School of Mechanical Engineering

FACULTY OF ENGINEERING

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MECH5170M

Connected and Autonomous Vehicles Systems

AV Steering system

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Introduction

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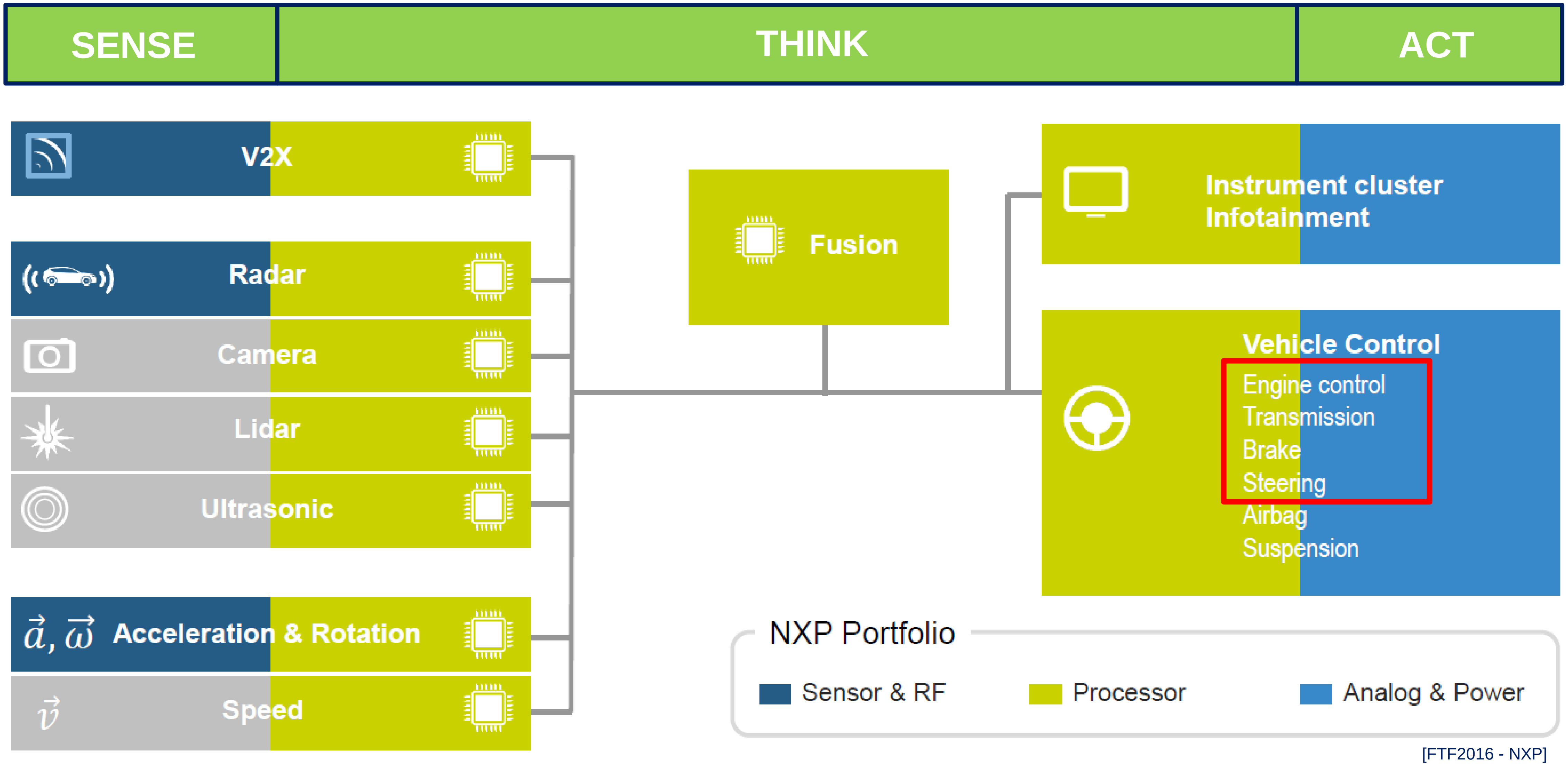
- Autonomous driving framework/requirement
- Steering requirements
- **Steering control**

Autonomous vehicle control framework



[FTF2016 - NXP]

Steering System

Requirements and Regulations

To steer the steered wheels in response to driver/ECU input and provide directional control of the vehicle

Function must therefore be to:

- Provide a **mechanical linkage** between the **steered wheels**
- Provide controlled kinematic relationships to achieve the **correct steer angles** of both **inner** and **outer wheels**

In all cases the system must be safe and comply with current regulations and must guarantee easy and safe steering of the vehicle

Requirements and Regulations

- If the actuating force at the steering wheel exceeds 250N power assistance is necessary.
- If such power assistance fails a force of 600N must not be exceeded.
- It must be possible to drive the vehicle accurately, i.e., without any unusual steering corrections.
- Play in the mechanical parts is not allowed.
- The entirety of the mechanical transmission devices must be able to cope with all loads and stresses occurring in operation.
- Unusual driving manoeuvres, such as driving over obstacles, and accident like occurrences must not lead to any cracks or breakages.

General Parameters and Terms

Steering Ratio:

Defined as the steering **wheel rotational angle** in degrees (lock to lock) compared to the **steer angle of the road wheel** (lock to lock).

Effort – It must be possible to turn the front wheels into a position corresponding to a turning circle of 12m in 6 seconds.

Typical values of steer wheel angles:

Passenger car **±35°**

London Taxis **±60°**

Typical steering wheel angles

Passenger Car 3 to 3.5 turns lock to lock

Typical Steering Ratios

Passenger Cars	15 – 20:1
Trucks	30 – 40:1

Ratio Calculation:

Given

Steering wheel lock to lock	3.5 turns
Road wheels lock to lock	±35°

Ratio = (3.5 x 360)/(2x35) = 1260 degrees/70 degrees

giving Ratio = 18:1

The steering wheel will rotate 18° for 1° of the road wheel.

The torque at the steering wheel will be 1/18th the torque required at the road wheel.

Steering systems

Conventional (parallelogram)

Rack & Pinion

Manual steering (Mechanical)

Power steering (Mechanical + Hydraulic / Electric)

By-wire steering (Electronic + Hydraulic / Electric)

Parallelogram

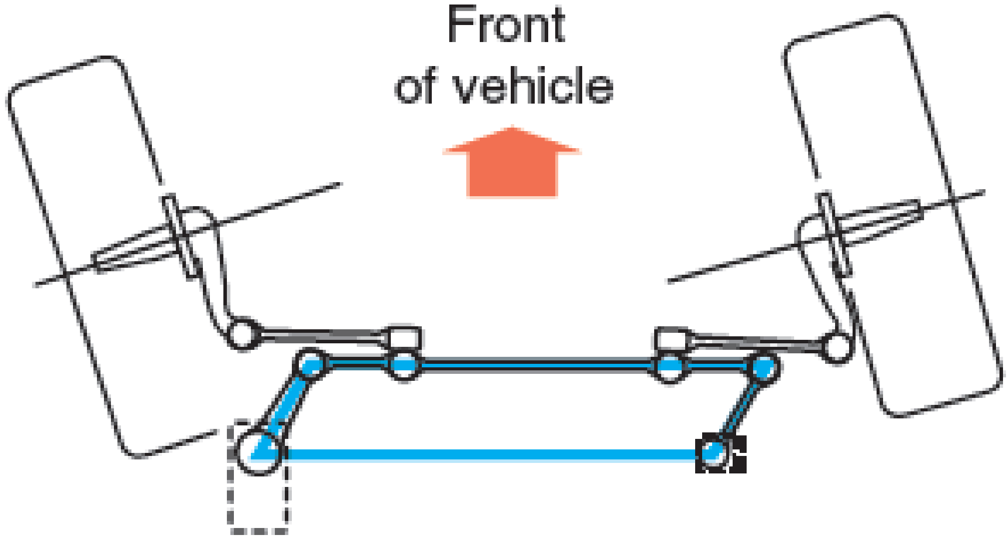


Figure 65.9 The shape of a parallelogram is made by the steering linkage during a turn.

