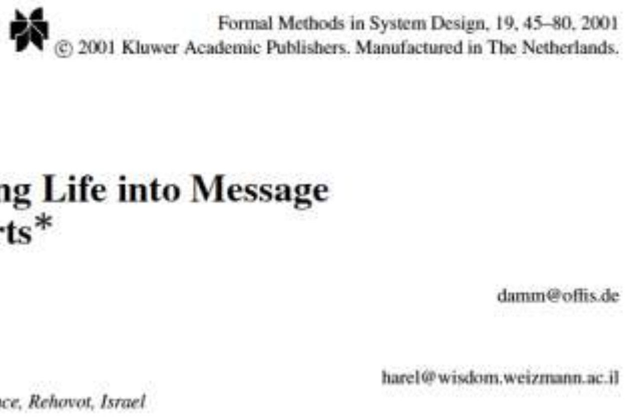
# On the no´s and must´s in system design

**Werner Damm**

**joint work with Bernd Finkbeiner, Universität des Saarlandes, and Astrid Rakow, Carl von Ossietzky Universität Oldenburg**

# Thanks, David!



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**LSCs: Breathing Life into Message Sequence Charts***

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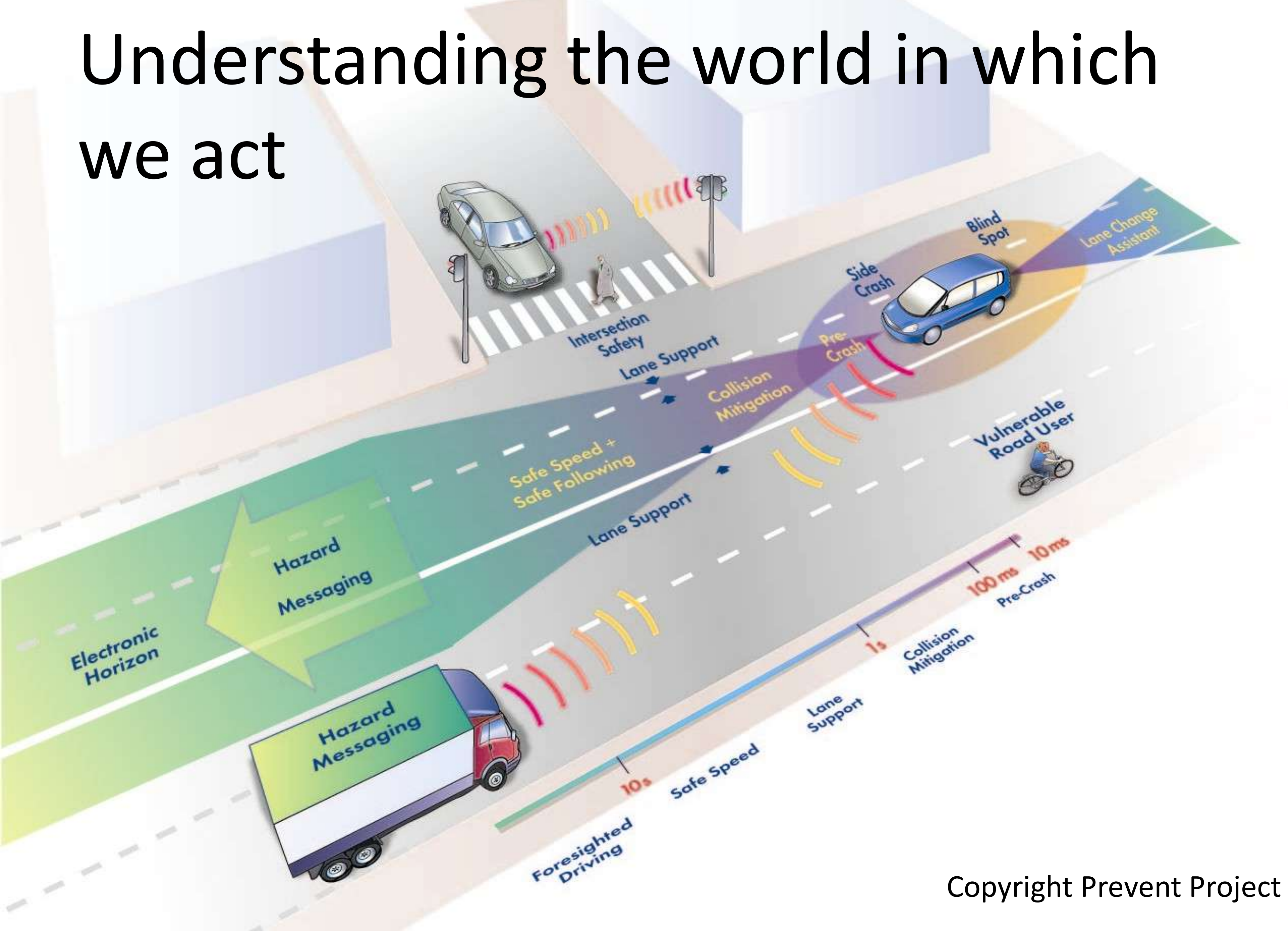
- "… Mandatory conditions (that is, hot ones), together with other hot elements, make it possible to specify *forbidden scenarios,* i.e., ones that the system is not allowed to exhibit. This is extremely important and allows the behavioral specifier to say early on which are the "yes-stories" that the system adheres to and which are the "no-stories" that it must not adhere to.

# Structure of Presentation

- Motivation
- Optimal World Models
- Compositional Synthesis and Weakest Assumptions
- Strong and Weak Assumptions
- An industrial vision
- Conclusion

# MOTIVATION

# Understanding the world in which we act



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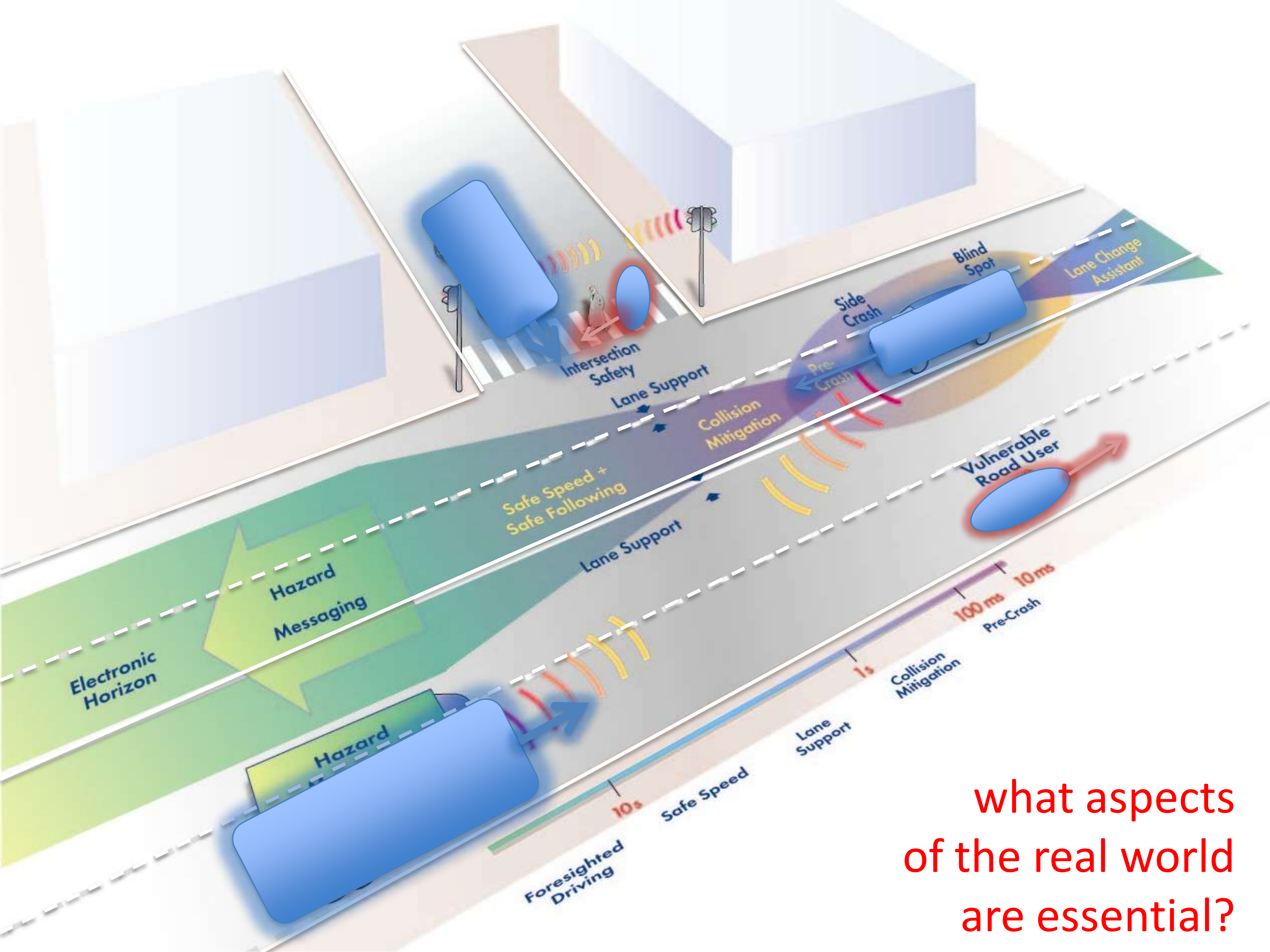


what aspects
of the real world
are essential?

