Strengthening the Rail Mode of Transport by Condition Based Preventive Maintenance

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Research Programs of DLR

- Aeronautics
- Space
- Energy
- Security
- Transport


Figure : Next Generation Train®, DLR

Institute of Transportation Systems

Residence:	Braunschweig, Berlin
Since:	2001
Director:	Prof. Dr.-Ing. Karsten Lemmer
Employees:	About 150 employees from various scientific disciplines
Fields of Research:	Automotive Railway Systems Traffic Management
Range of Tasks:	Basic research Creating concepts and strategies Prototype development
Quality:	DIN EN ISO 9001 VDA 6.2 ISO 17025 (RailSiTe®)

Institute of Transportation Systems

1. Condition Based Preventive Maintenance

2. Localization

3. Prognostics

Motivation

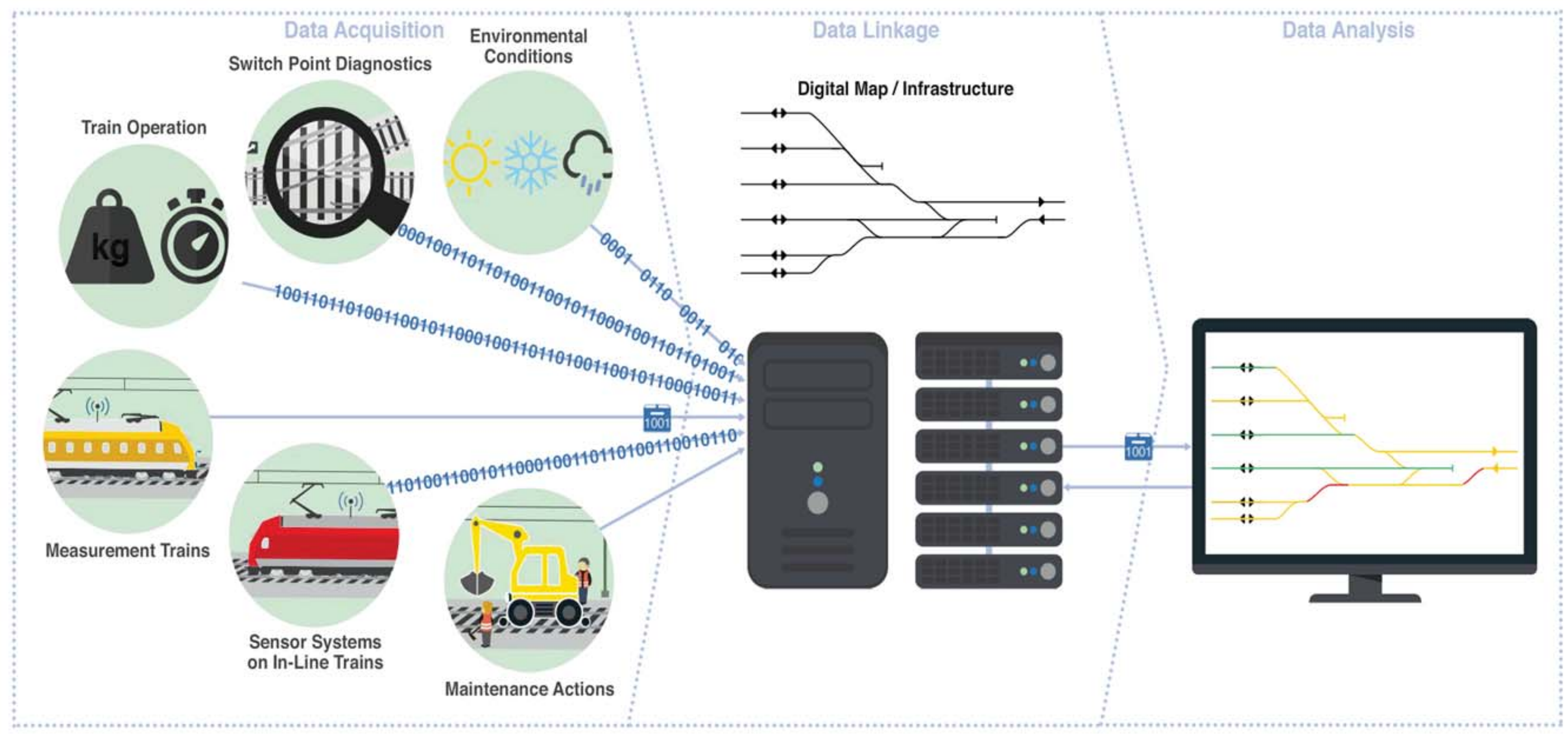
- **conflicting demands:** profitability, availability, safety, and punctuality
- **potential solution:** optimized scheduling of maintenance actions taking account of the actual infrastructure condition and its expected degradation
- **critical railroad infrastructure:** railway track (misaligned track sections + railsurface failures)

(a) Misalignment

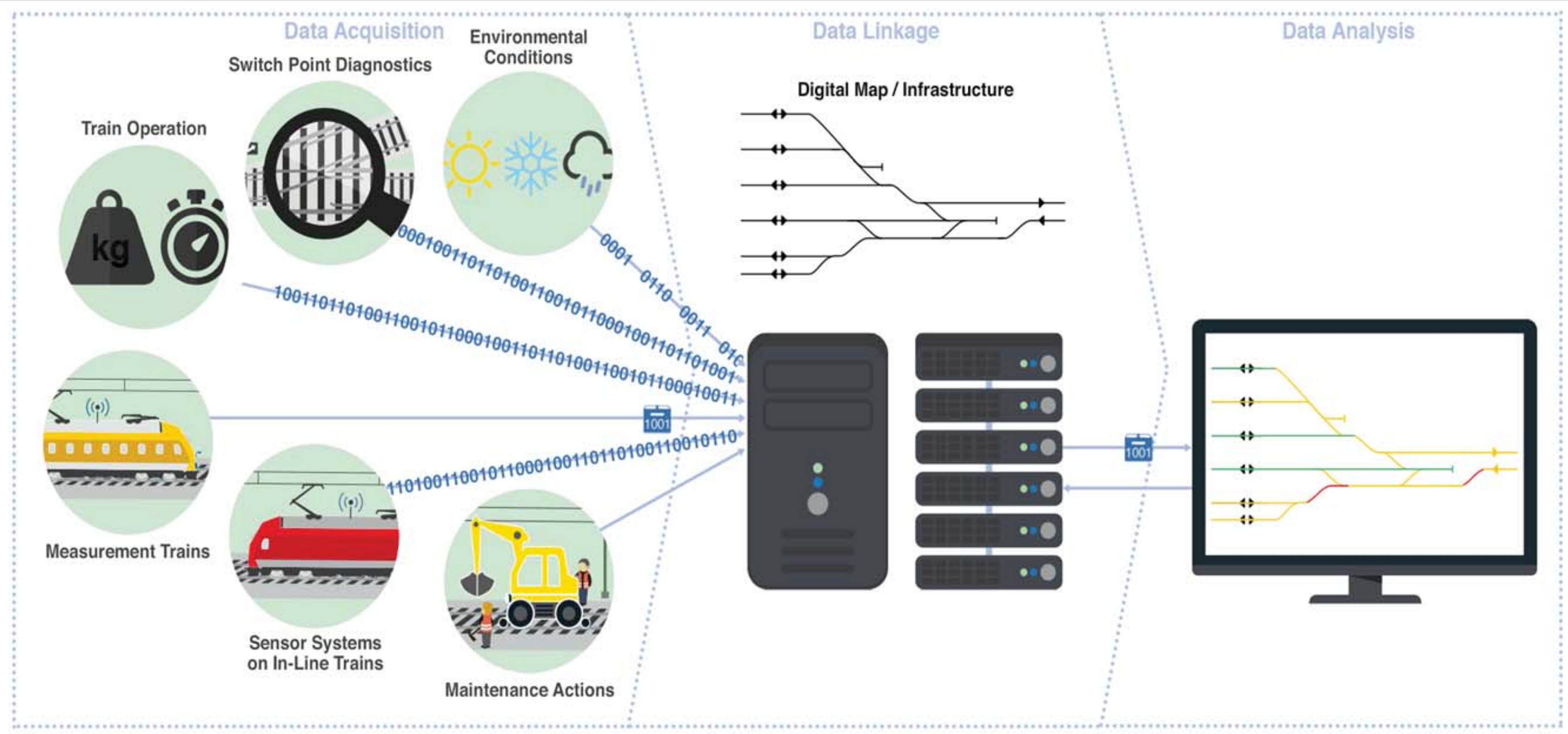
(b) Squat

(c) Corrugation

Preventive Maintenance Framework



Preventive Maintenance Framework



In-Line trains equipped with **low-cost sensor systems** are a key element for a **continuous** condition monitoring.

