POLITECNICO DI MILANO

Electronic Stability Control (ESC)

Automation and Control in Vehicles

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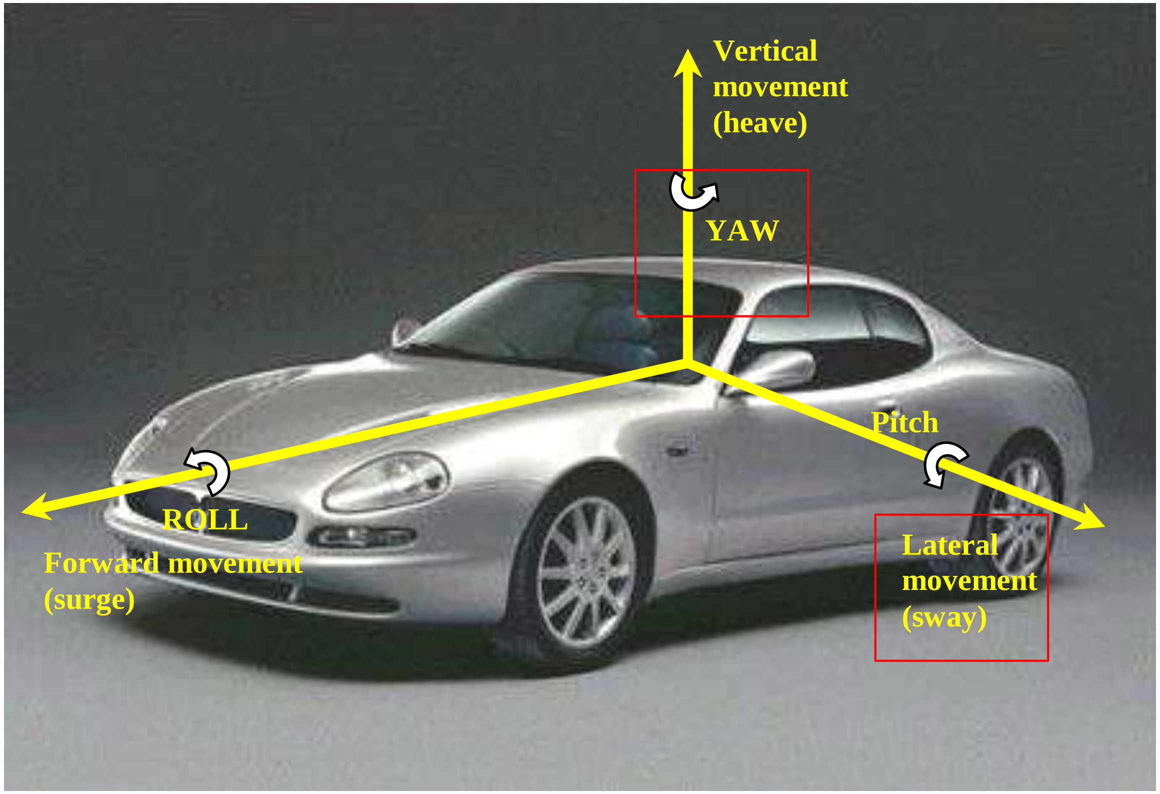
Prologue



“Stability-control” is mainly referred to the automatic control of

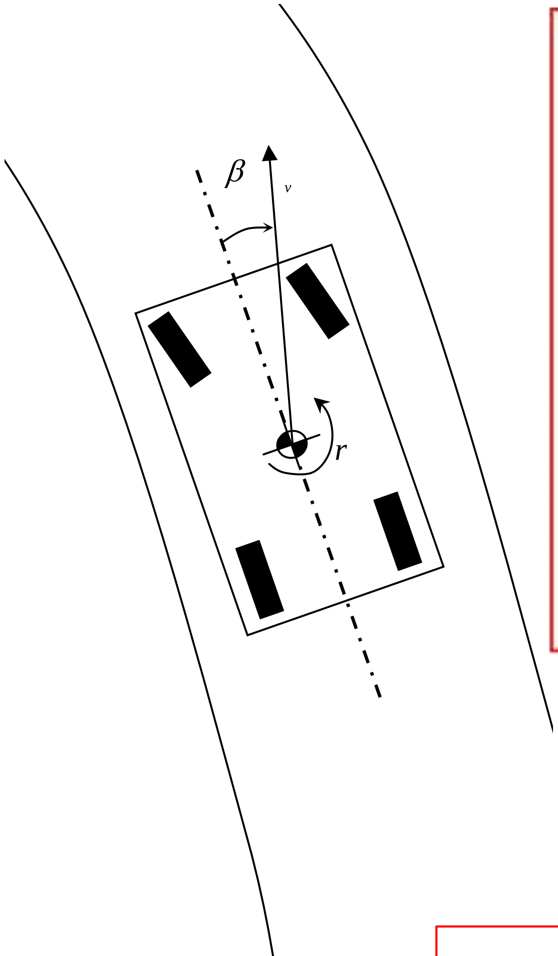
-Yaw-dynamics (main)

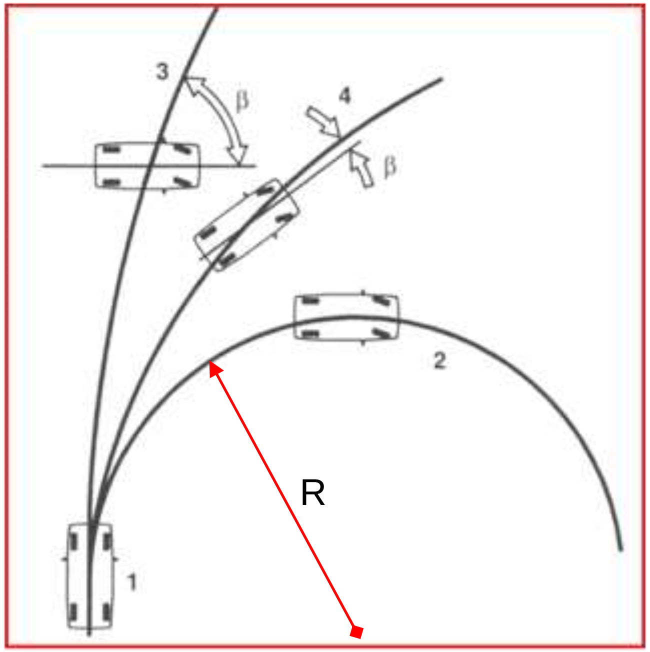
- Lateral dynamics

Correct (generic) Acronym:

Electronics Stability Control (ESC)

Lateral/yaw dynamics control: control problem





During cornering a car has:

A not-zero rotation speed *r*

A (possibly not-zero) drift angle β (*«SIDE-SLIP angle»*)

Both of these quantities must be controlled in order to give the driver the "control" (feeling) of the vehicle

SINCE

Large drift angles (> 2-3°) make it very difficult to control the car for a (standard) driver

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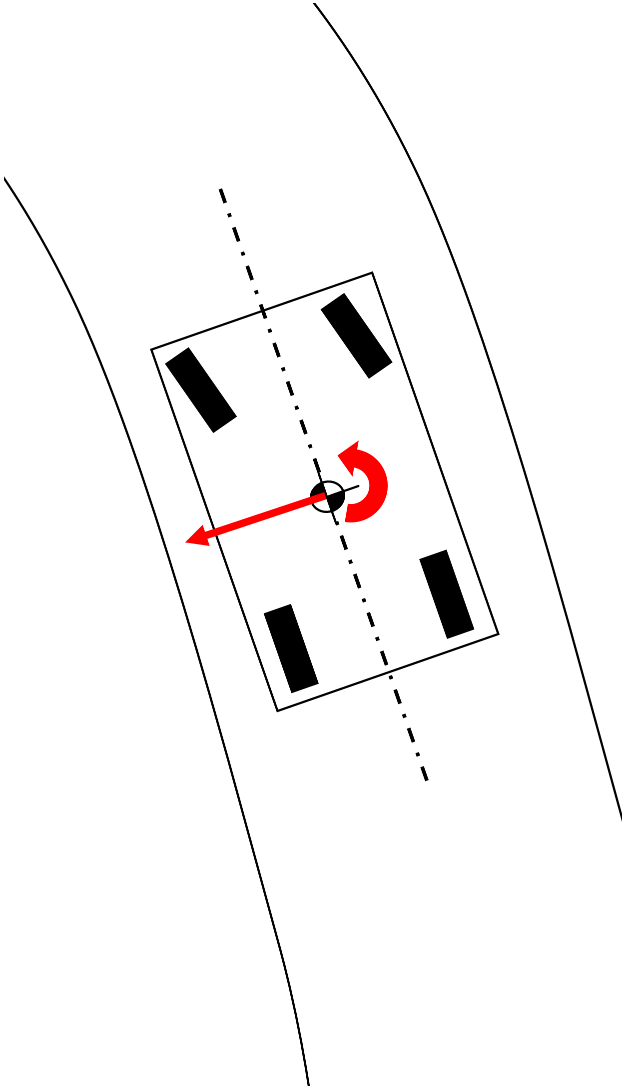
The yaw control can not however "per se", increase the maximum lateral grip of the vehicle

$$M\frac{V^2}{R} = F_z\mu_y \quad \Rightarrow \quad V = \sqrt{\frac{RF_z\mu_y}{M}}$$

