Reliability of Smart Systems

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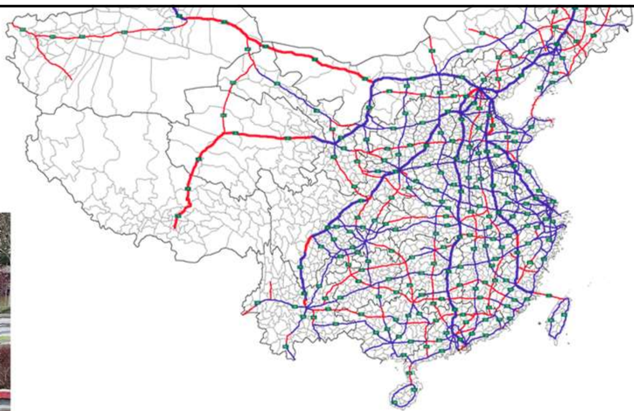
What is the reliability gain achieved by the health monitoring system?

[Question asked by an aircraft manufacturer]

What is a smart system?

A system that can utilize *information* to optimize its operation

Smart systems



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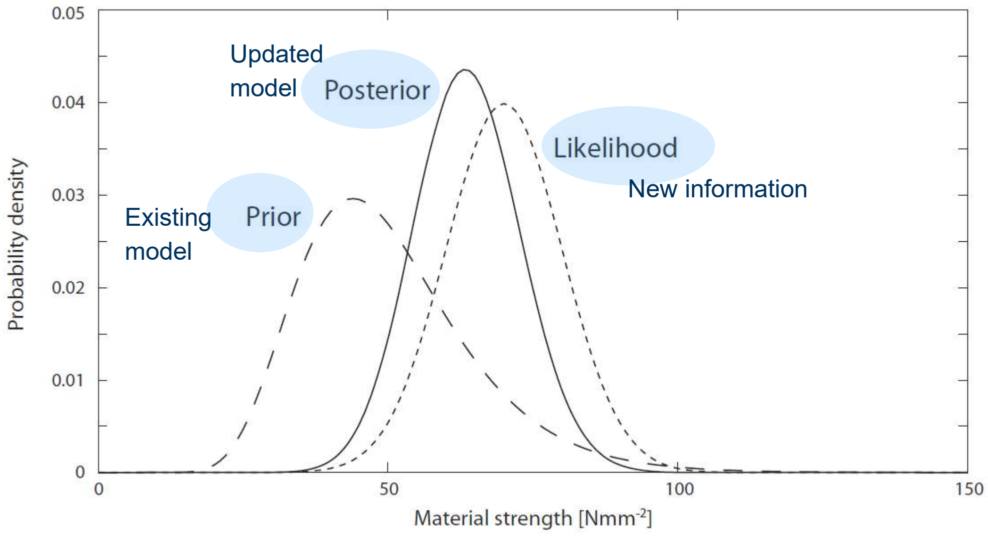
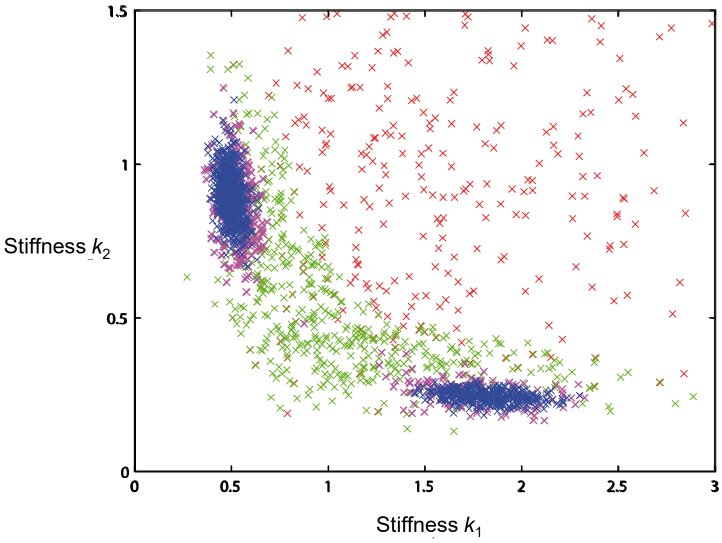
Information in reliability: Bayesian toolbox

Bayesian analysis



Bayesian analysis: learning as an inverse problem

Advanced Monte Carlo methods
for Bayesian analysis



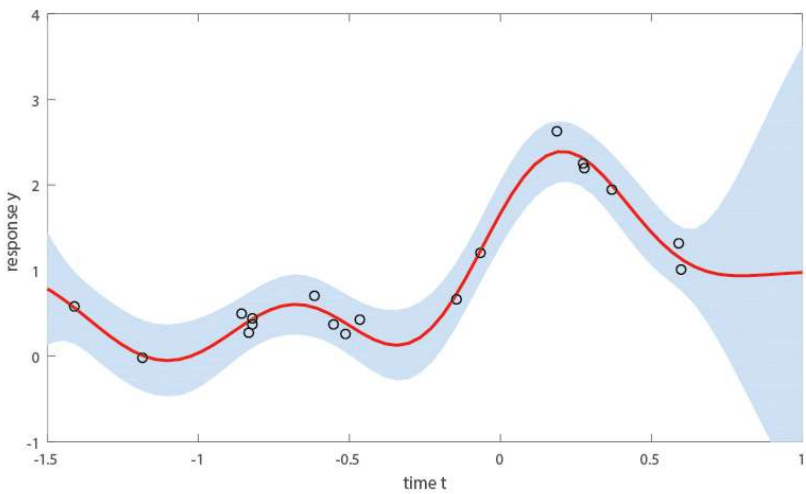
Straub D., Papaioannou I., (2015). *Journal of Engineering Mechanics*, **314**: 538–556.