Electric Power Steering

Electrically powered steering uses an electric motor to drive either:

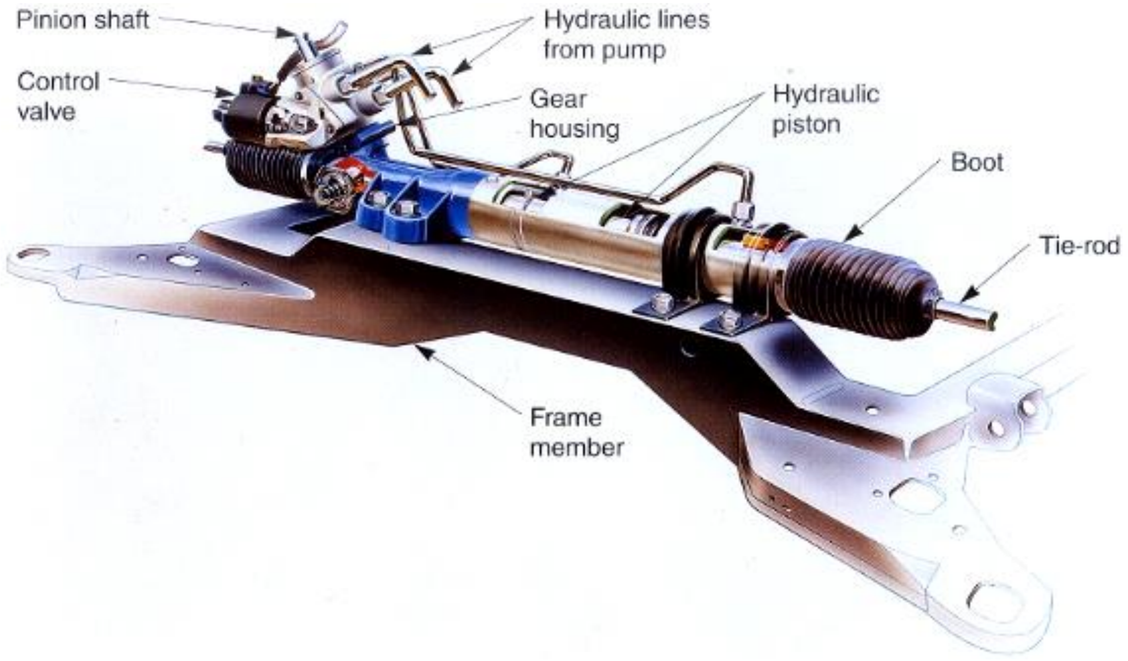
- the power steering hydraulic pump or
- the steering linkage directly

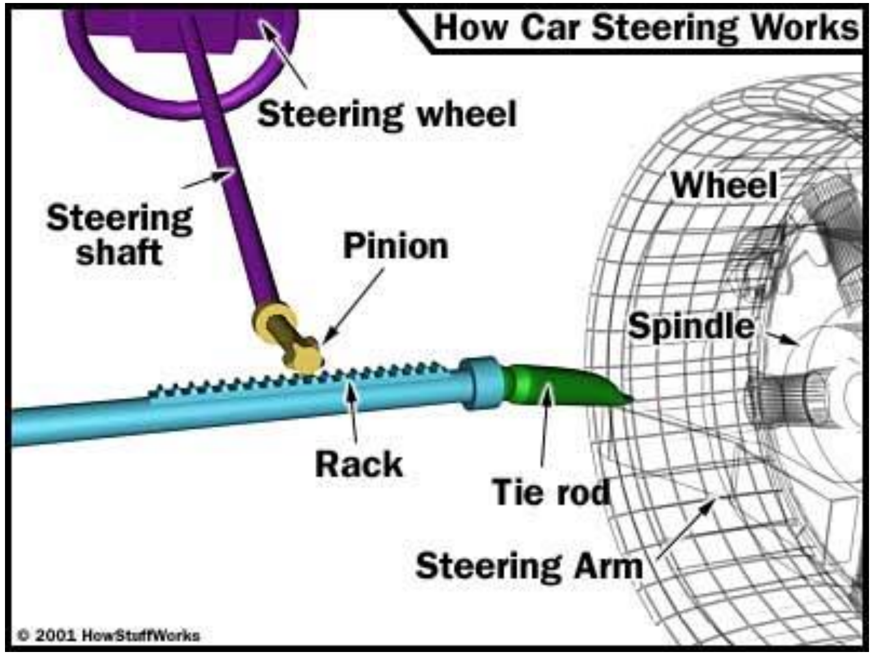
The power steering function is therefore independent of engine speed

Basic Rack-and-Pinion Steering

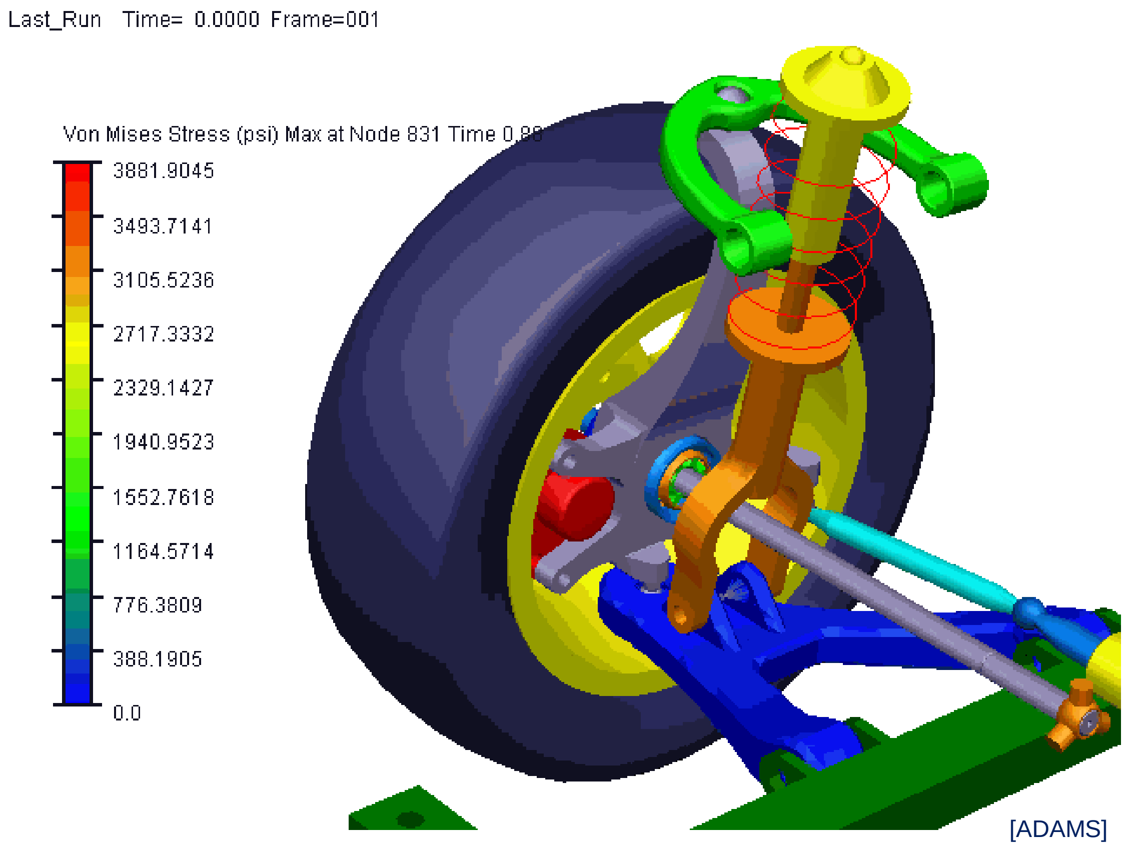
Pinion Gear- rotated by the steering wheel and steering shaft; it's teeth mesh with the teeth on the rack.

