Traffic Sequence Charts – A Formal Visual Specification Language for Requirement Capture and Specification Development of Highly Autonomous Cars

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Structure of Presentation

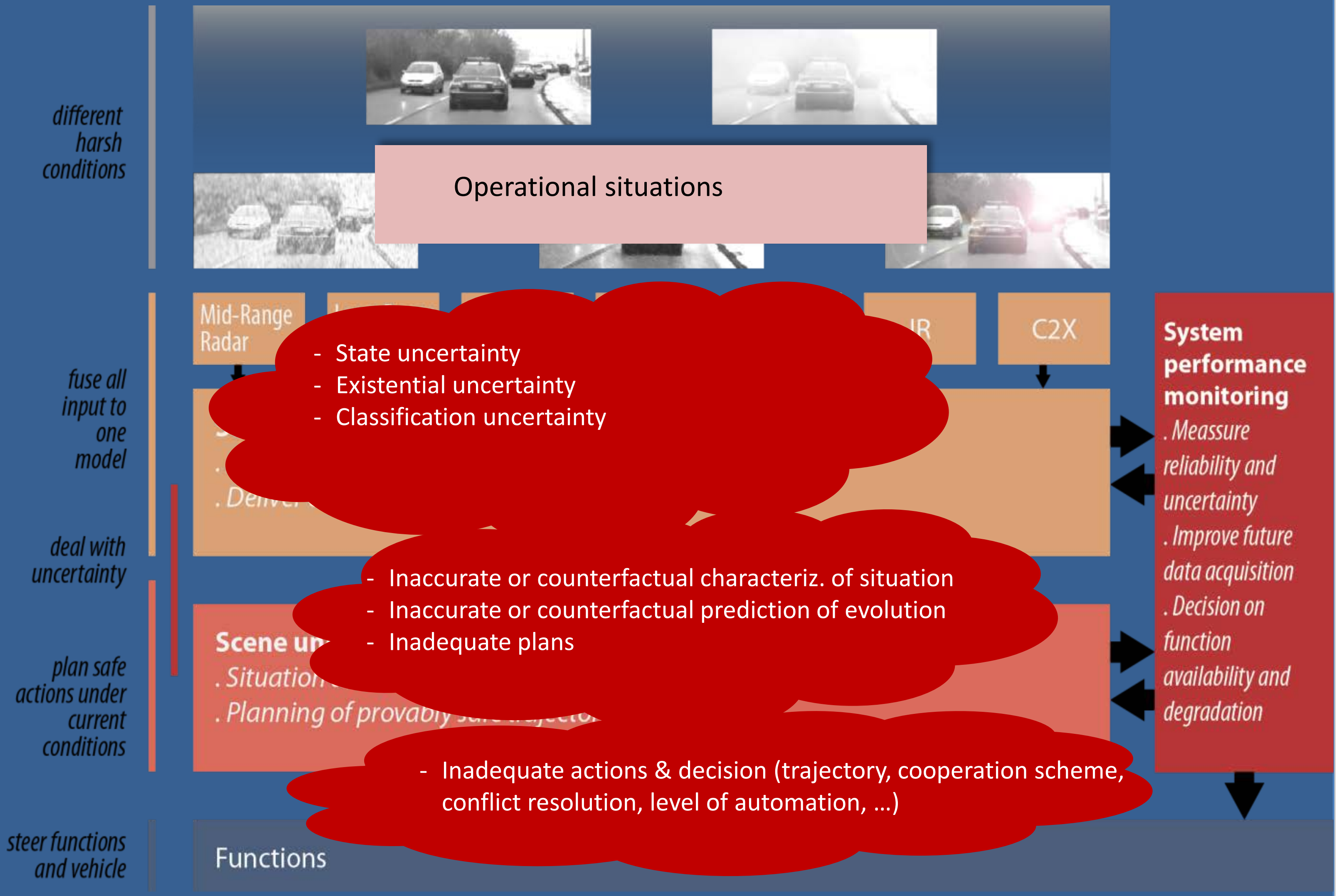
- The Application Context
- Traffic Sequence Charts:
  - relevance
  - key concepts
  - semantics
- Why we need a formal semantics
- References

Verification challenges for autonomous driving

1. Can we capture at design time the space of all possible traffic situations and environmental factors relevant for determining safe trajectories for autonomous vehicles?
2. Can we characterize the environmental conditions for all elements in the perception chain under which identification of objects can be guaranteed for a given desired confidence level?
3. Can we characterize the variability of dynamics of other participants to allow safe predictions of future evolution of traffic situations for a given confidence level?

The safety impact of object identification

Impact of perceptual insufficiencies on overall risk


different harsh conditions
fuse all input to one model
deal with uncertainty
plan safe actions under current conditions
steer functions and vehicle
Mid-Range Radar
IR
C2X
. Deriv
Scene un
. Situation
. Planning of provably safe trajector
Functions
System performance monitoring
. Meassure reliability and uncertainty
. Improve future data acquisition
. Decision on function availability and degradation

Operational situations

- State uncertainty
- Existential uncertainty
- Classification uncertainty

- Inaccurate or counterfactual characteriz. of situation
- Inaccurate or counterfactual prediction of evolution
- Inadequate plans

- Inadequate actions & decision (trajectory, cooperation scheme, conflict resolution, level of automation, …)

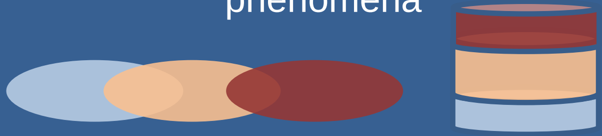
Overall Approach

Application perspective

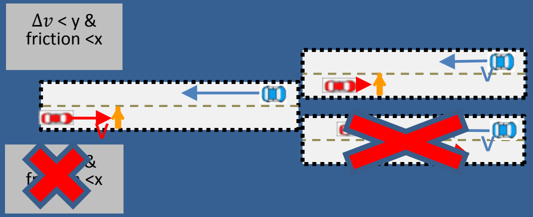
Formal foundations

Database containing critical scenarios

Scenario-specific criticality measure / phenomena



Safety requirements



generalize

deduce

Labelled data base of traffic situations

Build mathematical models of

- Criticality
- Behavior of traffic participants
- Addressing uncertainty
- Composable building blocks
  - Models of environment
  - Models of perception/sensing

