South African Road Design System - Recursive Performance Simulation

Road Pavements Forum Feedback

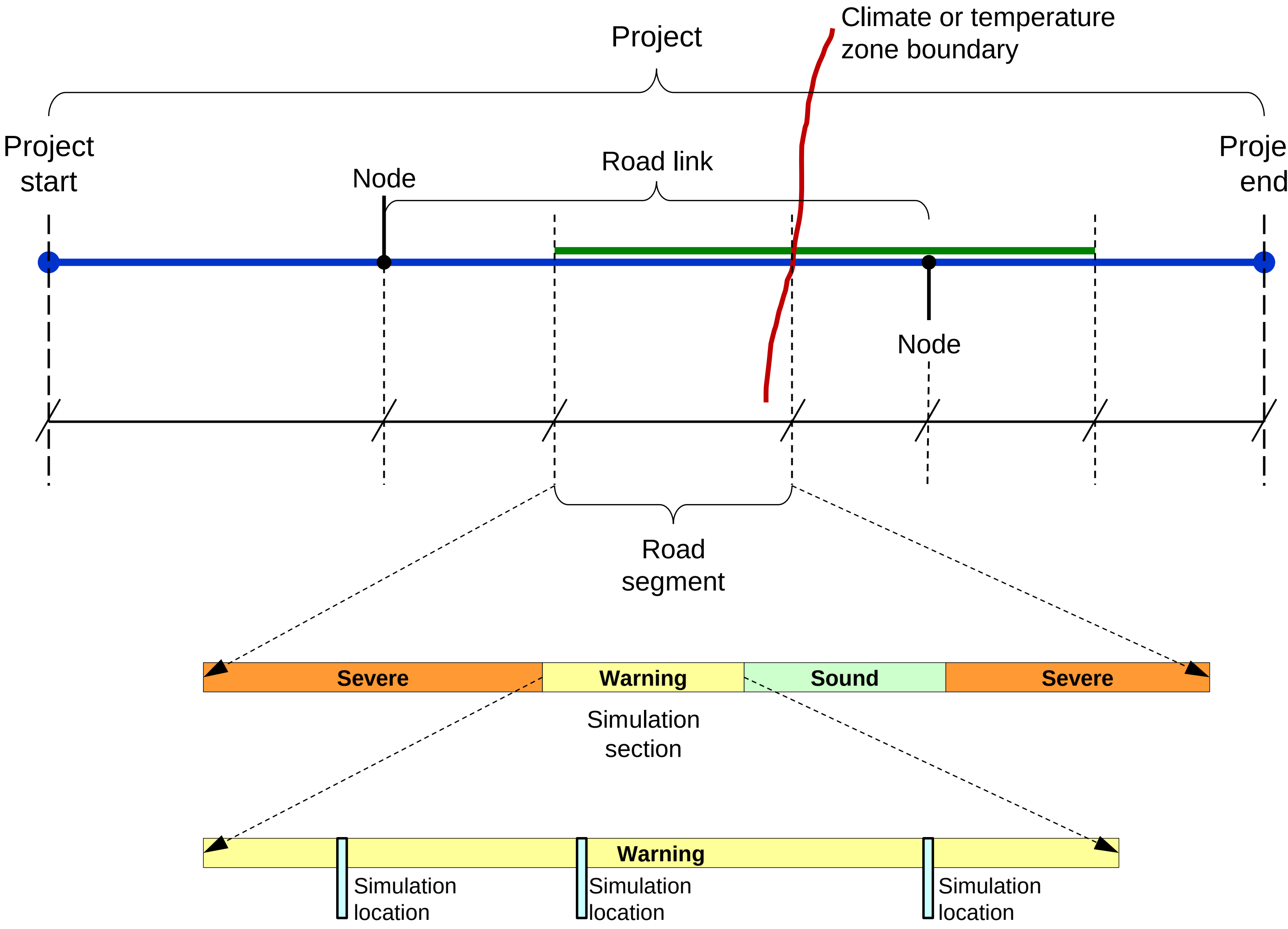
20 November 2014

H L Theyse

Recursive Performance Simulation

Design Investigation Context

Simulation sections



Project

Climate or temperature zone boundary

Project start

Node

Road link

Project end

Direction 1, lane 2

Direction 1, lane 1

Node

Road segment

Severe | **Warning** | **Sound** | **Severe**

Simulation section

Warning

Simulation location

Simulation location

Simulation location

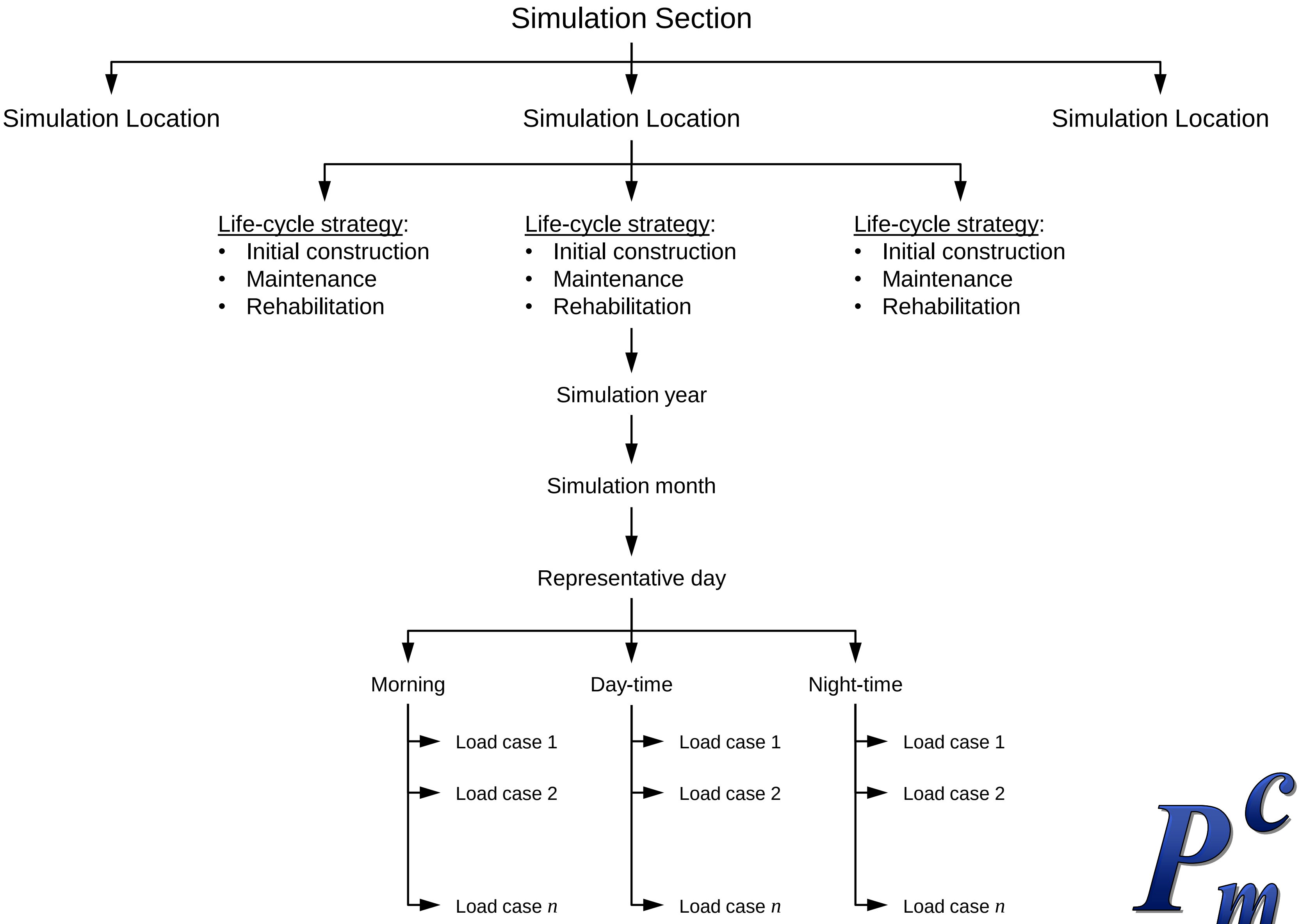
<u>Road segments</u>
Direction1:

- Environment
- Geometry

<u>Active lane simulation sections</u>:

- Pavement condition

Temporal recursive simulation



Simulation Section

Simulation Location

Simulation Location

Simulation Location

<u>Life-cycle strategy</u>:
- Initial construction
- Maintenance
- Rehabilitation

<u>Life-cycle strategy</u>:
- Initial construction
- Maintenance
- Rehabilitation

<u>Life-cycle strategy</u>:
- Initial construction
- Maintenance
- Rehabilitation