In-Line Trains == Moving Sensor Systems

- rail irregularities ⇒ vehicle response/vibration
- autonomous train-born measurement systems including...
- inertial measurement unit (IMU), acceleration sensors, microphone ... and other low-cost sensors

(d) RailDriVE®

(e) Data Logger

(f) Acceleration Sensor

LOCALIZATION

Track Selective: Location/Position of the train on the correct track

State-of-the-Art (Measurement Trains)

- localization based on the train's odometer
- uncertainty up to dozens of meters
- ⇒ **NO** automated and precise (below 10m) georeferencing

(railway network == large area with insufficient GNSS reception)

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Multi-Sensor Concept (In-Line Trains)

- GNSS (Global Navigation Satellite System) receiver
- odometer + speed sensor (Doppler radar)
- balise-antenna
- digital map of the railroad network
- ⇒ **track selective accuracy**

σ-Accuracies of Different Sensors

GNSS RTK	0.02 - 0.20 m (depending on baseline)
Balise	0.20 m
Odometer	0.4 % (of covered distance)
Speed	0.8 % (of covered distance)

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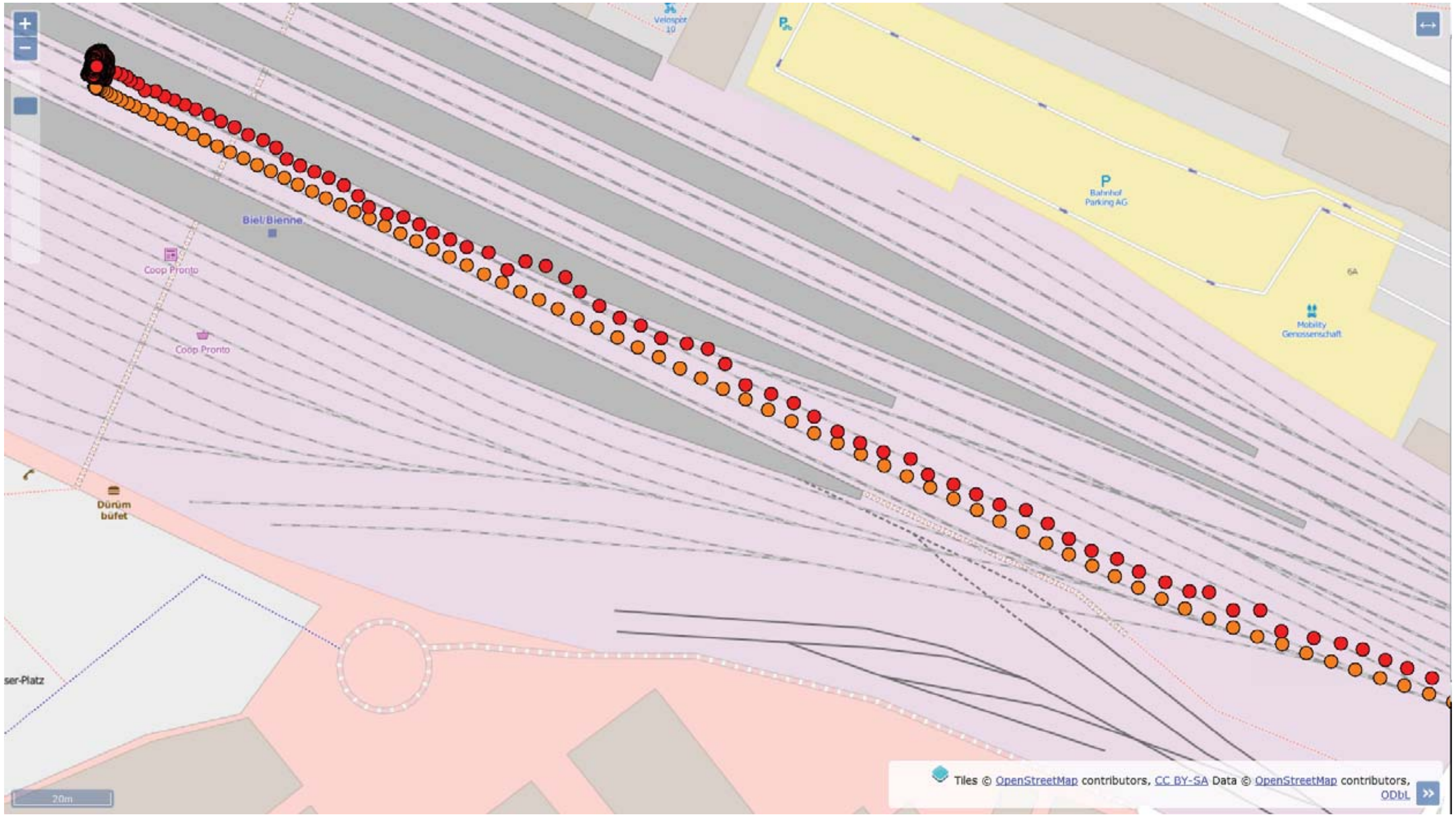
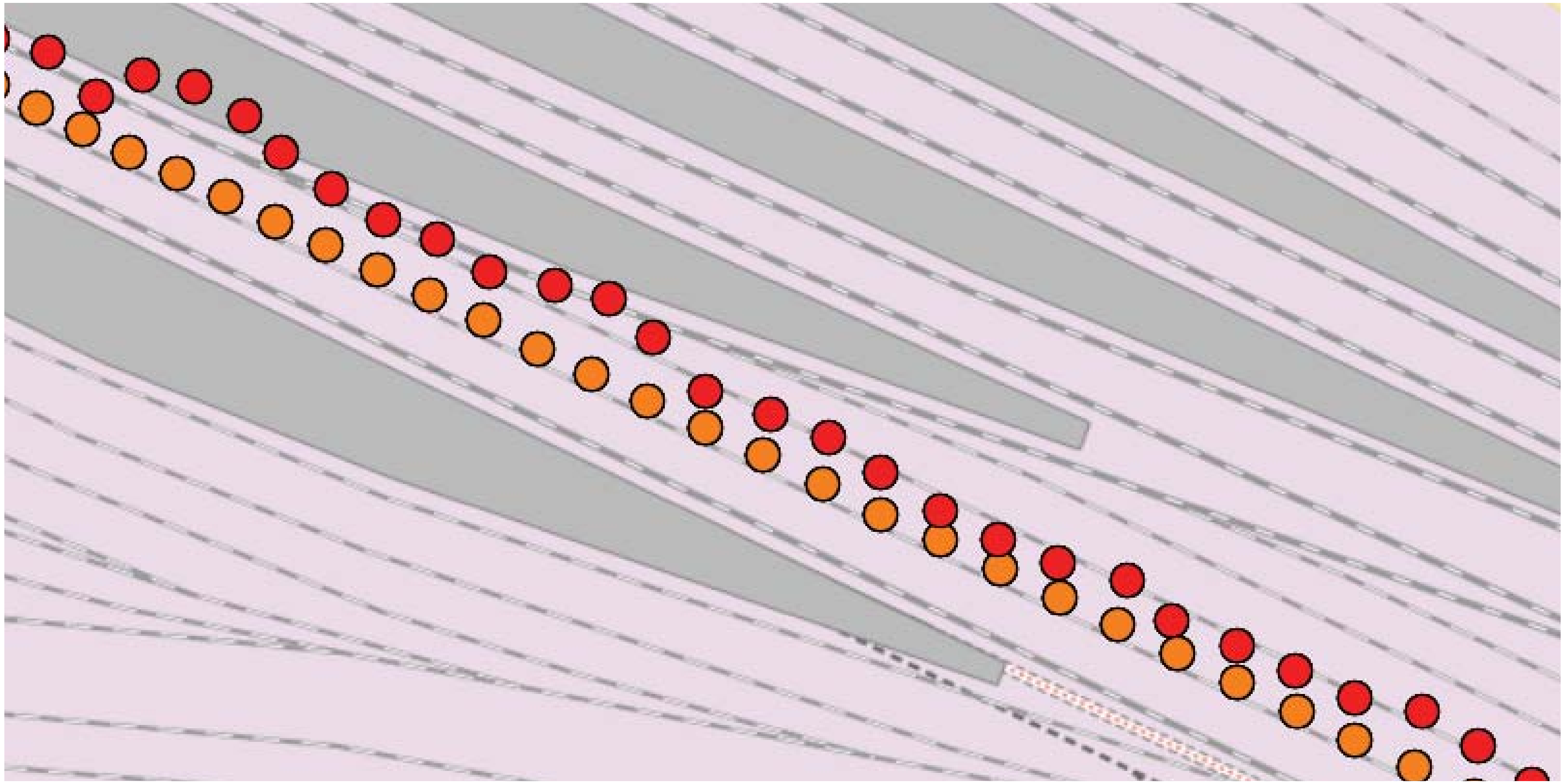
⇒ Data Fusion via **Extended Kalman Filter** for Localization

