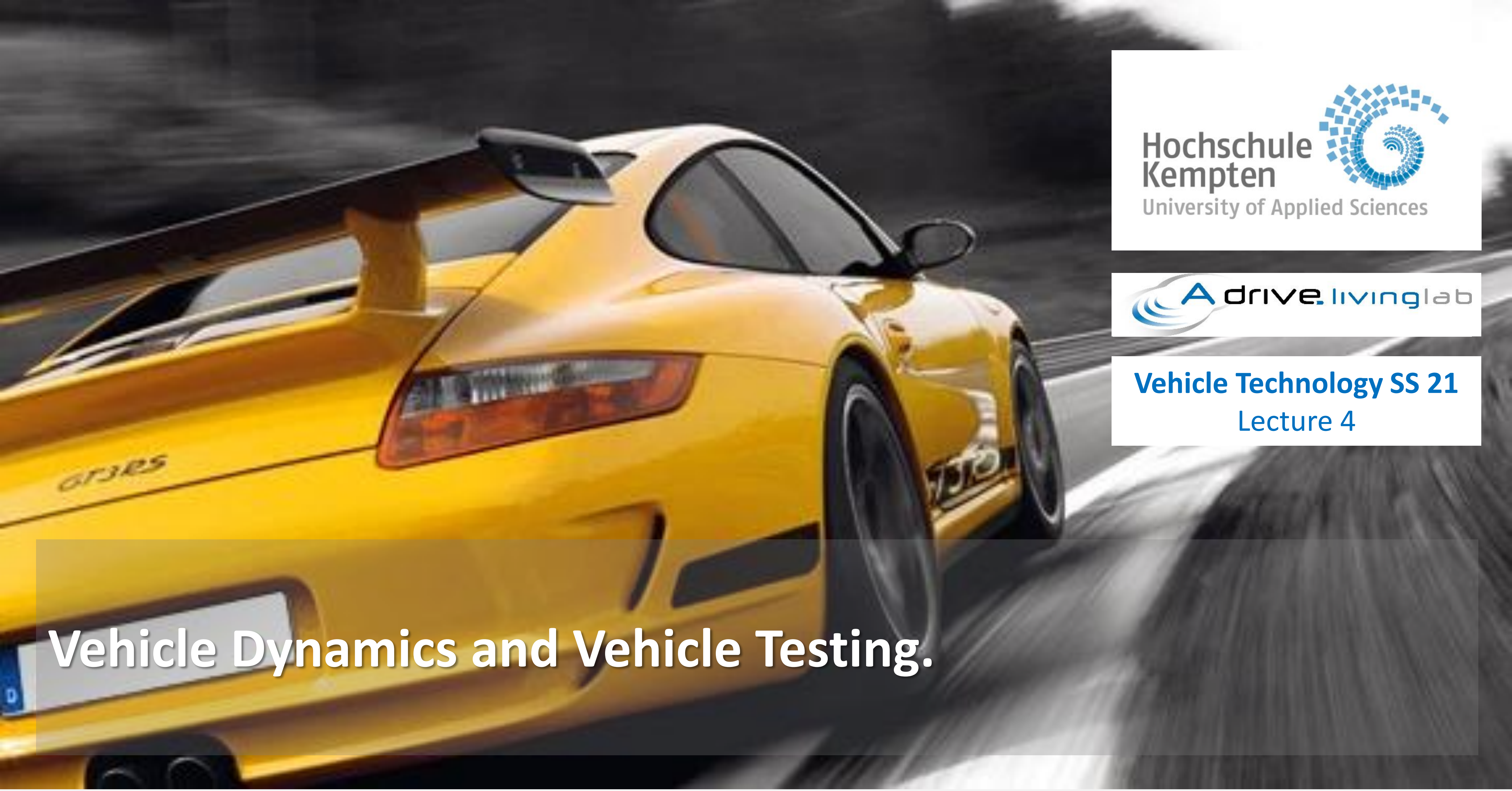


Hochschule Kempten
University of Applied Sciences

Vehicle Technology SS 21
Lecture 4

Vehicle Dynamics and Vehicle Testing.

Agenda

Nr.	Datum	Inhalt
1	19.03.	Introduction Vehicle dynamics
2	**26.03**	**Practical Training Vehicle Dynamics Simulation and Evaluation**
3	09.04.	Test and evaluation methods for vehicle attributes with practical simulation
4	16.04.	Chassis components and functions with practical simulation
5	30.04.	Basic vehicle dynamics calculation and vehicle models
6	**18.06**	**Track Day**
7	25.06.	ESP–Functions & Application & Process
8	**02.07.**	**ESP–Application & Hands-On Workshop**
9	09.07.	Project Day

Discussion Exercise 7: Lateral response behavior

Test Condition

- Speed: 100 kph
- a_y: **4** m/s²

Visualize:

- Steer.WhlAng, Car.ay, Car.YawRate, Car.Roll, Car.v

Parameter	Symbol	Unit	Left turn	Right turn	Average
Steady-state yaw velocity response gain	$\left(\frac{\dot{\psi}}{\delta_H}\right)_{ss}$	s^{-1}			
Lateral acceleration response time	T_{aY}	s			
Yaw velocity response time	$T_{\dot{\psi}}$	s			
Lateral acceleration peak response time	$T_{aY,max}$	s			
Yaw velocity peak response time	$T_{\dot{\psi},max}$	s			
Overshoot value of lateral acceleration	U_{aY}	—			
Overshoot value of yaw velocity	$U_{\dot{\psi}}$	—			

1. Change & Analyze Inertia Sensitivity:

1. Basic Tire

a. Inertia Izz * 4

b. Inertia Izz * 0.25

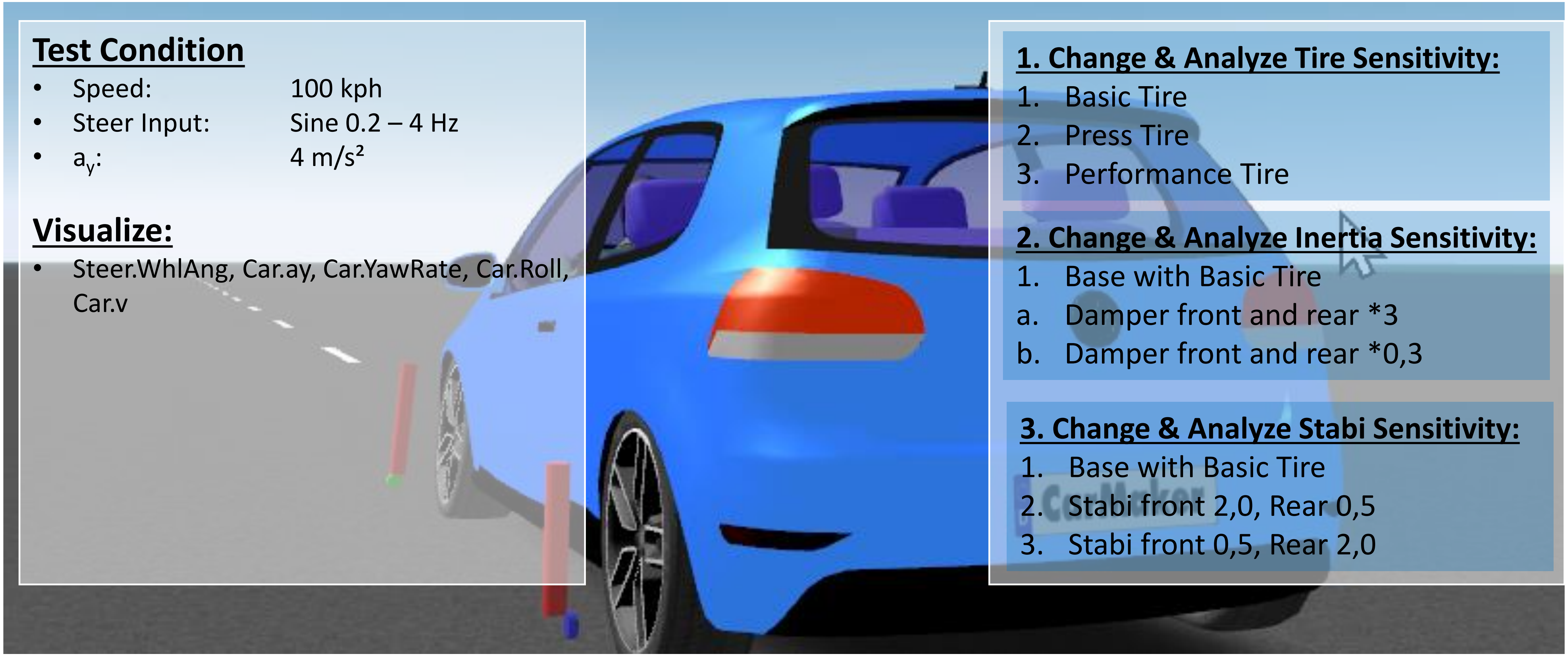
2. Change & Analyze Tire Sensitivity:

1. Basic Tire
2. Press Tire
3. Performance Tire

3. Change & Analyze Stabi Sensitivity:

1. Base with Basic Tire
2. Stabi front 2,0, Rear 0,5
3. Stabi front 0,5, Rear 2,0

Discussion Exercise 9: Frequency response behavior



Test Condition

- Speed: 100 kph
- Steer Input: Sine 0.2 – 4 Hz
- a_y: 4 m/s²

Visualize:

- Steer.WhlAng, Car.ay, Car.YawRate, Car.Roll, Car.v

1. Change & Analyze Tire Sensitivity:

1. Basic Tire
2. Press Tire
3. Performance Tire

2. Change & Analyze Inertia Sensitivity:

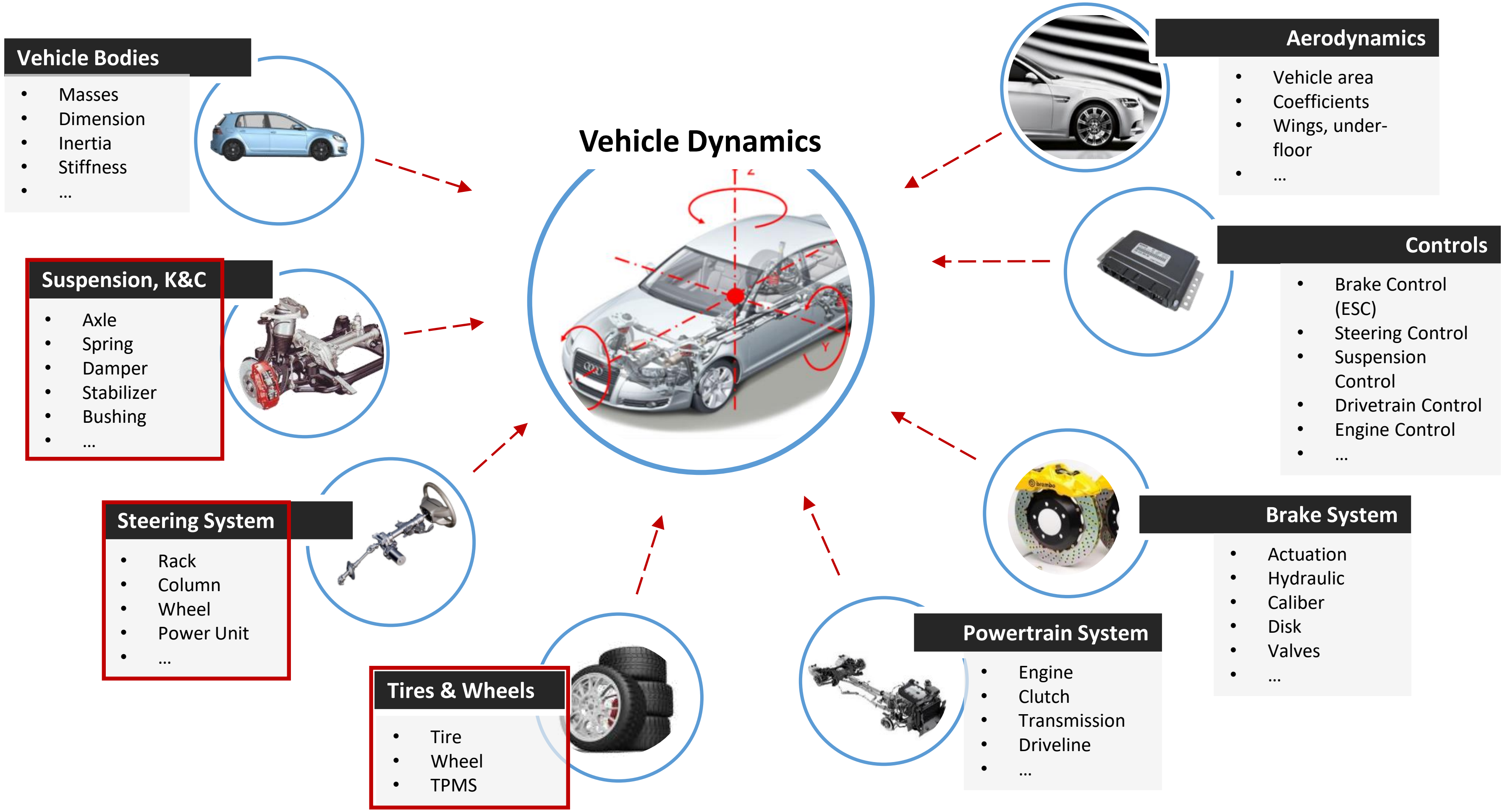
1. Base with Basic Tire

a. Damper front and rear *3
b. Damper front and rear *0,3

3. Change & Analyze Stabi Sensitivity:

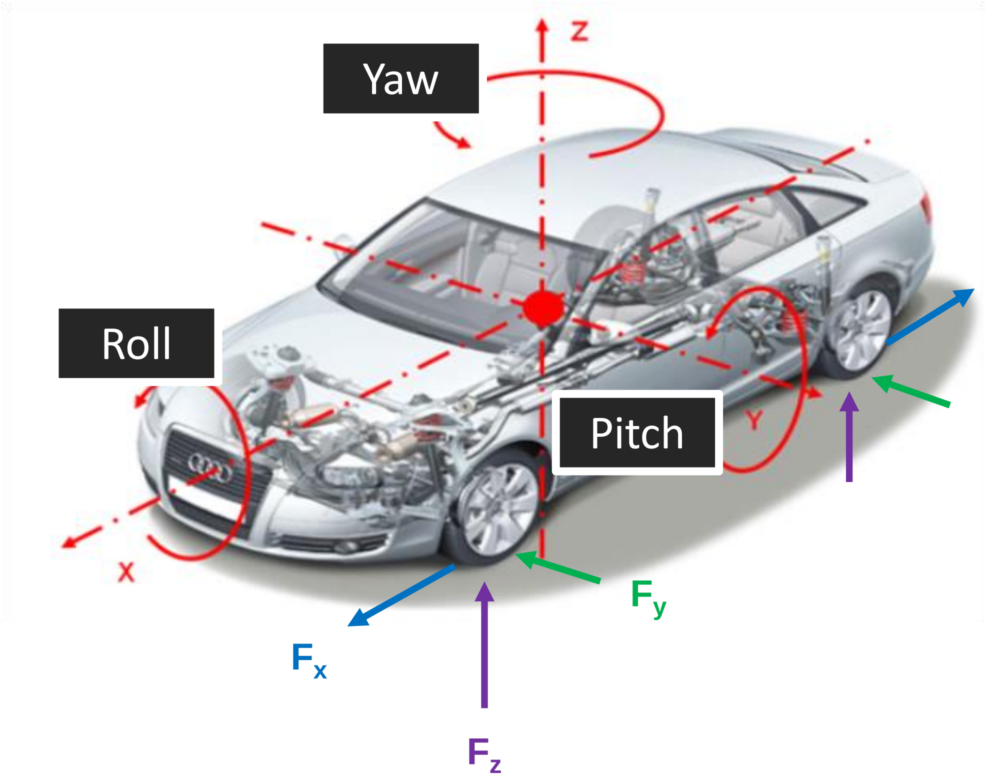
1. Base with Basic Tire
2. Stabi front 2,0, Rear 0,5
3. Stabi front 0,5, Rear 2,0

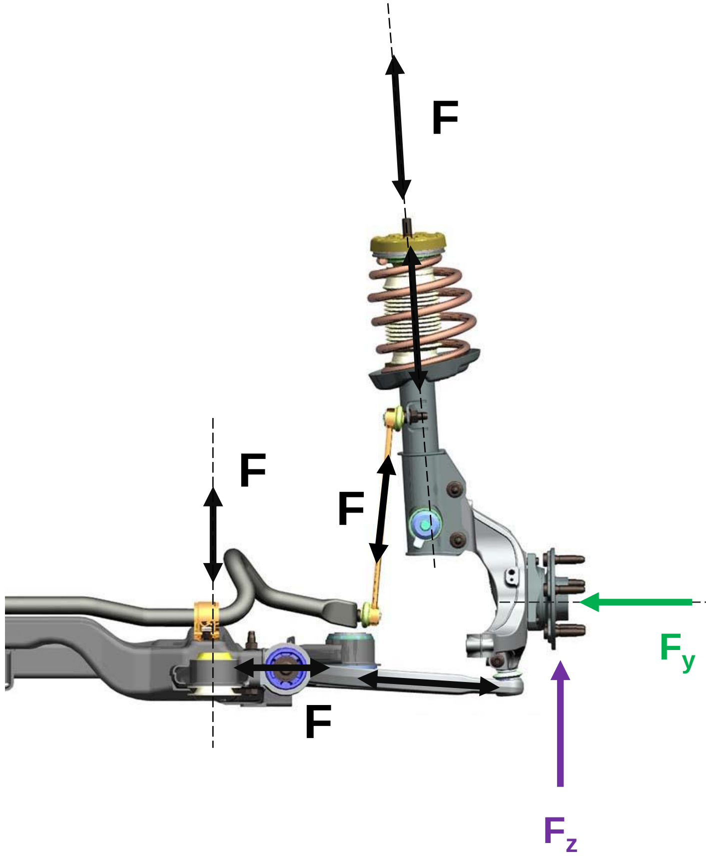
Vehicle dynamics behavior is impact by numerous components

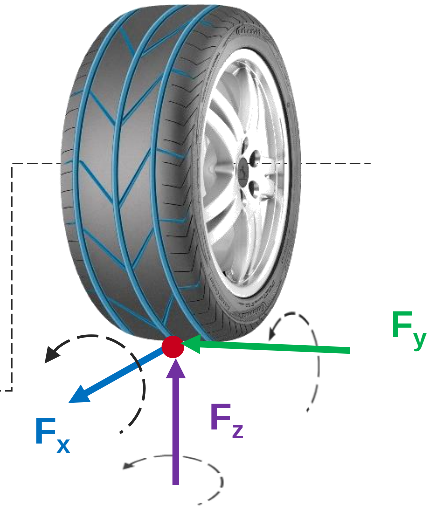


Chassis components and functions

The **vehicle motion dynamics** is a result of **external forces & moments** and leads to **internal forces & moments!**







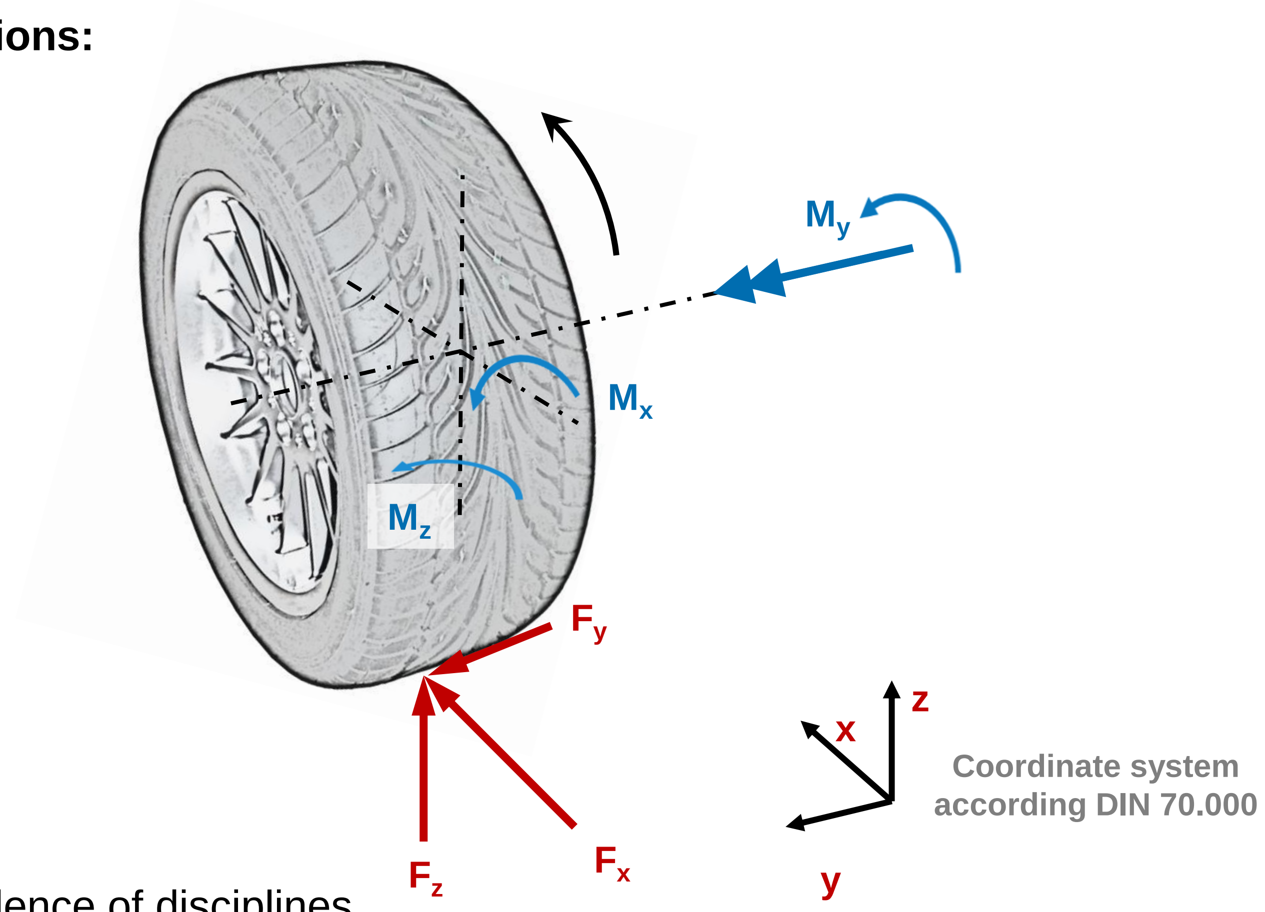
The tire is the "BLACK MAGIC" for transmission of forces between vehicle and track

Tires are the interface to the road environment

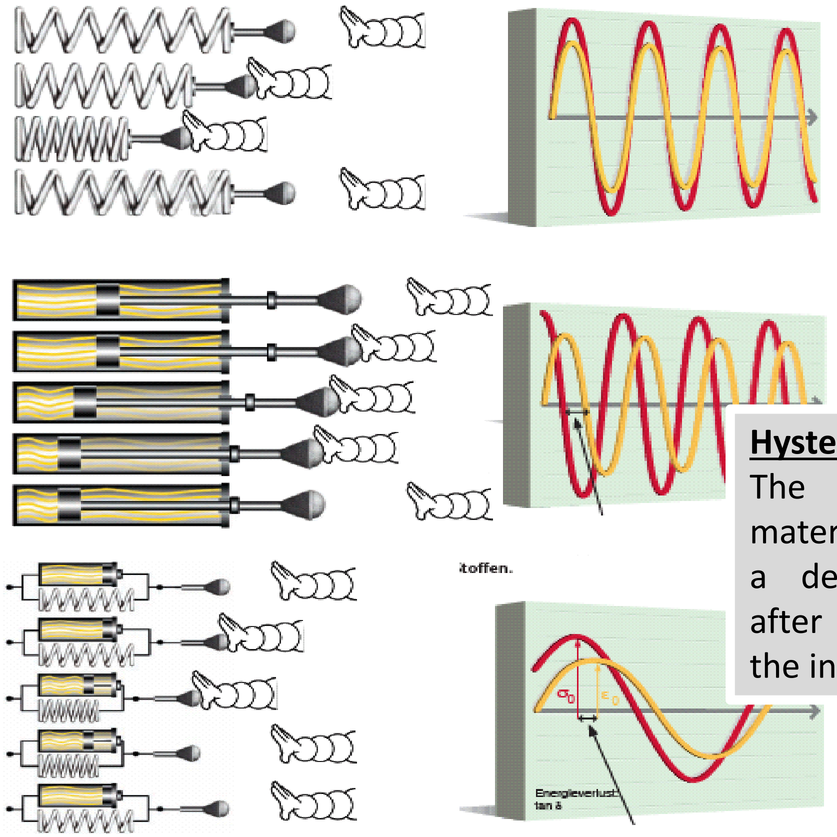
The behavior of the tire can be subdivide into 3 directions:

- Longitudinal Dynamic:
  - F_x = longitudinal force
  - M_y = Acceleration / Brake torque
  - referred as „longitudinal“.
- Lateral Dynamics:
  - F_y = lateral force
  - M_x = camber torque
  - M_z = Back alignment /toe torque
  - referred as “lateral”
- Vertical Dynamics:
  - F_z = Wheel load
  - referred as „vertical“.

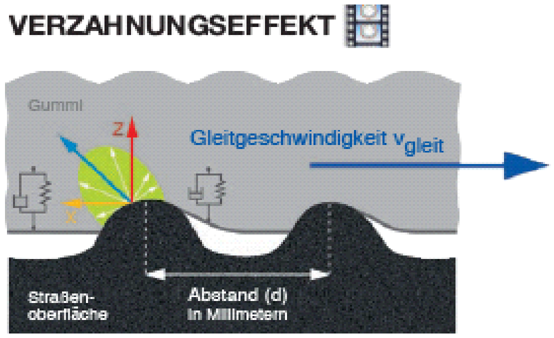
The overall performance is determined by the interdependence of disciplines



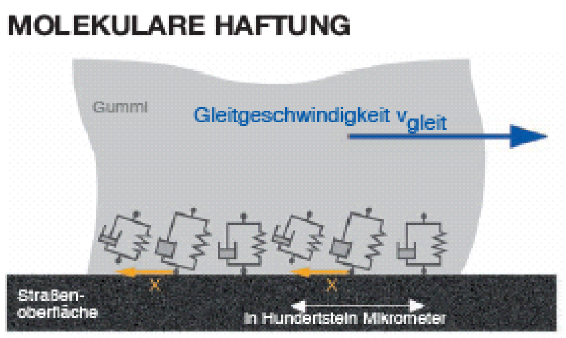
Tires, some fundamentals



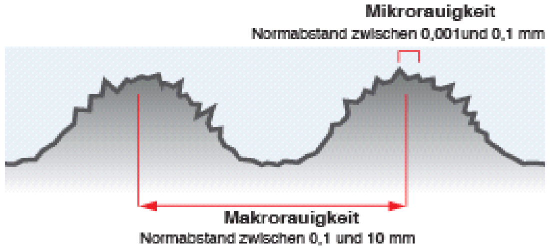
Hysteresis:
The viscous-elastic material returns from a deformation first after a while back to the initial position



Stößt der Gummiblock gegen eine Erhebung und verformt sich, so kehrt er hysteresebedingt nach der Entlastung nicht sogleich in seine Ausgangslage zurück. Diese asymmetrische Verformung erzeugt ein Kraftfeld, dessen Tangentialkomponente X dem Durchrutschen entgegenwirkt.