Simulation year

Simulation month

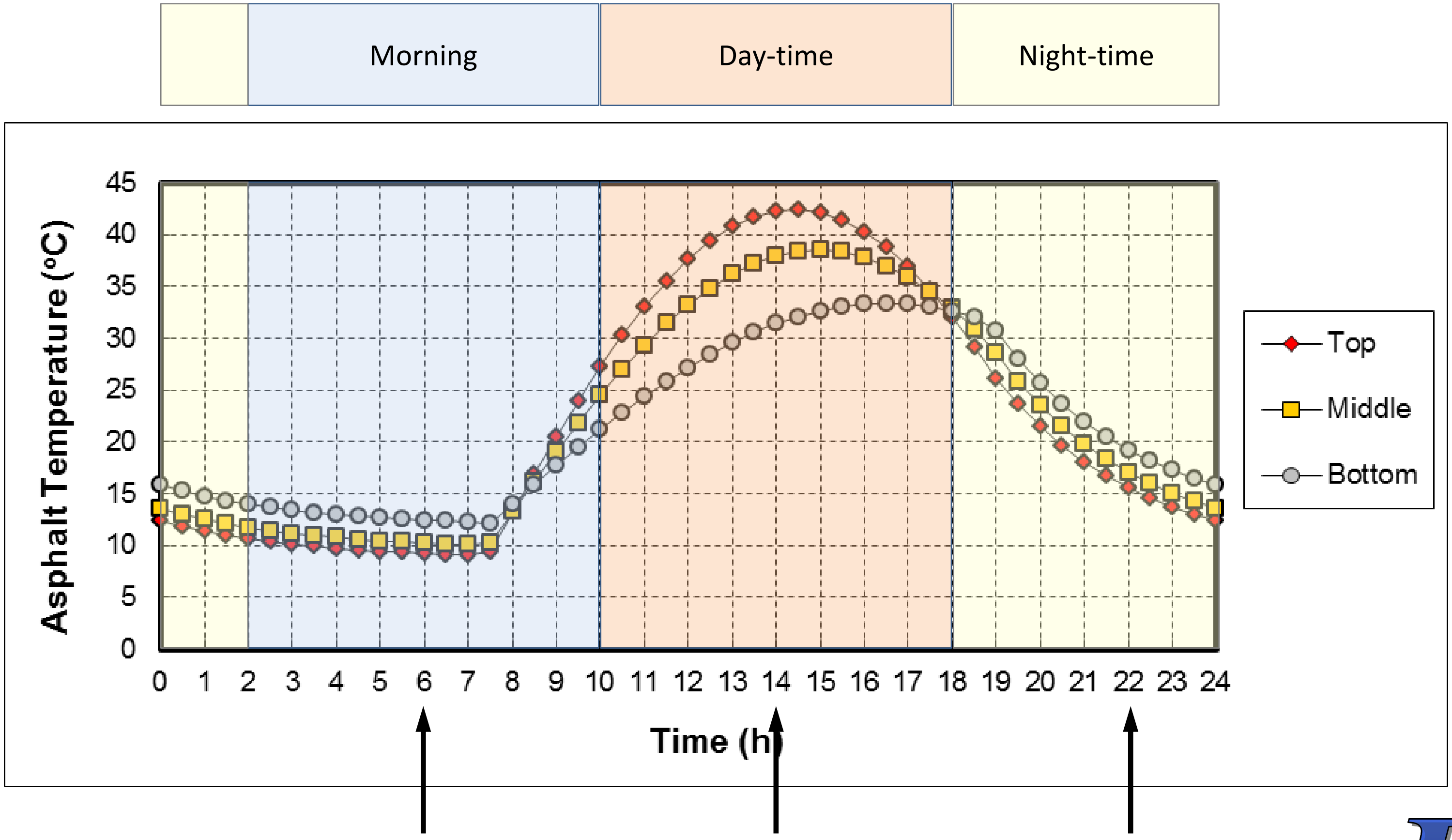
Representative day

Morning
- Load case 1
- Load case 2
- Load case *n*

Day-time
- Load case 1
- Load case 2
- Load case *n*

Night-time
- Load case 1
- Load case 2
- Load case *n*

Daily simulation periods



Representative hour:
Morning

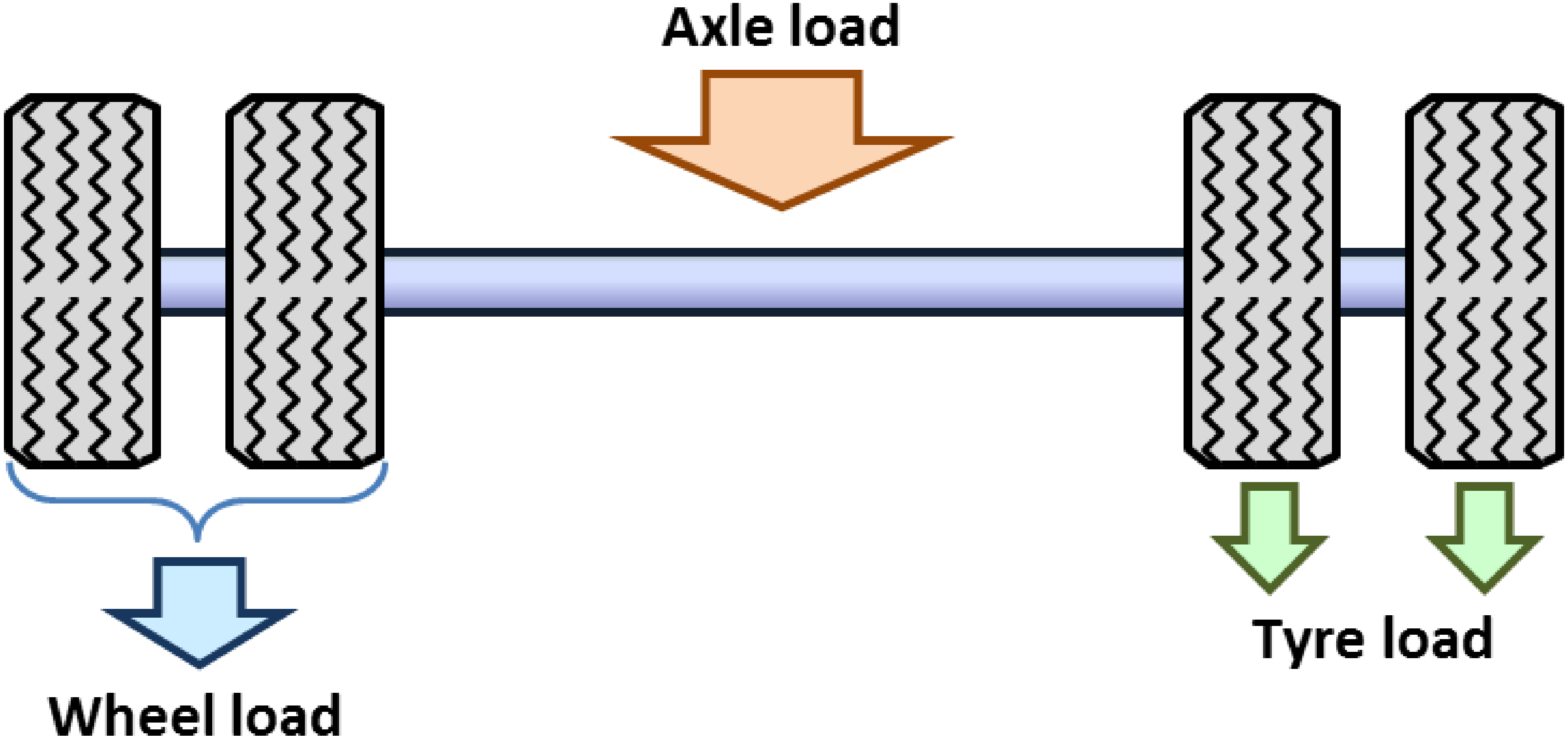
Representative hour:
Day-time

Representative hour:
Night-time

