SET Level

Simulation-based Development and Testing of Automated Driving

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

PROJECT of the PEGASUS FAMILY

Simulation Use Case 2 – A closed loop simulation for integration test and validation

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29.04.2021

Agenda

- Introduction to Simulation Use Case 2
  - Goals, Scenario, Architecture, Models, KPIs
- Demonstration of mid-term results
- Summary & Outlook
- Q & A

Introduction of Simulation Use Case 2

Motivation

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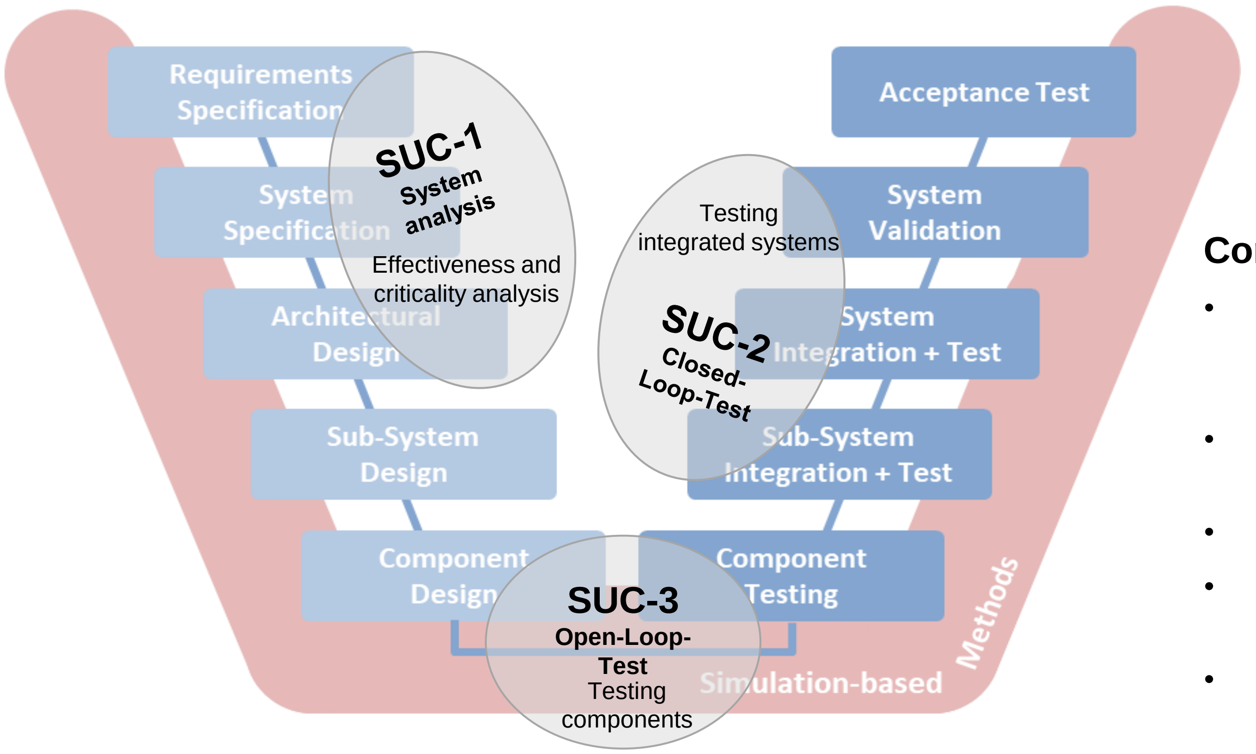

Simulation Use Cases (SUCs):

- Analysis example
- Test examples

Common Demonstration goals:

- Demonstration of the applicability and usability of standards (OSI, FMI, SSP, …)
- Usage of appropriate architectures and interfaces
- Elaboration of KPIs
- Use of the credible simulation process and ensurance of traceability
- Provide project internal feedback and identify need for further work

SUC 2 – Test Goal & Demonstration Goal

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General SUC 2 goals

- Integration test and validation during function/system development
- Test and validation of certain system components or certain functionality in interaction with the overall closed-loop system
- Test and validation of the overall closed-loop system

Mid-Term implementation

System under Test (SuT)

- Highly automatic driving (HAD) function as SuT

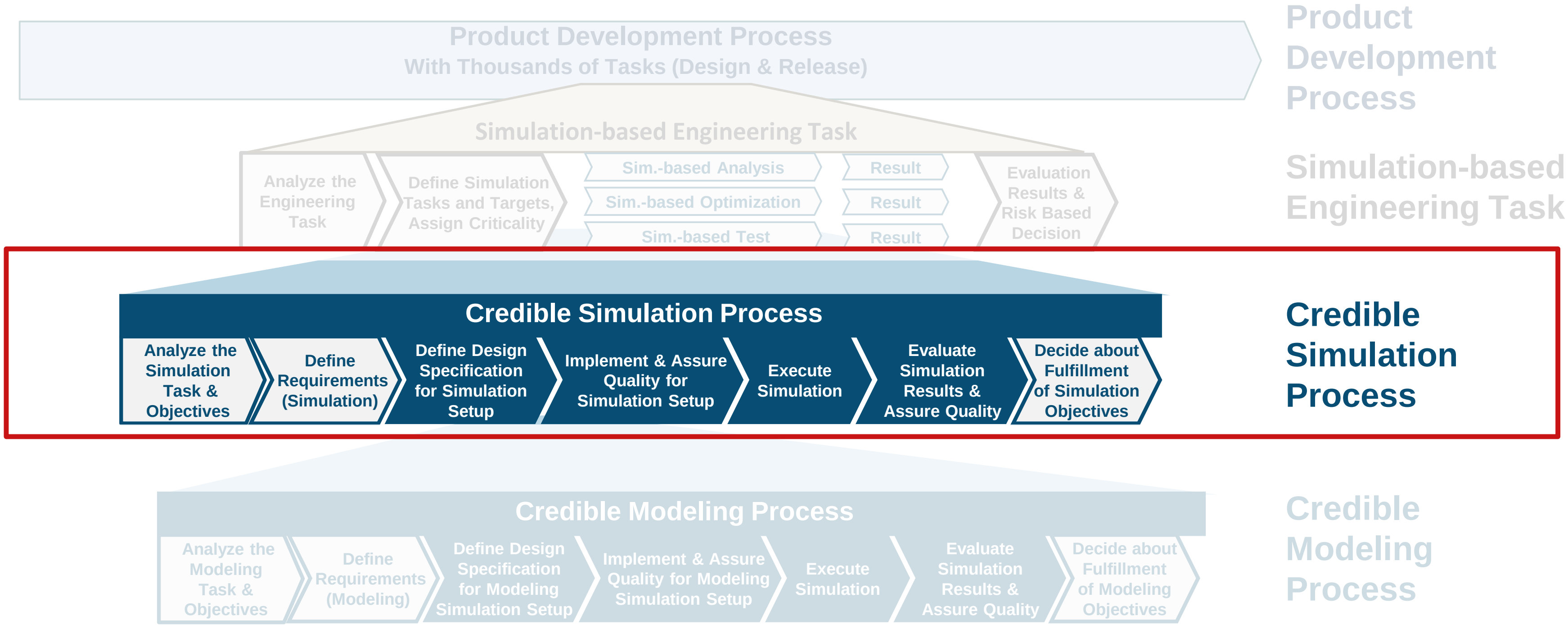
Test goal

- The primary goal is to test the **correct functionality** of the **SuT** in a given situation
- The situation shall provoke (temporary) **incomplete sensor information** (occlusion, differing sensor information)

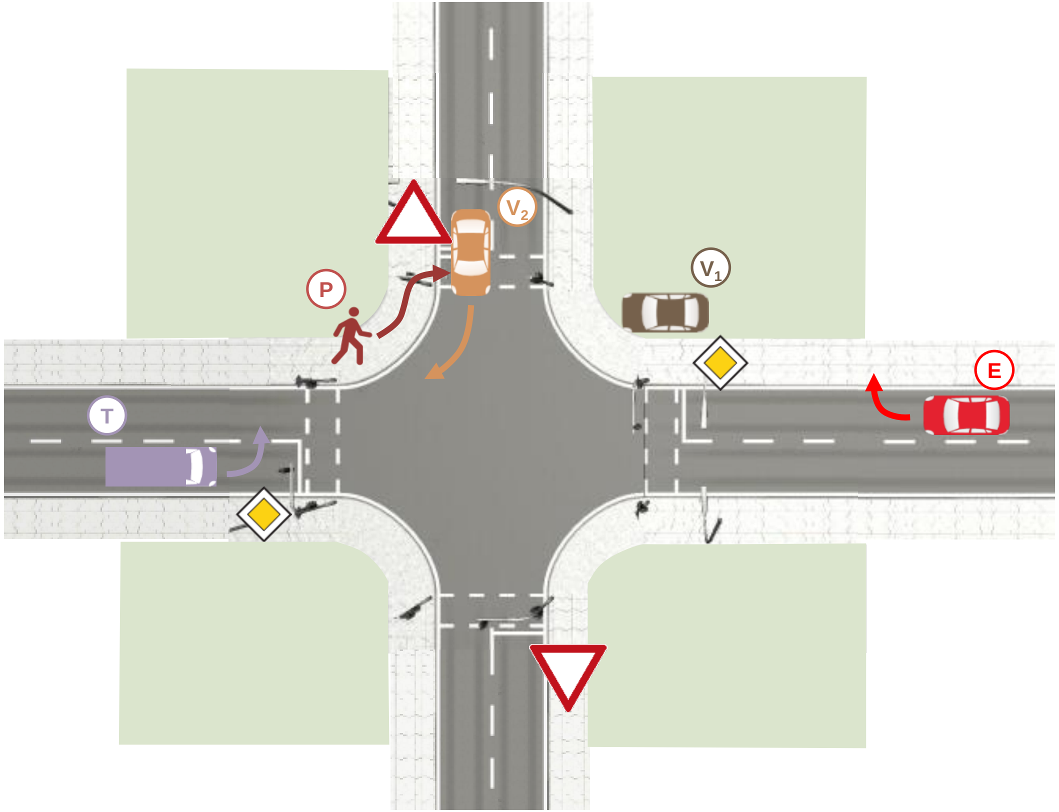
Demonstration goal

- The simulation shall contain **various models** from **different sources**
- The integration shall take place using **standardized interfaces (fmi , ASAM OSI®)**

SUC 2 – Applying the Credible Simulation Process



SUC 2 – Scenario Set-Up



EGO right turn at intersection, oncoming truck, crossing pedestrian

Road Users

- EGO: passenger car (E)
- 2 passenger cars (V_1)/(V_2), 1 truck (T), 1 pedestrian (P)