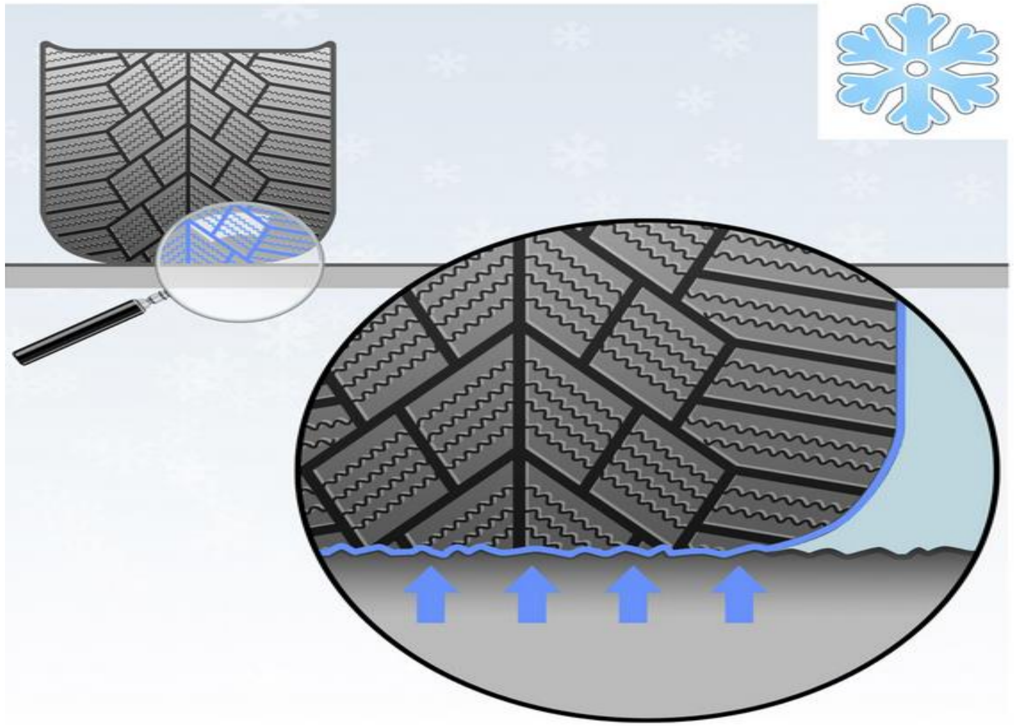


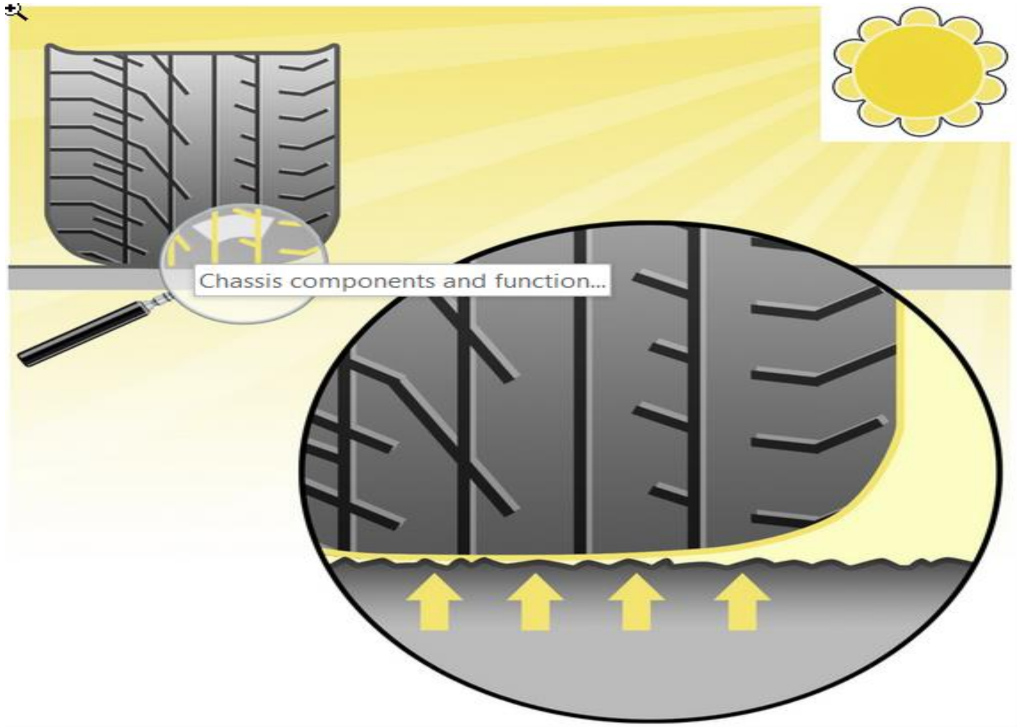
Die Molekülkette wird gedehnt: Aufgrund ihrer viskosen Eigenschaften, symbolisiert durch den Dämpferkolben, widerstehen die Moleküle zunächst der Verformung und erzeugen eine Reibungskraft X, die dem Durchrutschen entgegenwirkt.



- **Makrorauigkeit.** Dieser Begriff wird gebraucht, wenn der Abstand zwischen zwei 'großen" Erhebungen zwischen 100 Mikrometern und 10 Millimetern beträgt. Diese Größe unterstützt den Verzahnungseffekt sowie die Wasserabführung und -einlagerung. Über den Grad der Makrorauigkeit bestimmt das verwendete **Asphaltgranulat.**

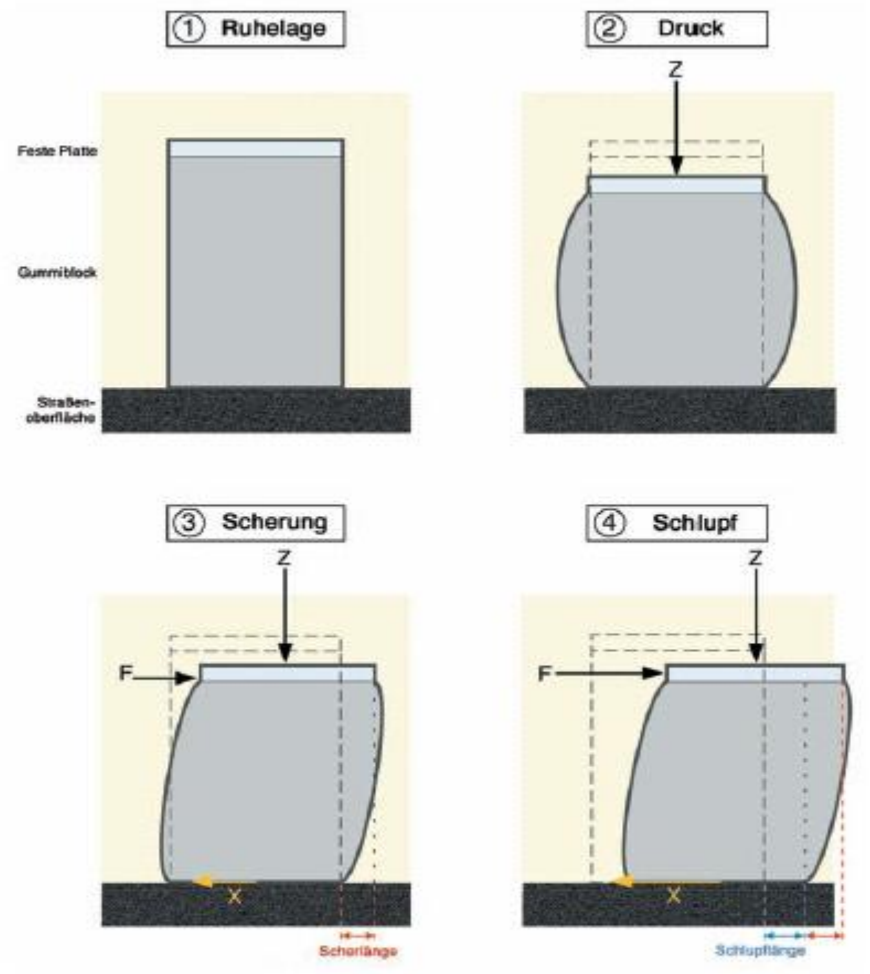
Tire slip mechanisms – shear, slide and slip

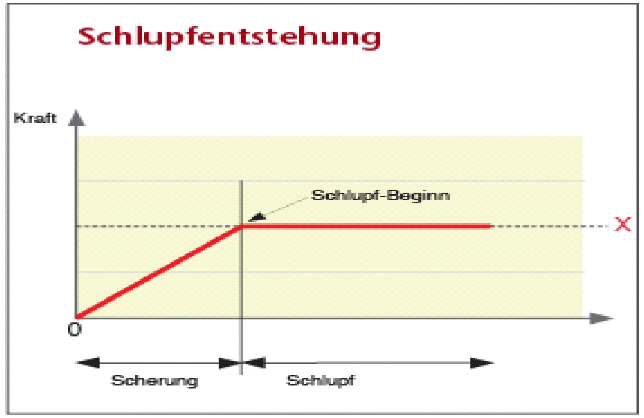


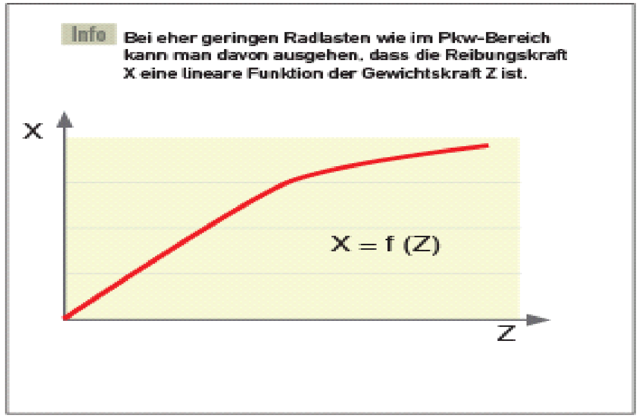


The soft tread compound of winter tires is still flexible even at low temperatures, so that winter tires remain slip-proof and optimally toothing with the road surface.

Target conflicts (trade-off) for the development







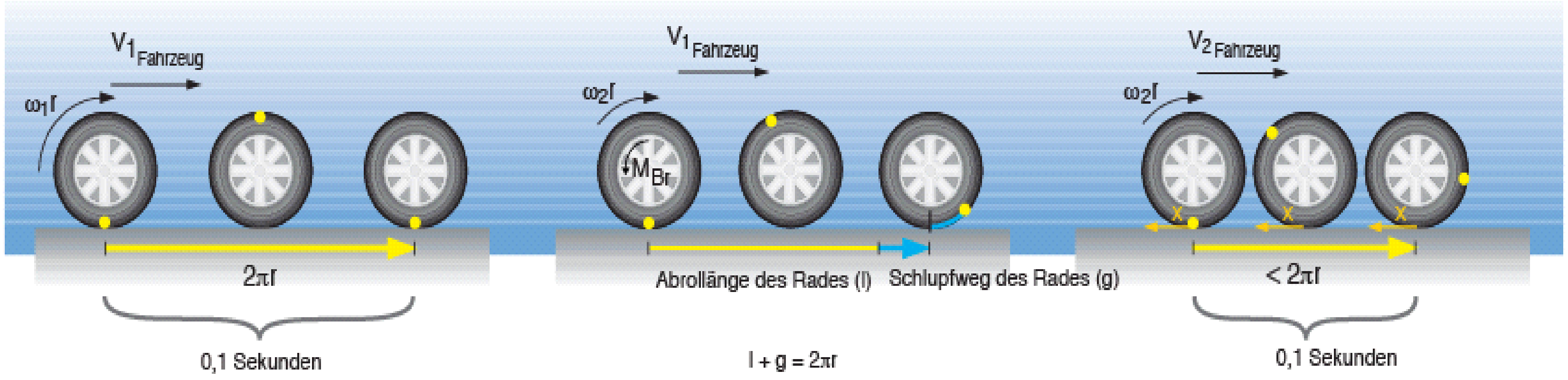
Tire longitudinal slip behavior

1 VOR BREMSBEGINN

Nehmen wir an, ein Rad lege eine Umdrehung (360°) innerhalb einer Zeit t = 0,1 s bei einer Fahrgeschwindigkeit v = 70 km/h zurück. Die in dieser Zeit vom rollenden Rad (und gleichzeitig vom Fahrzeug) zurückgelegte Strecke entspricht genau einer abgewickelten Radlänge oder, mathematisch ausgedrückt, $2 \cdot \pi \cdot r$.

2 WÄHREND DES BREMSVORGANGS

Sobald der Fahrer das Bremspedal niedertritt, fällt die Radumfangsgeschwindigkeit ($\omega \cdot r$) unter den Betrag der Fahrzeuggeschwindigkeit. Von diesem Moment an, wenn das Fahrzeug eine Strecke entsprechend $2 \cdot \pi \cdot r$ zurücklegt, vollführt das Rad keine vollständige Umdrehung mehr. Um der Vorwärtsbewegung des Fahrzeugs folgen zu können, rollt das Rad unter Schlupf ab. Dieser Radschlupf aktiviert die bekannten Haftungsmechanismen wie molekulare Haftung und Verzahnung. Die Reaktionskraft X wirkt dem Schlupf entgegen und das Fahrzeug verlangsamt sich: $v_{Fahrzeug}$ nimmt bis auf $\omega \cdot r$ ab. In besagten 0,1 s legt das Rad nun eine Strecke von weniger als $2 \cdot \pi \cdot r$ zurück.



$\boxed{V_{1\,Fahrzeug} = V_{Rad} = \omega_1 \cdot r}$

$\boxed{V_{1\,Fahrzeug} > \omega_2 \cdot r}$

$\boxed{V_{2\,Fahrzeug} = \omega_2 \cdot r}$

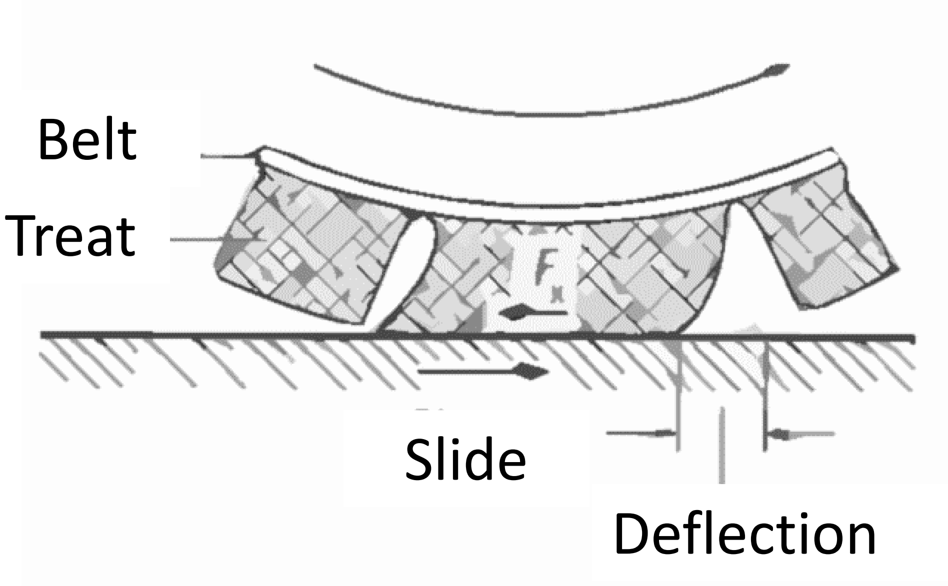
Definitionen:

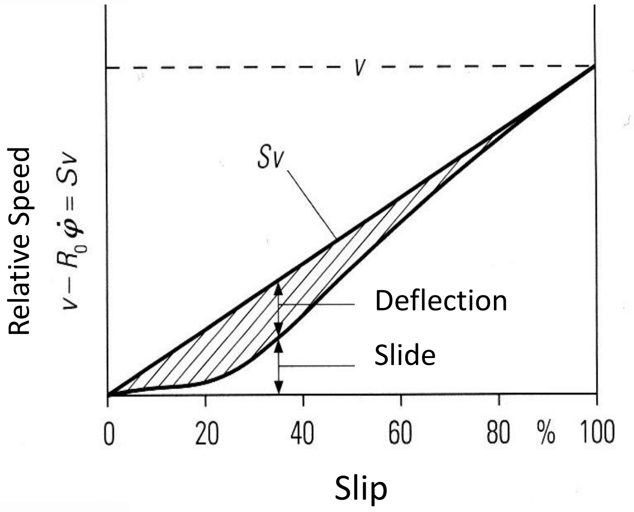
- ω = Winkelgeschwindigkeit des Rades, in 1/s
- r = Radradius, in m
- $\omega \cdot r$ = Radumfangsgeschwindigkeit, in m/s
- M_{Br} = Bremsmoment, in Nm

Wenn der Fahrer den Druck auf das Bremspedal beendet, nimmt die Fahrzeuggeschwindigkeit den Wert von $\omega \cdot r$ an: Der Schlupf nimmt ab.

Tire longitudinal characteristics: slip behavior

Tire longitudinal characteristics: slip behavior





Slip	Acceleration Slip	Brake Slip
$S = \frac{v_u - v}{v_u} \cdot 100\%$	$S_A = \frac{v_u - v}{v_u} \cdot 100\%$	$S_B = \frac{v - v_u}{v} \cdot 100\%$

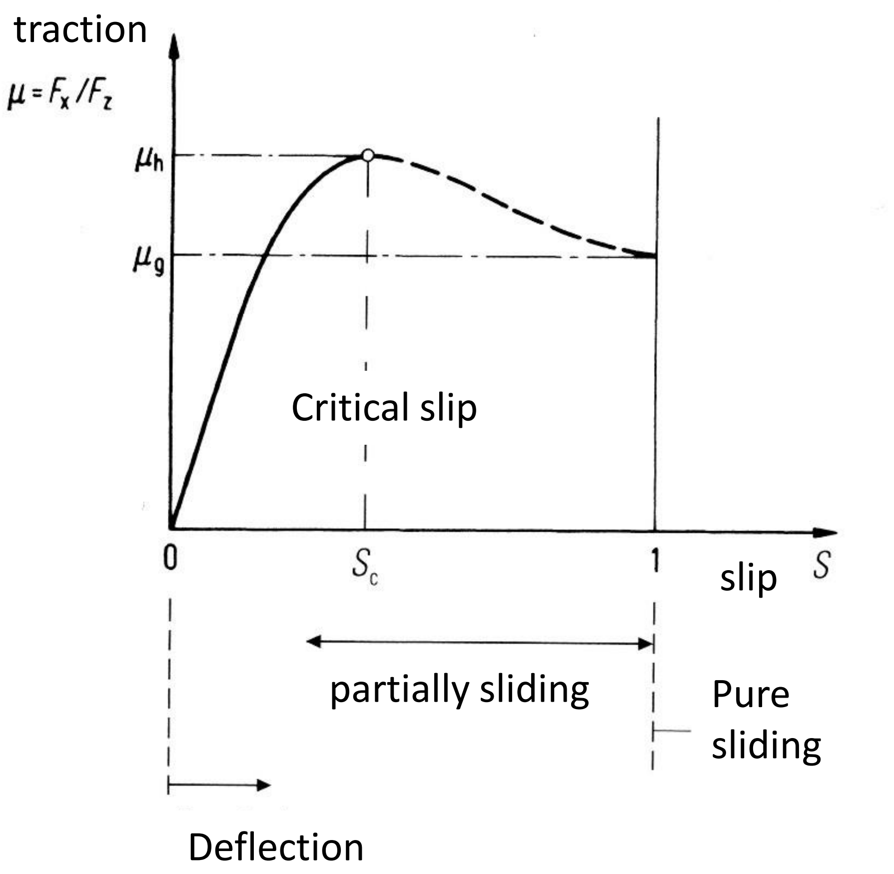
The longitudinal force F_x causes a shear deformation of the tire tread. When transferring this circumferential force between tire and road a slip (S or κ) occurs. The overall slip is put together as a deformation portion (deformation slip) and a sliding portion (sliding slip).

Tire longitudinal characteristics: slip behavior

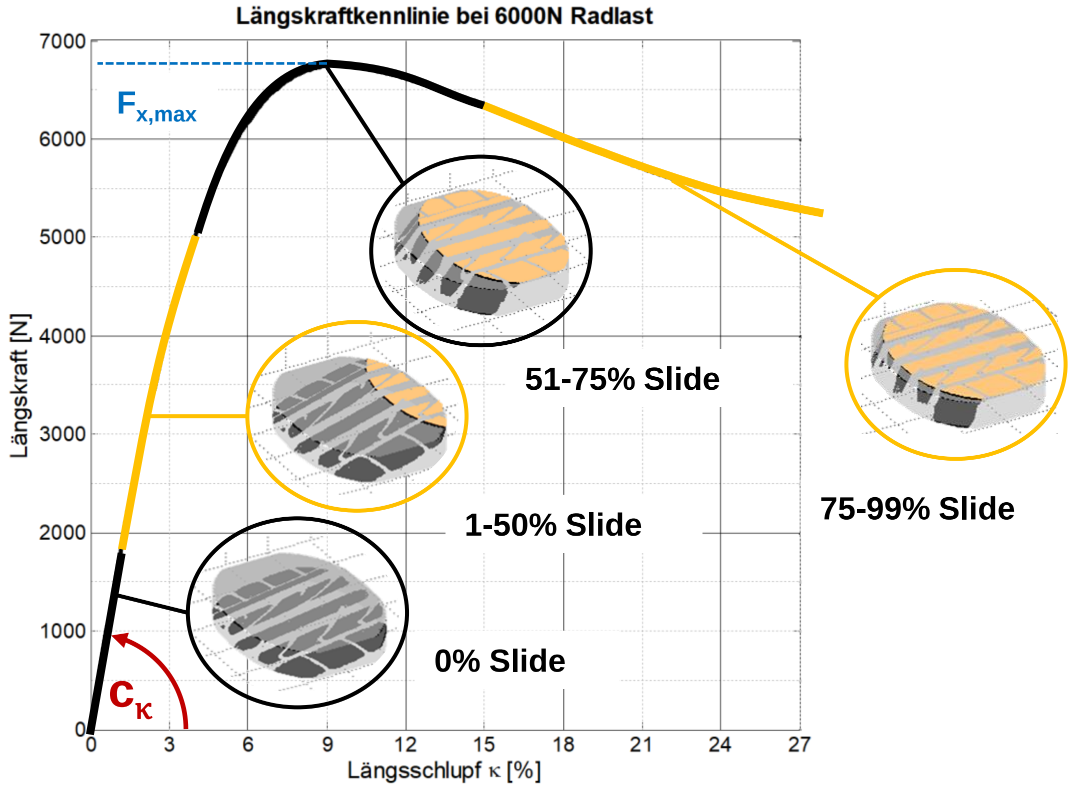
- Transferable force are defined by the adhesion coefficient μ.
- μ is at rubber friction a function of the slip

$$\mu = \frac{F_x}{F_z}$$

- μ_h defines the maximum traction, defined al friction coefficient.
- The corresponding slip is defined as “critical slip” S_c and ~10%.
- At 100% slip the traction is decreased to the sliding frication μ_g.



Tire longitudinal characteristics: slip behavior



$$F_x = c_\kappa \cdot S$$

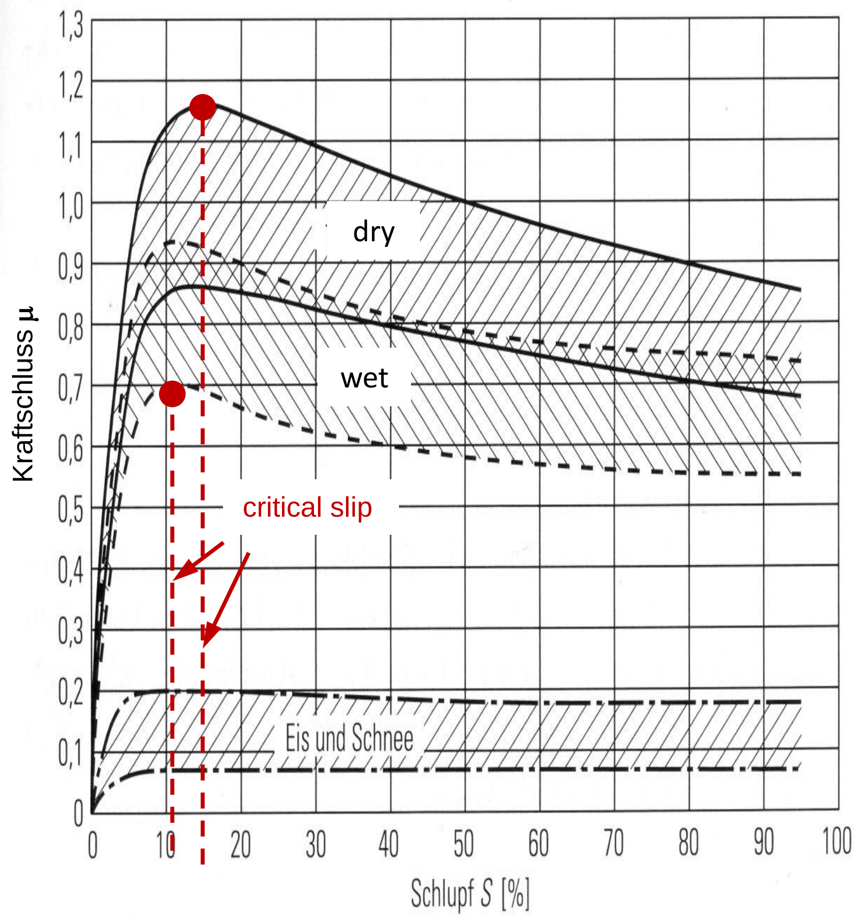
For small longitudinal forces, there is a linear relationship between S and Fx.

c_κ = slip stiffness

$$c_\kappa = \frac{dF_x}{dS} = f(F_z)$$

Influences:

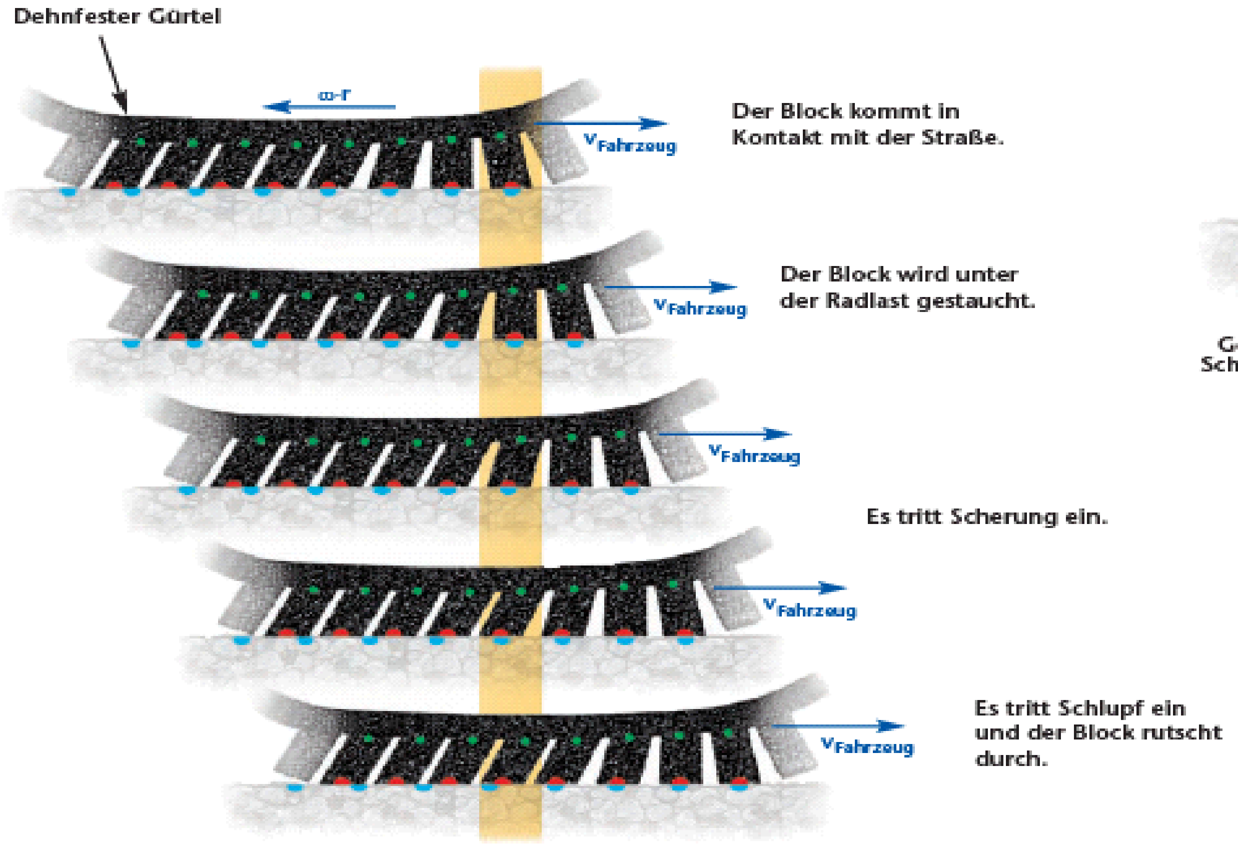
- Tire pressure
- Temperature
- Local friction