Bayesian analysis: sequential learning

Methods such as:

- Kalman filters
- Kriging
- Gaussian processes
- Dynamic Bayesian networks

are all special instances of a Bayesian analysis



Bayesian analysis: sequential learning

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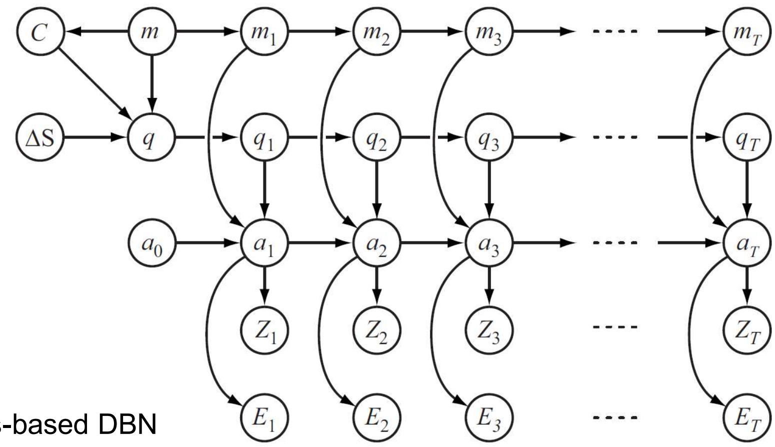
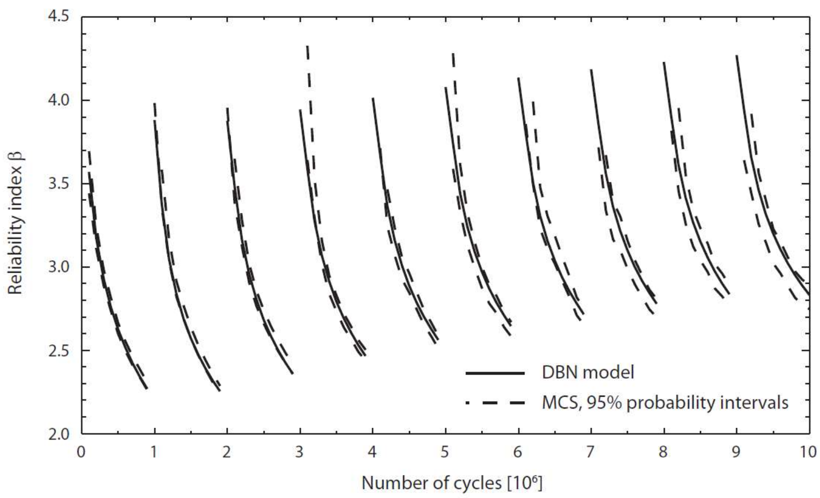


Physics-based DBN

Bayesian analysis: sequential learning

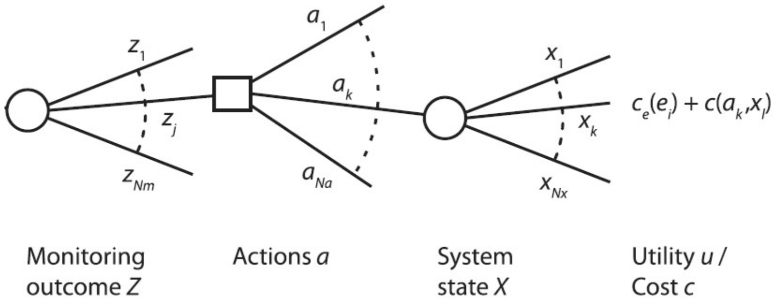
Reduced uncertainty translates to a change in reliability



Straub D. (2009). *Journal of Engineering Mechanics*, **135**(10): 1089-1099.

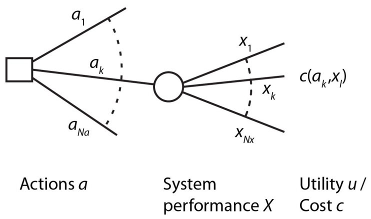
Bayesian decision making

Provides a formal approach to assessing the effect of information on the operation of the system
In autonomous systems, it can be used (but seldomly is) for optimizing the decisions



Value of information

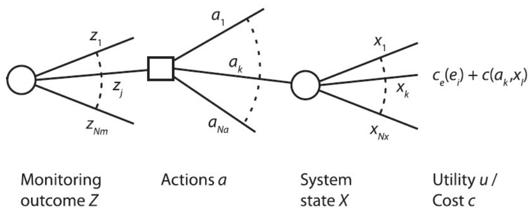
without additional information:



$$\max_a \int_X u(x,a)\, f(x|a) \mathrm{d}x$$

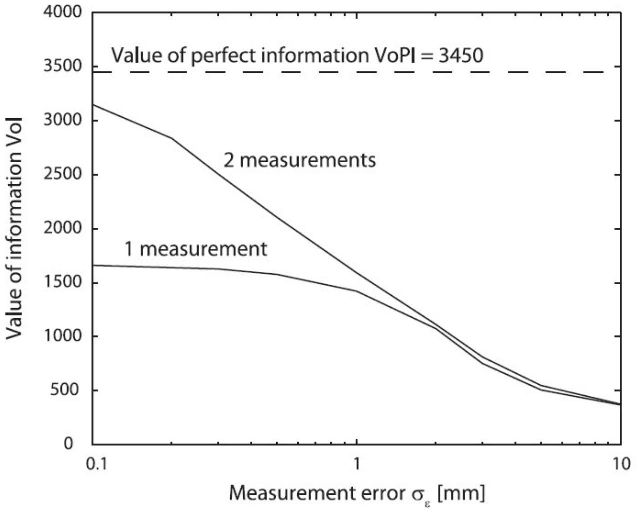
VoI

with additional information:



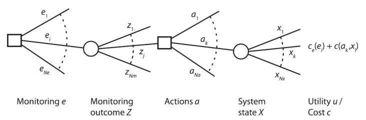
$$\int_Z f(z|e) \left[\max_a \int_X u(x,a)\, f(x|a,z,e) \mathrm{d}x \right] dz$$

