ERPUG – European Road Profile User´s Group 2023
25 – 27 October – 10 years anniversary
Athens, Greece

New M-E Pavement design and performance prediction method

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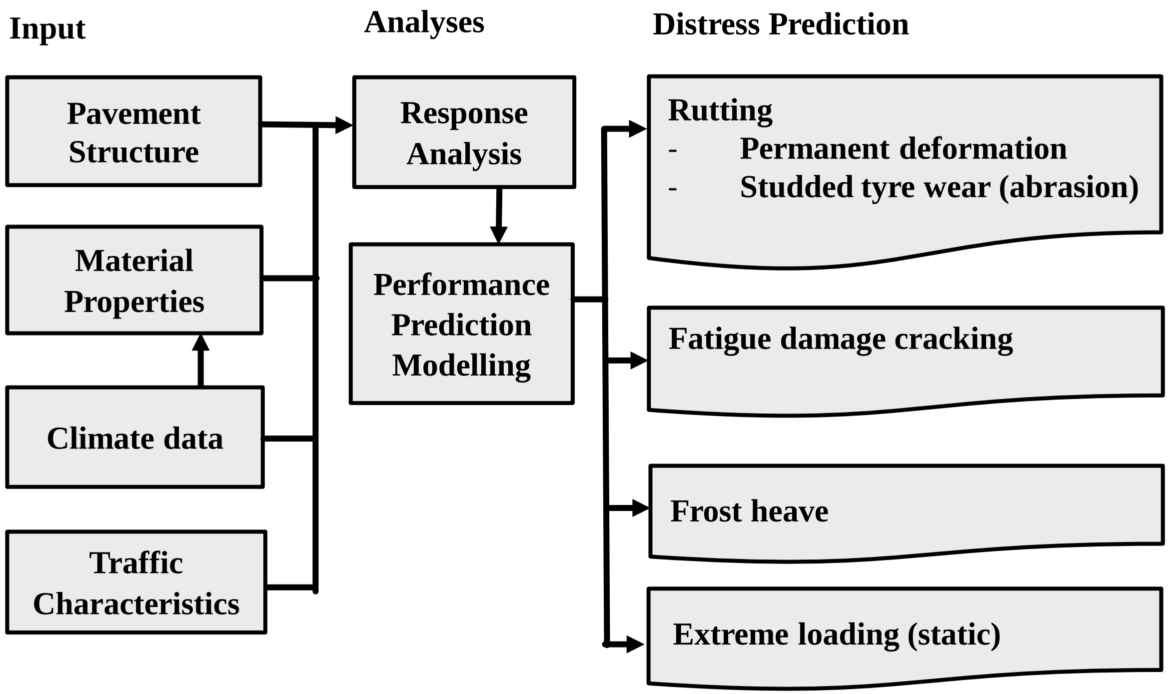
Overview

- Overview of the M-E design tool ERAPave PP
- Input parameters
    - Traffic, Climate, Material properties

  Response model
- Distress development (performance)
    - Rutting
    - Fatigue cracking
    - Studded tyre wear (abrasion)
    - Frost heave
    - Bearing capacity control
- Material databank
- Validation
- Further developments
- Summary

ERAPave PP

ERAPave PP (Elastic Response Analysis of Pavements – Performance Prediction) is a **Mechanistic-Empirical** pavement analysis and design tool for **flexible** pavement. ERAPave PP predicts the evolution of **rutting**, **fatigue cracking** and **studded tyre wear** for a given pavement structure having a set of material properties. It further predicts the expected **frost heave** and controls the stability of a **extreme static loading** condition.



ERAPAve PP

- The software can be downloaded from:
  - vti.se/en
    - Research
      - Highway engineering and maintenance
        - Pavement technology
          - Pavement design models for roads

Version 0.93 is now available

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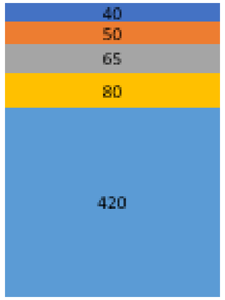
Output

Report

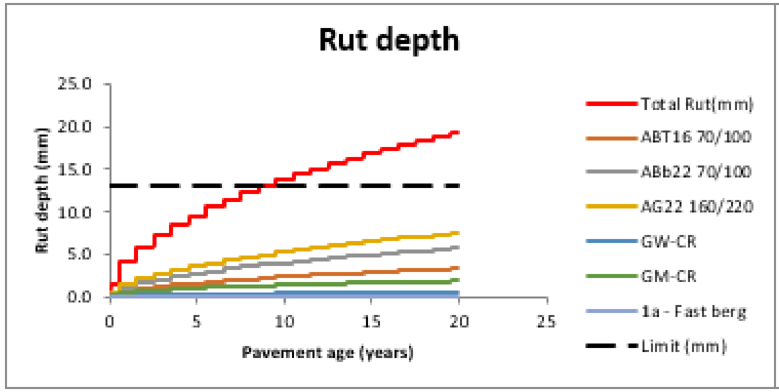
Summary

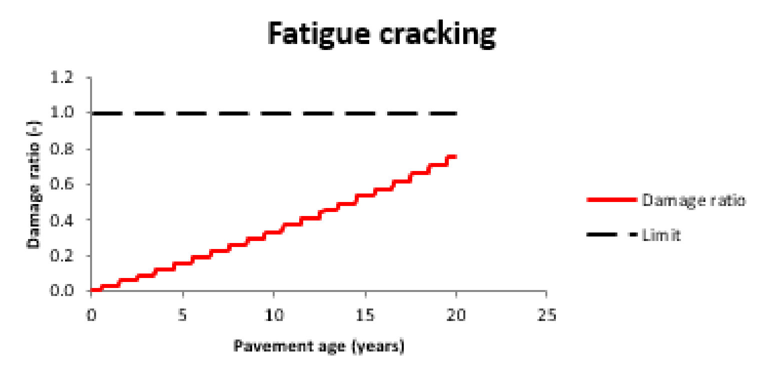
- Input data
- Predicted damages
  - rutting and wear
  - fatigue
  - Frost heave

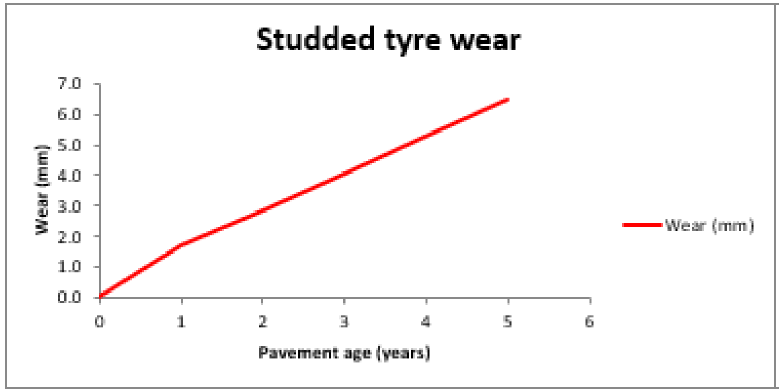
Road Section TEST
Date 2021-11-30

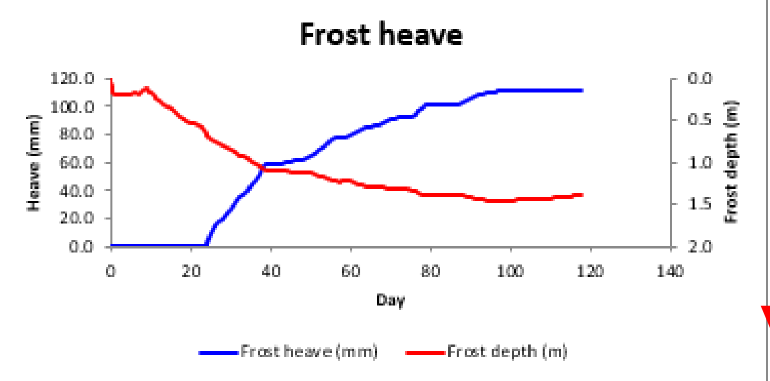


Layer	Rutting (mm)
ABT16 70/100	3.4
ABb22 70/100	5.8
AG22 160/220	7.6
GW-CR	0.7
GM-CR	1.9
1a - Fast berg	0.0
Total rutting	19.4
Studded tyre Wear	6.4
Fatigue life	0.7
Frost heave	111.5
Frost depth	1.4









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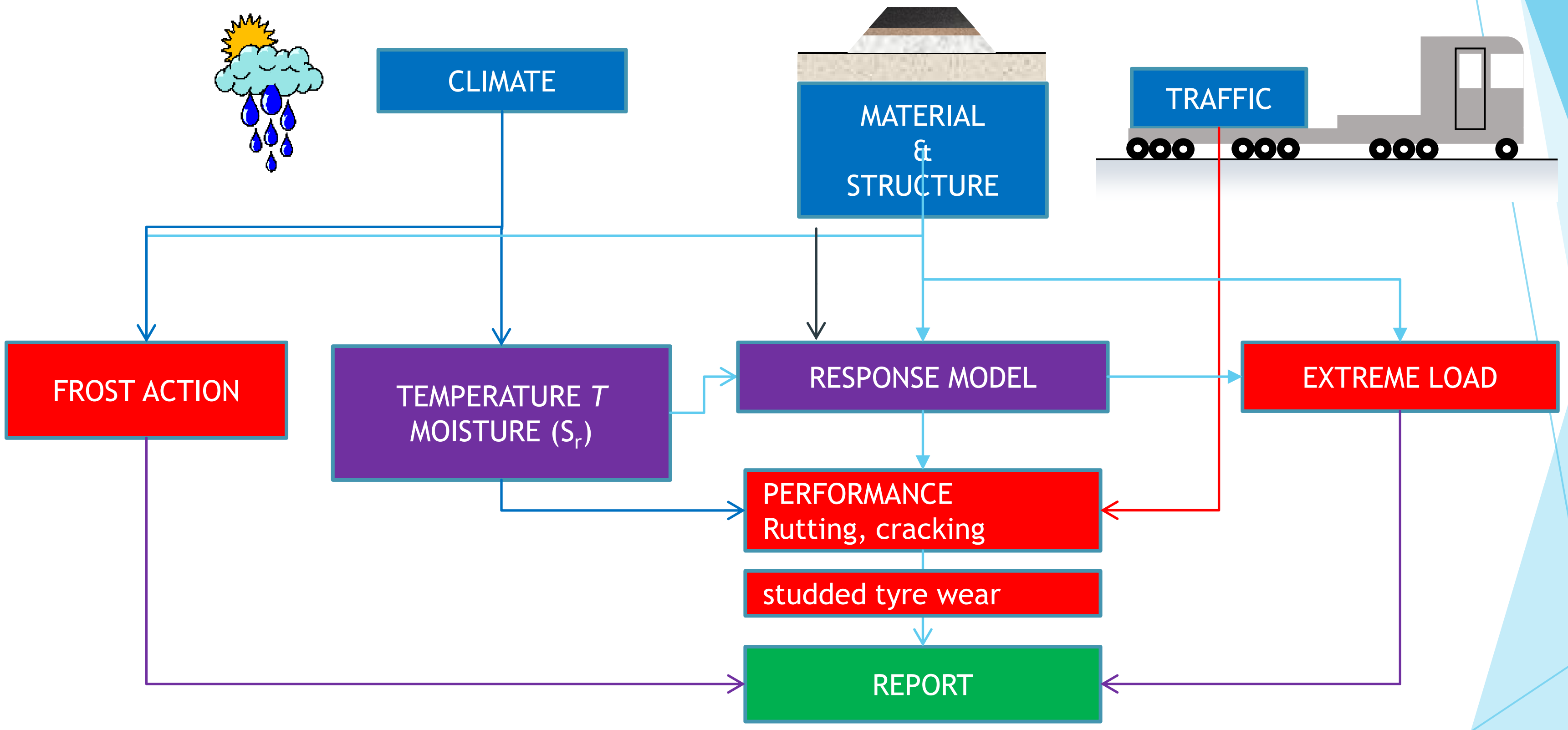
ERAPave PP components



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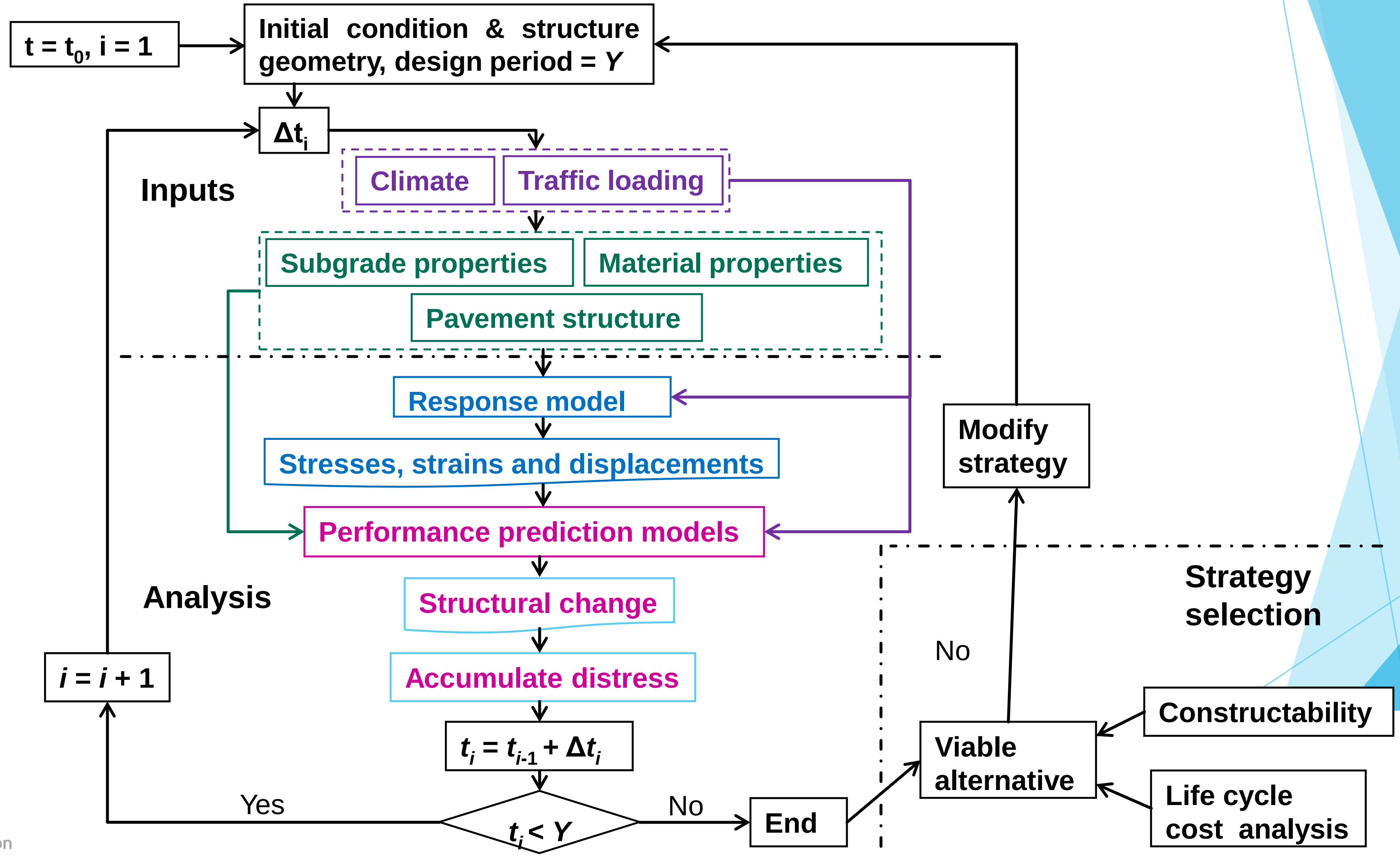
Flexible pavement design - rutting and fatigue cracking



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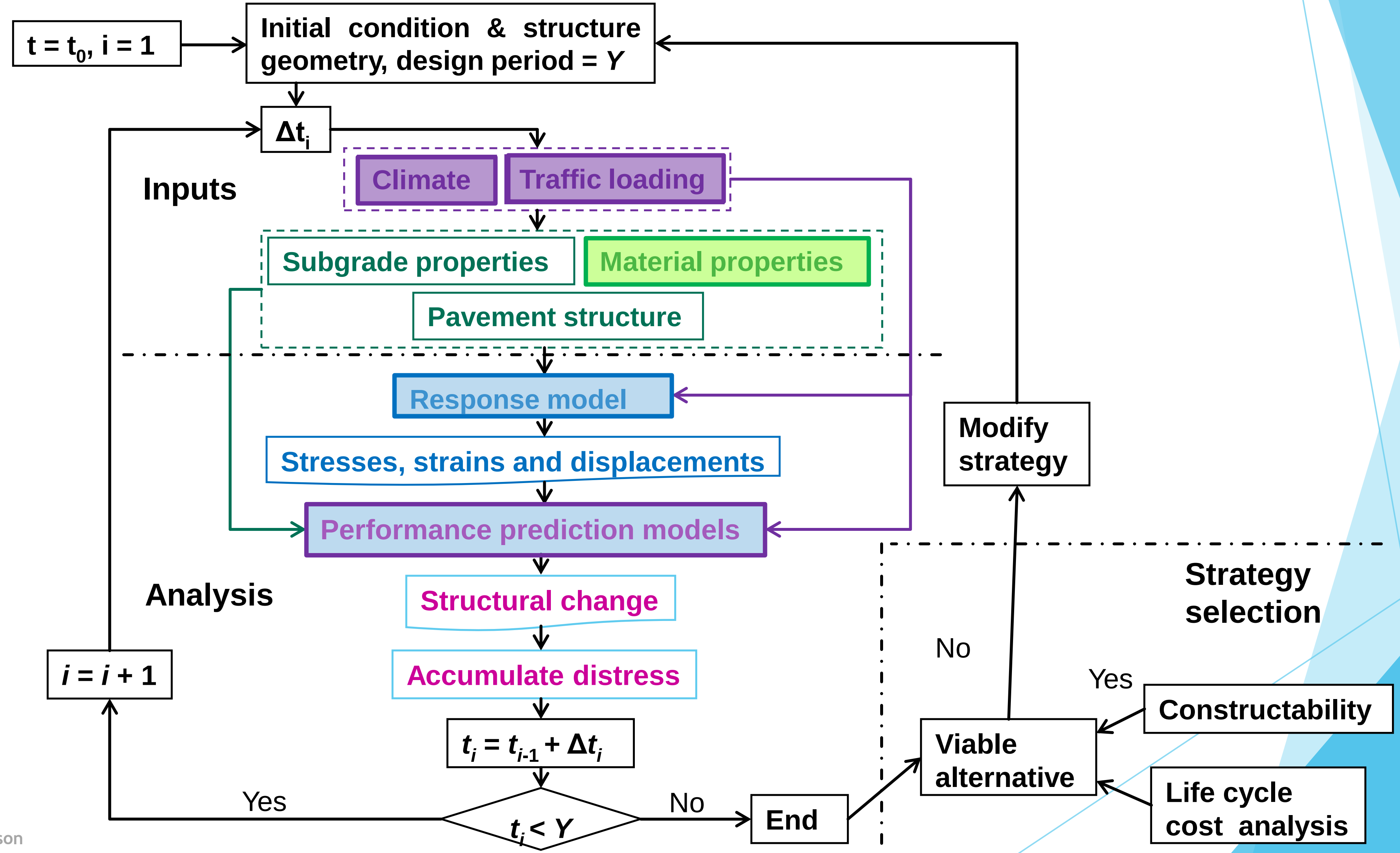
Flexible pavement design - rutting and fatigue cracking



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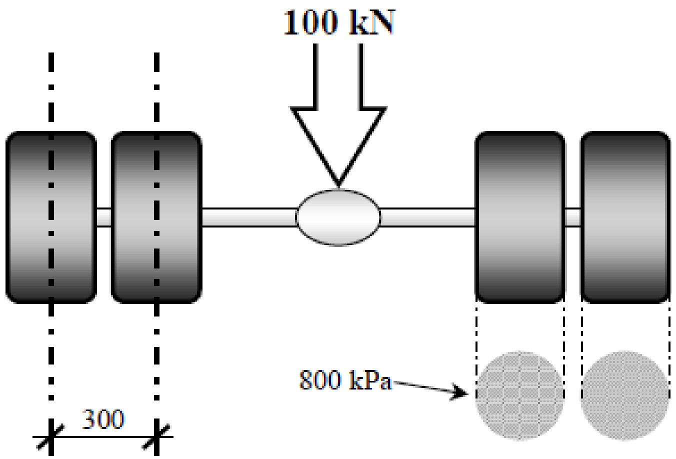
Traffic characteristics

- Traffic input is either:
  - Equivalent Single Axle Loads - ESAL´s
  - Axle Load Spectra – ALS from WIM-systems

  - Lateral wander is included
  - Traffic Growth factor is considered.