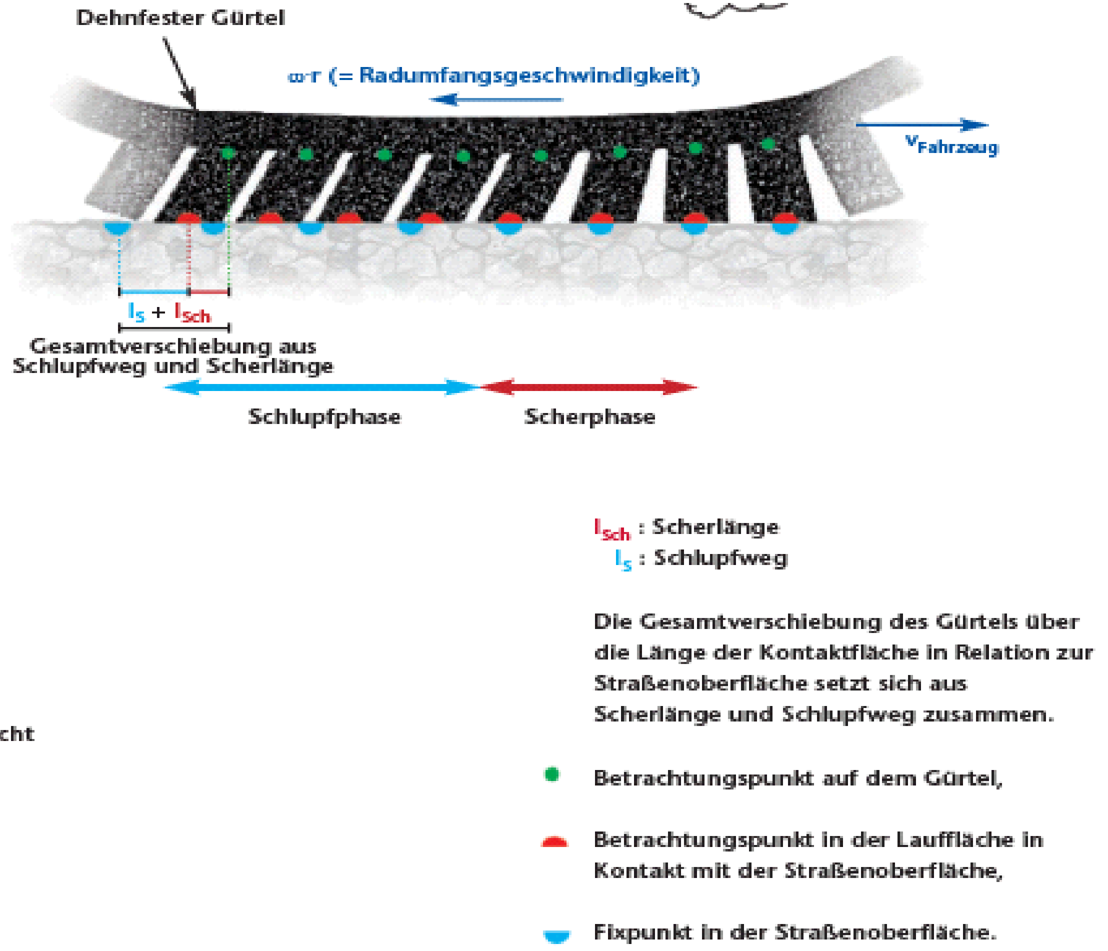


$$F_{x,\max} = \mu_h \cdot F_z$$

The maximal longitudinal force is depended on the friction (e.g. $\mu_h \approx 1{,}1$)

Tire longitudinal characteristics: slip behavior





Tire Rolling Resistance (RR) - Sources

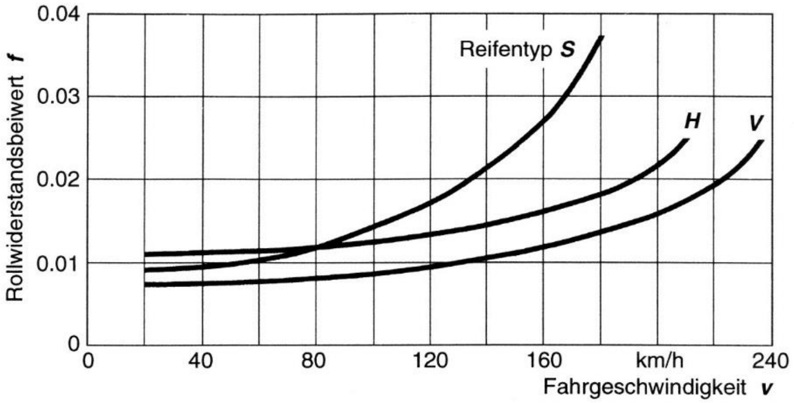
Tire surface and environmental air	Tread of the tire		Side wall and bead area
Air turbulence 	Slip to the ground 	Energy loss dissipation based on deformation Bend - Strain - Sheer 	Bend - Sheer 
< 15 %		**60 up to 70 %**	**20 up to 30 %**

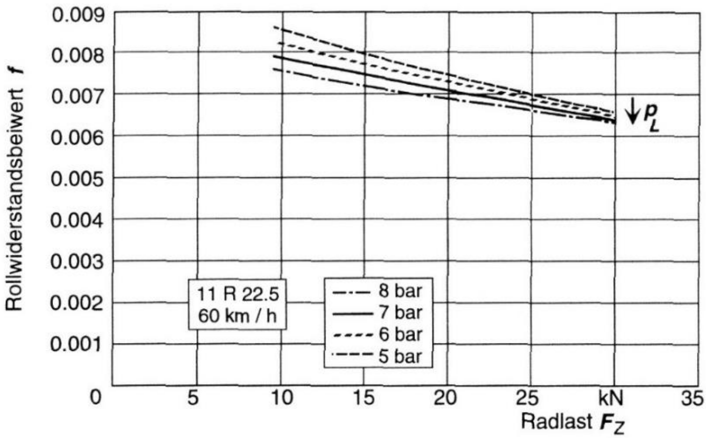
Tire Rolling Resistance (RR) - Sources

$$F_{R,roll} = f_R \cdot F_z$$

<u>Roll resistance is depended of:</u>

- wheel load
- tire pressure
- Tire temperature





$$f_R = f_{R0} + f_{R1} \cdot \left(\frac{v}{100\, km/h} \right) + f_{R4} \cdot \left(\frac{v}{100\, km/h} \right)^4$$

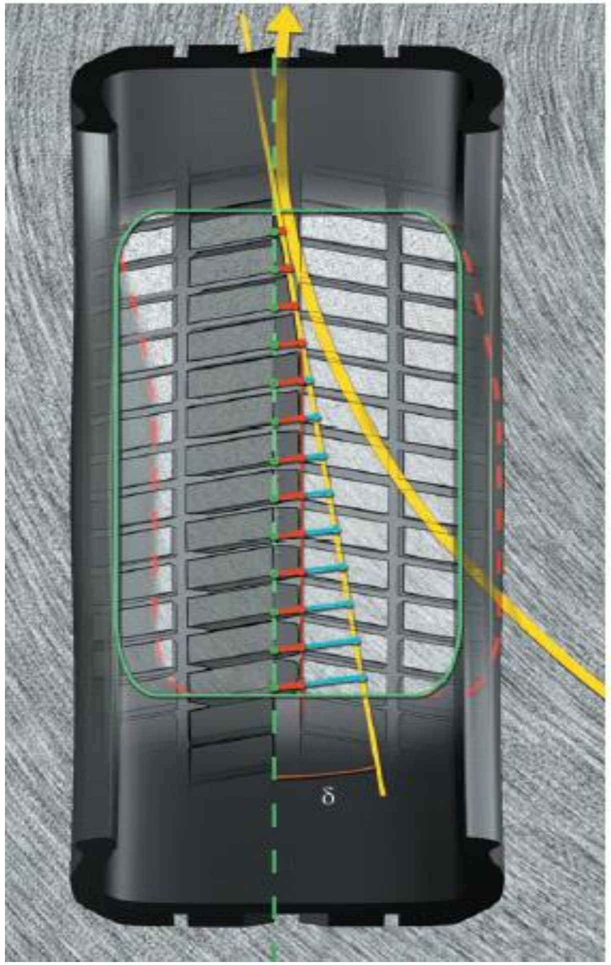
for HR-tires:

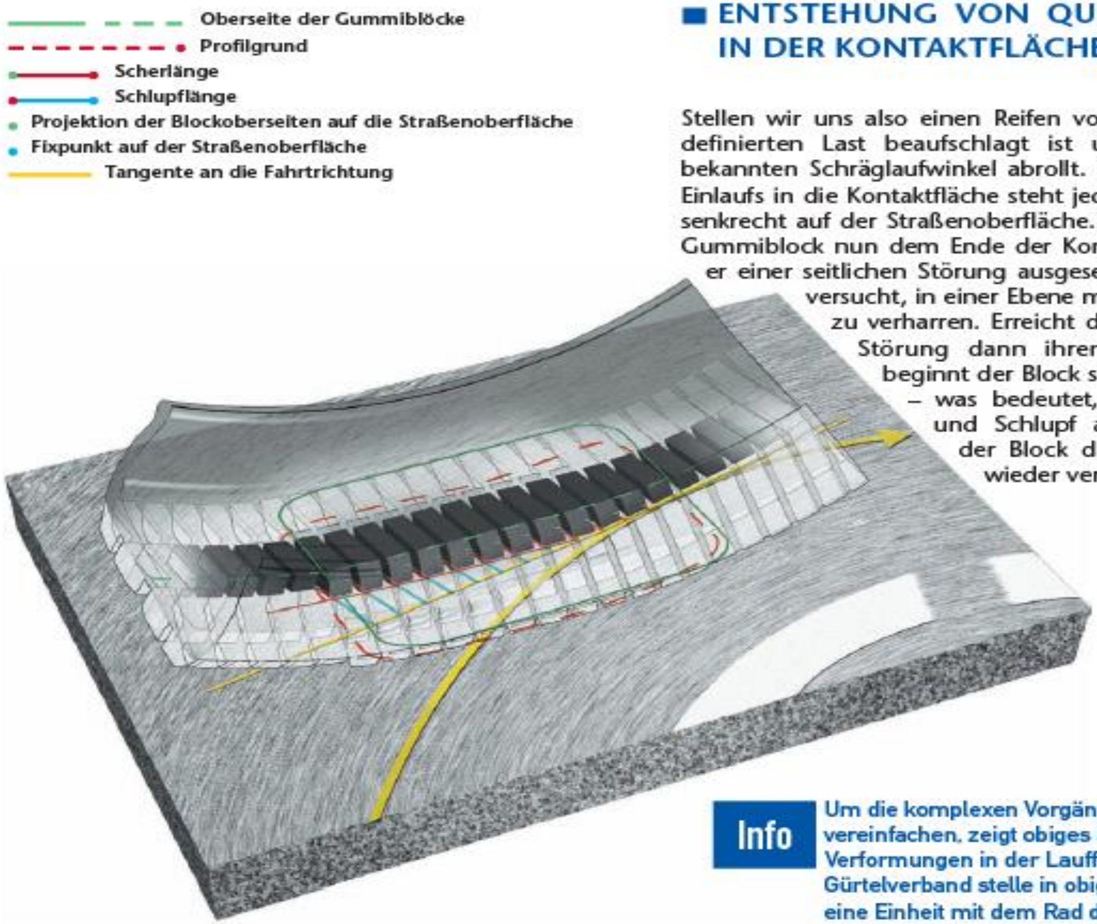
$f_{R0} \approx 0{,}009$
$f_{R1} \approx 2{,}0 \cdot 10^{-3}$
$f_{R4} \approx 0{,}25 \cdot 10^{-3}$

F_R is often assumed to be constant and at a value of 0,01.

Tire lateral characteristics: side slip behavior

Tire lateral characteristics: side slip behavior





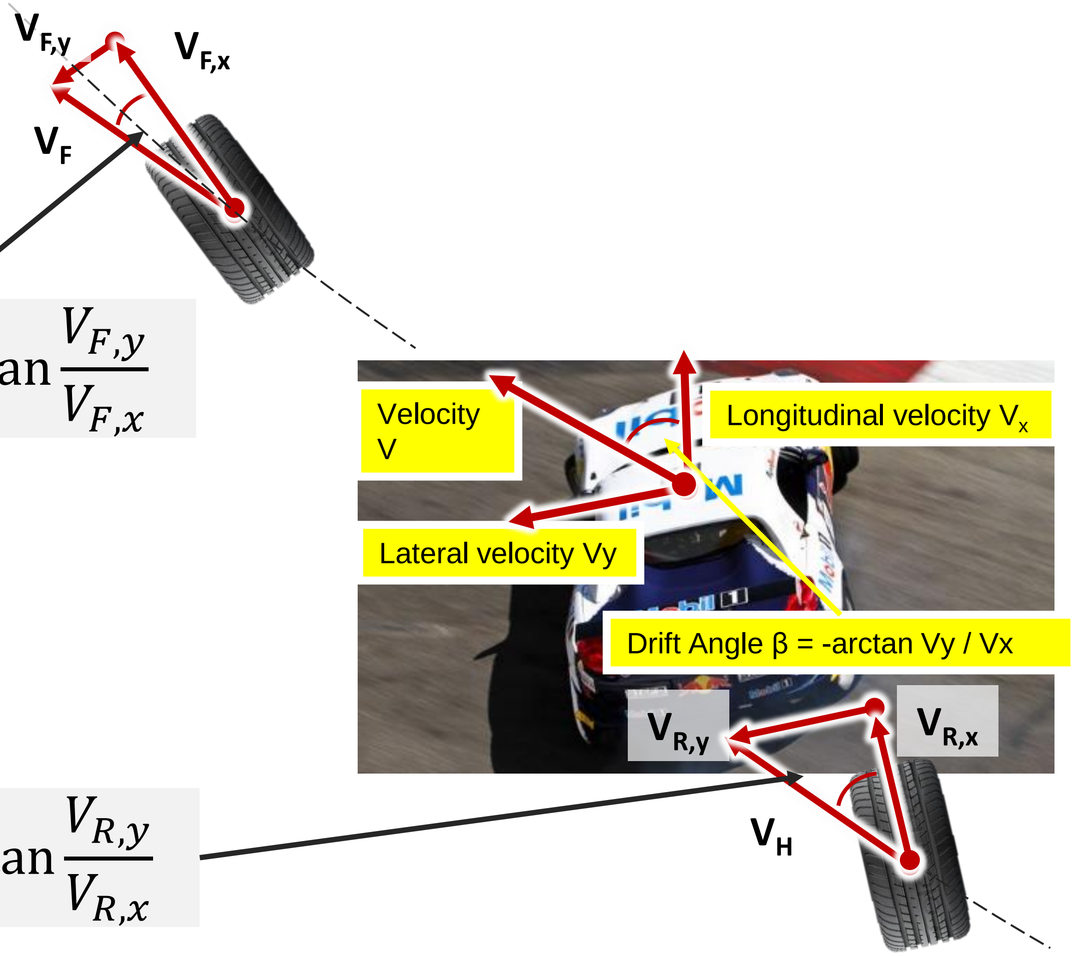
ENTSTEHUNG VON QUERKRÄFTEN IN DER KONTAKTFLÄCHE

Stellen wir uns also einen Reifen vor, der mit einer definierten Last beaufschlagt ist und mit einem bekannten Schräglaufwinkel abrollt. Im Moment des Einlaufs in die Kontaktfläche steht jeder Gummiblock senkrecht auf der Straßenoberfläche. Nähert sich der Gummiblock nun dem Ende der Kontaktfläche, wird er einer seitlichen Störung ausgesetzt, während er versucht, in einer Ebene mit der des Rades zu verharren. Erreicht die Gummiblock-Störung dann ihren Maximalwert, beginnt der Block seitlich zu gleiten – was bedeutet, dass Scherung und Schlupf auftreten, bevor der Block die Kontaktfläche wieder verlässt.

Info Um die komplexen Vorgänge zu vereinfachen, zeigt obiges Schaubild nur die Verformungen in der Lauffläche. Der Gürtelverband stelle in obiger Illustration eine Einheit mit dem Rad dar.

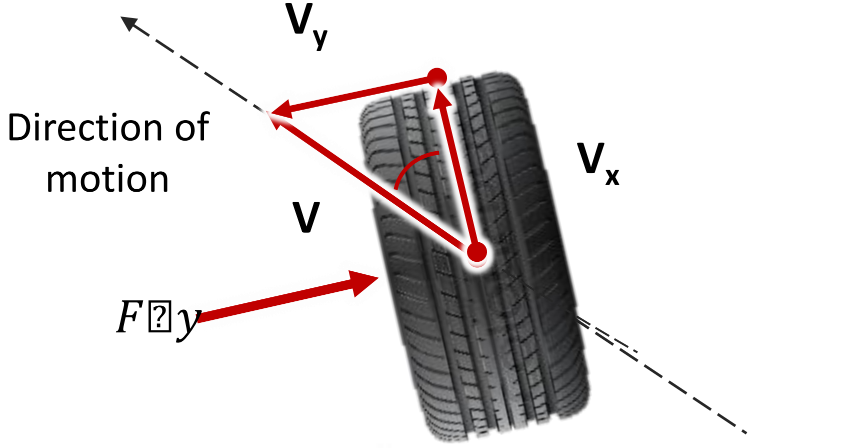
Tire lateral characteristics: side slip behavior

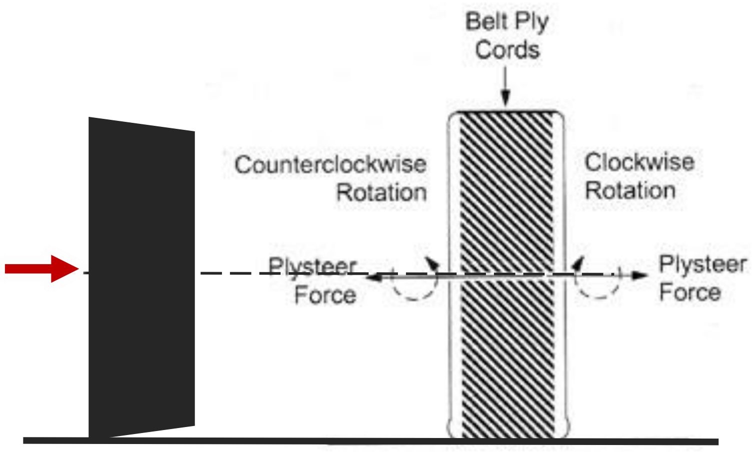
$$\alpha_F = -\arctan\frac{V_{F,y}}{V_{F,x}}$$



$$\alpha_R = -\arctan\frac{V_{R,y}}{V_{R,x}}$$

Tire lateral characteristics: side slip behavior





Conicity

Ply steer

<u>Side slip α:</u>

- Angle between direction of motion and direction of wheel plane.

$$\alpha = -\arctan\frac{V_y}{V_x}$$

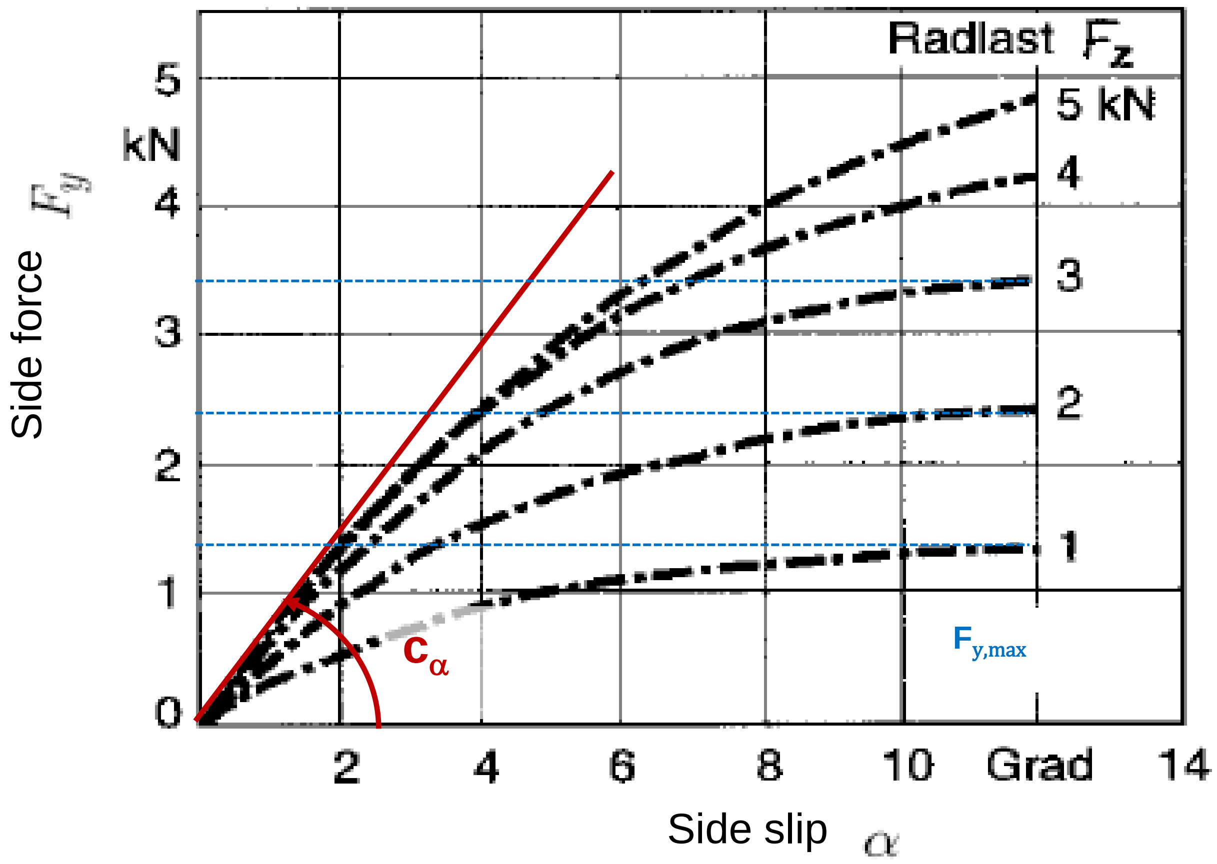
<u>Tire side force generated by:</u>

- Rolling diagonal to the direction of motion (side slip angle **α**).
- Inclination of the tire from its vertical position to the road (camber γ).
- Tire conicity (geometrical)
- Ply steer (tread/belt construction)

<u>Side force as result of side slip angle:</u>

- Wind, centrifugal or gravity forces requested tire forces.
- The vehicle must apply side slip.

Tire lateral characteristics: side slip behavior



$$F_y = c_\alpha \cdot \alpha$$

- For side slip angle to approximately 4°, there is a linear relationship between **α** and Fy.
- c_α is called side slip stiffness.

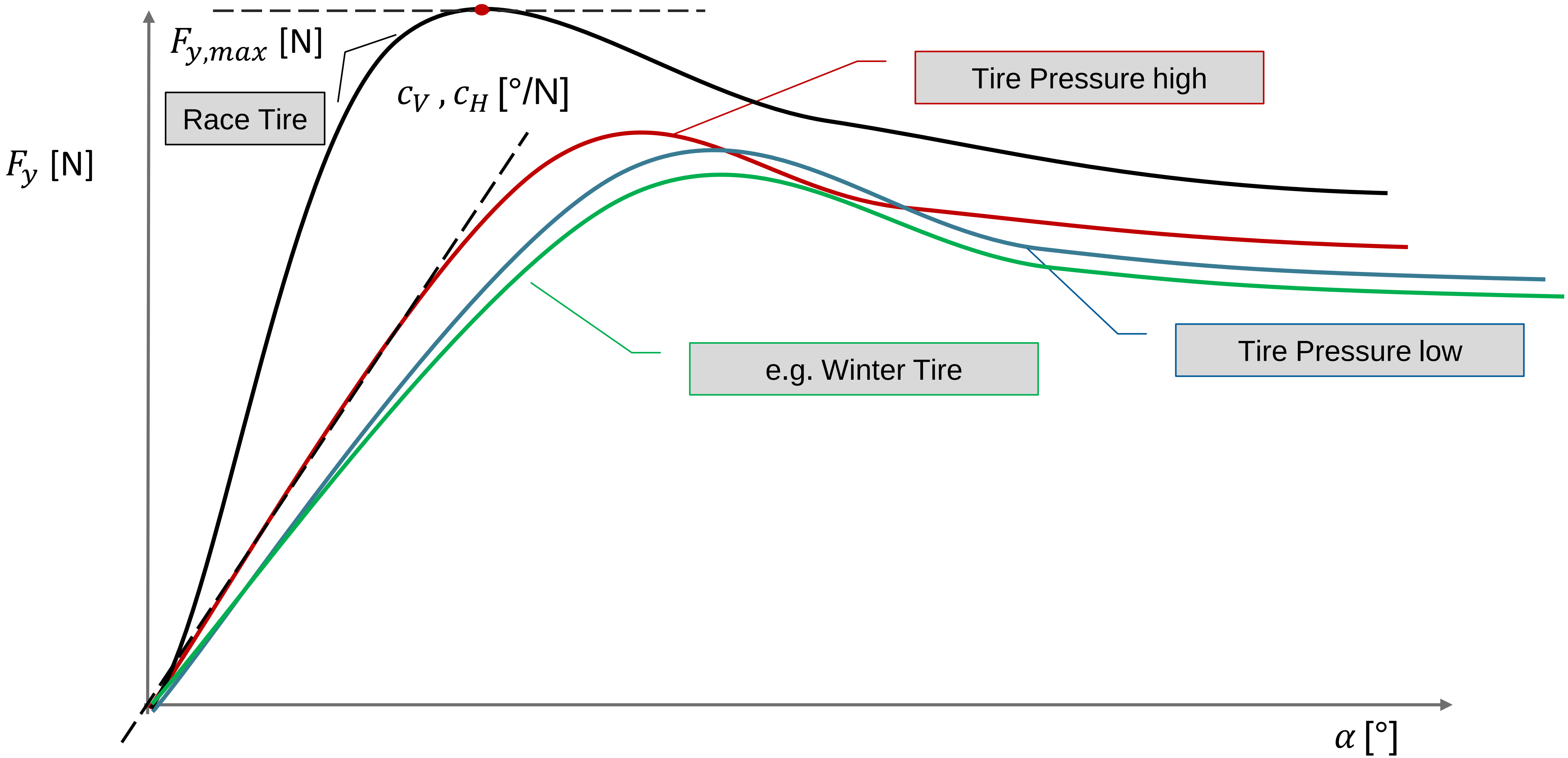
$$c_\alpha = \frac{dF_y}{d\alpha} = f(F_z)$$

- **Influences to c_α:**
  - Tire pressure.
  - Temperature.
  - Local friction
  - Wheel load

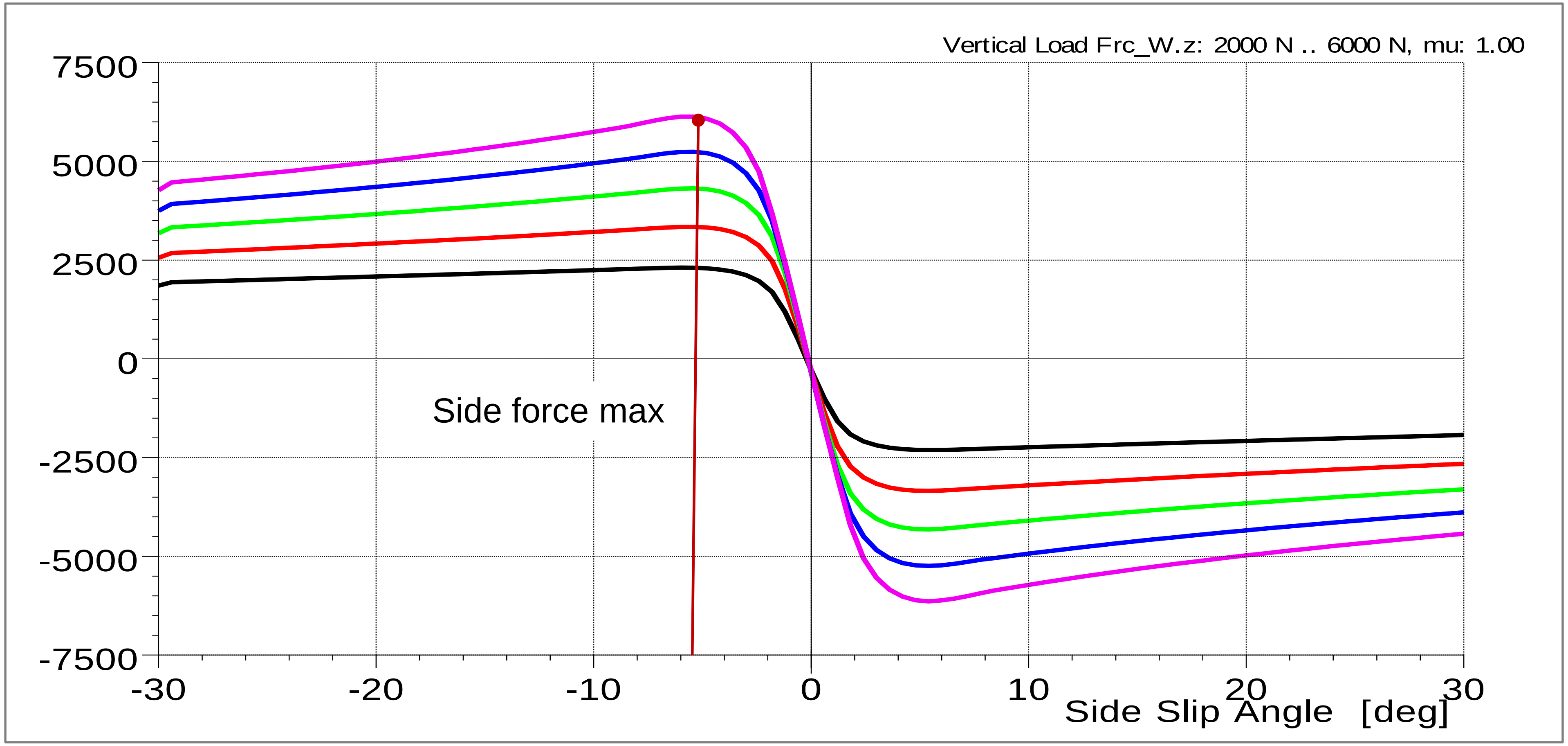
$$F_{y,\max} = \mu_{y,\max} \cdot F_z$$

- The maximum transferable lateral forces are dependent on maximum adhesion in lateral direction.

