Pre-Conference Workshop: New approaches to address pavement failure more realistically in asphaltic pavement design methods

Design and management approaches addressing asphalt pavement performance

Michael P. Wistuba

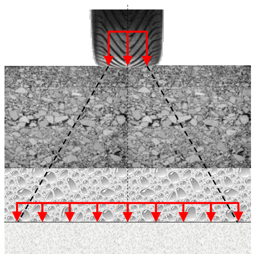
Braunschweig Pavement Engineering Centre
Technische Universität Braunschweig

Background

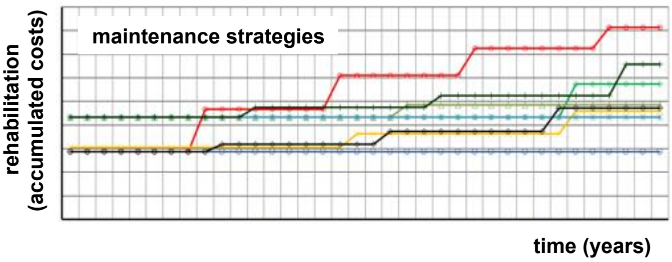
ISBS
Institut für Straßenwesen
TU Braunschweig

Predicting asphalt pavement performance

- Key element in pavement design
  - minimum layer thicknesses to support loading in function of material properties
  - ranking of materials
  - estimation of residual value

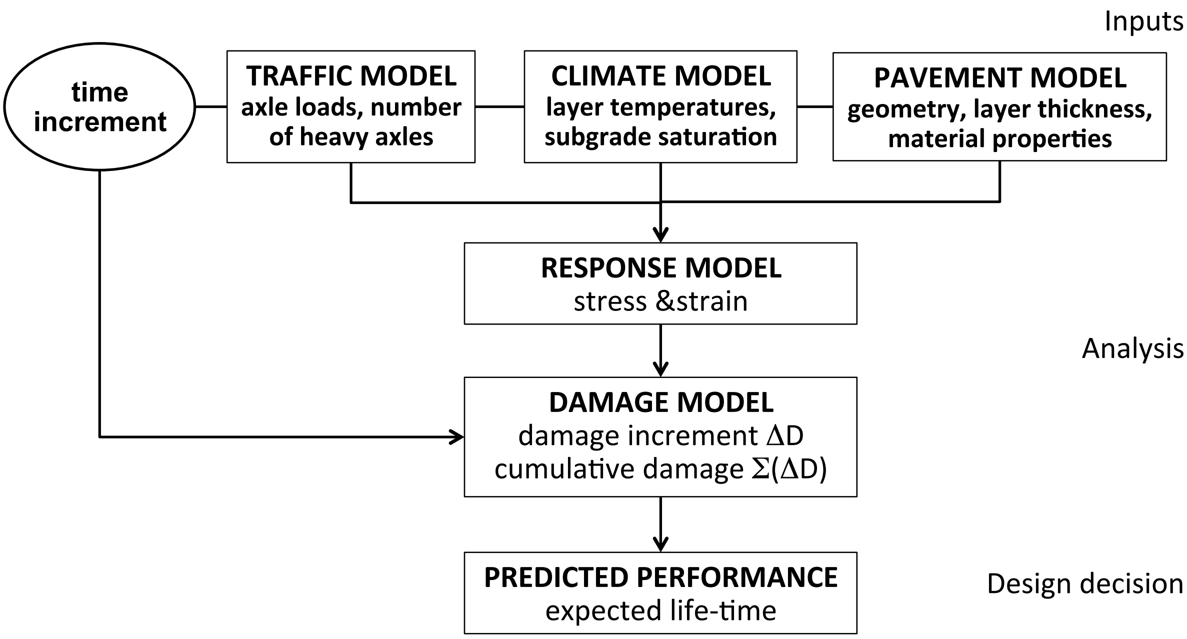


- Key element in pavement management
  - life-cycle-analysis
    - residual value
    - maintenance intervals
    - budgetary needs



Predicting asphalt pavement performance

(a) Mechanical Empirical Pavement Design (MEPD)



ISBS
Institut für Straßenwesen
TU Braunschweig

Predicting asphalt pavement performance

(a) Mechanical Empirical Pavement Design (MEPD)

- **German pavement design guide**

  RDO Asphalt 09 "Richtlinien für die rechnerische Dimensionierung des Oberbaus von Verkehrsflächen mit Asphaltdeckschicht"

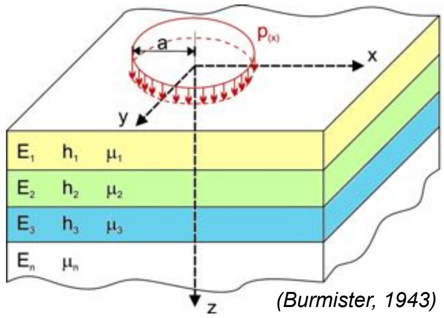
- **basic, traditional pavement design approach as in many other countries**

German pavement design guide

ISBS
Institut für Straßenwesen
TU Braunschweig

Multilayer Elastic Theory

- **layered elastic model**
  - homogeneous, isotropic, linear elastic
  - infinite horizontal layer extension
  - infinite vertical subgrade extension
  - stick or slip layer interfaces



(Burmister, 1943)

- **limited number of input data**
  - layer thicknesses
  - material properties (elastic modulus, Poisson ratio, layer friction)
  - force (magnitude of wheel load) and load geometry (tire patch load)
- **materials are not stressed beyond their elastic ranges**
  - suitable for short-term loading at low to moderate (?) temperatures

German pavement design guide

ISBS
Institut für Straßenwesen
TU Braunschweig

- simple model applicable **for high numbers of load repetitions**
- **E. g., German design guide:**

  11 load classes for consideration of truck traffic

  13 characteristic temperature distributions

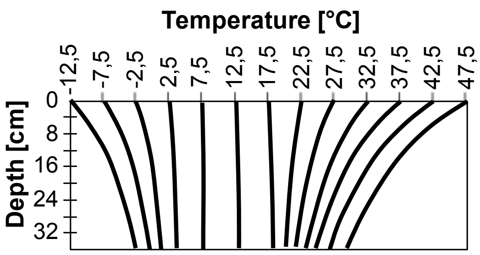
  = **143 loading cases** for design analysis (advantage: short calculation time)

$$\sigma_r = \frac{E}{(1+\nu)\cdot(1-2\cdot\nu)}\cdot\left\{(1-\nu)\cdot\frac{\delta u}{\delta r}+\nu\cdot\left(\frac{u}{r}+\frac{\delta w}{\delta z}\right)\right\}$$

$$\sigma_t = \frac{E}{(1+\nu)\cdot(1-2\cdot\nu)}\cdot\left\{(1-\nu)\cdot\frac{u}{r}+\nu\cdot\left(\frac{u}{r}+\frac{\delta w}{\delta z}\right)\right\}$$

$$\sigma_z = \frac{E}{(1+\nu)\cdot(1-2\cdot\nu)}\cdot\left\{(1-\nu)\cdot\frac{\delta w}{\delta z}+\nu\cdot\left(\frac{u}{r}+\frac{\delta u}{\delta r}\right)\right\}$$

$$\tau_{rz} = \frac{E}{2\cdot(1+\nu)}\cdot\left\{\frac{\delta u}{\delta z}+\frac{\delta w}{\delta r}\right\}$$

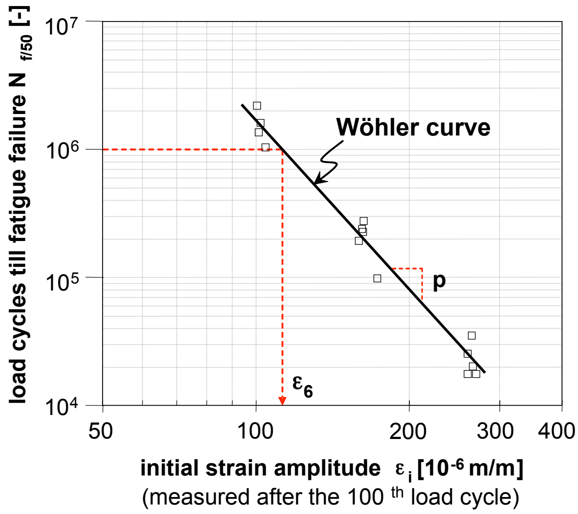


German pavement design guide

ISBS
Institut für Straßenwesen
TU Braunschweig

Dominant deterioration mechanism considered

- **material fatigue** is crucial design criterion to avoid structural failure
- **Wöhler curves** are derived from laboratory fatigue testing
- **linear summation of the damaging effects of individual loads (Miner)**



(ε6 for CE declaration)

Fatigue law:

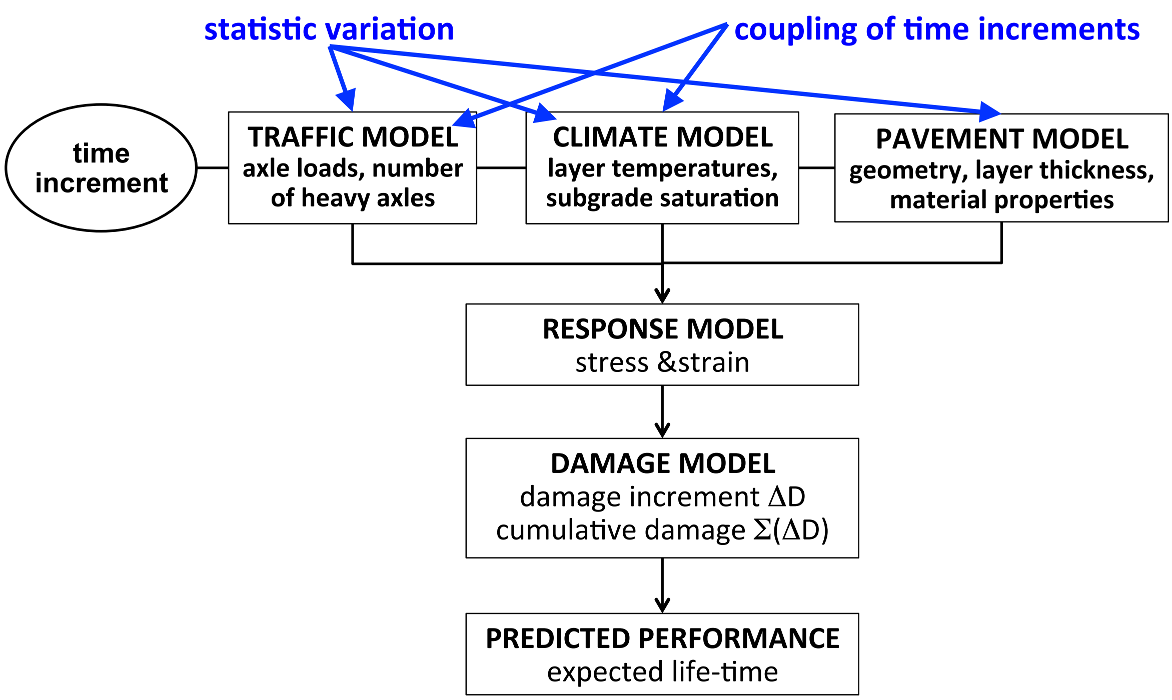
$$N_f = k_1 \cdot \left(\frac{1}{\varepsilon_0}\right)^{k_2}$$

