Improvement of Lane Keeping Assistance ADAS Function utilizing a Kalman Filter Prediction of Delayed Position States

virtual vehicle

Enabling future vehicle technologies

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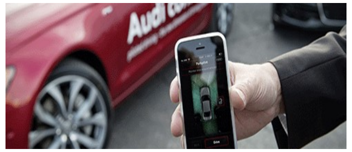
Presentation Outline

- Autonomous/Automated Driving Roadmap
- ADAS/AD Function Infrastructure
- MWC & Lane Keeping System Controller
- ADAS/AD Demonstrator Vehicle
- Description of the Implementation Problem
- Diagnosis of the Problem via Simulation
- Kalman Filter Predictor based Mitigation
- Results and Discussion

Levels of Automation (SAE Level 0-5)

Level 0: No Automation (warning of driver)
e.g. acoustic/haptic warning, display etc.

Level 1: Driver Assistance (e.g. break assistant etc.)
driver assistance system of "either steering or acceleration/deceleration"



Level 2: Partial Automation
Combined driver assistance system (e.g., Adaptive Cruise Control (ACC), Lane Keeping Assistant (LKA), or traffic jam assistant: road measurement and/or distance measurement)

Level 3: Conditional Automation
Relevant driving tasks by system, driver ready to take over

Level 4: High Automation
All driving tasks by system, limited roadway and environmental conditions (e.g. highway)

Level 5: Full Automation
All driving tasks in all situations by system ("no steering wheel/pedals"): autonomous driving

