VERIFICATION
VALIDATION
METHODS

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

Christian Neurohr, German Aerospace Center (DLR)

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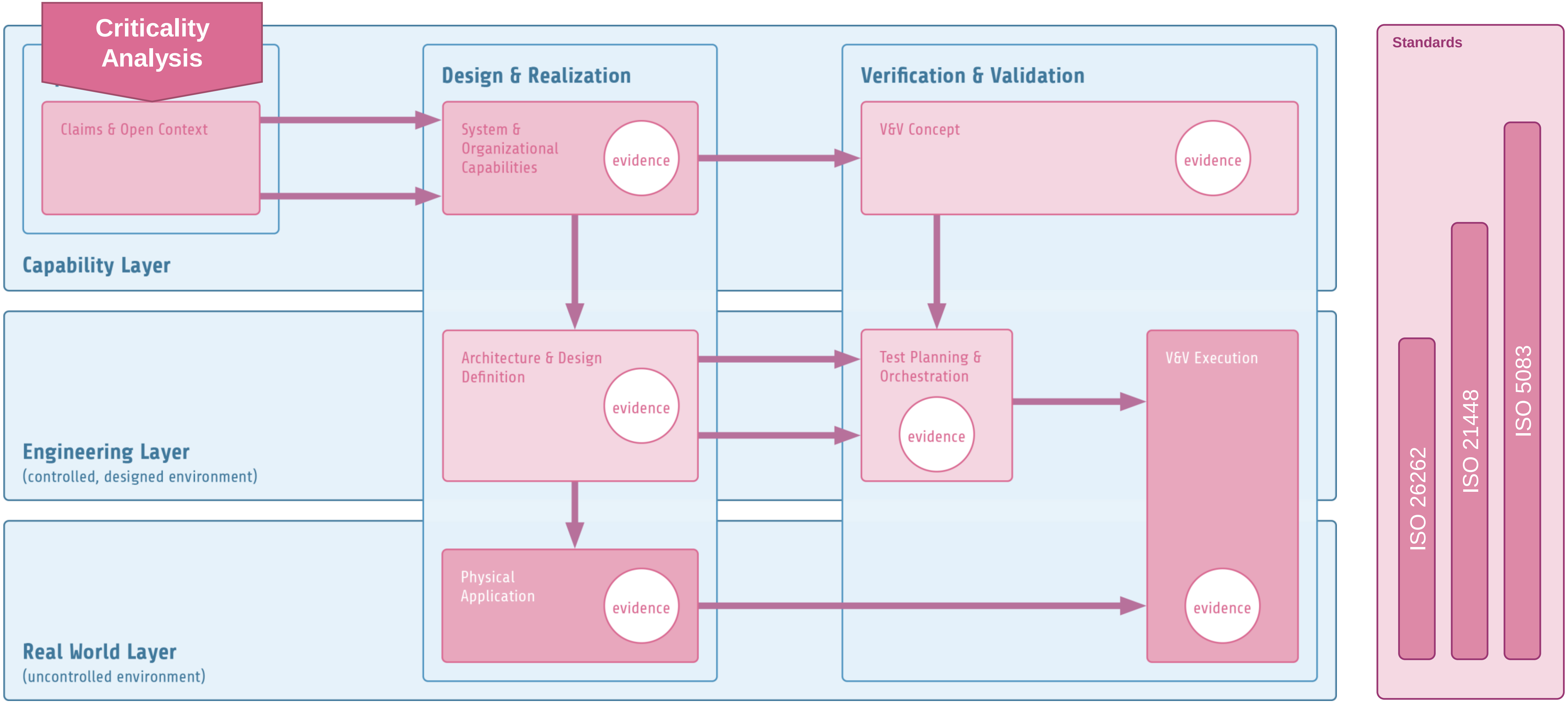
V&V Process in Assurance Framework