Lateral/yaw dynamics control: control problem



Provide

- -a lateral force
- -a yaw torque

To achieve

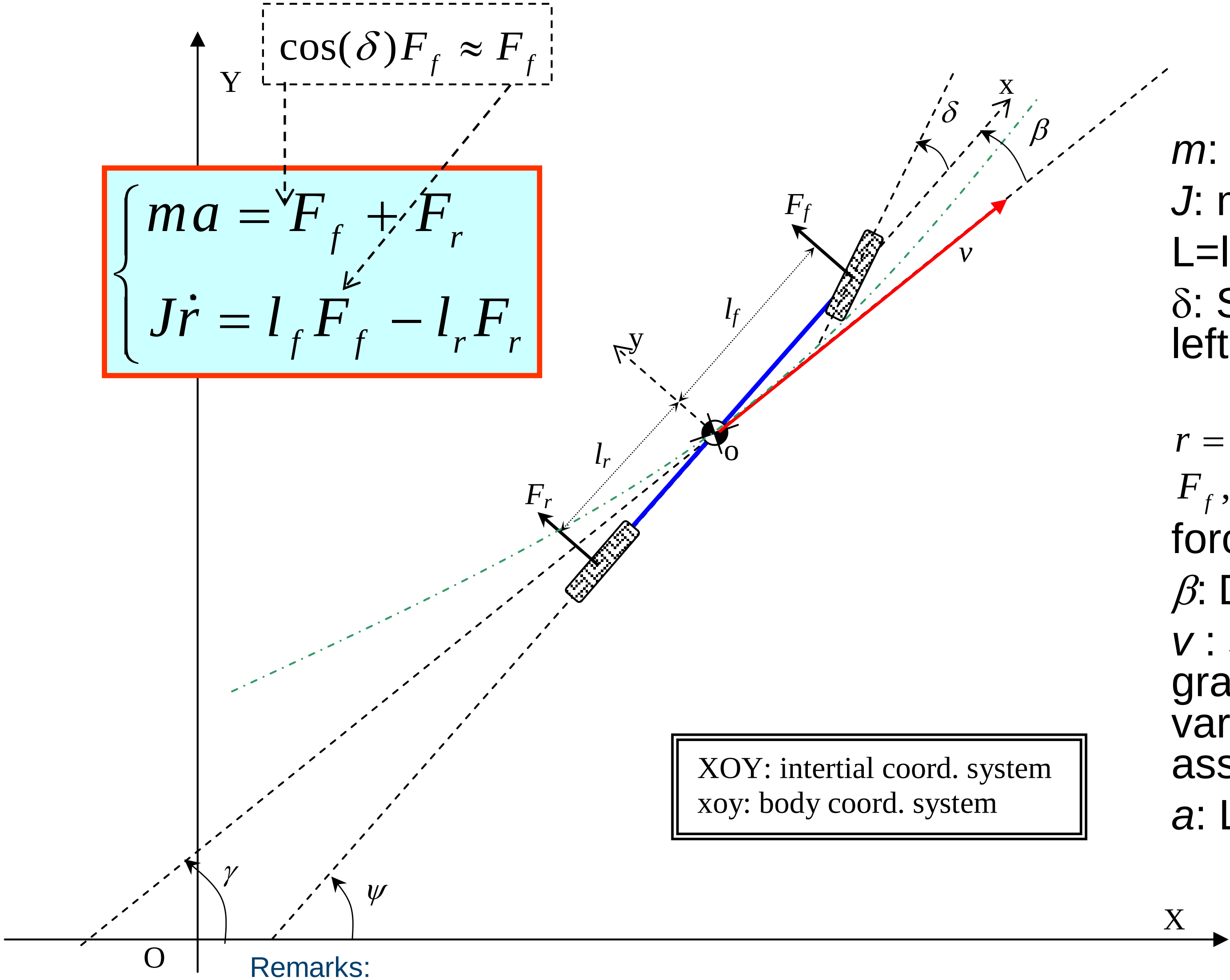
- -Minimization of the drift (side-slip) angle
- -a rotation speed consistent with the curvature radius (given by steer angle) of the road and the vehicle speed

Problem: actuators?

Two categories:

1. Use road-tire contact forces:
   - Active differential brake (ESP-like)
   - Active differentials
   - Active Steering
2. Use aerodynamic forces

Dynamic modeling for lateral/ yaw control: "single-track model"



$$\begin{cases} ma = F_f + F_r \\ J\dot{r} = l_f F_f - l_r F_r \end{cases}$$

m: Mass

J: moment of inertia (yaw)

L=lf+lr (wheelbase)

δ: Steering angle (positive left-side

$r = \dot{\psi}$: Speed (rotation)

F_f, F_r: Lateral contact forces (front and rear)

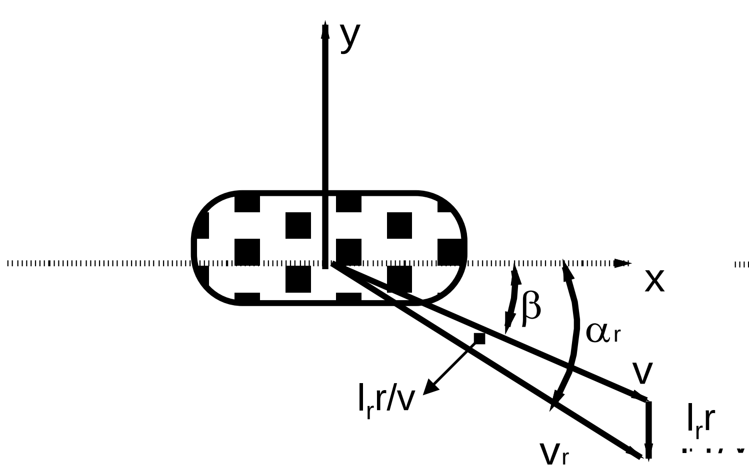
β: Drift (side-slip) angle

v : speed of center of gravity (constant or slowly-varying amplitude is assumed)

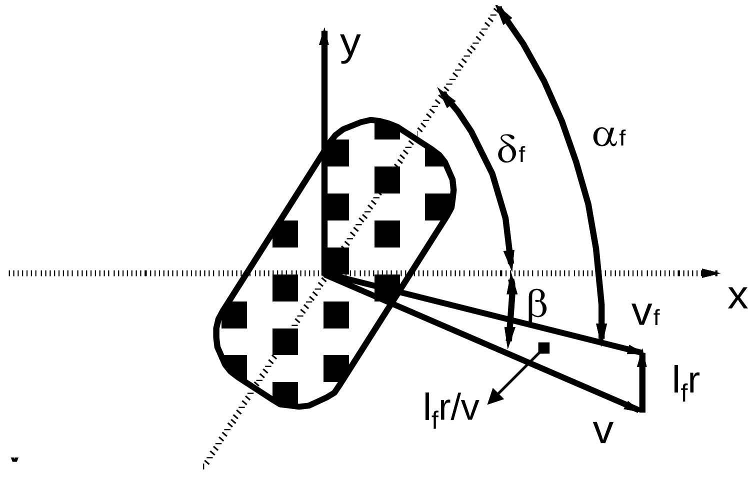
a: Lateral acceleration

Remarks:
- single-track-model: can not take into account roll dynamics and lateral load transfer
- the model can be easily extended to all-wheel-steering architecture

Dynamic modeling for lateral/ yaw control: "single-track model"



Rear wheel



Front wheel

We assume $F(\lambda,\alpha,F_z)=\alpha C(\lambda,F_z)$ (λ,F_z) fixed

We calculate tire drift-angles (not-zero in order to develop lateral forces)

$$F_r = C_r\alpha_r \qquad \alpha_r = \beta + \frac{l_r r}{v} \qquad\qquad F_f = C_f\alpha_f \qquad \alpha_f = \beta + \delta - \frac{l_f r}{v}$$

C_f, C_r : "drift-stiffness"

Dynamic modeling for lateral/ yaw control: "single-track model"

$$F_f = C_f \alpha_f \qquad \alpha_f = \beta + \delta - \frac{l_f r}{v} \qquad F_r = C_r \alpha_r \qquad \alpha_r = \beta + \frac{l_r r}{v}$$

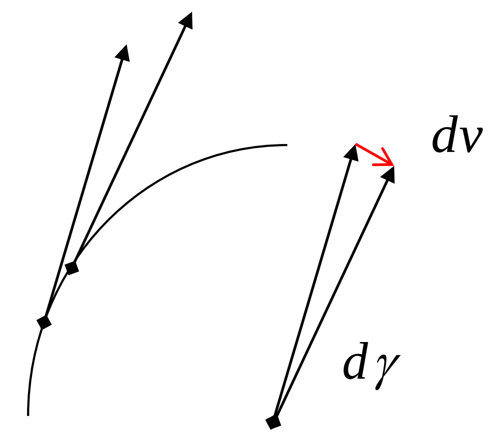
$$\beta + \gamma = \psi \qquad \boxed{a = v\dot{\gamma}} \qquad a = v\left(r - \dot{\beta}\right)$$

(Assumption: no change in modulus of the velocity)

We can rewrite the dynamic system in function of the state variables β and r

$$\begin{cases} ma = F_r + F_f \\ J\dot{r} = l_f F_f - l_r F_r \end{cases}$$

$$\begin{cases} mv(r - \dot{\beta}) = C_r\left(\beta + \frac{l_r r}{v}\right) + C_f\left(\beta + \delta - \frac{l_f r}{v}\right) \\ J\dot{r} = l_f C_f\left(\beta + \delta - \frac{l_f r}{v}\right) - l_r C_r\left(\beta + \frac{l_r r}{v}\right) \end{cases}$$



$$dv = v d\gamma \Rightarrow {dv}/{dt} = v\,{d\gamma}/{dt} \Rightarrow a = v\dot{\gamma}$$

Dynamic modeling for lateral/ yaw control: "single-track model"

State-space – Normal form – 2nd order linear system
(time-varying if v is slowly-varying)

$$\begin{cases} \dot{\beta} = \left(-\dfrac{C_r + C_f}{mv}\right)\beta + \left(1 + \dfrac{C_f l_f - C_r l_r}{mv^2}\right) r + \left(-\dfrac{C_f}{mv}\right)\delta \\ \dot{r} = \left(\dfrac{C_f l_f - C_r l_r}{J}\right)\beta + \left(-\dfrac{C_f l_f^2 + C_r l_r^2}{vJ}\right) r + \left(\dfrac{C_f l_f}{J}\right)\delta \end{cases}$$

