ME 4220 Automotive Engineering Vehicle Dynamics

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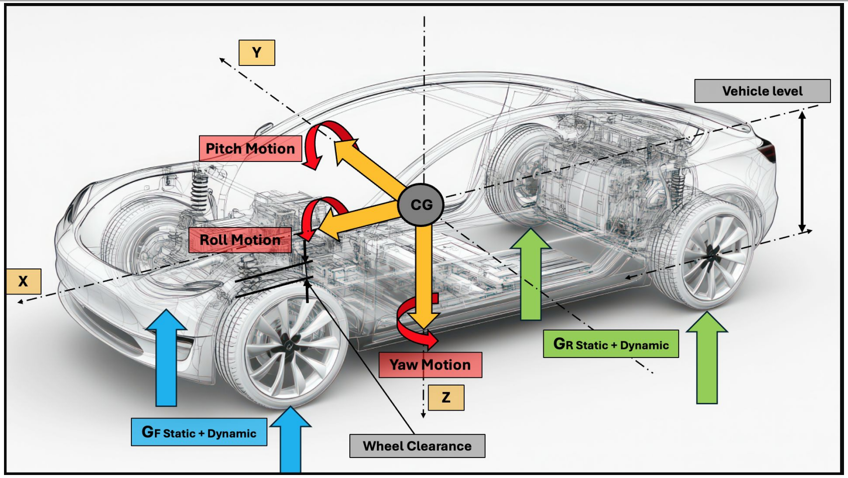


Winter Semester 2025
Vehicle Dynamic
ME 4220 Course

Introduction

- Applied mechanics and mathematics utilized in vehicle modeling
- Vehicle axis systems, centre of gravity, loads, inertias

Vehicle Dynamics

Longitudinal Dynamics

- Dynamic axle loads at acceleration or deceleration
- Traction limited acceleration, climbing, traction control
- Traction limited braking, brake stability
- Brake forces distribution
- Vehicle resistances and engine output requirements

Vertical Dynamics

- Vibration, noise classification, propagation and phenomenon's
- Simple vertical dynamics modeling
- Road excitation
- Suspension springing and shock absorbing

Lateral Dynamics

- Lateral acceleration, forces and slip angle
- Low speed cornering
- Vehicle under-steering, over-steering and self steering
- Vehicle stationary and non-stationary cornering, line change
- Lateral dynamics modeling

Interaction between longitudinal, vertical and lateral vehicle dynamics

- 3-Dimensional interaction
- Vehicle pitch and roll motions and General considerations
- Vertical Force Variations
- Braking, accelerating while cornering, braking on split μ surface
- Vehicle Dynamics Target Conflicts

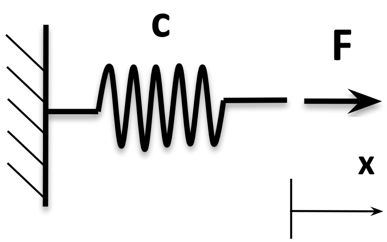
Chassis systems in vehicle dynamics

- Suspension design, classification, kinematics and elastokinematics
- Introduction to brake systems, and importance in vehicle dynamics control

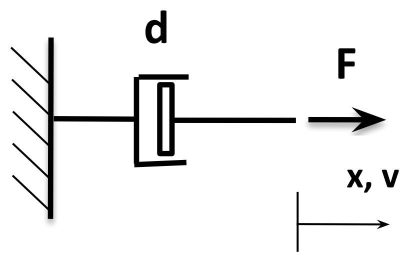
Tire as major and most important component in vehicle dynamics

- History
- Requirements
- Design / construction
- Force transfer and road contact
- Longitudinal dynamics: traction and braking
- Vertical dynamics: ride and NVH
- Lateral dynamics: cornering

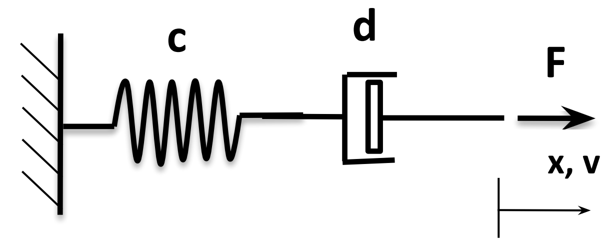
Longitudinal dynamics influence on lateral forces: accelerating, braking while cornering
Nonuniformiry and vehicle interaction
Tire performances, performances balance and conflicts
Modeling



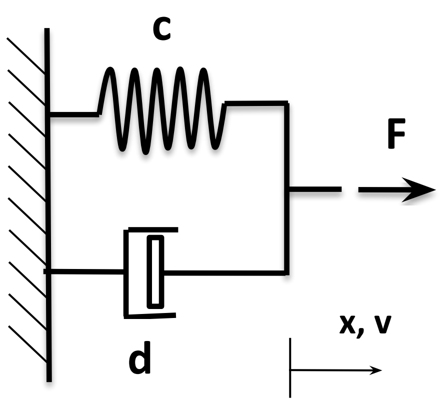
$$F = cx$$



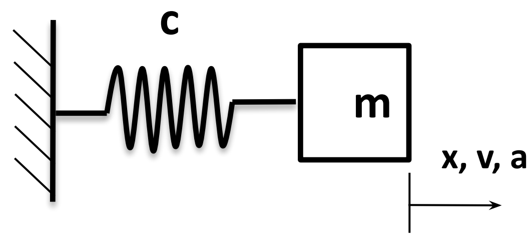
$$F = dv$$



$$v = \frac{dF}{dt}\frac{1}{c} + \frac{F}{d}$$

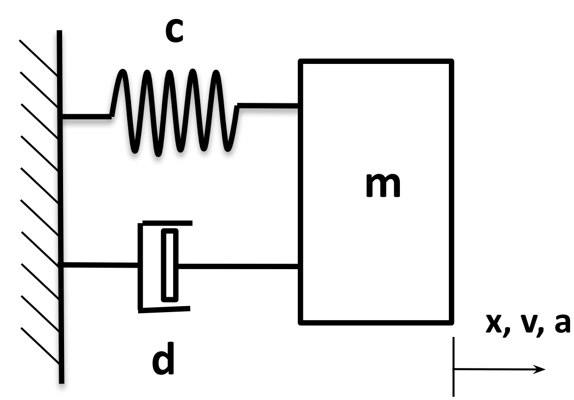


$$F = cx + dv$$

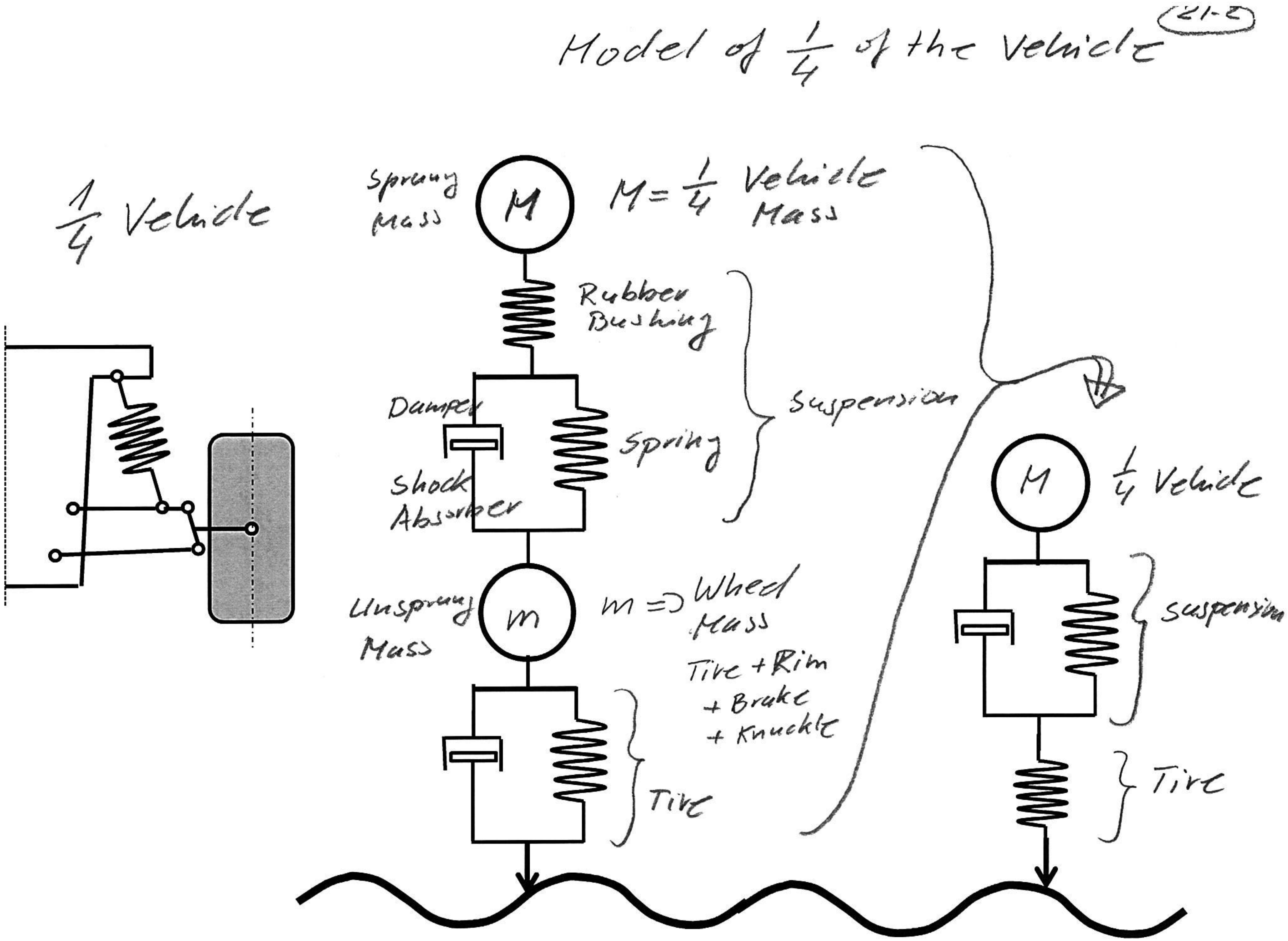


$$cx + ma = 0$$

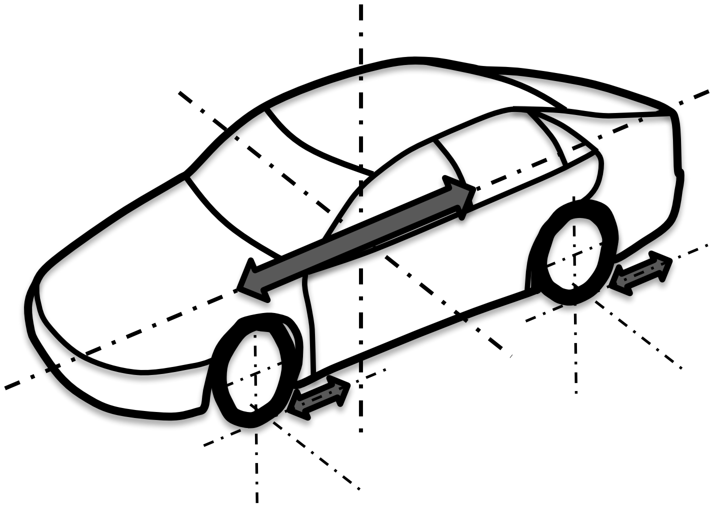
$$\omega = \sqrt{c/m}$$

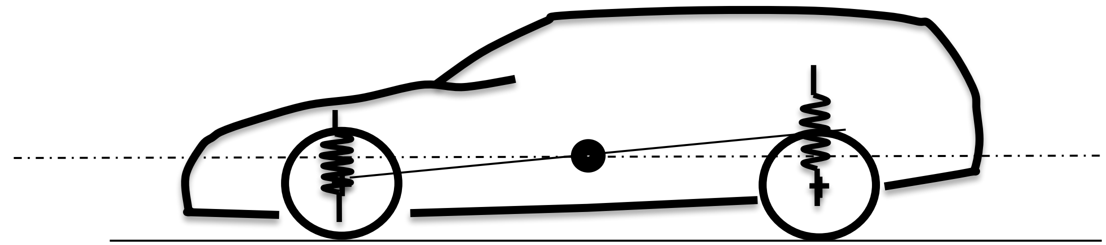


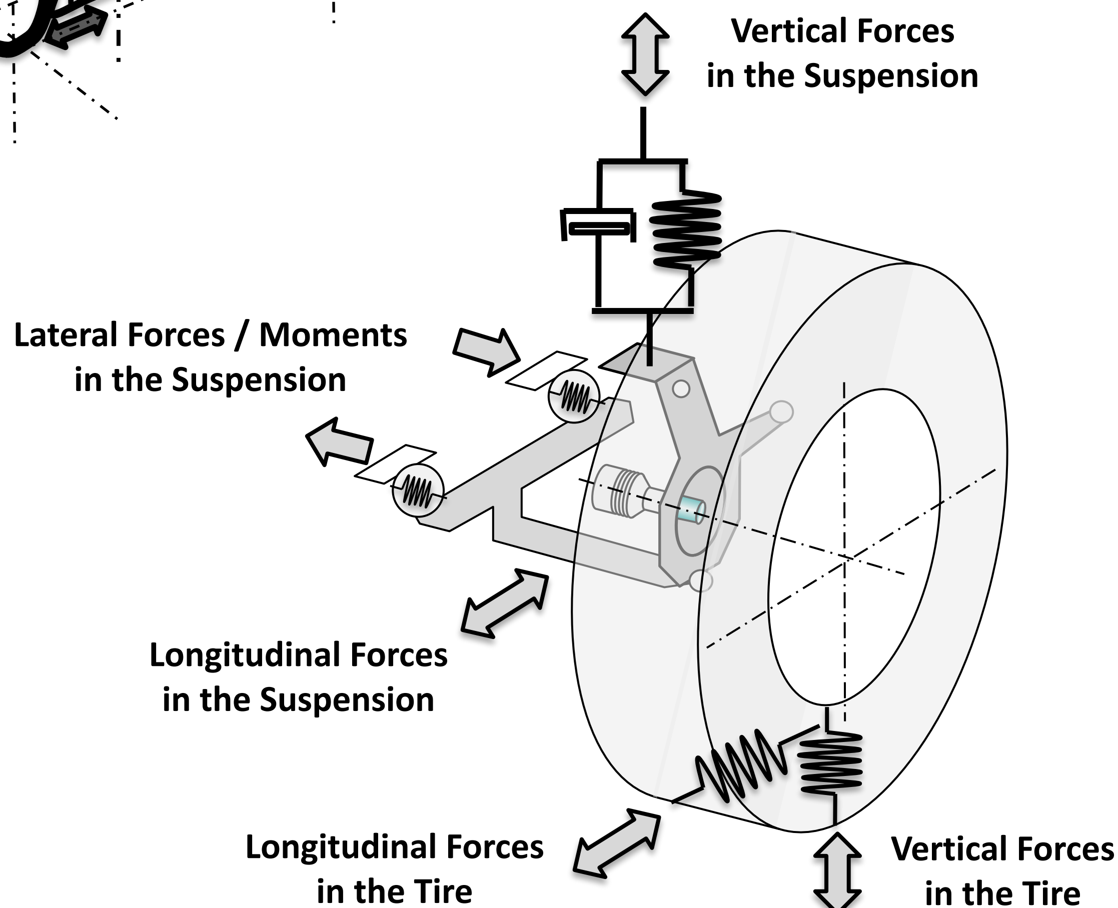
$$cx + dv + ma = 0$$


Model of 1/4 of the Vehicle
21-2
1/4 Vehicle
Sprung Mass
M
M = 1/4 Vehicle Mass
Rubber Bushing
Damper
Spring
Shock Absorber
Suspension
Unsprung Mass
m
m => Wheel Mass
Tire + Rim + Brake + Knuckle
Tire
M
1/4 Vehicle
suspension
Tire

