NADim-seminar
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Oslo

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FINDING A BETTER WAY

ERAPave PP

A new software for structural design of pavements

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Overview

Background: PMS – Objekt

ERAPave PP

- Response model
- Traffic Loading
- Climate dependency
- Performance predictions

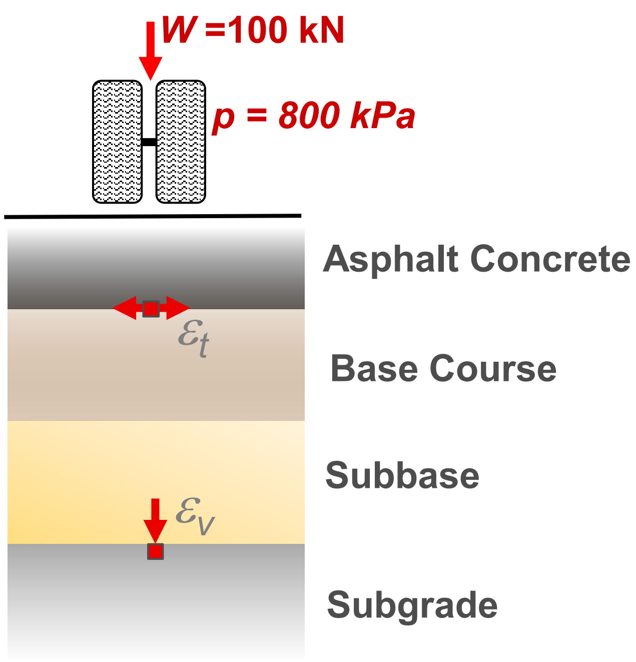
Studded tyre abrasion

Validation (response and performance prediction)

Climate development

Summary

PMS Objekt



Inputs:
- Pavement structure
- Material type
- Climate zone
- Number of standard axels

Software for structural design of flexible pavements.
Launched in the year 2000.

Based on Axisymmetric Linear Elastic Analysis (Bisar)

Loading are ESAL´s (standard axels):

$$N_{ekv} = ÅDT_t \cdot 3.65 \cdot A \cdot B_{just} \cdot \sum_{j=1}^{n} \left(1 + \frac{k}{100}\right)^j$$

Sweden is divided into 5 Climate zones
The year is divided into 6 seasons.

Criteria:
- Fatigue cracking
- Rutting
- Frost heave
- Extreme loading

Studded tyre wear is done separately.

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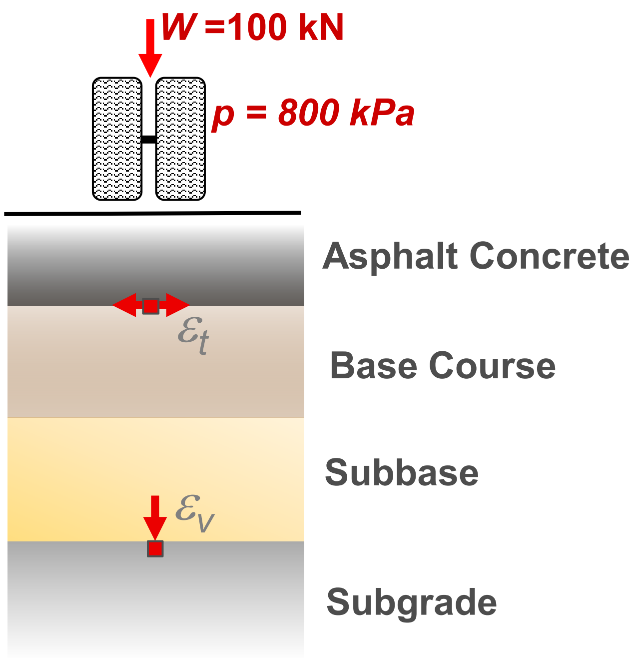
PMS Objekt



Criteria:

Fatigue cracking:

$$N_{till,bb} \geq N_{ekv} \qquad N_{till,bb} = \frac{365}{\sum_{i=1}^{m} \frac{n_i}{N_{bb,i}}} \qquad N_{bb,i} = f_s \frac{2.37 \cdot 10^{-12} \cdot 1.16^{(1.8T_i+32)}}{\varepsilon_{bb,i}^4}$$

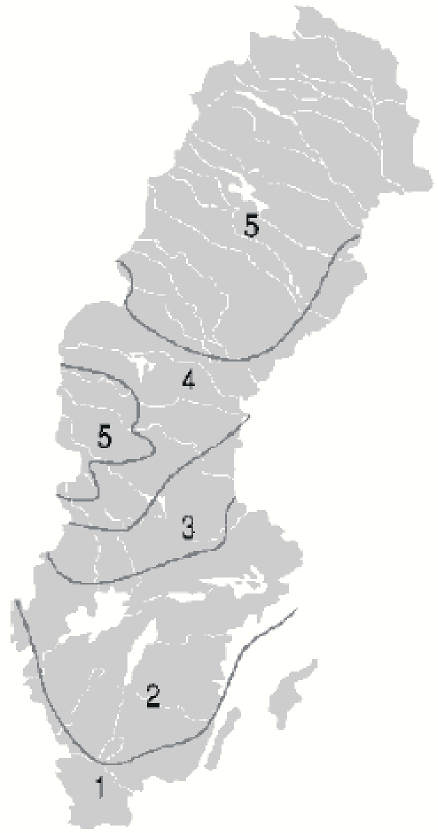
Rutting:

$$N_{till,te} \geq 2N_{ekv} \qquad N_{till,bb} = \frac{365}{\sum_{i=1}^{m} \frac{n_i}{N_{te,i}}} \qquad N_{bb,i} = f_d \frac{8.06 \cdot 10^{-8}}{\varepsilon_{te,i}^4}$$

Frost heave: Max heave in mm for different road categories.

Extreme loading: Static 130 kN loading on 200 x 600 mm area

PMS Object



Tabell 4.2-1 Klimatperiodens längd DK 2 [antal dygn under året]

	Klimatzon				
	1	2	3	4	5
Vinter	49	80	121	151	166
Tjällossningsvinter	10	10			
Tjällossning	15	31	45	61	91
Senvår	46	15			
Sommar	153	153	123	77	47
Höst	92	76	76	76	61

Tabell 4.2-2 Temperatur i bitumenbunden beläggning, DK 2 [°C]

	Klimatzon				
	1	2	3	4	5
Vinter	-1,9	-1,9	-3,6	-5,1	-7
Tjällossningsvinter	1	1			
Tjällossning	1	2,3	4,5	6,5	7,5
Senvår	4	3			
Sommar	19,8	18,1	17,2	18,1	16,4
Höst	6,9	3,8	3,8	3,8	3,2

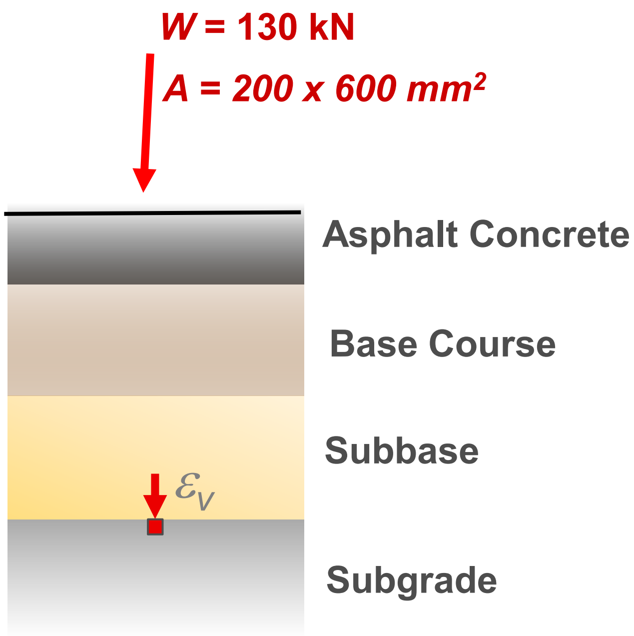
Tabell 4.5-1 Styvhetsmoduler, Ms, (MPa) för bitumenbundet slitlager, typ AB.

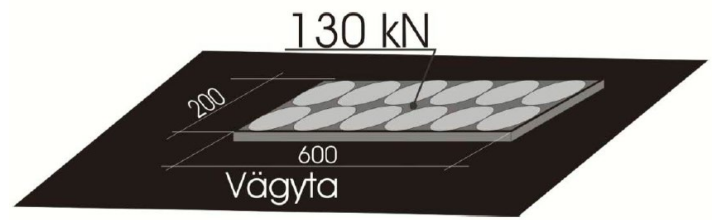
Tjocklek < 50 mm	Klimatzon				
	1	2	3	4	5
Vinter	14500	14500	15500	17000	18500
Tjällossningsvinter	13000	13000			
Tjällossning	13000	12000	10500	9500	9000
Senvår	11000	11500			
Sommar	3500	4000	4500	4000	4500
Höst	9000	11000	11000	11000	11500

Tabell 4.5-7 Styvhetsmoduler, Ms, (MPa) för obundna överbyggnadsmaterial

	Bärlager	Förstärkningslager		Skyddslager
		Okrossat	Krossat	
Vinter	1000	1000	450	1000
Tjällossningsvinter	150	1000	450	1000
Tjällossning	300	160	450	70
Senvår	450	240	450	85
Sommar	450	240	450	100
Höst	450	240	450	100

PMS Objekt





Tabell 4.4-5 Maximal vertikal trycktöjning på terrassytan på materialtyp 2, 3 samt 4A

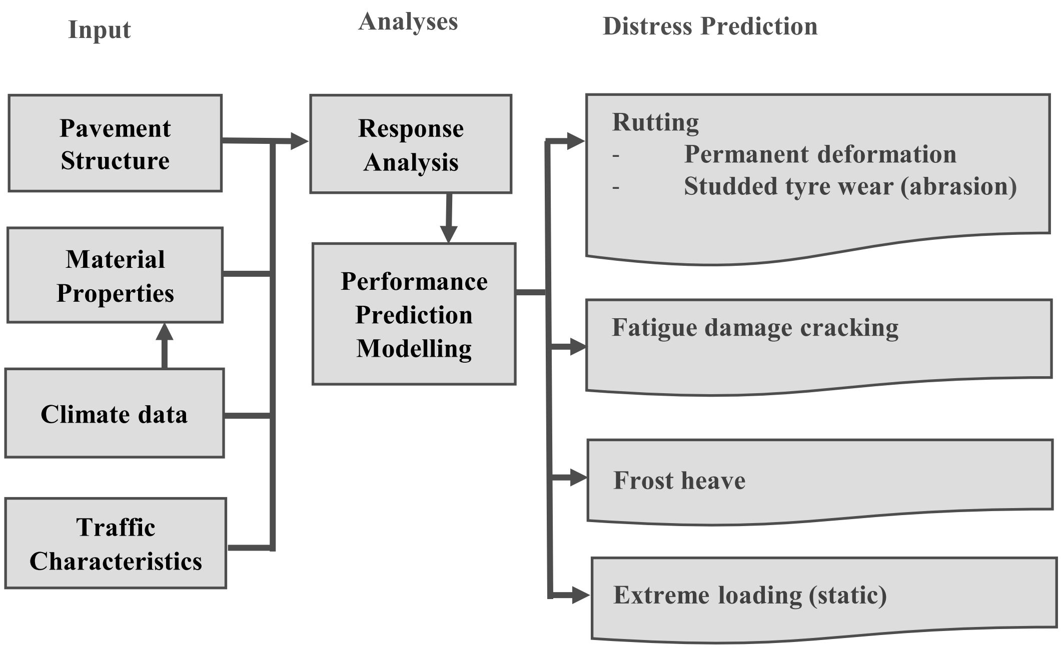
Klimatzon	1	2	3	4	5
Töjning	0,0025	0,0024	0,0023	0,0022	0,0021

Tabell 4.4-6 Maximal vertikal trycktöjning på terrassytan på materialtyp 4B, 4C, 4D, 4E, 4F samt 5