GNSS (red dots) vs. Multi-Sensor concept (orange dots)

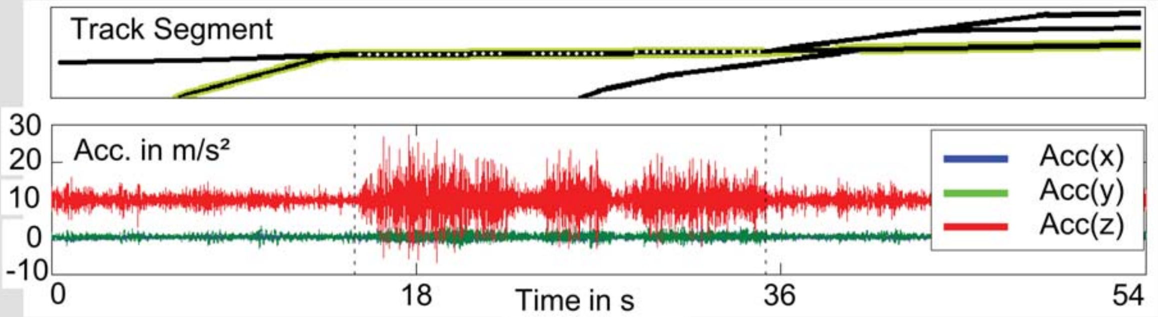


GNSS (red dots) vs. Multi-Sensor concept (orange dots)



Failure (Corrugation)

Localization



Failure (Squat)