The discrepancy between the real world and what the aircraft perceives as real decide over life and death

14.09.1993 -
Aircraft thought it was still airborne, because only two tons weight lasted on the wheels due to a strong side wind and the landing maneuver. The computer did not allow braking.
*The plane ran over the runway into a rampart.*

# THE SYSTEM ENGINEERING CHALLENGE

Given

a (physical) system S under development

what real-world aspects

could potentially impact S

in a way that endanger its proper functioning?

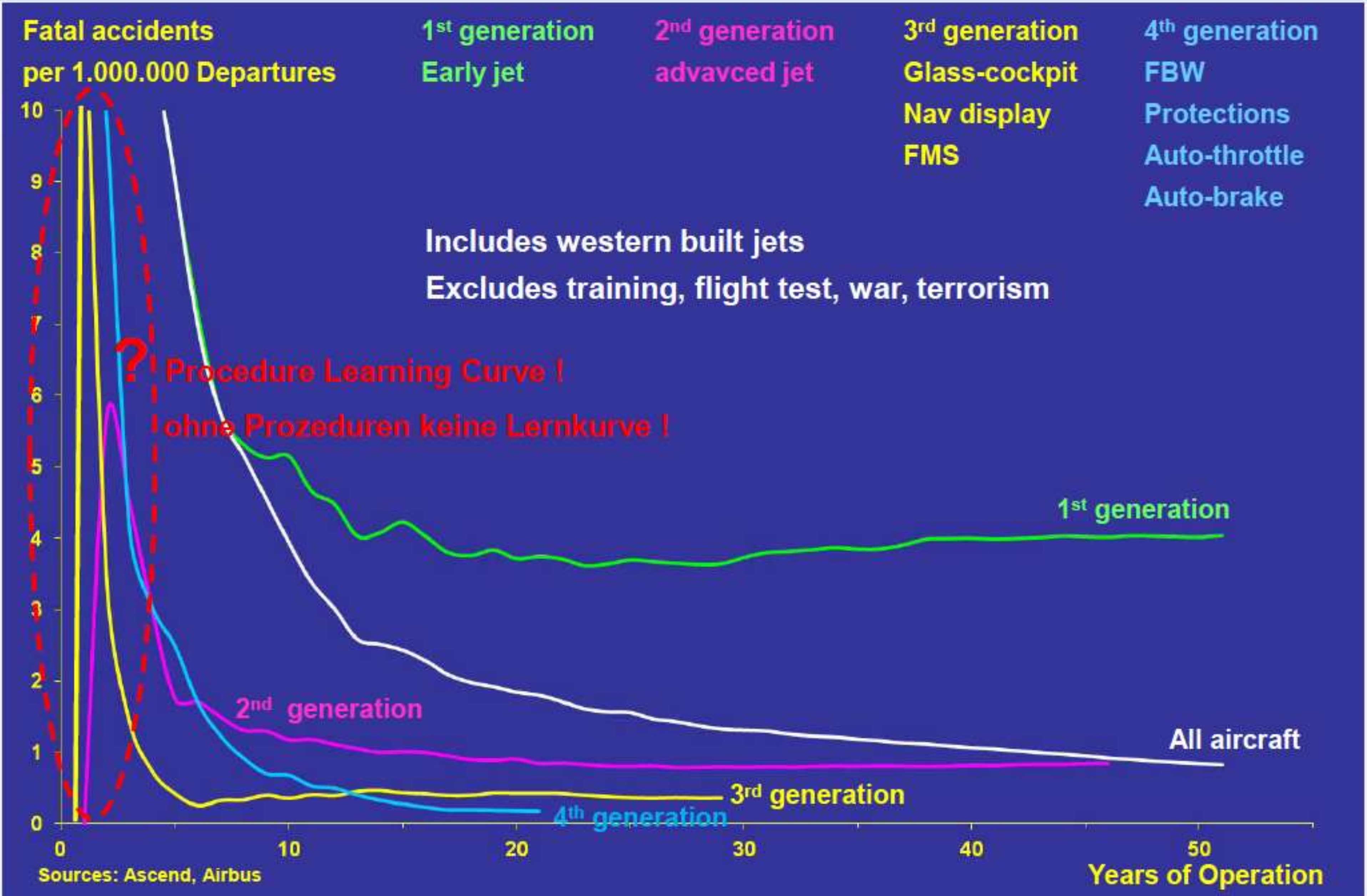
# Questions

- are all “relevant” real-world artifacts part of my world model?
- can the system observe all “relevant” real-world artifacts?
- can we characterize (formally) the notion of “relevance”?
- is there a notion of optimal world models?
- can we characterize the environments, into which our system can be safely deployed?

# Industrial Practice: learning processes

- Company XY
  - all flight incidents are analyzed
  - to identify the process step in which the potential for an incident should have been detected
  - existing models are extended to allow the prediction of such potential incidents
  - measures protecting against such hazards are integrated into the design (and aircrafts)
  - safety processes are used to demonstrate resilience against root cause for such hazards

# Fatal Accident Rate since Entry Into Service – valid through 2010



Includes western built jets

Excludes training, flight test, war, terrorism

Procedure Learning Curve !

ohne Prozeduren keine Lernkurve !

Sources: Ascend, Airbus

# Why we should be concerned

- Even in aerospace learning curve approach fails with introduction of new a/c generation
- Increasing degrees of automation in driving necessitates rigorous measures for qualification / certification of employed world models

# Structure of Presentation

- What is “relevant”: a theoretical approach
- Compositional Controller Design
- On no´s and must´s in system design
- Industrial Deployment
- Conclusion

# WHAT IS RELEVANT? A THEORETICAL APPROACH

# World Models I

- Let $V_S$ be a finite set of *system variables*
  - modeling actions under the system's control, such as the setting of actuators
- $\boldsymbol{V_E}$ be an **arbitrary** set of *environment variables*,
  - in the context of control theory corresponding to the variables of the plant model
- Environment variables are partitioned into disjoint sets of
  - *disturbances* $\boldsymbol{V_D}$

    modeling *uncontrollable environment observations*, and
  - *controllable environment variables* $V_C$

    modeling phenomena in the environment which can be influenced by the system through the system variables

# World Models II

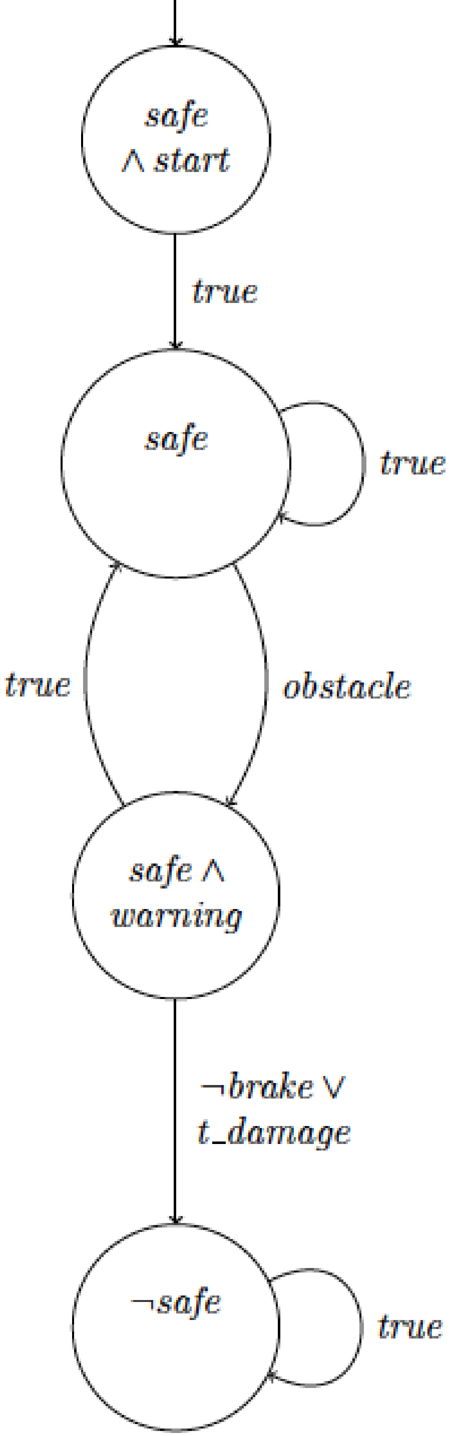
- restrict only a finite subset $V_E \subseteq \boldsymbol{V}_E$ called the *perimeter* of the world model
- assign *arbitrary* valuations to the environment variables outside the perimeter of the model
- We assume finitely typed variables, wlog of type boolean

