Active Rear Wheel Steering

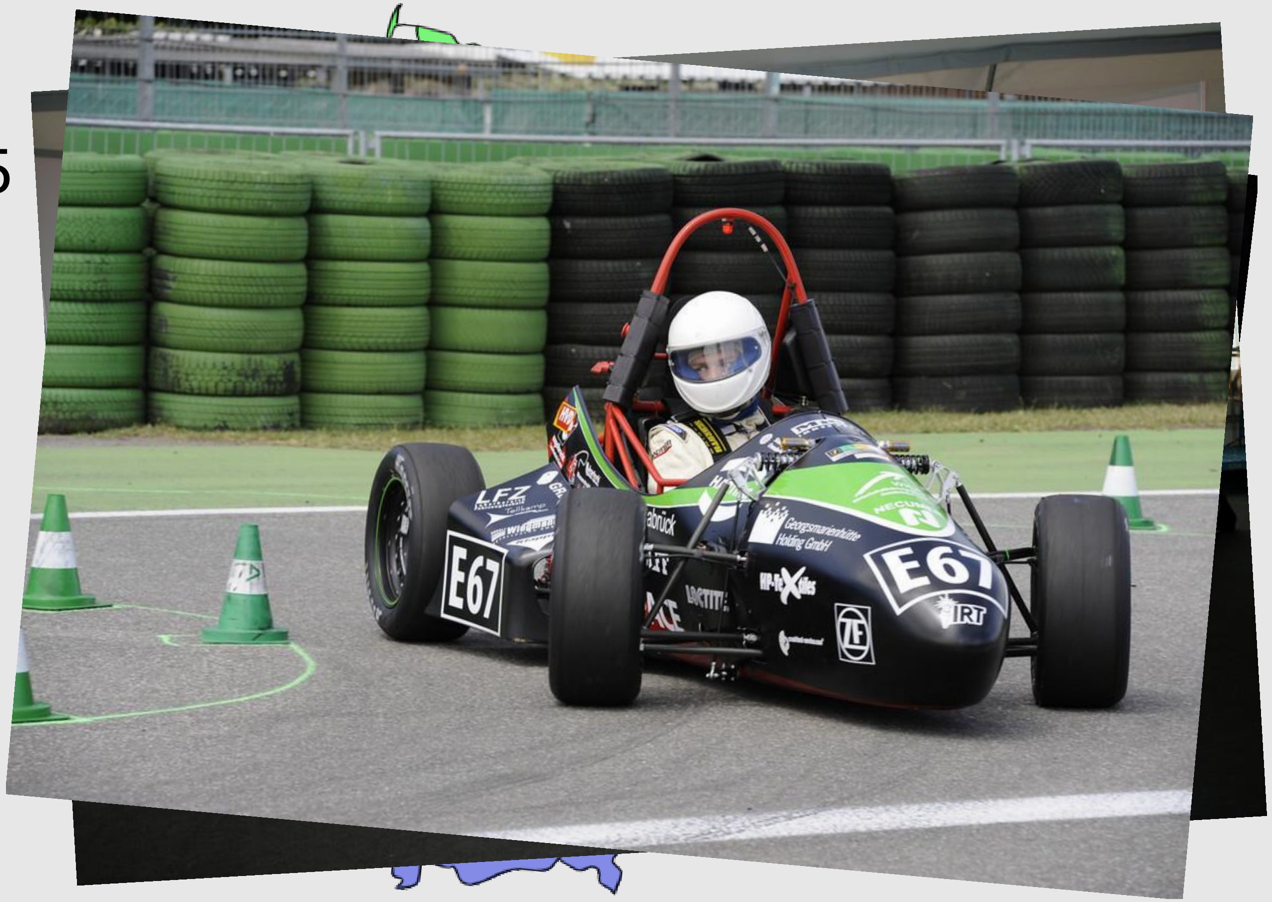
Torben Brockhage, Ignition Racing Team electric
Philipp Bergmann, Ignition Racing Team electric

Structure

- Introduction of the team and the car
- Motivation to develop rear wheel steering
- Mechanical realization
- Electric drivetrain
- Vehicle dynamics and simulation
- Control systems and software
- Results

Ignition Racing Team eletric

- FSE team from the UAS Osnabrück
- 45 active team members in 2014/2015
- First participation FSC 2007
- Since 2011 participation in FSE



IR15 eXcess

- 5th electric car
- 225 kg overall
- Single motor at rear axle (YASA 750)
- Full-carbon fiber monocoque
- 378 V, 6.6 kWh Lithium-Polymer accumulator
- Only car using Rear Wheel Steering (RWS) at FSG and FSS 2015

Motivation to develop Rear Wheel Steering

- Improving the lateral dynamics of the car
- Active changes in vehicles performance possible
- System weight is quite low (only 3 kg overall)
- System is easy exchangeable
- Innovation in Formula Student

First Task: name the system – find cool acronym

4-wheel

steering system

moving

cool

fancy

adaptive

active

stear4fear

electrical

toe correction

rear wheel

mechatronic

Active Steering System (ASS)

First Task: name the system – find cool acronym

4-wheel

steering system

moving

cool

adaptive

…ncy

active

stea…ear

electrical

toe correction

rear wheel

mechatronic

excess

got nice

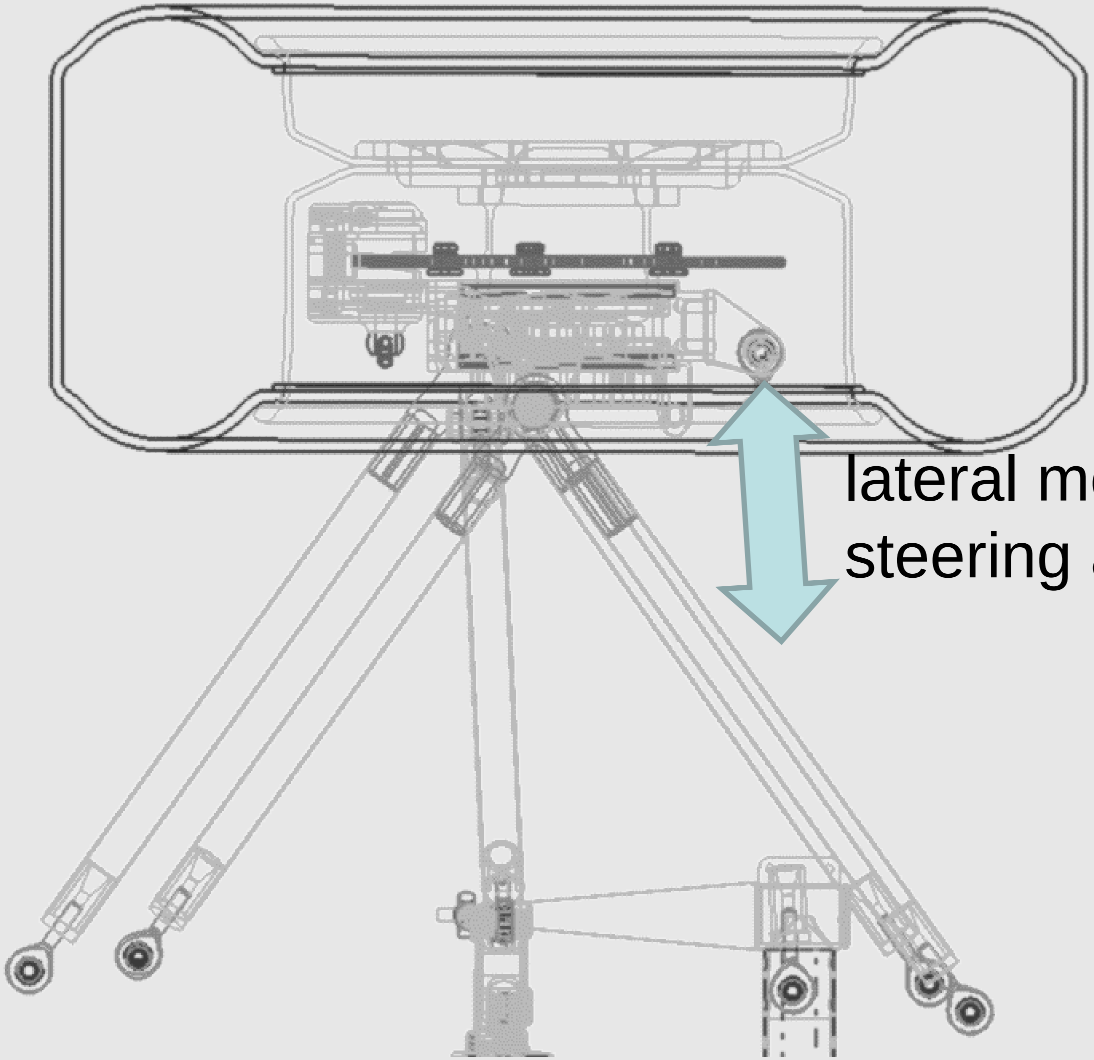
ASS

Active Steering System (ASS)

Concept

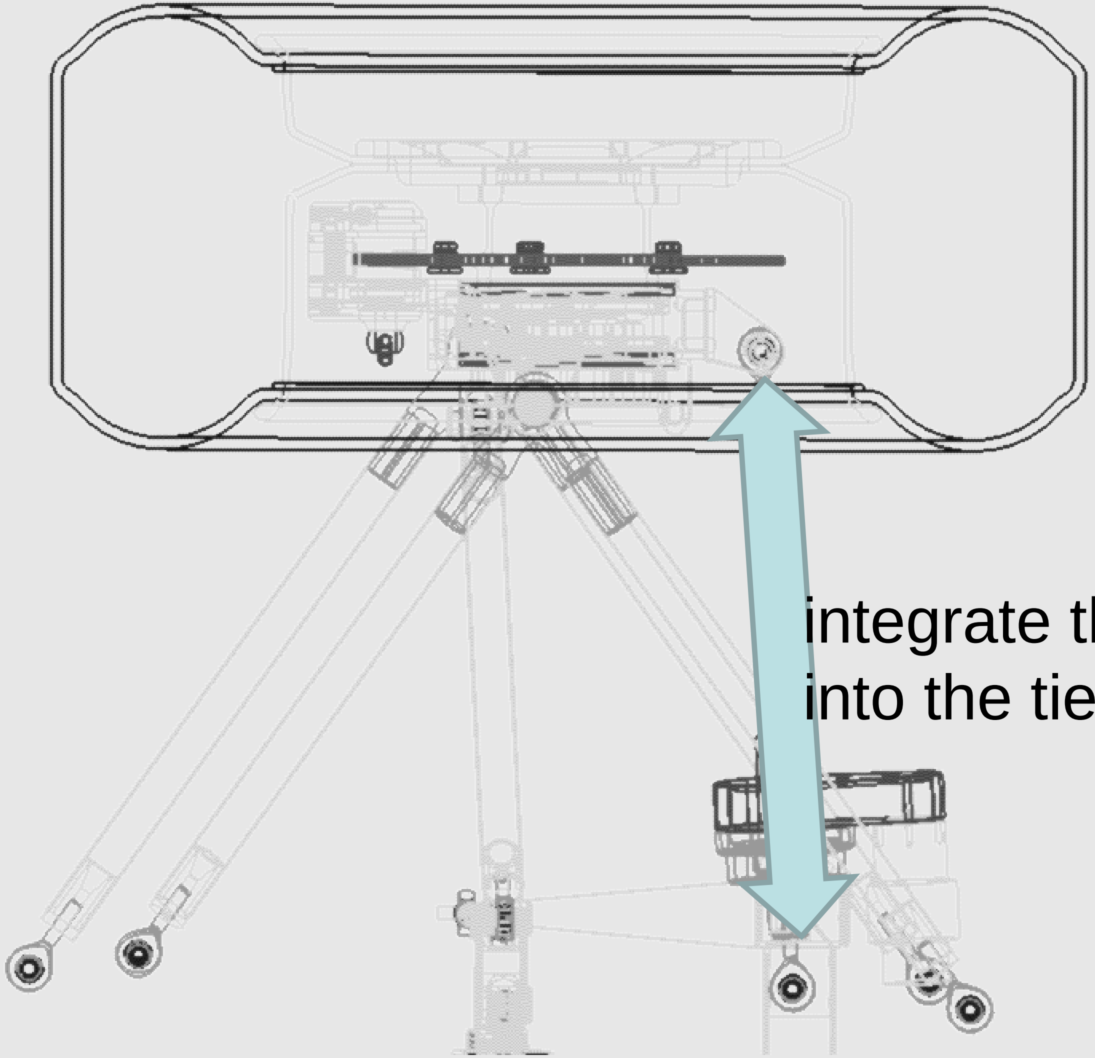
- Goal: actuator steers the rear axle (± 3 ° allowed)