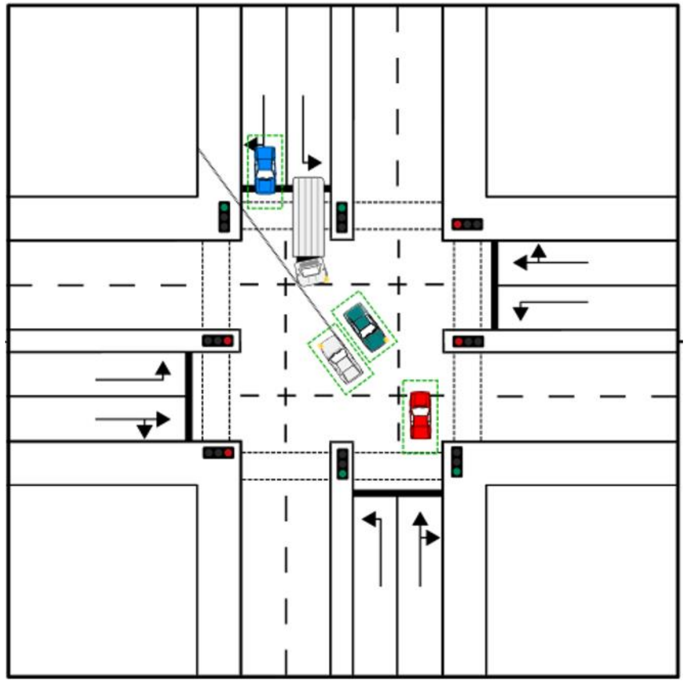


Criticality Analysis in VVM

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

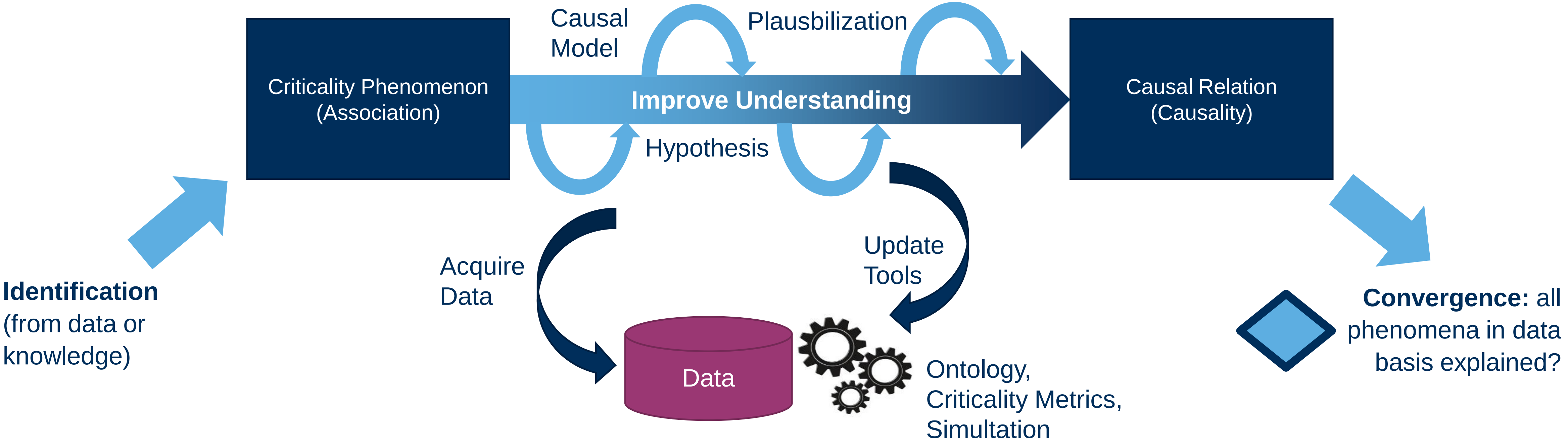
- **main goal:** gain knowledge on the **open context** w.r.t. the emergence of criticality and its conditions → structuring of the **operational domain**
  - identification of influencing factors associated with increased criticality → criticality phenomena
  - improve understanding of criticality phenomena 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“