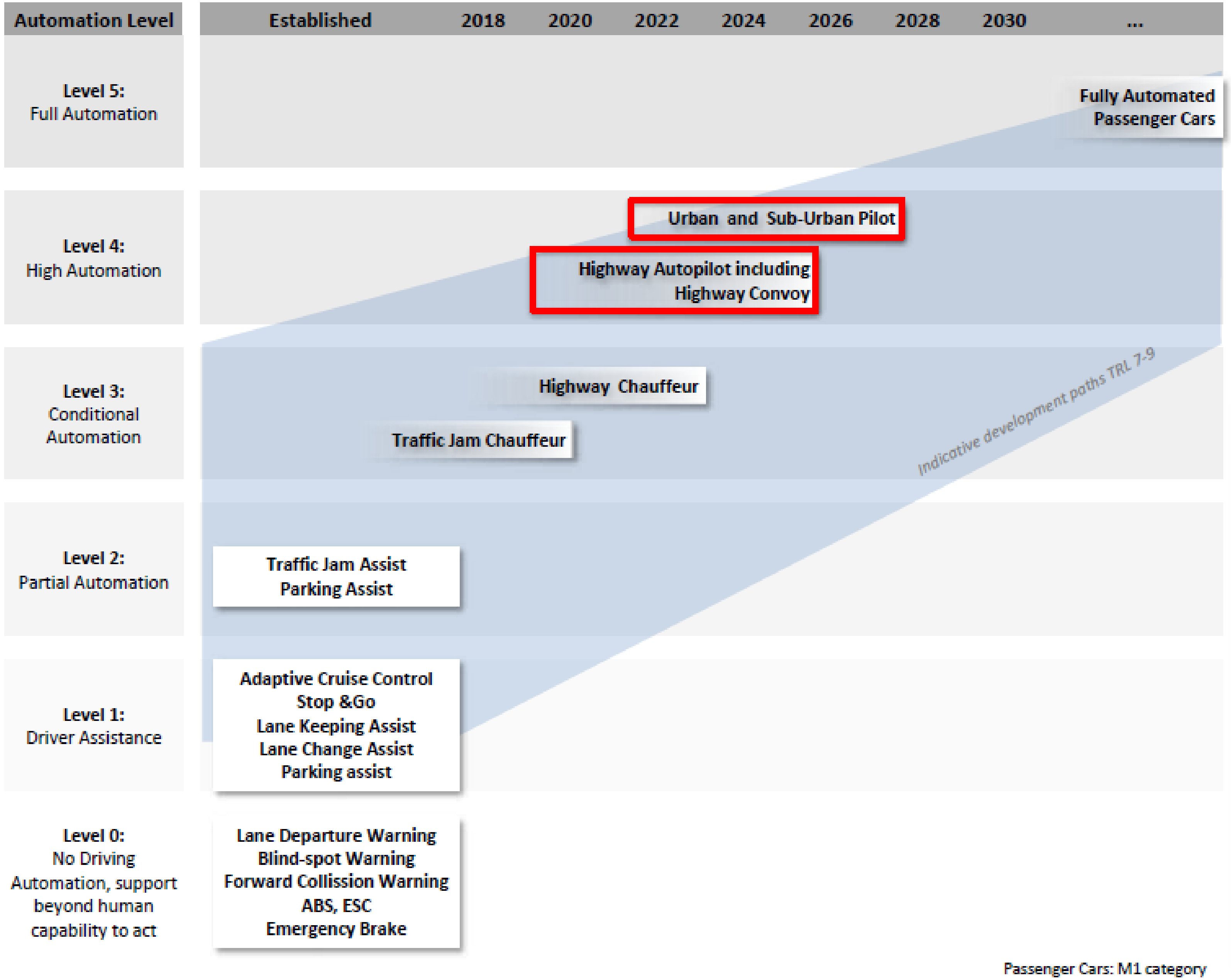
Monitoring: human driver

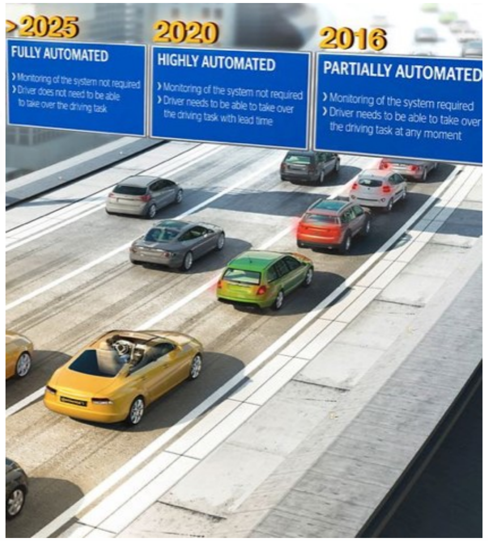
Monitoring: system

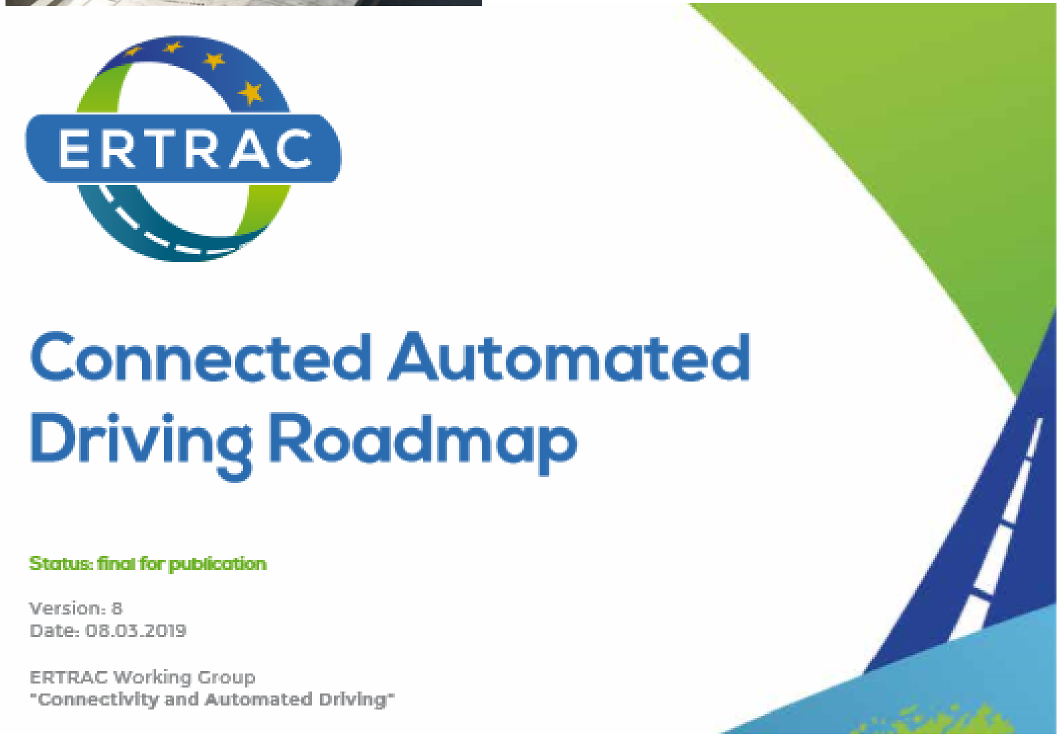
Quelle: AVL

Wording:
Automated driving ≠ Autonomous driving
Levels of automation 0 to 5

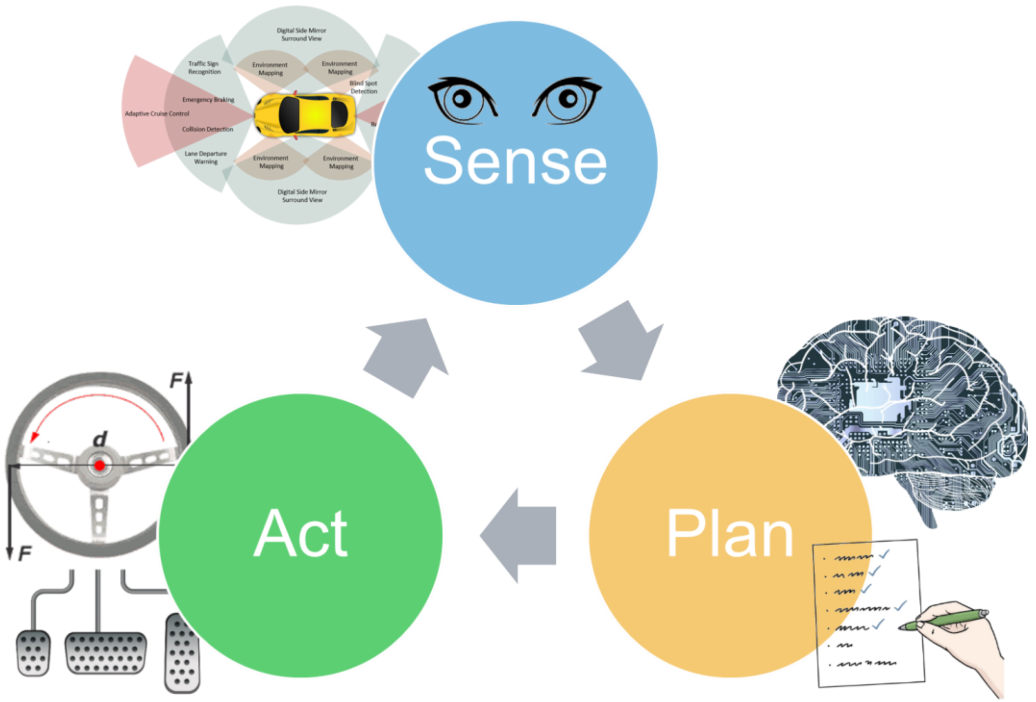
Automated/Autonomous Driving Roadmap

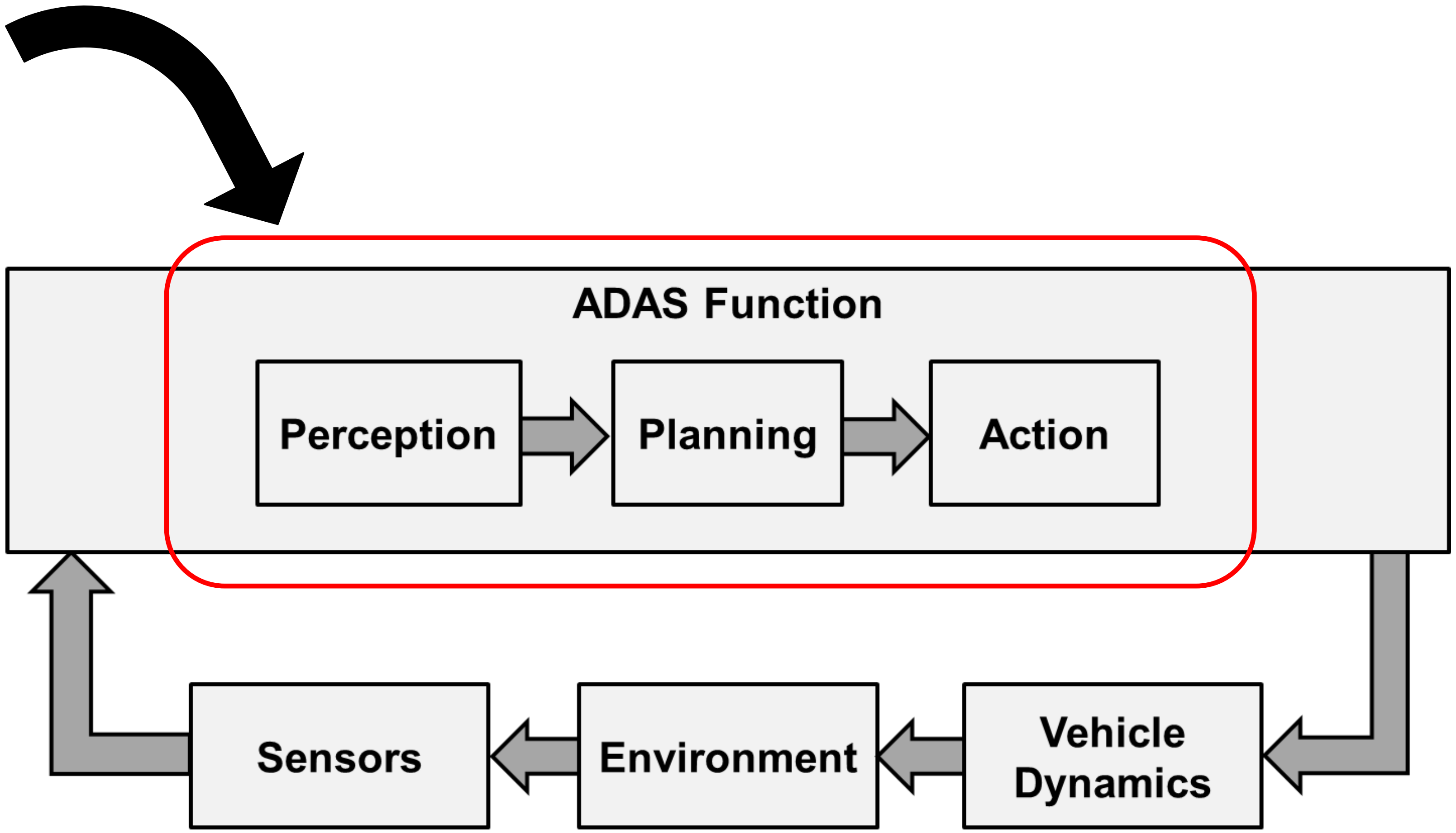




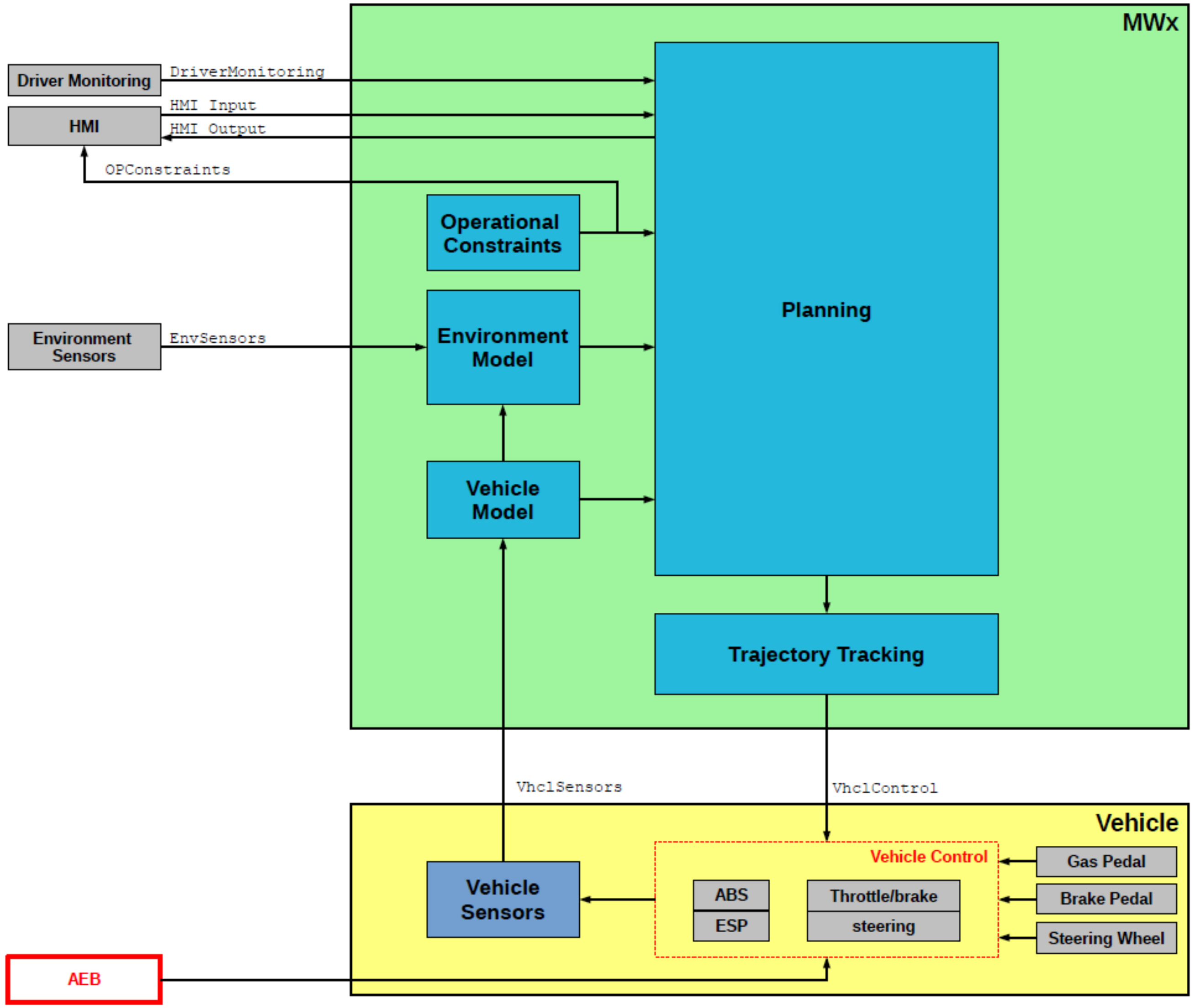


ADAS/AD Function Infrastructure

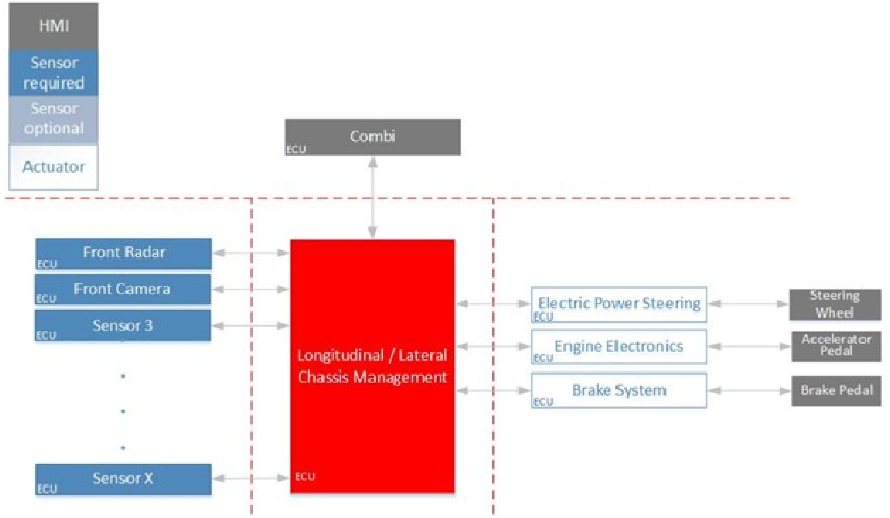




Virtual Vehicle MWC Controller Architecture

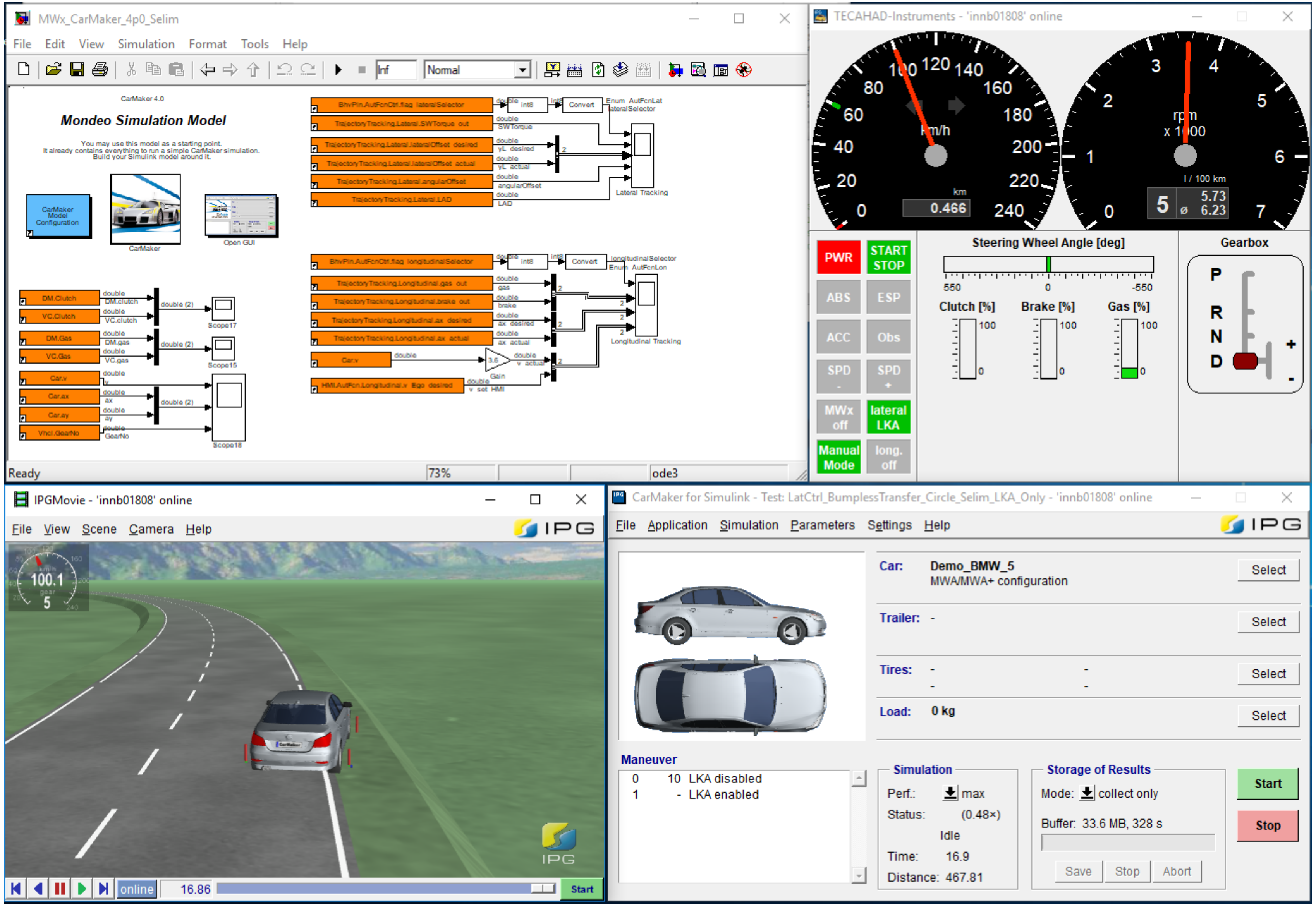


- An in-house developed Level 3+ Motorway Chauffeur Implementation
- State-based multi-controller combining
  - LKA (Lane Keeping Assistant)
  - ACC (Adaptive Cruise Controller)
  - TJA (Traffic Jam Assistant)
  - TP (Trajectory Planner)
- MATLAB/SIMULINK based development of individual MWC modules combining:
  - IPG-CarMaker based vehicle dynamics model
