INSTITUT FÜR KRAFTFAHRZEUGE
ika | RWTH AACHEN UNIVERSITY

AdaptIVe
Automated Driving Applications and Technologies for Intelligent Vehicles

# CAD Webinar Series (III): AdaptIVe

## Evaluation of Automated Vehicle Systems

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# // Bottleneck for the Introduction of Automated Driving?

**ACC** (*SAE Level 1*)

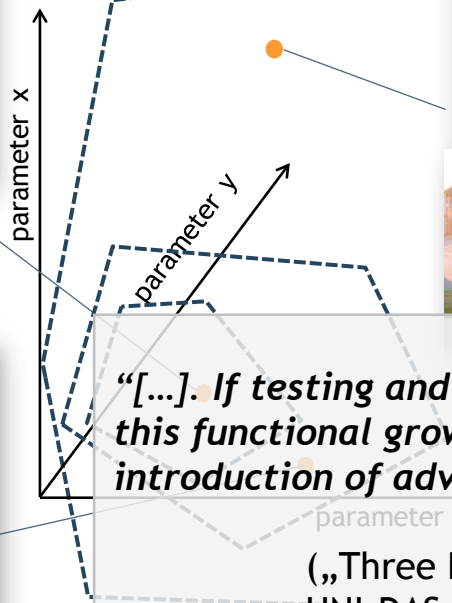
Source: Audi (2013)

**Motorway Automation** (*SAE Level 3*)

Source: BMW (2015)

**Urban Robot Taxi** (*SAE Level 4*)

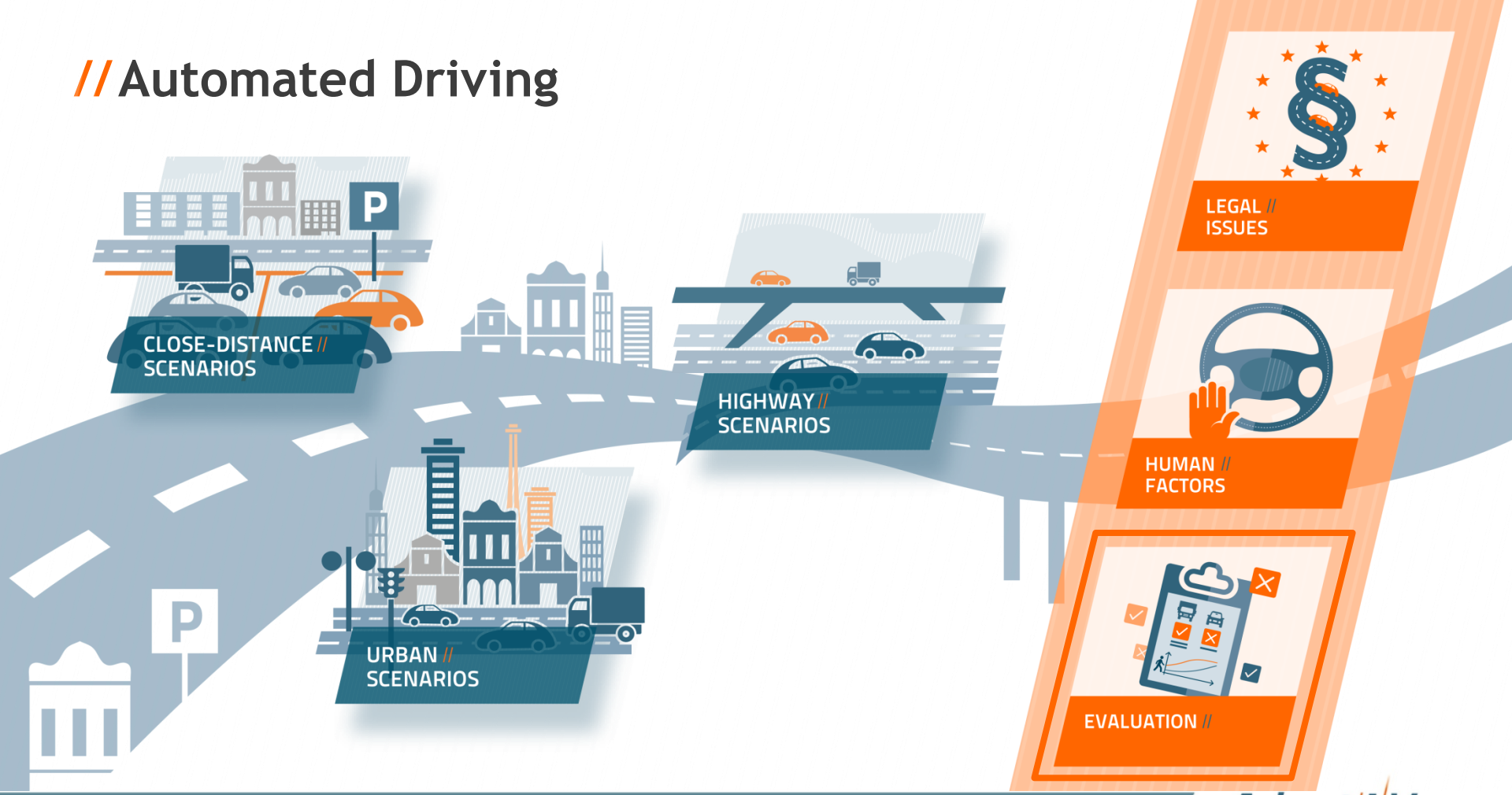
Source: Google (2015)



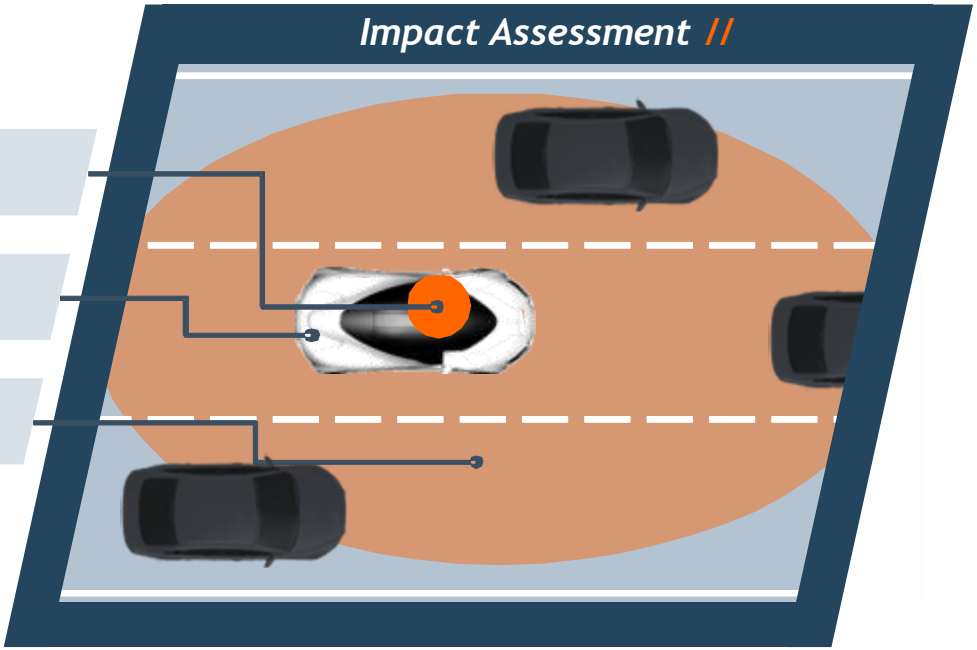

***"[…]. If testing and assessment methods cannot keep pace with this functional growth, they will become the bottleneck of the introduction of advanced DAS to the market."***

(„Three Decades of Driver Assistance Systems", UNI-DAS, IEEE ITS Magazine, 2014).