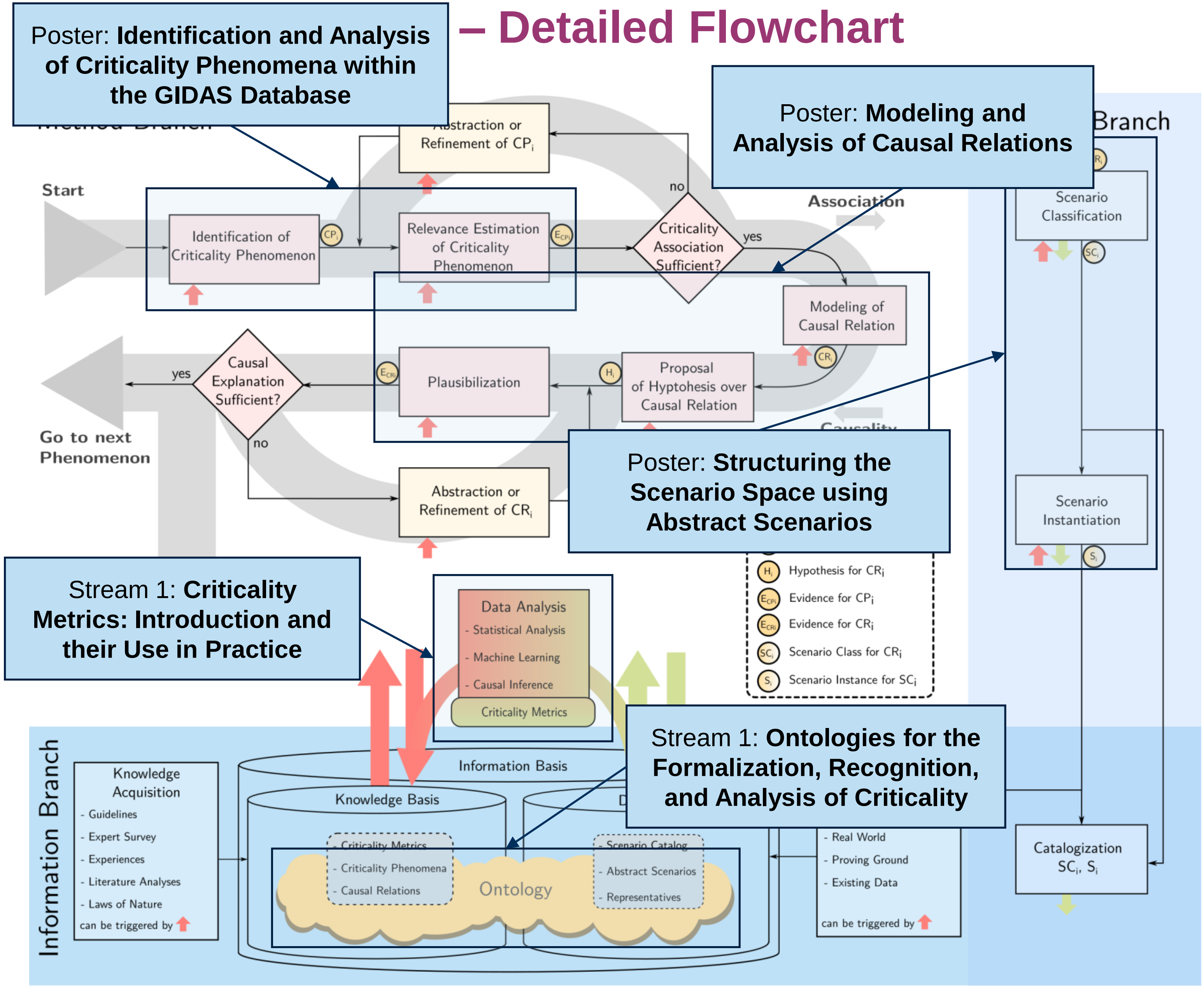
Criticality Analysis – the Basic Concept



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



- **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	Criticality Phenomenon	Ontological Classification	Estimated Criticality
2978	22.9%	36746	Occlusion	Perception	Medium
600	4.6%	7401	Occluded Pedestrian	Perception	High
1076	8.3%	13280	Occluded Bicyclist	Perception	High
844	6.5%	10413	Occluded Intersecting Vehicle	Perception	Medium
0	0%	0	Occluded Obstacle	Perception	Medium
-	-	-	Occluded Lane Markings	Perception	High
313	2.4%	3865	Occluded Traffic Sign	Perception	Depends
-	-	-	Occluded Traffic Light	Perception	High