OFFIS

Addressing ghost images and other automation risks through learning

Initial environment and functional model

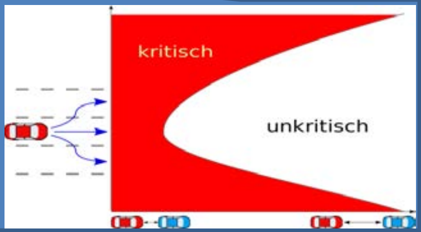
Intended functionality

Injection of non-nominal behaviours (such as ghots objects)

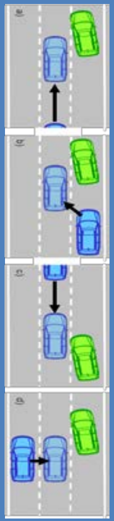
Fault-injection

Analysis

Identify Scenarious ensuring Safety of the intended function (SOTIF)



Refinement of environment model and/or functiional model



Refinement

Truly Critical Scenario?

No

Yes

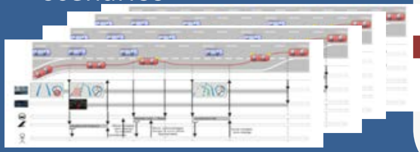
Add Scenarion to catologue of identified automation risks

Simulation based analysis of anomalies: fake or true risk?