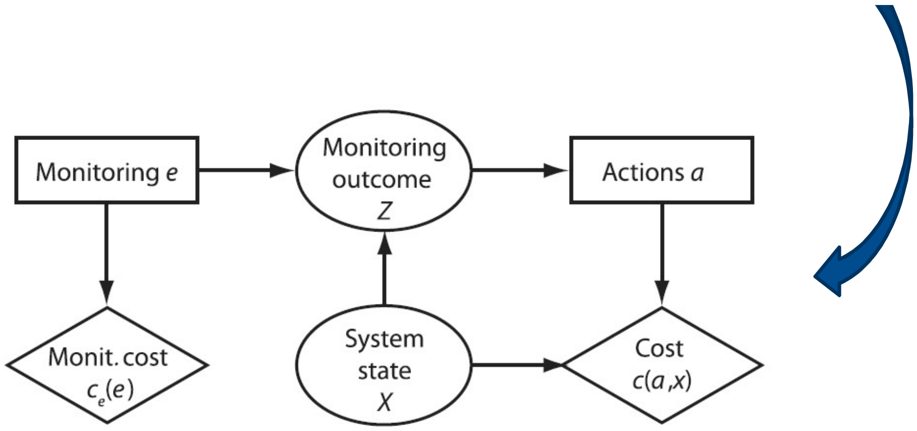
Value of information



Straub D. (2014). *Structural Safety* **49**: 75-86

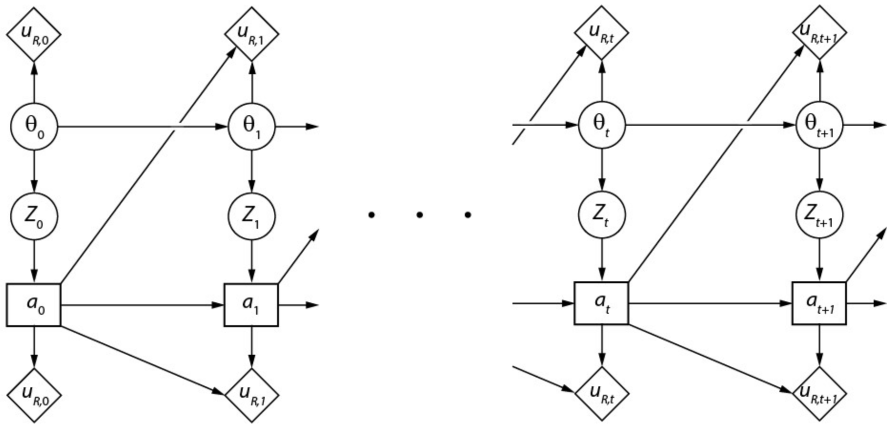
Influence diagrams as concise graphical representations of decision problems





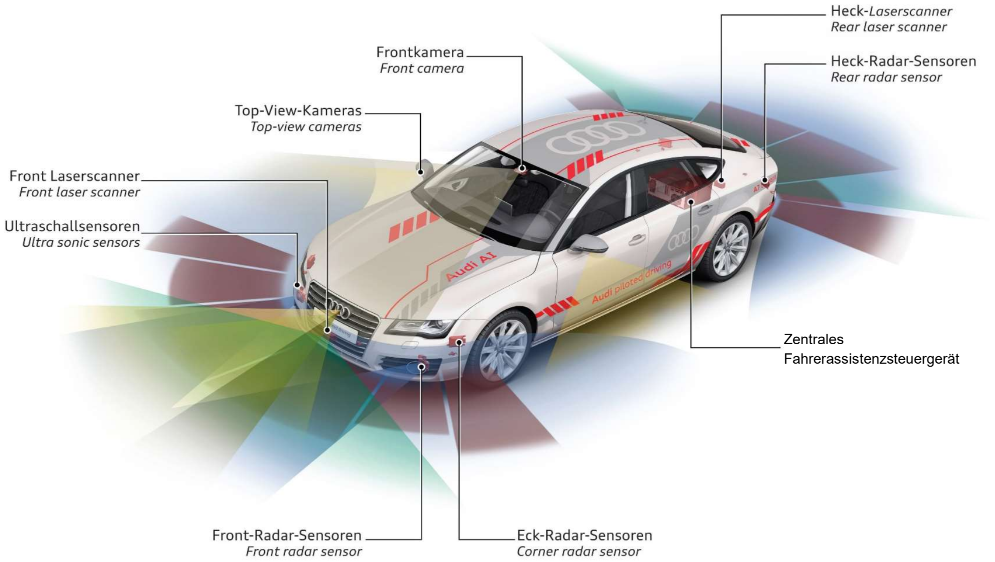
Sequential decision making

e.g. Partially observable Markovian decision processes (POMDP)



Autonomous systems:
Reliability of environment sensing

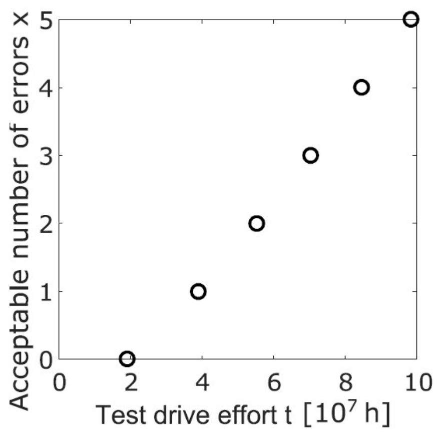
Sensor systems in autonomous cars



Adapted from: https://www.audi-mediacenter.com/de/fotos/album/audi-a7-piloted-driving-concept-646 (28.09.2016)

Reliability of environment sensing

- Existing standards (e.g. ISO 26262) not directly applicable
- Reliability of sensors is highly dependent on environment
- Model-based approaches require long development times
- Classical testing requires reference truth
- High reliability requirements necessitate large test efforts



Berk M. et al. (2017). *WCX17: SAE World Congress, Detroit.*

Assess sensor reliability in service
(shadow mode)

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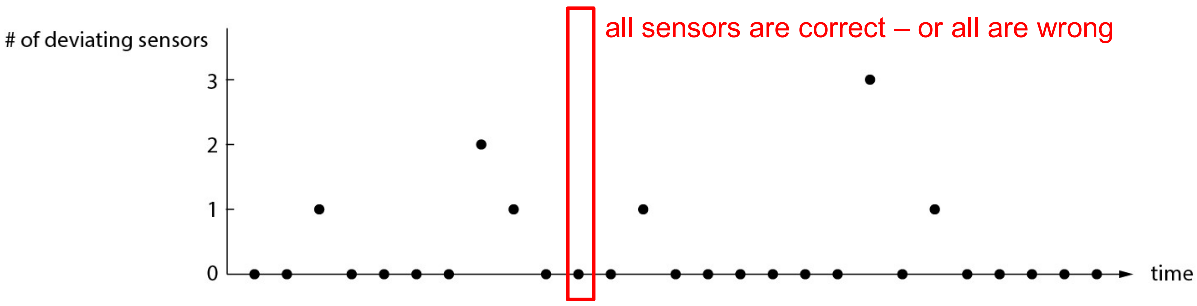
Assess sensor reliability in service
(shadow mode)

Challenge: No reference truth is available

7 sensors installed on a vehicle:



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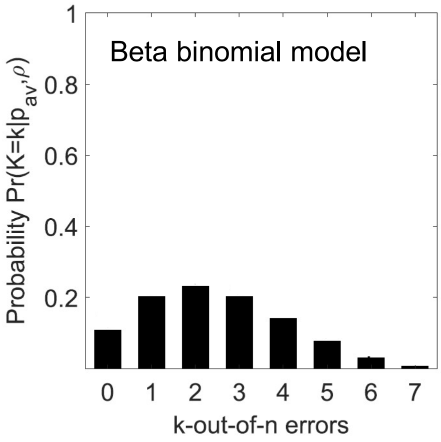
Assessing sensor reliability without ground truth