Traffic Loading: Standard axels

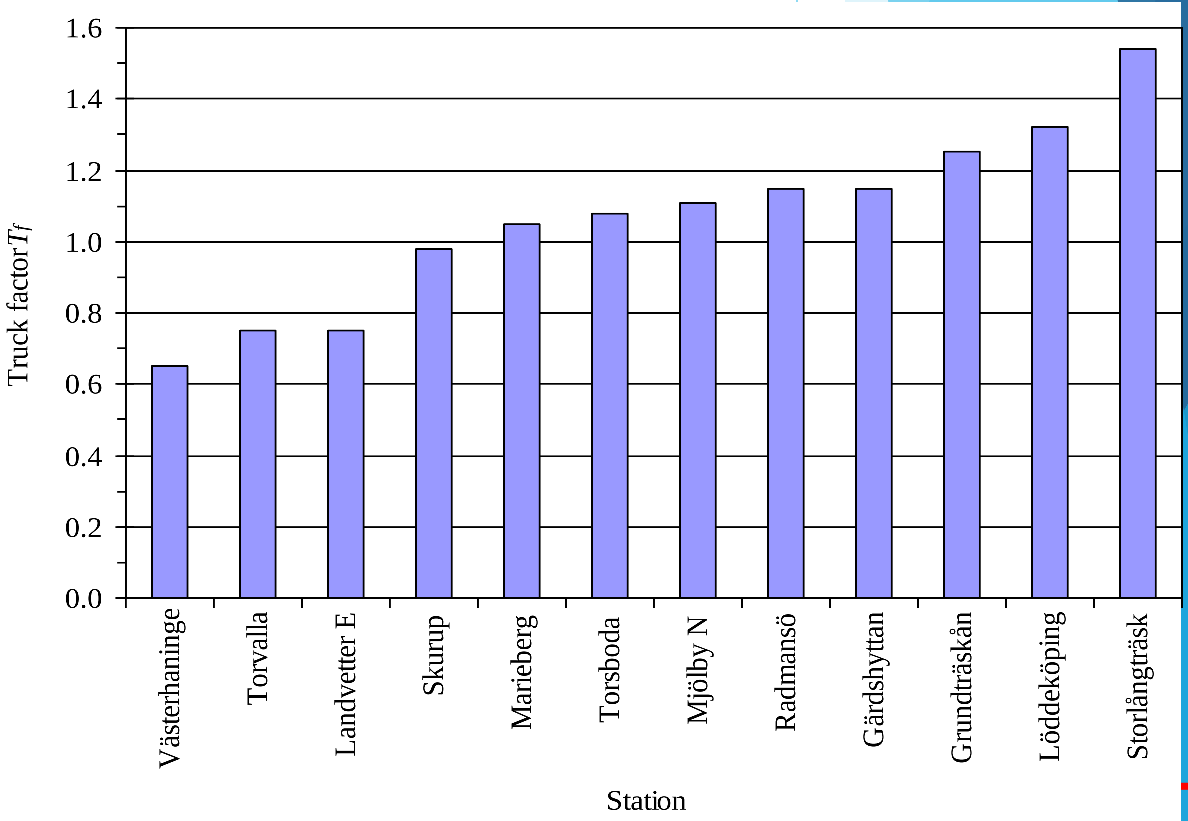
- Standard axels – Dual tyre configuration W = 100 kN, p = 800 kPa, c/c 300 mm



$$N_{ekv} = AADT_l \cdot 3.65 \cdot S_h \cdot T_f \cdot \sum_{j=1}^{n} \left(1 + \frac{k}{100}\right)^j$$

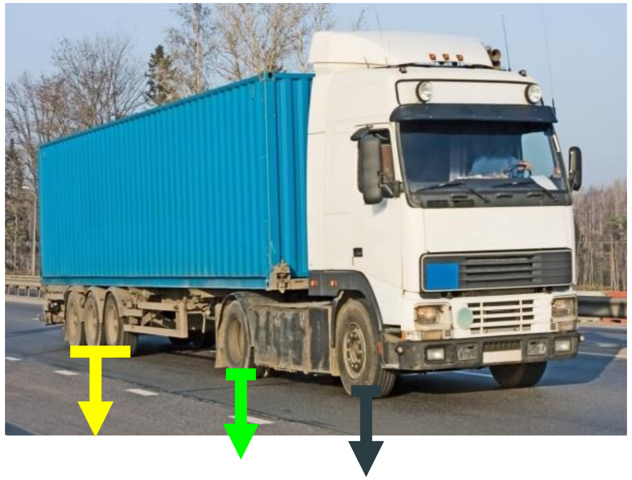
$$T_f = \frac{1}{N_{hv}} \cdot \sum_{i=1}^{4} N_i \cdot \sum_{j=1}^{n_j} \left(\frac{W_{ij}}{W_{i_{stand}}}\right)^4 \cdot \frac{f_j^{norm}}{100}$$

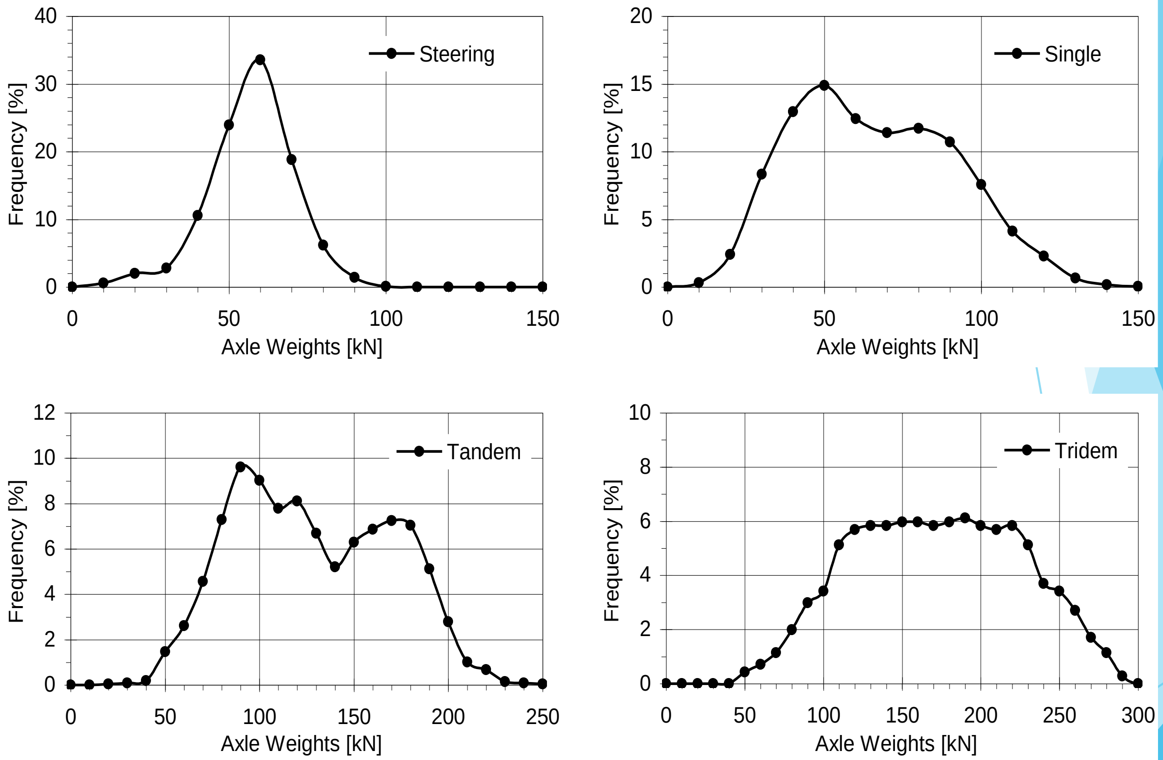
Truck factor based on 12 WIM locations.



Traffic loading: Axle Load Spectra (ALS)

Weigh-In-Motion (WIM) data





Steering axles

Single axles

Tandem axles

Tridem axles

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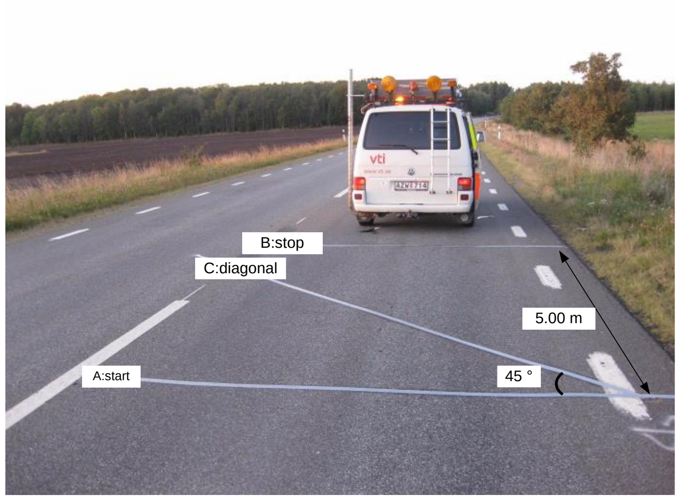
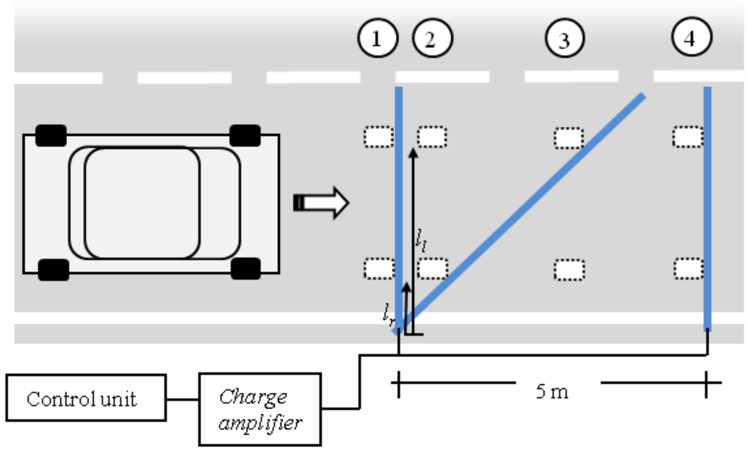
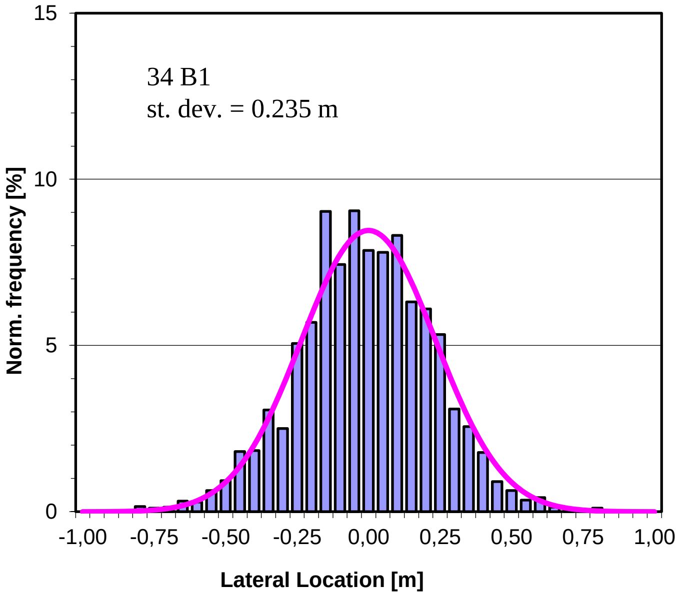
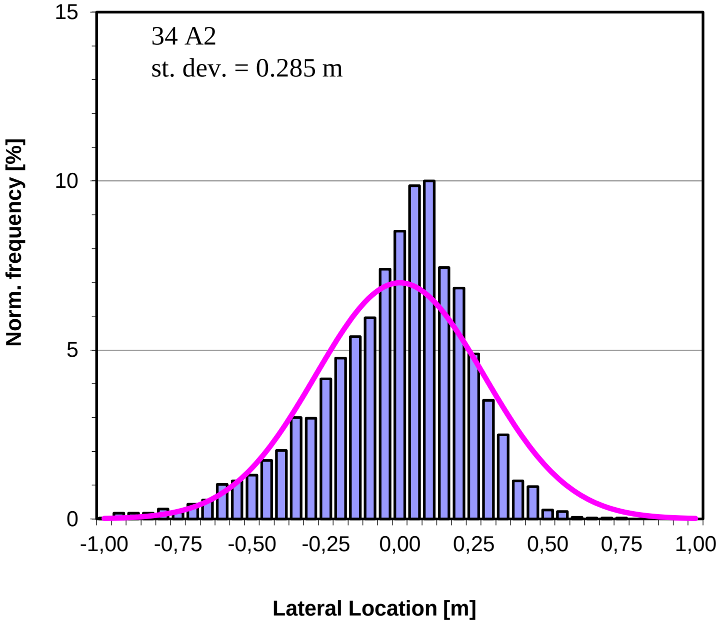
Traffic Loading: Lateral Wander









Climate dependency

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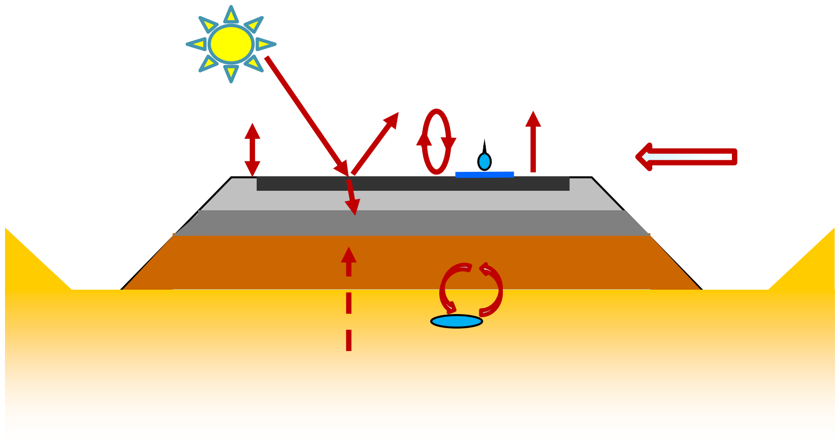
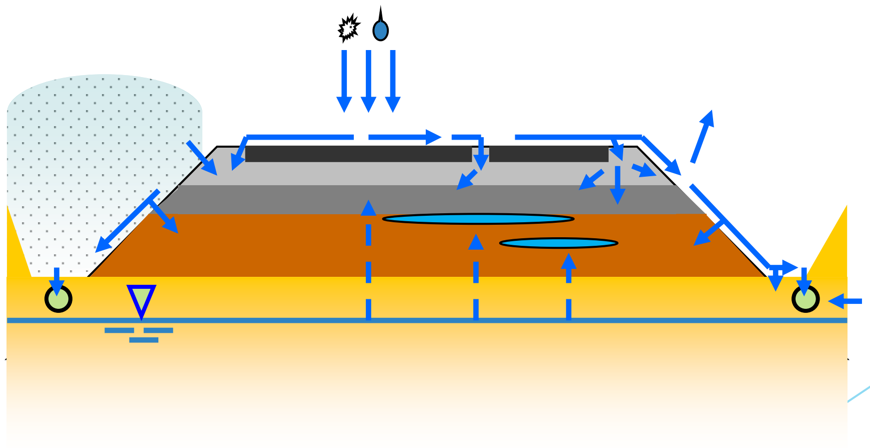
Climate dependency

Pavement response and degradation is highly dependent on the climate variables.
The two most important variables are **temperature *T*** and **moisture content *w*** (or degree of saturation S_r).