# // Automated Driving



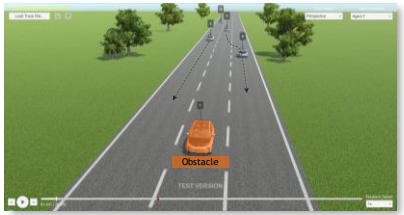
# // Evaluation of AdaptIVe functions



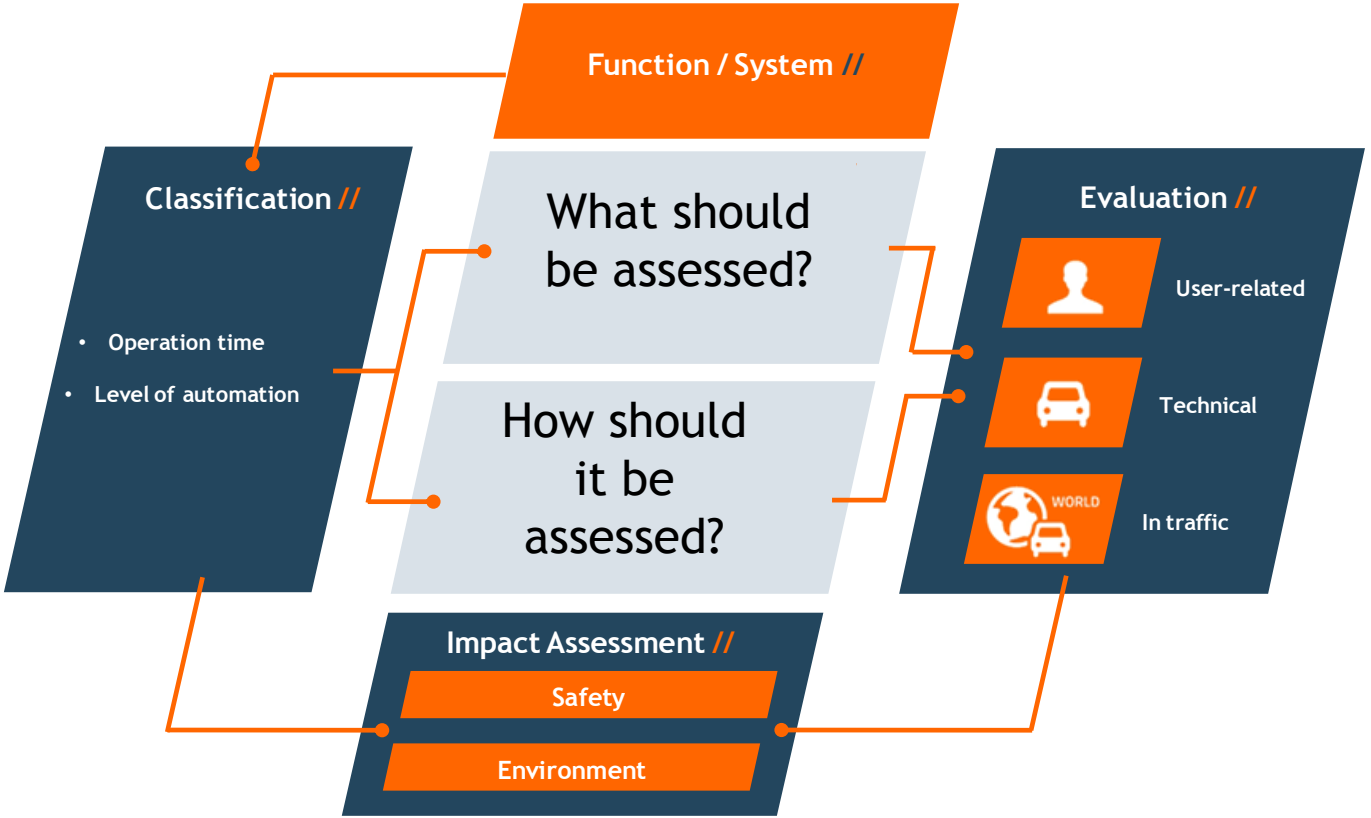

// Real-traffic

// Test track

// Simulations



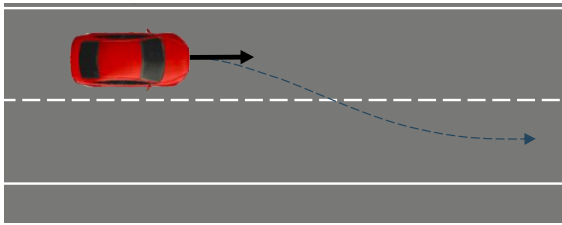
# // Evaluation Approach in AdaptIVe



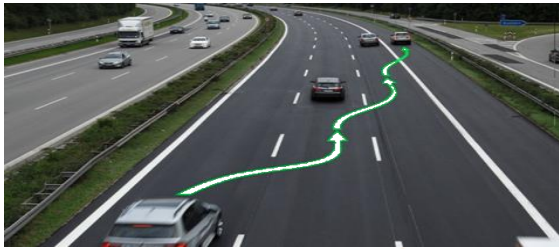
# // Definitions for Evaluation

- **Traffic Scenario**: A traffic scenario describes **a larger traffic context**, which includes different (not pre-defined) driving scenarios.

- **Driving Scenario**: A driving scenario is the **abstraction and the general description of a driving situation** without any specification of the parameters of the driving situation.

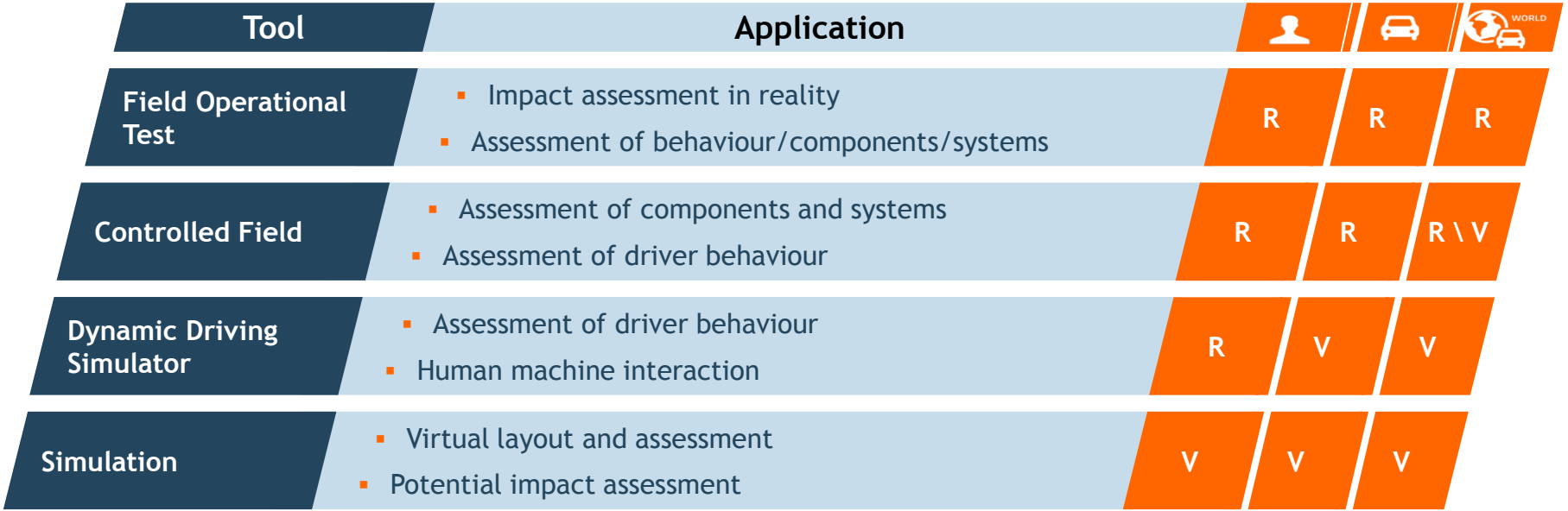


- **Driving Situation**: A driving situation is **a specific driving manoeuvre** (e.g. a concrete lane change with defined parameters).



# //Evaluation Tools

- Which tool should be applied for which type of assessment?




R: real, V: virtual

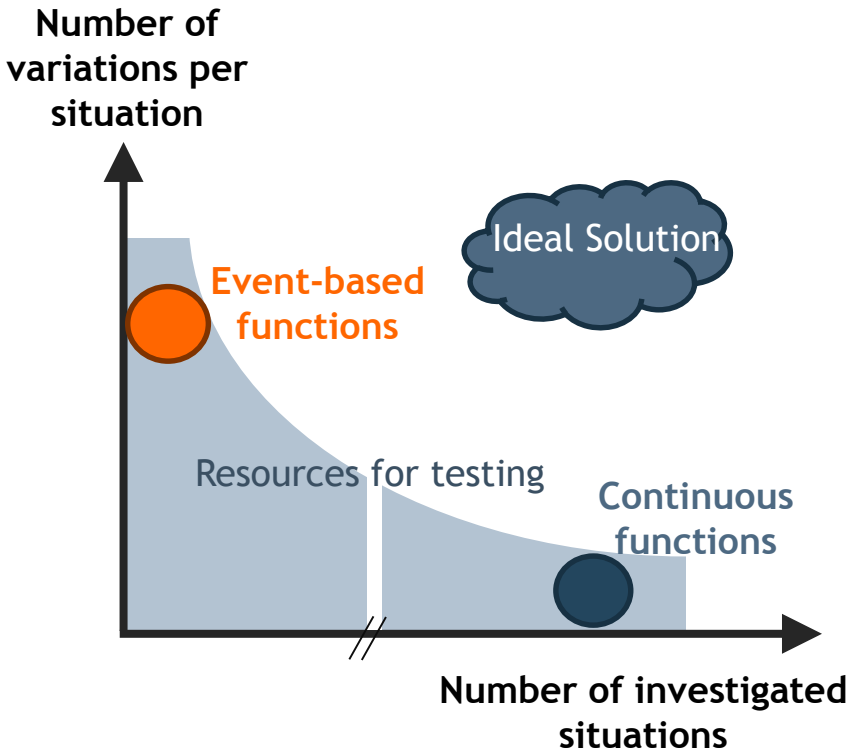
# // Classification of Automated Driving Functions