Rack- long steel bar with teeth along one section; slides sideways as the pinion gear turns.

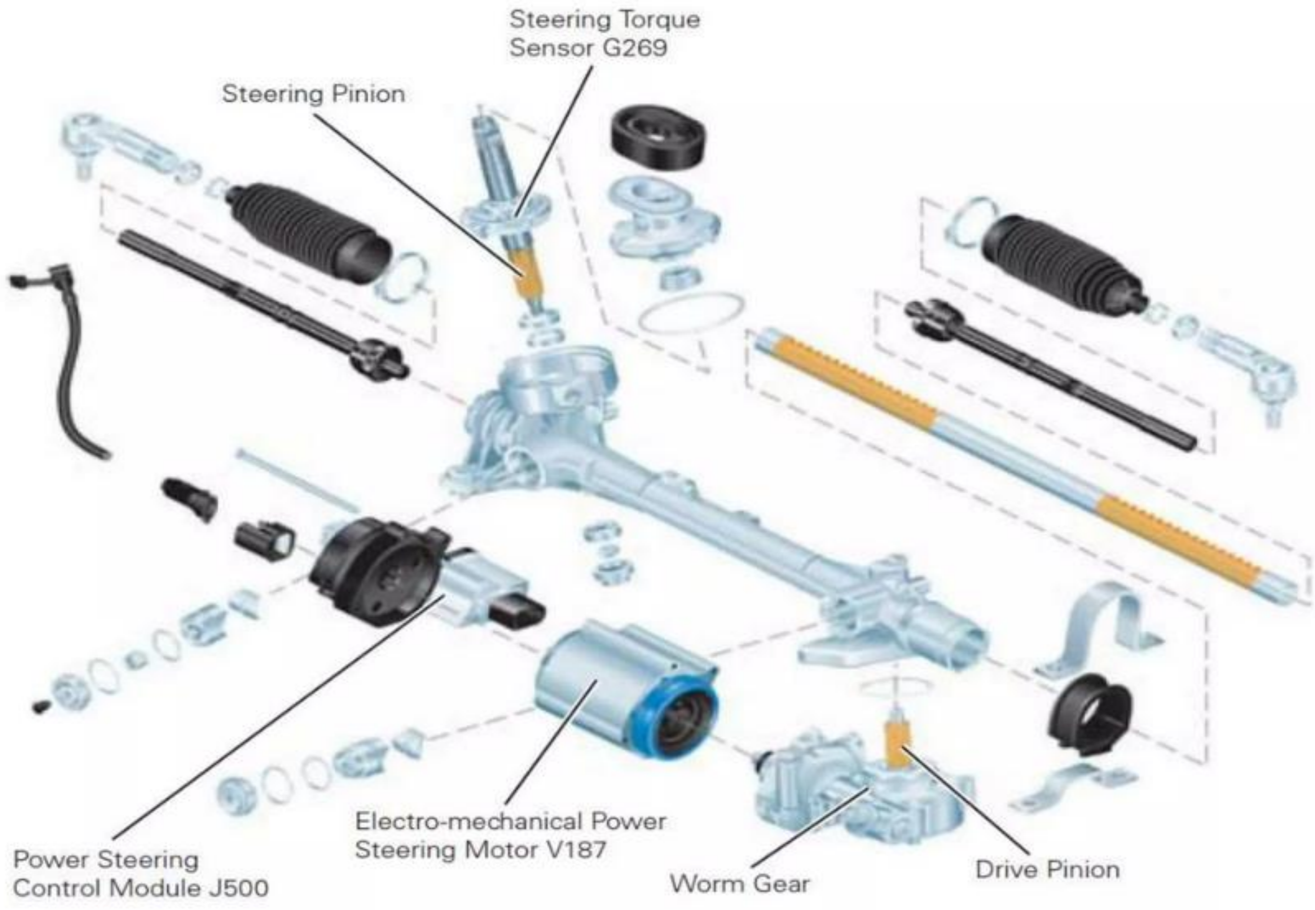




Steering rack and pinion



[ADAMS]



Electric steering system for autonomous vehicles

Example of the electric steering system:

High torque

High speed

Technical Specification	
Operating Voltage	Nominal **13.8V DC**
Maximum current draw	**80 Amps**
System Weight	**6.45** kg
Maximum Torque Output	**110 Nm**
No Load Rotation Speed	**780** degrees per second

Ackerman Geometry

Basic layout for passenger cars & trucks

δ_o = outer steering angle

δ_i = inner steering angle

R = turn radius

L = wheelbase

T = track width

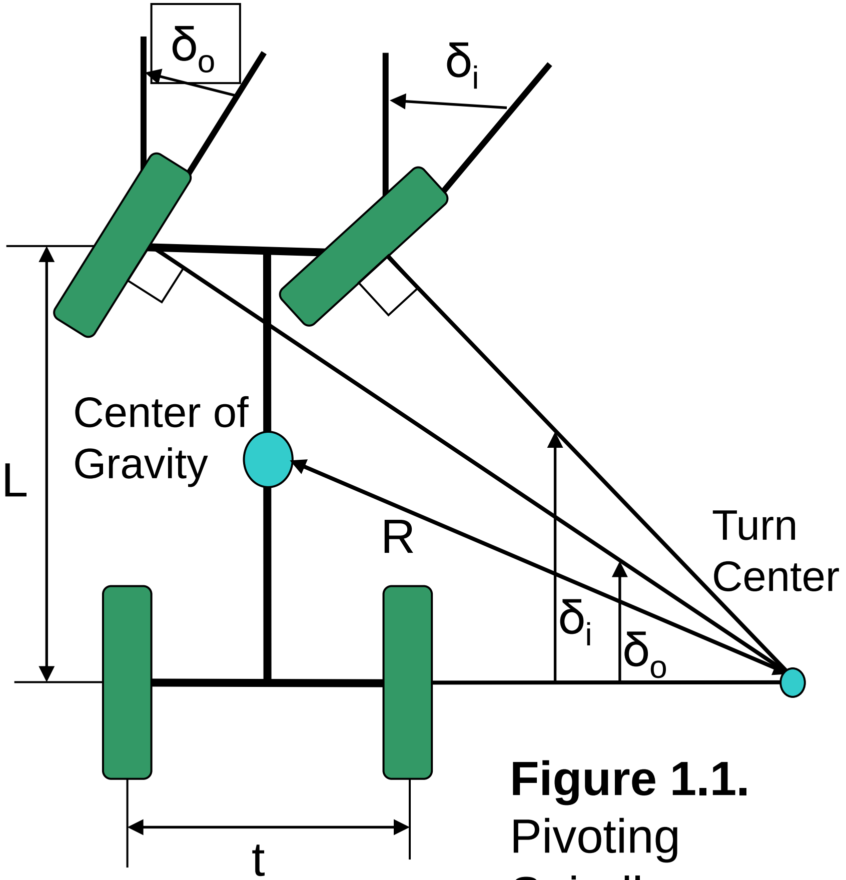


Figure 1.1. Pivoting Spindle

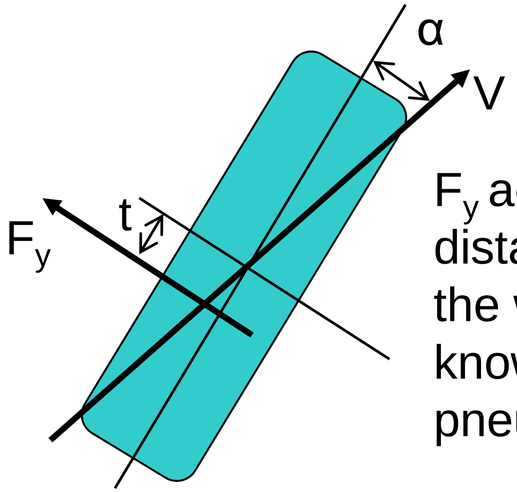
(Gillespie, 1992)