Incomplete knowledge can be represented by a likelihood function



Assessing sensor reliability without ground truth

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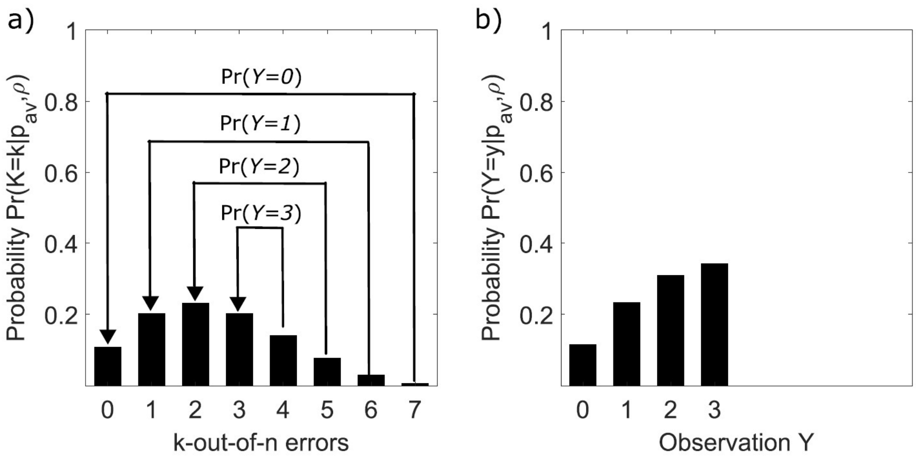
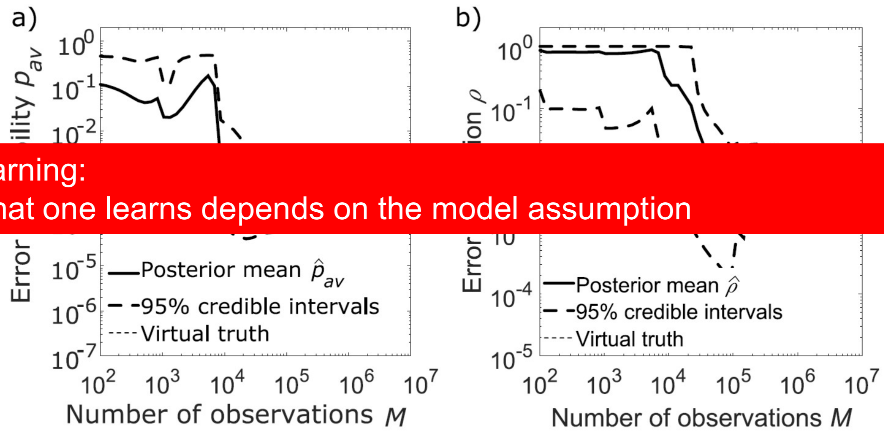


Assessing sensor reliability without ground truth

Model parameters can be learned with partial information



Warning:
What one learns depends on the model assumption

Berk M. et al.
(in preparation)

Structural health monitoring:
Smart integrity management

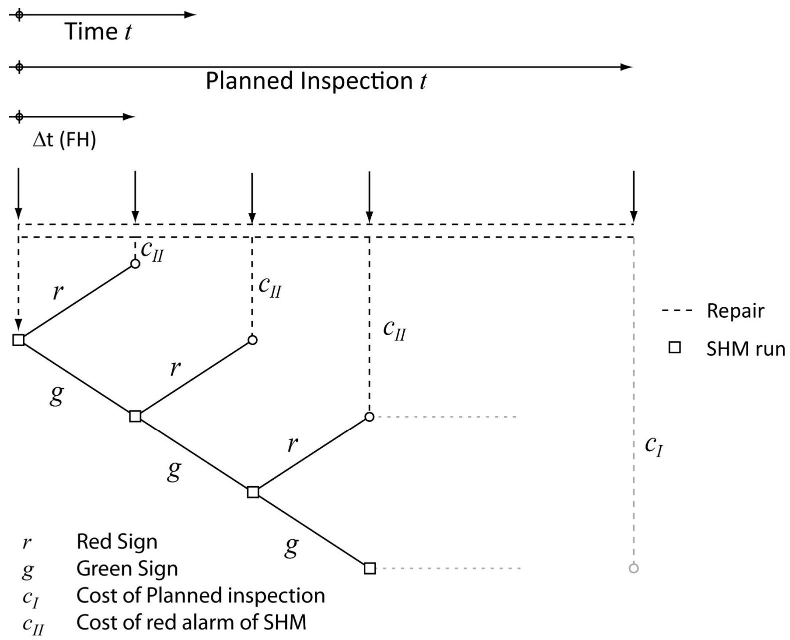
What is the reliability gain achieved by the health monitoring system?

[Question asked by an aircraft manufacturer]