- Classification by operation time:
  - **Event based operating**
    - Function that is only active for a short period in time (typically vehicle stands still at the end or the automated driving ends)
    - Examples: Parking, Minimum Risk Manoeuvres

  - **Continuously operating**
    - Function that is active for a longer period in time (typically vehicle is still moving at the end of an manoeuvre respectively automated driving is continued)
    - Example: Highway Pilot

# //How to limit the test amount?

- Different approaches for **event-based** and **continuously operation functions:**
  - **Event-based functions:** similar approaches as in previous research project e.g. interactIVe
  - **Continuously operating functions:** small field test on public road in order to assess the function in many different situations



# // Evaluation Tools in AdaptIVe

- Identification of an appropriate evaluation methodology for the technical, user-related, in-traffic behaviour and impact assessment

| Tool | Technical | User-related | In-traffic | Impact | | | |
|---|---|---|---|---|---|---|---|
| Field Operational Test | Yes Continously | Yes | (Yes) | No | R | R | R |
| Controlled Field | Yes Event-based | Yes | No | No | R | R | R \ V |
| Dynamic Driving Simulator | No | Yes | No | No | R | V | V |
| Simulation | No | No | Yes | Yes | V | V | V |

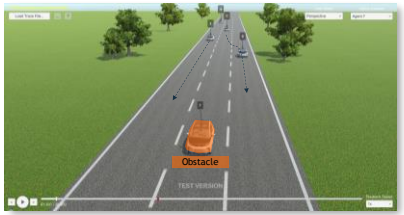
# // Evaluation of AdaptIVe functions

| | // Parking | // Urban | // Highway |
|---|---|---|---|
| *Technical Assessment* | Ford Daimler | CRF | BMW, Conti, VTEC, VW |
| *User-related Assessment* | - | VCC | VW |
| *In-traffic Assessment* | | TNO | |
| *Impact Assessment* | Environment: ika | Environment: ika | Enviro.: ika Safety: BMW |

// Real-traffic

// Test track

// Simulations



# // Technical Assessment
## Method & Results

# //Technical Assessment

## Event-based//

1. **Defining evaluation scope**
   - Definition of research questions, hypotheses & indicators
2. **Planning of assessment**
   - Analyse system description and adaption of hypotheses
   - Planning of test cases
   - (Risk assessment)
3. **Tests in controlled field**
   - Number of test variations
   - Logging of test data
4. **Assessment of tests**
   - Analysis of hypotheses based on test data & indicators

## Continuous//

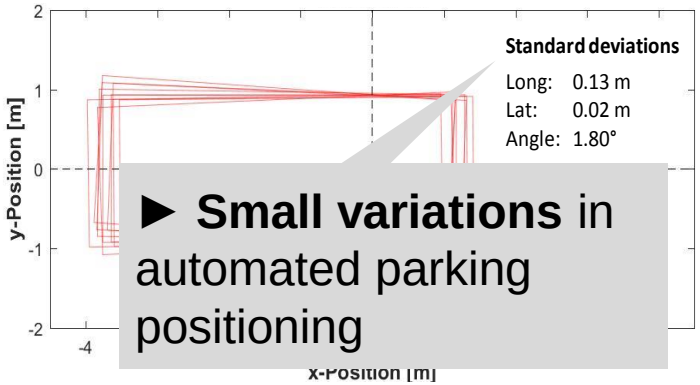
1. **Defining evaluation scope**
   - Definition of research questions, hypotheses & indicators
2. **Planning of assessment**
   - Analyse system description and adaption of hypotheses
   - Planning of test cases and test route
   - Definition evaluation criteria (distributions & boundaries)
   - Risk assessment
3. **Pre-/component tests in controlled field**
   - Basic tests of functionality
   - Sensor tests
4. **Tests in real traffic**
   - Test route and test amount to be determined
5. **Assessment of tests**
   - Analysis of hypotheses based on test data & indicators

# // Technical Assessment

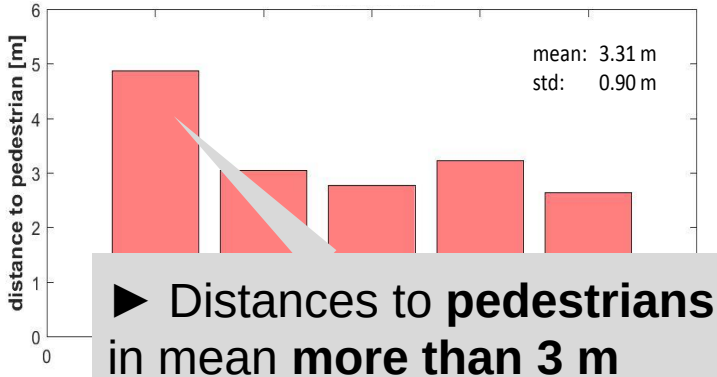
- For assessment of event-based automated driving functions, **classical use-case based testing** was conducted.
- **Five repetitions** per **test case** were conducted.
- Tests executed in a **closed environment.**

# // Technical Assessment

- **Close distance functions** can be evaluated by **classical use-case based testing**.
- It turned out that close distance functions are providing **accurate positioning in parking applications**.
- Safe **distances to pedestrians were kept** in all test cases.