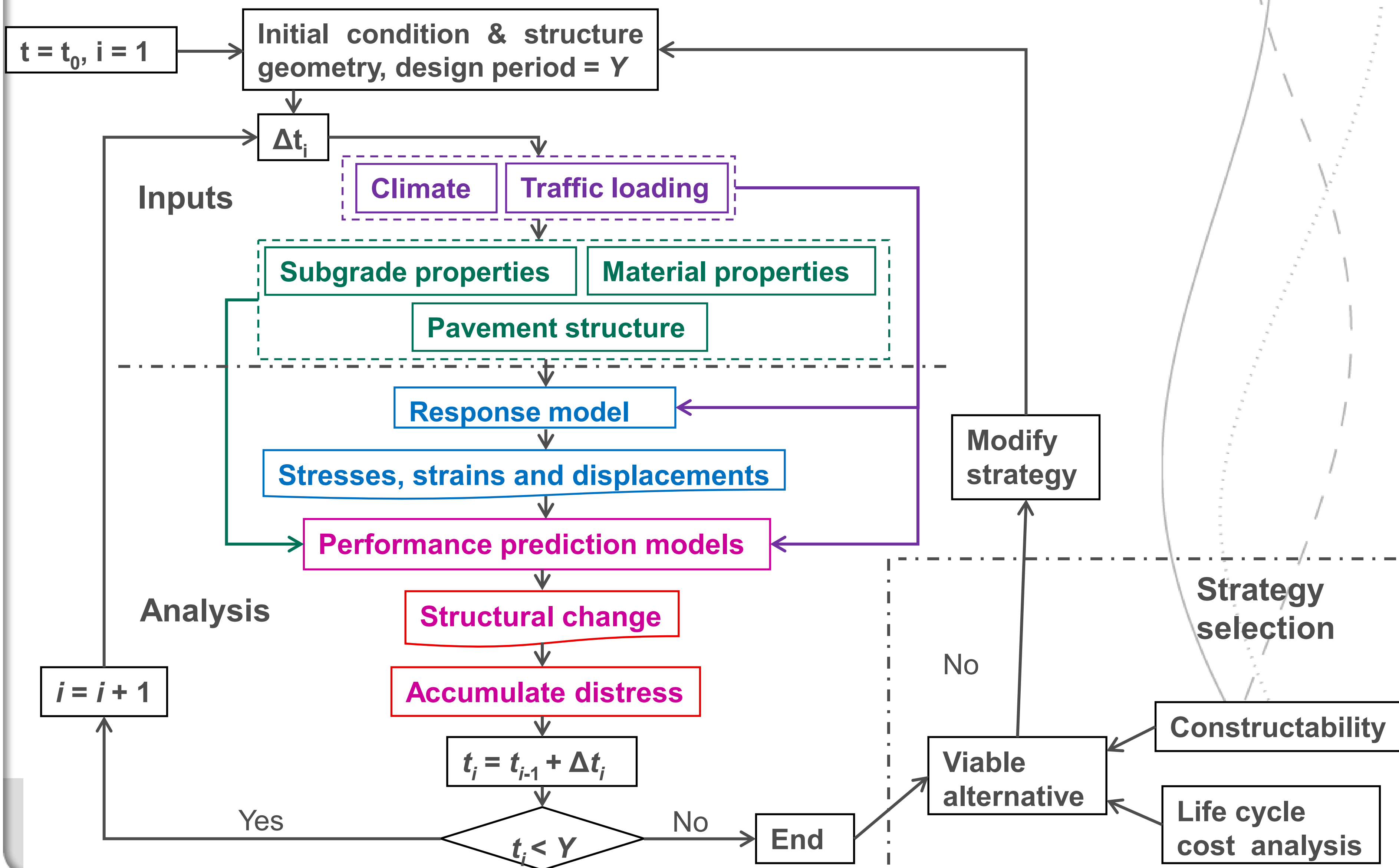
Klimatzon	1	2	3	4	5
Töjning	0,0013	0,0012	0,0011	0,0010	0,0010

What is ERAPave PP?

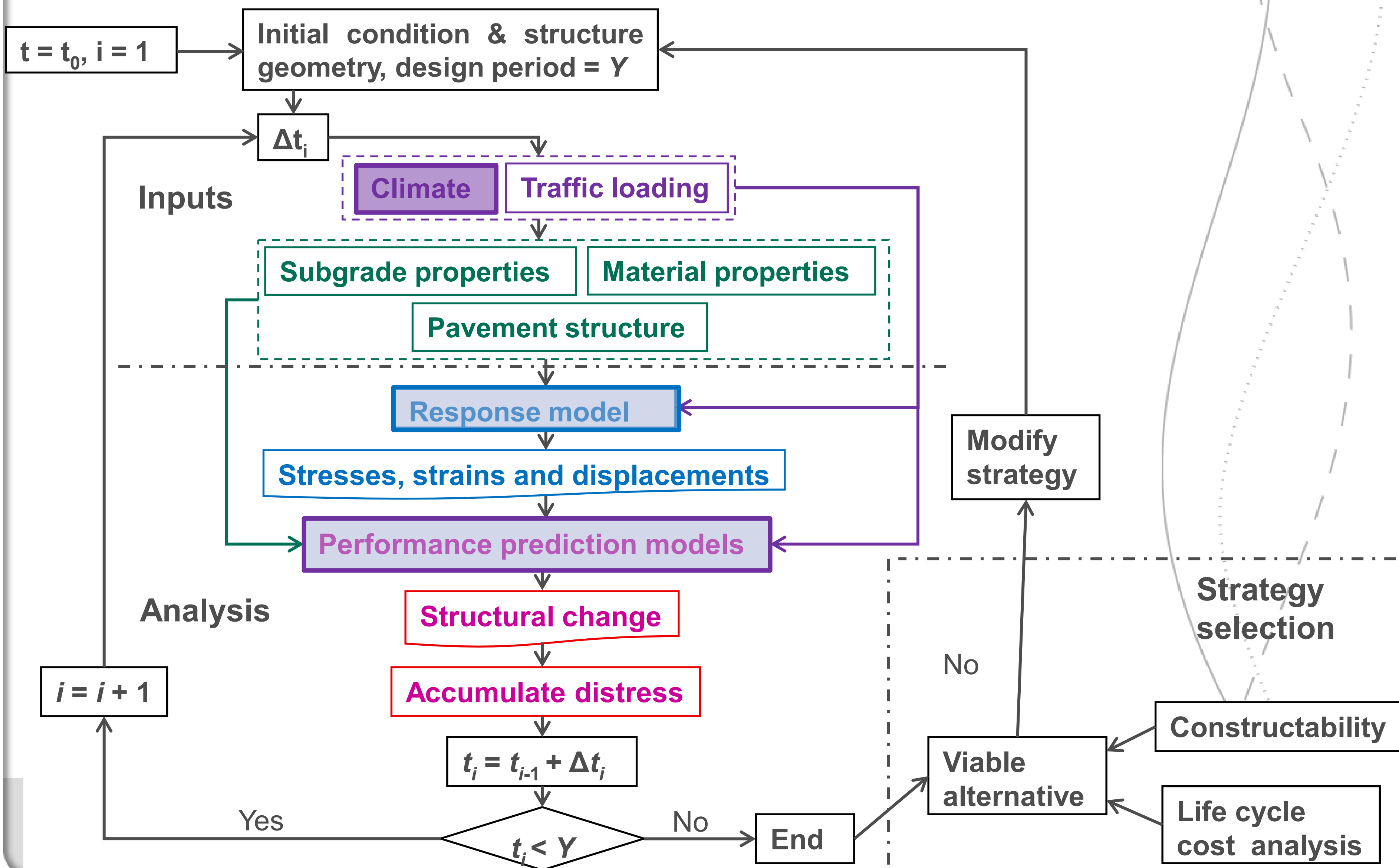
ERAPave PP (Elastic Response Analysis of Pavements – Performance Prediction) is a **M**echanistic-**E**mpirical pavement analysis and design tool for **flexible** pavement. ERAPave PP predicts the evolution of **rutting** and **fatigue cracking** for a given pavement structure having a set of material properties. It further predicts studded tyre wear and the expected frost heave.



Flexible pavement design - rutting and fatigue cracking

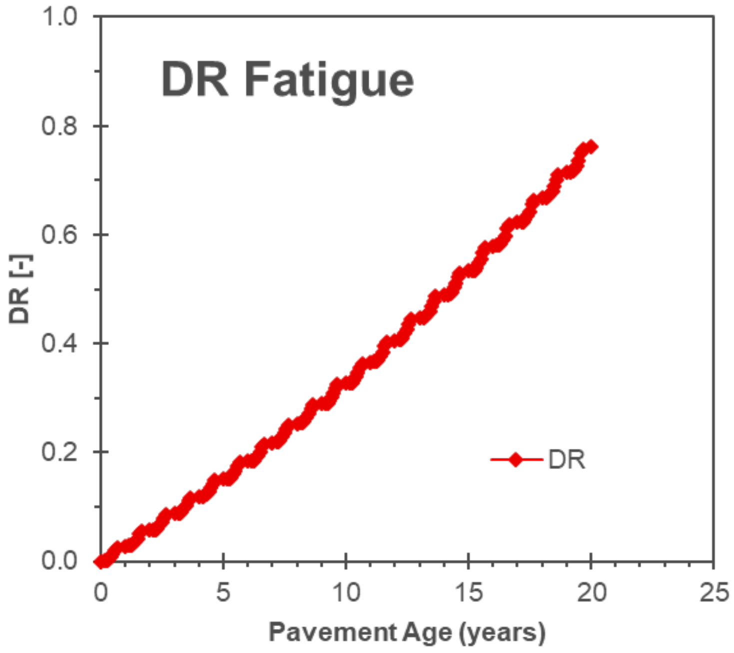


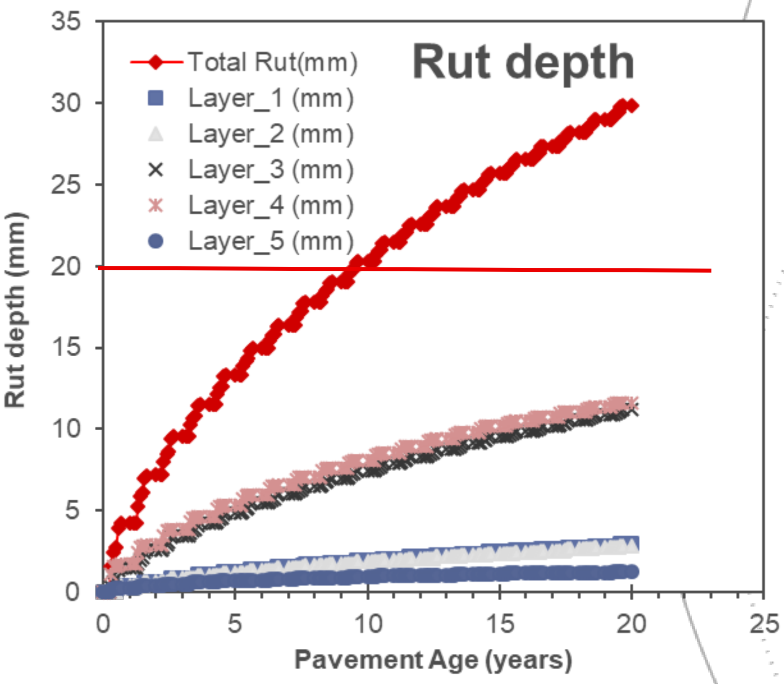
Flexible pavement design - rutting and fatigue cracking



Typical results – ERAPave PP

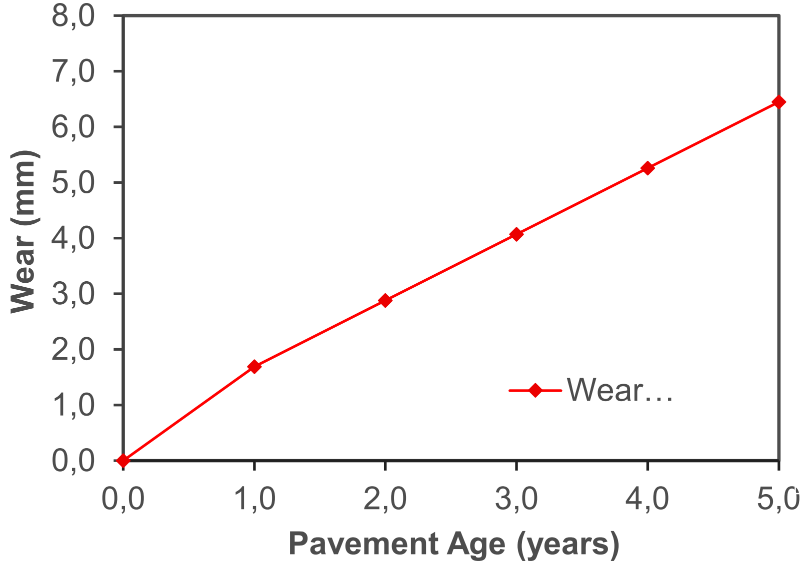
Fatigue of critical AC layer and permanent deformation (rut)