Quelle:DLR

Safety through Guided Simulation

Data base:
Formal characterization of scenarios

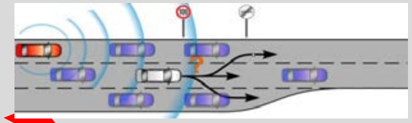


Functional model

Environment perception

Source: Bosch

Tracking / Planning



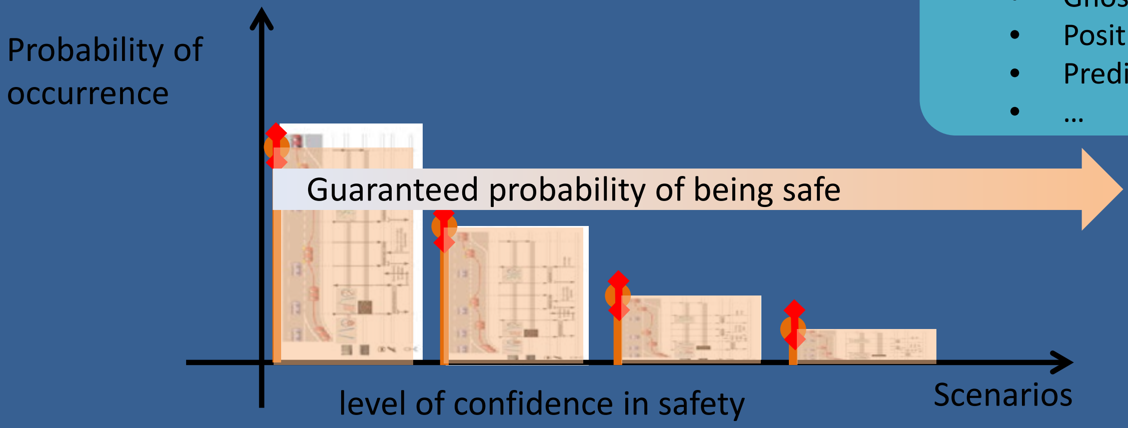
Source: Arne Bartels, Volkswagen

Decision

Source: Bosch

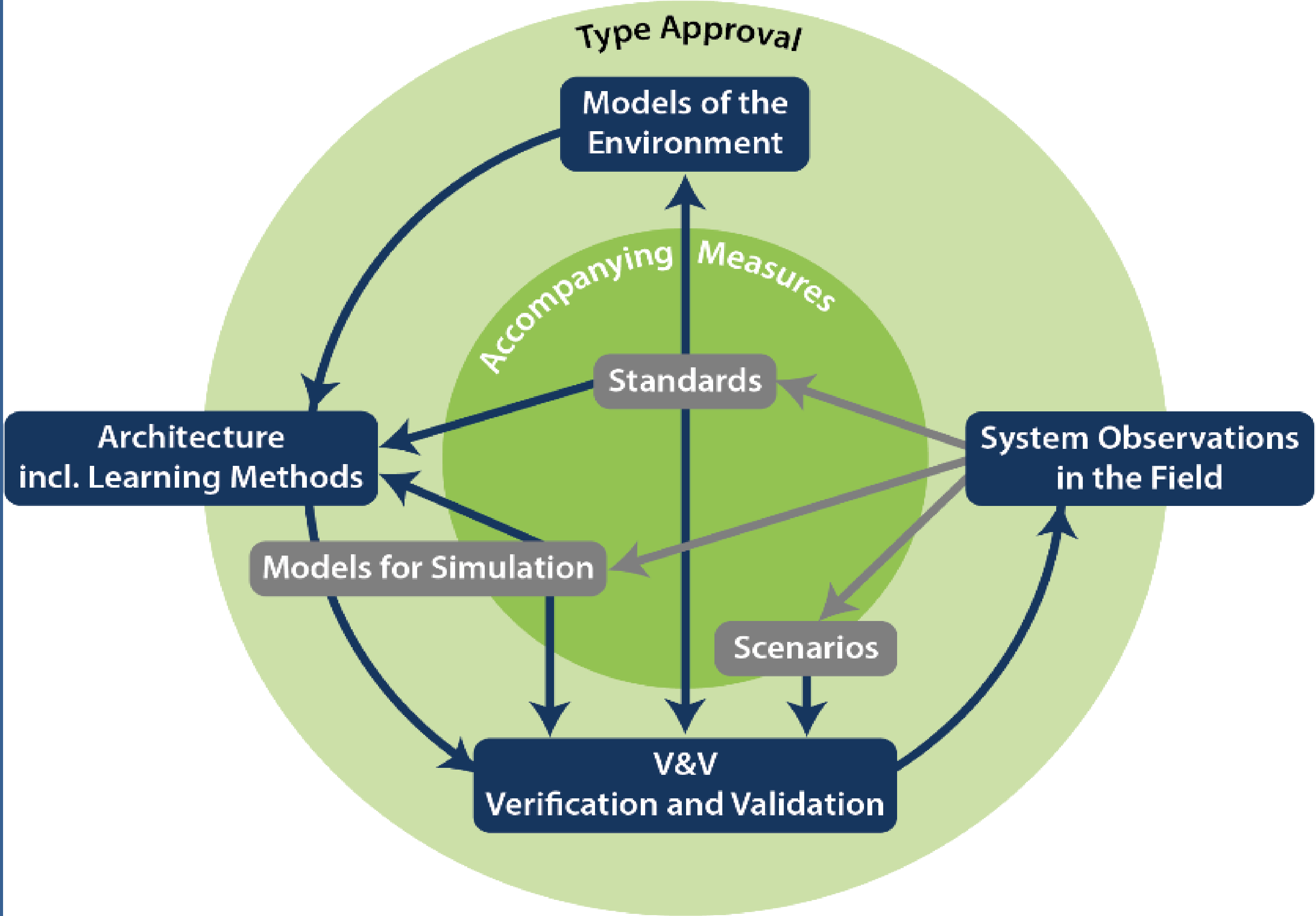
Injection of failures/uncertainties:

- Ghost objects
- Position / velocity uncertainty
- Prediction uncertainty
- …



- Extract scenario data base from real-world scenes
- Generation of test cases
- coverage of real-world scenes

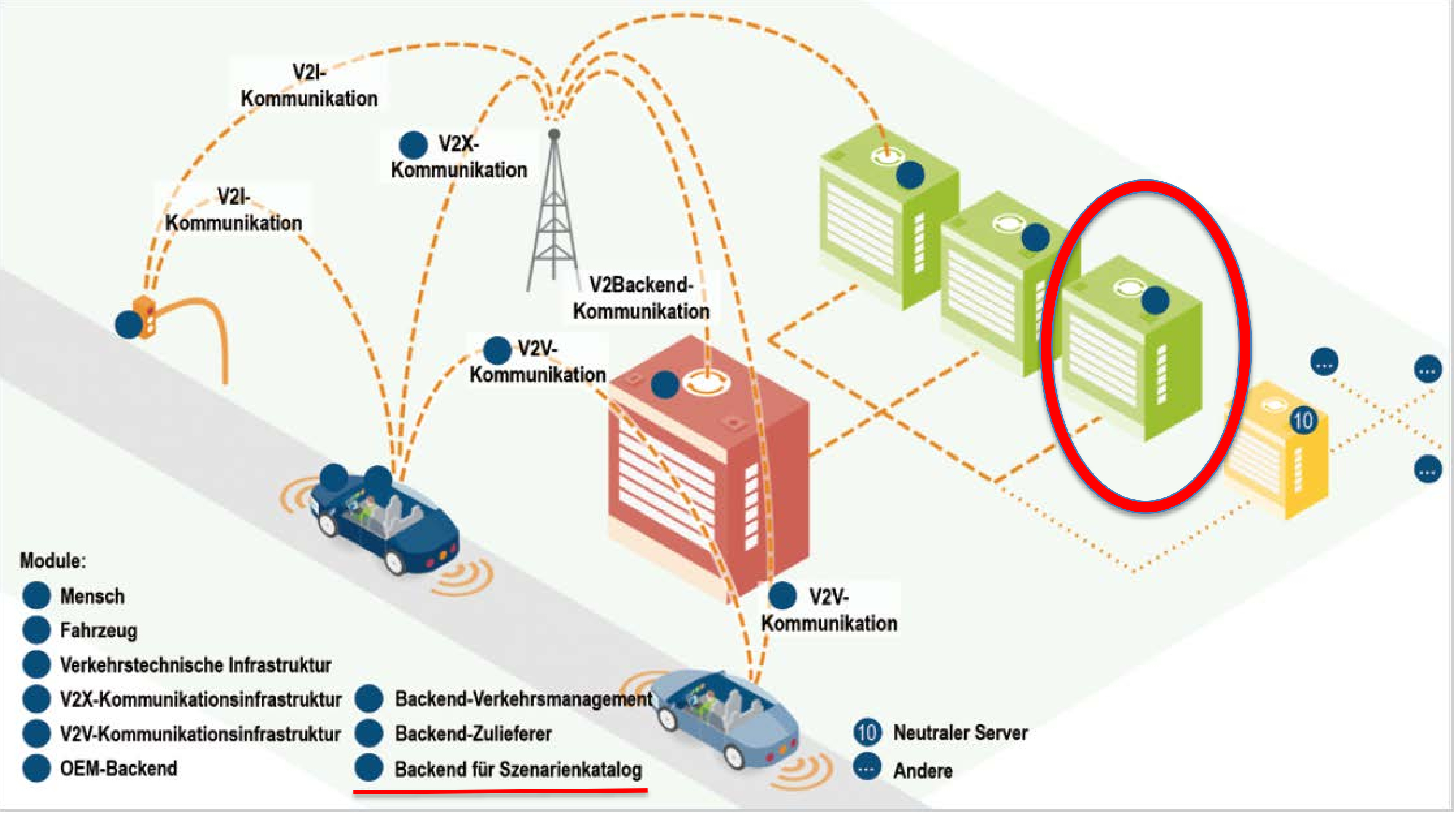
SafeTRANS Recommendations: Learning in the Field