Cornering Stiffness and Lateral Force

Lateral force (F_y) is the force produced by the tire due to the slip angle

Cornering stiffness (C_α) is the rate of change of the lateral force with the slip angle

$$C_\alpha = \frac{\Delta F_y}{\Delta \alpha}$$



F_y acts at a distance (t) from the wheel center known as the pneumatic trail

[Milliken, et. al., 2002]

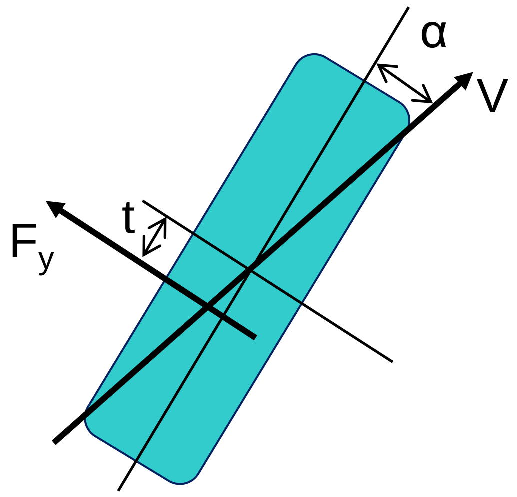
Slip Angle

The slip angle (α) is the angle at which a tire rolls and is determined by the following equations:

$$\alpha_f = \frac{W_f * V^2}{C_{\alpha f} * g * R}$$

$$\alpha_r = \frac{W_r * V^2}{C_{\alpha r} * g * R}$$

W = weight on tire
C_α = Cornering Stiffness
g = acceleration of gravity
V = vehicle velocity
R = turn radius



[Gillespie, 1992]

Steering angle

The steering angle (δ) is also known as the Ackerman angle and is the average of the front wheel angles

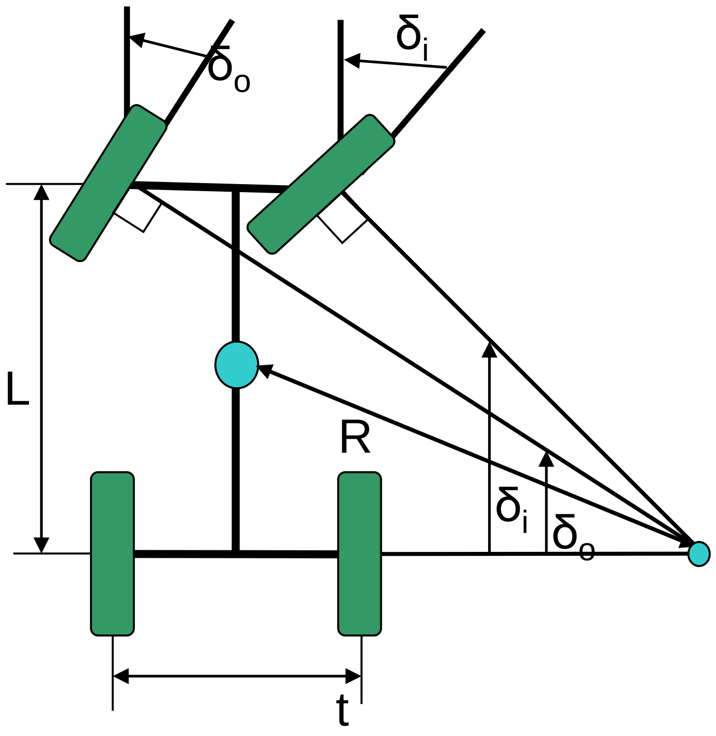
For low speeds it is:

$$\delta = \frac{L}{R}$$

For high speeds it is:

$$\delta = \frac{L}{R} + \alpha_f - \alpha_r$$

α_f = front slip angle
α_r = rear slip angle



[Gillespie, 1992]

Aligning Torque of a Single Tire

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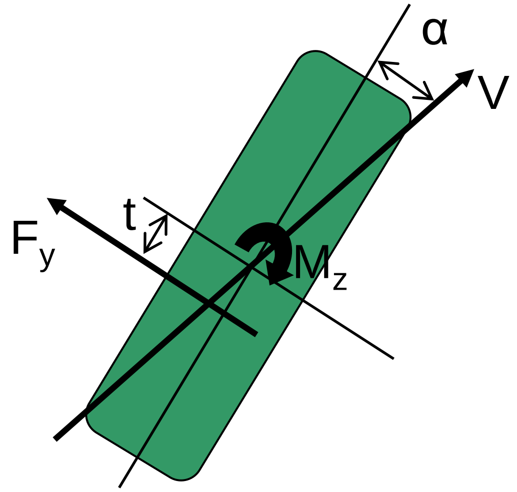
Aligning Torque (M_z) is the resultant moment about the center of the wheel due to the lateral force.

$$M_z = F_y * t$$

Top view of a tire showing the aligning torque.



(Milliken, et. al., 2002)

Neutral Steer

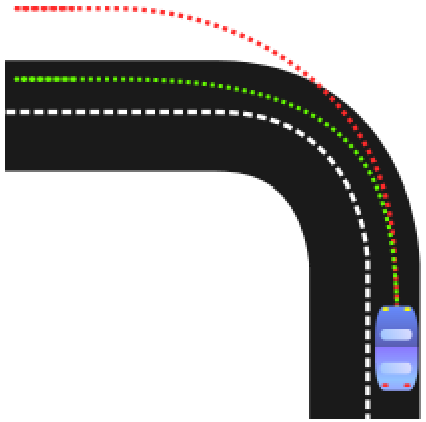
No change in the steer angle is necessary as speed changes

The steer angle will then be equal to the Ackerman angle

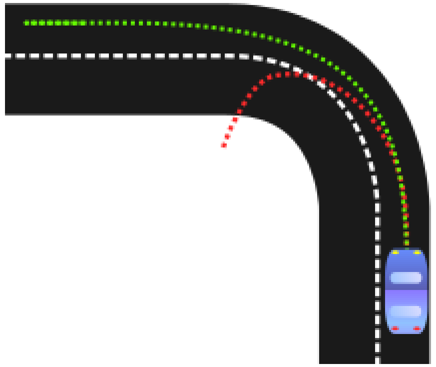
Front and rear slip angles are equal

(Gillespie, 1992)

Understeer



Oversteer

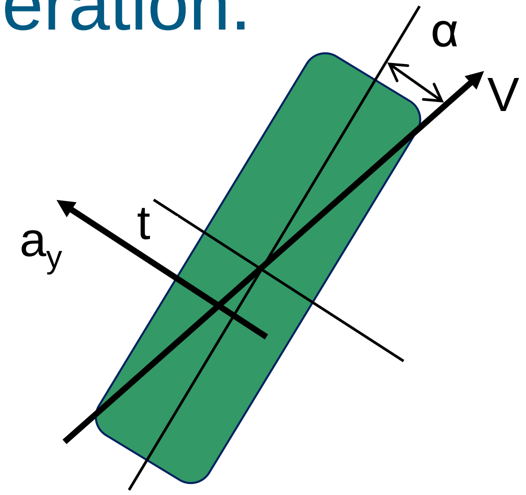


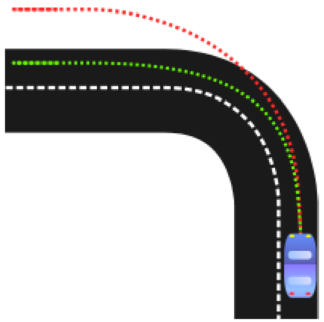
[Images from Wikipedia]