Miner rule (linear accumulation of incremental damage)**:**

$$C = \sum\left(\frac{N_{vorh}}{N_{zul}} \cdot p\right) \leq 1$$

Predicting asphalt pavement performance

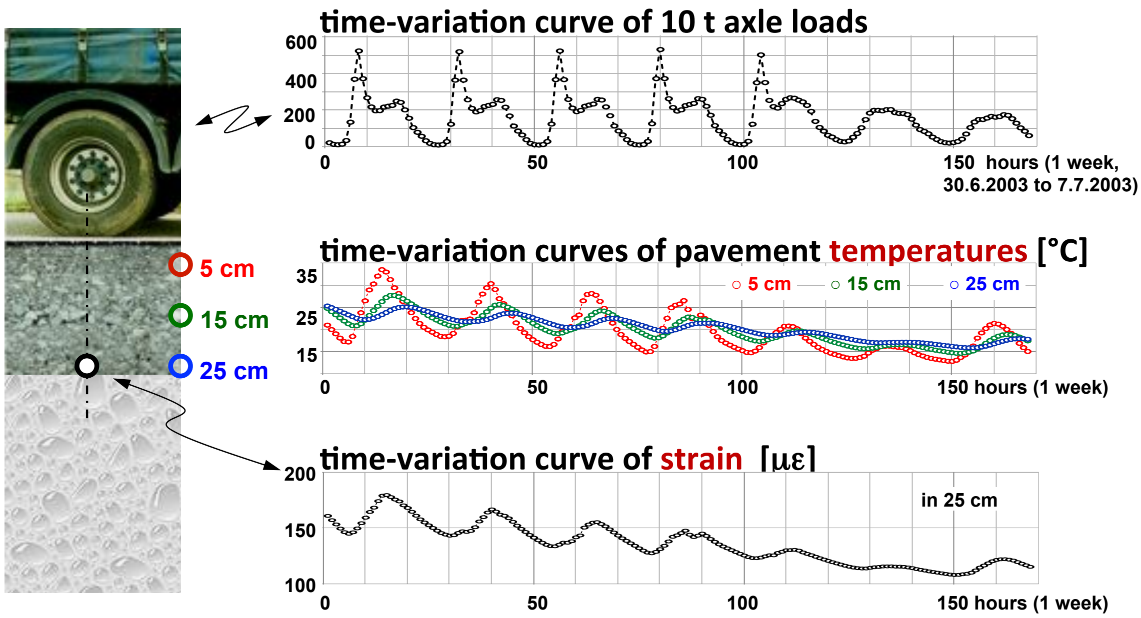
ISBS
Institut für Straßenwesen
TU Braunschweig



Stress analysis in time increments

ISBS
Institut für Straßenwesen
TU Braunschweig

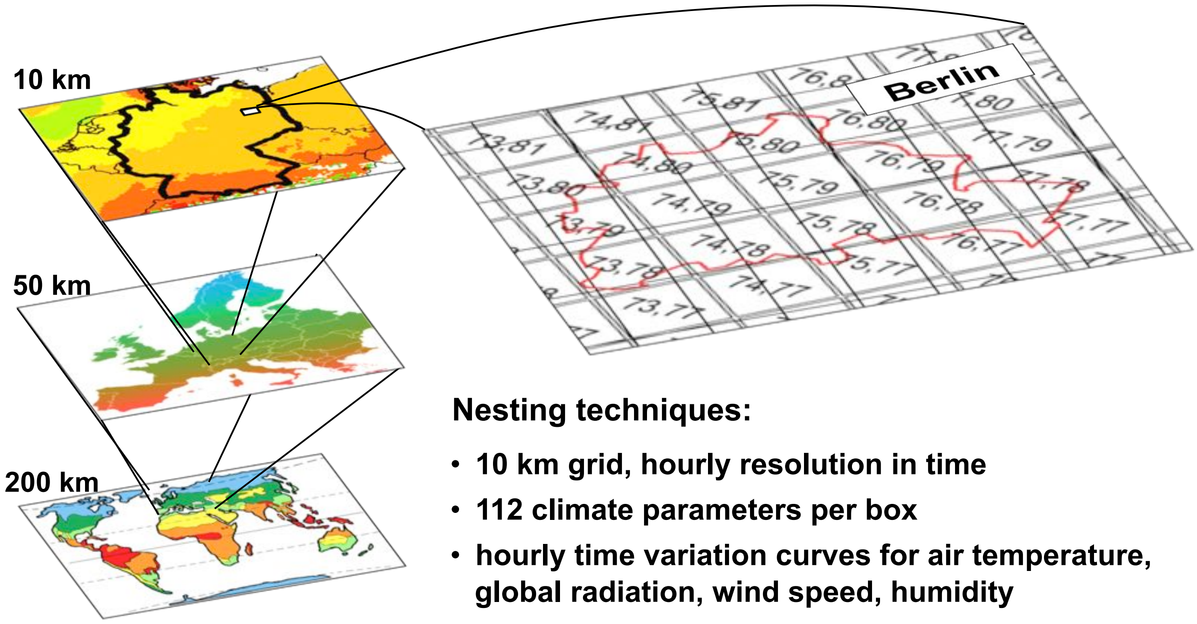
- time-accurate superposition of traffic & temperature



→ superposition and analysis of damage in time increments

Regional climate model (REMO)

ISBS
Institut für Straßenwesen
TU Braunschweig



Nesting techniques:

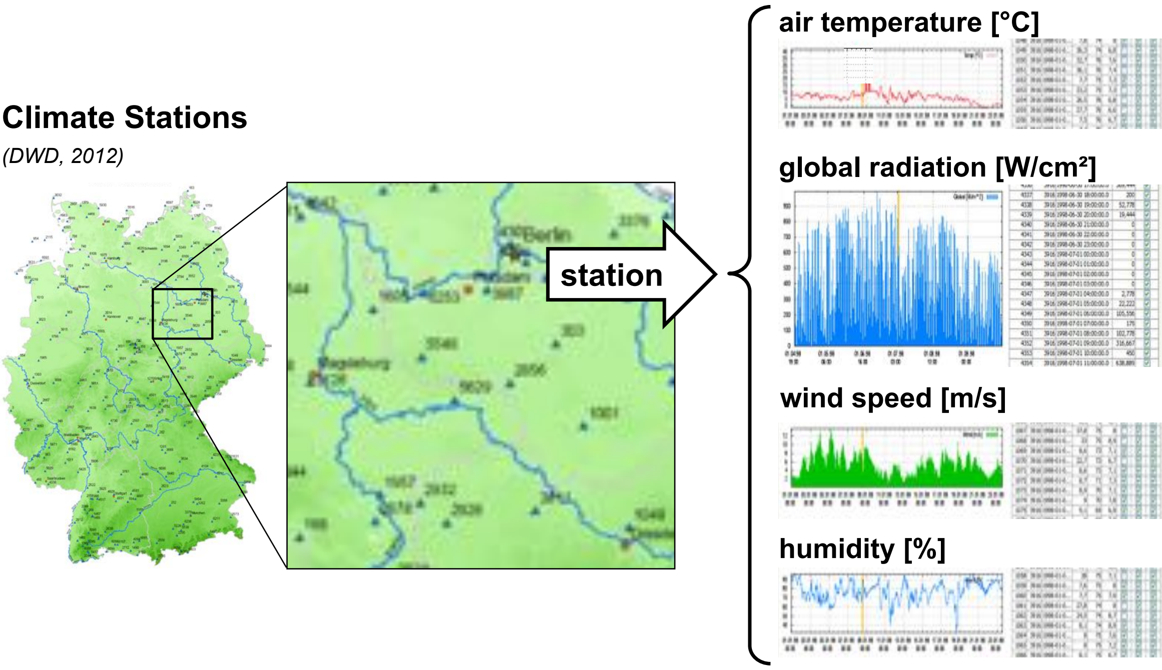
- 10 km grid, hourly resolution in time
- 112 climate parameters per box
- hourly time variation curves for air temperature, global radiation, wind speed, humidity

Regional climate model (REMO)

ISBS
Institut für Straßenwesen
TU Braunschweig

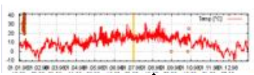
Climate Stations

(DWD, 2012)



