PROJECT of the PEGASUS FAMILY

VERIFICATION VALIDATION METHODS

Mid-Term Presentation 15 / 16 March 2022

Criticality Analysis for the **Verification & Validation** of **Automated Driving Systems**

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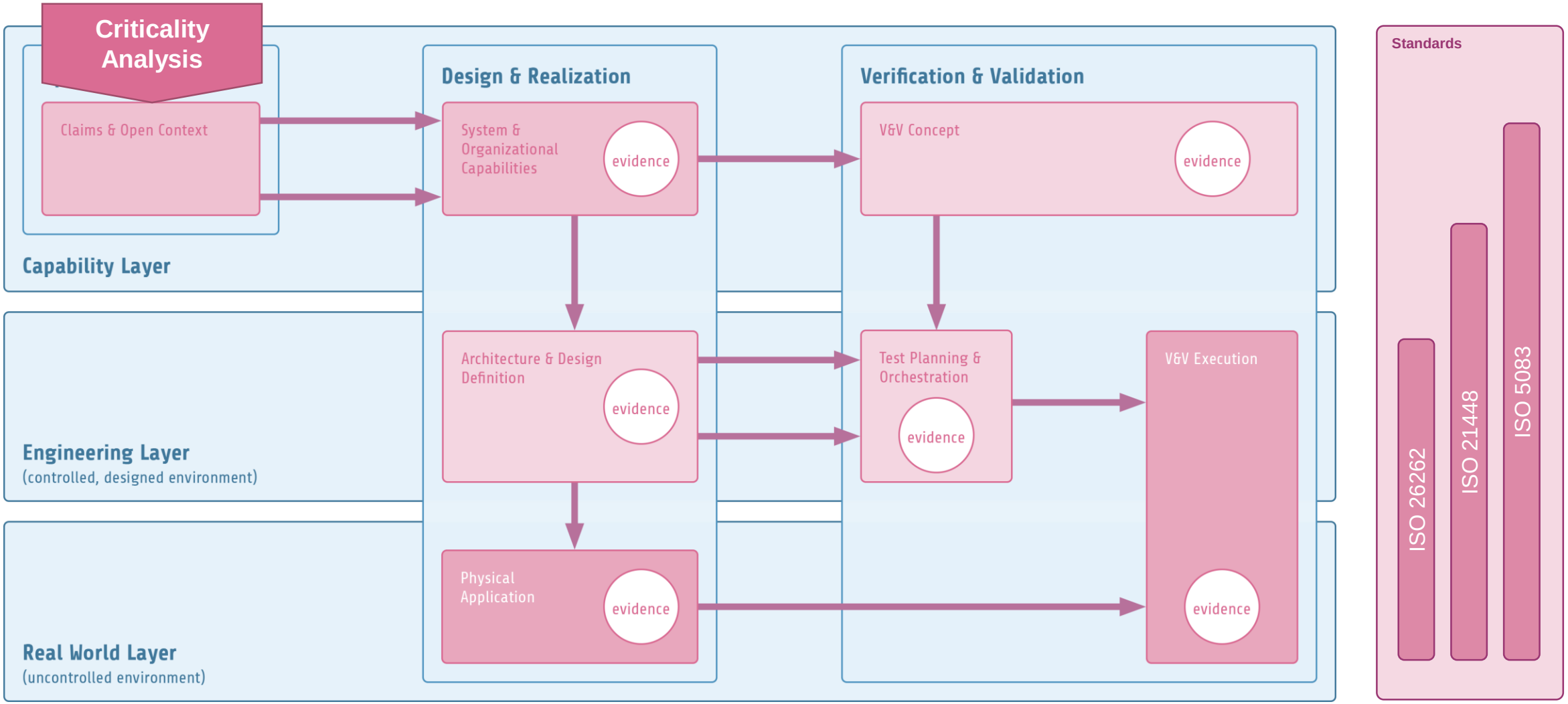
on the basis of a decision by the German Bundestag

V&V Process in Assurance Framework

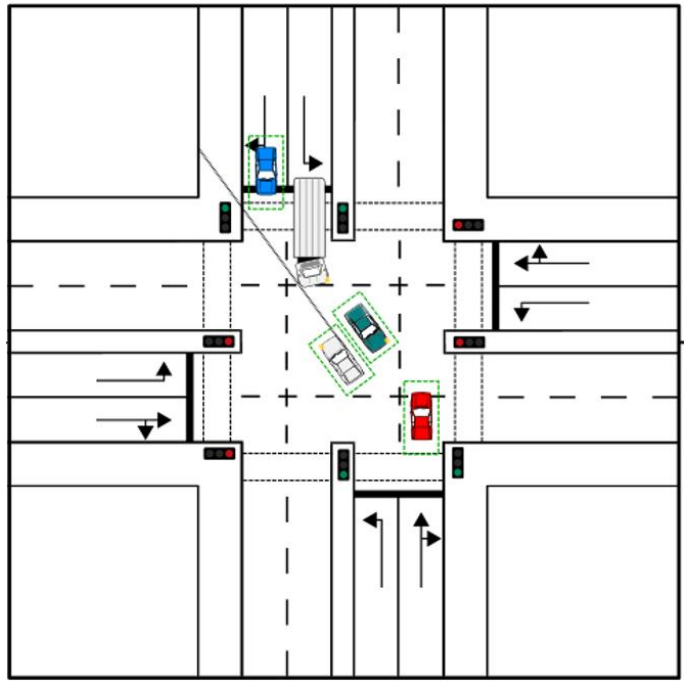


Criticality Analysis in VVM

- **criticality** (of a traffic situation) is the combined risk of the involved actors when the situation is continued