# World Models III

A *world model* is a tupel

$$M = (V_E, N, n_0, E, L_N, L_E)$$

- $V_E \subseteq \mathbf{V}_E$ is the *perimeter* of the world model
- $N$ is a possibly infinite set of *nodes*, $E \subseteq N \times N$
- $L_N : N \rightarrow P(P(V_C))$ assigns sets of valuations of controllable variables which agree on the variables within the perimeter of the model (intuitively: state of the plant)
- $L_E : E \rightarrow P(P(V_S \cup \mathbf{V}_D))$ defines for each edge sets of system moves and disturbances (which agree on the variables within the perimeter of the model)



# A simple world model

... for an ADAS to maintain **safe distance to objects ahead** on same lane (cars, cargo, ...), two lane hwys,

*secondary objective* **avoid braking**

disturbances

appearance of an obstacle

tire-burst

controllable actions

brake

states

safe: the distance to the object ahead of the ego car is greater than some constant

warning: an obstacle has been detected ahead of the ego car

The world model explains how the plant state changes depending on disturbances and controllable actions

# From yes/no to: could we do better?

- No world model will ever be complete
- Hence no formal verification of a cyber physical system can “guarantee” safety (e.g. no crash)

We *“measure” the benefit of extending a world model W*

to include a new real world artifact  a

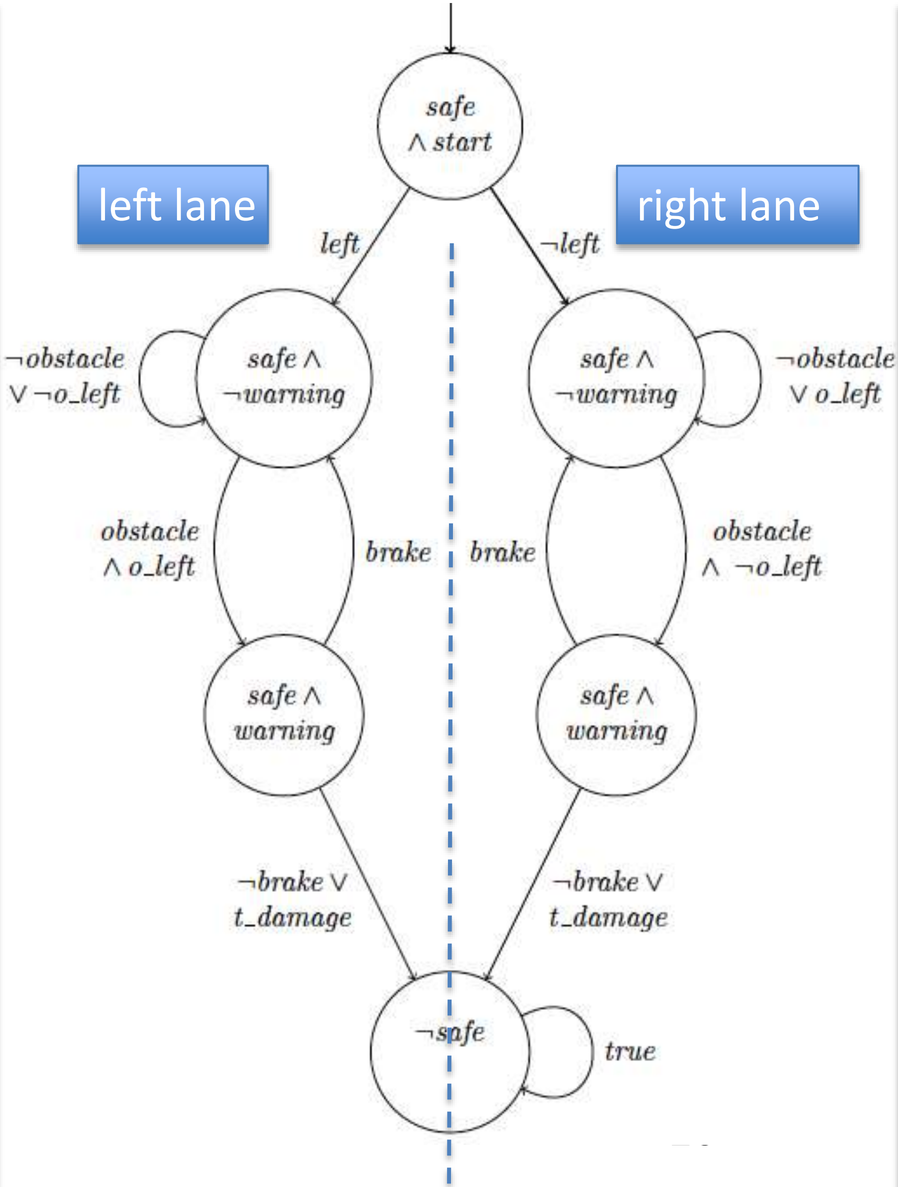
by comparing the strategic capabilities of W and W∪{a}:

**Does the richer world model allow to define strategies,**

**which, in comparable environment moves,**

***allow more often to achieve the systems objective*?**

# A richer world model



disturbances

appearance of an obstacle

o_left: on left lane

tire-burst

controllable actions

brake

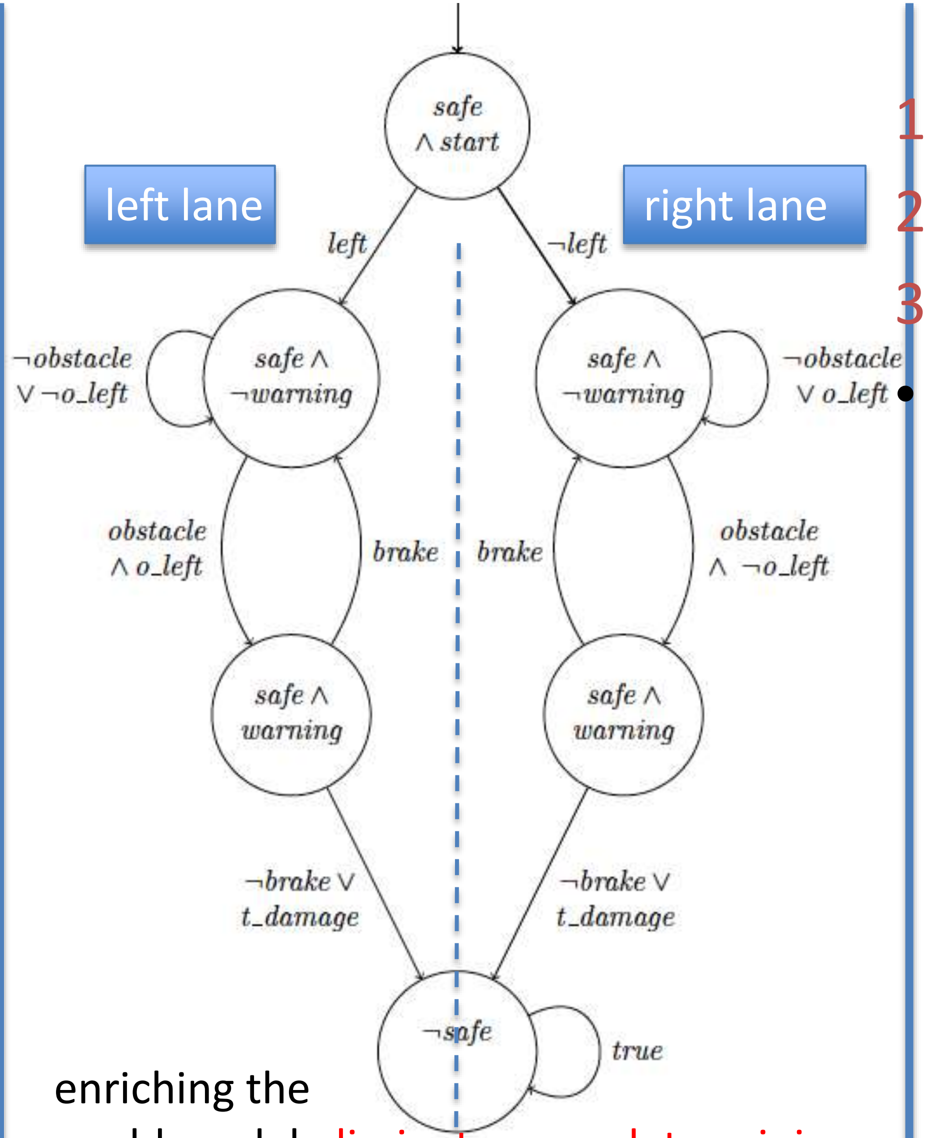
left: take left lane

states

safe: the distance to the object ahead of the ego car is greater than some constant

