Challenges and Approaches for the Correlation of virtual and real testing

UNECE VMAD SG2 Workgroup Meeting Feb. 17th 2021

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Workgroup Lead International Alliance for Mobility Testing and Standardization

Targets / Takeaways

1. Describe the main challenges correlating virtual and real testing / applying virtual testing methods for ADAS/AD
2. Show examples and existing approaches
3. Discuss the key topics model, tool and toolchain

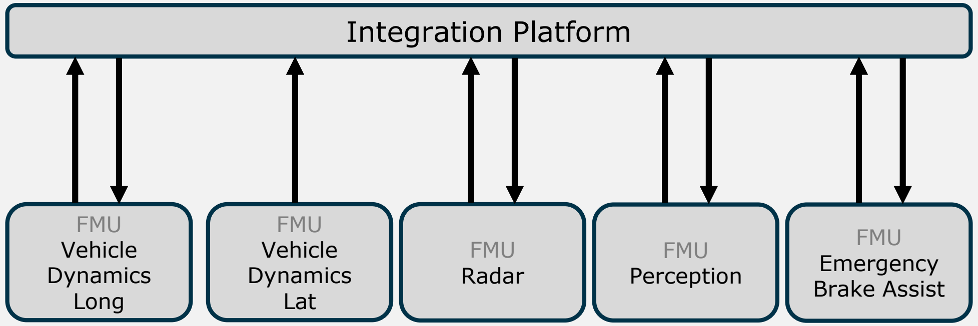
The virtual vehicle

The virtual vehicle in a virtual testing toolchain

- **Steering model** (lane keeping and path driving)
- **Brake model** (including high dynamics; e.g., for emergency braking)
- **ABS controller** (in case of dynamic braking)
- **Suspension model** (movement of chassis and influences on field of view of sensors, special use case truck with trailer)
- **Powertrain model** and **powertrain management** (acceleration capabilities; e.g., for overtaking or highway entrance)
- **E.g. Virtual lanes** (relevant properties, reflections, interruptions, color)
- **Sensor models** (e.g. camera model with relevant effects which can be also simulated in the virtual environment)

Source: IAMTS/AVL

Conclusion 1:
Virtual Testing in ADAS/AD means setting up a virtual vehicle with different components out of different domains in different tools…



Source: simplified based on Marius Feilhauer: "Simulationsgestützte Absicherung von Fahrerassistenzsystemen", Dissertation, Stuttgart 2018

Table 59. Simulation Software Examples

Simulated ADS Process	Simulation Type	Description	Example Software Applications
1a, 2	Sensor Fusion	Represents applications that emulate sensor data when an environment is presented to them. The sensor data could be developed either in the form of vector graphics or as a sensor point cloud.	MATLAB ADS Toolbox
1b	V2V/V2I Communication	Represents applications that emulate communications interaction between vehicles and other infrastructure elements so that parameters such as latency and error rates can be incorporated into data packets.	Riverside Modeler, OMNET, etc.
3	Simulate World Models	Represents applications that emulate the world model, either based on sensor data or from a known environment.	Cognata, MATLAB ADS
5	Vehicle Dynamics	Represents applications that emulate the physical characteristics of a vehicle when subject to path-planning and navigation decisions.	Simulink, CarSim, etc.
Process	Transportation Network Modeling	Represents applications that can emulate V2V, V2I, and vehicle-to-pedestrian interaction with respect to the navigation of each of the elements in a transportation network.	Vissim, Aimsun, TransModeler, etc.

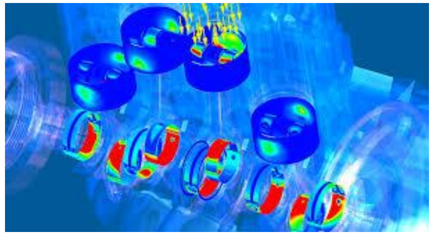
Source: NHTSA: A Framework for Automated Driving System Testable Cases and Scenarios

Modelling and Modelling Requirements

Public

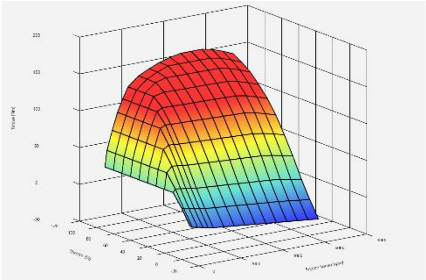
Model Fidelity Levels –
What is required and how to describe it?

Powertrain / Engine



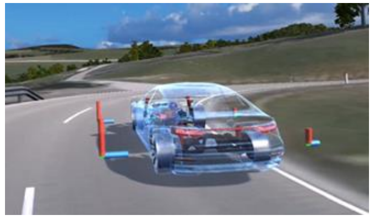
3D Engine Model

vs.



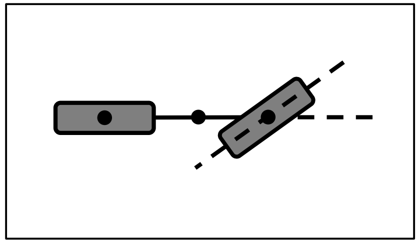
Engine Map

Vehicle / Chassis



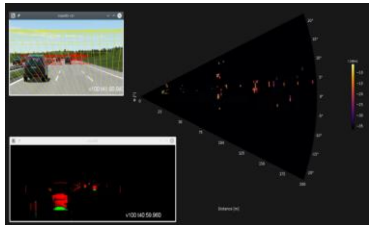
Multi DOF 3D Model

vs.



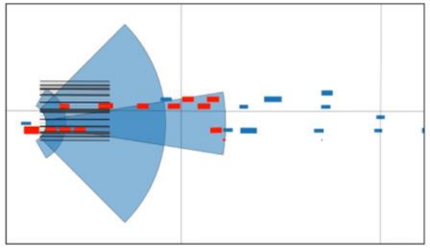
Single Track Model

Sensor



Ray-Tracing-based Model

vs.

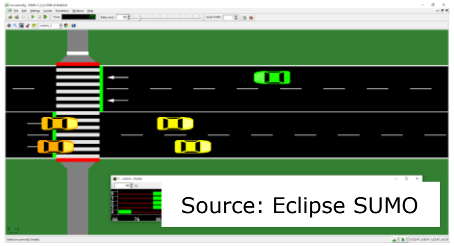


Geometrical Model

Environment

Photo-realistic Simulation

vs.



2D Simulation

Fidelity Levels for Subsystem Models
Example Vehicle Dynamics Lane Keep Assist

- General model fidelity levels of a mechanical system:

Model fidelity level	Description
0	None
1	Steady state models
2	Transient models
3	Oscillatory models

Source:
ISO/DIS 11010-1
Passenger cars — Simulation model classification —
Part 1: Vehicle dynamics

- Example (excerpt) for brake system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
BRM 0	no brake pressure modulation					
BRM 1	Steady-state	Pressure in wheel brake cylinder, system oriented	Pressure in wheel brake cylinder proportional to master cylinder pressure	Pressure in wheel brake cylinder as a function of target deceleration, vehicle mass, tyre radius, brake friction coefficient	e.g target deceleration	Pressure in wheel brake cylinders
BRM 2.1	Transient	Pressure in wheel brake cylinder, system oriented	Volume flow and pressure due to elasticity in the brake system	Bernoulli, characteristic curves and lines, (Typ1), pV-characteristics; <10 DGLs 1. ORD	Pressure in the master brake cylinder	Pressure in wheel brake cylinders
BRM 2.2	Transient with control	Pressure in wheel brake cylinder, system oriented	BRM2.0 with valve and pump actuation	BRM 2.0 with valve current and pump voltage >10 DGLs 1. Ord, 1 DGL 2. Ord.	Pressure in the master brake cylinder, Valve and pump actuation	Pressure in wheel brake cylinders, voltage of pump motor
BRM 3.1	Oscillatory with control	Pressure in wheel brake cylinder, system oriented	BRM 2.x with brake pipe dynamics up to 40Hz	BRM2.x with brake pipe dynamics based on acoustic theory	Pressure in the master brake cylinder, Valve and pump actuation	Pressure in wheel brake cylinders, voltage of pump motor

Fidelity Levels for Subsystem Models
Example Vehicle Dynamics Simulation for Lane Keep Assist

Model Class	Fidelity	Details
Vehicle	VHM 2.2	3D Model with rigid bodies incl. wheel bounce
Aerodynamics	AEM 1.2	longitudinal drag forces, front and rear lift forces
Brake	BRM 1.0	Pressure in wheel brake cylinder, system oriented
Powertrain	PTM 1.0	static correlation accelerator pedal to sum of driving forces
Steering	STM 3.1	Elasto-kinematics steering model includes steering ratio, elasticity, mass, inertia, damping and coulomb friction
Suspension	SUM 1.3	kinematic and compliance is stored in table
Tire	TIM 2.1	All forces and moments are calculated with PT1 behavior

Source: joint project focusing on virtual-based homologation of LKAS between: PORSCHE, AVL, Hochschule Kempten University of Applied Sciences, TÜV SÜD

Fidelity Levels for Subsystem Models
Example Environment Simulation

What are fidelity levels / model parameters for e.g. street lights:

- Luminous flux
- Luminous intensity
- Luminance
- Light color

…

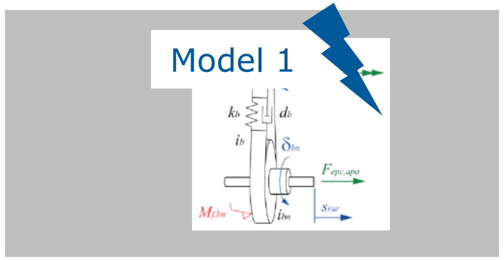
- LED flickering effects (as some perception methods evaluate this)

Conclusion 2:
Defined Model Fidelity Levels (also for Sensor and Environmental Models) will help to setup the virtual testing toolchain and to assess it!