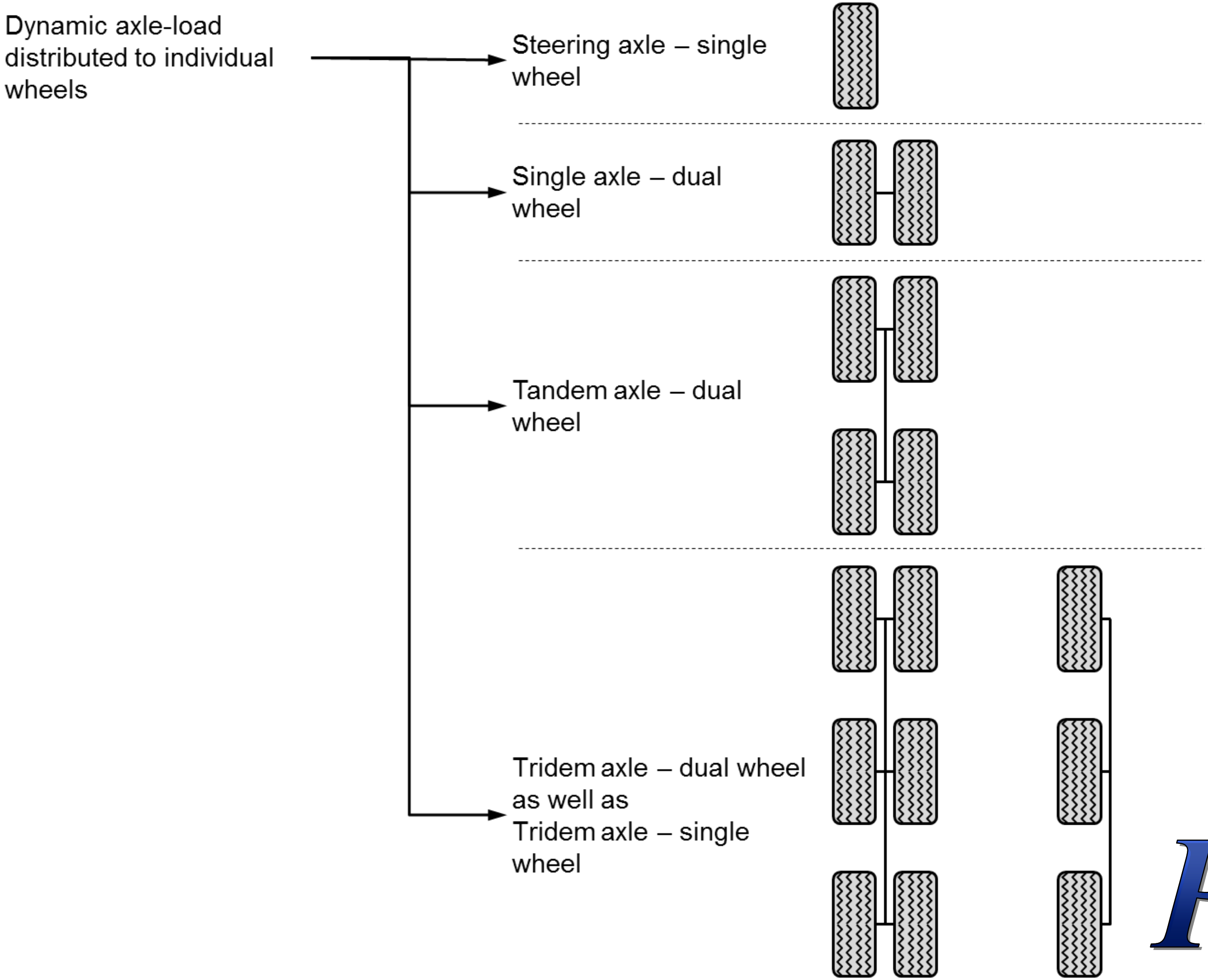
Recursive Performance Simulation

Traffic loads

Load definitions



Load cases



Dynamic axle-load distributed to individual wheels

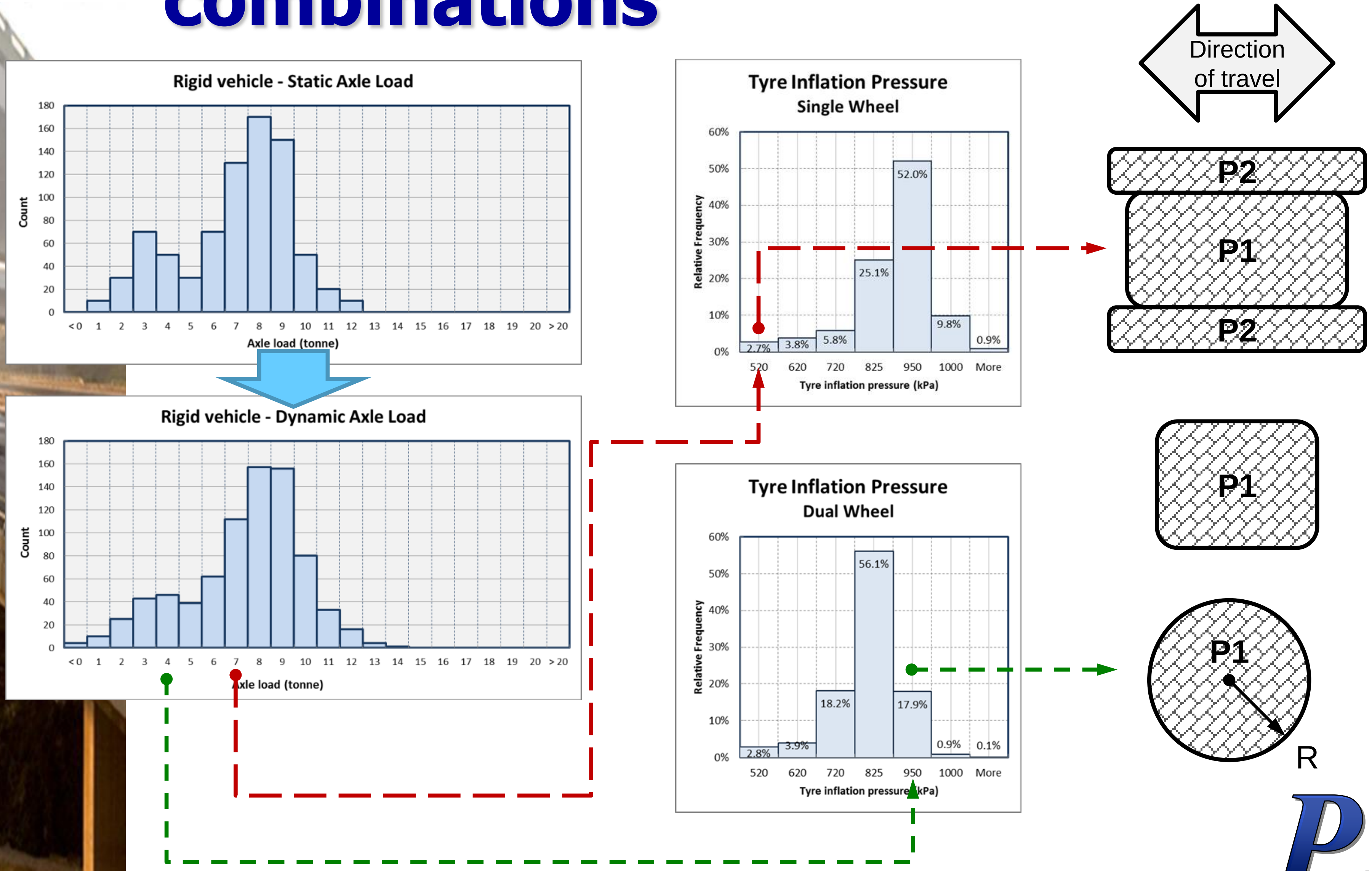
Steering axle – single wheel

Single axle – dual wheel

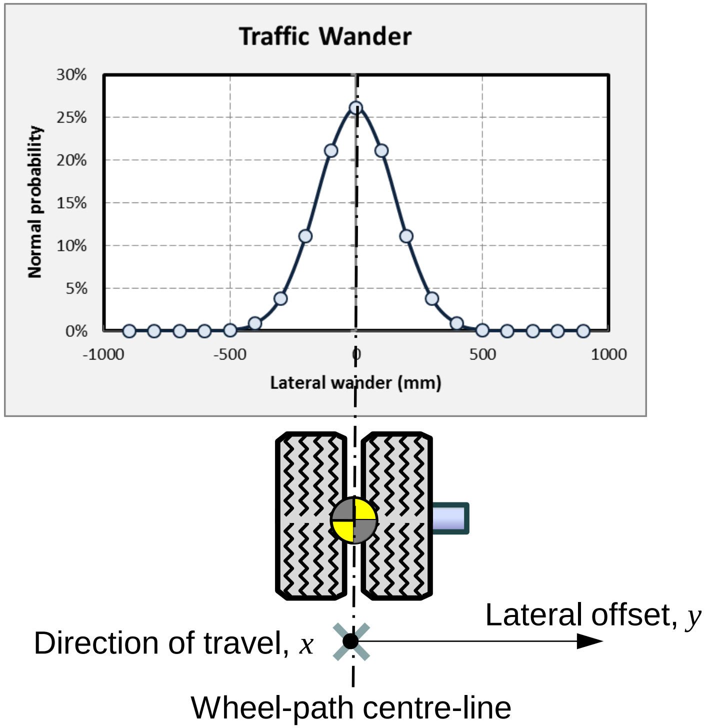
Tandem axle – dual wheel

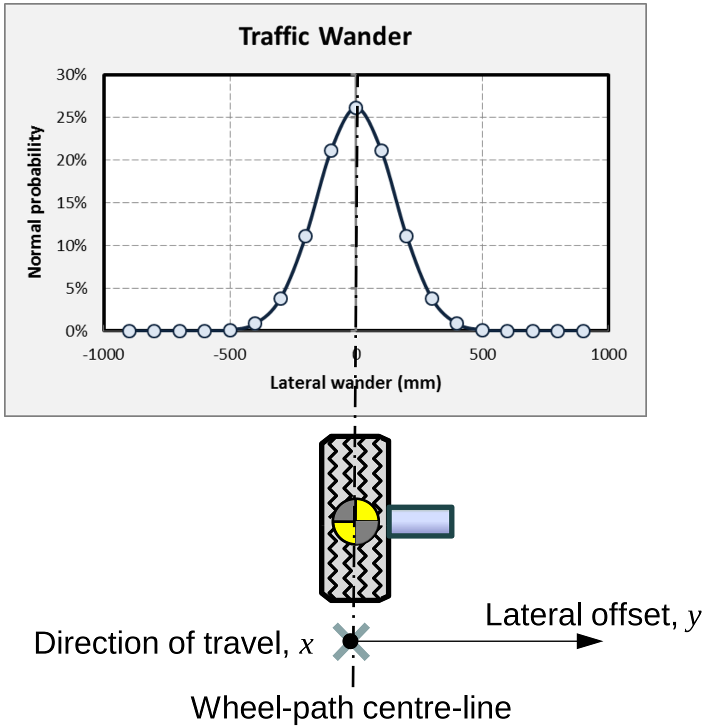
Tridem axle – dual wheel as well as Tridem axle – single wheel