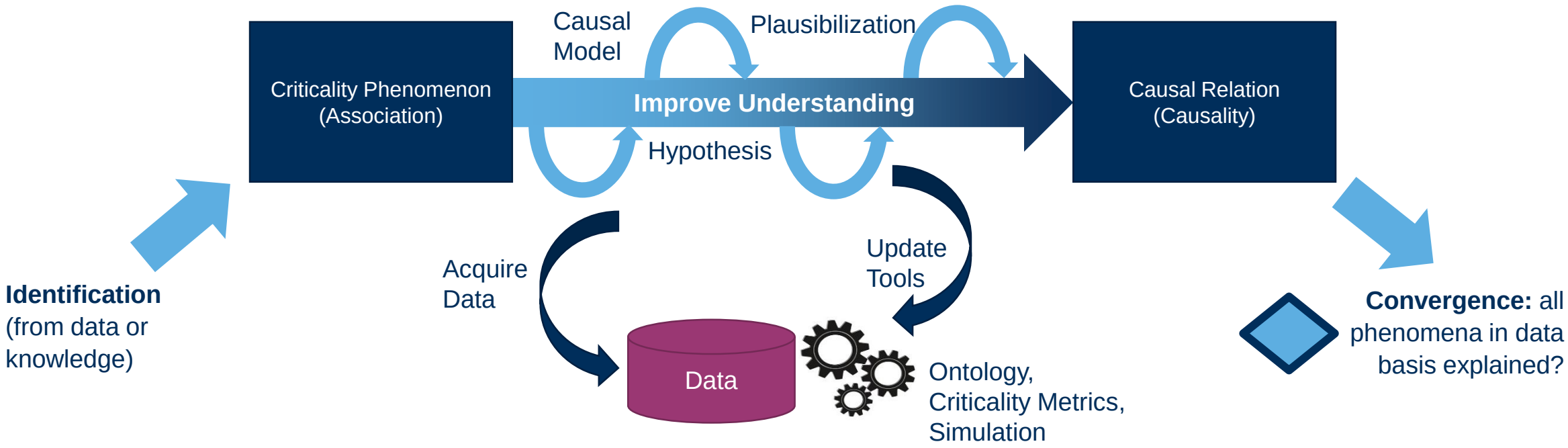
- **main goal:** gain knowledge on the **open context** w.r.t. the emergence of criticality and its conditions → structuring of the **operational domain**
  - identification of influencing factors associated with increased criticality → criticality phenomena
  - improve understanding of criticality phenomena by analysis of underlying **causal relations** → derivation of **target behavior**
  - abstraction leads to classification of scenarios → **contribution** to **scenario-based verification & validation**

- **tools employed for criticality analysis:**
  - ontologies, criticality metrics, simulation
  - acquisition & management of knowledge and data
  - statistical analysis, machine learning, causal inference



use case „urban intersection“

Criticality Analysis – the Basic Concept



Assumptions:

- set of criticality phenomena is limited and manageable → finiteness (of artefacts)
- relevant phenomena leave traces in growing data basis → completeness (of artefacts)

– Detailed Flowchart

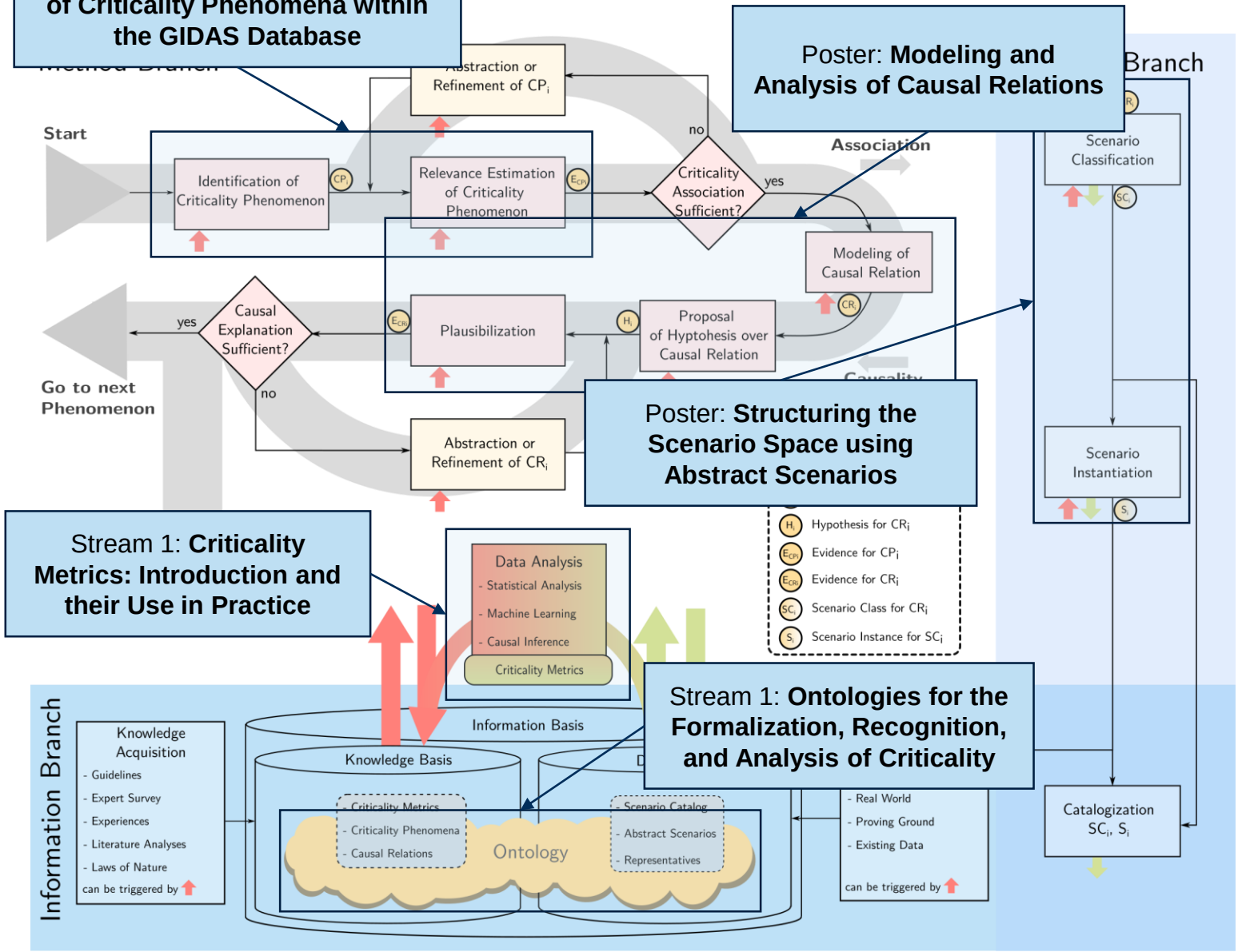
Poster: **Identification and Analysis of Criticality Phenomena within the GIDAS Database**

Poster: **Modeling and Analysis of Causal Relations**

Poster: **Structuring the Scenario Space using Abstract Scenarios**

Stream 1: **Criticality Metrics: Introduction and their Use in Practice**

Stream 1: **Ontologies for the Formalization, Recognition, and Analysis of Criticality**



- **Method Branch** – identification of criticality phenomena, modeling of causal relations, plausibilization of hypotheses, criticality metrics
- **Information Branch** – knowledge and data management for the criticality analysis, ontologies.
- **Scenario Branch** – use scenarios as the ‘substrate’ of the criticality analysis, a means for structuring processes and description of reality

Example: the Criticality Phenomenon ‚Occlusion‘

- identify the criticality phenomen ‚**occlusion**‘ (e.g. via **expert knowledge)**
  - find adequate **level of abstraction** and interesting **concretizations**
  - use **ontological representation** to organize knowledge

Absolute Cases	Relative Cases	Projection
2978	22.9%	36746
600	4.6%	7401
1076	8.3%	13280
844	6.5%	10413
0	0%	0
-	-	-
313	2.4%	3865
-	-	-