Simulation Toolchain and Virtual Vehicle Integration

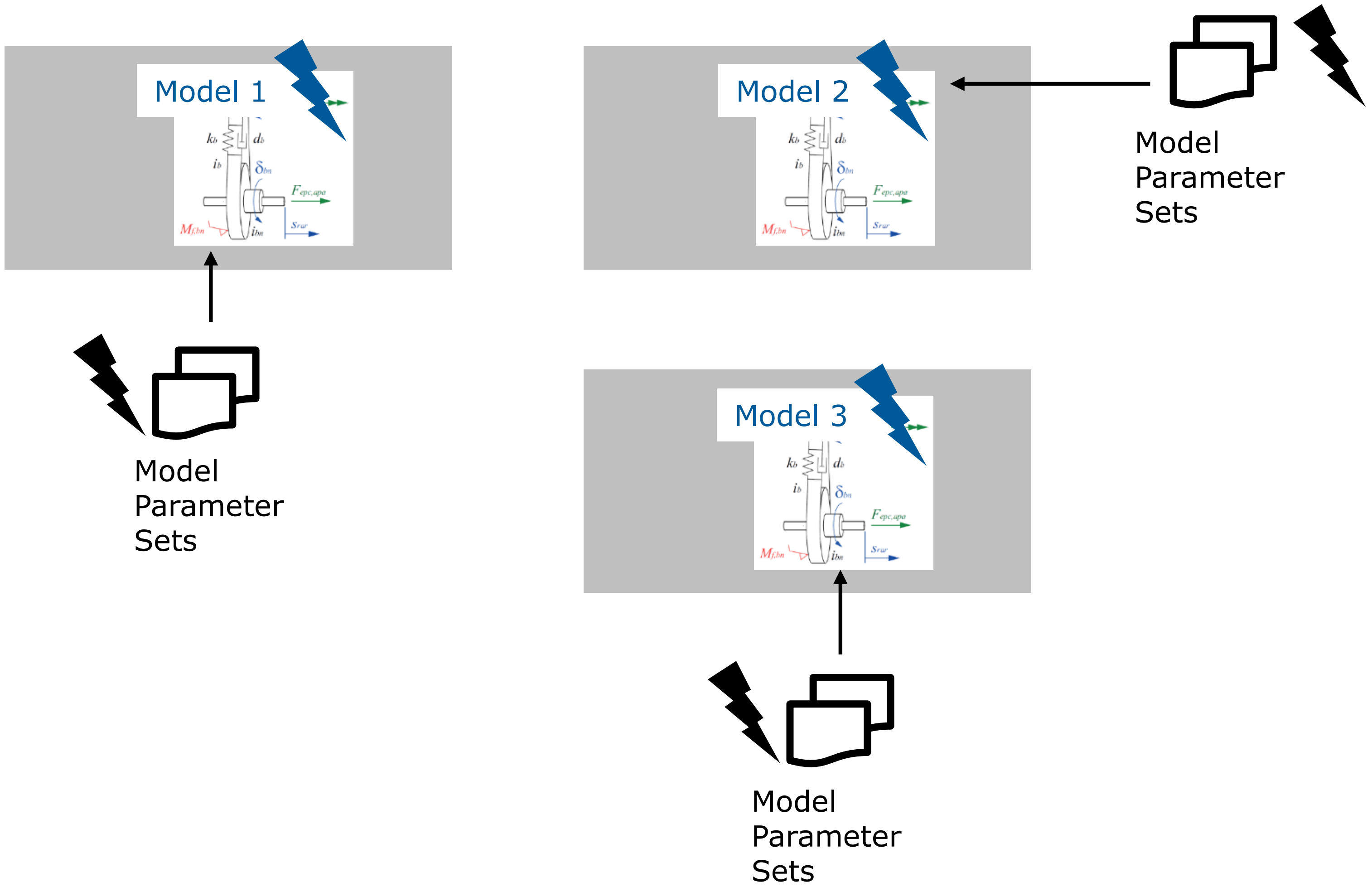
Public

Typical setup for system simulation

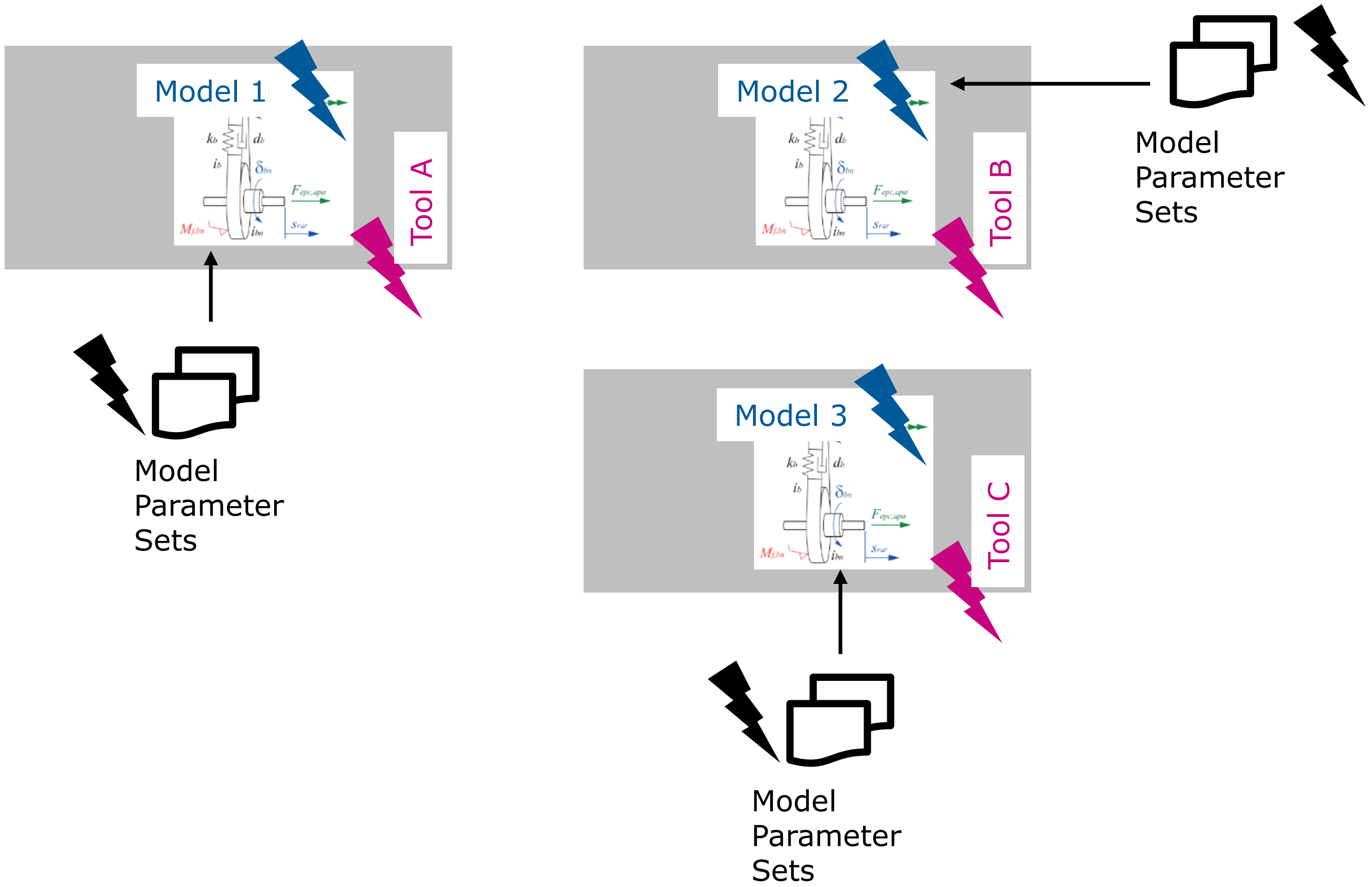


Typical setup for system simulation

Typical setup for system simulation



Typical setup for system simulation



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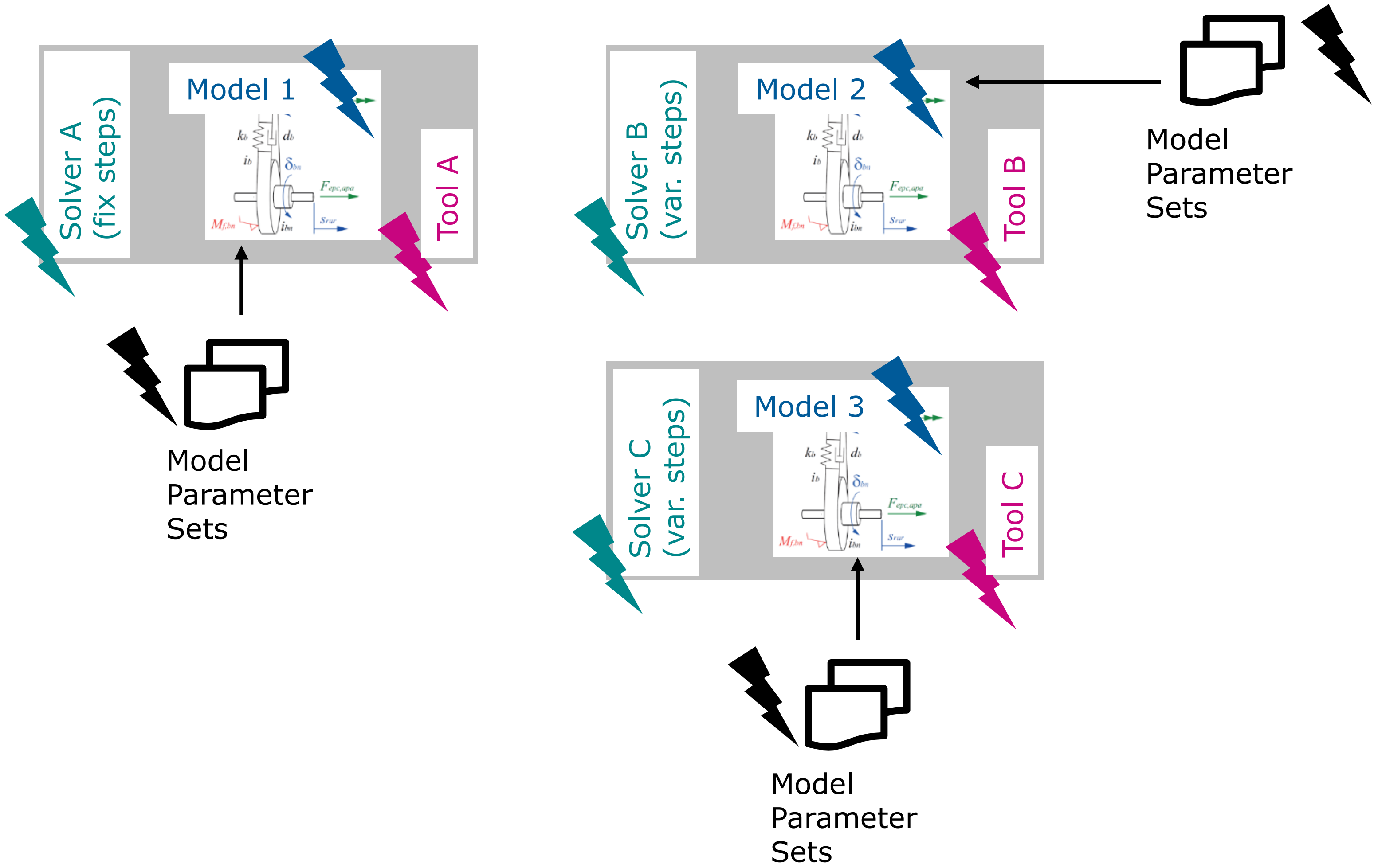