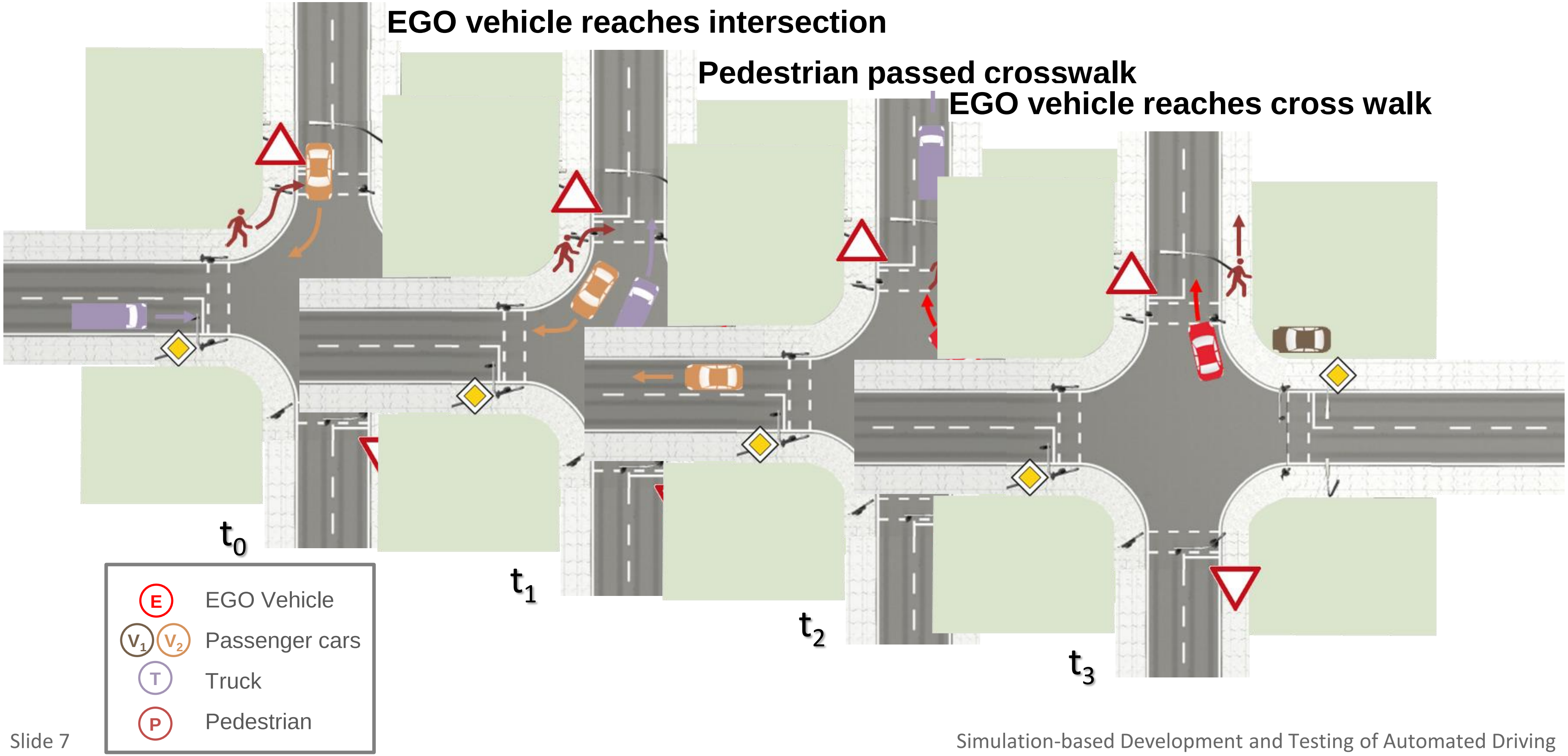
Traffic Control

- EGO controlled by HAD function
- All other road users follow specific trajectories

Standards

- ASAM OpenDRIVE® 1.6 for road layout
- ASAM OpenSCENARIO® 1.0 for scenario description

SUC 2 – Scenario



SUC 2 – Evaluation Metrics

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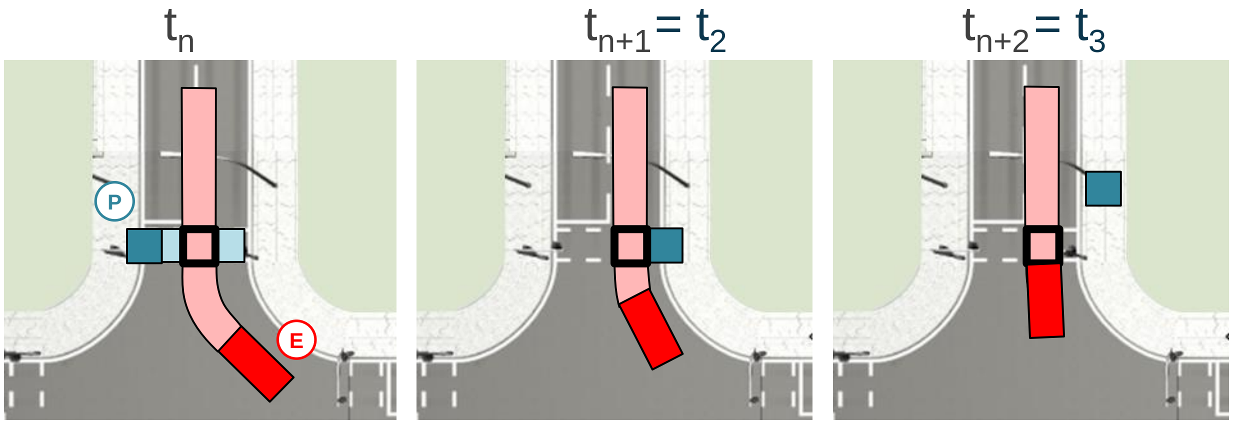
- **Post Encroachment Time**

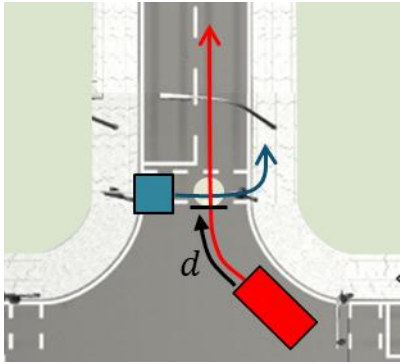
$$\text{PET} = t_{n+2} - t_{n+1}$$

PET low → high risk

PET = 0 → accident



- **Time-to-Brake**
  - Time left for a braking maneuver with the acceleration a_{brake}
  - Metric for the criticality of the situation



$$\text{TTB} = \frac{d - \frac{v_{EGO}^2}{2*|a_{brake}|}}{v_{EGO}}$$

SUC 2 – Simulation Set-Up

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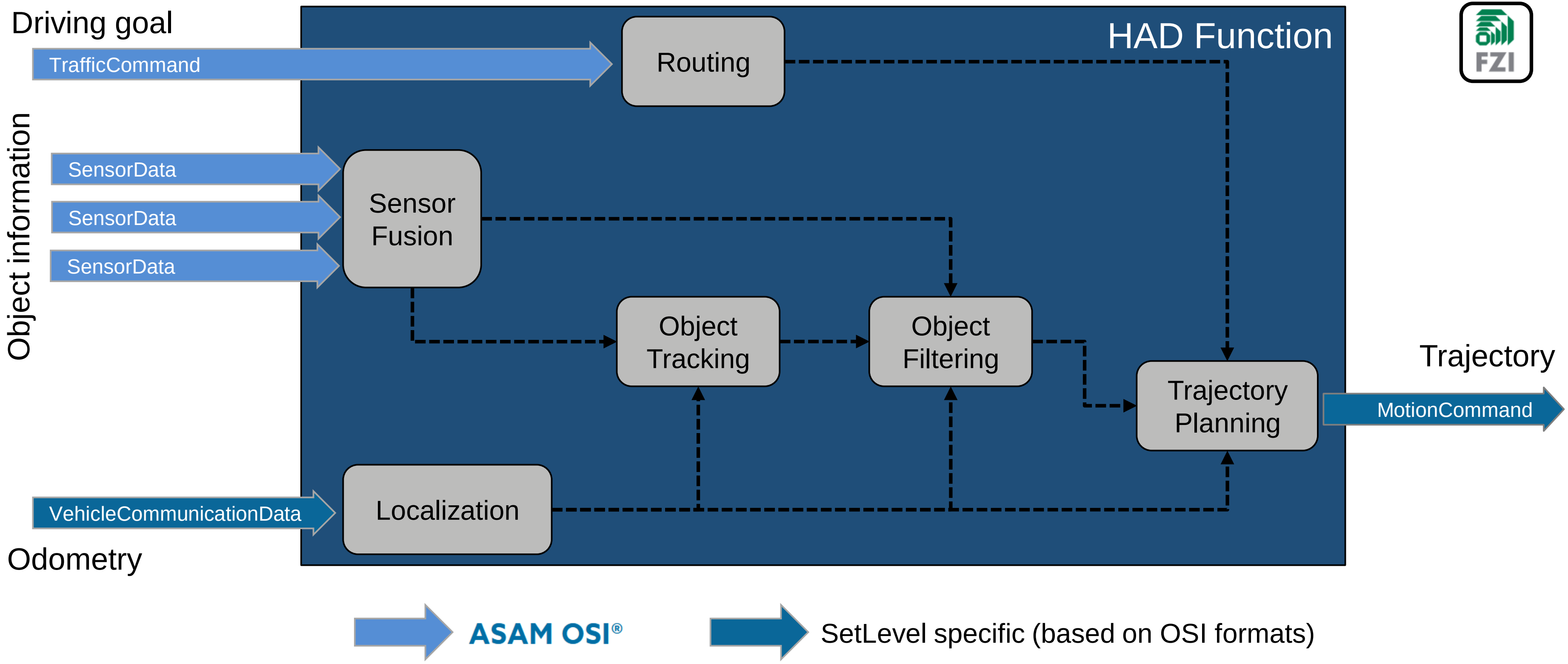
- **Tools**
  - CarMaker
  - ModelDesk, ASM, MotionDesk
- **Models**
  - HAD function (automation & sensor fusion)
  - Motion control
  - Vehicle dynamics
  - Sensors
    - 1x Camera
    - 1x Object-based lidar
    - 1x Object-based radar
- **Applied Standards**
  - fmi, ASAM OSI®, ASAM OpenDRIVE®, ASAM OpenSCENARIO®

https://fmi-standard.org/ https://www.asam.net/

SUC 2 – HAD Function (System under Test)