Longitudinal Dynamics

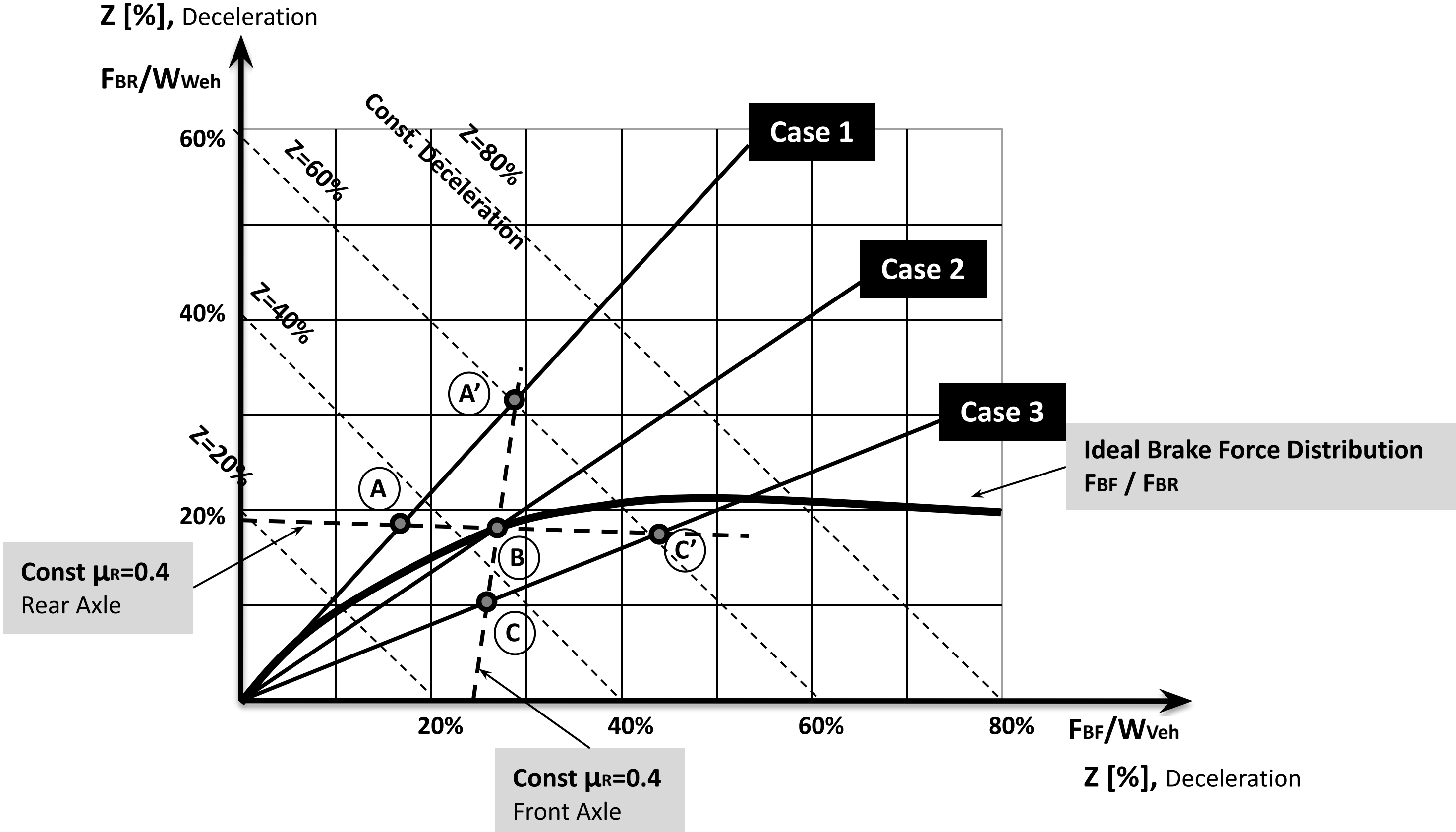






Excitation Forces:

- Acceleration
- Braking
- Load change



Case 1: Rear wheels blocked first: Unstable Situation

Case 2: Front and Rear wheels blocked at the same time: Unstable Situation, No Steering

Case 3: Front wheels blocked first: Stabile Situation, No Steering

Vehicle Output / Power Requirements

During driving following Vehicle Resistances needs to be overcome:

- **Acceleration Resistance** $F_{R,Acc}$
- **Wheel Resistance** $F_{R,W}$
- **Air Resistance** $F_{R,A}$
- **Climb Gradient Resistance** $F_{R,Climb}$
- **Towing Resistance** $F_{R,T}$

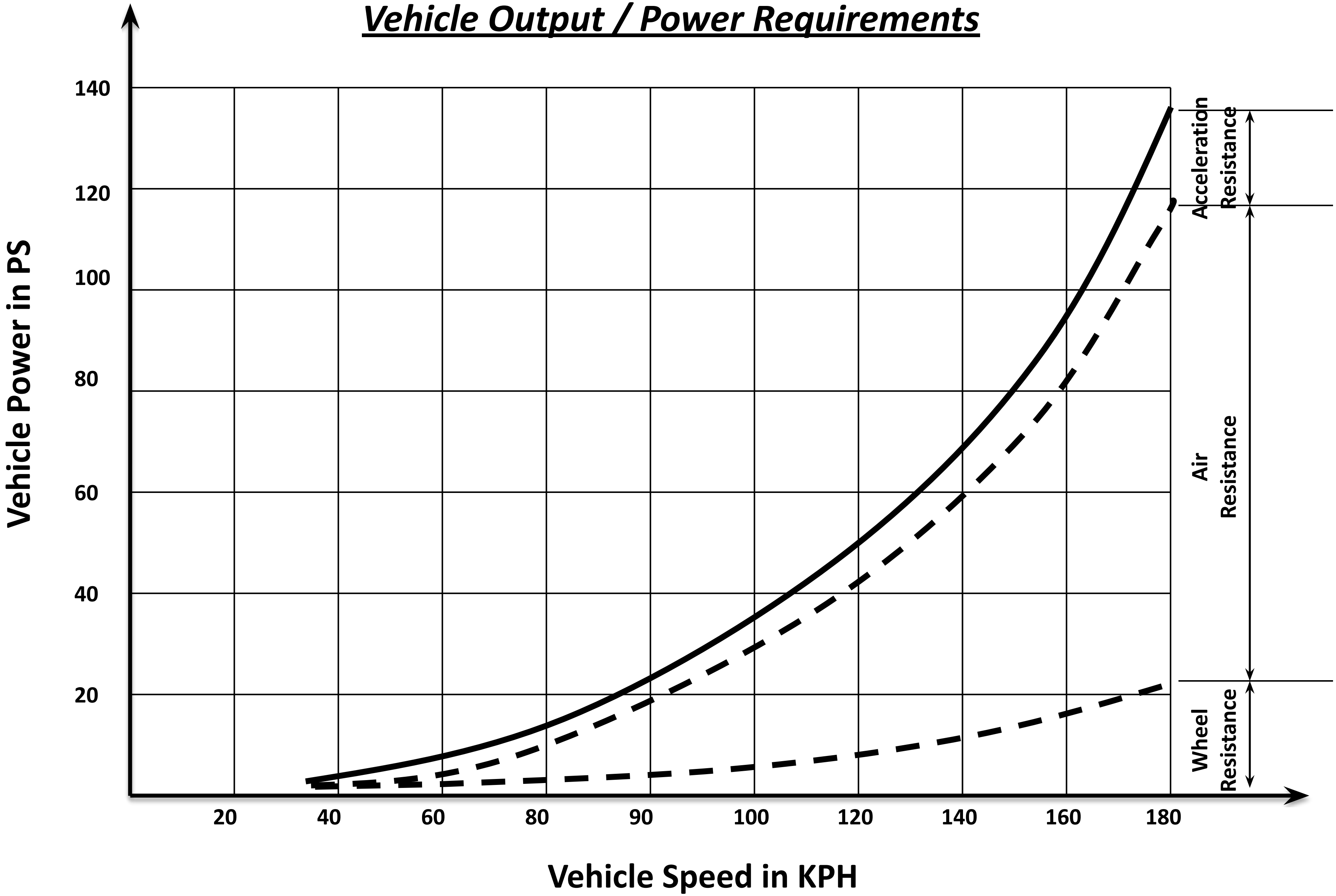
 Total Vehicle Resistance: $F_R = F_{R,W} + F_{R,A} + F_{R,Climb} + F_{R,Acc} + F_{R,T}$

Special Cases:

 constant drive w/o gradient: $F_R = F_{R,W} + F_{R,A} + F_{R,T}$ $\quad F_{R,Climb} = F_{R,Acc} = 0$

 constant drive on gradient: $F_R = F_{R,W} + F_{R,A} + F_{R,Climb} + F_{R,T}$ $\quad F_{R,Acc} = 0$

Vehicle Output / Power Requirements



Vehicle Output / Power Requirements

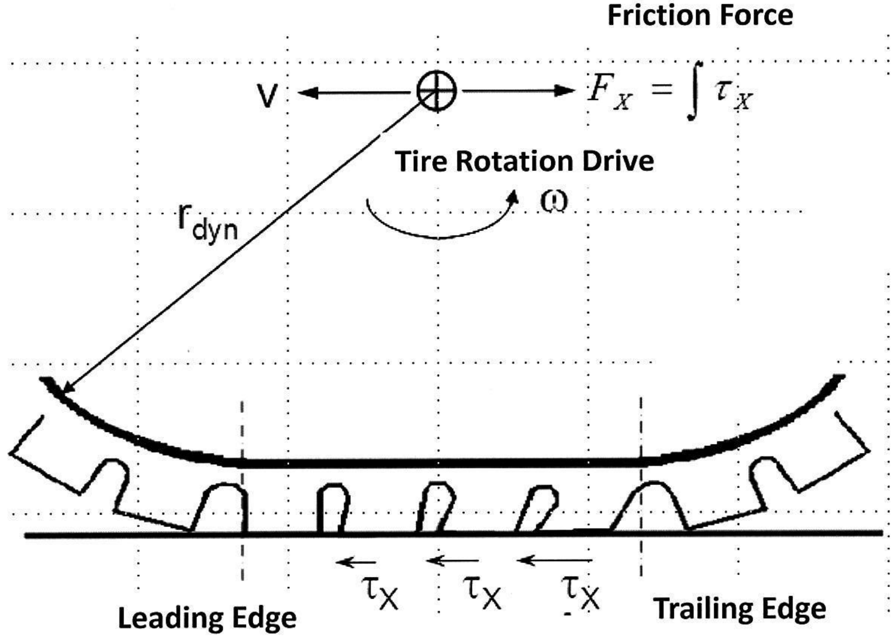
During driving following Vehicle Output / Power is required in order to overcome Vehicle Resistances:

Total Vehicle Resistance Power:

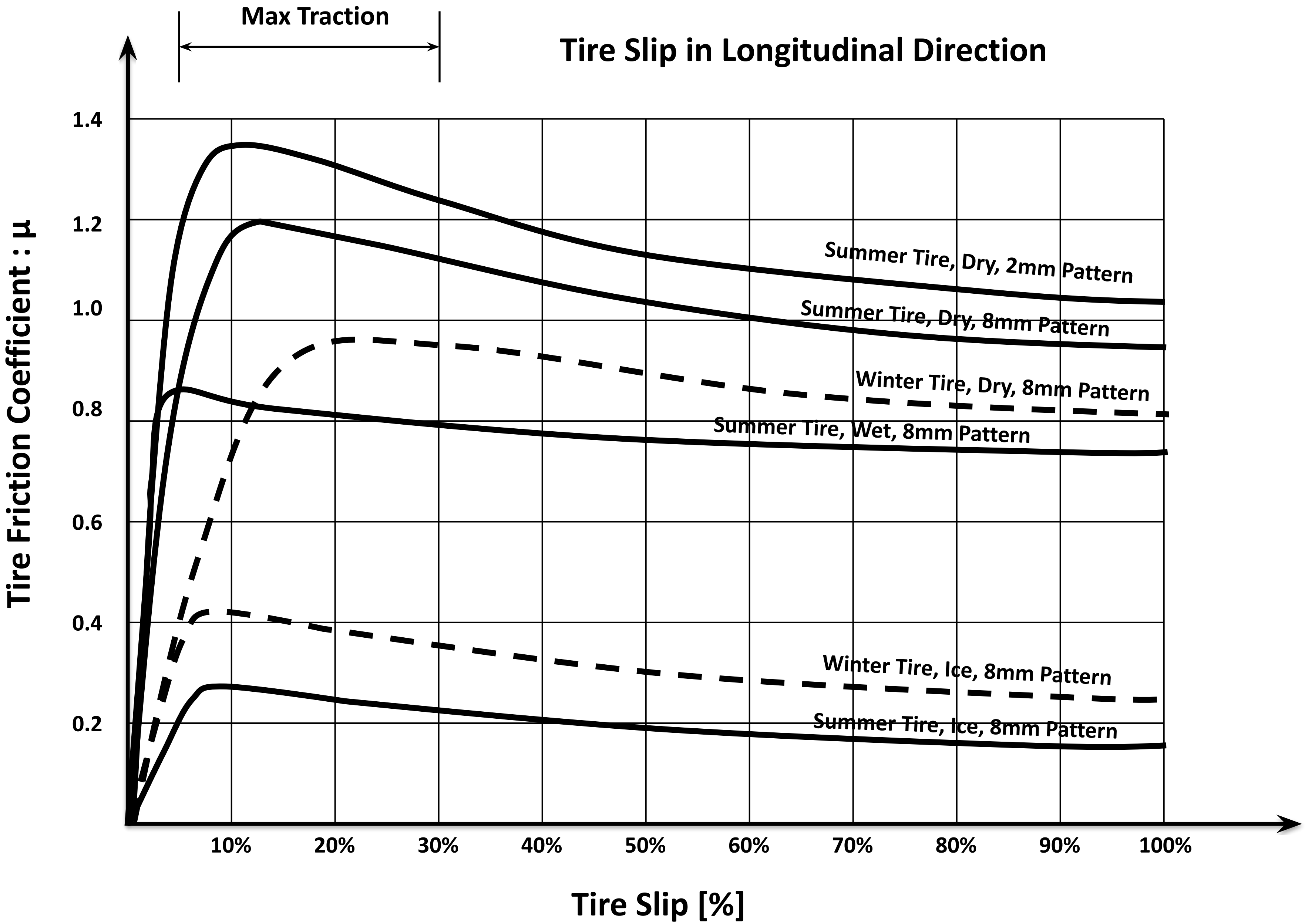
$$P_R = P_{R,W} + P_{R,A} + P_{R,Climb} + P_{R,Acc} + P_{R,T}$$

$$P_R = F_{R,W}\ v$$

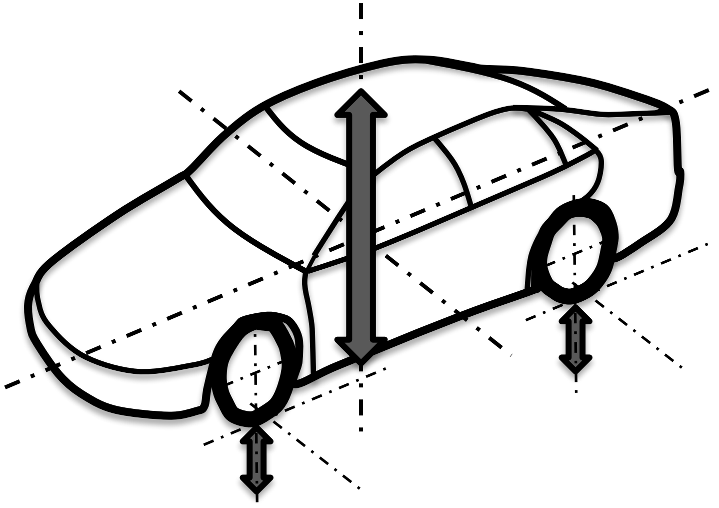
Tire / Wheel Slip *in Longitudinal Direction*

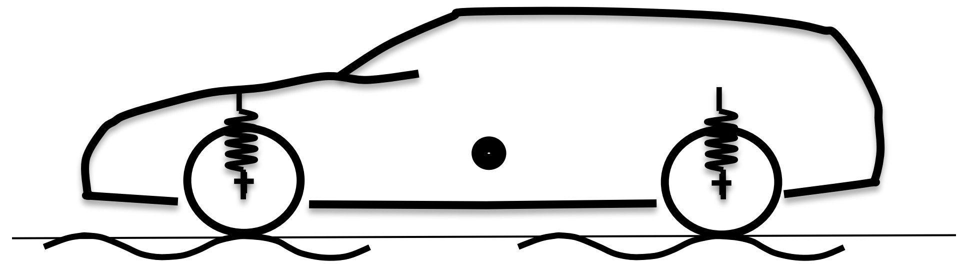


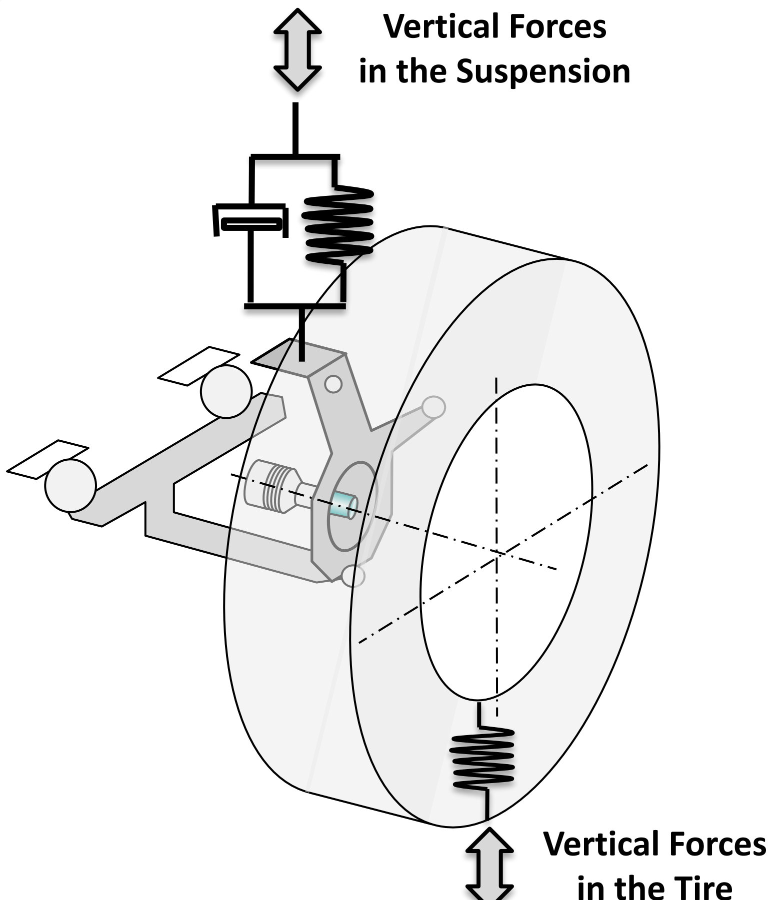
Friction of the tread pattern, Different speeds of the tread blocks