Concept



lateral movement of the steering arm

Concept



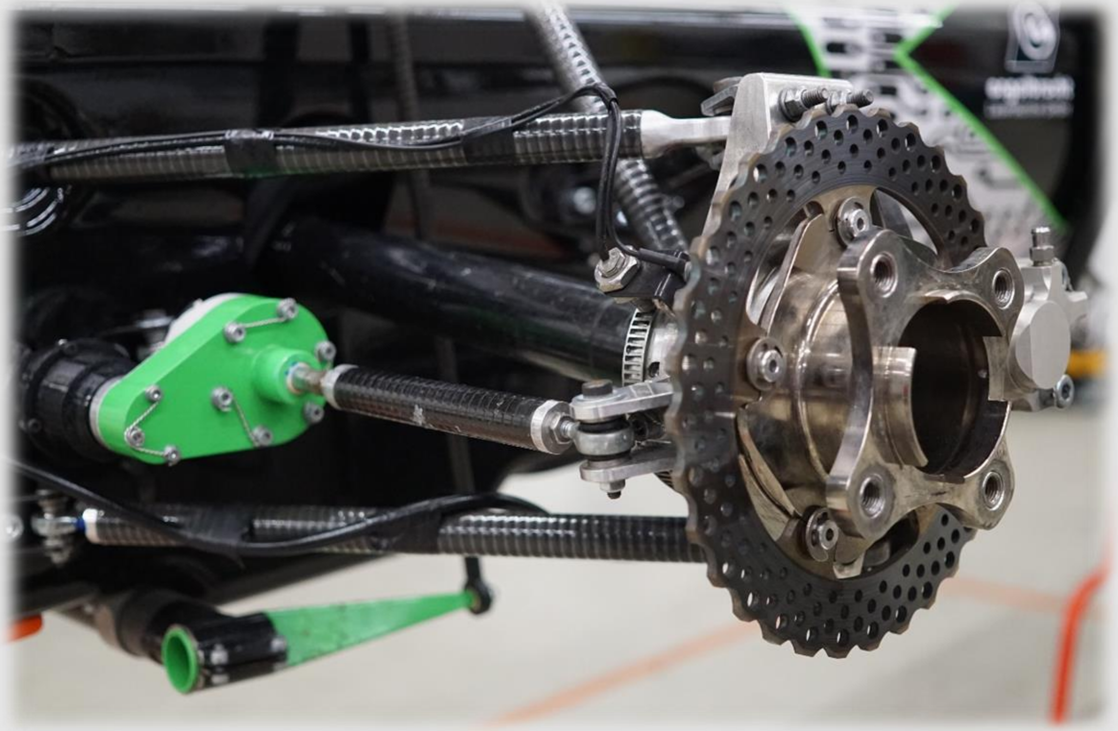
integrate the actuator into the tie rod

Concept Decisions

- Goal: actuator steers the rear axle (± 3 ° allowed)
- One actuator per wheel
- Integrate the actuator into the tie rod
- Driven by electric motor

Mechanical Requirements

- Transform rotary movement from the motor in linear movement
- Self-locking in case of system failure
- Small weight and small volume
- Fit actuators into the rest of the suspension

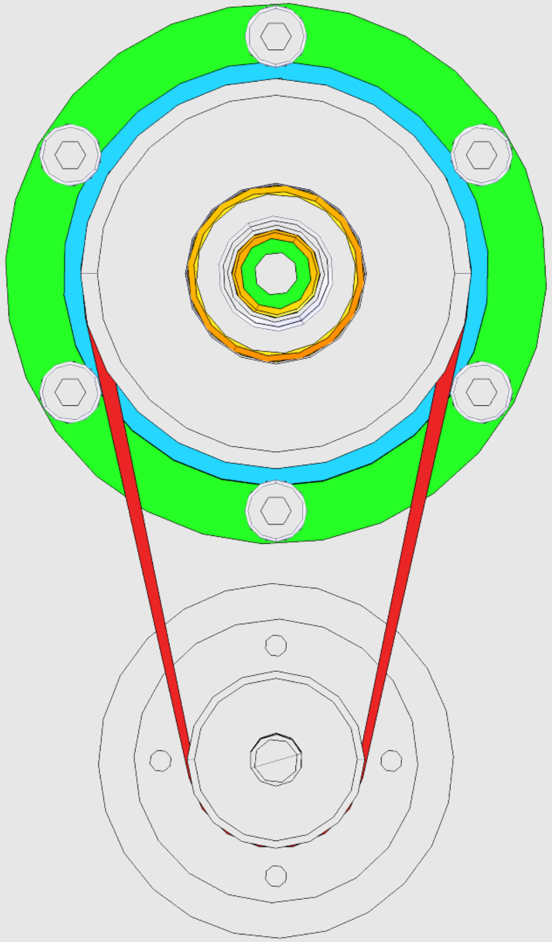


The Trapezoidal Thread Spindle

- Transform rotary in linear movement
- Small lead angle
    - self-locking
- Special nitriding steel
    - reduced wear
    - constant friction coefficient

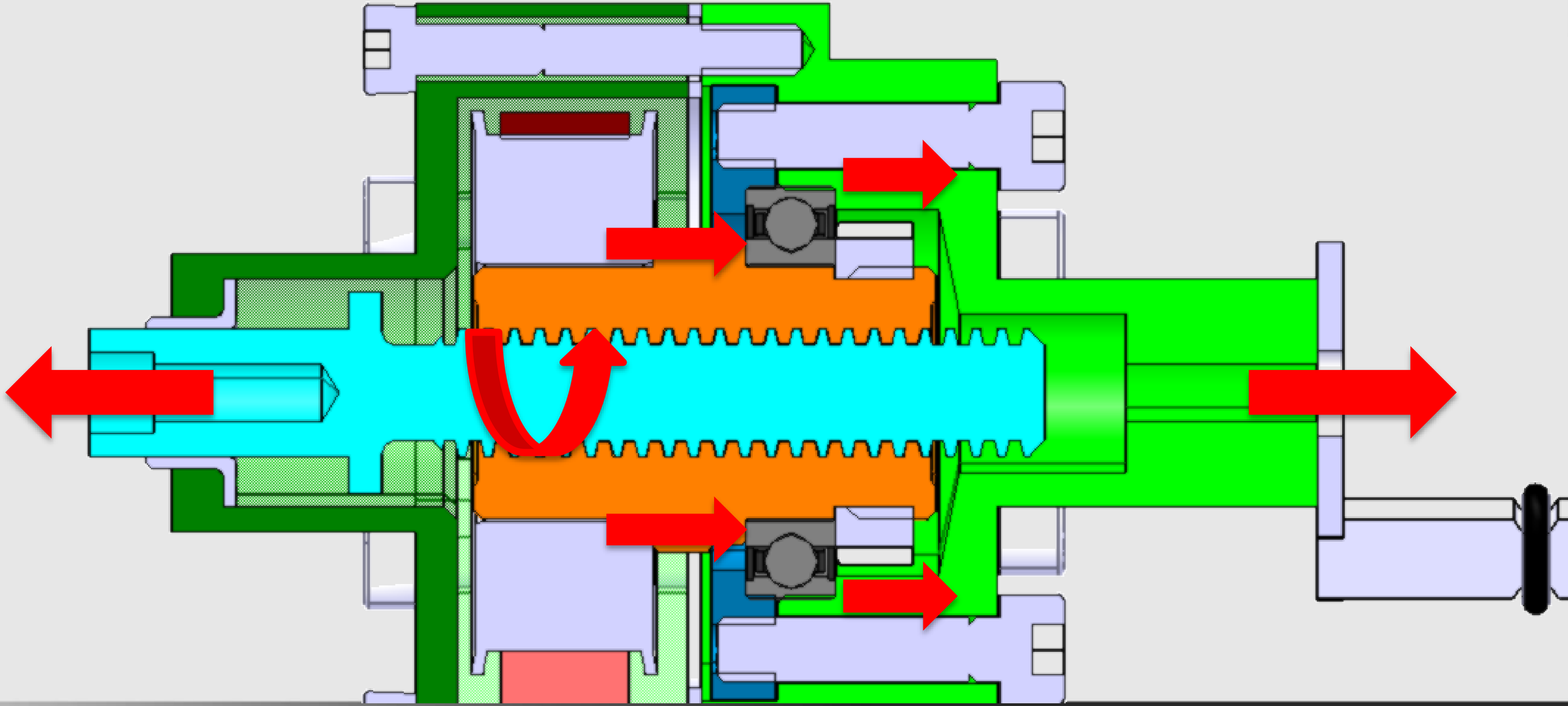
Realization of the Actuator – Belt Drive

- Transmits the torque from the motor to the spindle nut
- Transmission ratio 1:2
- Decouples the motor from the linear forces