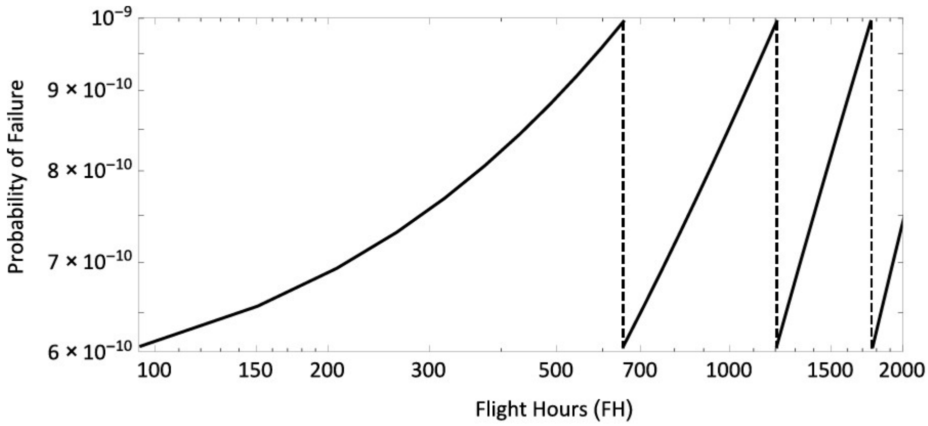
Model of aircraft operation

Monitoring data is used to updated reliability

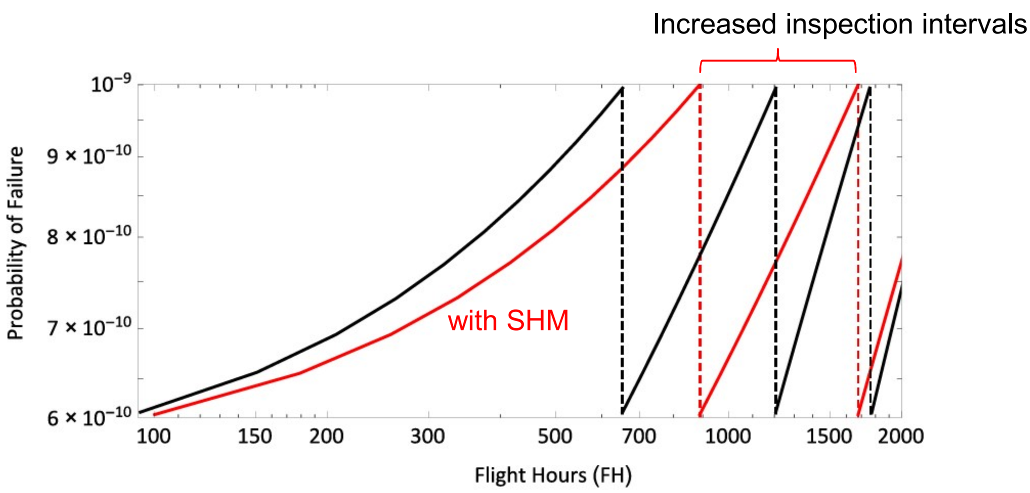
Whenever reliability threshold is exceeded, an inspection is required



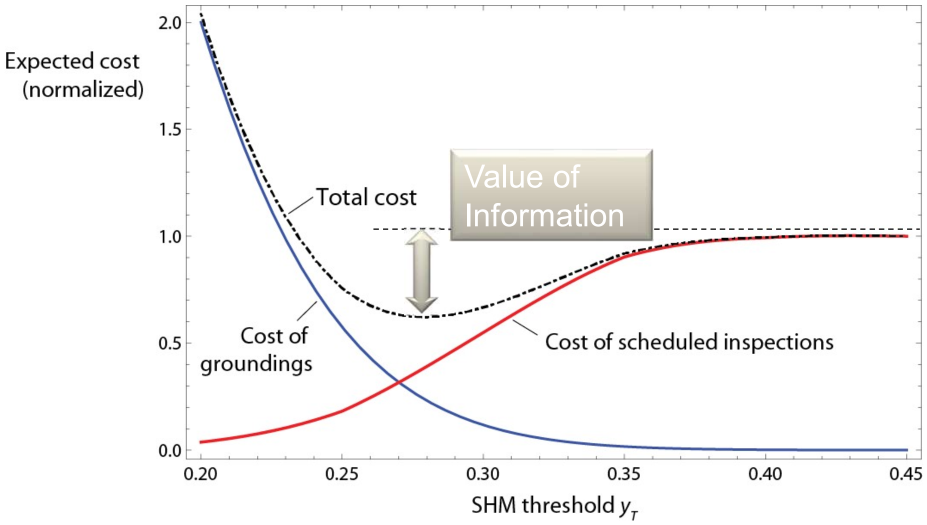
Reliability without monitoring information



Reliability with monitoring information



Optimal calibration of monitoring-based decisions



Cottone G., Gollwitzer S., Heckenberger U., Straub D. (2013). *Proc. IWSHM 9*, Stanford University.

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SHM is frequently applied in infrastructure systems

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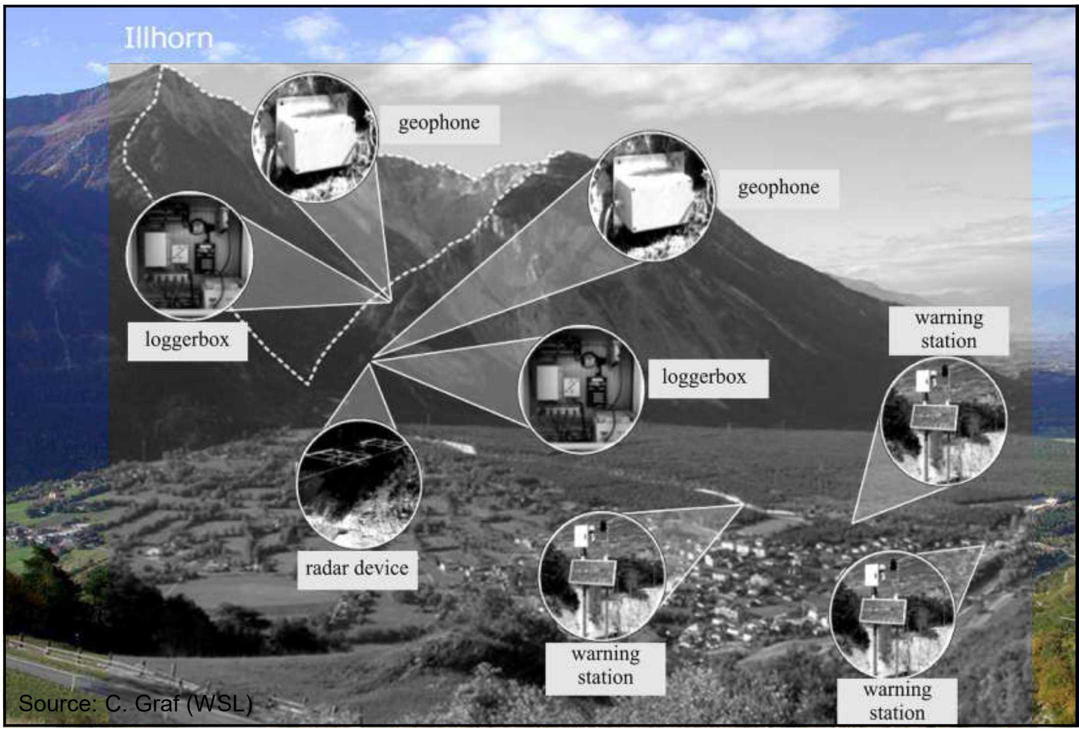
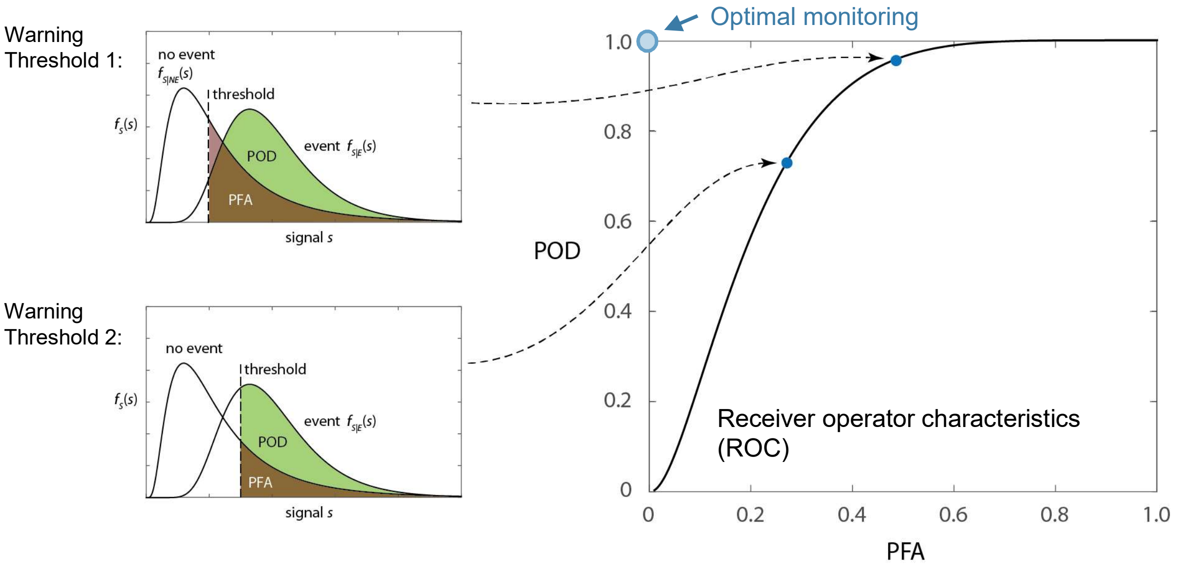
Monitoring and sensors for risk control: Reliability of warning systems