Pavement temperature distribution

ISBS
Institut für Straßenwesen
TU Braunschweig

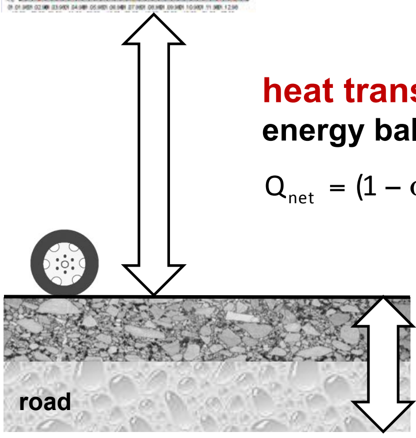


climate data: **meteorological observations at climate station**

heat transfer at pavement surface

energy balance law

$$Q_{net} = (1-\alpha)\ G + \varepsilon_a\ F\ T_{air}^4 - \varepsilon_b\ F\ T_{surf}^4 - \lambda \frac{\Delta T}{d} + \alpha_K (T_{air} - T_{surf}) = 0$$



heat flux within pavement layers

Fourier heat balance law

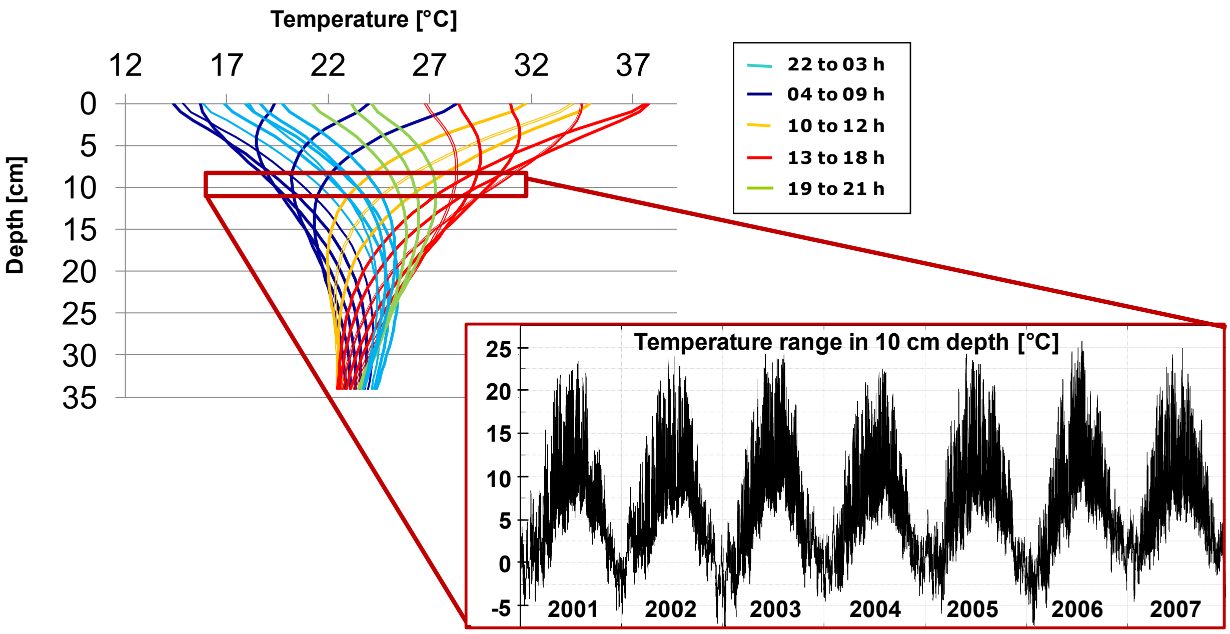
$$C\dot{T} = -\mathrm{div}\ q \qquad T(x,t=0) = T_0(x)$$

$$q = -k\ \mathrm{grad}\ T \qquad q_n = \alpha\ (T - T_\infty)$$

C ... vol. heat capacity
q ... heat flux vector
k ... heat conduction coeff.
α ... heat transfer coeff.
T_∞ ... ambient temperature

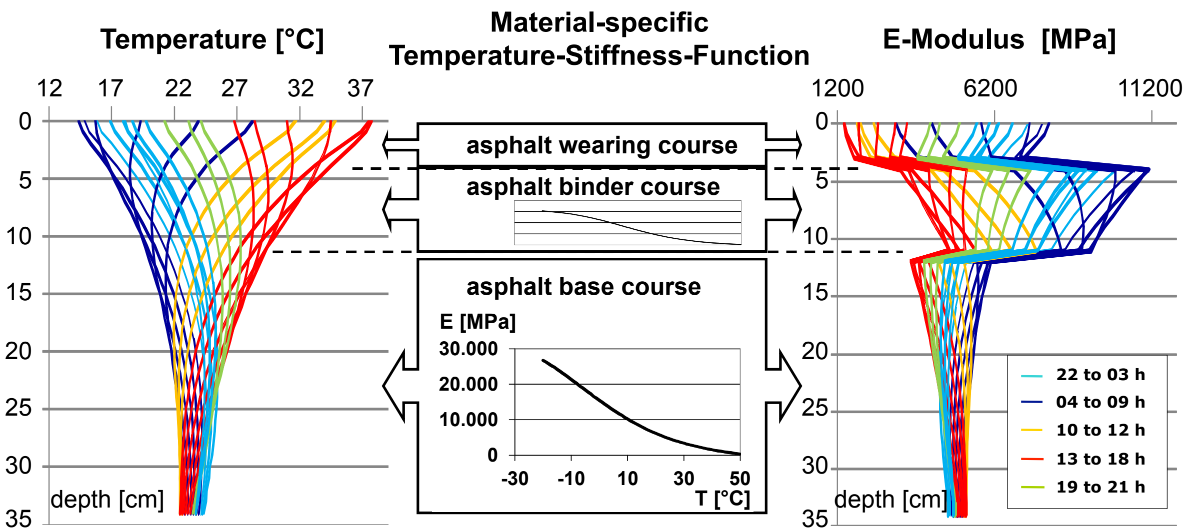
[Krebs & Böllinger, 1981; Wistuba, 2002; Villaret et al., 2007]

Pavement temperature distribution



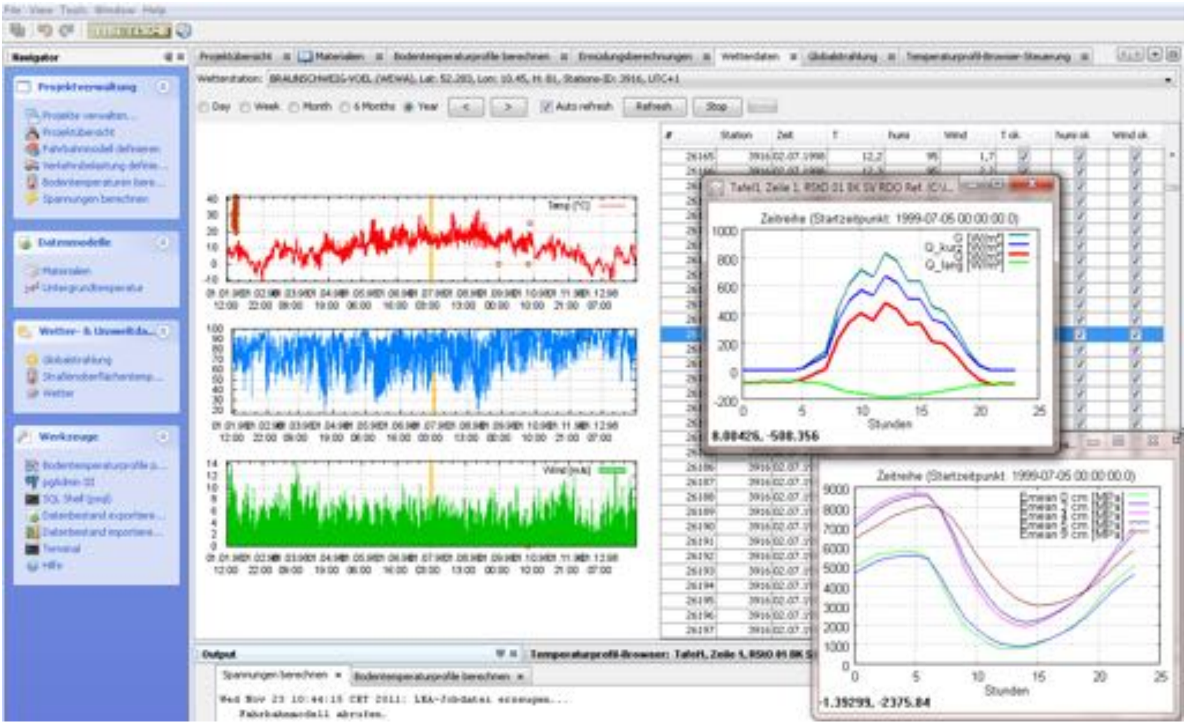
Pavement temperature distribution

ISBS
Institut für Straßenwesen
TU Braunschweig



Software for incremental stress analysis

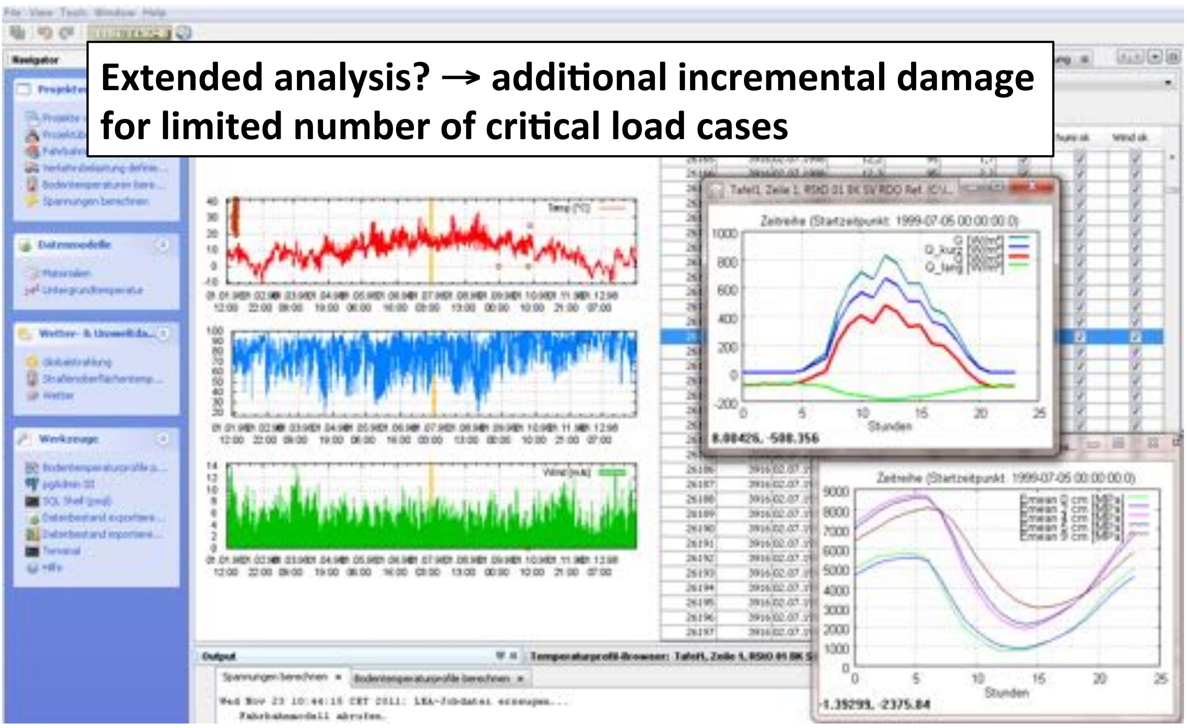
ISBS
Institut für Straßenwesen
TU Braunschweig