Axle load – tyre inflation pressure combinations



Traffic wander

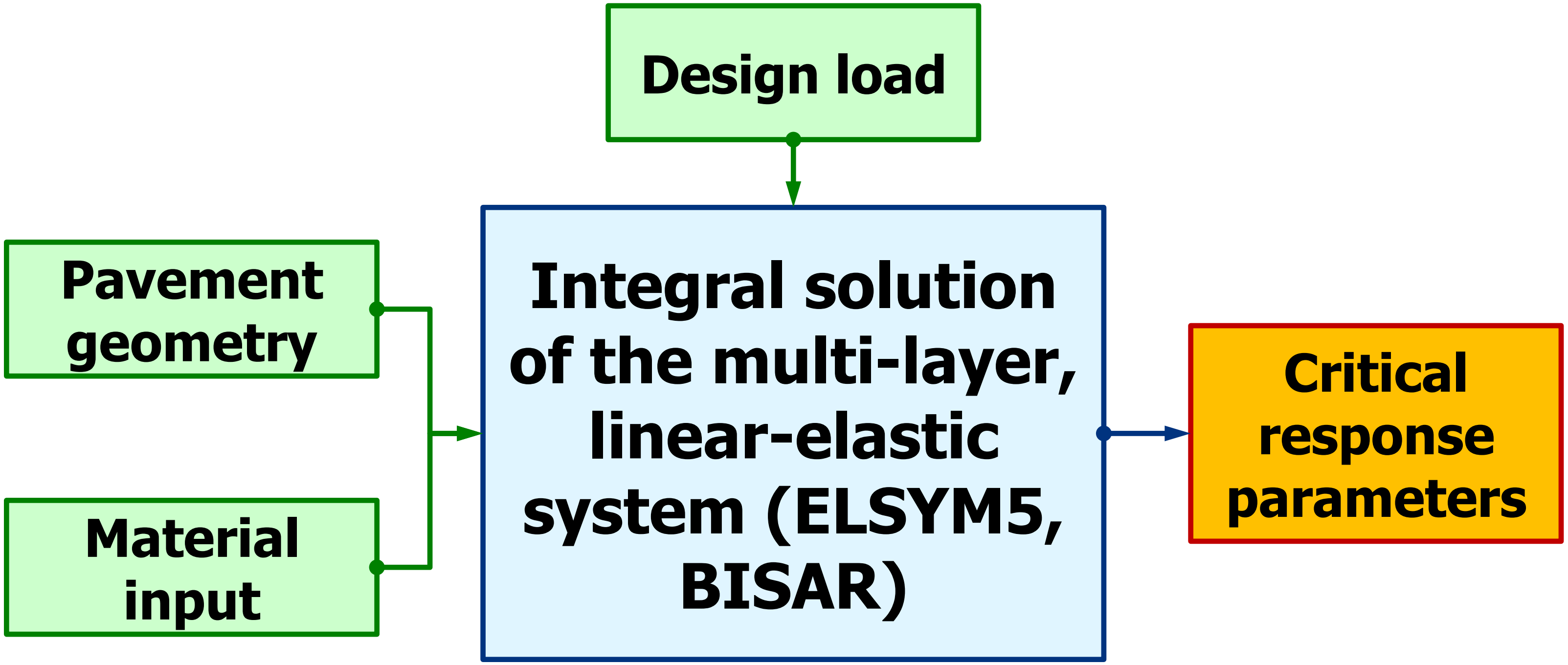




Recursive Performance Simulation

Primary Pavement Response Model - PPRM

Yesterday



Design load

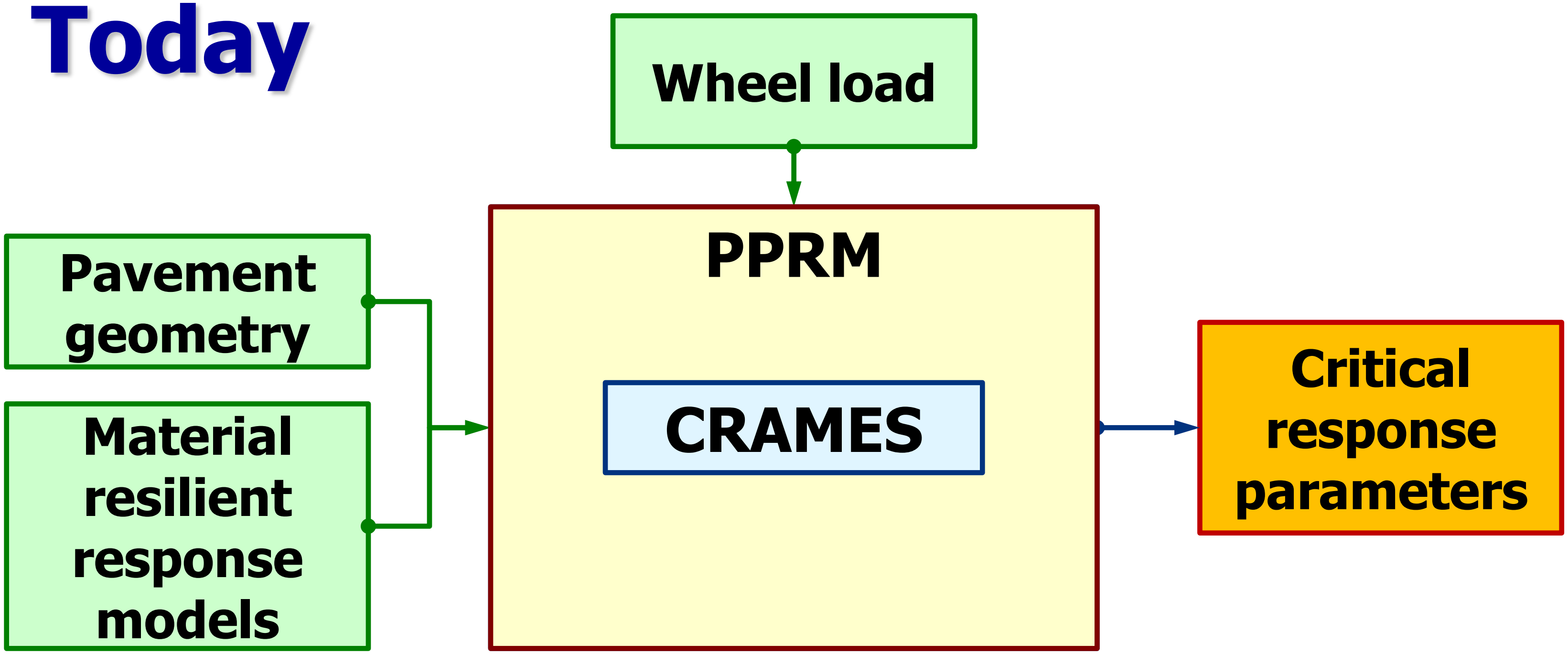
Pavement geometry

Material input

Integral solution of the multi-layer, linear-elastic system (ELSYM5, BISAR)

Critical response parameters

Today



Wheel load

Pavement geometry

Material resilient response models

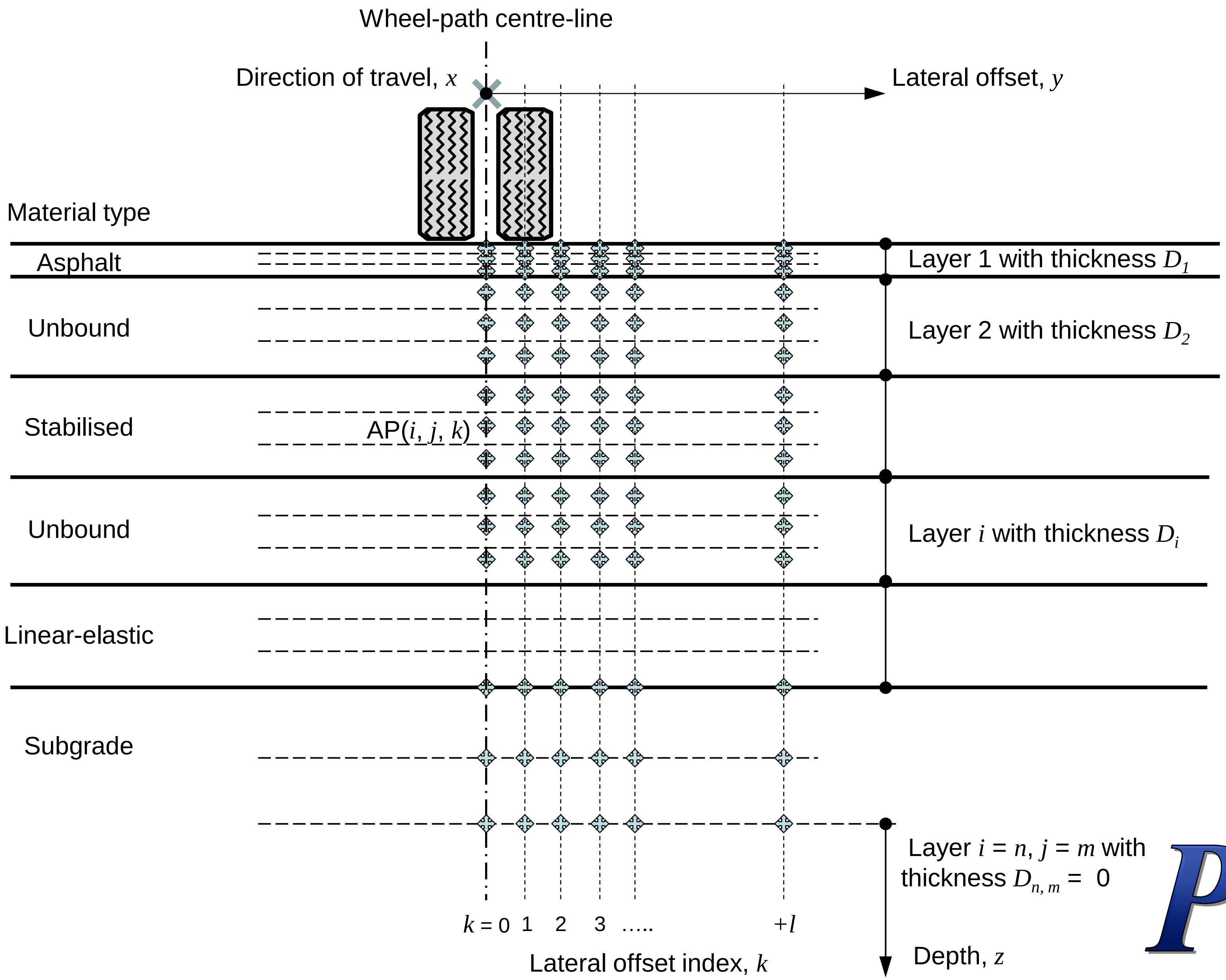
PPRM

CRAMES

Critical response parameters

- Primary Pavement Response Model functions
  - Effective stress analysis
    - Thermal stress in asphalt
    - Suction pressure and residual compaction stress in unbound material
  - Convergence of stress-dependent resilient response models

Analysis points (APs)



Wheel-path centre-line

Direction of travel, x

Lateral offset, y

Material type

Asphalt

Unbound

Stabilised

Unbound

Linear-elastic

Subgrade

AP(i, j, k)

Layer 1 with thickness D_1

Layer 2 with thickness D_2

Layer i with thickness D_i

Layer $i = n$, $j = m$ with thickness $D_{n,m} = 0$

Depth, z

$k = 0$ 1 2 3 ….. $+l$

Lateral offset index, k

Recursive Performance Simulation

Material Models

Material models - Models coded to date

- Asphalt
  - Resilient response
    - Dynamic modulus model
  - Effective stress
    - Thermal stress
  - Fatigue
    - Initial strain based model
    - Subsequent stress based model
  - Plastic strain
    - Shear strain based model

Material models - Models coded to date

- Unbound granular material
  - Resilient response
    - Stress-dependent chord modulus model
  - Effective stress
    - Suction pressure
    - Residual compaction stress
  - Plastic strain
    - Stress Ratio based model

Material models - Models coded to date

- Subgrade
  - Resilient response
    - Linear-elastic model with stiffness reduction
  - Plastic strain
    - Subgrade Elastic Deflection based model
      - Fine-grained subgrade material
      - Coarse (gravel) subgrade material

Development Cycles

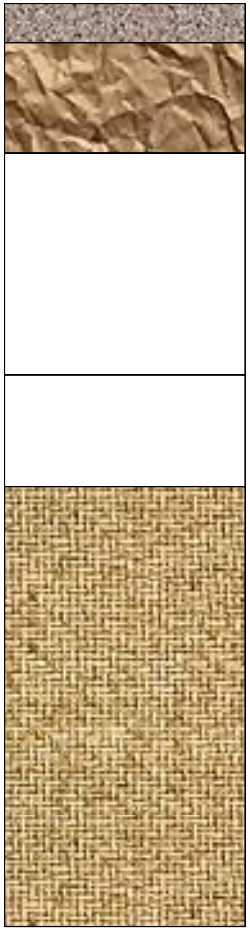
- **Step 1**
  - **Laboratory calibrated models**
  - **Implement in recursive simulation**
  - **Is the correct behaviour simulated?**
- Step 2
  - Field calibration under controlled conditions
- Step 3
  - Field calibration under operational conditions