  - Individually designed controller logic for each MWC module in SIMULINK

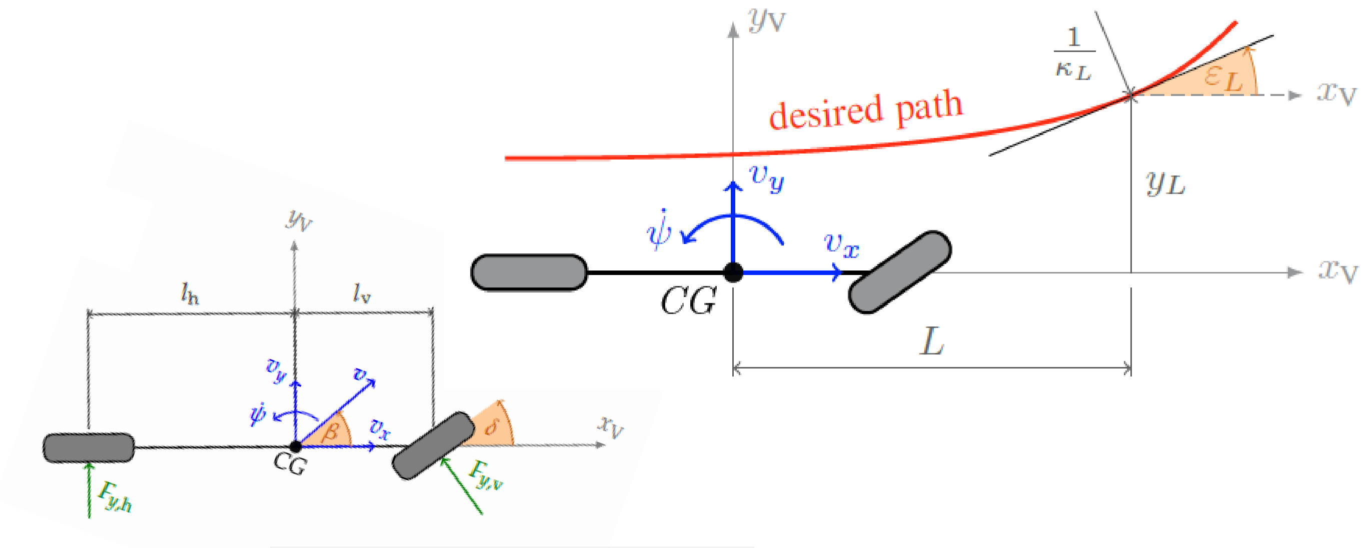


Simulation Environment

- CarMaker – Matlab/Simulink environment was developed during a former project
- Many autonomous functions (ACC, LKA, TJA, TP and their combination MWx) were developed in a realistic environment and tested in simulation



Lane Keeping (LKA) Controller Architecture*



$$\frac{\mathrm{d}x}{\mathrm{d}t} = Ax + b\delta + b_S\kappa_L \qquad x := \begin{bmatrix} v_y & \dot{\psi} & y_L & \varepsilon_L \end{bmatrix}^\top$$

$$A = \begin{bmatrix} -\frac{c_{s,v}+c_{s,h}}{m v_x} & \frac{-c_{s,v} l_v + c_{s,h} l_h}{m v_x} - v_x & 0 & 0 \\ \frac{-c_{s,v} l_v + c_{s,h} l_h}{I_z v_x} & -\frac{c_{s,v} l_v^2 + c_{s,h} l_h^2}{I_z v_x} & 0 & 0 \\ -1 & -L & 0 & v_x \\ 0 & -1 & 0 & 0 \end{bmatrix}$$

$$b = \begin{bmatrix} \frac{c_{s,v}}{m} & \frac{c_{s,v} l_v}{I_z} & 0 & 0 \end{bmatrix}^\top \qquad b_S = \begin{bmatrix} 0 & 0 & 0 & v_x \end{bmatrix}^\top$$