Overview

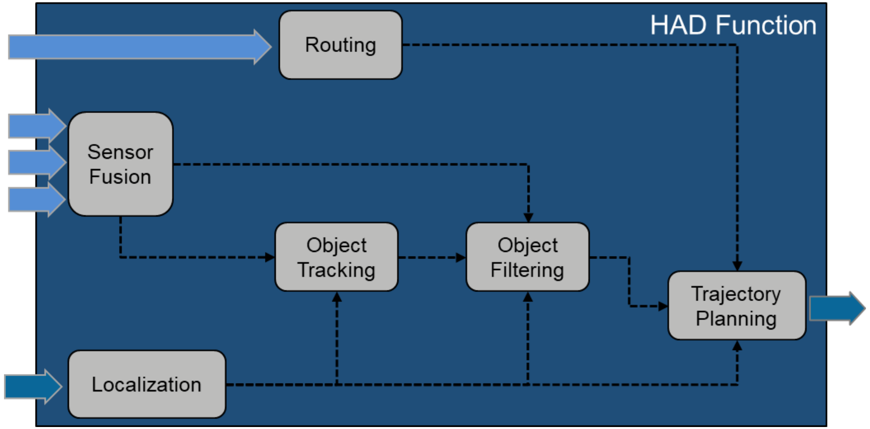


 https://www.asam.net/

SUC 2 – HAD Function (System under Test)

Modelling details

- Characteristics
  - Object list fusion
  - Object tracking with constant velocity & timeout
  - Reaction to road users
    - Differentiation according to classes
    - Relations to ego vehicle and lanes
- Modeling basics
  - Intelligent Driver Model (by Kesting, Driver and Helbing)
  - Extension for tight cornering
- Implementation
  - Modular, distributed system based on ROS
  - Synchronized via ROS services
  - OSI messages are converted into equivalent ROS messages



SUC 2 – Models

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- **Sensor models**
  - Object based model
  - Basic sensor characteristics implemented
    - Existence uncertainties (e.g. field-of-view, range, occlusion, …)
    - State Uncertainties (e.g. position error, velocity error, dimensions error, …)

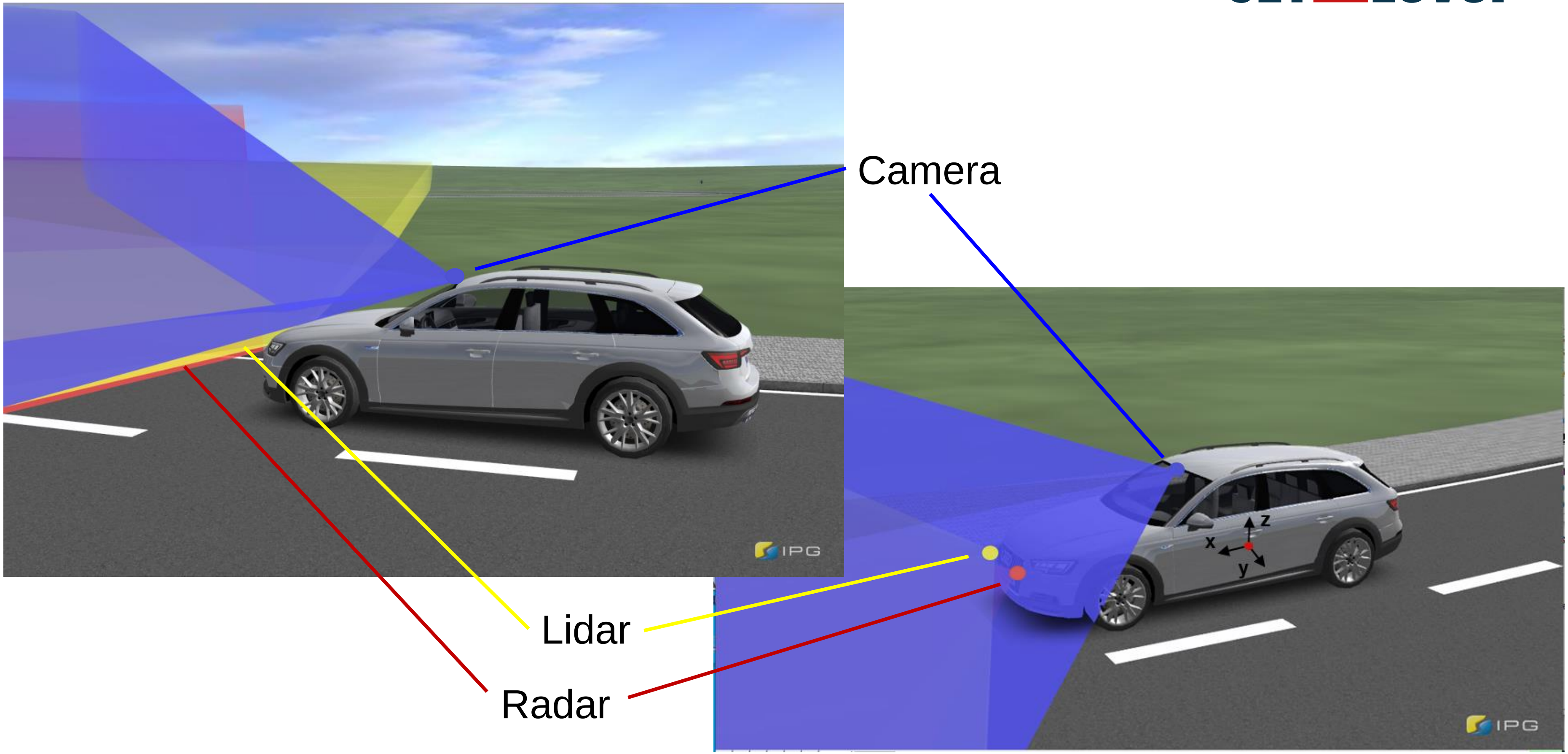
BOSCH

FZD

- **Motion Control & Vehicle Dynamics**
  - Ideal 2D one-track dynamic model
  - Nonlinear control
  - Model boundaries
    - Restricted motor torque, max. steering angle, max. velocity, max friction coefficient µ
    - Leads to constraints in useable tire-road friction