Recursive Performance Simulation

Recursive simulation results

Recursive simulation results – Maximum rut

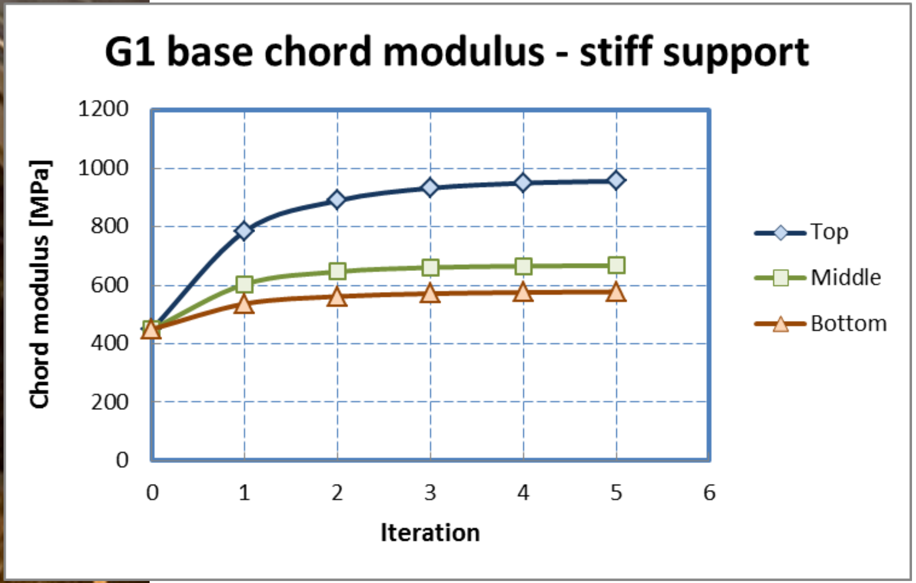
- Pavement rut on the wheel-path centre-line
- Aggressive traffic loading - N3
- Sand subgrade selected to illustrate subgrade deformation
- “Slow” version given stress-dependent base layer model

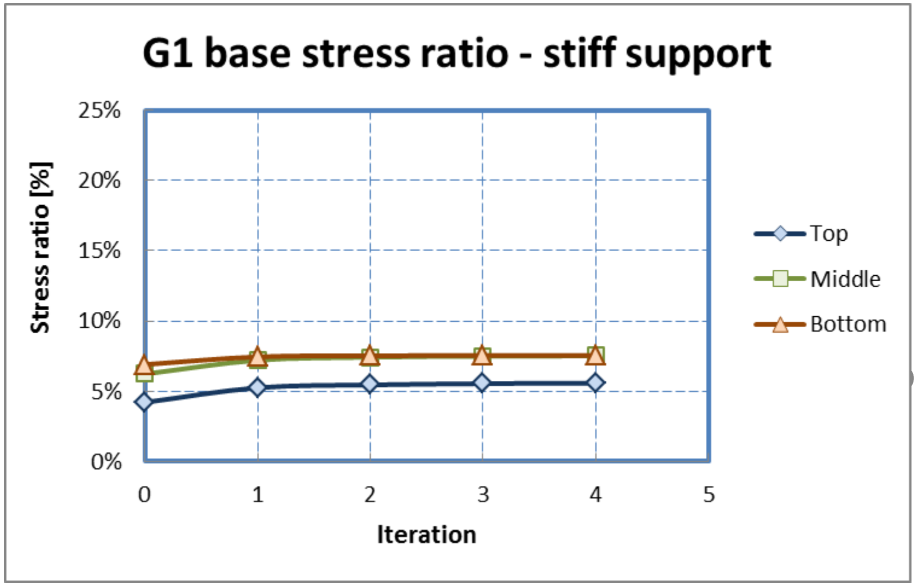


40 AC
150 G1
300 C3
150 G7
Subgrade

Recursive simulation results – Maximum rut

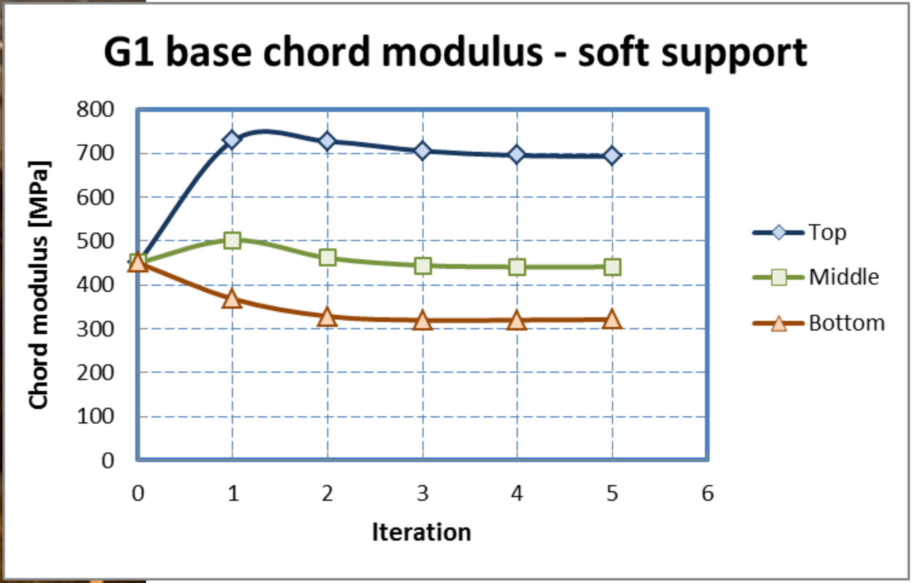
- G1 base stress-dependent chord modulus
  - VD = 88 %; S = 49 %
  - Results shown for one load case, repeated for every tyre load – contact stress combination
  - Effective subbase stiffness 1200 MPa

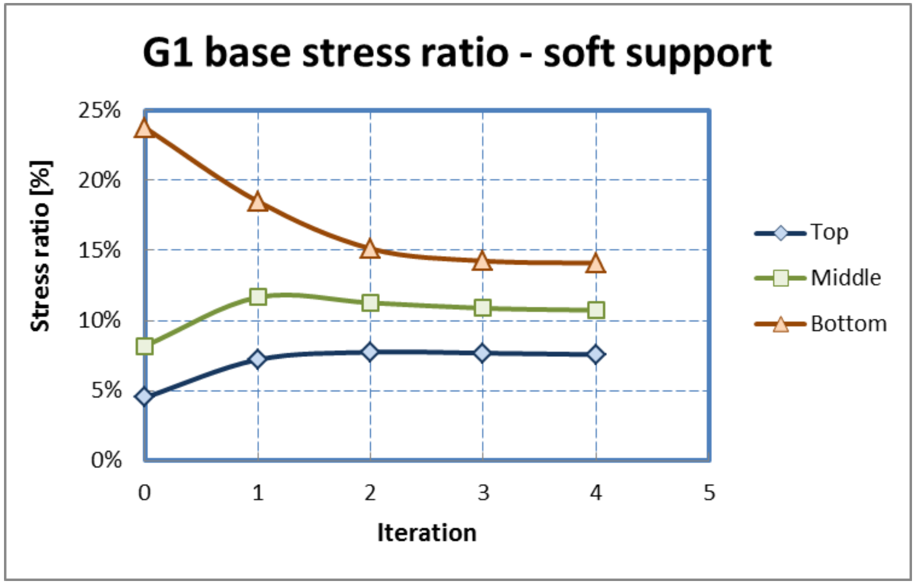




Recursive simulation results – Maximum rut

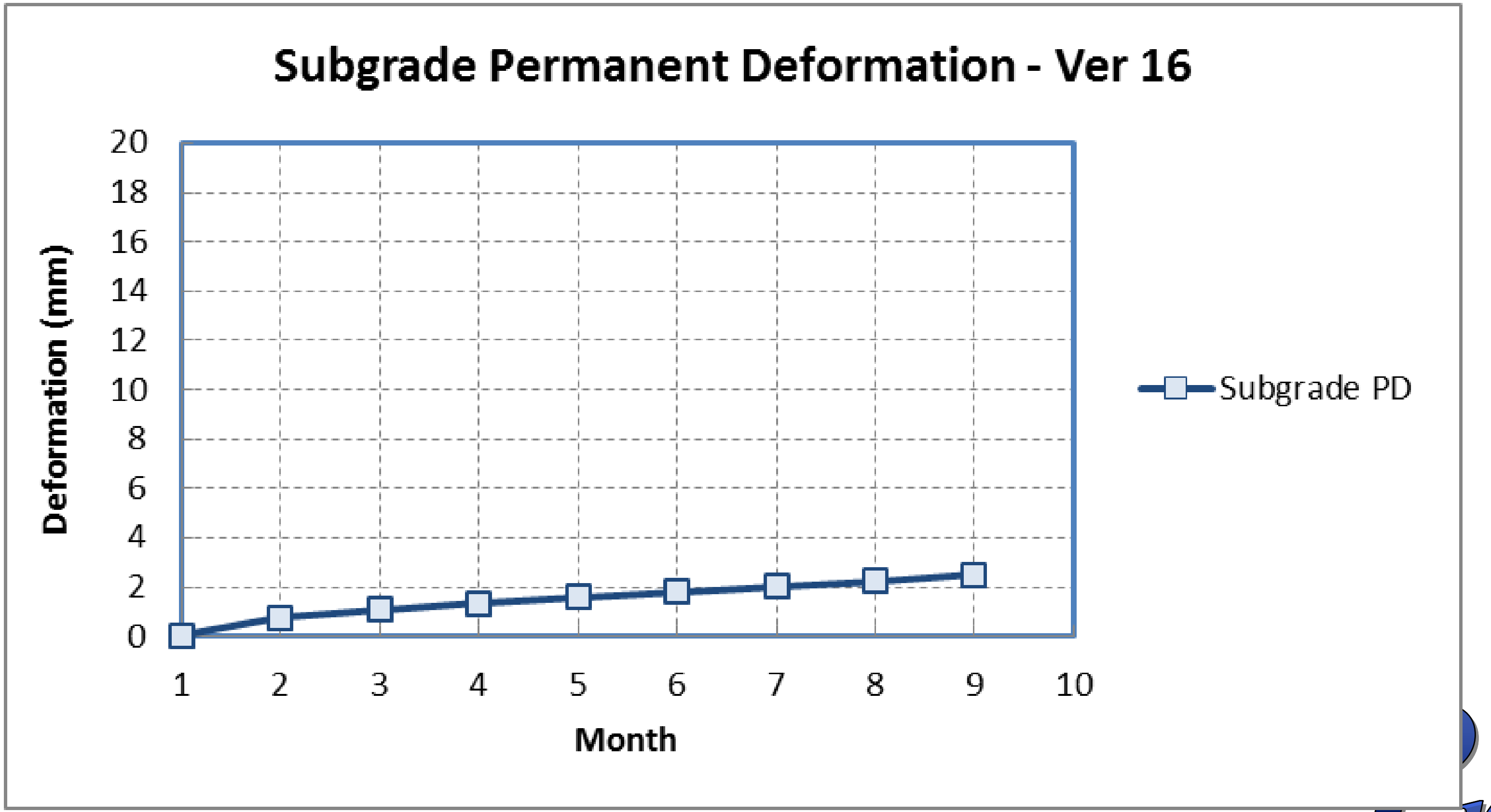
- G1 base stress-dependent chord modulus
  - VD = 88 %; S = 49 %
  - Results shown for one load case, repeated for every tyre load – contact stress combination
  - Effective subbase stiffness 300 MPa