- Preview controller using lateral offset (y_L) and heading (ε_L) error
- Linear state feedback controller based on LQR methodology and the lane keeping model

$$\delta = -k^\top x$$

- Functional *J(t)*

$$J[\delta(t)] = \int_0^\infty \left(x^\top(t) Q x(t) + R\delta^2(t) \right) \mathrm{d}t$$

- Solve the optimization problem minimizing *J(t)*

$$\min_{k} J$$

* Nestlinger, G., & Stolz, M. (2016). *Bumpless transfer for convenient lateral car control handover*. 132-138. 9th IFAC Symposium on Intelligent Autonomous Vehicles, Leipzig, Deutschland. https://doi.org/10.1016/j.ifacol.2016.07.721

Automated Drive (AD) Demonstrator Test Vehicle

- **Drive by wire:**

  DataSpeed ADAS Kit:
  drive, brake, steer, visualize by wire

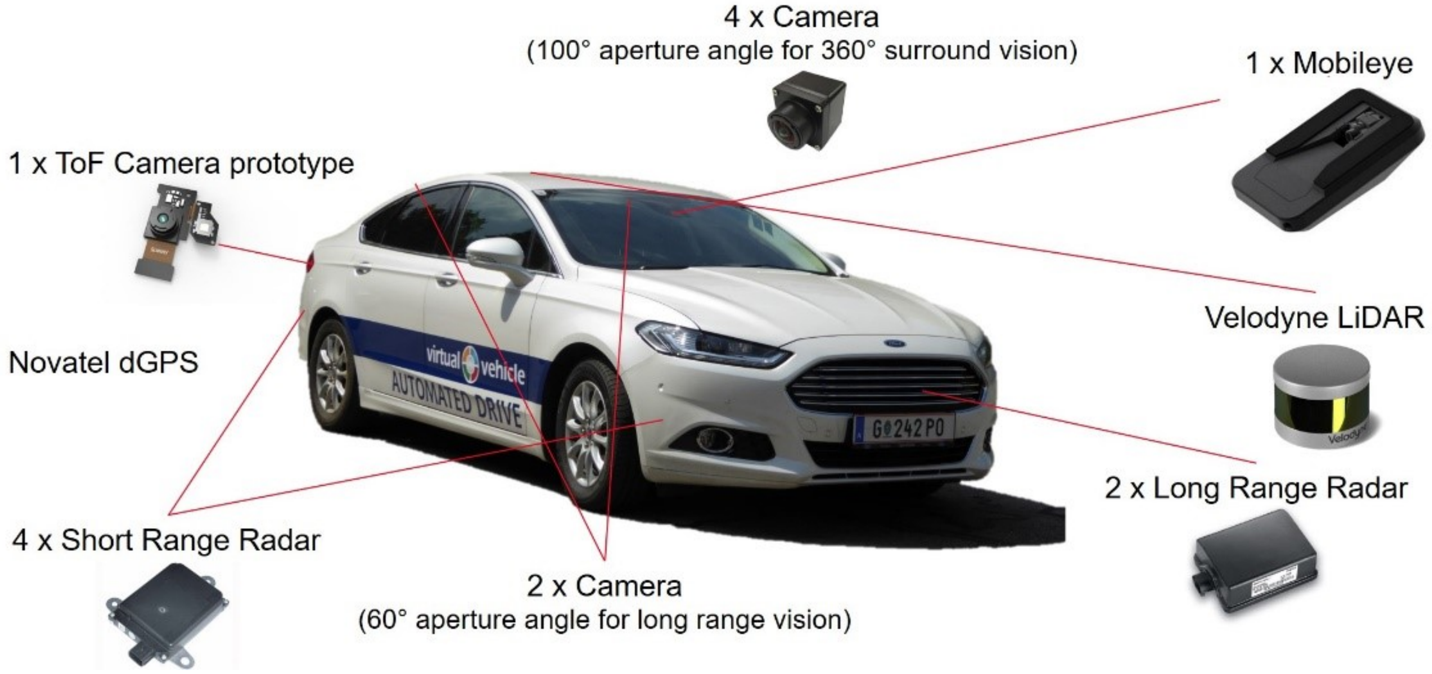
- **Sensors:**

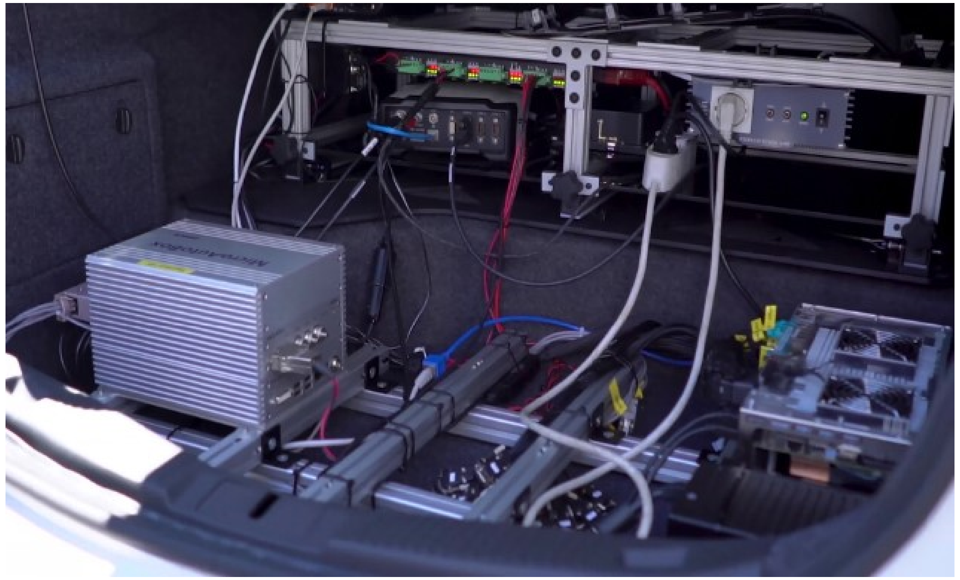
  Cameras, ultrasonic sensors, inertial sensors, RTK-GPS, Radars, Lidar(s), ToF…

- **Interfaces:**

  HMI touch display, CAN,
  ROS (Robot operating System) Kinetic
  Nvidia Drive PX/2 (Ubuntu 16.04)
  dSPACE MicroAutoBoX II
  PC (Win/Linux)

- **Applications**:
  - ❑ *Measurement (sensor data acquisition, sensor fusion)*
  - ❑ *Development and test (ADAS/AD)*
  - ❑ *Energy management (hybrid car)*
  - ❑ *Proving ground platform*





AD Demonstrator Sensor Layout

2x Long Range Radar
Continental ARS408

4x Short Range Radar
Continental ARS408

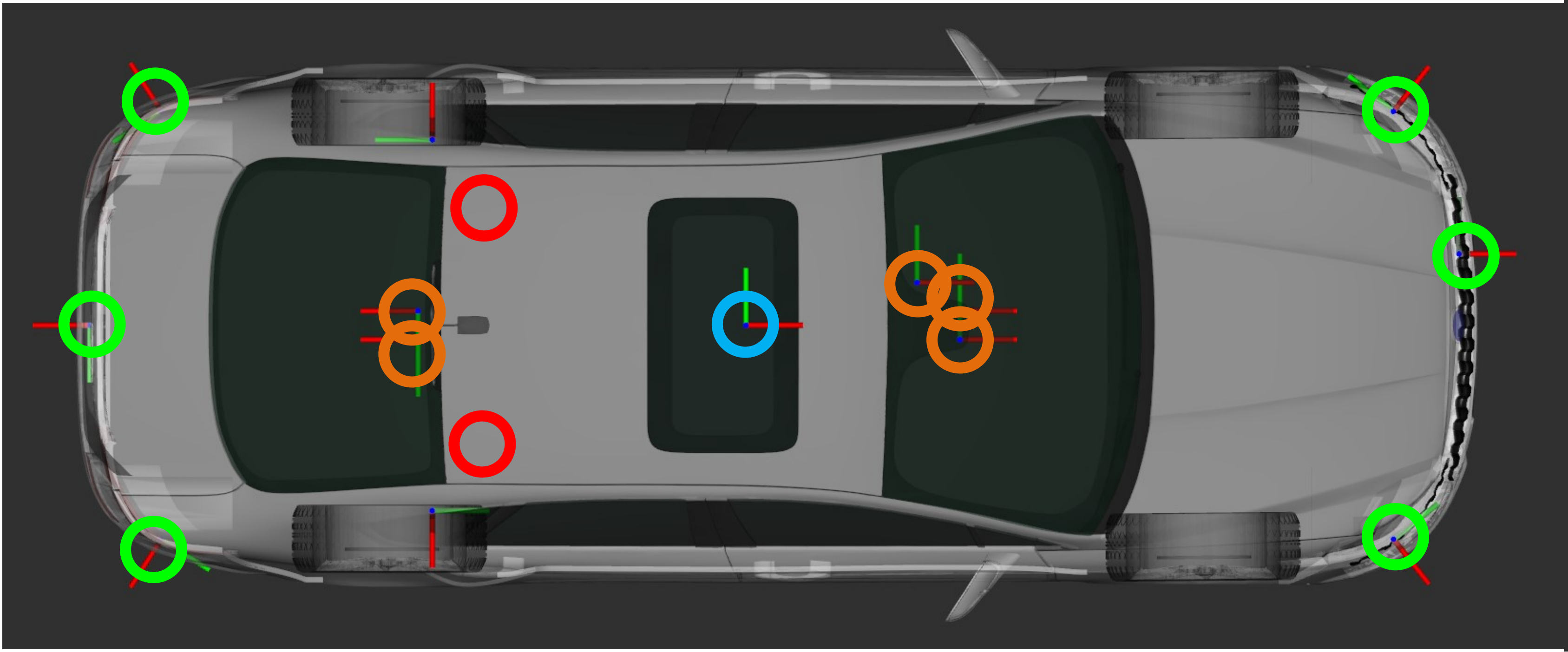
4x Camera
(100° aperture angle for 360°)