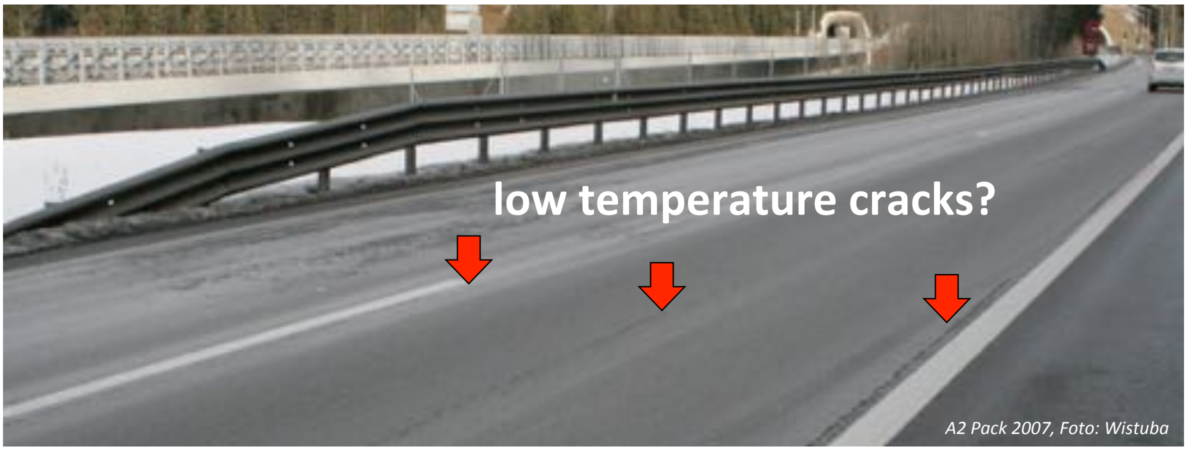
Software for incremental stress analysis

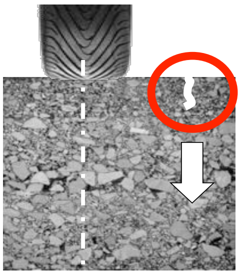
ISBS
Institut für Straßenwesen
TU Braunschweig

Extended analysis? → additional incremental damage for limited number of critical load cases



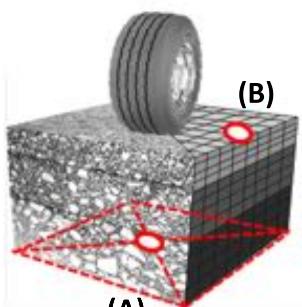
Longitudinal low temperature top down cracking

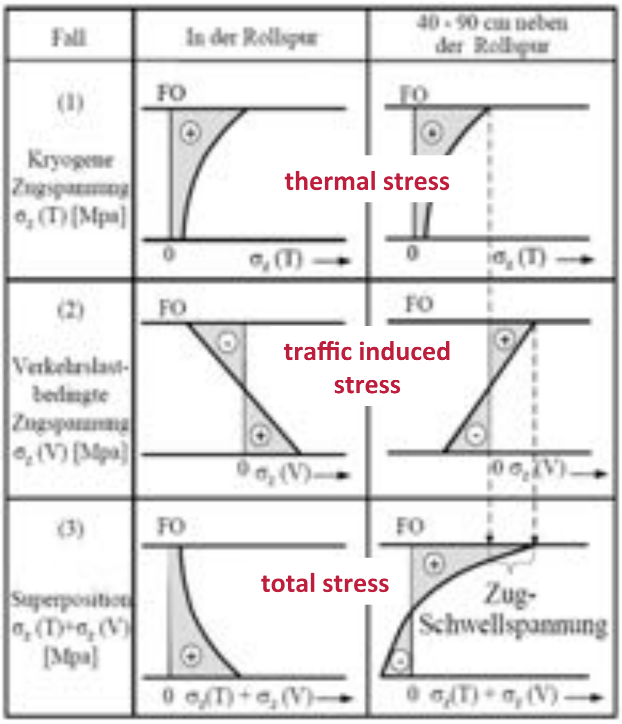




Longitudinal low temperature top down cracking

- **Question: can low-temp. stress be explained from LE calculation?**
  - ➢ **due to a negative temperature gradient (drop in temperature) and**
  - ➢ **low stress relaxation at low temperature**



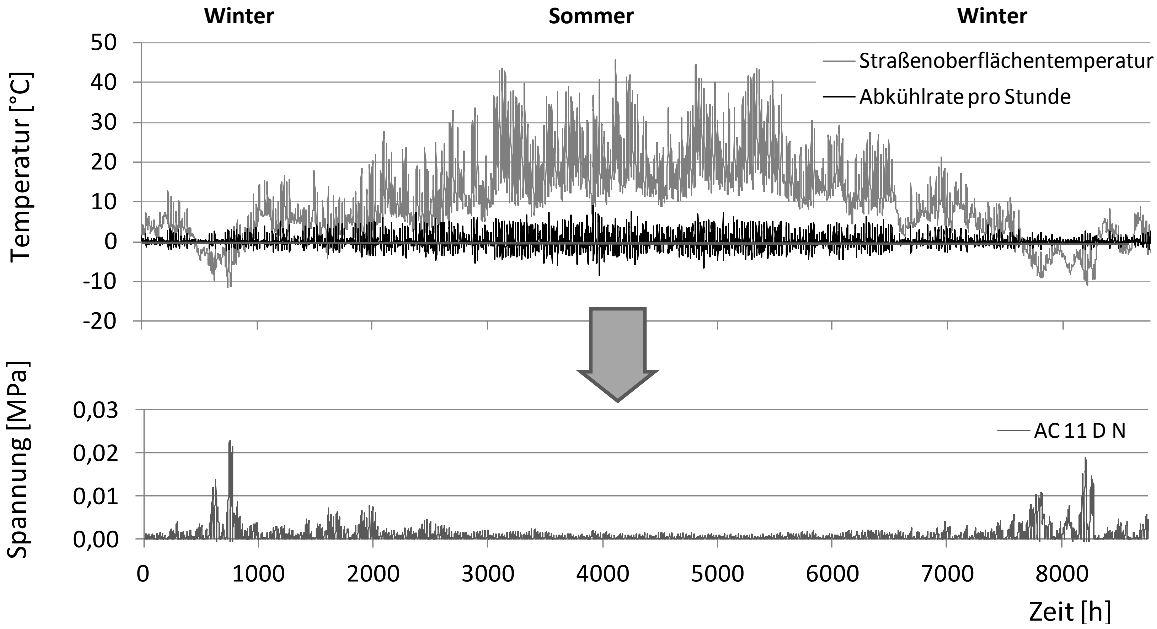


Arand 1995

ISBS
Institut für Straßenwesen
TU Braunschweig

Longitudinal low temperature top down cracking

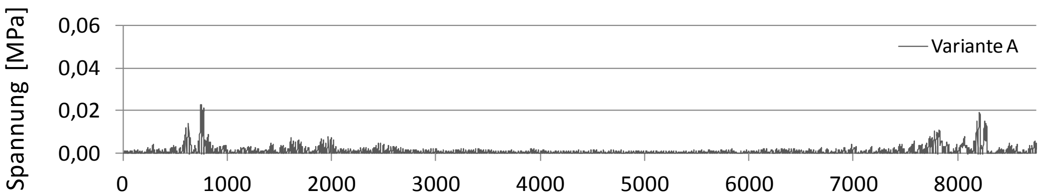
Thermal stress at surface 1 m beside wheel track



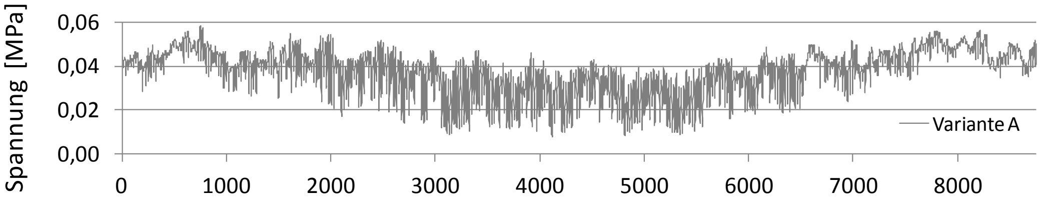
ISBS
Institut für Straßenwesen
TU Braunschweig