Example values for parameters:

m = weighs from till 1400

lf = 1.30m

lr = 1.25m

J = 2000kgm ^ 2

Cf = Cr = 90000N/rad

v = 30m / s

Simplified model (Cf = Cr = C, lf = lr = l):

$$\begin{cases} \dot{\beta} = \left(-\dfrac{2C}{mv}\right)\beta + r + \left(-\dfrac{C}{mv}\right)\delta \\ \dot{r} = \left(-\dfrac{2Cl^2}{vJ}\right) r + \left(\dfrac{Cl}{J}\right)\delta \end{cases}$$

Dynamic modeling for lateral/ yaw control: "single-track model"

$$\begin{cases} \dot{\beta} = \left(-\dfrac{2C}{mv}\right)\beta + r + \left(-\dfrac{C}{mv}\right)\delta \\ \dot{r} = \left(-\dfrac{2Cl^2}{vJ}\right)r + \left(\dfrac{Cl}{J}\right)\delta \end{cases}$$

Transfer function from steering angle to yaw speed:

$$F_{\delta r}(s) = \frac{\frac{Cl}{J}}{s + \frac{2Cl^2}{vJ}}$$

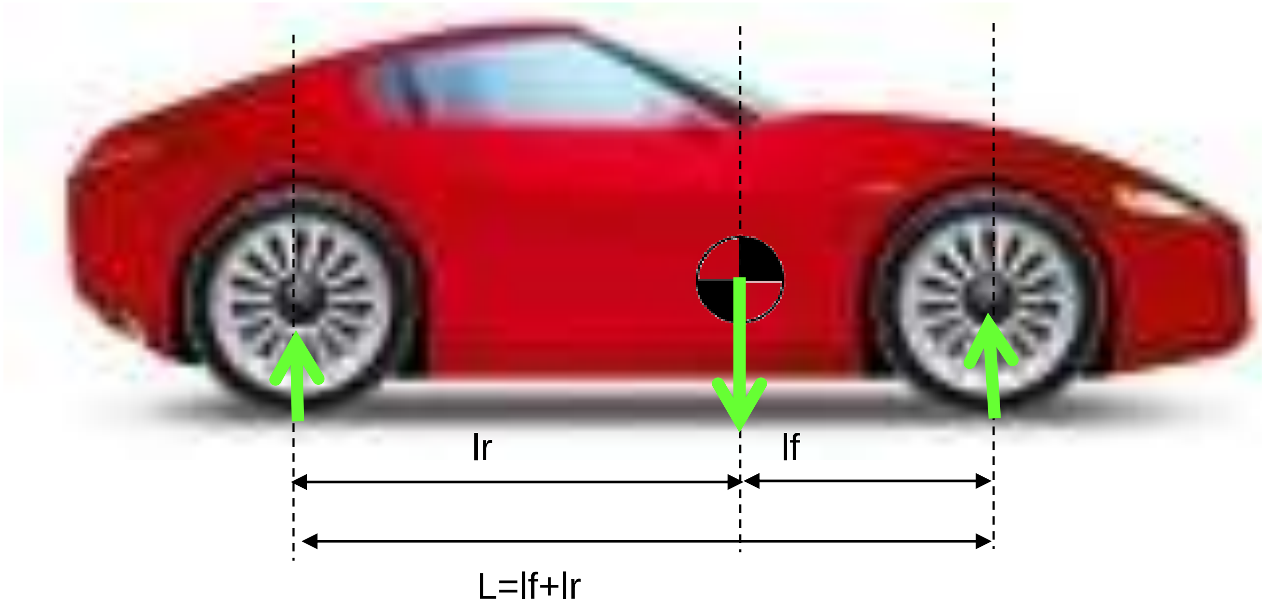
Gain: $\dfrac{v}{2l}$ Pole: $s = -\frac{2Cl^2}{vJ}$

Transfer function from steering angle to side-slip:

$$F_{\delta\beta}(s) = \frac{-\frac{C}{mv}\left(s + \frac{2Cl^2 - mv^2 l}{vJ}\right)}{\left(s + \frac{2Cl^2}{vJ}\right)\left(s + \frac{2C}{mv}\right)}$$

Poles: $s = -\frac{2Cl^2}{vJ}$ $s = -\frac{2C}{vm}$

Remark – under-steering gain (Kus)



$$M = M_f + M_r$$

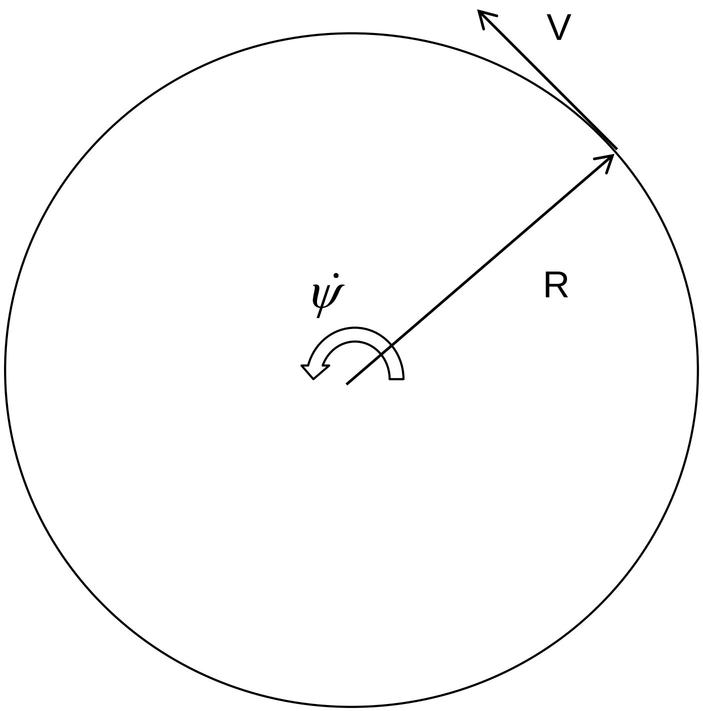
$$M_f l_f = M_r l_r$$

$$\Downarrow$$

$$M_f = \frac{M l_r}{l_r + l_f} \qquad M_r = \frac{M l_f}{l_r + l_f}$$

Remark – under-steering gain (Kus)

$$\dot\psi R = V \quad \dot\psi = \frac{V}{R} \quad a_y = \dot\psi V$$



$$\boxed{\delta = \frac{L}{R}\tau + \left(\frac{M_f}{C_f} - \frac{M_r}{C_r}\right)\frac{V^2}{R}\tau}$$

Steering-pad equation

Assuming (for simplicity) steer ratio $\tau = 1$

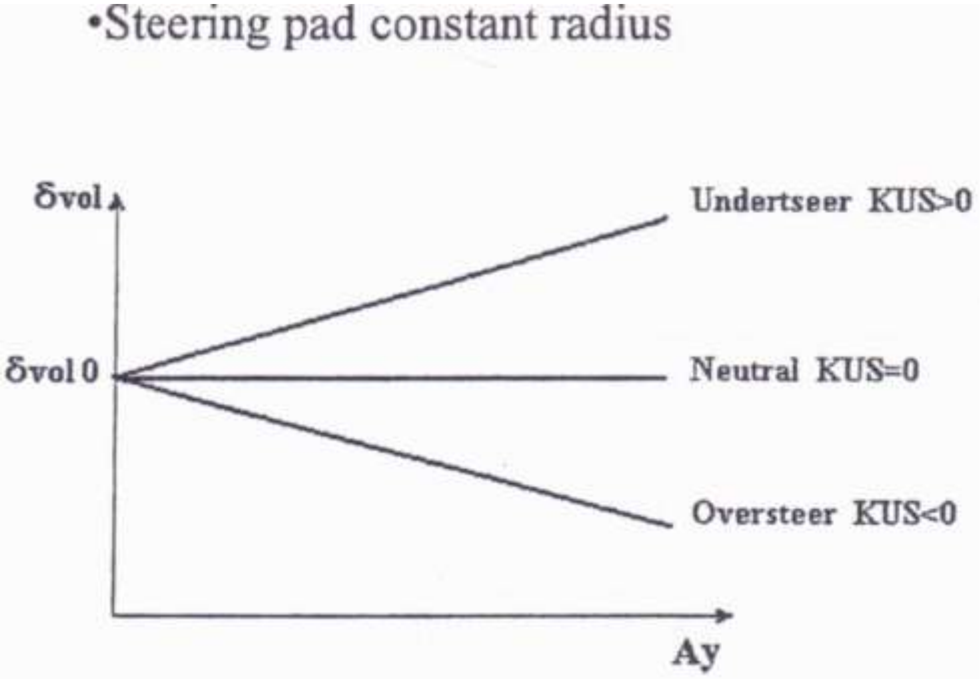
$$\delta = \frac{L}{R} + \left(\frac{M_f}{C_f} - \frac{M_r}{C_r}\right)\frac{V^2}{R}$$

