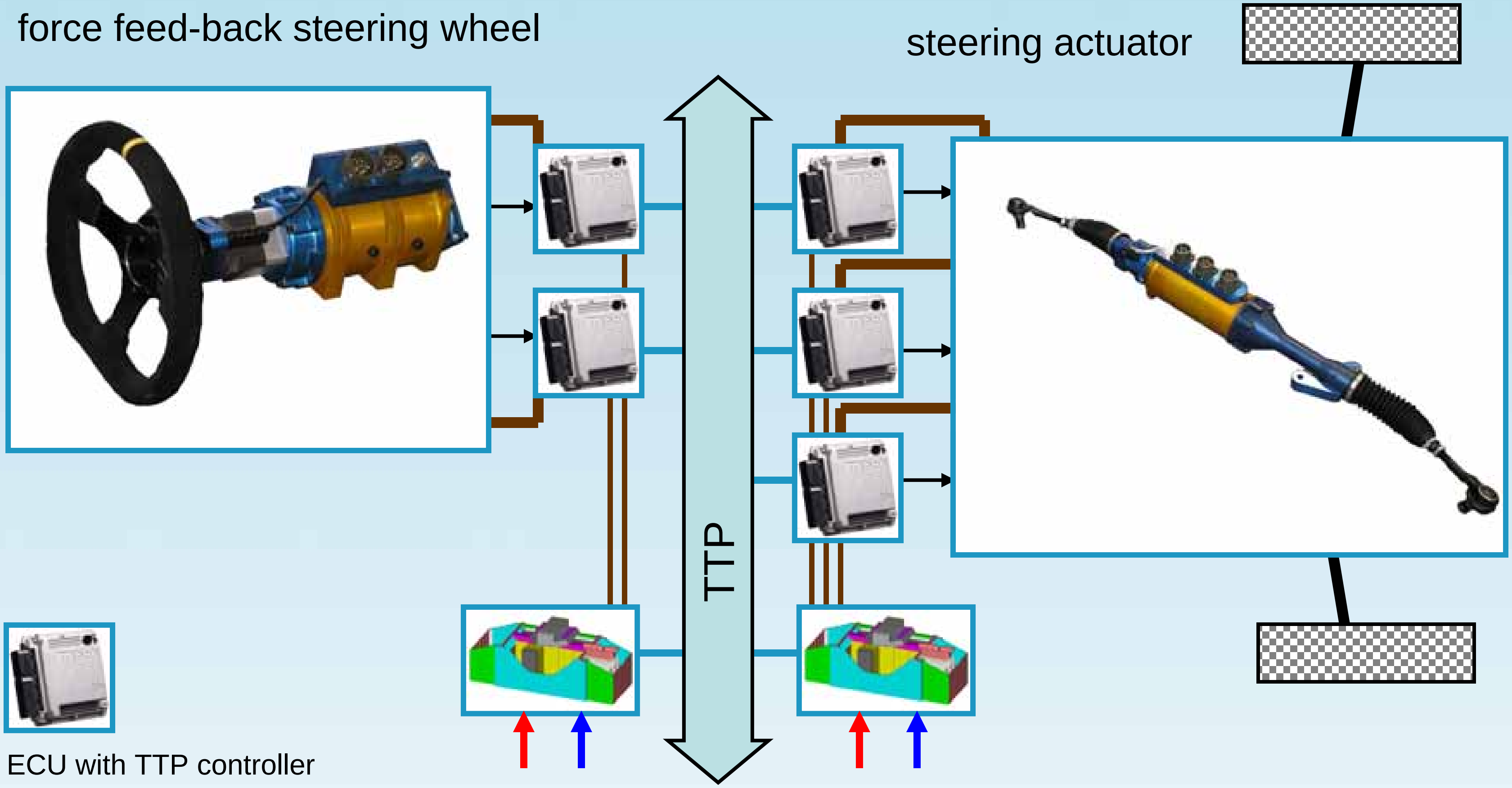
Integrated Global Chassis Control
- A Top-Down Design Approach