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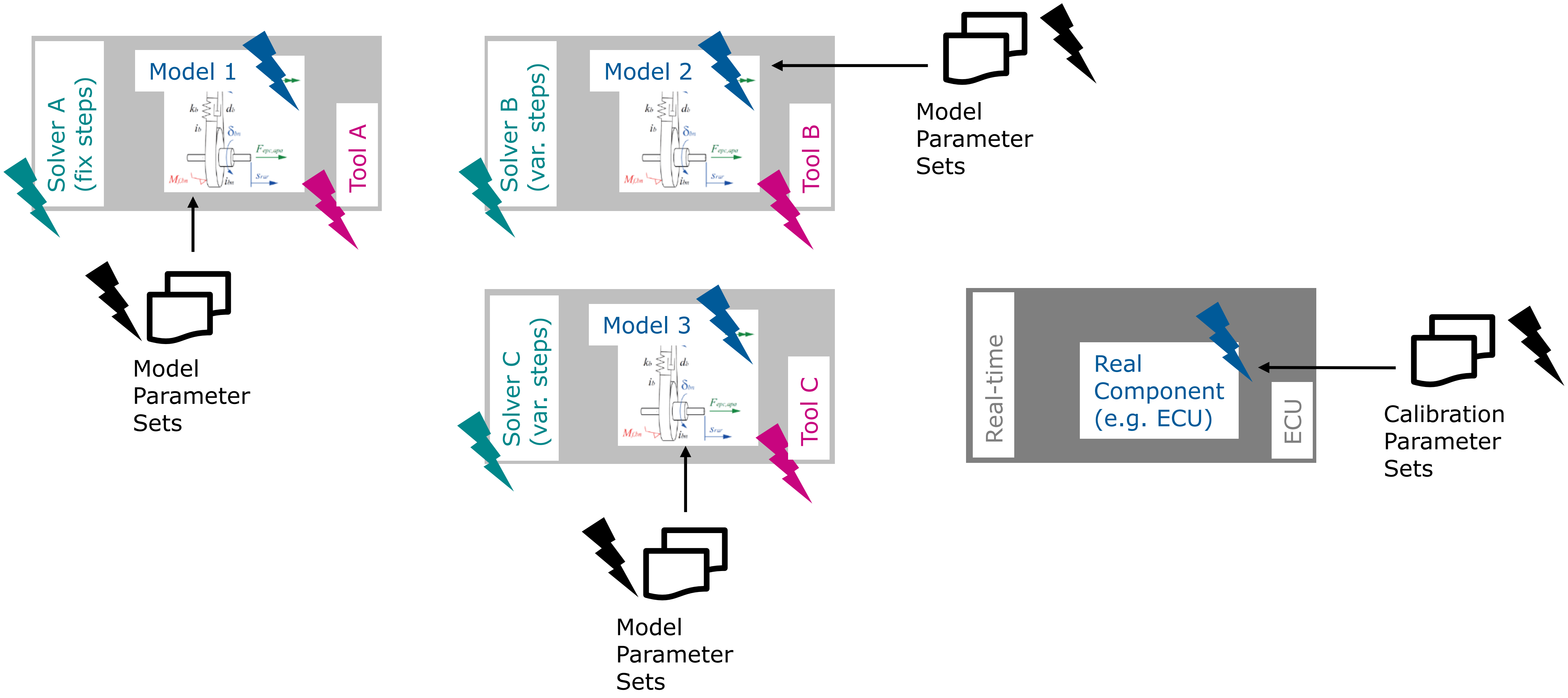
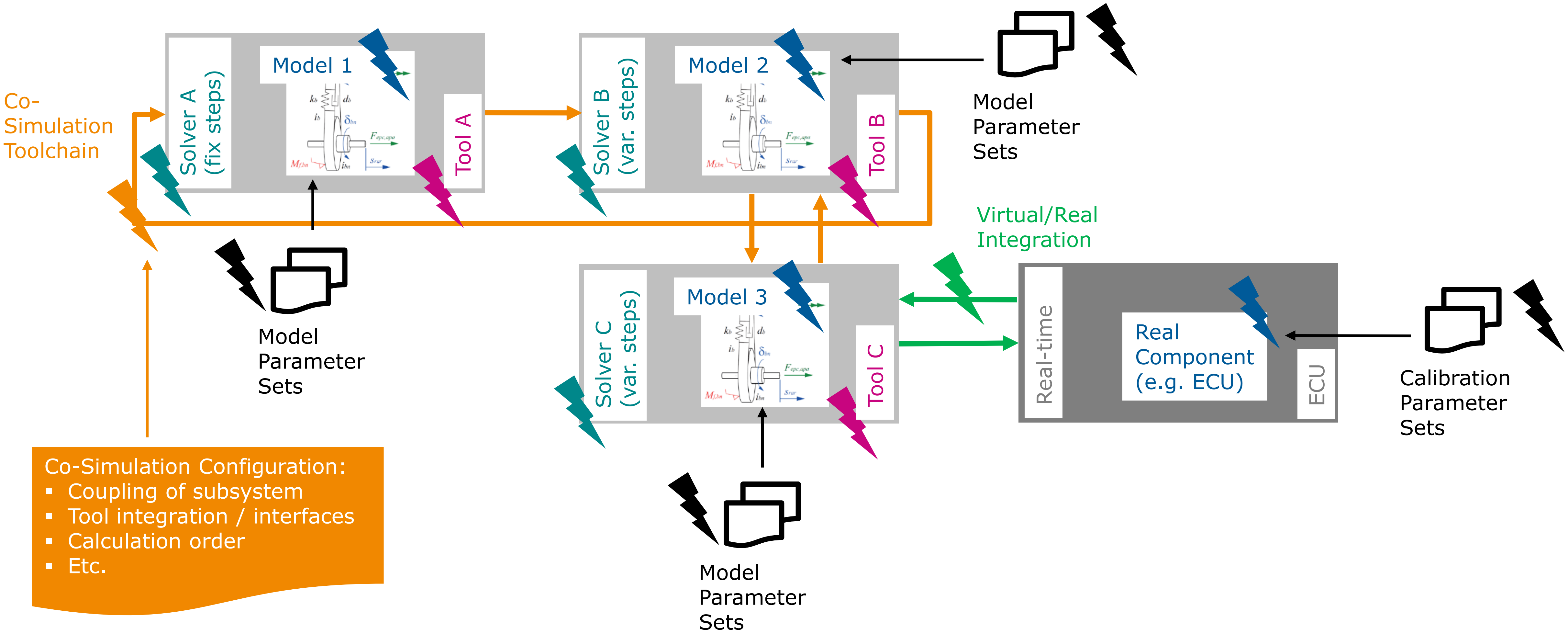


Typical setup for system simulation



The Co-Simulation Challenge
Influence Coupling Error

Requirements and Challenges (Details):

Technical View:

- Multi-domain development
- Multi-tool approach
- Multi-vendor
- Dynamic coupling
- ➢ **Virtual prototype representation**

Mathematical View:

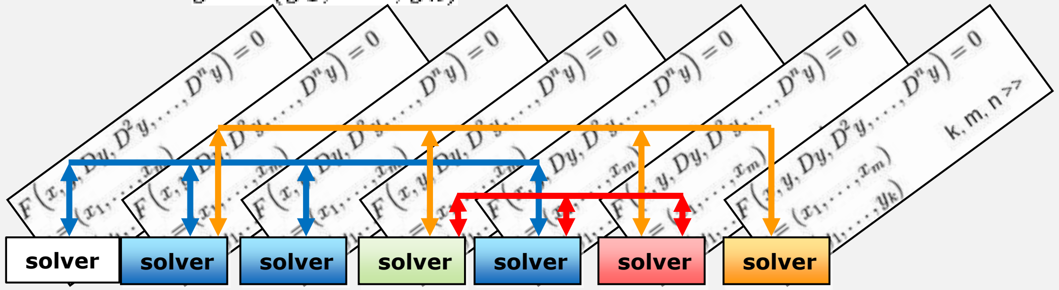
- Multi-method
- Multi-solver
- Multi-rate
- Dynamic coupling
- ➢ **Coupling error**

$$F\left(x, y, Dy, D^2y, \ldots, D^ny\right) = 0$$

$$x = (x_1, \ldots, x_m)$$

$$y = (y_1, \ldots, y_k)$$

k, m, n >>

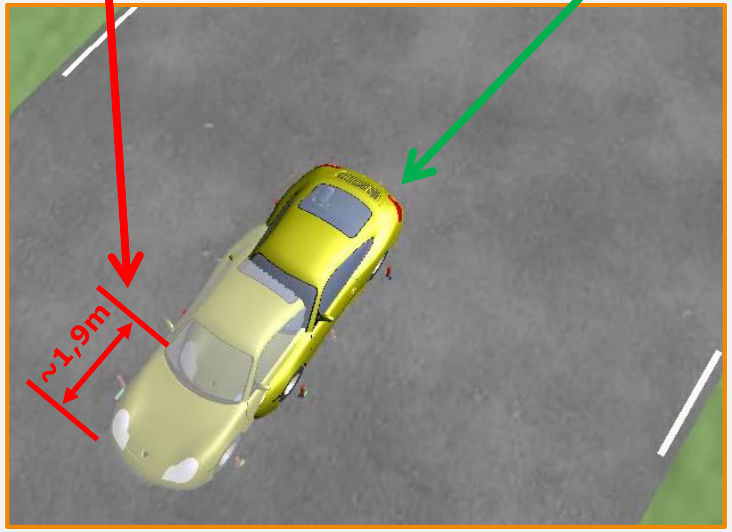


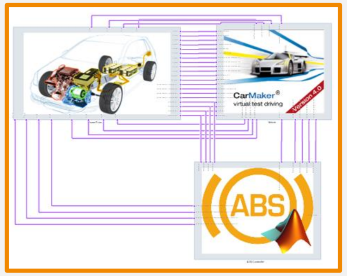
Example:

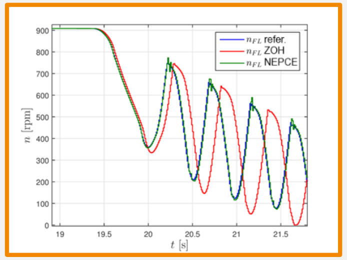
AEB Scenario:
“Full braking after acceleration to 100 km/h”

Significantly longer braking distance (~1.9 m) due to coupling error!

Correct (co-)simulation result coupling algorithm

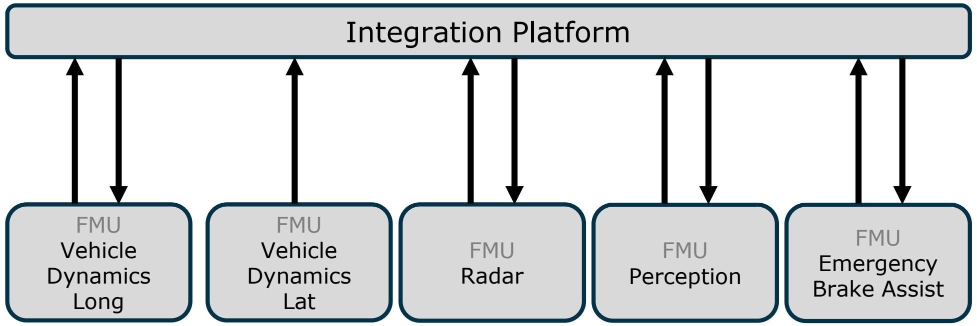




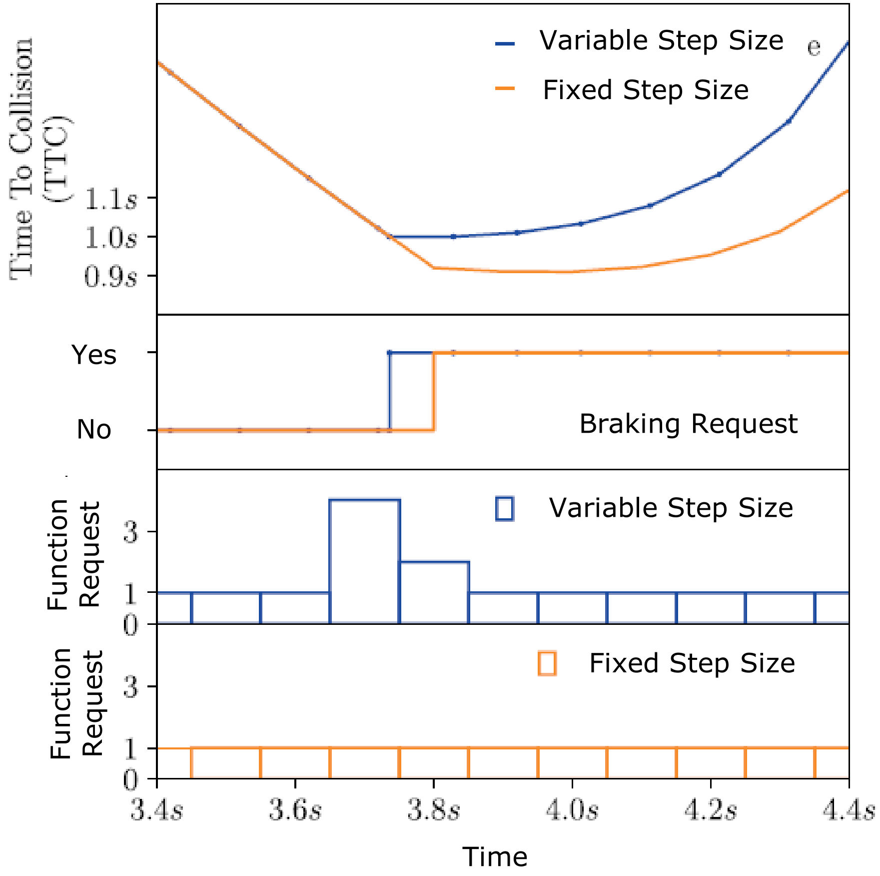


Source: AVL

The Co-Simulation Challenge
Influence of Step-Size



Source: simplified based on Marius Feilhauer: "Simulationsgestützte Absicherung von Fahrerassistenzsystemen", Dissertation, Stuttgart 2018



Source: Marius Feilhauer: "Simulationsgestützte Absicherung von Fahrerassistenzsystemen", Dissertation, Stuttgart 2018

Connection between coupling algorithms and step size

- Changing step size of one model from 0.03 s (magenta) to 0.01 s (blue)
- Different coupling (parallel, par. fast.) algorithms help to find the best trade off between simulation time and error

Conclusion 3:
…It is not sufficient to validate on "integrated system level" only.
…It is not sufficient to validate each sub-model only.

Both must be done to identify failures!
Evaluation of Co-Simulation accuracy must be considered!

Determinism in Simulation Tools and Toolchains

Source: https://carla.org/2020/12/22/release-0.9.11/

Conclusion 4:
Determinism must be evaluated
(on tool and toolchain level, especially for systems integrating real components)

Validation Process

IAMTS Reference Process
for the correlation of the virtual and real world

iamts
International Alliance for Mobility Testing and Standardization
A Program of SAE ITC

Operational Design Domain | Scenarios and Test Cases | System Analysis

Preparation of Toolchain Validation

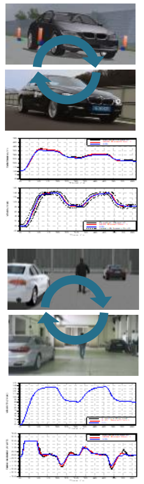
- Analyze ODD
- Evaluate Testing Scenarios
- Define Model Requirements based on Model classes and Fidelity Levels
- Define Toolchain Requirements

Model and Toolchain Requirements

Developed Models | Measurement Data

Execution of Toolchain Validation

1. Validate Subsystems Models
2. Validate Vehicle-System
3. Sensor System
4. Validate integrated System
   4.1 Replay with Raw Data
   4.2 Replay with Perception
   4.3 Closed-loop with ADAS/AD Function



KPIs and Results for System Simulation and Toolchain Validation and Qualification

Scenarios and Test Cases

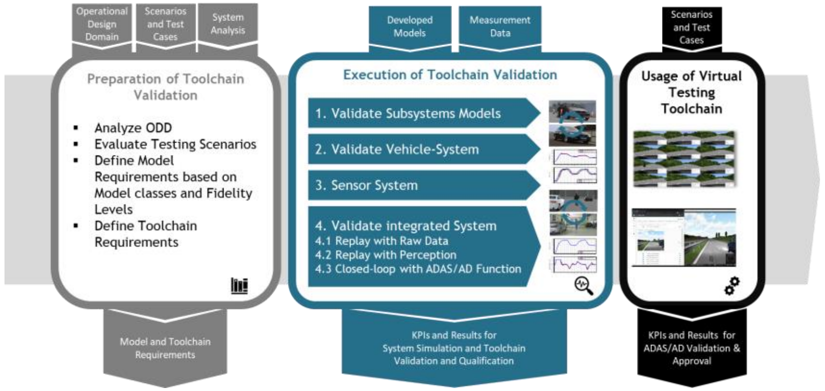
Usage of Virtual Testing Toolchain

KPIs and Results for ADAS/AD Validation & Approval

Source: IAMTS

General Remarks VMAD Context

- The process describes a comprehensive approach to correlate the virtual and the real world
- It refers to the REGULATION (EU) 2018/858 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL which already distinguishes between a Validation and an Approval Process
- Because of the different integration steps, it provides a traceable approach to identify problems and deviations