Tire characteristics for understeer behavior (qualitative)

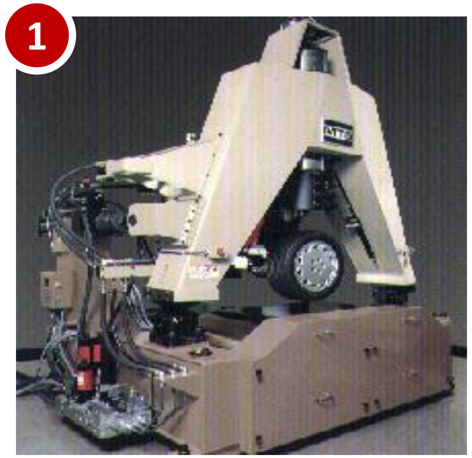


Tire lateral characteristics: side slip behavior



Tire characteristics measurement

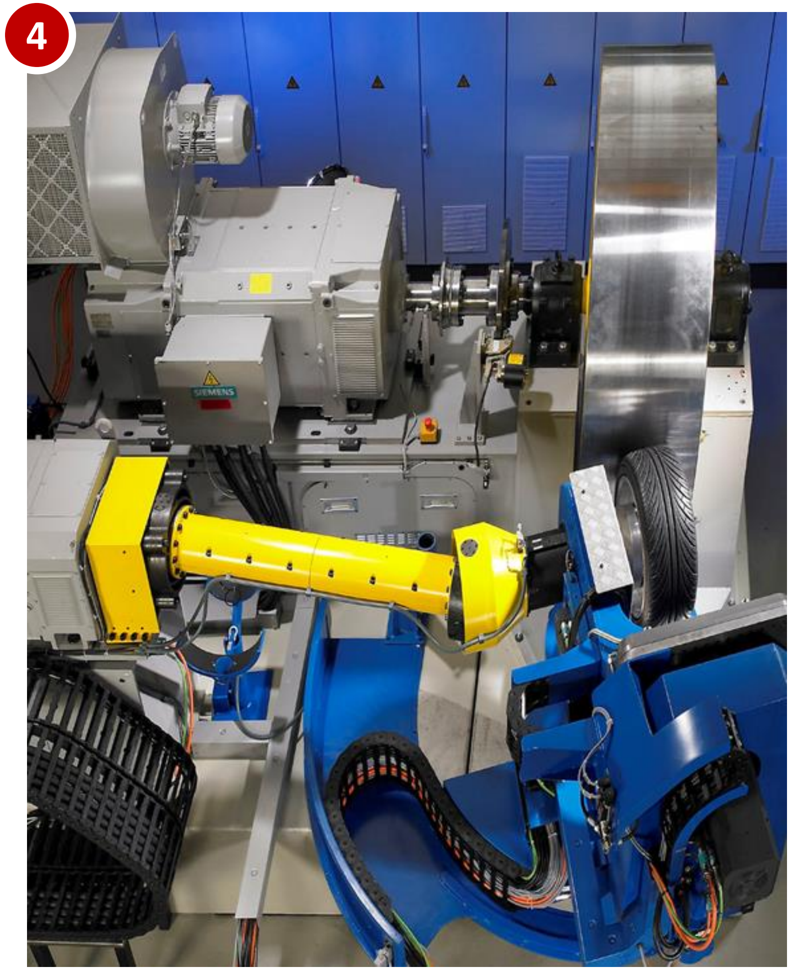
1



2

3

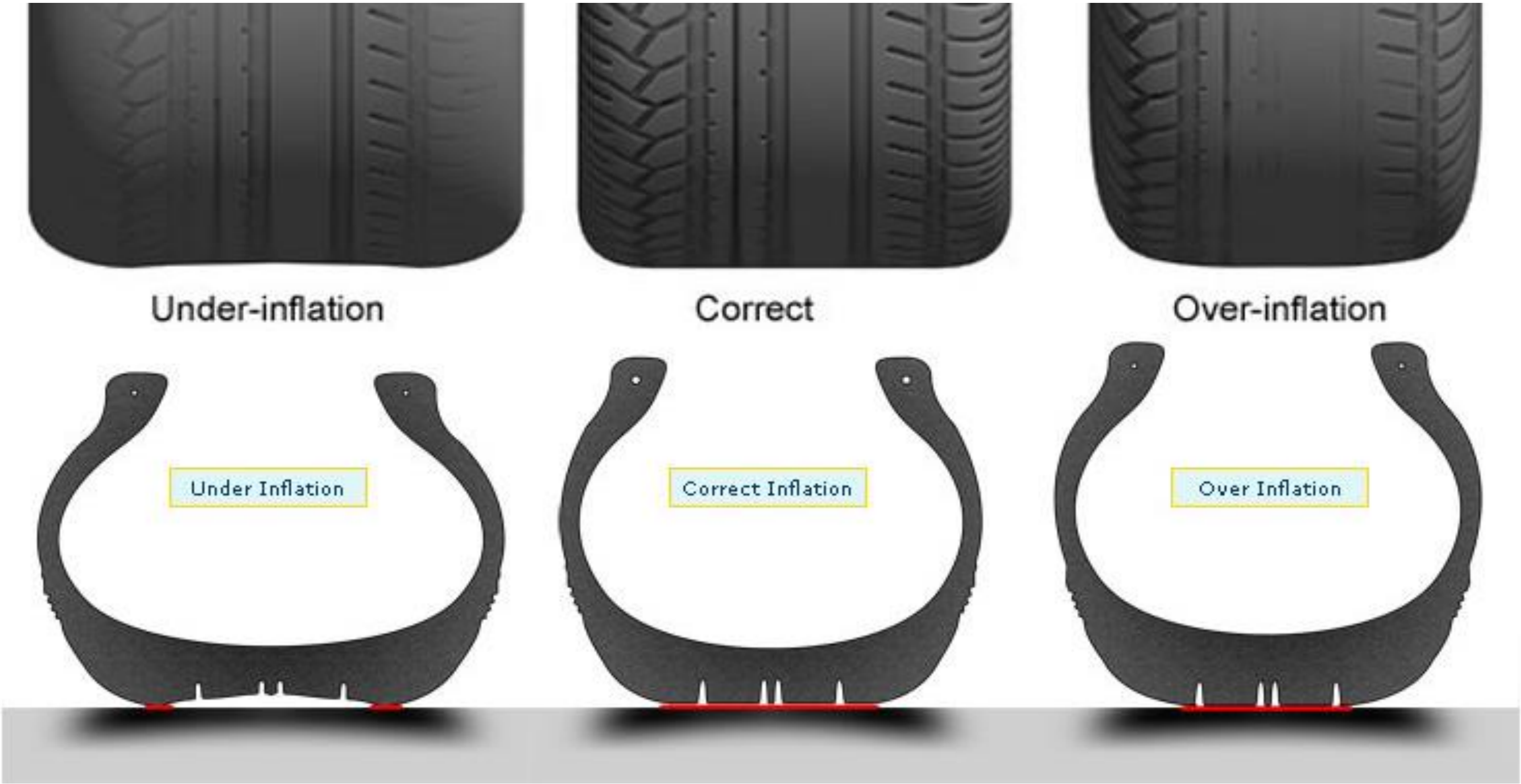
4

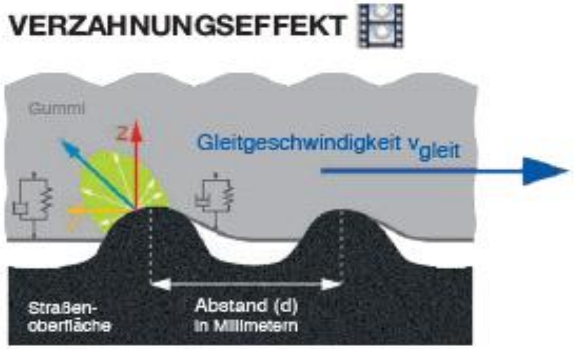


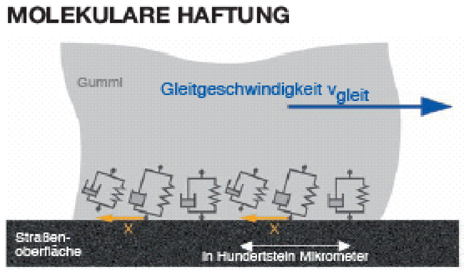
1. Flat Belt Test Rig
2. Measurement Vehicle
3. Inner Drum Test Rig
4. Roller Drum Test Rig

Chassis components and functions – Tire & Wheels

Correct inflation pressure for a good foot print

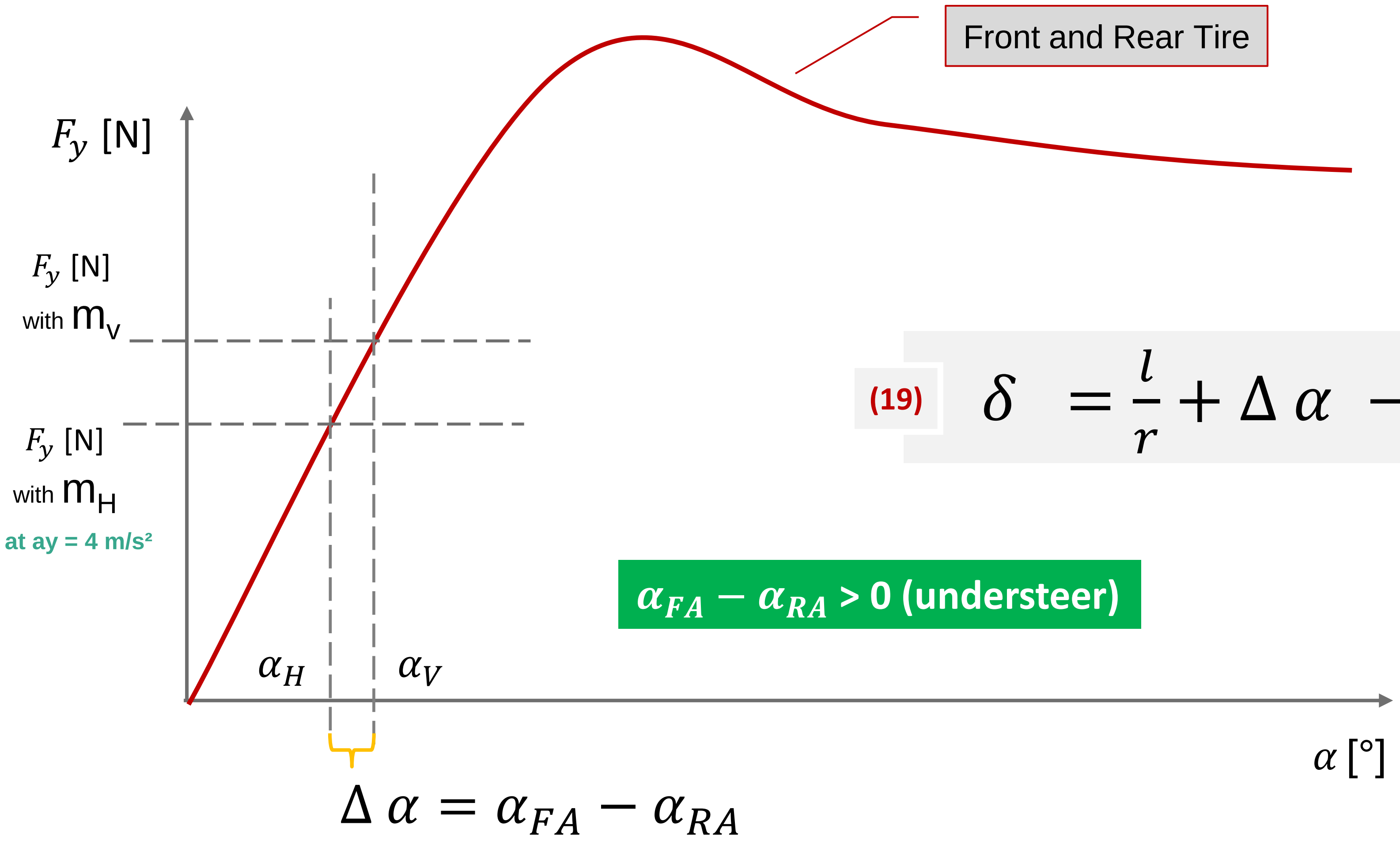






Influence to the brush, tooth and molecular adhesion effect is obvious.

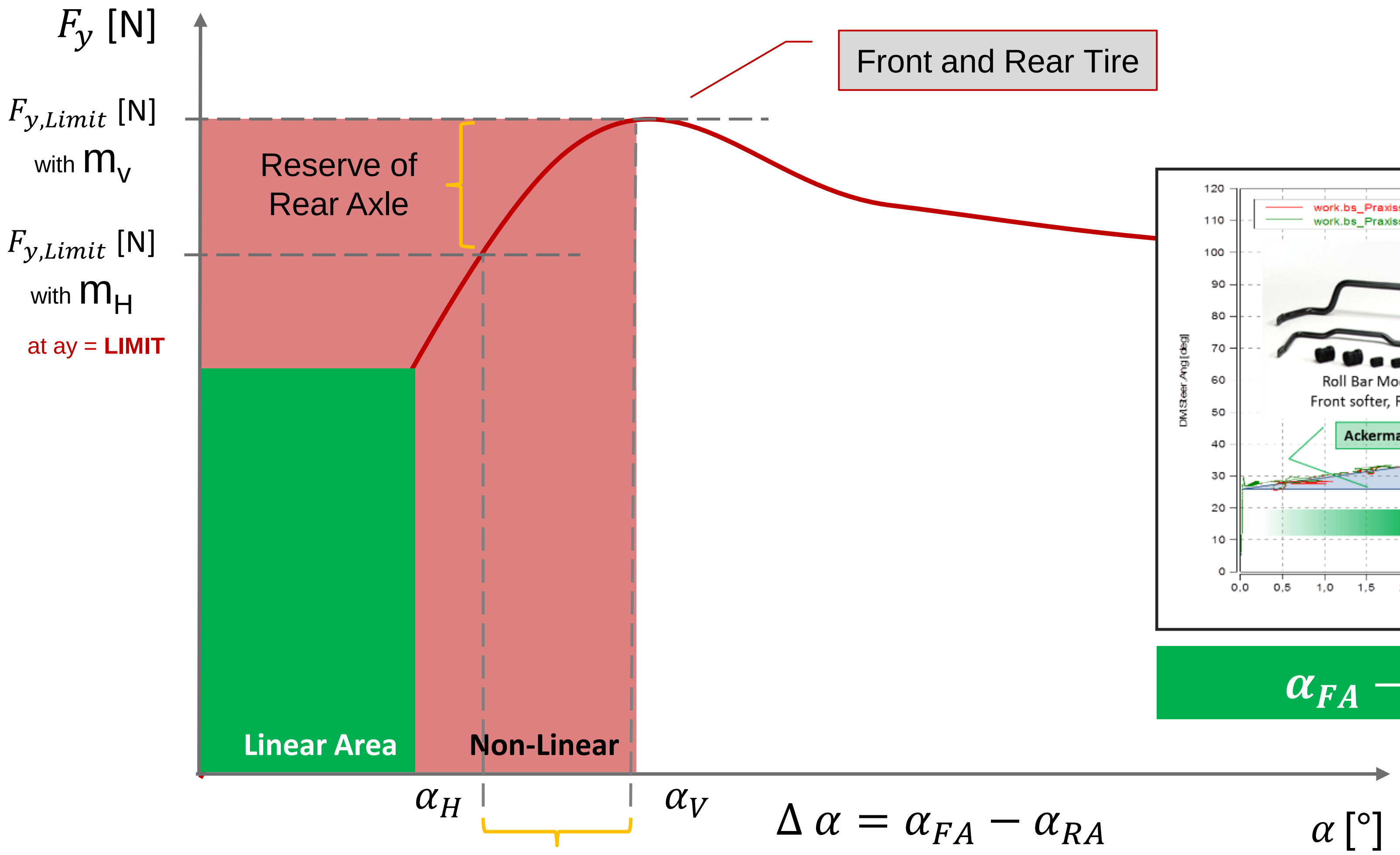
Case 1: Understeer behavior with wheel load distribution

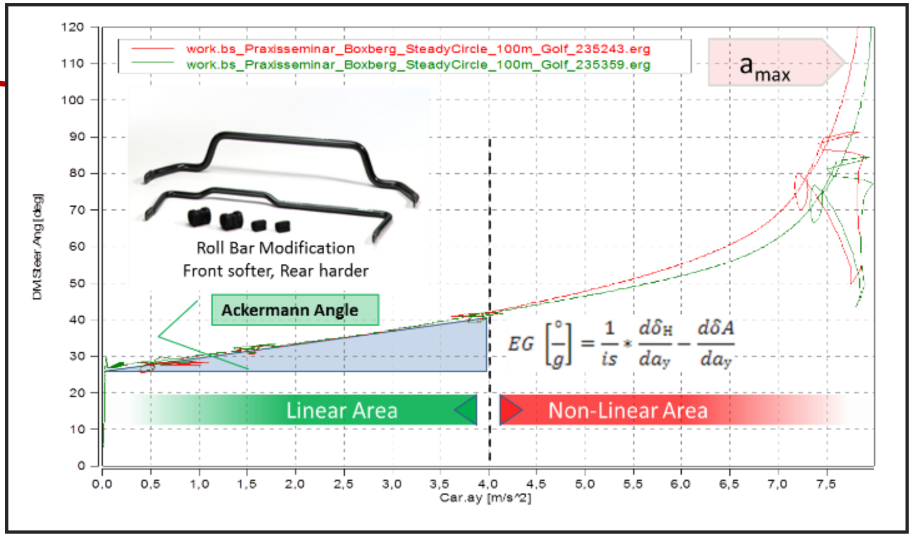


$$\delta \;= \frac{l}{r} + \Delta\,\alpha \;\rightarrow [\alpha_{FA} - \alpha_{RA}] \quad (19)$$

$\alpha_{FA} - \alpha_{RA}$ > 0 (understeer)

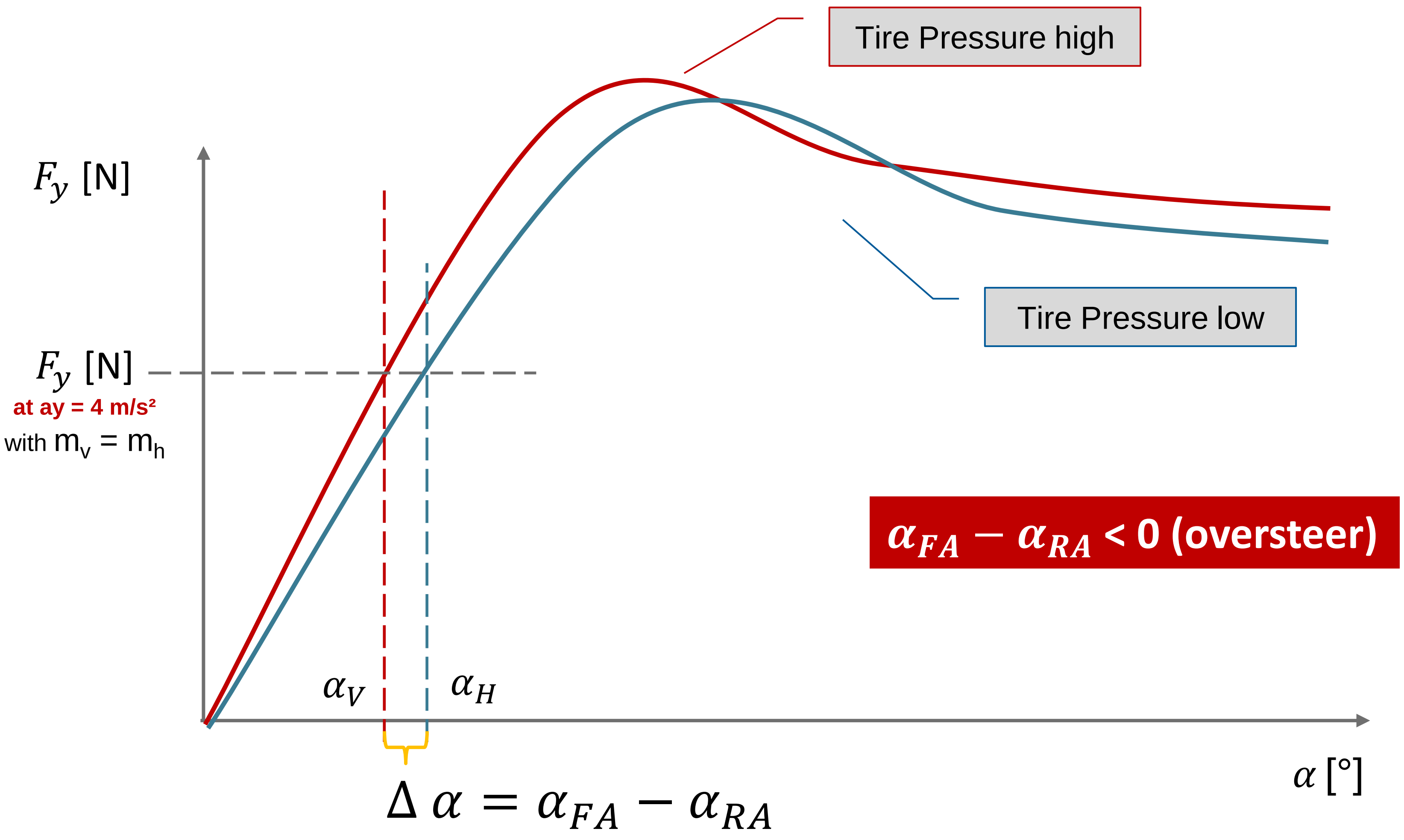
Case 1: Understeer behavior with wheel load distribution





$\alpha_{FA} - \alpha_{RA} > 0$ **(understeer)**

Case 2: Oversteer behavior with tire pressure difference



Exercise 10: Steady State Circular Driving with modified Tires

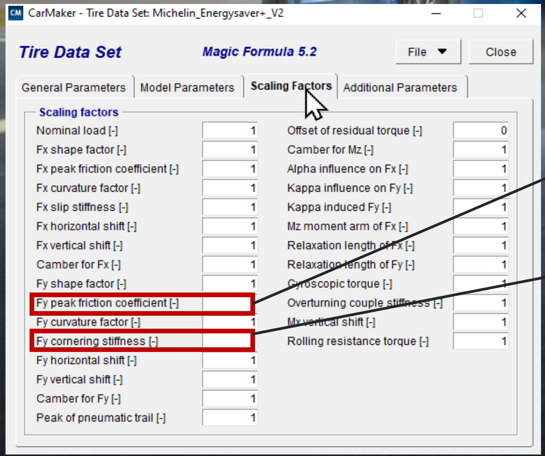
Test Condition
- Constant Radius: 100 m
- Speed: 0 – max kph
- da_y: 0,2 m/s²/s

SWA, a_y, Yaw, Radius: steady state condition

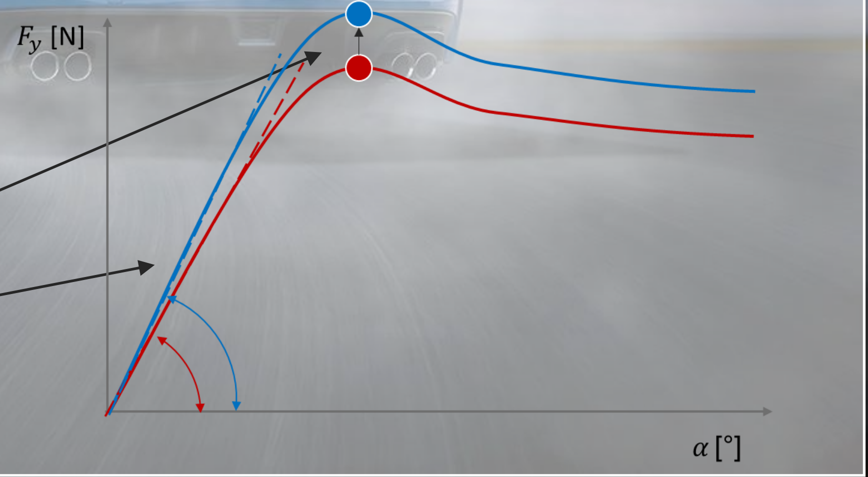
Visualize:
- Steer.WhlAng, Car.v, Car.ay, Car.Roll, Car.SideSlipAngle

1. Change & Analyze Tire Sensitivity:
1. Abstimmreifen (front/rear)
2. Performance front / Abstimm rear
3. Abstimm front / Performance rear

