VERIFICATION
VALIDATION
METHODS

VVMethoden – TP2

Criticality Analysis for the Verification and Validation of Automated Vehicles

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Criticality Analysis in VVM

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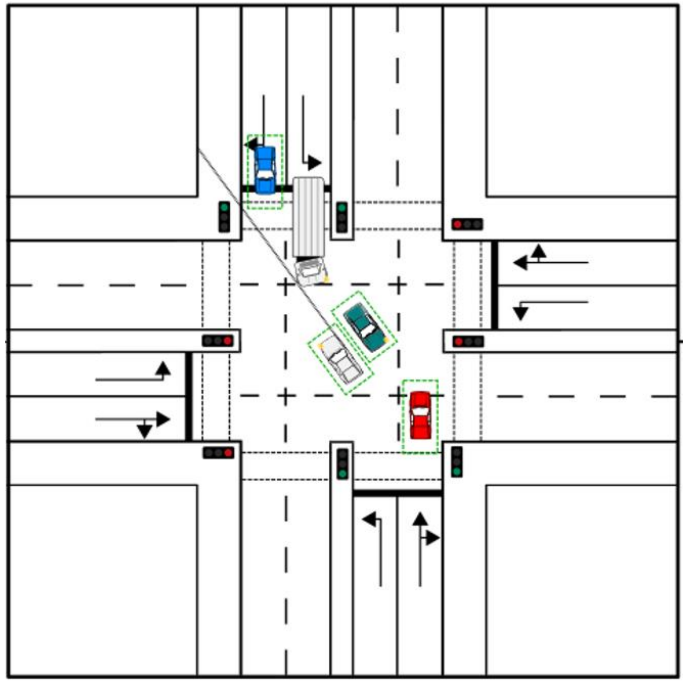
Goal: develop a **deep understanding** for the structure of the open context with respect to the emergence of criticality and its conditions.

- Identification and modelling of relevant influencing factors associated with criticality → **criticality phenomena**
- Improved understanding of criticality phenomena by analysis of **causal relations**
- Abstraction leads to classification of scenarios and **condensation of test space**

- **Employed tools:**
  - Metrics, ontologies, simulation
  - Acquisition & management of knowledge and data
  - Statistical analysis, machine learning



Use Case „Urban Intersection"

Criticality Analysis – Basic Concept

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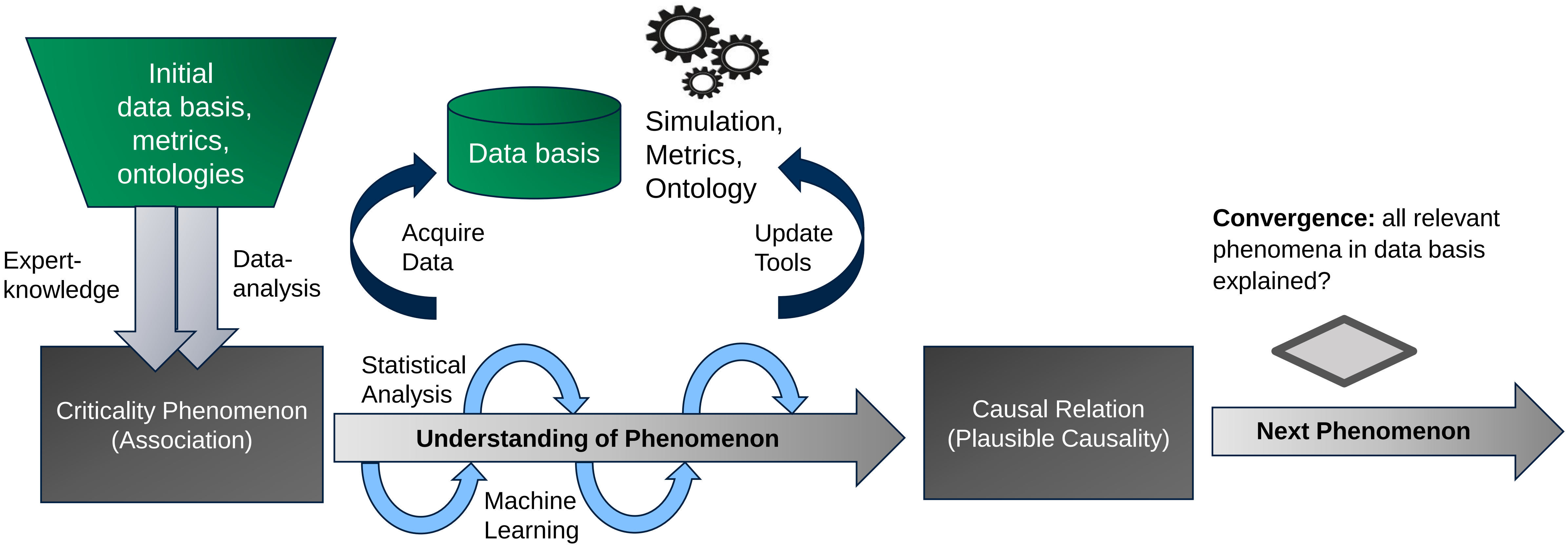