Type Approval
Models of the Environment
Accompanying Measures
Standards
Architecture incl. Learning Methods
System Observations in the Field
Models for Simulation
Scenarios
V&V
Verification and Validation

Bundesministerium
für Verkehr und
digitale Infrastruktur

ETHIK-KOMMISSION

AUTOMATISIERTES UND VERNETZTES FAHREN



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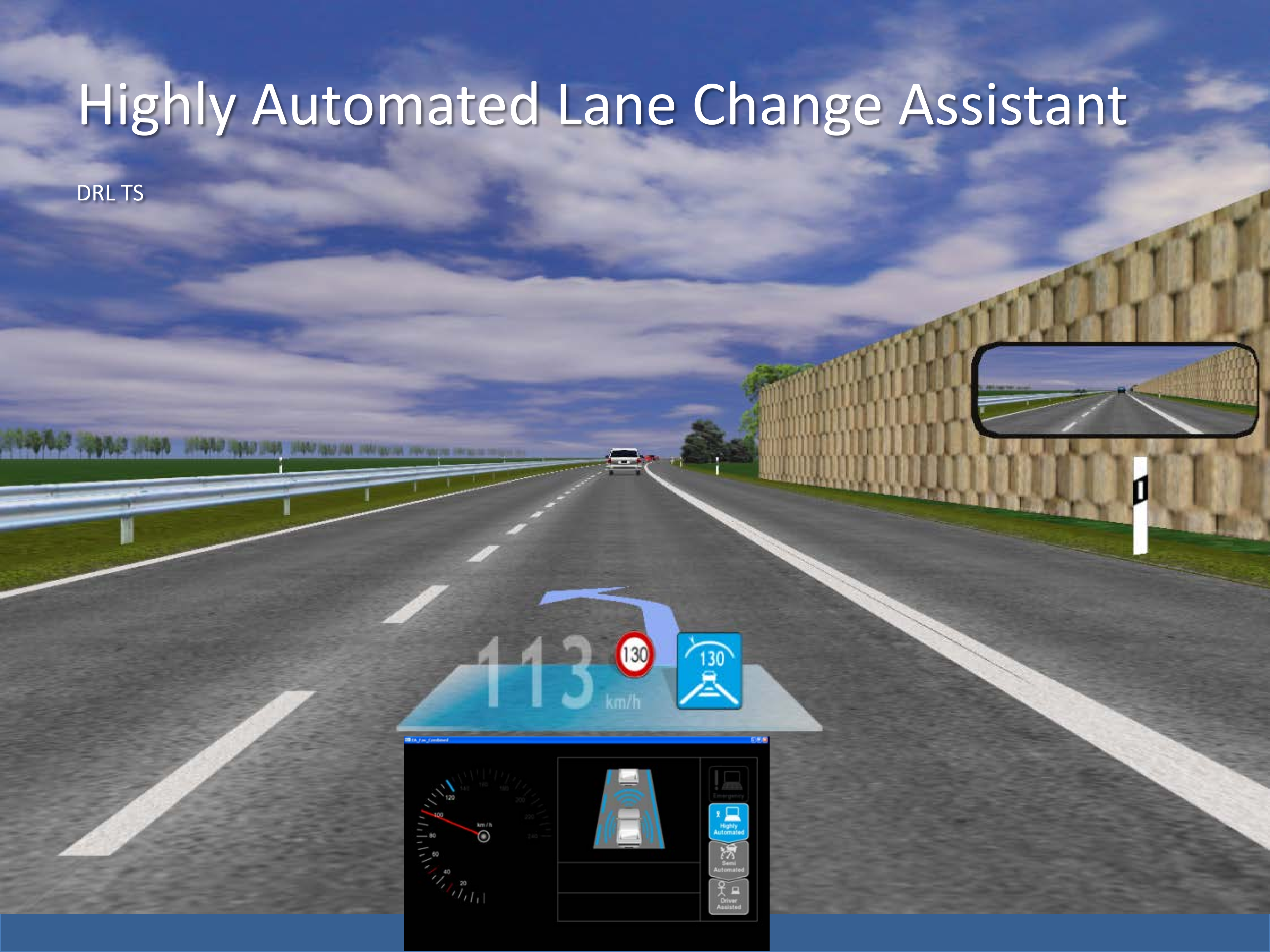
Design Objectives TSCs