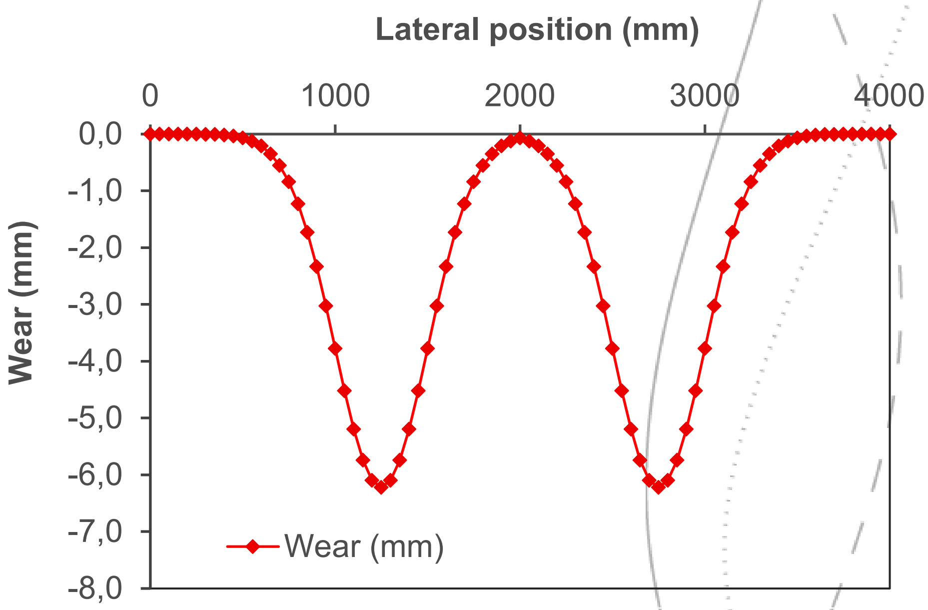




Typical results - ERAPave PP

Studded tyre wear

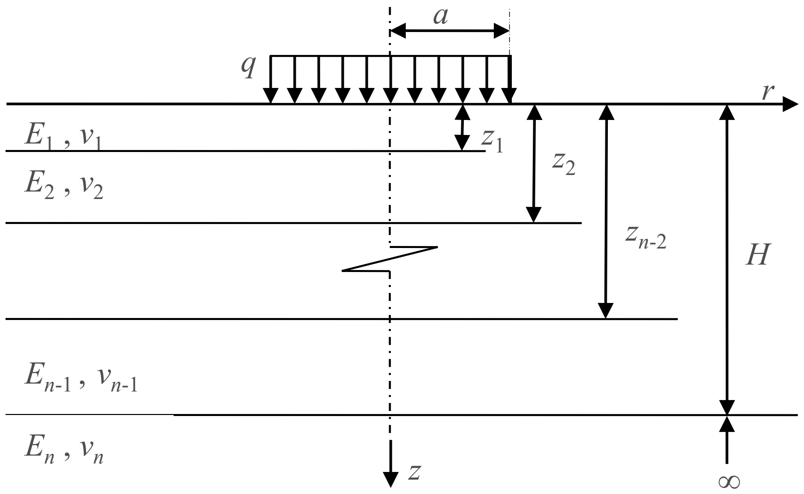


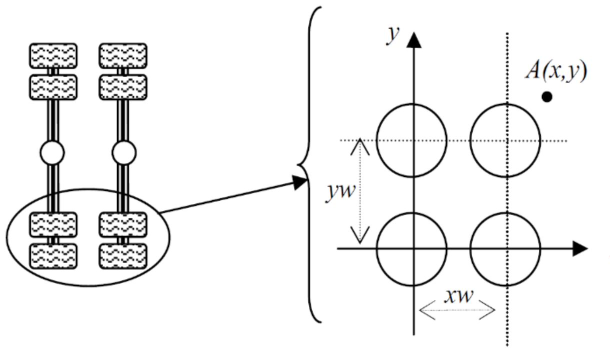


Response model

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.

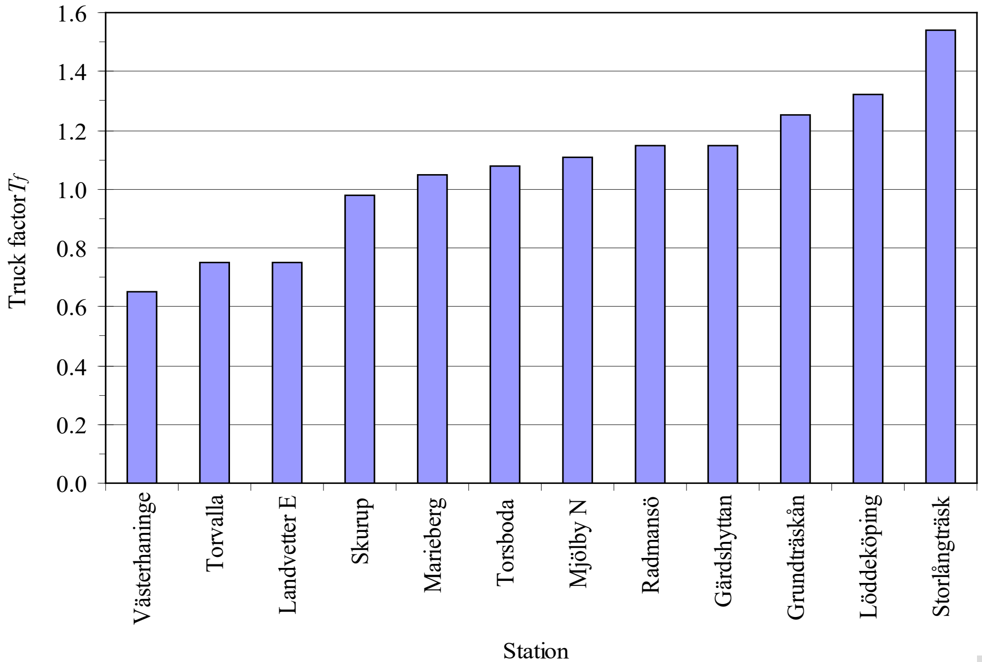




Traffic Loading: Standard axel´s

ESAL´s (Standard axels – Dual tyre configuration *W* = 100 kN, *p* = 800 kPa)

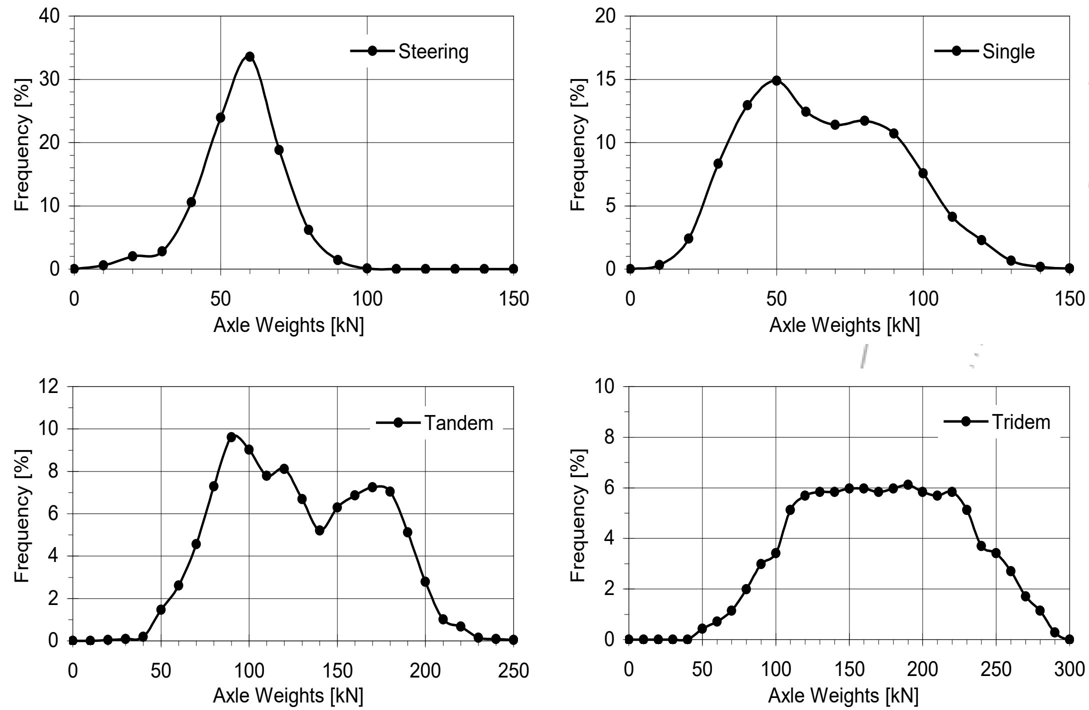
$$N_{ekv} = \mathring{A}DT_k \cdot 3.65 \cdot A \cdot B_{just} \cdot \sum_{j=1}^{n} \left(1 + \frac{k}{100}\right)^j$$



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

Traffic loading: Axle Load Spectra (ALS)