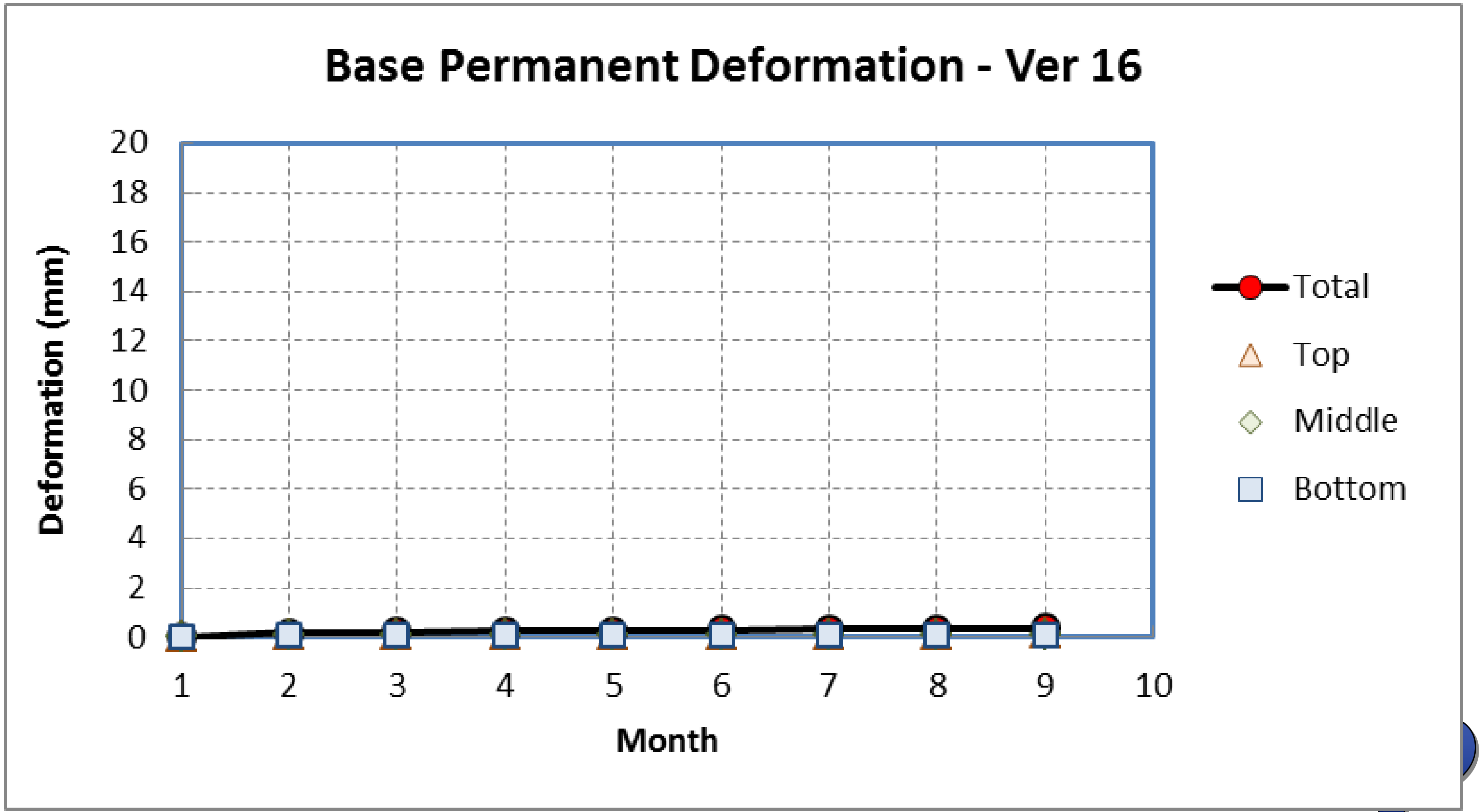
Recursive simulation results – Maximum rut

- Subgrade deformation



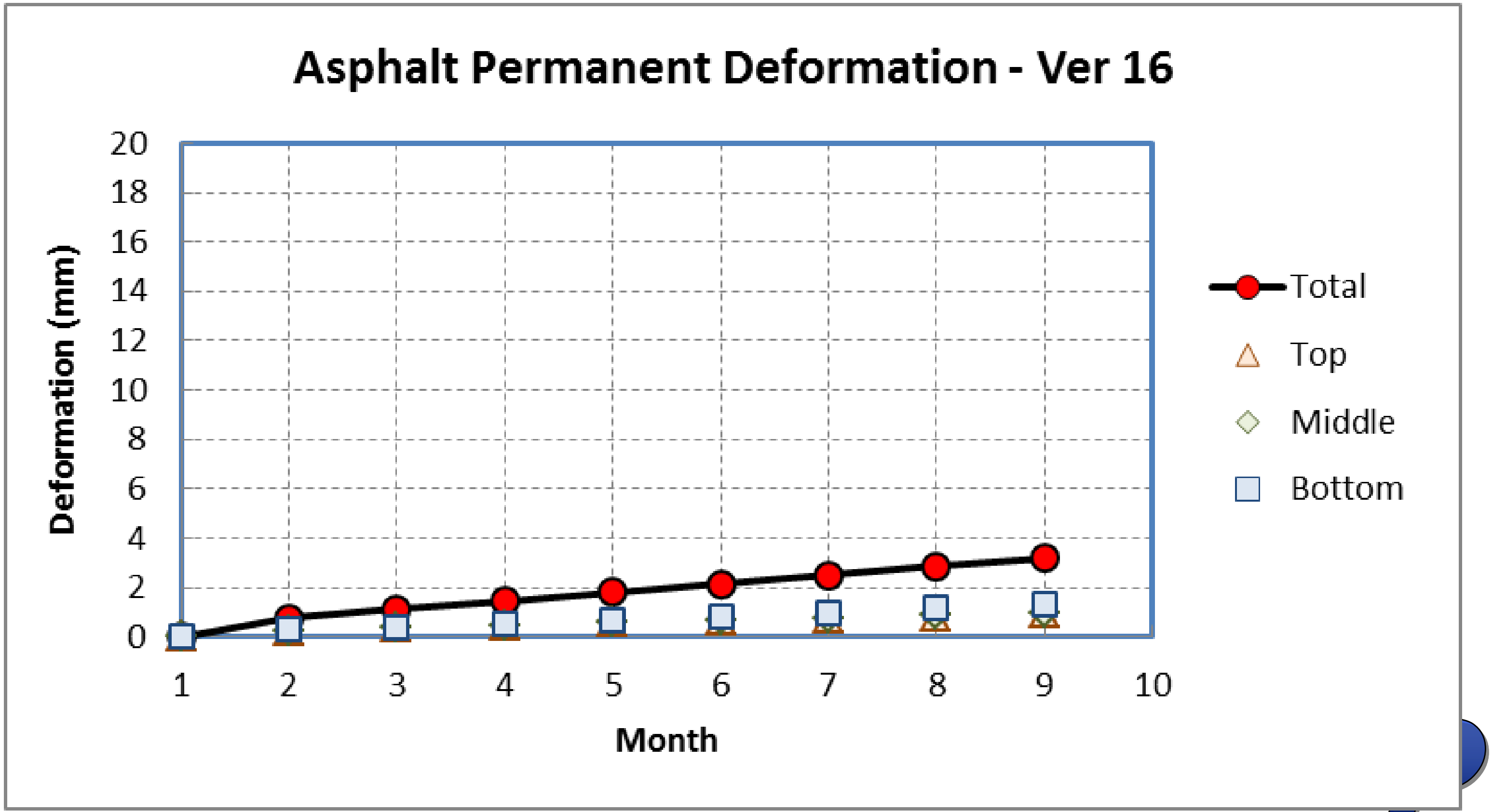
Recursive simulation results – Maximum rut

- G1 base layer deformation



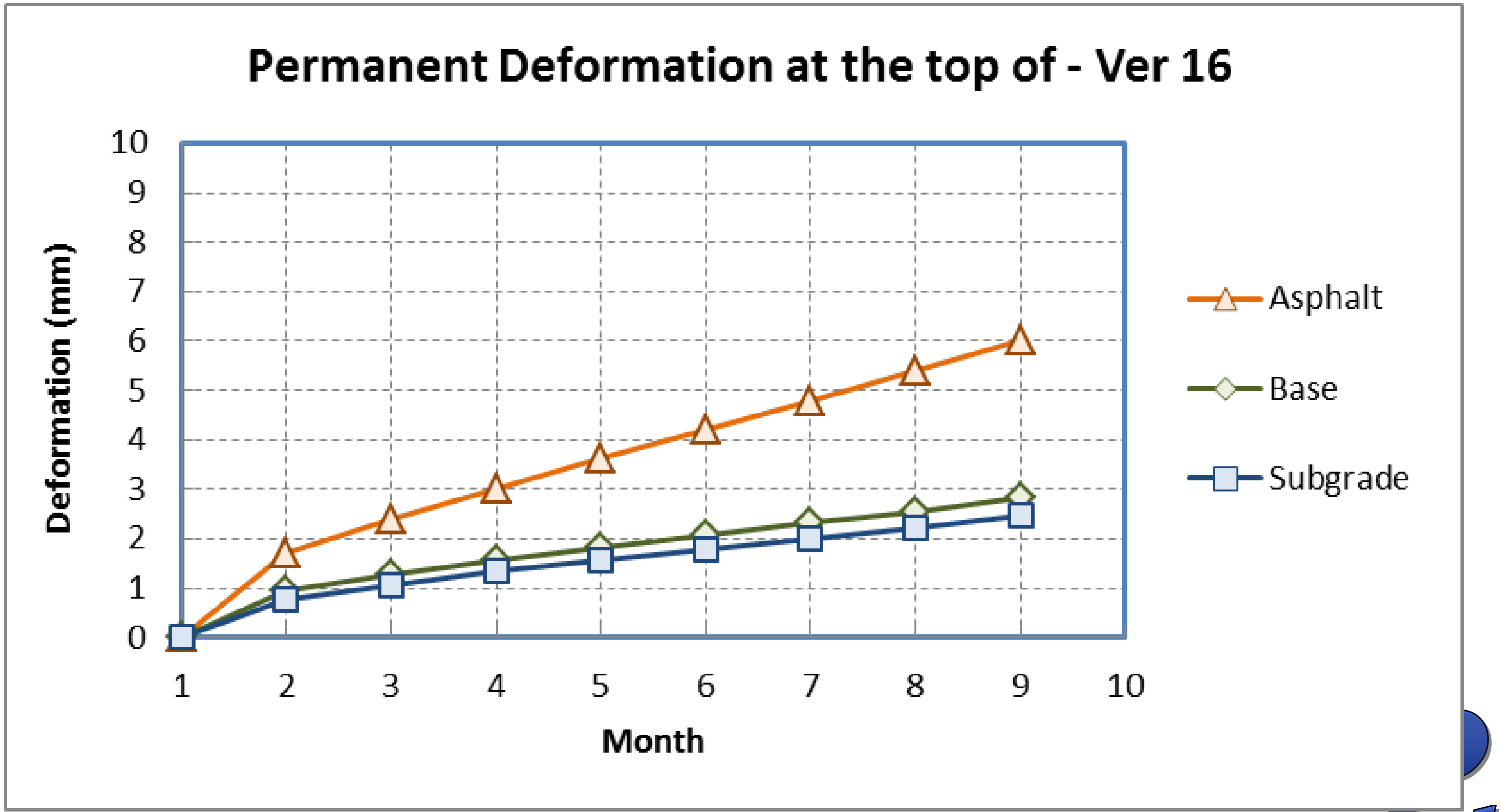
Recursive simulation results – Maximum rut