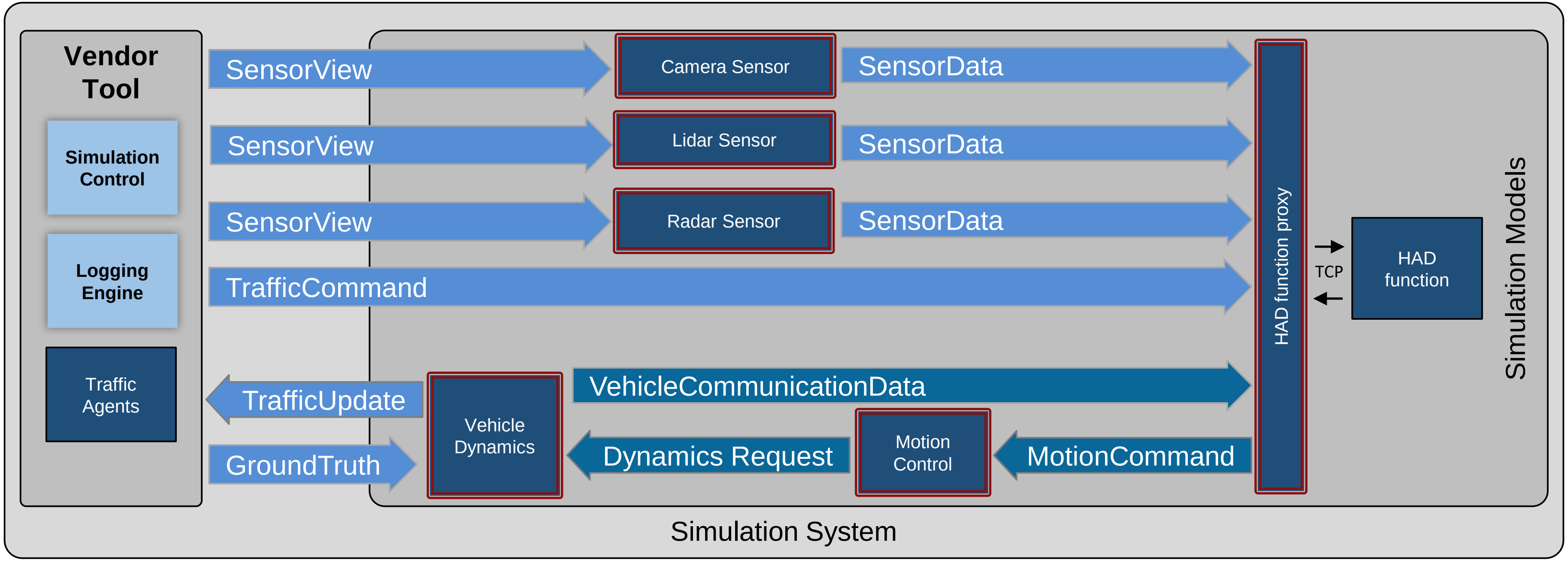
Fraunhofer LBF

SUC 2 – Sensor Set-Up

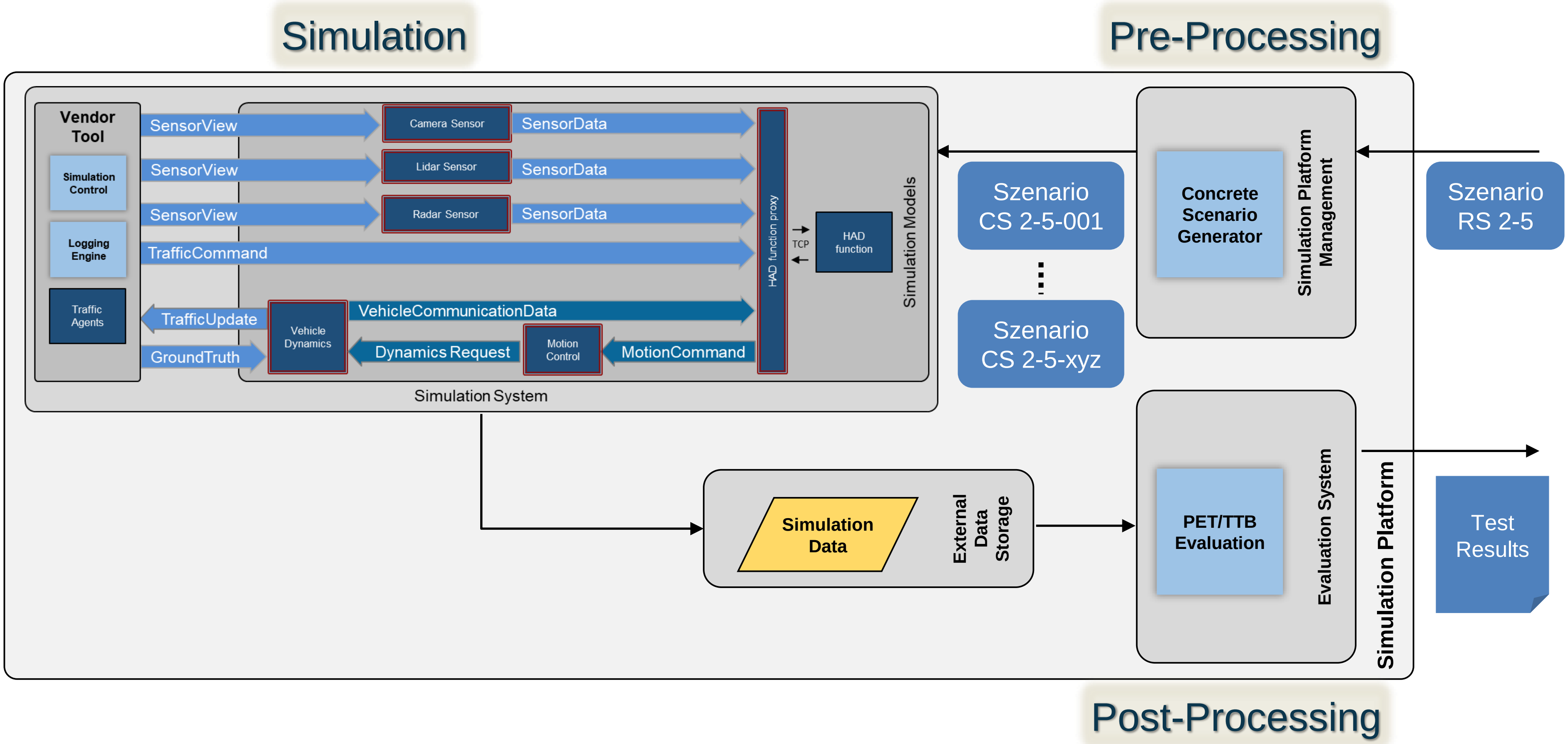


SUC 2 – Architecture (1/2)

SET Level



SUC 2 – Architecture (2/2)



SUC 2 – Parameter Variation

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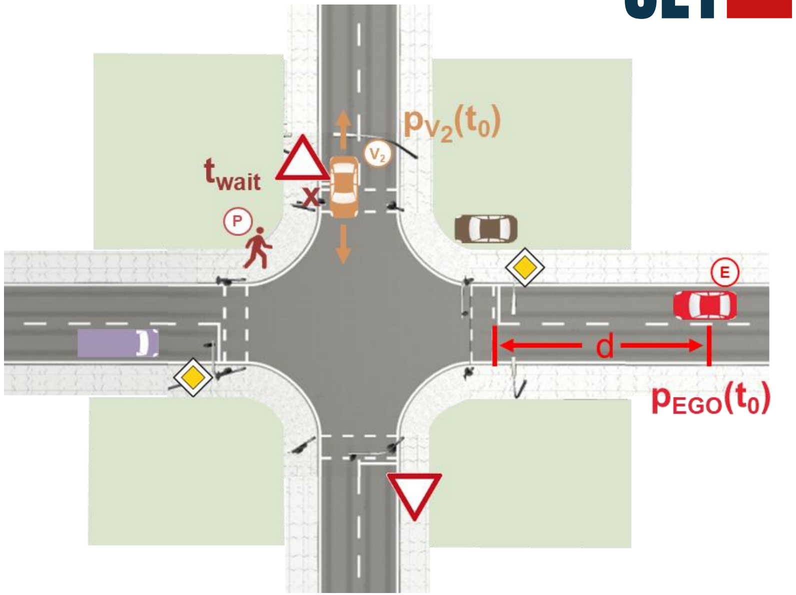
- Parameter variation of
  - (E) **EGO** start position $p_{EGO}(t_0)$
  - (V2) V_2 start position $p_{V_2}(t_0)$
  - (P) waiting time t_{wait} when **P** reaches cross-walk



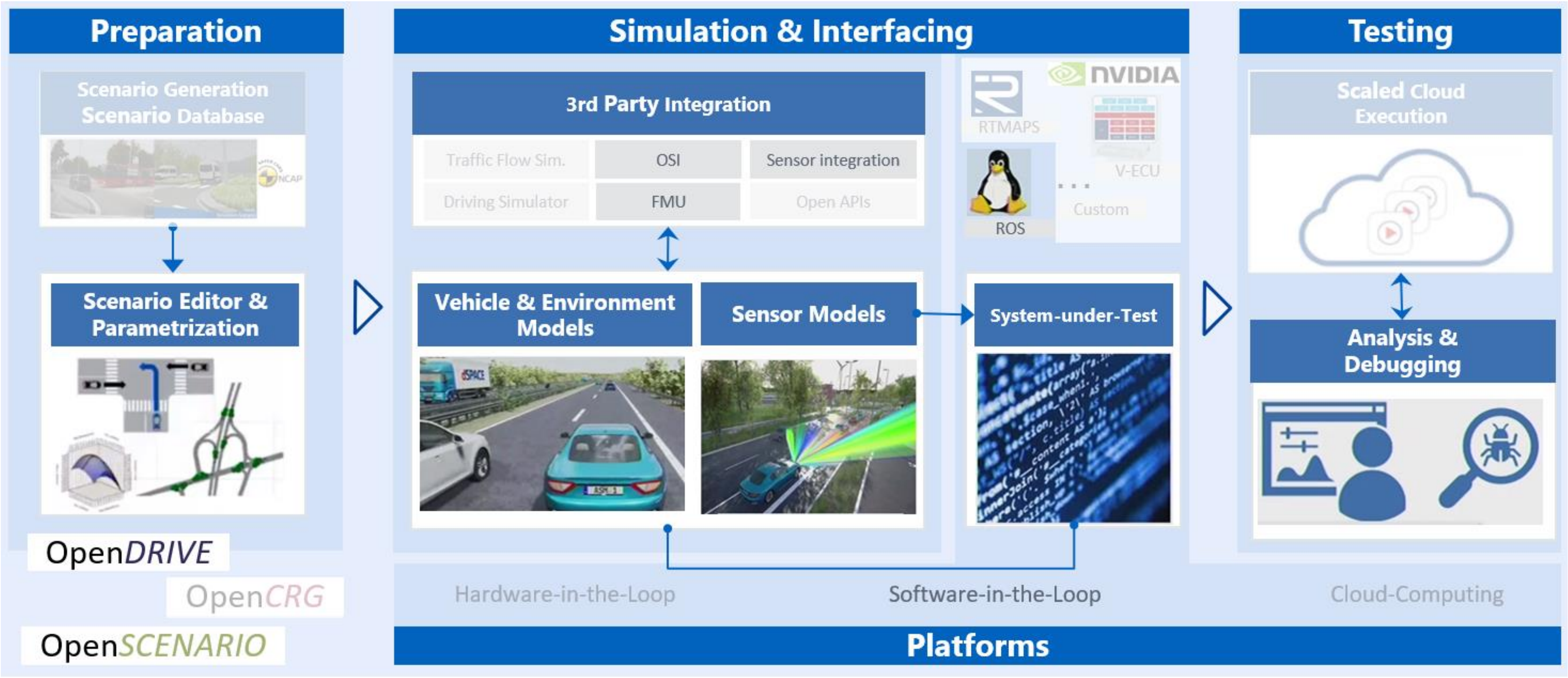
- The variation shall lead to
  - Different **occlusion duration** regarding pedestrian detection
  - Differences in **distance between EGO and P** when re-detected after occlusion

Two main parameter sets chosen for demonstration

dSPACE	**#7**	long occlusion, good sight on (P)
IPG Automotive	**#11**	shorter occlusion, late sight on (P)

dSPACE End-to-End Simulation Environment

SET Level



dSPACE ModelDesk Road and Scenario Editor

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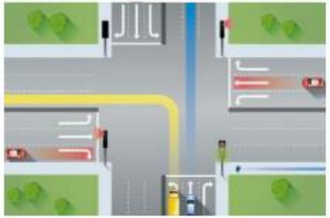
Preparation | Interfacing | Testing