Jingxin Shi
jingxin.shi@tttech.com
TTTech Germany GmbH

TTTech Steering-by-Wire System



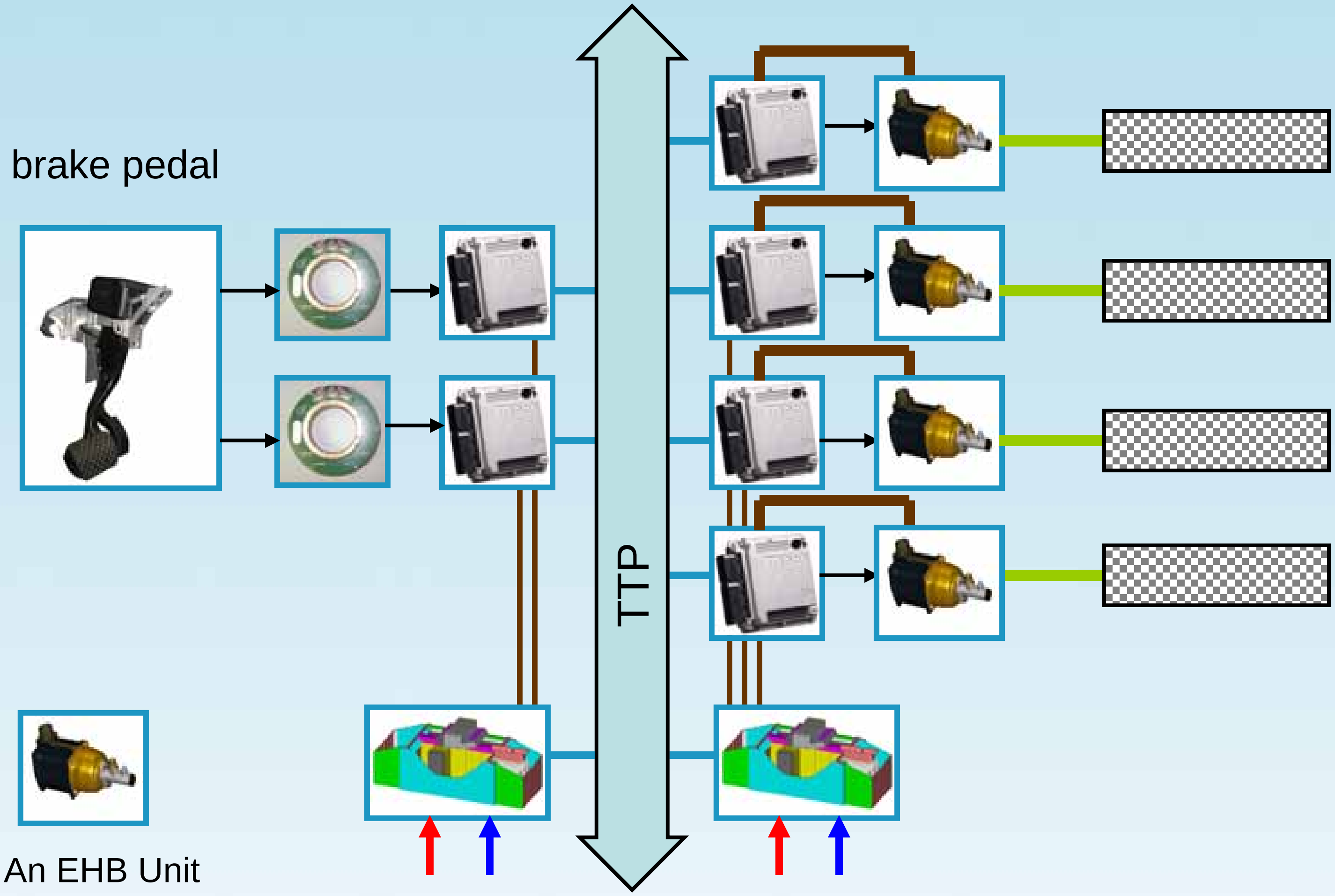
force feed-back steering wheel

steering actuator

TTP

ECU with TTP controller
and power electronics for
the control of by-wire motors

TTTech Braking-by-Wire system

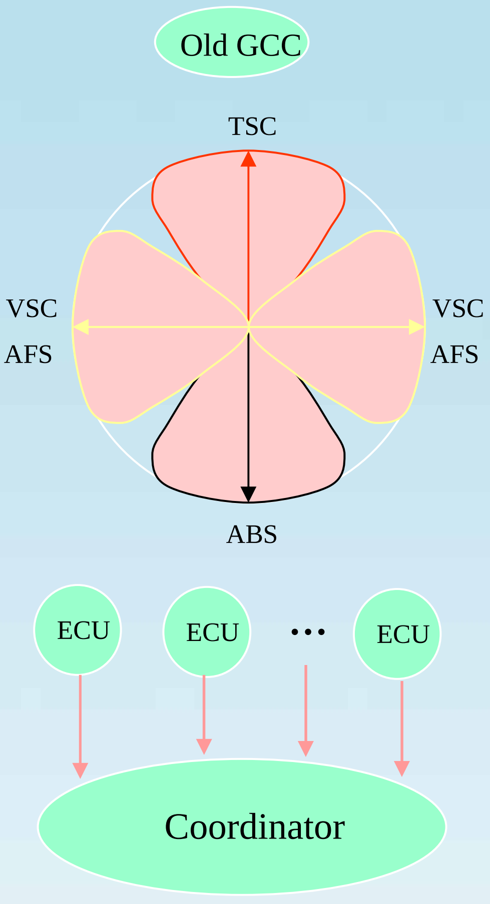


brake actuators

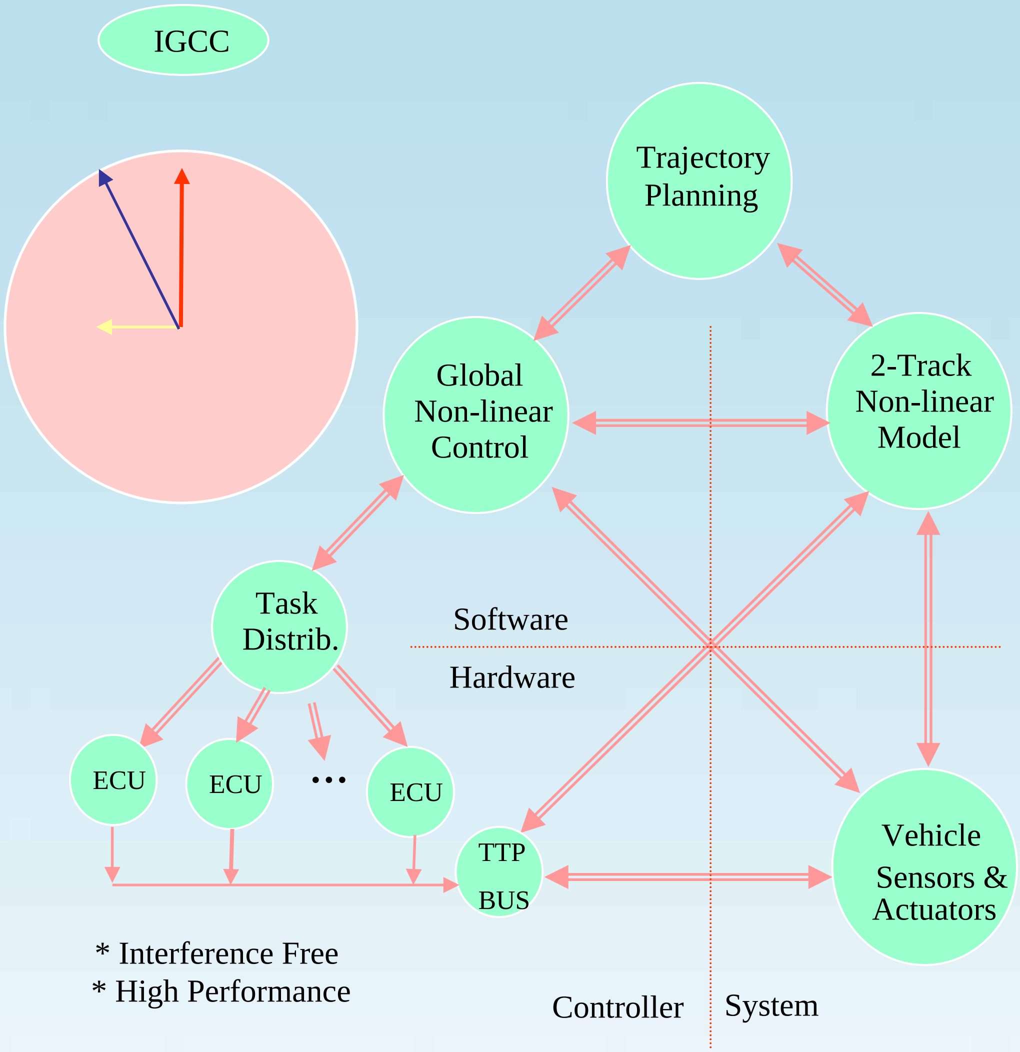
brake pedal

An EHB Unit

IGCC - Top-Down Design Procedure

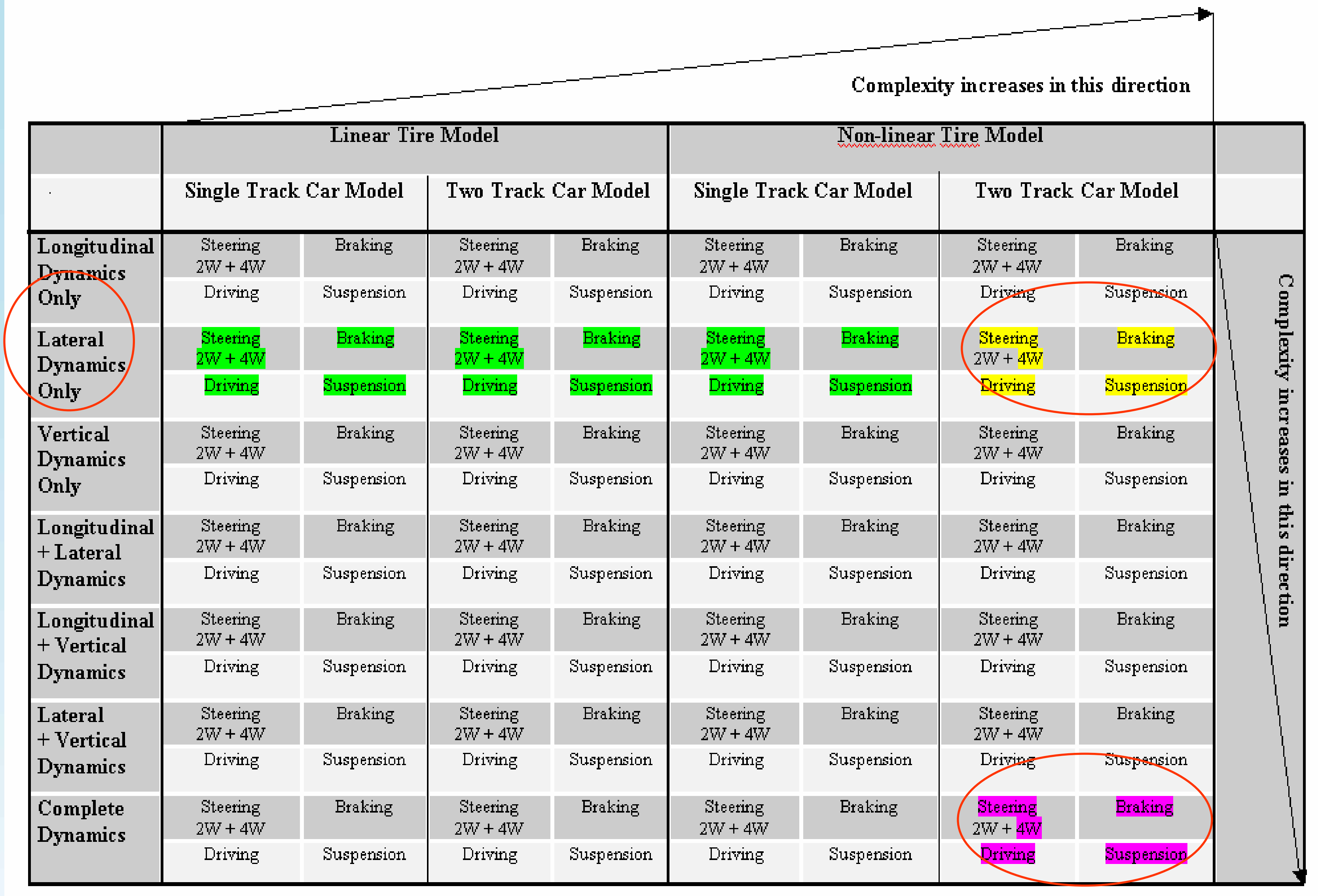


* Performance Limited
* Possible Interference



* Interference Free
* High Performance

Classification of Vehicle Dynamics Control Systems



Complexity increases in this direction

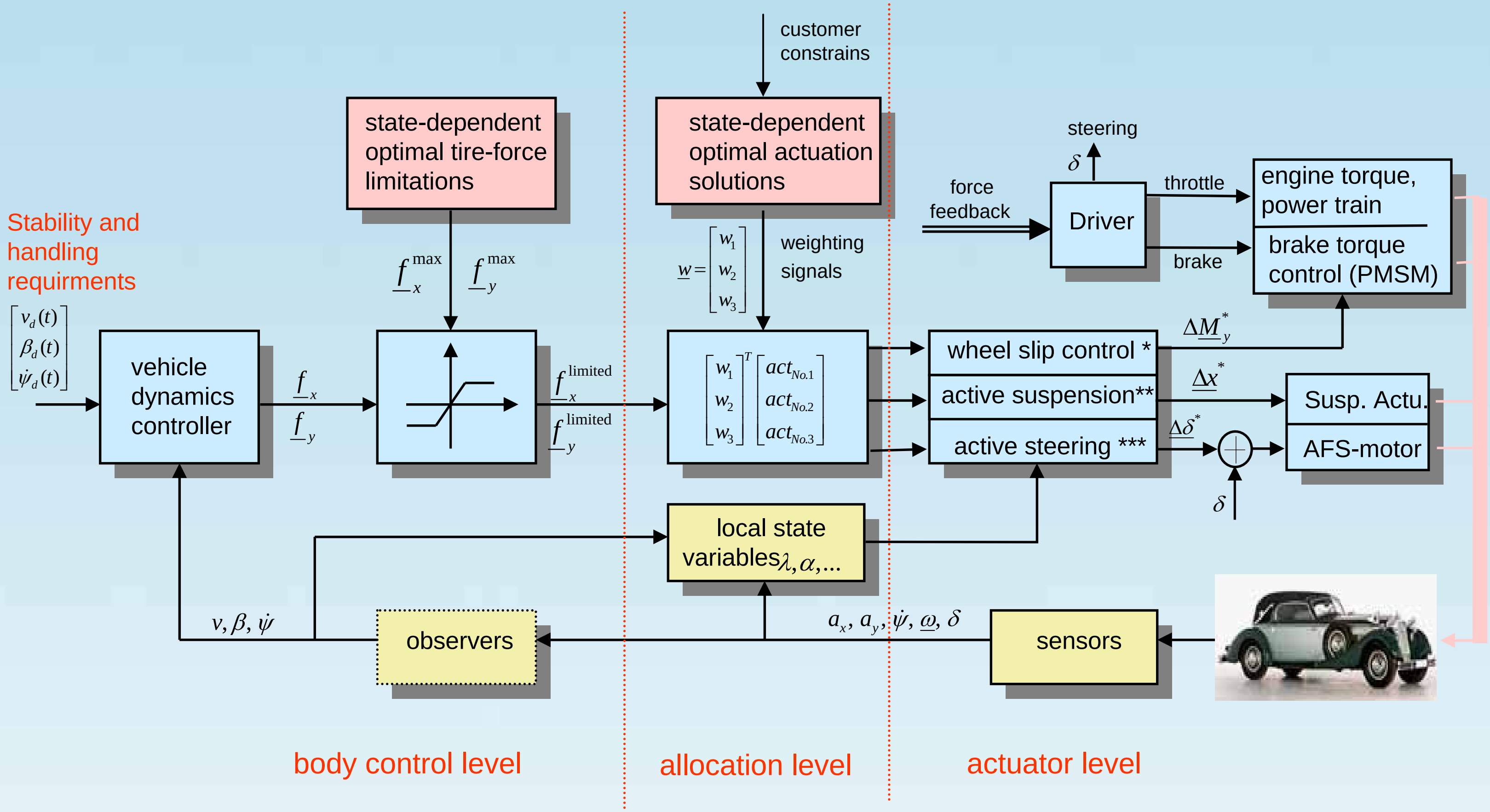
	Linear Tire Model				Non-linear Tire Model			
	Single Track Car Model		Two Track Car Model		Single Track Car Model		Two Track Car Model	
Longitudinal Dynamics Only	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking
	Driving	Suspension	Driving	Suspension	Driving	Suspension	Driving	Suspension
Lateral Dynamics Only	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking
	Driving	Suspension	Driving	Suspension	Driving	Suspension	Driving	Suspension
Vertical Dynamics Only	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking
	Driving	Suspension	Driving	Suspension	Driving	Suspension	Driving	Suspension
Longitudinal + Lateral Dynamics	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking
	Driving	Suspension	Driving	Suspension	Driving	Suspension	Driving	Suspension
Longitudinal + Vertical Dynamics	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking
	Driving	Suspension	Driving	Suspension	Driving	Suspension	Driving	Suspension
Lateral + Vertical Dynamics	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking
	Driving	Suspension	Driving	Suspension	Driving	Suspension	Driving	Suspension
Complete Dynamics	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking	Steering 2W + 4W	Braking
	Driving	Suspension	Driving	Suspension	Driving	Suspension	Driving	Suspension

Complexity increases in this direction

Challenging Topics in the Top-down IGCC Design

Decoupling: u to x	May be solved by state transformation and/or input transformation, but the information needed for the transformation is often with uncertainties
Time-varying control limitation	Not only time-varying, the input-output relation may not be monotone. However, control resource should be fully utilized
Observer design	Sensor information is often not enough, parameters with large uncertainties, some quantities are time-varying but assumed to be constant
Control redundancy	The number of control inputs is more than the number of the state variables to be controlled, reasonable constrains are required
On-line optimization	Problem with convergence, rate of convergence, local minimum, available sampling rate
Tire model in the loop	For high performance VDC, tire model in the control loop may be required, but a tire model for real-time applications may not be accurate enough and have uncertain parameters

Overview of TTTech Integrated Global Chassis Control



* slip control with integrated ABS/ASR functions per wheel
** suspension control with integrated leveling and active dumping functions of lower task priority
*** steering control with integrated local functions (variable steering ratio etc.)