Weigh-In-Motion (WIM) data



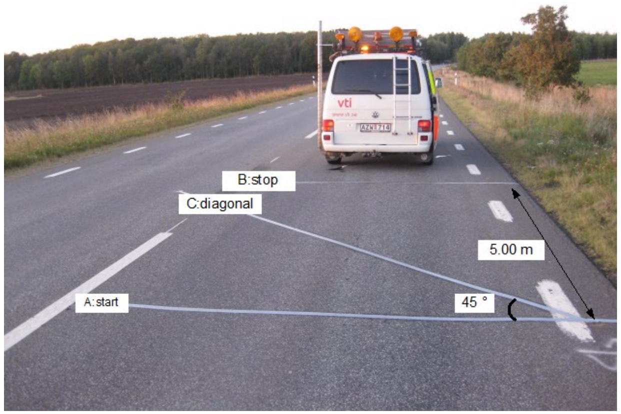
Steering axles

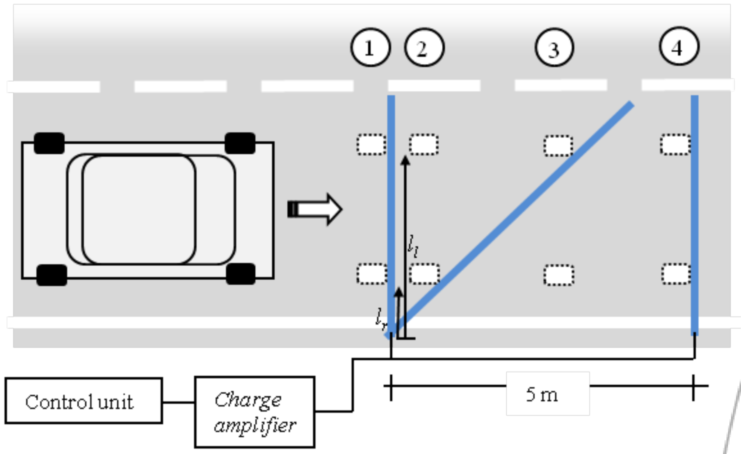
Single axles

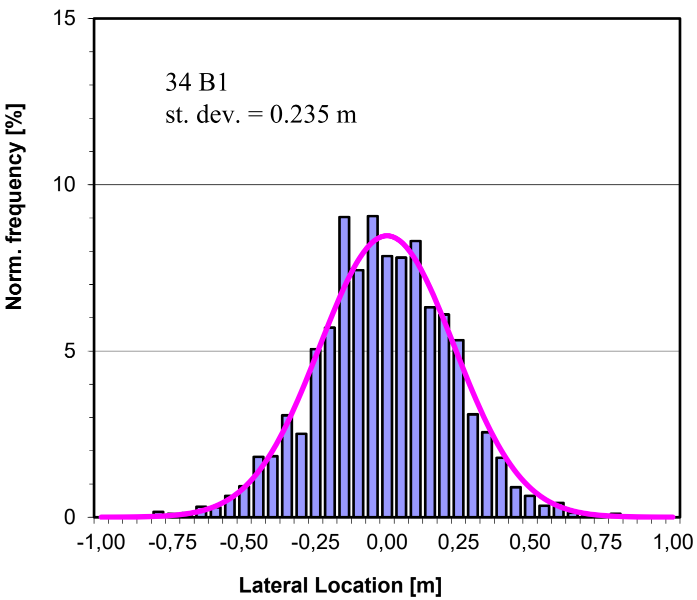
Tandem axles

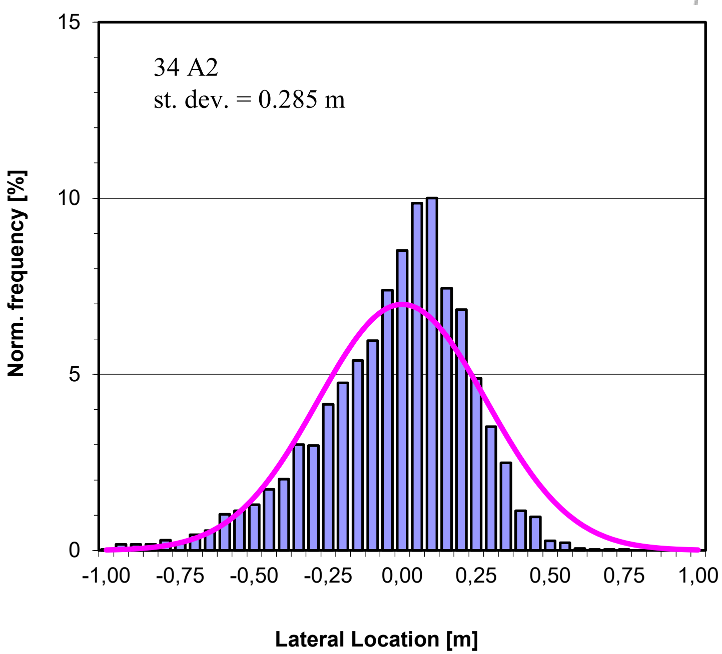
Tridem axles

Traffic Loading: Lateral Wander







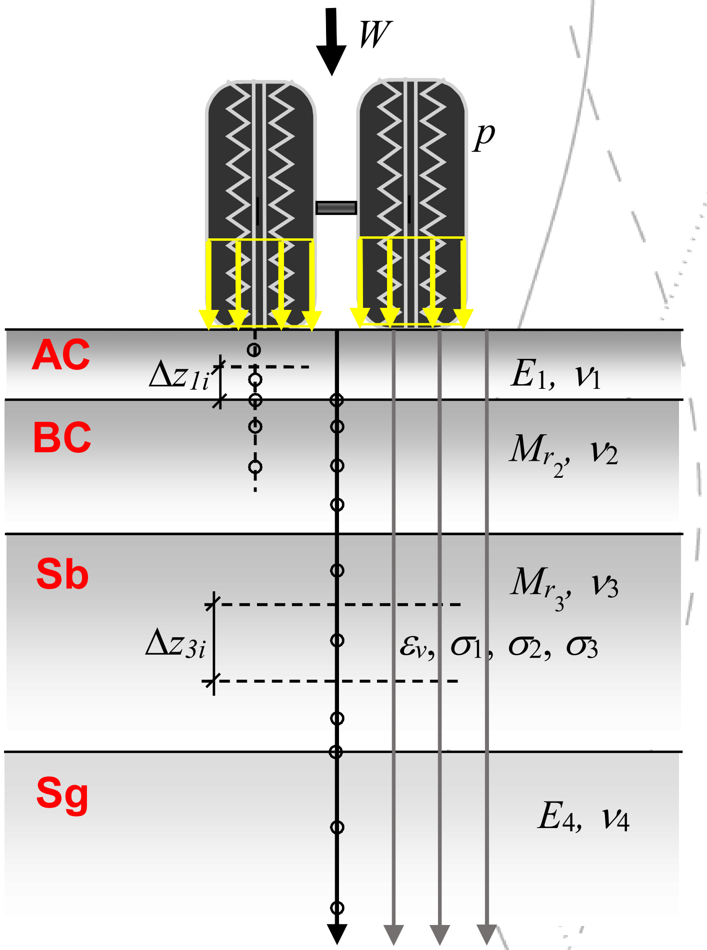


Response modelling

Non-linear elastic modelling of the pavement structure.

Based the MLET.

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



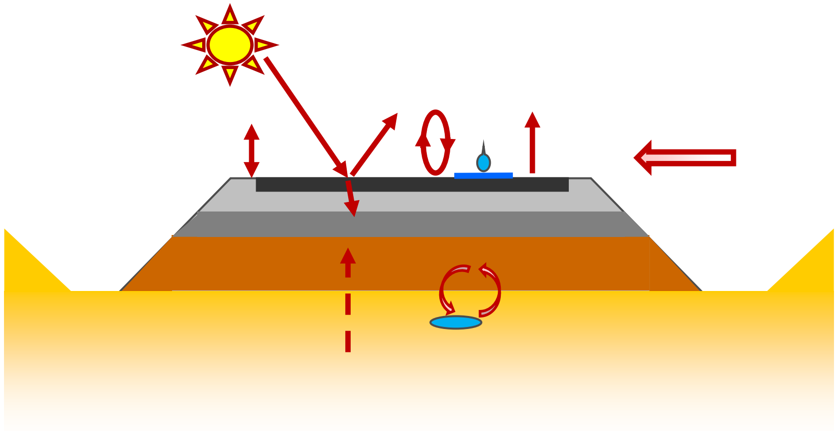
$$\hat{\delta}_p = \sum_{i=1}^{n}\sum_{j=1}^{m} \hat{\varepsilon}_{p_{ij}} \cdot \Delta z_{ij}$$

Climate dependency

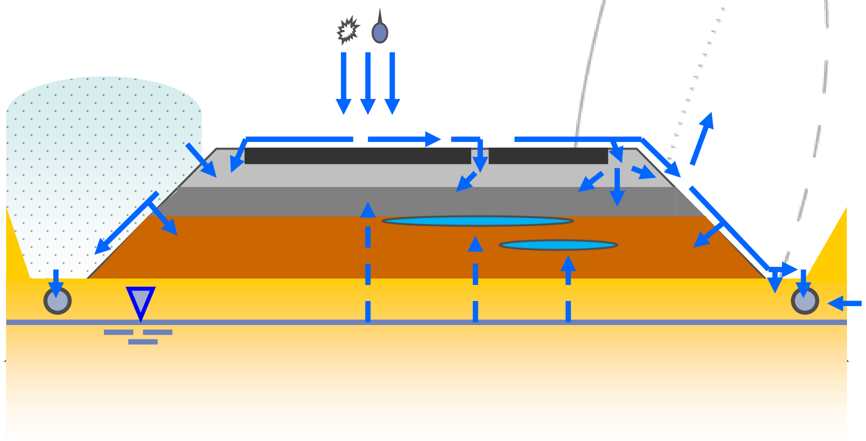
Pavement response and degradation is highly dependent on the climate variables.

The two most important variables are **temperature *T*** and **moisture content *w*** (or degree of saturation S_r).

Heat balance



Water balance



Temperature of asphalt bound layers

Two models are included in ERAPave PP.

Sigmoidal model (master curve estimations)

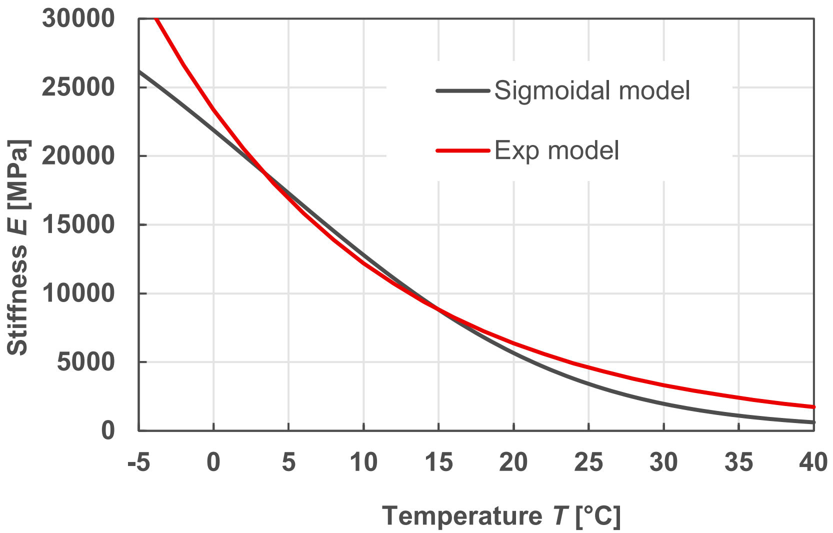
$$\log|E| = a + \frac{b}{1+e^{(c-d\log f_r)}}$$

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

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

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



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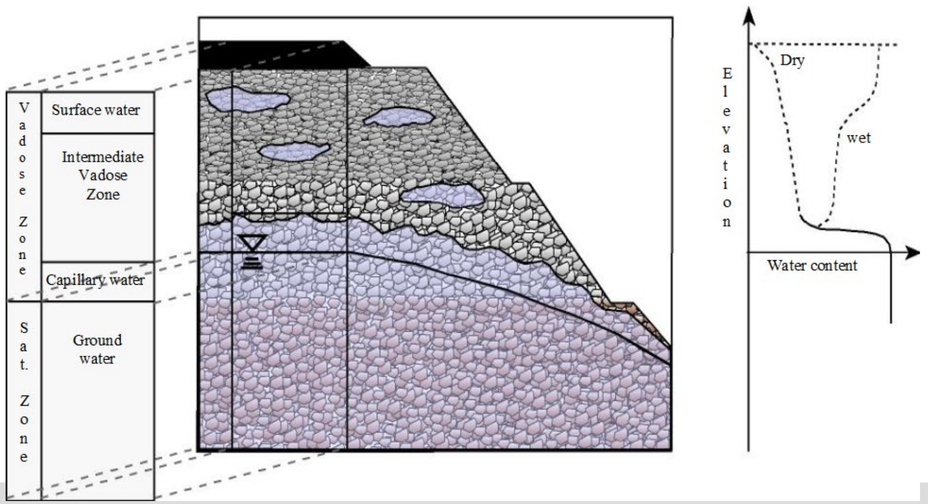
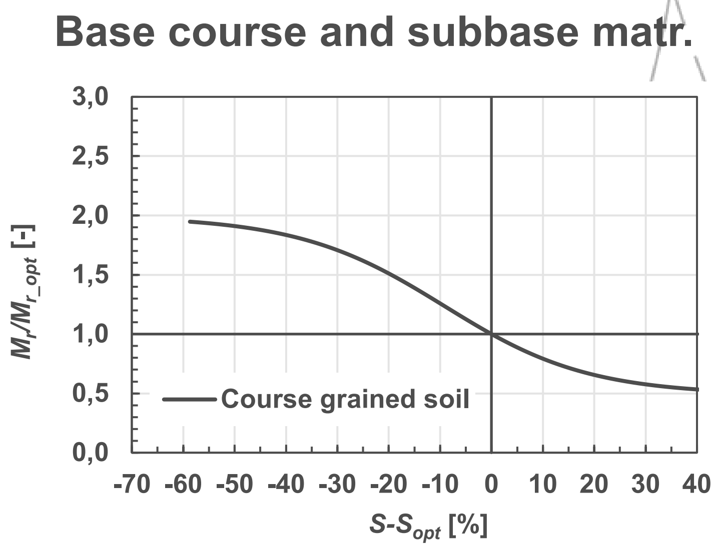
Moisture of unbound layers and subgrades

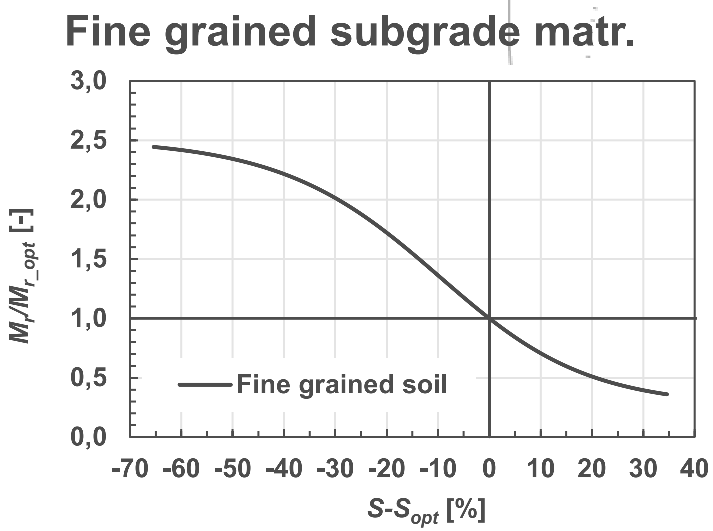
Stiffness – moisture content (degree of saturation) relationship is given as.

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

a, *b* and k_m are material parameters.