Max Traction
Tire Slip in Longitudinal Direction
Tire Friction Coefficient : μ
1.4
1.2
1.0
0.8
0.6
0.4
0.2
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Tire Slip [%]
Summer Tire, Dry, 2mm Pattern
Summer Tire, Dry, 8mm Pattern
Winter Tire, Dry, 8mm Pattern
Summer Tire, Wet, 8mm Pattern
Winter Tire, Ice, 8mm Pattern
Summer Tire, Ice, 8mm Pattern

Vertical Dynamics







Excitation Forces:

- **Dynamic interaction with the Rod Surface**

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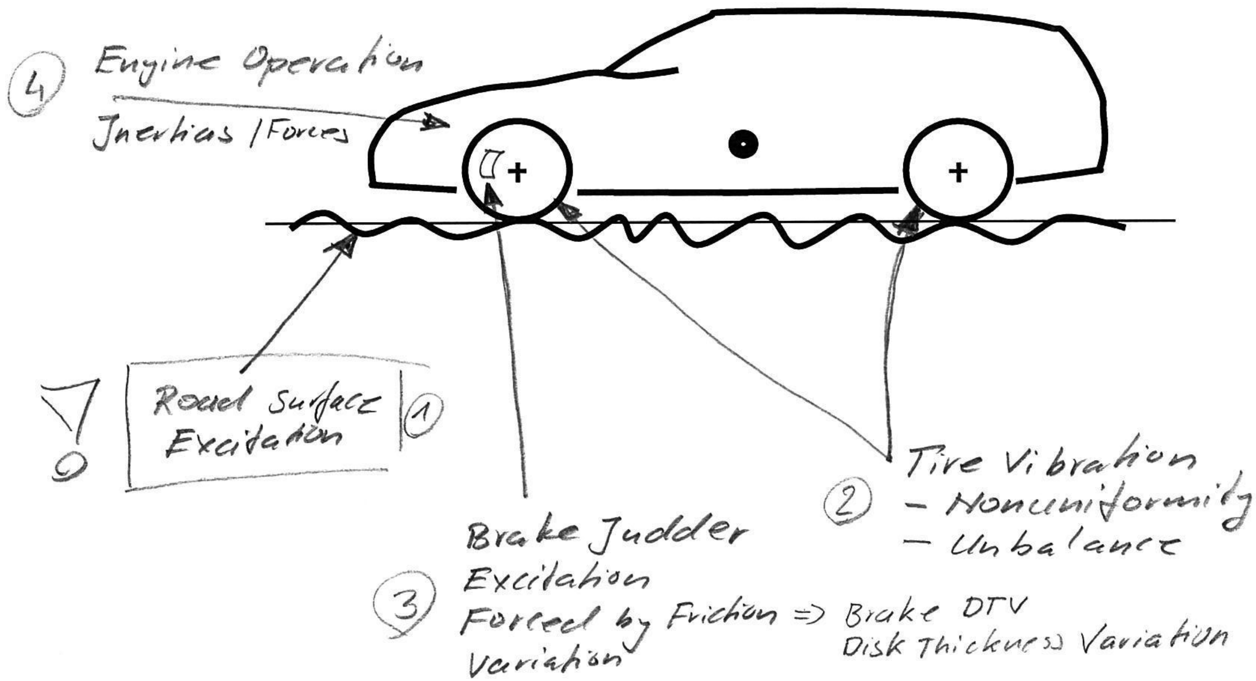
136-1

Sources of Vehicle Vertical Vibration

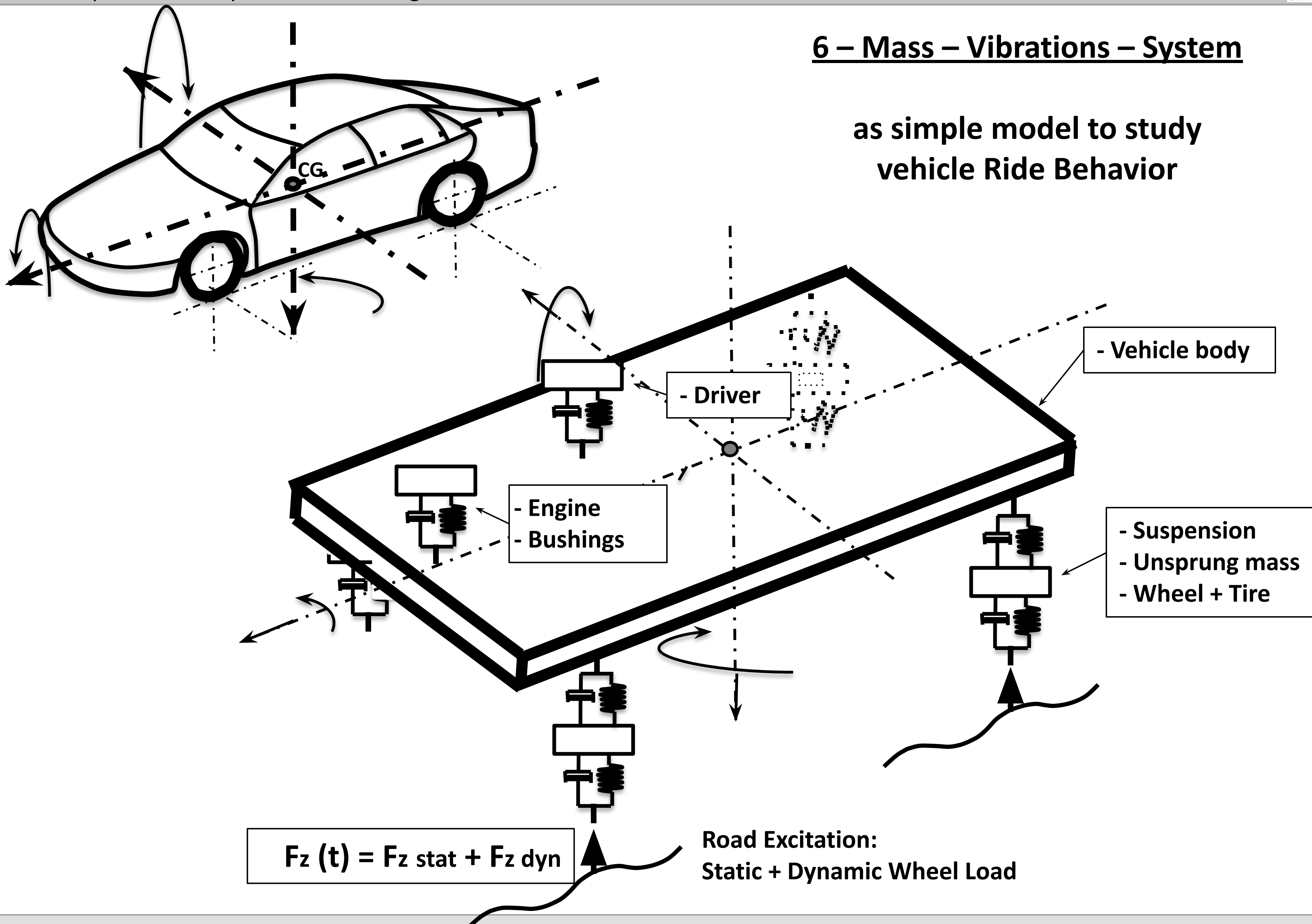
Forced Vibration

(5) Driving maneuvers



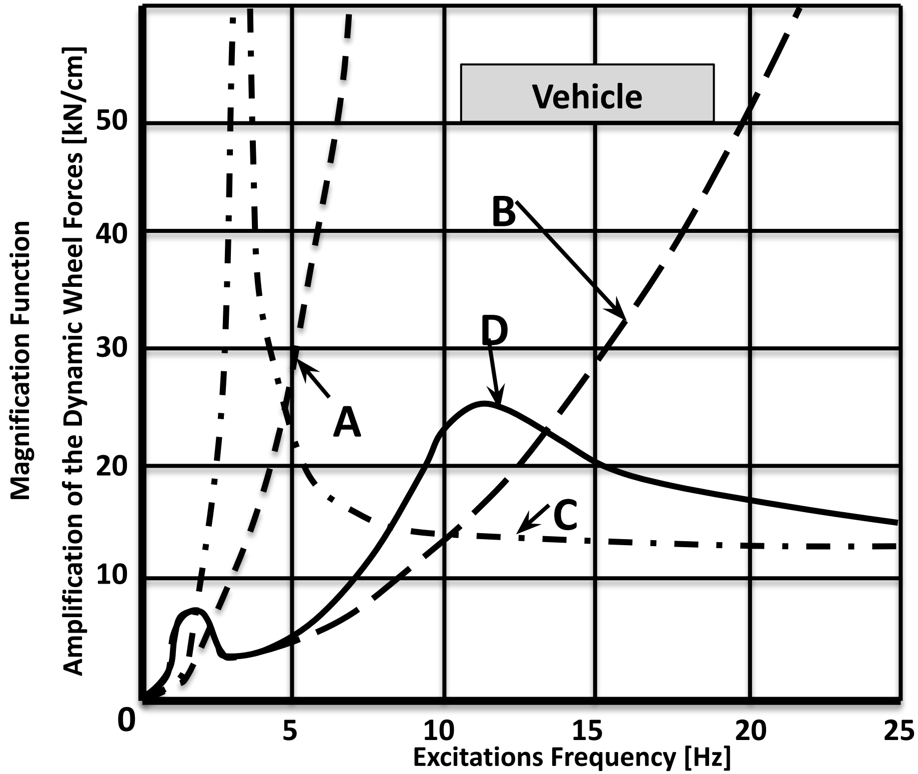
6 – Mass – Vibrations – System

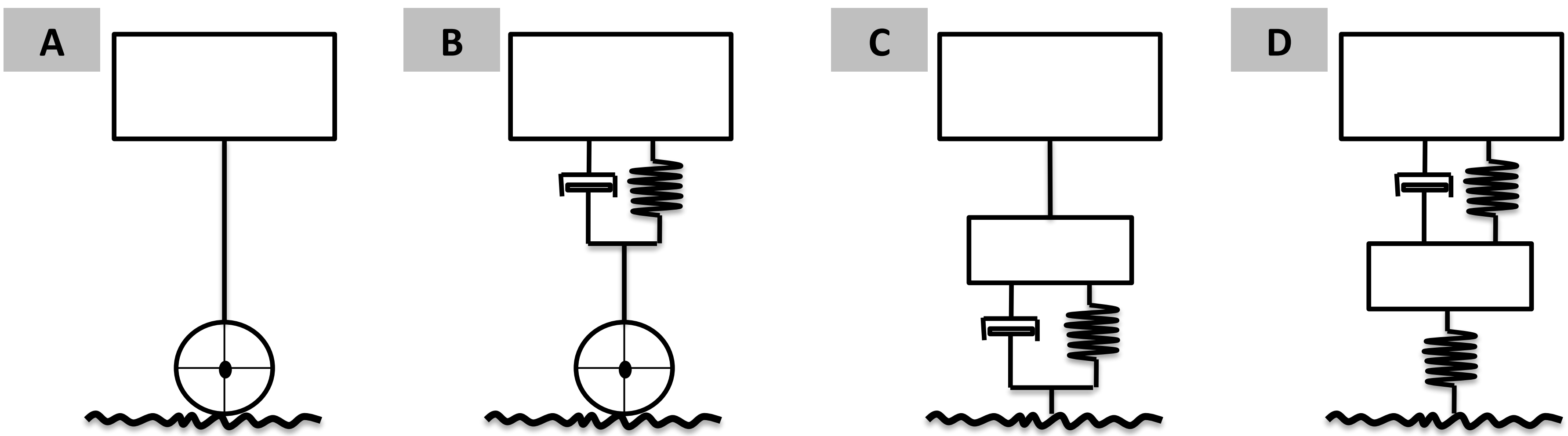
as simple model to study vehicle Ride Behavior