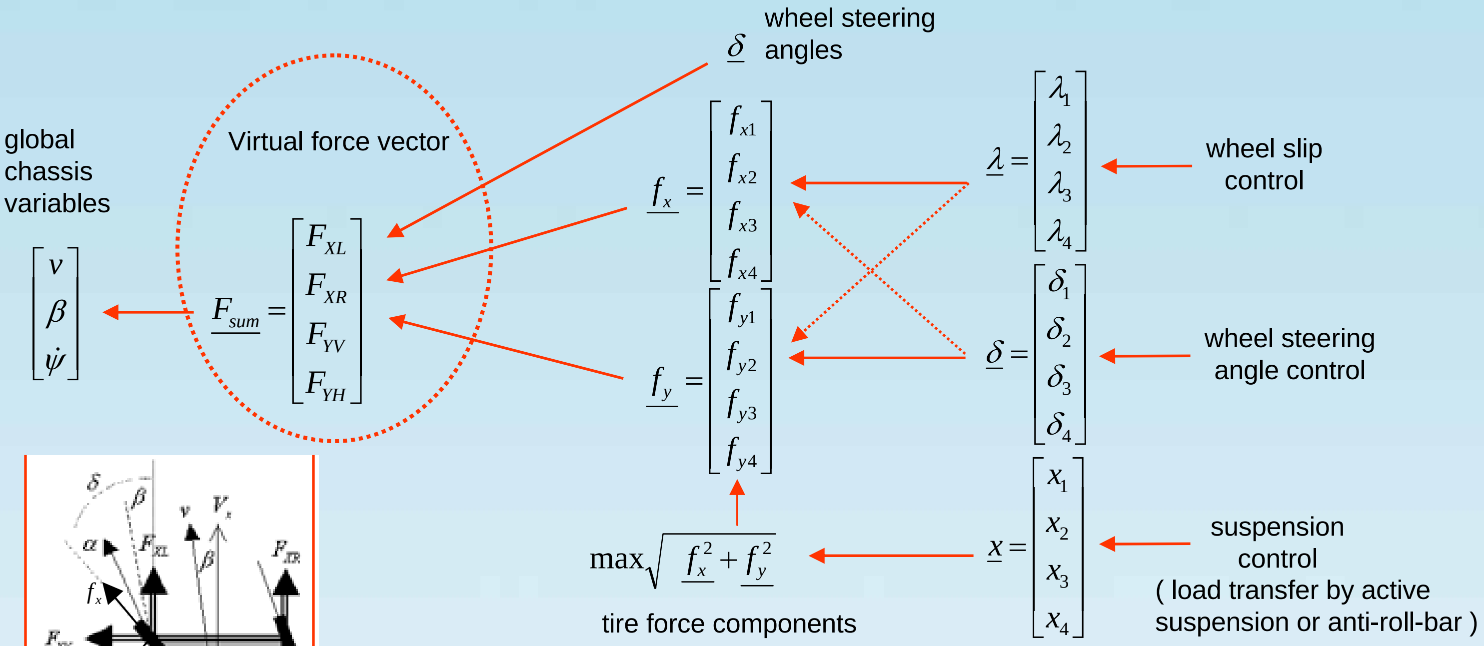
Design Specifications

Requirements of a Top-Down Design Approach

1. Using two-track non-linear vehicle model and non-linear tire model
2. Global non-linear solution (without linearization)
3. Taking into account disturbances such as road surface condition, aerodynamics and road inclination etc.
4. Actuator interventions without any interference
5. Control design needs from system ,as little information as possible
6. Clear and compact form of the solutions (matrix vector form)
7. Simple mathematics, emphasis on physics
8. Embraces many special cases published so far
9. Fast enough response time, large stability region and high control accuracy
10. Easy to implement

Vehicle Dynamics Decomposition

Vehicle Dynamics Decomposition



global chassis variables

$$\begin{bmatrix} v \\ \beta \\ \dot{\psi} \end{bmatrix}$$

Virtual force vector

$$\underline{F_{sum}} = \begin{bmatrix} F_{XL} \\ F_{XR} \\ F_{YV} \\ F_{YH} \end{bmatrix}$$

$\underline{\delta}$ wheel steering angles

$$\underline{f_x} = \begin{bmatrix} f_{x1} \\ f_{x2} \\ f_{x3} \\ f_{x4} \end{bmatrix} \quad \underline{f_y} = \begin{bmatrix} f_{y1} \\ f_{y2} \\ f_{y3} \\ f_{y4} \end{bmatrix}$$

$$\underline{\lambda} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix}$$

wheel slip control

$$\underline{\delta} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix}$$

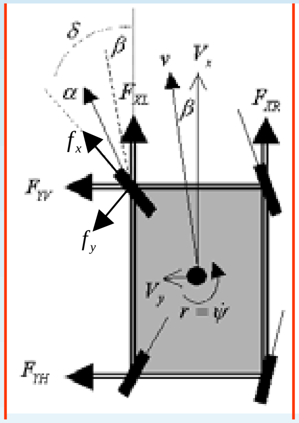
wheel steering angle control

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

suspension control
(load transfer by active suspension or anti-roll-bar)

$$\max \sqrt{\underline{f_x}^2 + \underline{f_y}^2}$$

tire force components



$$\underline{F_{sum}} = A_x(\underline{\delta})\,\underline{f_x} + A_y(\underline{\delta})\,\underline{f_y}$$

local control systems

actuator control

IGCC Design Procedures

1. Non-linear robust control of $v, \beta, \dot{\psi}$ by proper designed virtua force vector $\underline{F}_{sum} = [F_{XL} \quad F_{XR} \quad F_{YV} \quad F_{YH}]^T$

$$\underline{s} = \begin{bmatrix} m(v - v_d) \\ m(\beta - \beta_d) \\ J(r - r_d) \end{bmatrix}$$

$$\underline{s}^* = A^T \underline{s} \qquad A^T = \ldots$$

$$\underline{F}_{sum} = f\left(\underline{s}^*\right)$$

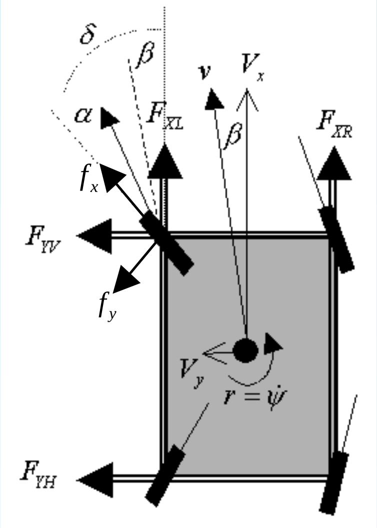
- *two-track non-linear vehicle model-based control design*
- *robust with respect to aerodynamics and road inclination etc.*
- *very simple control structure for real-time implementation*

2. Distribution of the resulting virtual-force-vector to the horizontal tire force components

- *implementation of 4 virtual force components by 8 tire force components*
- *very simple calculation without on-line matrix inverse, i.e. pseudo-inverse*

$$\underline{f}_x^* = f\left(A_x, \underline{F}_{sum}\right) \qquad A_x(\underline{\delta}) \in R^{4 \times 4}$$

$$\underline{f}_y^* = f\left(A_y, \underline{F}_{sum}\right) \qquad A_y(\underline{\delta}) \in R^{4 \times 4}$$

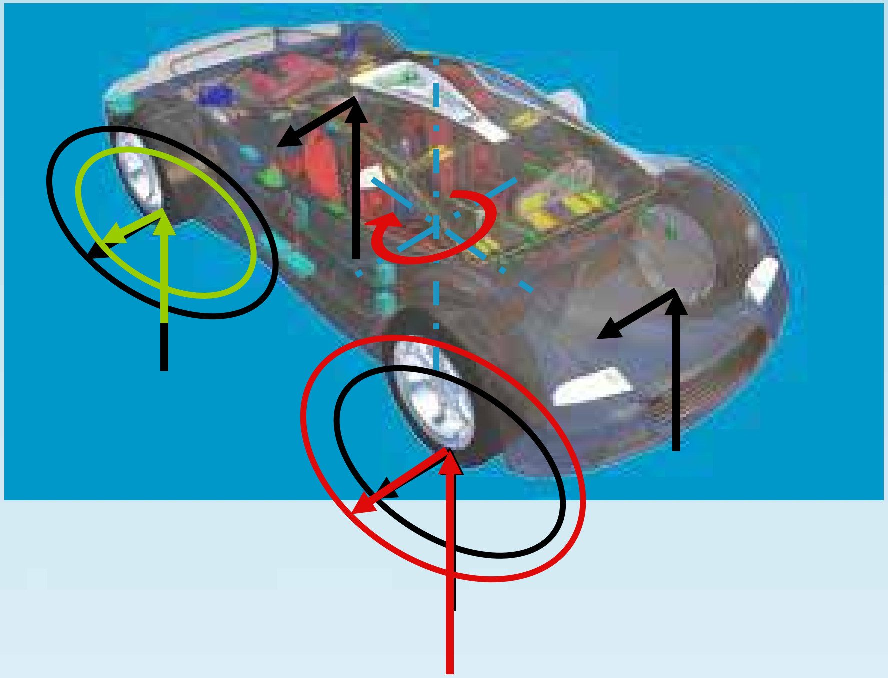


IGCC Design Procedures (cont.)