Under-Steering Gain: $K_{US} = \left(\frac{M_f}{C_f} - \frac{M_r}{C_r}\right)$

Low-speed steer angle: $\delta_0 = \frac{L}{R}$

$$\delta = \delta_0 + a_y K_{US}$$

Remark – under-steering gain (Kus)



$$K_{US} = \left(\frac{M_f}{C_f} - \frac{M_r}{C_r} \right)$$

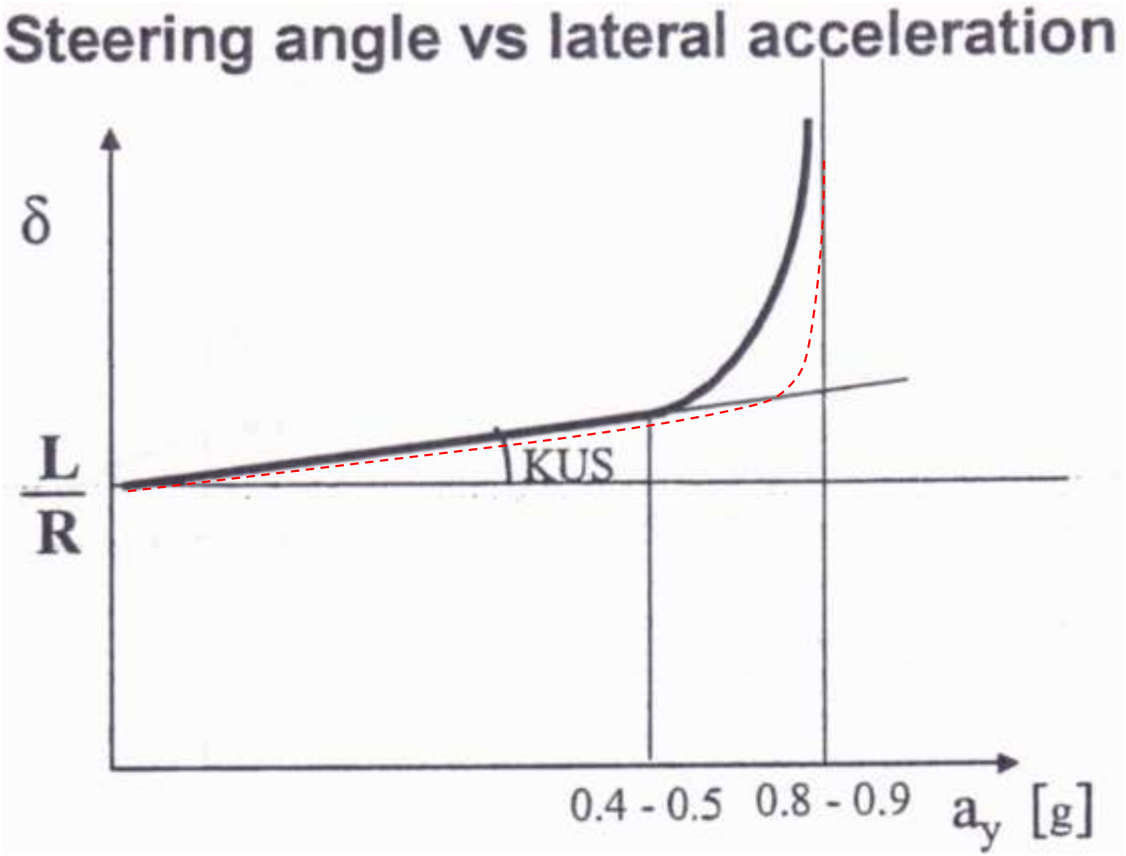
$$F(\lambda, \alpha, F_z, \gamma) \approx C(\lambda, F_z, \gamma)\alpha$$

$$C \propto \frac{1}{\lambda}, F_z$$

Effect of load transfer on equivalent Kus?

Effect of high-lambda?

Remark – under-steering gain (Kus)



Trade-off between:

Smooth and long non-linear region

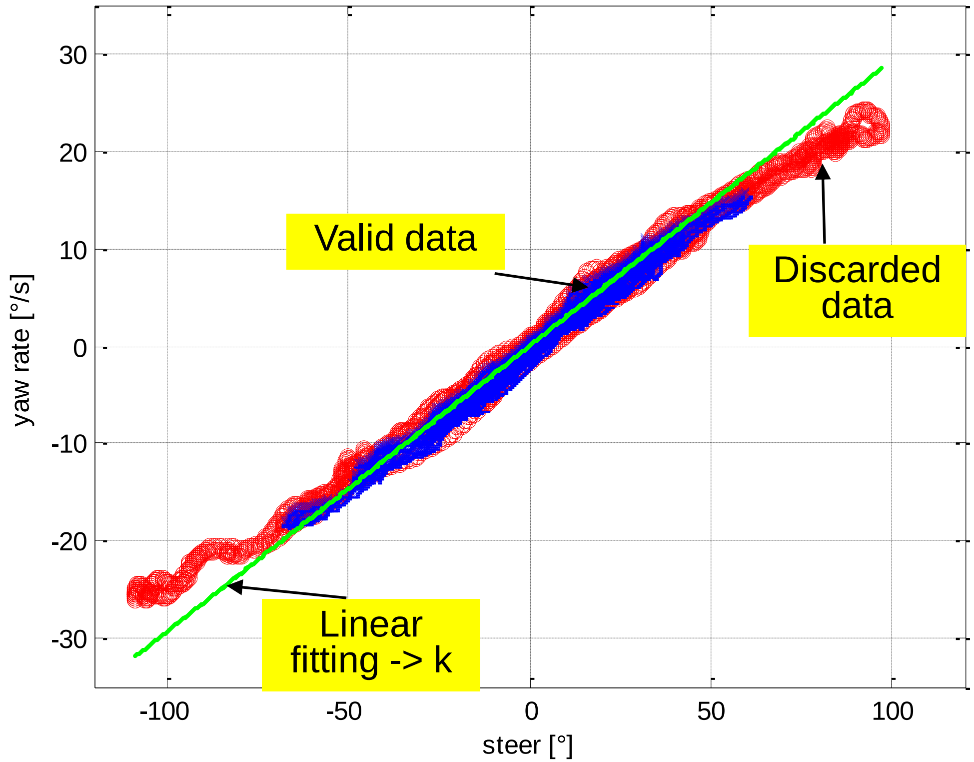
Short and steep non-linear region

Sensitivity around the limit
Early-warning
High-slip-angle region

Remark: KUS estimation from data (single speed) - Example

Test on a proving ground; constant speed = 60 km/h.

1) Only the samples with speed in the range 58km/h - 62 km/h, AND lateral acceleration smaller than 0.6g are considered.
2) Plot on a steer-angle vs. yaw-rate map.
3) Linear fitting; estimation of k, from the estimated k -> K_{us}



$$\delta = \delta_0 + a_y K_{US}$$

$$\delta = \frac{L}{R} + \dot{\psi} V K_{US}$$

$$\delta = \frac{L}{\frac{V}{\dot{\psi}}} + \dot{\psi} V K_{US}$$

$$\delta = \frac{\dot{\psi} L}{V} + \dot{\psi} V K_{US} = \left[\frac{L + K_{US} V^2}{V} \right] \dot{\psi}$$

$$\dot{\psi} = \left[\frac{V}{L + K_{US} V^2} \right] \delta = k\delta$$

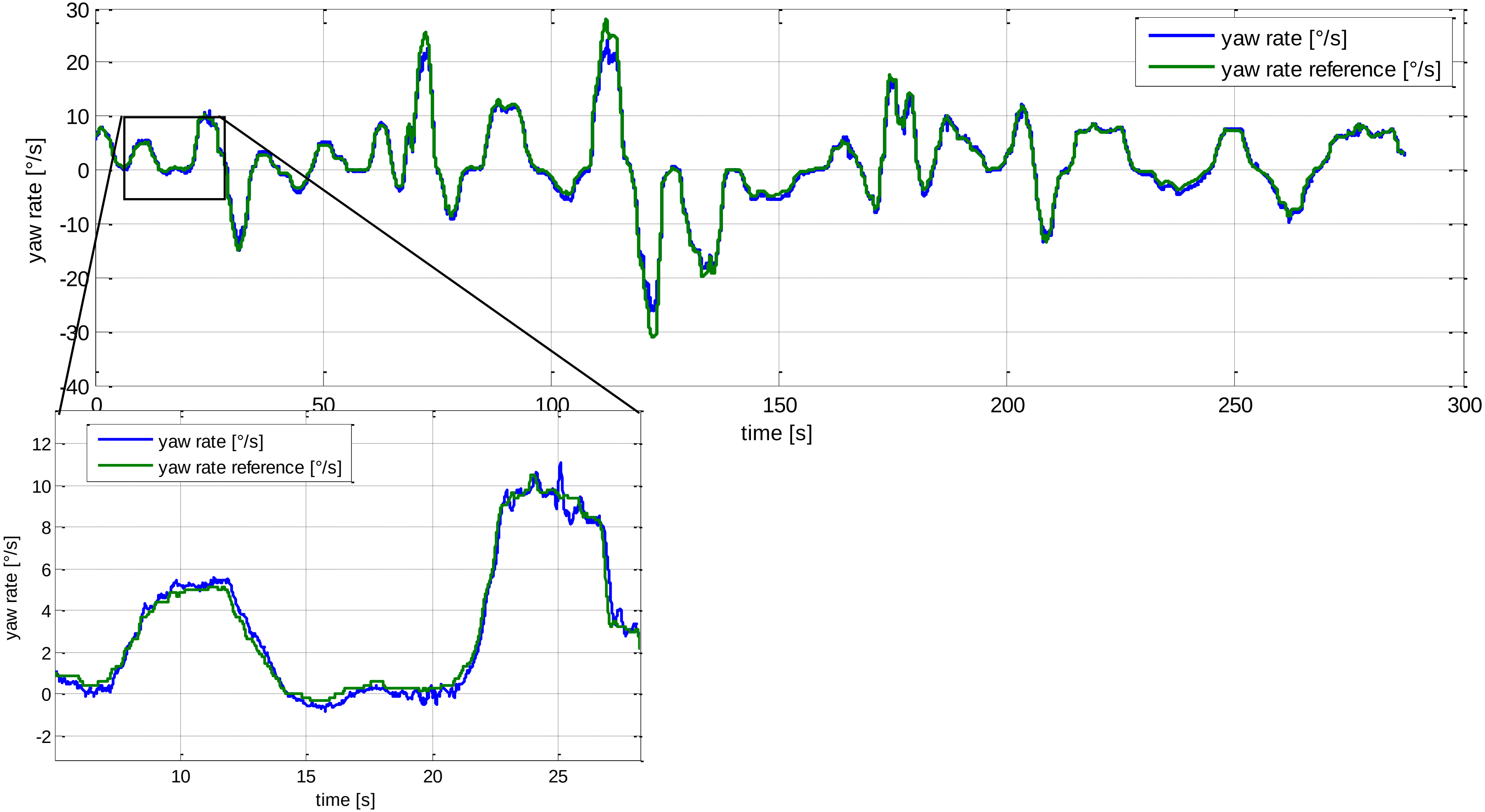
$$K_{US} = \frac{V - kL}{kV^2}$$

Estimated K_{us}= 47° /g

Remark: KUS estimation from data (single speed) - Validation

Estimated K_{us} = 47° /g.