warning: an obstacle has been detected ahead of the ego car

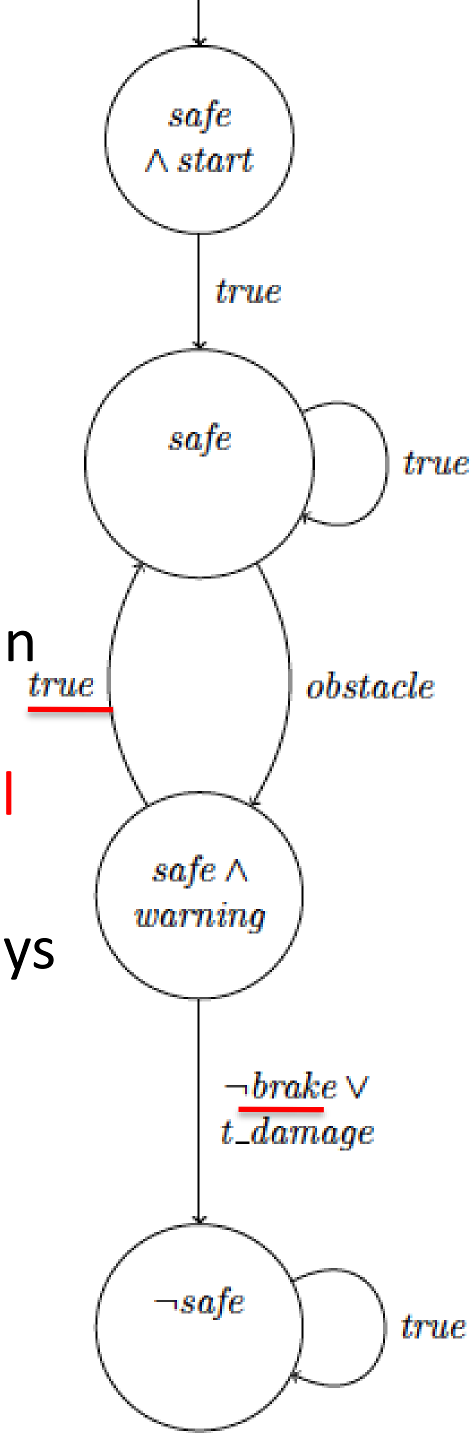
# Beyond YES/NO



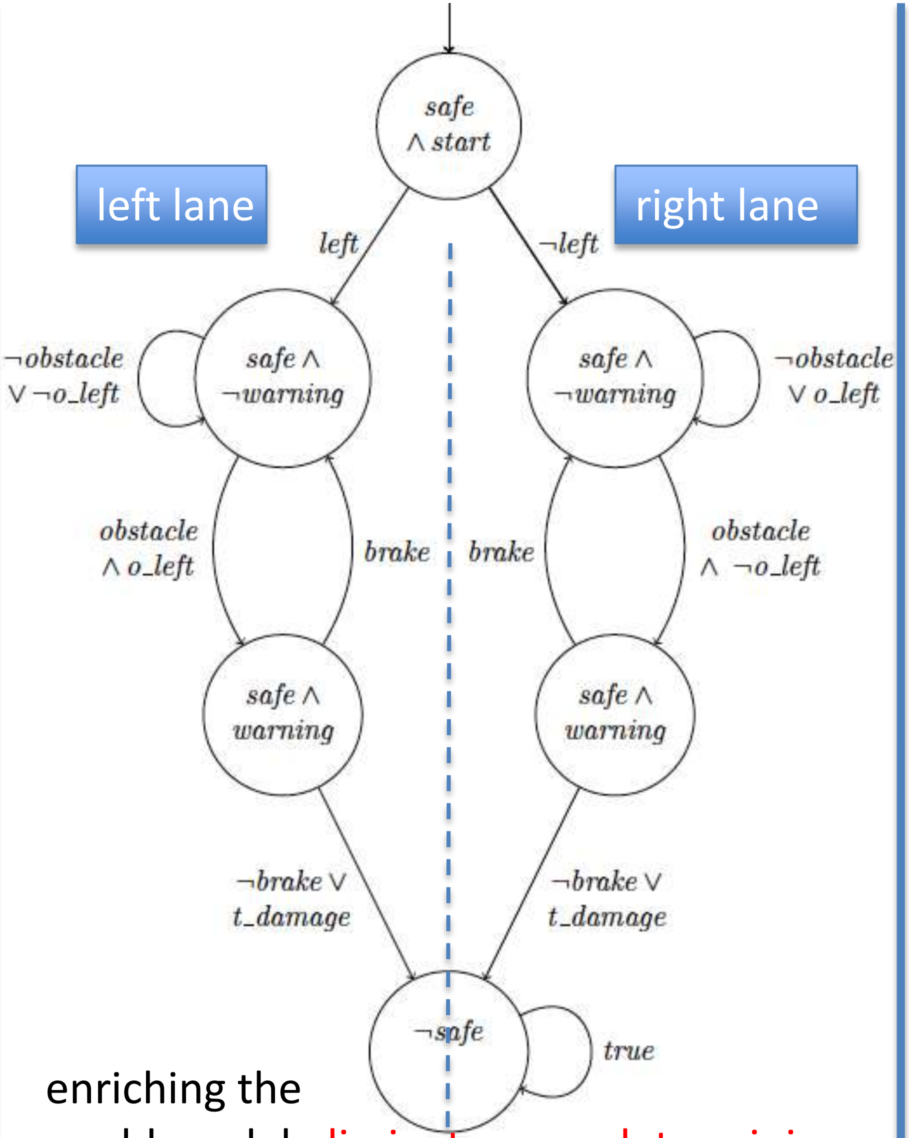
enriching the world model eliminates non-determinism

1. Never brake
2. Brake iff warning
3. Brake always

- all strategies fail in both models to always achieve all objectives: tire damage can always cause system to become unsafe



# Comparing strategies: remorse-free dominance



enriching the world model eliminates non-determinism

$s_1$ Never brake

$s_2$ Brake iff warning

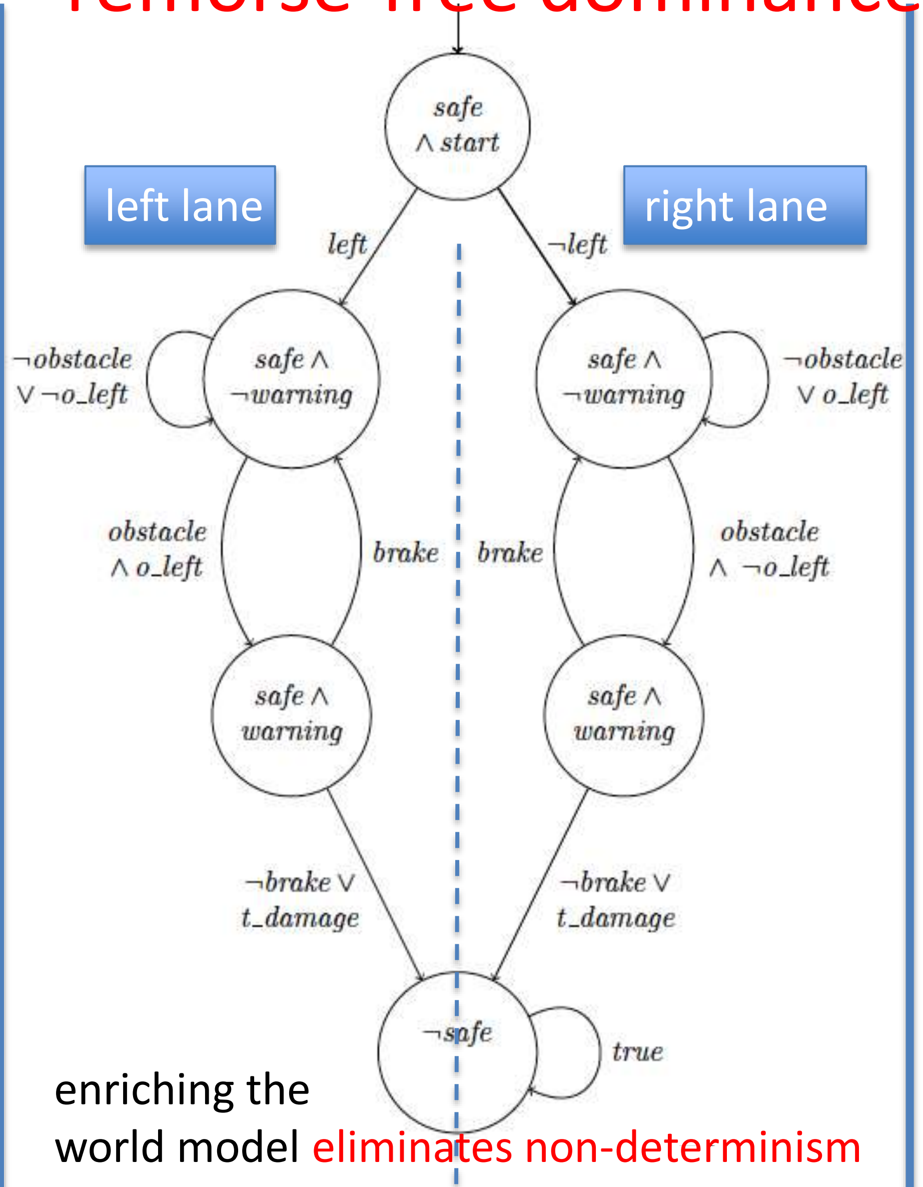
$s_3$ Brake always

- compare strategies wrt remorse: *could I "have done better"* = achieved higher priority objectives