Criticality Phenomenon	Ontological Classification	Estimated Criticality
Occlusion	Perception	Medium
Occluded Pedestrian	Perception	High
Occluded Bicyclist	Perception	High
Occluded Intersecting Vehicle	Perception	Medium
Occluded Obstacle	Perception	Medium
Occluded Lane Markings	Perception	High
Occluded Traffic Sign	Perception	Depends
Occluded Traffic Light	Perception	High

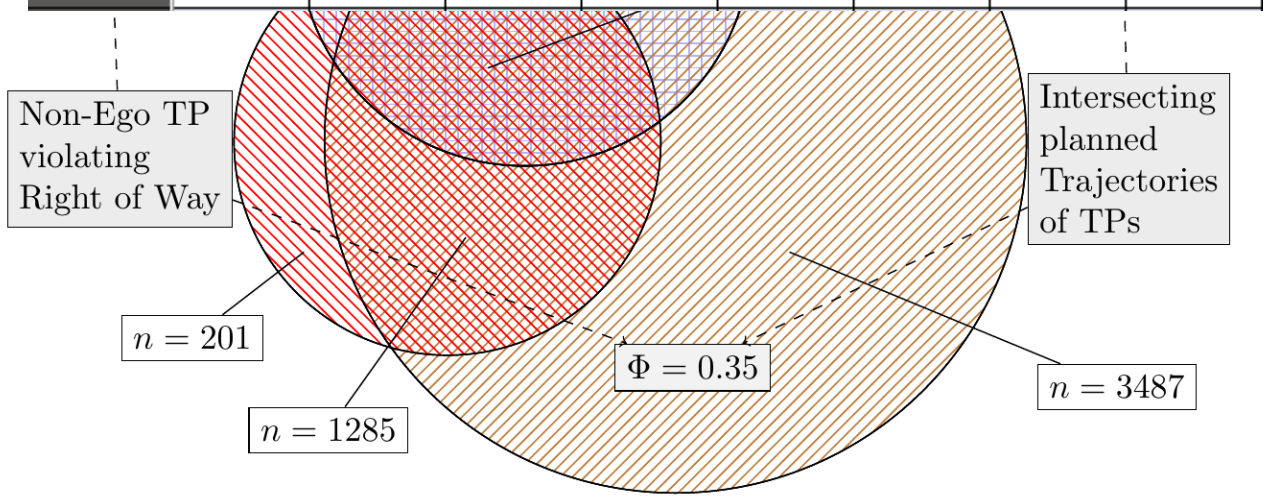
- gather **empirical evidence** for the relevance of ‚occlusion‘
  - searching the **GIDAS** database yields
    - $\frac{2978}{12997} \approx 22,9\%$ accidents associated with ‚occlusion‘
  - strong indication that „occlusion“ is a **relevant phenomenon** in non-automated traffic

GIDAS
German In-Depth Accident Study
- since 1999 -

Estimation of Relevance for Criticality Phenomena

- **analysis of GIDAS** accident database,
  - for relevant VVMethods subset $\mathbf{N = 12997}$ accidents „cases“ in **urban areas** involving a **passenger car**
  - Analysis of each case regarding the presence of **116** criticality phenomena identifiable in the database
- for each phenomenon, obtain **absolute** and **relative frequencies** of occurence
  - ranking phenomena according to frequency allows **estimation of relevance**
  - interesting cases appear as **combinations** of **criticality phenomena**

FALL	CP_40	CP_41	CP_44	CP_45	CP_46	CP_47	CP_48	CP_50
56810	0	1	0	0	0	0	0	0
34320	0	1	0	0	0	0	0	0
75142	1	1	0	0	0	1	0	0
88195	0	0	0	0	0	1	0	0
25900	0	0	0	0	0	0	0	0
45624	0	1	0	0	0	1	0	0
46218	1	1	0	0	0	0	1	0
57032	0	1	0	0	0	0	0	0
25736	0	0	0	0	1	0	0	0
47414	0	1	0	0	0	0	1	0
10412	0	0	0	0	0	0	1	0
48849	0	1	0	0	0	1	0	0
76273	0	0	0	0	0	0	0	0



From Association to Causality:
Causal Effect Analysis of Criticality Phenomena

- use **causal graphs** to model **assumptions** about the underlying **causal relations** of criticality phenomena

- incorporate **criticality metrics** as to make the **impact** of phenomena **measureable**

- acquire **data** that enable the **computation** of the **causal effect** of the phenomenon on measured criticality, using either
  - real-world data or
  - synthetic data (simulation)

- iterative **abstraction** & **refinement** of causal assumptions during **plausibilisation** of the **causal relation**