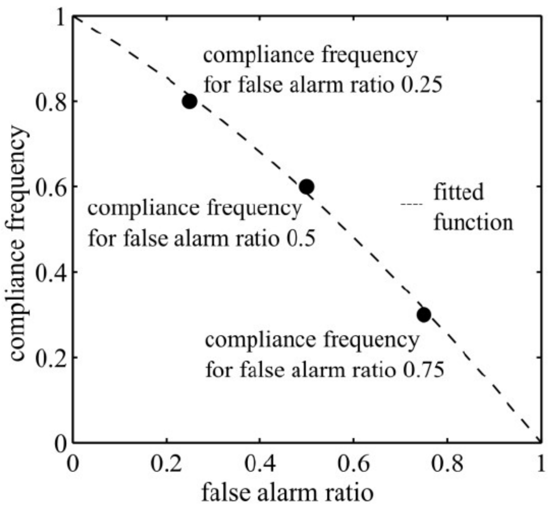


Sättele M., Bründl M. Straub D. (2015) *RESS*, **142**:192-202

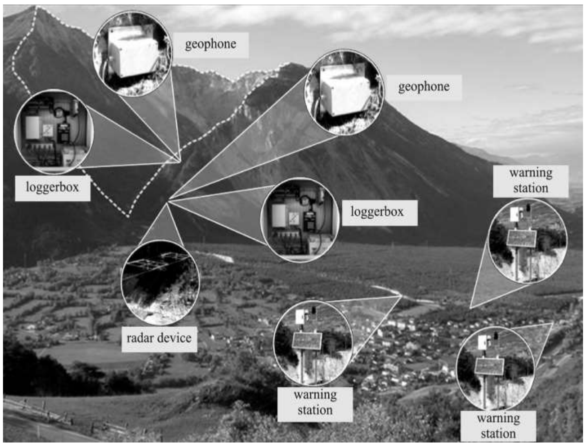
Warning and alarm systems: POD vs PFA

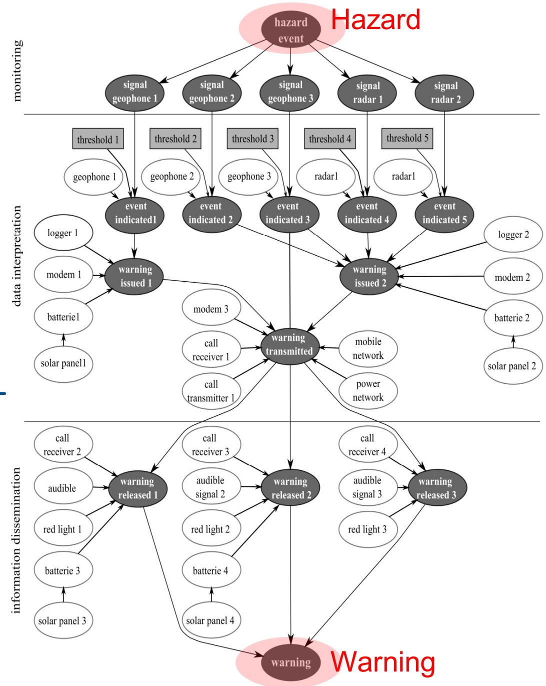


Smart users: The cry wolf effect

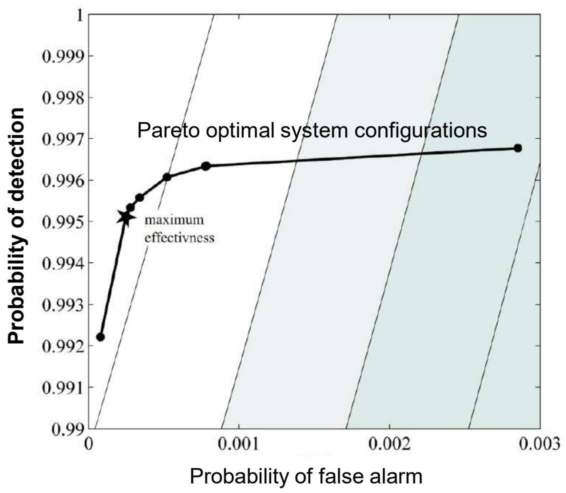


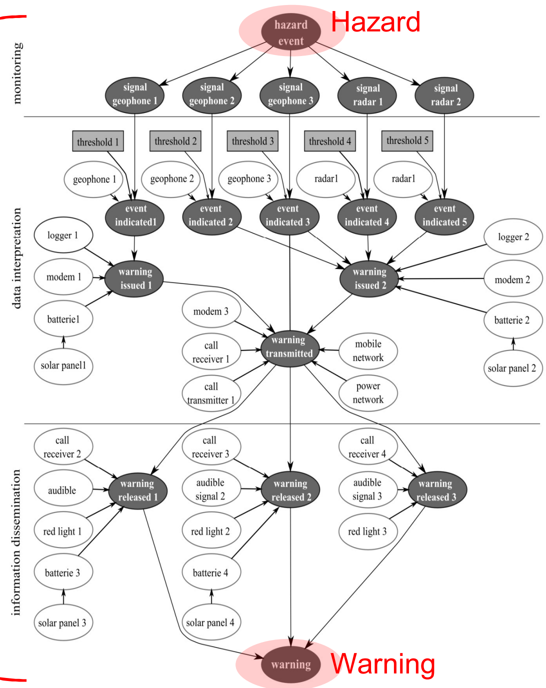
Bayesian network model of the warning system