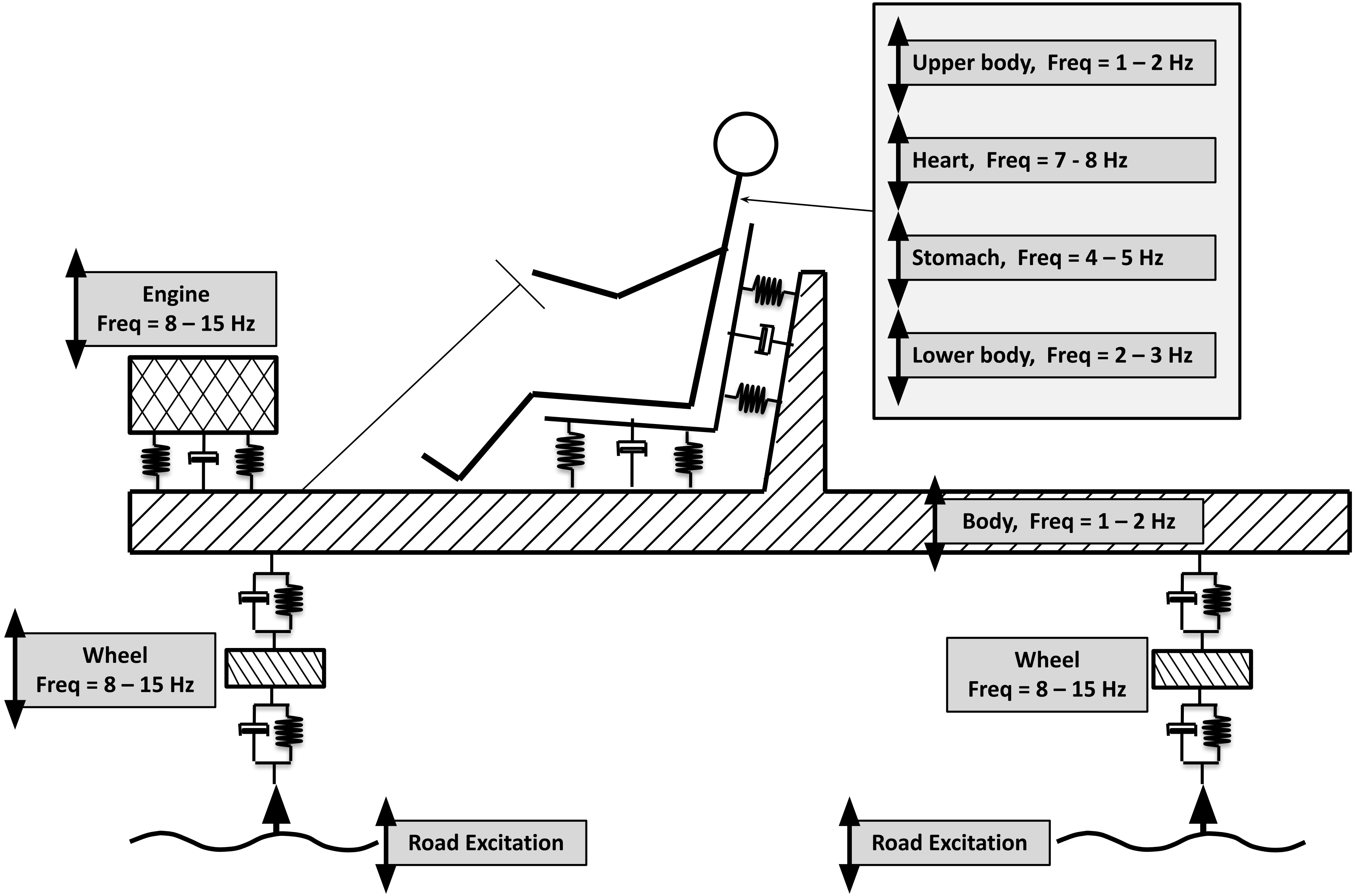
$F_z(t) = F_{z\,stat} + F_{z\,dyn}$

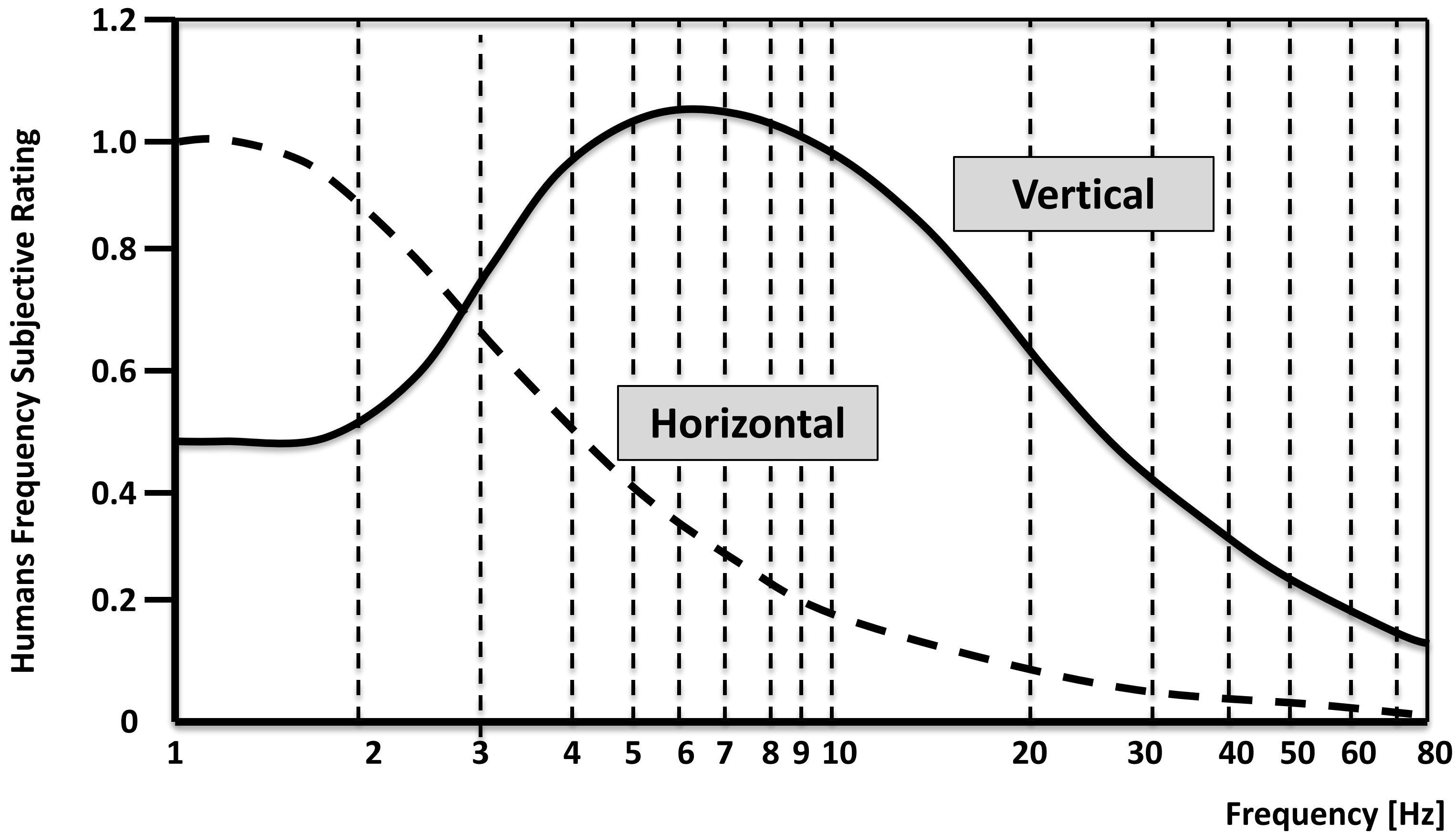
Road Excitation:
Static + Dynamic Wheel Load


Magnification Function
Amplification of the Dynamic Wheel Forces [kN/cm]
Excitations Frequency [Hz]
Vehicle
A
B
C
D
0
5
10
15
20
25
10
20
30
40
50


A
B
C
D

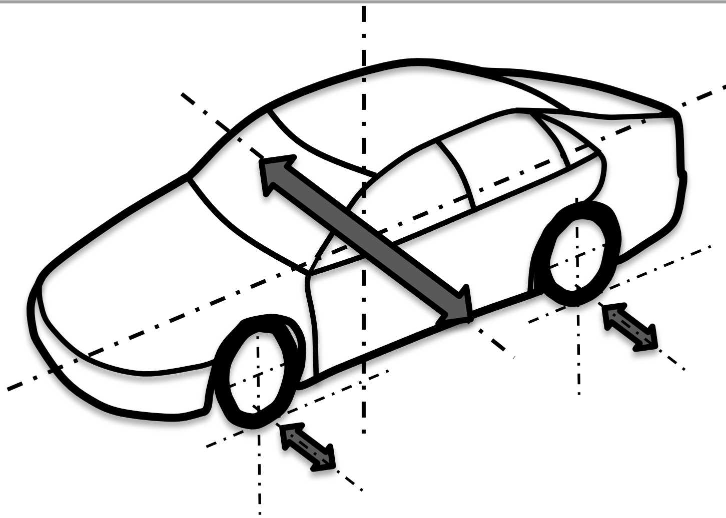
Vibrations Model: Vehicle / Seat / Human

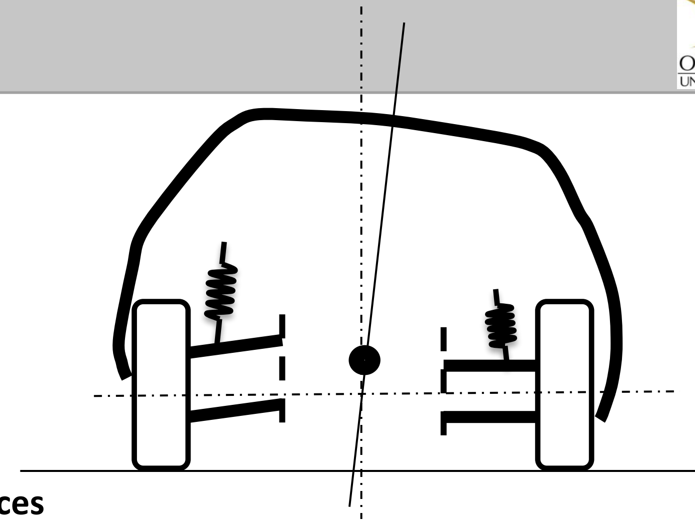


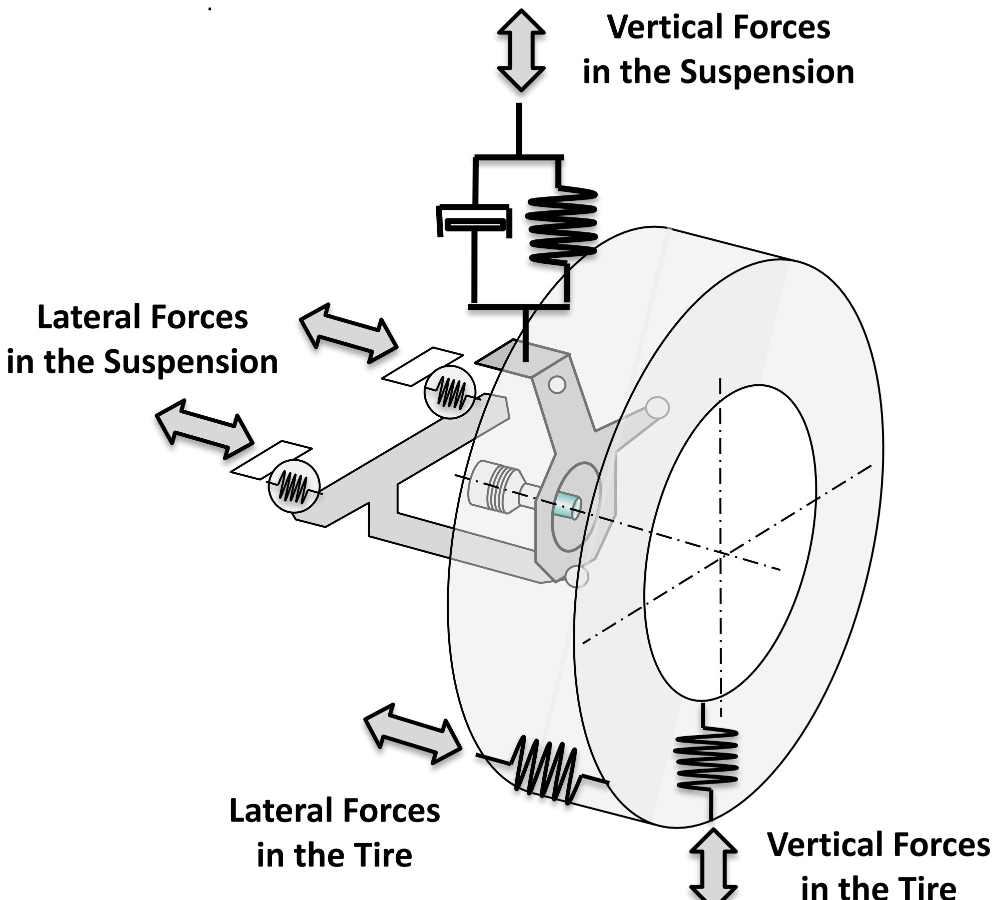


Frequency Rating Carve for Horizontal and Vertical Vibrations for Humans (seating / standing)

Lateral Dynamics





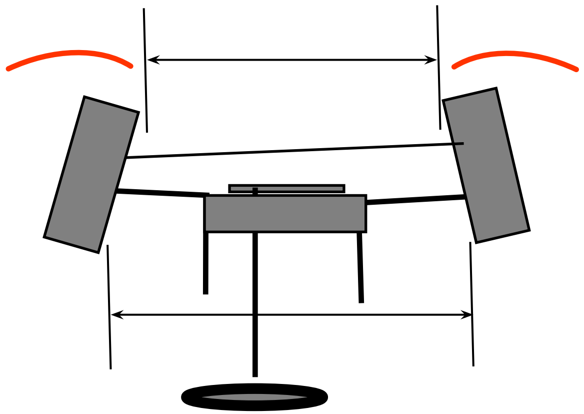


Excitation Forces:

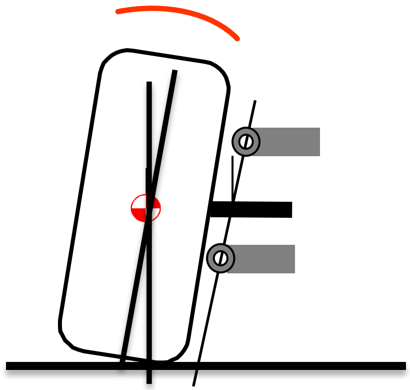
- Cornering

Wheel Positions in the suspension

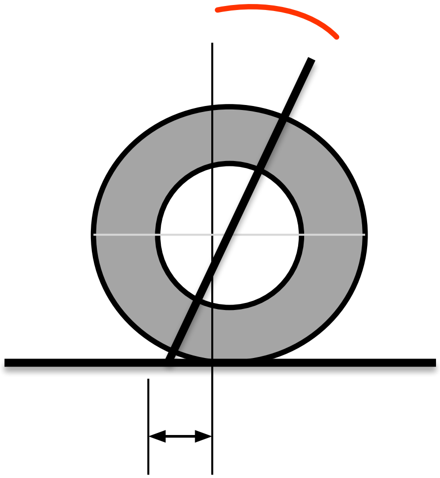
Toe Angle



Camber Angle



Caster Angle

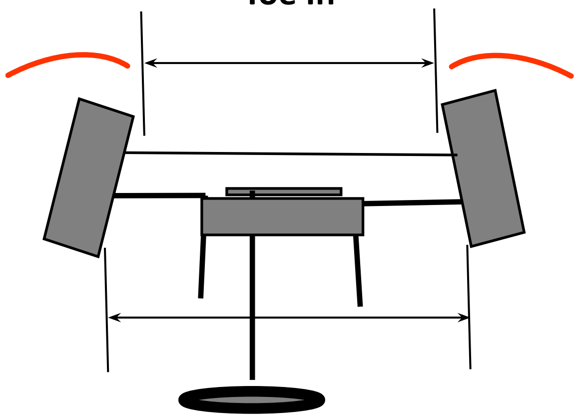


Toe, Camber, Caster

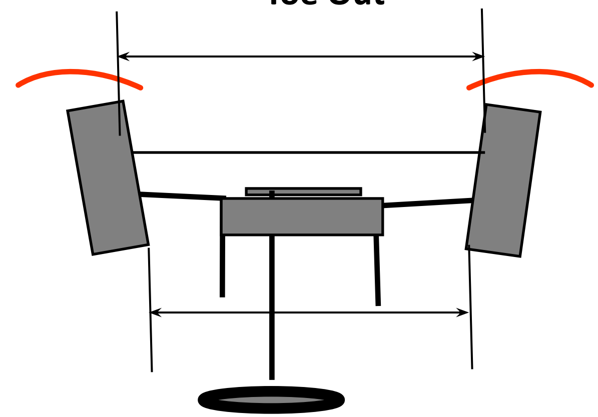
Design and tuning know how was gained at the OEMs from years of extensive testing and simulations, over the decades of suspension development from solid axle to independent wheel suspension.

Toe Angle

Toe In



Toe Out



Toe Angle Influence:

- Major impact on driving directional stability
- Tire wear / wheel resistance, min wear at 0 degree
- Straight line stability
- Corner entry handling characteristic

Toe In :

 discourages initiation of turn

 if to extensive, to much tire wear outboard

 enhance straight -line stability

 by small disturbance (due to steering or road / elastokinemetic of the suspension) still keeping straight course, not initiating turn

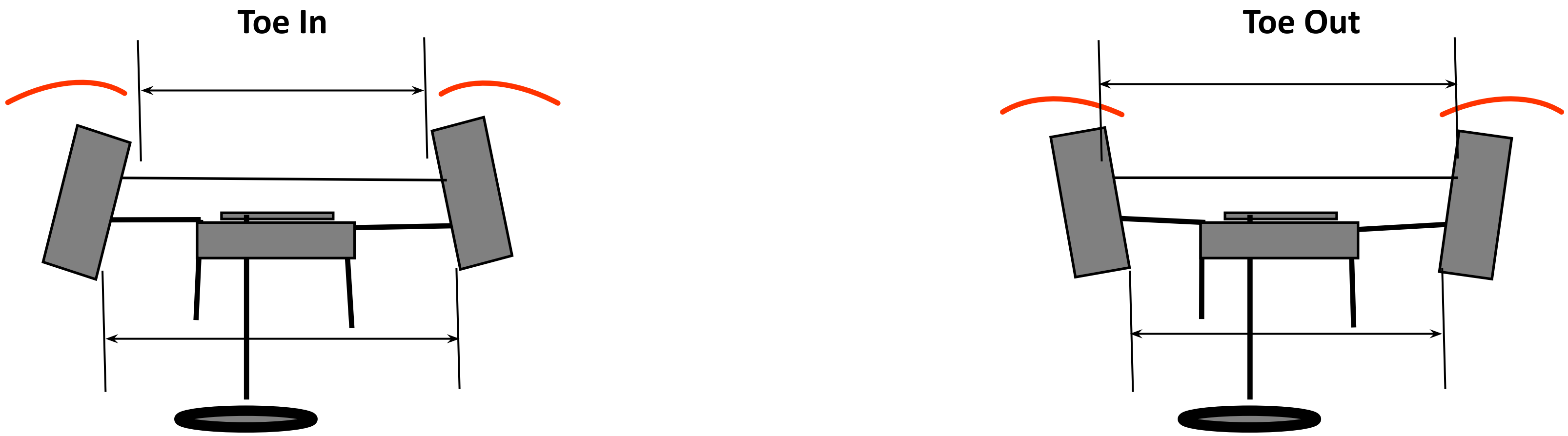
Toe Out :

 encourages initiation of turn

 if to extensive, to much tire wear inboard

 by steering, the inboard wheel will try to turn much tighter radius than the outboard wheel

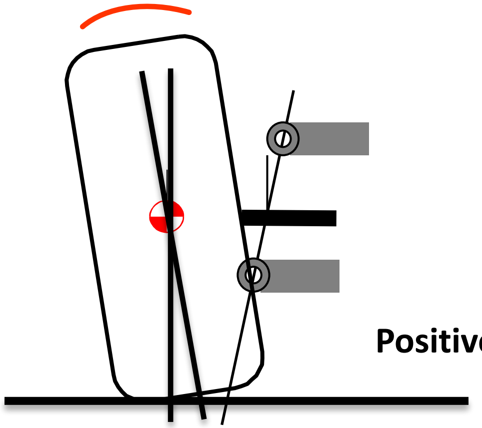
Toe Angle



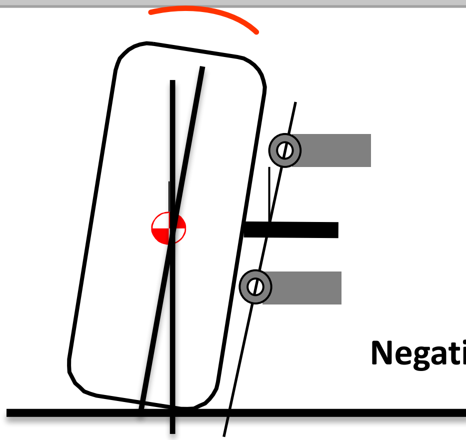
Toe Angle additional points

- Toe setting are trade off between straight-line stability done by toe-in and quick steering response given by toe-out
- Passenger cars are mostly tuned with toe-in, to ensure good straight line stability.
- Race cars can be tuned with Toe-out to ensure faster and more sensitive turns.
- If rear suspension has independent link suspension design, also toe angle needs to be tuned in order to ensue driving stability and prevent tendency over steering during straight line driving (due to small steering or suspension elastokinematics movements)