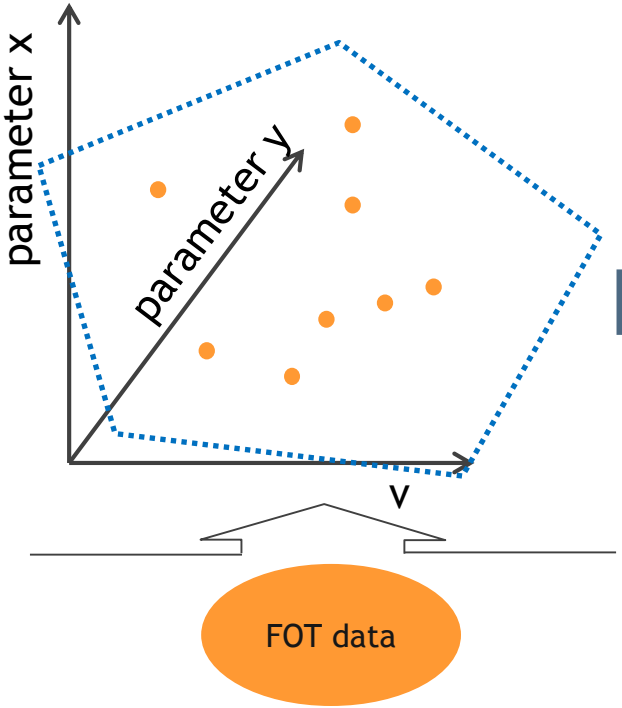


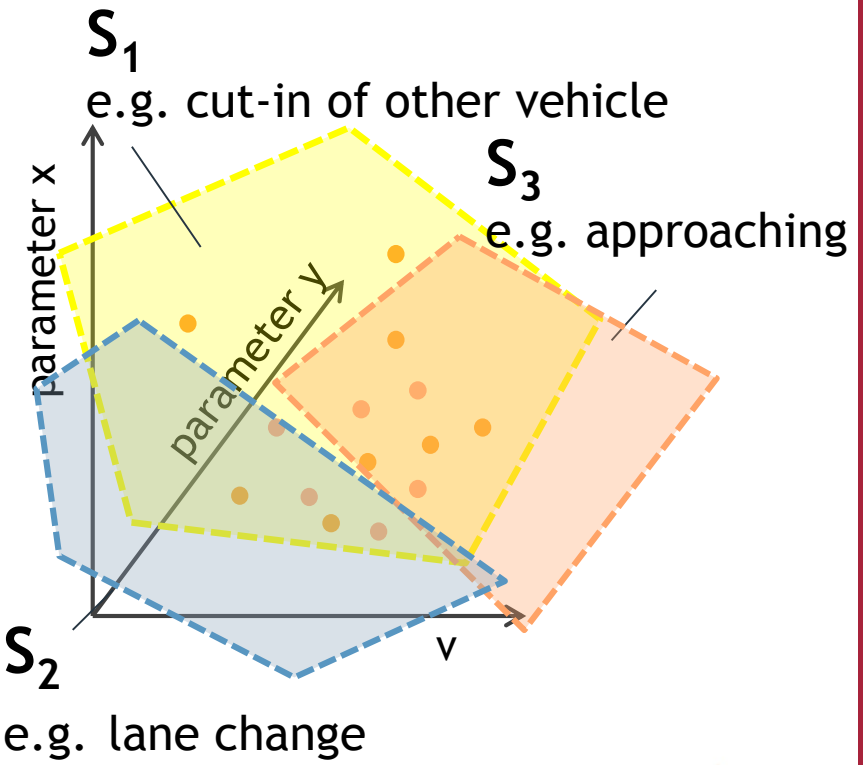

► **Small variations** in automated parking positioning




► Distances to **pedestrians** in mean **more than 3 m**

# //Scenario Classification of Real-World Data

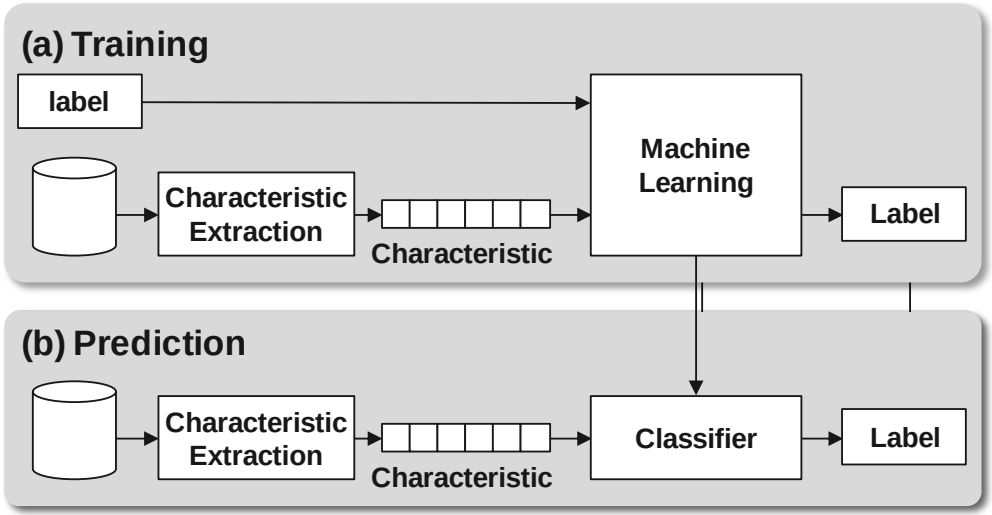


# // Scenario Classification of Real-World Data

- **Benmimoun (2011)**
  - Offline classification
  - Uses **decision trees parameterized by hand**
  - No easy adaptation, no consideration of time series
- **Reichel (2010), Roesener (2016)**
  - Proficient using of **Machine Learning Techniques**
  - Partial automated
  - Choice of classifier based on expert knowledge

▶ **Machine learning techniques provide an efficent & automated data clustering**

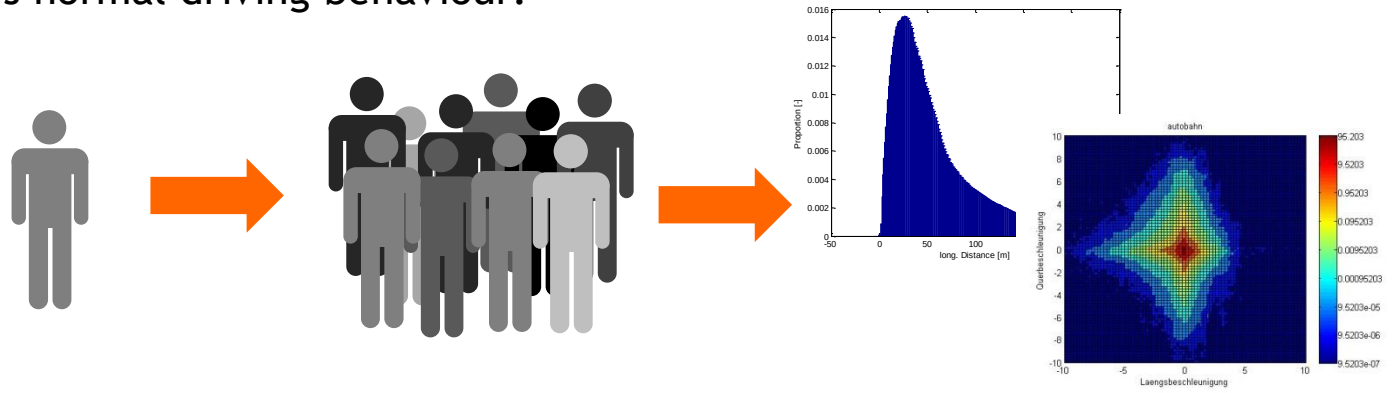



Reichel (2010), Roesener (2016)

# // Baseline for Assessment of Automated Driving

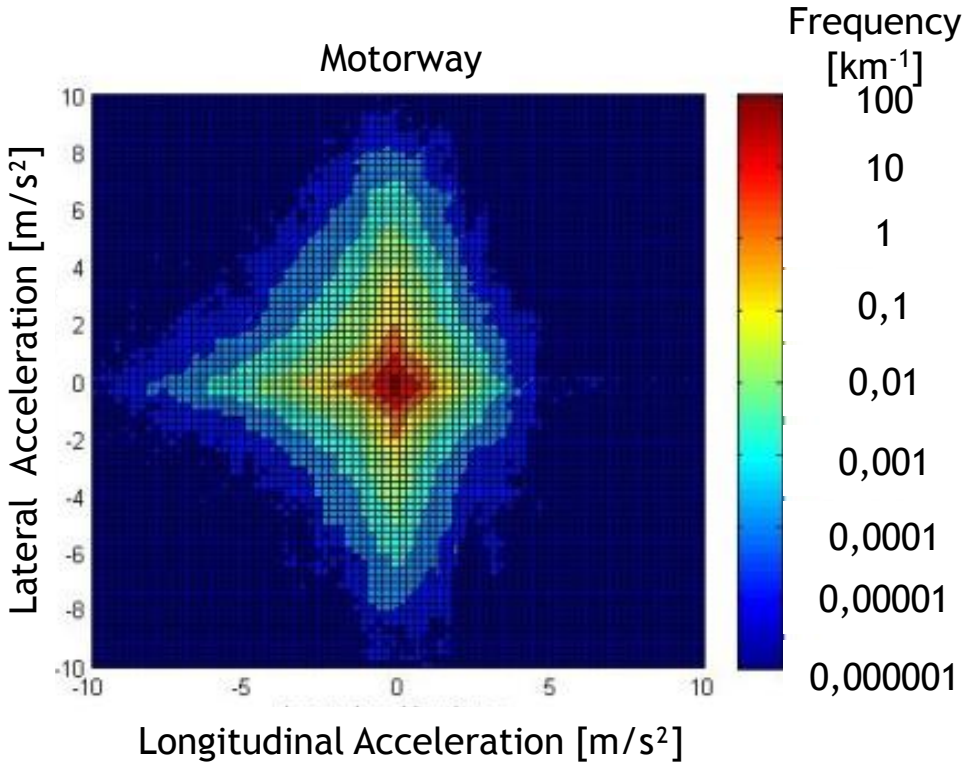
- Description of the baseline for the evaluation
  - Objectives of automated driving functions
    - Objective is a collision free traffic
    - Operation in mixed traffic conditions (→ not disturbing normal traffic)

    → The functions have to be operated within range of normal driver behaviour
  - What is normal driving behaviour?



# // Baseline for Assessment of Automated Driving

- Analysis of **euroFOT data**
- Plot displayed: Acceleration during normal driving
- Data from 98 vehicles
- Motorway, rural roads and urban roads



# //Scenario-based Assessment of Automated Driving

Data Source//

AdaptIVe demonstrator

Reference: euroFOT

► **Human driving** as a **baseline**

Classification of Scenarios//

Classifier Scenario 1

Classifier Scenario 2

Classifier Scenario x

► Classification of scenarios by using **time series classification algorithms (Hidden Markov Models)**

PIs

Scenario-based Assessment//

Assessment//

Calculation of:

- Derived Measures
- Performance Indicators

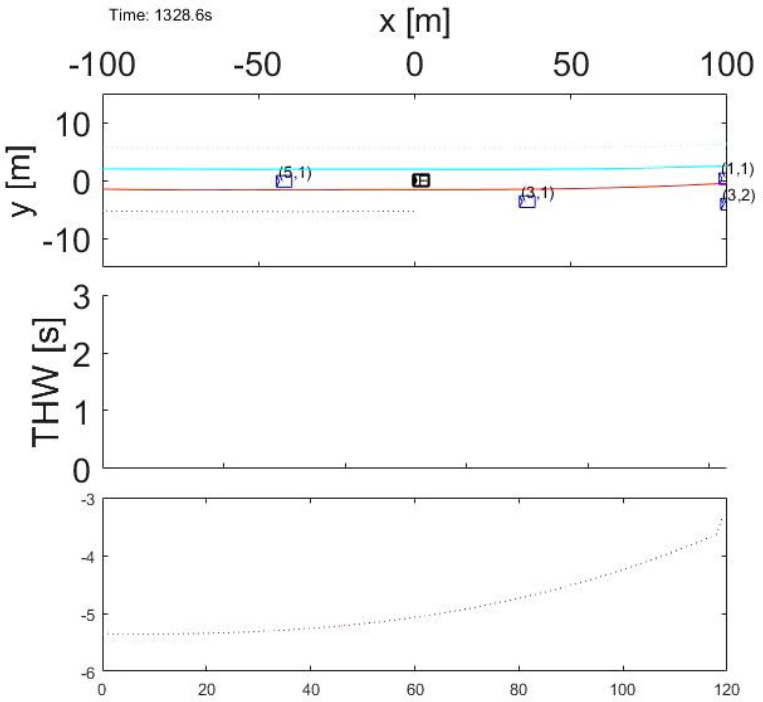
Δ Frequency (Scenario)