Proving ground: «Langhe»



Reference model for yaw rate?

$$\begin{cases} \dot{\beta} = \left(-\dfrac{C_r + C_f}{mv}\right)\beta + \left(1 + \dfrac{C_f l_f - C_r l_r}{mv^2}\right) r + \left(-\dfrac{C_f}{mv}\right)\delta \\ \dot{r} = \left(\dfrac{C_f l_f - C_r l_r}{J}\right)\beta + \left(-\dfrac{C_f l_f^2 + C_r l_r^2}{vJ}\right) r + \left(\dfrac{C_f l_f}{J}\right)\delta \end{cases}$$

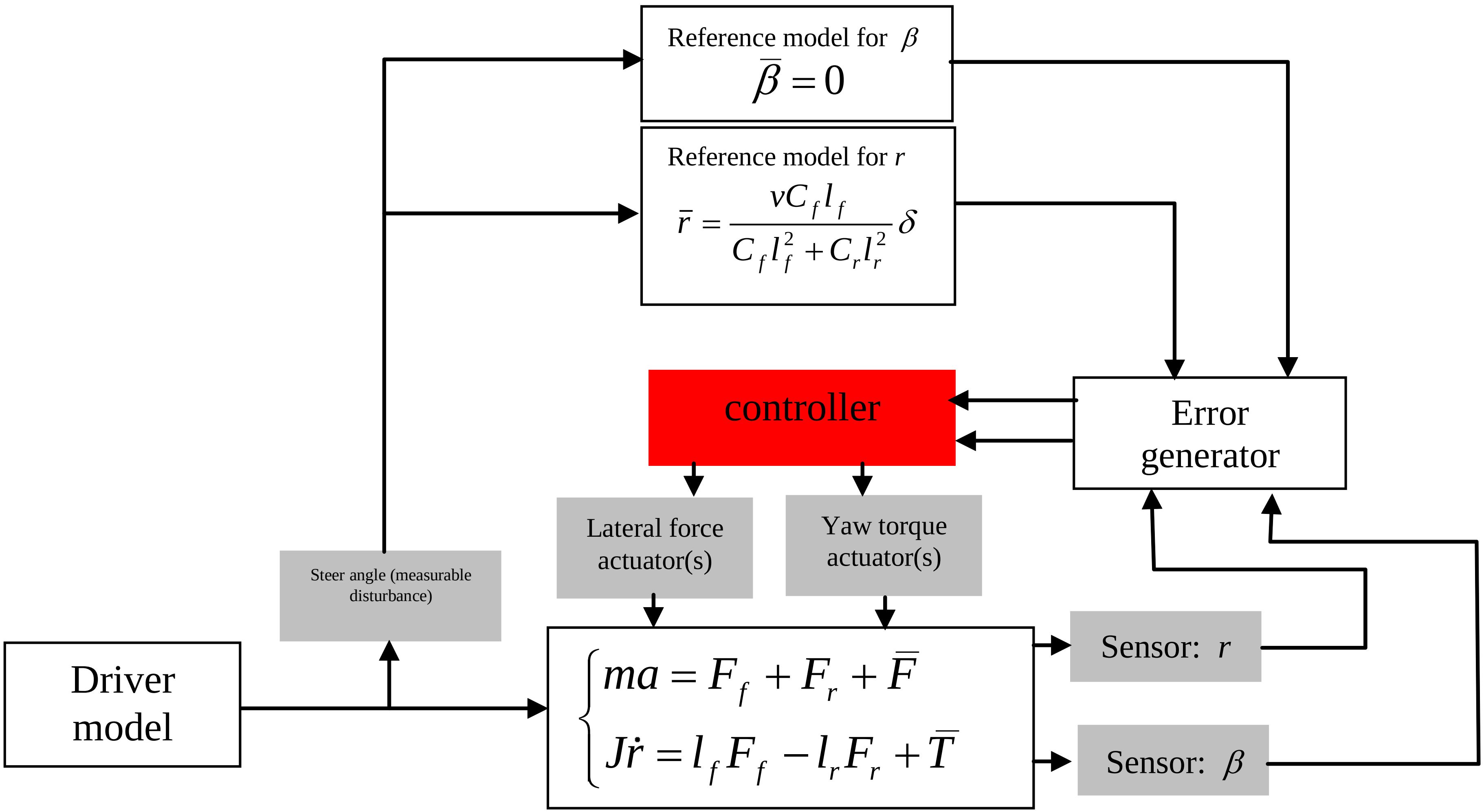
$$if \quad \beta \approx 0, \quad \dot{r} = 0$$

$$\begin{cases} \dot{\beta} = \left(-\dfrac{C_r + C_f}{mv}\right)\beta + \left(1 + \dfrac{C_f l_f - C_r l_r}{mv^2}\right) r + \left(-\dfrac{C_f}{mv}\right)\delta \\ \cancel{\dot{r}} = \cancel{\left(\dfrac{C_f l_f - C_r l_r}{J}\right)}\beta + \left(-\dfrac{C_f l_f^2 + C_r l_r^2}{vJ}\right) r + \left(\dfrac{C_f l_f}{J}\right)\delta \end{cases}$$

$$0 = \left(-\dfrac{C_f l_f^2 + C_r l_r^2}{vJ}\right) r + \left(\dfrac{C_f l_f}{J}\right)\delta$$

$$\boxed{\bar{r} = \frac{v C_f l_f}{C_f l_f^2 + C_r l_r^2}\delta}$$

General framework of lateral/yaw control (ESC: Electronic Stability Control)



SENSORS:

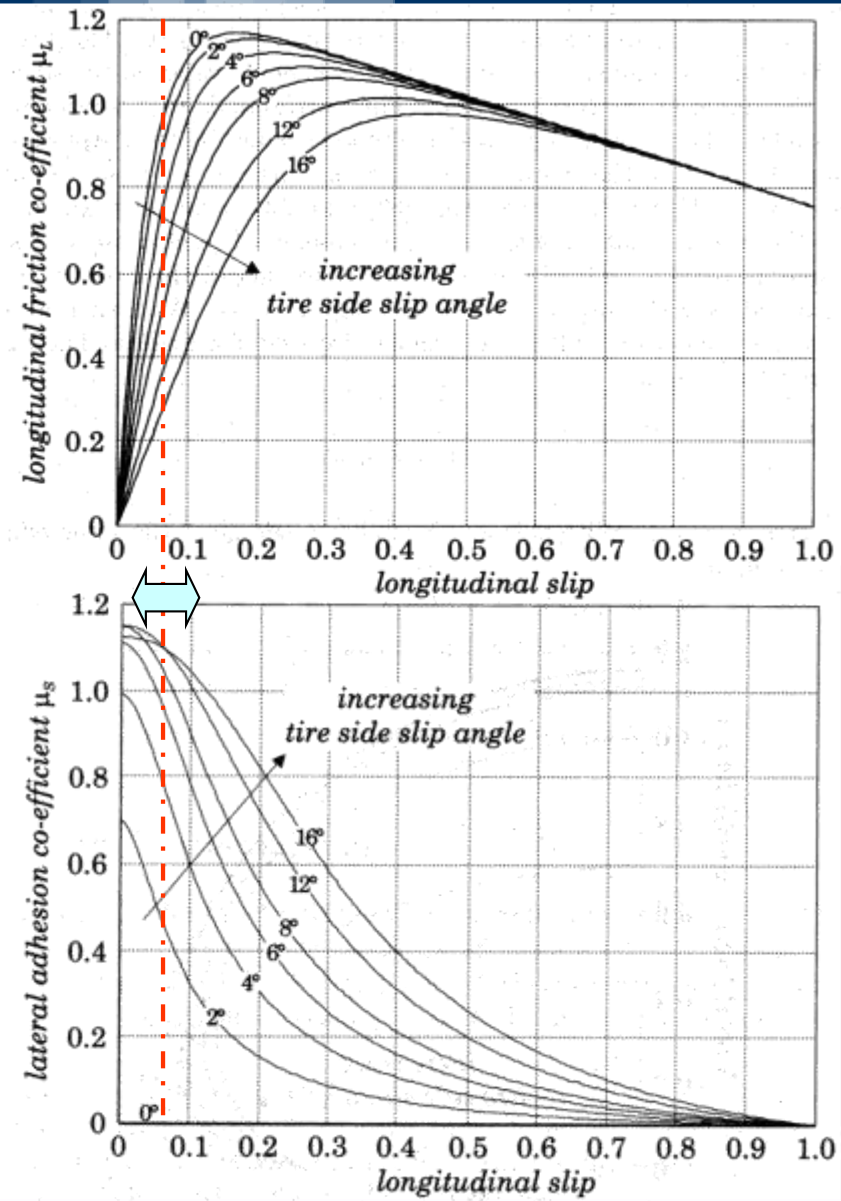
- steering angle
- speed
- yaw rate

-<u>estimate</u> side-slip angle

ACTUATORS $\bar{F}$ $\bar{T}$

-Brakes (ESP / VDC / ...)
-differentials
-Active Steering
-active aerodynamic surfaces