Camber Angle



Positive Camber

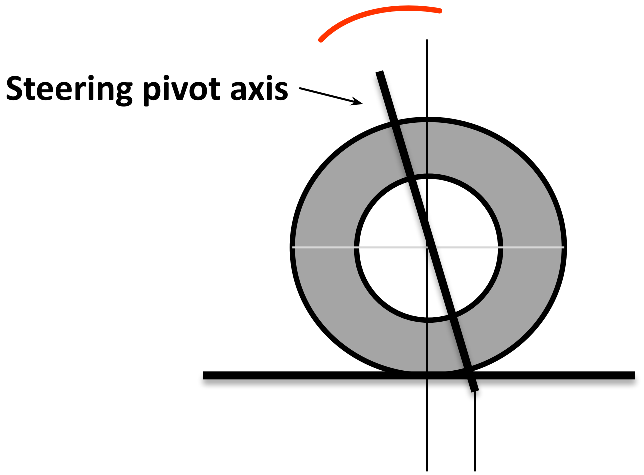


Negative Camber

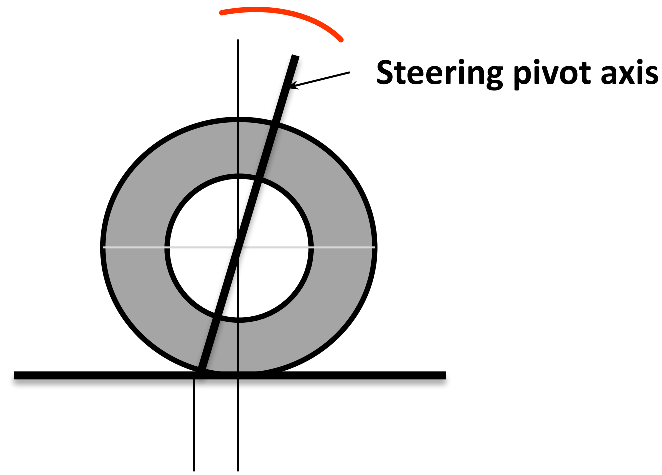
Camber Angle highlights

- **Camber angle is very much influencing tire cornering force**
- **Major influence on vehicle lateral road holding and stability**
- **In average tire is developing max cornering force ct 0.5 degree negative camber (camber counterbalancing / interacting with the tire deformation: sidewall and tread pattern)**
- **optimizing vehicle / tire lateral / cornering performance means: developing suspension which is operating always close to ca. 0.5 degree negative camber (this is very difficult because of suspension kinematics and springing and vehicle comfort requirements which are related to soft bushings: elastokinematics)**
- **during driving / cornering the camber is changing (dynamic camber), camber should:**
    - **inside wheel gain towards positive camber**
    - **outside wheel gain towards negative camber**
- **Dynamic camber definition: very important suspension tuning know how.**

Caster Angle



Negative Caster: Leading

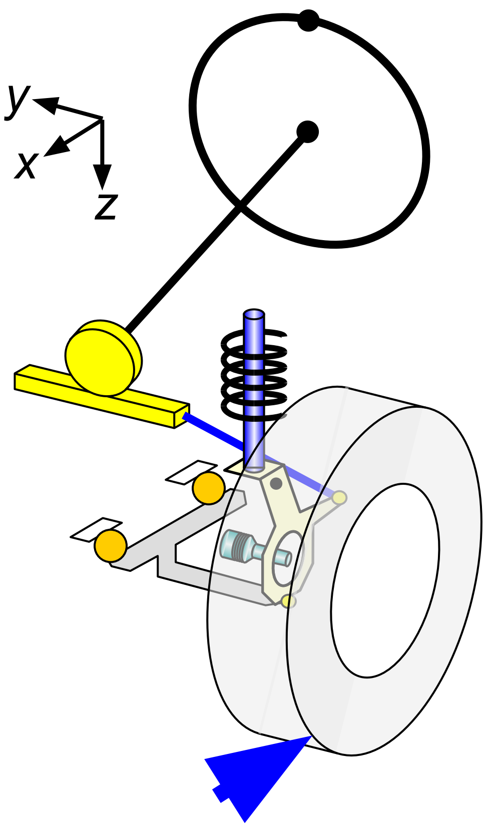


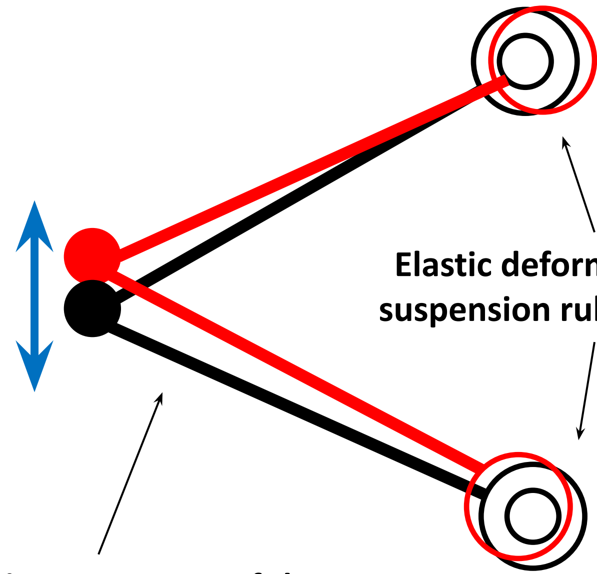
Positive Caster: Trailing

Positive Caster:

- usually 3 – 5 degree
- utilized in most of the vehicles / front axle
- if front wheels turned: positively influences camber
  - inside wheel is gaining positive camber
  - outside wheel is gaining negative camber
  - both are favorable for cornering

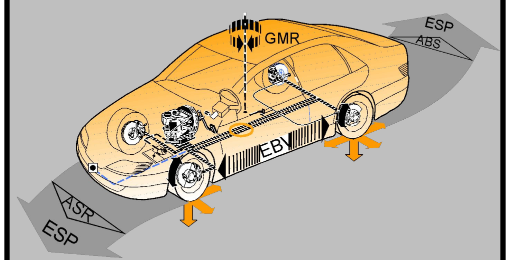
Suspension elastokinematics of the suspension links and bushings





Driver – Vehicle - Environment
Close Loop Control System:

Driver
- Navigations Level
- Track Guide Level
- Stability Level



Vehicle

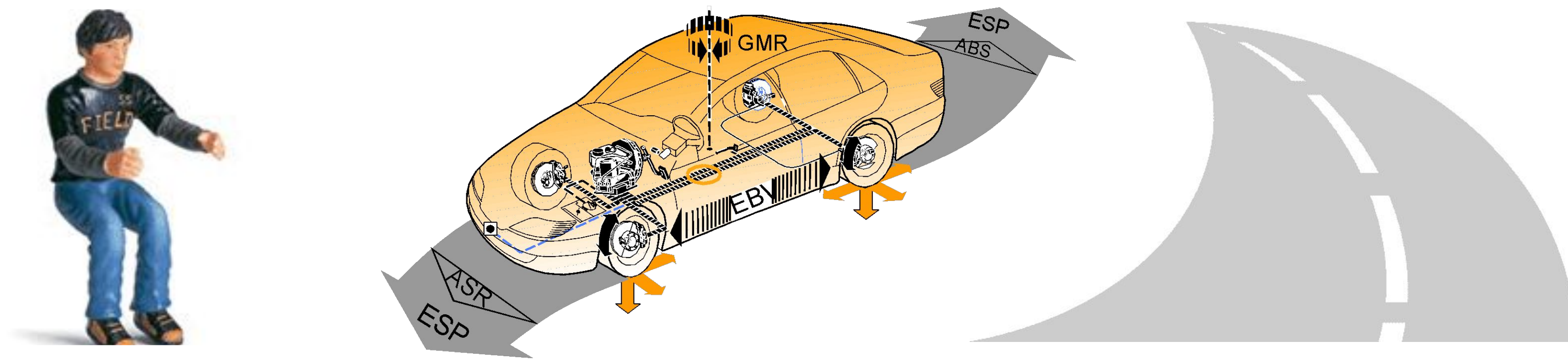
Longitudinal
Lateral
Vertical
Dynamic

Environment
- Streets / Roads
- Traffic
- Road Surface

Current speed / Track

Safe Drive Area

Possible Route



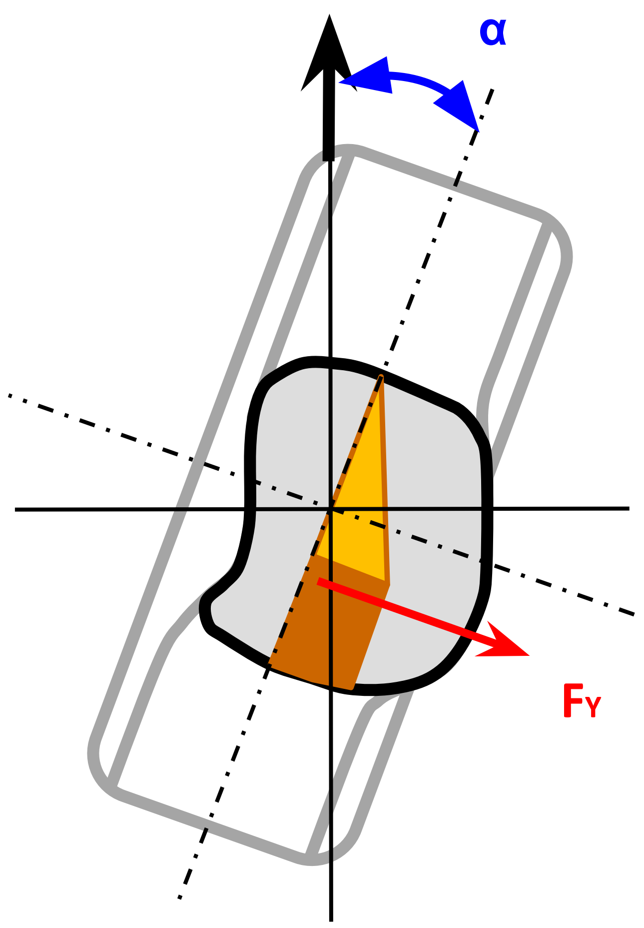
Control System: Driver – Vehicle – Road/Envioremement

- **Navigation Level**
- **Track / Course Level**
- **Stability Level**

System Stability depend on:
Driver
Vehicle
Environment

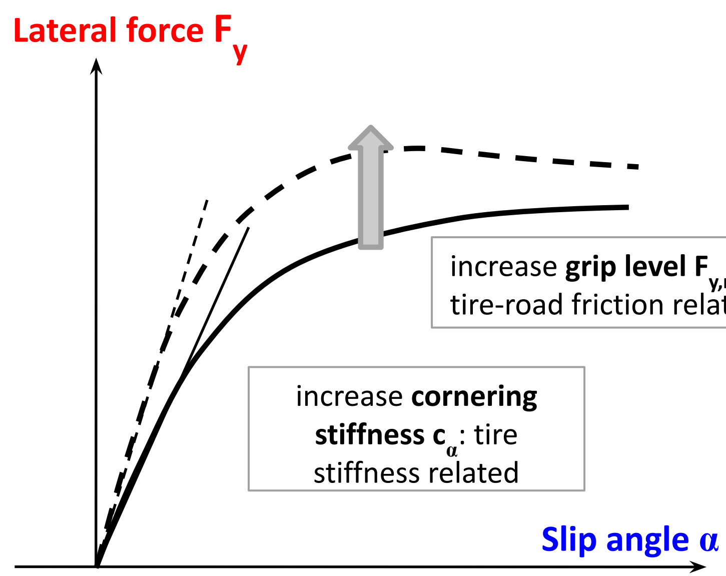
Vehicle Development / Engineering:

- **responsible for the Vehicle System Optimization**
  - **Driver / Vehicle Interaction !!!**
  - **Vehicle / Road Interaction**
  - **Driver / Environment Interaction**



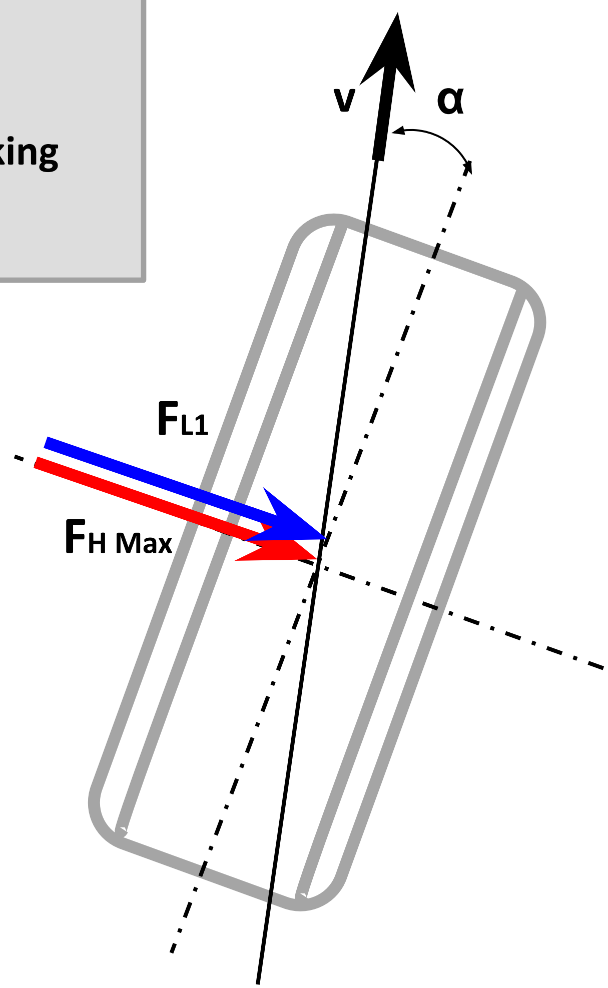
Wheel Slip Angle α , definition:

- Wheel slip angle is the angle between the wheel rolling / heading direction and the direction towards wheel is steering / pointing.
- Slip angle is the result of tire deformation in lateral direction, and it is proportional to the lateral force acting on the tire.
- No lateral force => No lateral deformation => No slip angle



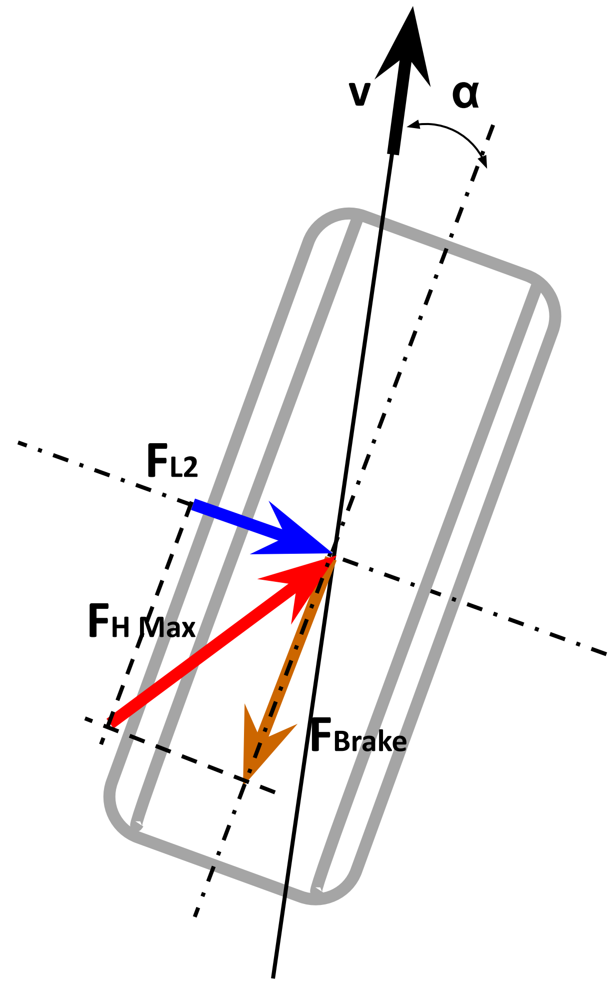
$F_{H\,Max}$	Max Horizontal Force
G_v	Vertical Force
F_{L1}	Lateral Force
F_{L2}	Lateral Force at Braking
F_{Brake}	Brake Force