3. Control of the suspension system to ensure the magnitude (capacity) of the required horizontal tire forces – vertical load control (VLC)

Active load distribution

- *conventional: passive load distribution without control*
- *builds up higher forces where needed*
- *reduces forces where they are not desired*
- *increases handling performance and stability range*



- the vertical load at each of the 4 corners will be adjusted

- all required horizontal tire force vectors will reside in their corresponding friction circle

- considering the load transfer under non-linearity of tires

- works for both pro-cornering and contra-cornering cases automatically

IGCC Design Procedures (cont.)

4. Implementation of the required tire forces by on-line nonlinear optimization

- *estimation of the tire forces using a simplified non-linear tire model*
- *inversing tire model by Sliding Mode optimization (fast convergence)*

Forward Tire Model

Inversed Tire Model

5. Local wheel slip and wheel steering angle control to ensure the desired tire force components

- *robust wheel- slip control with on-line perturbation compensation*
- *control of the active steering motors to ensure the required wheel steering angles*

IGCC Design Procedures (cont.)

6. Vehicle state observer (VSO)

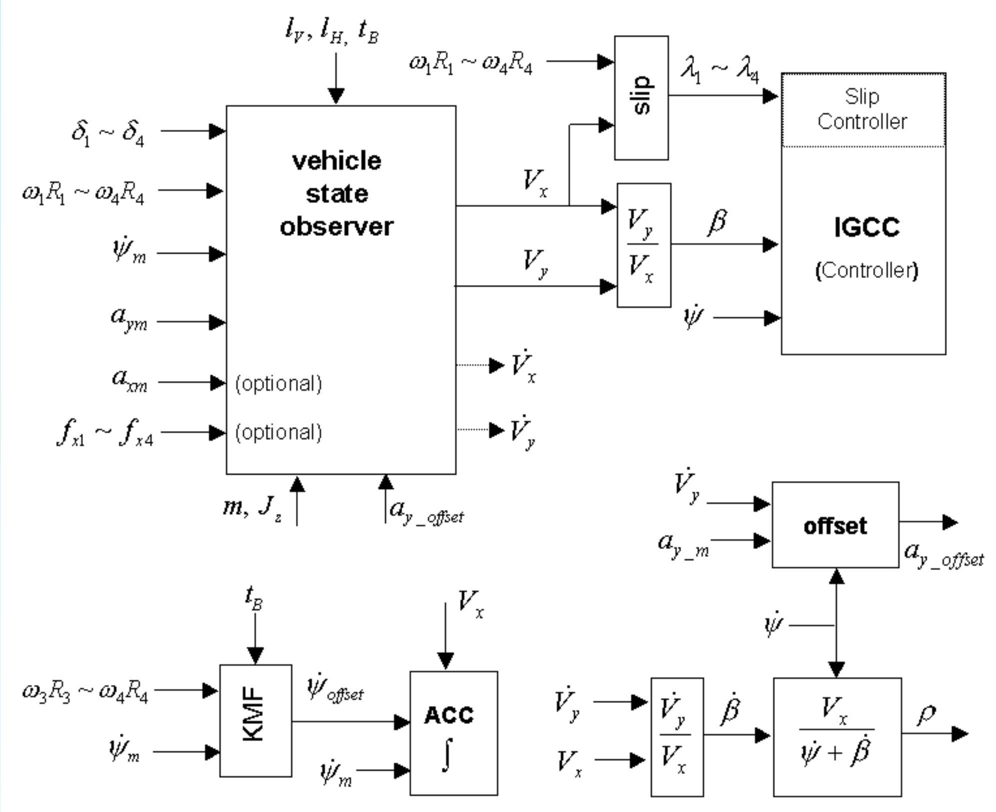
- *design based on a two-track vehicle model (valid for non-linear region of tires)*
- *global convergence proven*
- *on-line cornering stiffness adaptation*
- *works for lateral acceleration close to 1.0g*
- *works for road μ close to 0.1*
- *sample time at least 10ms*
- *tested with large number of driving data*

observed internal variables

$$f_{zi},\ f_{xi},\ f_{yi},\ C_{\alpha i}(t),\ \alpha_i$$

$$i = 1 \sim 4$$

VSO structure



VSO project co-operated with MAGNA STEYR Fahrzeugtechnik AG & Co KG, Graz, Austria