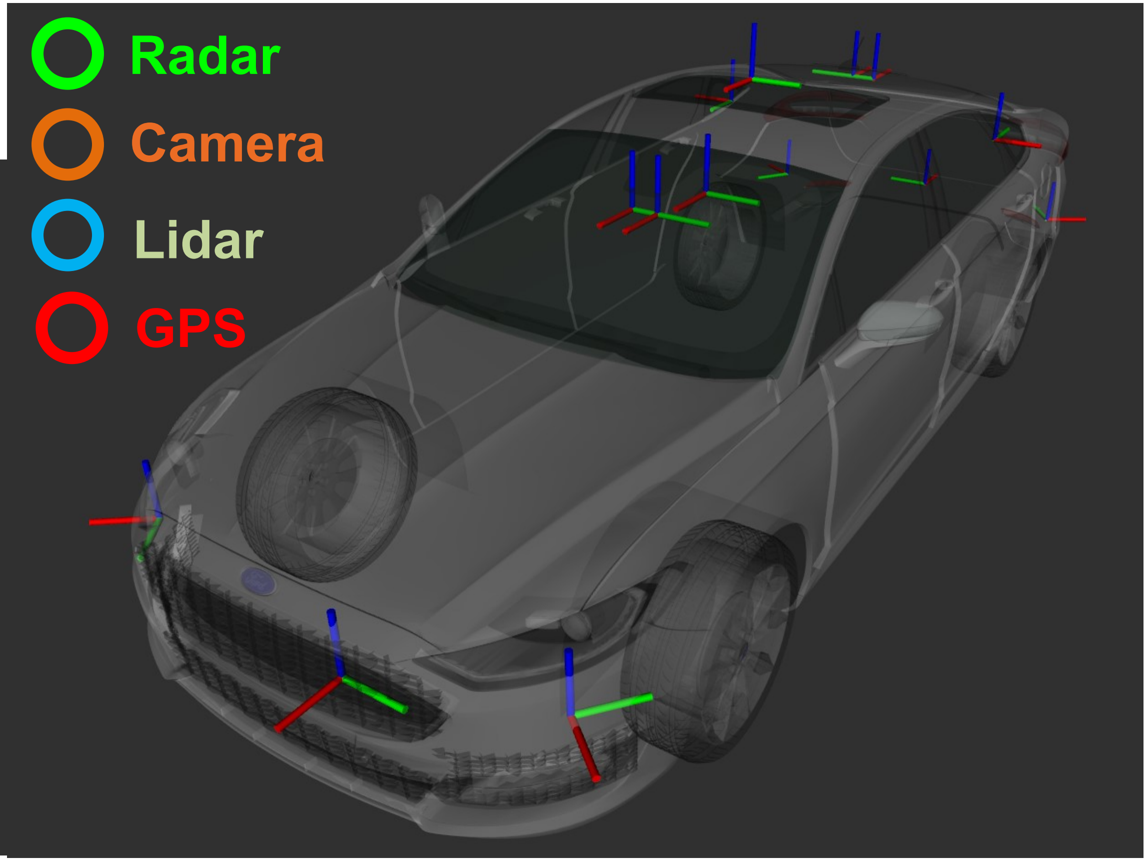
2x Camera
(60° aperture angle for long range)