*in "comparable situations"* = same sequence of disturbances

- $s_2$ dominates $s_3$:
  - whenever $s_3$ achieves up to prio_x in some sequence of disturbances, so will $s_2$
  - but $s_2$ avoids (unnecessary) braking in safe state with no warning

# Comparing strategies: remorse-free dominance



enriching the
world model eliminates non-determinism

$s_1$ Never brake

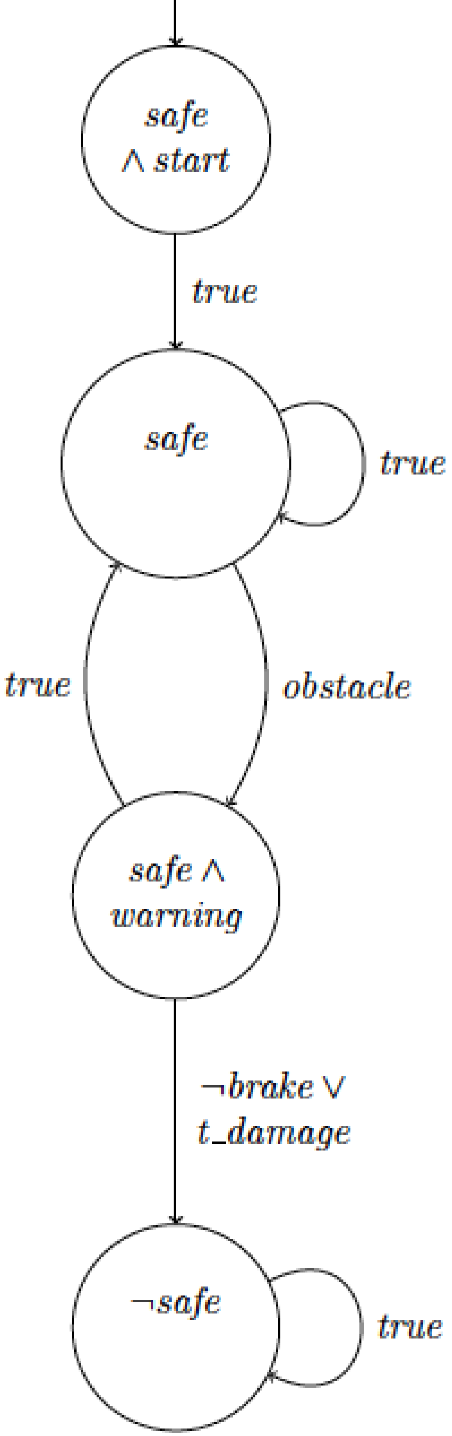
$s_2$ Brake iff warning

$s_3$ Brake always

- compare strategies wrt remorse: *could I "have done better"* = achieved higher priority objectives

*in "comparable situations"* = same sequence of disturbances

- $s_2$ dominates $s_1$:
  - whenever $s_1$ achieves up to prio_x in some sequence of disturbances, so will $s_2$
  - but $s_1$ can cause crash in sequences of disturbances where $s_2$ will remain safe



$s_1$ Never brake

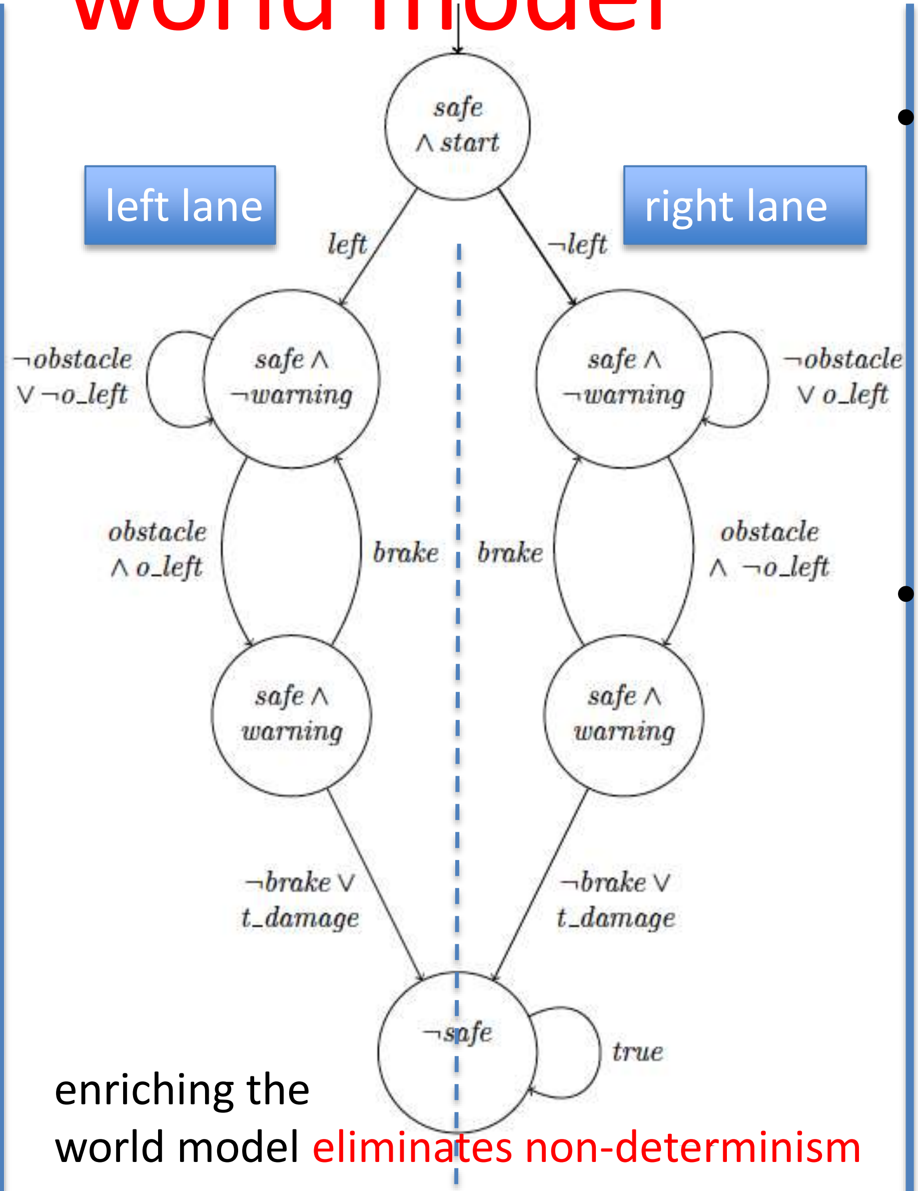
$s_2$ Brake iff warning

$s_3$ Brake always

- $s_3$ is not dominant, because it brakes even in the middle safe state, where there is no danger for safety (hence braking is causing remorse because both $s_2$ and $s_1$ avoid this)
- $s_1$ does not dominate $s_2$ , because it does not avoid crashes in sequences of disturbances, where this is avoided by $s_2$
- $s_2$ does not dominate $s_1$, because for some sequence of disturbances braking is not necessary to avoid crash (if obstacle is on other lane)

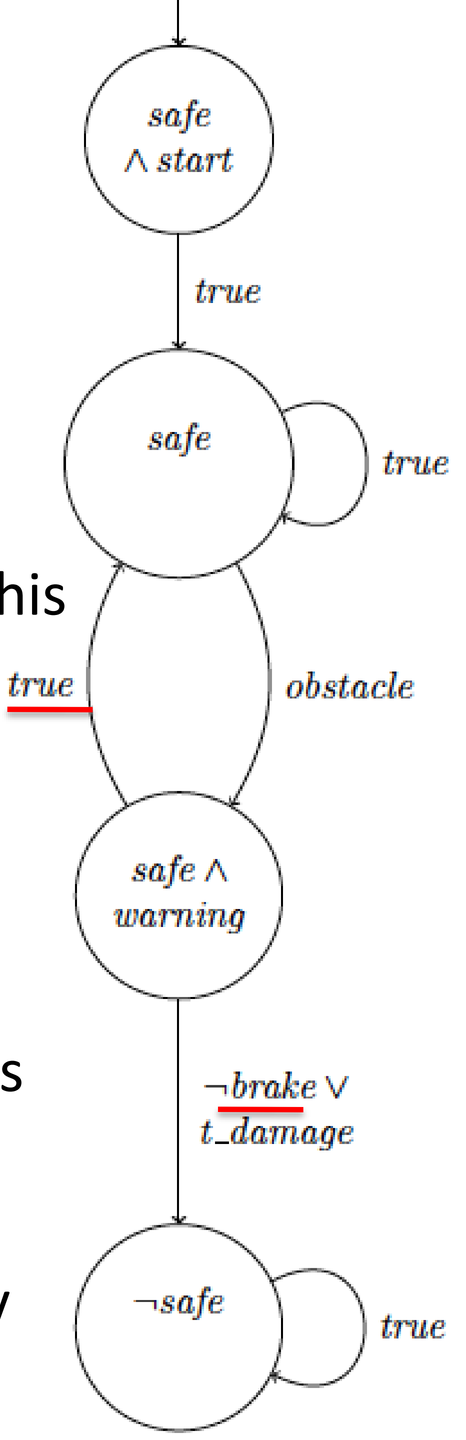
The simple world model does not permit a dominant strategy