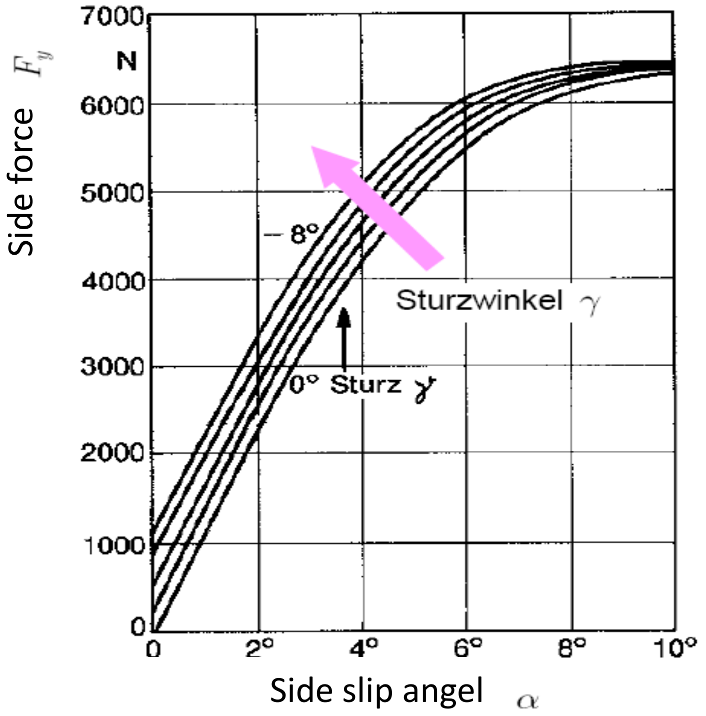
Build your own tire
- Fy peak friction + 50%
- Fy cornering stiff + 50%

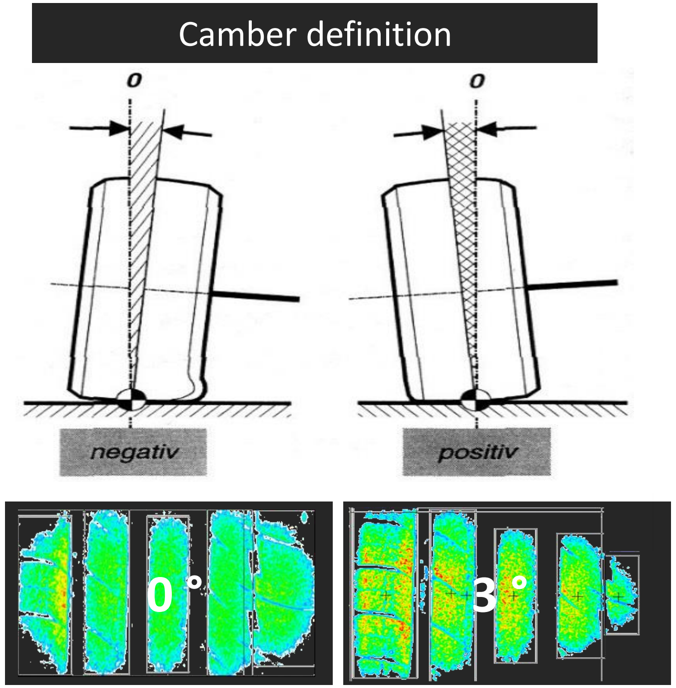


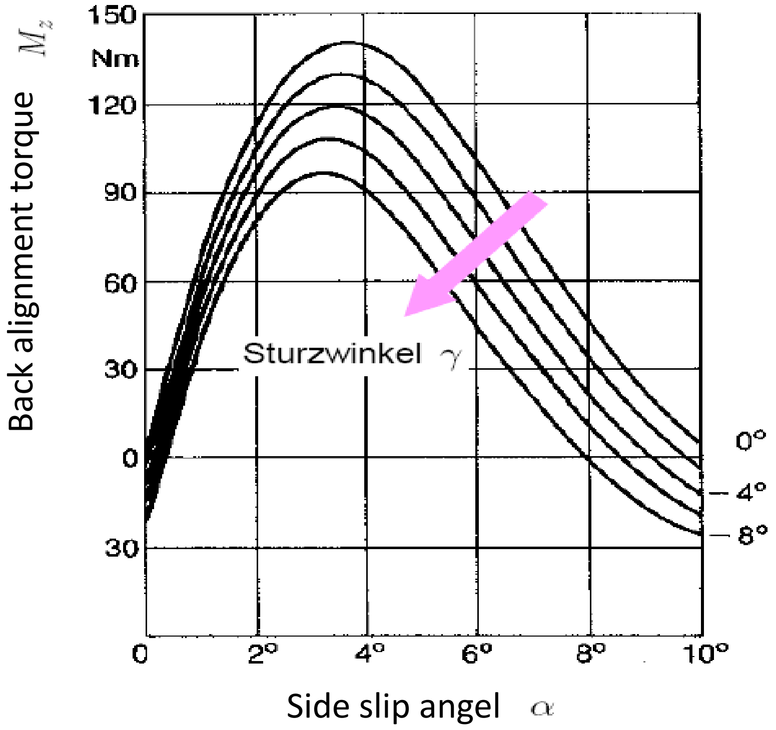
2. Change & Analyze Tire Sensitivity:
1. Make Model Check
2. Basic Tire w/o change
3. Tire +50% front / Basic Tire rear
4. Basic Tire front / Tire +50% rear



Tire lateral characteristics: side slip behavior

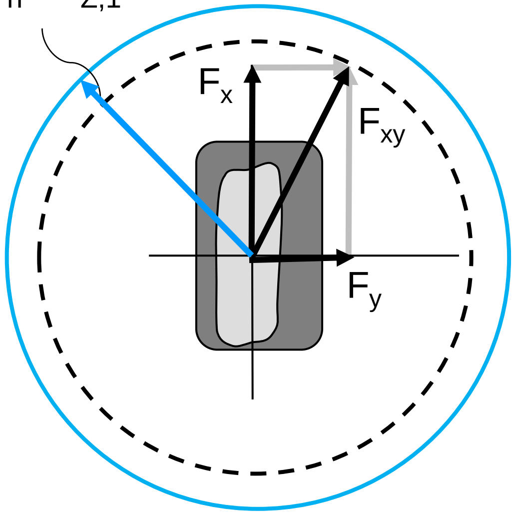






A negative camber angle allows for the same side slip angle slightly greater lateral forces.

XY combined tire characteristics: Kam'sche Cycle



$$F_{xy}^2 = F_x^2 + F_y^2 \quad (39)$$

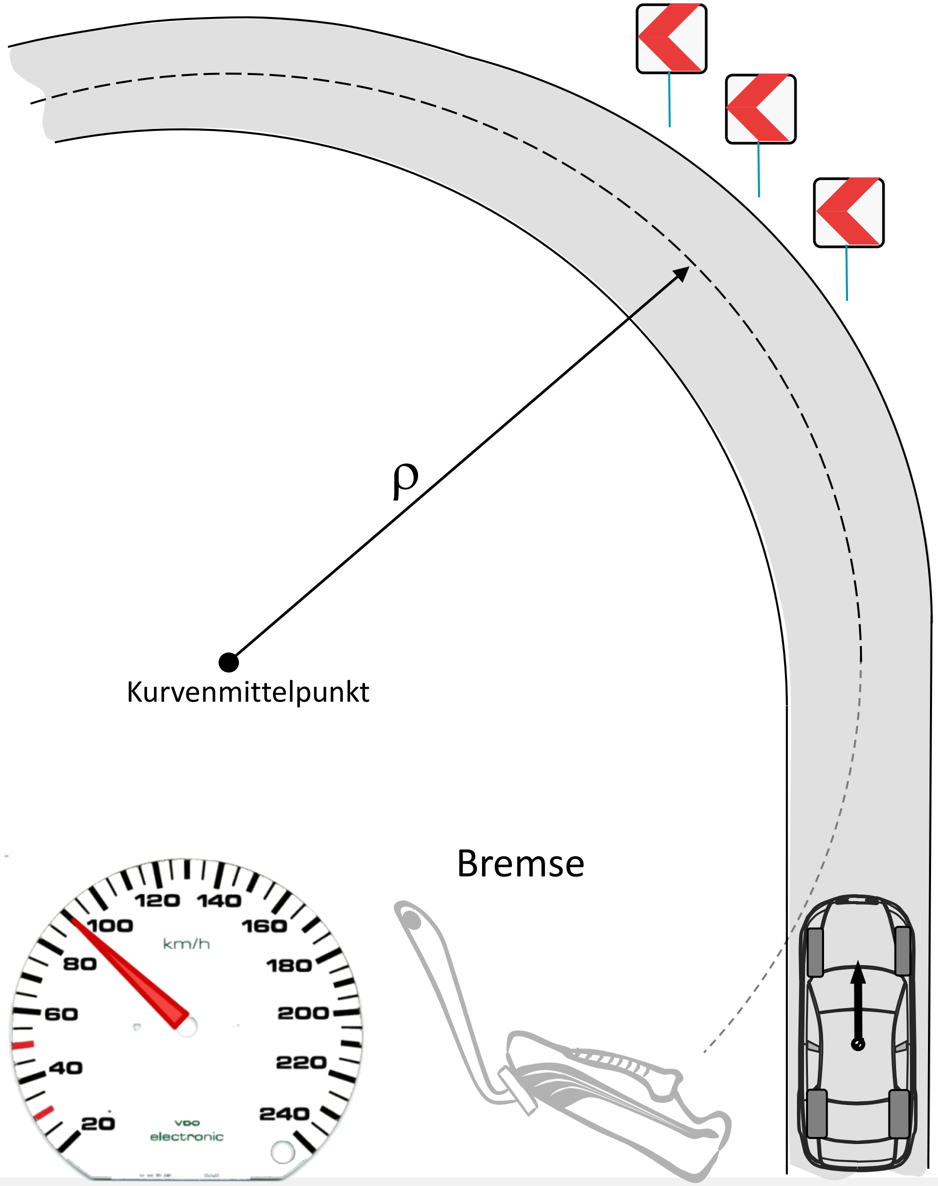
$$F_{xy} \leq F_{max} = \mu_h \cdot F_z \quad (40)$$

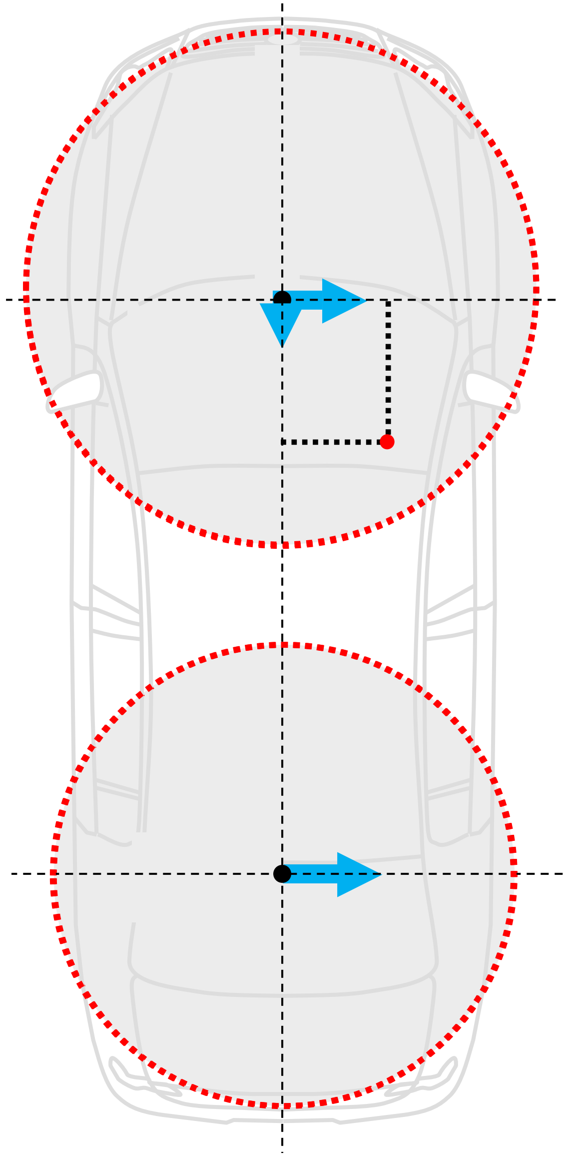
The sum of these forces is at most as large as the maximum transferable force between tire and road, which is the product of coefficient of adhesion and wheel load.
So that the vehicle in the longitudinal and lateral direction can be performed stably, i.e. the wheel moves without high sliding, the limit of adhesion between the wheel and the road must not be exceeded.

Chassis components and functions – Tire & Wheels

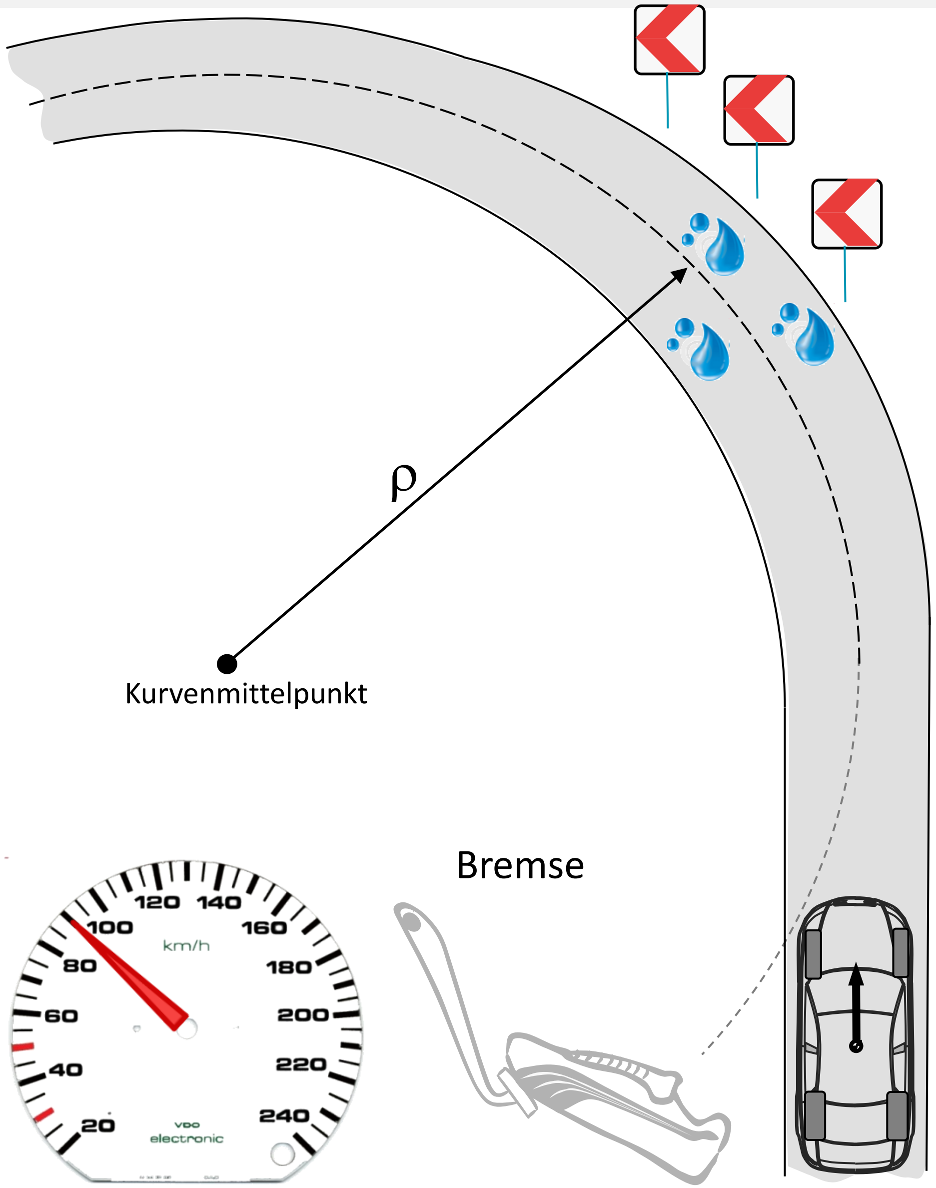
1

$\mu_h \approx 1{,}0$

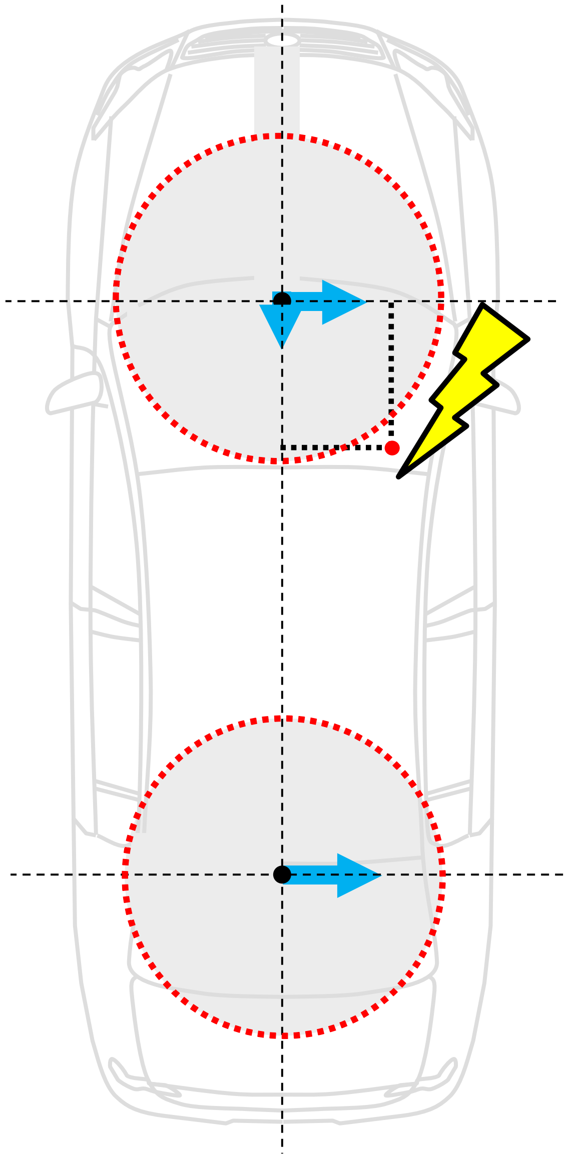




Chassis components and functions – Tire & Wheels



$\mu_h \approx 0{,}5$



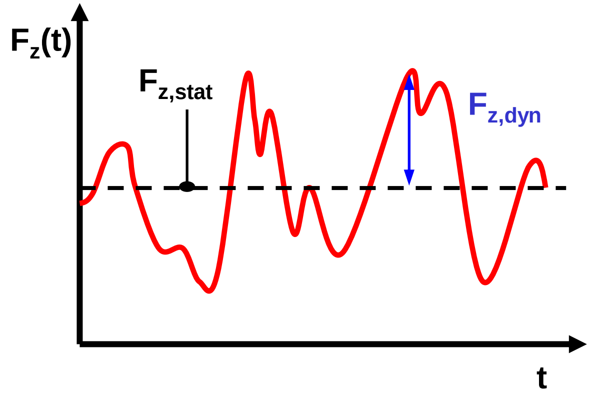
Exercise 11: Brake in Cornering at different lateral and longitudinal acc.

Test Condition
- Constant Radius: 100 m
- Speed: 0 – max kph
- a_y: 4, 6, 8 m/s²
- a_y: 4, 6, 8 m/s²

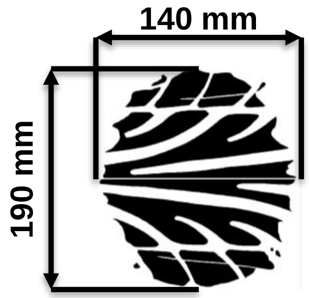
SWA, a_y, Yaw, Radius: steady state condition

Visualize:
- Steer.WhlAng, Car.v, Car.ay, Car.ax, Car.YawRate, Car.SideSlipAngle, DM.Brake all signals vs. time
- tx vs. ty for path visualization

Tire vertical characteristics: dynamic wheel load



Sample:
245/40 R18, 2,2 bar, F_z = 4.700 N



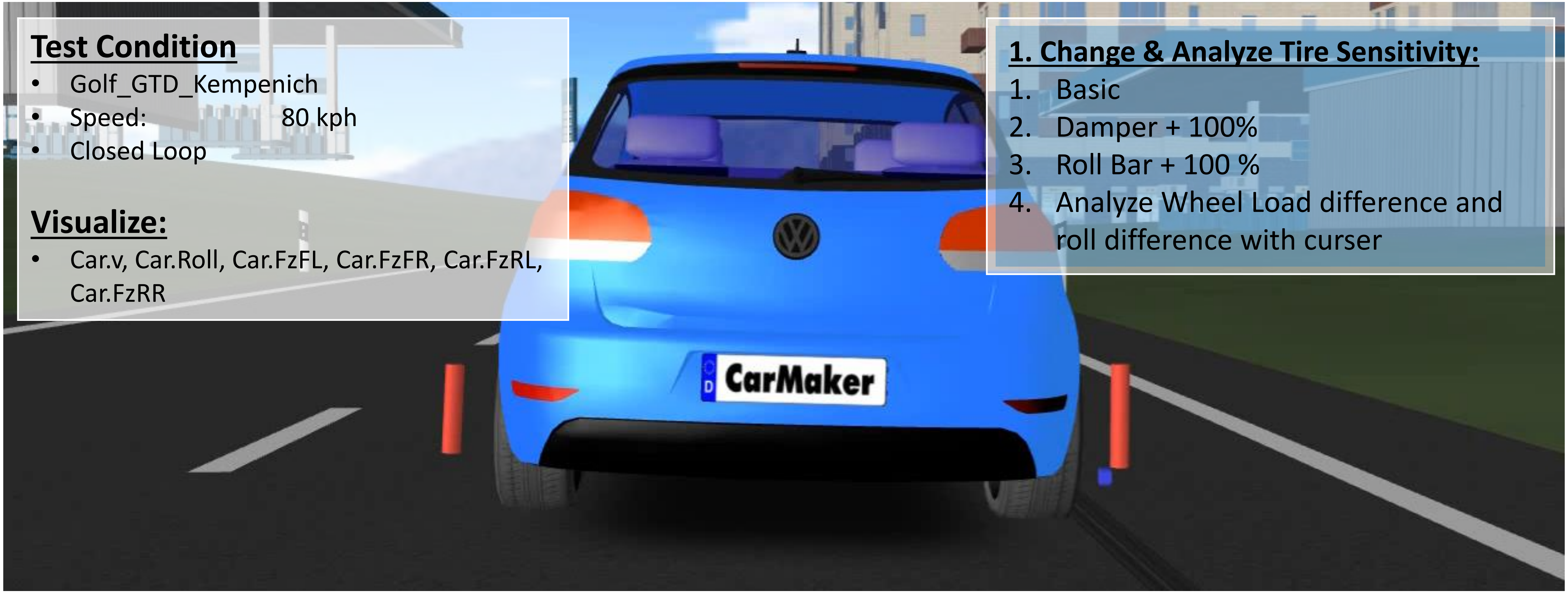
- Brutto foot print ≈ 230 cm²
- Netto foot print ≈ 150 cm²

The acting vertical tire force (wheel load) shall be composed of:
- **Static wheel load** $F_{z,stat}$ = constant (Gravity and vehicle mass).
- **Dynamical wheel load** $F_{z,dyn}$ = f(t) (Relative motion of the body related to the ground).

Due to the elasticity of the rubber and the air in the tire, it comes to vertical defection. This leads to the formation of a contact area A between the road and tread - the tire contact area (foot print). About this all forces must to be transferred.

Influences to the effective foot print:
- Wheel load.
- Tire inflation pressure
- Tire construction.
- Tire dimension.
- Profile.

Exercise 12: Uneven Road



<u>Test Condition</u>

- Golf_GTD_Kempenich
- Speed: 80 kph
- Closed Loop

<u>Visualize:</u>

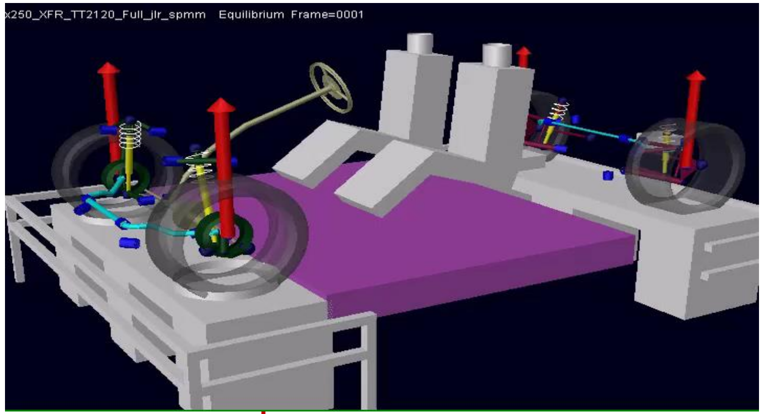
- Car.v, Car.Roll, Car.FzFL, Car.FzFR, Car.FzRL, Car.FzRR