Heat balance

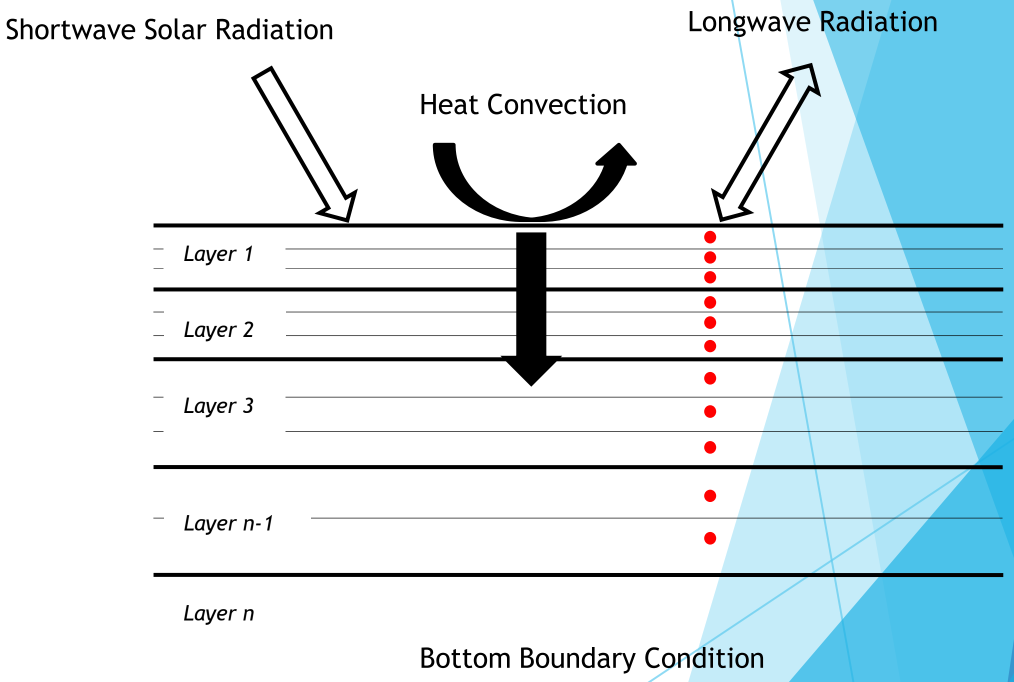


Water balance



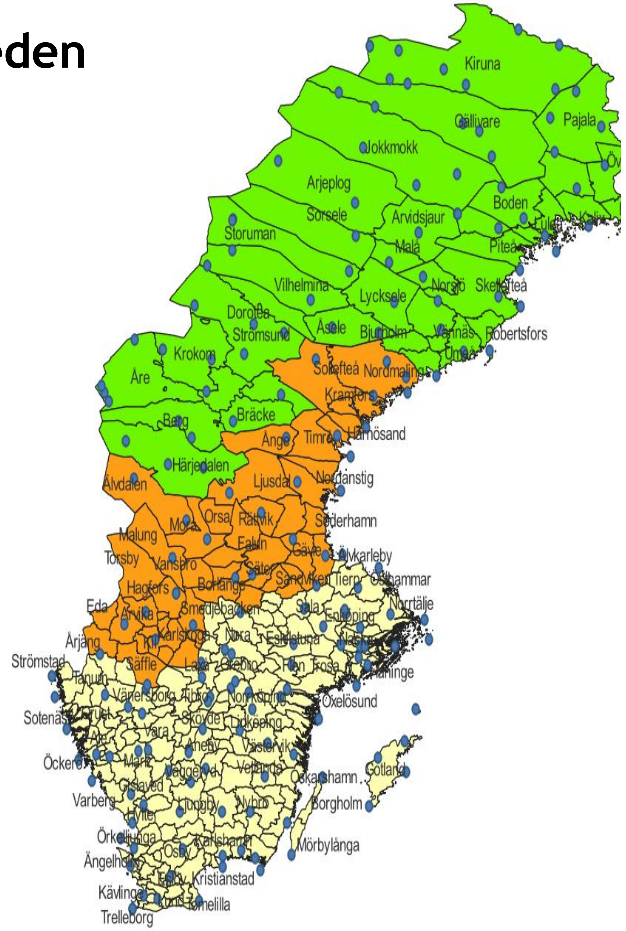
Heat balance: Temperature model

- 1-D Finite control volume method (FCVM)
- A numerical approach for solving the heat equation
- Discretization into small control volumes
- Input for analysis
  - Air temperature
  - Wind speed
  - Solar radiation

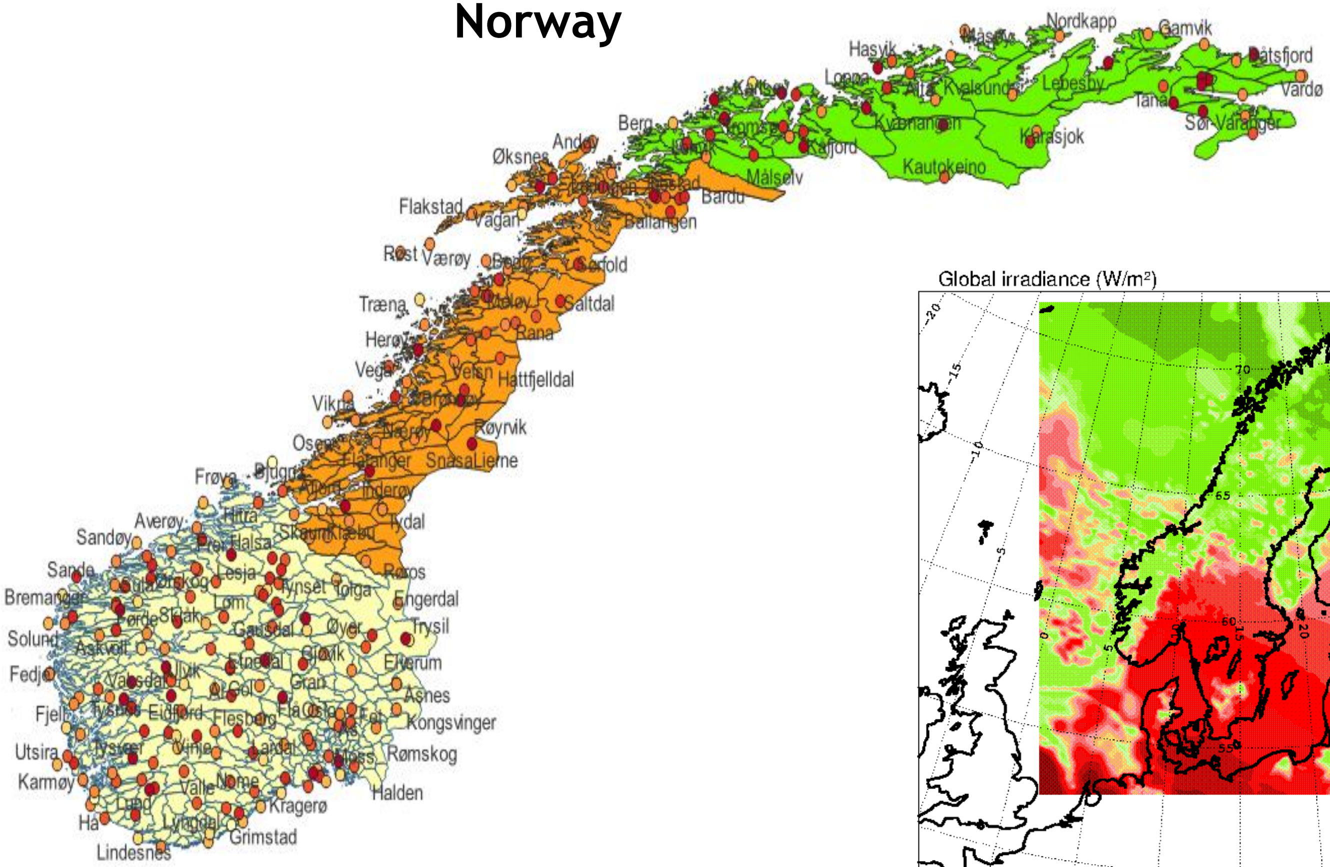


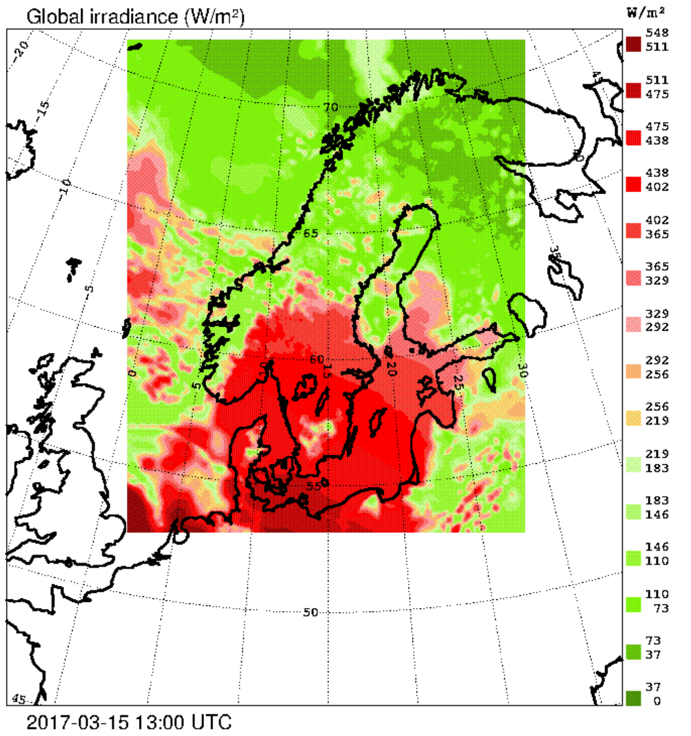
Climate data – Smhi.se and Frost.MET.no API

Sweden



Norway





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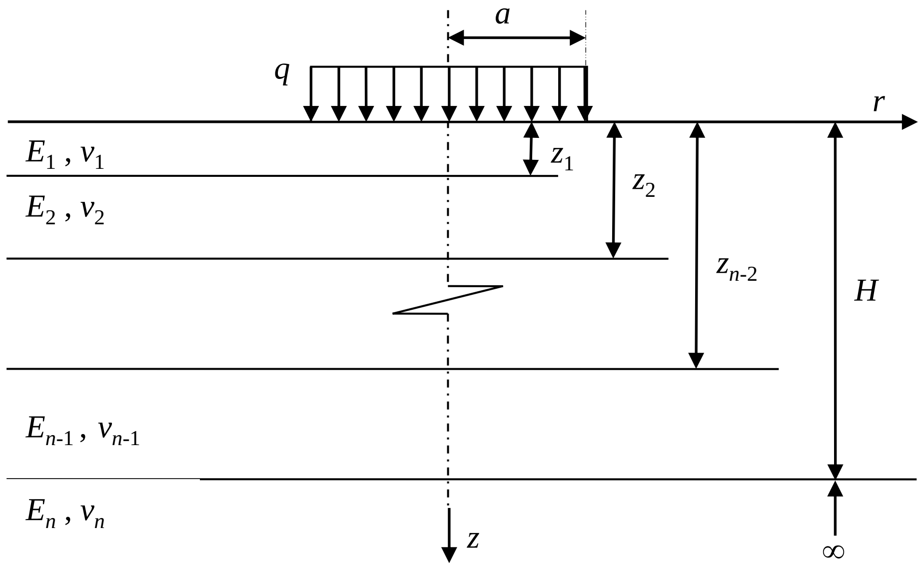
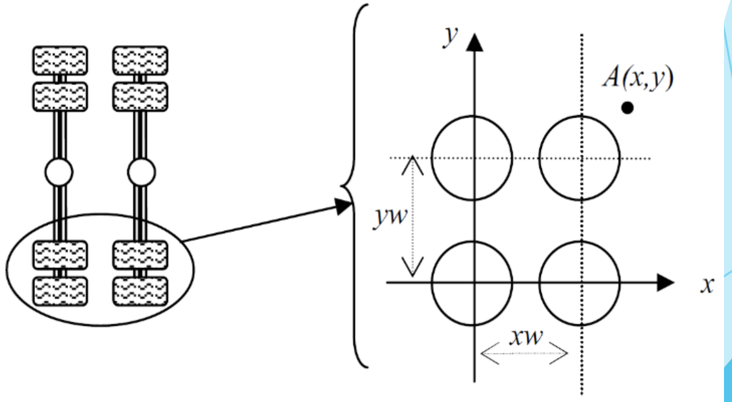
Response model

MLET - Multi-layer elastic theory

The elastic response of the tyre pavement interaction is estimated by a linear/nonlinear MLET (multi layer elastic theory) approach giving the stresses and strains at desired locations.



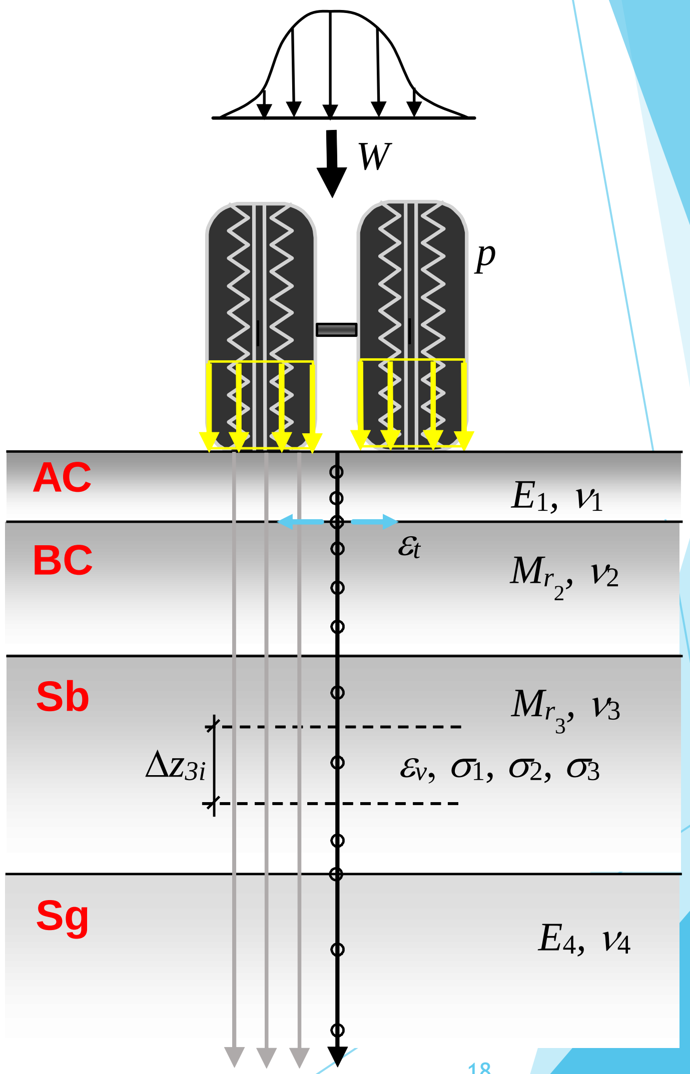


Response modelling

Based the MLET (MultiLayer Elastic Theory).

- AC is temp. dependent - lin. elastic matr.
- UGM:s are lin. or non-lin. (stress dependent) elastic material.

Lateral Wander is assumed normal distributed.



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Response calculations

Stiffness of asphalt bound layers - Temperature dependency

Two models are included in ERAPave PP.

Sigmoidal model (master curve estimations)

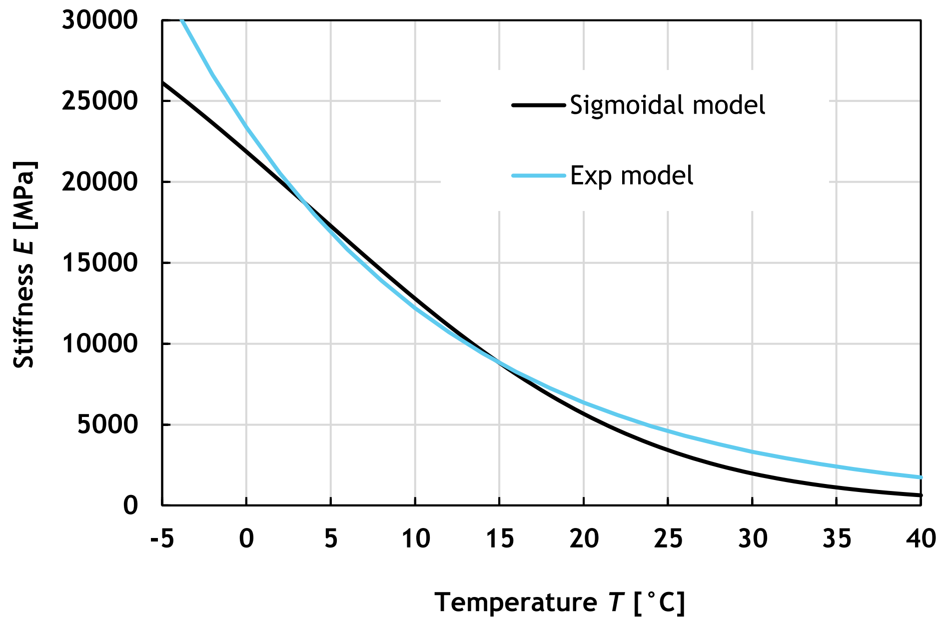
$$\log|E| = a + \frac{b}{1+e^{(c-d\log f_r)}}$$

a, *b*, *c* and *d* are material parameters and f_r is reduced frequency linked to the vehicle speed and thickness of the HMA layer.

Exponential model

$$E = E_{ref}\,e^{-b(T-T_{ref})}$$

b is material parameter and E_{ref} is the stiffness at reference temperature T_{ref}.