Mobileye

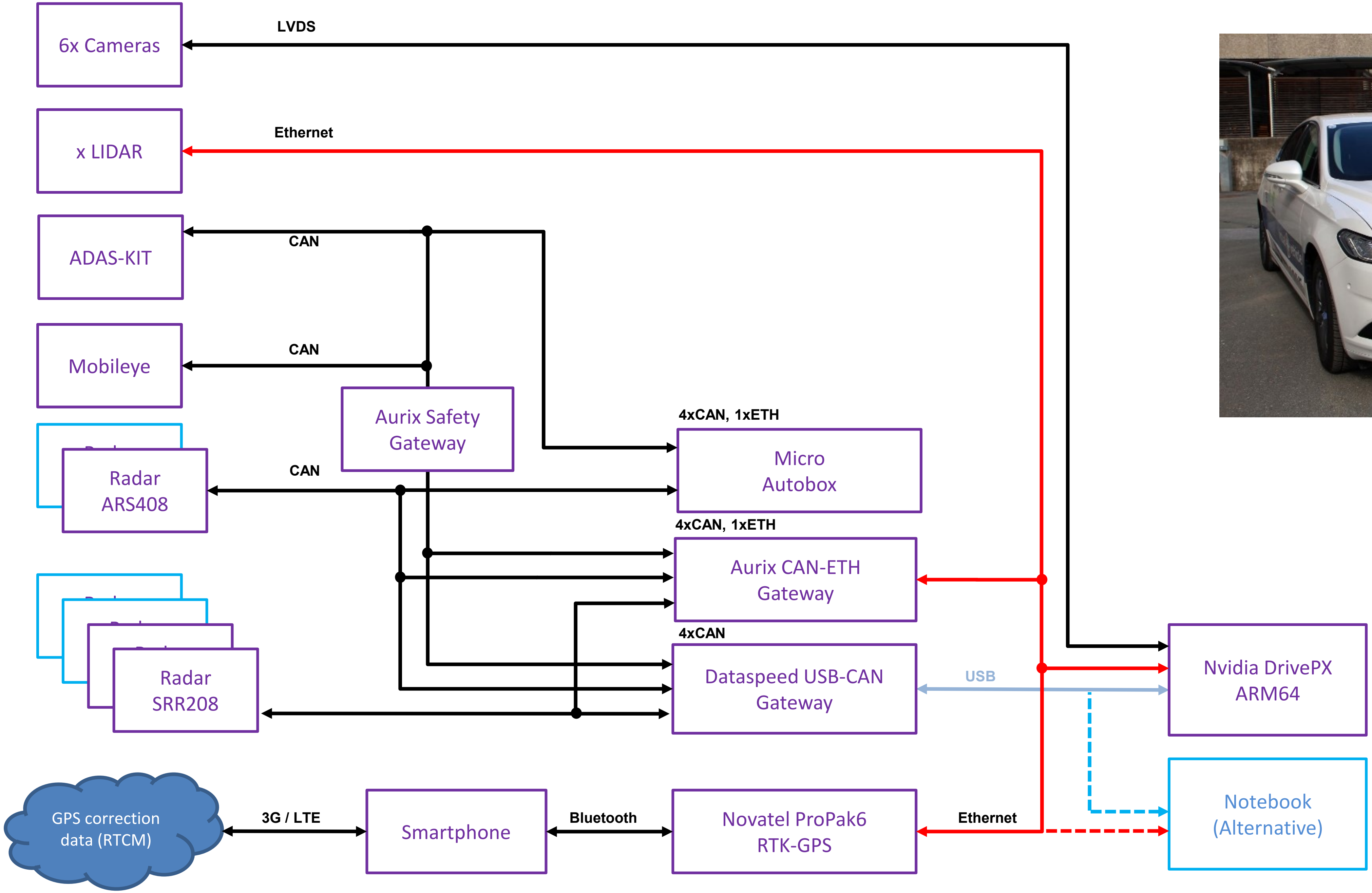
1x Lidar
Velodyne VLP-16

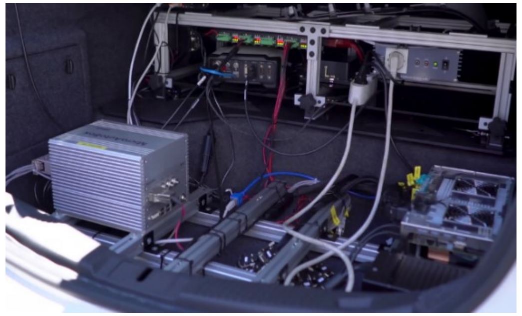
RTK-GPS
Novatel ProPak 6





AD Demonstrator-E/E Architecture

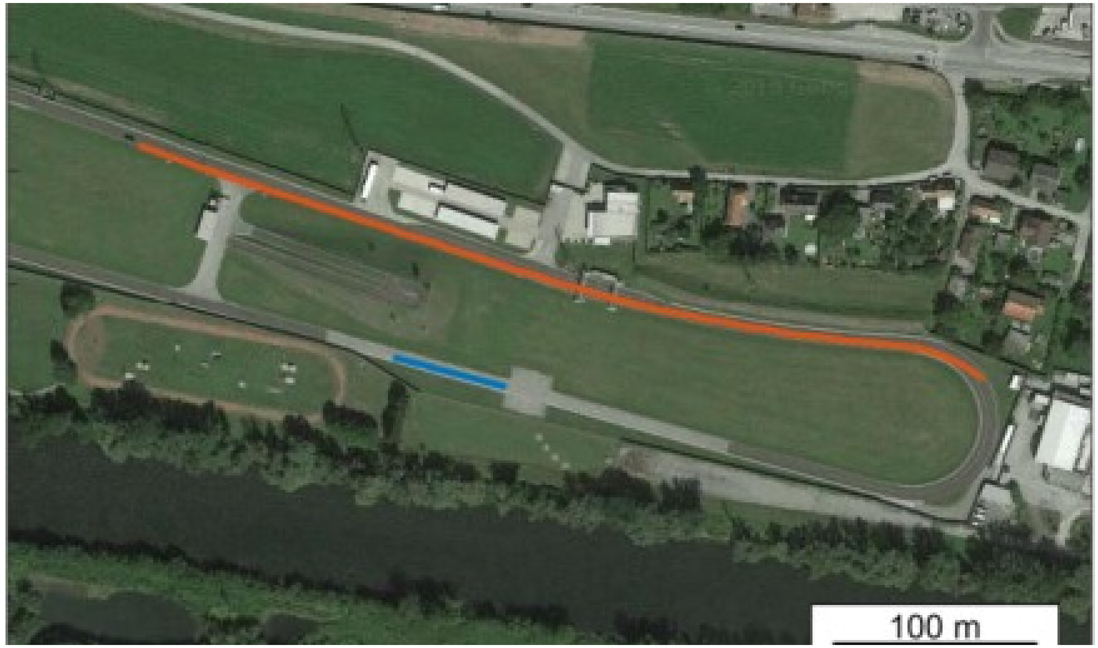


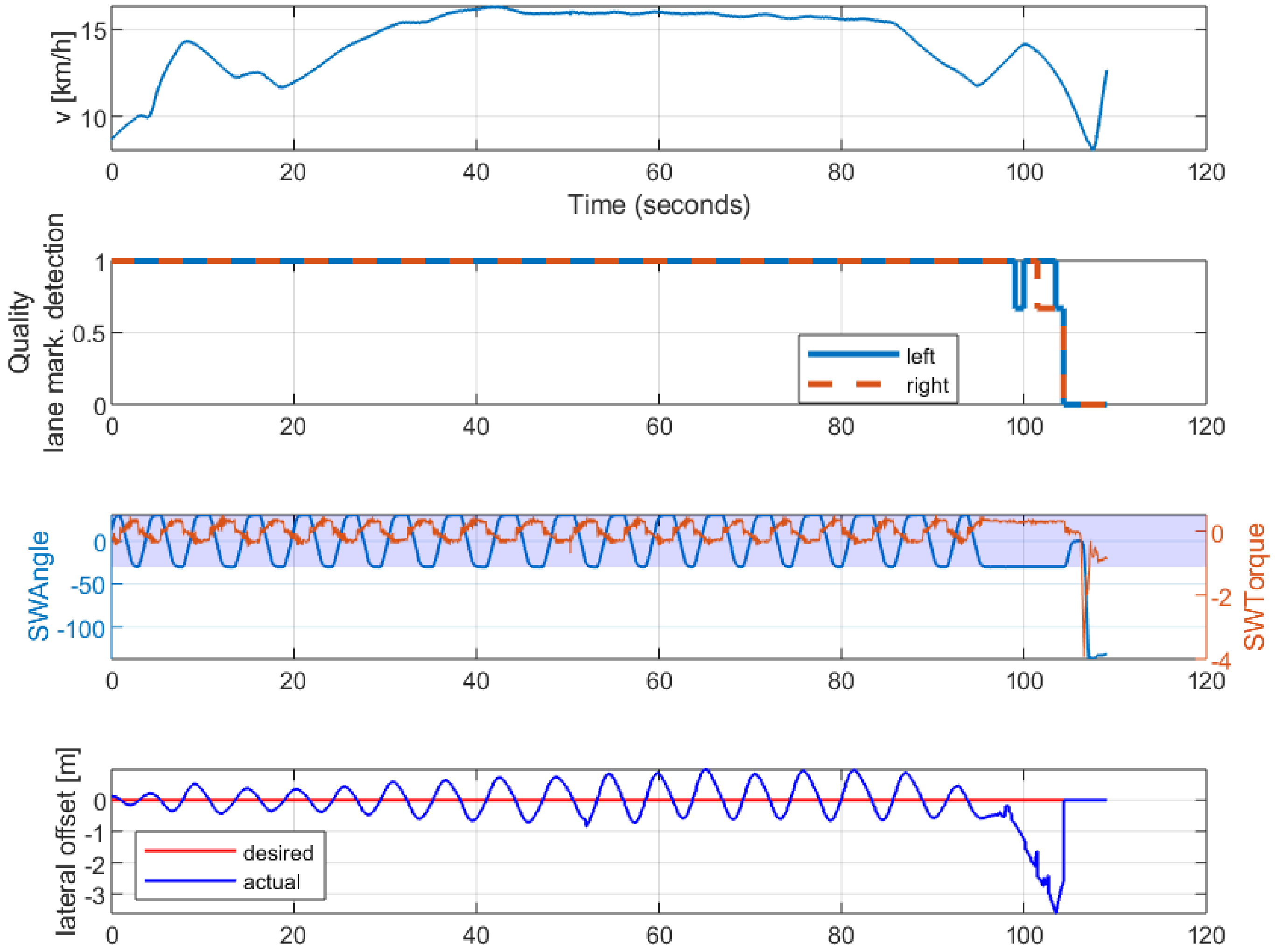


Description of the Implementation Problem

- The developed LKA controller was implemented on the AD Demonstrator using the MATLAB/SIMULINK Embedded coder to run on the dSPACE MicroAutobox-II real-time ECU
- LKA Function based on DataSpeed ADAS Kit and MobilEye Camera alone

Initial Implementation Performance Results

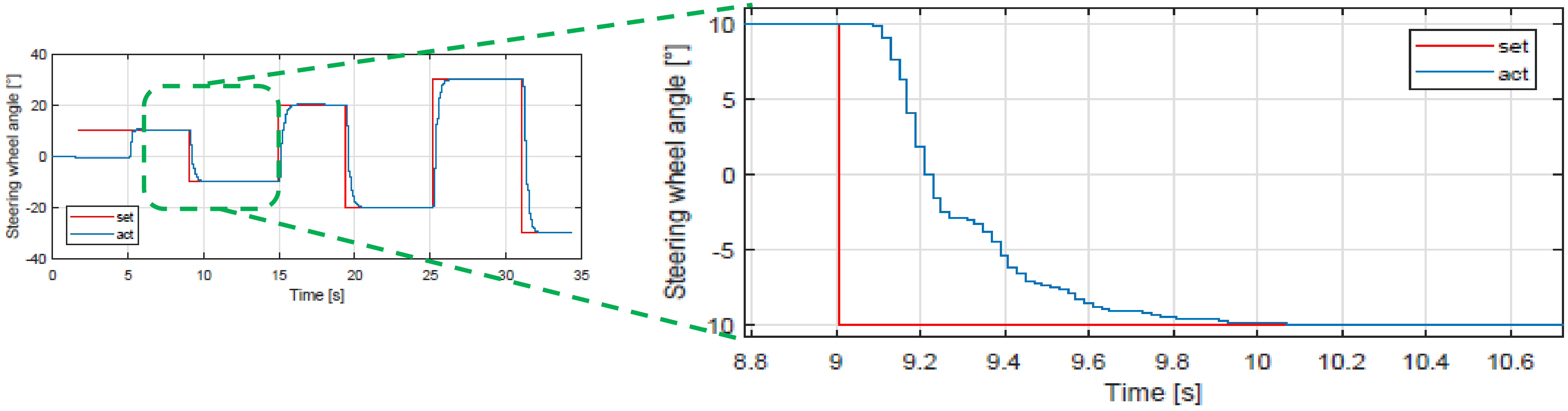




- Our first "successful" LKA test at the AVL test track in Gratkorn in late July 2018
- First trials with the same simulation algorithms had performance issues
  - Performance problems with tracking
  - Limited speed (~35 km/h)
  - Oscillations and unstable behavior at high speeds
  - Gain and parameter tuning didn't help much

Problem Details

- LKA Performance Diagnosis:
  - LKA working only at low speeds
  - Has oscillatory behavior in keeping the lane
- Both problems originate from the delays in sensors and the control actuator
- Steering actuator has a consistent delay of 80 – 100 *ms* which were measured with experiments
- MobilEye 630 sensor providing the lane information has unknown (and unfortunately unmeasurable) delay
- We are estimating that the delay in the camera is about 300~500 *ms*



Diagnosis of the Problem via Simulation

- To verify the diagnoses, the same uncertainties can be implemented in the simulation environment
- Simulation in the CarMaker-Matlab/Simulink simulation environment with
  - 80 *ms* steering actuator delay
  - 300 *ms* position sensor (MobileEye 630) delay (providing lateral offset y_L and angular offset ε_L)