# It paid to enrich the world model



enriching the world model eliminates non-determinism

- In the refined model, there is a “best in class” strategy: picking this will never cause remorse
- The simple model does not contain sufficiently many real world artifacts so as to allow construction of a dominant strategy



# Optimal world models

- Intuitively, given a fixed set of prioritized objectives, only a subset of all real world artifacts are required to define the "best possible strategy" for these objectives

A world model W is optimal
if it allows do define a ("best") strategy
which not only dominates all other strategies in W,
but also those definable in all refinements of W

# Optimal world models

A world model W is optimal
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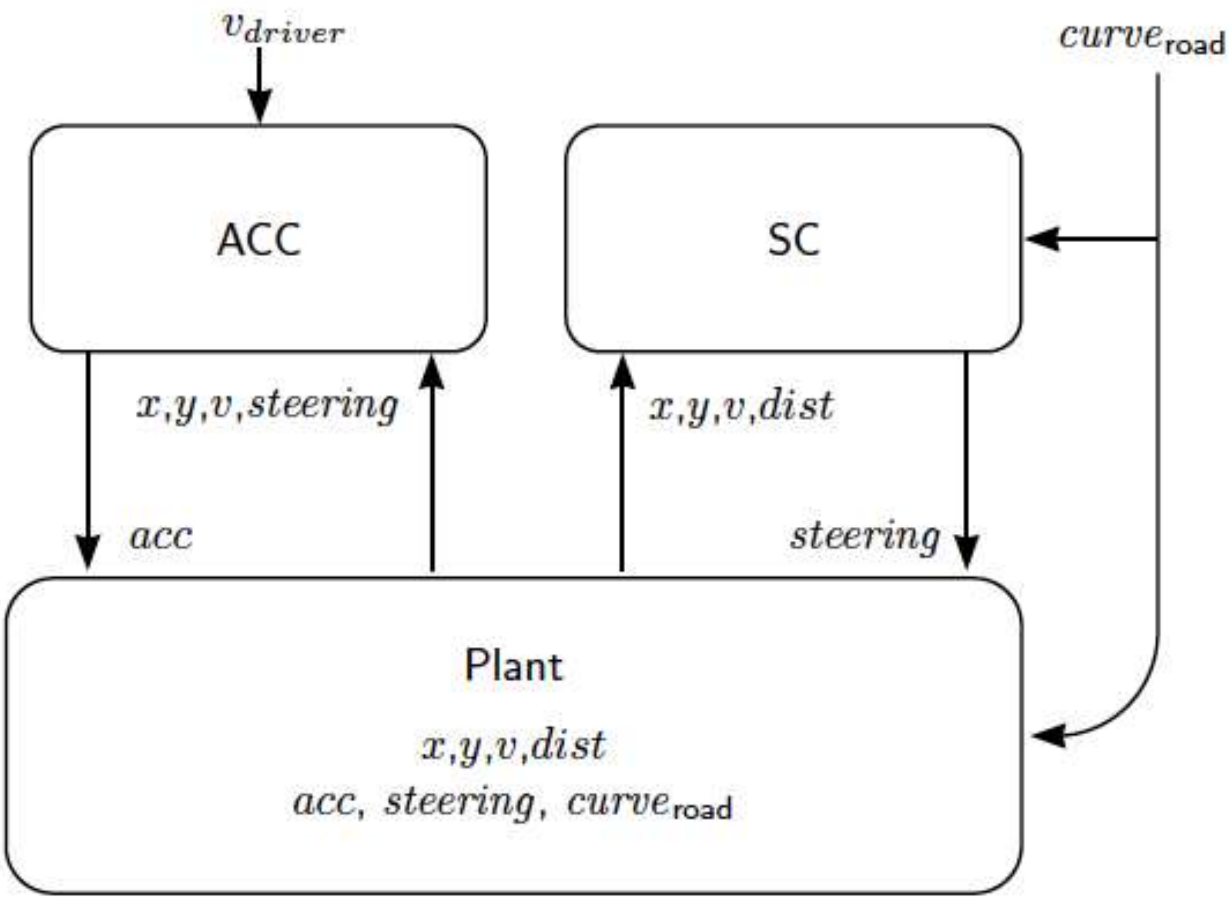
Theorem

Let W be a world model, ϕ an objective specification given as prioritized list of LTL formula

(1) We can automatically check whether W is optimal for ϕ
(2) If true, we can automatically synthesize a „best" strategy

# CONTRACT BASED CONTROLLER DESIGN

# A running Example



# Control objectives

1. top priority: maintain stability of the car

$$\varphi_{global} = \Box((\mu \cdot g)^2 - (\frac{v^2}{r})^2 \geq acc^2)$$

2a. keep car on lane

$$\varphi_{SC_{high}} = \Box(|dist| \leq 0.5 \cdot width_{lane})$$

2b. approximately achieve driver selected speed

$$\varphi_{ACC_{high}} = \forall \hat{v} : \Box((\uparrow_{v_{req}} \wedge \Box_{\leq t_{\Delta}} \hat{v} = v_{req}) \Rightarrow$$
$$(\Diamond_{\leq t_{\Delta}}((v \;\; is \;\; v_{req} \pm x\%) \mathsf{U} (\uparrow_{v_{req}} \wedge (v_{req} \neq \hat{v}))))$$

3a. follow center of lane

$$\varphi_{SC_{low}} = \Box(|dist| \leq 0.2 \cdot width_{lane})$$

3b. follow driver selected speed almost exactly

# Contract Based Design

- Given an objective specification
- under which assumptions on the environment will the system be able to meet its objectives (up to priority n)
- contract: pair of assumptions, objective spec (for each priority)

# Contract Based Design

Examples

- assumptions of the combined ACC-SC relate to the interaction with the driver in choosing a desired speed, and to the evolution of the street (e.g. curvature of the next road segment).
- assumptions of the ACC controller additionally relate to uncontrolled plant actuators, such as the actuators of the lanekeeping controller, SC.

# Admissable objective specifications

- We provide automatic methods adressing these for *admissable* specifications
- An objective specification is called *admissible wrt world model M* if it possesses a remorse-free dominant strategy
- Intuitively, a specification is admissible as long as we do not require a process to “guess” variables it cannot see or to “predict” future inputs.

# Example

- The objective specification

  $$\varphi_{ACC} = \langle \varphi_{global}, \varphi_{ACC_{high}}, \varphi_{ACC_{low}} \rangle$$

  is not admissible, because no strategy can predict the future settings of steering control

  - s hopes for non-interference of SC, and achieves $\varphi_{ACC_{low}}$ when no interference
  - s´ bets on interference, and gives up $\varphi_{ACC_{low}}$
  - s and s´ are incomparable

# Weakest Environment Assumptions

Given

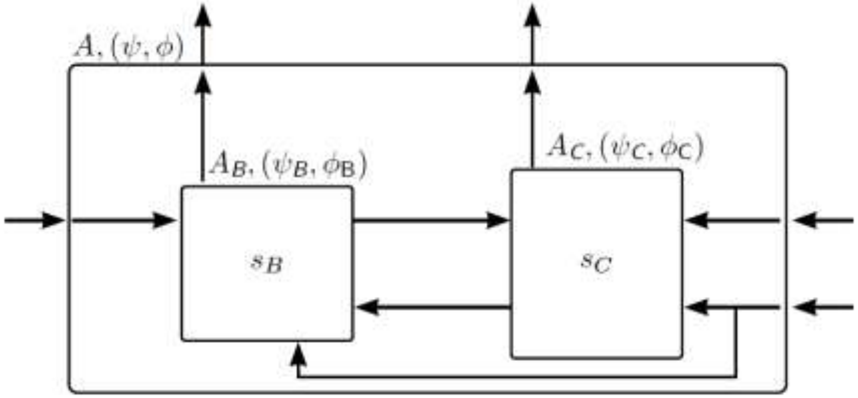
- an objective specification $\phi_A$ admissible for A together with its static interface

we can effectively compute

- a remorse-free dominant strategy s(A, $\phi_A$)
- a (weakest) environment assumption w(A, $\phi_A$)

s.t. s(A, $\phi_A$) is winning for $\phi_A$ iff the environment of A satisfies w(A, $\phi_A$)

# Incremental Design



- Assume A is to be realized by using C already meeting subset $\phi_C$ of A´s objectives $\phi_A$
- *Can we find a specification $\phi_B$ of subsystem B, s.t. when put together with C,*

  *any implementation of $\phi_B$ will jointly meet $\phi_A$ whenever the assumptions derived in B's contracts and assumptions of C relating to the environment of A are met?*

# Incremental Design Theorem

- Given
  - an objective specification $\phi_A$ admissible for A together with its static interface and subsystems B, C, with their interfaces and their interconnection structure,
  - a subset $\phi_C$ of $\phi_A$ admissible for C
  - a remorse-free dominant strategy $s_C$ realizing $\phi_C$ under assumptions $\psi_C$.