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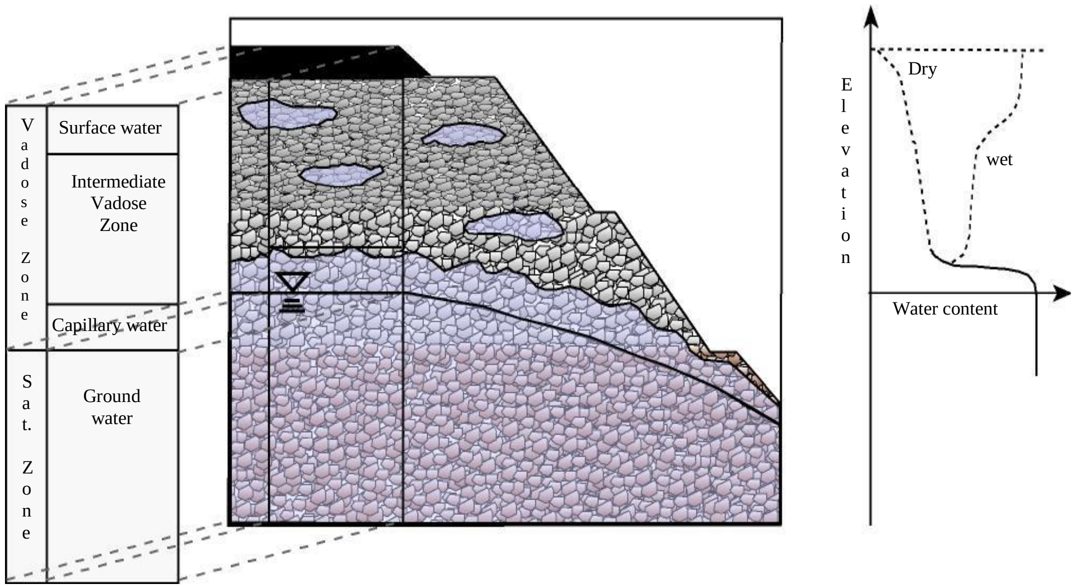
Response calculations

Stiffness of unbound layers and subgrades - Moisture dependency

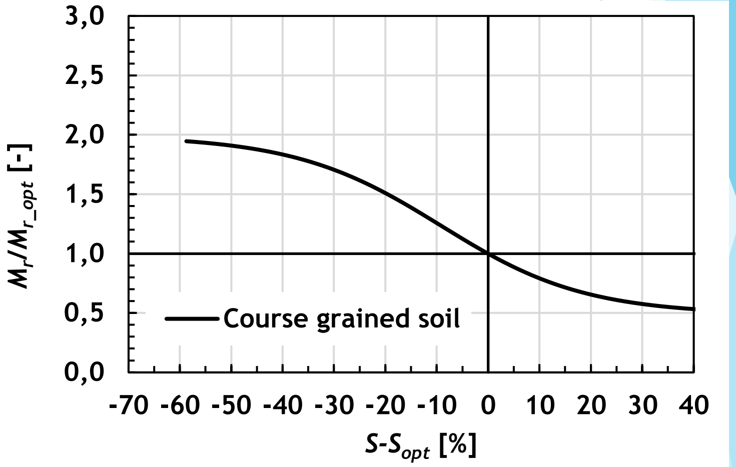
Stiffness – moisture content (degree of saturation) relationship is given as:

$$\log \frac{M_R}{M_{R_{opt}}} = a + \frac{b-a}{1+\exp\left(\ln\frac{-b}{a} + k_m\left(S - S_{opt}\right)\right)}$$

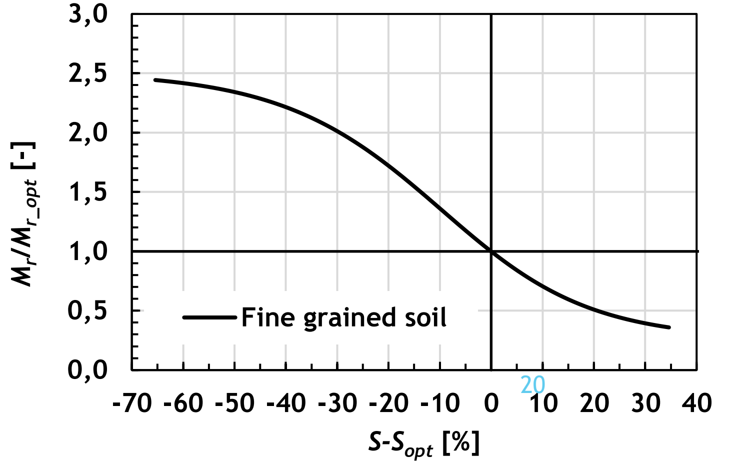
a, b and k_m are material parameters.



Base course and subbase matr.



Fine grained subgrade matr.



Performance prediction

- Fatigue cracking (bottom-up)
- Rutting (permanent deformation)
- Abrasion (studded tyre wear)
- Frost heave

Abrasion (studded tyre wear)

Rutting (plastic deform.)

Fatigue cracking (bottom-up)

Frost actions & frost heave damage

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Performance predictions

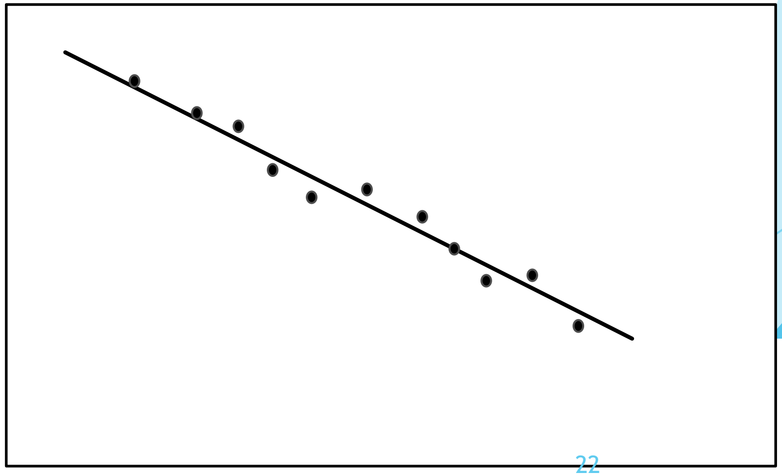
Bottom-up fatigue cracking

Fatigue law: $N_f = a\varepsilon_{bt}^{-b}E^{-c}$ $\quad (N_f = a\varepsilon_{bt}^{-b})$

$$\log(N_f) = f_1 - f_2 \log \varepsilon_{bt} - f_3 E$$

Lab to field: $a_{field} = s a_{lab}$

- Miner´s rule used for summation: $D = \dfrac{\sum n_i}{\sum N_{f_i}}$ $\quad 0 \le D \le 1$



Typical input parameters:
$f_1 = 14$ (12 - 15)
$f_2 = b = 4$ (3 - 5)
$f_3 = c = 0$

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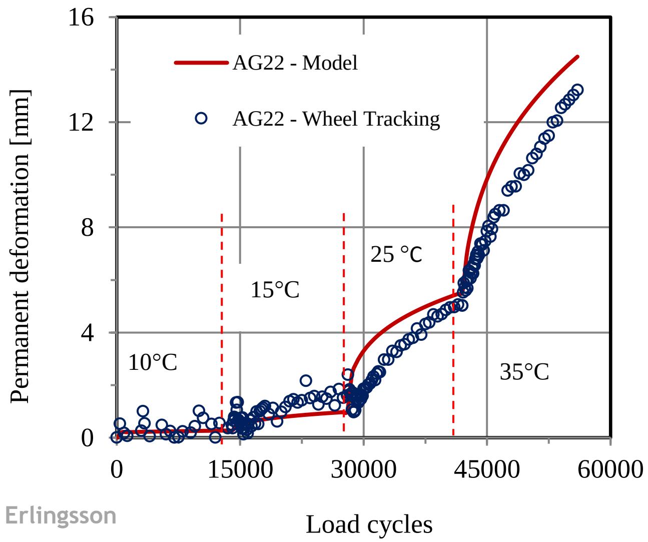
Performance predictions

Plastic deformation (rut)

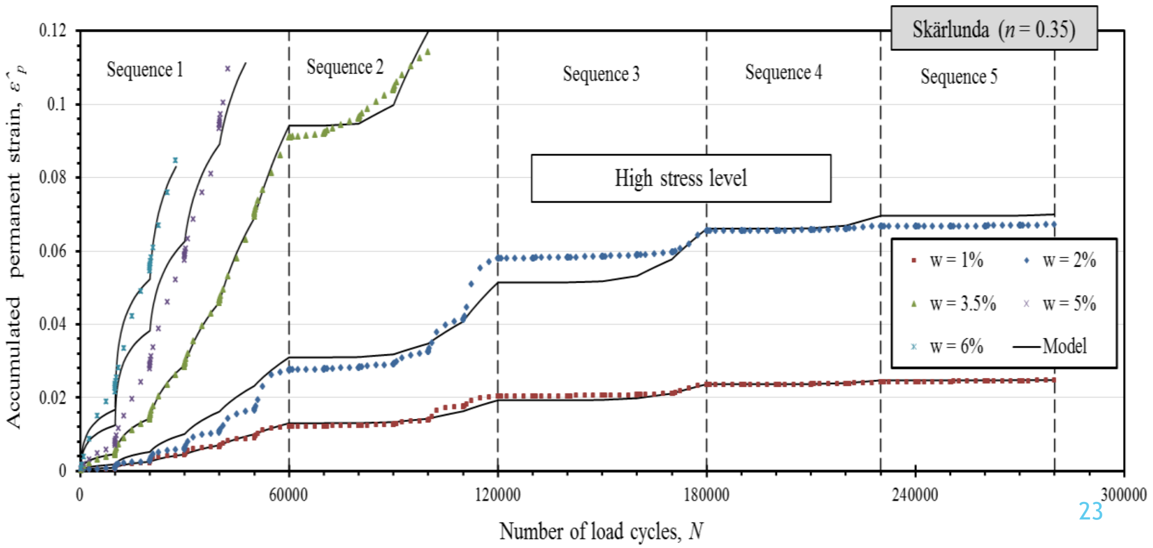
- **AC:** $\hat{\varepsilon}_p(N) = a_1 T^{a_2} N^{a_3} \Delta\varepsilon_r$ $\qquad \Delta\varepsilon_r = \Delta\varepsilon_r(T)$
- **UGM & soils:** $\hat{\varepsilon}_p(N) = aN^{b\Delta\varepsilon_r}\Delta\varepsilon_r = (c_1 + c_2 S_r)N^{b\Delta\varepsilon_r}\Delta\varepsilon_r$ $\qquad \Delta\varepsilon_r = \Delta\varepsilon_r(S_r)$

$$\hat{\varepsilon}_p(N) = \left(\frac{\varepsilon_0}{\Delta\varepsilon_r^{ref}}\right) e^{\left(\frac{\rho}{N}\right)^{\beta}} \Delta\varepsilon_r$$

AC layers



Unbound layers



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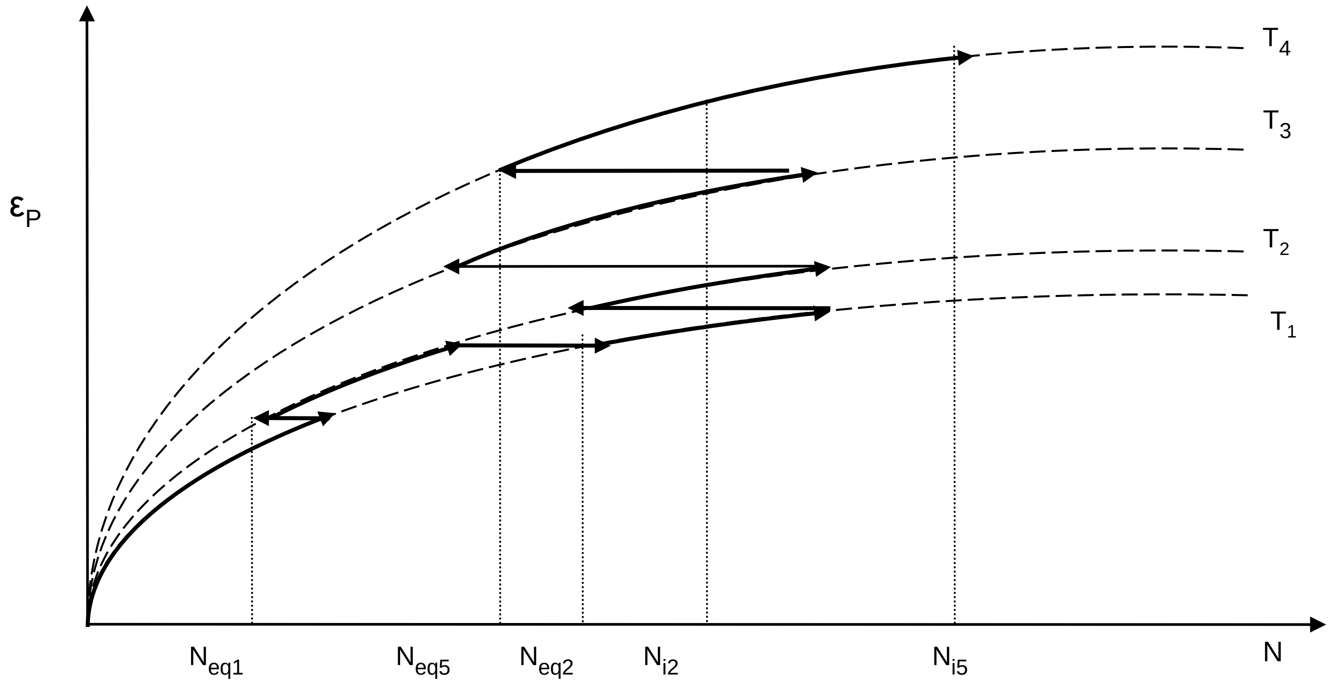
Accumulation (Superposition) of perm. strain

Time hardening approach



Step j

$$N_{eq_j} = \left[\frac{\hat{\varepsilon}_{p_{j-1}}}{\hat{\varepsilon}_{p_j}(N=1)} \right]^{\frac{1}{m}}$$

$$\hat{\varepsilon}_{p_j} = \hat{\varepsilon}_{p_{j-1}} + \hat{\varepsilon}_{p_j}(N=1) \cdot \left[\left(N_{eq_j} + \Delta N \right)^m - N_{eq_j}^m \right]$$

j= j+1

Next j

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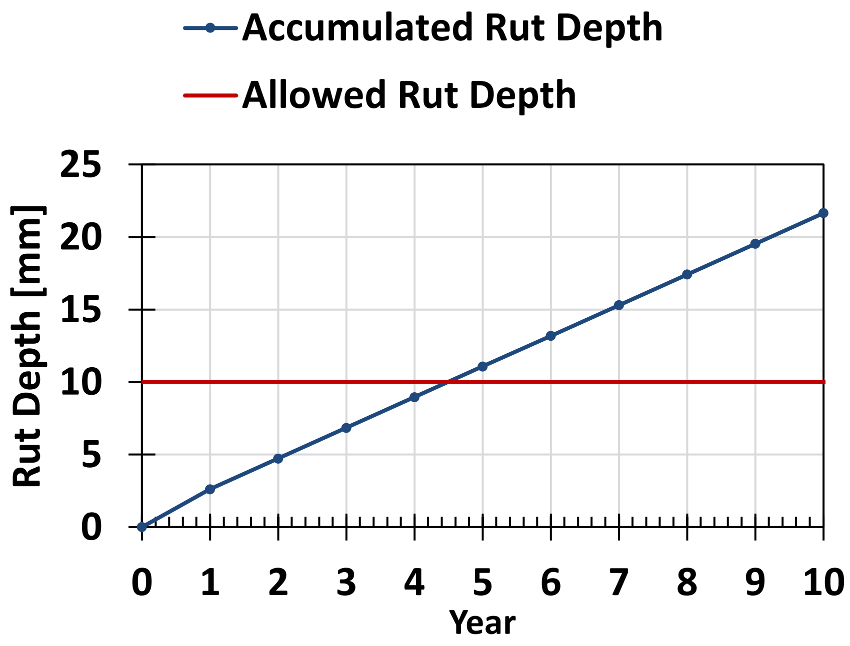
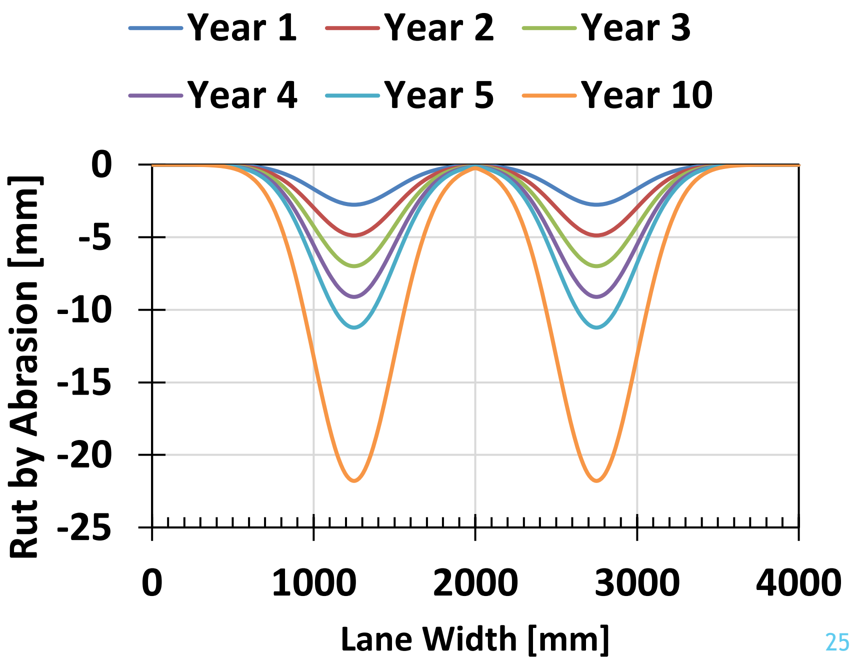
Studded tyre abrasion

An empirical model based on laboratory testing and calibrated/validated in in-service road tests.