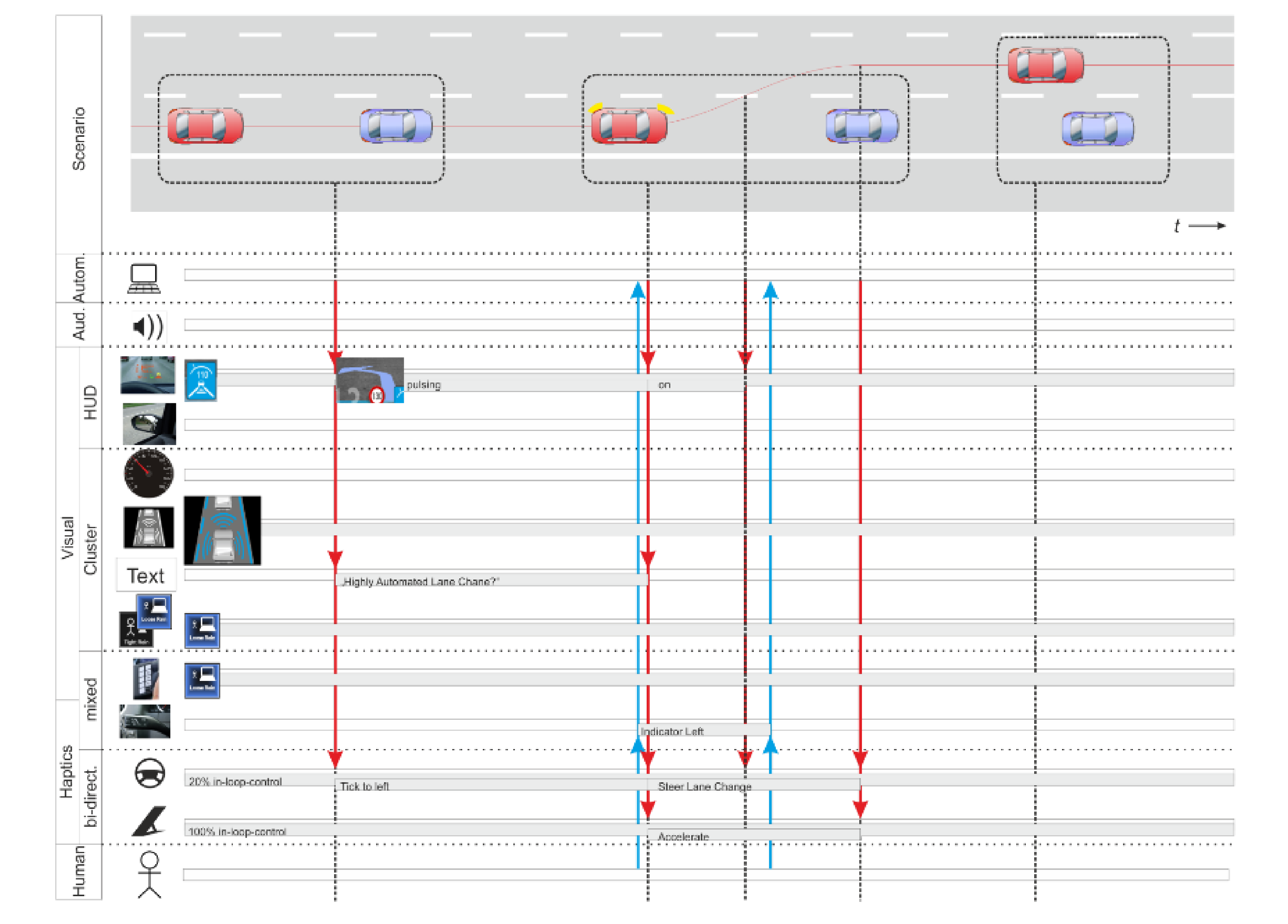
- To provide a concise, intuitive specification language for capturing expected and forbidden behaviours of autonomous vehicles in the space of all possible traffic situations
- To prevent exponential blow up in requirement capture
- To serve as a formal basis for scenario catalogues in a type approval
- To serve as a formal basis for testing on all levels (MIL, HIL, runtime monitoring)