Source: IAMTS

But:

- It is not required to go every time through all steps (e.g. if subsystem models already existing)
- As there are different stages of the model and toolchain integration there are different KPIs on different levels (low level KPIs to assess the validity of subsystem models or high level KPIs to access the validity of the integrated system)
- **Applying a correlation process in a regulation needs a tailoring, not every step could be prescribed in a regulation (maybe only the high level KPIs while the rest is part of an audit process) → needs to be worked out**

Validation of the Vehicle System Relevance (1)

Test Variations		Key Performance Indicators (KPIs)				GSR result
Run	v_ego [kph]	Max. decel. [m/s²]	TTC at 1st reaction [sec]	Collision y/n	Braking distance [m]	
1	20	-8.545	1.240	n	2.103	Pass
2	42	-9.836	1.286	n	6.595	Pass
3	60	-9.921	1.307	n	14.77	Pass

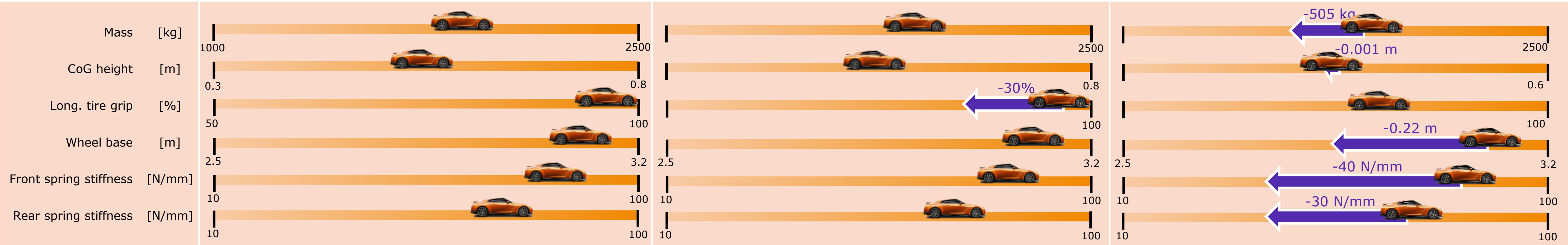
Test Variations		Key Performance Indicators (KPIs)				GSR result
Run	v_ego [kph]	Max. decel. [m/s²]	TTC at 1st reaction [sec]	Collision y/n	Braking distance [m]	
1	20	-8.034	1.281	n	2.091	Pass
2	42	-8.624	1.294	n	7.973	Pass
3	60	-8.744	1.255	n	14.785	Pass

Test Variations		Key Performance Indicators (KPIs)				GSR result
Run	v_ego [kph]	Max. decel. [m/s²]	TTC at 1st reaction [sec]	Collision y/n	Braking distance [m]	
1	20	-7.884	1.273	n	2.352	Pass
2	42	-8.195	1.303	n	8.831	Pass
3	60	-8.269	1.330	n	17.509	Pass

Source: AVL

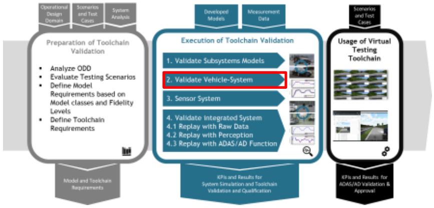
Validation of the Vehicle System Relevance (2)

		Limousine			Limousine with winter tires			Compact class		
Run	**V_ego [km/h]**	**Max. decel. [m/s²]**	**TTC at 1st reaction [sec]**	**Braking distance [m]**	**Max. decel. [m/s²]**	**TTC at 1st reaction [sec]**	**Braking distance [m]**	**Max. decel. [m/s²]**	**TTC at 1st reaction [sec]**	**Braking distance [m]**
1	20	-8.545	1.240	2.103	-7.884	1.273	2.352	-8.034	1.281	2.091
2	42	-9.836	1.286	6.595	-8.195	1.303	8.831	-8.624	1.294	7.973
3	60	-9.921	1.307	14.77	-8.269	1.330	17.509	-8.744	1.225	14.785



Source: AVL

Validation of Vehicle System Example for Lane Keep Assist

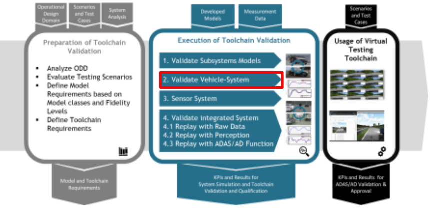


Maneuver	Physical testing	Simulation and validation
Static		
COG measurement		
Spring deformation meas.		
Steering ratio meas.		
Longitudinal		
Acceleration		
Braking		
Coasting		
Lateral response		
Steady-state cornering	ISO 4138	ISO 19364
Sine with Dwell	UN/ECE-R13H, FMVSS 126	ISO 19365
Slalom		
Severe lane change	ISO 3888-2	
Lateral transient response		
Step steer	ISO 7401	ISO 22140 NWIP
Sine sweep	ISO 8726	ISO 22140 NWIP
On-center handling	handling	
Weave test	ISO 13674-1	Pfeffer validation program
Transition test	ISO 13674-2	ISO 19364

KPIs (Lateral transient response)
Steady-state yaw velocity response gain
Lateral acceleration response time
Yaw velocity response time
Lateral acceleration peak response time
Yaw velocity peak response time
Overshoot value of lateral acceleration
Overshoot value of yaw velocity

Source: joint project focusing on virtual-based homologation of LKAS between:

Validation of Vehicle System
Example for Lane Keep Assist



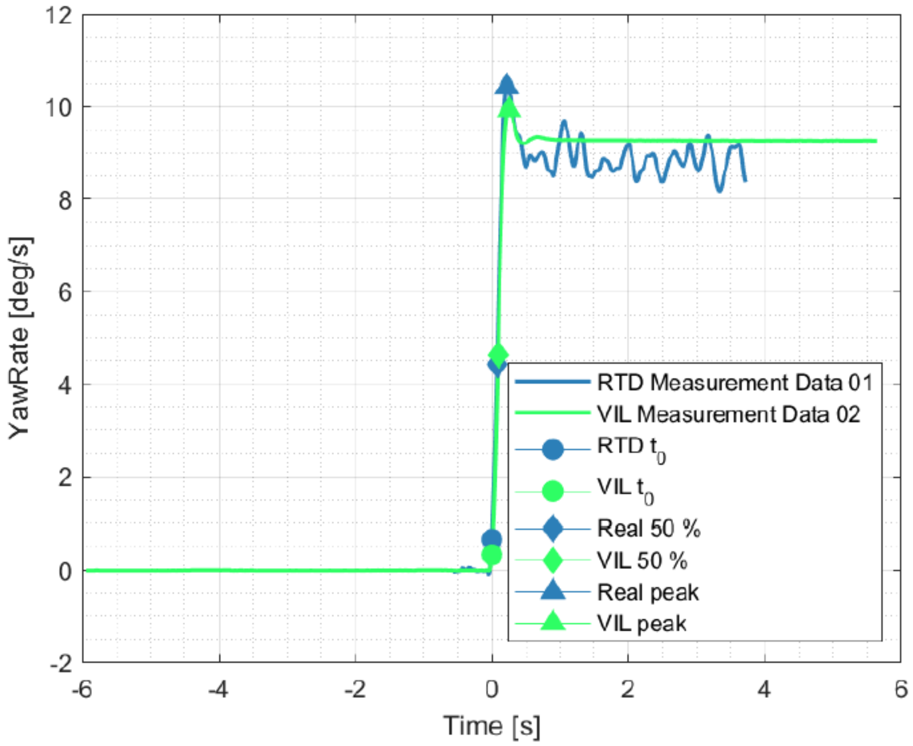


Figure 4.18: Step Steer: Time vs. YawRate

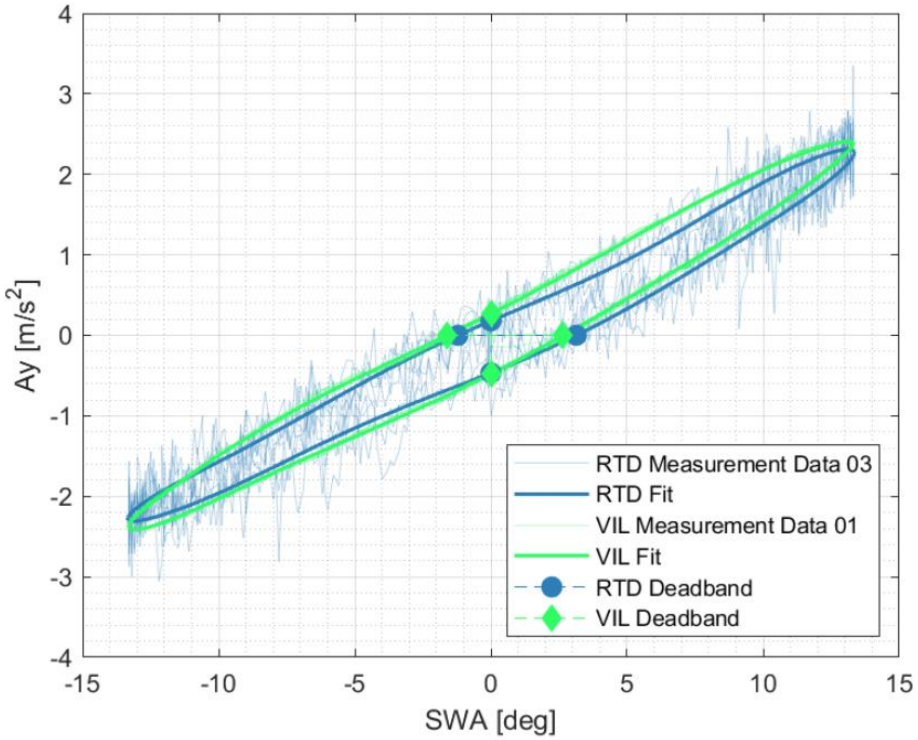
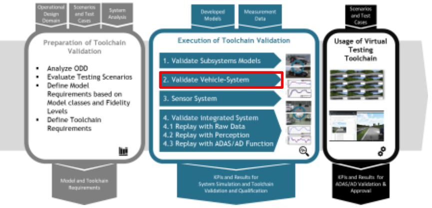