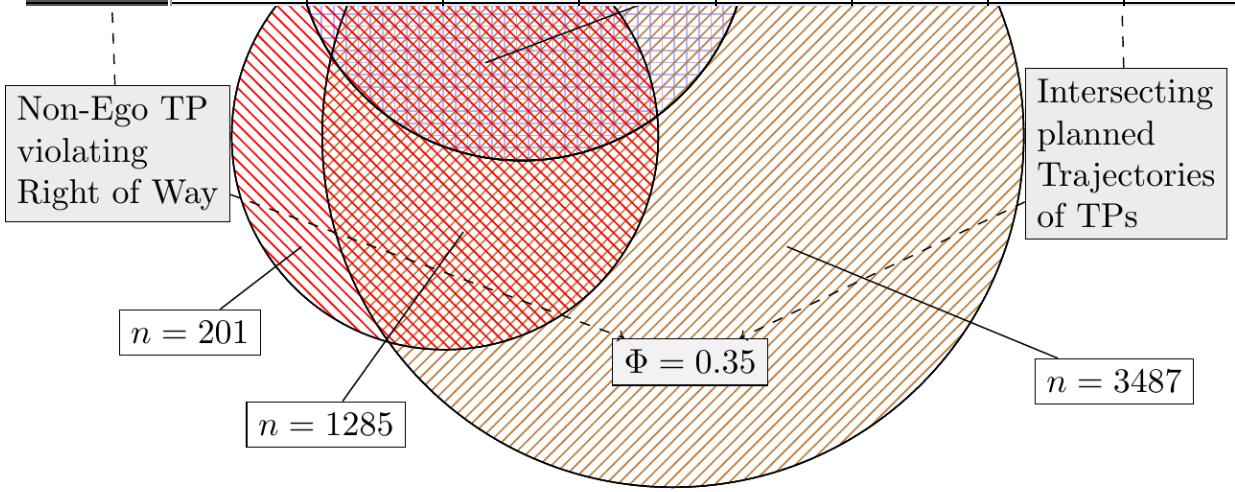
- gather **empirical evidence** for the relevance of ‚occlusion‘
  - searching the **GIDAS** database yields
    - $\frac{2978}{12997} \approx 22{,}9\%$ accidents associated with ‚occlusion‘
  - strong indication that „occlusion“ is a **relevant phenomenon** in non-automated traffic