- Asphalt wearing course deformation



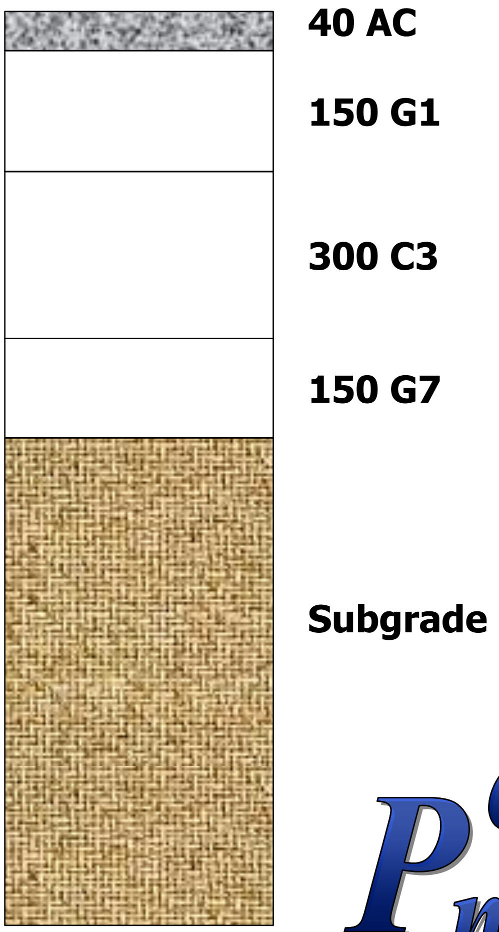
Recursive simulation results – Maximum rut

- Maximum rut on wheel-path centre-line



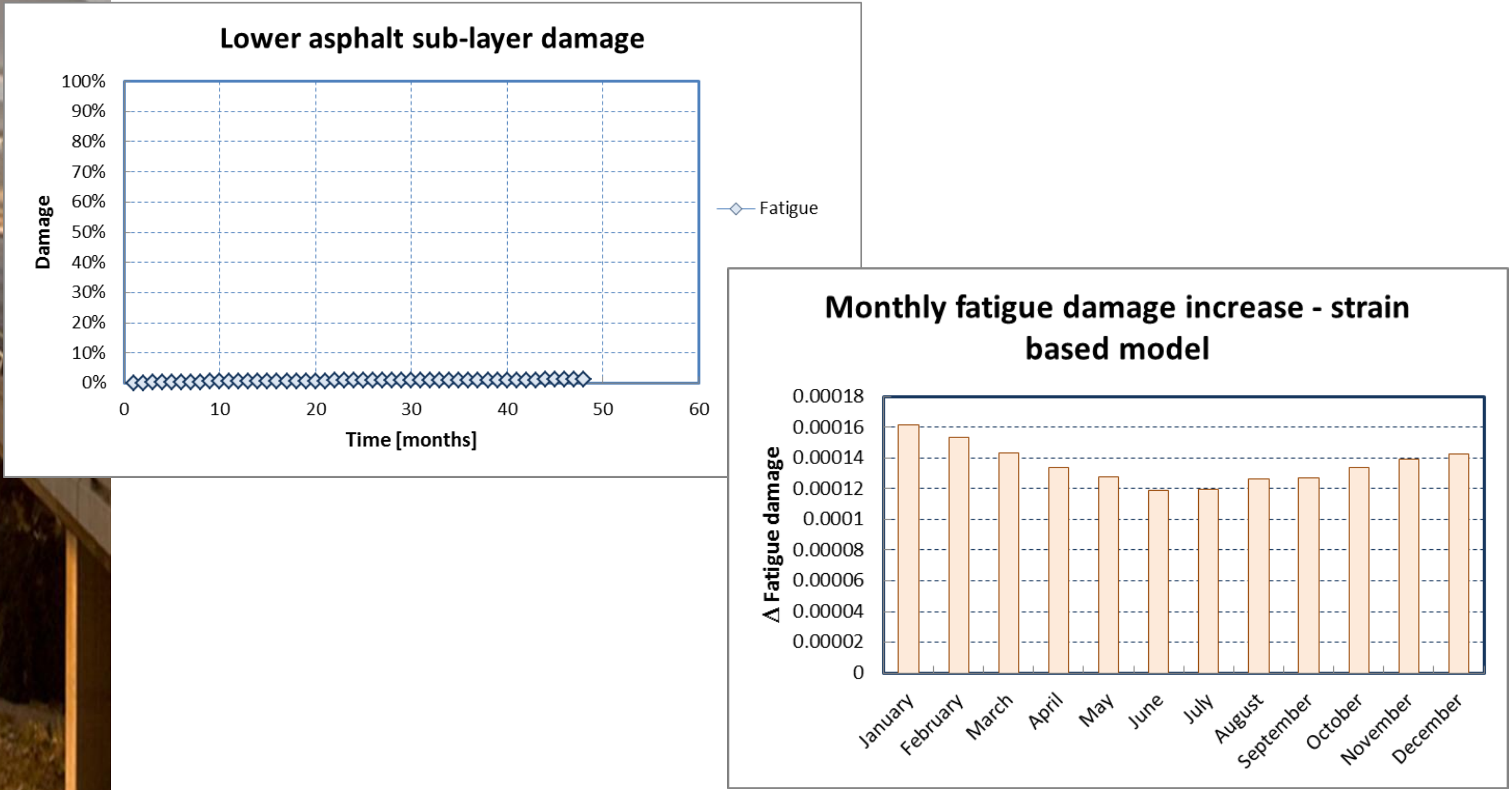
Recursive simulation results – Stiffness reduction

- Layer stiffness reduction on the wheel-path centre-line in each sub-layer
- Aggressive traffic loading - N3
- “Fast” version without stress-dependent layers



Recursive simulation results – Stiffness reduction

- Asphalt strain based fatigue (Ver. 22)



Recursive simulation results – Stiffness reduction

- Two problems with asphalt strain based fatigue
  - Very little fatigue
  - Higher monthly fatigue increment in summer months

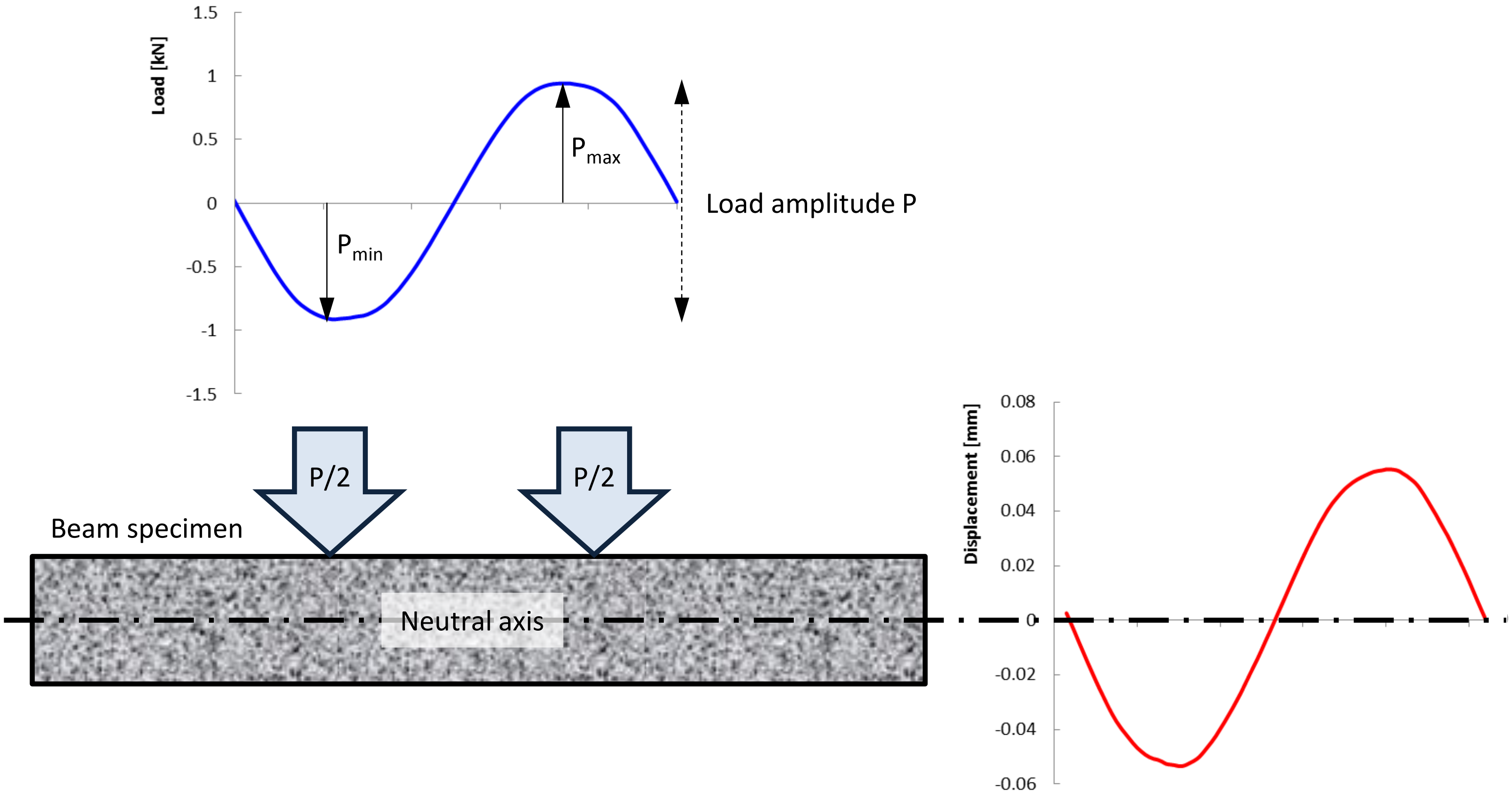
Recursive simulation results – Stiffness reduction

- Low level of simulated fatigue
  - Fatigue tests done on commercial equipment
  - AASHTO T321 test method

  "… the loading device shall be capable of (1) repeated sinusoidal loading … (3) forcing the specimen back to its original position (i.e. zero deflection) at the end of each load pulse."