Localization

Railway Network

(a) Misalignment

(b) Squat

(c) Corrugation

$\Downarrow$

In-Line Trains + Low-Cost Sensors + Localization

$\Downarrow$

Key Performance Indicators (**KPIs**) of Monitored Track Segments

Railway Network

(a) Misalignment

(b) Squat

(c) Corrugation

$\Downarrow$

In-Line Trains + Low-Cost Sensors + Localization

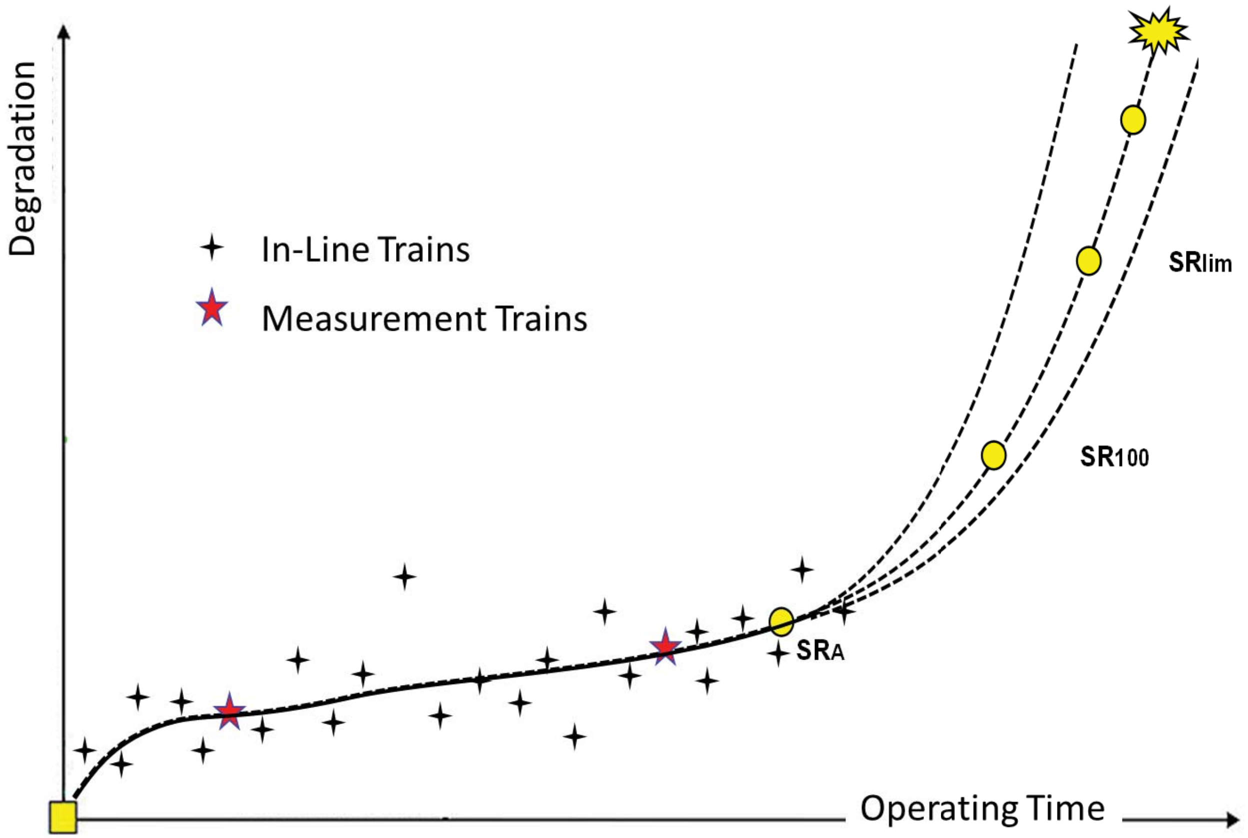
$\Downarrow$

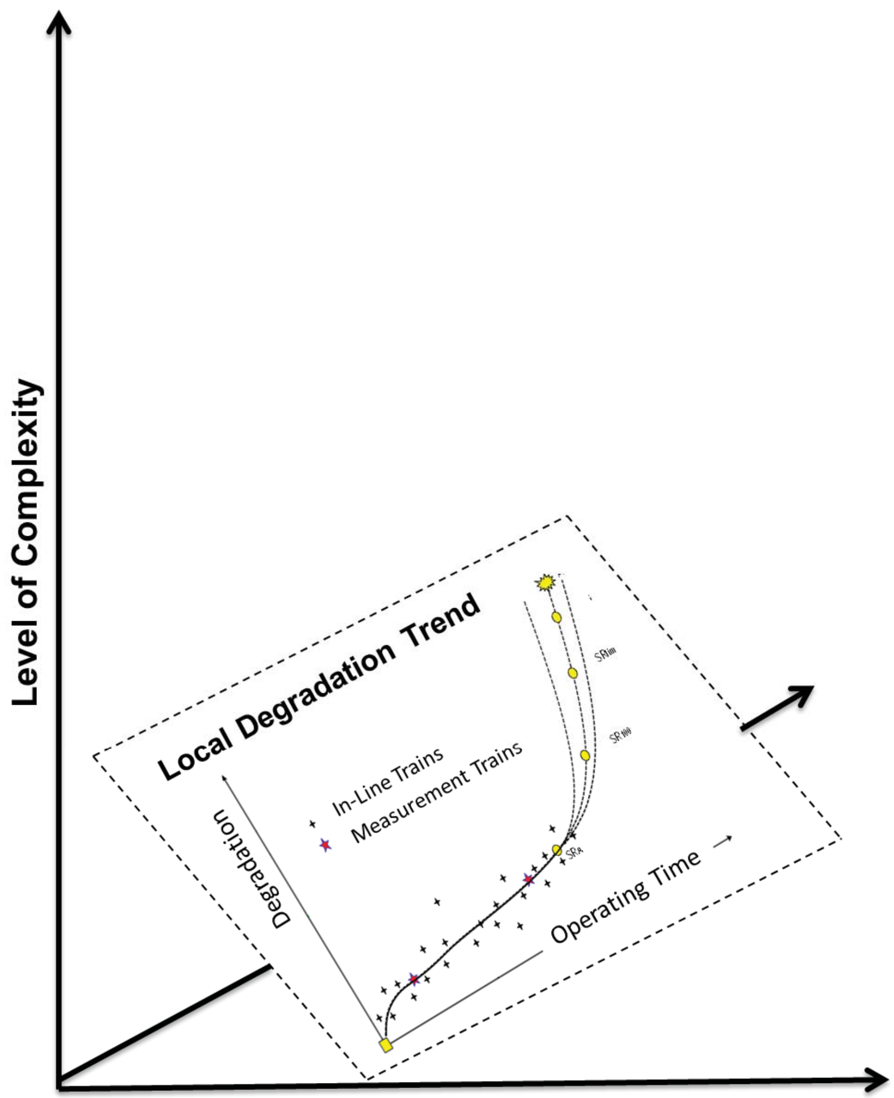
Key Performance Indicators (**KPIs**) of Monitored Track Segments

$\Downarrow$

Expected Future Degradation? $\Rightarrow$ **Prognostics**

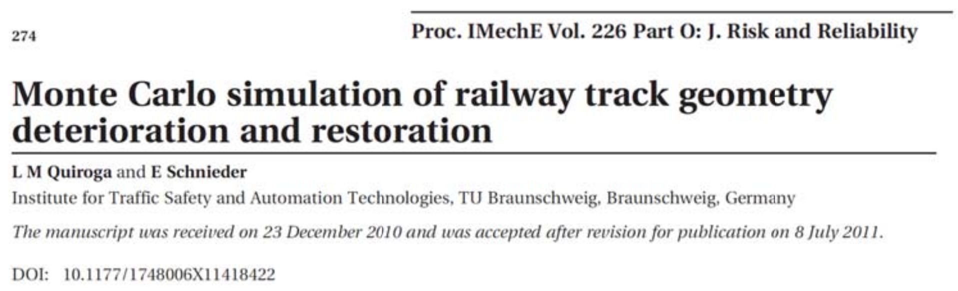
PROGNOSTICS





Local Degradation Models

- various approaches
- common: number of influencing parameters
- e.g. soil/rail quality, operating conditions, weather...
- $\Rightarrow$ $\theta \equiv$ parameter vector
- in general, θ is uncertain (random variable)


274 Proc. IMechE Vol. 226 Part O: J. Risk and Reliability

Monte Carlo simulation of railway track geometry deterioration and restoration

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The manuscript was received on 23 December 2010 and was accepted after revision for publication on 8 July 2011.