Vehicle Dynamics Model in Simulink

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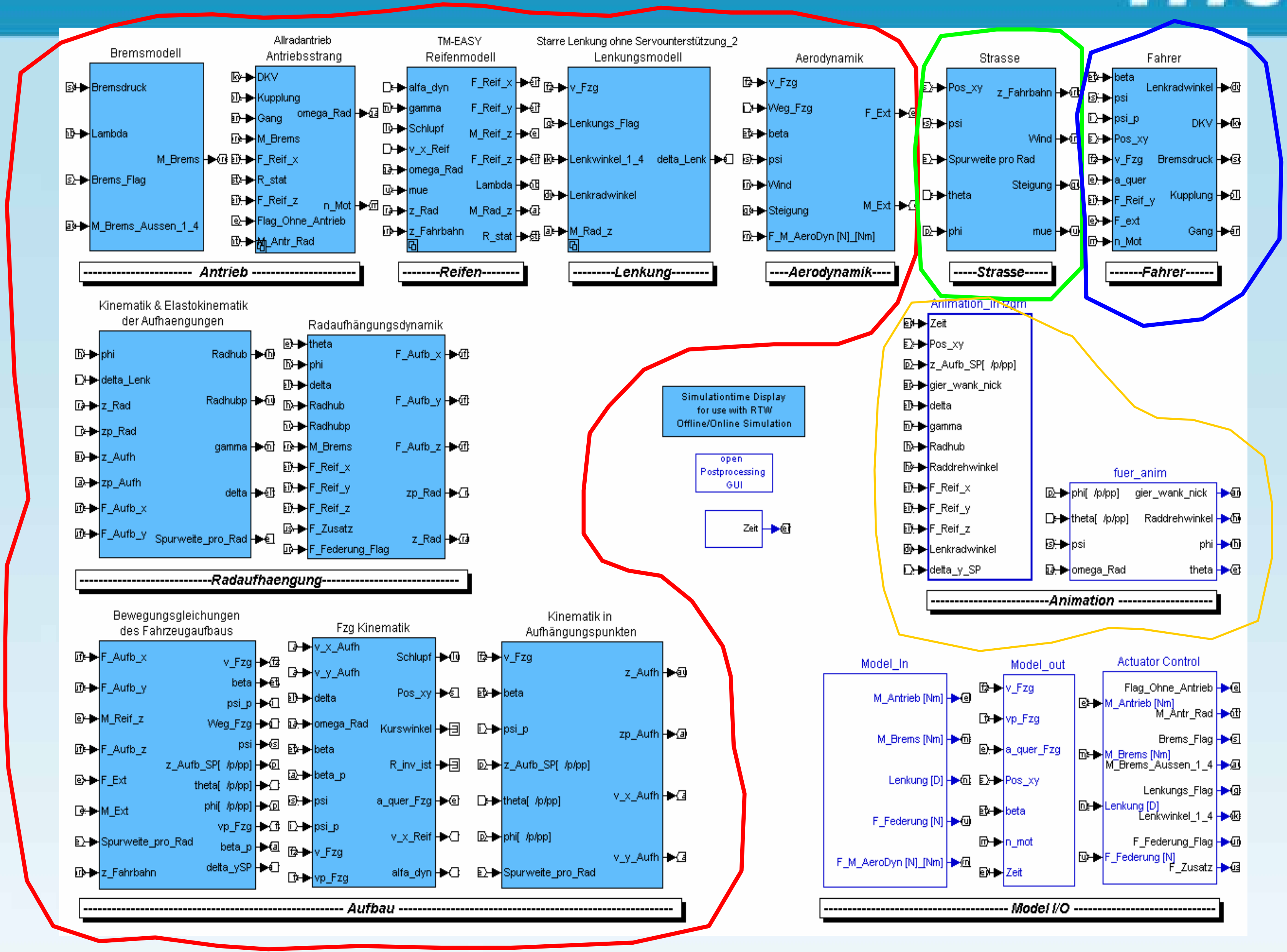
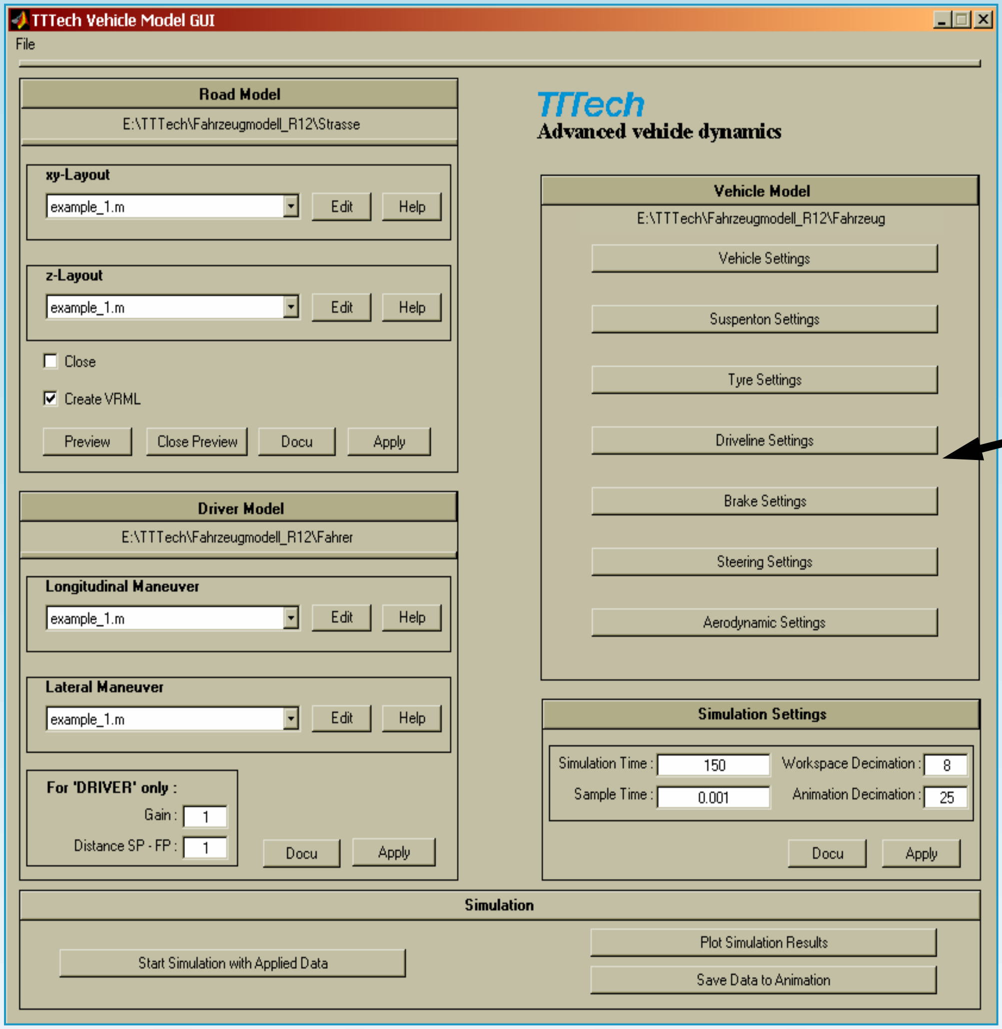


Simulation Control

Definition of road properties

Definition of driver properties

Configuration of vehicle components



TTTech Vehicle Model GUI

Road Model

E:\TTTech\Fahrzeugmodell_R12\Strasse

xy-Layout: example_1.m

z-Layout: example_1.m

☐ Close

☑ Create VRML

Driver Model

E:\TTTech\Fahrzeugmodell_R12\Fahrer

Longitudinal Maneuver: example_1.m

Lateral Maneuver: example_1.m

For 'DRIVER' only :