Modulation of each individual wheel slip



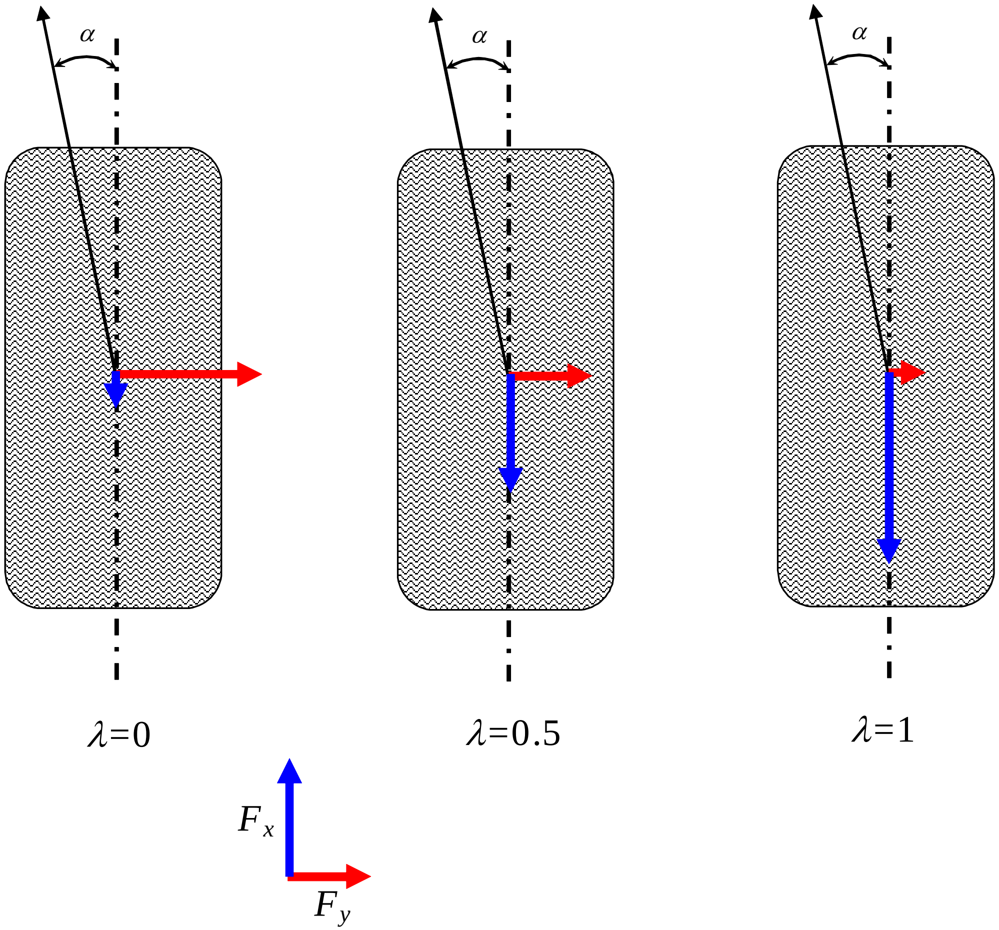
Assuming some knowledge of:

vertical load
tire side-slip angle
road conditions

it is possible to modulate the longitudinal+lateral forces of the 4 wheels

by changing the longitudinal slip through the braking action

Lateral force and yaw torques modulation with active brake control



b=vehicle track

$$F_y = \sum_{i=1}^{4} F_{y_i}(\lambda_i) \equiv \bar{F}$$

$$F_x = \sum_{i=1}^{4} F_{x_i}(\lambda_i)$$

$$\begin{aligned} T = & -F_{x_{FL}}(\lambda_{FL})\frac{b}{2} + F_{x_{FR}}(\lambda_{FR})\frac{b}{2} + \\ & - F_{x_{RL}}(\lambda_{RL})\frac{b}{2} + F_{x_{RR}}(\lambda_{RR})\frac{b}{2} + \\ & + F_{y_{FL}}(\lambda_{FL})l_f + F_{y_{FR}}(\lambda_{FR})l_f + \\ & - F_{y_{RL}}(\lambda_{RL})l_r - F_{y_{RR}}(\lambda_{RR})l_r \equiv \bar{T} \end{aligned}$$

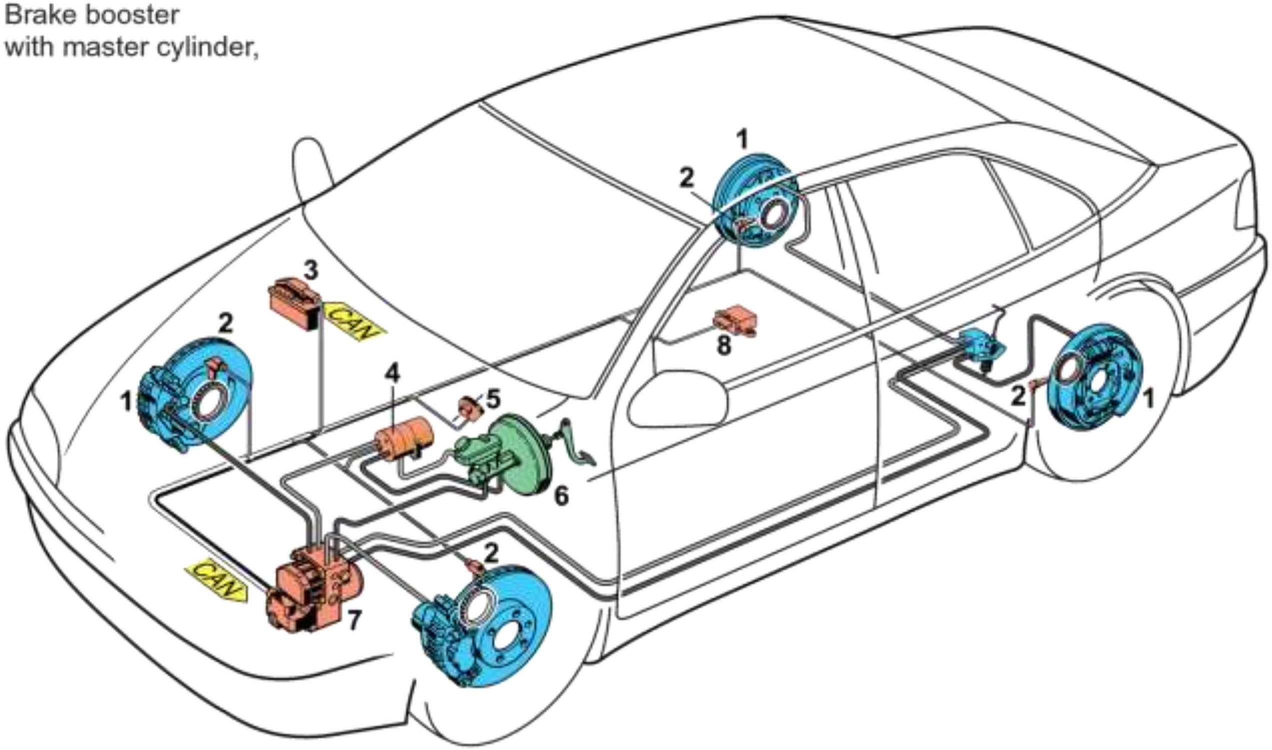
4 control variables (lambda)

2 equations

Lateral force and yaw torques modulation with active brake control
Example: ESP (Bosch)

ESP – Complete closed-loop control system (component locations)

1 Wheel brakes,
2 Wheel-speed sensors,
3 ECU,
4 Primer pump (eVLP),
5 Steering-wheel sensor,
6 Brake booster with master cylinder,
7 Hydraulic modulator with primary-pressure sensor,
8 Yaw sensor with lateral-acceleration sensor.



Main sensors:
yaw speed
lateral acceleration sensor (for the estimation of β)
steering angle
angular wheel speed