Parameters needed: v, $AADT_L$, Lane width (st. dev.), de-icing, W_p, SST
Two models:
The Nordic abrasion sub-model: A_N, D_{max}, MAS_4
Prall sub-model: A_P





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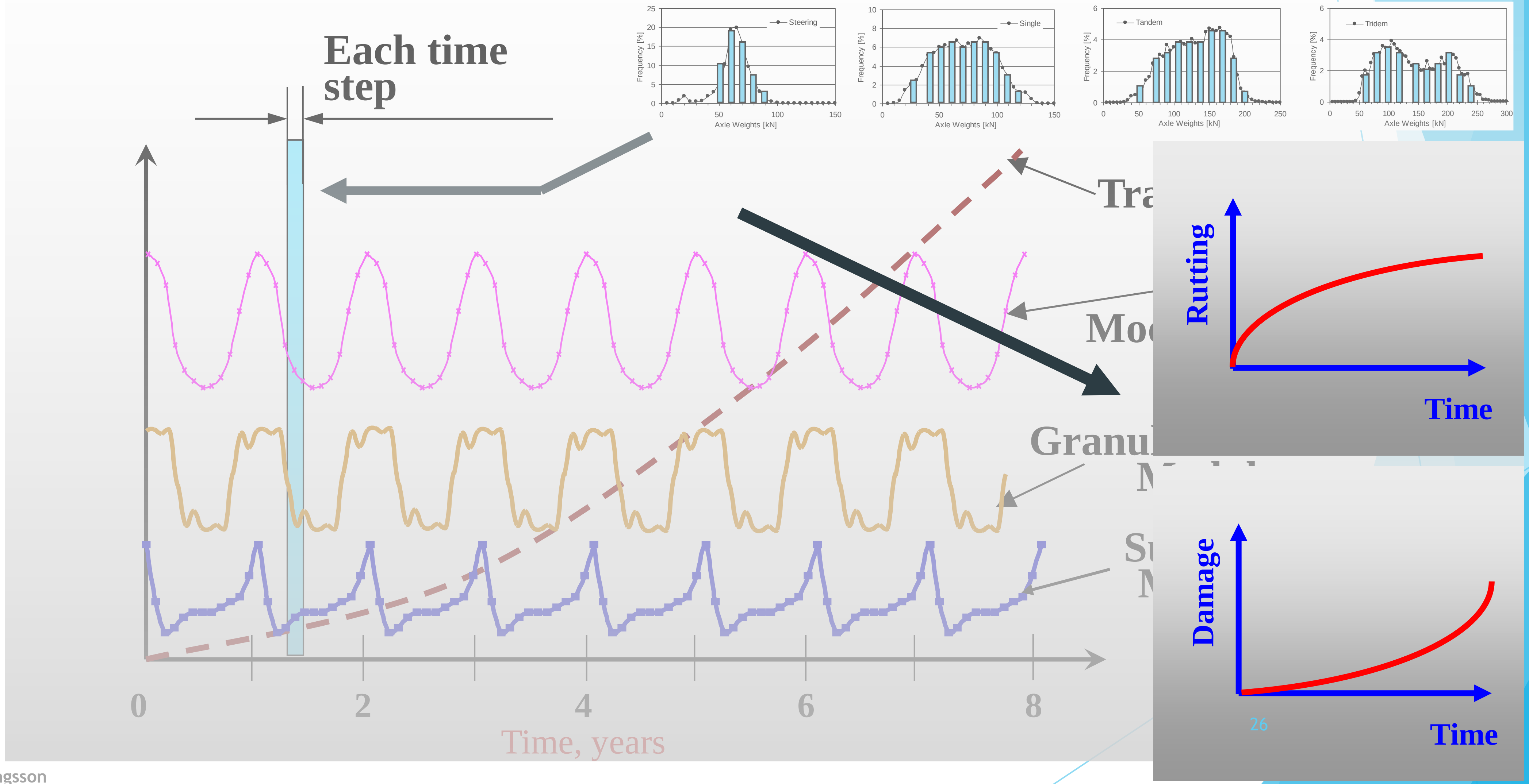
Performance Predictions



Validation (calibration)

- **Climate Predictions**
  - Temperature
- **Response and Performance Predictions**
  - Small scale laboratory testing (RLT tests & ELWT tests)
  - Full scale laboratory testing: APT (HVS)
  - In-service roads
    - LTPP sections
    - Instrumented test sections

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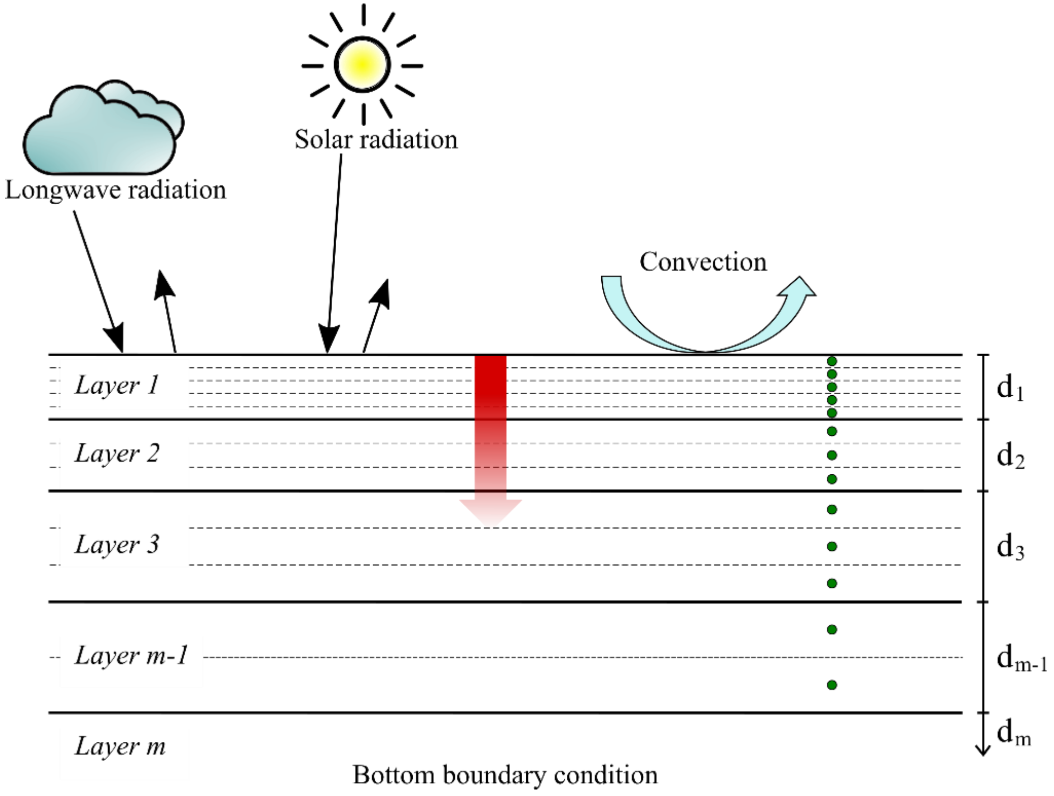
Validation - Climate modelling



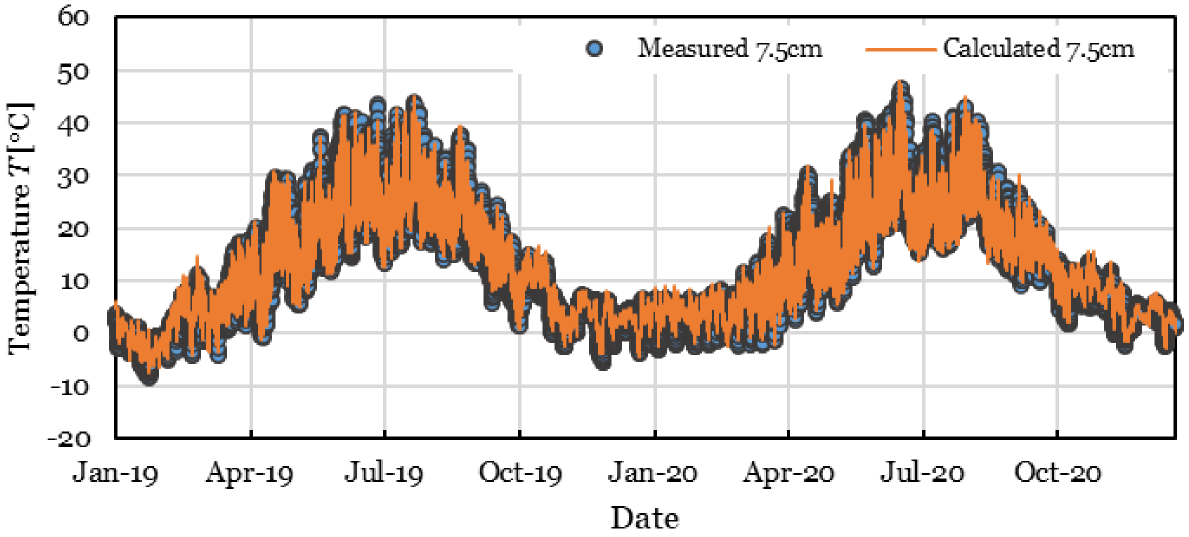
- External factors considered at the upper boundary condition:
  - Air temperature
  - Solar shortwave radiation
  - Longwave infrared radiation
  - Convective heat transfer (wind speed)
- Bottom boundary condition modelled as constant temperature (5m depth)
- Temperature distribution in the cross-section given by the 1-D diffusion partial differential equation

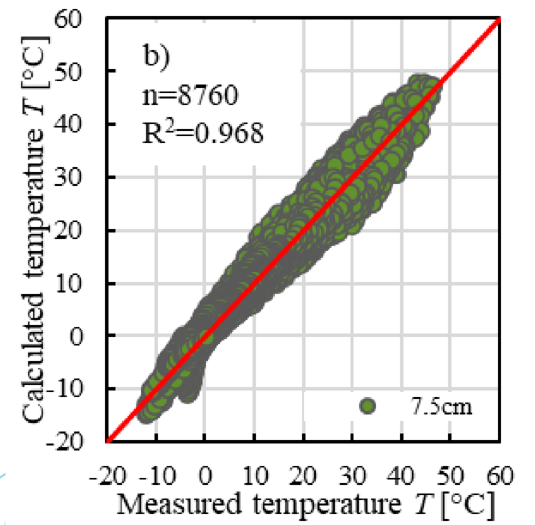
$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

where:
ρ is the density, kg/m^3
c_p is the heat capacity, J/(kg K)
k is the conductivity, W/(mK)

- Discretization into finite control volumes (FCV)

Validation - Temperature prediction in AC layers





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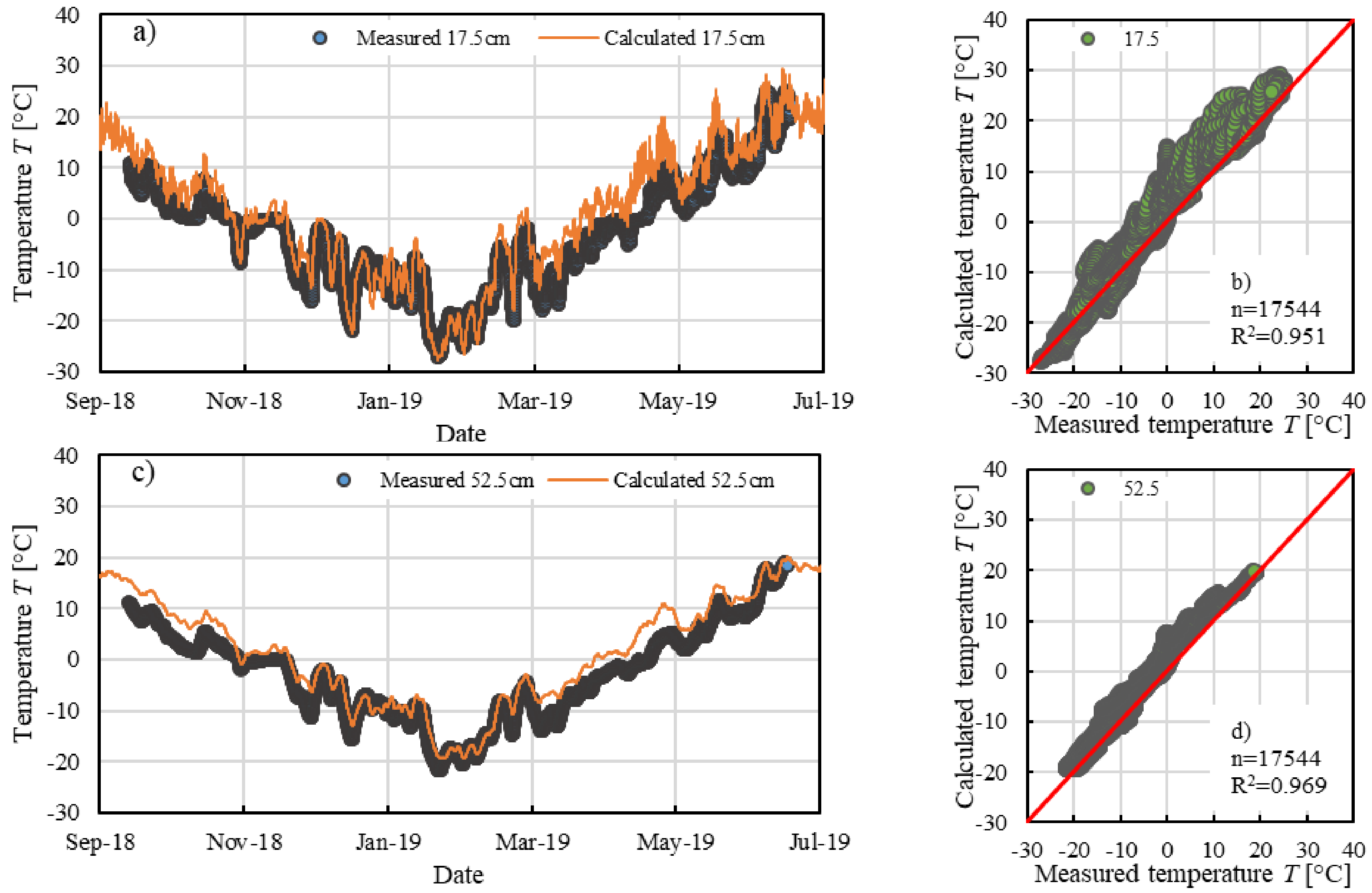
Validation - Temperature predictions in granular layers



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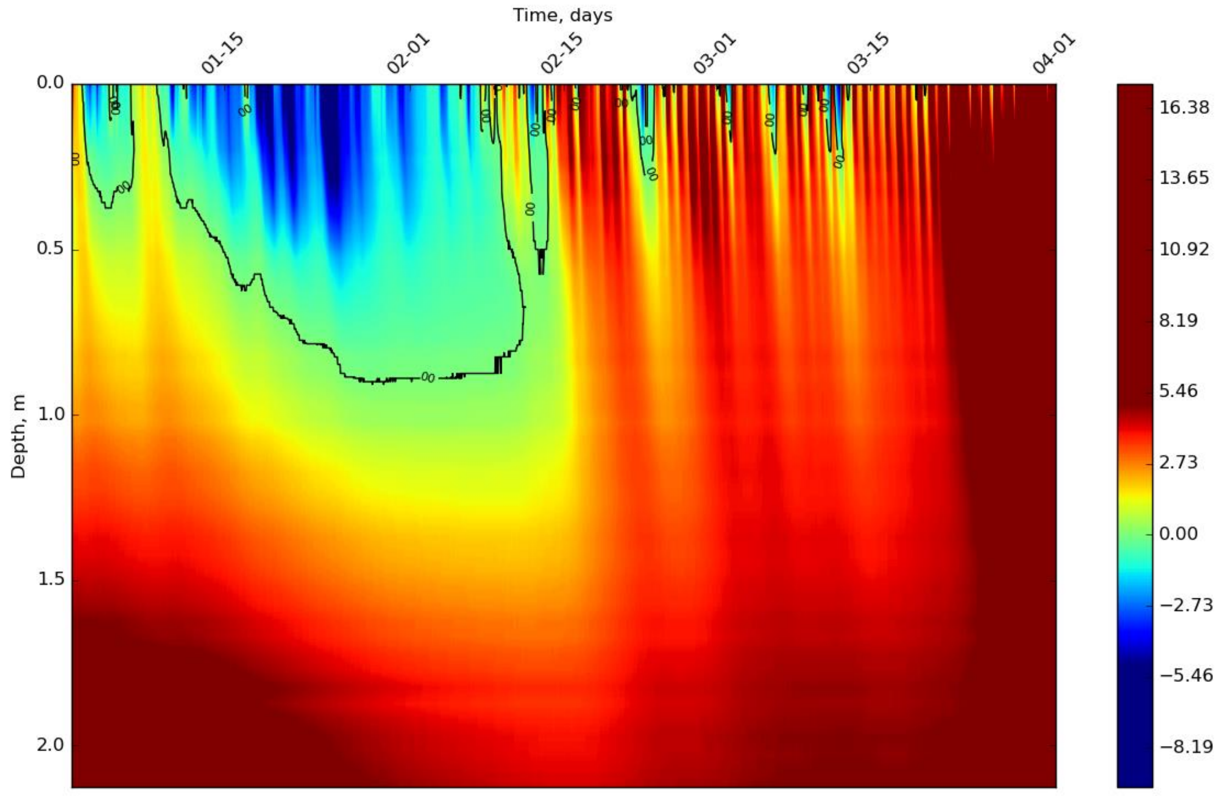
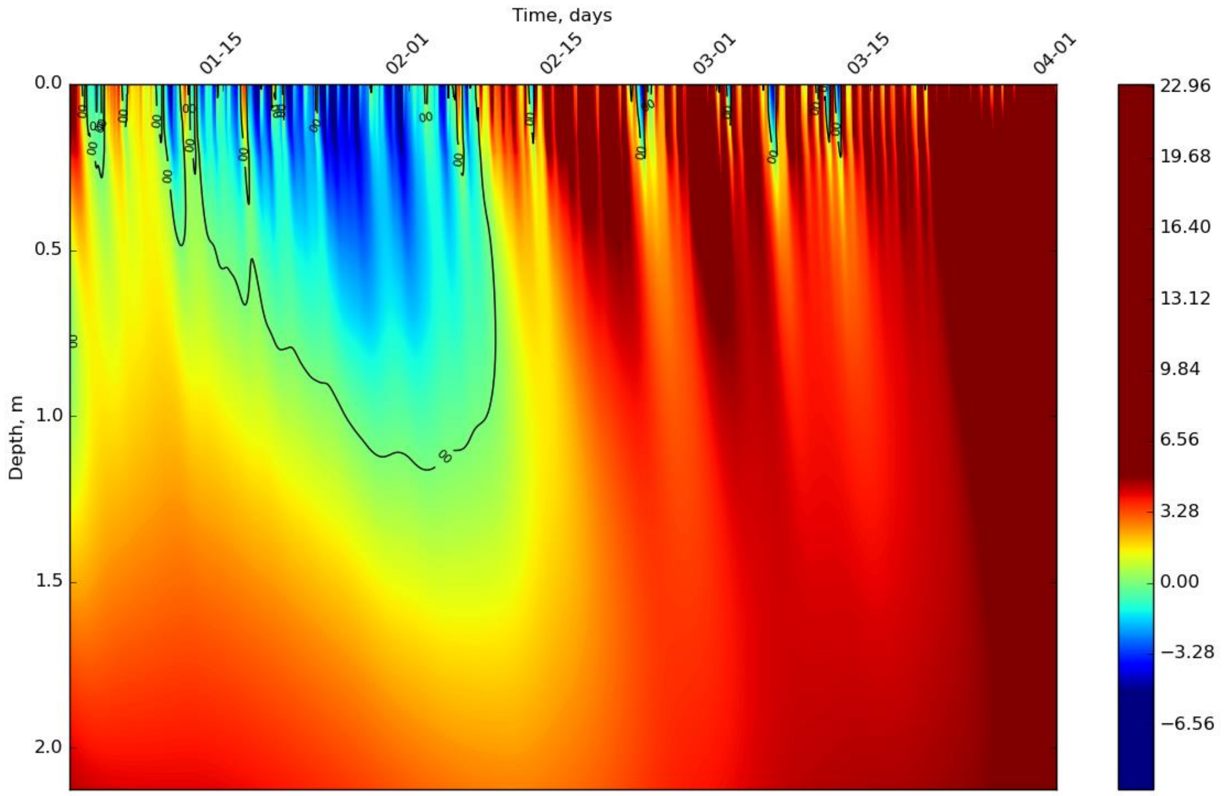
Validation – Frost depth penetrations