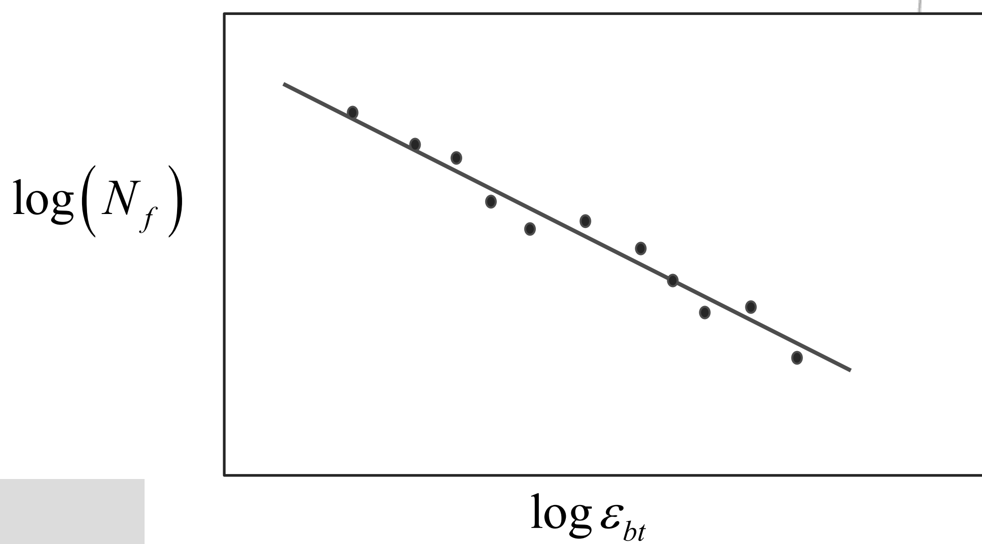
Performance predictions

Bottom–up cracking

Fatigue law: $N_f = sa\varepsilon_{bt}^{-b}E^{-c}$ $\log(N_f) = f_1 - f_2 \log \varepsilon_{bt} - f_3 E$

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

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



Performance predictions

Plastic deformation (rut)

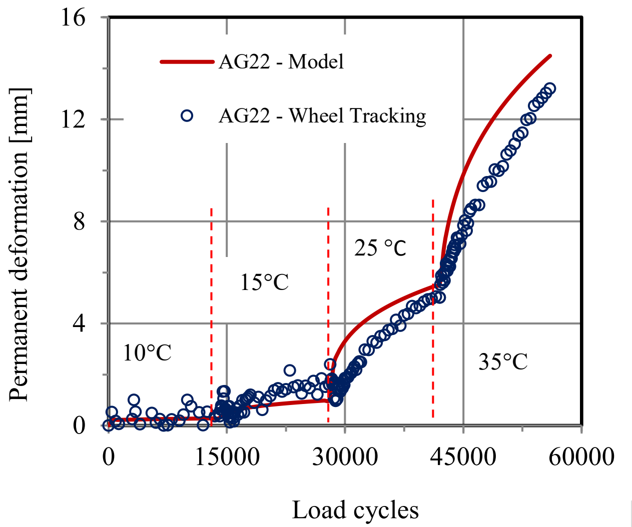
AC:

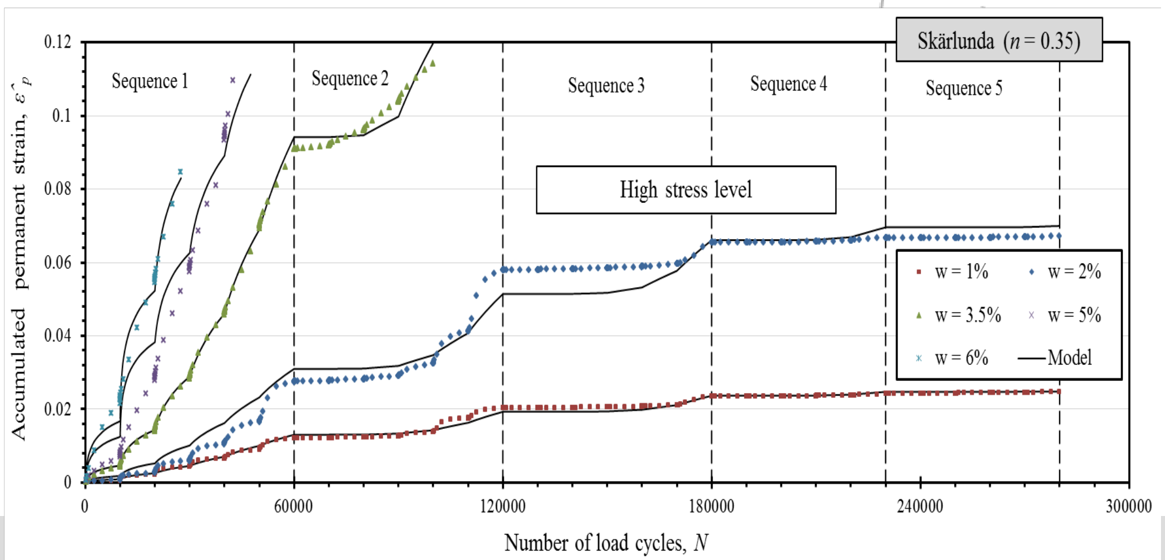
$$\hat{\varepsilon}_p(N) = a_1 T^{a_2} N^{a_3} \Delta\varepsilon_r \qquad \Delta\varepsilon_r = \Delta\varepsilon_r(T)$$

UGM & soils:

$$\hat{\varepsilon}_p(N) = (c_1 + c_2 w) N^{b\Delta\varepsilon_r} \Delta\varepsilon_r \qquad \Delta\varepsilon_r = \Delta\varepsilon_r(w)$$

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





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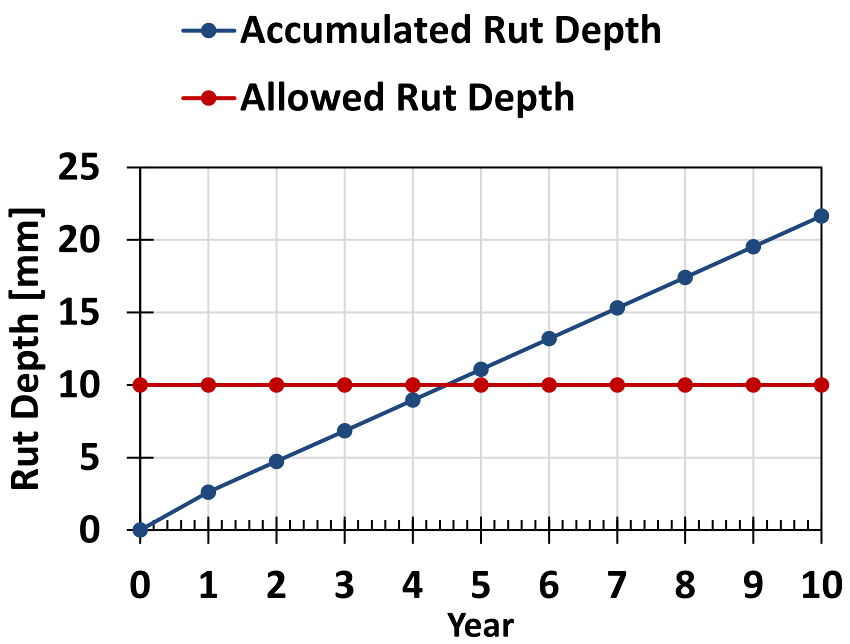
Studded tyre abrasion

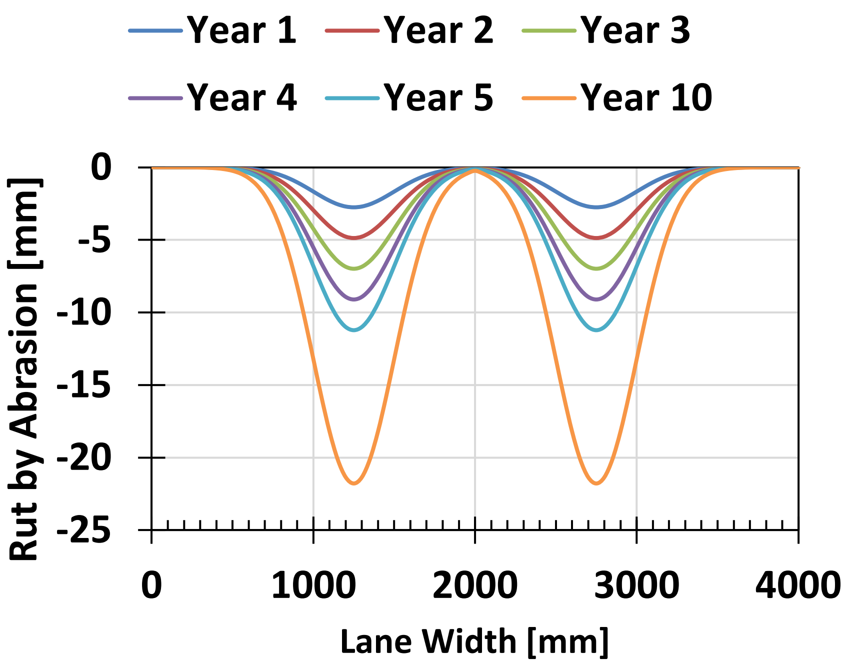
An empirical model based on laboratory testing and calibrated/validated in a in-service road tests.

Parameters needed: v, $AADT_L$, Lane width (st. dev.), de-icing, W_p, SST

Two models:

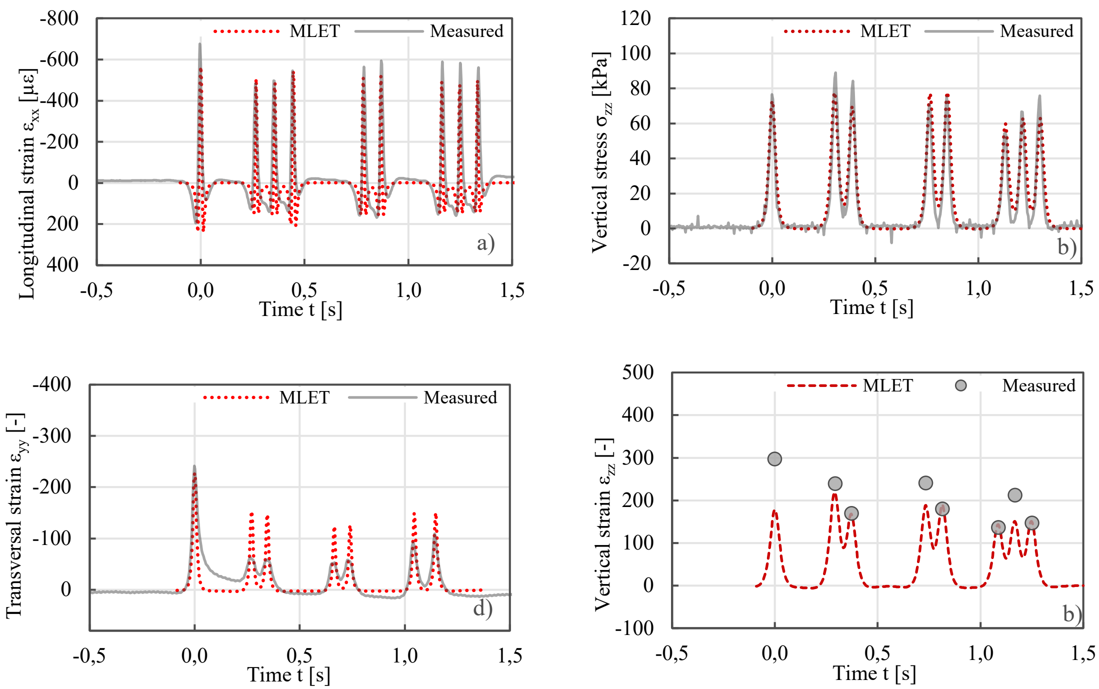
- **The Nordic abrasion sub-model:** A_N, D_{max}, MAS_4
- **Prall sub-model:** A_P