Longitudinal low temperature top down cracking

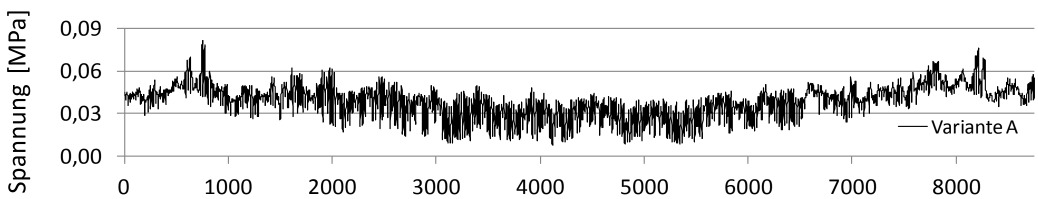
Low temperature stress at surface



Traffic induced stress at surface

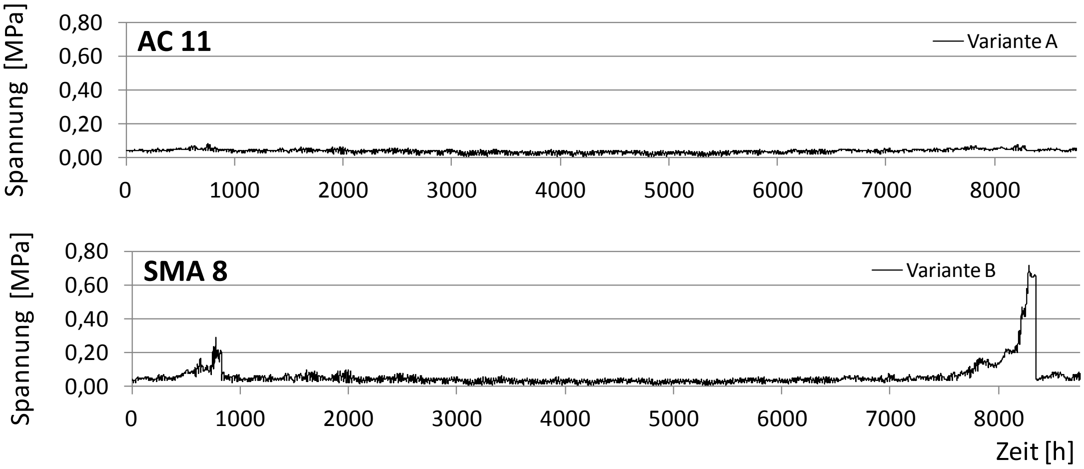


Total stress at surface



Longitudinal low temperature top down cracking

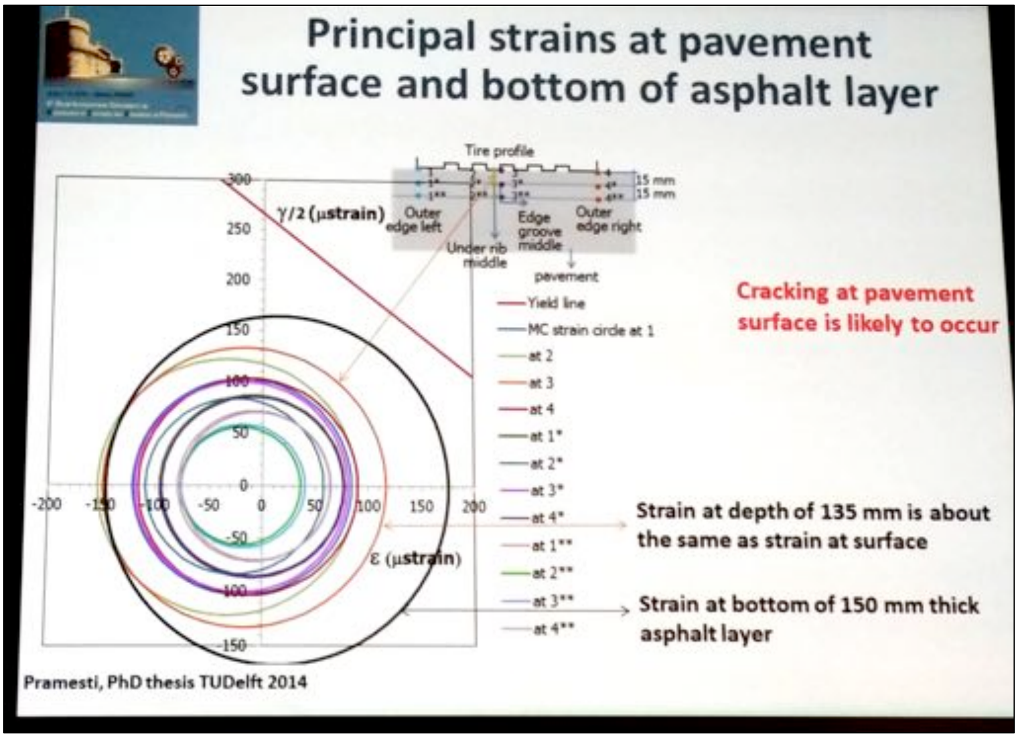
- **can not be explained from LE calculation of low-temperature stress (only in very rare cases and for extremely hard bitumens). Generally, this type of crack is supposed to be driven by other crack mechanisms (shear at moderate and high temperatures?)**



Walther, A. & Wistuba, M. 2012. Mechanistic Pavement Design Considering Bottom-Up And Top-Down-Cracking. ***Proc.****, 7th RILEM Int. Conf. On Cracking in Pavements, 20-22 June, 2012, Delft.*

Predicting asphalt pavement performance

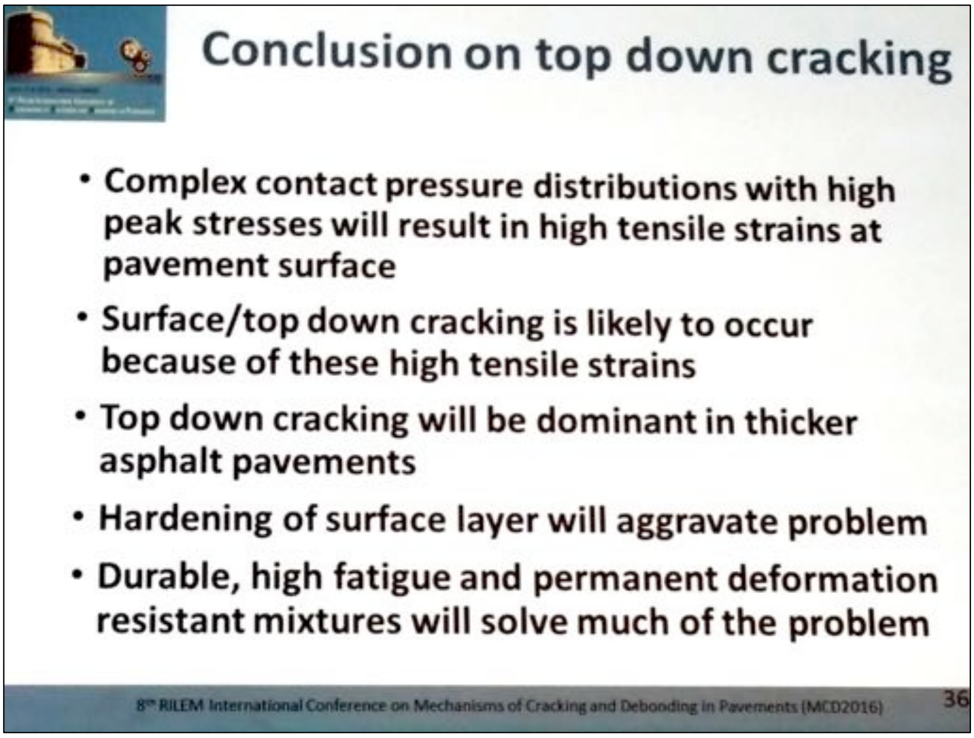
Molenaar, Keynote MCD 2016 Nantes



Predicting asphalt pavement performance

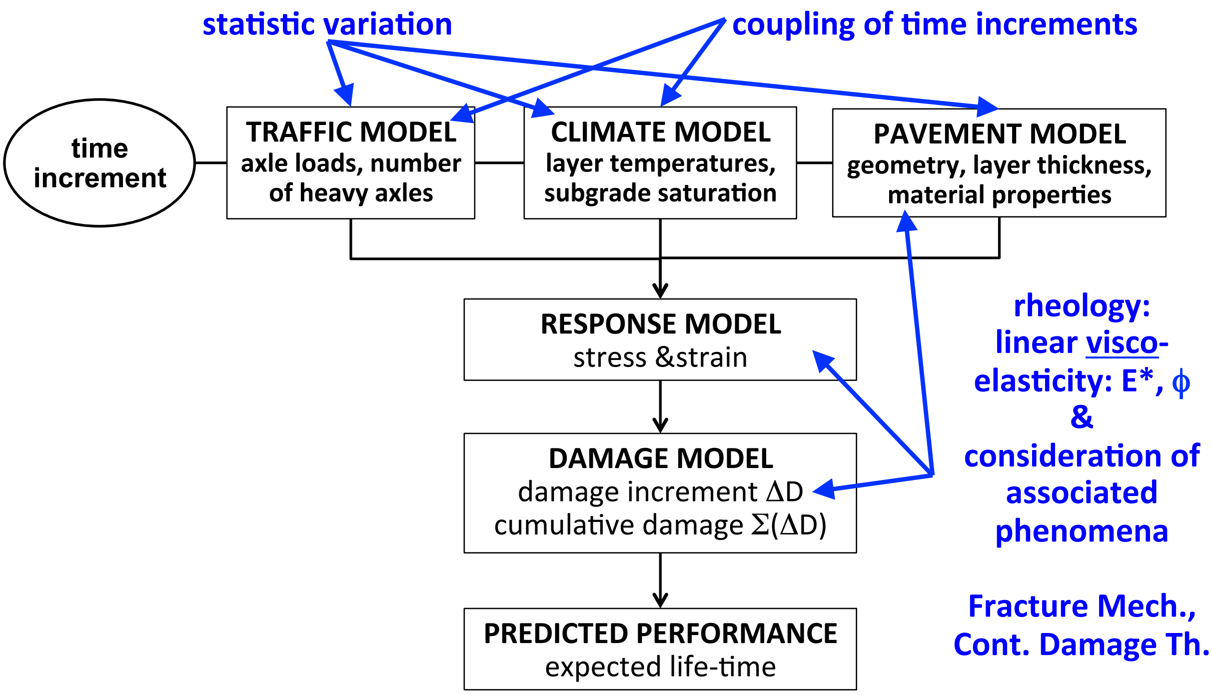
ISBS Institut für Straßenwesen TU Braunschweig