<u>1. Change & Analyze Tire Sensitivity:</u>

1. Basic
2. Damper + 100%
3. Roll Bar + 100 %
4. Analyze Wheel Load difference and roll difference with curser

Virtual and real K&C test benches in a modern development

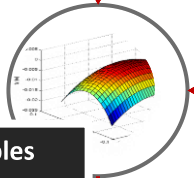
Virtual K&C Test Bench
MBS-Model



Real K&C Test Bench
Sample ABD SPMM 5000

- Bounce Test
- Roll Test
- Steer Test
- Side Force Test
- Accel. & Brake Test

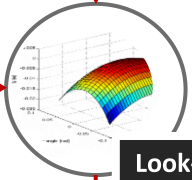
K&C Variants



Look-up Tables

Validation

K&C Variants

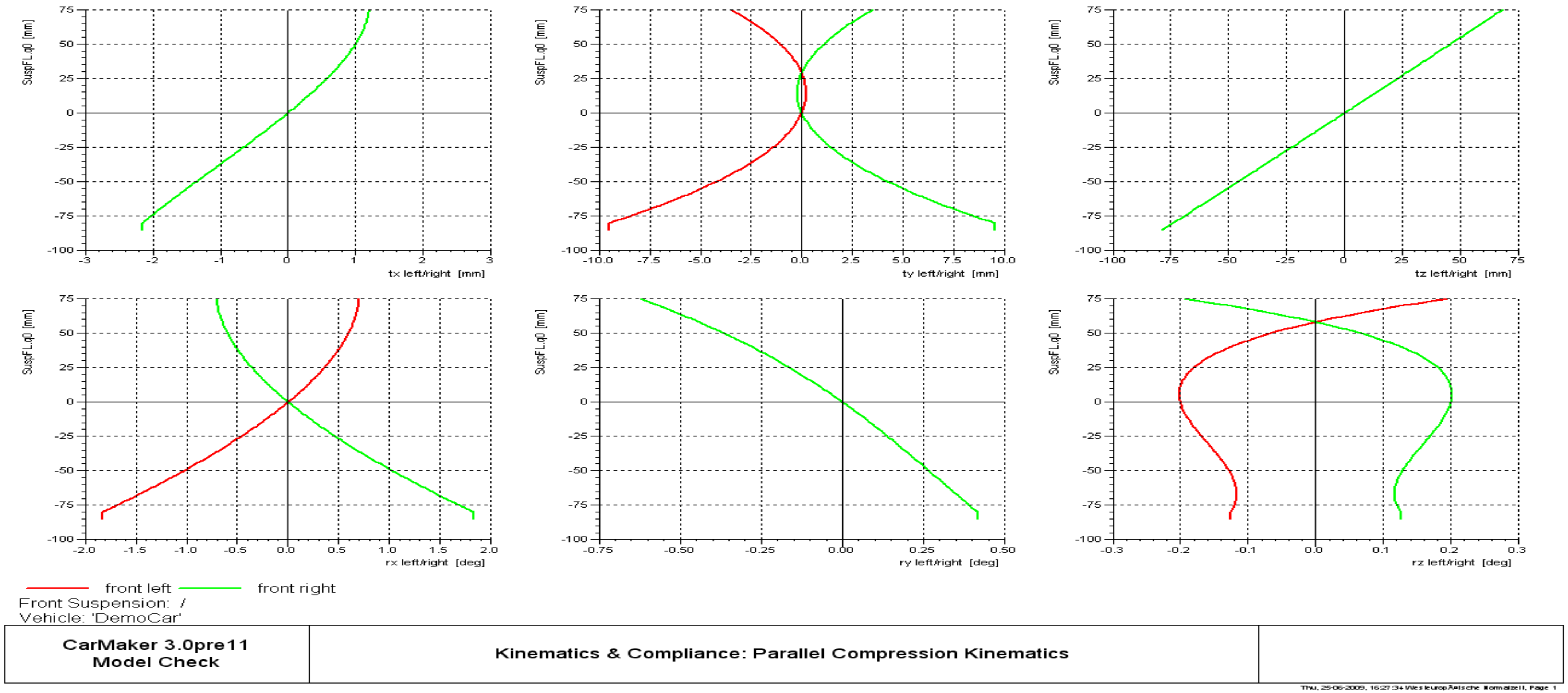


Look-up Tables

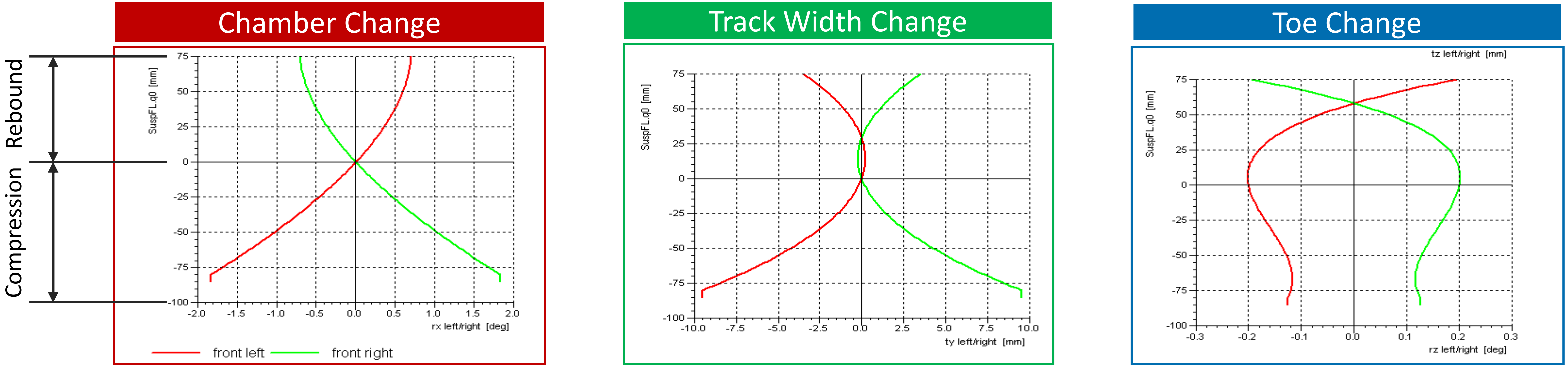
Parametrization

Parametrization

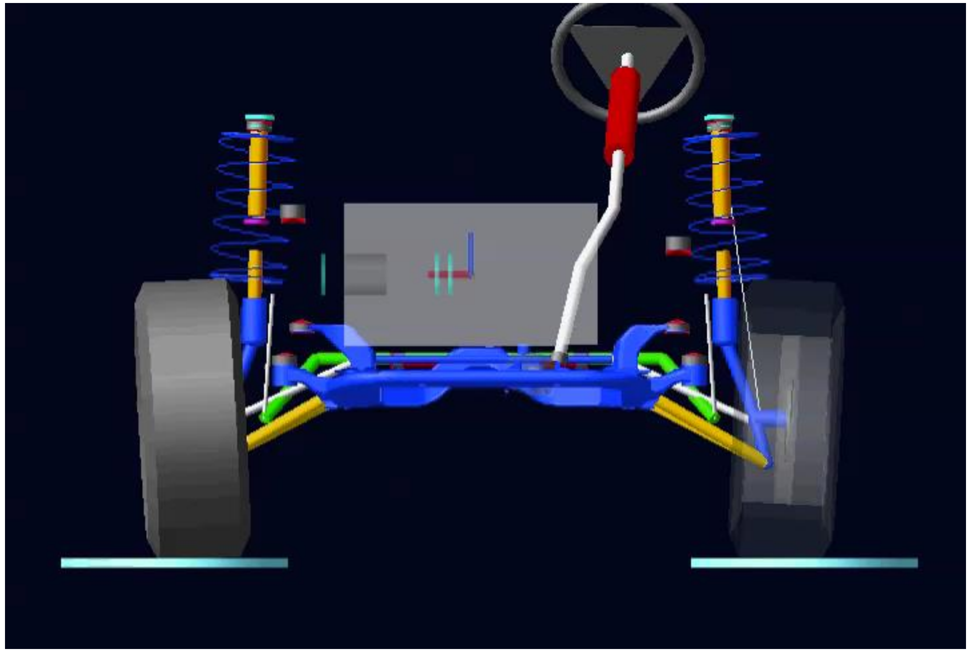
Suspension – Kinematics & Compliance

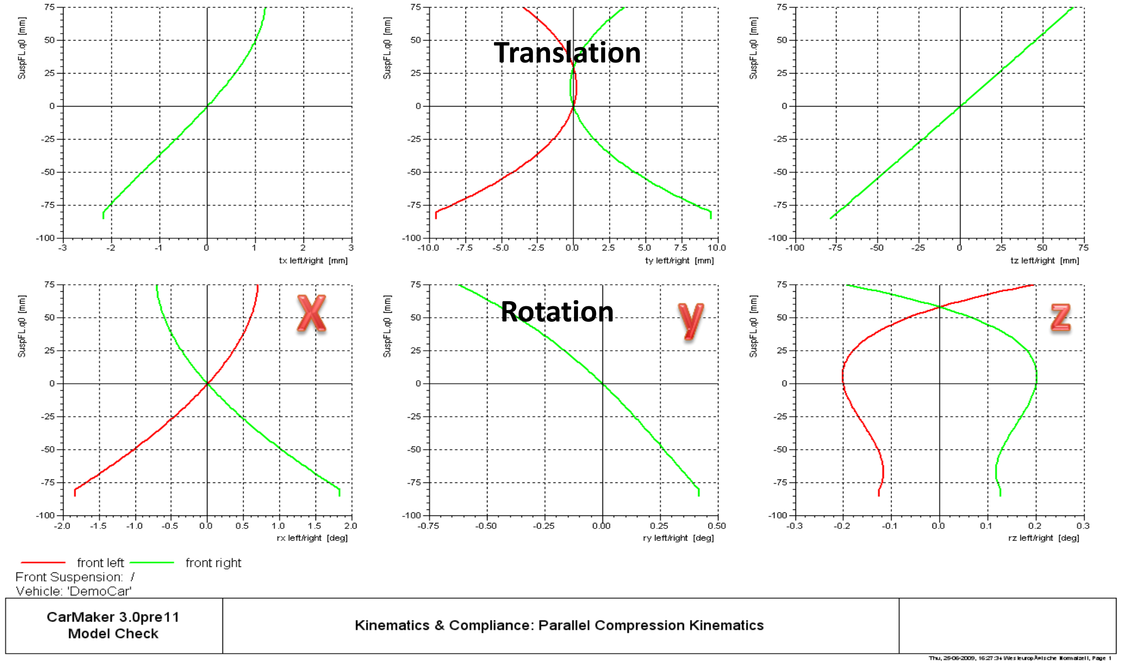


Suspension – Kinematics & Compliance

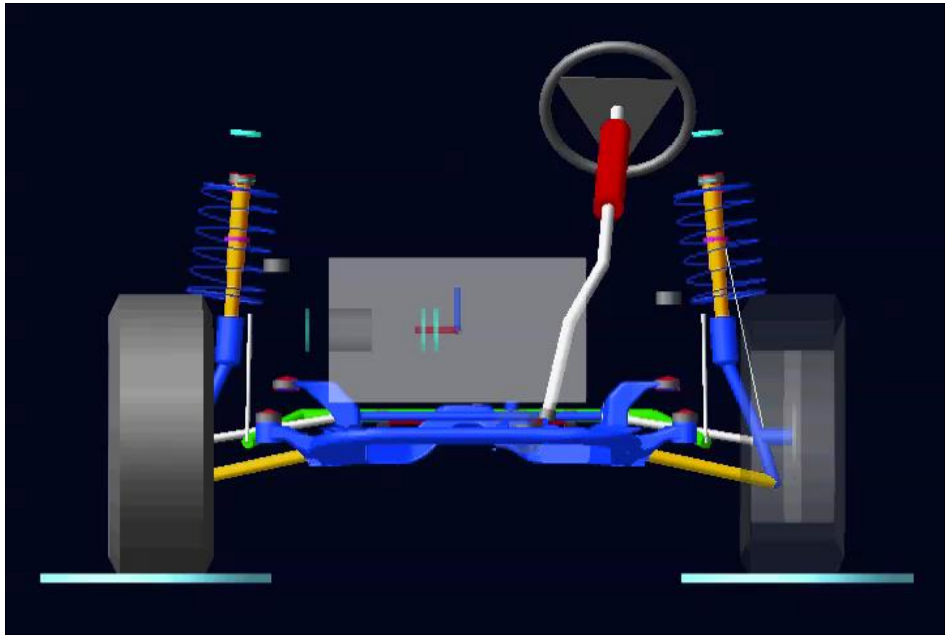


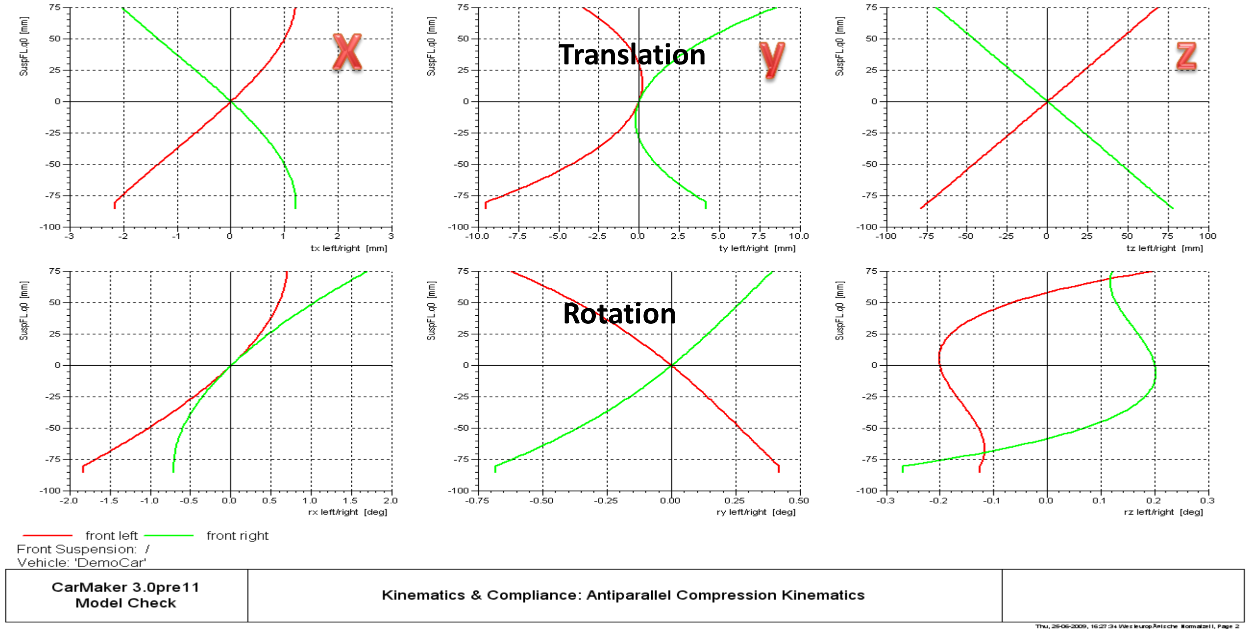
Kinematics & Compliance – Stroke or Bounce Test



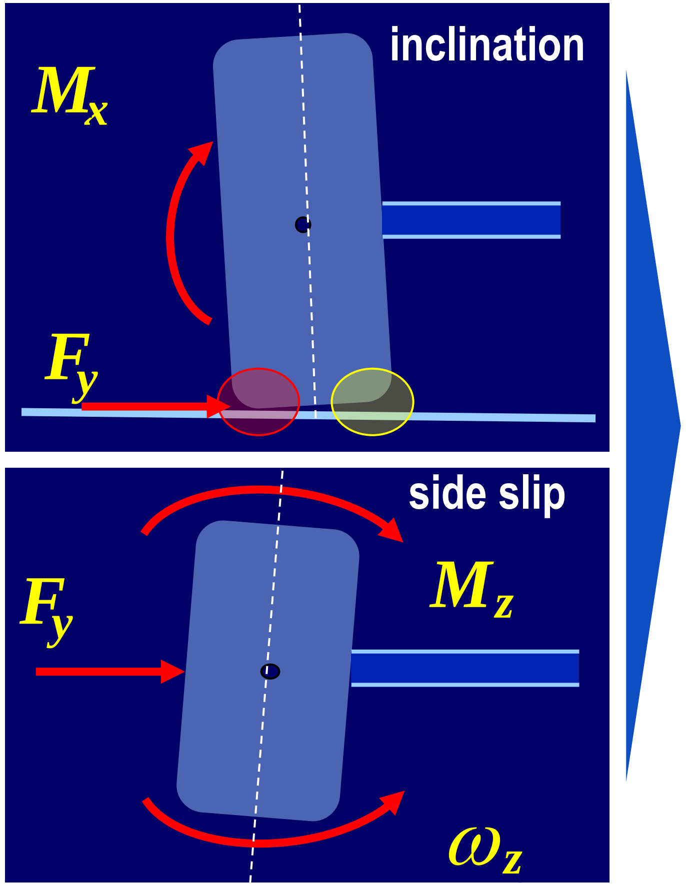


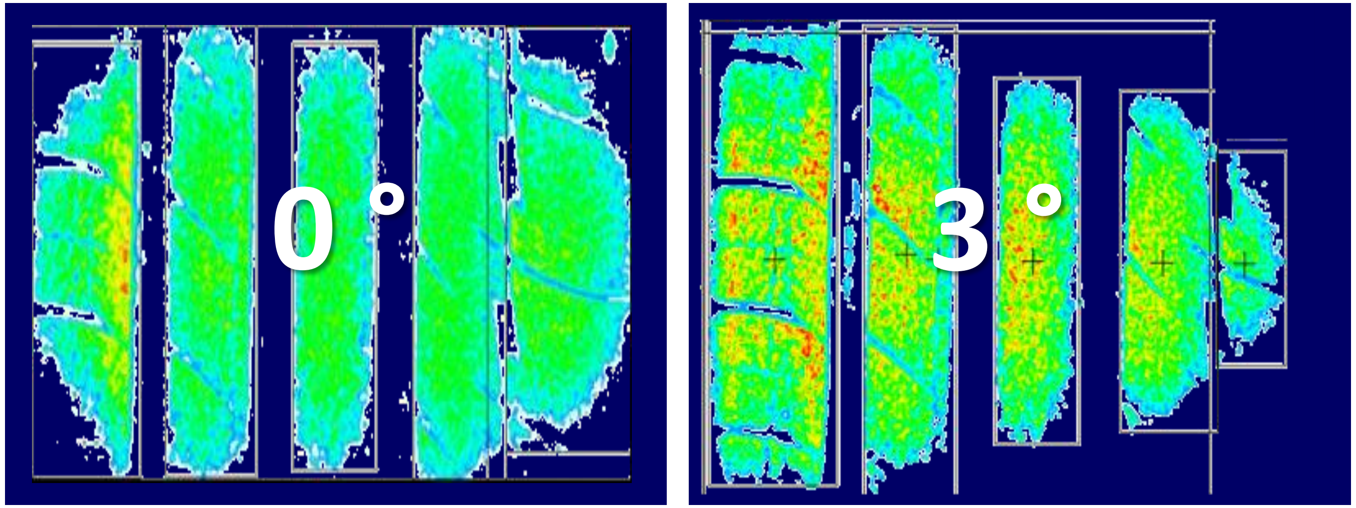
Kinematics & Compliance - Roll Test





Suspension – Kinematics & Compliance

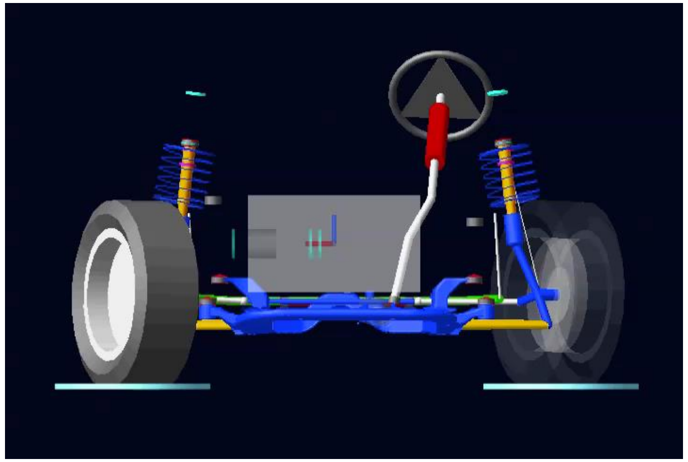




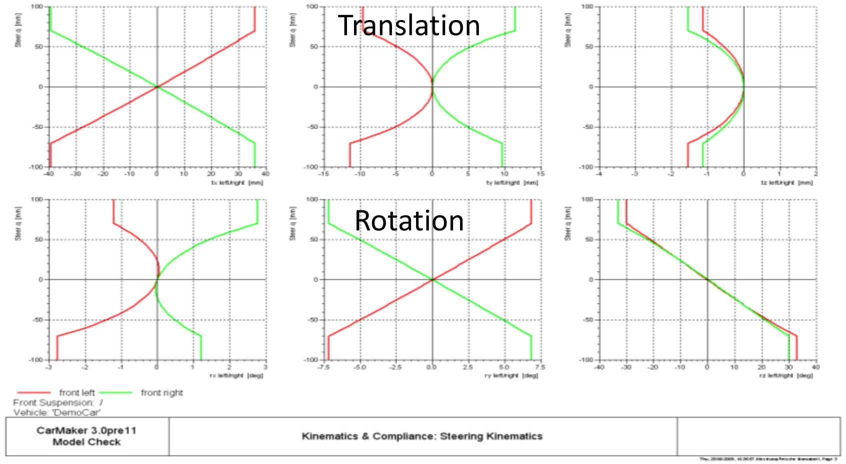
Vehicle Dynamics Rule No. 2:

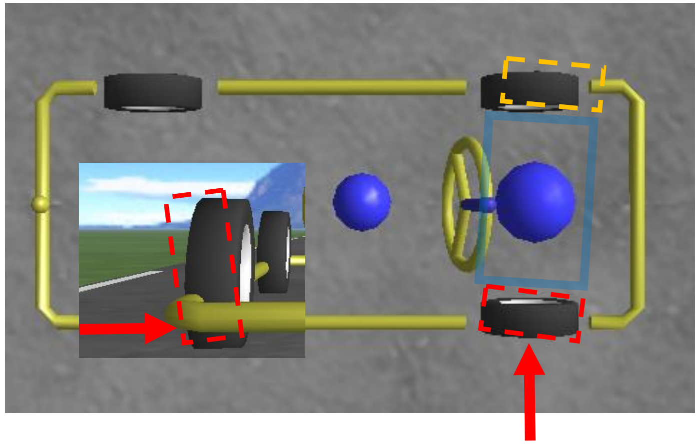
Produce a harmonic foot print

Suspension – Kinematics & Compliance

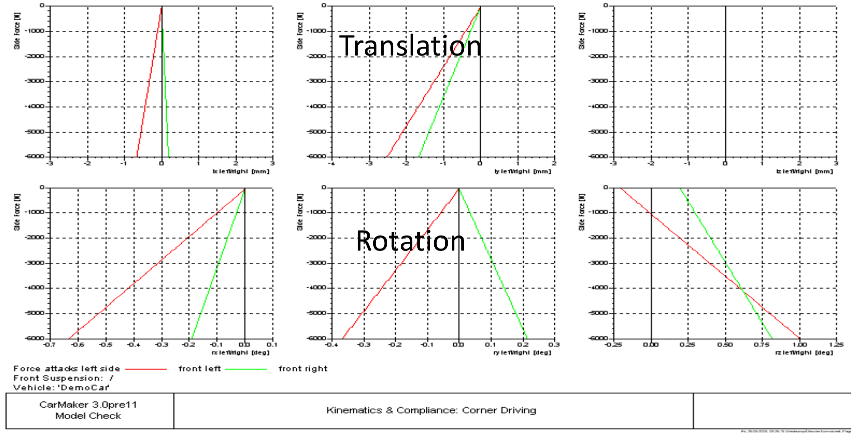


Steer Test

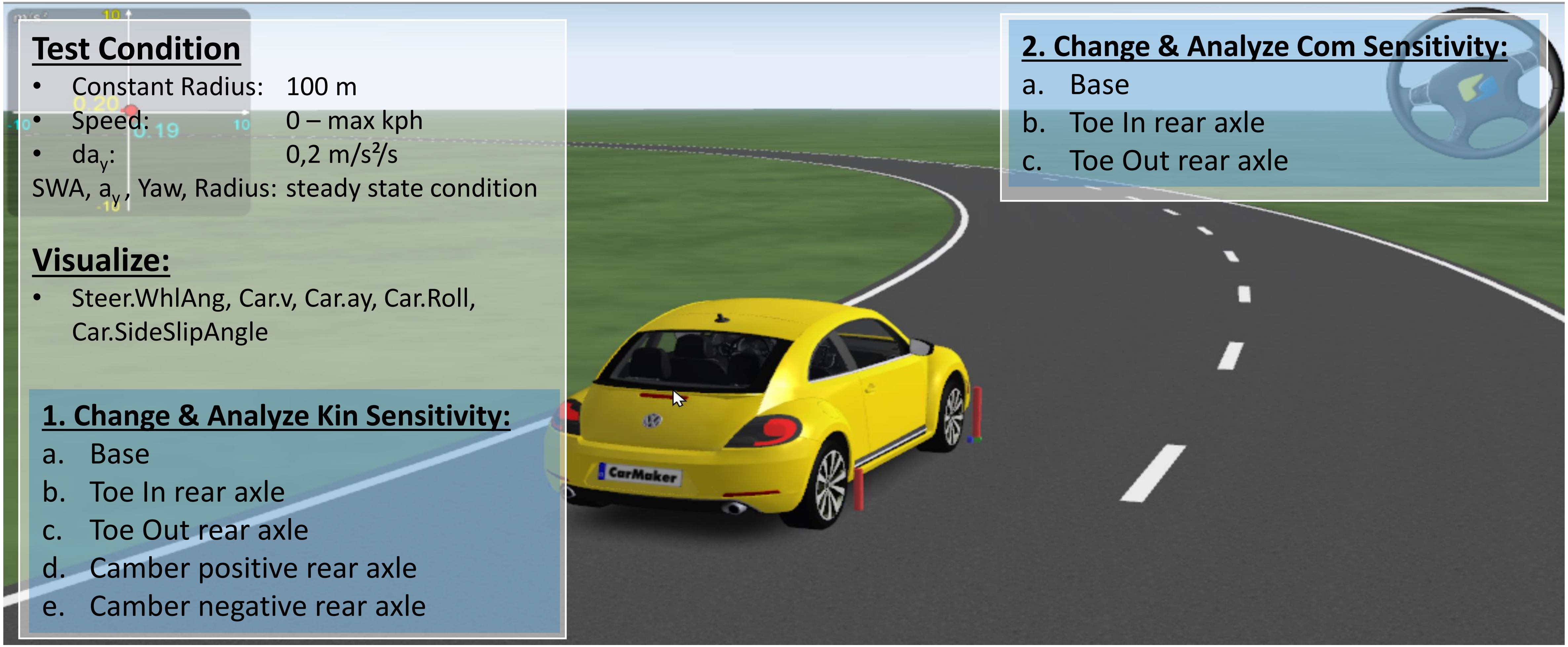




Side Force Test



Exercise 13: Brake in Cornering at different lateral and longitudinal acc.