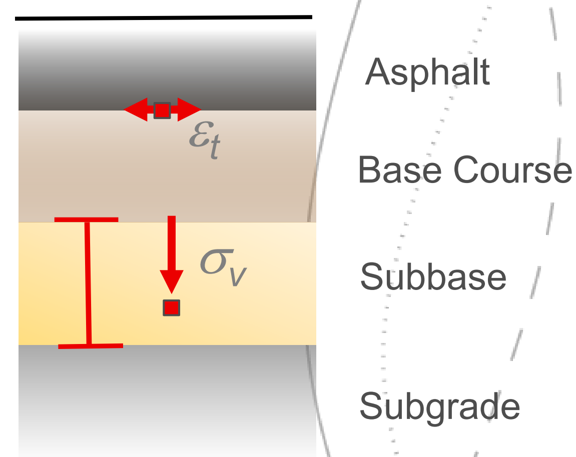




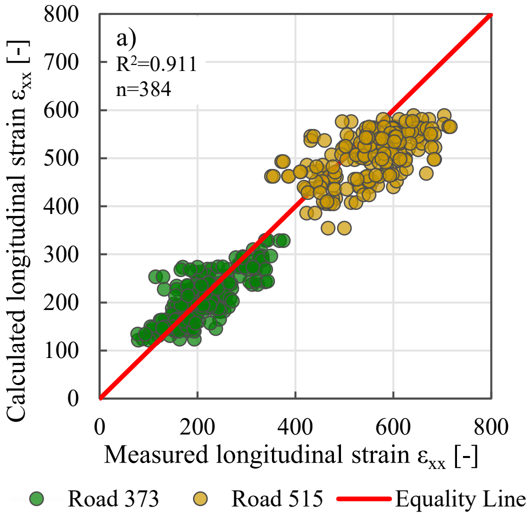
MLET - Response validation

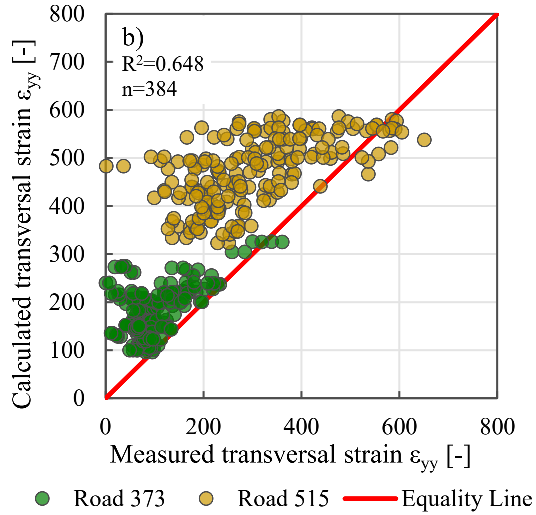
In-service road measurements

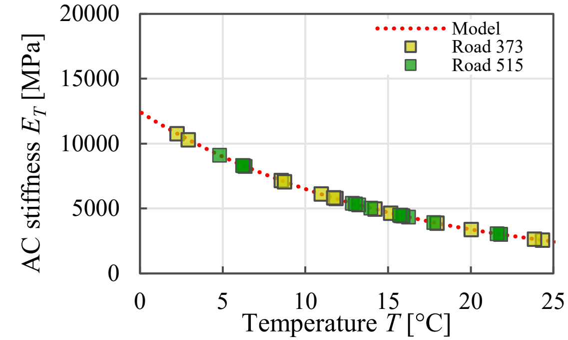


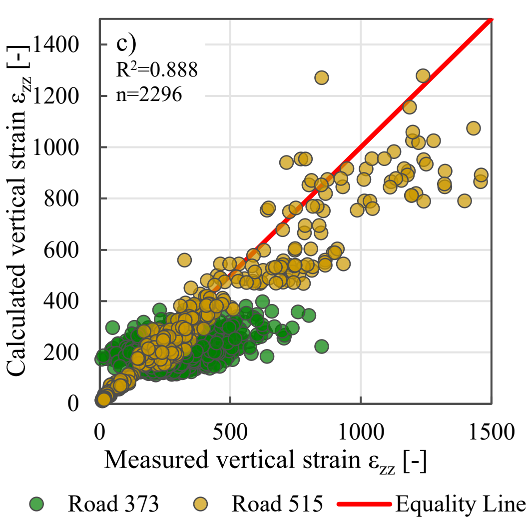


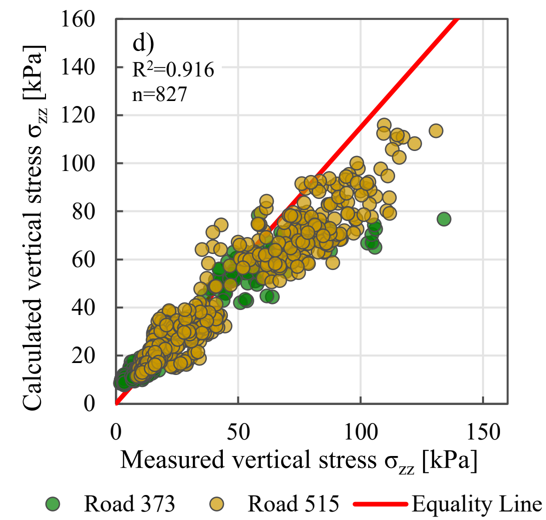
General agreement between calculation & measurements

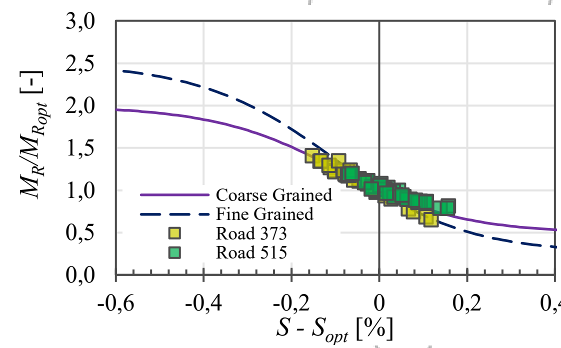






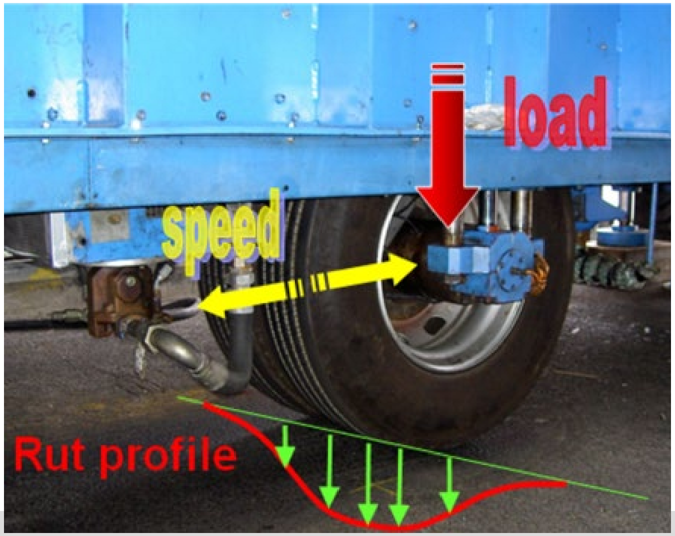


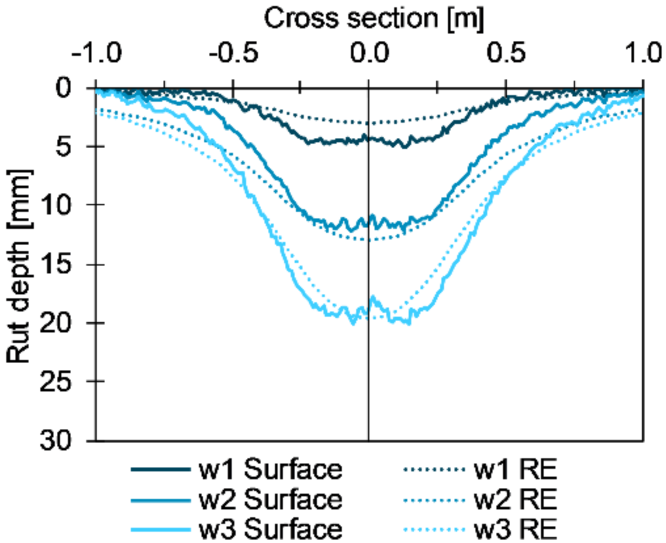


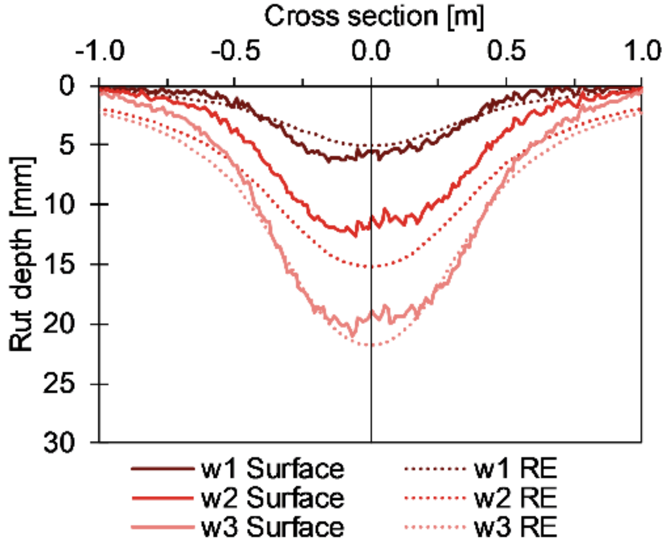


Validation - Performance prediction

Rutting development in an APT test







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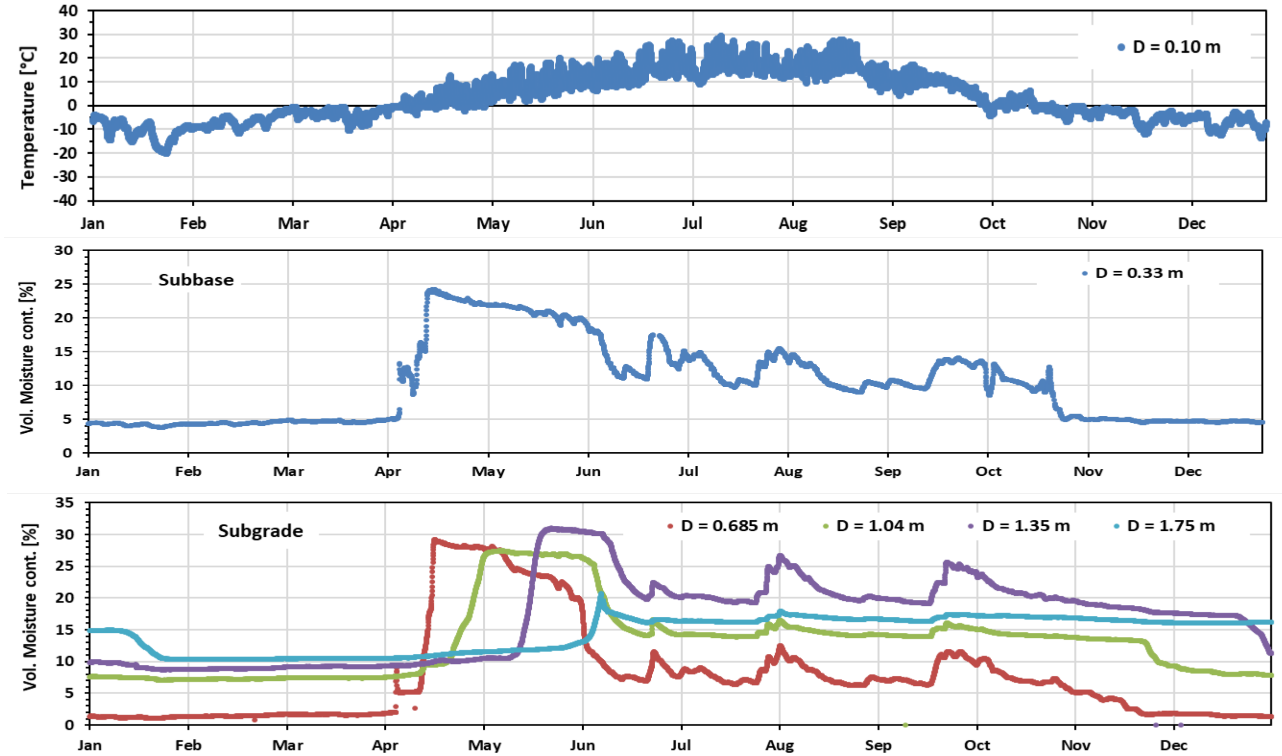
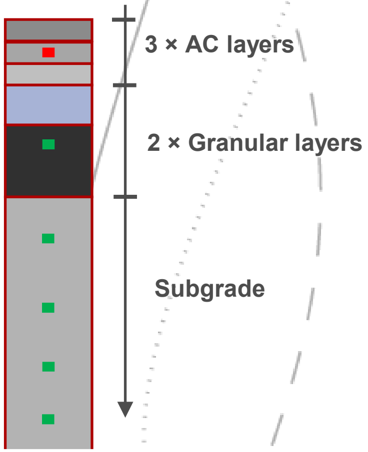
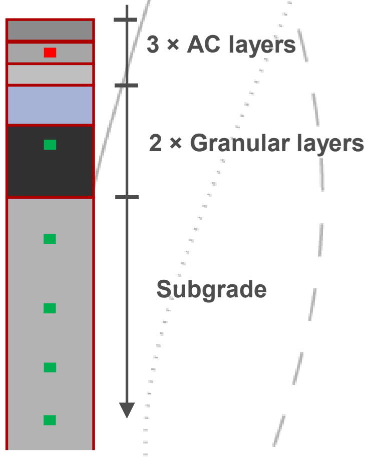
Climate data