Assumptions: Humans are able to drive reasonably safe by recognizing a limited and manageable set of abstract classes of danger, i.e. criticality phenomena → **Finiteness**

The relevant phenomena leave traces in a continously growing data basis → **Convergence**

Criticality Phenomenon „Occlusion“

- Identify the criticality phenomen ‚Occlusion‘ (e.g. via expert knowledge)
  - Find adequate level of abstraction plus relevant concretizations
  - Use ontological representation and classification to organize knowledge

Absolute Cases	Relative Cases
2701	21.79%
573	4.62%
1031	8.32%
982	7.92%
0	0%
n.i.	n.i.
221	1.78%
n.i.	n.i.

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

- Check available data basis for empirical evidence whether the phenomena are relevant
  - Searching the GIDAS database yields
    - $N = 12394$ accidents in urban arreas involving a passenger car
    - $2701 \approx 21{,}79\%$ are associated with „Occlusion“
  - Strong indication that Occlusion is a relevant phenomenon (even for automated vehicles)

Causal Relation „Static occlusion of traffic participant“

- Use directed acyclic graphs to represent **hypotheses about** the underlying **causal relation**
- Incorporate **criticality metrics** as to make criticality measurable, e.g. Time-To-Collision, required acceleration, …
- Collect evidences for causal relations using **real-world data** and **simulation**
- Use **abstraction/refinement** to find an adequate level of abstraction