Cornering ONLY



$$F_{L1} = F_{H\,Max} = G_v\,\mu$$

Cornering and Braking

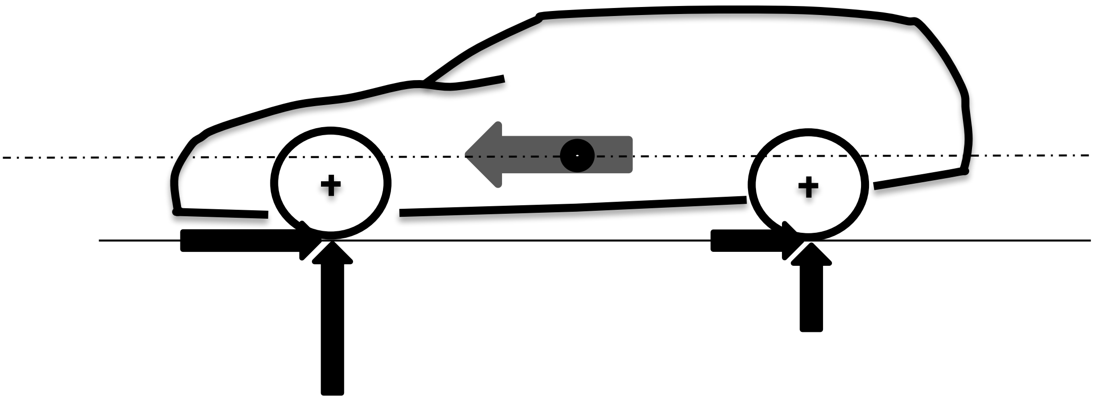


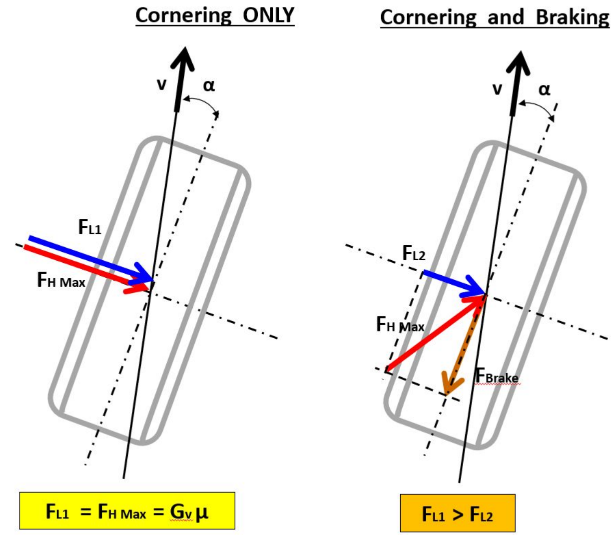
$$F_{L1} > F_{L2}$$

Influence of longitudinal dynamics events on lateral dynamic behavior

- Acceleration, while cornering
- Load change, while cornering
- Braking, while cornering
- Braking on split μ

is requiring steering correction compensation



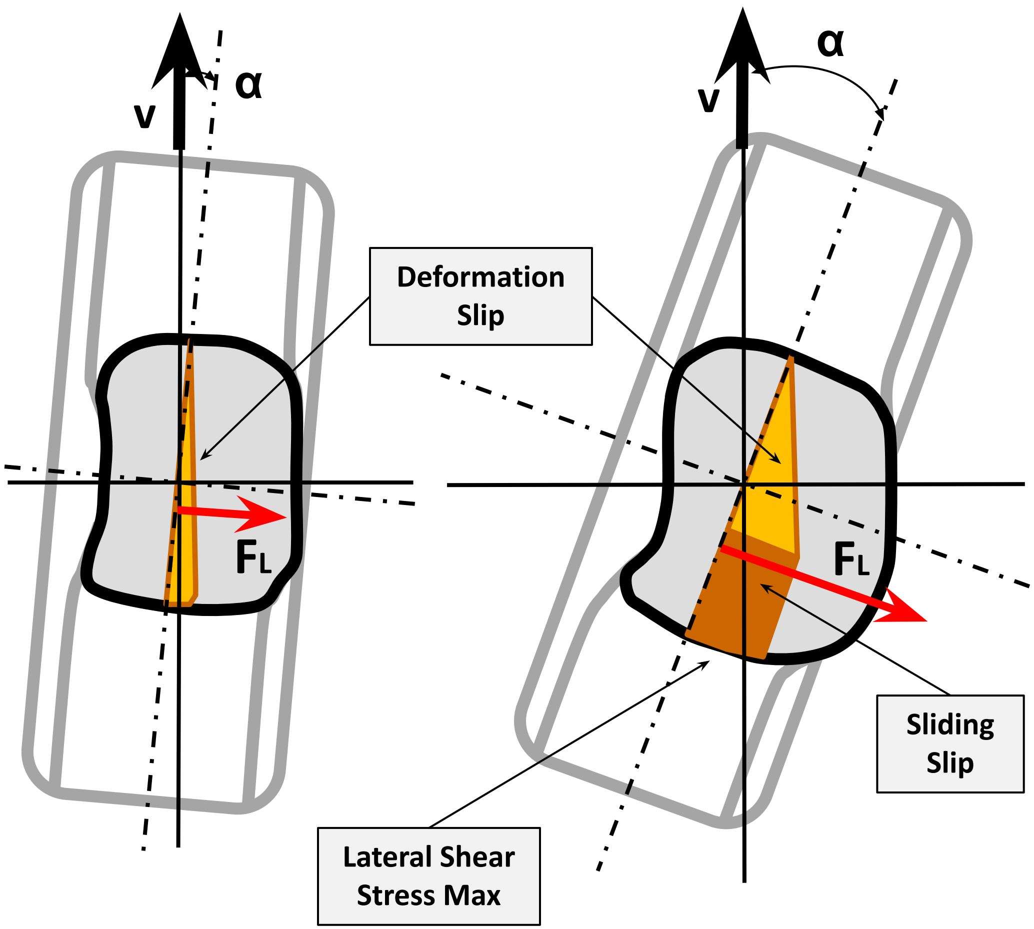


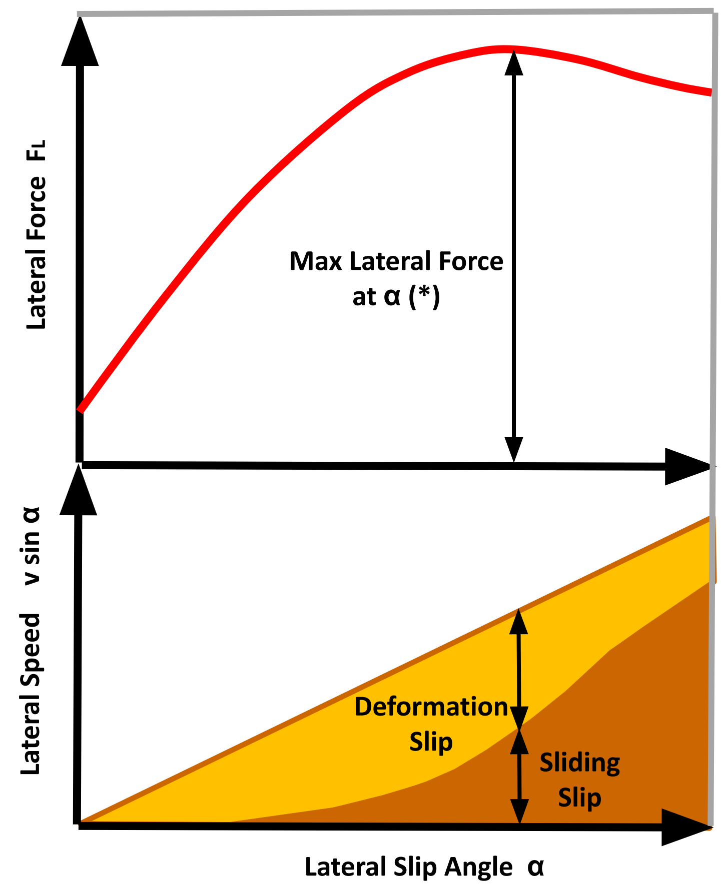
Max available lateral force is changing between front / rear and left / right wheels of the vehicle

Reduction of max available lateral force due to:

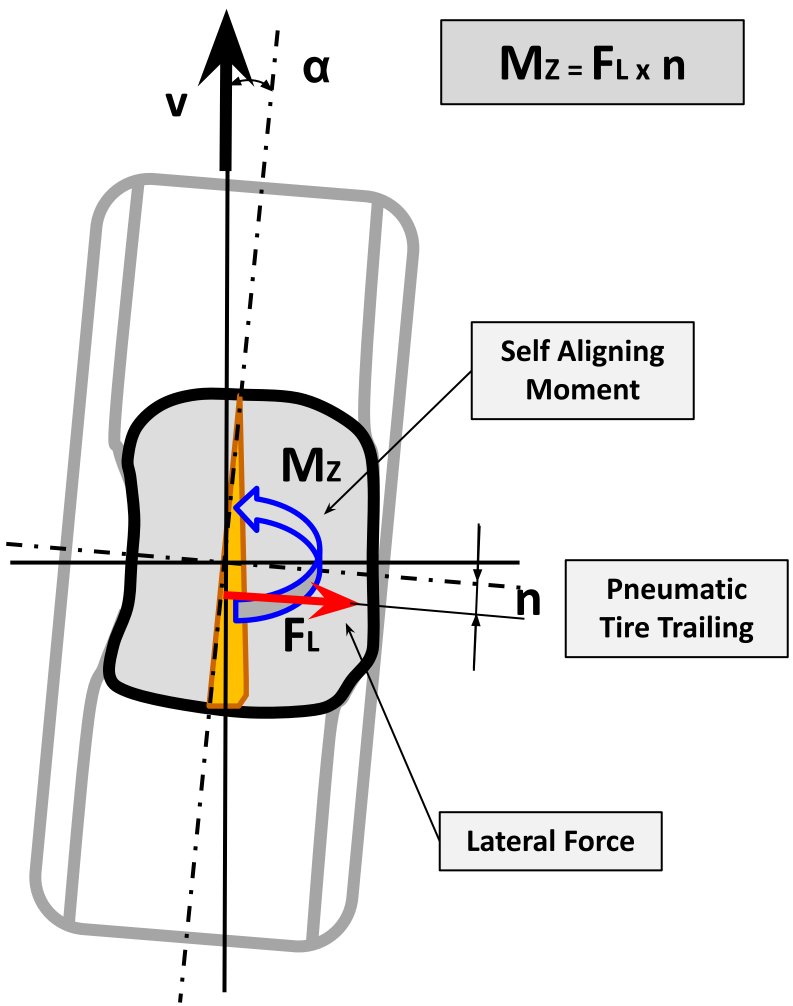
- Vertical loads distribution
- Longitudinal force action

Vehicle Cornering, build up of the tire slip in the cornering





Vehicle Cornering, Self-aligning Moment, Pneumatic Tire Trailing



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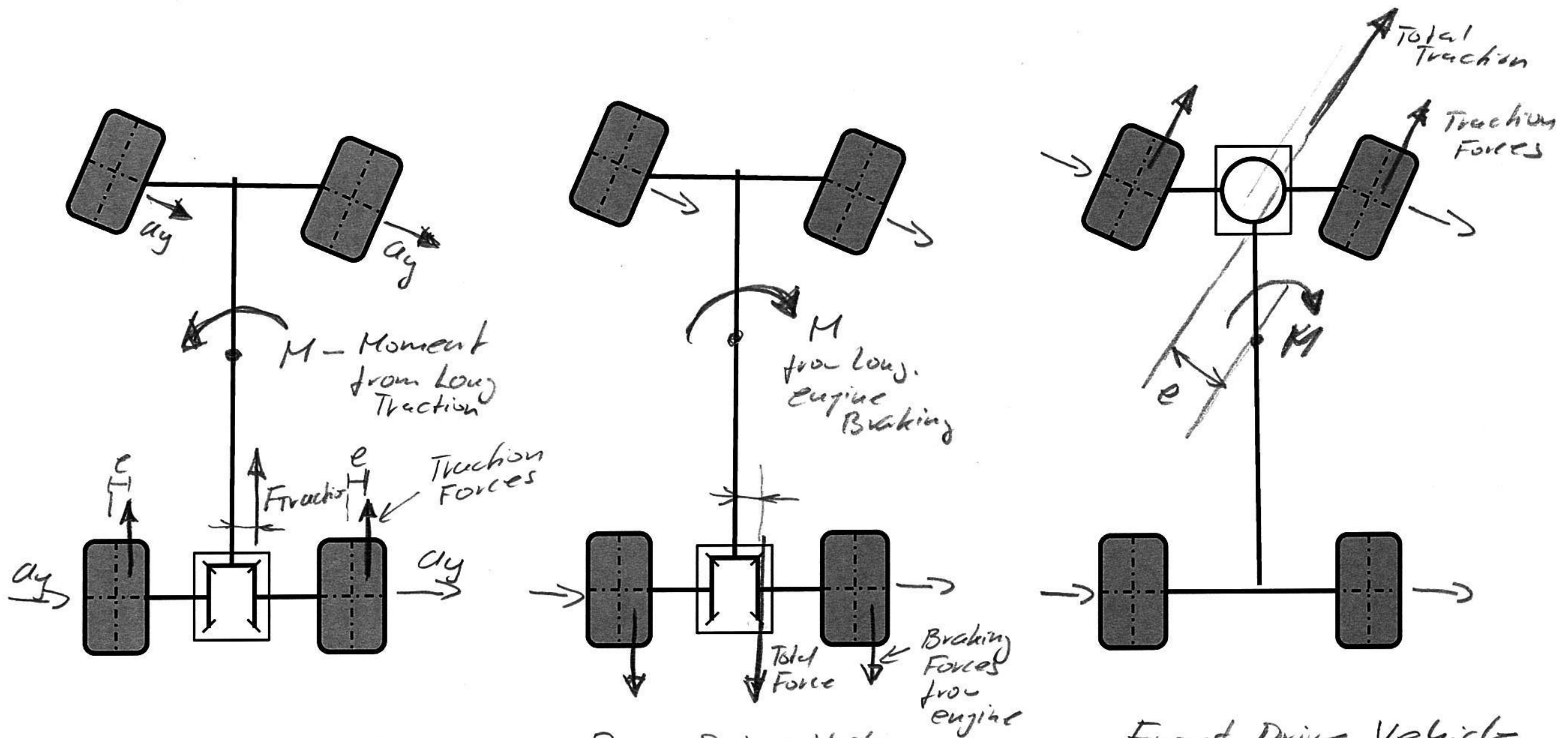
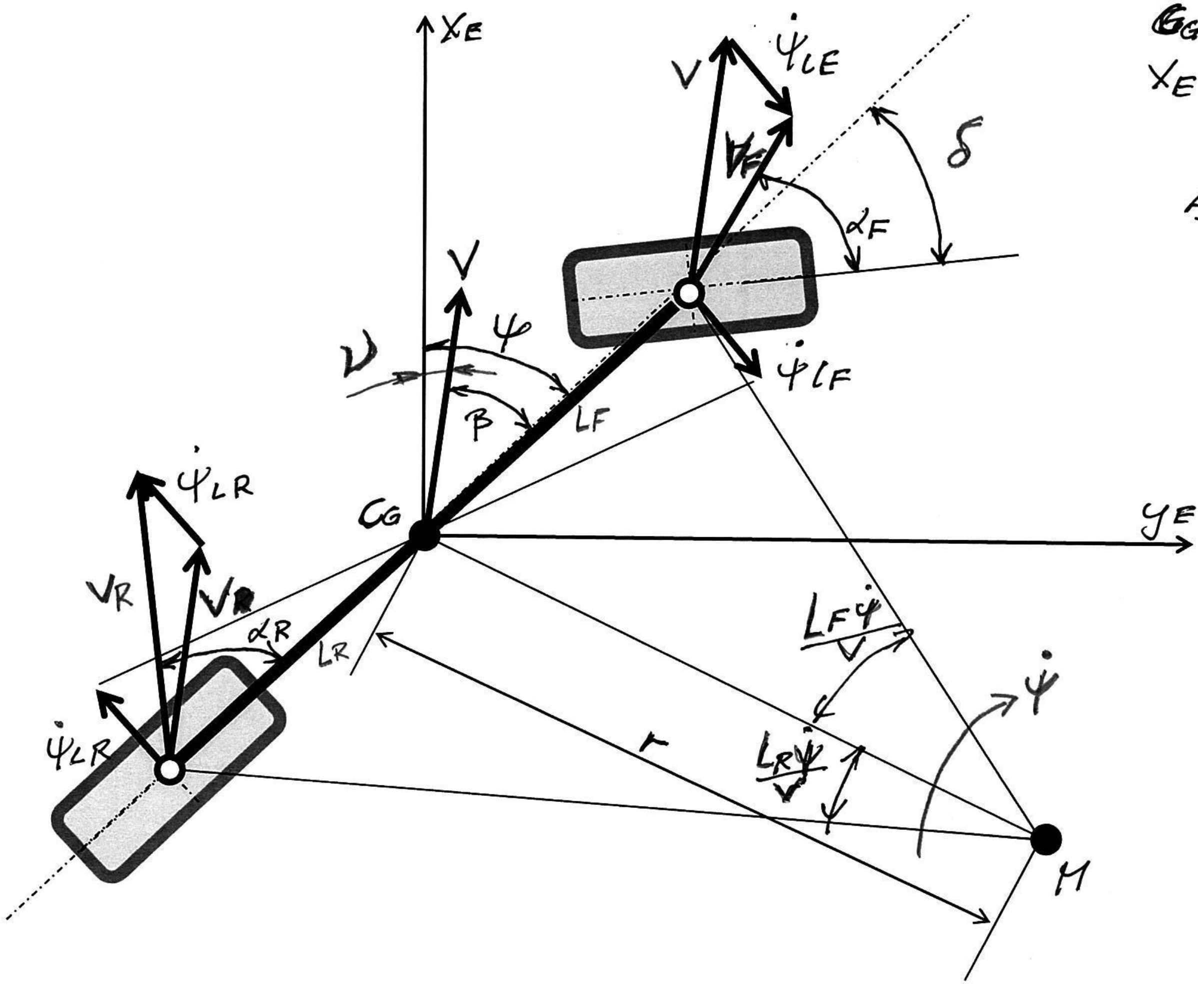
Yaw Moments comming from the Logitudinal Forces during cornering