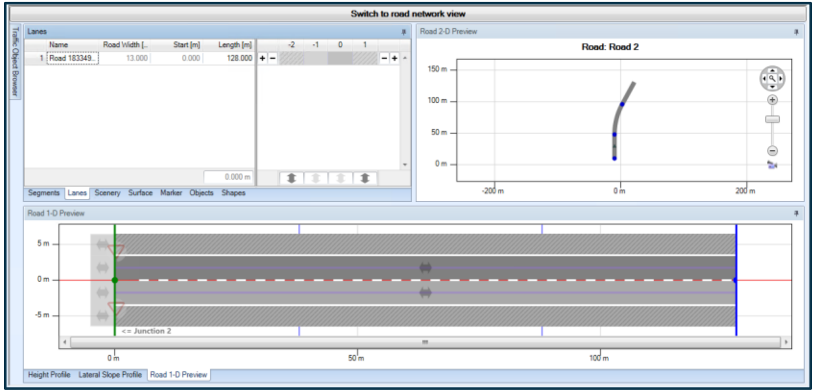
Import of road networks and scenarios

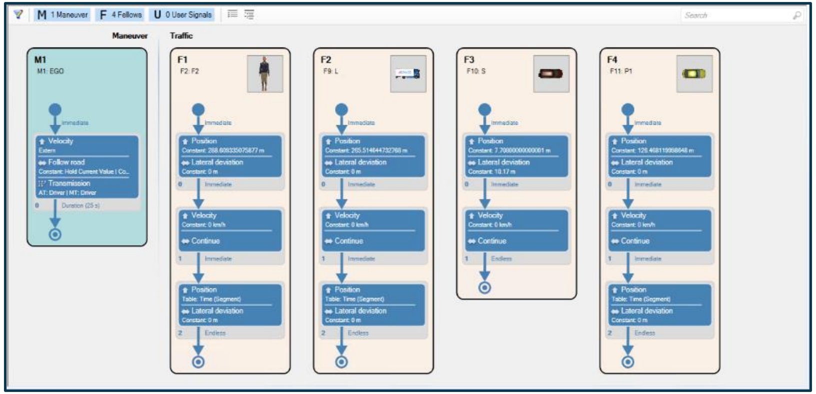
ASAM OpenDRIVE®



ASAM OpenSCENARIO®

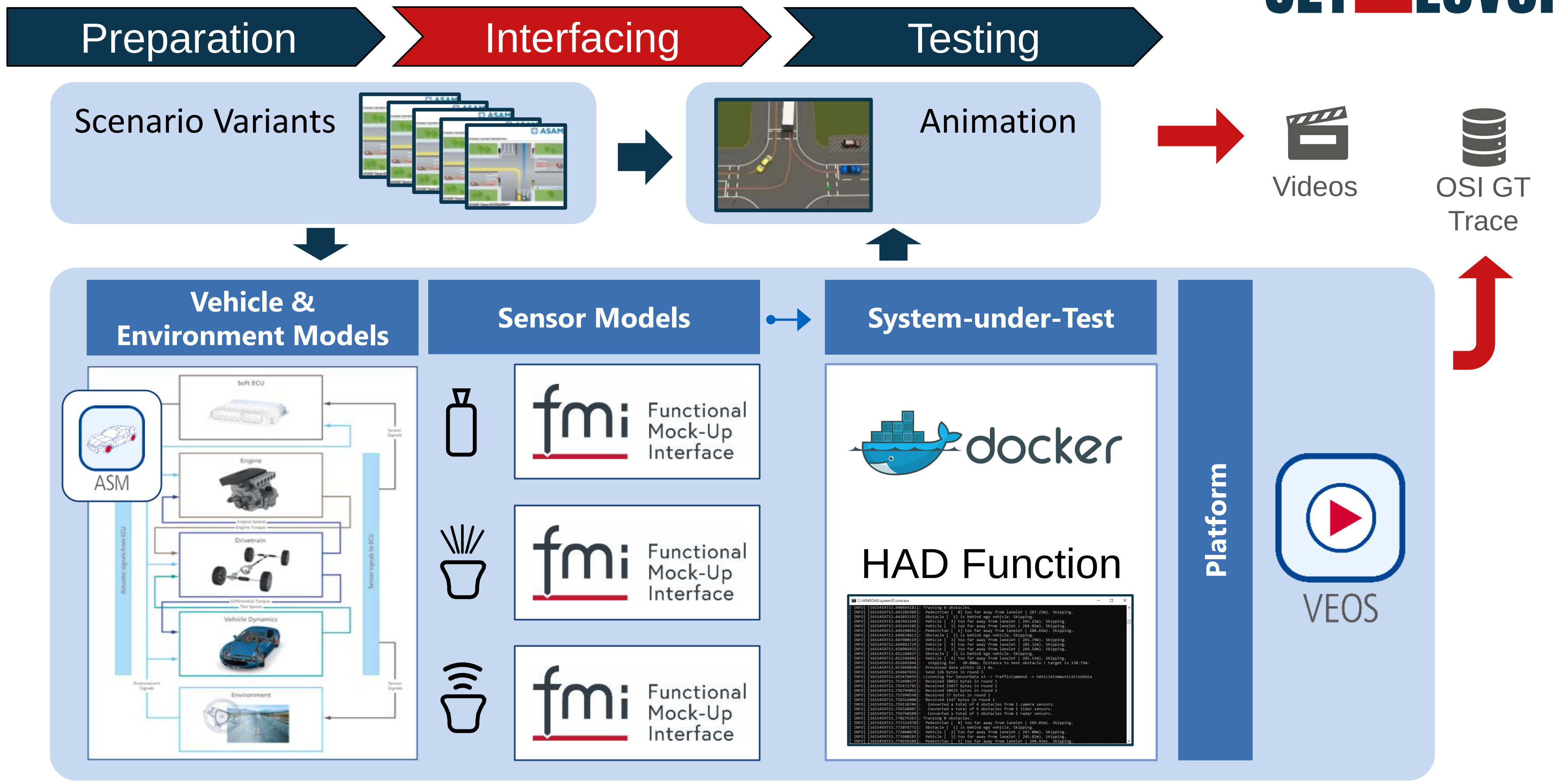
ModelDesk





dSPACE Implementation and Model Integration

SET Level

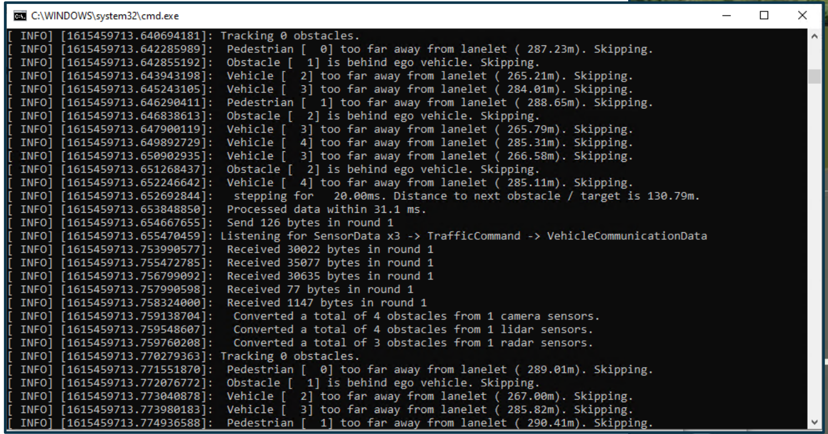


dSPACE Execution of Simulation

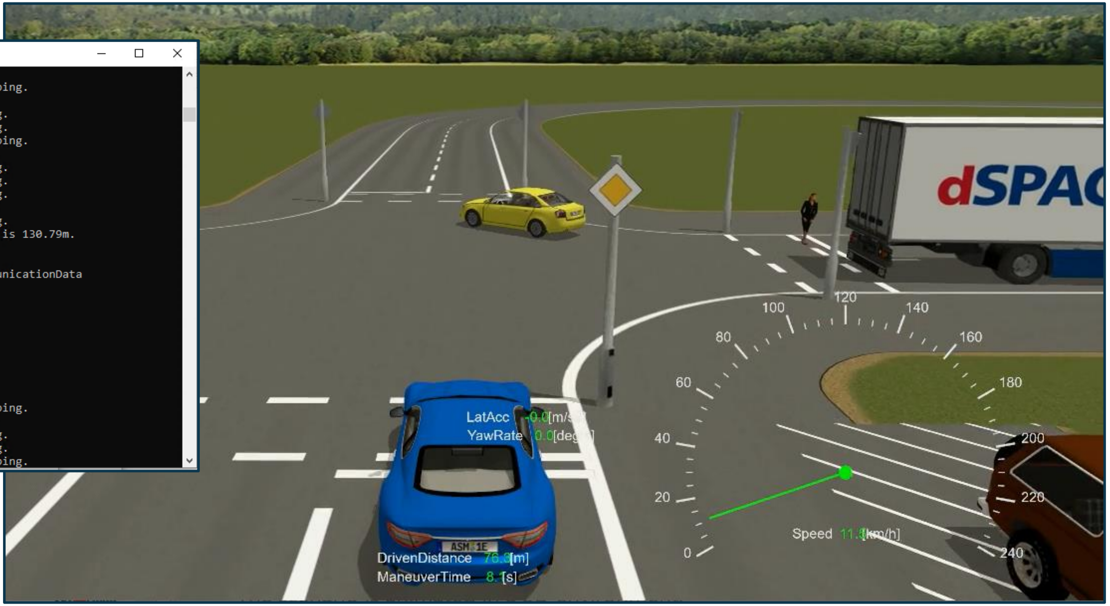
SET Level

Preparation → Interfacing → Testing

Tool demo with external HAD function


C:\WINDOWS\system32\cmd.exe

```
[ INFO] [1615459713.640694181]: Tracking 0 obstacles.
[ INFO] [1615459713.642285989]:  Pedestrian [  0] too far away from lanelet ( 287.23m). Skipping.
[ INFO] [1615459713.642855192]:  Obstacle [  1] is behind ego vehicle. Skipping.
[ INFO] [1615459713.643943198]:  Vehicle [  2] too far away from lanelet ( 265.21m). Skipping.
[ INFO] [1615459713.645243105]:  Vehicle [  3] too far away from lanelet ( 284.01m). Skipping.
[ INFO] [1615459713.646290411]:  Pedestrian [  1] too far away from lanelet ( 288.65m). Skipping.
[ INFO] [1615459713.646838613]:  Obstacle [  2] is behind ego vehicle. Skipping.
[ INFO] [1615459713.647900119]:  Vehicle [  3] too far away from lanelet ( 265.79m). Skipping.
[ INFO] [1615459713.649892729]:  Vehicle [  4] too far away from lanelet ( 285.31m). Skipping.
[ INFO] [1615459713.650902935]:  Vehicle [  3] too far away from lanelet ( 266.58m). Skipping.
[ INFO] [1615459713.651268437]:  Obstacle [  2] is behind ego vehicle. Skipping.
[ INFO] [1615459713.652246642]:  Vehicle [  4] too far away from lanelet ( 285.11m). Skipping.
[ INFO] [1615459713.652692844]:   stepping for   20.00ms. Distance to next obstacle / target is 130.79m.
[ INFO] [1615459713.653848850]:  Processed data within 31.1 ms.
[ INFO] [1615459713.654667655]:  Send 126 bytes in round 1
[ INFO] [1615459713.655470459]: Listening for SensorData x3 -> TrafficCommand -> VehicleCommunicationData
[ INFO] [1615459713.753990577]:  Received 30022 bytes in round 1
[ INFO] [1615459713.755472785]:  Received 35077 bytes in round 1
[ INFO] [1615459713.756799092]:  Received 30635 bytes in round 1
[ INFO] [1615459713.757990598]:  Received 77 bytes in round 1
[ INFO] [1615459713.758324000]:  Received 1147 bytes in round 1
[ INFO] [1615459713.759138704]:   Converted a total of 4 obstacles from 1 camera sensors.
[ INFO] [1615459713.759548607]:   Converted a total of 4 obstacles from 1 lidar sensors.
[ INFO] [1615459713.759760208]:   Converted a total of 3 obstacles from 1 radar sensors.
[ INFO] [1615459713.770279363]: Tracking 0 obstacles.
[ INFO] [1615459713.771551870]:  Pedestrian [  0] too far away from lanelet ( 289.01m). Skipping.
[ INFO] [1615459713.772076772]:  Obstacle [  1] is behind ego vehicle. Skipping.
[ INFO] [1615459713.773040878]:  Vehicle [  2] too far away from lanelet ( 267.00m). Skipping.
[ INFO] [1615459713.773980183]:  Vehicle [  3] too far away from lanelet ( 285.82m). Skipping.
[ INFO] [1615459713.774936588]:  Pedestrian [  1] too far away from lanelet ( 290.41m). Skipping.
```