Highly Automated Lane Change Assistant

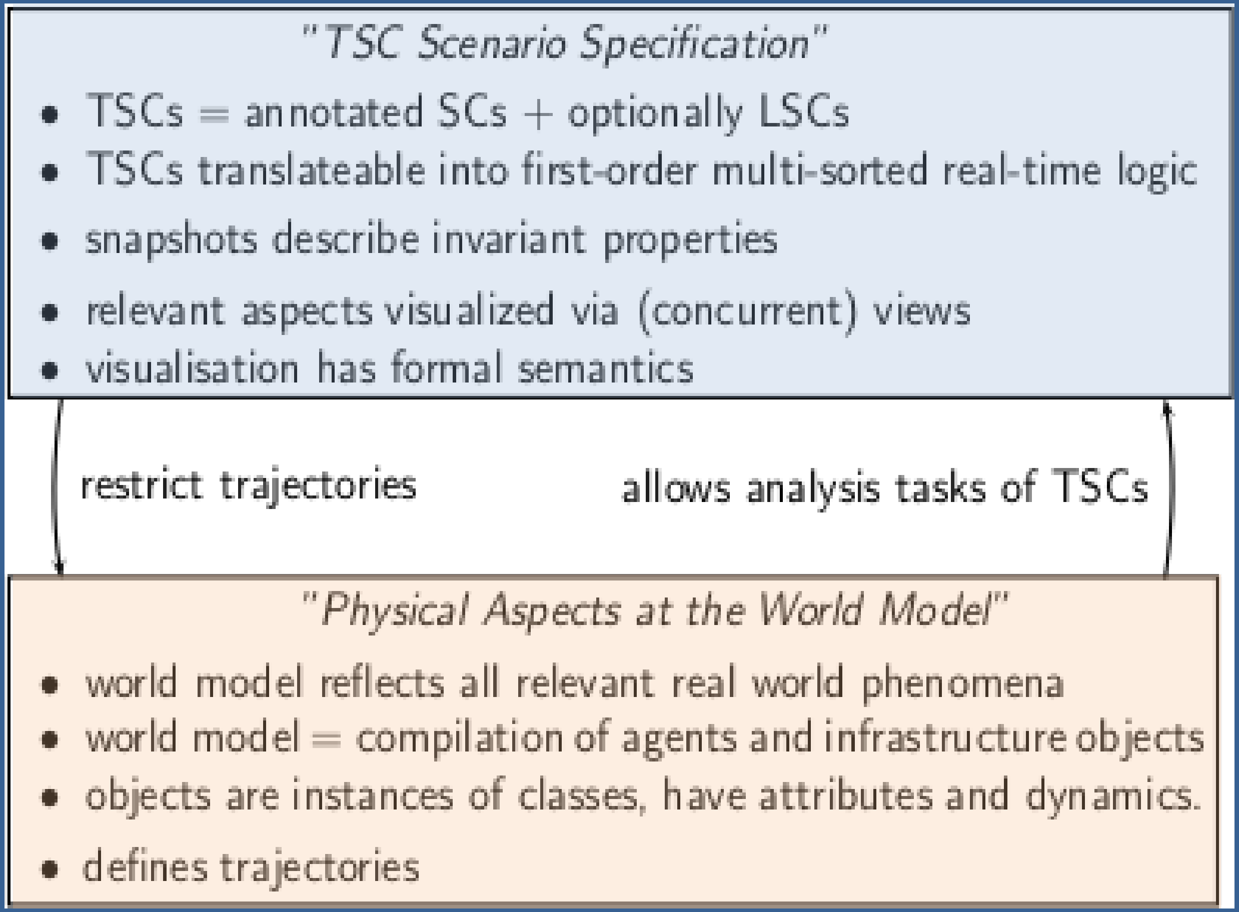
DRL TS



Example TSC – DLR TS



More than pictures



"TSC Scenario Specification"

- TSCs = annotated SCs + optionally LSCs
- TSCs translateable into first-order multi-sorted real-time logic
- snapshots describe invariant properties
- relevant aspects visualized via (concurrent) views
- visualisation has formal semantics

restrict trajectories

allows analysis tasks of TSCs

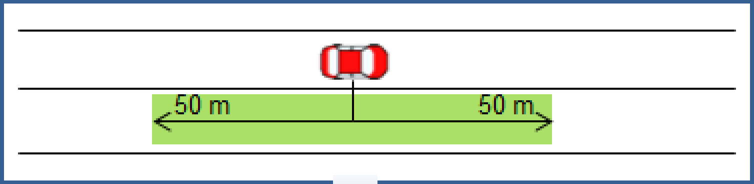
"Physical Aspects at the World Model"

- world model reflects all relevant real world phenomena
- world model = compilation of agents and infrastructure objects
- objects are instances of classes, have attributes and dynamics.
- defines trajectories

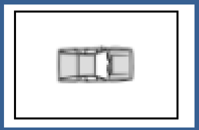
- Formal world model (unbounded composition of (probabilistic) hybrid automata)
  - defines type, attributes, and relations of objects
  - Physical aspects (e.g. dynamics)

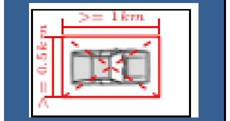
More than pictures

- Traffic snapshot describe a traffic situation as invariants
  - captures infinitely many possible real life situations surrounding the ego vehicle

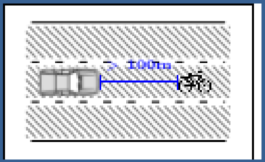


$$\exists\, ego: CAR: ego.pos = (X_{ego}, 2)\ and$$
$$\forall c: CAR: c.pos.y = 1 \rightarrow c.pos.x \notin [X_{ego} - 50, X_{ego} + 50]$$