Measured



Predicted



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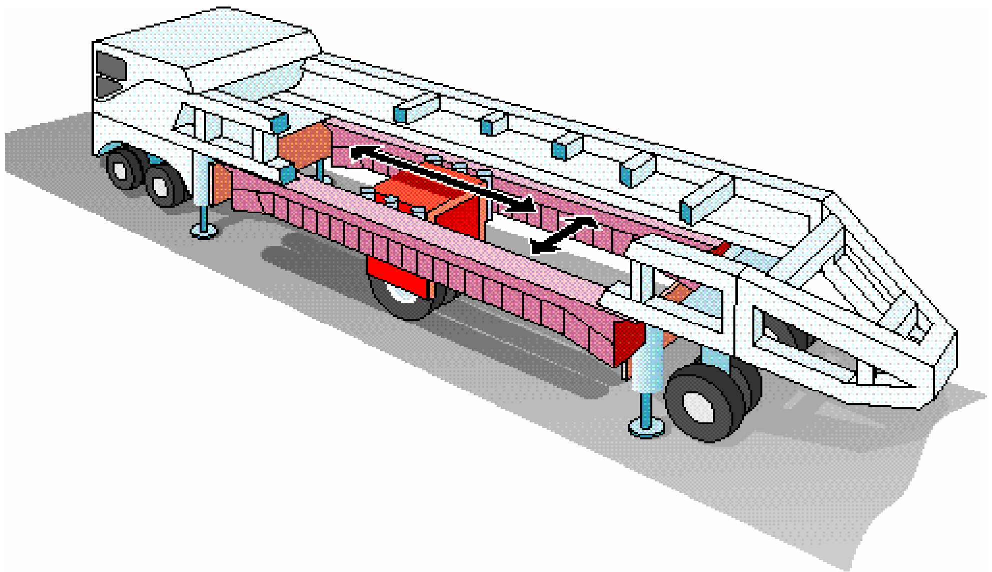
Validation: The Heavy Vehicle Simulator (HVS)

The Heavy Vehicle Simulator (HVS) is a mobile APT test facility.



Validation HVS: Construction of test object

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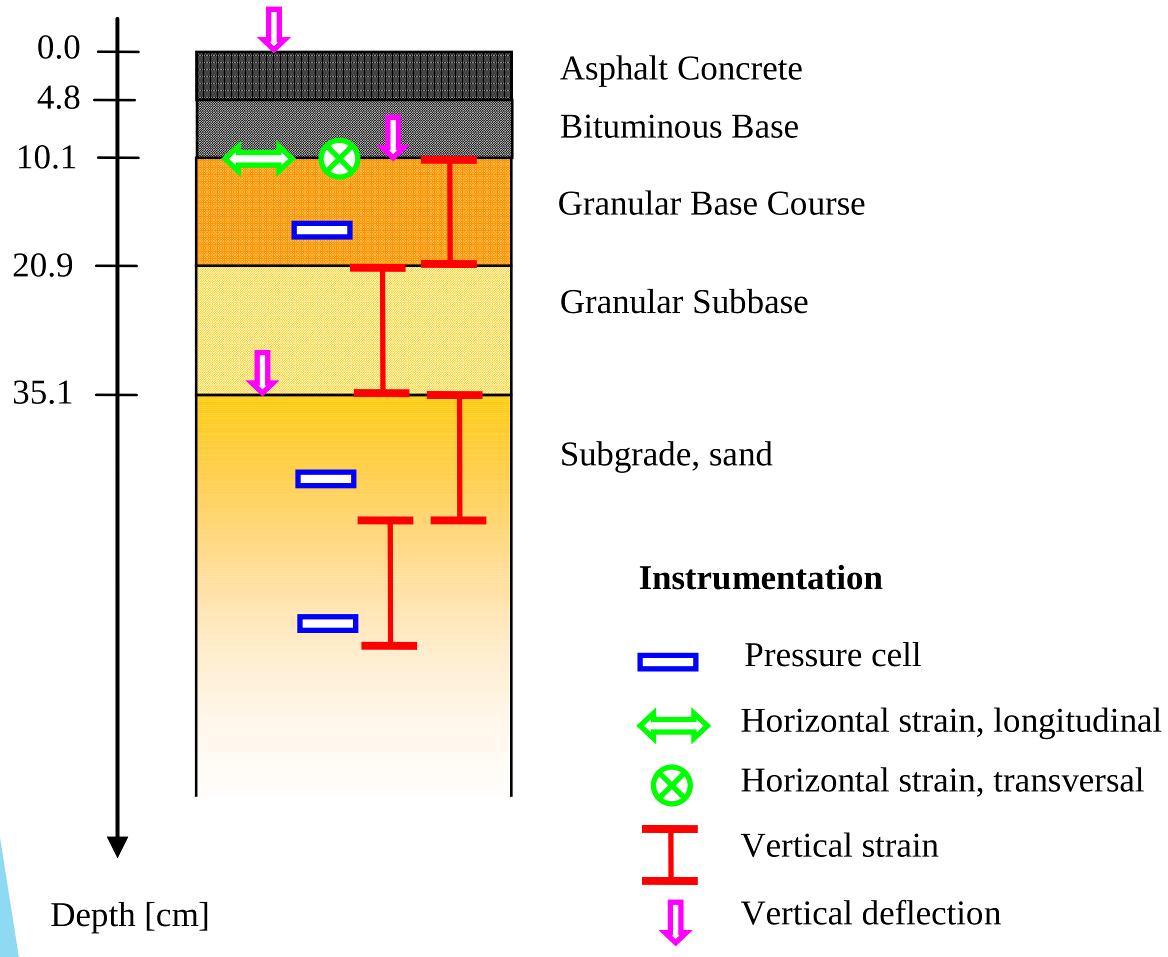
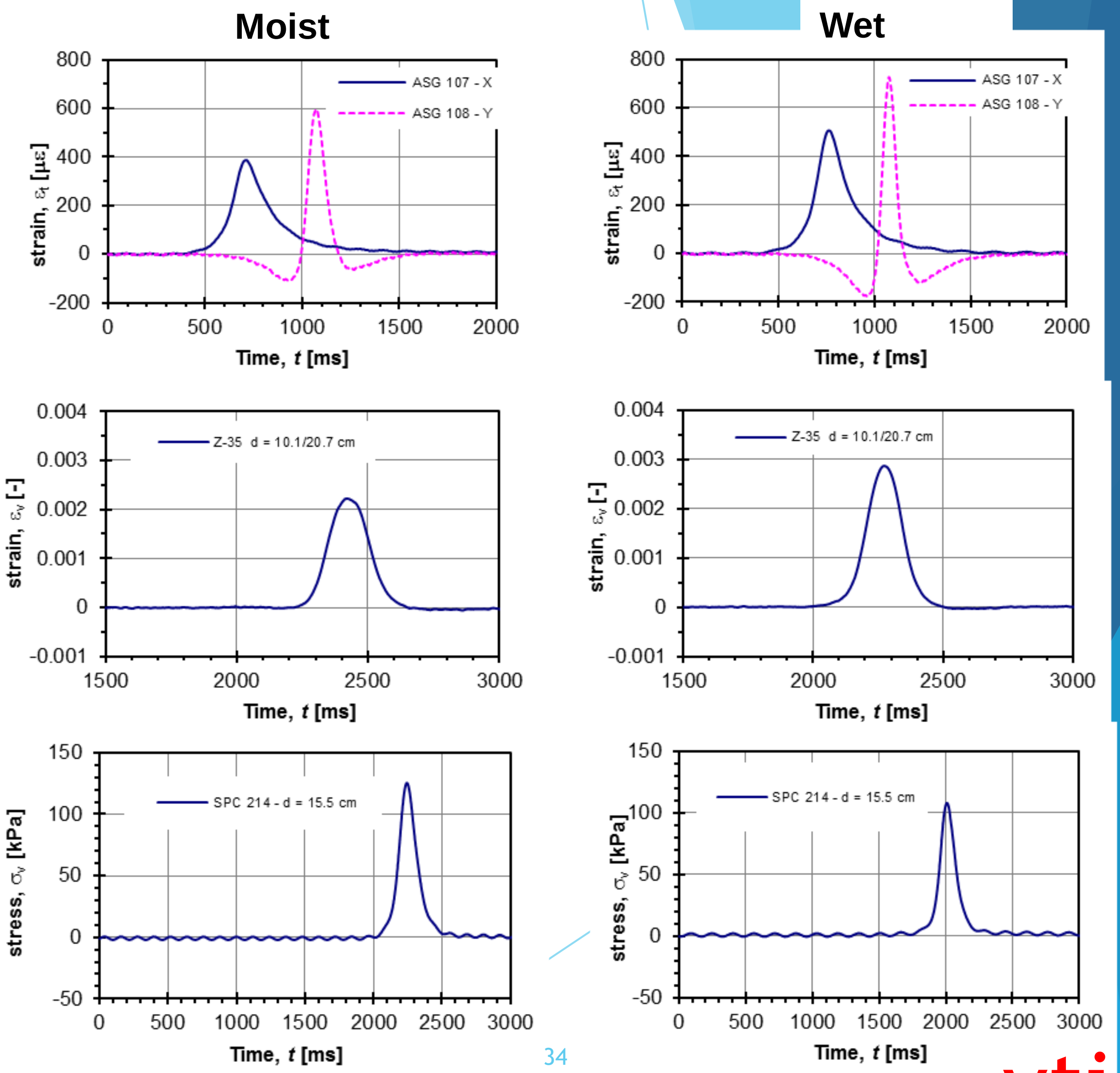
Instrumented test structure: An example





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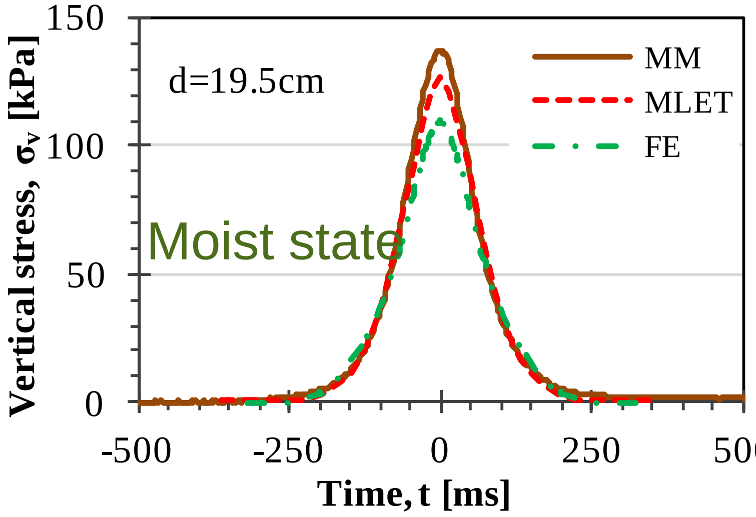
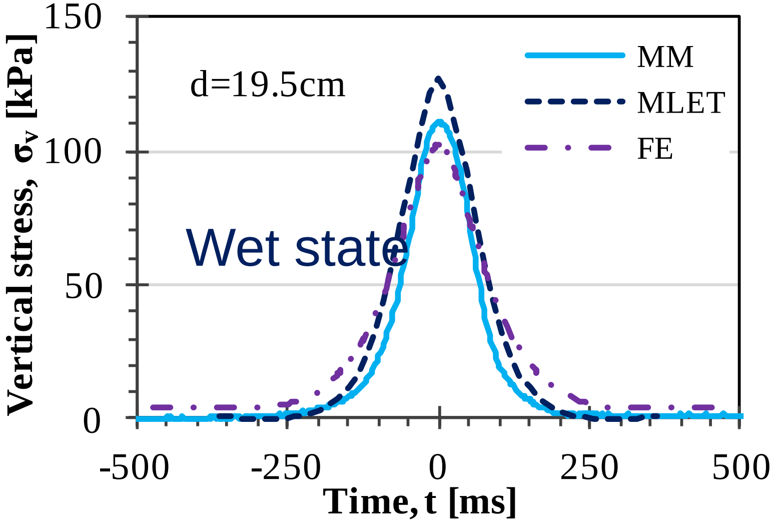
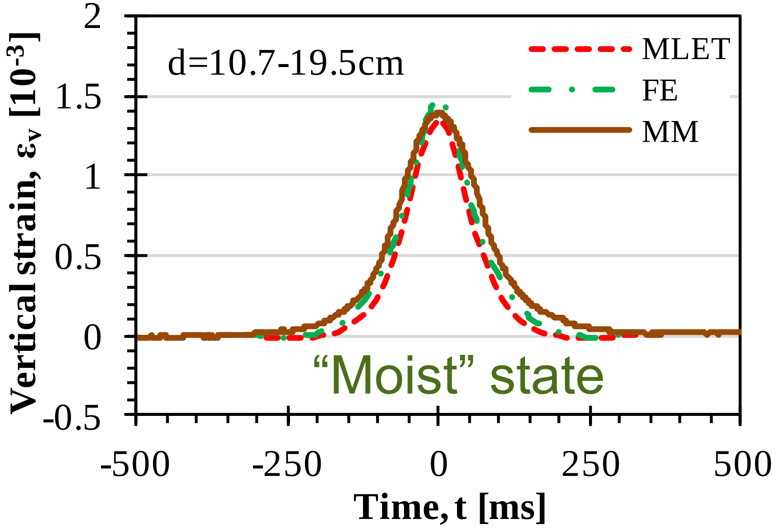
Response - comp. of measured and predicted values

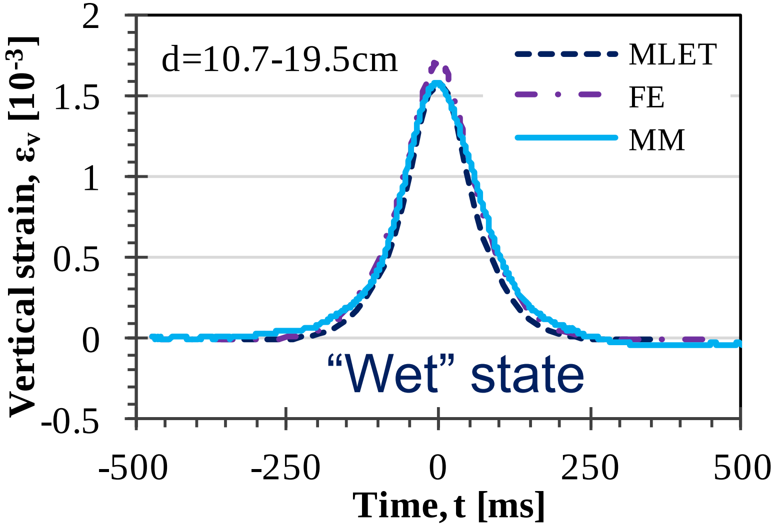
The response – vertical stress





The response – vertical strain





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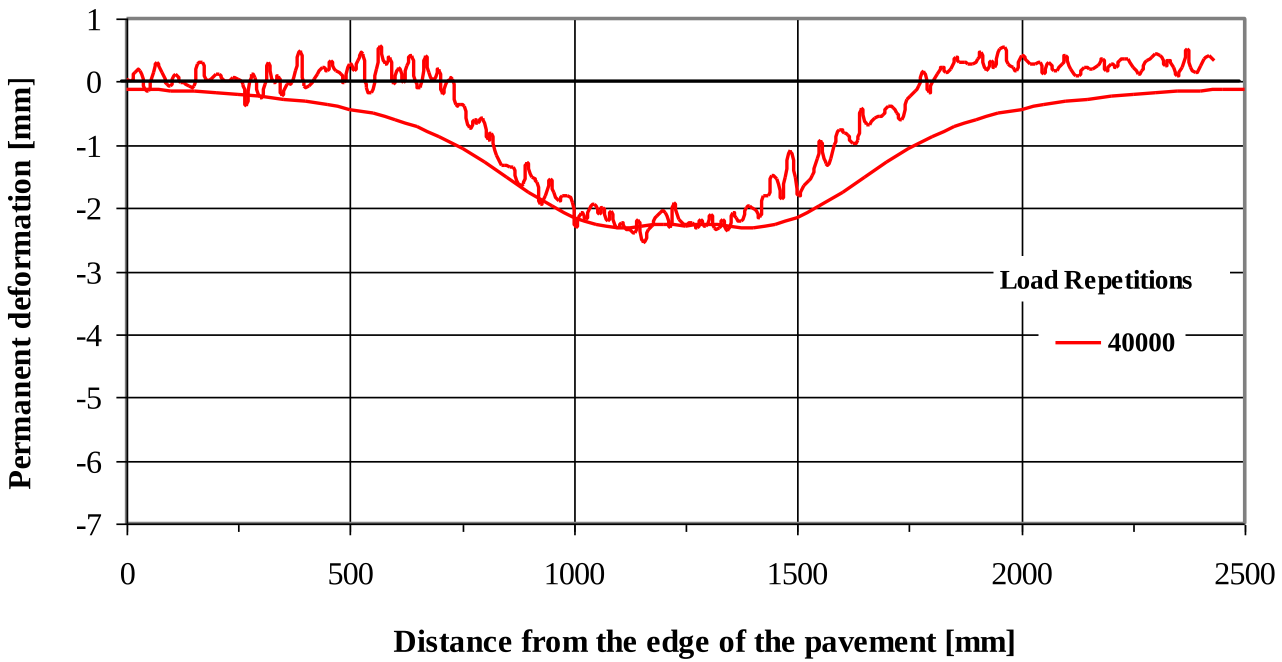
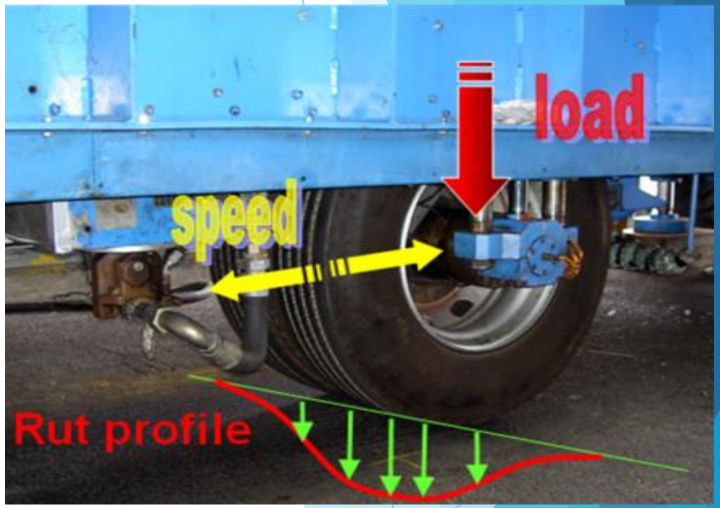
HVS rutting profile