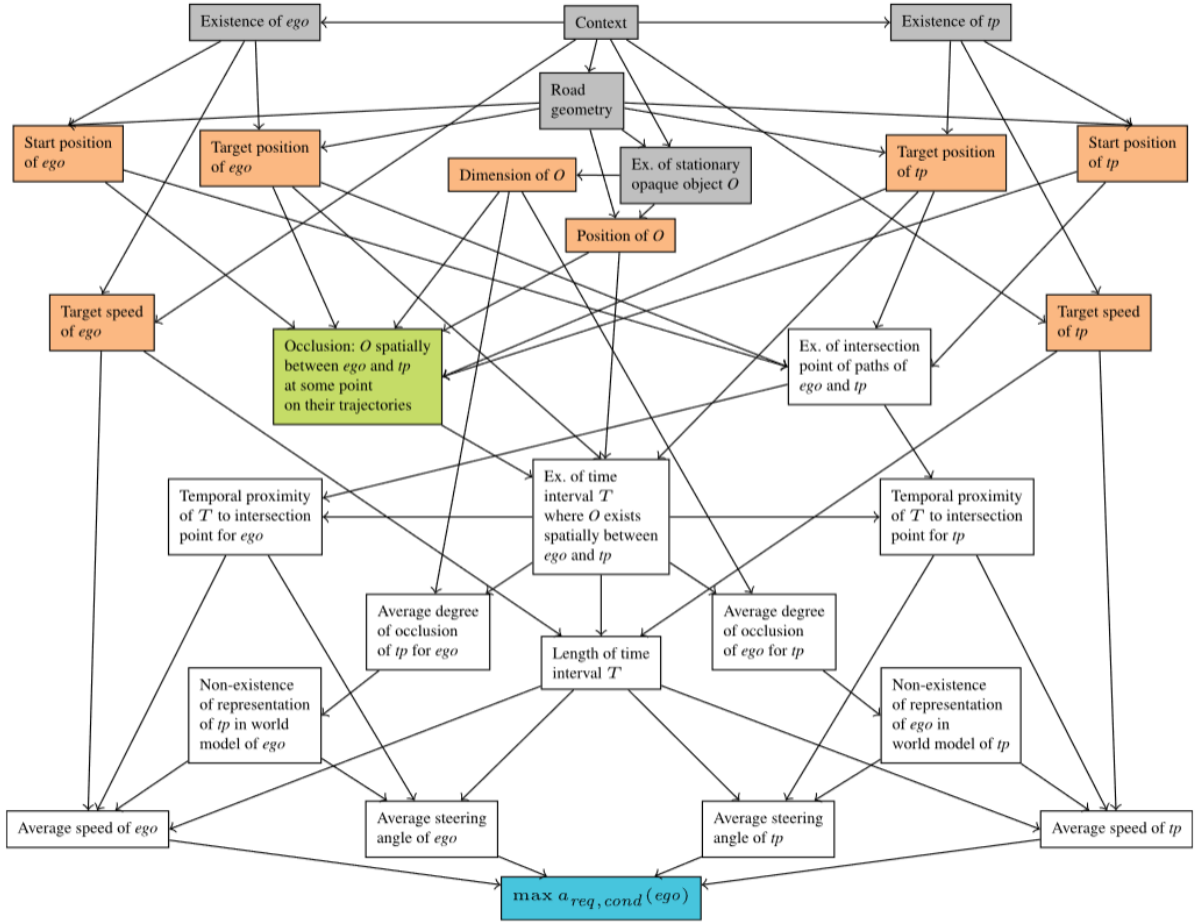
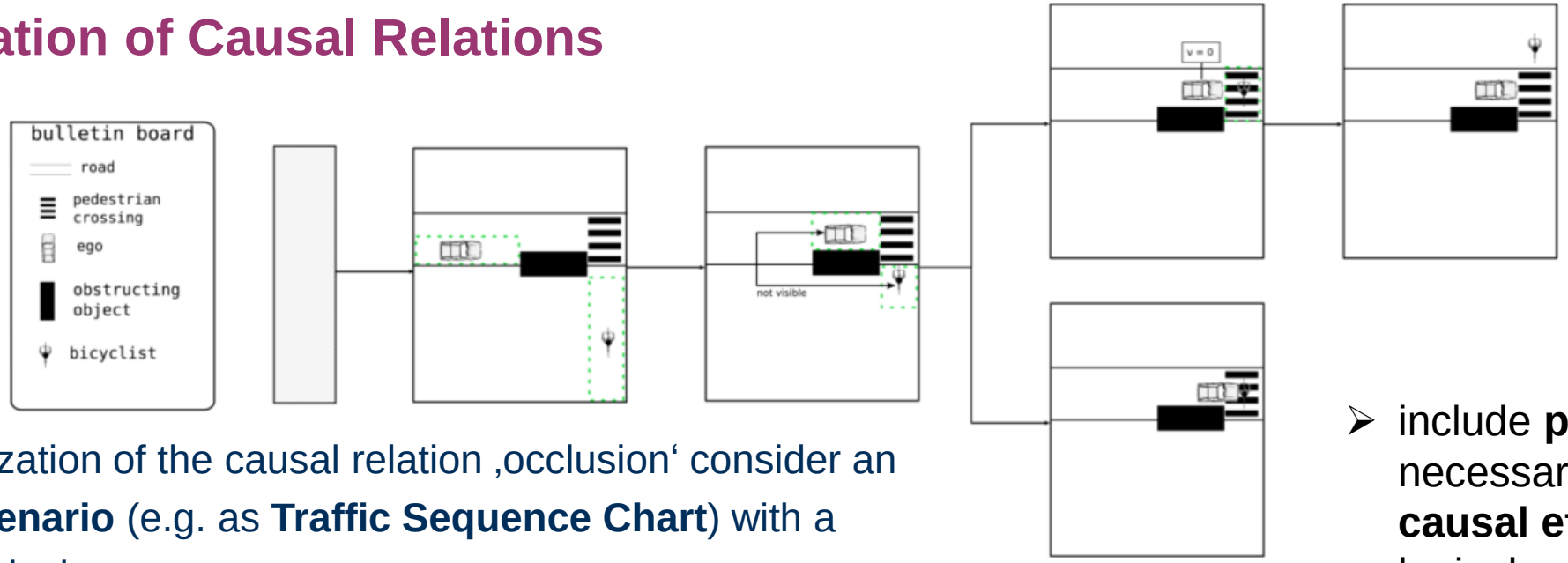


Figure: causal graph for evaluating the causal effect of „occlusion“ on the criticality metric $a_{req,cond}(ego)$.

Plausibilization of Causal Relations



- for plausibilization of the causal relation ‚occlusion' consider an **abstract scenario** (e.g. as **Traffic Sequence Chart**) with a potential occlusion
- for realization of the occlusion scenario in a simulation derive a **logical scenario**
- example parameter space for simulation using **CARLA**

Parameter	Range
ego start position (x, y)	$[-58, -33] \times [-29, -28]$
ego target position (x, y)	$[50, 55] \times [-29, -28]$
ego target speed (km/h)	$[25, 60]$
bicyclist start position (x, y)	$[31, 32] \times [3, 15]$
bicyclist target position (x, y)	$[-50, -45] \times [-34, -33]$
bicyclist target speed (km/h)	$[10, 25]$
Dimension of O (discretized as number of parking cars)	$\{0, 1, 2, 3, 4, 5, 6, 7\}$
Position of O (x, y)	$[2, 20] \times ([-35, -34] \cup [-26, -25])$

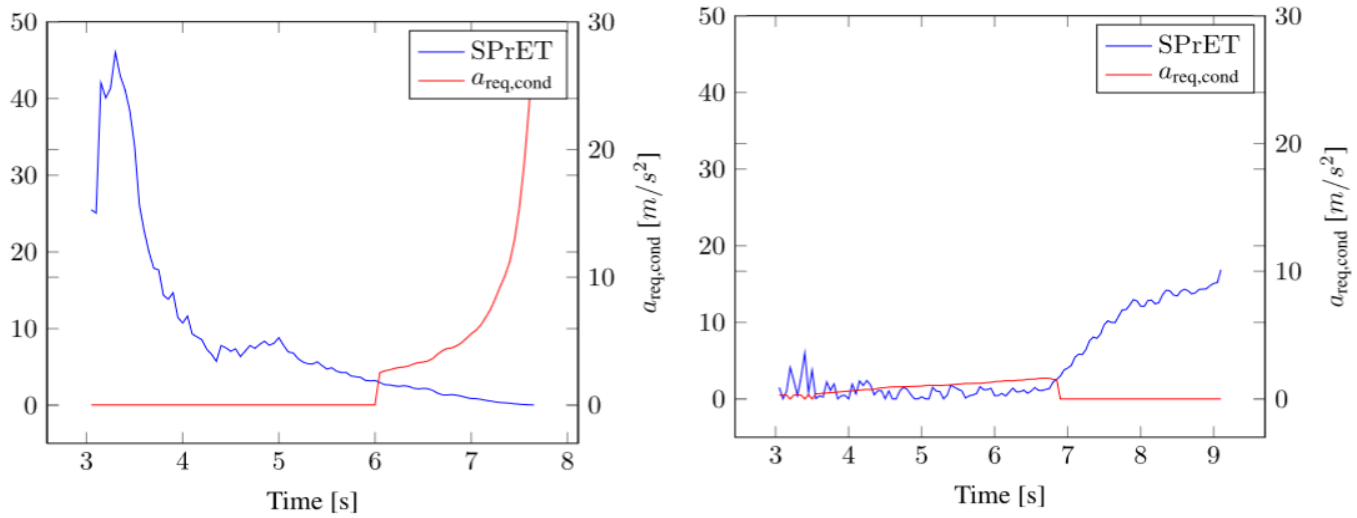
- include **parameters** necessary to **estimate causal effects** in a logical scenario
  - minimal adjustment set of variables from causal graph analysis