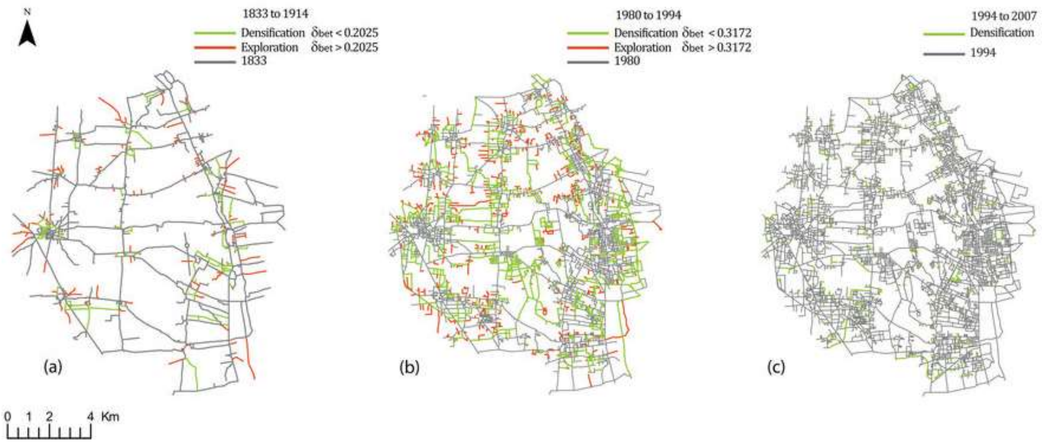
Optimization of sensor interpretation through influence diagram





Smart society:
Planning in flexible infrastructure systems
under large scale uncertainties

Infrastructure planning and management is a sequential decision process

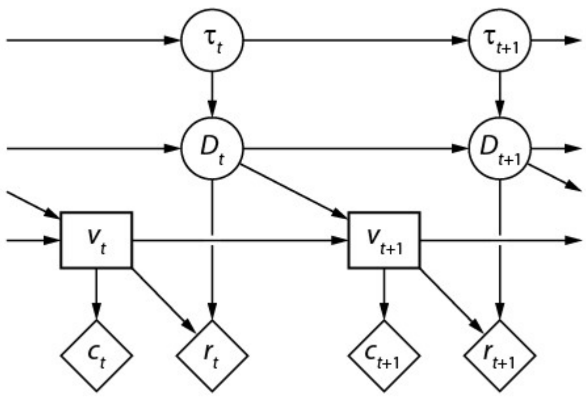


Source: Strano, E., V. Nicosia, V. Latora, S. Porta and M. Barthélemy (2012). Elementary processes governing the evolution of road networks. *Nature Scientific Reports* **2**: 296.

Infrastructure planning and management is a sequential decision process

Smart managment considers future information and potential for adaptation in current decisions about infrastructure investments

POMDP models allow investigating this effect

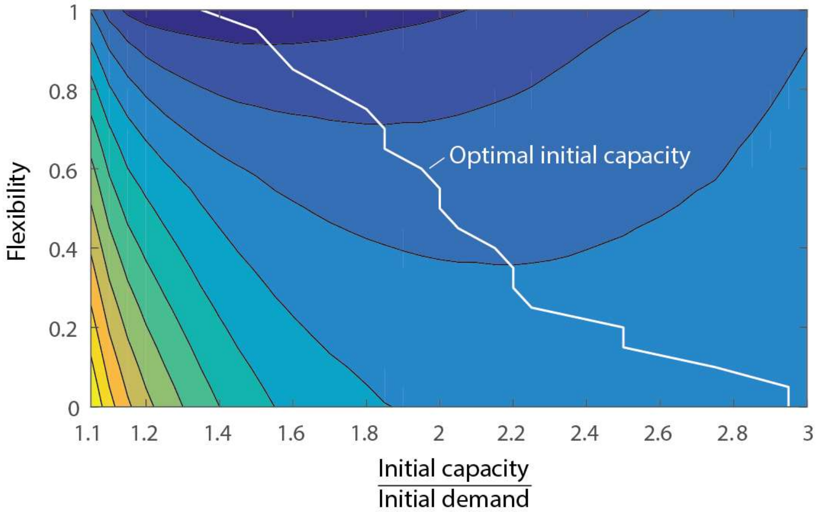


Špačková O., Straub D. (2017). *Sustainable and Resilient Infrastructure*, **2**(1): 37-58.

Decisions on current capacity should consider future ability for adaptation

Infrastructure planning example

Optimal initial overdesign in function of system flexibility



Straub and Špačková (2016).

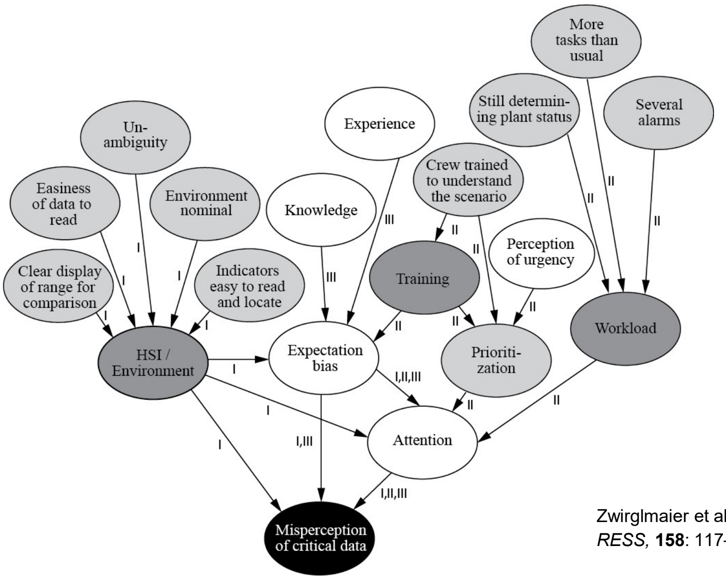
Reliability of smart systems: Challenges & opportunities

Up to what degree can smart systems be modelled explicitly?