Comparison between measurement and calculation





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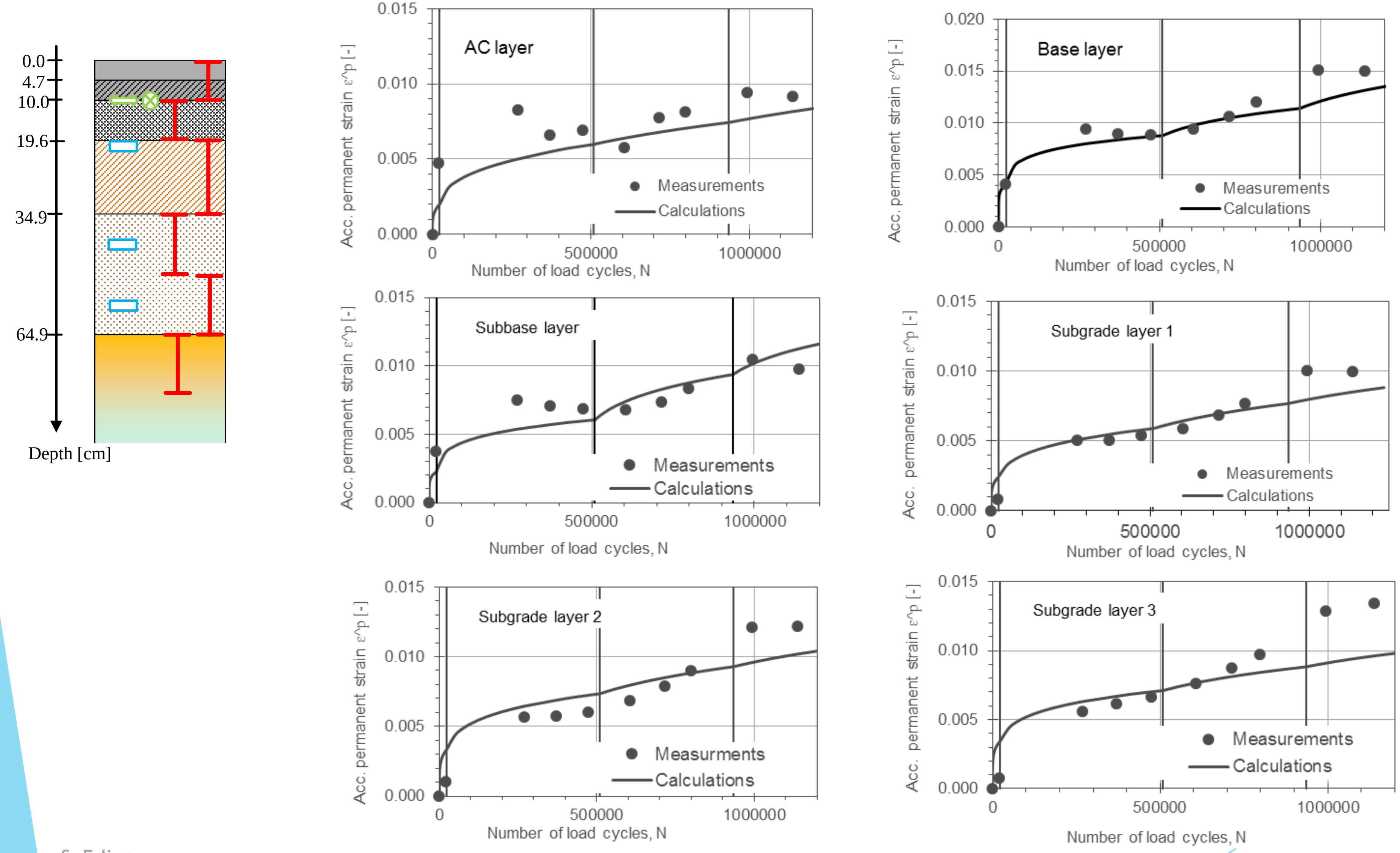
HVS - Validation - vertical permanent strain



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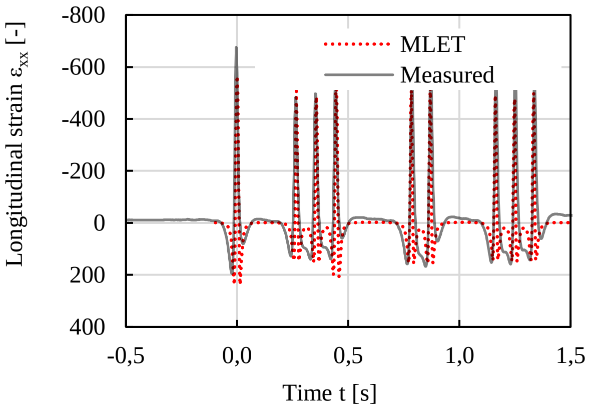
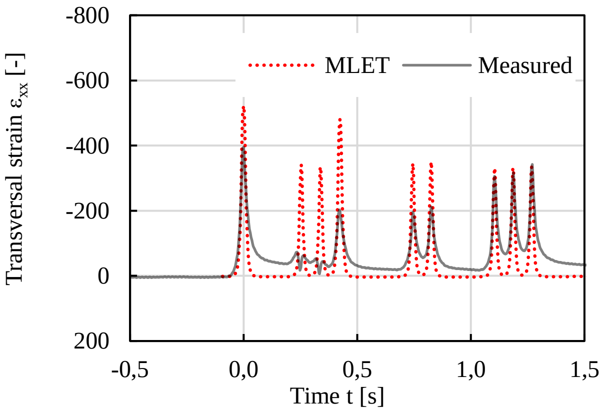
Instrumented in service test sections

MLET - Modelling of response behaviour

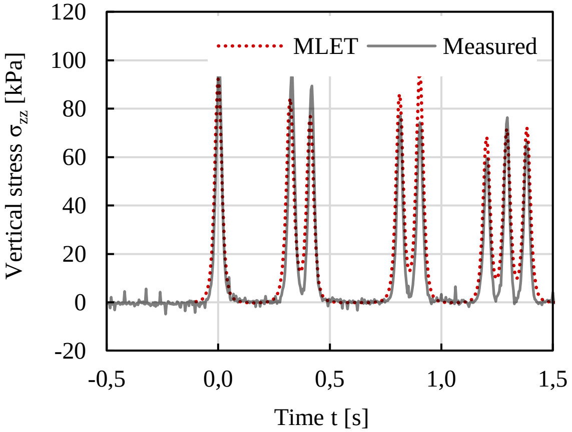
August 2018



May 2019



June 2019



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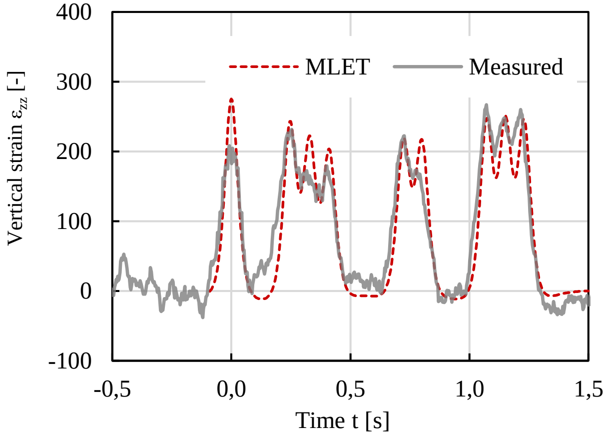
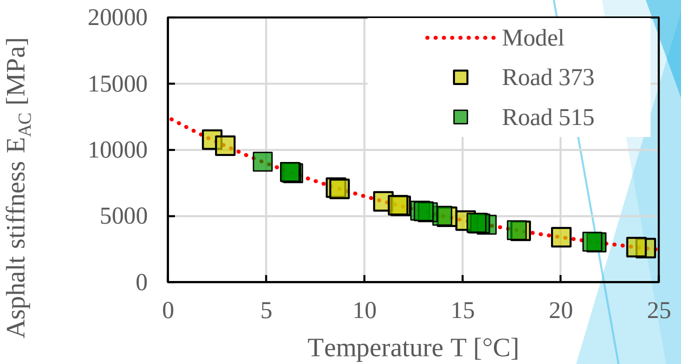
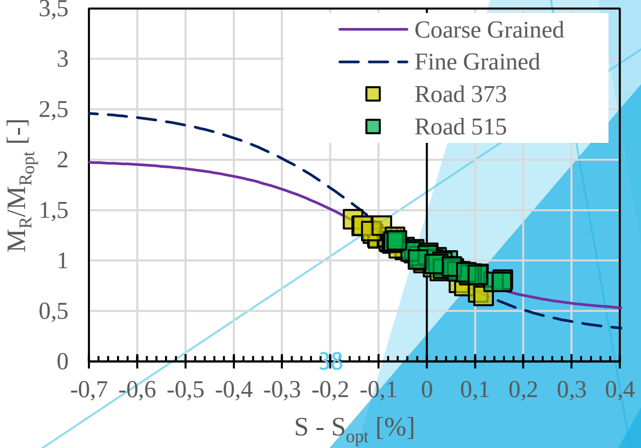


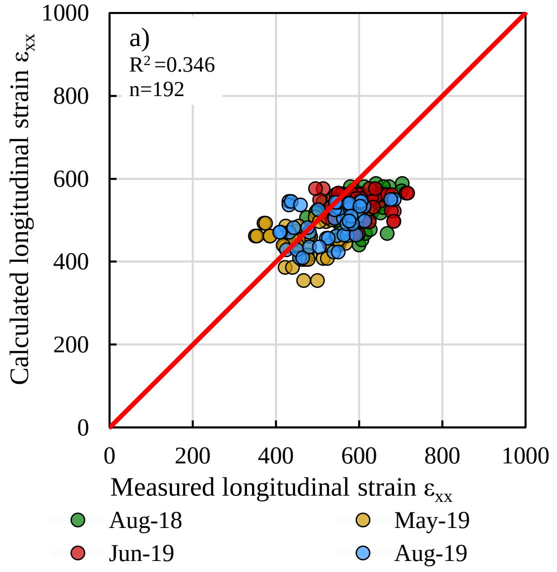




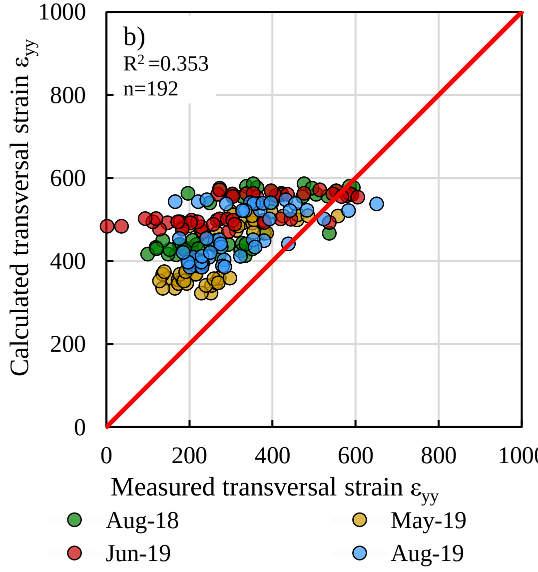
Validation - MLET Response calculations

Two thin pavement structures - peak responses: comparison of measured and predicted values

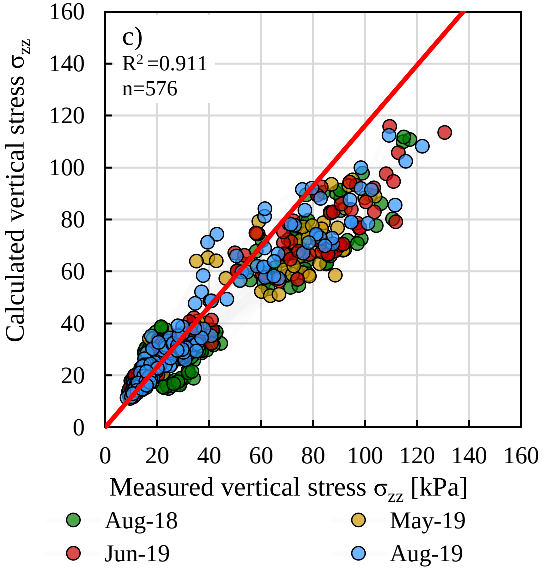
Longitudinal strain



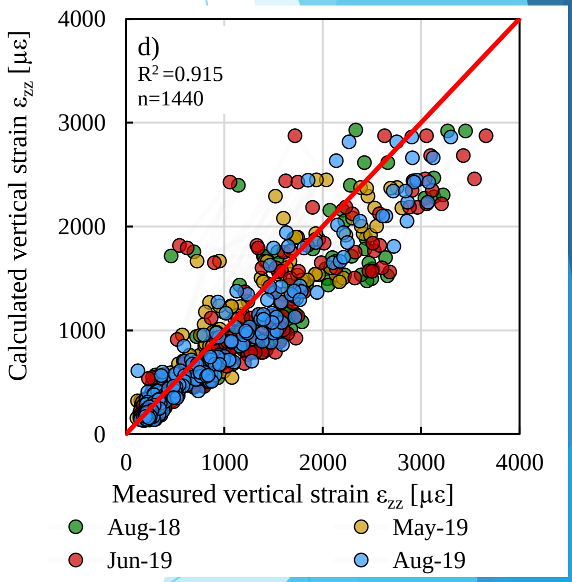
Transversal strain



Vertical stress



Vertical strain



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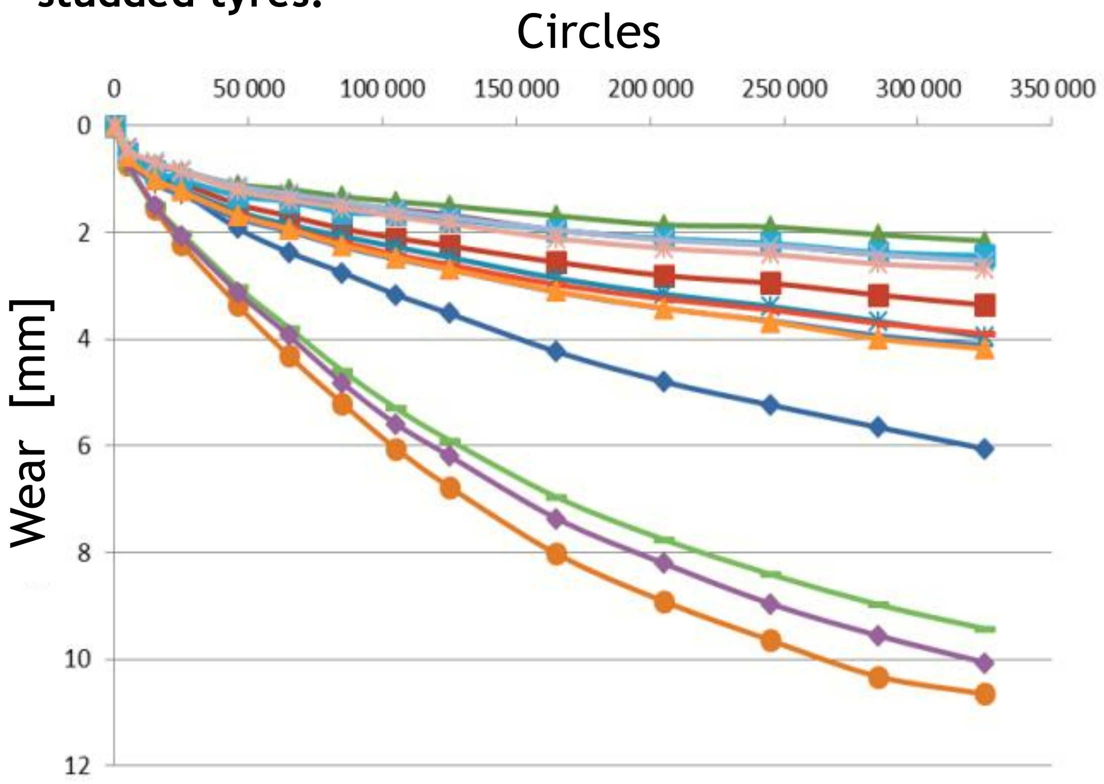
Studded tyre model - calibration

RS rotating in 70 km/h

- Indoor facility:
- Constant temperature & humidity

Studded tyre wear

Impact of different aggregates on abrasion due to studded tyres.