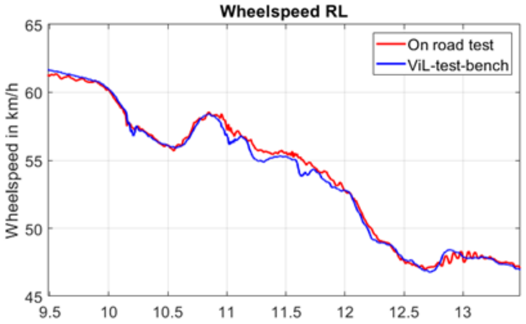
Figure 4.20: Weave Test: Steering Wheel Angle vs. Ay

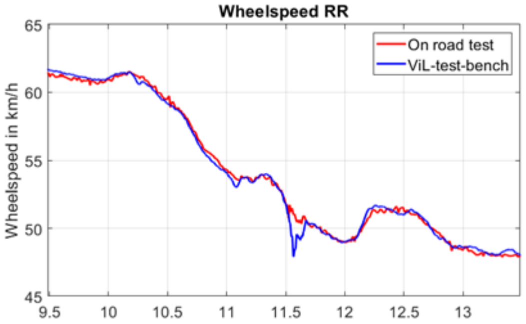
RTD: Real Test Drive
VIL: Vehicle-in-the-Loop at testbed

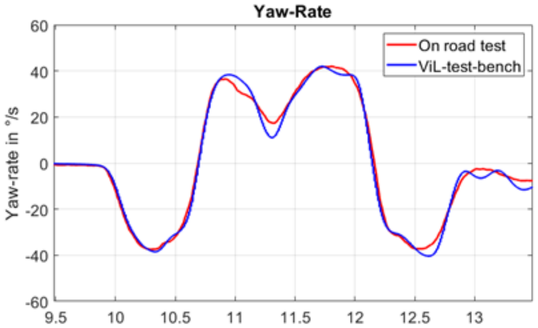
Source: joint project focusing on virtual-based homologation of LKAS between: PORSCHE, AVL, Hochschule Kempten University of Applied Sciences, TÜV SÜD

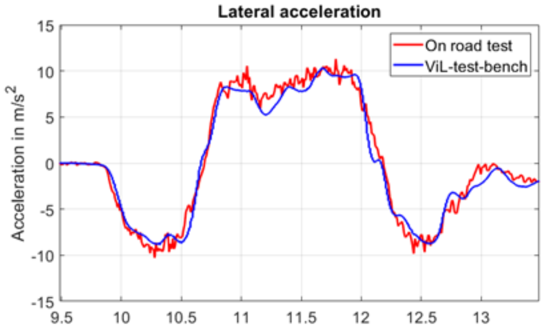
ISO 3888-2 Lane change maneuver with ESC intervention

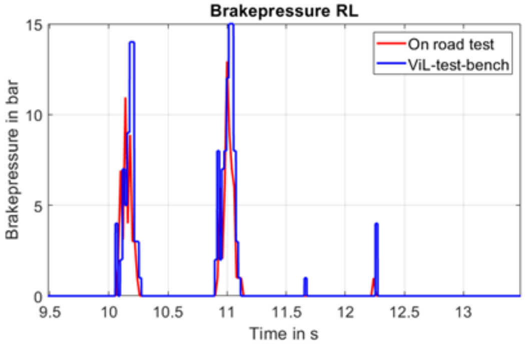


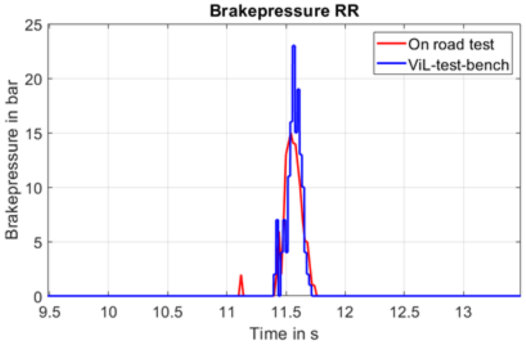


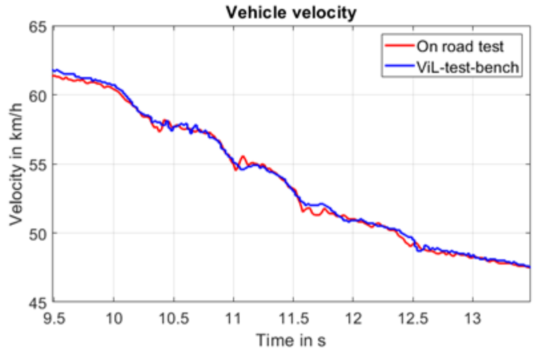


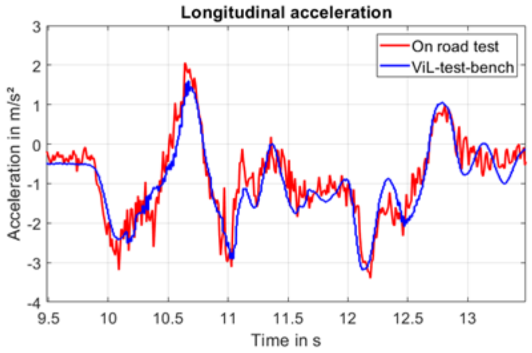












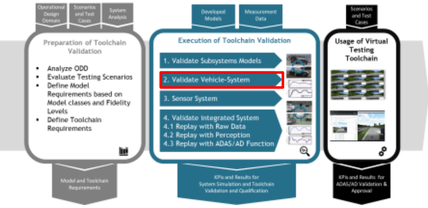
Source: KFZB Kraftfahrzeuge TU Berlin · AVL · Technische Universität Berlin

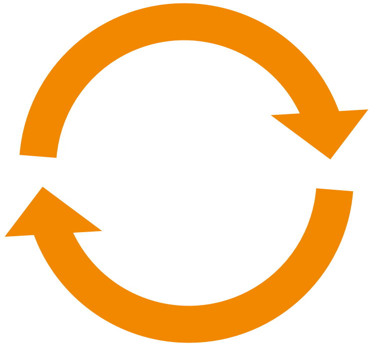
Steering at the Powertrain Test Bench – A New Validation Method for Highly Automated Systems up to the Limits of Vehicle Dynamics

André Hartwecker, M.Sc. Chair of Automotive Engineering, TU Berlin
Prof. Dr.- Ing. **Steffen Müller** Chair of Automotive Engineering, TU Berlin
Osama Al-Saidi, M.Sc. Chair of Automotive Engineering, TU Berlin

8th INTERNATIONAL SYMPOSIUM ON DEVELOPMENT METHODOLOGY, Wiesbaden, 13th November 2019

Validation of Vehicle System
Conclusion





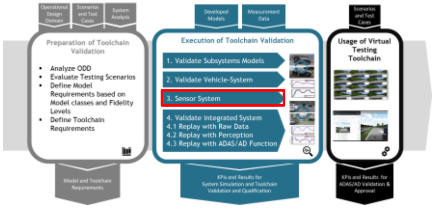
<u>Conclusion 5:</u>

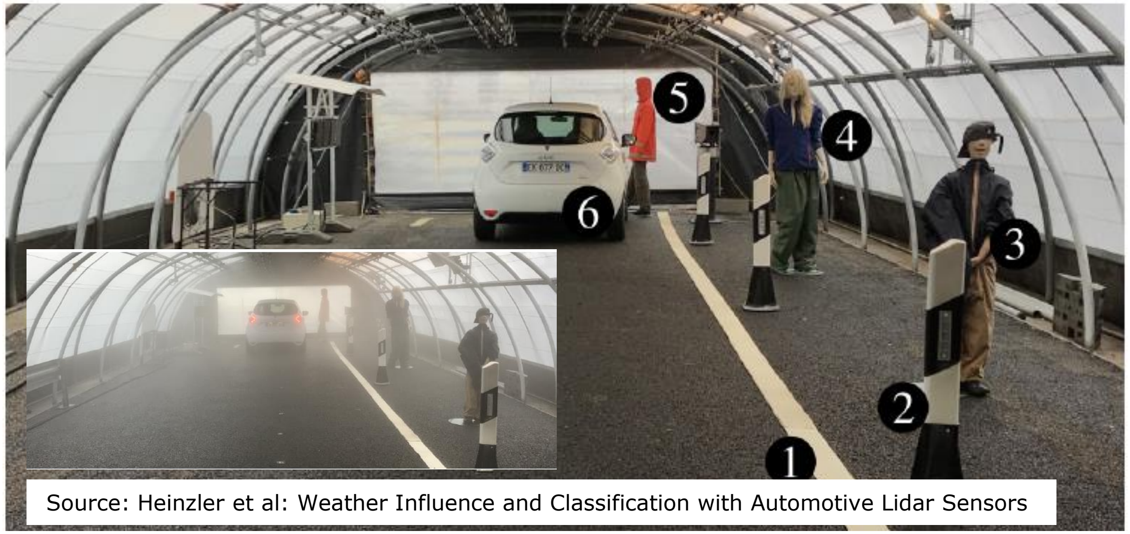
For the Validation of the Vehicle System, several standards are existing and can be also applied in the area of automated driving.