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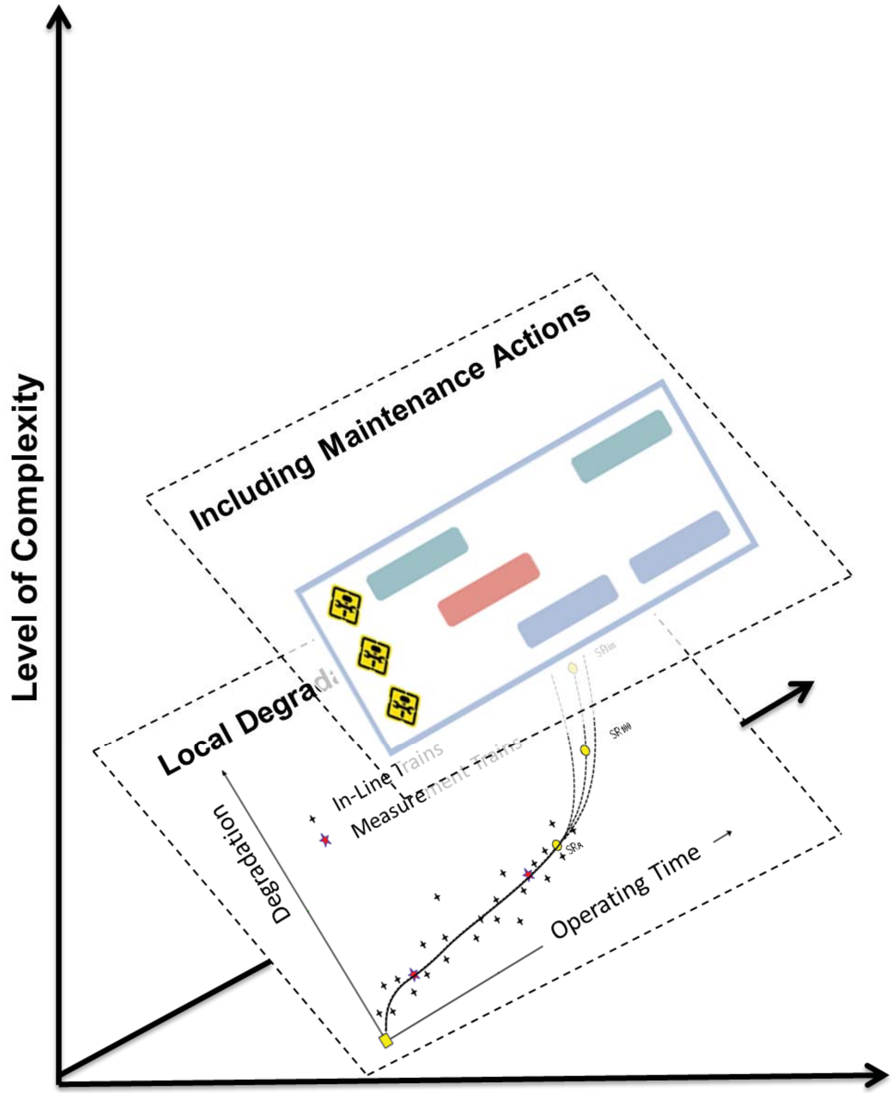
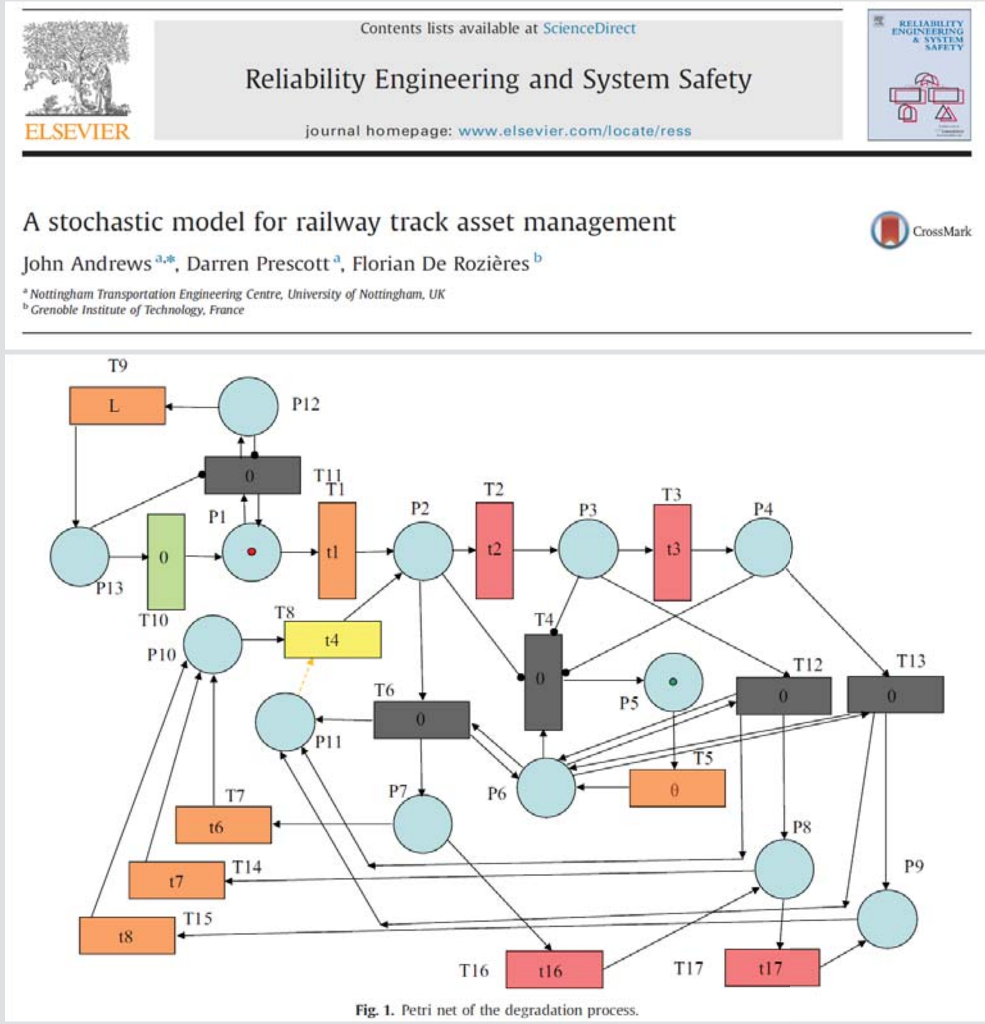
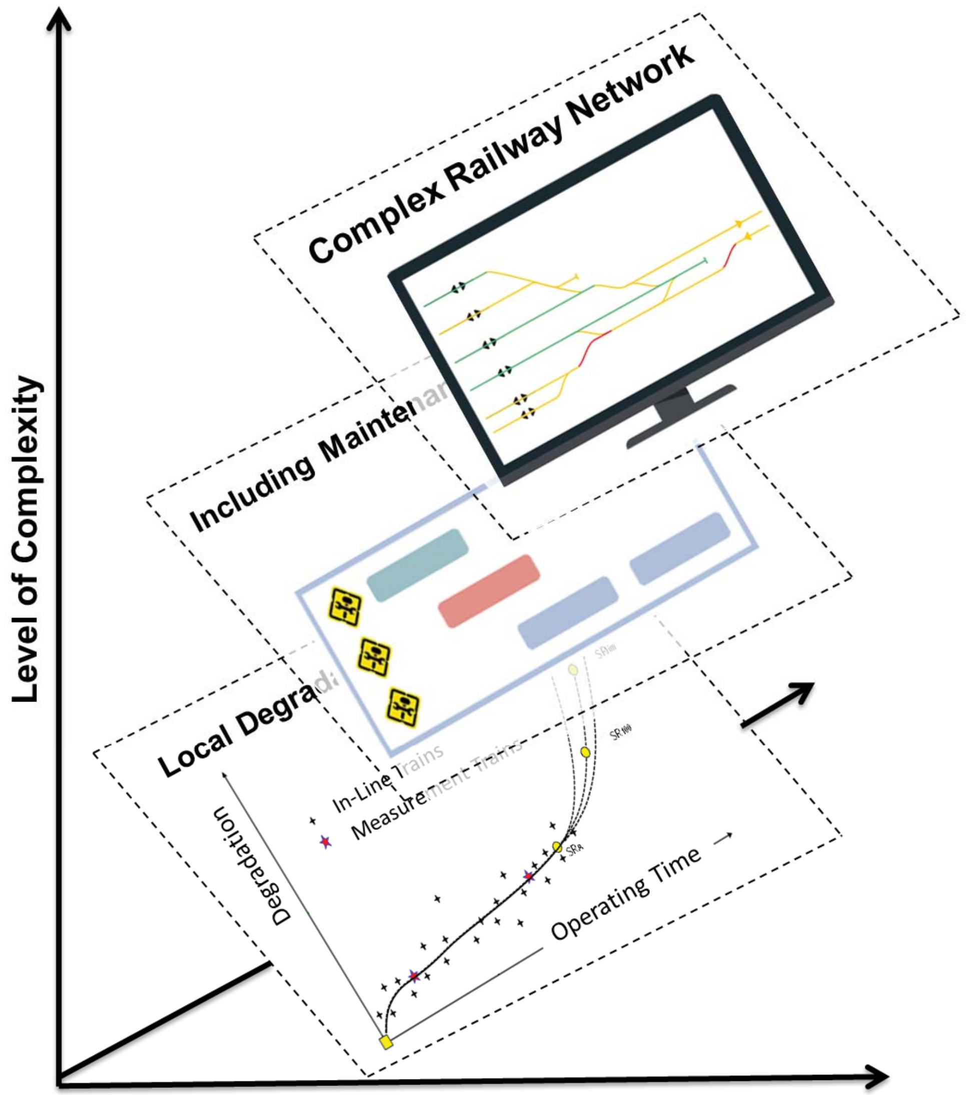