Videos

OSI GT Trace

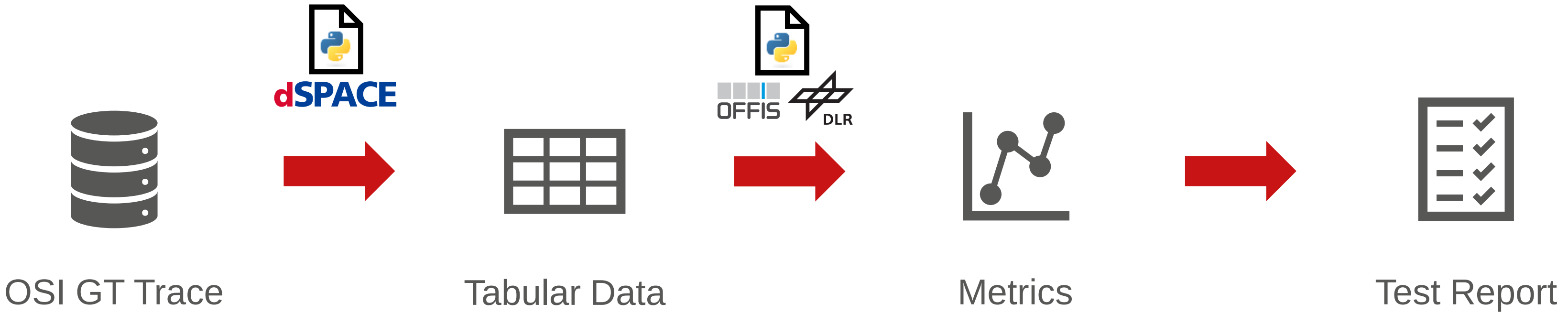
Simulation Use Case 2: Closed-loop Simulation

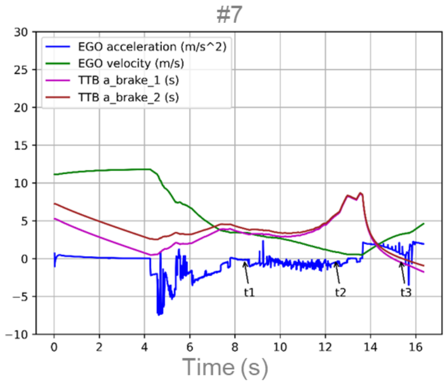
SET Level

dSPACE Test Case Evaluation

SET Level

Preparation → Interfacing → **Testing**

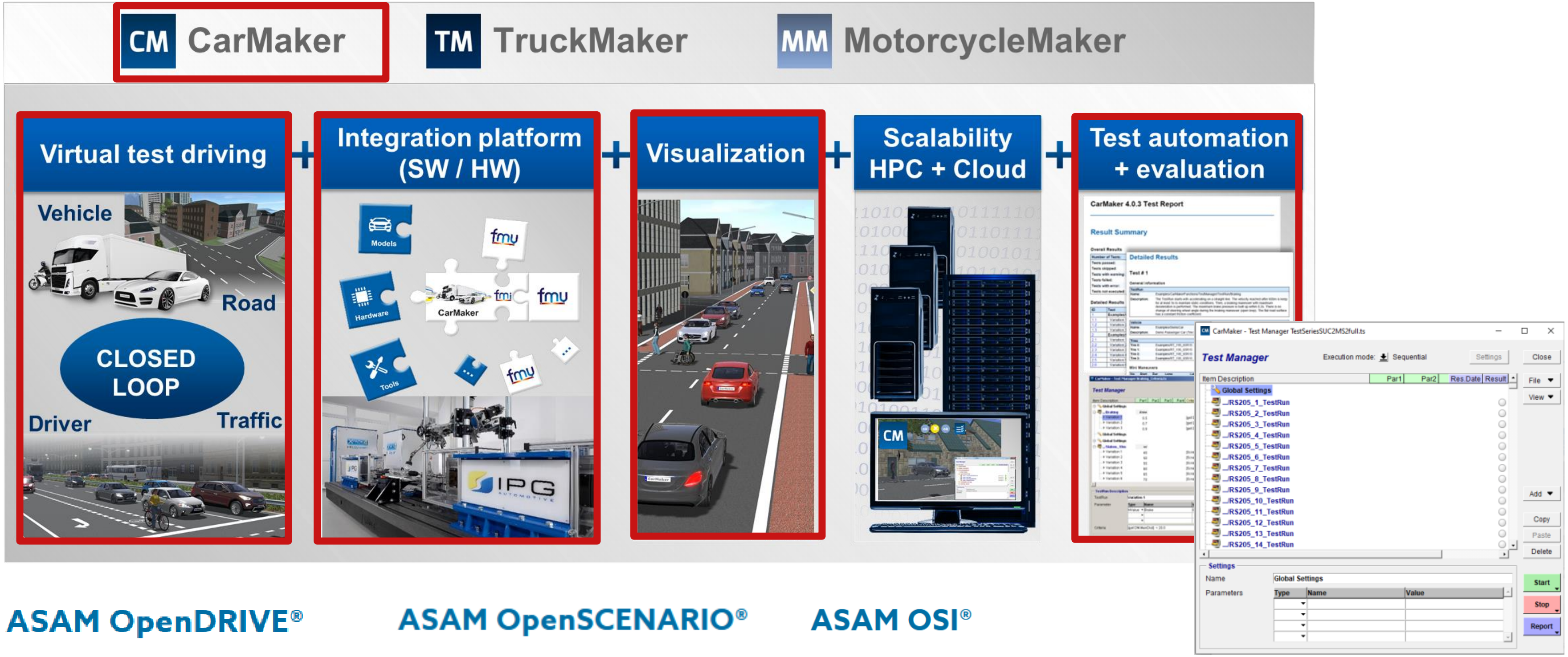




IPG – Simulation Environment

SET Level

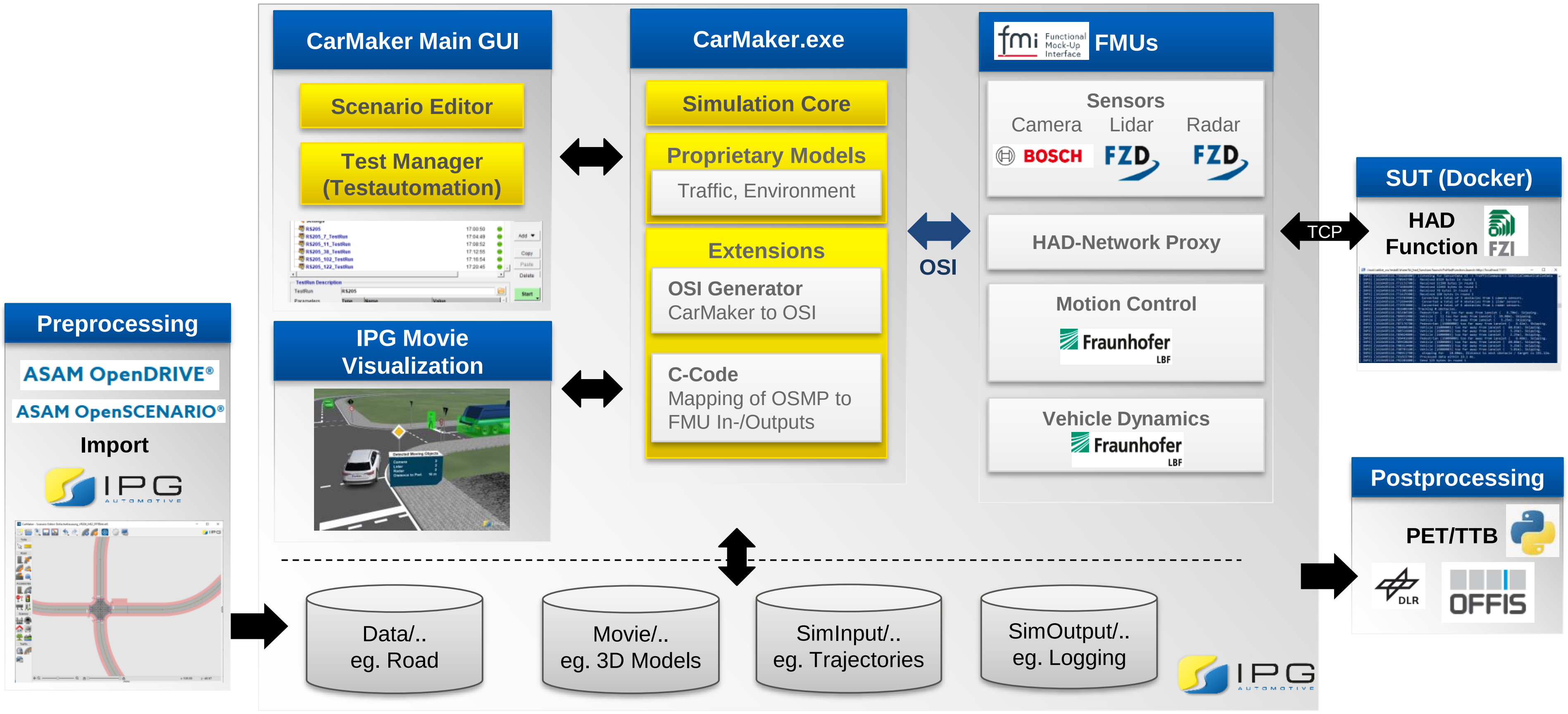
Open Integration and Test Platforms for Virtual Test Driving