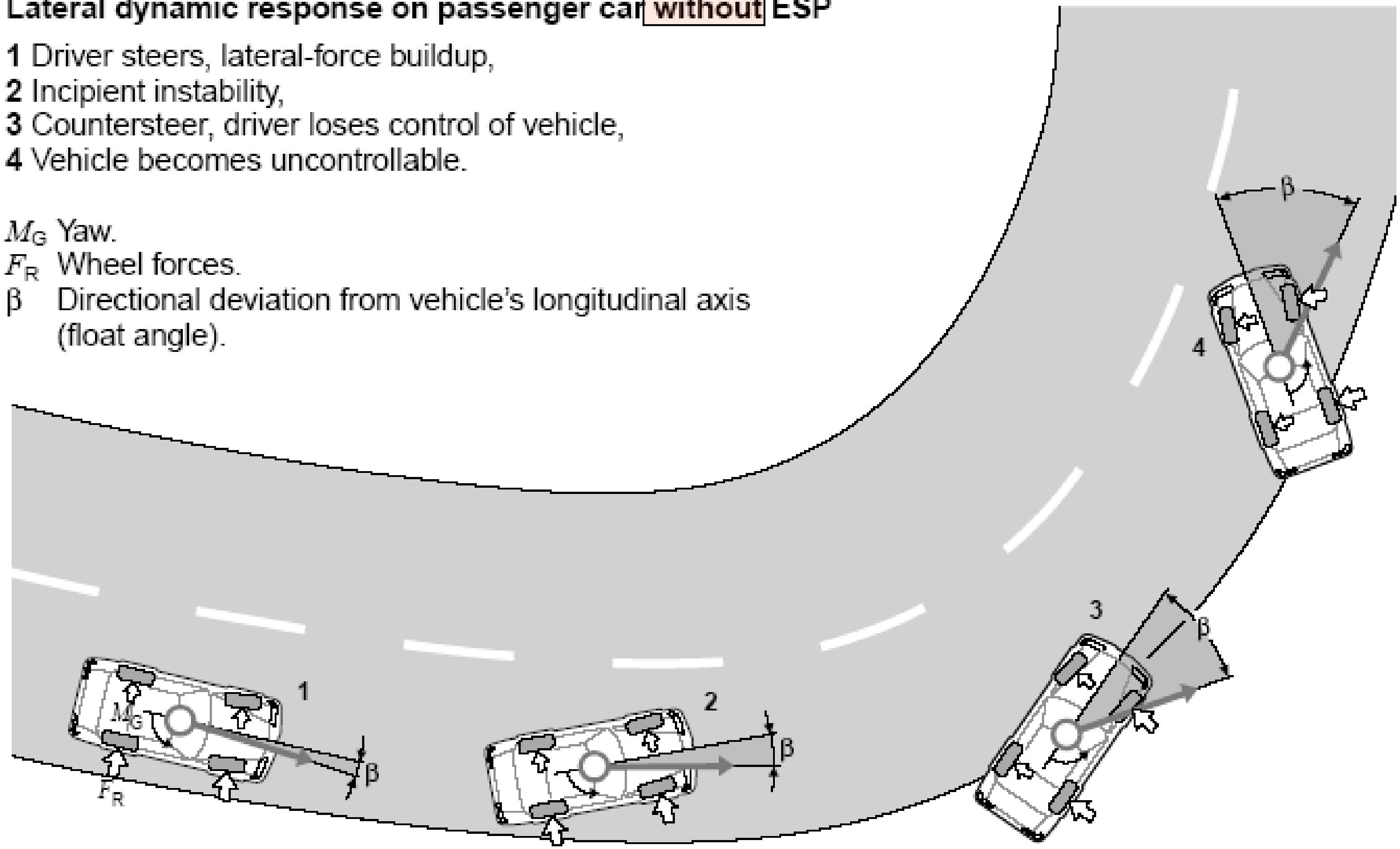
Main actuators:
4 brake pressures

Lateral force and yaw torques modulation with active brake control
Example: ESP (Bosch)

Lateral dynamic response on passenger car without ESP

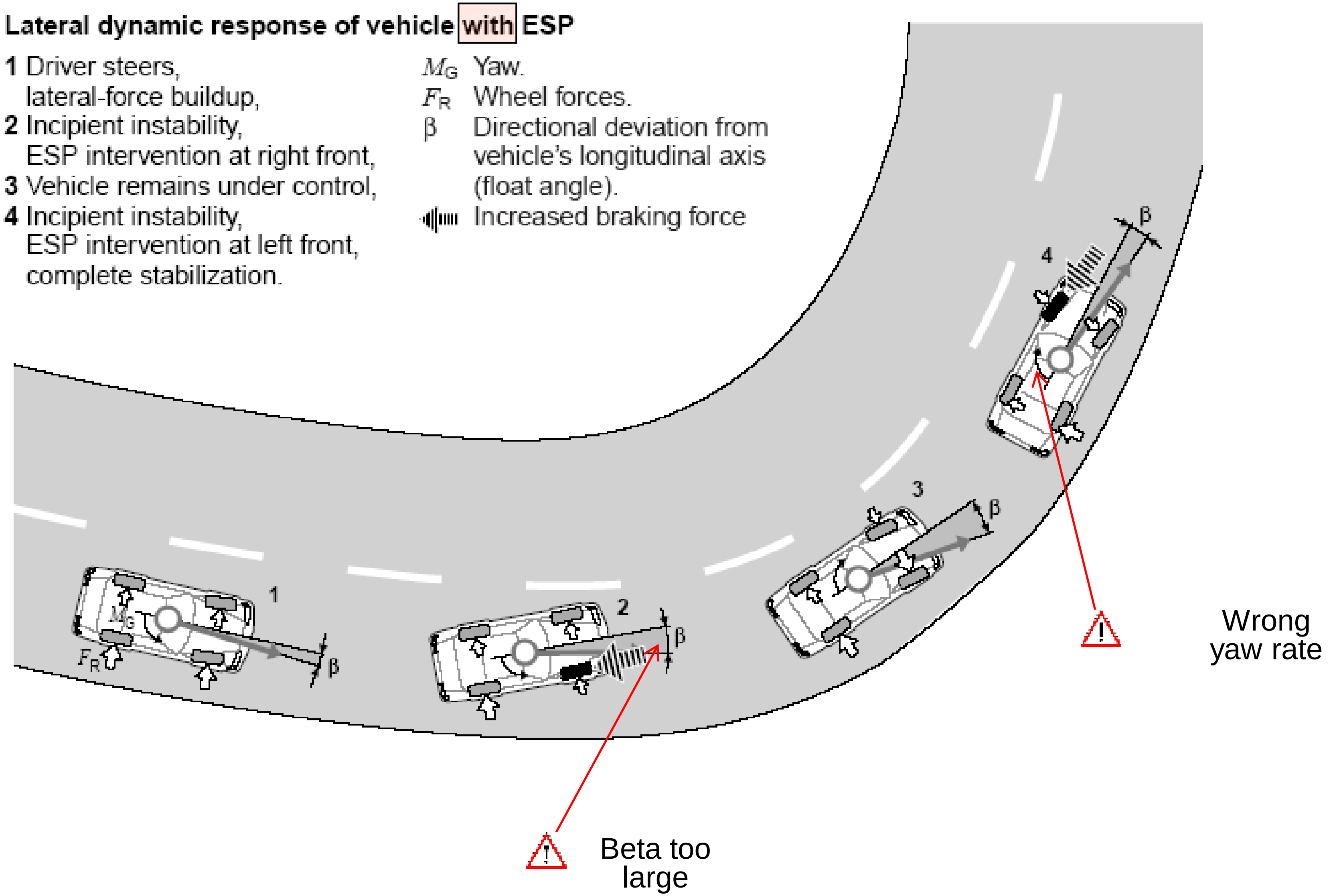
1 Driver steers, lateral-force buildup,
2 Incipient instability,
3 Countersteer, driver loses control of vehicle,
4 Vehicle becomes uncontrollable.

M_G Yaw.
F_R Wheel forces.
β Directional deviation from vehicle's longitudinal axis (float angle).



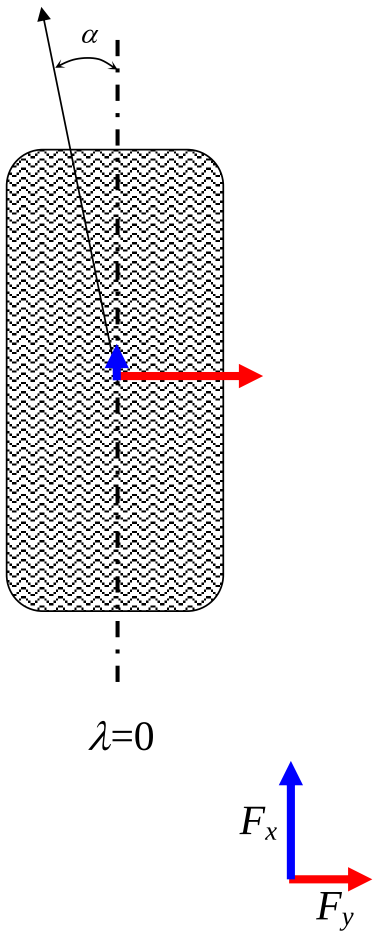
source: Boschtech-25d

Lateral force and yaw torques modulation with active brake control
Example: ESP (Bosch)



source: Boschtech-25d

Lateral force and yaw torques modulation with active traction control

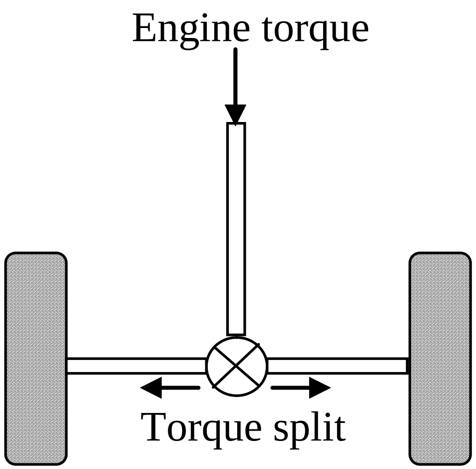


The logic used is exactly symmetric: it modulates the motor torque instead of the braking torque (negative coefficients slip instead of positive).

Reqires electronically-controlled differentials

Taken from: Boschteh-25d

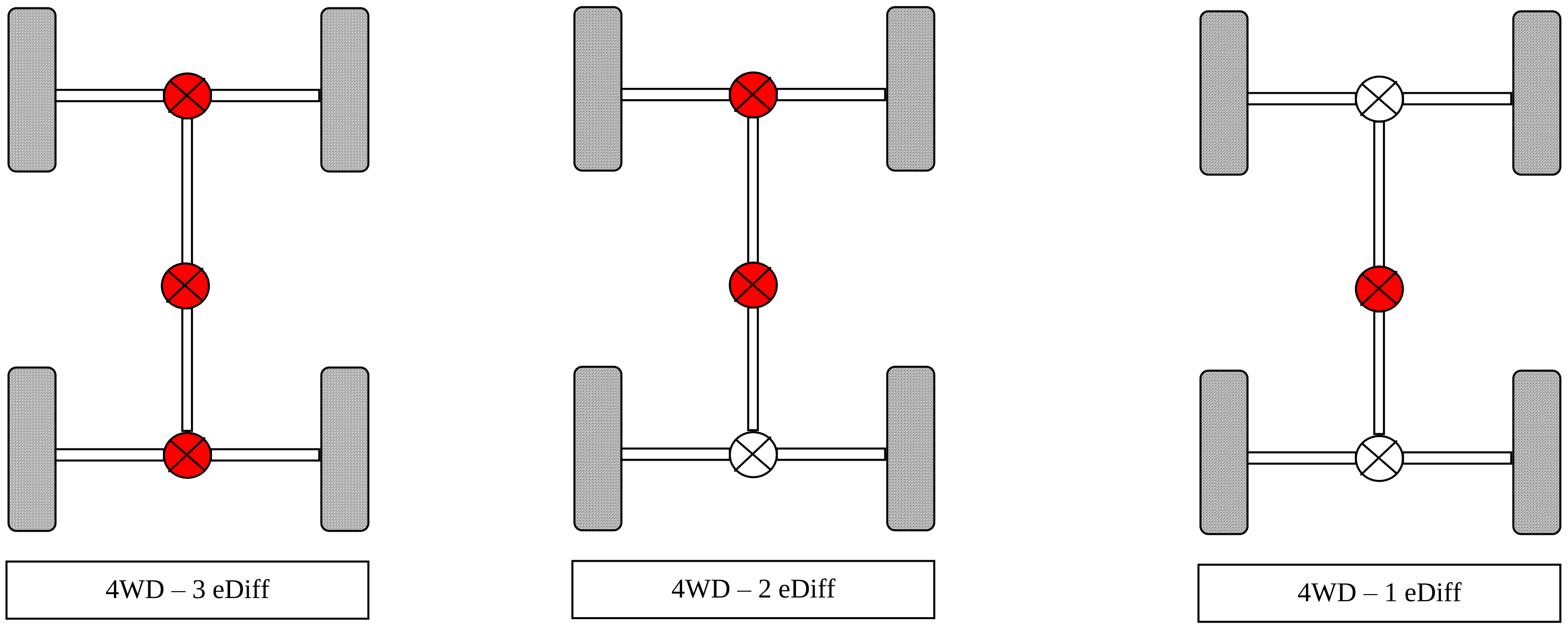
Lateral force and yaw torques modulation with active traction control



A traditional passive differential tries to distribute engine torque 50% -50% on the two drive shafts.