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In service roads - LTPP sections

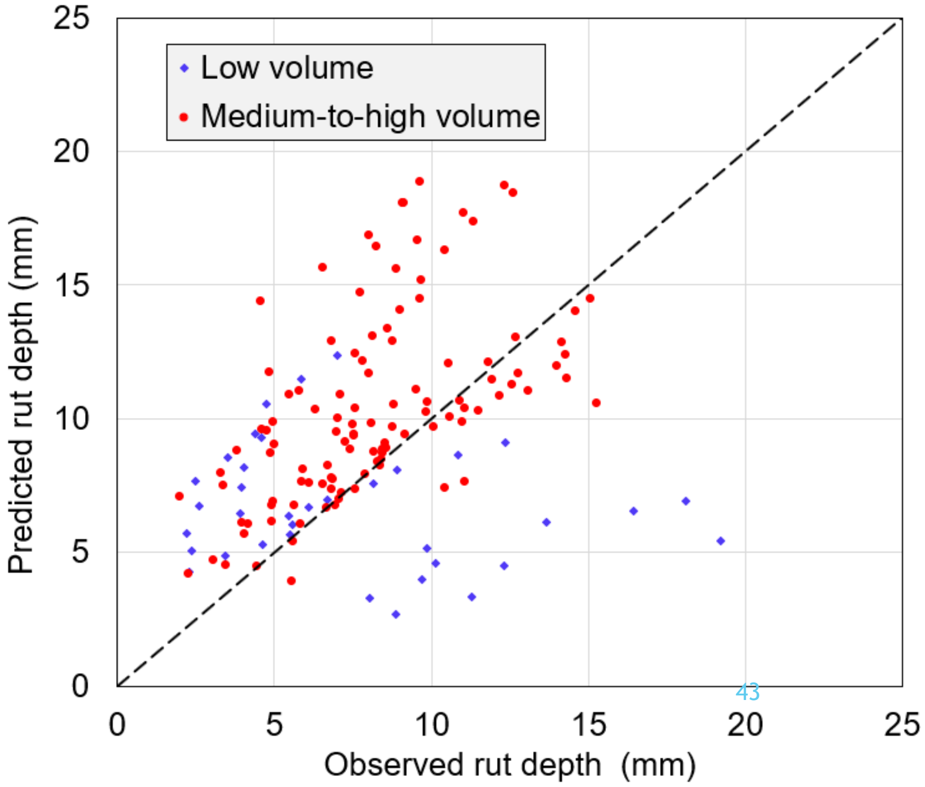
- 20 unique sections from the Swedish LTPP database
  - 5 low volume section and 15 medium-to-high volume sections

AADT was used to develop a calibration factor

Category	Road ID	Thickness (mm)			Oppening year traffic (AADT)	Location
		AC	Base	Subbase		
Low volume	C-292-101	85	160	800	787	Uppsala
	C-292-104	35	50	160	787	Uppsala
	U-580-101	80	110	520	400	Västmanland
	U-580-105	80	110	520	400	Västmanland
	W-RV71-101	50	125	500	559	Dalarna
Medium-to-high volume	E-RV34-201	95	120	550	1776	Östergötland
	F-E4-201	150	70	440	5626	Jönköping
	F-RV31-101	50	115	500	2575	Jönköping
	G-126-101	40	160	300	1461	Kronoberg
	G-126-107	40	160	500	1461	Kronoberg
	H-RV34-101	75	125	400	2605	Kalmar
	N-E62-201	180	120	600	6026	Halland
	U-RV56-201	70	150	450	4695	Västmanland
	U-RV56-209	70	75	-	4695	Västmanland
	W-266-101	70	130	500	1897	Dalarna
	W-RV80-101	50	120	500	1403	Dalarna
	X-RV56-101	50	125	400	1053	Gävleborg
	X-RV56-107	50	125	500	1053	Gävleborg
	Y-RV90-101	80	100	900	1748	Västernorrland
	Z-E45-308	130	80	420	2552	Jämtland

Calibration - Original prediction results

- Original predictions show bias with respect to traffic volume – under-predicting for low volume sections while over-predicting for medium-to-high volume sections
- Not possible to obtain an optimum calibration equation that captures effectively the various design scenarios



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In service roads - LTPP sections - Calibration approach

- Lack of data from field sections has made it difficult to perform a layer-by-layer model calibration
- A global calibration factor (*k*) was introduced to capture the deviation between observed (RD_{obs}) and predicted (RD_{pred}) surface rut depths.
- Both values include both studded tyre wear and permanent deformation.
- As traffic volume was observed to have a significant influence on predicted results, the opening annual average daily traffic volume (AADT) was used to derive *k*.

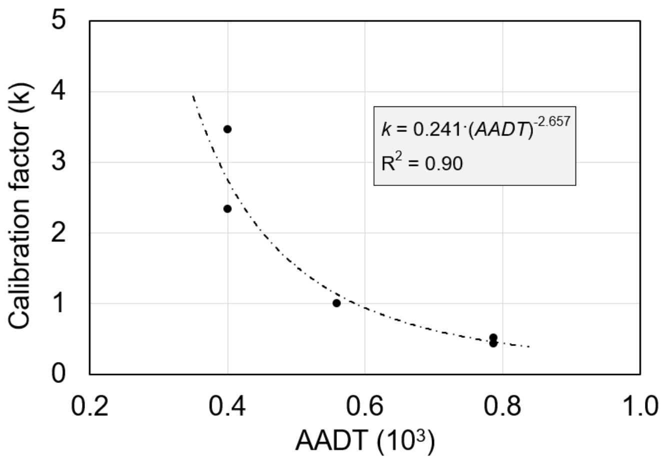
$$k = {RD_{obs}}/{RD_{pred}}$$

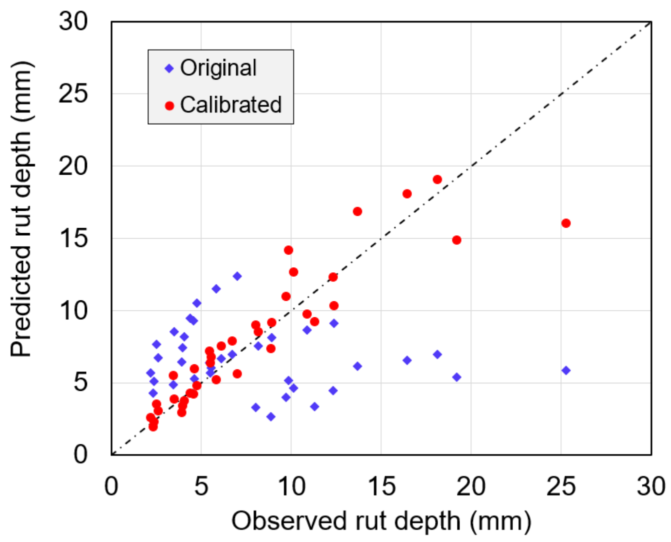
$$k = a_1 * AADT^{a_2}$$

Calibration - LTPP Field sections

Low volume sections

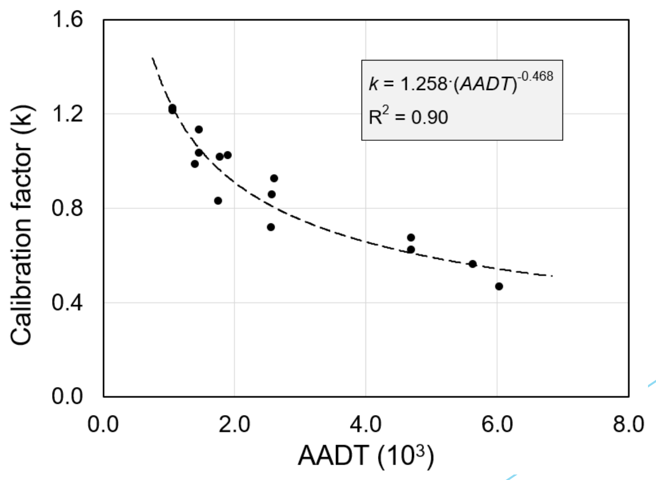
- Sections with opening year AADT of 1000 vehicles or less
- Calibrated model provides acceptable results with R^2 of 0.9
- Further calibration and validation with more representative sections is required

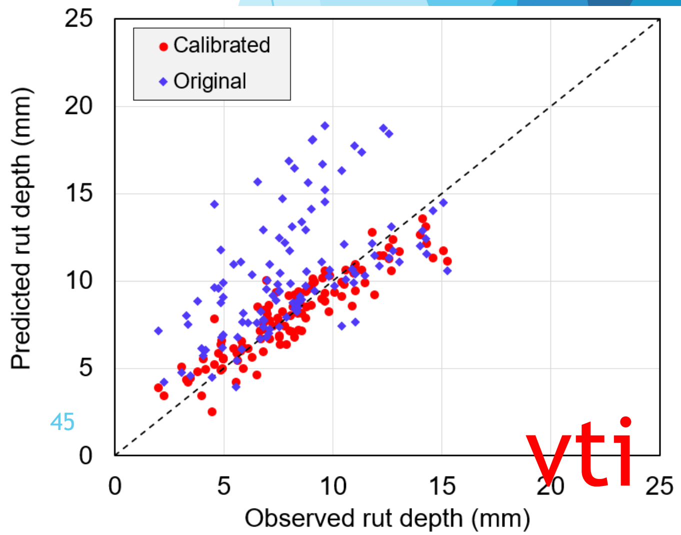




Medium-to-high volume sections

- Sections with opening year AADT of more than 1000 vehicles
- Calibrated model provides acceptable results with R^2 of 0.9
- Model validation is required to evaluate the capability of the calibrated model





Instrumented/LTPP in-service roads

Next steps

- Two new test sites:
  - Upgrade of test site E18
  - New test site E16 Amsberg

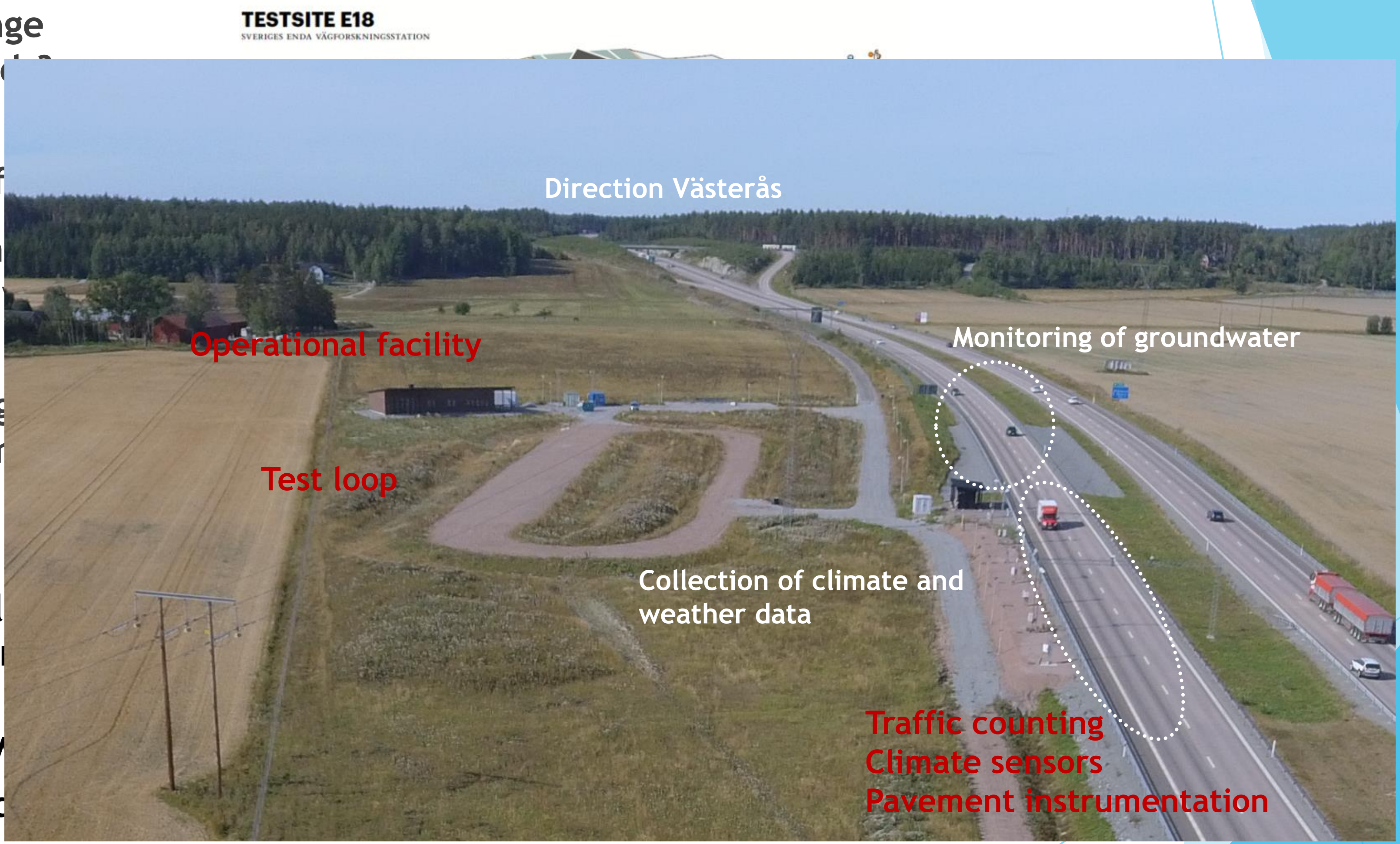
Test site E18

An environmental and road research site on Motorway E18 established in 2010.

- How are climate change affecting Swedish road
- How is groundwater contaminated by traff
- How much salting is n Sweden and how can reduce it´s impact?
- How effective is ploug salting during the wir months?

The research program will pavement mechanics (performance).

- traffic monitoring (V
- sensor monitoring (c
- a new testing loop



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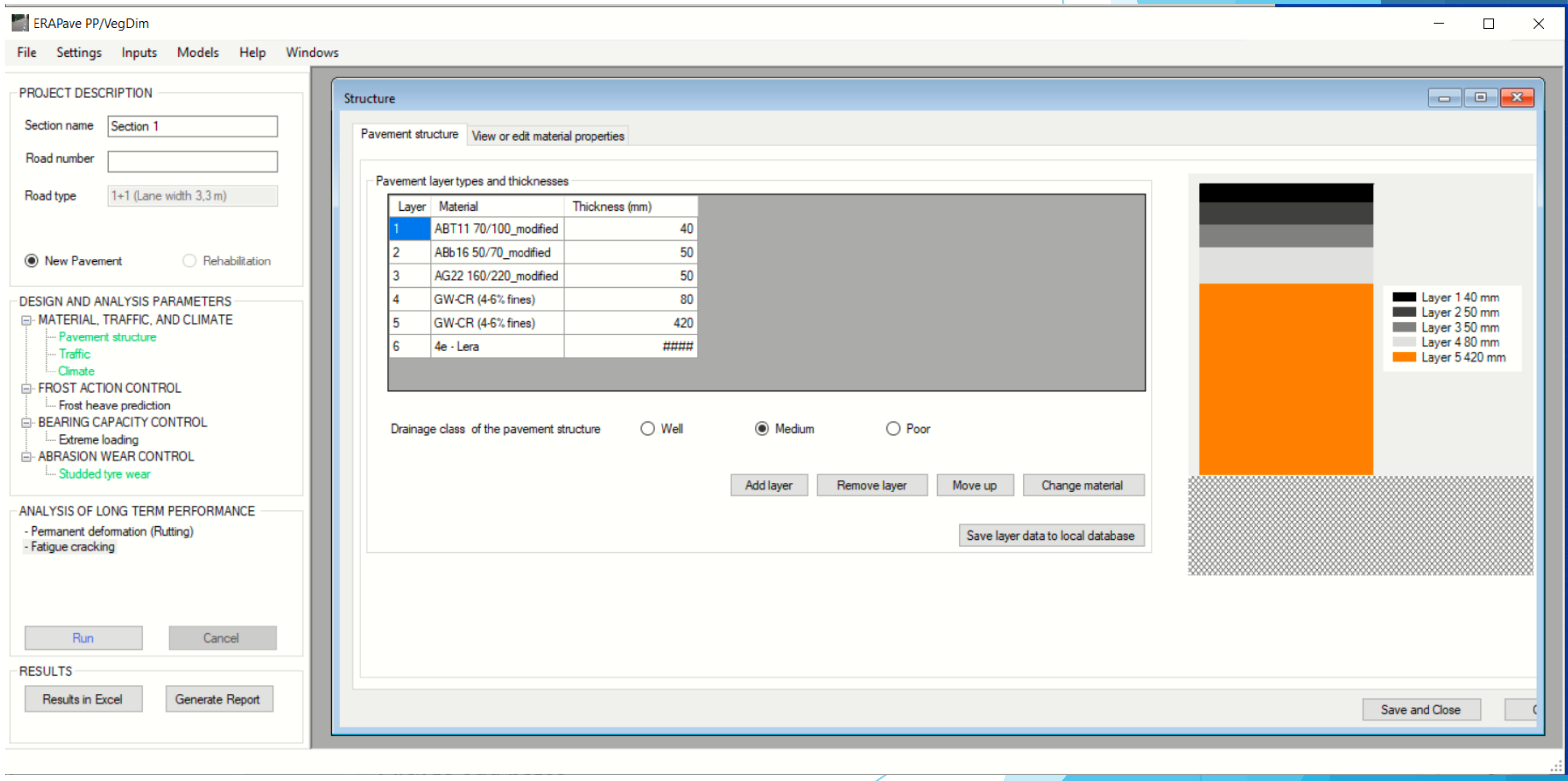
Test site E16 Amsberg

- A new research station **Test site E16 Amsberg** is under construction.
- The objective is to remotely monitor climate, traffic and pavement performance for better understanding their interactions.

- The monitoring programme will include:
- **Climate**
- Weather station (Air temperature, wind speed, precipitation and solar radiation)
- Temp in AC layers, Frost rod, moisture rod, suction, groundwater table.
- **Traffic**
- Video camera, WIM system, Inductive loops.
- **Pavement Performance**
- ASG - Tensile strain (longitudinal & transversal),
- SPC – Soil pressure cells
- Emu coils – vertical strain
- Accelerometers & Geophones (surface deflections).

Material databank

- A Material databank is under development.
- Includes:
- Common types of AC materials:
  - Surface course
  - Binder course
  - Road base
- Unbound base course
  - Crushed rock aggregate
  - Open graded material
  - etc.
- Subbase
- Subgrade



Summary

- ERAPave PP is a new M-E based software for structural design of flexible pavements.
- The software is still under development (Version 0.93 available).

Some further developments:

- The user-interface needs further improvements. A user manual will be published.
- A material databank is under development.
- The climate (water balance - moisture) needs to be better included in the design (performance calculations).

and

- Further validation of performance predictions is needed.
  - Smoothness (IRI), Low temperature cracking ……..
- Performance based laboratory/field testing
- Update of the studded tyre (abrasion) model
- Rehabilitation (Design of overlays)
- Surface profile parameters

Thank you for your attention!

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