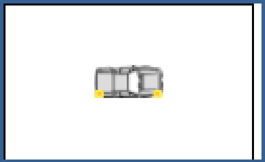

car

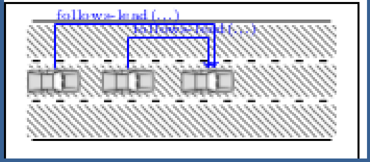


no car

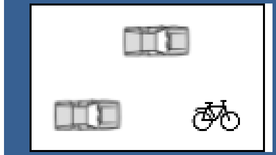


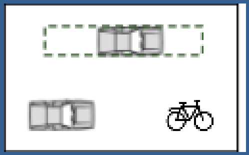
distance


signal



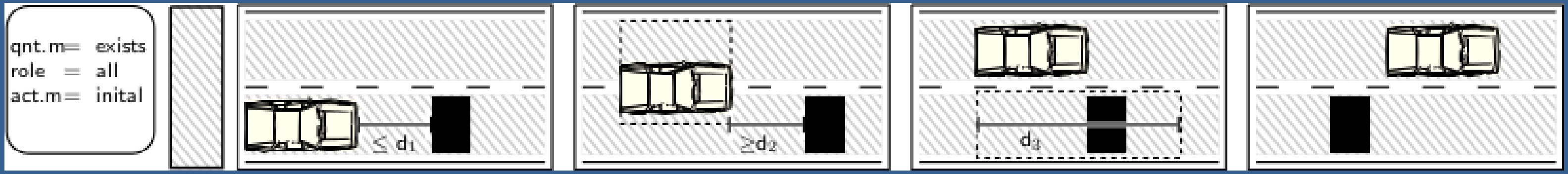
platoon


relative

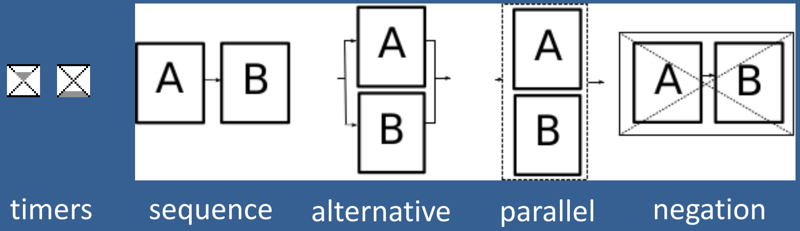

somewhere

More than pictures

- Traffic snapshot charts describe evolution over time

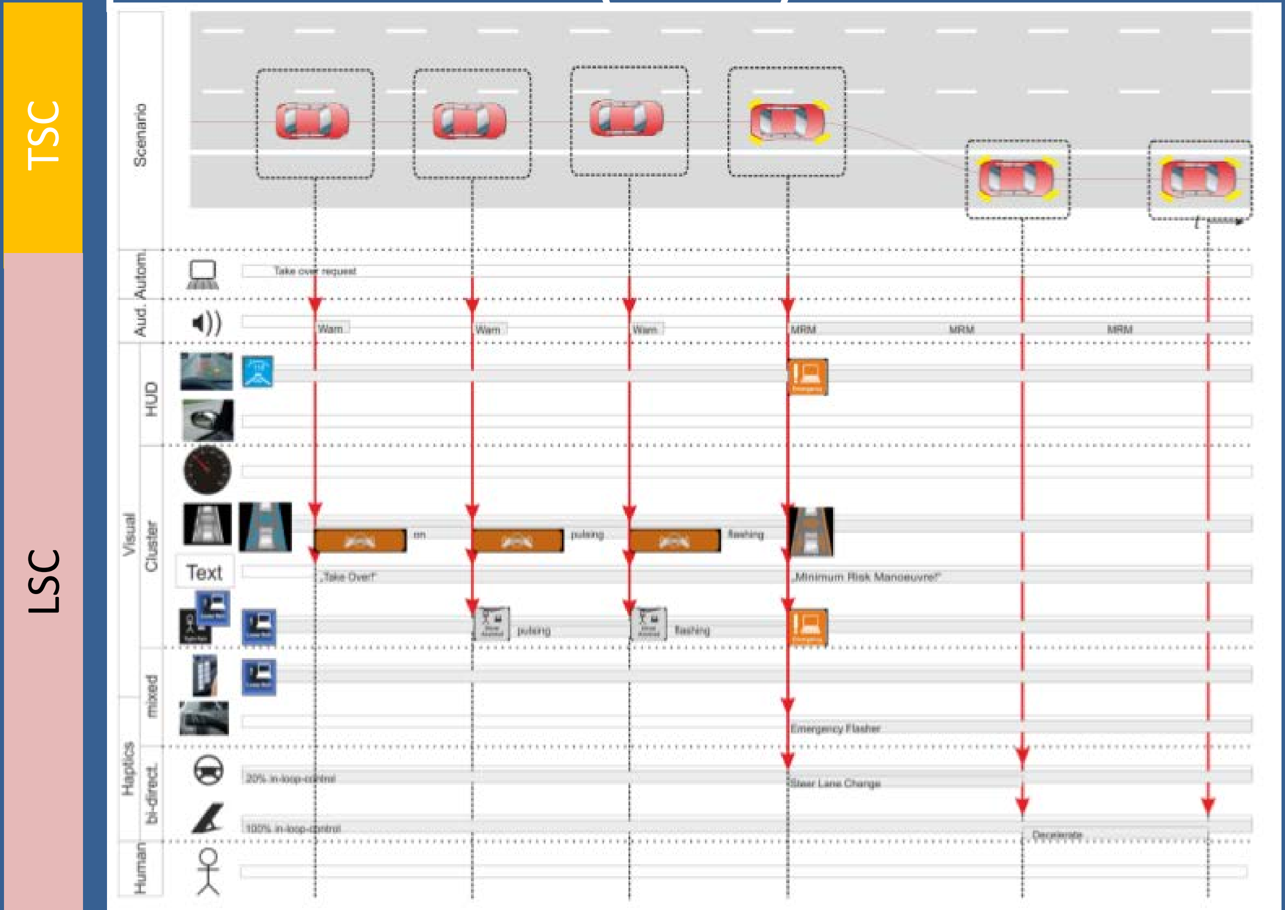


- timers and end-to-end latencies
- probabilities
- mandatory vs optional vs forbidden
- negation, concatenation, concurrency, and alternatives
- activation mode (initial, always), quantification mode (universal, existential)
- activation conditions (pre-charts)
  - e.g. only if *health-state=nominal* and *light-conditions are good*
  - e.g. only if *initially relative speed* and *distance are good*
  - Mandatory conditions and case splitting

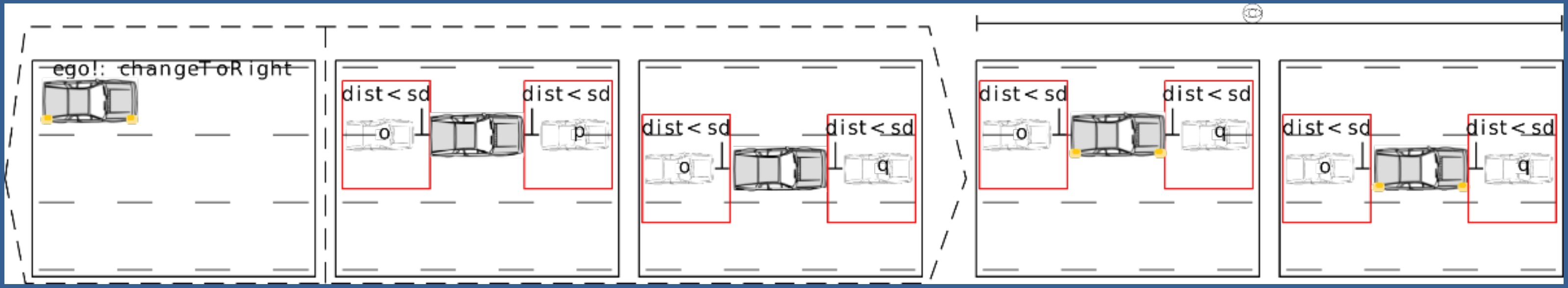


Canonical extension to cooperative car2x based maneuvers

- Interplay with the well-known concept of Live Sequence Charts (LSCs)



Translation from Charts to Formulae



If ego signals a lane change and intends to change to right lane with sufficient free space then ego has to signal the lane change

- Formal semantics of one TSC translates to formula in first-order multi-sorted real-time logic
  - Existential TSCs describe possible scenarios
  - Universal TSCs describe requirements
- Formal semantics of sets of TSC given by conjunction
  - Hence, no need for specifying all possible combinations requirements in each possible scenario

Benefits

- Staged requirement analysis processes
  - from sketches (possible behaviors) to requirements (mandatory behaviors or forbidden behaviors)
  - from ideal observer to object identification through sensor fusion and exchange of perceived world models
  - from nominal behavior to degraded behaviors
  - from ego perspective to cooperative situation awareness and cooperative maneuvers
- Verification of consistency of requirements
- “Play out” generate set of all possible runs for validation of requirements
- Automatic generation of monitors
  - For design time verification on all levels (MIL, HIL, VIL of ADF)
  - For runtime verification and detection of disallowed activations of ADF
- Automatic test case generation for requirement-based/scenario-based testing

Why we need a formal semantics

- (C1) Given the ill-structuredness of the space of real world traffic situations,
  how can we achieve completeness of scenario catalogs, i.e. demonstrate with high confidence that all relevant real-world situations have been captured?