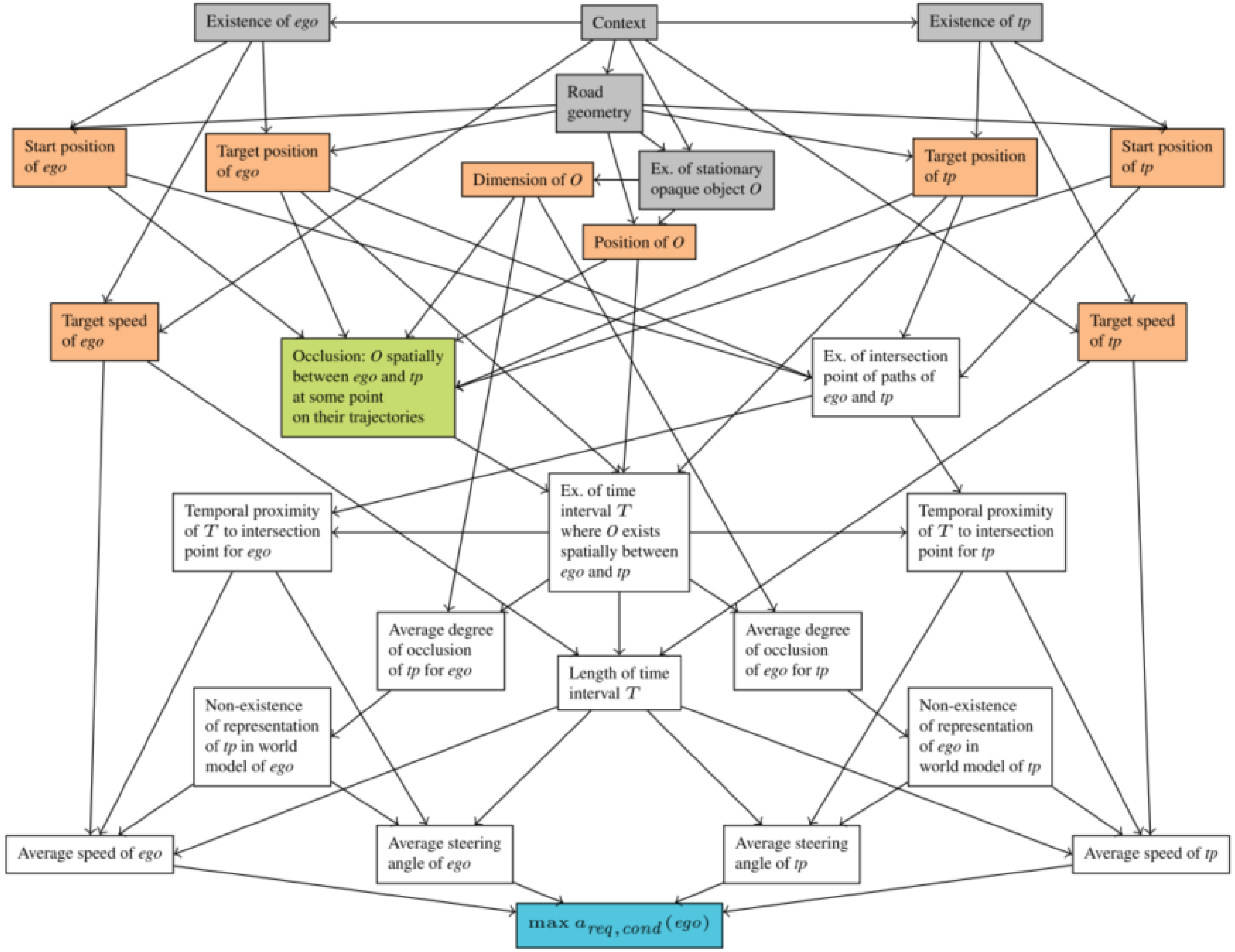
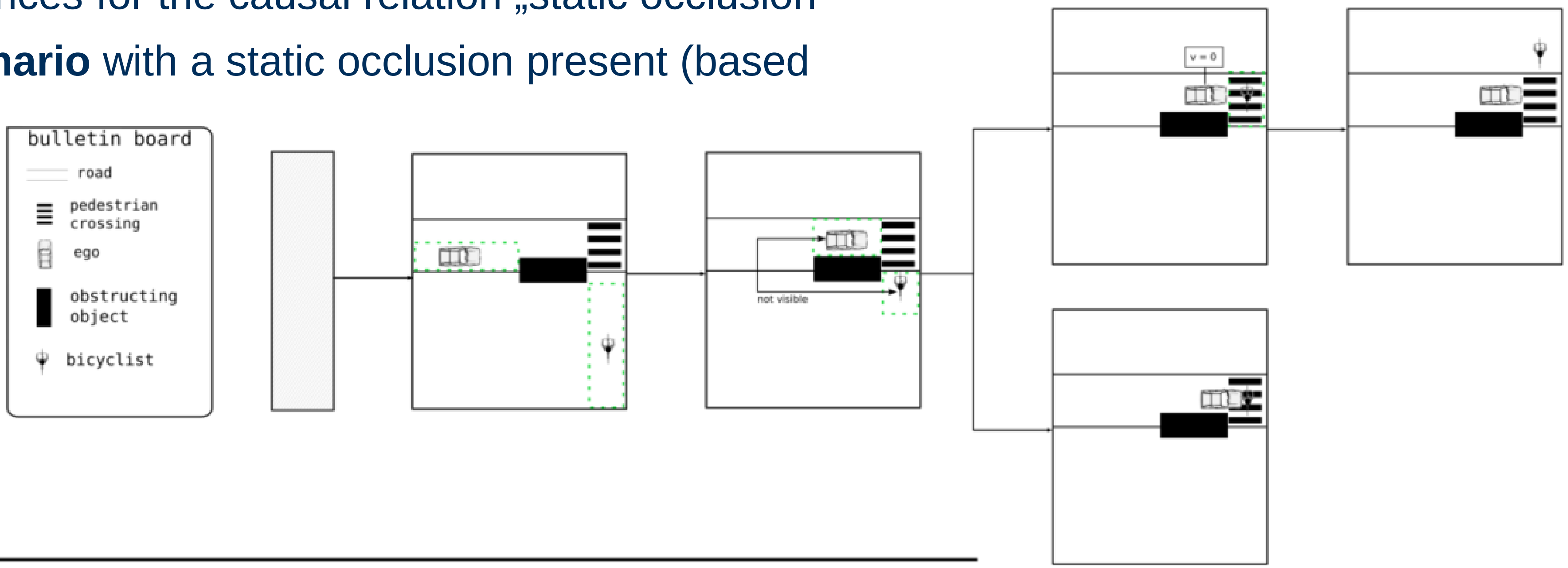