Simulation of ‚Occlusion of Bicyclist through Parking Cars' (FUC2-3)

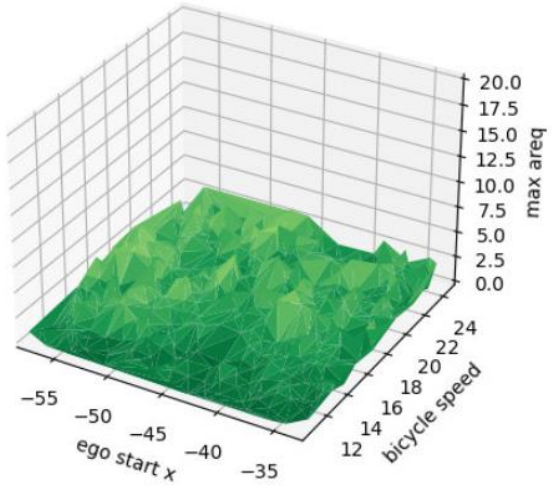
Video: showing four instantiations of an occlusion scenario with varying critcality using the CARLA simulator.

Generate and Evaluate Synthetic Data for Plausibilization

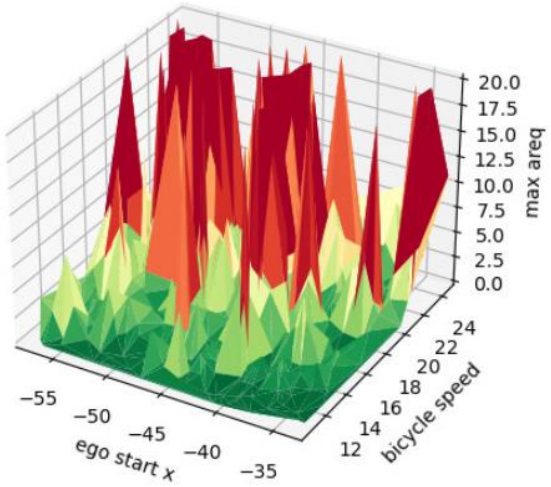
- **stochastic variation** of adjustment variables to obtain **concrete scenarios** for simulation



- **evaluate** for **each simulation run**
  - criticality metric(s) from the causal model
  - the presence of the criticality phenomenon



Group A: no occlusion present



Group B: occlusion present

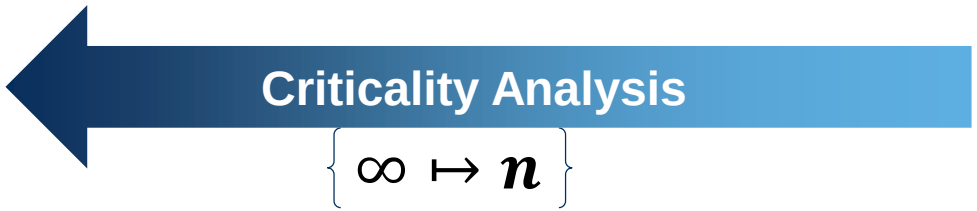
- perform **analysis** of the resulting **data set,** computing quantities of interest, e.g.

$$\mathbb{E}(a_{\text{req,cond}}(ego)|occlusion = 1) = 3.15\ (\pm 3.10) m/s^2 =: E_1$$
$$\mathbb{E}(a_{\text{req,cond}}(ego)|occlusion = 0) = 1.10\ (\pm 0.75) m/s^2 =: E_2$$
$$E_1 - E_2 = \mathbf{2.05} \quad E_1/E_2 = \mathbf{2.86}$$

Summary

- a methodical **criticality analysis** contributes to structuring the open context
  - **decomposition** of the **operatonal domain** according to emergence of criticality
  - exemplary conduction within VVMethods for complex urban environments

- **finitely many artifacts** result from the criticality analysis, namely
  - criticality phenomena
  - causal relations
  - abstract scenarios



- **basic concept** of the criticality analysis: move from **associations** (criticality phenomena) to **causality** (causal relations)

- the criticality analysis is sub-divided into **three branches**, namely
  - method branch, information branch, scenario branch

VERIFICATION
VALIDATION
METHODS

Thank you!

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PROJECT of the PEGASUS FAMILY

A project developed by the VDA Leitinitiative autonomous and connected driving

Supported by:
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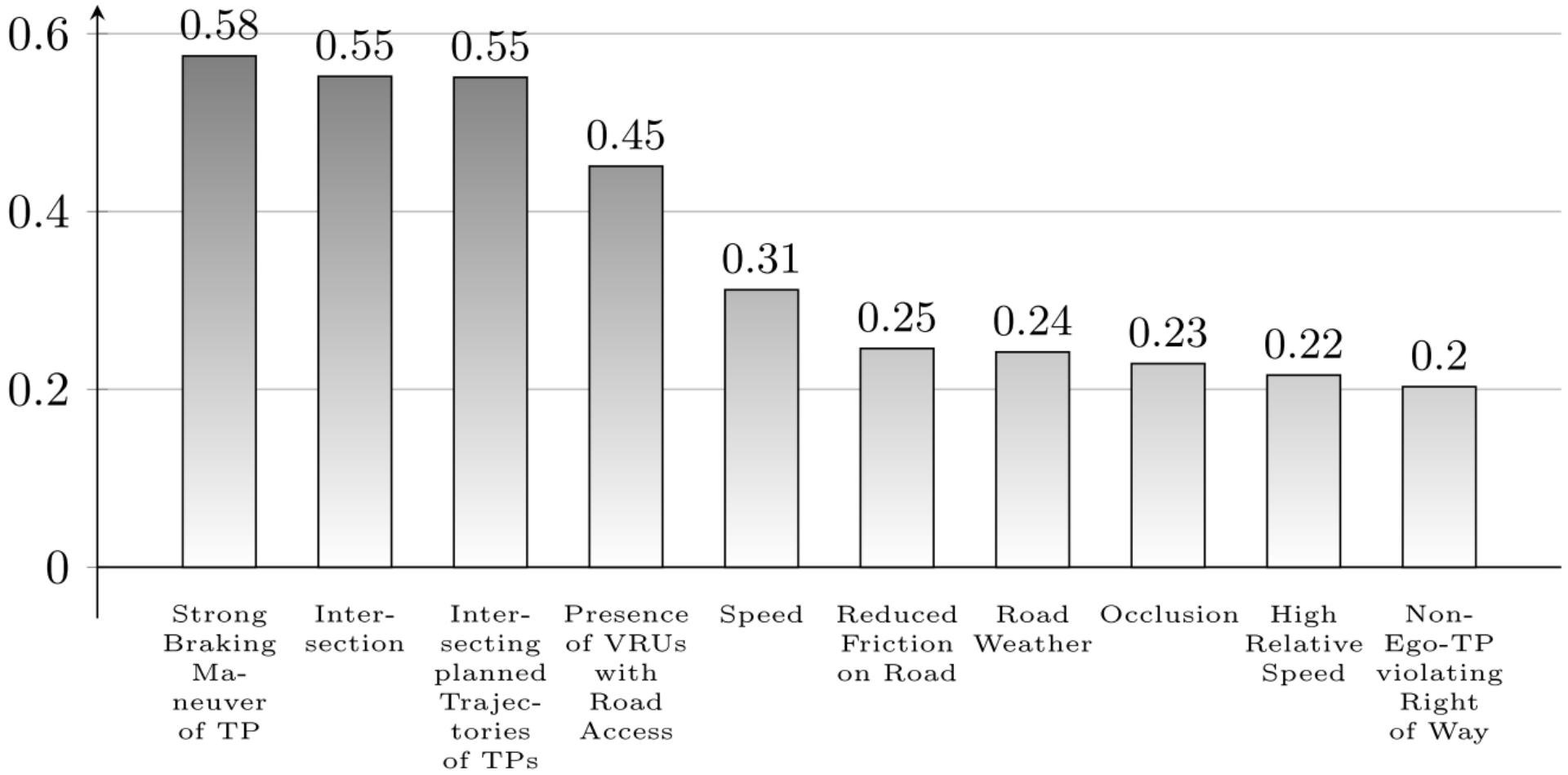
Publications for Further Reading