Molenaar, Keynote MCD 2016 Nantes

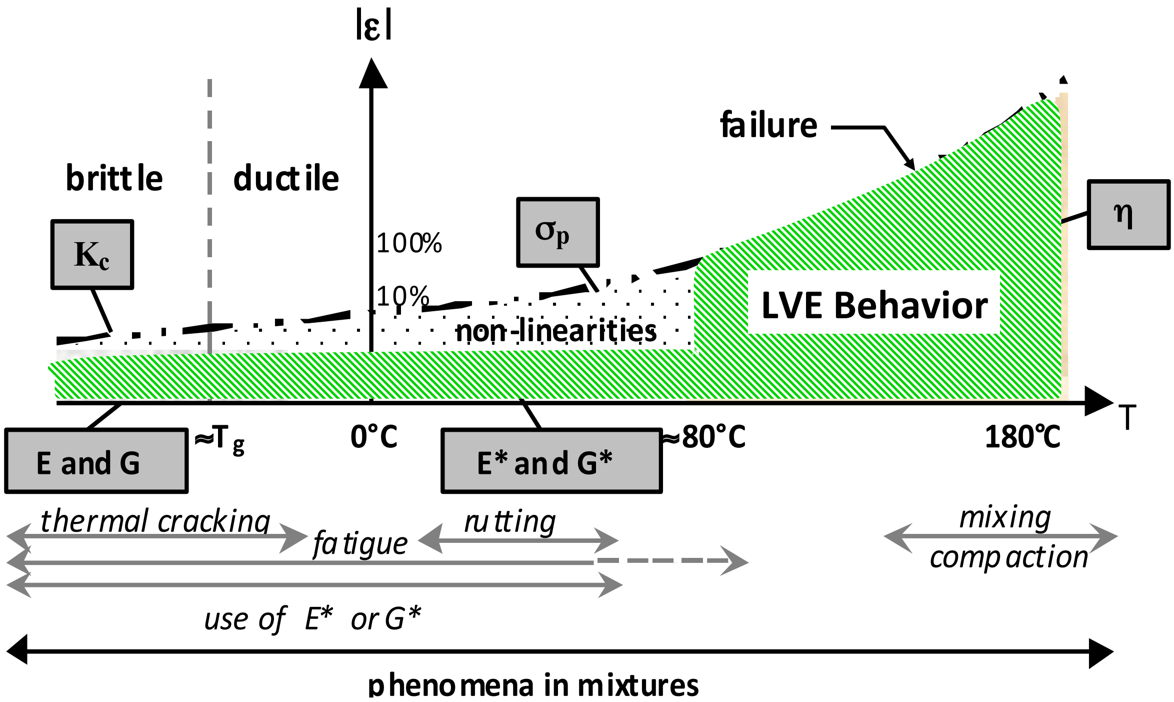


Predicting asphalt pavement performance

ISBS Institut für Straßenwesen TU Braunschweig

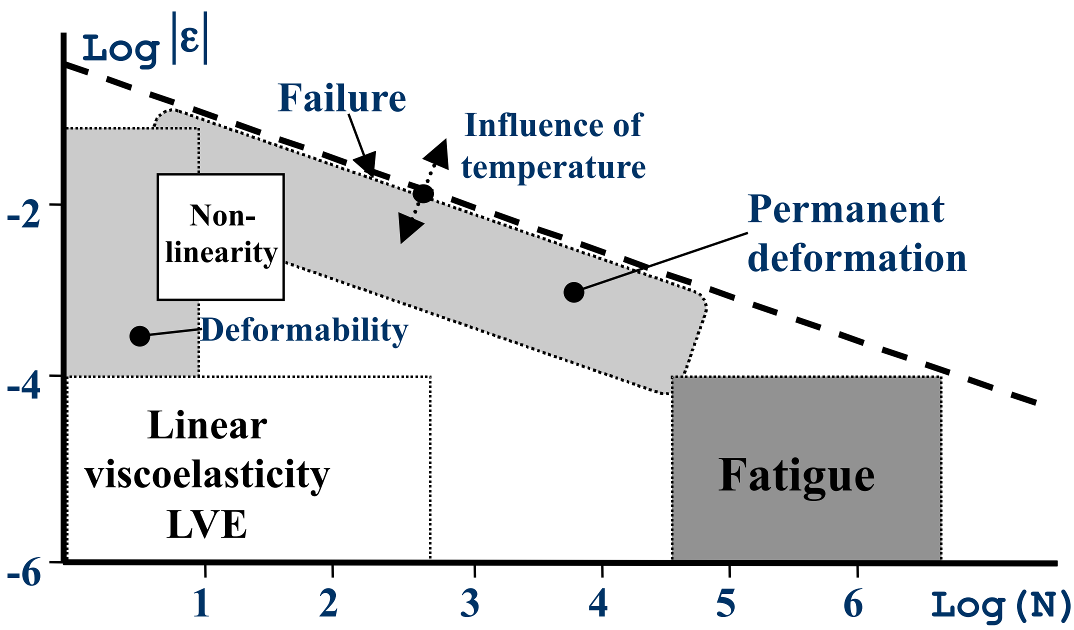


Linear visco-elastic bitumen behavior



[Di Benedetto]

Domains of asphalt mix behaviour



[Di Benedetto]

Associated phenomena

ISBS
Institut für Straßenwesen
TU Braunschweig

- Linear viscoelasticity
- Non linearity

1, 2

- Fatigue
- Healing
- Thixotropy

4

- Crack propagation
- Permanent deformation

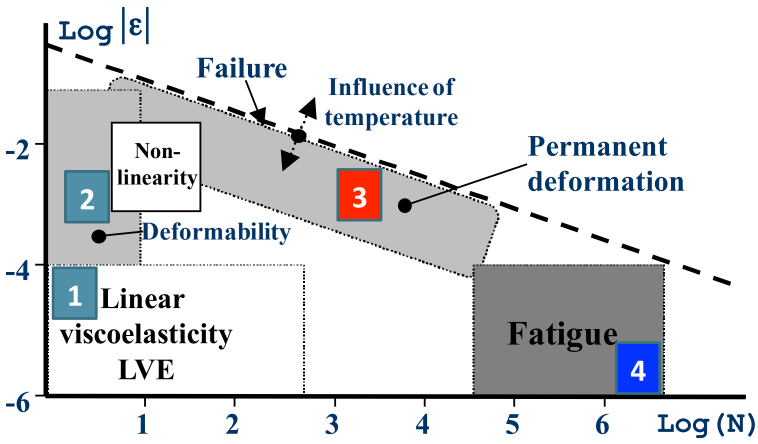
3

- Brittle failure
- Viscoplastic flow

2 3

- Thermo-mechanical coupling
- transfer to 3D

5



[Di Benedetto]

Fracture mechanics

ISBS
Institut für Straßenwesen
TU Braunschweig

- **Low temperature cracking represents a serious distress for asphalt pavements in cold regions. Crack failure properties of asphalt mixture are crucial for design.**
- **They are used as input in the Thermal Cracking model which is part of the current Mechanistic Empirical Pavement Design Guide acc. to AASHTO 2008.**
- **Fracture strength properties of asphalt mixture can be successfully predicted from SCB fracture testing without performing IDT tests at low temperature.**

  See paper N° 66860 (Cannone Falchetto, Moon & Wistuba: Numerical correlation between low temperature SCB fracture and IDT strength of asphalt mixture using FEM analysis)

Continuum Damage Theory

ISBS
Institut für Straßenwesen
TU Braunschweig

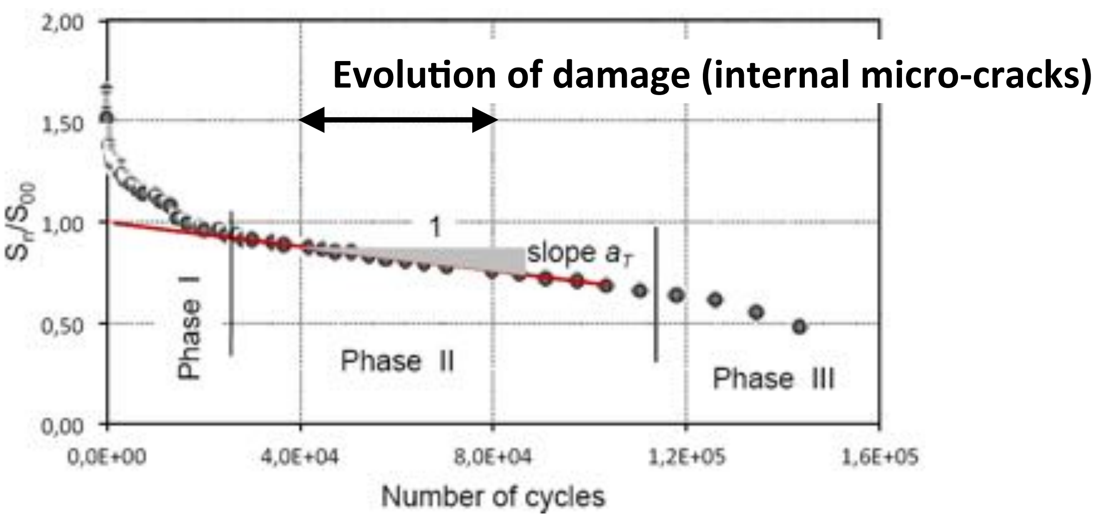
- Characteristic curve representing the evolution of internal damage D in the mixture in function of pseudo strain energy W^R and of a material property α

$k_2 = 2\alpha$ (Lee et al., 2003; Kim et al. 2006)

$$\dot{D} = \left(-\frac{\partial W^R}{\partial D}\right)^{\alpha} \qquad N_f = k_1 \cdot \left(\frac{1}{\varepsilon_0}\right)^{k_2}$$

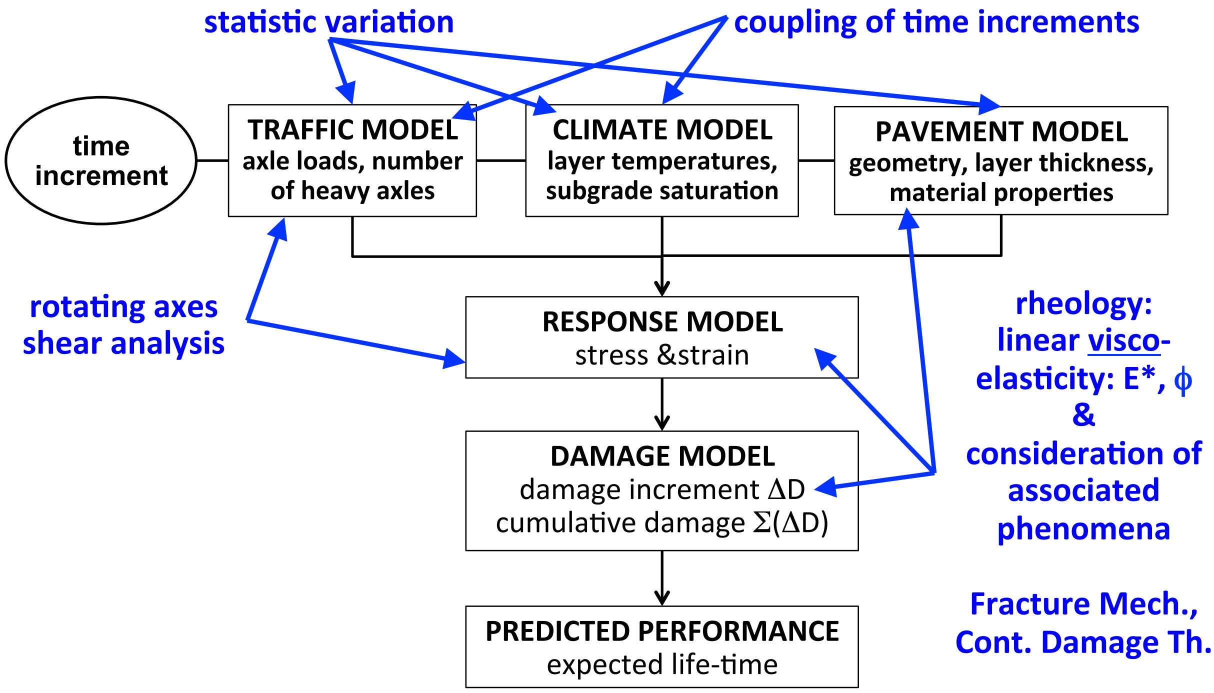
Continuum Damage Theory

ISBS
Institut für Straßenwesen
TU Braunschweig



[Di Benedetto]