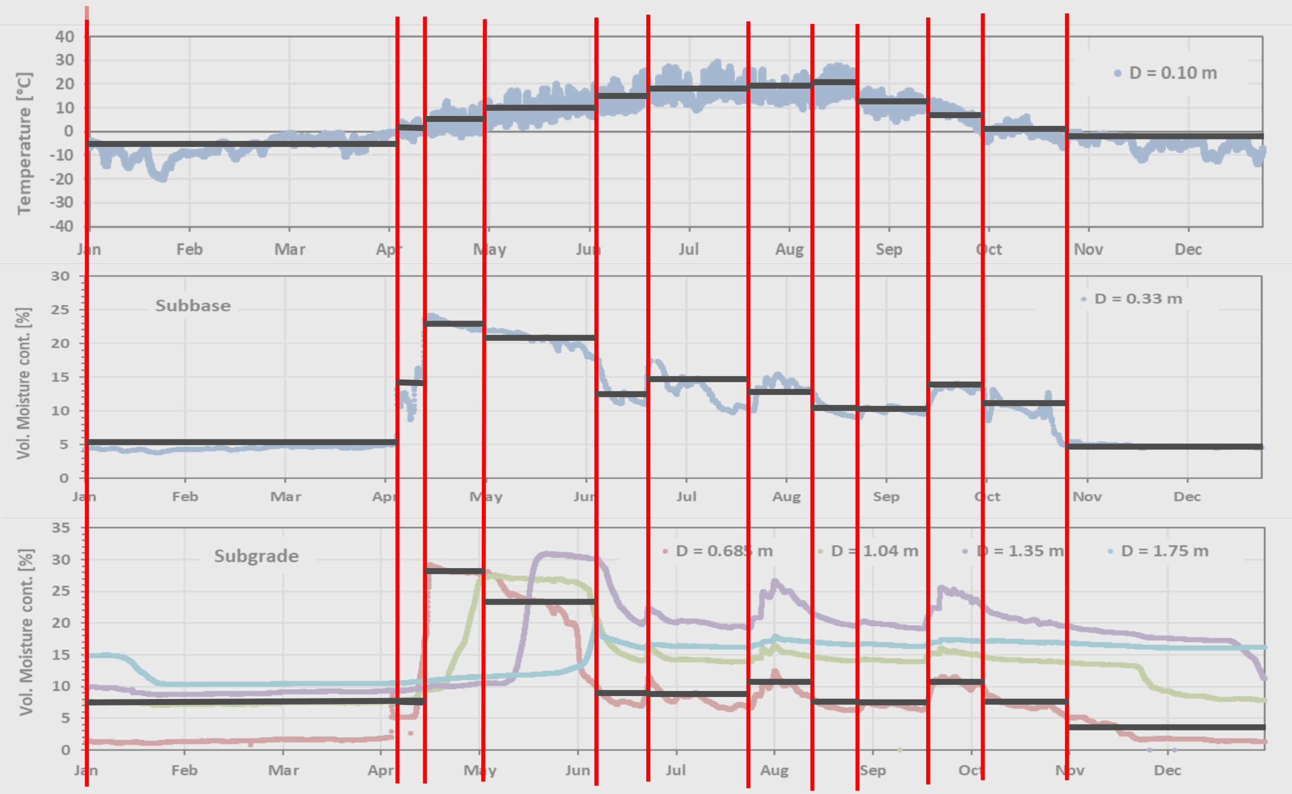


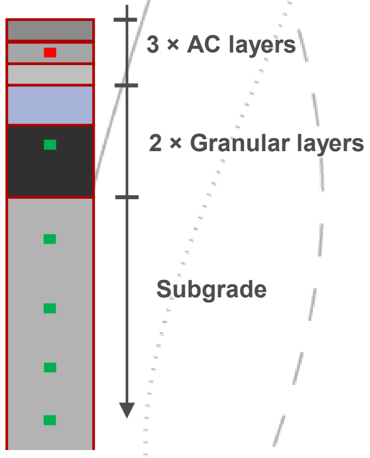


Climate data cont.

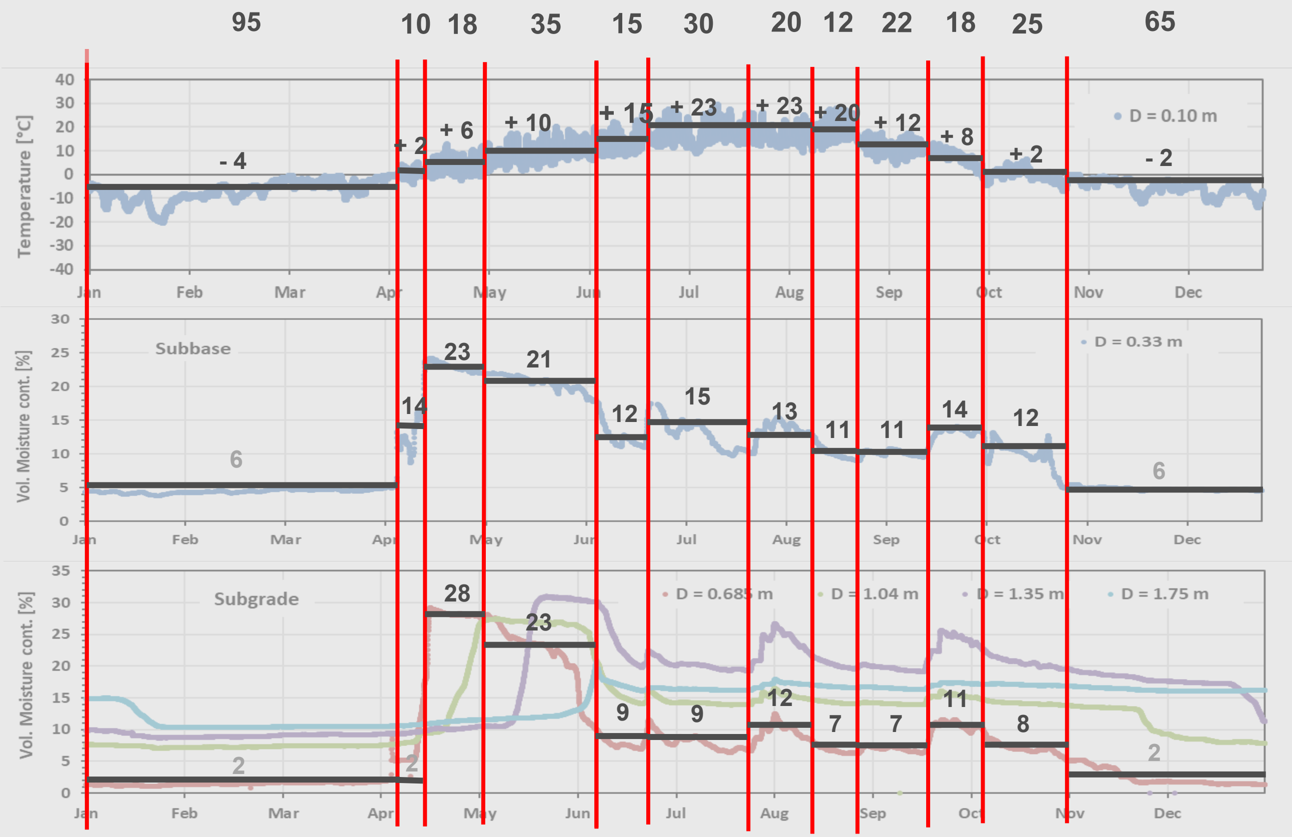


Climate data cont.





Climate data cont.



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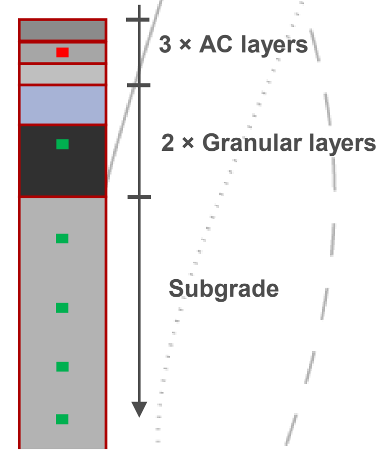
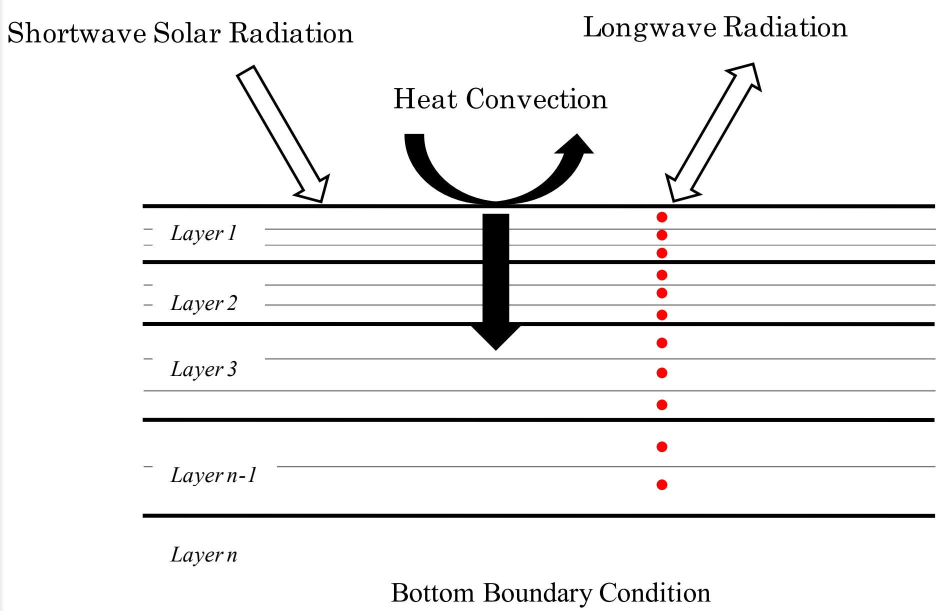


$$w = \frac{\gamma_w}{\gamma_{dry}} \theta_{vol}$$

$$e = \frac{G_s \gamma_w}{\gamma_{dry}} - 1$$

$$S = \frac{w G_S}{e}$$

Climate model - Finite control volume method



Considered external factors contributing to heat intake:

- Conduction from air temperature

- Solar shortwave radiation

$$q_{solar} = (1 - \alpha) Q_{Solar}$$

- Longwave infrared radiation

$$q_{in} = \varepsilon_a \sigma {T_{air}}^4$$

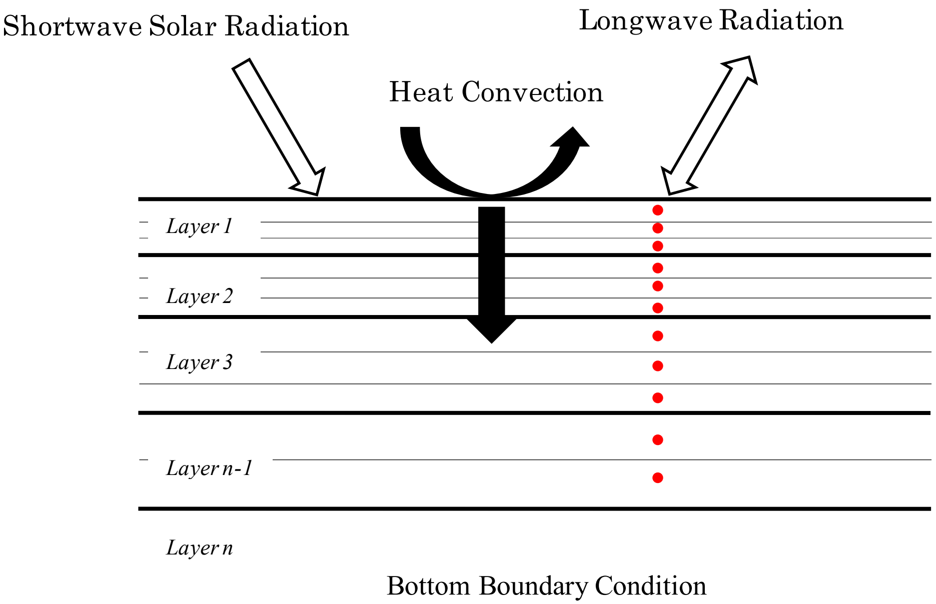
- Convective heat transfer (wind speed)

$$q_c = h_c (T_s - T_{air})$$

$$h_c = 698.24a \left(0.00144 \left\{ abs \left[\frac{T_s + T_{air}}{2} \right] \right\}^{0.3} \times U^d + 0.00097 [abs(T_s - T_{air})]^{0.3} \right)$$