Δ Effect (Scenario)

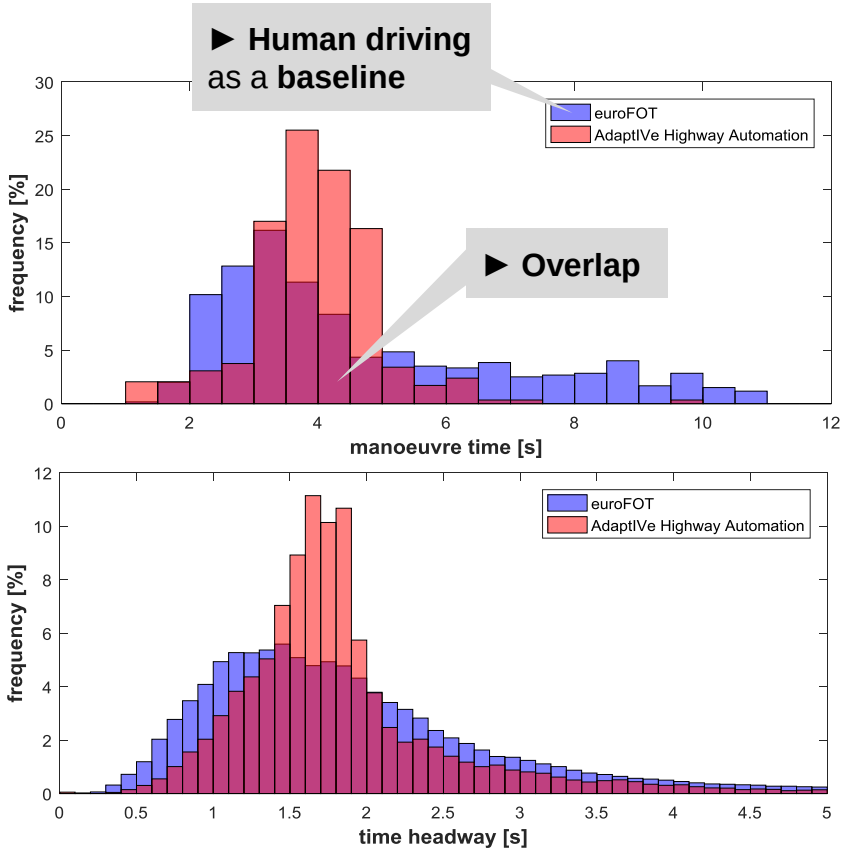
► Assessment of Δ**frequency** and Δ**effect** induced by system in **scenario**

# // Scenario Classification – Scenario „Cut-in“



# // Technical Assessment - Results

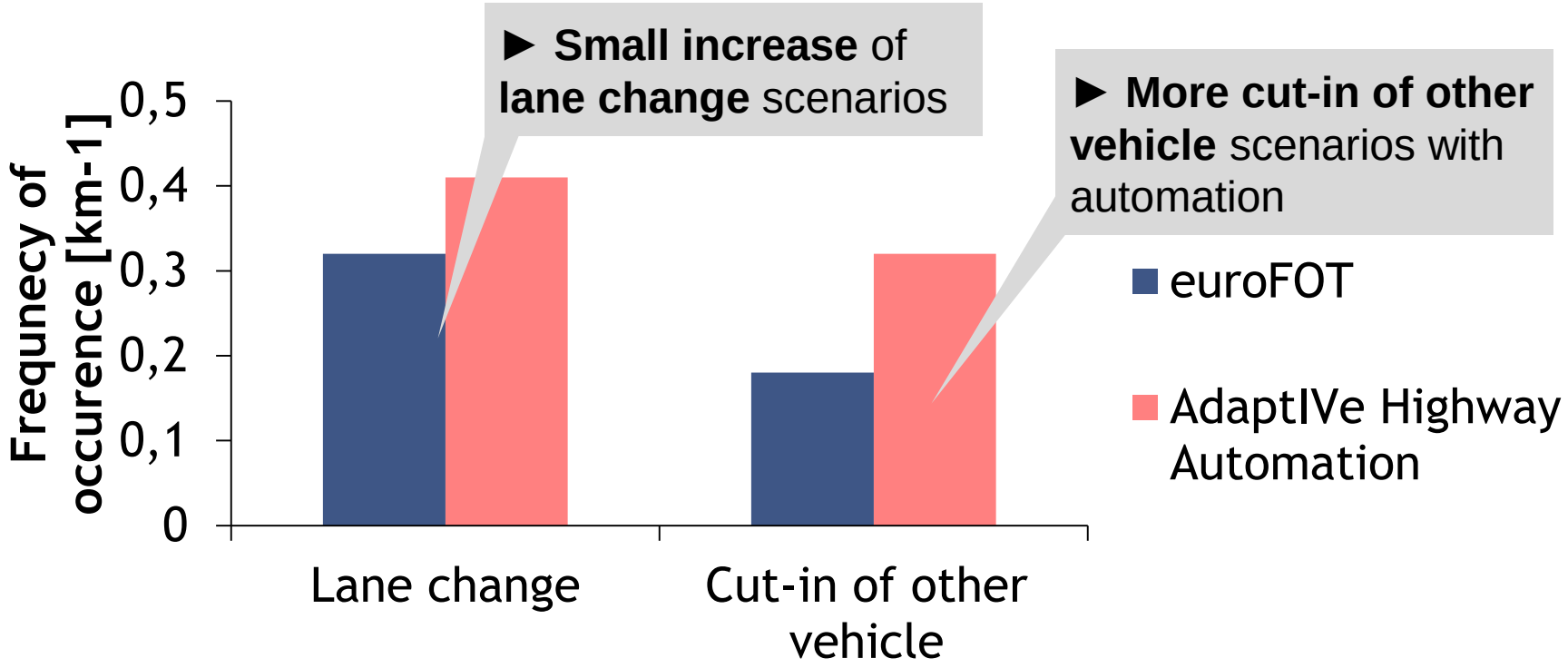



The **AdaptIVe Highway-Chauffeur is** showing a **control capability similar to human driving** from euroFOT. Two results stand out:

- Top figure: **duration** of **lane change** is much **more uniform** with automation
- Bottom figure: **time headway** in **vehicle following** shows **much less variability** with automation

# // Application of Method – Frequencies





# // User-related Assessment
## Method & Results

# // User-related Assessment

- Method
  - Behavioural observations - two observers in the car
  - 21 test persons, Highway-Chauffeur as an example
  - Logging of driving data – e.g. speed, distance, lane keeping
  - Questionnaires
    - Mental workload
    - Trust
    - Usability (SUS)
    - Usefulness/Satisfactoriness
    - Experienced effects
    - Expected benefits/disadvantages

# // User-related Assessment



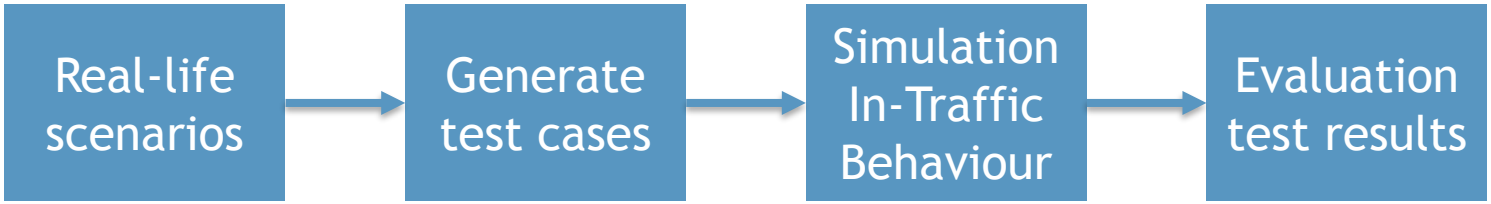
- **Key Results**
- **The drivers used the system as it was intended to be used**
  - **The system affected driving positively in several ways**
    + Better speed adaptation to speed limits and conditions, less speed variations
    + Better distance keeping ahead
    + Better lane choice (prescribed use of the right lane)
    + Better indicator usage
    + Fewer dangerous lane changes
  - Due to 130 kph system limit, overtaking manoeuvres are longer