The steered wheels must be steered to a greater angle than the rear wheels

The steer angle on a constant radius turn is increased by the understeer gradient (K) times the lateral acceleration.

$$\delta = \frac{L}{R} + K * a_y$$





a_y – is a lateral acceleration

Understeer Gradient

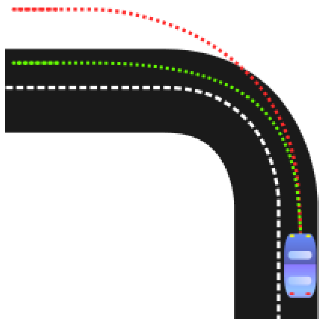
If we set equation 6 equal to equation 2 we can see that $K*a_y$ is equal to the difference in front and rear slip angles.

Substituting equations 3 and 4 in for the slip angles yields:

$$K = \frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}}$$

Since

$$a_y = \frac{V^2}{g * R}$$

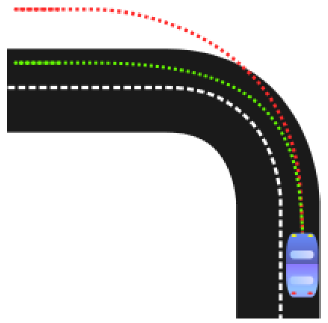


Characteristic Speed

The characteristic speed is a way to quantify understeer.

Speed at which the steer angle is twice the Ackerman angle.

$$V_{char} = \sqrt{\frac{57.3 * L * g}{K}}$$

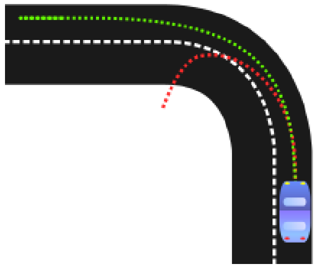


Oversteer

The vehicle is such that the steering wheel must be turned so that the steering angle decreases as speed is increased

The steering angle is decreased by the understeer gradient times the lateral acceleration, meaning the understeer gradient is negative

Front steer angle is less than rear steer angle



Critical Speed

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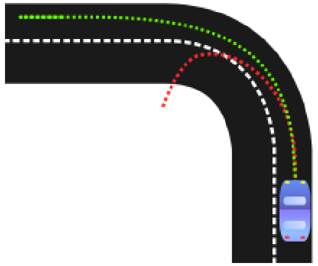
The critical speed is the speed where an oversteer vehicle is no longer directionally stable.

$$V_{crit} = \sqrt{\frac{57.3 * L * g}{-K}}$$

Note: K is negative in oversteer case



Lateral Acceleration Gain

Lateral acceleration gain is the ratio of lateral acceleration to the steering angle.

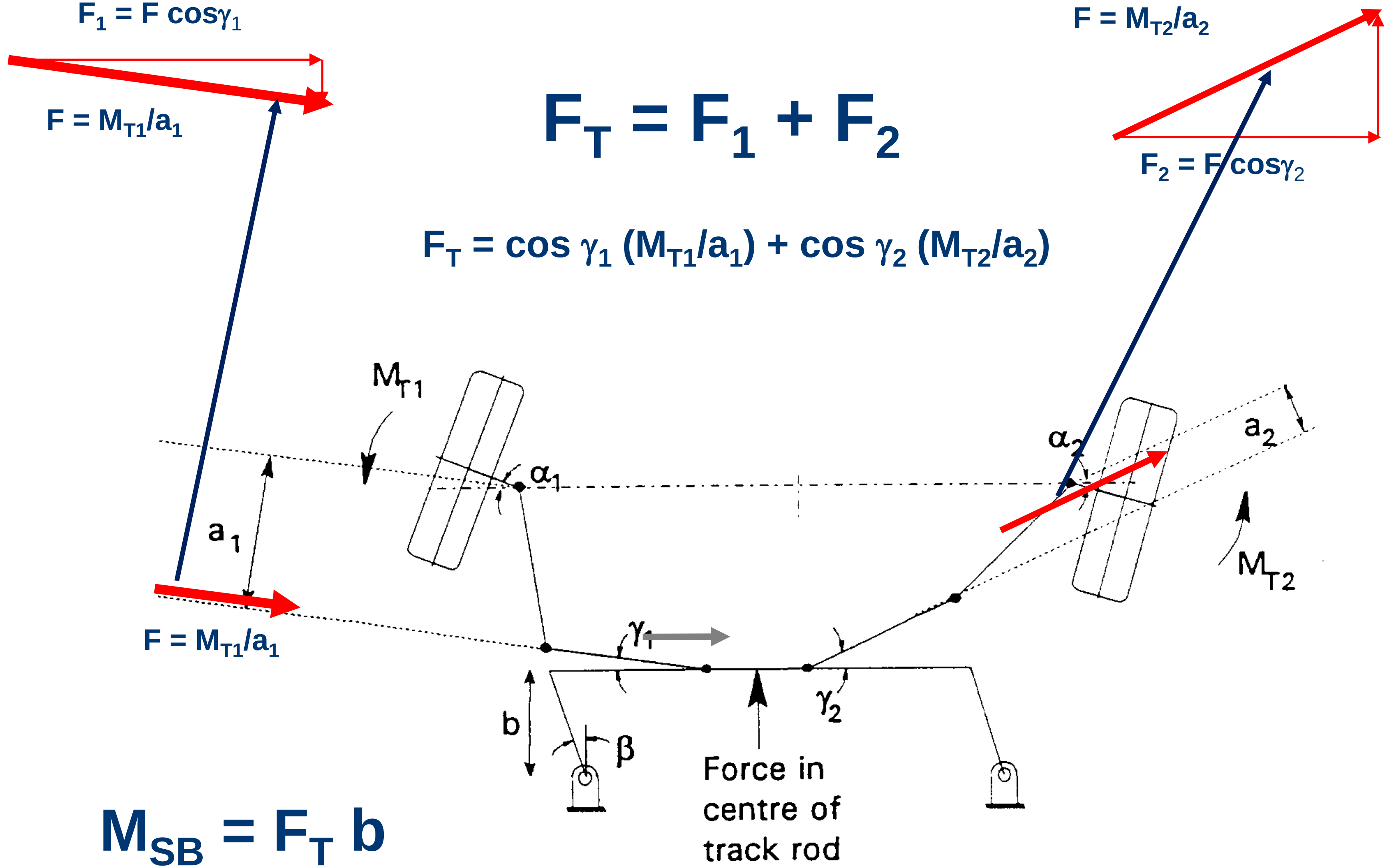
Helps to quantify the performance of the system by telling us how much lateral acceleration is achieved per degree of steer angle