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

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



- 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**

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**

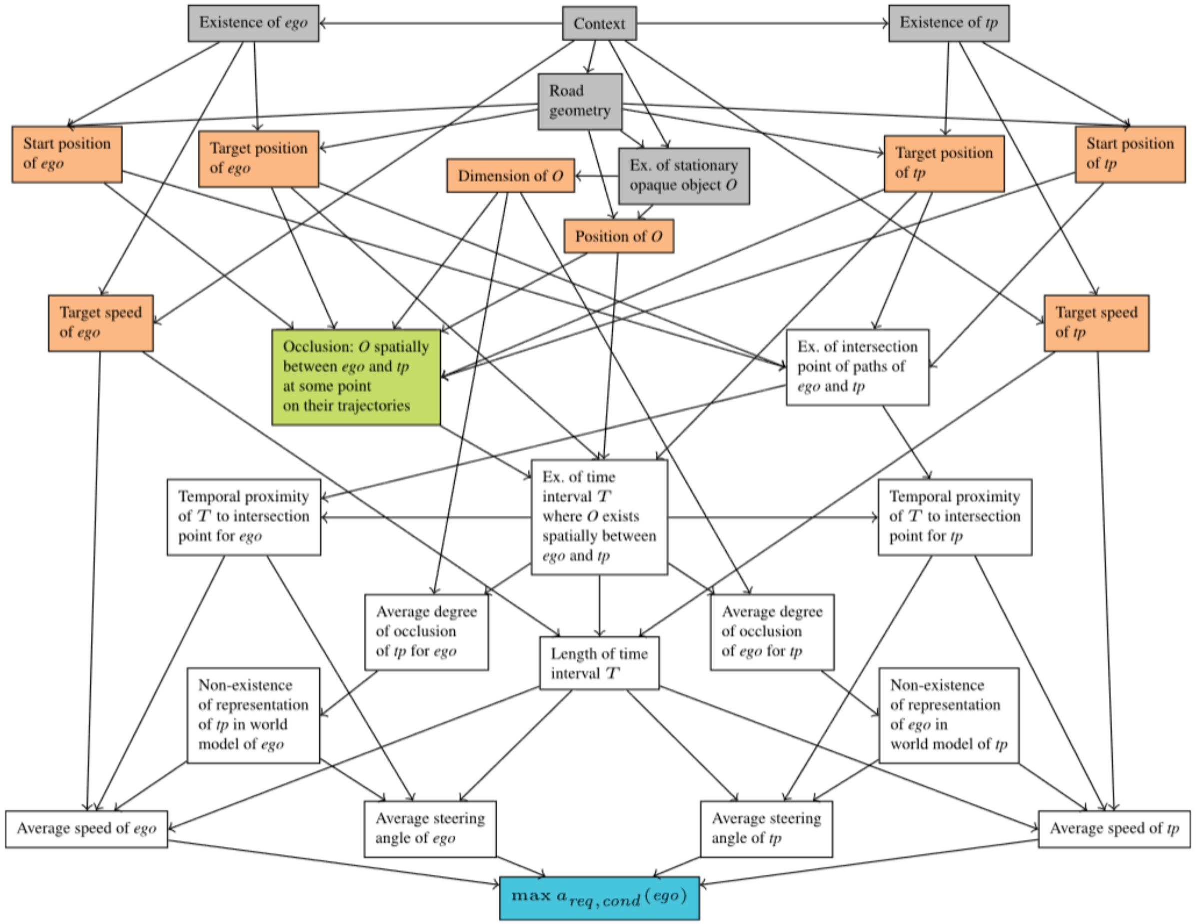
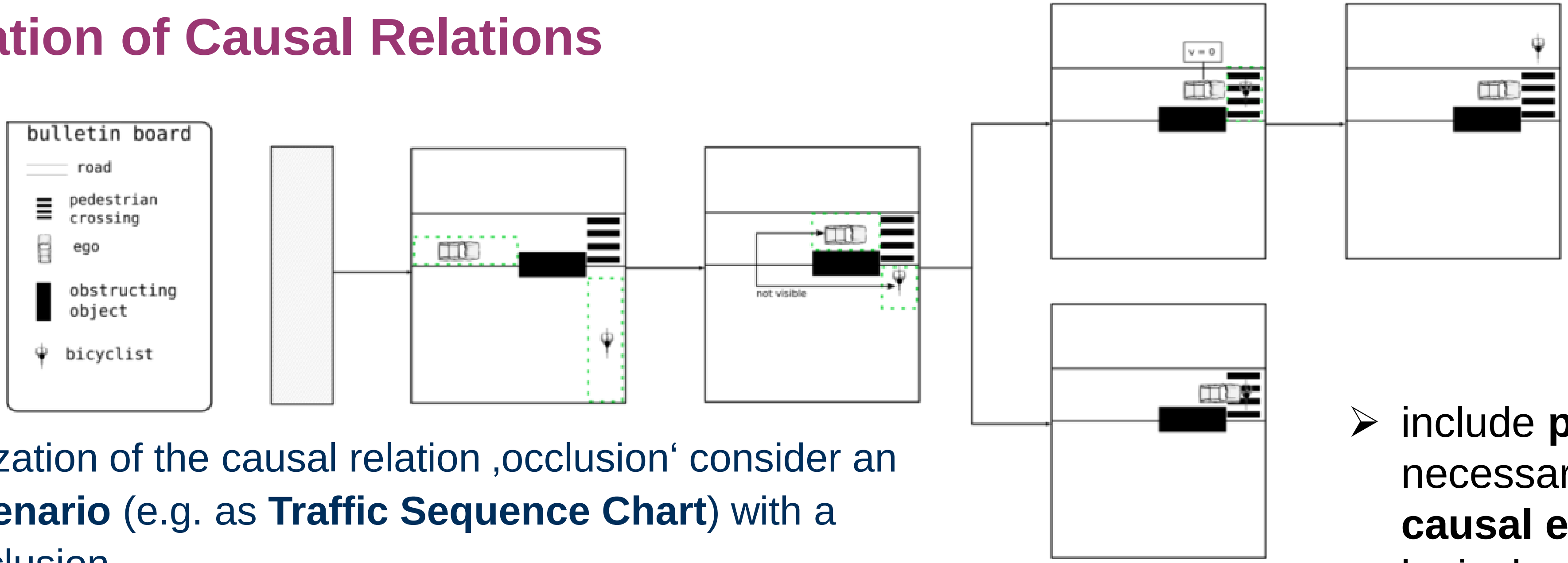


Figure: causal graph for evaluating the causal effect of „occlusion“ on the criticality metric $a_{req,cond}(ego)$.