// More details in the AdaptIVe Deliverable D7.2

# // In-Traffic Assessment
## Method & Results

# // In-Traffic Assessment - Method

- Research focus:
  - **How is the vehicle interacting with other traffic participants?**
  - **How do other traffic participants react on the (automated) vehicle?**

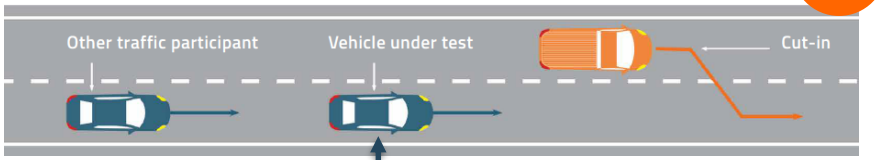



- In-traffic Assessment used generated real-life scenarios with Monte-Carlo **simulations**

# // In-Traffic Assessment

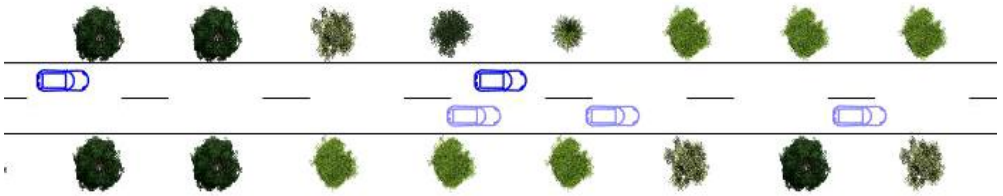
// Urban

## // Test scenario & system to test 1

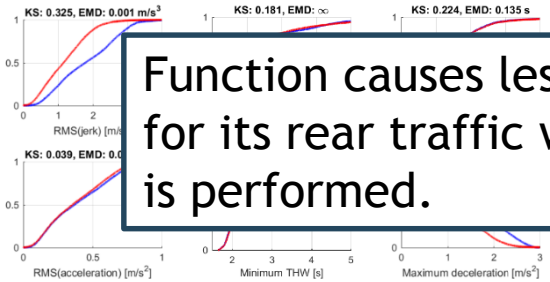



Traffic Jam Assist
(Adaptive Cruise Control)

## // Simulation 2



## // Analysis (Evaluation) 3




Function causes less oscillations for its rear traffic when a cut-in is performed.

// More details in AdaptIVe Deliverable D7.2

# // Safety Impact Assessment
## Method & Results

# // Target Areas


| | | | |
|---|---|---|---|
| // Safety impact assessment | | | ✓ |
| // Enviromental impact assessment | ✓ | ✓ | ✓ |

# // Safety Impact Assessment - Methodology

// Highway

- Challenges:
  - Continuous intervention by automated driving functions
    // Simulated reconstructed accidents is not sufficient; rather traffic scenario must be simulated
  - Simulated the driver behaviour while manual driving
    // Adequate driver model is required to consider human errors
  - Implementation of an automated driving function

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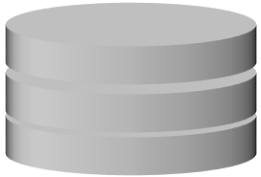
# // Safety Impact Assessment - Methodology

// Highway

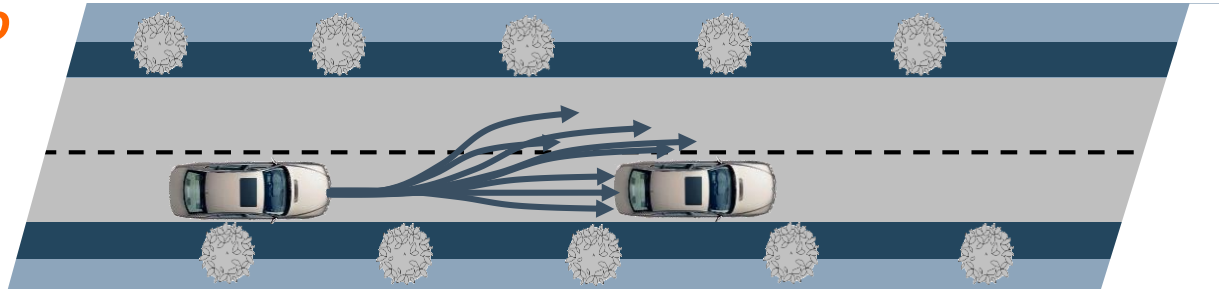


Accident data (e.g. GIDAS) / Critical situations (FOT)

Description of function

Simulation of traffic scenarios

## Top-Scenario



Simulation of driving scenarios



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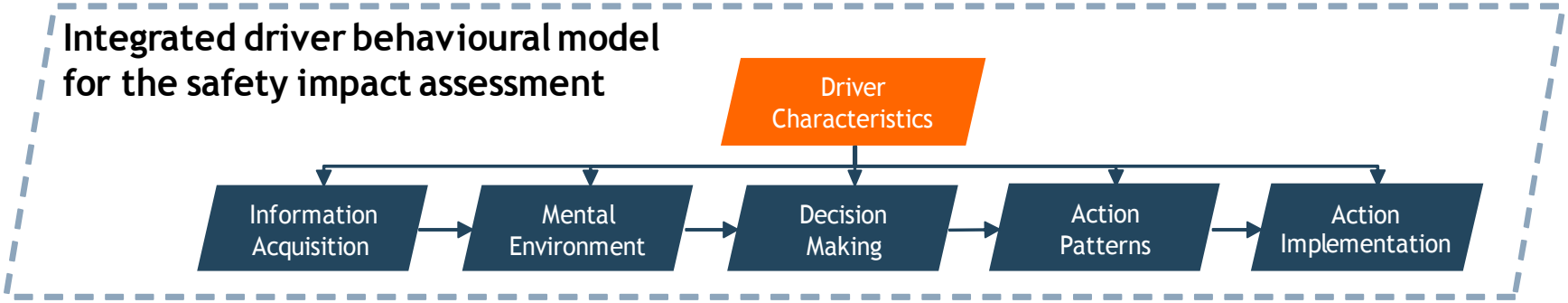
# // Safety Impact Assessment – Driver Model

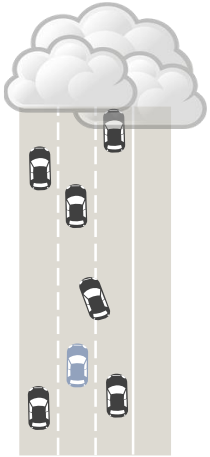
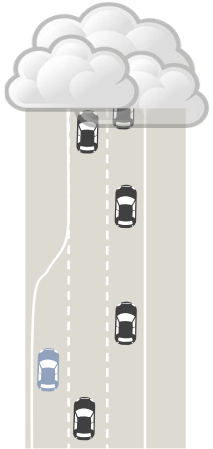
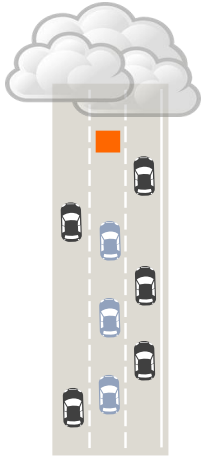
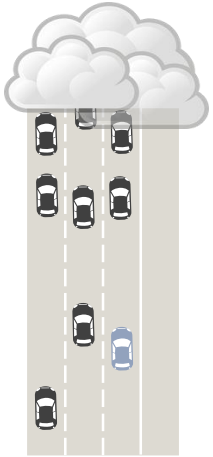
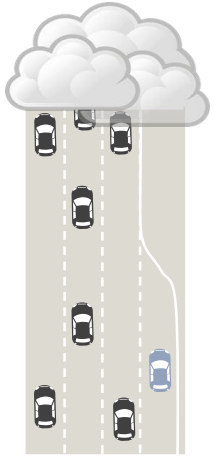
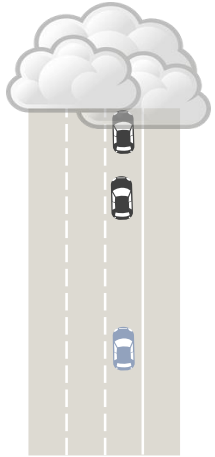
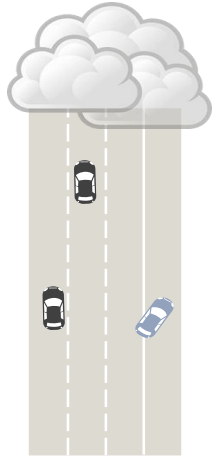


- Challenge: Simulation human driving behaviour in the baseline
- **Stochastic Cognitive Model (SCM) is used in the simulation**
- A core aspect of the SCM driver behavioural model is the application of stochastically methods in order to represent the behaviour of different drivers (e.g. gaze control)