Test Condition

- Constant Radius: 100 m
- Speed: 0 – max kph
- da_y: 0,2 m/s²/s

SWA, a_y, Yaw, Radius: steady state condition

Visualize:

- Steer.WhlAng, Car.v, Car.ay, Car.Roll, Car.SideSlipAngle

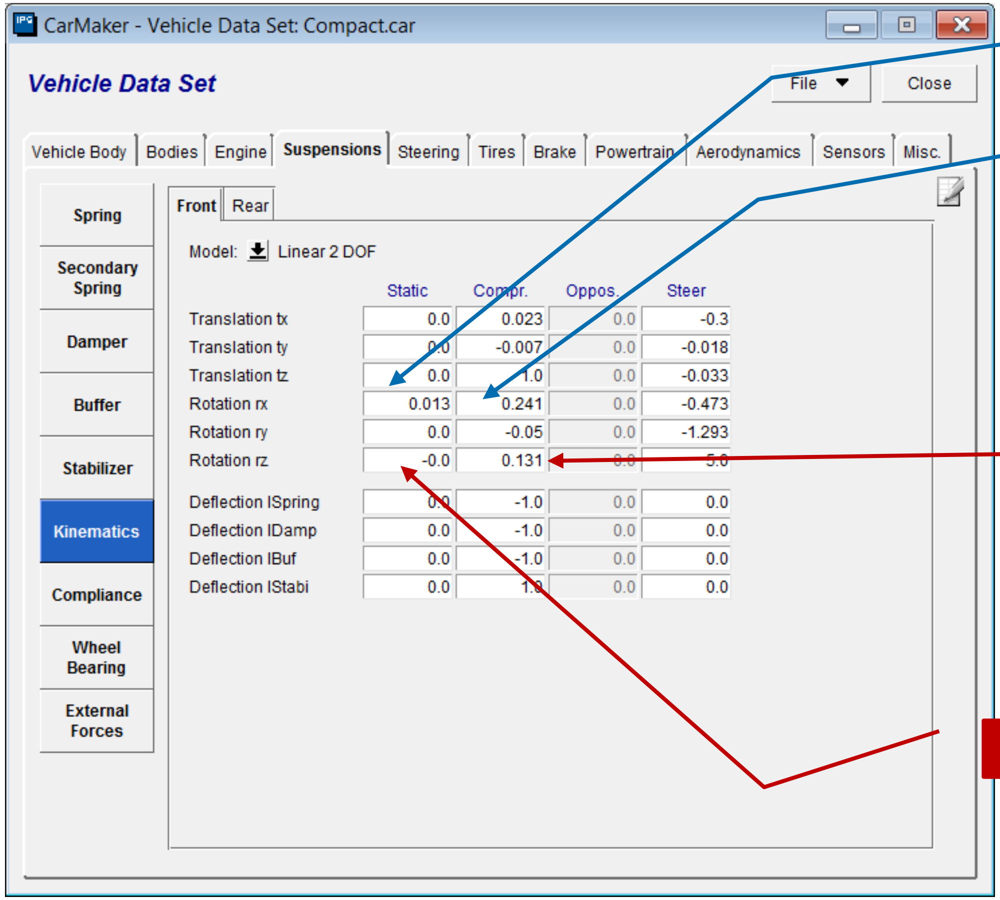
1. Change & Analyze Kin Sensitivity:

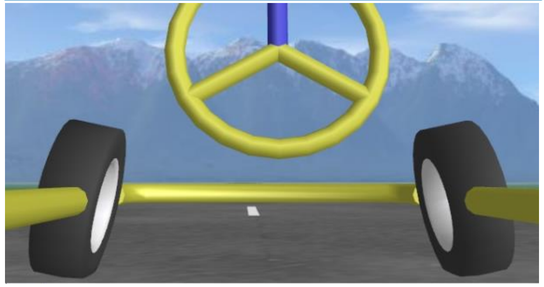
a. Base
b. Toe In rear axle
c. Toe Out rear axle
d. Camber positive rear axle
e. Camber negative rear axle

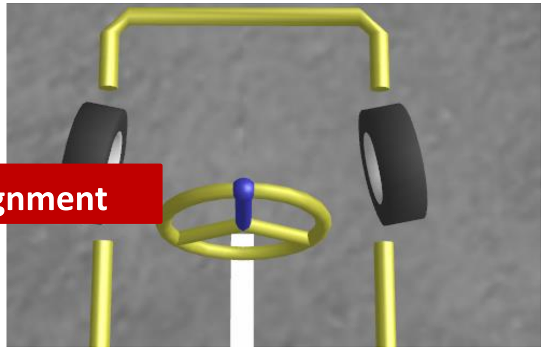
2. Change & Analyze Com Sensitivity:

a. Base
b. Toe In rear axle
c. Toe Out rear axle

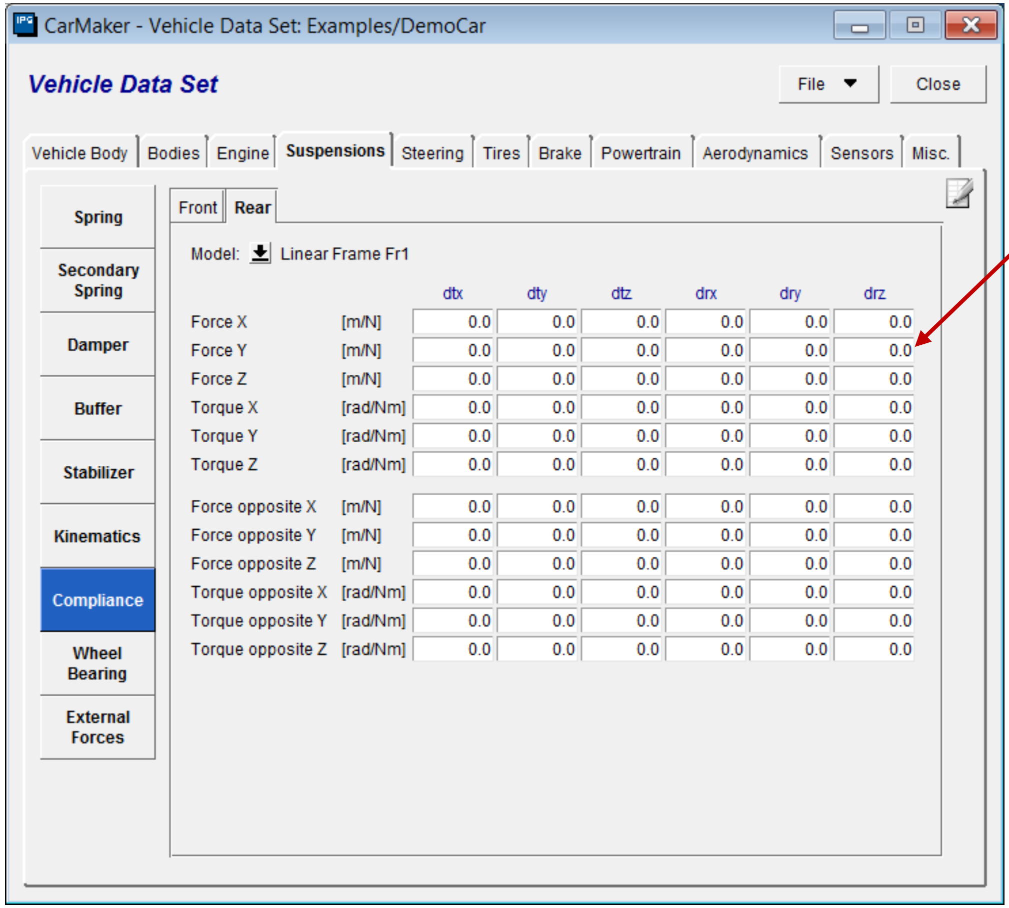
Linear 2DOF kinematic model (bounce &steer) parameter



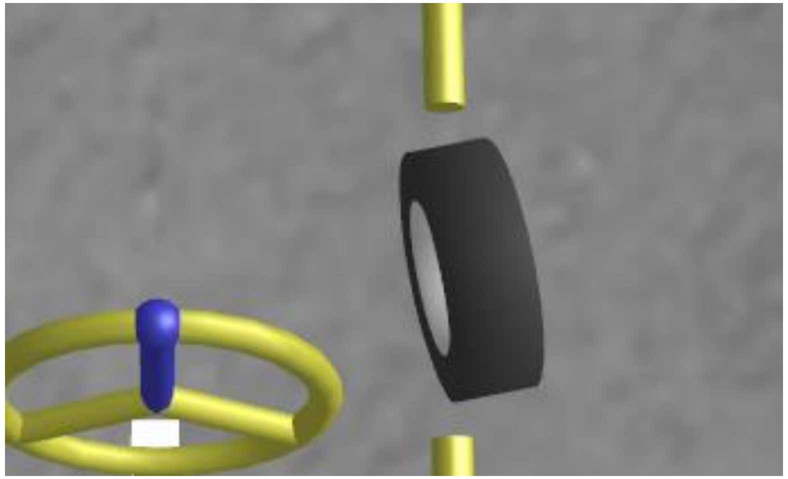




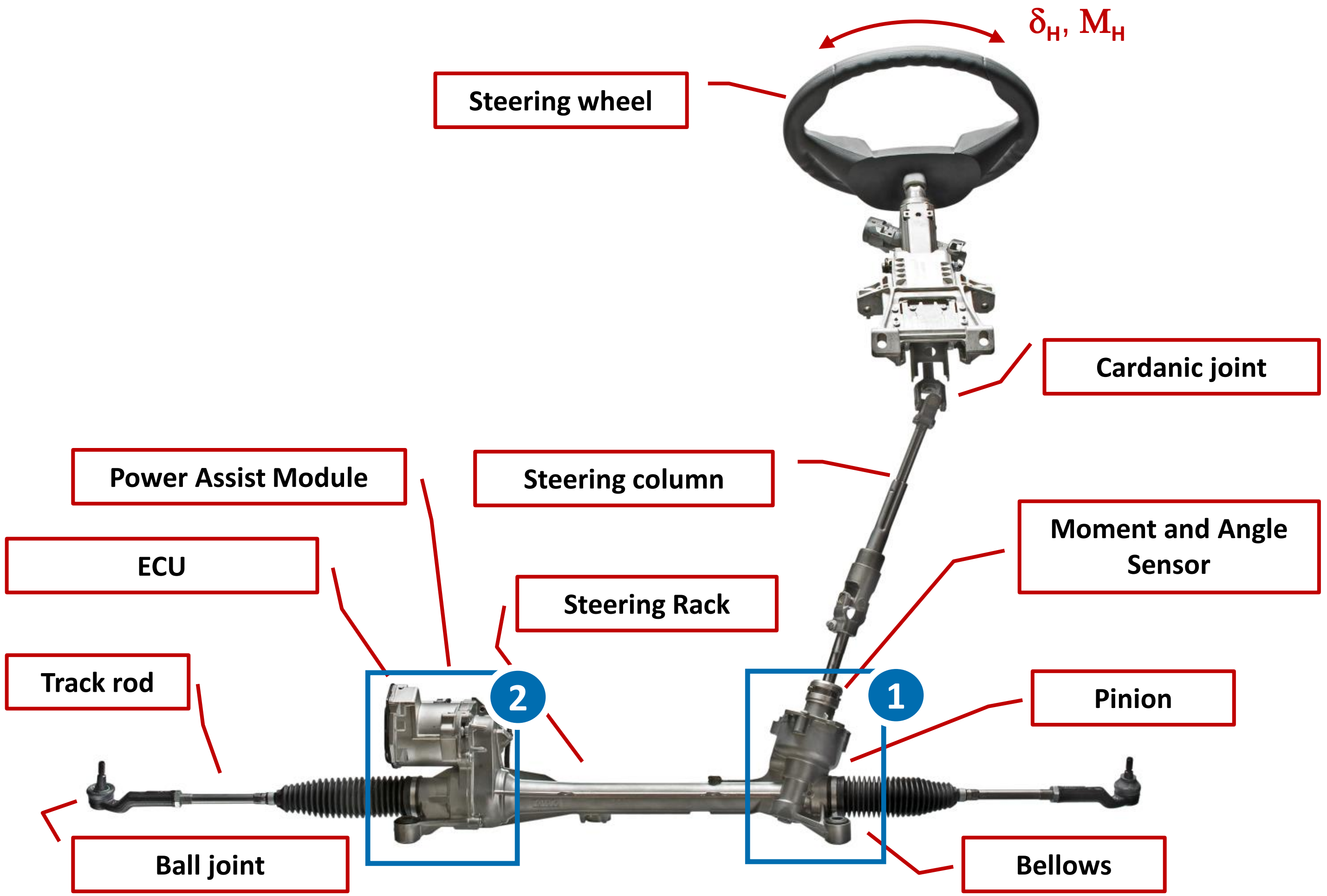
Linear compliance model parameters

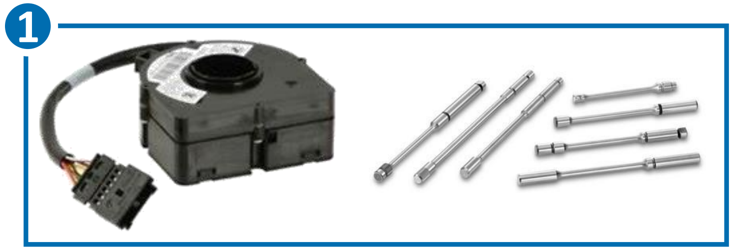


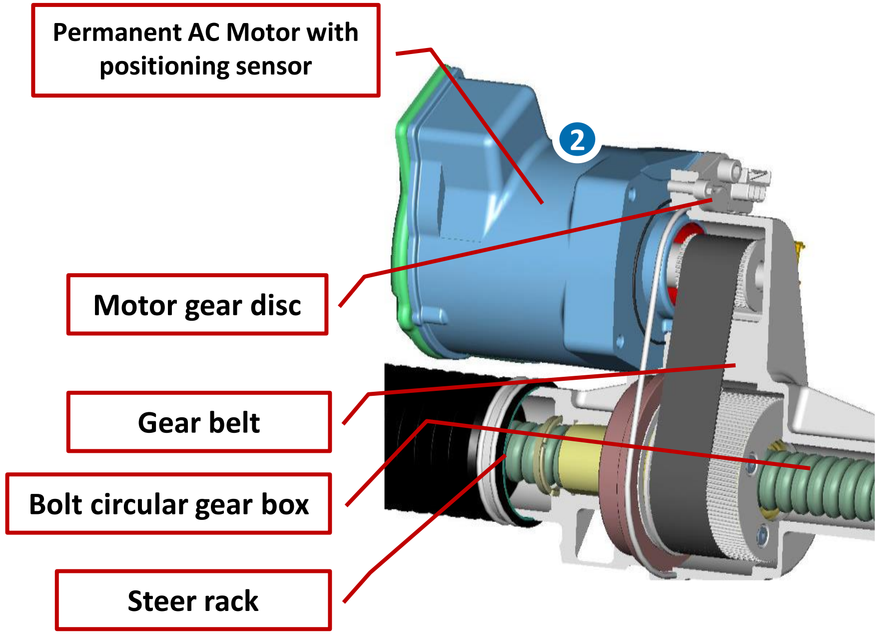
Side Force Steer



Steering system – Electrical Power Steer (EPS) EPS apa (axle parallel)

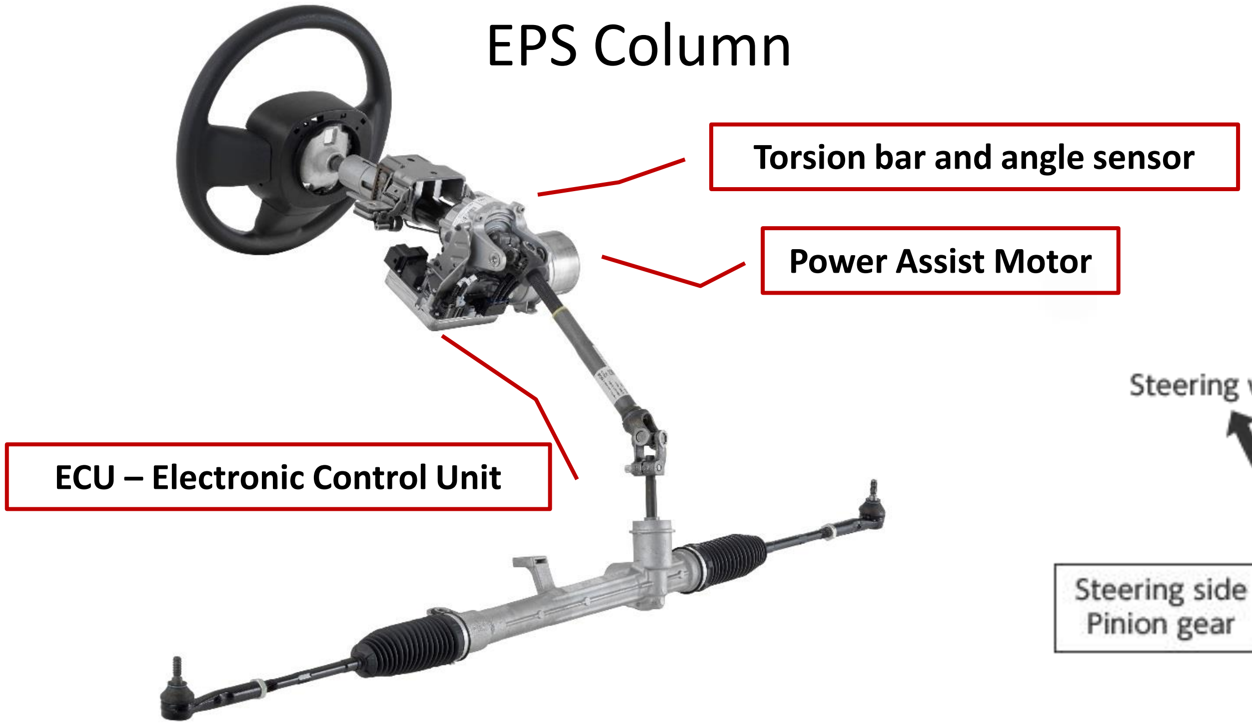




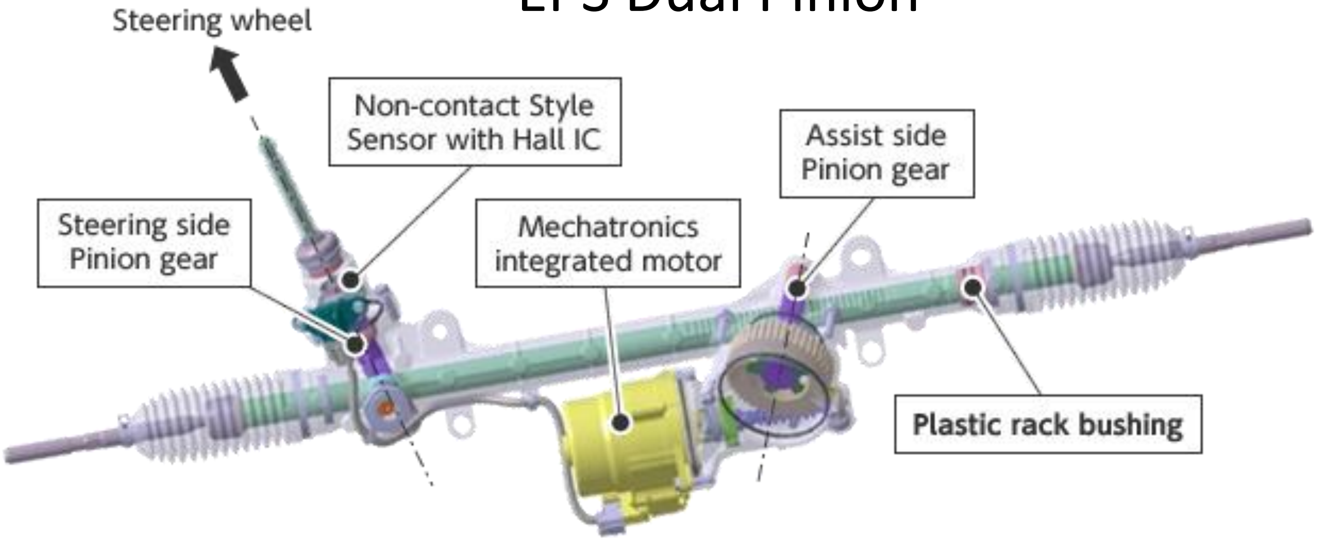


Steering system – Electrical Power Steer (EPS)

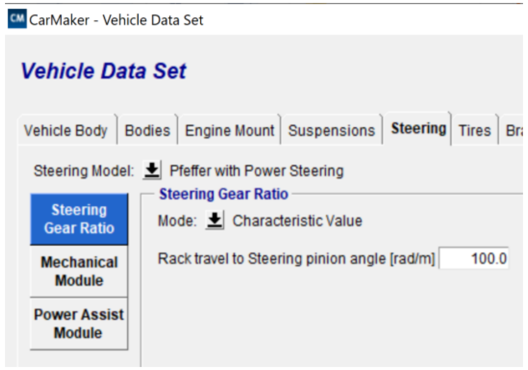
EPS Column

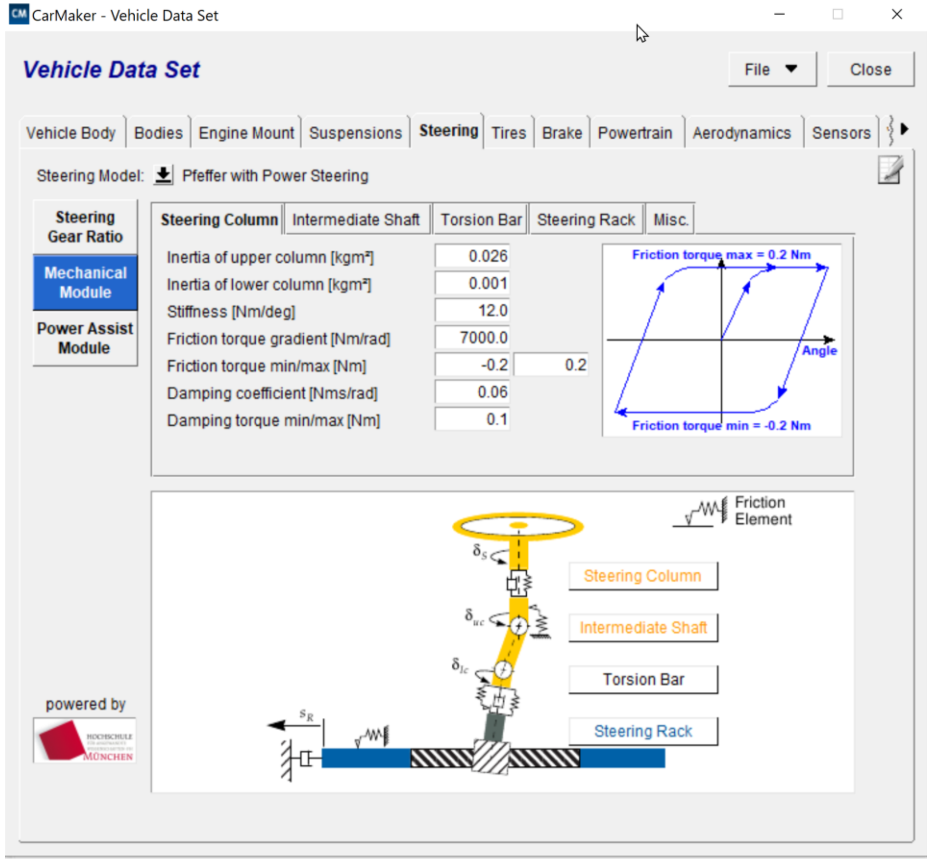


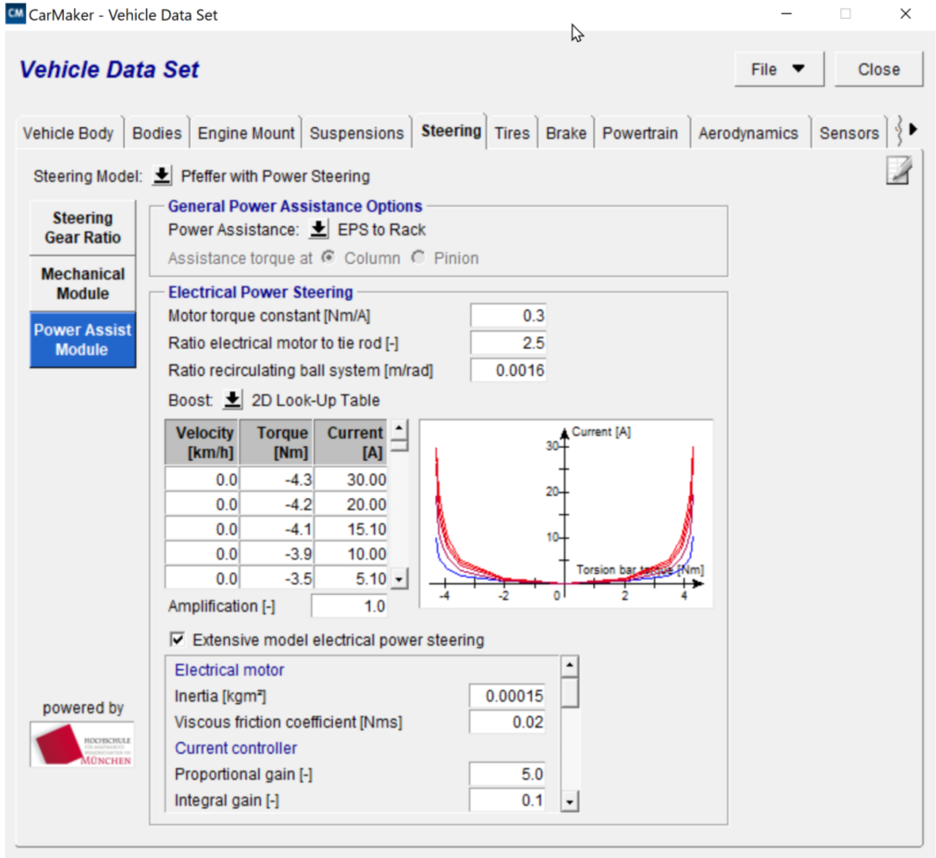
EPS Dual Pinion



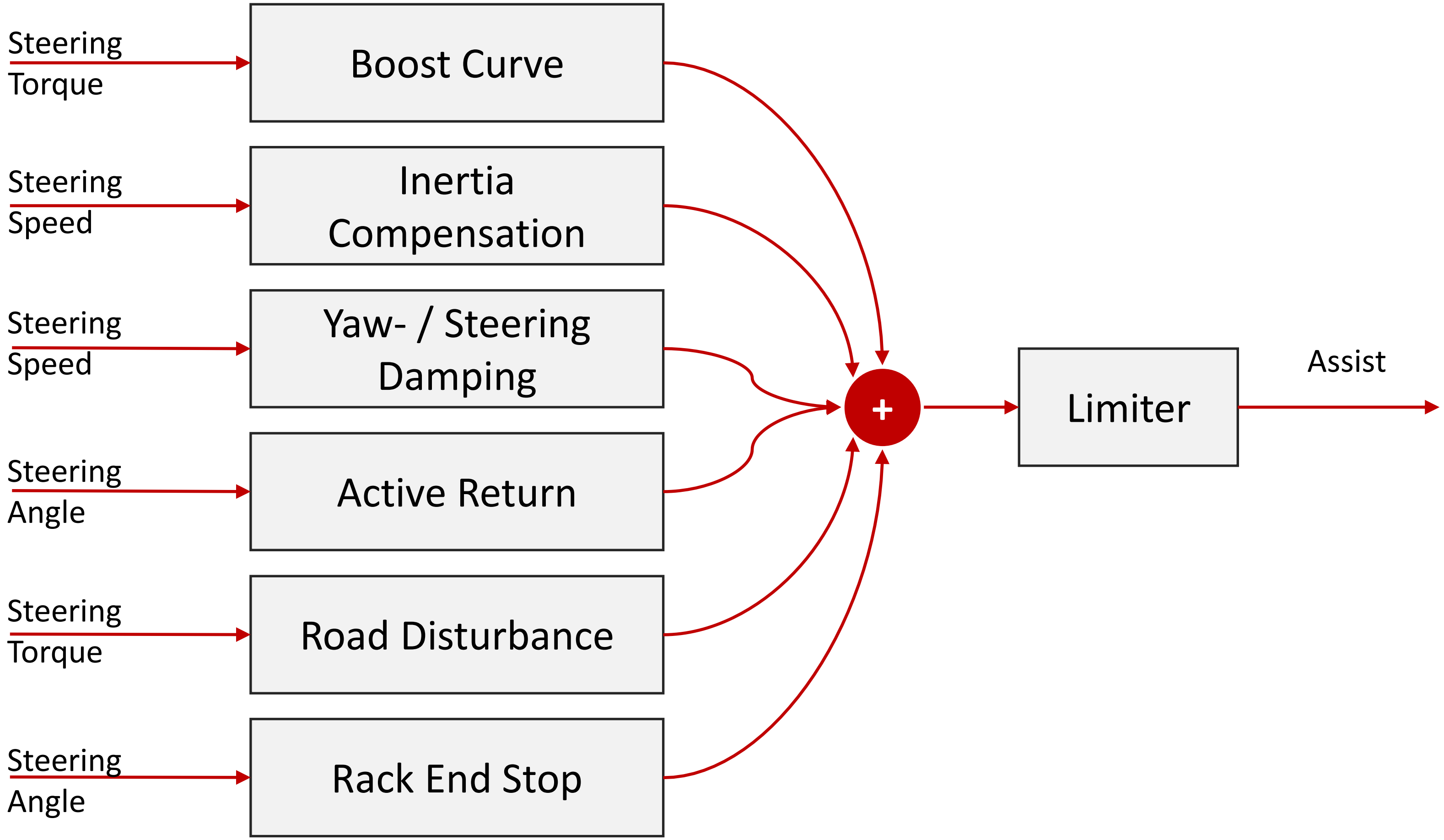
EPS Steering Model and related parameter