"active“ differentials: the torque split can be electronically varied

Lateral force and yaw torques modulation with active traction control



There are several possible configurations

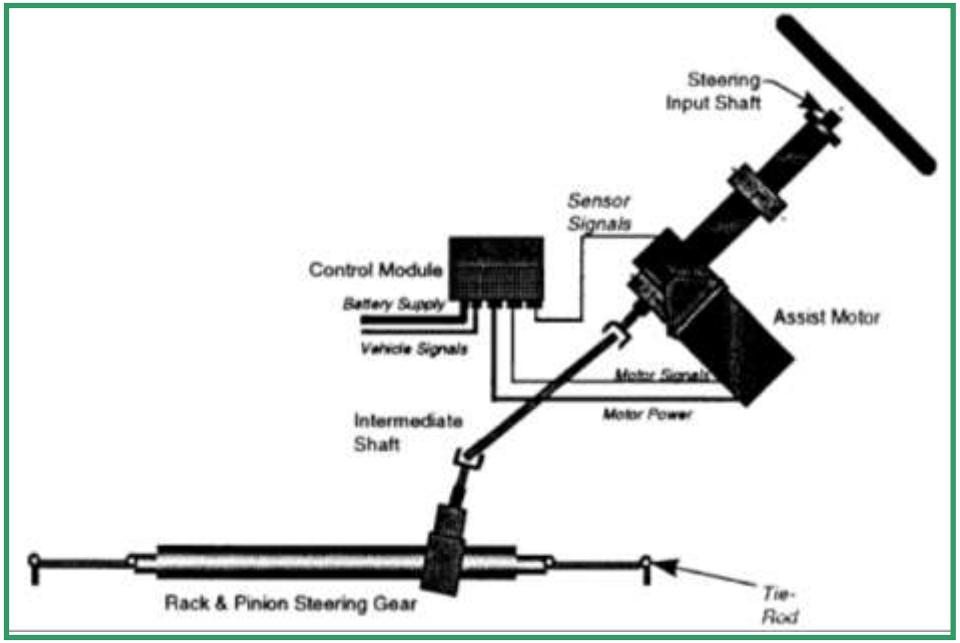
Unlike ESP, does not require a braking condition (works well even at low speed, in acceleration, on low-grip surface)

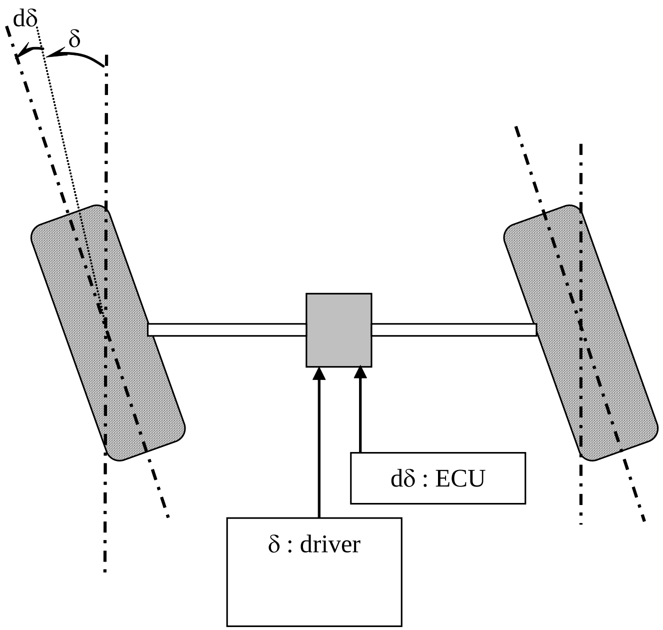
Suitable mainly for off-road vehicles

Does not dissipate energy by braking, but dissipates energy on differentials

Requires components (differentials) that are not built-in

Lateral force and yaw torques modulation with active steer





-The most natural and intuitive way to control yaw and lateral dynamics
-Precondition: "steer-by-wire"
-Steering angle conceptually consists of two terms: dδ+δ
-Is modulated by the controller only dδ [with amplitude and bandwidth constraints]
-With or without feedback on the driver (discussion)

Lateral force and yaw torques modulation with active steer

Possible configurations:

-2WS (BMW 5-Series MY03)

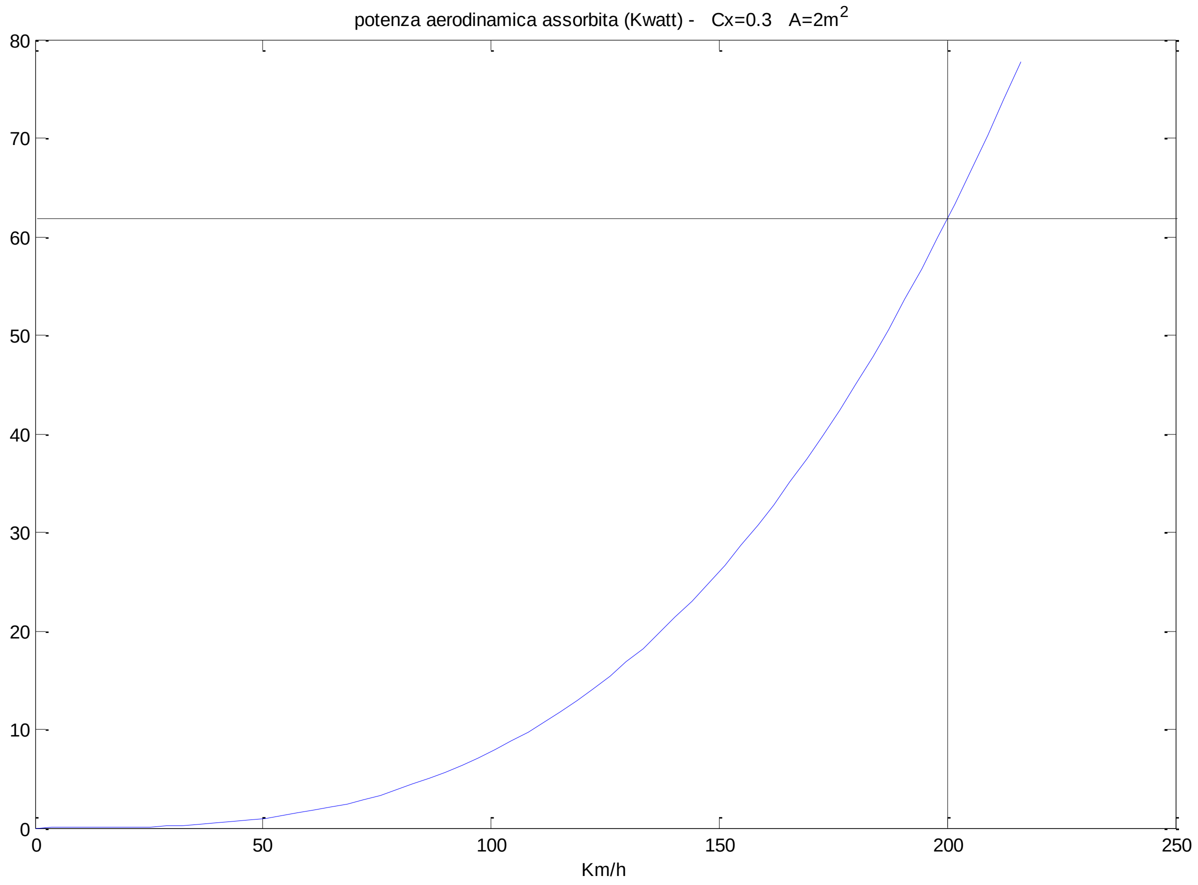
-4WS

-Feedforward (*Honda Prelude*)

- 4WS rear-active feedback (Renault, 2008)

Not to be confused with passive rear steering-wheels

Lateral force and yaw torques modulation with active aerodynamic-surfaces



aerodynamic forces

$$F_{Drag} = \frac{1}{2}\rho C_x A v^2$$

$$F_{Lift} = \frac{1}{2}\rho C_z A v^2$$

Both significant only at high speeds

Architectures

Lateral force and yaw torques modulation: summary

Type	Current status	Notes	Expected development
Active Brakes (ESP)	In production (large volumes)	Can use ABS actuators	Consolidation
Active Differentials	In production (niche)	Requires active differentials	niche
Active steering	In production (niche)	Requires a steer-by-wire systems	?
Active aerodynamic surfaces	Only R&D	Only high-speed applications	(niche)

Remark: Powered Two Wheelers (PTW): stability-control approaches (actuators)