$$\frac{a_y}{\delta} = \frac{\dfrac{V^2}{57.3Lg}}{1 + \dfrac{KV^2}{57.3Lg}}$$

Horizontal Force at Centre of Track Rod

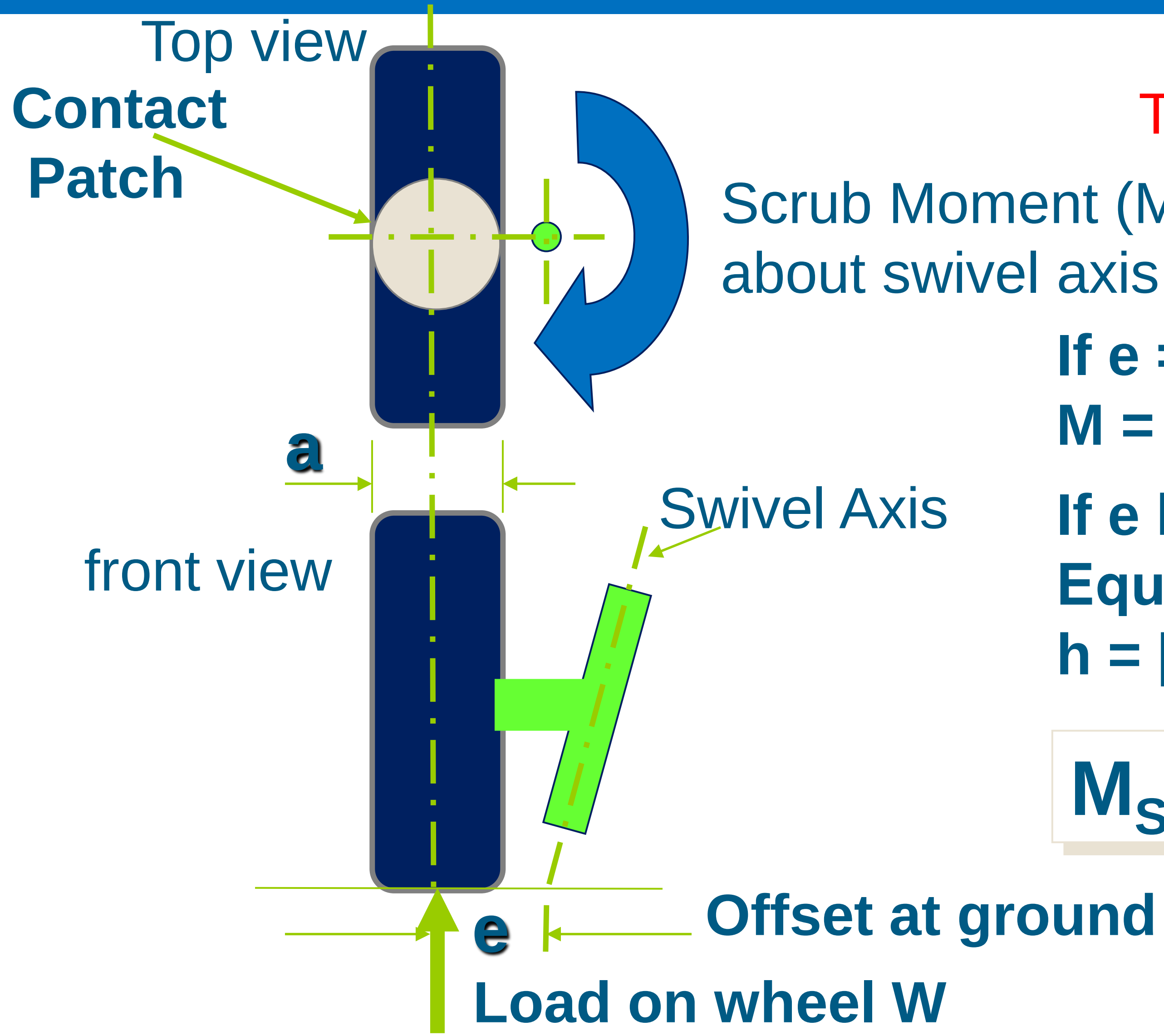
$$F_T = F_1 + F_2$$

$$F_T = \cos\gamma_1 (M_{T1}/a_1) + \cos\gamma_2 (M_{T2}/a_2)$$



$$M_{SB} = F_T\, b$$

Forces in a Stationary Vehicle
Scrub Moment



Tyre Scrub or Parking Torque

If e = 0

$M = \mu W (a/3)$

If e has a value

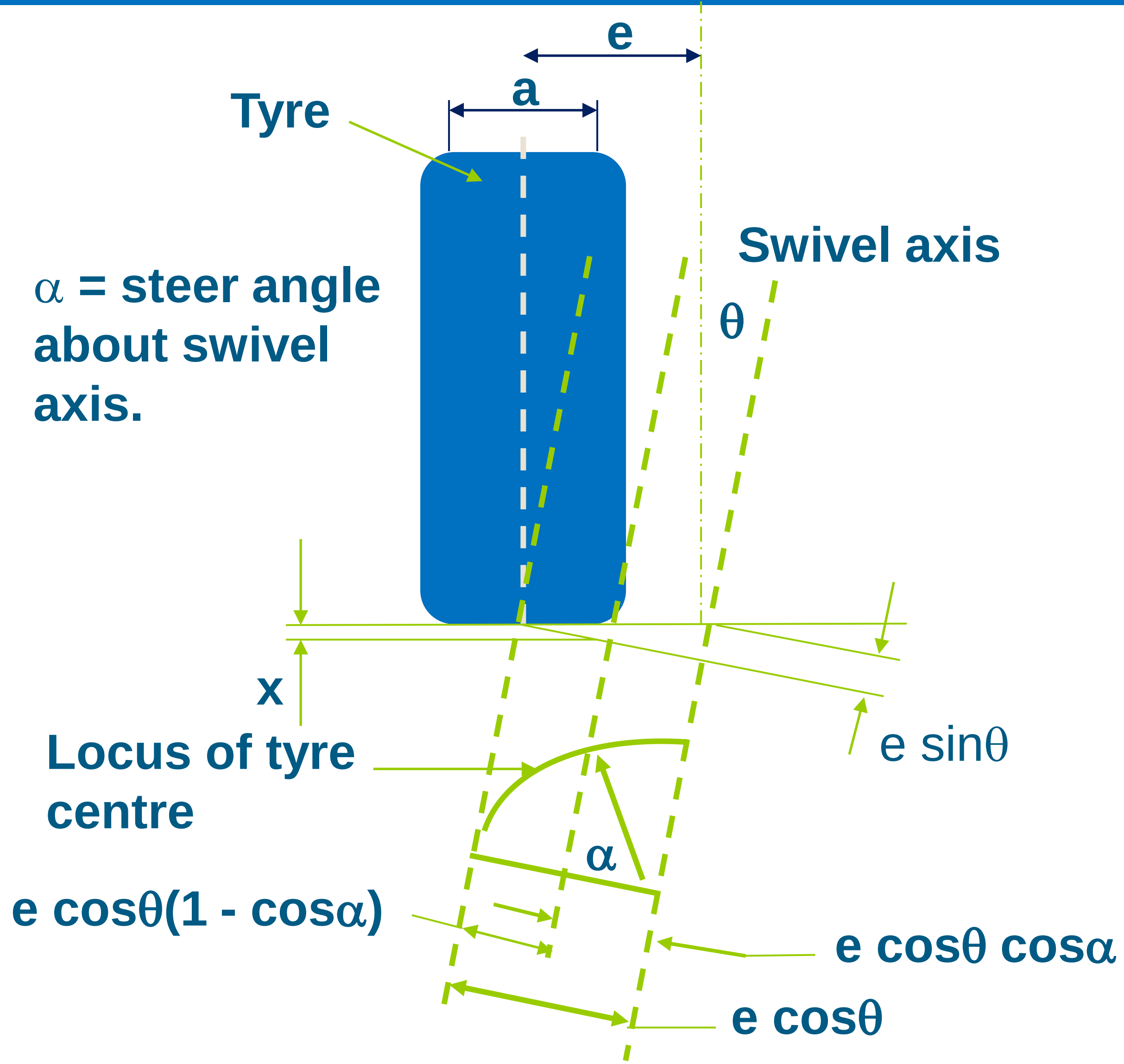
Equivalent offset is "h"

$h = [e^2 + (a/3)^2]^{1/2}$

$$M_S = \mu_e W h$$

[Parker, 2000]