- **„Criticality Analysis for the Verification and Validation of Automated Vehicles“**
  - IEEE Access (Journal),
  - VVM Partners: DLR (formerly OFFIS), Bosch, ZF, Stellantis
  - Links: ResearchGate, IEEExplore

- **„Criticality Metrics for Automated Driving: A Review and Suitability Analysis of the State of the Art”**
  - Preprint (submitted to Journal)
  - VVM / SET Level Partners: DLR (formerly OFFIS), Bosch, FZI, DLR, AVL
  - ResearchGate, arXiv

- **„6-Layer Model for a Structured Description and Categorization of Urban Traffic and Environment”**
  - IEEE Access (Journal)
  - VVM Partners: ika, DLR (formerly OFFIS), ZF
  - Links: ResearchGate, IEEExplore

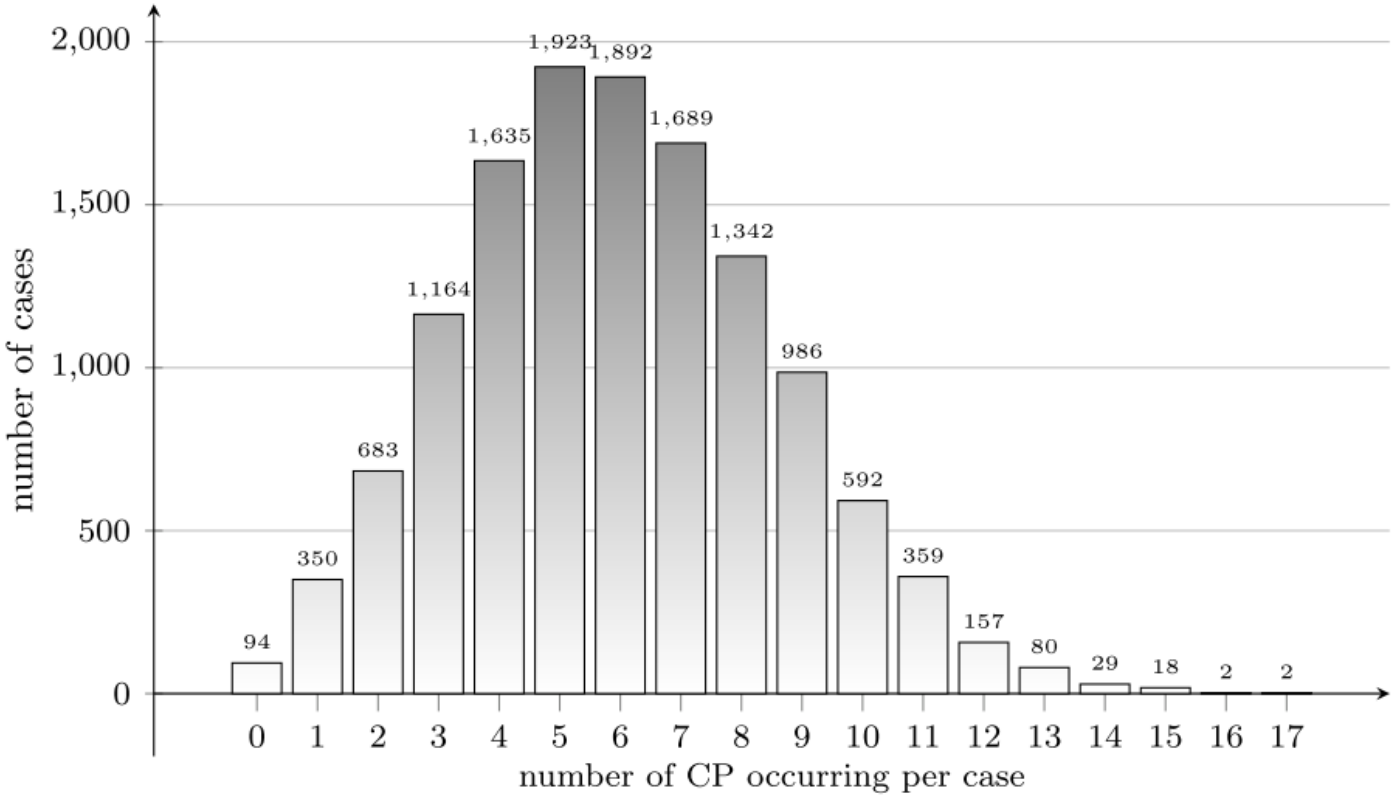
Top Ten Criticality Phenomena in GIDAS



Edge Cases as Combinations of Criticality Phenomena

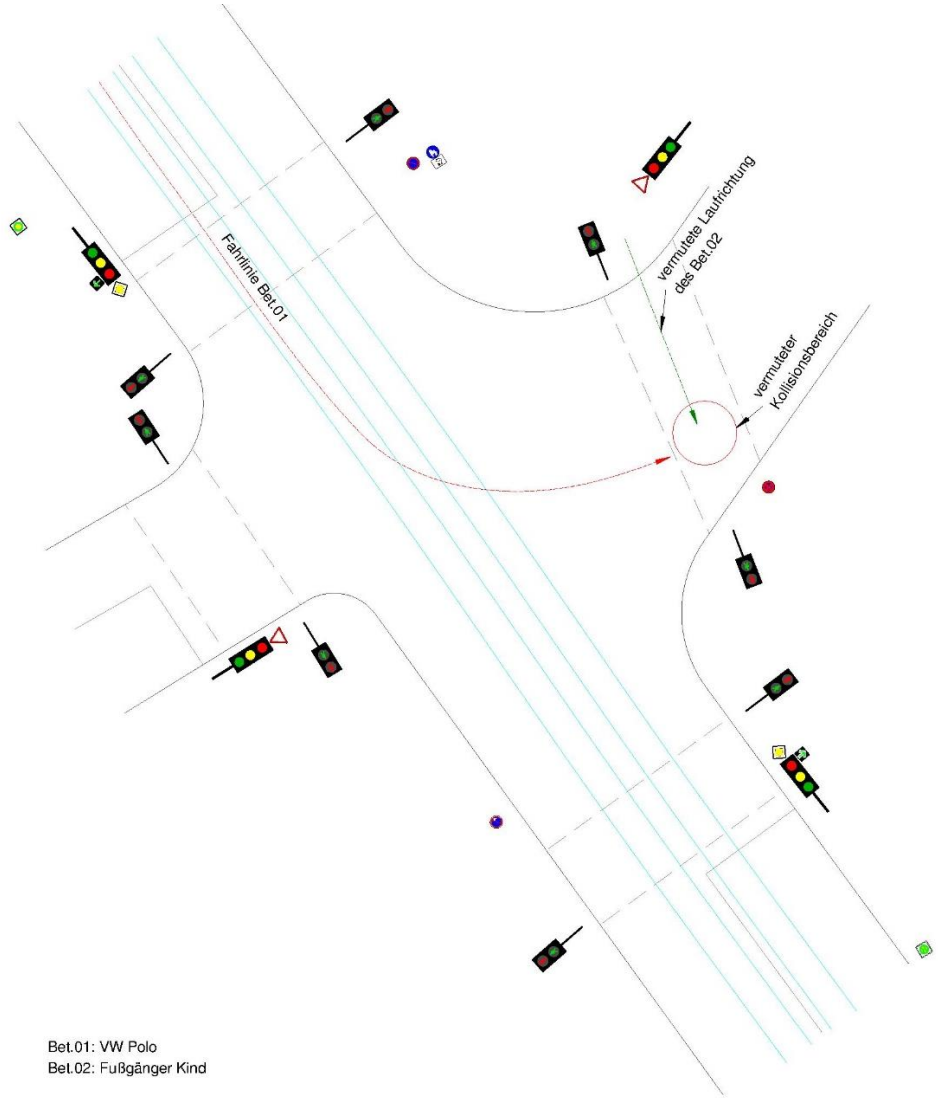
- Accidents in (human) traffic are **multi-causal**.

- After filtering out abstraction/refinement relations …
  - most accidents (~55%) in urban areas feature **between 4 and 7** criticality phenomena per case
  - 94 accidents feature no CP; either **not relevant for AVs** or due to **incompleteness of CP collection**
  - 4 special „loaded“ cases with **more than 15 CP** will be discussed in the afternoon session



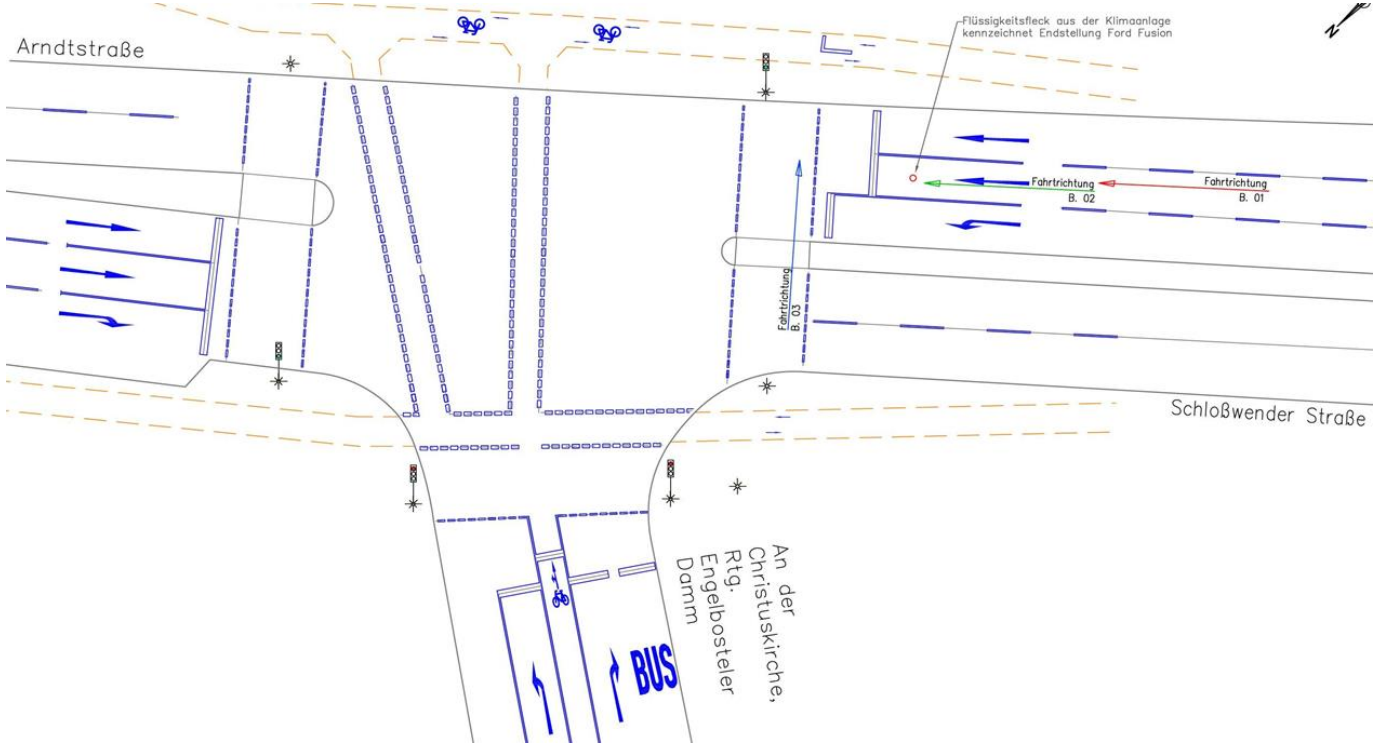
Edge Case #1: Car vs. Pedestrian (featuring 16 CP)