ASAM OpenDRIVE®   ASAM OpenSCENARIO®   ASAM OSI®

IPG – SUC 2 Implementation

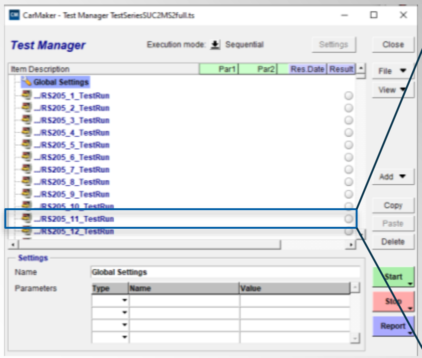
SET Level



IPG – SUC 2 Simulation Results

SET Level

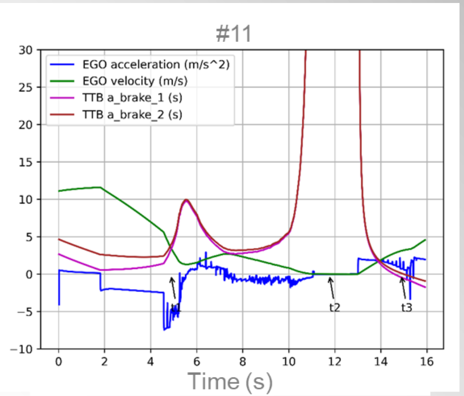
Scenario Variations



Example: Variation #11

Log-File

Postprocessing



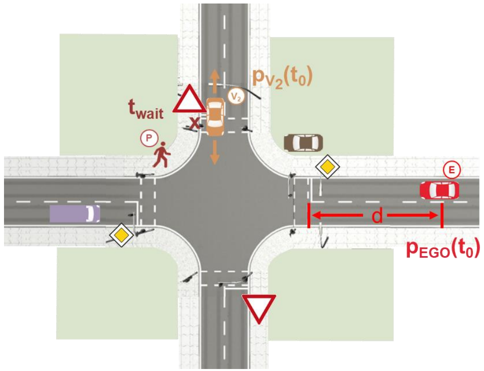
DLR OFFIS

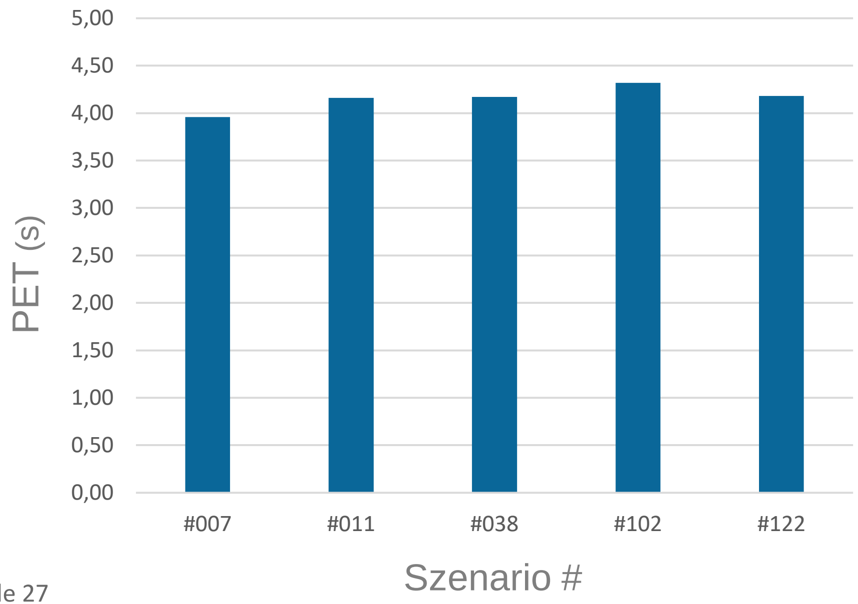

120 140 160
100 180
80 200
60 220
40 240
20 260
280
km/h
50.0
gear
0
SUT Information
Det. Moving Objects 0
Dist. to Pedestrian
Dist. to Target 131 m
CarMaker
IPG

SUC 2 – Results

Post Encroachment Time (PET)

#	7	11	38	102	122
$d_{EGO}(t_0)$	81	51	81	51	51
$y_{V_2}(t_0)$	20	12.5	12.5	12.5	20
t_{wait}	0.5	0	1.5	1.5	0



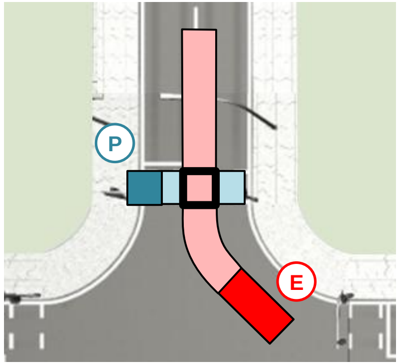


PET results show:

→ The test was successful. No collisions!

→ Similar PET results for all five runs.

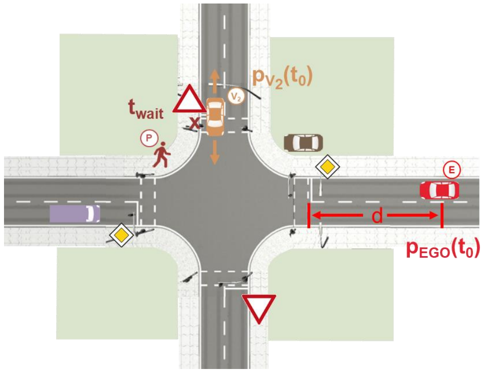
$$PET = t_3 - t_2$$



SUC 2 – Results

Time-to-brake (TTB) - Continuous Plots

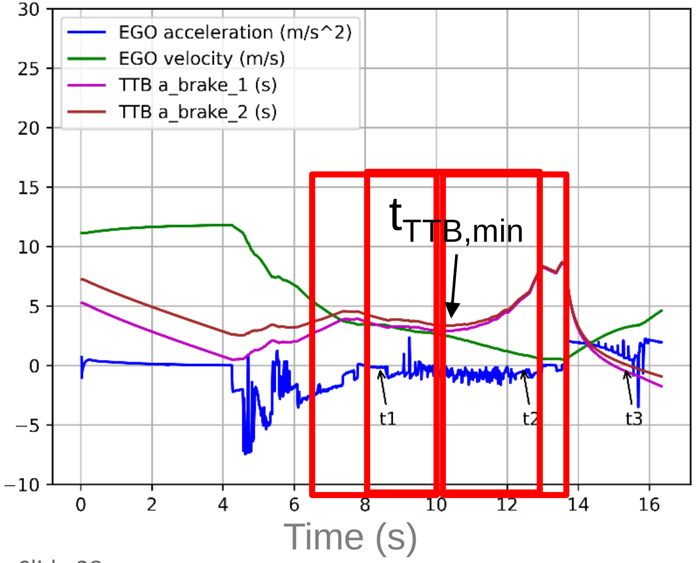
#	7	11	38	102	122
$d_{EGO}(t_0)$	81	51	81	51	51
$y_{V_2}(t_0)$	20	12.5	12.5	12.5	20
t_{wait}	0.5	0	1.5	1.5	0



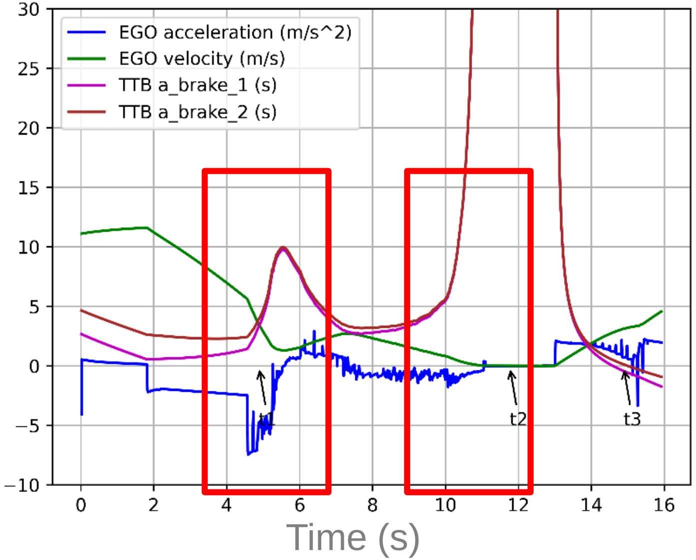
SET Level

$$a_{brake,1} = -2\,\frac{m}{s^2}$$
$$a_{brake,2} = -7\,\frac{m}{s^2}$$

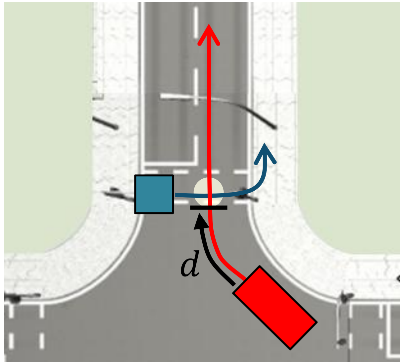
#7



#11



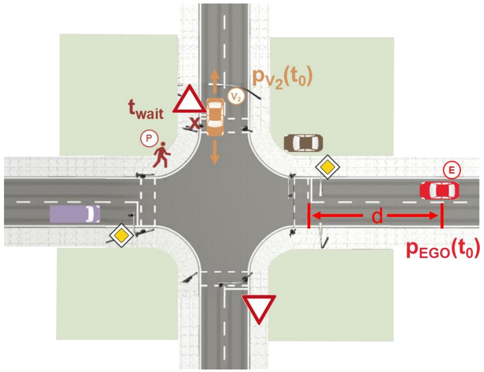
$$TTB = \frac{d - \frac{v_{EGO}^2}{2*|a_{brake}|}}{v_{EGO}}$$



SUC 2 – Results

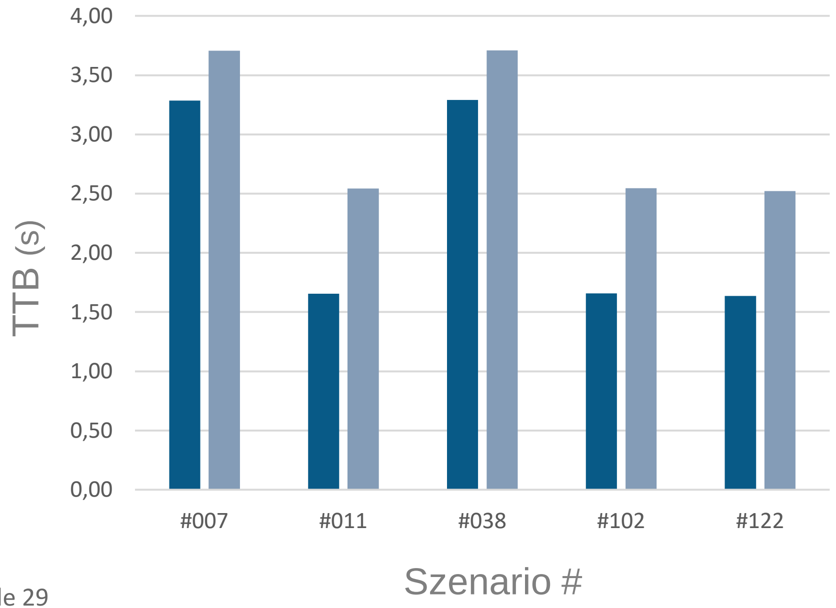
Time-to-brake (TTB) – Minimal TTB

#	7	11	38	102	122
$d_{EGO}(t_0)$	81	51	81	51	51
$y_{V_2}(t_0)$	20	12.5	12.5	12.5	20
t_{wait}	0.5	0	1.5	1.5	0



SET Level

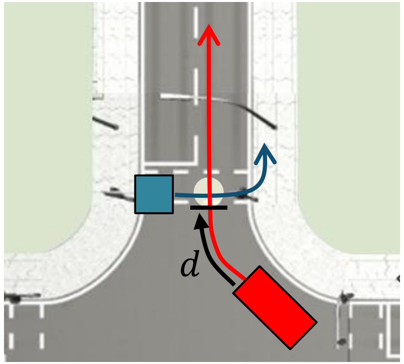
$$a_{brake,1} = -2\ \frac{m}{s^2}$$
$$a_{brake,2} = -7\ \frac{m}{s^2}$$



TTB results show:
→ Always more than 1.6/2.5 s left for braking!