# Incremental Design Theorem

Let $\phi_B = \text{Rem}(\phi_C, \phi_A) \wedge \psi_C$ be admissable for B

Then

for any remorse-free dominant strategy $s_B$ realizing $\phi_B$

$s_C$⍰$s_B$ is remorse-free dominant for A and $\phi_A$

# ON NO´S AND MUST´S IN SYSTEM DESIGN

# introducing modalities

- **Strong** assumptions characterize allowed design context
  - – If component´s environment does not meet strong assumption, product liability does not apply
- **Weak** assumption define a subspace of the allowed design context
  - – Example: different conformance levels
  - – Example: different degradation levels

# Example I (autonomous driving)

- highly autonomous driving requires sufficient levels of coherency between relevant real world objects and digital world model used by car
- weak assumptions characterize conditions on environment (light, road surface) and health state of complete sensor chain under which this functionality is available
- strong assumptions state that when autonomous driving is allowed to be active: health state of complete sensor chain is ok, and no dangerous environment conditions prevail

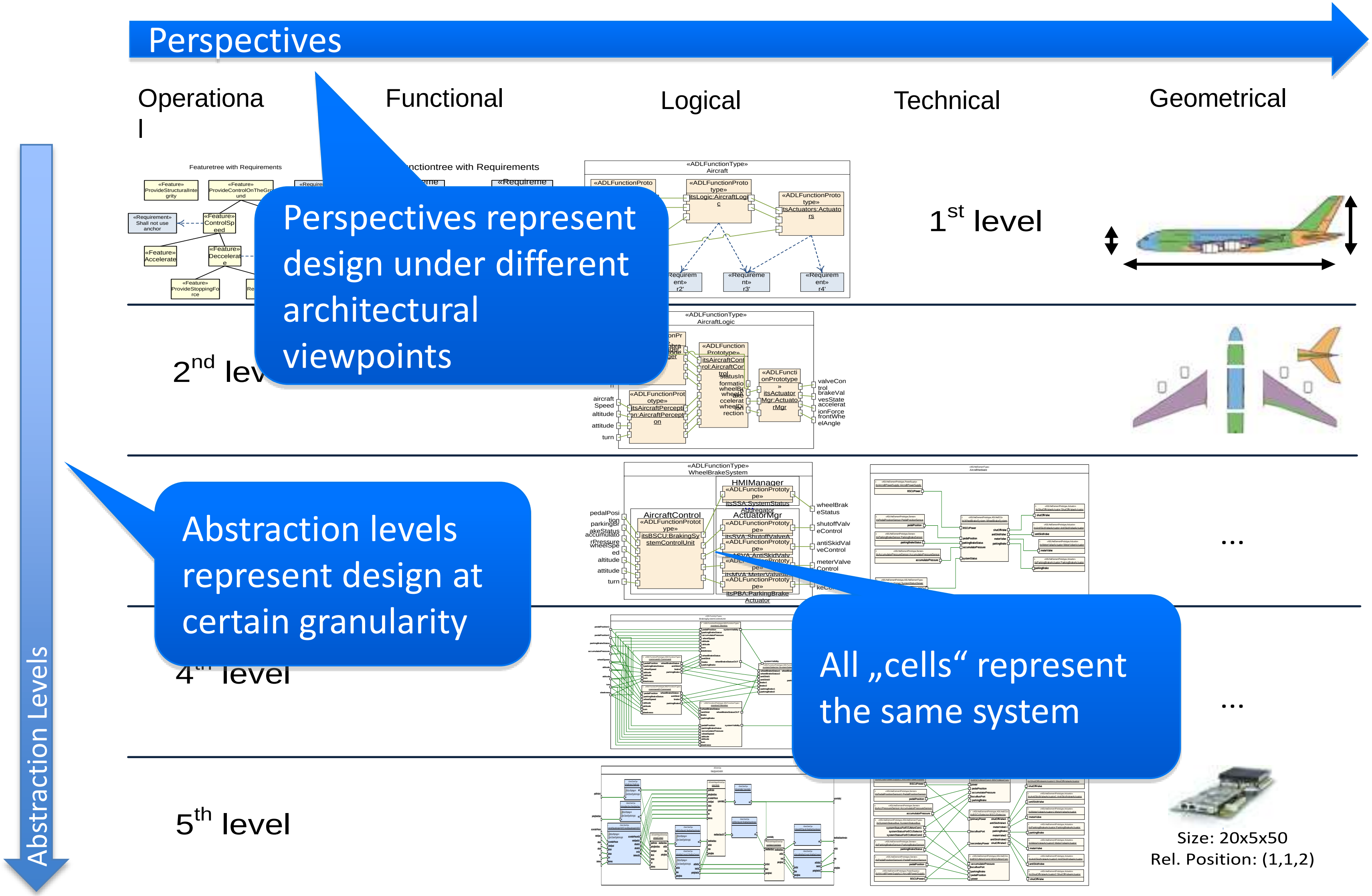
# Example II (safety)

- when using world models incorporating failure modes and failures, the methods discussed allow to automatically derive failure hypothesis under which the system is guaranteed not to reach top-level hazards
- strong assumptions characterize e.g. requirements on allowed component failure types induced from overall safety assurance levels

# weak and strong assumptions

- Weak assumptions can in principle be generated automatically using approach of previous sections, but will most likely be derived manually, using adaptations of methods like fault-tree analysis to general system design
- It is a separate design step to then selectively derive from these the required strong assumptions

# A Systems Engineering Meta-Model



Perspectives

Operational

Functional

Logical

Technical

Geometrical

Abstraction Levels

1st level

2nd lev

4th level

5th level

…

…

Size: 20x5x50
Rel. Position: (1,1,2)

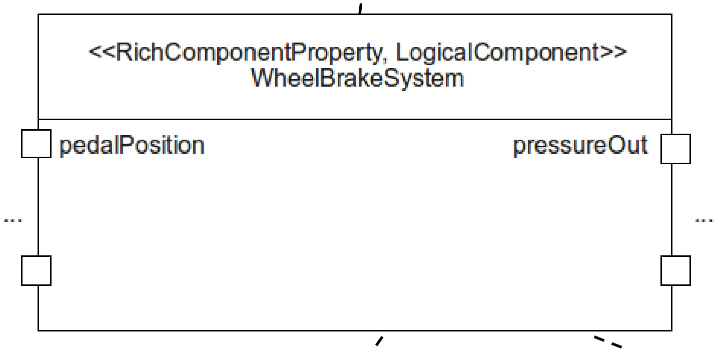
Perspectives represent design under different architectural viewpoints

Abstraction levels represent design at certain granularity

All „cells“ represent the same system

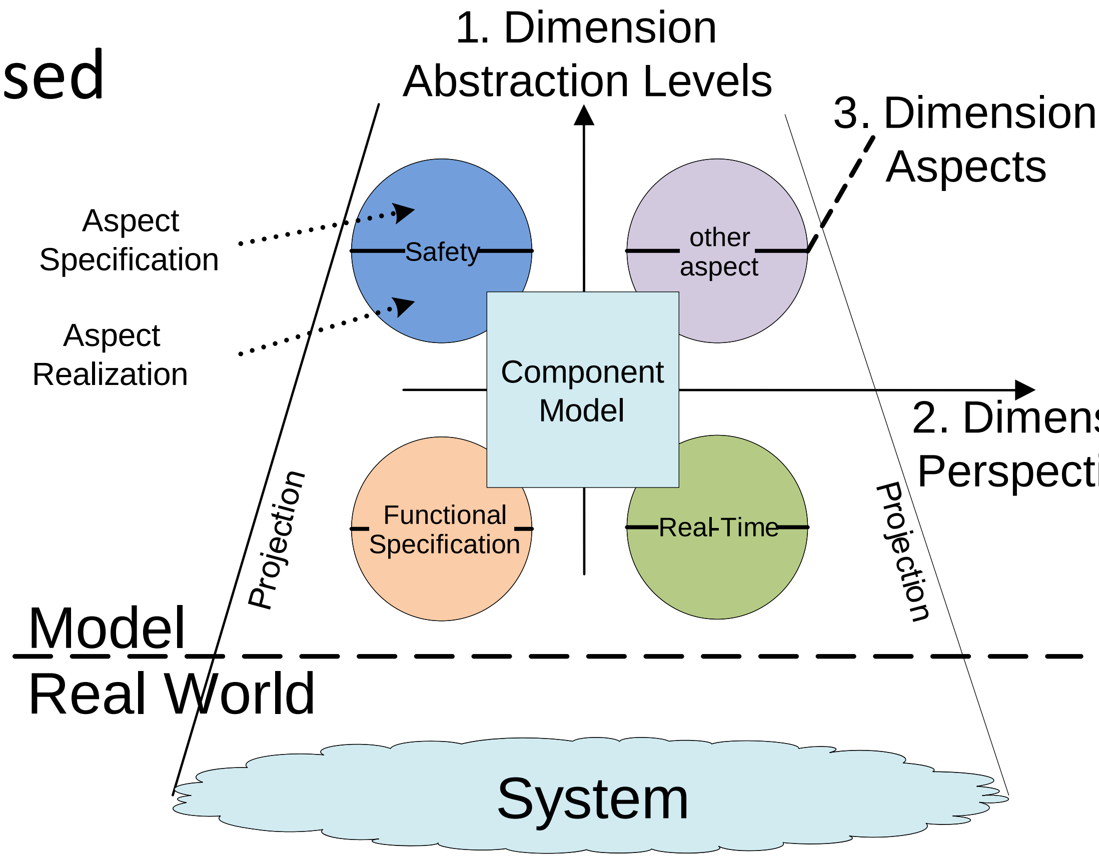
# Multi-aspect contract based specifications