- **Environment**
  - Rain
  - Reduced Friction on Road
  - Limited Global Light Source
- **Infrastructure**
  - Intersection
  - Pedestrian Crossing
  - Degraded Road Quality
  - Degraded Lane Markings
  - Intersecting Tram Rails
- **Involved Actors, Maneuvers, Misconduct**
  - Intersecting Planned Trajectories of TPs
  - Presence of VRUs with Road Access
  - Presence of URUs with Road Access
  - Dark Clothing of VRU
  - Pedestrian crossing Road directly
  - Non-Ego-TP running a Red Traffic Light
  - Non-Ego-TP violating Right of Way
  - Strong Braking Maneuver of Ego/Non-Ego-TP



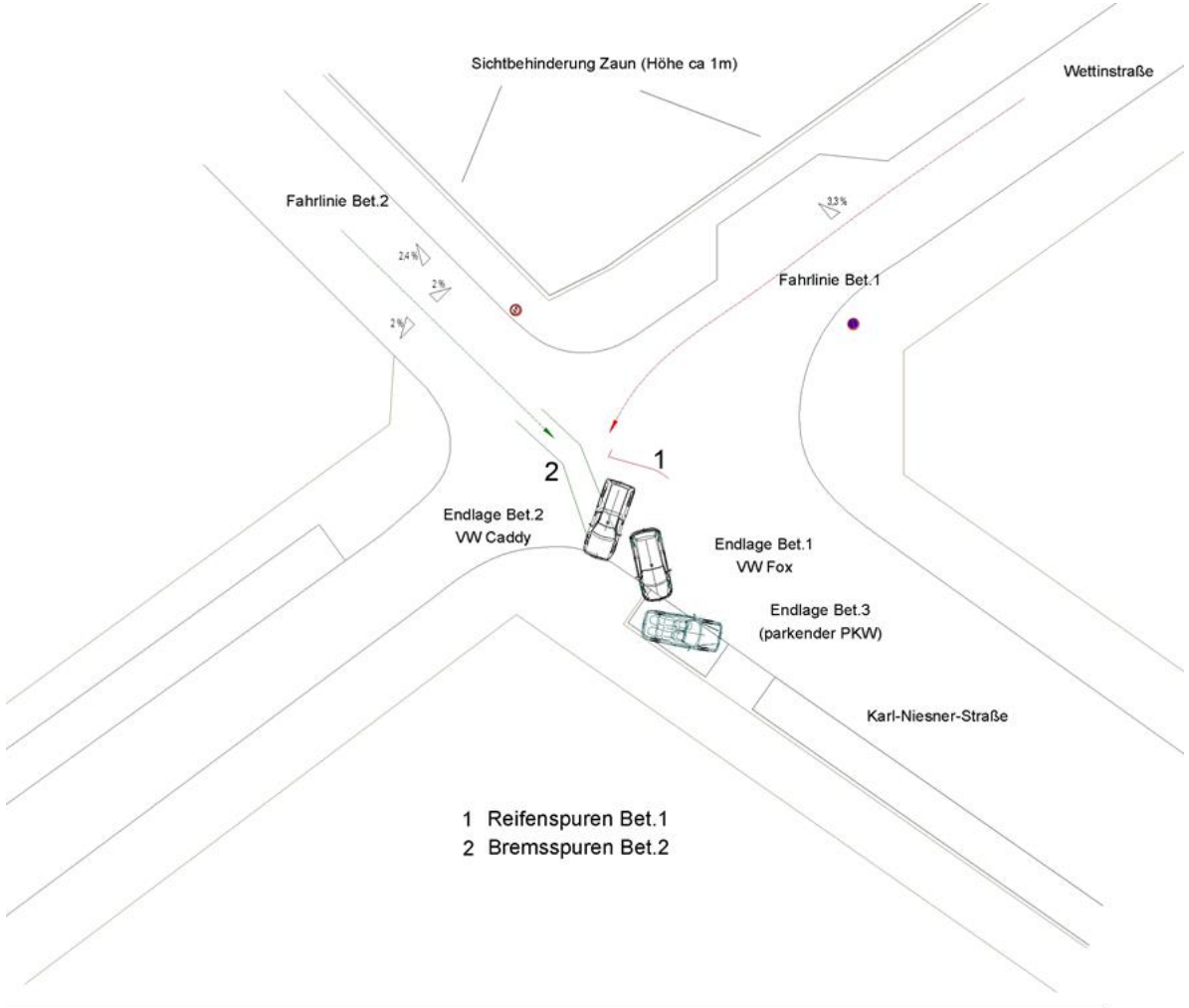
Edge Case #2: Car vs. Car vs. Pedestrian (featuring 17 CP)

- **Environment**
  - Wind
- **Infrastructure**
  - Intersection
  - Pedestrian Crossing
  - Degraded Road Quality
- **Involved Actors, Maneuvers, Misconduct**
  - Intersecting Planned Trajectories of TPs
  - Presence of VRUs with Road Access
  - Impaired VRU with Road Access
  - Presence of URUs with Road Access
  - Occluded Pedestrian
  - Pedestrian crossing Road directly
  - Dark Clothing of VRU
  - Non-Ego-TP running a Red Traffic Light
  - Non-Ego-TP violating Right of Way
  - Strong Braking Maneuver of Ego/Non-Ego-TP
  - Strong initial Braking Maneuver of Ego/Non-Ego-TP
  - Small Distance to Front
  - Small Distance to Back



Edge Case #3: Car vs. Car vs. Parking Car (featuring 17 CP)

- **Environment**
  - Extreme (change in) Temperature
- **Infrastructure**
  - Intersection
  - Bad Road Surface
- **Perception**
  - Occluded Traffic Sign
  - Occluded Intersecting Vehicle
  - Occluded Vehicle
- **Involved Actors, Maneuvers, Misconduct**
  - Intersecting Planned Trajectories of TPs
  - Non-Ego-TP violating Right of Way
  - Non-Ego-TP aggressive driving
  - Passing of Parking Vehicle
  - Non-Ego-TP impaired driving ability
  - Excessive Speed of Non-Ego-TP
  - High Relative Speed
  - Presence of URUs with Road Access
  - Strong Braking Maneuver of Ego/Non-Ego-TP
  - Interaction with Emergency Vehicles



Edge Case #4: Car vs. Bicyclist (featuring 16 CP)

- **Environment**
  - Extreme (change in) Temperature
- **Infrastructure**
  - Intersection
  - Bad Road Surface
  - Degraded Road Quality
- **Perception**
  - Occluded Bicyclist
- **Involved Actors, Maneuvers, Misconduct**
  - Intersecting Planned Trajectories of TPs
  - High Relative Speed
  - Non-Ego-TP violating Right of Way
  - Lane Closure
  - Passing of Parking Vehicle
  - Risky Lane Change of Non-Ego-TP
  - Bicycle Lane Change onto Road
  - Wrong-Way Bicyclist
  - Strong Braking Maneuver of Ego/Non-Ego-TP
  - Presence of VRUs with Road Access
  - Dark Clothing of VRU
  - Non-Ego-TP on Wrong Non-Driveable Lane