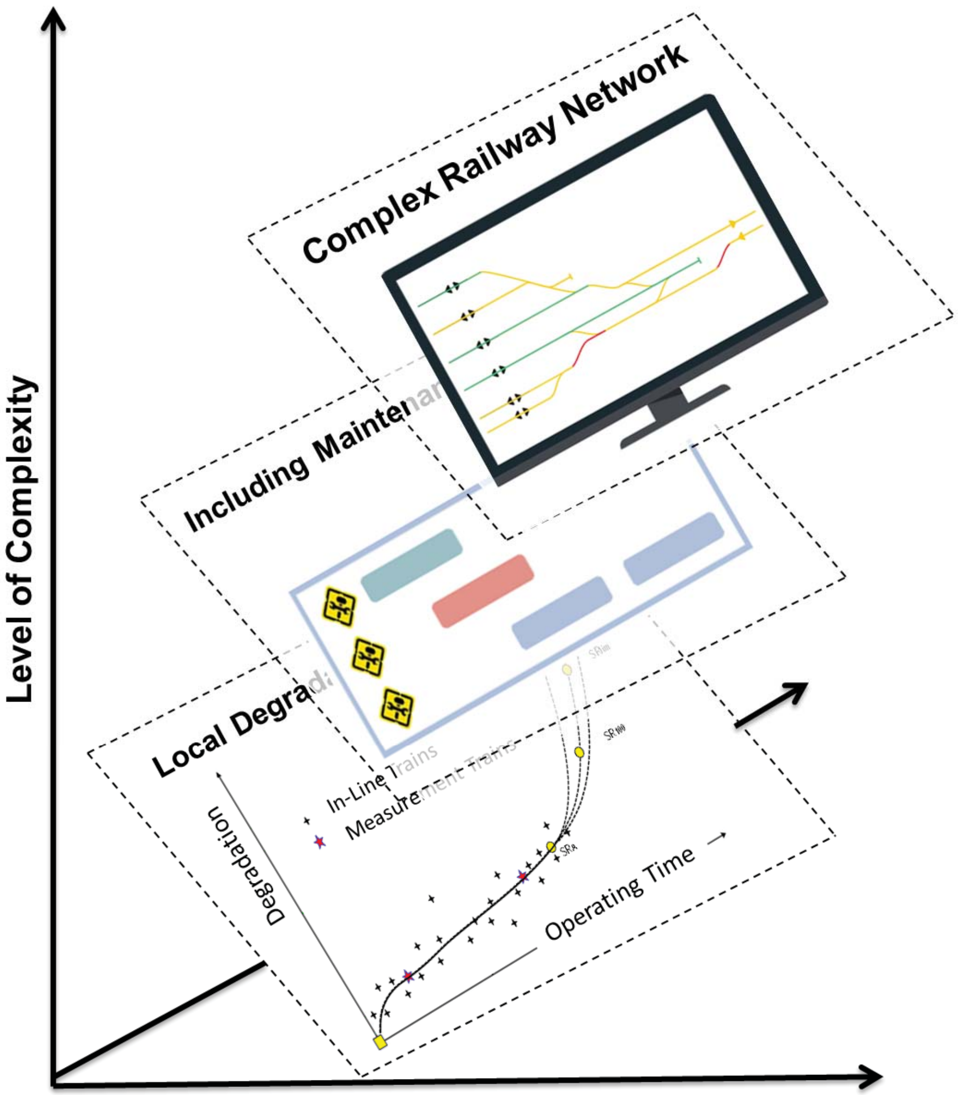
More than degradation

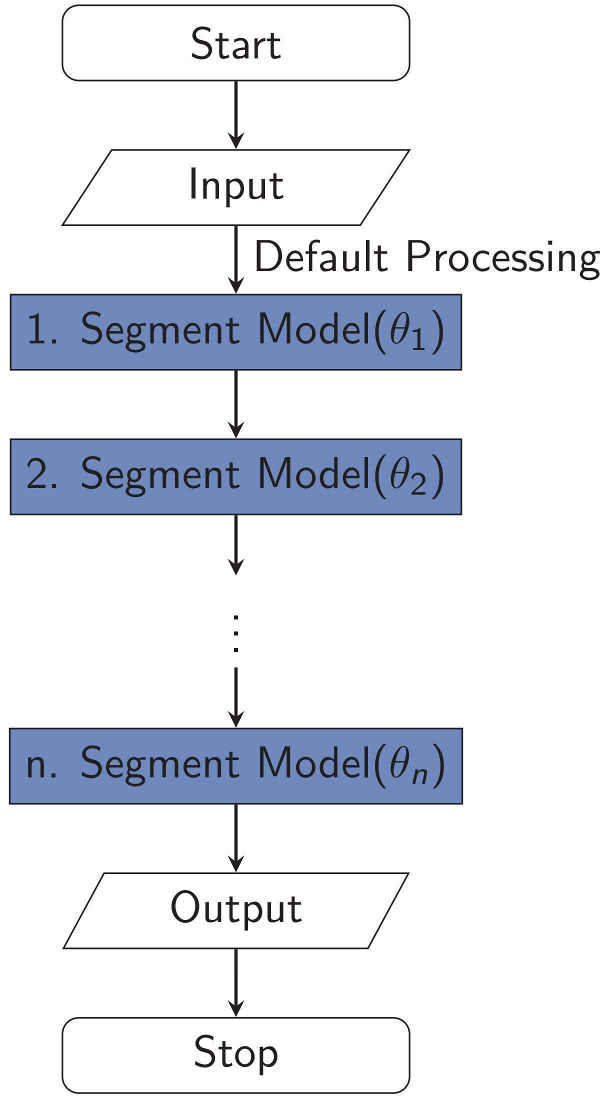


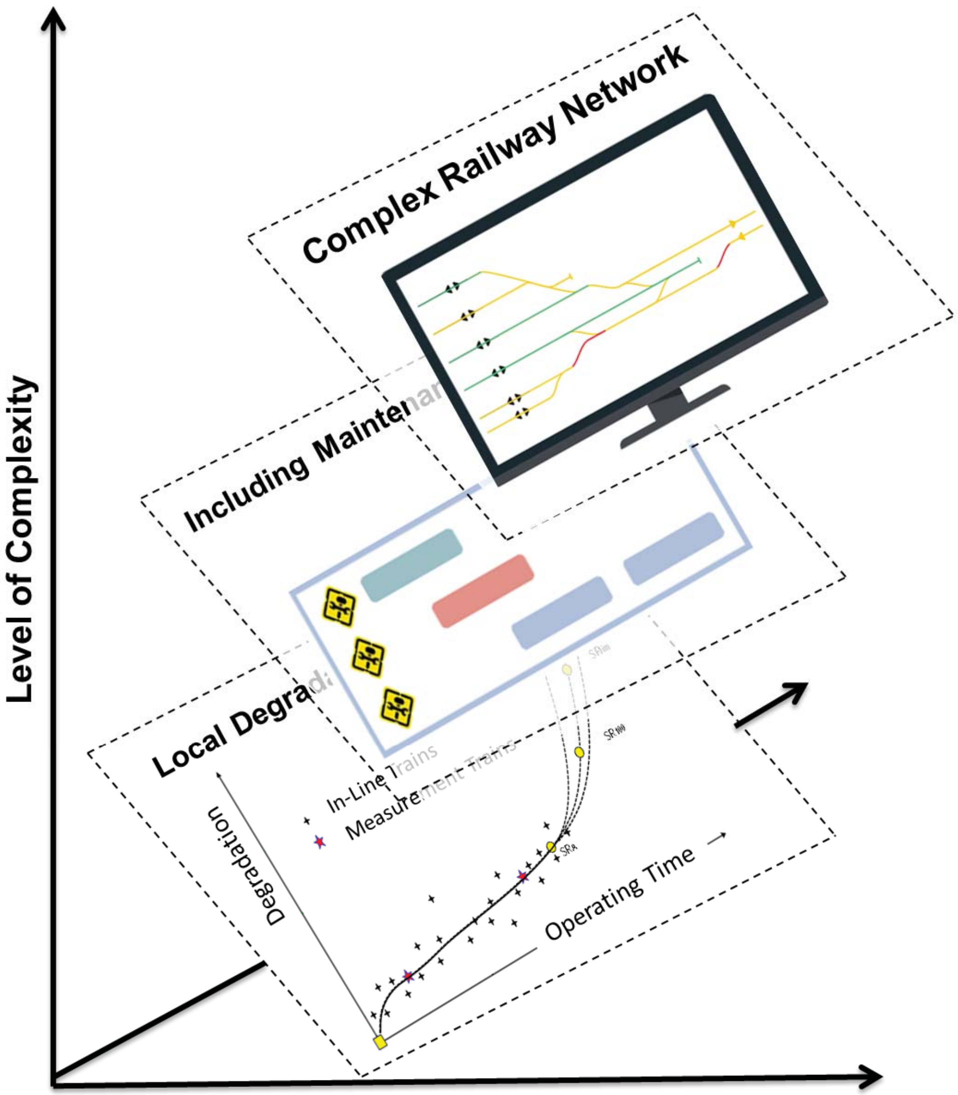


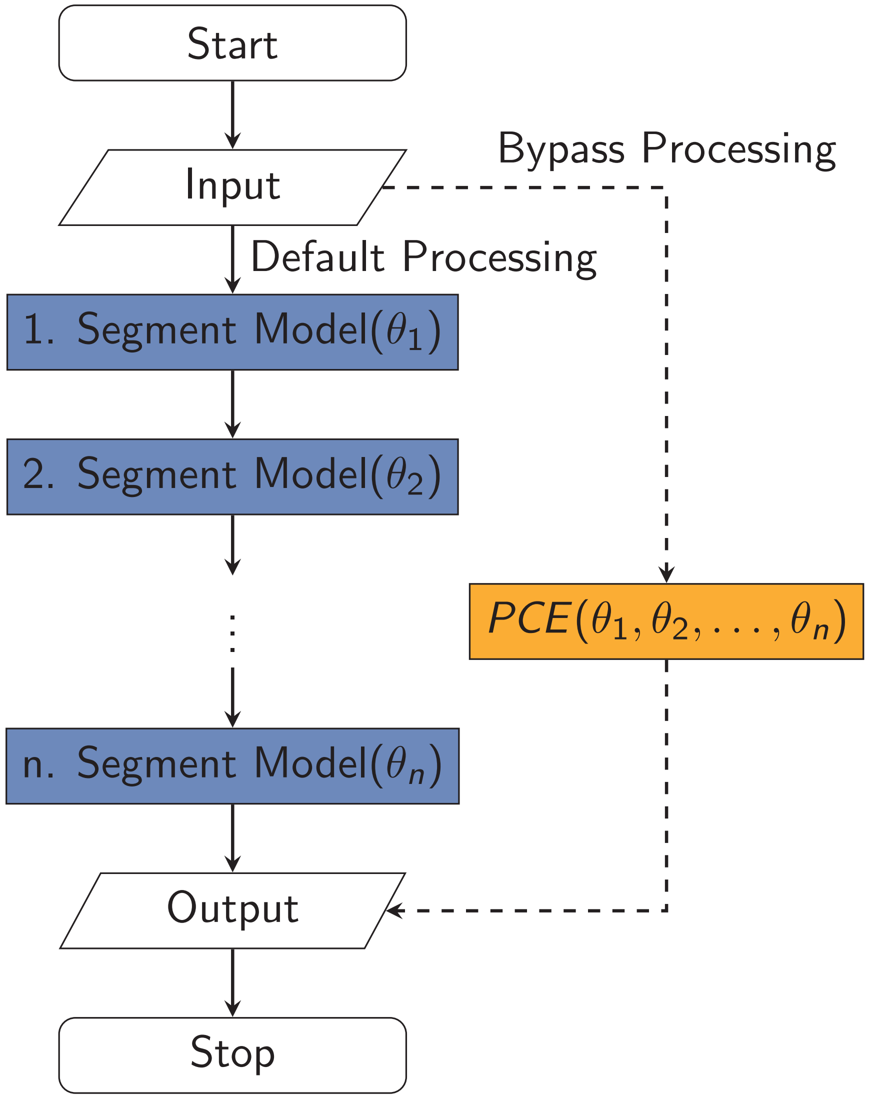
Holistic Approach

- incorporation of several track segments
- difficult to parameterize
- complex and cpu-intensive analyzes
- Polynomial Chaos Expansion (PCE) might help to decrease computational burden


Level of Complexity
Complex Railway Network
Degradation
Operating Time


Start
Input
Default Processing
1. Segment Model(θ_1)
2. Segment Model(θ_2)
⋮
n. Segment Model(θ_n)
Output
Stop


Level of Complexity
Complex Railway Network
Including Mainten
Local Degrad
In-Line Trains
Measurement Trains
Degradation
Operating Time


Start
Input
Bypass Processing
Default Processing
1. Segment Model(θ_1)
2. Segment Model(θ_2)
⋮
n. Segment Model(θ_n)
$PCE(\theta_1, \theta_2, \ldots, \theta_n)$
Output
Stop

Polynomial Chaos Expansion

- handy surrogate model, $\hat{g}(\theta)$
- needs to be parameterized

$$y = g(\theta) \approx \hat{g}(\theta) = \sum_{i=0}^{l_{pce}} a_i \Psi_i(\theta)$$

$\Psi_i(\theta)$ - proper orthogonal functions (Hermite Polynomials)

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$$y = g(\theta) \approx \hat{g}(\theta) = \sum_{i=0}^{l_{pce}} a_i \Psi_i(\theta)$$