# // Safety Impact Assessment – Top Scenarios

// Highway

| Top 1 | Top 2 | Top 3 | Top 4 | Top 5 | Top 6 | Top 7 |
|---|---|---|---|---|---|---|
| Cut-In | End of Lane | Obstacle in the lane | Traffic jam | Highway entrance | Rear-end accident | Single driving accident |
|  |  |  |  |  |  |  |



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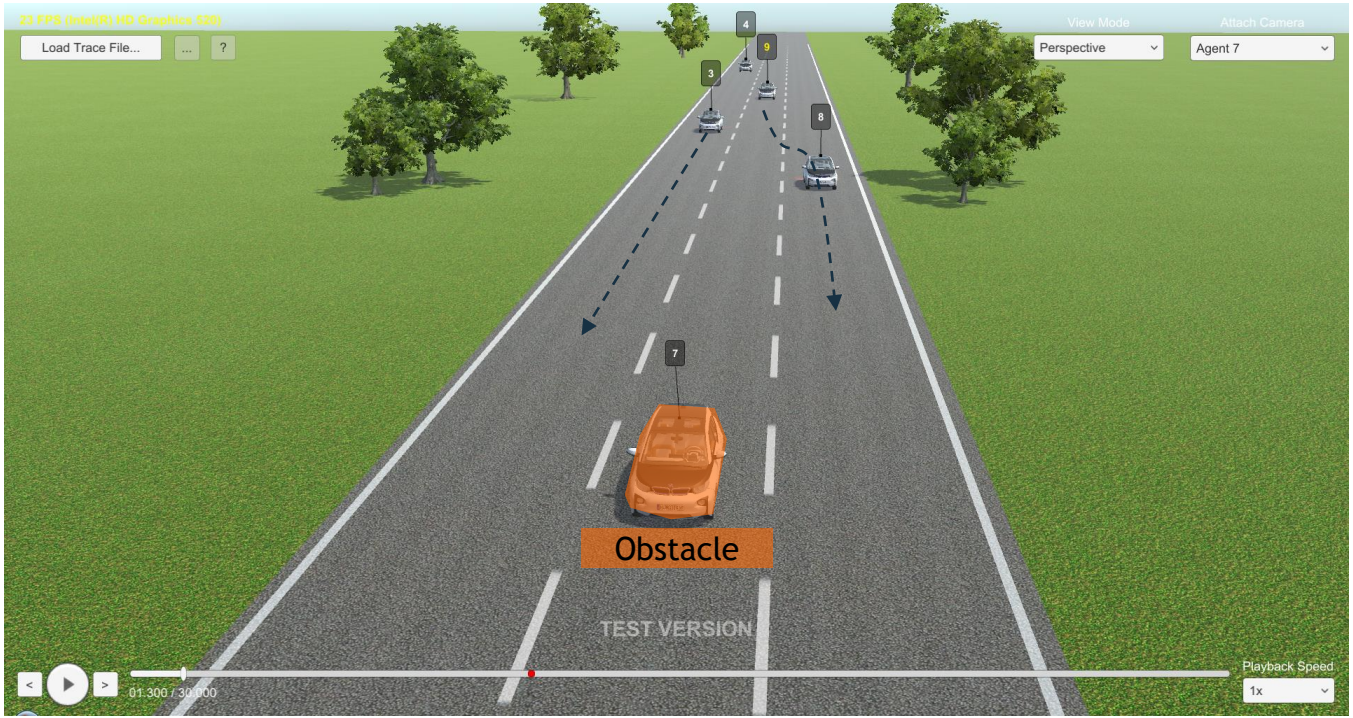
# // Safety Impact Assessment – Obstacle in lane

// Highway

- Simulation tool openPASS



# // Environmental Impact Assessment

## Method & Results

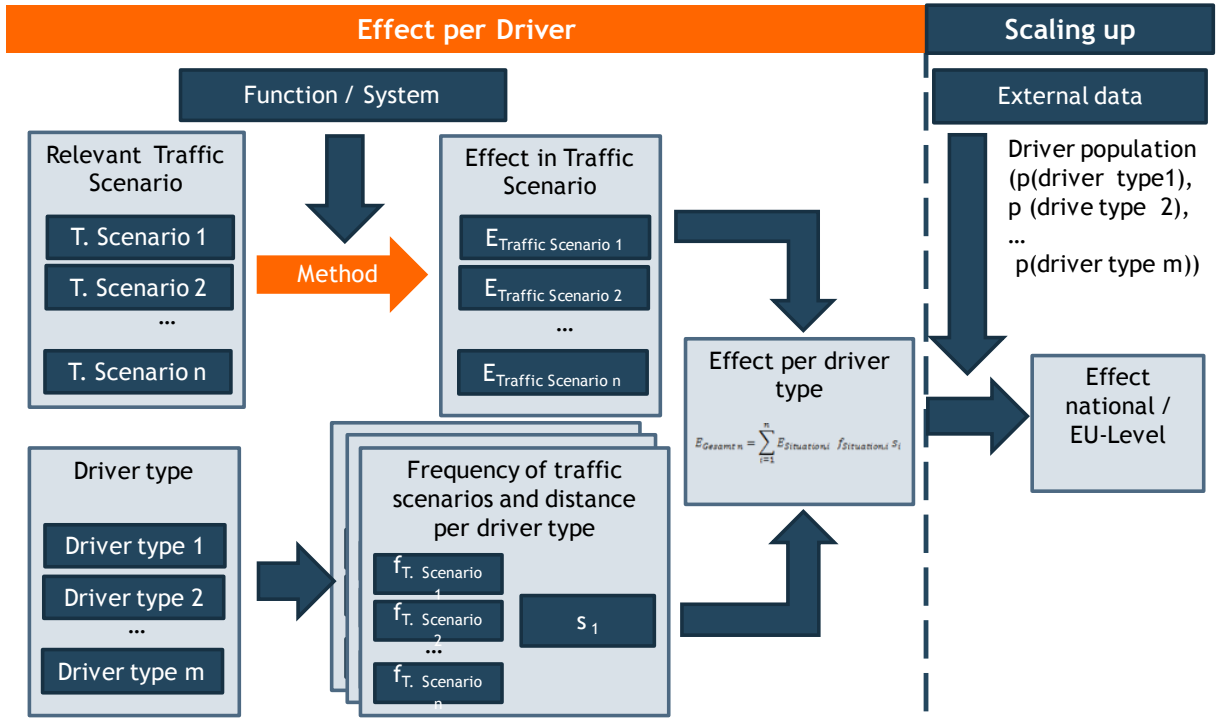
# // Environmental Impact Assessment - Method