BUT: The focus and the KPIs needs to be reviewed and adapted:

E.g. is the breakaway torque and the friction of the steering system highly relevant as the AD function might be more sensitive than a real driver

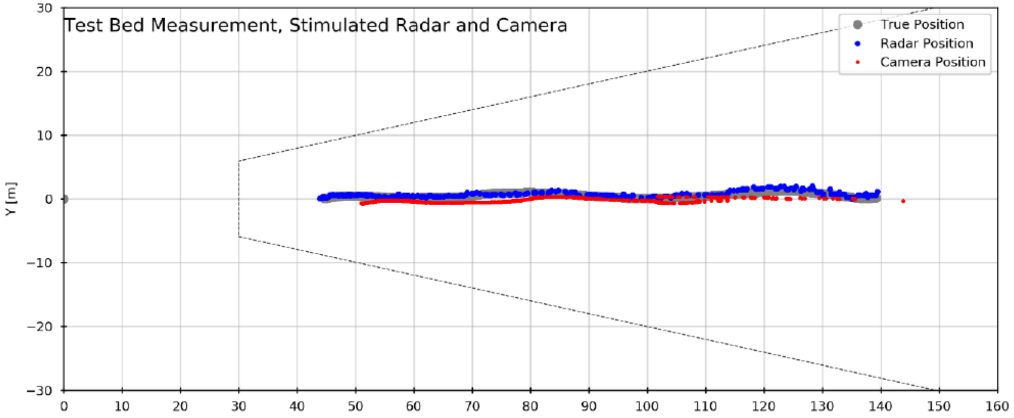
Examples:
Validation of the Sensor System

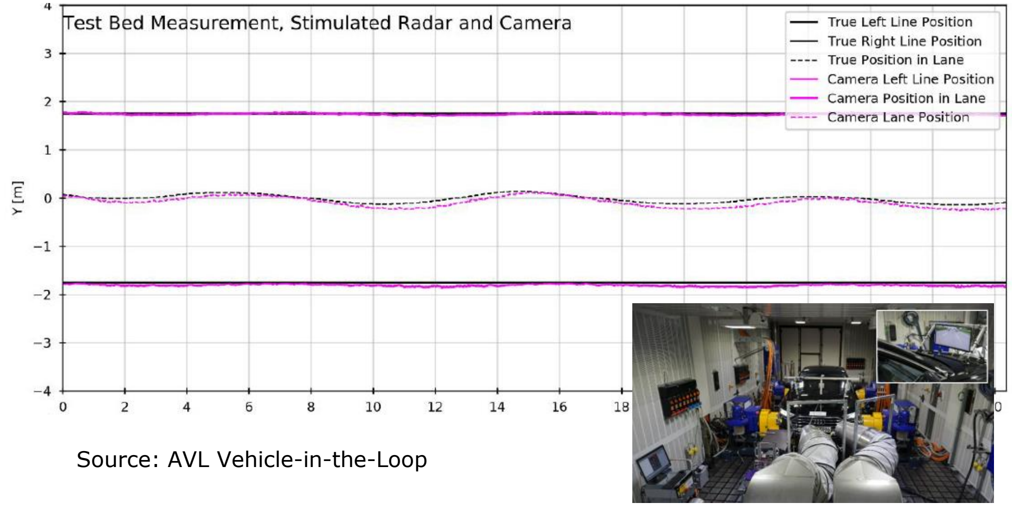




Source: Heinzler et al: Weather Influence and Classification with Automotive Lidar Sensors

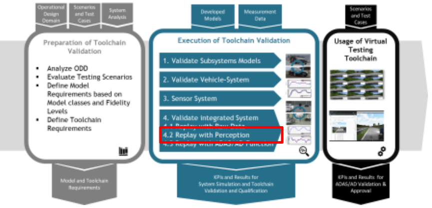
Source: Virtual Vehicle Research GmbH





Source: AVL Vehicle-in-the-Loop

Example: Replay with Perception Influence of Camera Position (Stimulation)

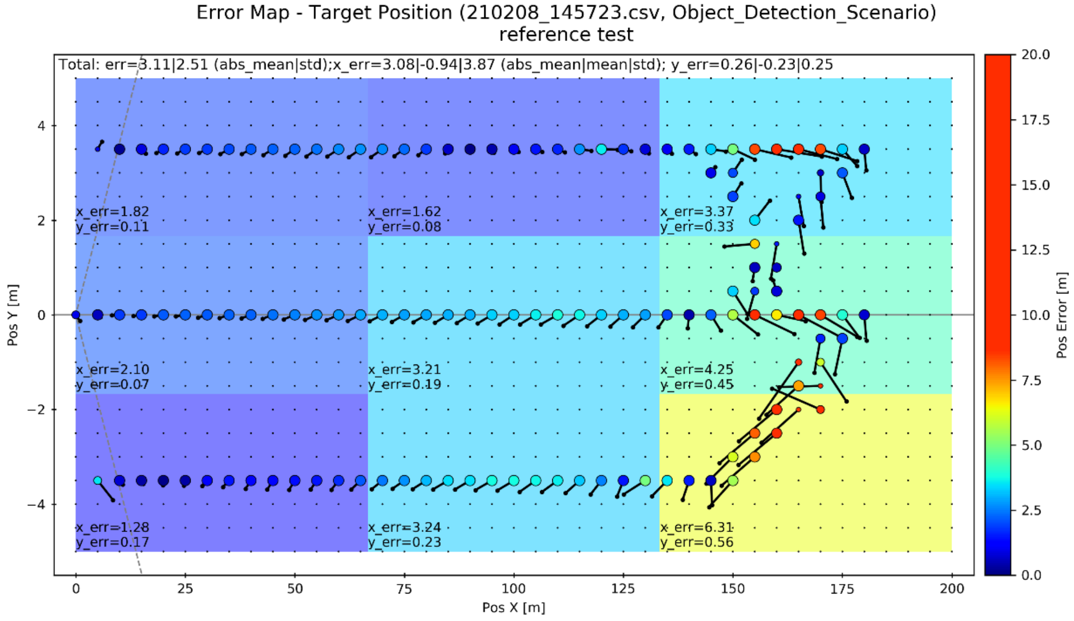


Camera well aligned (reference)

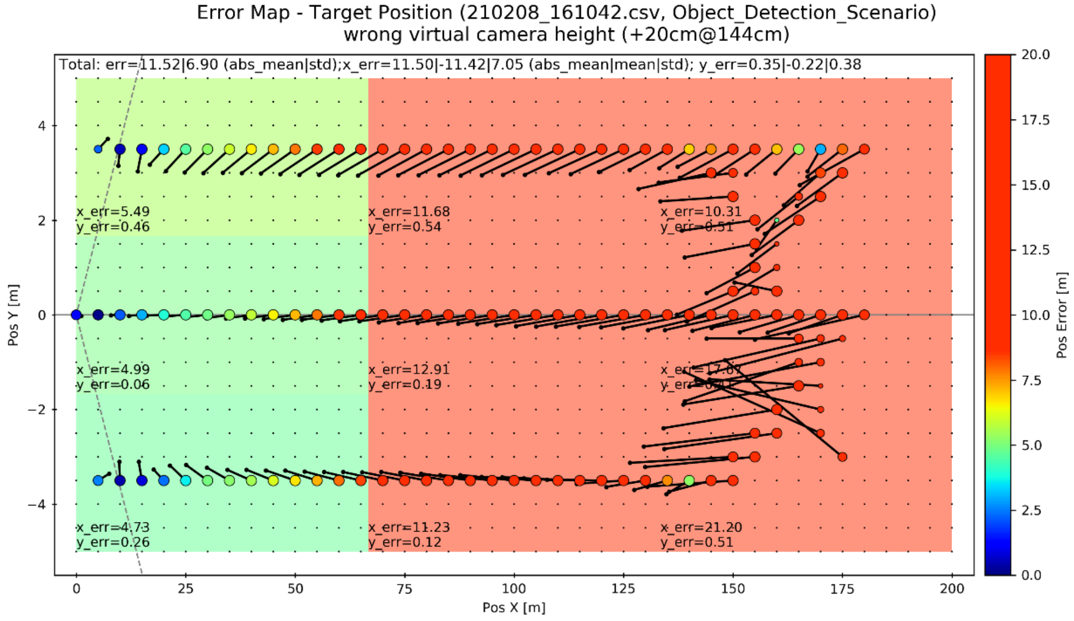
Object 1 in Lane 1

Object 2 in Lane 2

Object 3 in Lane 3



Camera +20cm height failure



Source: AVL Vehicle-in-the-Loop

Remarks:

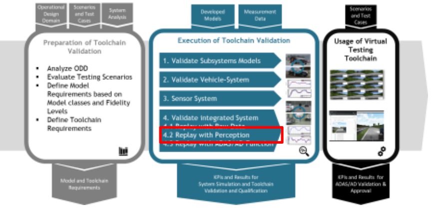
Pos 0 – ca. 135 m: staying in lane

Pos: above ~ 135 m: lane changes

Legend:

size of points:	detection quality
Color:	error
Line an black points:	deviation to real object
colored square:	mean error for distance range