  - Challenge C1 will be addressed by generalizing from data bases of observed traffic flows. A minimal requirement for checking for completeness is thus the need to formally define, whether a particular observed traffic behavior is already covered or not by the current scenario catalog, thus requiring the definition of a formal satisfaction relation.
  - Moreover, as experienced in the play-out approach for Live Sequence Charts, a formal semantics provides a basis for playing out the current scenario catalog, thus generating traffic flows which an expert can judge for unrealistic or missing real-life traffic flows.

Why we need a formal semantics

- (C2) Given the remaining likelihood of experiencing failures in perception and interpretation after deployment, how can we establish process learning from field incidents and accidents leading to updates of the scenario catalog avoiding re-occurrence of this incident in the field?

- Challenge C2 requires a formal semantics to identify the gaps between the space of possible worlds described in the scenario catalog, and the concrete in-field incident or accident. Specifically, forthcoming regulations will require autonomously driving cars to record all those perceived environmental artifacts relevant to trajectory planning as well as the car's trajectory control for a sufficiently long time-period. A formal semantics allows to check the failed scenario(s), offering a basis for refining the scenario specifications to cope with the observed failure in perception or interpretation of the real world.

Why we need a formal semantics

- (C3) Given the complexity space of real-world traffic situations, how can one at all achieve sufficiently concise specifications to make construction of scenario catalogues viable?

- Challenge C3 demands the use of a declarative specification language, where one single scenario specification stands for a possibly extremely large set of real world traffic situations, defined unambiguously through the satisfaction relation. Also, declarative specification languages allow for separation of concerns, such as focusing on particular kinds of critical situations in isolation, knowing that the car can only pass the test if all scenarios are passed.

Why we need a formal semantics

- (C4) How can we assure, that the interpretation of scenarios and thus interpretation of test results is unambiguous across all test platforms?

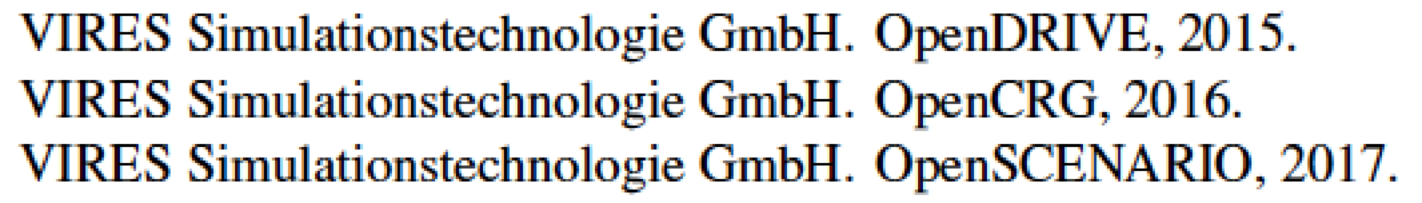
- Challenge C4 can be addressed by automatically synthesizing monitors for compliance testing, using the reference formal semantics.

Related Work: OpenScenario

– emerging industry standard

- Definition of ontology
- No formal semantics
- Correspond to existential TSCs

- Links: http://www.openscenario.org/



VIRES Simulationstechnologie GmbH. OpenDRIVE, 2015.
VIRES Simulationstechnologie GmbH. OpenCRG, 2016.
VIRES Simulationstechnologie GmbH. OpenSCENARIO, 2017.

Papers on TSCs

- Kemper S., Etzien C. “A Visual Logic for the Description of Highway Traffic Scenarios. ” (2014) https://doi.org/10.1007/978-3-319-02812-5_17
- Technical report ATR 117, www.avacs.org
- A formal semantics for TSCs, Principles of Modelling, Festschrift to the honor of Edward Lee, LNCS 10760 , 2018
- Traffic Sequence Charts - A Visual Language for Capturing Traffic Scenarios, Proceedings ERTS 2017
- Statistical Model Checking for Scenario-based verification of ADAS, Sebastian Gerwinn, Eike Möhlmann,Anja Sieper, in Proc Workshop on "Control Strategies for Advanced Driver Assistance Systems and Autonomous Driving Functions“, Springer Verlag, 2018
- Exploiting Learning and Scenario-based Specification Languages for the Verification and Validation of Highly Automated Driving, *Werner Damm, Roland Galbas, to appear in Proc* **SEFAIAS 2018**, First Workshop on Software Engineering for AI in Autonomous Systems co-located with ICSE 2018

Background Material

- SafeTRANS Recommendations on Verification of Highly Autonomous Systems
- The Enables Project
- The Pegasus Project
- Recommendations of the Ethik-Kommission of the German Ministery of Transportation
- Acatech Study Neue Automobilität

Other Relevant Links

- http://www.enable-s3.eu/
- http://www.pegasusprojekt.de/en/about-PEGASUS
- LSCs
  - Werner Damm, David Harel: “LSCs: Breathing Life into Message Sequence Charts.” Formal Methods in System Design 19(1): 45-80 (2001) https://doi.org/10.1023/A:1011227529550
  - David Harel, Rami Marelly: “Come, Let’s Play” http://www.springer.com/computer/programming/book/978-3-540-00787-6