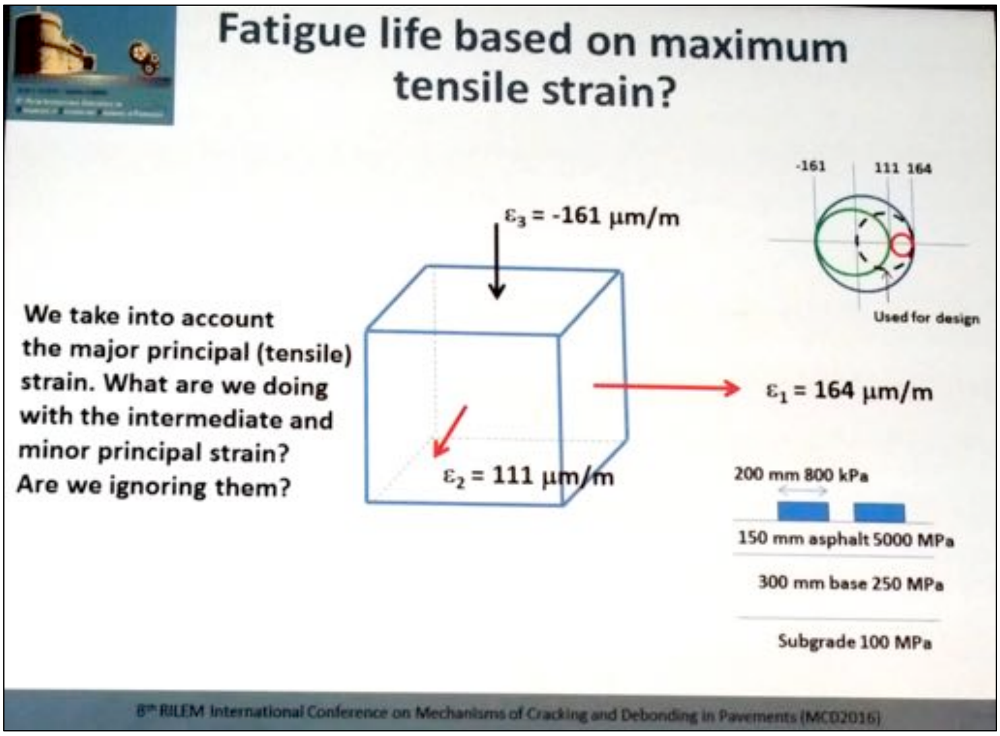
Predicting asphalt pavement performance



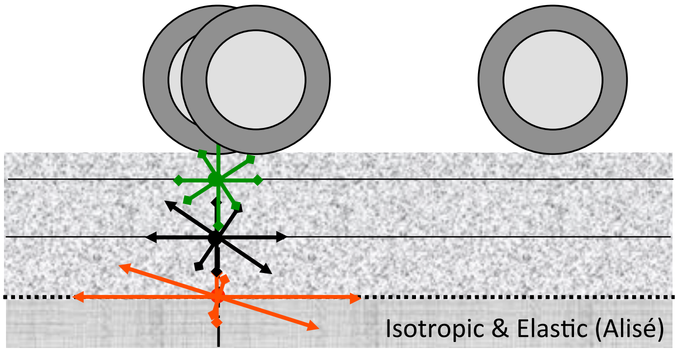
ISBS
Institut für Straßenwesen
TU Braunschweig

Predicting asphalt pavement performance

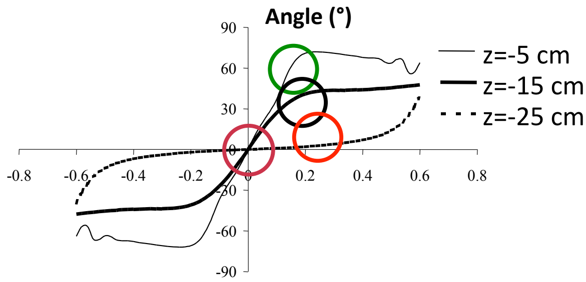
Molenaar, Keynote MCD 2016 Nantes



Rotating axles: stress paths in layers

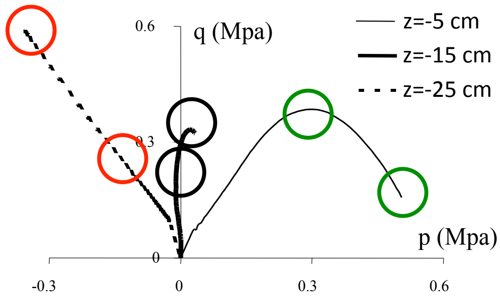


Rotation of axes



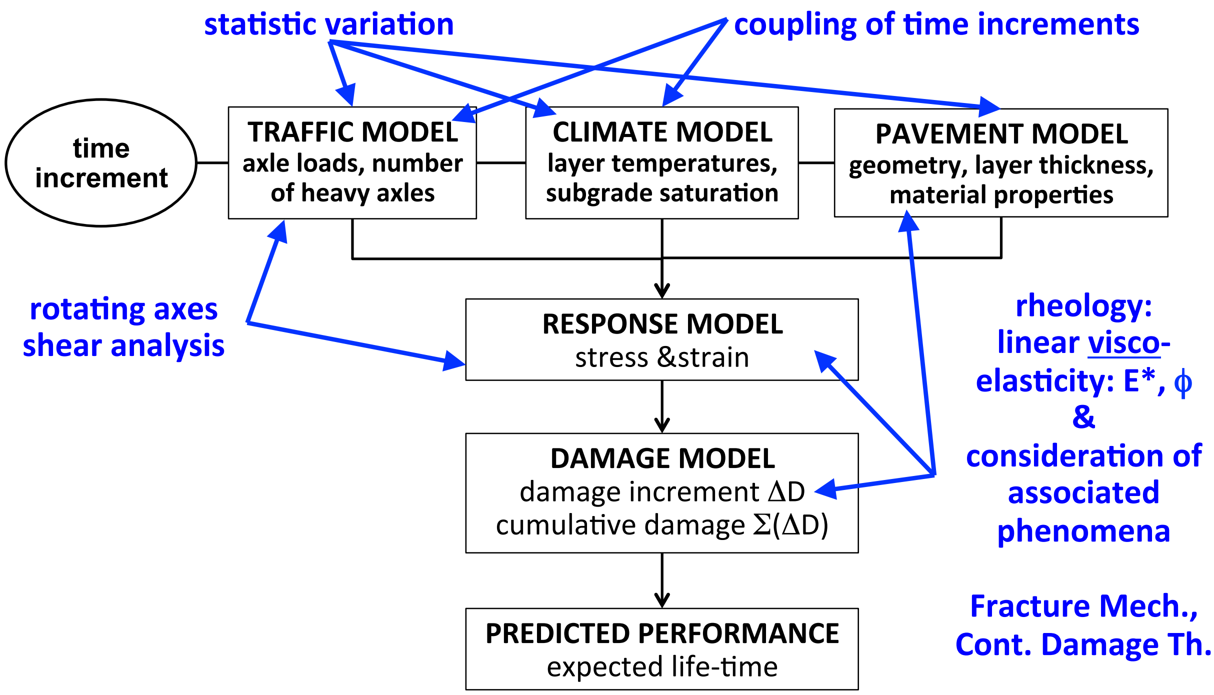
Distance from the center of the wheel (m)

Principal stress

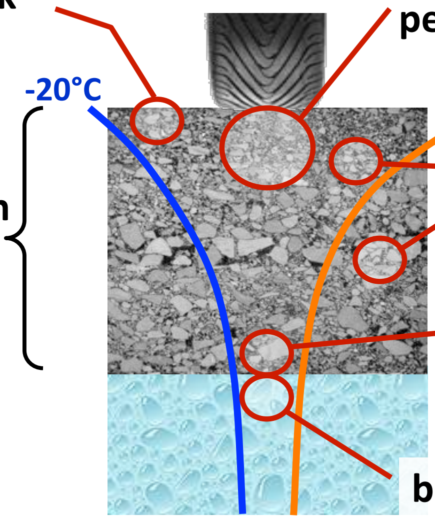


[Di Benedetto]