// Highway

Analysis of the environmental impact with respect to

- Energy demand
- Traffic flow
- Travel time

Consider different driver types

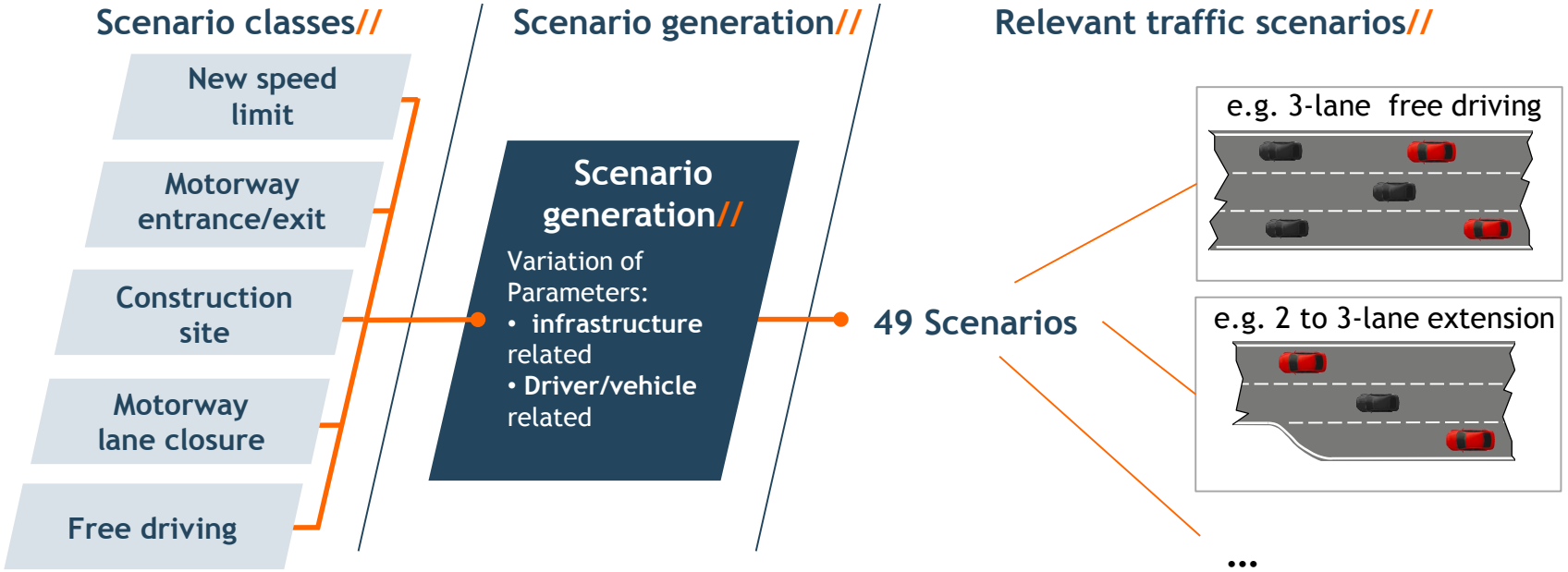





AdaptIVe

# // Environmental Impact Assessment - Method

// Highway






AdaptIVe

# // Environmental Impact Assessment

// Highway



Adapt!Ve

# // Environmental Impact Assessment - Results

## Motorway

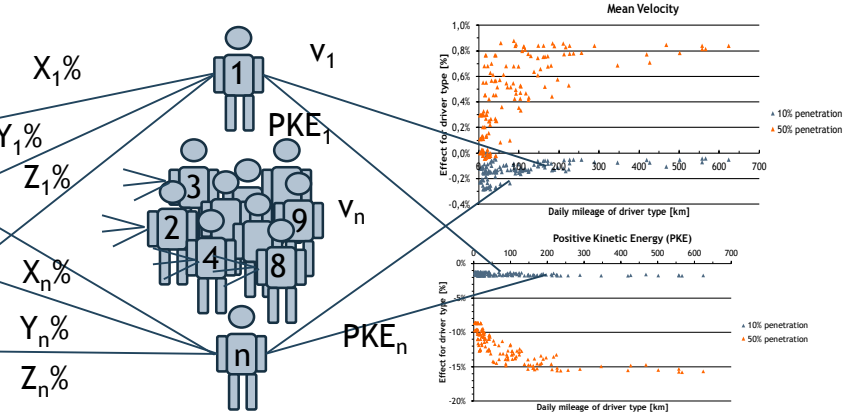
| | | 10% penetration | | 50% penetration | |
|---|---|---|---|---|---|
| Scenario | Lanes | PKE | Mean velocity | PKE | Mean velocity |
| Highway entry | 2 | -1.45% | -0.06% | -20.98% | 0.61% |
| Highway exit | 2 | -1.47% | 0.05% | -17.85% | 0.87% |
| New speed limit, 100-120 | 3 | -2.62% | 0.17% | -13.44% | 0.51% |
| New speed limit, 120-80 | 3 | -2.18% | 0.02% | -12.71% | 0.24% |
| Construction site | 2 | -3.56% | 0.73% | -24.36% | 6.30% |
| Construction site | 3 | -2.56% | 0.71% | -13.55% | 3.00% |
| Free driving, 130 km/h | 2 | -2.28% | -0.11% | -17.40% | 0.51% |
| Free driving, 130 km/h | 3 | -2.07% | -0.05% | -16.73% | 0.83% |

## Urban

| | 10% penetration | | 50% penetration | |
|---|---|---|---|---|
| Scenario | PKE | Mean velocity | PKE | Mean velocity |
| 4-way-intersection with traffic lights | -6.59% | -2.92% | -27.75% | -3.32% |
| T-intersection with traffic lights | -5.24% | -1.43% | -21.97% | -1.30% |
| New Speed Limit, 30-50 | -1.66% | 0.04% | -10.80% | 0.42% |
| New Speed Limit, 50-70 | -1.50% | 0.03% | -11.36% | 0.40% |
| New Speed Limit, 70-50 | -1.50% | 0.02% | -11.66% | 0.36% |
| New Speed Limit, 50-30 | -1.55% | 0.03% | -11.13% | 0.42% |
| Free Driving, 30 km/h | -1.19% | 0.14% | -17.25% | 1.57% |
| Free Driving, 50 km/h | -1.07% | 0.12% | -18.88% | 1.45% |
| Free Driving, 70 km/h | -1.25% | 0.10% | -20.10% | 1.31% |
| … | … | … | … | … |

# // Environmental Impact Assessment - Overall Results

| | | 10% penetration | |
|---|---|---|---|
| Scenario | Lanes | PKE | Mean velocity |
| Highway entry | 2 | -1.45% | -0.06% |
| Highway exit | 2 | -1.47% | 0.05% |
| New speed limit, 100-120 | 3 | -2.62% | 0.17% |
| New speed limit, 120-80 | 3 | -2.18% | 0.02% |
| Construction site | 2 | -3.56% | 0.73% |
| Construction site | 3 | -2.56% | 0.71% |
| Free driving, 130 km/h | 2 | -2.28% | -0.11% |
| Free driving, 130 km/h | 3 | -2.07% | -0.05% |




Effect per scenario → Defined drvier types → Results per single driver

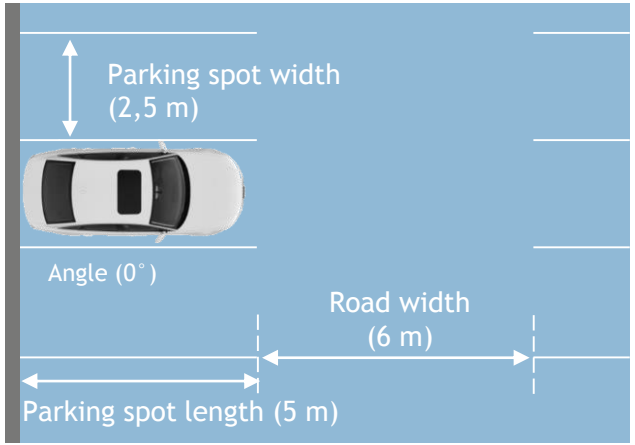
$$\sum \text{driver}_i \cdot w_i$$

| | Mean Velocity | PKE |
|---|---|---|
| 10% penetration | -0.12% | -1.54% |
| 50% penetration | 0.53% | -12.77% |

# // Environmental Impact Assessment

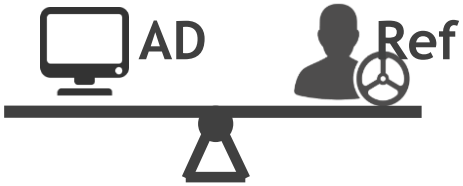
- **Method**
  - Analysing the required parking space for automated vehicle
  - Assumption: If the driver is not in the car, it is possible to park more narrow
    1. Parking maneuver analysis to find the optimal trajectory
    2. Required parking lot and road width calculation
    3. Additional parking space determination
- **Results**

| Vehicle Class | Benefit of automated driving |
|---|---|
| Minis | 17% |
| Upper Class | 5% |
| Average Vehicle | 10% |



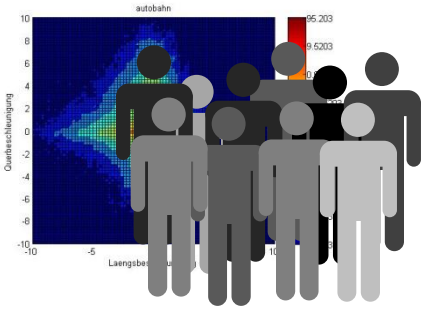
# //Summary

- The **baseline** for assessment of automated driving should be **human driving behaviour**




- The AdaptIVe user-related assessment shows, that the **systems affected driving positively** in **several ways**, e.g. better speed adaptation to speed limits and conditions, less speed variations)

- Automated driving is leading to a **change in frequency of occurence of (safety) relevant scenarios** due a **different driving behaviour compared to humans.**



# // Many thanks to the AdaptIVe SP7 team!

- **Felix Fahrenkrog, Lei Wang** - BMW Group
- **András Várhélyi** - Lund University
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- **Fabio Tango** – CRF
- **Pablo Mejuto** – CTAG
- **Jan Sauerbier, Adrian Zlocki** – ika, RWTH Aachen University

# // Many Publications from our Work Available!

- "*A Scenario-based Assessment Method for Automated Driving by Using Time-Series Classification of Human Driving Behaviour*", IEEE ITSC 2017, Rio de Janeiro, 2017.
- "*A Comprehensive Evaluation Approach for Automated Driving*", 25th Enhanced Safety of Vehicles 2017, Detroit, Michigan, 2017.
- "*Verification of Automated Driving Based on Real-World Driving Data*", ITS European Congress 2017, Strasbourg, France, 2017.
- "*Environmental Impact Assessment of Automated Driving*", 23rd ITS World Congress, Melbourne, Australia, 2016.
- "*Technical evaluation and impact assessment of automated driving*", Road Vehicle Automation 3, Springer Lecture Notes in Mobility, 5.2016.
- to be continued…

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Adapt/:/Ve

Automated Driving Applications and Technologies for Intelligent Vehicles

*Thank you.*

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