Gain : 1

Distance SP - FP : 1

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Advanced vehicle dynamics

Vehicle Model

E:\TTTech\Fahrzeugmodell_R12\Fahrzeug

Simulation Settings

Simulation Time : 150

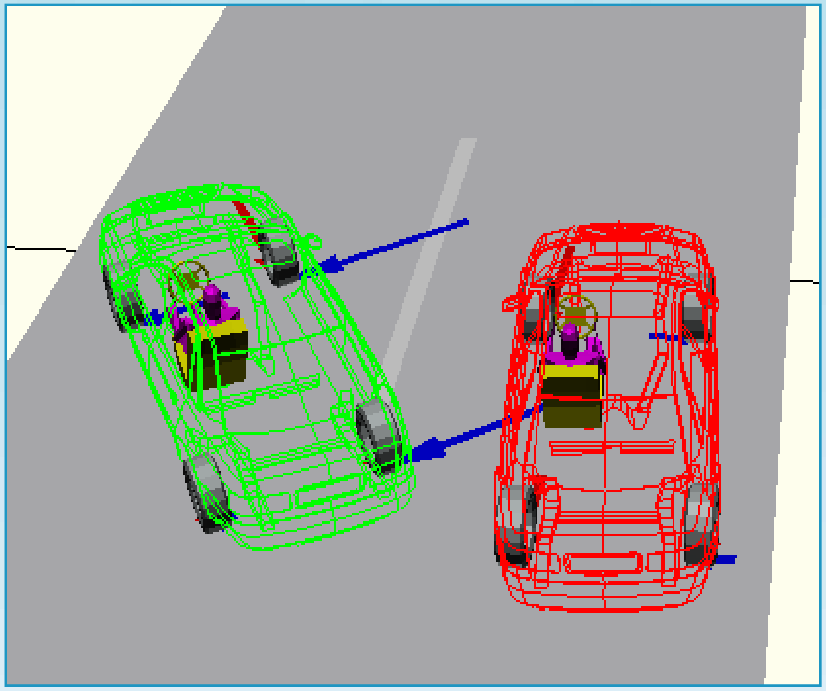
Sample Time : 0.001

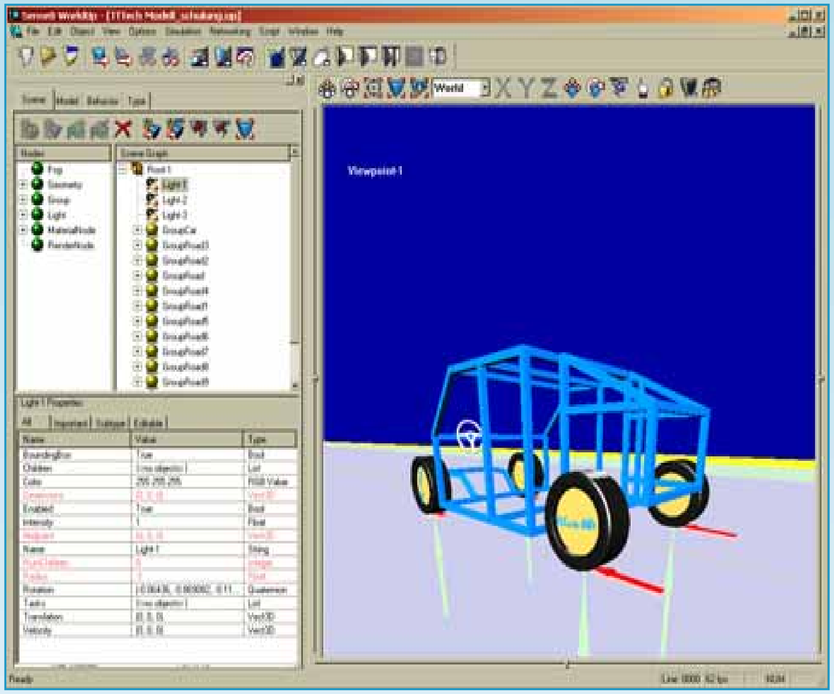
Workspace Decimation : 8

Animation Decimation : 25

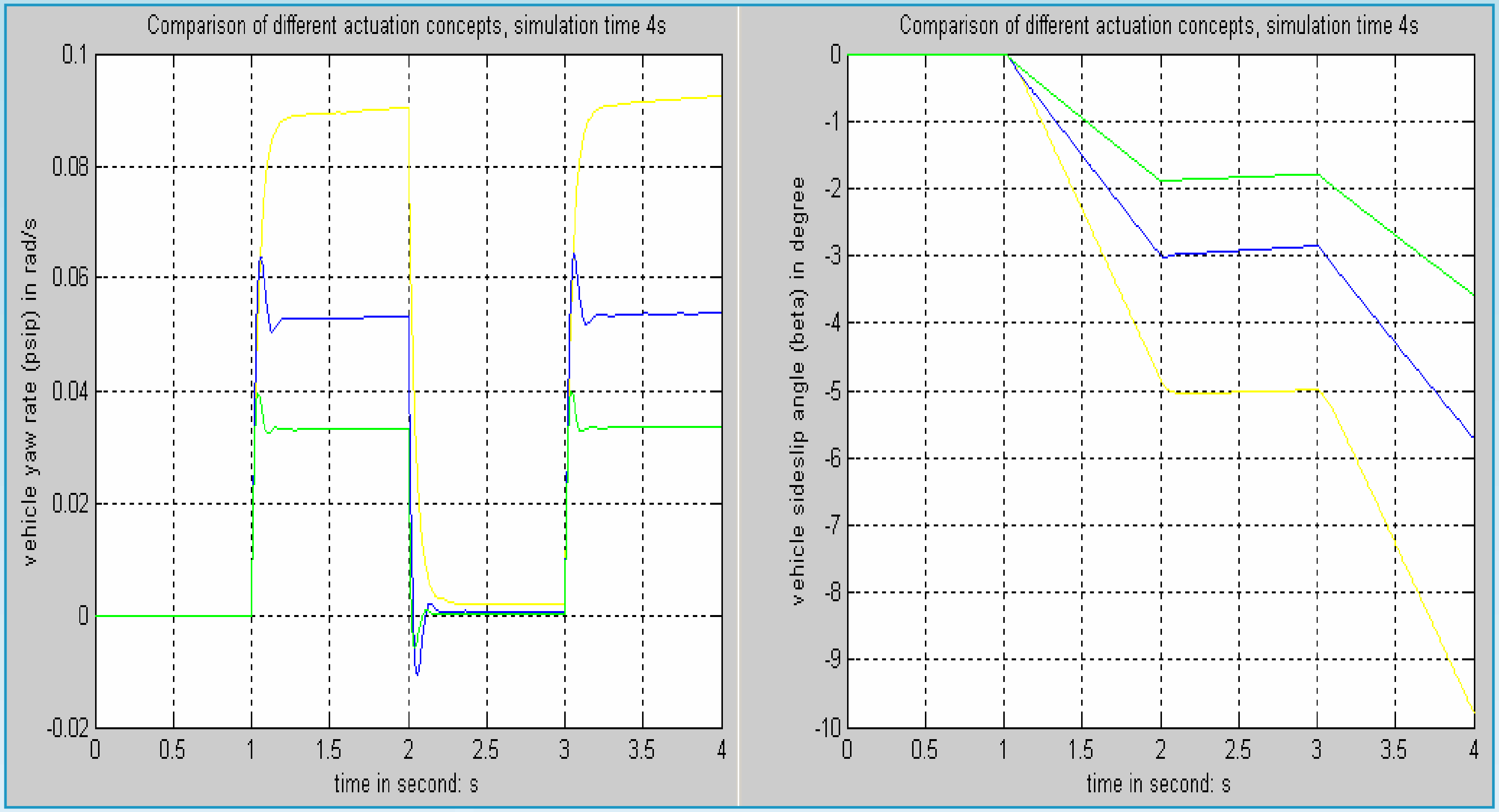
Simulation

Animation Tools





Simulation Results of IGCC

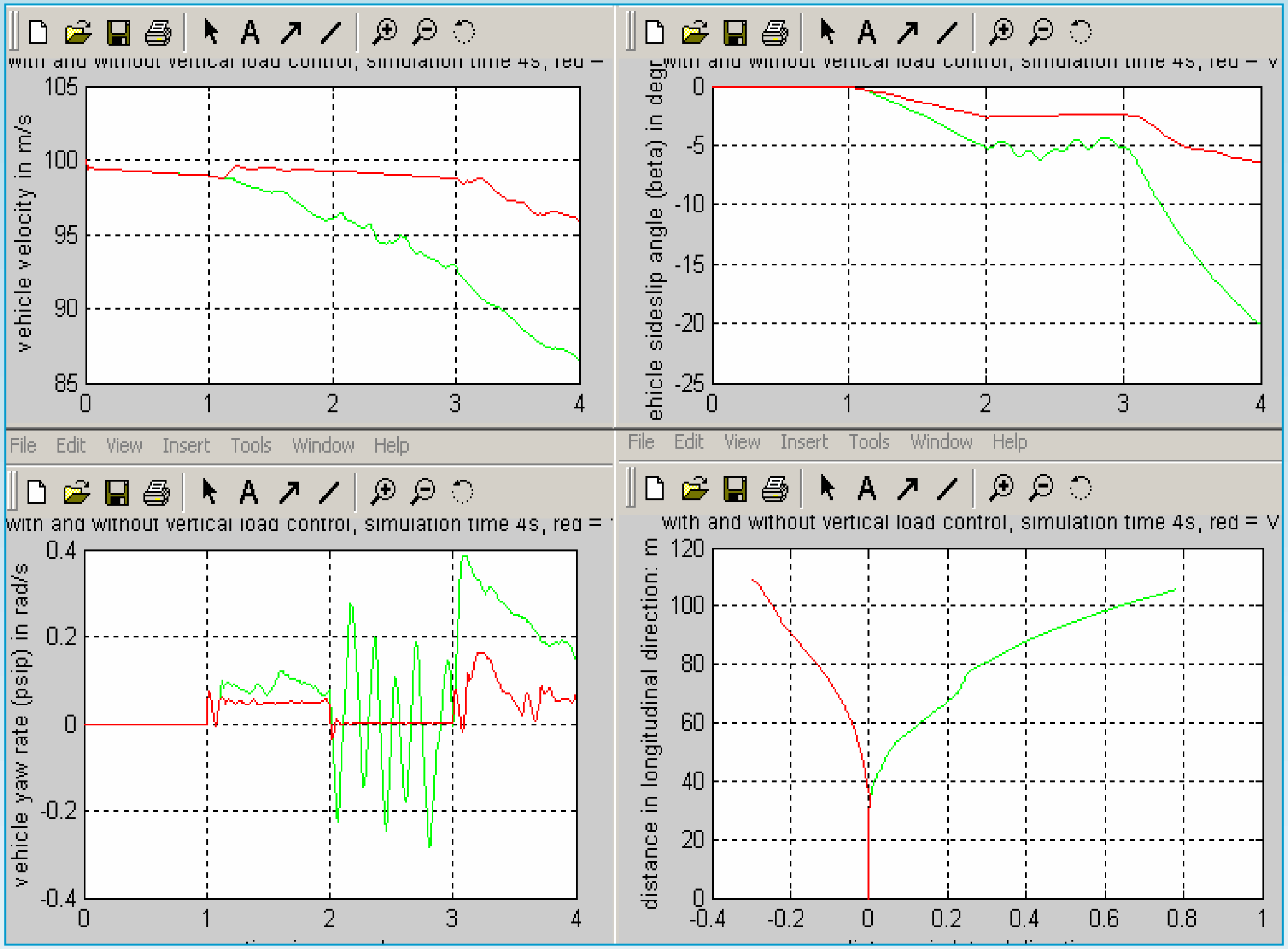


yaw rate & slip angle

blue: with 4WS control; yallow: with drive/brake control;
green: with drive/brake & 4WS control;

Applied torque disturbance: Mz_dist = +5000 Nm during 1s~2s and 3s~4s; v_Fzg(0)=100 km/h; Mu = 0.8

Simulation Results of IGCC (cont.)