Jacking Moment



x = e cosθ(1 - cosα)sinθ

$$\frac{dx}{dt} = \frac{dx}{d\alpha}\frac{d\alpha}{dt}$$

$$\frac{dx}{dt} = e \sin\theta \cos\theta \sin\alpha \frac{d\alpha}{dt}$$

Rate of work done in jacking the vehicle

$$W\frac{dx}{dt} = We \sin\theta \cos\theta \sin\alpha \frac{d\alpha}{dt}$$

Rate of work around swivel axis

$$M_J \frac{d\alpha}{dt}$$

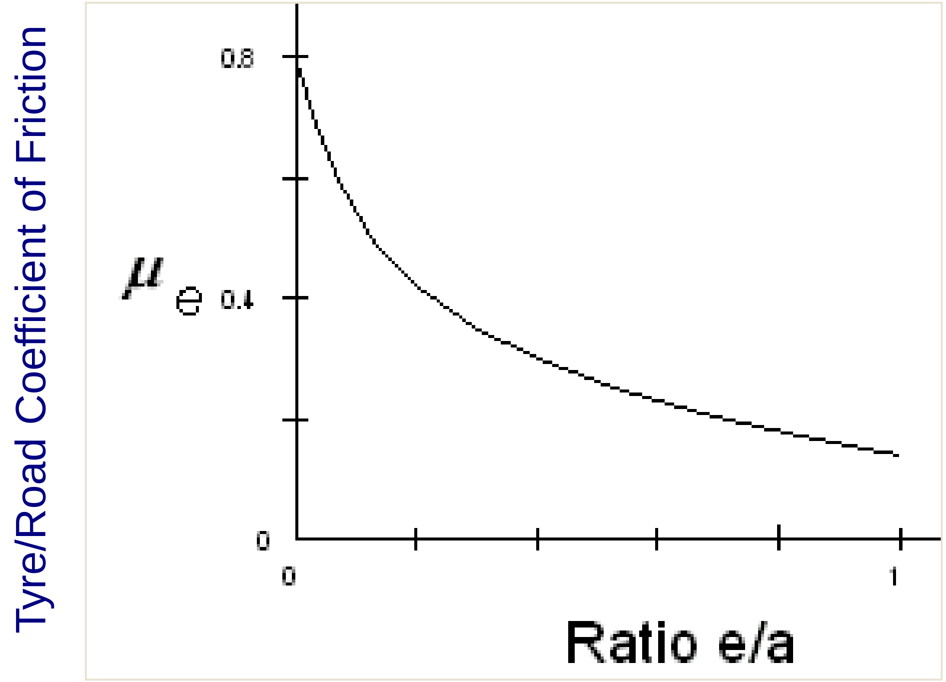
Equating gives

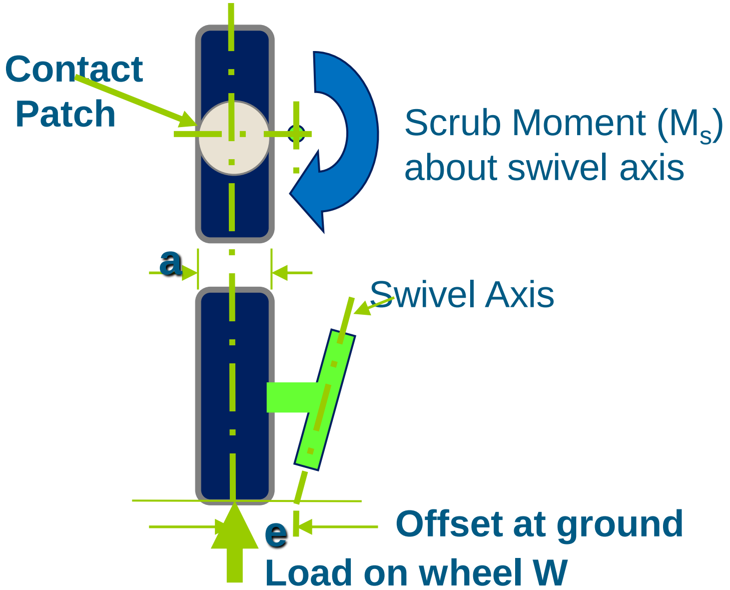
$$M_J = We \sin\theta \cos\theta \sin\alpha$$

Forces in a Stationary Vehicle

Total Moment

$$M_T = M_S + M_J$$





Design Calculations

Calculate Kingpin Torque

Determine Cylinder Force

Calculate Cylinder Area

Determine Cylinder Stroke

Calculate Swept Volume

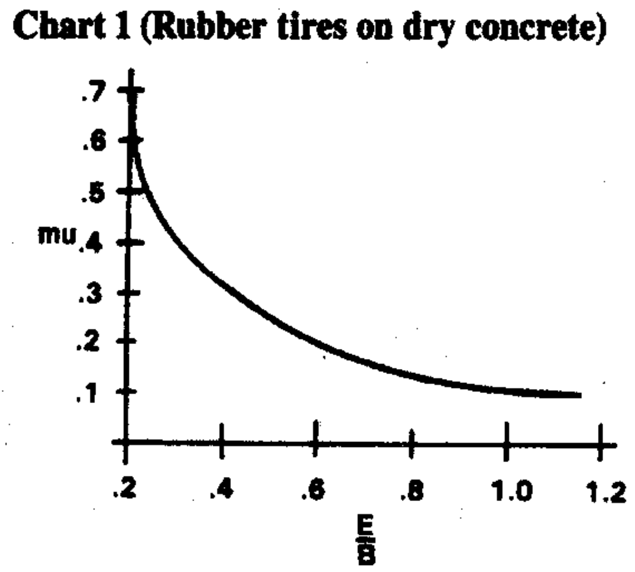
Calculate Displacement

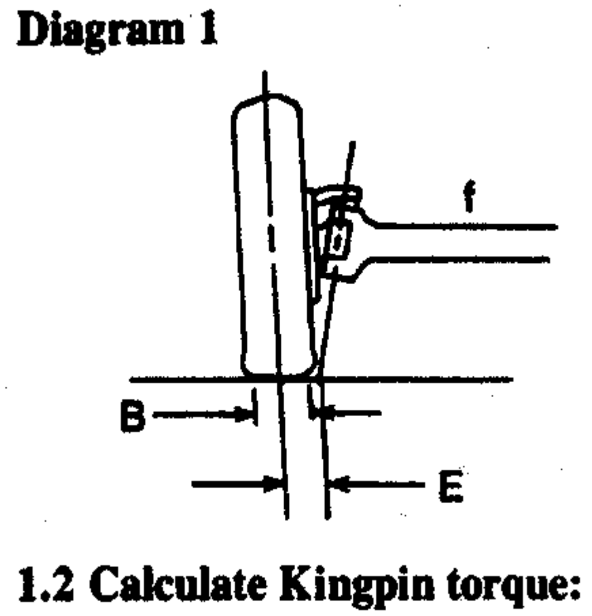
Calculate Minimum Pump Flow

Decide if pressure is suitable

Kingpin Torque (T_k)

First determine the coefficient of friction (μ) using the chart.
E is the Kingpin offset and B is the nominal tire width





Coefficient of Friction Chart and Kingpin Diagram (Parker)

(Parker, 2000)

Kingpin Torque

Information about the tire is needed. If we assume a uniform tire pressure then the following equation can be used.