FIGURE 6: Causal relation $CR_{stat-occ-tp}$, represented as a DAG, connecting the criticality phenomenon $CP_{stat-occ-tp}$ to criticality measured via conditional required acceleration ($a_{\text{req,cond}}$). Unobserved variables are gray and independent variables are orange. The exposure variable 'occlusion' is marked green. The outcome variable 'max $a_{\text{req,cond}}(ego)$' is marked blue.

Plausibilization of Causal Relations using Simulation

- In order to generate evidences for the causal relation „static occlusion“ consider an **abstract scenario** with a static occlusion present (based on VVM Use Case 2-3)



- For realization in simulation (e.g. OpenPASS, CARLA, …) derive an associated **logical scenario**

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)	$[2, 20] \times ([-35, -34] \cup [-26, -25])$

Evaluation of Criticality Metrics and Data Analysis

- As to generate data, use **stochastic variation** of parameters (e.g. p = 13) to obtain **concrete scenarios** (e.g. n = 1000) for simulation and evaluate suitable criticality metrics (e.g. m = 2)

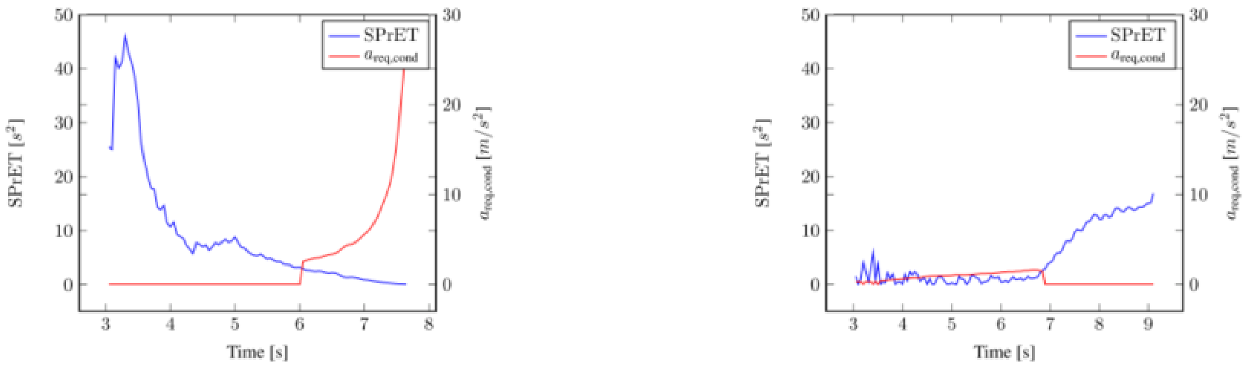


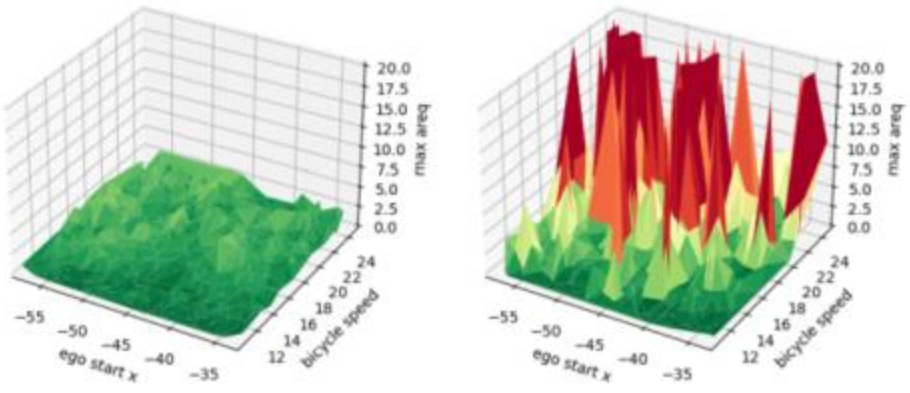
FIGURE 11: SPrET and $a_{\text{req,cond}}$ over time for a critical occlusion (left) and an uncritical non-occlusion (right) scenario.