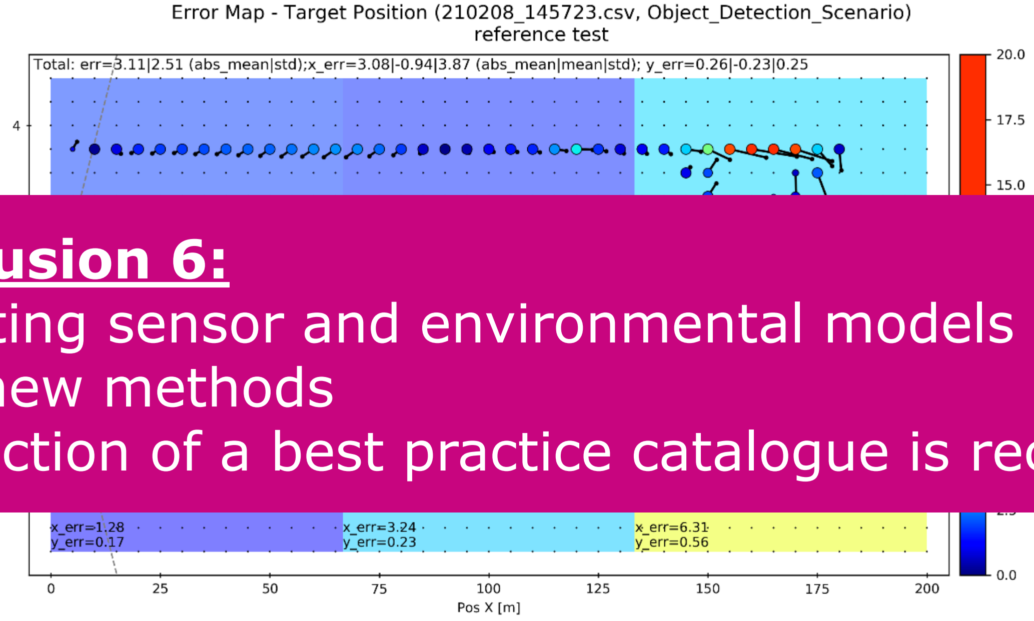
Example: Replay with Perception
Influence of Camera Position (Stimulation)

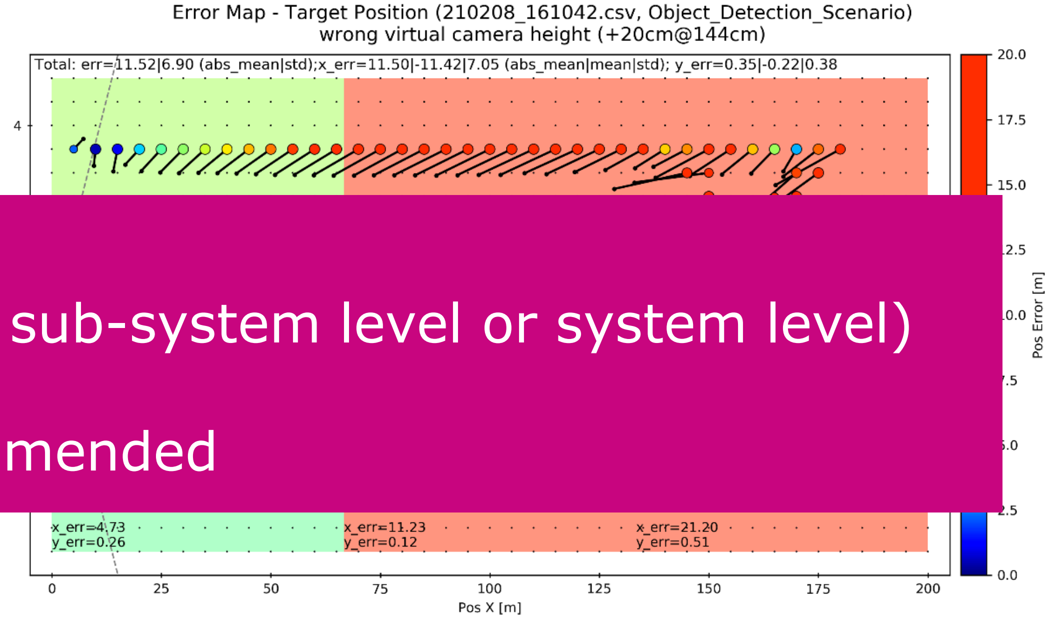


Camera well aligned (reference)

Camera +20cm height failure

Object 1
in Lane 1





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Conclusion 6:
Validating sensor and environmental models (on sub-system level or system level) need new methods
A collection of a best practice catalogue is recommended

Remarks:
Pos 0 – ca. 135 m: staying in lane
Pos: above ~ 135 m: lane changes

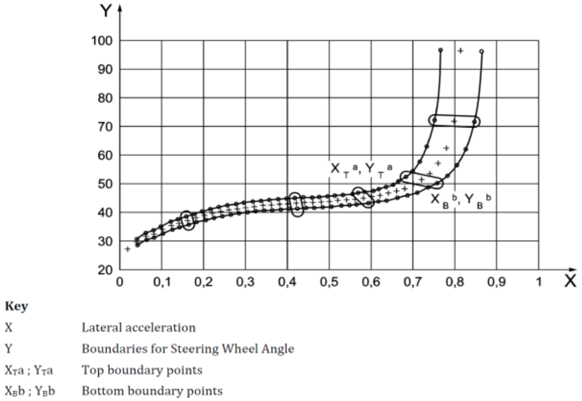
Legend:

size of points:	detection quality
Color:	error
Line an black points:	deviation to real object
colored square:	mean error for distance range

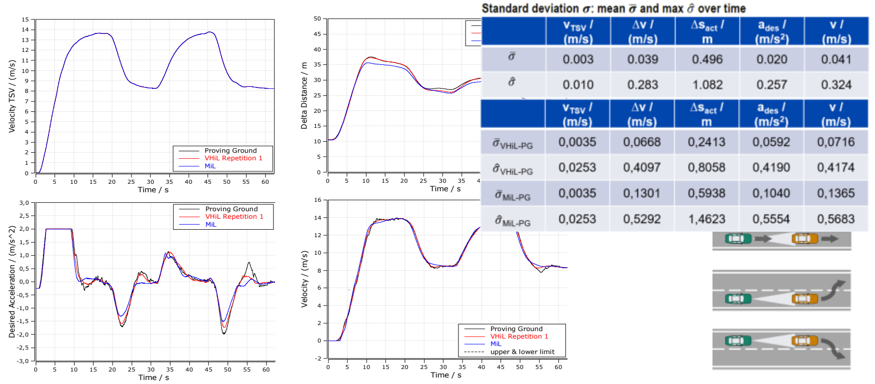
Evaluation and KPIs

Example:
Metrics for Validation

- Validation based on time-based data
  - Compare state changes
  - Compare against tolerance band
  - Apply statistical methods (standard deviation, regression analysis)
- Validation based on KPIs
  - Compare dedicated KPIs
  - Apply statistical methods (standard deviation, regression analysis)
- Validation of numerical behavior
  - E.g. check long-term behavior (integration errors)
  - Etc.



Source:
ISO **19364 Passenger cars —Vehicle dynamic simulation and validation — Steady-state circular driving behaviour**



	v_{TSV} / (m/s)	Δv / (m/s)	Δs_{act} / m	a_{des} / (m/s²)	v / (m/s)
$\bar{\sigma}$	0.003	0.039	0.496	0.020	0.041
$\hat{\sigma}$	0.010	0.283	1.082	0.257	0.324

	v_{TSV} / (m/s)	Δv / (m/s)	Δs_{act} / m	a_{des} / (m/s²)	v / (m/s)
$\bar{\sigma}_{VHiL-PG}$	0,0035	0,0668	0,2413	0,0592	0,0716
$\hat{\sigma}_{VHiL-PG}$	0,0253	0,4097	0,8058	0,4190	0,4174
$\bar{\sigma}_{MiL-PG}$	0,0035	0,1301	0,5938	0,1040	0,1365
$\hat{\sigma}_{MiL-PG}$	0,0253	0,5292	1,4623	0,5554	0,5683

Source:
Riedmaier, S.; Nesensohn, J.; Gutenunst, C.; Düser, T.; Schick, B.; Abdellatif, H.: **Validation of X-in-the-Loop Approaches for Virtual Homologation of Automated Driving Functions**, GSVF Symposium 2018, Graz

Metric	Test run	Tolerance
First peak yaw rate ($\dot{\Psi}_1$ in Figure 2)	Last run without ESC intervention First run with ESC intervention Last run	±15%
Time of yaw rate crossing zero (T_C in in Figure 2)	Last run without ESC intervention First run with ESC intervention Last run	±0,1 s
Second peak yaw rate ($\dot{\Psi}_2$ in Figure 2)	Last run without ESC intervention	±20%
	First run with ESC intervention	±25%
	Last run	±25%
Lateral displacement of the vehicle C.G.	Last run without ESC intervention	±15%
	First run with ESC intervention	±18%
	Last run	±18%

Source:
ISO/DIS 19365 **Passenger cars — Validation of vehicle dynamic simulation — Sine with dwell stability control testing**

Conclusion 7:
Knowing the error and the limitation is already a value, minimizing the error for certain use cases is the second step

Conclusion

Public

Conclusion

- The whole process from sub-systems to the integrated system is relevant for the validation of the virtual testing toolchain
  - Not everything has to be executed every time (e.g. if sub-models are clearly defined and already validated)
  - Some parts of the process can be considered in the audit
  - The toolchain validation tests must be different to the ADAS/AD validation tests
- Defining fidelity levels for the sub-models helps structuring and traceability
- The evaluation and the KPIs must considered not only the important physical signals but also the co-simulation quality, determinism, etc.
- Established validation methods for vehicle dynamics needs to be reviewed and enhanced
- Validating sensor and environmental models (on sub-system level or system level) needs new methods, a collection of a best practice catalogue is recommended before deriving concrete methods
- The validation process needs to consider also mixed environments (with real hardware) like Hardware-in-the-Loop, Drive-in-the-Loop and Vehicle-in-the-Loop