Predicting asphalt pavement performance



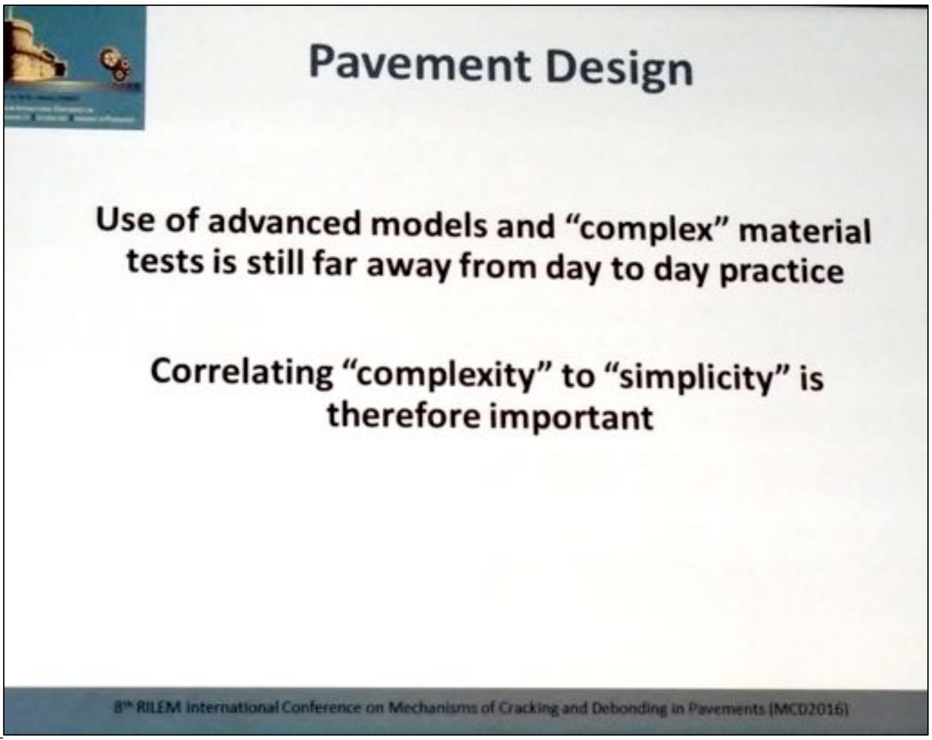
Key issues in pavement design



Predicting asphalt pavement performance

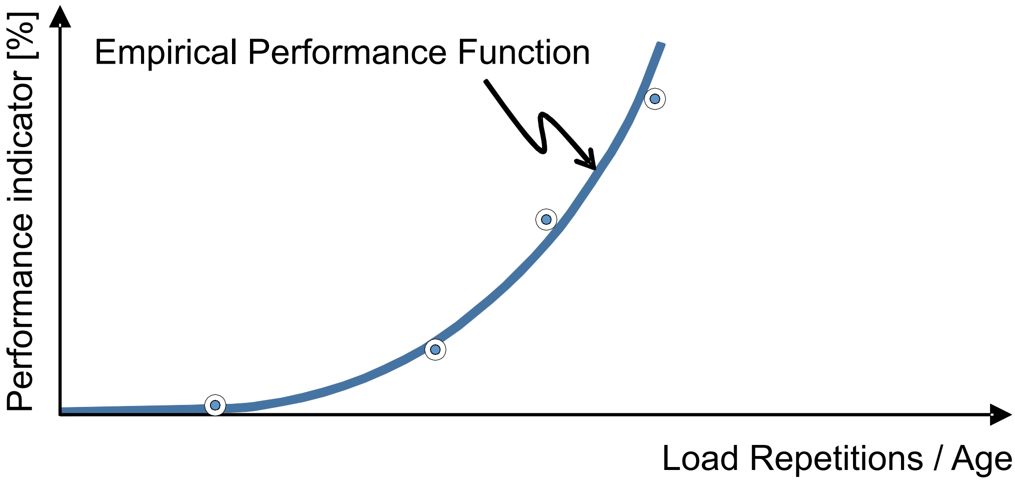
ISBS
Institut für Straßenwesen
TU Braunschweig

Molenaar, Keynote MCD 2016 Nantes



(b) Pavement management: Empirical Perform. Function

Pavement condition parameters are measured in time intervals, and a time-correlation function is derived describing the temporal change of the condition parameter

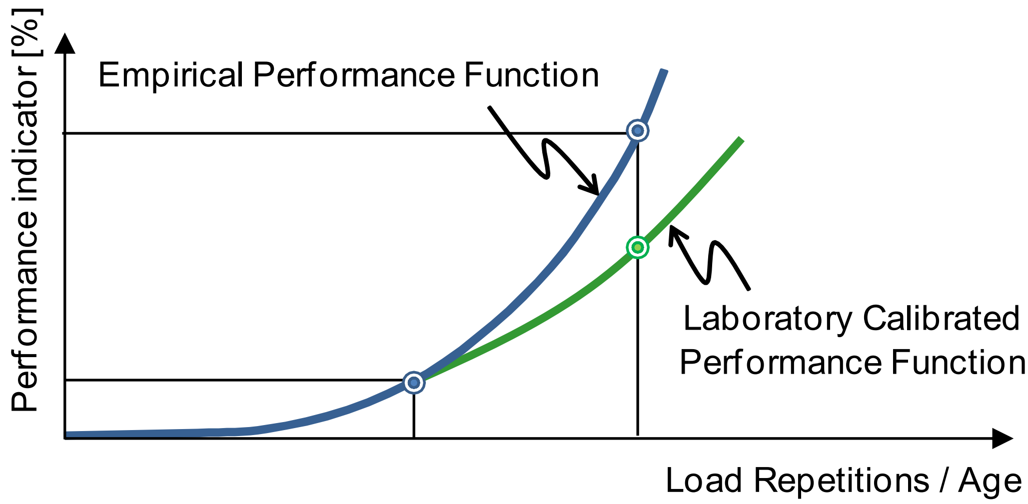


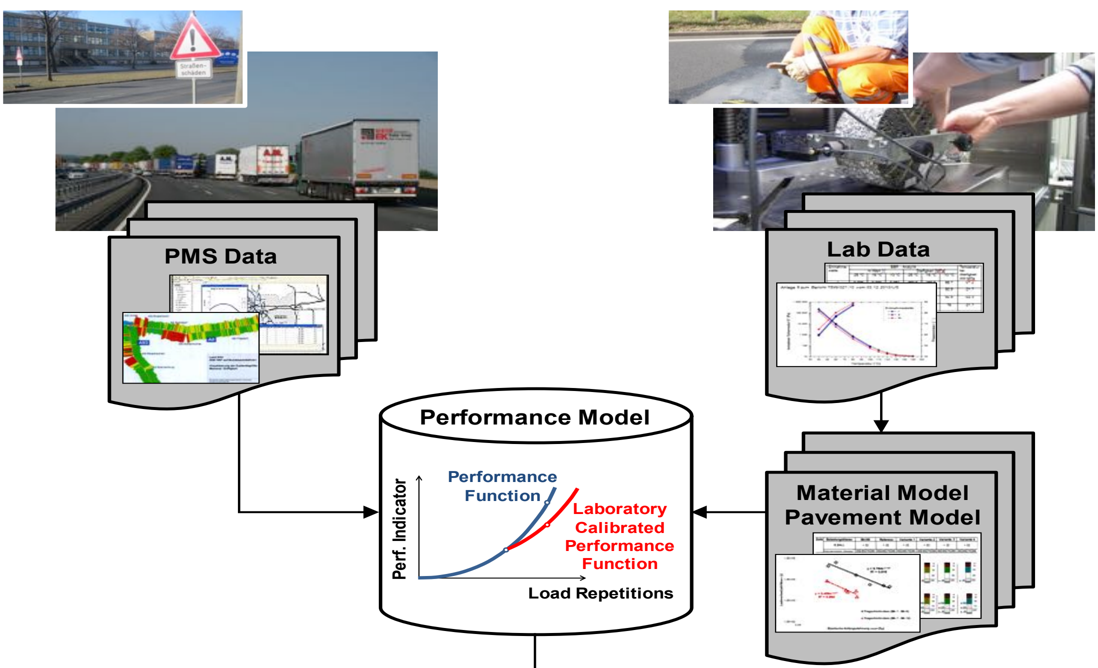
Empirical Performance Function (EPF)

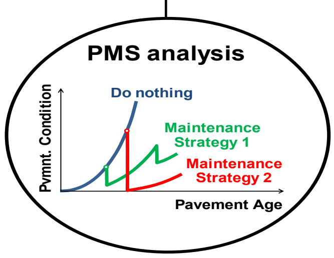
- **EPF do not incorporate structural parameters but are based on surface characteristics / defects only**
  - **EPF do not work for innovative materials and structures (new products, recycled materials)**
- **few effort has been made to incorporate a material science based approach for performance prediction in the frame of PMS**
- **need for analysis of pavement condition in function of incremental distress mechanism → linked with MEPD approach**

Linking empirical with mechanical information

- use information obtained from material testing in the laboratory and from structural performance modeling
- calibration of empirical performance function





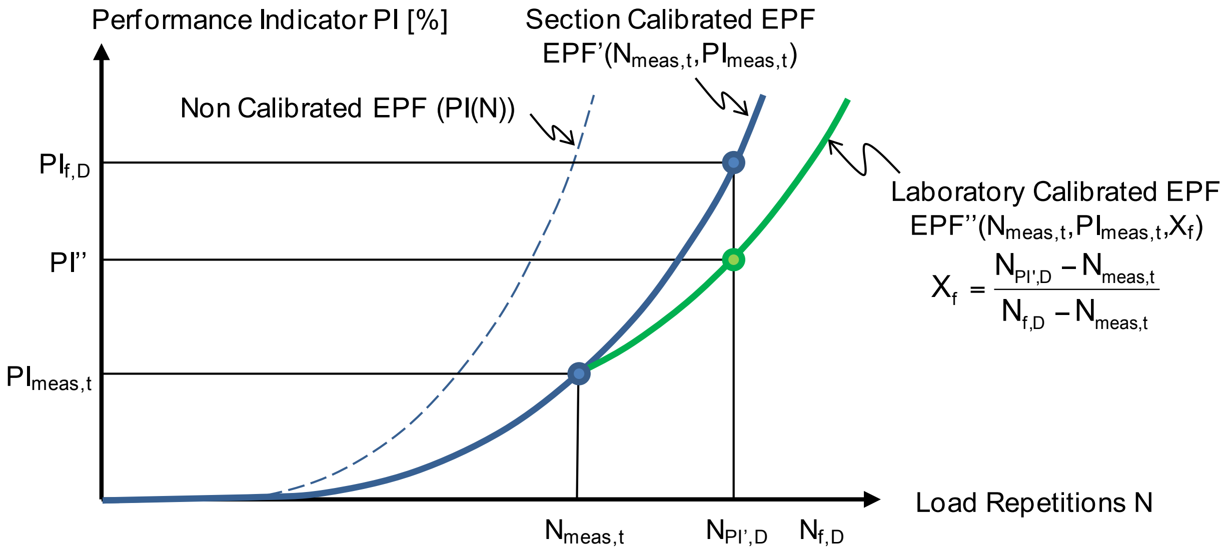


Holistic PMS approach: linking data obtained from empirical analysis to data obtained from mechanistic analysis

Linking empirical with mechanical performance

ISBS Institut für Straßenwesen TU Braunschweig

- **ERAnet-Road-Project "InteMat4PMS" (2012)**
- **PROMAT project (2016)**



$PI''_{t+N} = PI_{meas,t} + EPF''(\Delta N) = PI_{meas,t} + X_f \cdot EPF'(\Delta N)$ where $\Delta N = N_t - N_{meas,t}$

Predicting asphalt pavement performance

ISBS Institut für Straßenwesen TU Braunschweig

Concluding remarks

- **need for consideration of thermo-mechanical behavior of bituminous mixtures and pavement structures**
- **the influence of load *and temperature* on damage evolution is a key issue**
- **for life-cycle-analysis of pavement structures linking empirical *and* mechanical information is of advantage**

Thank you for your contribution!