A Sectional Drawing of the Actuator

- Axial forces are transferred by deep groove ball bearing



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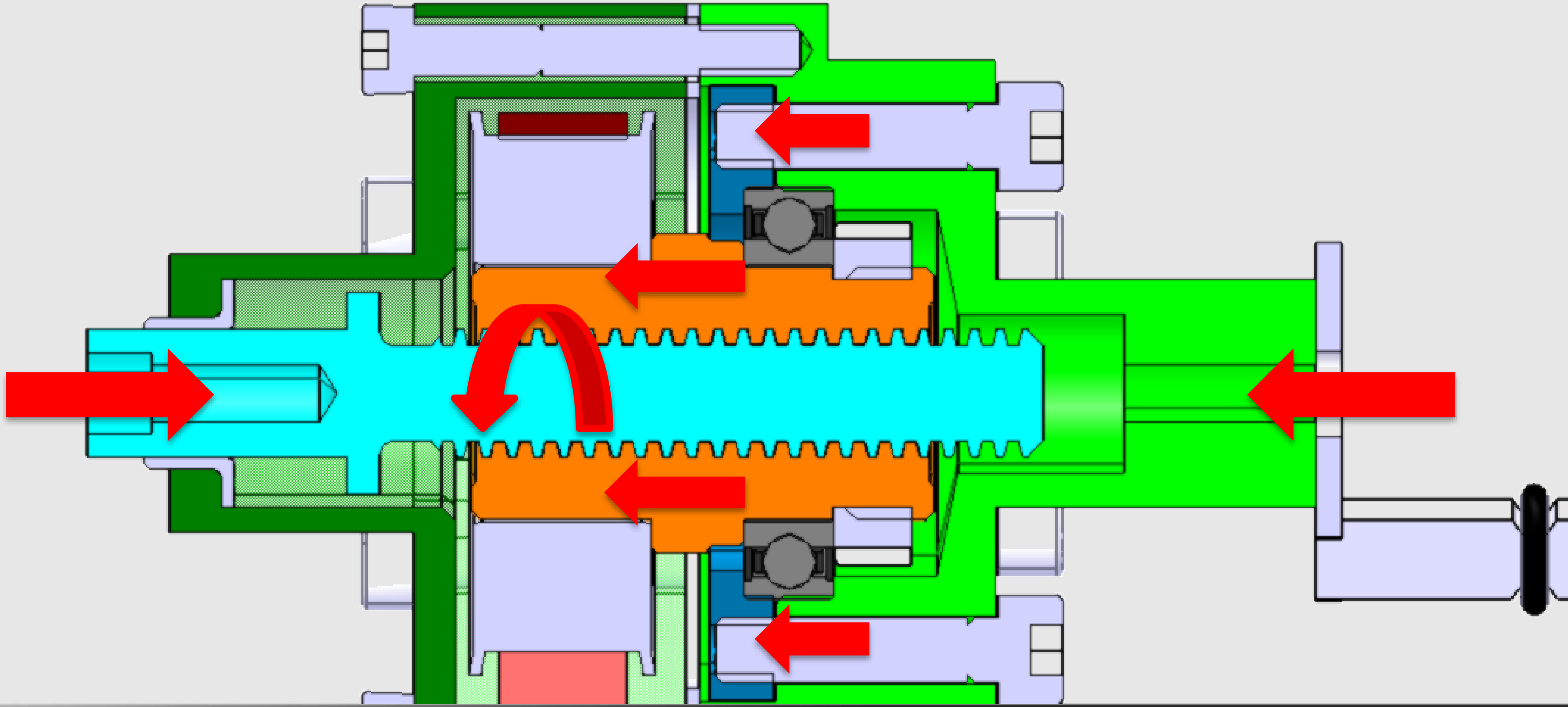
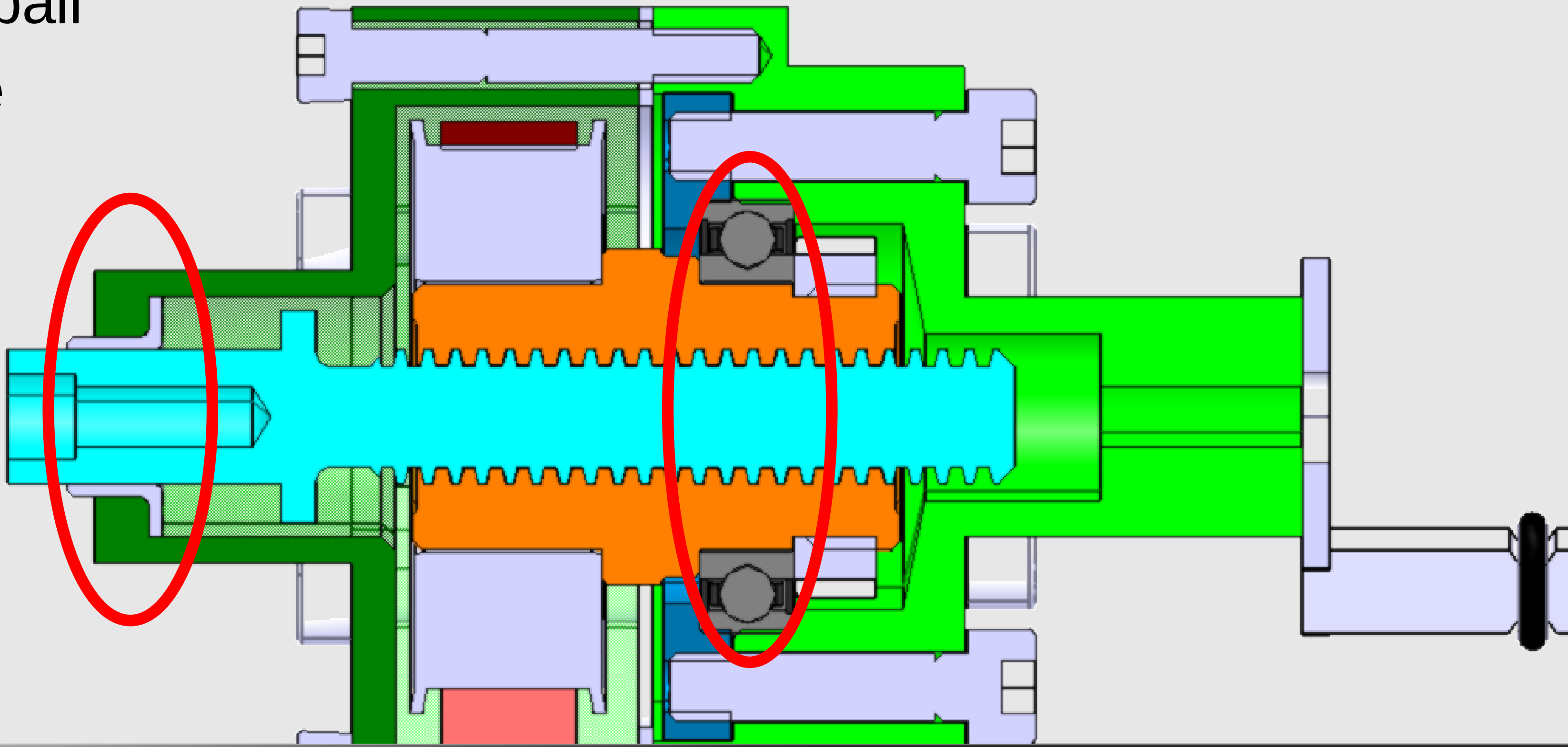


A Sectional Drawing of the Actuator

- Axial forces are transferred by deep groove ball bearing
- Fixed by locating grooved ball bearing and a floating slide bearing inside the housing
- The spindle transfers the movement to the tie rod



Electrical Drivetrain

- Max. force in the rear tie rod 1.6kN
  - Simulated in MSC Adams CAR (based on caster, align torque, max. lateral forces and steering arm length)
- Power
  - max. speed : $1200\ \frac{1}{min}$ → steer 3° in 0.2 seconds
  - max. torque:

$$M_S = \frac{F_T}{2*\pi*\eta_S} * \frac{\nabla}{1000} = \frac{1600}{2*\pi*0.3} * \frac{2}{1000} = 1.69\ Nm$$

→ Power: 187 W mechanical!

Electrical Drivetrain

- Developed own calculation program
- Includes all relevant data
- Calculates electric parameters based on mechanical parameters

IRTe Rear Wheel Steering Caluclation

Suspension Data		
Positioning-Force Wheel	1600	N
Positioning Speed:	35	mm/s
max .steer angle	3	°
steer angle / positioning way	0,425	deg/mm
Mechanical Data		
spindle gradient	1	mm
spindle efficiency	0,25	
ratio belt drive	2	
planet gear ratio	4,8	
planet gear efficiency	0,8	
Motor Data		
max. current motor controller	10	A
torque constant	0,0169	Nm/A
nominal current	2,79	A
thermic time constant winding	19,3	s
Kennliniensteigung	17500	1/min/Nm
RPM factor	565	1/min*V
Load Data		
Load cycle	0,2	
Load Time	20	min

Mechanical Calculation		
positioning way:	14,11765	mm
minium positioning speed (0,2s for 80% Travel)	28,23529	mm/s
positioning power	56	W
spindle nut speed	2100	1/min
spindle nut torque	1,018592	Nm
spindle nut power	224	W
belt drive torque	0,509296	Nm
belt drive speed	4200	1/min
planet gear torque	0,132629	Nm
planet gear speed	20160	1/min
motor speed	20160	1/min
motor torque	**0,132629**	Nm
Motor Power	280	W

eletrical calculation		
Max. Voltage	29,4	V
Nom. Voltage	25,9	V
Min. Voltage	21	V
Peak Power	476	W
Peak Current	22,66667	A
Energy Comsumption	31,73333	Wh
Capacity	1,225225	Ah
Req Voltage at Motor for act. Speed	35,68142	V
motor current	**7,847877**	A
Drop through torque	2321,01	1/min
real voltage	39,7894	V
Motor efficiency	85	%

Electrical Drivetrain

- Position controlled electric drivetrain
- Motor: Brushless DC Motor, Ø40 mm x 26 mm (170 g)
- Planetary-gearbox: 4,8:1 (118 g)
- Position encoder: 512 position per turn
- Controller: 240 W peak power per side – 10 A, 24 V (170 g)

Vehicle Dynamics

Reasons to use RWS:

- Velocity pole shifting
- Yaw control
- Side slip angle influence
- Active toe correction
- … aaannnd it is pretty cool ;-)