Rear Drive Veh.	Rear Drive Veh.	Front Drive Vehicle
during Acceleration	durring engine Braking	during Acceleration
UNDERSTEERING	OVERSTERING	OVERSTEERING
		Traction Forces are Taking us in " "

Motions Vectors and Parameters of bicycle model



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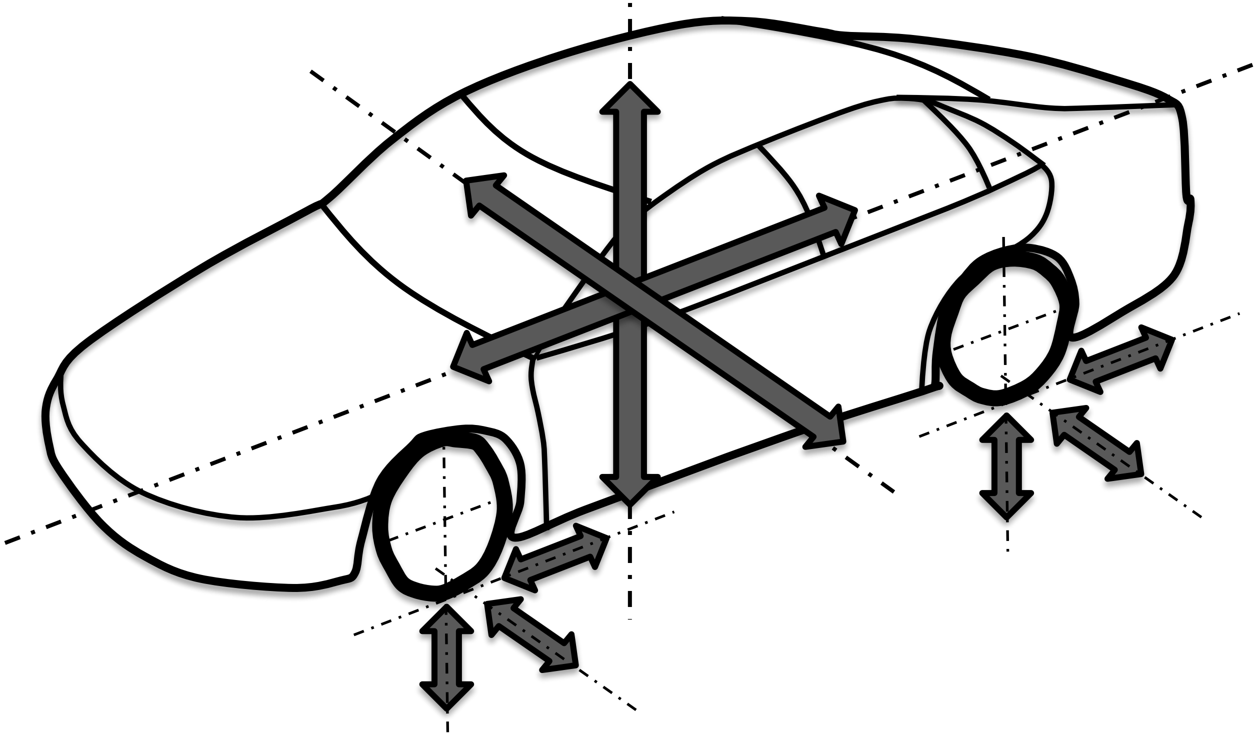
M - Momentpol
r - course Radius
C_G - Centre of Gravity
X_E, Y_E - stationary coordinate system

Angles

α_F, α_R - Slip Angle Front & Rear
β - Veh. slip, drift
δ - steer Angle
ν - course Angle
ψ - Yaw Angle

Speeds

$\dot\psi$ - Yaw speed
$\dot\psi_{LF}, \dot\psi_{LR}$
V - speed Veh.
V_F, V_R - Resulting speed Front and Rear Wheels

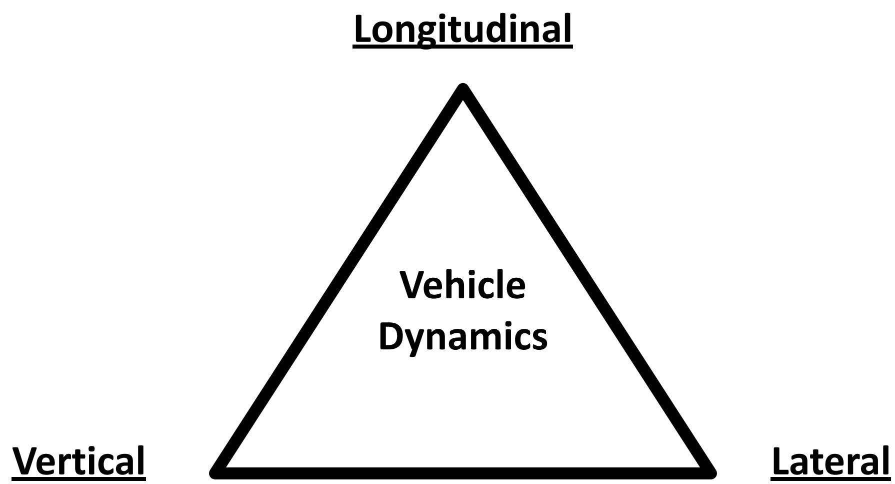


To design and tune vehicle chassis means

⇩

To consider forces / accelerations in all 3 directions at the same time:

- **Longitudinal driving forces**
- **Cornering forces**
- **Braking forces**
- **Road interactions forces**



Depend on:

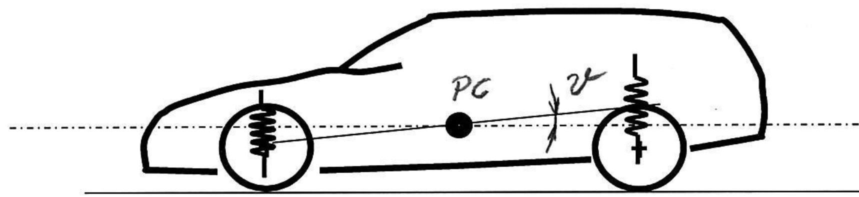
⇩

Vehicle design (chassis), Tuning
And State of the Vehicle on the Road

⇩

Interaction of the Vehicle Chassis with the Road in All 3 Directions

- **Tires**
- **Suspension links and bushings**
- **Springs and shock absorbers**
- **Brakes**
- **Drive train**



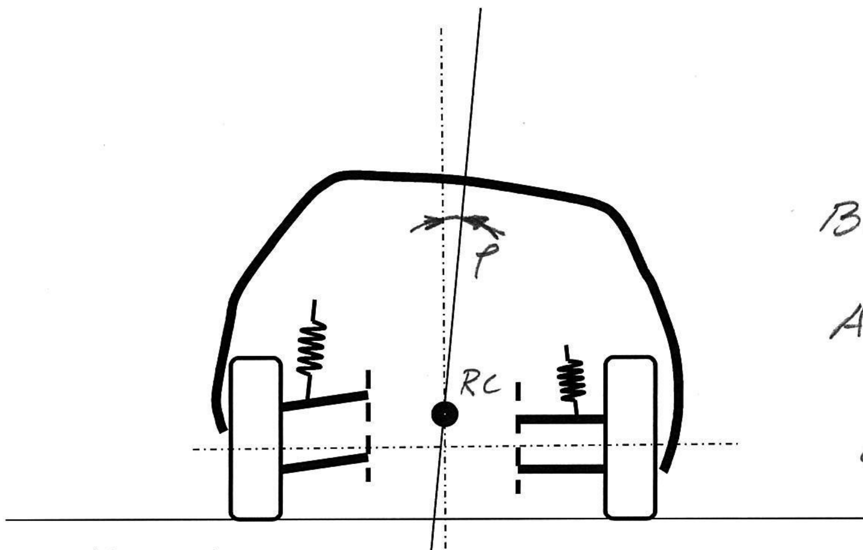
Pitch

⊕

Roll

⇓

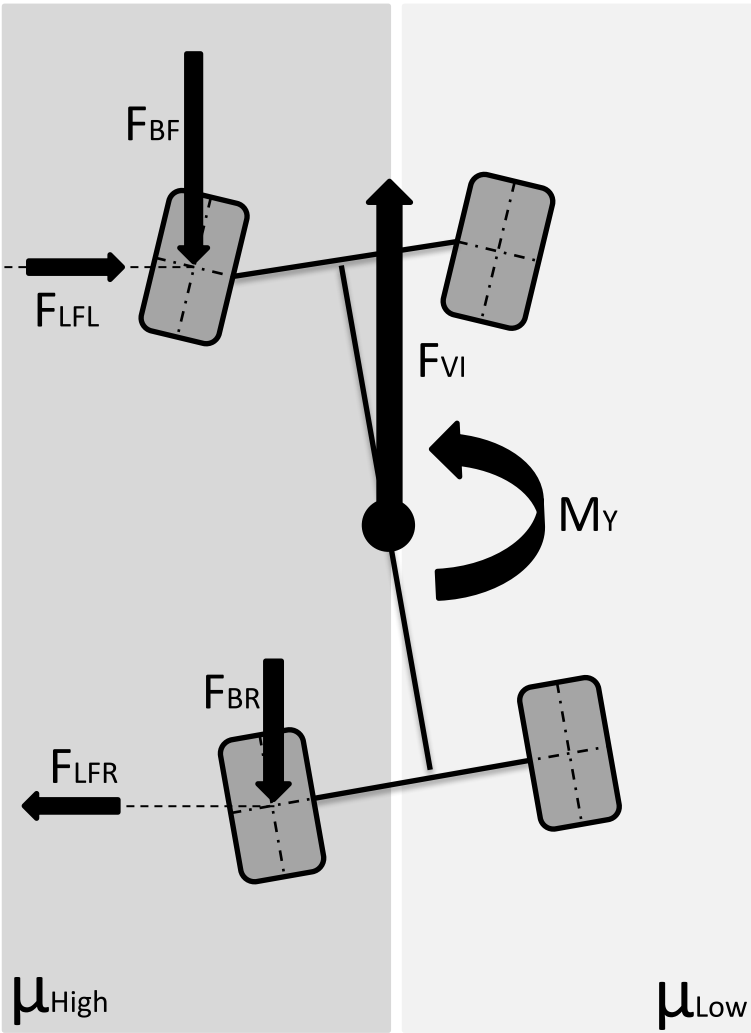
Braking
or
Accelerating
while
cornering

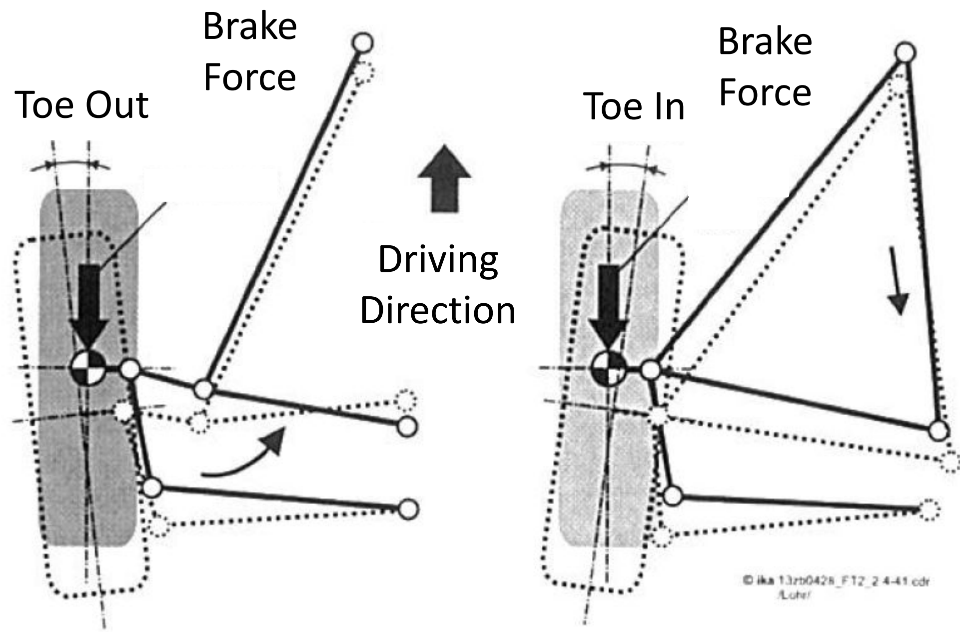


Braking on the Left turn: Front Right wheel max. Vertical Force (U-Turn in Mi)