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

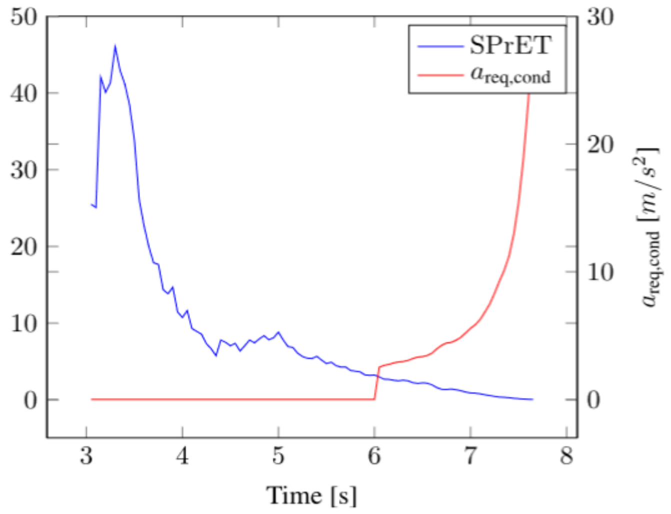
Simulation of ‚Occlusion of Bicyclist through Parking Cars' (FUC2-3)

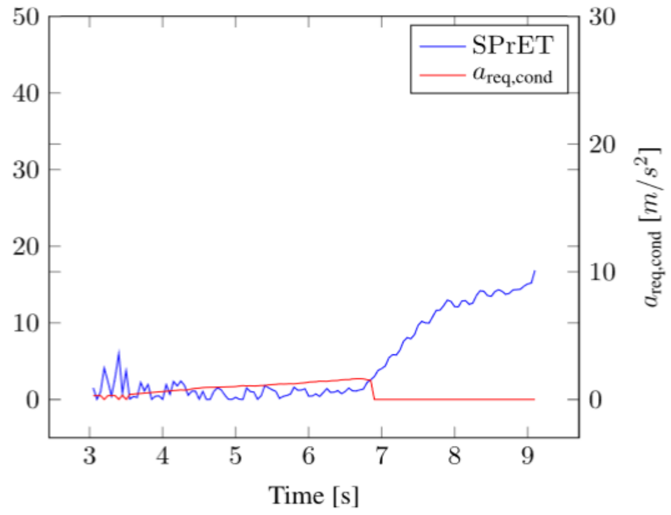
Video: showing four instantiations of an occlusion scenario with varying critcality using the CARLA simulator.

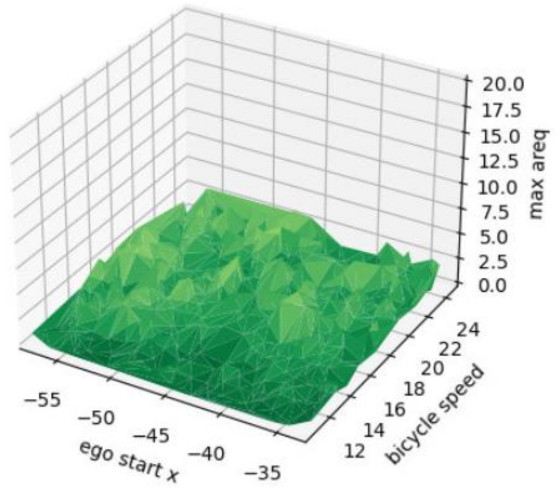
Generate and Evaluate Synthetic Data for Plausibilization

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

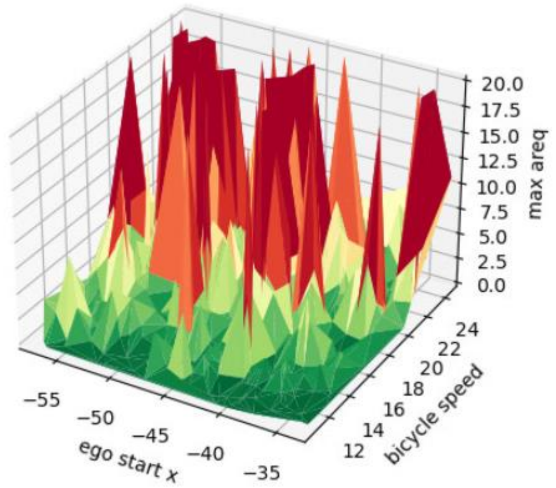
- **evaluate** for **each simulation run**
  - criticality metric(s) from the causal model
  - the presence of the criticality phenomenon







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

Criticality Analysis

$\{\infty \mapsto \boldsymbol{n}\}$

- **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

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Thank you!

Dr. Christian Neurohr
Researcher
DLR SE – Institute of System Engineering for Future Mobility
christian.neurohr@dlr.de

PROJECT of the PEGASUS FAMILY

A project developed by the
VDA Leitinitiative
autonomous and connected driving

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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