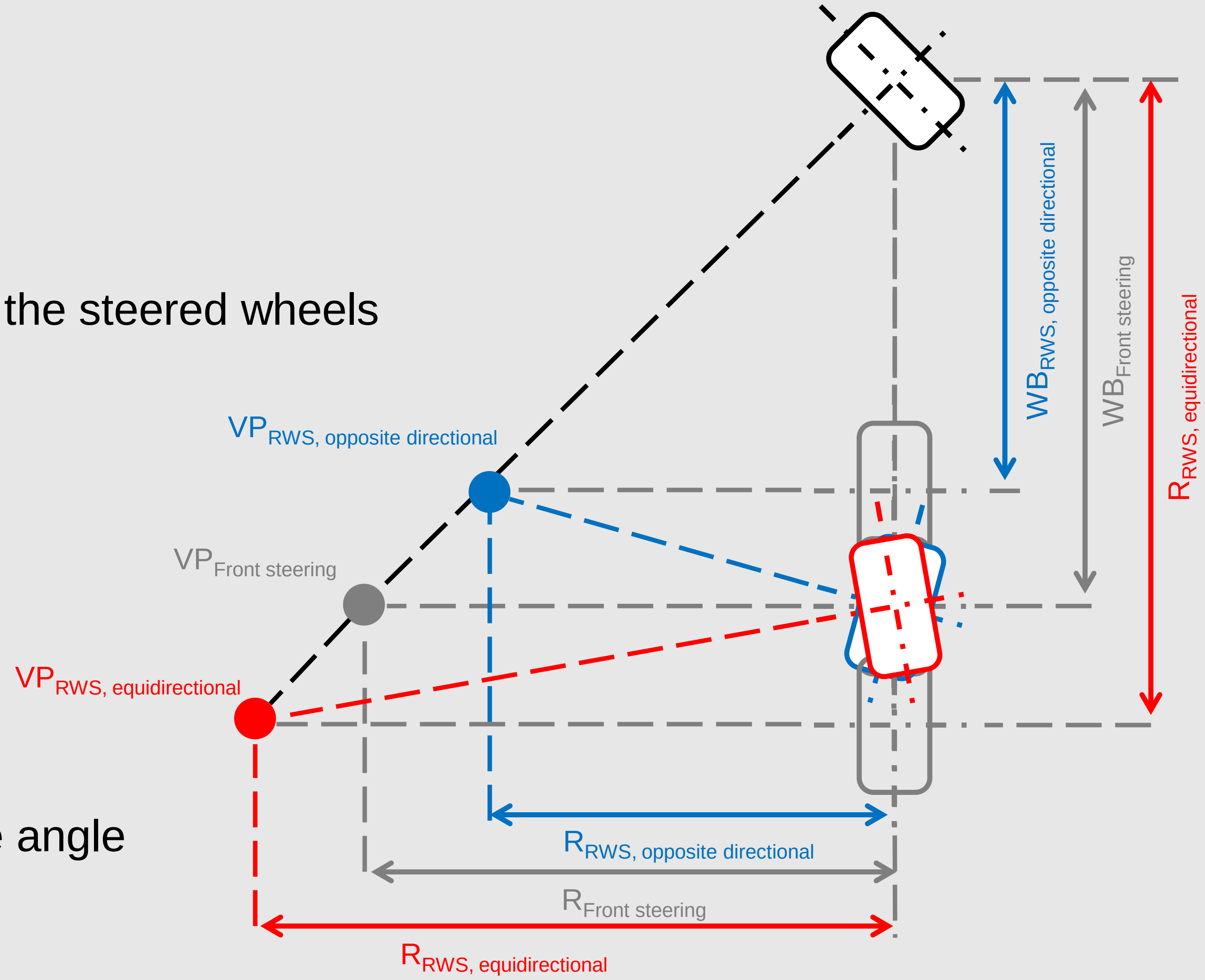
Mitschke, Wallentowitz;
Dynamik der Kraftfahrzeuge

Vehicle Dynamics

Velocity Pole Shifting:

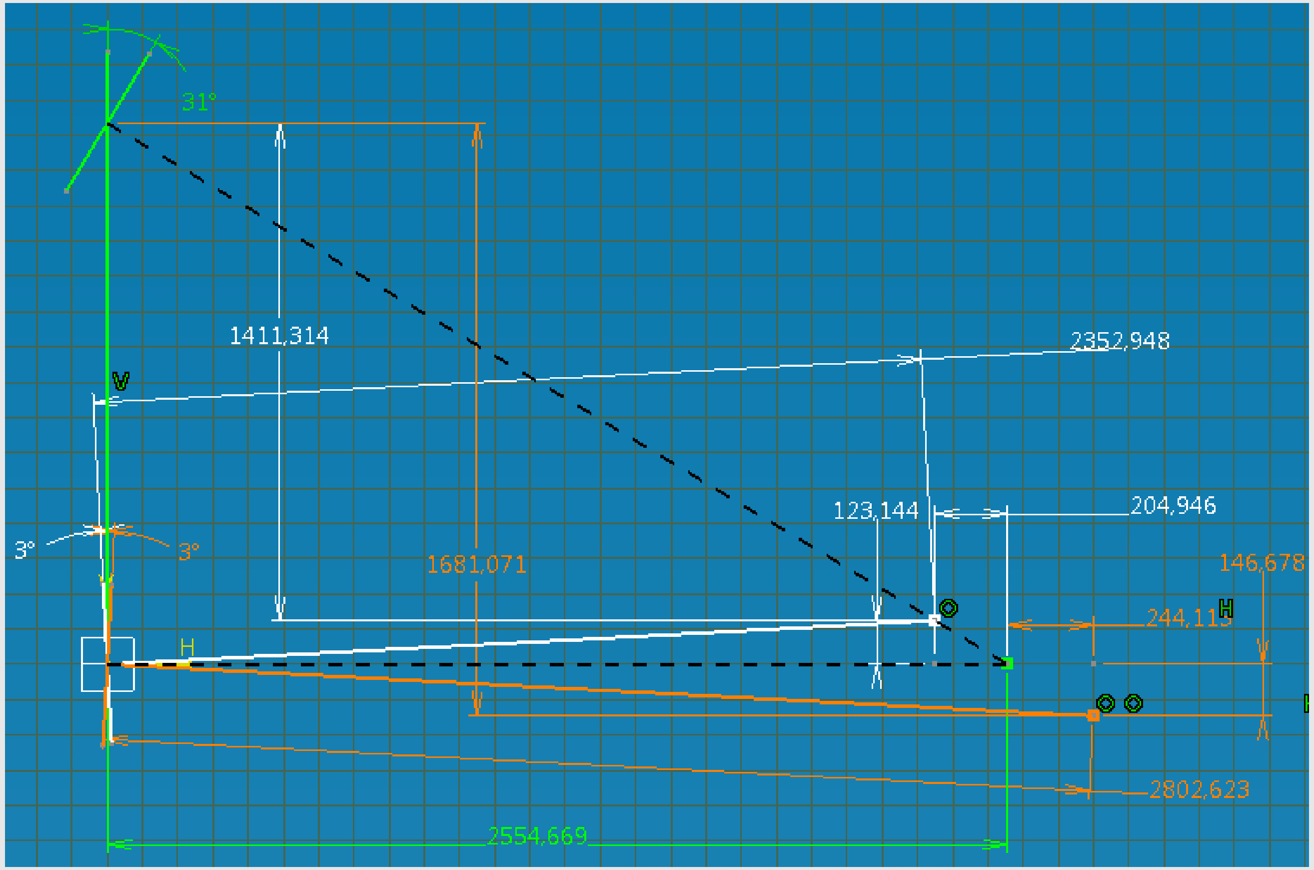
- RWS creates a virtual wheelbase
- VP: intersection of the lines based orthogonally on the steered wheels
- Steering inversely:
  - VP moves towards the front axle
  - WB and turning cycle are reduced
- Steering accordantly
  - VP moves behind the rear axle
  - WB and turning cycle are increased
- No VP when front and rear wheels steer with same angle

→ Vehicle moves parallel



Vehicle Dynamics

Velocity Pole Shifting:

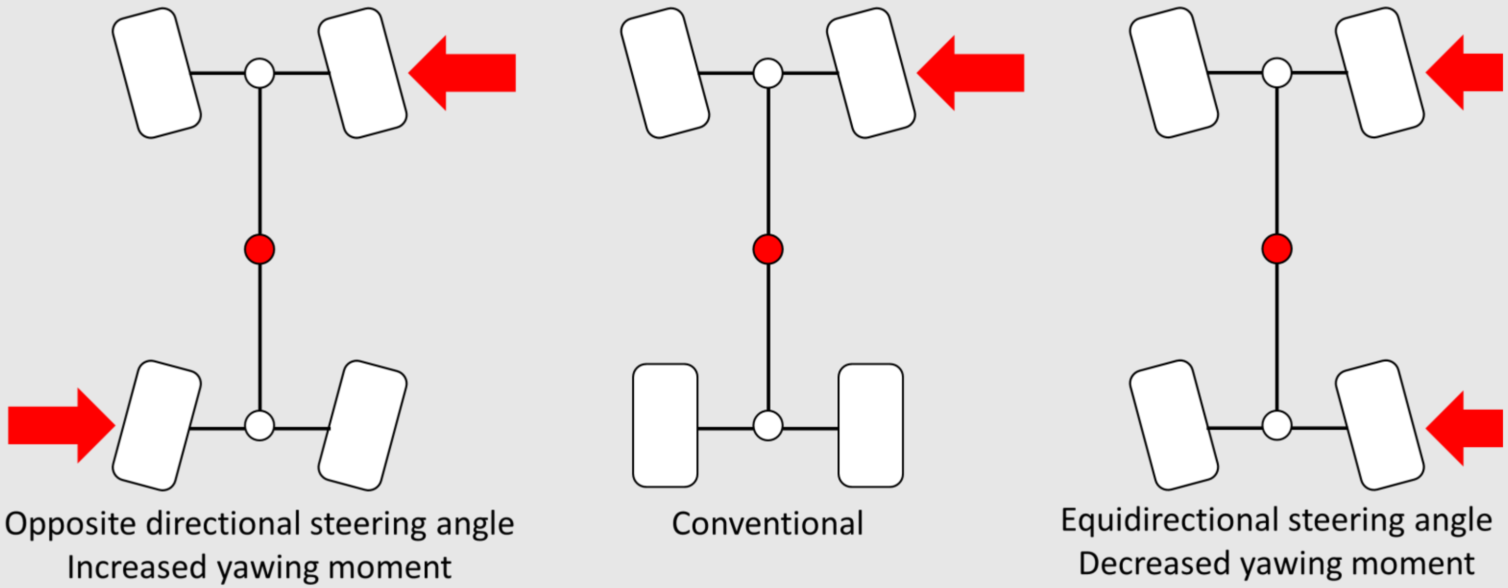


Steering	Accordantly	Inversely	Neutral
Wheelbase [mm]	1681	1411	1535
Turning cycle radius [mm]	2802	2352	2554

Vehicle Dynamics

Yaw control:

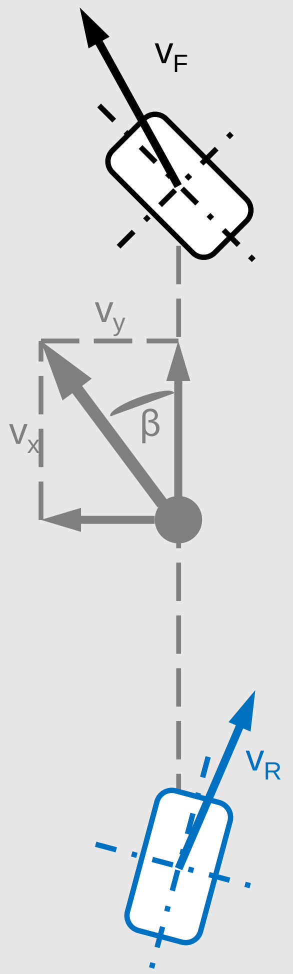
- RWS creates and supports lateral forces on the rear tires
- Inversely:
  - Improvement of yaw moment
  - Higher lateral acceleration
- Accordantly:
  - Weakening of the yaw moment
  - Improvement of understeering



Vehicle Dynamics

Side slip angle influence:

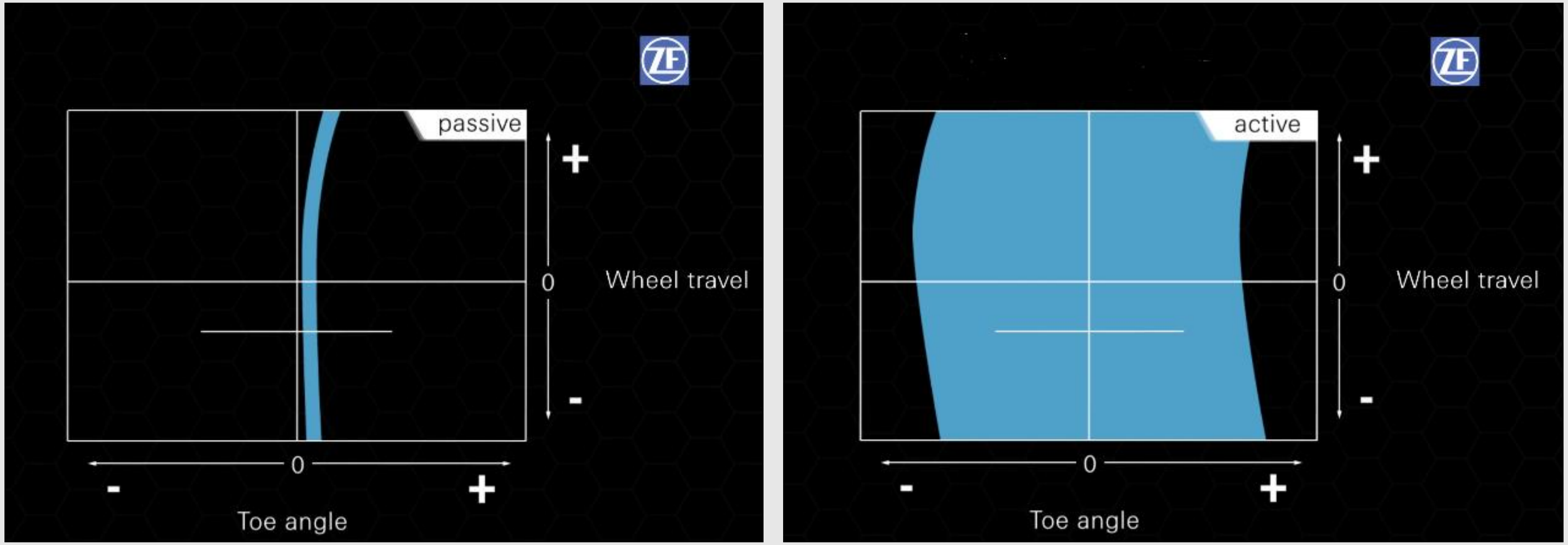
- Describes the orientation of the car and its velocity
- Effects caused by using RWS:
  - Rear axle is immediately taken into account of the vehicle‘s movement → lateral forces on tires
  - β will decrease
  - RWS systems can improve the vehicle stability during over- or understeering situations



Vehicle Dynamics

Active toe correction

- Passive feature → new degree of freedom while developing the kinematics



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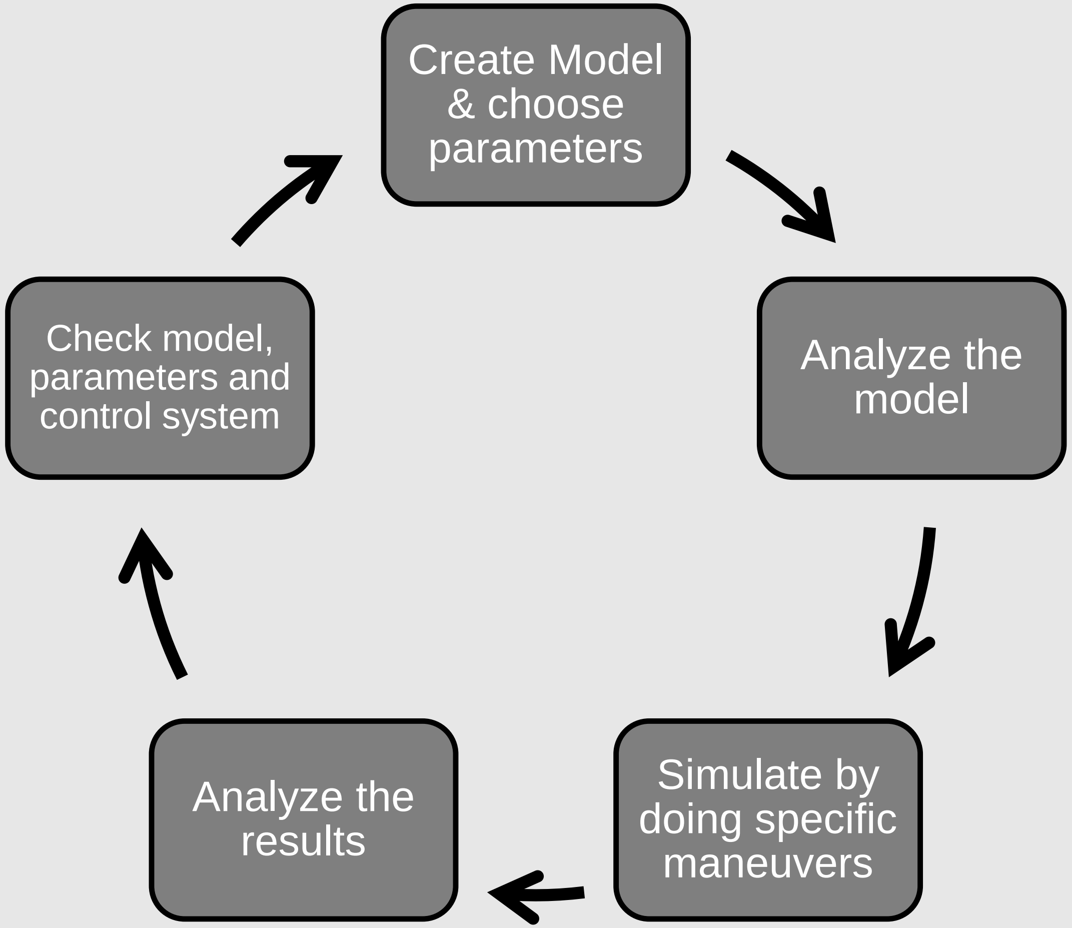
Simulation


Create Model & choose parameters
Analyze the model
Simulate by doing specific maneuvers
Analyze the results
Check model, parameters and control system

Simulation

- Linear one track model modified to rear wheel steering as a LTI state space system

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} -\frac{c_f+c_r}{mv} & -\left(1+\frac{c_f l_f - c_r l_r}{mv^2}\right) \\ -\frac{l_f{}^2 c_f + l_r{}^2 c_r}{Jv} & -\frac{c_f l_f - c_r l_r}{J} \end{bmatrix} \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} \frac{c_f}{mv} & \frac{c_r}{mv} \\ \frac{l_f c_f}{J} & -\frac{l_r c_r}{J} \end{bmatrix} \begin{bmatrix} \delta_f \\ \delta_r \end{bmatrix} \qquad \underline{Y} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix}$$

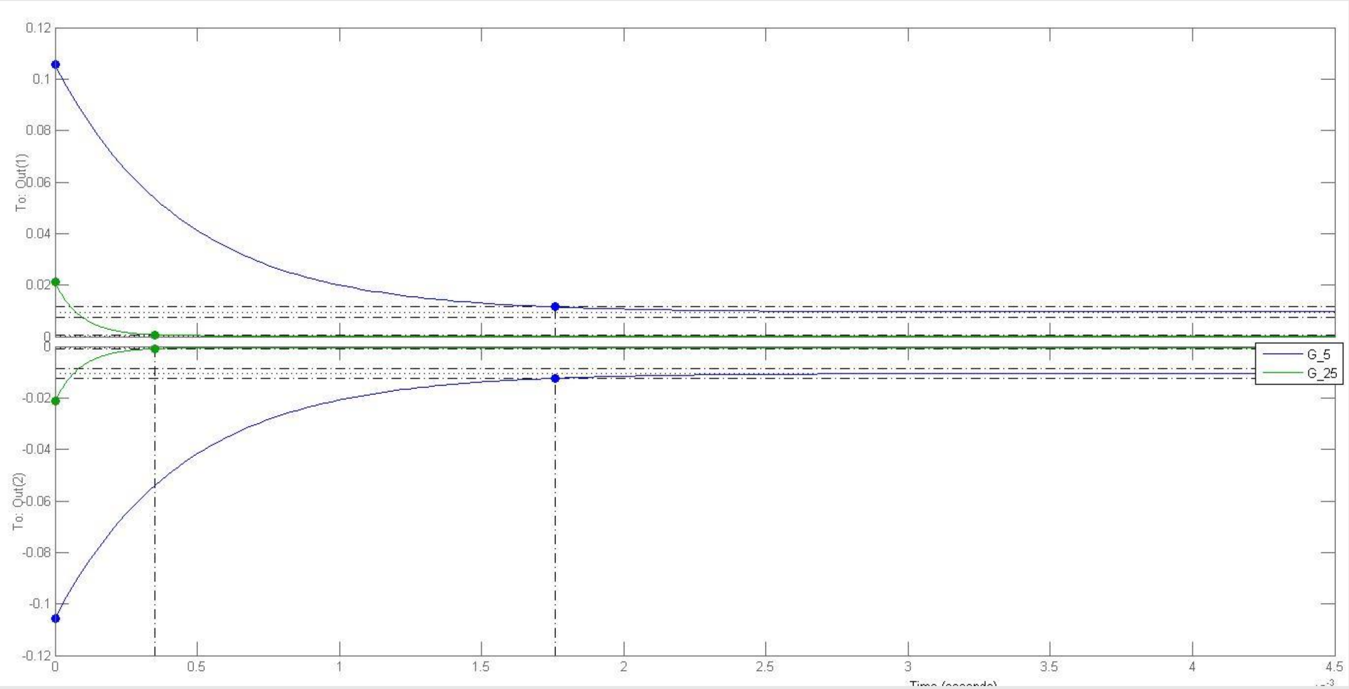
- Simulation using MATLAB script + Simulink model → fast and effective
- Parameters were choosen simplified and based on literature vales

Simulation

Modell analysis:

- MIMO system
- PTD1 behavior
- Most important characteristic: step response

  → level of the required dynamics of the drivetrain

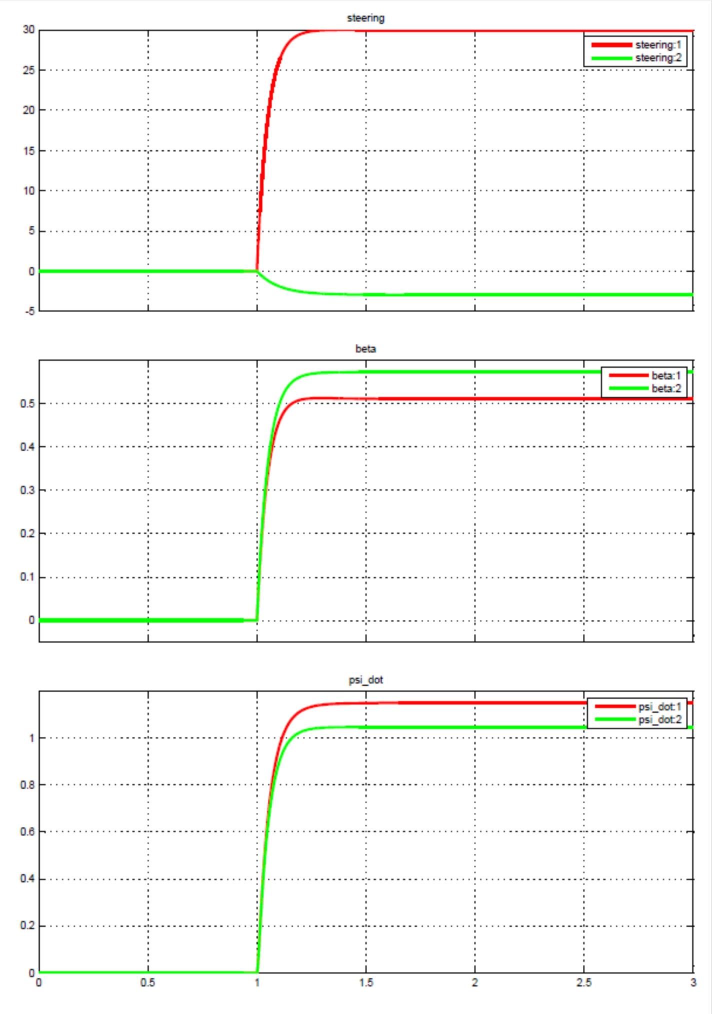


Step responses at $5 \ \& \ 25 \ \frac{m}{s}$

Simulation

Results:

- Proof of theory:
  - Improving of yaw rate at low speeds & weakening at high speeds
  - Side slip angle is reduced
  - Vehicle remains stable
- Basic idea how the control system needs to work
- Changing point of rear steering direction at 11 $\frac{m}{s}$

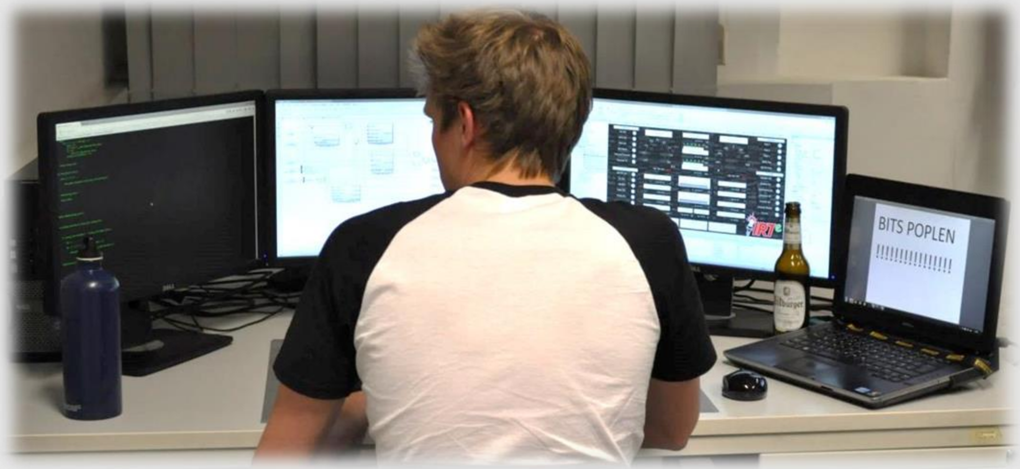


ASS - No ASS

Control System and Software

Main tasks:

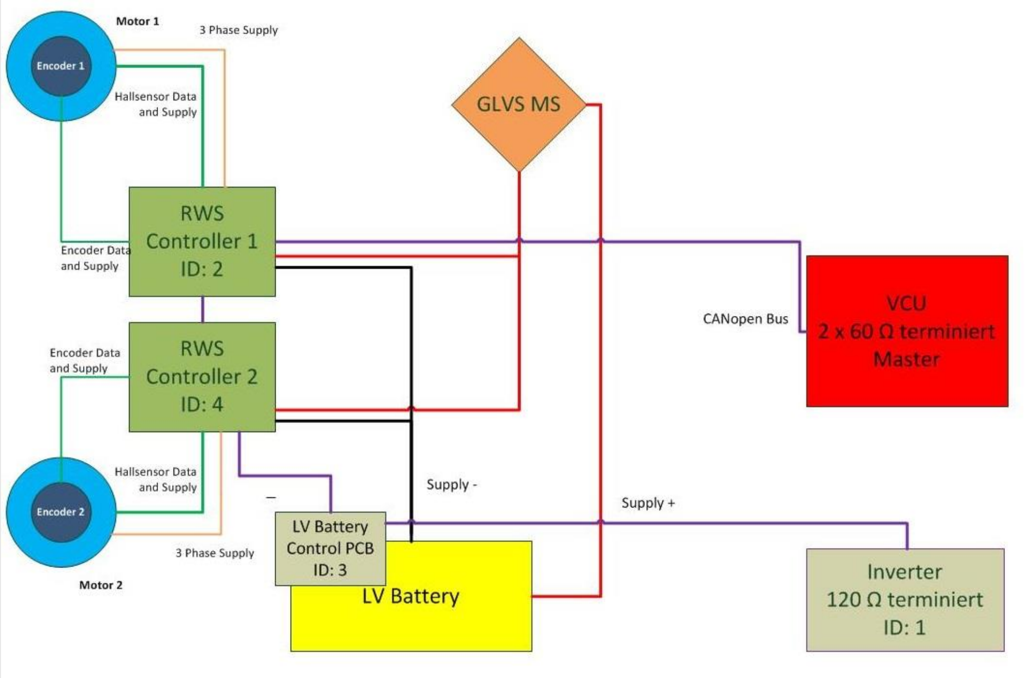
- Parametrization drivetrain
- Communication
- Develop control system
- Implementation into main software
- Start up and visualization
- Data analysis and improvement



Control system and software

Drivetrain + communication:

- Fit values like max. acceleration, speed, PID tuning, operation mode to the requirements
- Two actuators → twice parametrization
- CANopen bus @ 1mbit/s
- Triggered signals to remain functionality
- Choose necessary messages wisely



Control system and software

Control systems

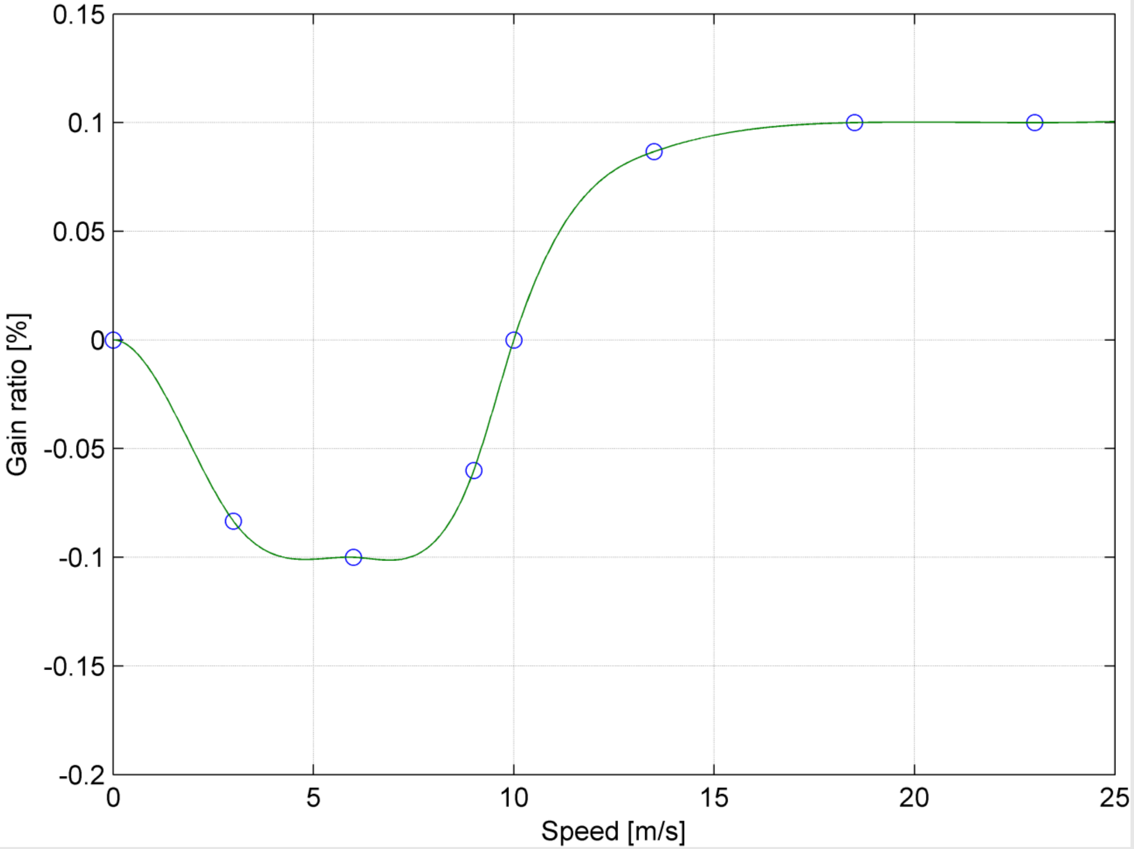
- Review on project targets: reliability, reproducibility, easy handling, stability
- Main question: open or closed loop control

	Advantages	Disadvantages
Open Loop	• React immediately • Reproducible • Stable	• No elimination of external influences • Target will not always be reached • Accuracy depends on model
Closed loop	• Elimination of external influences • Target will be reached	• May be instable • Might react slow • Hardly reproducible

Control system and software

Controller:

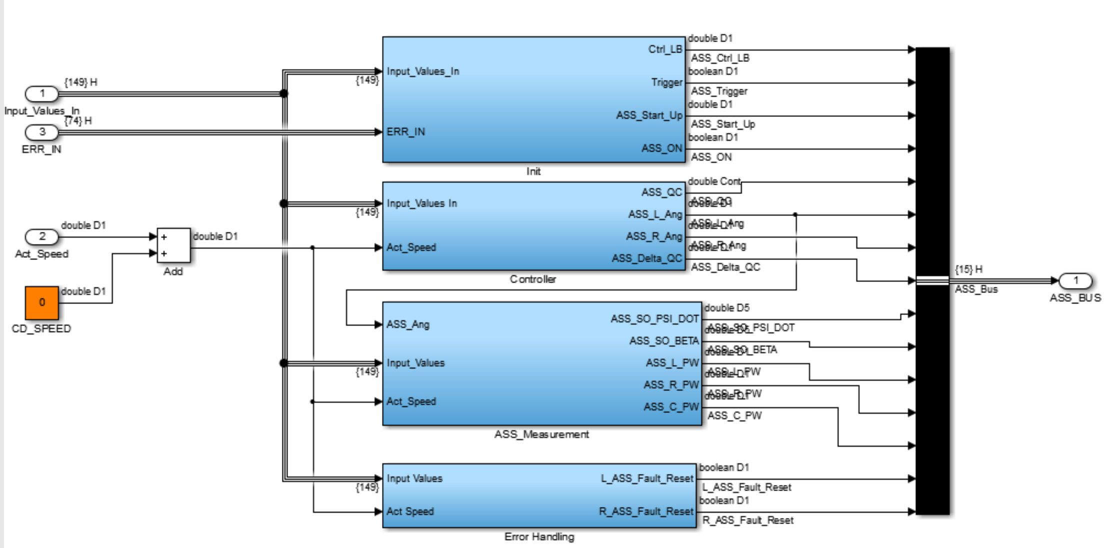
- Basis nonlineare factor, based current vehicle speed for front steering angle
- Created from simulation results
- Using cubic spline interpolation
- Further influence by:
  - Desired driver acceleration
  - Motor current
  - Security checks