Consider human reliability:

Smart systems based on AI may become equally complex

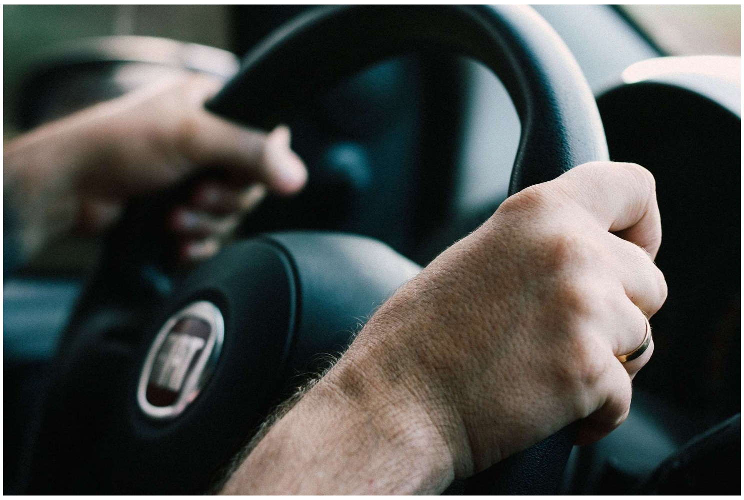
The performance can be strongly dependent on environment & situation



Zwirglmaier et al. (2017). *RESS*, **158**: 117–129.

Need for explicit and quantitative demonstration of reliability of complex processes currently carried out by engineers or users

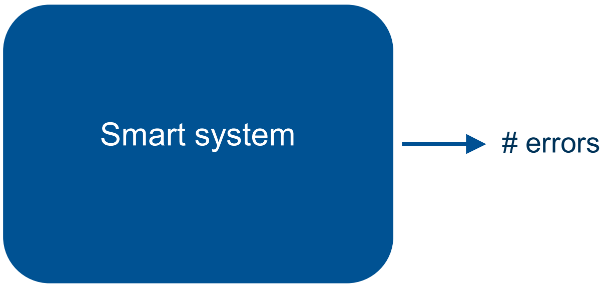
… and with much higher reliability



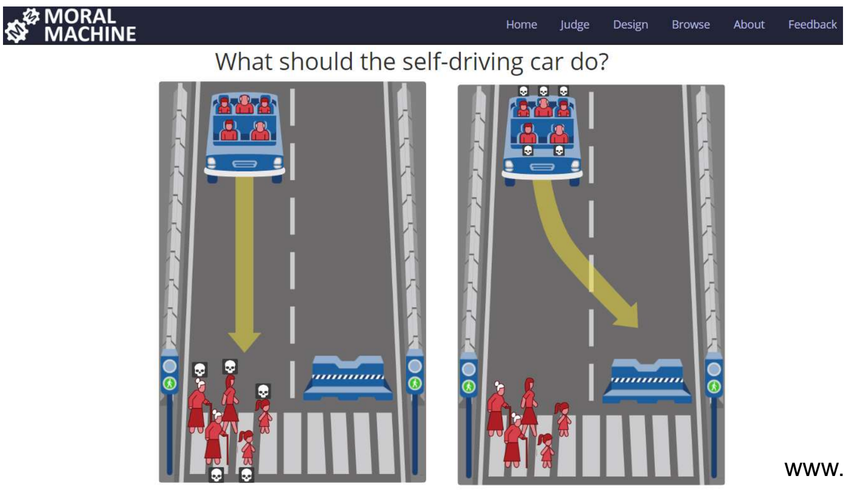
Blackbox approach

Opportunities:
- Shadow mode
- Virtual testing and verification

Challenges:
- High reliabilty levels
- Data protection



Implicit choices have to be made explicit

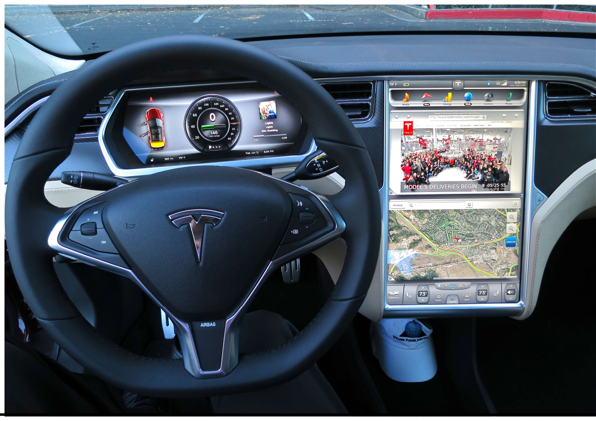


www.moralmachine.mit.edu

Smart systems allow for adaptation

Decision rules can be changed much easier than hardware updates

Reliability can be increased over the life-time of a system



Selected references

Luque J., Straub D.: Risk-based optimization of inspection strategies in structural systems. *Structural Safety*, under review.

Berk M., Kroll H.-M., Schubert O., Buschardt B., Straub D.: Bayesian self-referencing reliability assessment of sensor systems: Theory and application to automotive environment sensing. *In preparation*.

Špačková O., Straub D. (2017). Long-term adaptation decisions via fully and partially observable Markov decision processes. *Sustainable and Resilient Infrastructure*, **2**(1): 37-58.

Zwirglmaier K., Straub D., Groth K. (2017). Capturing cognitive causal paths in human reliability analysis with Bayesian network models. *Reliability Engineering & System Safety*, **158**: 117–129.

Straub D., Špačková O. (2016). Optimizing adaptable systems for future uncertainty. Keynote*, 14th Probabilistic Workshop*, Ghent.

Straub D., Papaioannou I., Betz W. (2016): Bayesian analysis of rare events. *Journal of Computational Physics*, **314**: 538–556.

Sättele M., Bründl M., Straub D. (2015). Reliability and Effectiveness of Warning Systems for Natural Hazards: Concepts and Application to Debris Flow Warning. *Reliability Engineering & System Safety*, **142**: 192-202

Straub D., Papaioannou I. (2015). Bayesian Updating with Structural Reliability Methods. *Journal of Engineering Mechanics, Trans. ASCE*, **141**(3), 04014134.

Straub D. (2014). Value of information analysis with structural reliability methods. *Structural Safety*, **49**: 75-86.

Cottone G., Gollwitzer S., Heckenberger U., Straub D. (2013). Reliability-Oriented Optimization of Replacement Strategies for Monitored Composite Panels in Aircraft Structures. *Proc. 9th International Workshop on Structural Health Monitoring IWSHM*, Stanford University.

Straub D. (2009). Stochastic modeling of deterioration processes through dynamic Bayesian networks. *Journal of Engineering Mechanics*, Trans. ASCE, **135**(10), pp. 1089-1099.

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