Diagnosis of the Problem via Simulation

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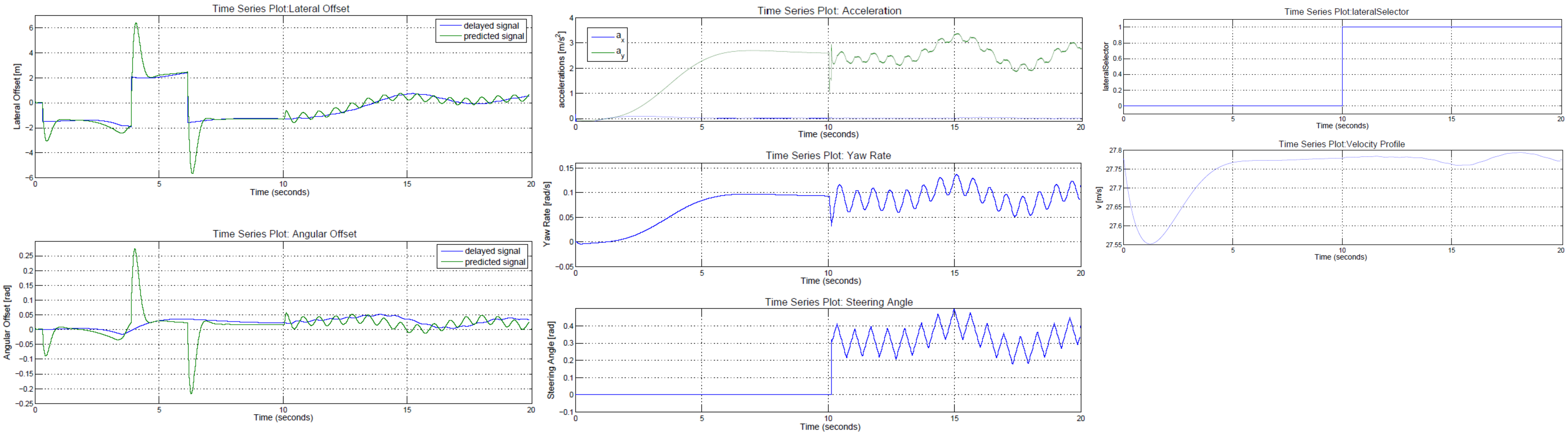
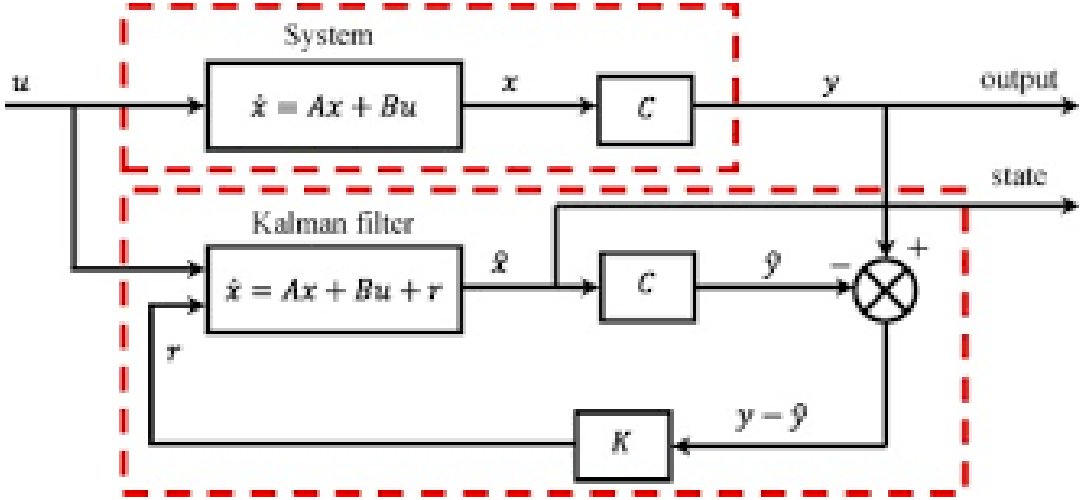


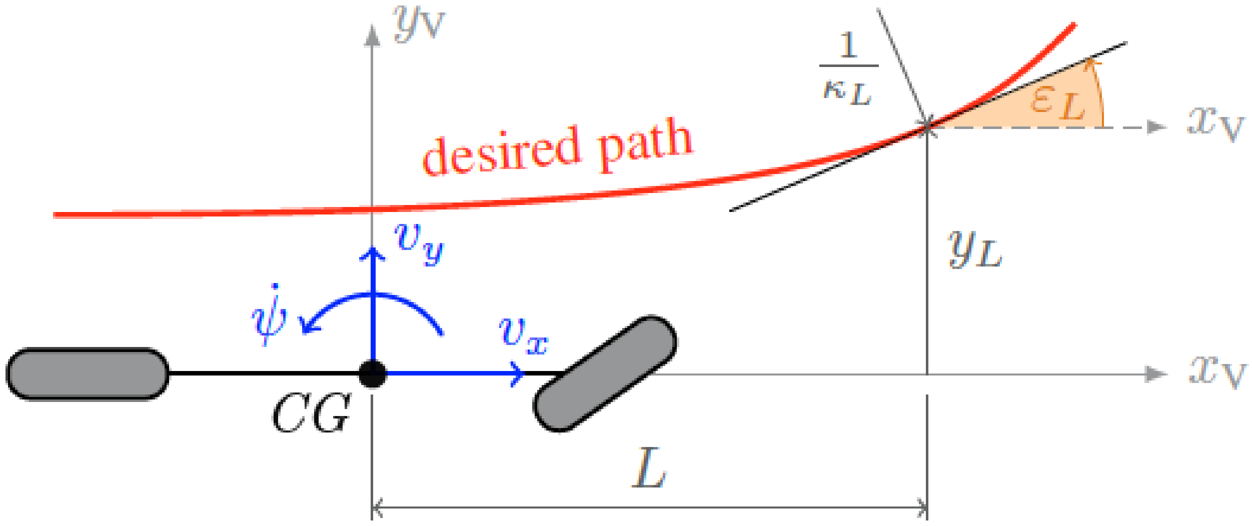
Kalman Filter Predictor based Mitigation

- In order to compensate the sensor and actuator delays, we designed a model based Kalman Filter predictor for the delayed position measurements of lateral and angular offsets: y_L, ε_L
- Kalman Filter as an optimal single step observer:



- Physical model: Kinematic Lane-keeping Model

$$\dot{y}_L = v_x \varepsilon_L - v_y - L\dot{\psi}$$
$$\dot{\varepsilon}_L = v_x \kappa_L - \dot{\psi}$$



Kalman Filter Predictor based Mitigation

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- Discrete-time state space model for KF (based on the lateral tracking model)

$$\boldsymbol{x_{k+1}} = \boldsymbol{F_k x_k} + \boldsymbol{B_k u_k} \quad \text{(state Equation)}$$

$$\boldsymbol{z_k} = \boldsymbol{H_k x_k} \quad \text{(measurement Equation)}$$

$$F_k = \begin{bmatrix} 1 & v_x \Delta t \\ 0 & 1 \end{bmatrix} \qquad x_k = \begin{bmatrix} y_L \\ \varepsilon_L \end{bmatrix}$$

$$B_k = \begin{bmatrix} -\Delta t & -L\Delta t & 0 \\ 0 & -\Delta t & v_x \Delta t \end{bmatrix} \qquad u_k = \begin{bmatrix} v_y \\ \dot{\psi} \\ \kappa_L \end{bmatrix}$$

$$H_k = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

- Recursive Kalman Filter Equations

Predict

Predict	Predicted (*a priori*) state estimate	$\hat{\mathbf{x}}_{k\mid k-1} = \mathbf{F}_k \hat{\mathbf{x}}_{k-1\mid k-1} + \mathbf{B}_k \mathbf{u}_k$
	Predicted (*a priori*) error covariance	$\mathbf{P}_{k\mid k-1} = \mathbf{F}_k \mathbf{P}_{k-1\mid k-1} \mathbf{F}_k^{\mathrm{T}} + \mathbf{Q}_k$
Update	Innovation or measurement pre-fit residual	$\tilde{\mathbf{y}}_k = \mathbf{z}_k - \mathbf{H}_k \hat{\mathbf{x}}_{k\mid k-1}$
	Innovation (or pre-fit residual) covariance	$\mathbf{S}_k = \mathbf{R}_k + \mathbf{H}_k \mathbf{P}_{k\mid k-1} \mathbf{H}_k^{\mathrm{T}}$
	Optimal Kalman gain	$\mathbf{K}_k = \mathbf{P}_{k\mid k-1} \mathbf{H}_k^{\mathrm{T}} \mathbf{S}_k^{-1}$
	Updated (*a posteriori*) state estimate	$\hat{\mathbf{x}}_{k\mid k} = \hat{\mathbf{x}}_{k\mid k-1} + \mathbf{K}_k \tilde{\mathbf{y}}_k$

Kalman Filter Predictor based Mitigation

An a-priori *n*-step predictor :

- Compensates the delay of the sensor for more than 1 time step obtained from the Kalman Filter
- We assumed constant F_k **and** u_k

for $i = 1{:}n$

$$\hat{x}_k = F_k \hat{x}_{k+i-1} + B_k u_k$$

end

- The recursion is repeated *n* steps at every time instant after the Kalman Filter recursion
- *n* is dependent on the delay in the sensor data and the time step of the control algorithm