Control system and software

Implementation:

- VCU: dSPACE MicroAutoBox II → Simulink
- Initialization by using last motor positons saved in VCU's flash storage
- Error detection by motor controllers, driver resettable at very low speeds and no steering
- Power measurement to shut down when LV battery is empty
- dSPACE ControlDesk for fast parameter optimizing



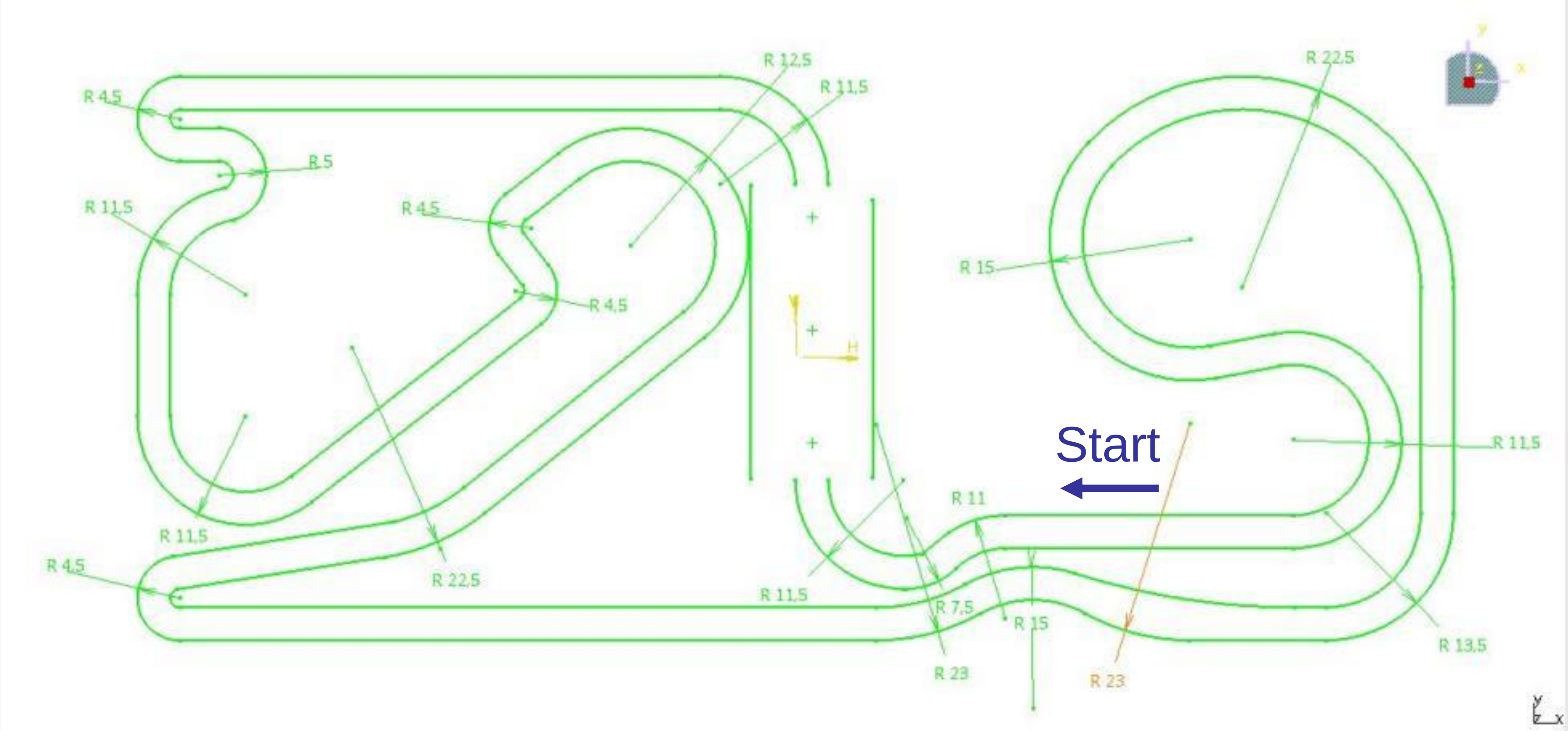
VIDEO ☺

Testing

- Unfortunately we had several problems … only 150 km before FSG
- But, pretty amazing results!
- Setup:
  - Hoosier LC0 at 14 psi
  - Very rough, dry surface
  - 1200 Nm
  - Max. Power 55kW → Endurance Test
  - Focus: Laptimes!

Testing

Track (length: 670m)