Loss of all wheel braking during landing or Rejected Take Off shall be less than $5*10^{-7}$ per flight

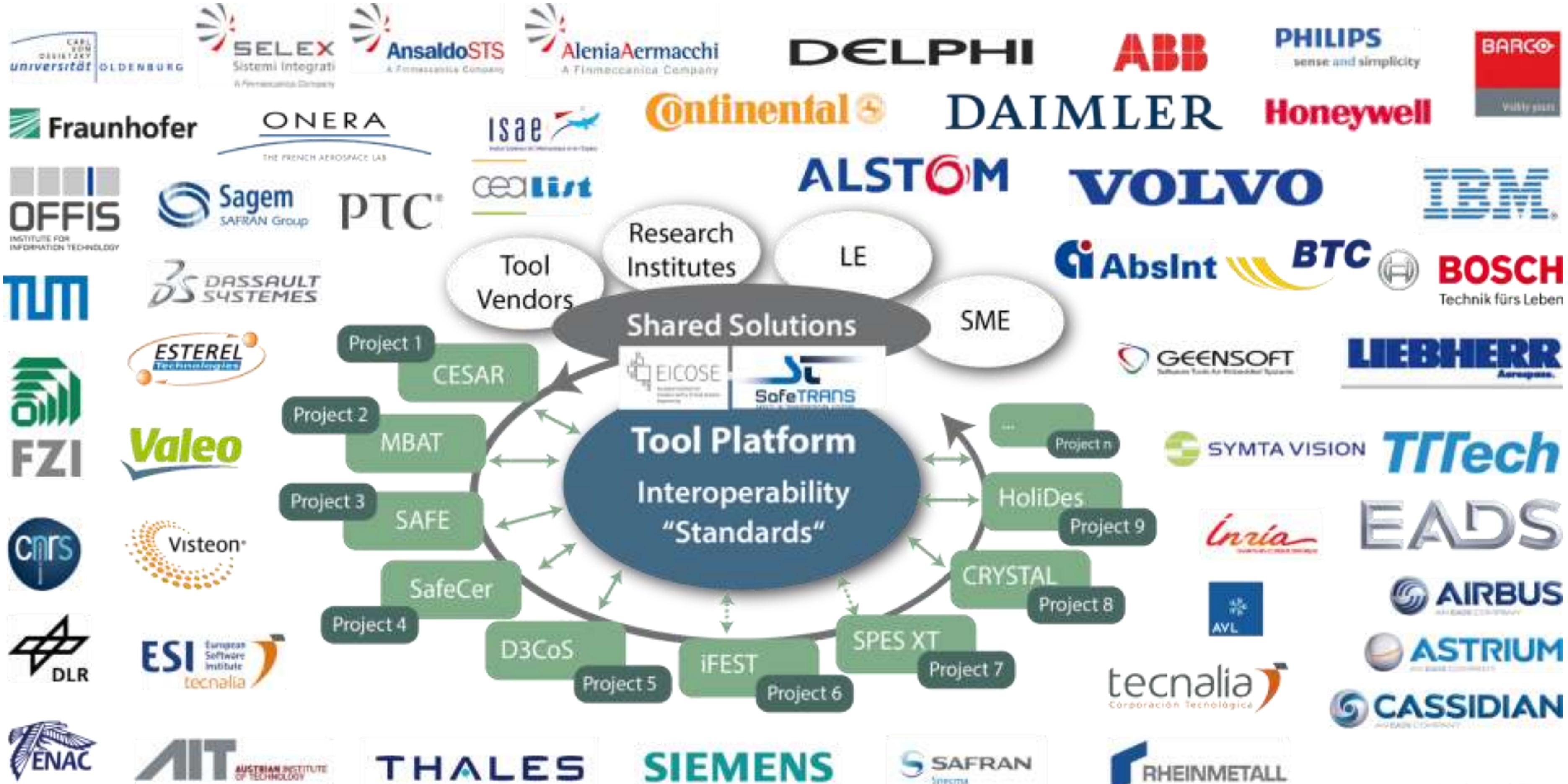


The pilot shall be allowed to override the autobrake function

When brake pedal is pressed, pressure to wheels should be supplied within 10ms



# An Innovation Eco-System for Critical Systems Engineering



Tool Vendors

Research Institutes

LE

SME

Shared Solutions

Tool Platform

Interoperability "Standards"

Project 1 CESAR

Project 2 MBAT

Project 3 SAFE

Project 4 SafeCer

Project 5 D3CoS

Project 6 iFEST

Project 7 SPES XT

Project 8 CRYSTAL

Project 9 HoliDes

Project n …

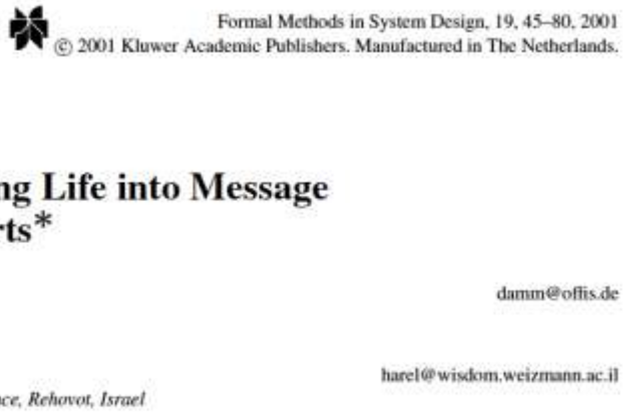
Graphic: SafeTRANS

# CONCLUSION

# Such modalities have already been introduced in live sequence charts

- strong assumptions correspond to hot conditions in live sequence charts: violation leads to abortion

- weak assumptions correspond to cold conditions in live sequence charts: they allow to consider different cases



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# Foundational Contributions

- the identification of a class of *admissible linear time temporal logic formula* for which the distributed controller synthesis problem is decidable (in double exponential time);
- the capability to effectively derive a weakest assumption on the environment of a system under which a global specification ϕ given as admissible LTL formula is realizable
- the capability to effectively synthesize an *optimal strategy* realizing ϕ, in the sense that if ϕ fails to realize the global specification, than also any other strategy would fail to realize the global specification

# Industrial Impact

- The contract based approach to systems engineering is increasingly seen as a key enabler to drastically reduce development time
- Product level tools supporting the methodology are now available on the market
- Key element in the current large scale European Initiative on building a reference platform for critical systems engineering

# Selected References

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- Werner Damm, Bernd Finkbeiner, *Automatic Compositional Synthesis of Distributed Systems*, accepted for publication at the 19th International Symposium on Formal Methods, Singapur, May 2014
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- Werner Damm, Henning Dierks, Jens Oehlerking, and Amir Pnueli. *Towards component based design of hybrid systems: Safety and stability.* In Zohar Manna and Doron Peled, editors, Time for Verification: Essays in Memory of Amir Pnueli, volume 6200 of Lecture Notes in Computer Science (LNCS), pages 96-143, 2010.
- W. Damm, B. Josko, T. Peikenkamp: *Contract based ISO CD 26262 safety analysis.* In: Proc.SAE World Congress and Exhibition, 2009.

# Relevant Projects

- Foundations
  - SFB TR AVACS “Automatic Verification and Analysis of Complex Systems”, www.avacs.org
- Industrial
  - Speeds http://www.speeds.eu.com/
  - Danse http://www.danse-ip.eu/home/
  - CESAR http://www.cesarproject.eu/
  - MBAT http://www.mbat-artemis.eu/home/
  - Crystal http://www.crystal-artemis.eu/
  - SPES XT http://spes2020.informatik.tu-muenchen.de/spes_xt-home.html