TABLE 2: Significant ($\alpha = 10^{-9}$) results of correlation analysis between variables and $a_{\text{req,cond}}(ego)$ using Spearman's ρ.

Variable	**Correlation** (ρ)	p-**value**
Occlusion	0.29	$p < 10^{-20}$
Duration of occlusion	0.26	$p < 10^{-15}$
ego starting position (x)	−0.24	$p < 10^{-14}$
bicyclist starting position (y)	−0.35	$p < 10^{-29}$
bicyclist target speed	0.42	$p < 10^{-44}$
Position of O (y)	0.20	$p < 10^{-9}$

- For each simulation run evaluate whether the phenomenon was present (did an occlusion happen or not?)

- Perform statistical analysis of the resulting data set in $\mathbb{R}^{n\times(m+p)}$



Group A: no occlusion present   Group B: occlusion present

Further reading

VERIFICATION VALIDATION METHODS

- Journal Publication „Criticality Analysis for the Verification and Validation of Automated Vehicles“ published at IEEE Access (21.01.2021)
  - Joint publication by several VVM partners
  - Authors: Christian Neurohr (OFFIS), Lukas Westhofen (OFFIS), Martin Butz (Bosch), Martin Bollmann (ZF), Ulrich Eberle (Opel), Roland Galbas (Bosch)
  - ResearchGate
  - IEEExplore

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Thank you for the attention.

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Criticality Analysis – In a Nutshell