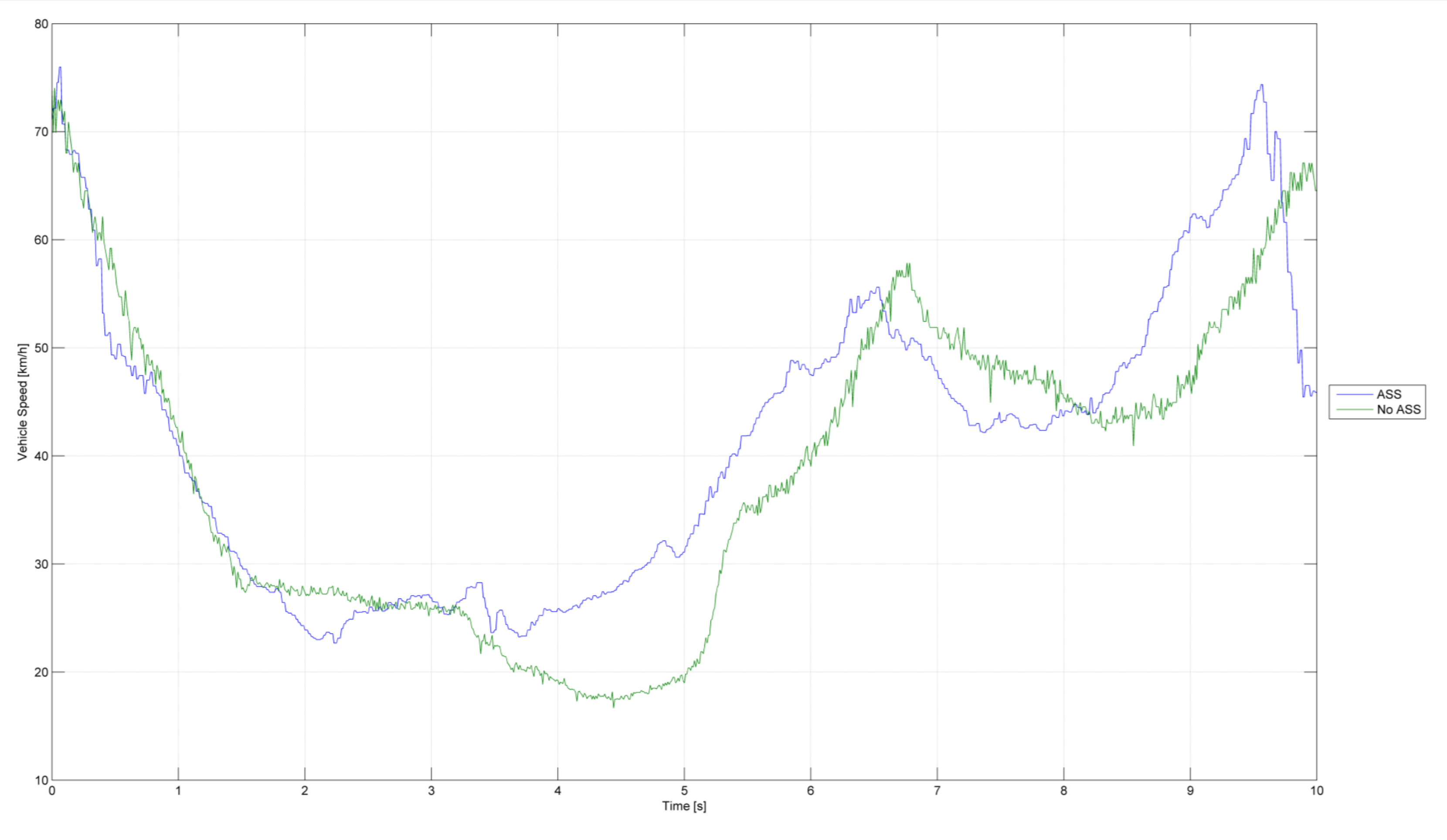


Testing

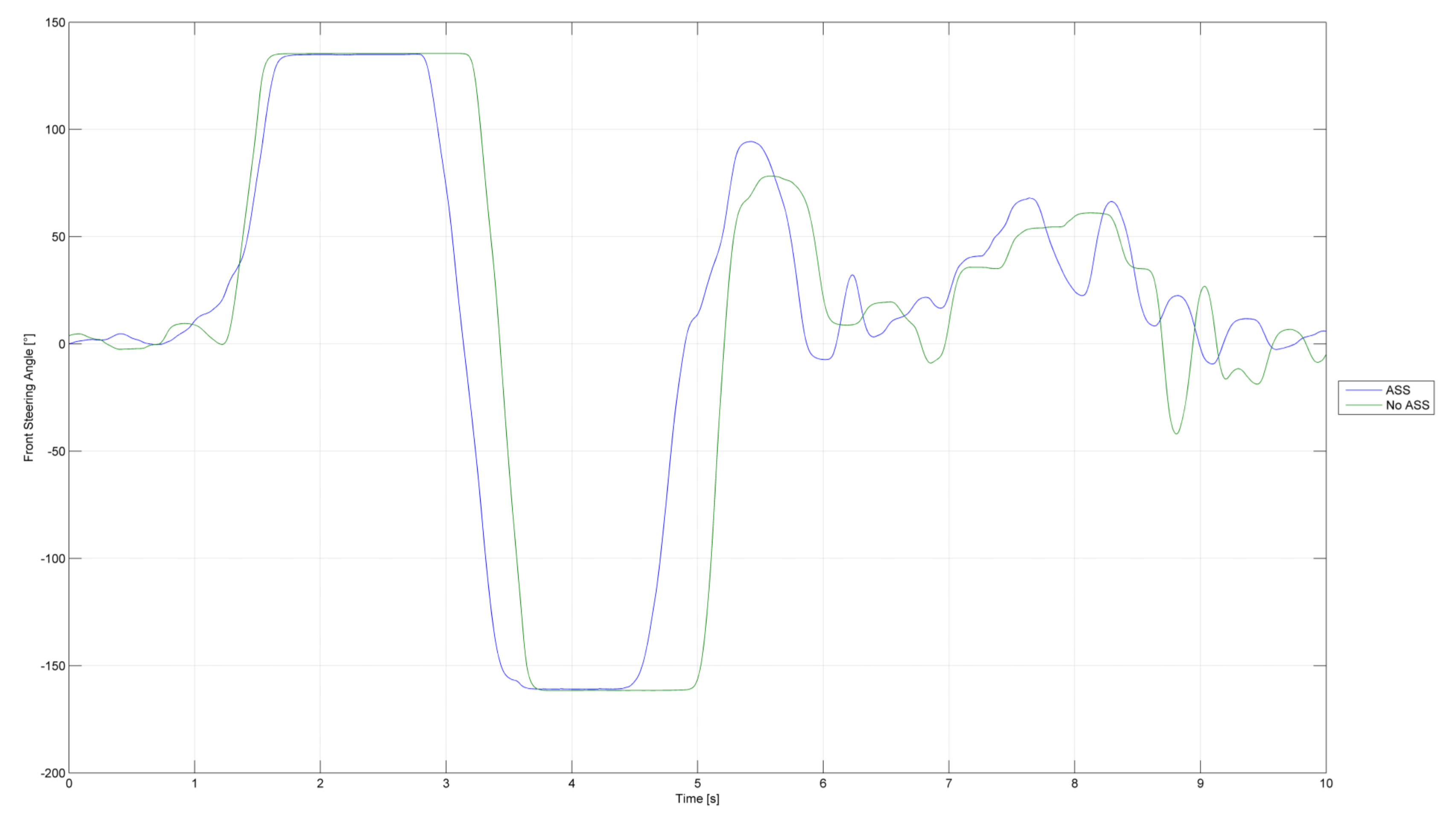
Overall results:

- Laptimes improved up to 1 s
  - Avg. speed using RWS: $50.51\ \frac{km}{h}$
  - Avg. speed without RWS: $48.54\ \frac{km}{h}$
- Vehicle corners recognizable faster
- Driver feedback:
  - Less steering forces
  - Handling is easier
  - Acclimatization is very necessary

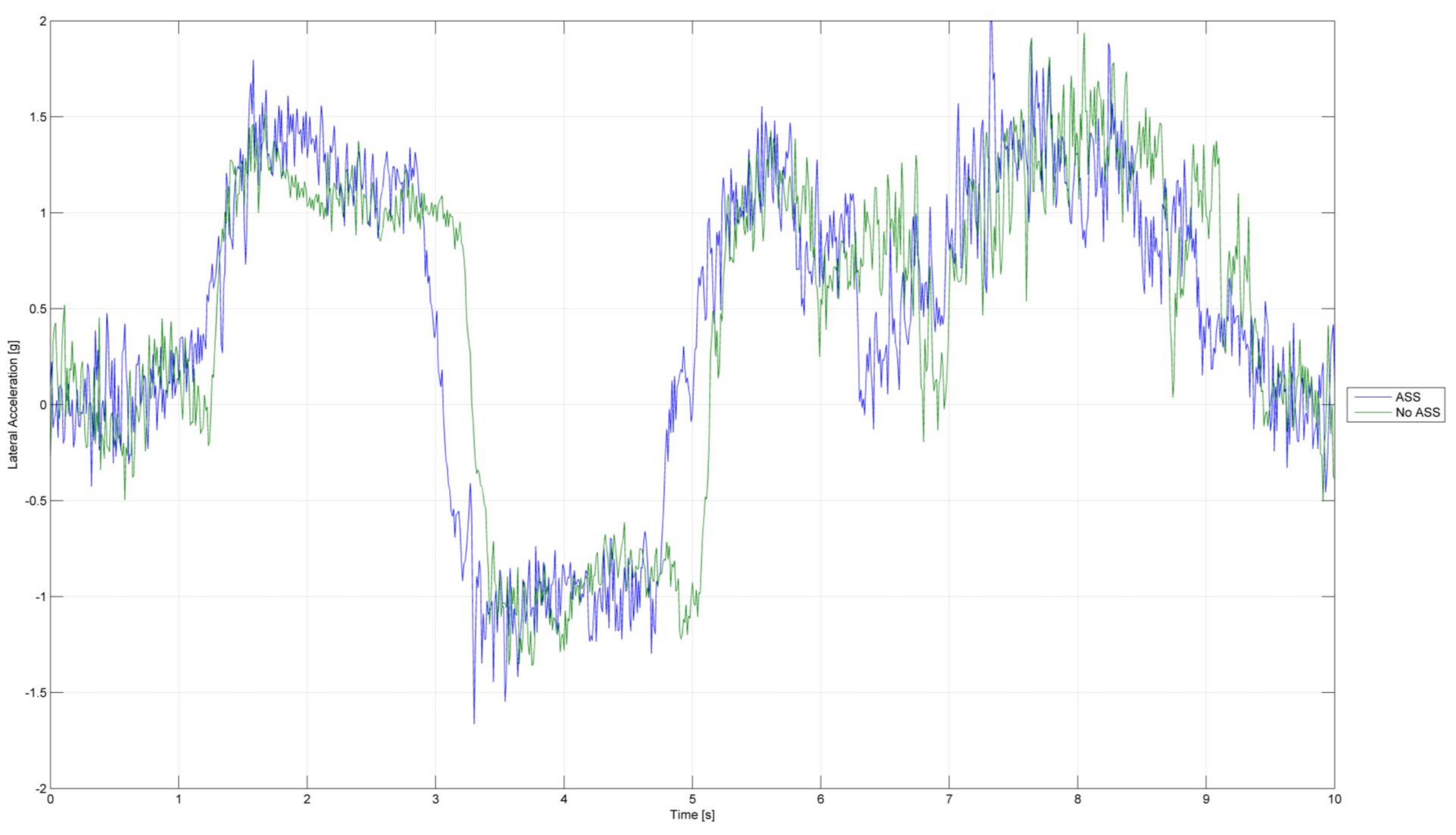
Testing


80
70
60
50
40
30
20
10
Vehicle Speed [km/h]
0
1
2
3
4
5
6
7
8
9
10
Time [s]
ASS
No ASS

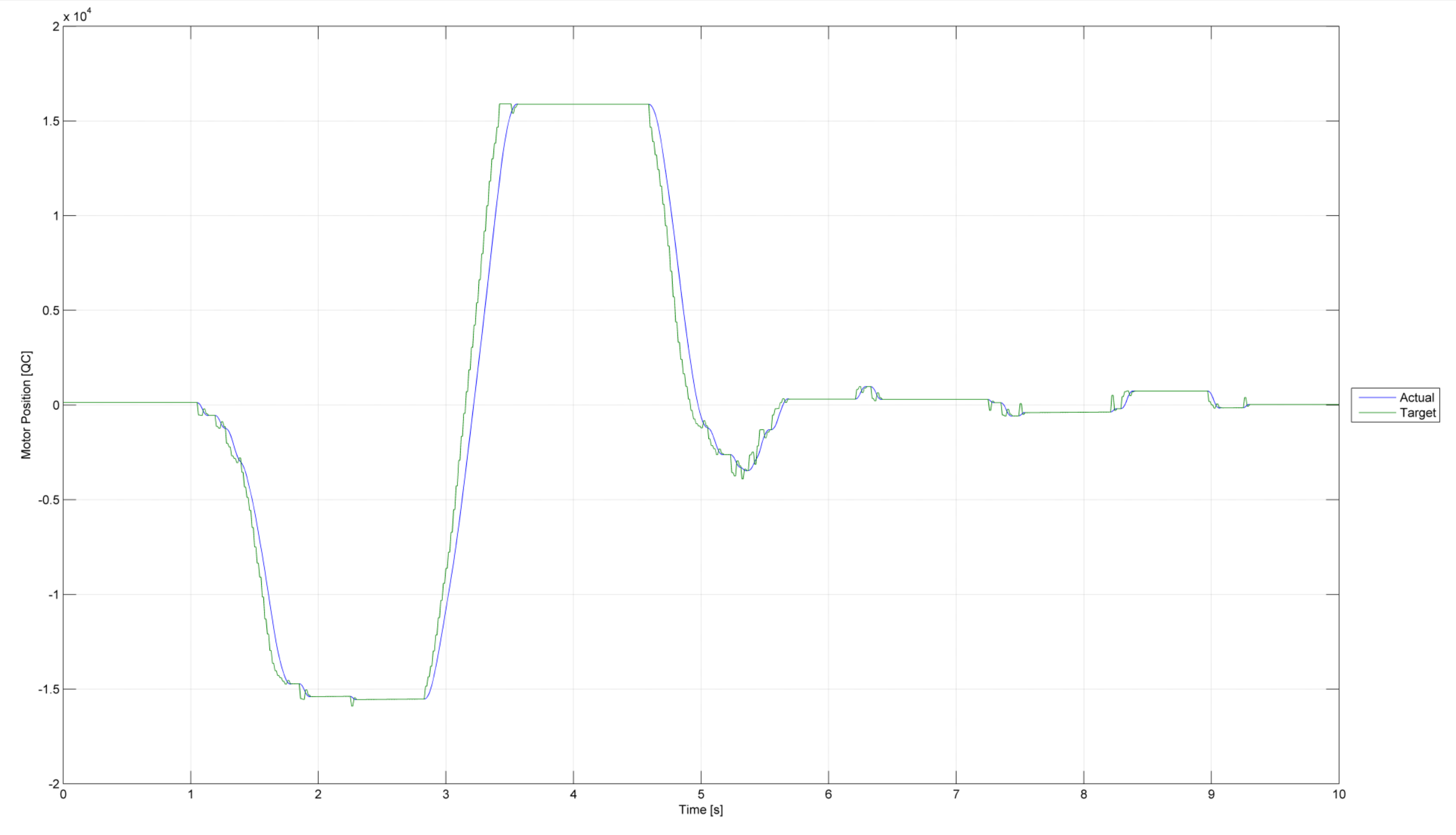
Testing


150
100
50
0
-50
-100
-150
-200
Front Steering Angle [°]
0
1
2
3
4
5
6
7
8
9
10
Time [s]
ASS
No ASS

Testing


Lateral Acceleration [g]
Time [s]
ASS
No ASS
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
4
5
6
7
8
9
10

Testing


x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Motor Position [QC]
0
1
2
3
4
5
6
7
8
9
10
Time [s]
Actual
Target

Resume

- Managed to reach all project targets!
- Increased the vehicle performance a lot and measureable
- A large amount of testing time is necessary
  - Optimize the control systems
  - Driver – car interaction
- Possible future prospects:
  - Reduce weight ;-)
  - Implement a closed loop control system
  - Compare it to 2 wheel driven torque vectoring

Thanks for your attention!

Feel free to ask Questions