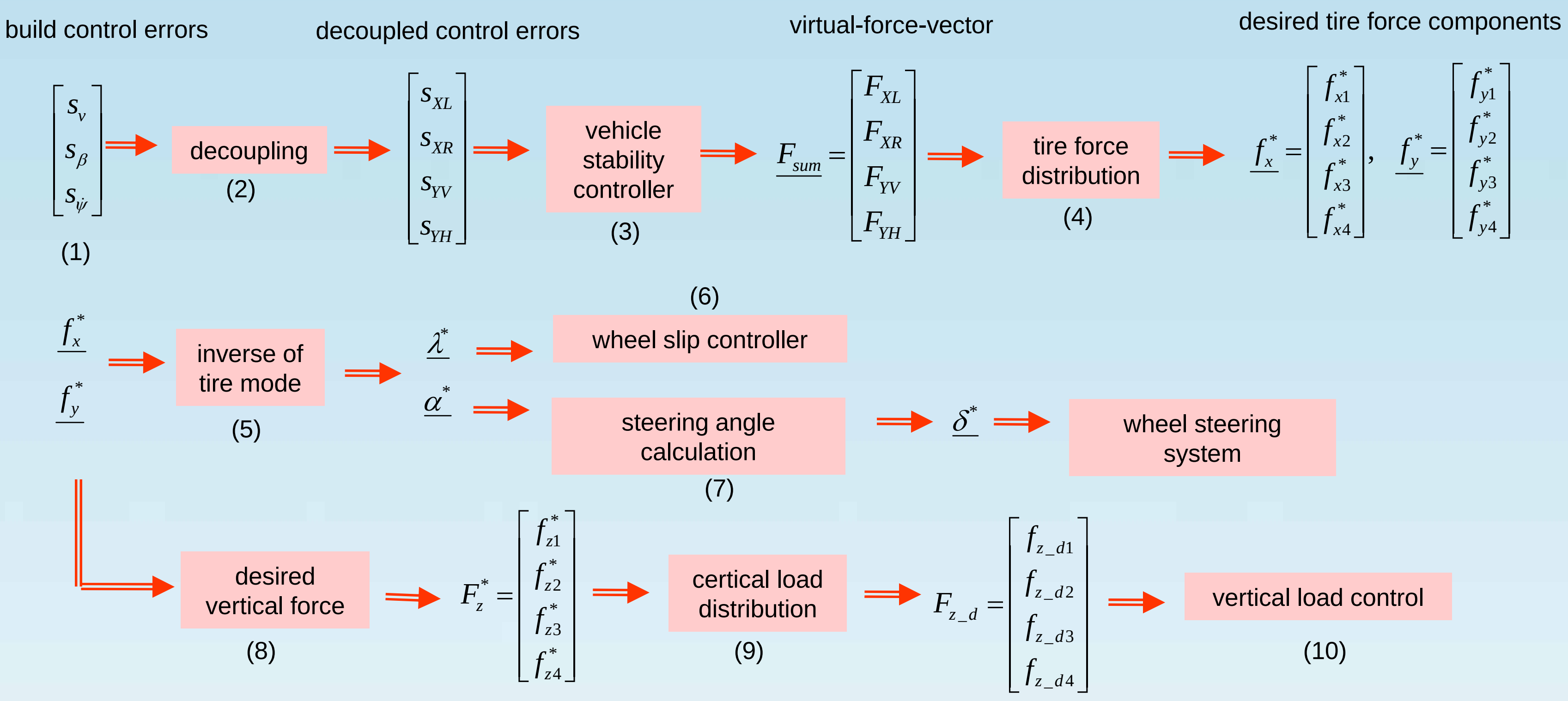


green: with drive/brake & 4WS control;

red: with drive/brake & 4WS control + VLC (vertical load control);

Torque disturbance Mz_dist was applied during 1s~2s and 3s~4s, with v_Fzg(0)=100 km/h, Mu = 0.8, Mz_dist = 16250 Nm

Summary of Overall Control System



build control errors

$$\begin{bmatrix} s_v \\ s_\beta \\ s_{\dot{\psi}} \end{bmatrix}$$

(1)

decoupling

(2)

decoupled control errors

$$\begin{bmatrix} s_{XL} \\ s_{XR} \\ s_{YV} \\ s_{YH} \end{bmatrix}$$

vehicle stability controller

(3)

virtual-force-vector

$$\underline{F_{sum}} = \begin{bmatrix} F_{XL} \\ F_{XR} \\ F_{YV} \\ F_{YH} \end{bmatrix}$$

tire force distribution

(4)

desired tire force components

$$\underline{f_x^*} = \begin{bmatrix} f_{x1}^* \\ f_{x2}^* \\ f_{x3}^* \\ f_{x4}^* \end{bmatrix}, \quad \underline{f_y^*} = \begin{bmatrix} f_{y1}^* \\ f_{y2}^* \\ f_{y3}^* \\ f_{y4}^* \end{bmatrix}$$

$\underline{f_x^*}$

$\underline{f_y^*}$

inverse of tire mode

(5)

$\underline{\lambda^*}$

$\underline{\alpha^*}$

(6)

wheel slip controller

steering angle calculation

(7)

$\underline{\delta^*}$

wheel steering system

desired vertical force

(8)

$$F_z^* = \begin{bmatrix} f_{z1}^* \\ f_{z2}^* \\ f_{z3}^* \\ f_{z4}^* \end{bmatrix}$$

certical load distribution

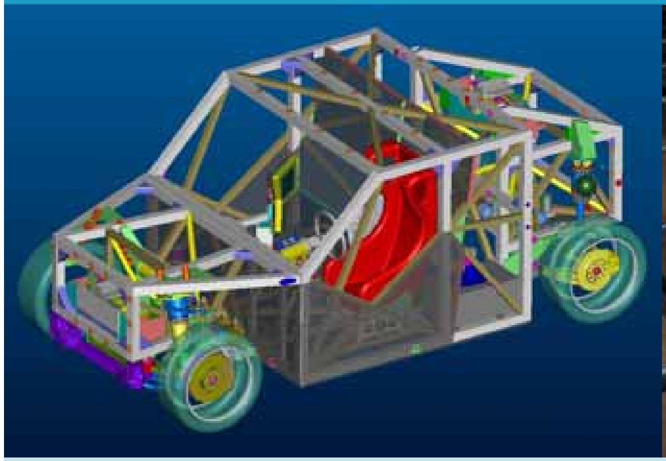
(9)

$$F_{z\_d} = \begin{bmatrix} f_{z\_d1} \\ f_{z\_d2} \\ f_{z\_d3} \\ f_{z\_d4} \end{bmatrix}$$

vertical load control

(10)

Conclusion



- Unified control design concept
- Valid for non-linear region of tires
- Robustness with respect to system disturbances
- Stability/convergence proven
- Embraces many special cases published so far
- Easy to implement