EPS Basic Functions

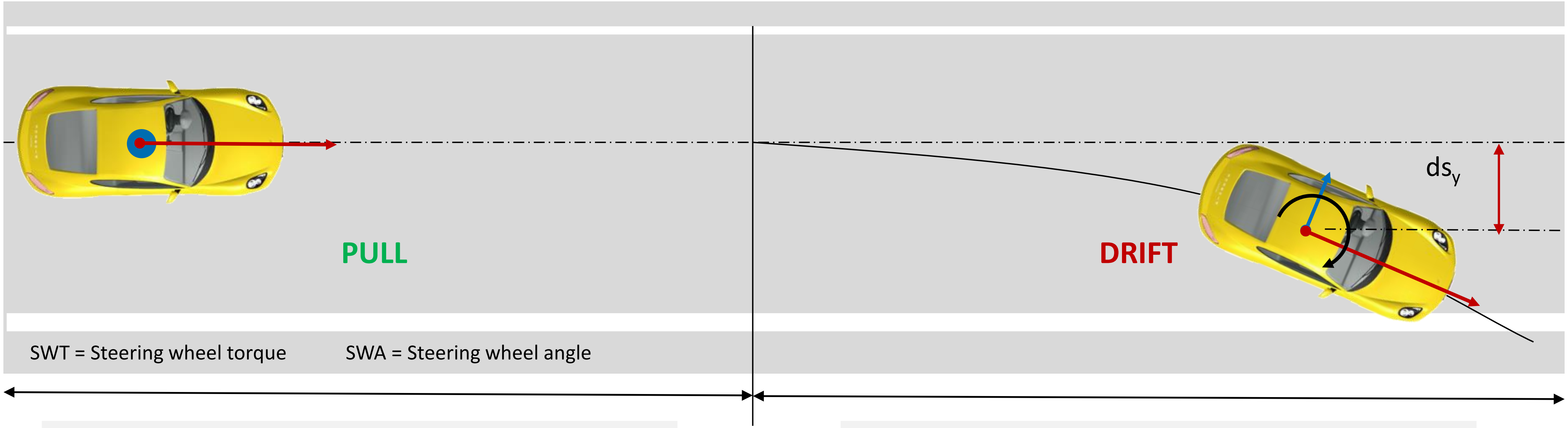


EPS functions and test maneuver for validation

EPS

EPS-Functions	Test Maneuver (sample)
Basic	
Boost Curve	Slowly Increase Steer (20 – 160kph
Inertia Compensation	Sine Sweep (0 – 120 kph)
Yaw Damping	Sine Sweep/Step Steer (0 – 120 kph)
Active Return	Bending Curve
Road Disturbance	Uneven Road /Single Events
Rack End Stop	Steer at Standstill
Enhanced Features	
Torque Overlay Interface	µ-Split Test
Pull/Drift Compensation	Weave Test (40 – 120, 2,5 – 40°)
Park Assistance	Parking Tests
Active Nibble Compensation	Road Shake Test (uneven/even)
Lane Assistance	Lane Keeping Tests

On-Center Steering Behavior



COMFORT

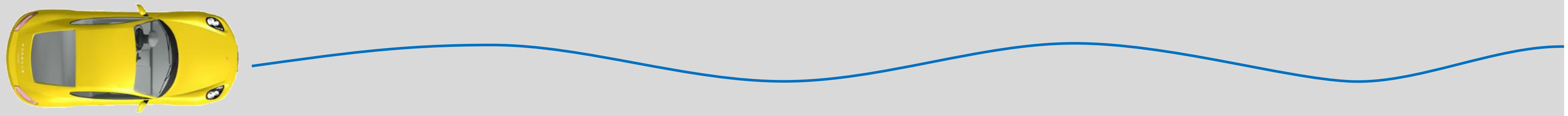
- **Subjective:** Steering Effort Center Point
- **Objective:** SWT / SWA Effort at YawRate = 0

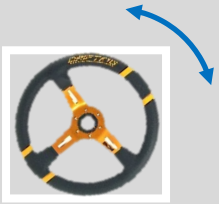
SAFETY

- **Subjective:** Straight running behavior
- **Objective:** YawRate Response at SWT = 0

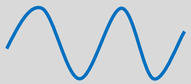
On-Center Handling Test - Weave (ISO 13674-1)

V = 60 – 80 – 100 – 120 – 140 - 160 km/h

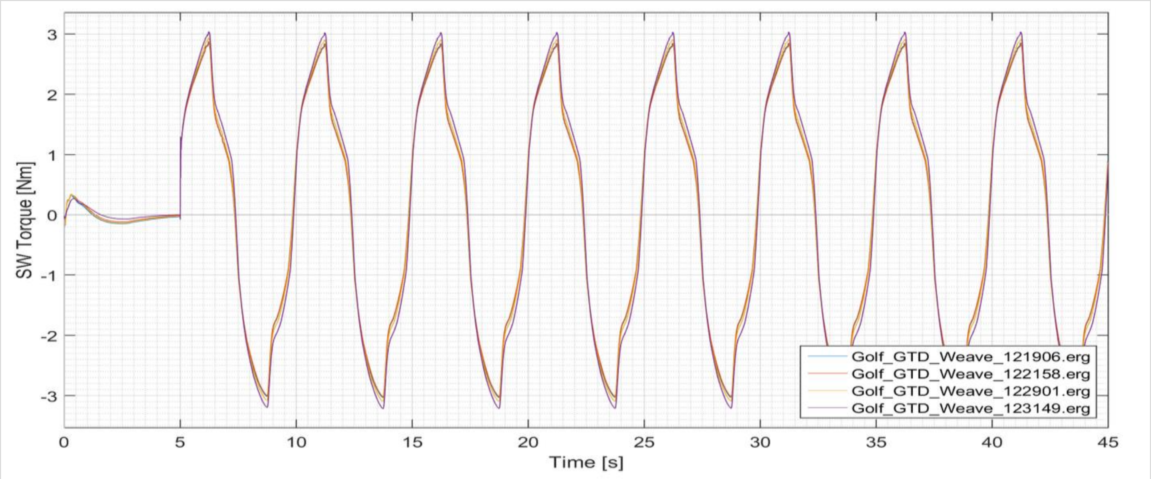




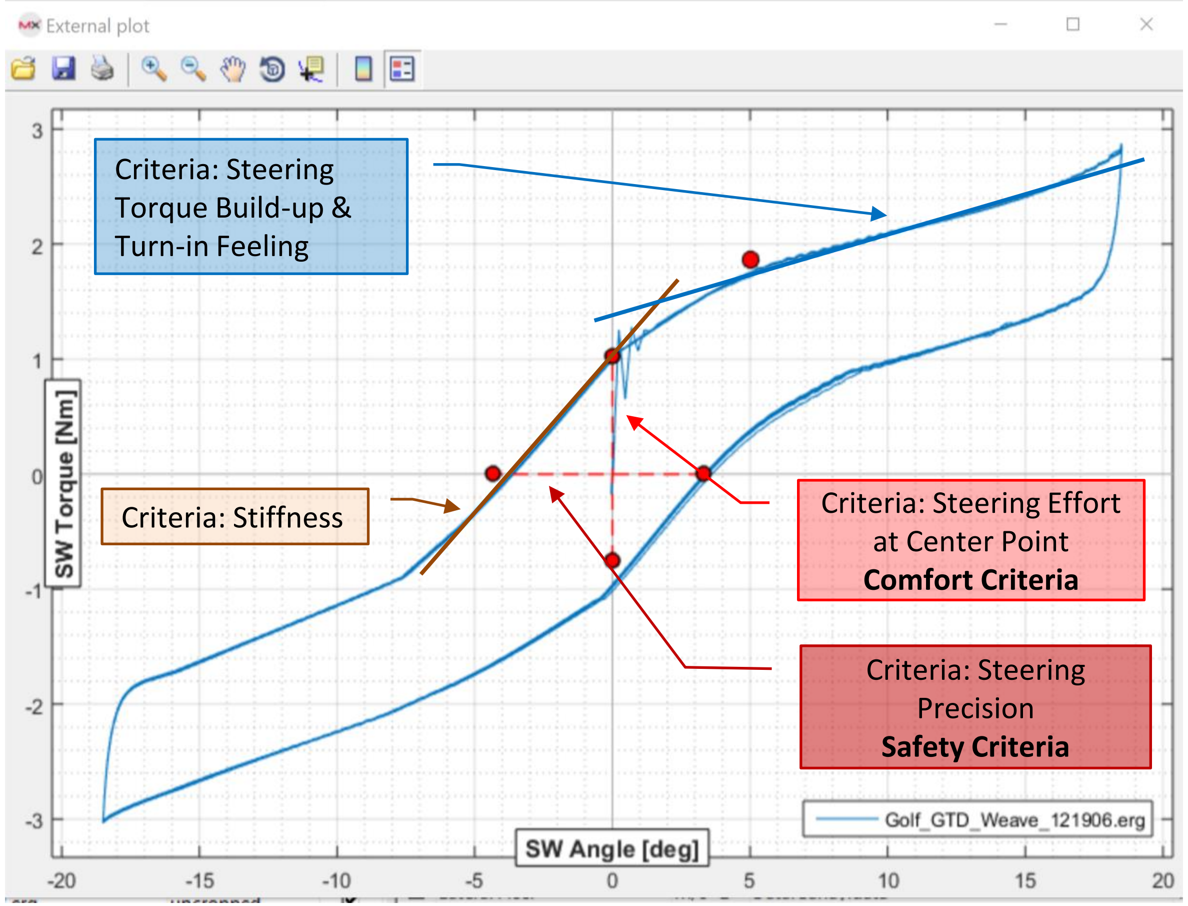
Steer Input: Sine 0.2 +/- 10%

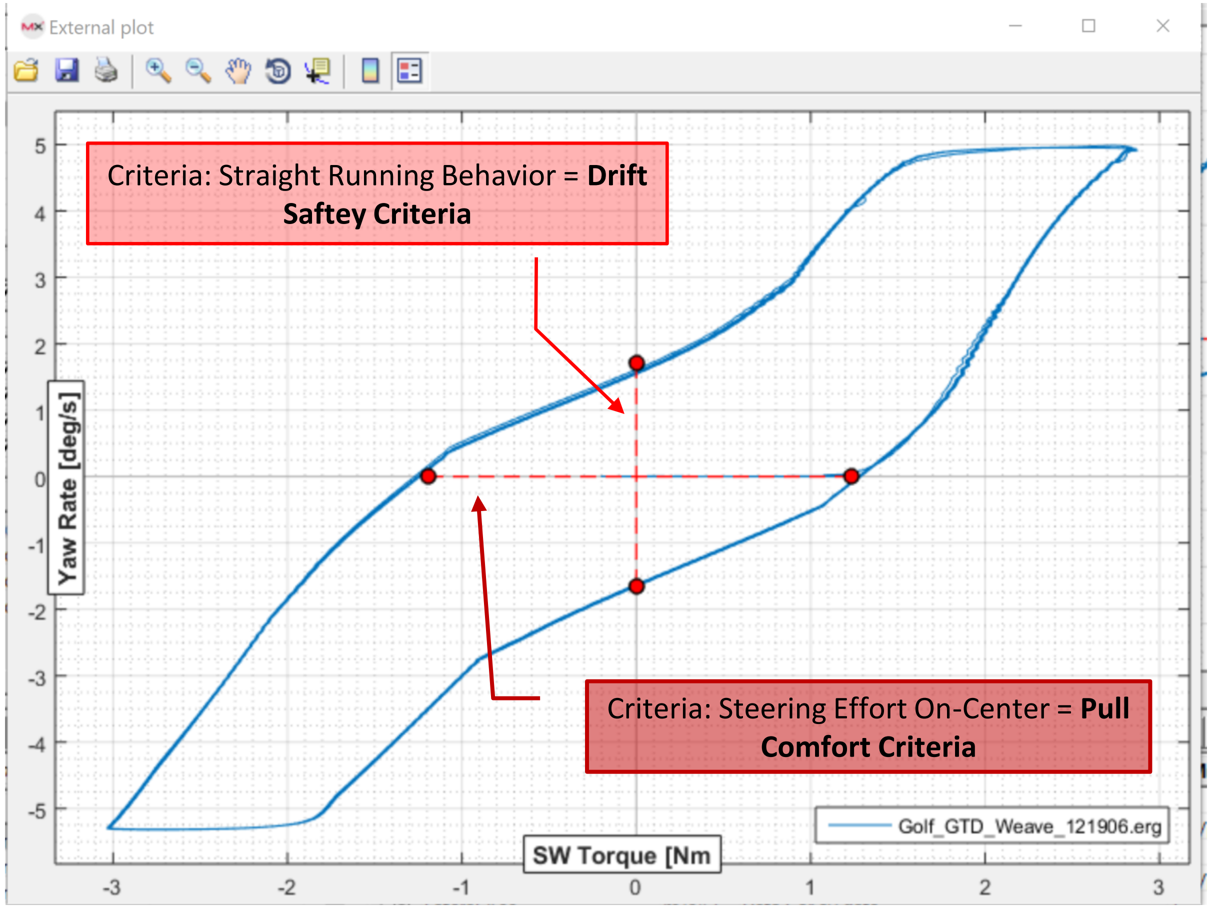


ay: < 0.2 g

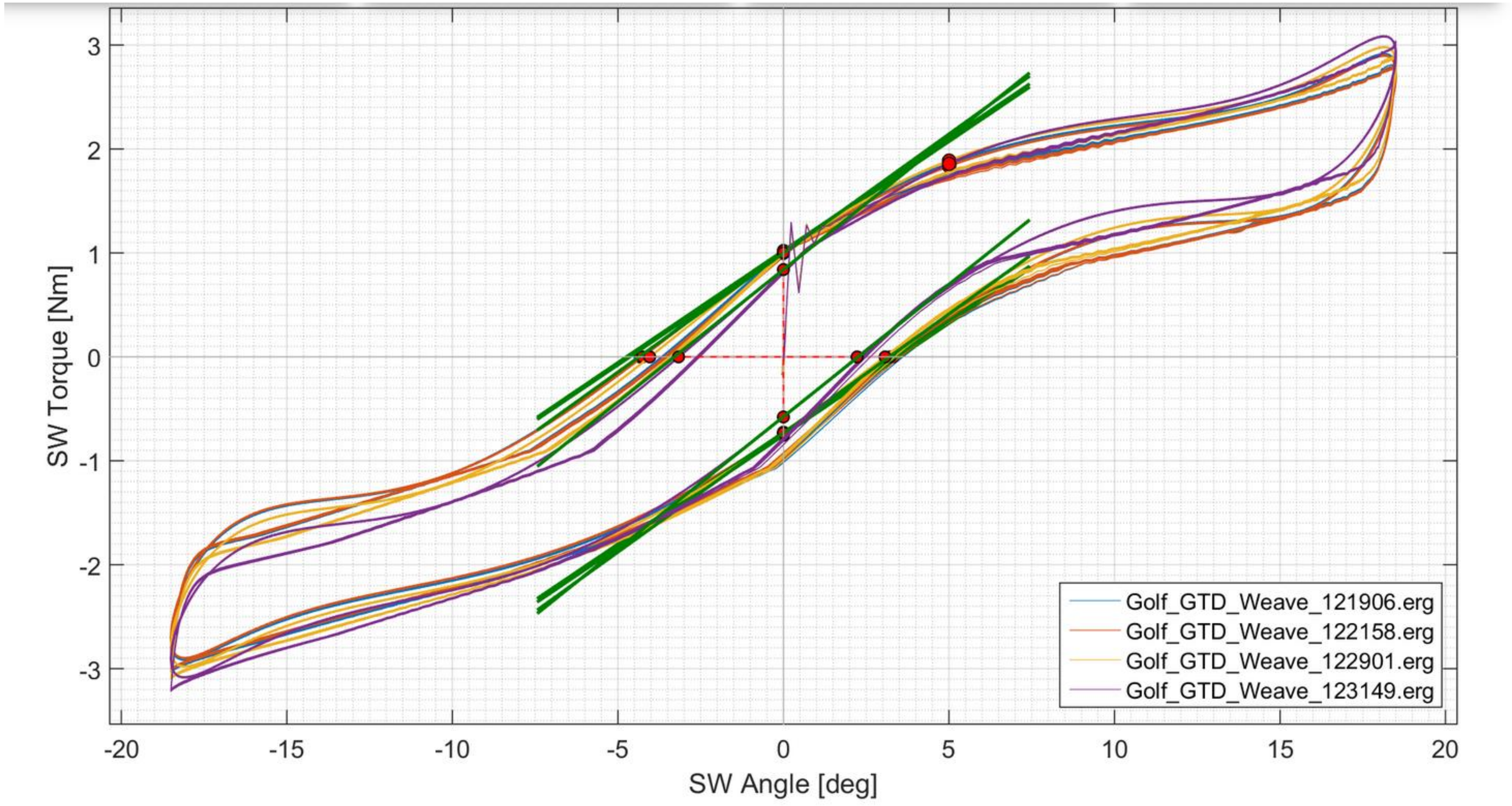


Steering On-Center Evaluation: On-Center Handling Test (ISO 13674)





Steering On-Center Evaluation: On-Center Handling Test (ISO 13674)

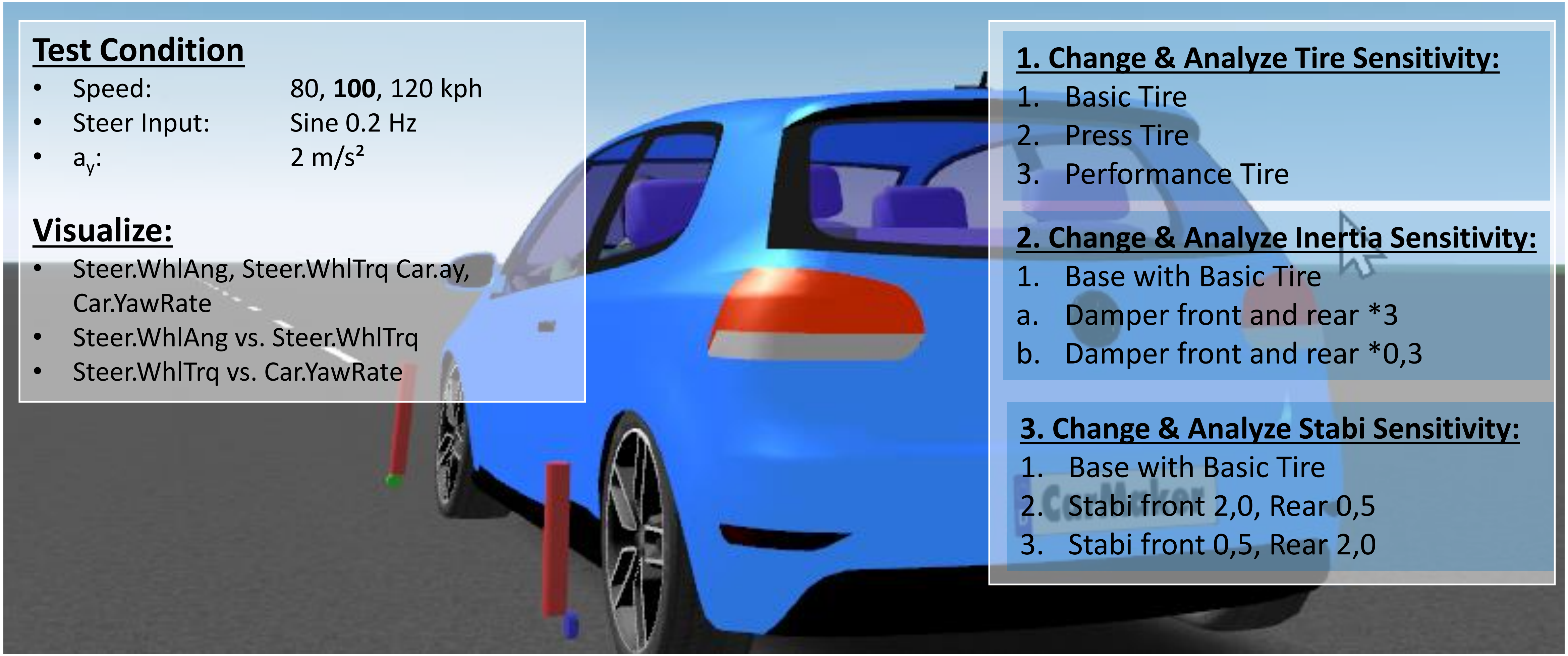


Golf 7 GTD

Basic Tire

Performance Tire

Exercise 14: On-Center Handling Test - Weave (ISO 13674-1)



Test Condition

- Speed: 80, **100**, 120 kph
- Steer Input: Sine 0.2 Hz
- a_y: 2 m/s²

Visualize:

- Steer.WhlAng, Steer.WhlTrq Car.ay, Car.YawRate
- Steer.WhlAng vs. Steer.WhlTrq
- Steer.WhlTrq vs. Car.YawRate

1. Change & Analyze Tire Sensitivity:

1. Basic Tire
2. Press Tire
3. Performance Tire

2. Change & Analyze Inertia Sensitivity:

1. Base with Basic Tire

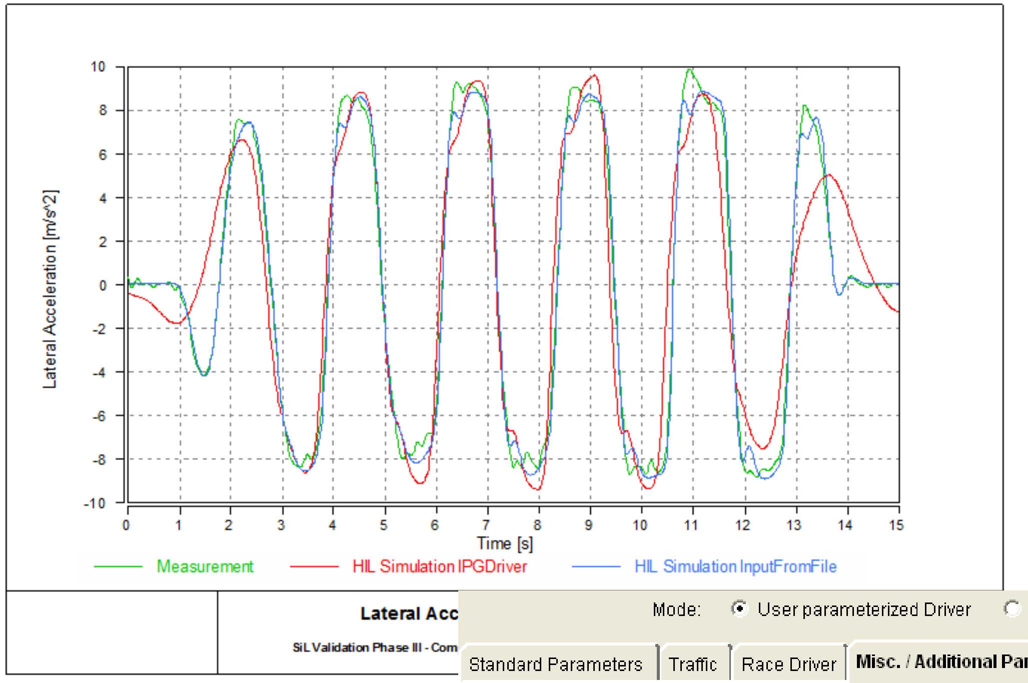
a. Damper front and rear *3

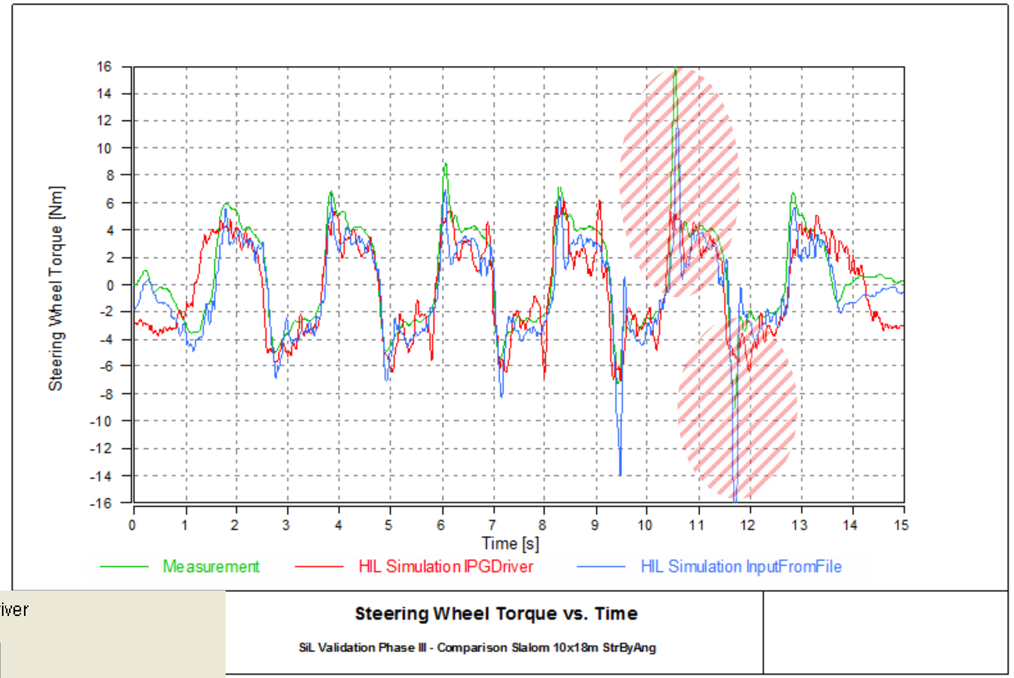
b. Damper front and rear *0,3

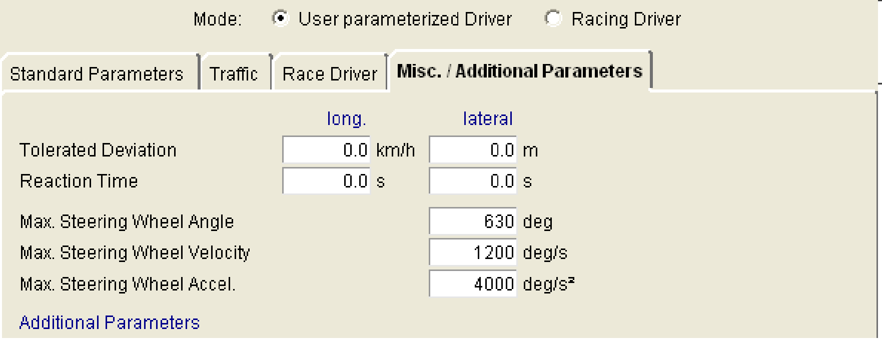
3. Change & Analyze Stabi Sensitivity:

1. Base with Basic Tire
2. Stabi front 2,0, Rear 0,5
3. Stabi front 0,5, Rear 2,0

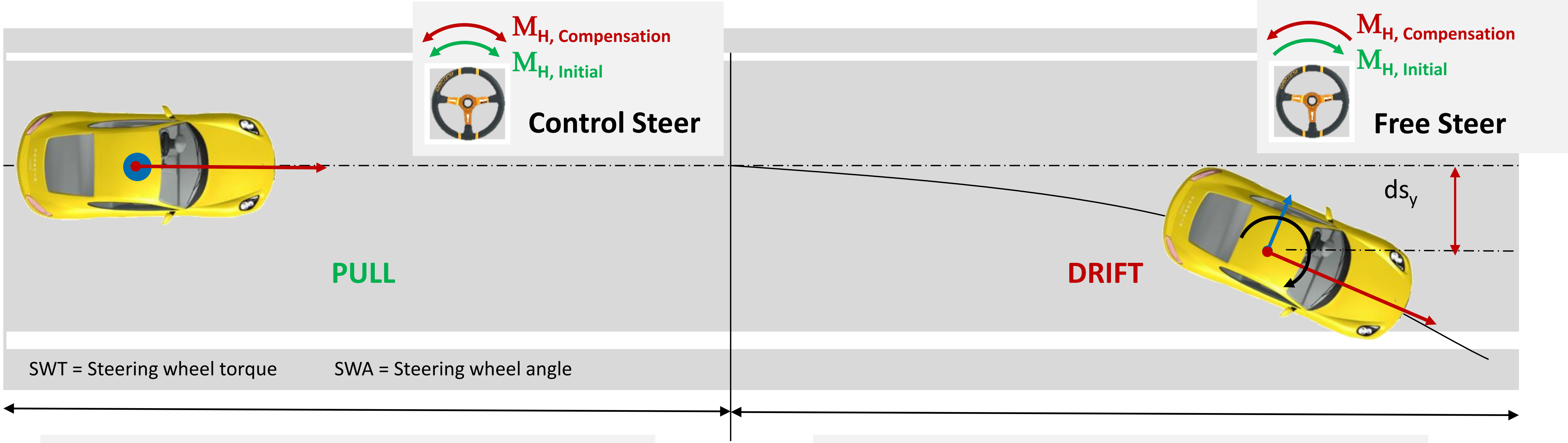
Sample Function and Test: Catch-up during virtual vehicle test → Slalom







Sample Function and Test: Pull-Drift Compensation (PDC)



- The driver has to pull steering torque to drive straight ahead
- This steering torque is measured and automatically supported to reduce the drivers effort

- The vehicle is drift off the center line. The vehicle response with a yaw rate
- The yaw rate is measured and a steering angle support is applied to reduce the yaw rate to zero.