Criticality Analysis

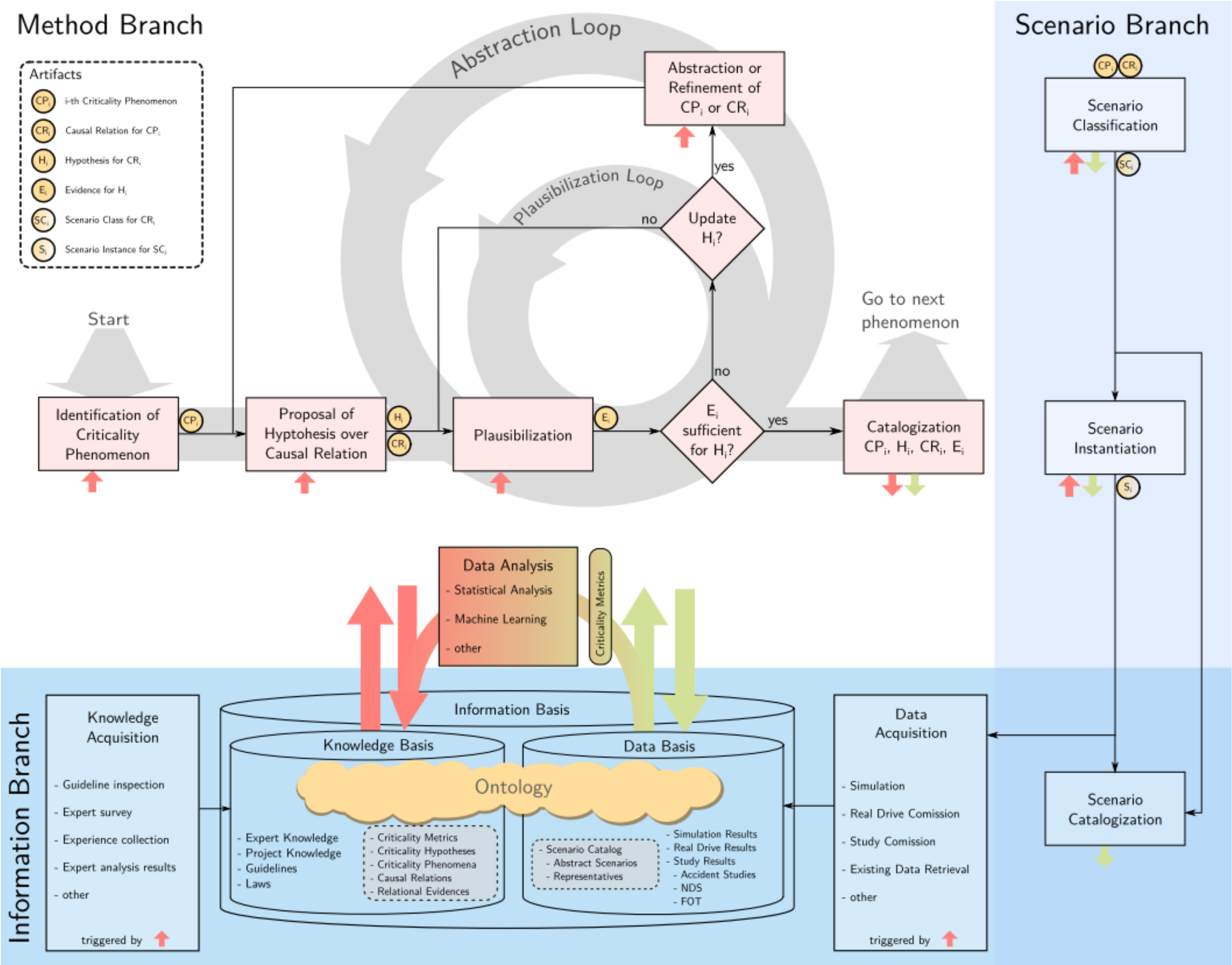
$$\{\infty \mapsto \boldsymbol{n}\}$$

- **Criticality Phenomena**
- **Causal Relations**
- **Abstract Scenario Catalog**

- How can we find all the **relevant artifacts** for the **safe operation** of fully **automated vehicles** within an infinite-dimensional space?

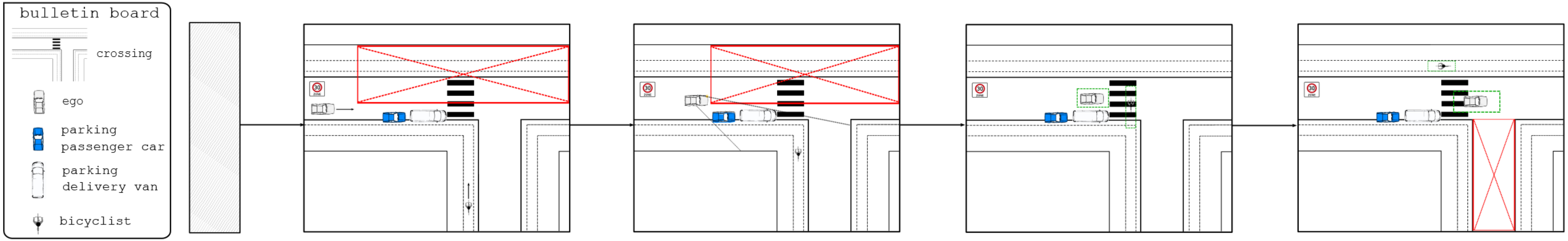
- Extract associations → phenomena
- Find plausible explanations → causality
- Use abstraction → catalogization

Criticality Analysis – Detailed Flowchart



- **Method Branch** – Identification of criticality phenomena, proposal of causal relations, evidence for plausibility of hypotheses.
- **Information Branch** – Knowledge and data management for the criticality analysis, Ontologies.
- **Scenario Branch** – Scenarios as the ‘substrate’ of the criticality analysis, a means for structuring processes and description of reality

Criticality Analysis – Abstract Scenarios



Abstract Scenario: „Occluded Bicyclist at T-intersection“

- Evaluate criticality metrics on scenarios with (and without) phenomena (e.g. occlusion) in order to collect evidences for causal relations
  → Set up simulative experiments using the framework of statistical hypothesis testing
- Build up catalogue of abstract scenarios and use mechanisms for instantiation to more concrete scenarios
- Derive suitable abstract scenario classes with respect to phenomena and causal relations
  → Employ Zone Graphs for classification