Accelerating on the Right turn: Right Rear wheel max Vertical

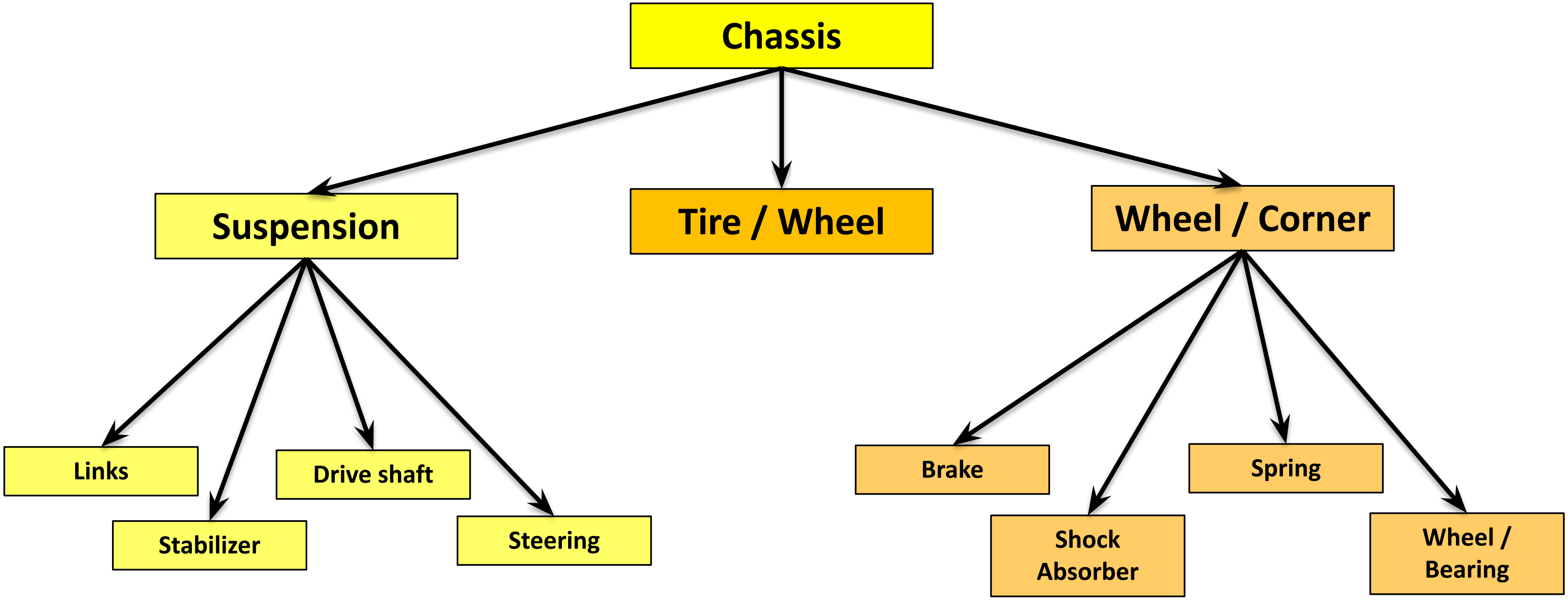
Braking on μ-split



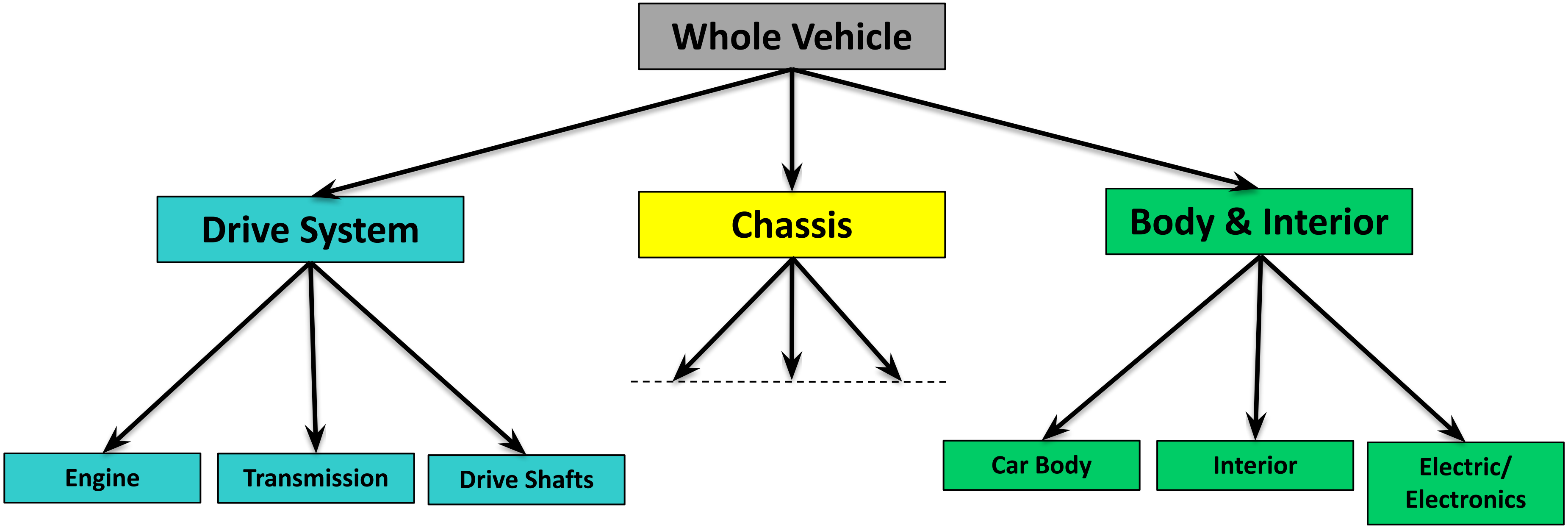


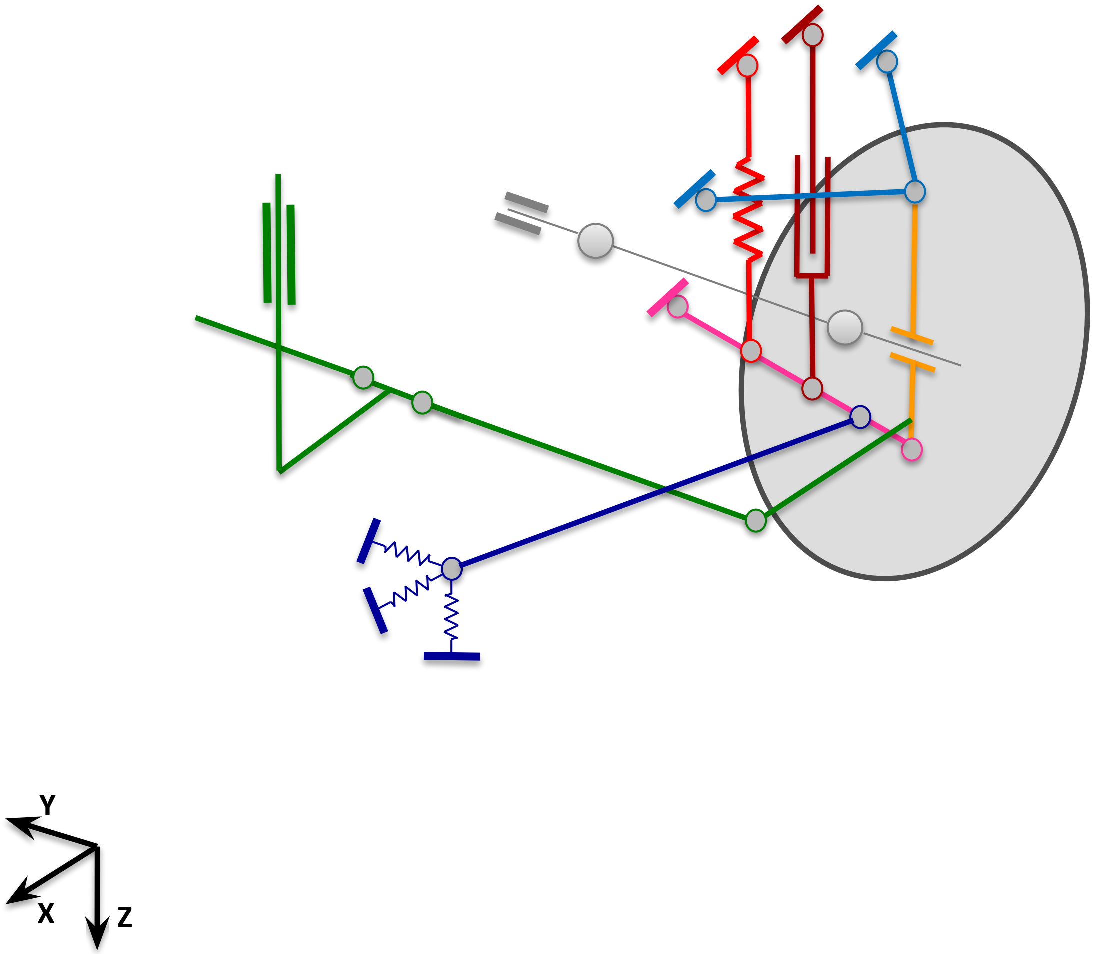
Optimization of
Front Suspension Elasto-Kinematics
for split μ braking

Vehicle Systems Groups Classification



Vehicle Systems Groups Classification





- Tire/wheel assembly
- Knuckle
- Drive shaft
- Lower lateral links
- Lower longitudinal links
- Upper links
- Spring
- Shock absorber (damper)
- Steering

Tire

Tire is the <u>only one connection point / structure</u> of the vehicle to the road, due to this transmits all forces between the vehicle and the road.

Accordingly it is <u>fundamentally important and most critical</u> to the vehicle driving behavior, especially: longitudinal, vertical and lateral vehicle dynamics

<u>Fundamental Tire Functions:</u>

- **Vehicle support on the road, springing, damping: Vertical Dynamics**
- **Vehicle lateral guide: Lateral Dynamics**
- **Driving and brake forces transmission: Longitudinal Dynamics**

Tire Requirements

The tire required performances and the tire design are strongly connected to each other.
The different tire requirements results in various target conflicts which are always requiring balanced approach in tire design and performance.

1. Safety:

- Maximal adhesion / traction at all roads surfaces, especially: wet, snow, ice.
- Direct handling response in the steering wheel.
- Evenly distributed lateral / cornering force (rise/increase), good lateral force guide in connection with intended handling maneuvers, good handling predictability.
- Balancing the wheel vertical force variations (to big: negatively influencing the road structure, to small: negatively influencing safety)
- Secure connection / seat on the rim
- High puncture safety
- High speed reliability
- Long life

Tire Requirements

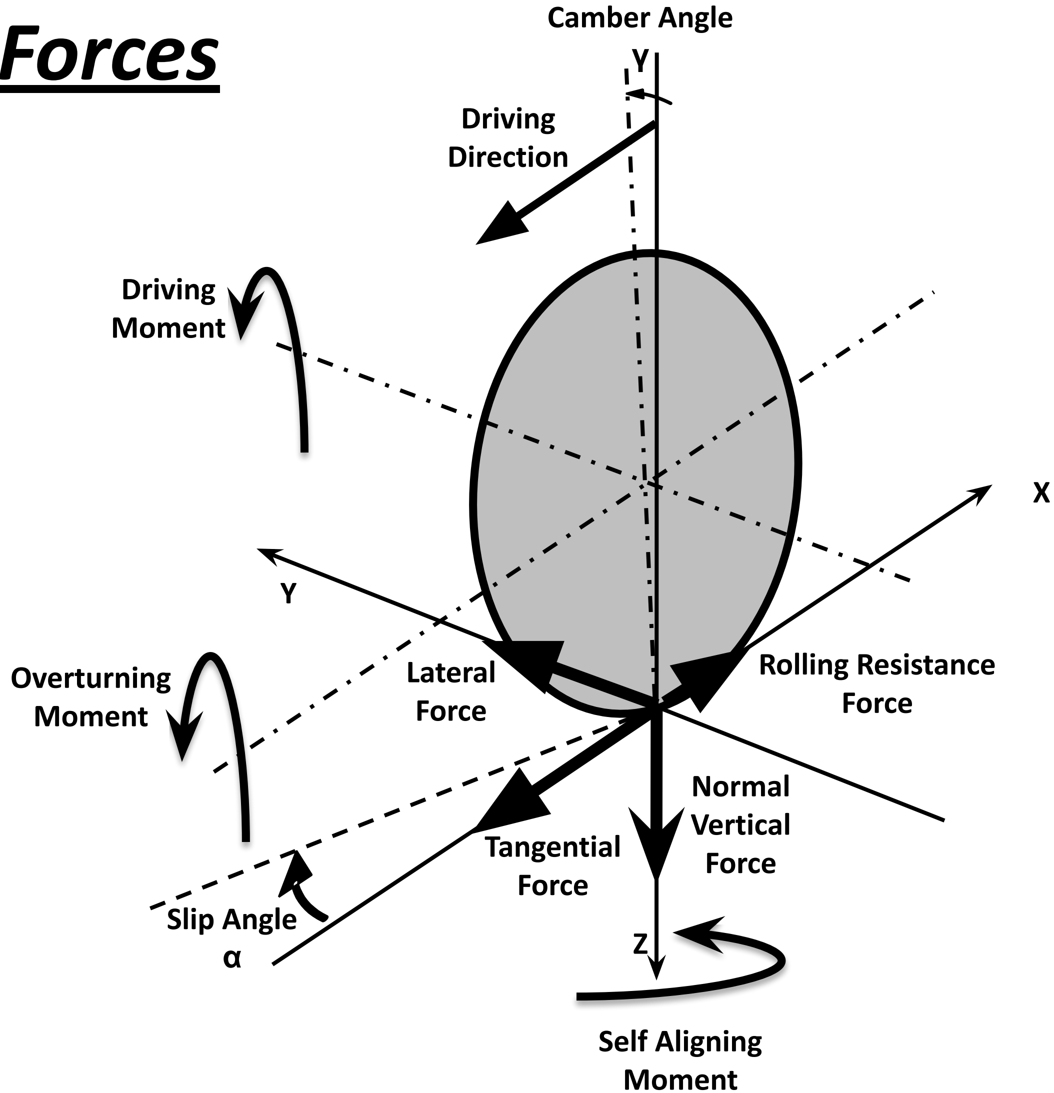
2. Comfort

- Good springing and damping
- Low noise: interior, exterior, pass by
- No vibrations or noises from tire nonuniformity
- Small as possible steering forces
- Simple replacement

3. Sustainability / Economics

- Low as possible rolling resistance
- High performance capacity at small volume
- Low as possible road dynamic forces
- Costs optimized
- Good durability
- Constant / even wear
- Long lasting

Tire Forces


Camber Angle
γ
Driving
Direction
Driving
Moment
X
Y
Overturning
Moment
Lateral
Force
Rolling Resistance
Force
Normal
Vertical
Force
Tangential
Force
Slip Angle
α
Z
Self Aligning
Moment

Tire Forces

Vertical:

- Wheel load, road interaction (static, dynamic)
- Vibration forces caused by Road roughness (comfort, coustic)

Comment

- *Braking forces (moment) are supported by brake and suspension*
- *Driving forces (moment) are supported by diferential, with it in the wheel mid point*

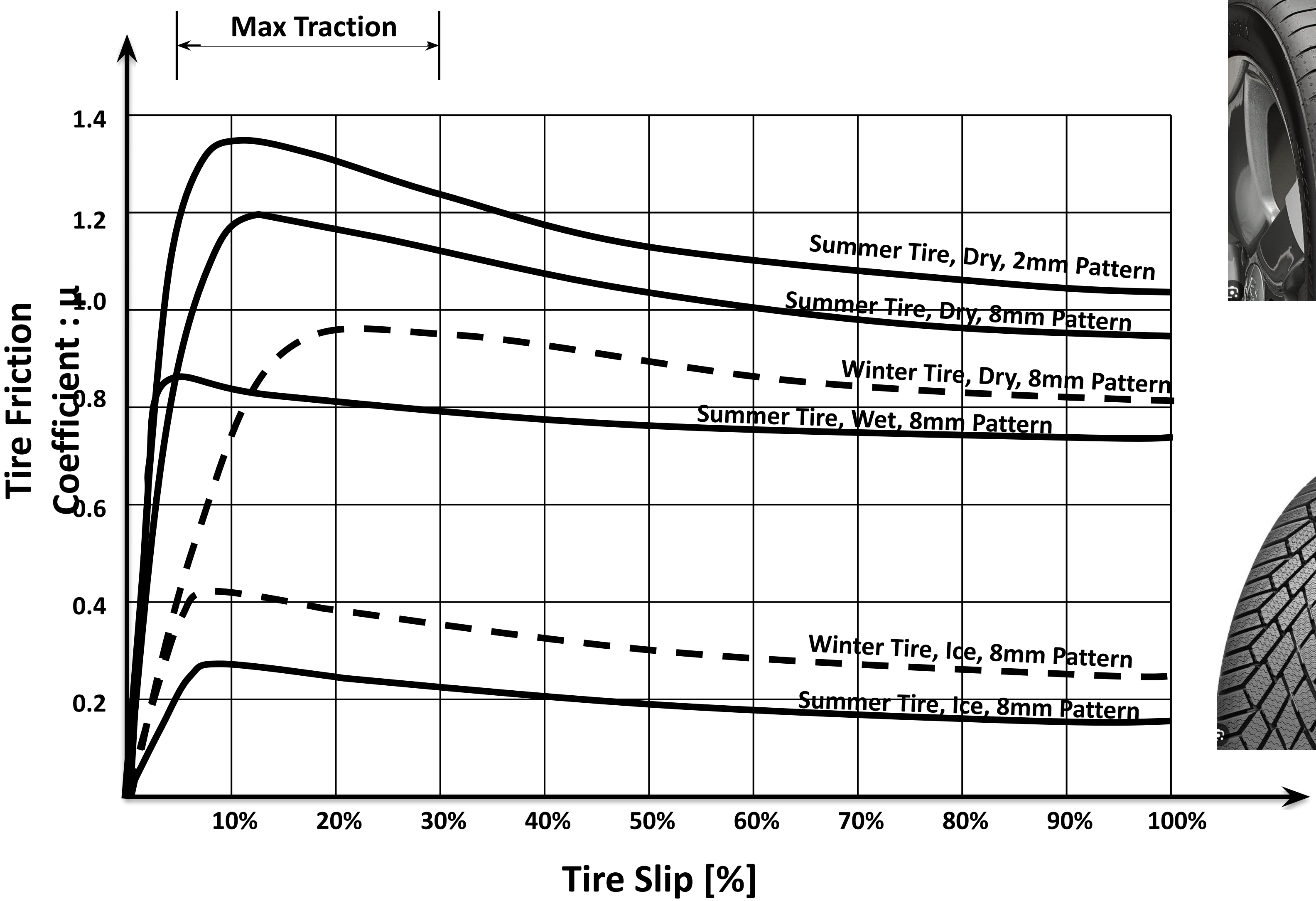
Lateral / Side Forces:

- Lateral forces
- Steering forces
- Aligning moment (self-aligning torque)

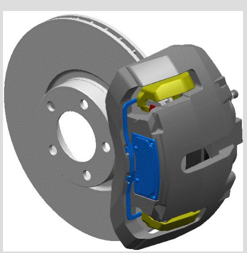
Tangential Forces :

- Traction forces
- Braking forces
- Rolling resistance

Influence of the road surface on tire tangential slip



Tire Nonuniformity as one of the vehicle periodic wheel excitations

	Tire Non-uniformity Unbalance Flat Spot	Tire Modes Acoustic Cavity Mode Irregular Wear	Tread Pattern Noise Tire / Road Friction Air pumping
	Axle and Engine Shake Steering Wheel Nibble	Modes of Structural Suspension and Body Parts	Air-borne Noise Sensitivity
	Brake Judder	Groan Creep Groan	Brake Squeal Noise

5 – 50 Hz | **50 – 500 Hz** | **500 – 10k Hz**

Frequency

Chassis vibration system due to tire periodic excitation