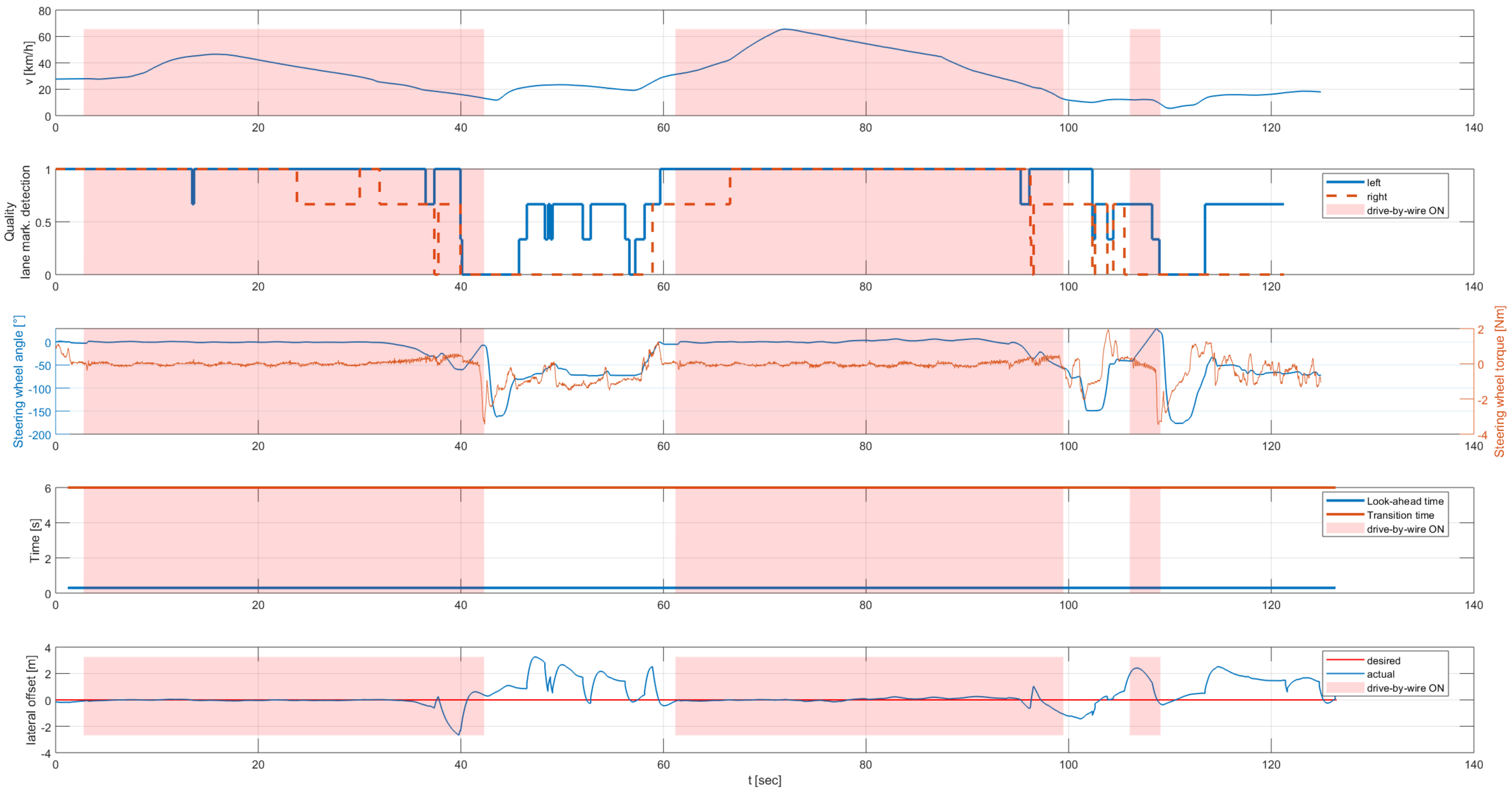
Simulative Comparison w/wo the Kalman Filter

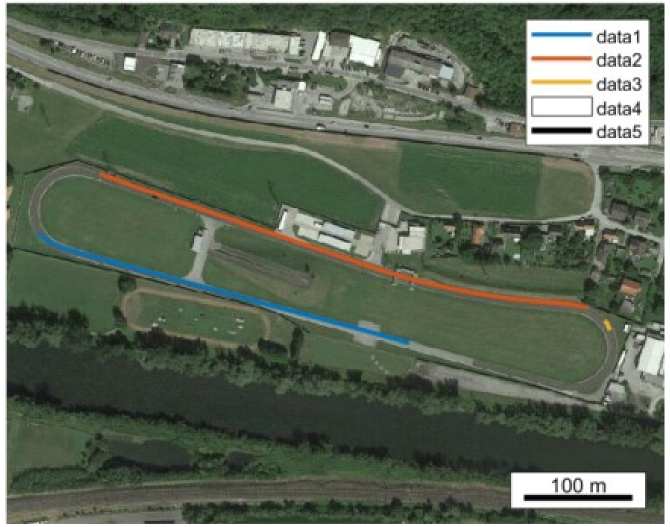
without the Kalman Filter Predictor

with the Kalman Filter Predictor

Simulative Comparison w/wo the Kalman Filter

Final Tests with the Enhanced LKA Function

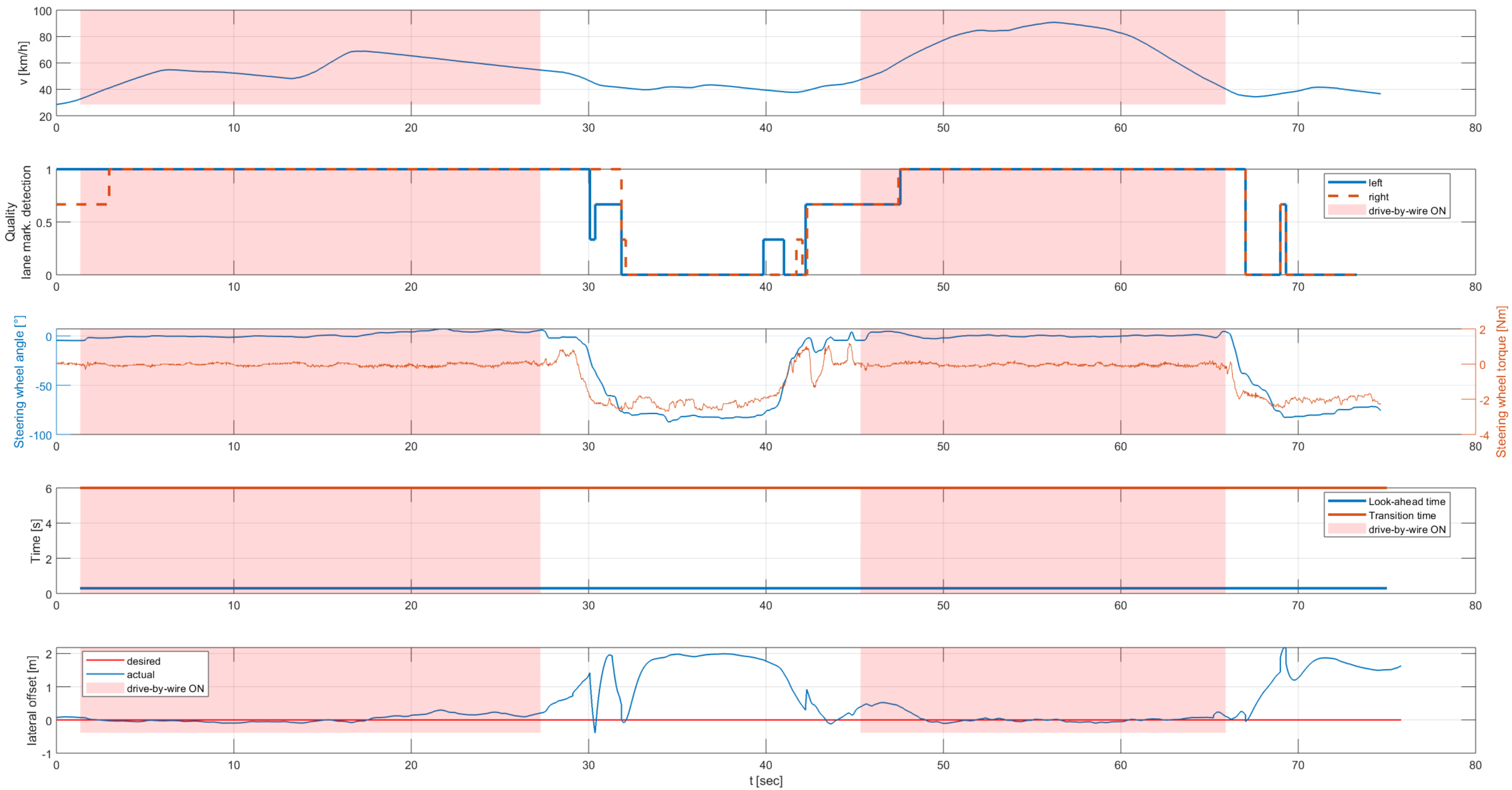


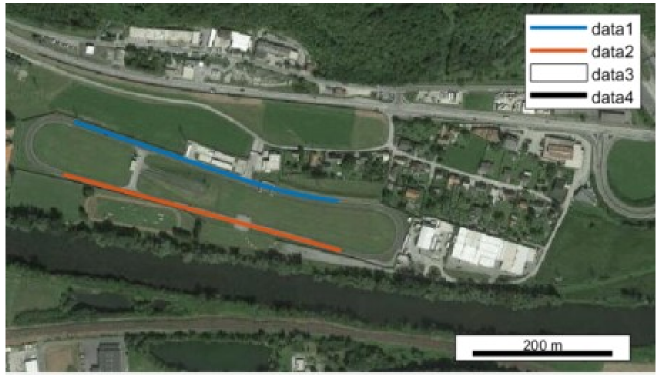


Our final LKA test in AVL test track in Gratkorn (26/11/2018)

"Test-1"

Final Tests with the Enhanced LKA Function





Our final LKA test in AVL test track in Gratkorn (26/11/2018)

“Test-2”

Final Tests with the Enhanced LKA Function

- Our final LKA test in AVL test track in Gratkorn (26/11/2018)
- "Test-2 Video"

Conclusions and Outlook

- MWC controllers were developed and tested based on a simulation environment
- Test track and test vehicle experience indicated that there are many differences between the simulation environment and the real-life implementations of the controllers
- We gained plenty of experience on how to detect the problems in the real vehicle implementations and how to address these issues
- Final state of the ADAS functions can be used for autonomous vehicle implementations for different classes of vehicles

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THANK YOU

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