$$T = W * \mu * \sqrt{\frac{I_o}{A} + E^2}$$

W = Weight on steered axle

I_o =Polar moment of inertia of tire print

A = area of tire print

μ. = Friction Coefficient

E = Kingpin Offset

Kingpin Torque

If the pressure distribution is known then the radius of gyration (k) can be calculated. The following relationship can be applied:

$$k^2 = \frac{I_o}{A}$$

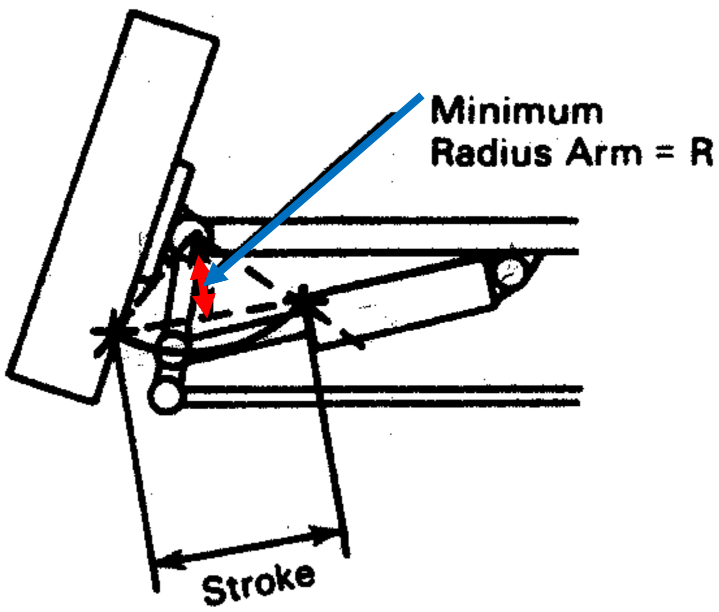
If there is no information available about the tire print, then a circular tire print can be assumed using the nominal tire width as the diameter

$$T_k = W * \mu \sqrt{\frac{B^2}{8} + E^2}$$

Calculate Approximate Cylinder Force (F_c)

$$F_C = \frac{T_K}{R}$$

F_c= Cylinder Force
R = Minimum Radius Arm
T_K= Kingpin Torque



Geometry Diagram (Parker)

Calculate Cylinder Area (A_c)

$$A_c = \frac{F_c}{P}$$

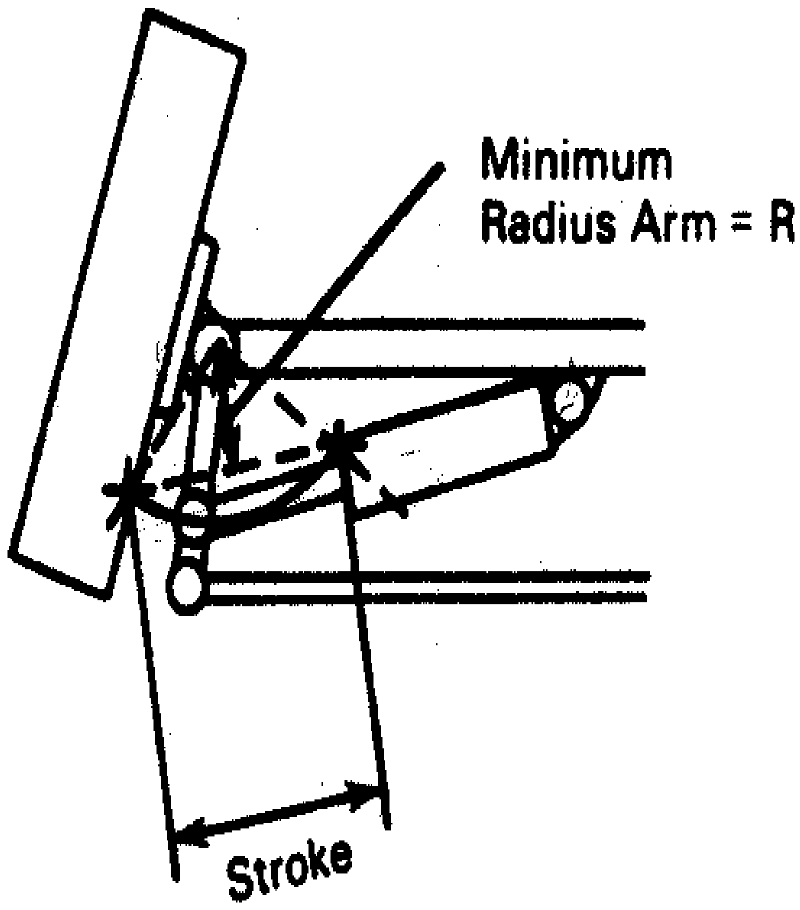
F_c = Cylinder Force

P = Pressure rating of steering valve

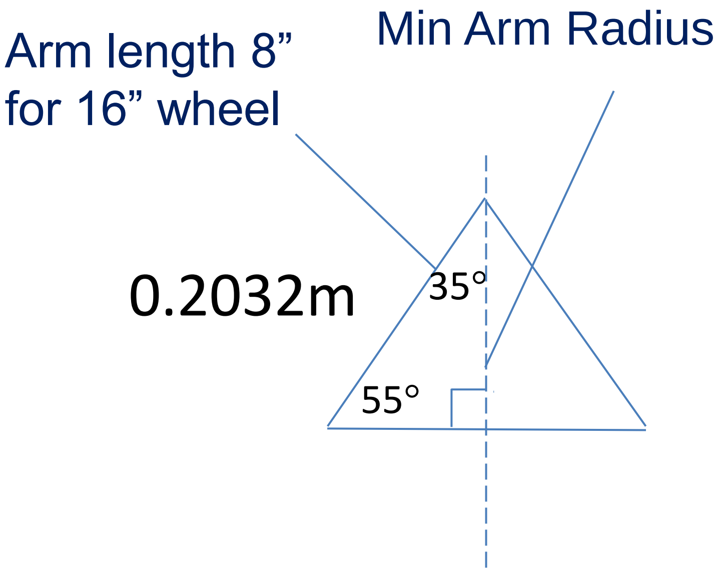
Select the next larger cylinder size

- For a single cylinder use only the rod area
- For a double cylinder use the rod end area plus the bore area

Determine Cylinder Stroke (S)



Geometry Diagram
(Parker)



Therefore 0.2032m x cos55º = 0.11655 m
Stroke is S=0. 11655m x 2 = 0.2331m

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Swept Volume (V_s) of Cylinder

Swept Volume - One Balanced Cylinder

$$V_S = \frac{\pi}{4} * (D_B^2 - D_R^2) * S$$

D_B = Diameter of bore
D_R = Diameter of rod
S = Stroke
V_s = Swept volume

Swept Volume of Cylinder

One Unbalanced Cylinder

$$V_s = \frac{\pi * D_B^2}{4} * S$$

Two Unbalanced Cylinders

$$V_s = \frac{\pi * S}{4}(2 * D_B^2 - D_R^2)$$

D_B = Diameter of bore
D_R = Diameter of rod
S = Stroke
V_s = Swept volume

Displacement

$$D = \frac{V_s}{n}$$

D = Displacement
n = Number of steering wheel (steering motor) turns lock to lock
V_s = Volume swept

Minimum Pump Flow

$$Q = \frac{D * N_s}{231}$$

N_s = steering speed in revolutions per minute
Q = Pump Flow is in LPM per revolution
D = Displacement

Steering Speed

The ideal steering speed is 120 rpm, which is considered the maximum input achievable by an average person

The minimum normally considered is usually 60 rpm

90 rpm is common

Technical Specification	
Operating Voltage	Nominal **13.8V DC**
Maximum current draw	**80 Amps**
System Weight	**6.45** kg
Maximum Torque Output	**110 Nm**
No Load Rotation Speed	**780** degrees per second

780 deg/s = 2.16 rev/s = 130 rev/min

Conclusions

- Requirements for AV remains the same as for driver vehicles
- Engine control can be achieved using Drive-By-Wire technology
- Steering control can be done by electronic steering racks

ANY QUESTIONS

???