- $a_{brake,1}$
- $a_{brake,2}$

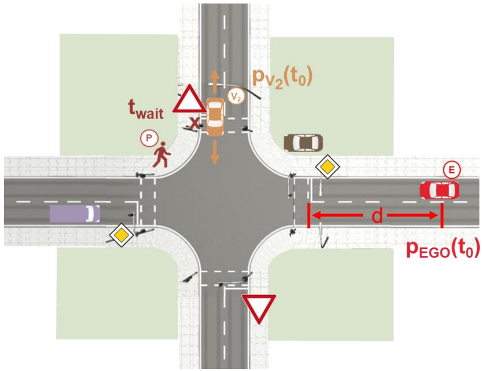
$$\text{TTB} = \frac{d - \frac{{v_{EGO}}^2}{2*|a_{brake}|}}{v_{EGO}}$$



SUC 2 – Results

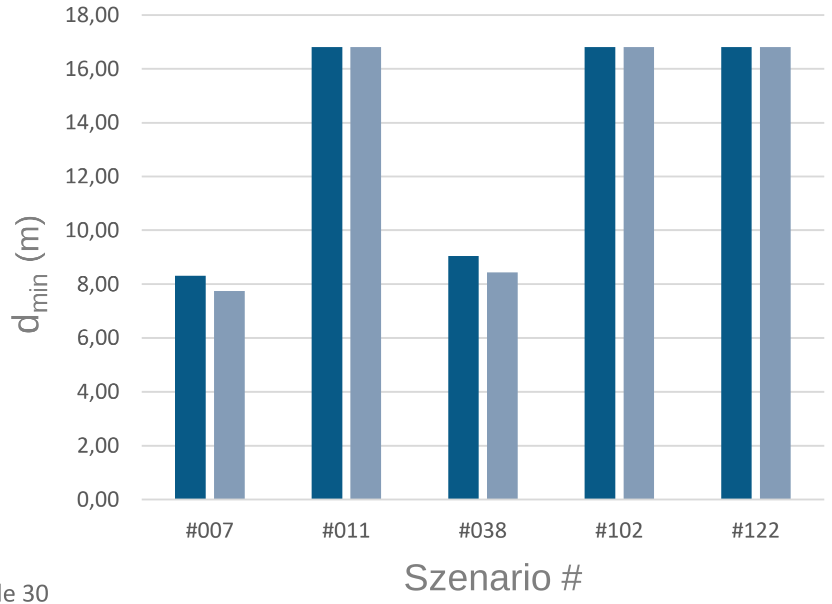
Time-to-brake (TTB) – Minimal Distance

#	7	11	38	102	122
$d_{EGO}(t_0)$	81	51	81	51	51
$y_{V_2}(t_0)$	20	12.5	12.5	12.5	20
t_{wait}	0.5	0	1.5	1.5	0



SET Level

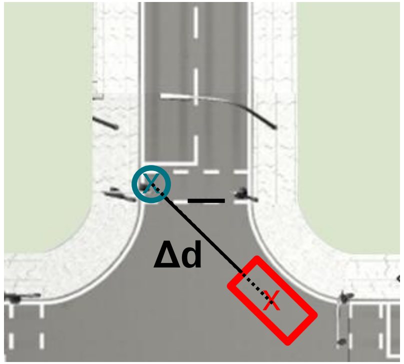
$$a_{brake,1} = -2\,\frac{m}{s^2}$$
$$a_{brake,2} = -7\,\frac{m}{s^2}$$



TTB results show:
→ Minimal distance always above 8.3/7.7 m!

$$d_{min} = \Delta d|_{t\,(TTB_{min})}$$

- $a_{brake,1}$
- $a_{brake,2}$



SUC 2 – Results

Summary & Conclusions

- Five manually chosen exemplary scenario variations
  - HAD function successfully tested using PET and TTB metrics

- No evaluation possible of…
  - … the suitability of the parameter ranges or
  - … the appropriateness for the validation process

→ Content of VERIFICATION VALIDATION METHODS

- Differences in the EGO behavior in between the two toolchains observable
  - Due to inconsistencies in the standards?
  - Or not sufficiently defined requirements?

→ Future work in SET Level

- Main goal is reached
  - to demonstrate the effectiveness of the composite simulation system!

SUC 2 - Project context

SetLevel
OSI CCB

Interface specification

WP 3.1

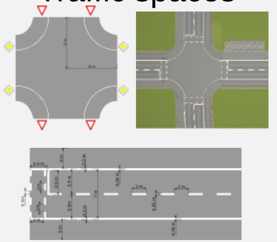
Simulation models

WP 2.1

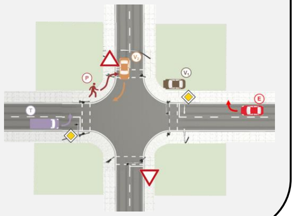
Methods & tooling for scenario generation

WP 1.2

Traffic spaces

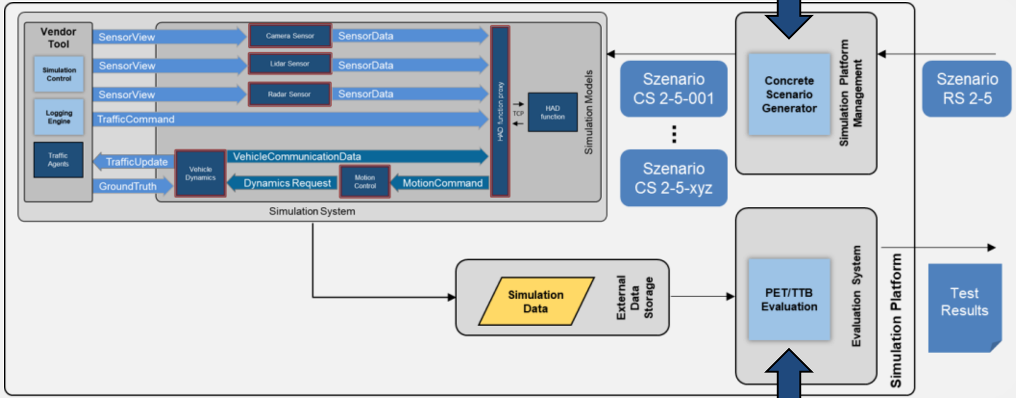


and reference scenarios



WP 4.3

Simulation integration



SUC 2

WP 2.1/WP 4.3

Evaluation scripts & metrics

SUC 2 – Summary (1/2)

SET Level

SUC 2 contributed to the project results by …

- … implementing and demonstrating exemplary **closed-loop simulation for integration testing** on the basis of **state-of-the art standards**
  → fmi, ASAM OSI®, ASAM OpenDRIVE®, ASAM OpenSCENARIO®
- … providing feedback of **experiences with applied standards and reasonable extensions** to standardization committees
- … establishing a **modular simulation tool chain** based on harmonized interfaces **which enables cooperation and model exchange** between different companies and simulation tools

https://fmi-standard.org/ https://www.asam.net/

SUC 2 – Summary (2/2)

SET Level

SUC 2 contributed to the project results by …

- .. demonstrating a **closed-loop test of a specific HAD function** in interaction with sensor and vehicle dynamic models using dSPACE & IPG AUTOMOTIVE **software-in-the-loop tool chains**

- … enriching the discussion on **scenario generation aspects** and **evaluation metrics**

- … applying the Credible Simulation Process in order to **structure the simulation development process** and to **enable traceability**

SUC 2 – Outlook (project end)

SET Level

- **Simulation quality**
  - Confidence statement of simulation results
  - Qualification / evaluation of models
  - Checking the trust range at runtime
  - Performance evaluation of the simulation
  - Identification of causes for differences between simulation tools

- **Simulation automation**
  - Use of ssp standard
  - Checking the suitability of ssp for fmi-based simulation elements

- **Simulation process**
  - Process standardization and documentation as basis for traceability

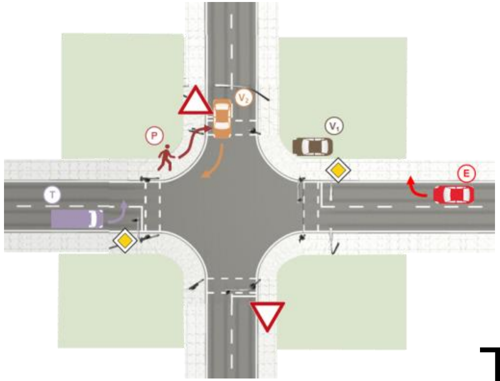
→ **Scope of further test scenario** in a closed-loop simulation on **fault injection**
  - Consequences for communication (ASAM OSI®), scenario definition (ASAM OpenSCENARIO®), etc.

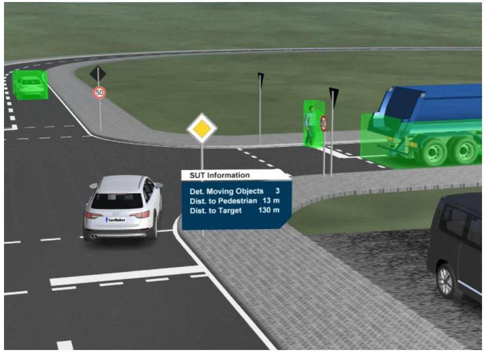
→ **Knowledge transfer**
  - Explicit through project deliverables
  - Implicit through contributions to architecture & interface standard developments as well as tool development

 https://ssp-standard.org/ https://fmi-standard.org/ https://www.asam.net/

Q & A

SET Level





Thank you for your attention!