Input parameters: Air temperature, Wind speed, Solar radiation

Climate model - Finite control volume method



- 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)

$$\rho_i c_{p_i} \Delta z_i \frac{T_i^n - T_i^{n-1}}{\Delta t} = \frac{T_{i-1}^n - T_i^n}{\frac{\Delta z_{i-1}}{2k_{i-1}} + \frac{\Delta z_i}{2k_i}} + \frac{T_{i+1}^n - T_i^n}{\frac{\Delta z_{i+1}}{2k_{i+1}} + \frac{\Delta z_i}{2k_i}}$$

- Adjustments at the boundary conditions

- At the surface:

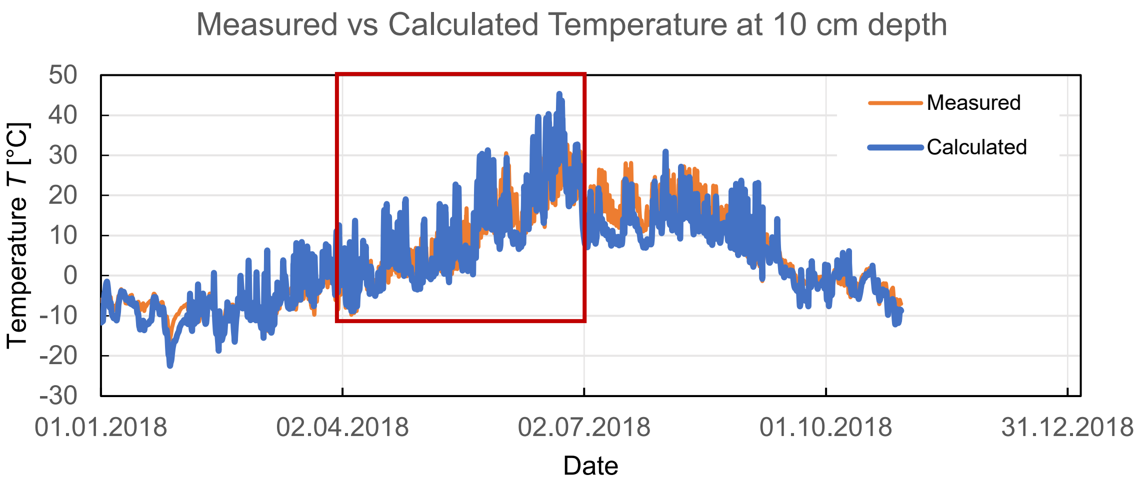
$$\rho_s c_{p_s} \Delta z_s \frac{T_s^n - T_s^{n-1}}{\Delta t} = \frac{T_1^n - T_s^n}{\frac{\Delta z_1}{2k_1} + \frac{\Delta z_s}{2k_s}} + q_{Solar} + q_{in} - q_{out} - q_c$$

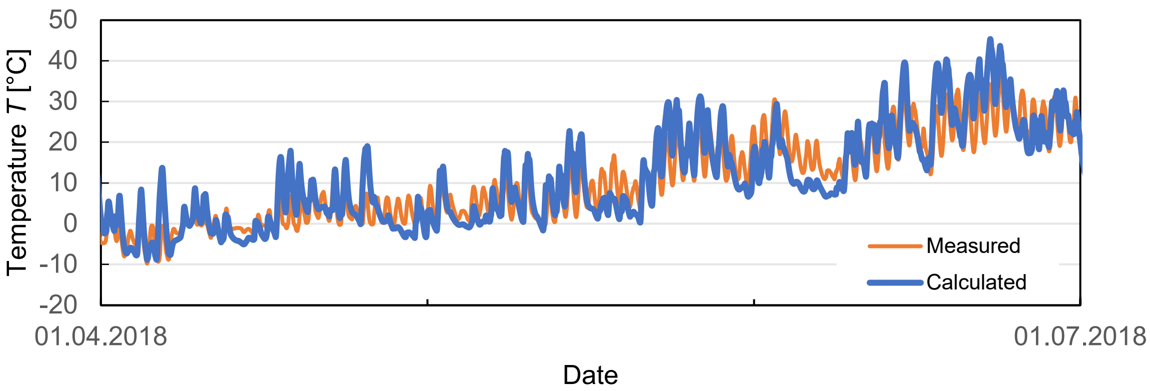
- At the bottom boundary:

$$\rho_i c_{p_i} \Delta z_i \frac{T_i^n - T_i^{n-1}}{\Delta t} = \frac{T_g^n - T_i^n}{\frac{\Delta z_{i-1}}{2k_{i-1}} + \frac{\Delta z_i}{2k_i}} + \frac{T_{i+1}^n - T_i^n}{\frac{\Delta z_{i+1}}{2k_{i+1}} + \frac{\Delta z_i}{2k_i}}$$

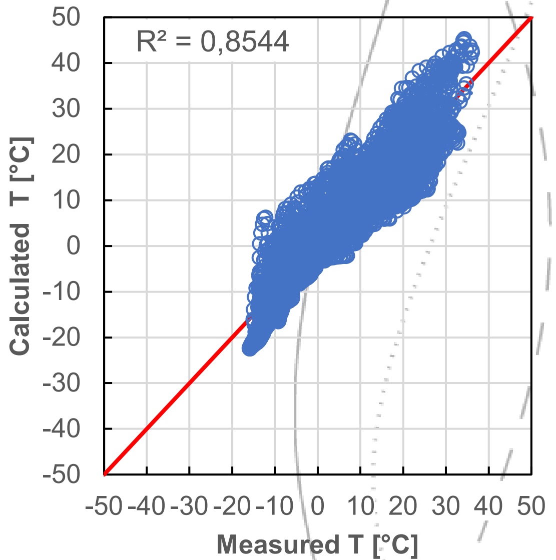
Temperature prediction

Temperature at 10 cm depth

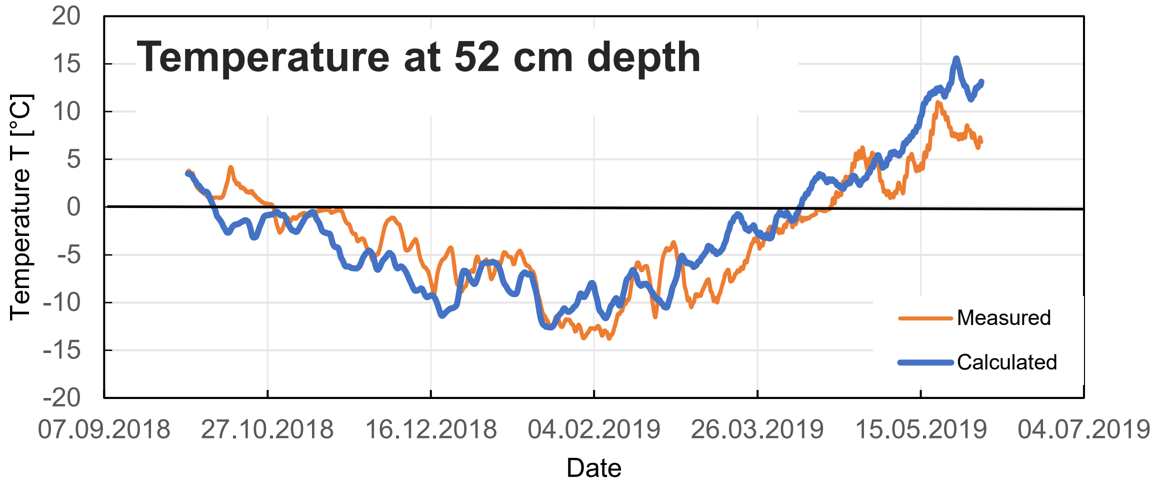


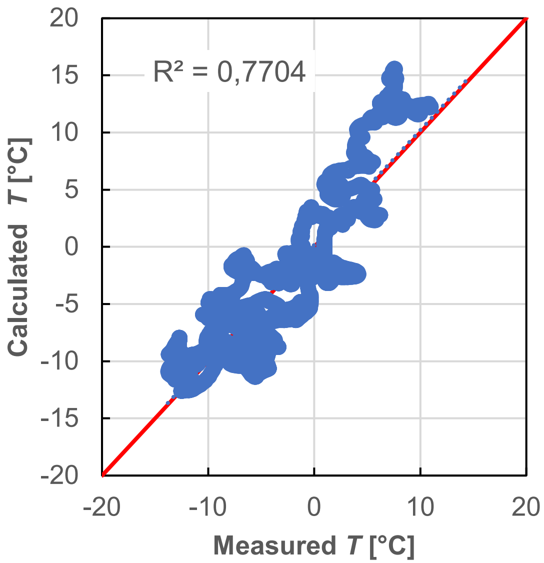


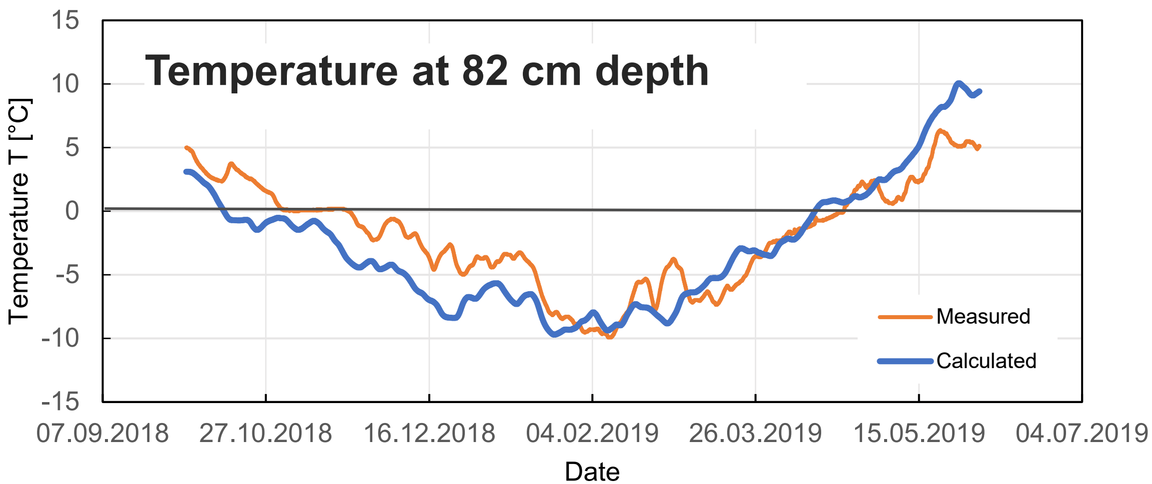
Air temperature
Wind speed (~3 km)
Solar radiation (~50 km)

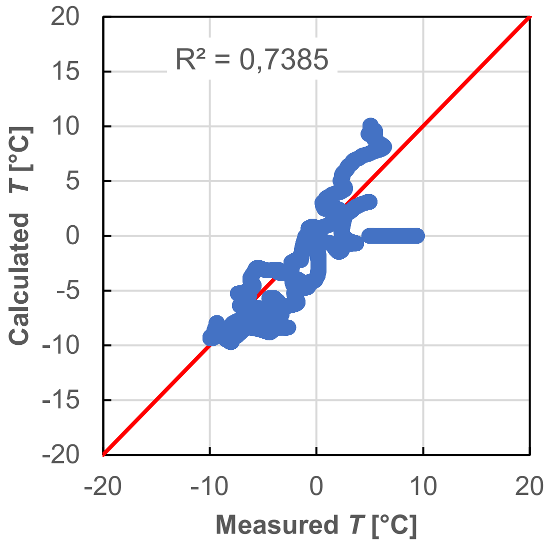


Temperature prediction cont.









Summary

ERAPave PP is a new M-E based software for structural design of flexible pavements.

The software is still under development.

Some further developments:

- The interface needs further improvements.
- The climate needs to be better included in the design (performance calculations).
- Validation of performance predictions is needed.
- Update of the studded tyre (abrasion) model.
- A material databank.

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Thank You for Your Attention!