$$a_i = \frac{\int_\Omega g(\theta)\, \Psi_i(\theta)\, pdf_\theta\, d\theta}{\int_\Omega \Psi_i(\theta)^2\, pdf_\theta\, d\theta} = \frac{\int_\Omega g'(\theta)\, pdf_\theta\, d\theta}{\int_\Omega \Psi_i(\theta)^2\, pdf_\theta\, d\theta}$$

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$$\int_\Omega g'(\theta)\, pdf_\theta\, d\theta = E[g'(\theta)] \approx \sum_{i=1}^{L} w_i g'(\Theta_i)$$

An ideal approximation method should provide:

- good approximation power
- workable computational load

$E\left[g'(\theta)\right] \approx \sum_{i=1}^{L} w_i g'(\Theta_i)$ by Numerical Integration Methods

Point Estimate Method (PEM)

- Generator Function, $GF[\cdot]$, makes the difference
- describes how sample points are directly determined in $\mathbb{R}^n$ by:
  - permutation
  - change of sign-combinations

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$$\int_{\Omega} g'(\theta) pdf_{\theta} d\theta \approx w_0 g'(GF_0) + w_1 \sum g'(GF_1) + w_2 \sum g'(GF_2)$$

Any statement about the ...

- approximation power ?
- computational load ?

DLR

$$E\left[g'(\theta)\right] \approx w_0 g'(GF_0) + w_1 \sum g'(GF_1) + w_2 \sum g'(GF_2)$$

- correct approximation for **monomials of order 5**
- PEM implies $\mathbf{2n^2+1}$ sample points ($\theta \in \mathbb{R}^n$)

- PEM provides a workable compromise on accuracy and computational load

Illustration: In-silico example

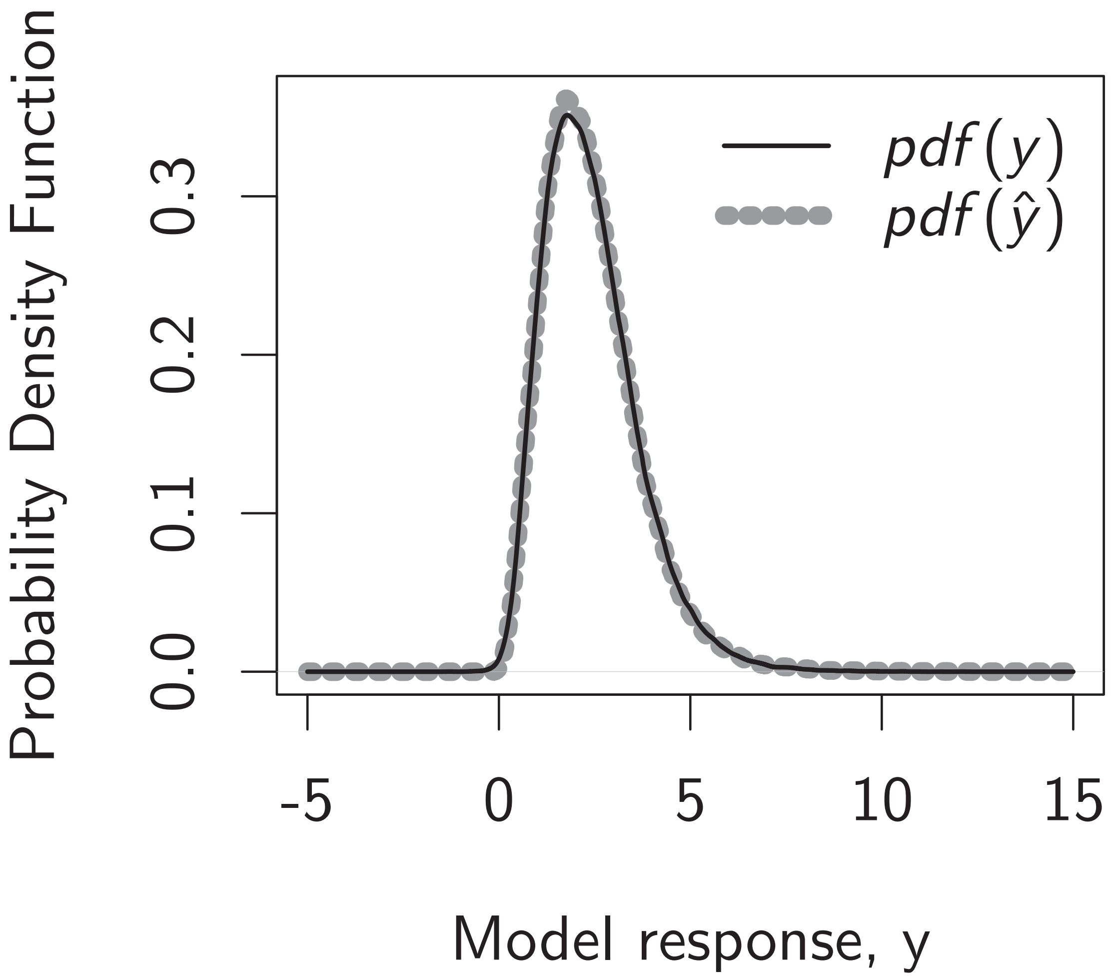
- many degradation models include exponential terms

