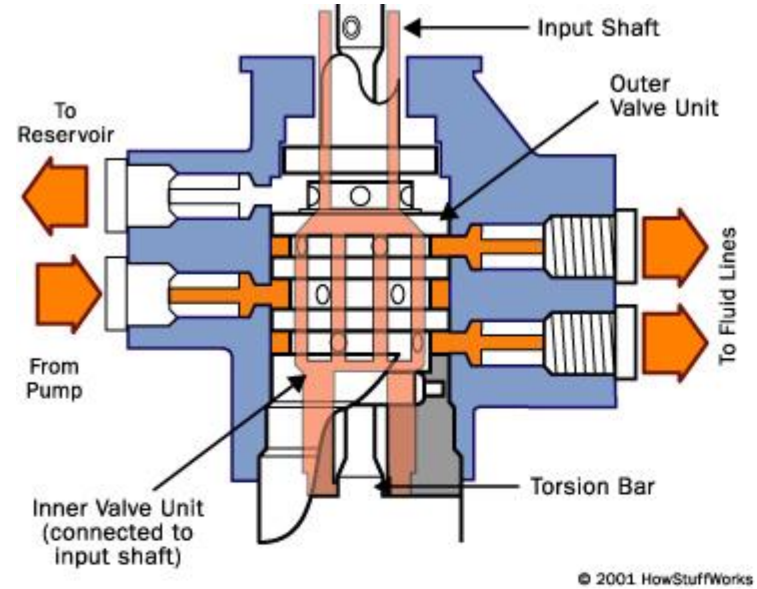
Hydraulic power assisted steering



Hydraulic power steering system for a small front wheel driven car with rack-and-pinion steering box.

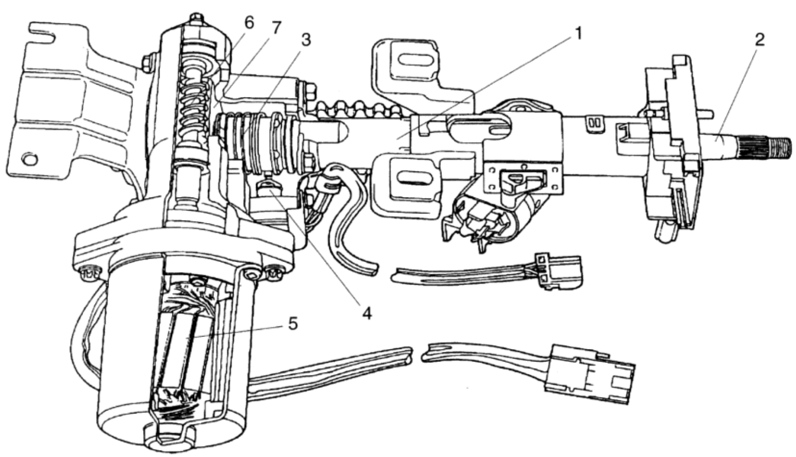
Hydraulic power assisted steering

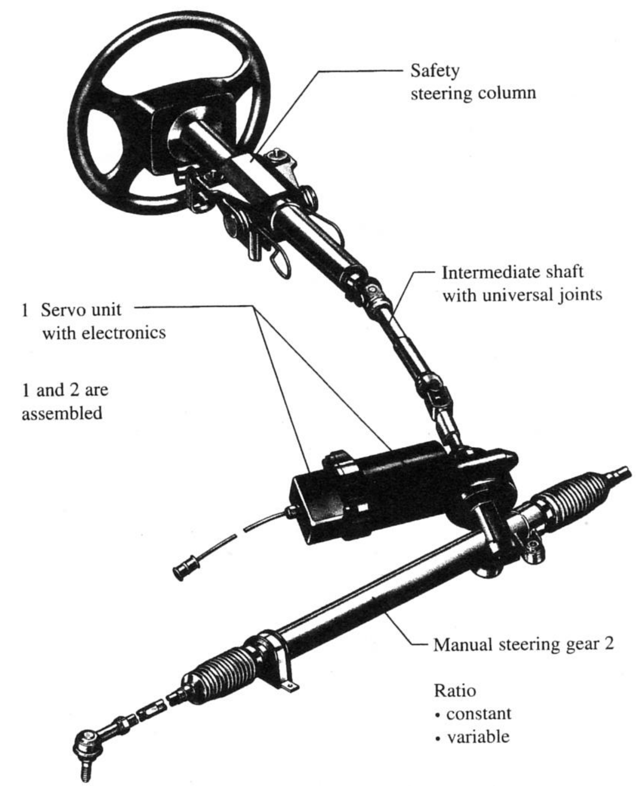




Schematic view of a hydraulically assisted rack-and-pinion steering box. Details of the hydraulic control valve on the steering column.

Electrically power assisted steering





Reimpel et a. Fig 4.18: Electric power steering system EP showing an electric motor working on the steering column. A perspective view of the assembly and below a detail of the motor with reduction gearbox.