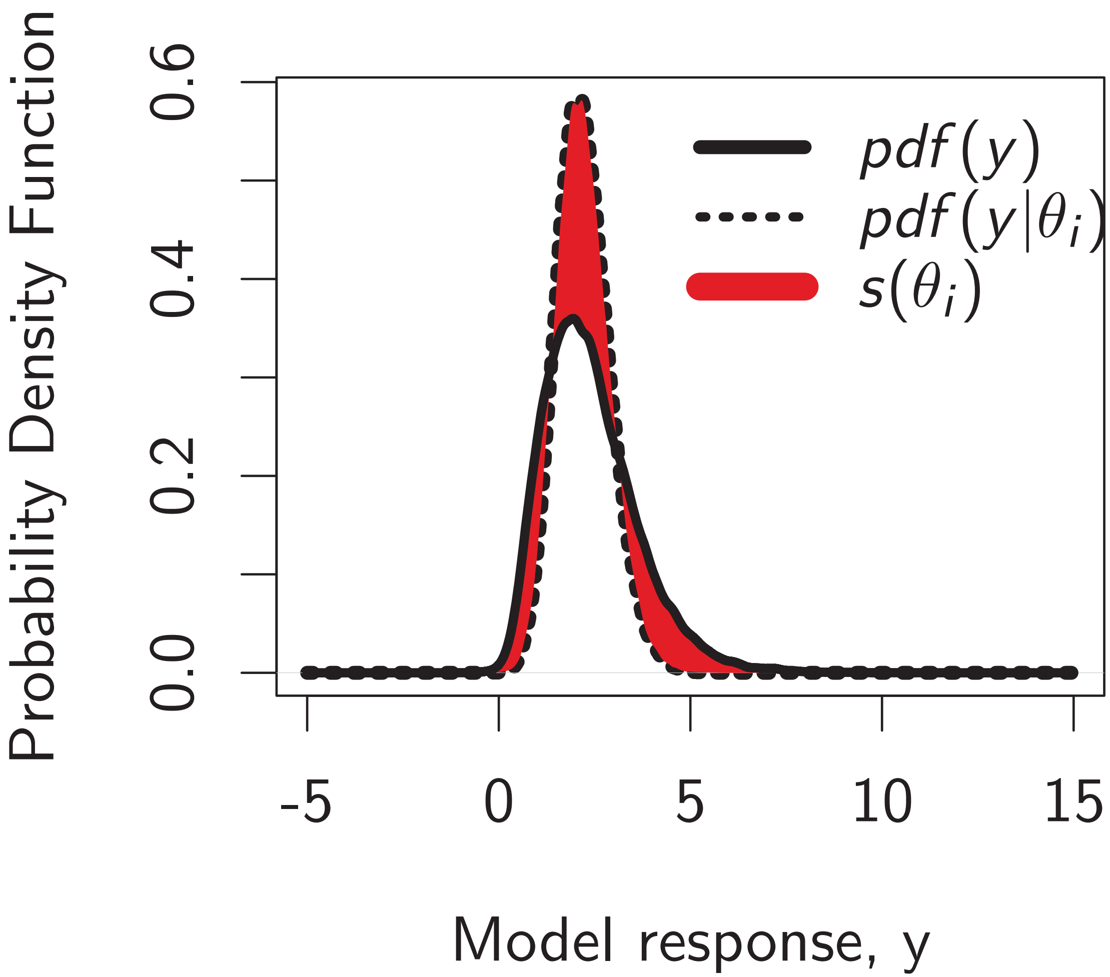
$$y = g(\theta, t) = \theta_1 e^{-\theta_2 (e^{-\theta_3 t})}$$

$$\begin{aligned} \theta_1 &\sim \mathcal{N}(5, 1) \\ \theta_2 &\sim \mathcal{N}(2, 1) \\ \theta_3 &\sim \mathcal{N}(3, 1) \end{aligned}$$

DLR

$$y = g(\theta, t) = \theta_1 e^{-\theta_2 (e^{-\theta_3 t})}$$

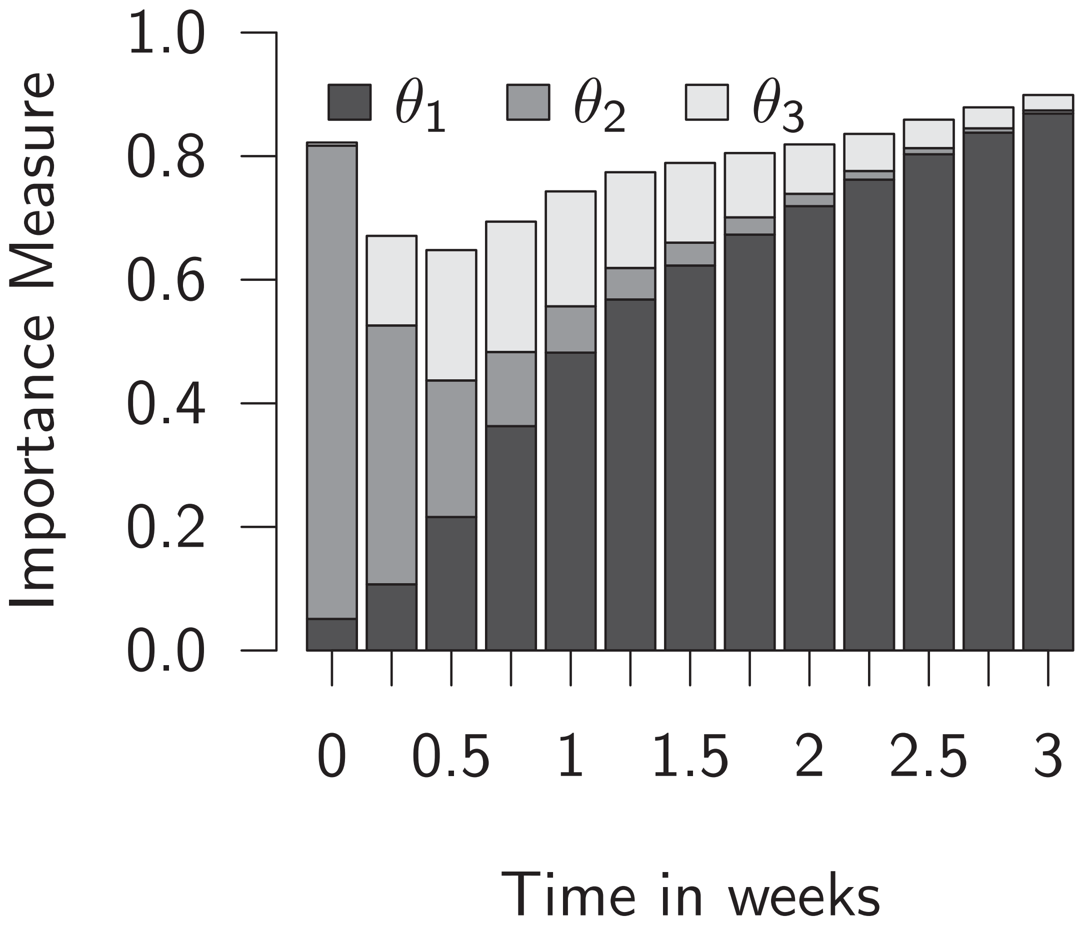




Importance Measure

$s(\theta_i) = \int_\Omega |pdf(y) - pdf(y|\theta_i)| dy$

- global sensitivity analysis
- impact on the entire pdf



Importance Measure

- θ_1 dominates the long-term progression

Summary

- In-line trains as moving sensors
- continuous track monitoring via low-cost sensor systems
- precise localization is mandatory
- ⇒ Multi-sensor concept for localization
- efficient algorithm to take account of uncertain parameters
- ⇒ combination of PCE and PEM

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