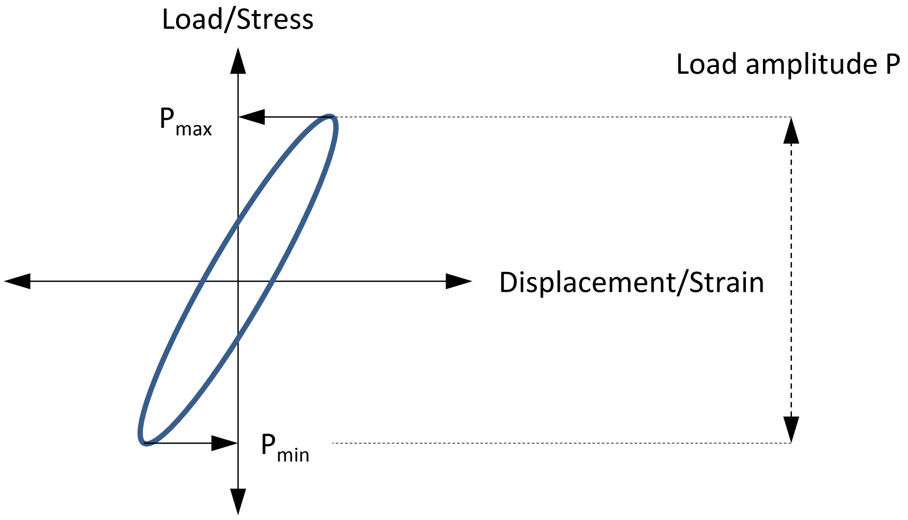
Recursive simulation results – Stiffness reduction

- Low level of simulated fatigue



Recursive simulation results – Stiffness reduction

- Low level of simulated fatigue



$$\sigma_t = \frac{lP}{bh^2}$$

$$\sigma_t = \frac{lP_{\max}}{bh^2} \text{ and } \sigma_t = \frac{lP_{\min}}{bh^2}$$

Recursive simulation results – Stiffness reduction

- Low level of simulated fatigue
  - Stress and strain levels reported by the equipment is twice the actual outer-fibre stress and strain
  - Model is calibrated with the error included in the strain level
    - Test supposedly done at 200 $\mu\varepsilon$
    - Forward simulation calculates working strain 60 $\mu\varepsilon$
    - 60 $\mu\varepsilon$ well below 200 $\mu\varepsilon$ - almost no fatigue simulated
    - Actual test strain is 100 $\mu\varepsilon$ and 60 $\mu\varepsilon$ is much closer to the test strain – more fatigue simulated

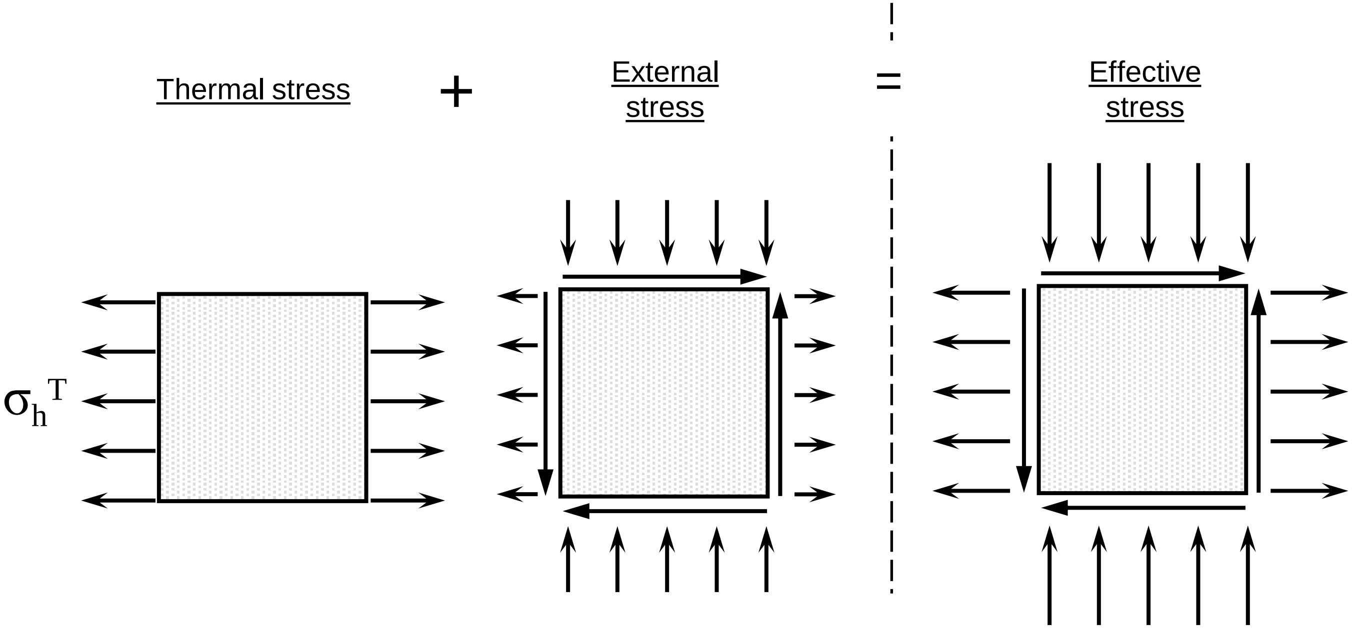
Recursive simulation results – Stiffness reduction

- Higher monthly fatigue increment in summer months
- Explanation
  - Strain highly dependent on stiffness
  - Stiffness highly dependent on temperature
  - High summer temperature
    - Low stiffness
    - High strain
    - Higher fatigue increment
- Design risk
  - Mixes with high stiffness will be selected for better fatigue performance which is incorrect

Recursive simulation results – Stiffness reduction

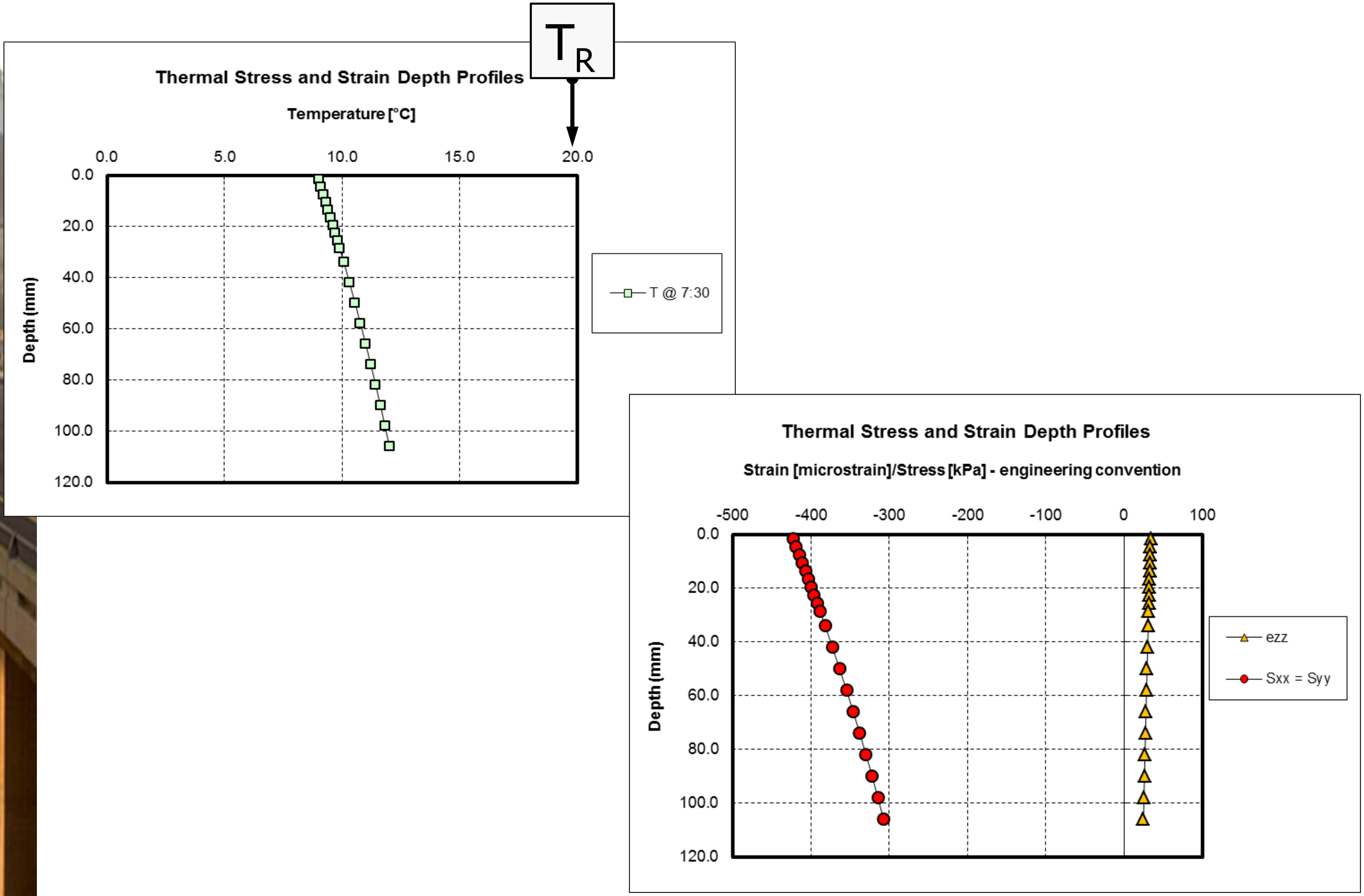
- Higher monthly fatigue increment in summer months
- Solution
  - Stress based fatigue
- Motivation
  - Fracture mechanics considers cracks to be a stress phenomenon
  - Allows direct introduction of thermal stress effects in fatigue simulation
    - Temperature change has a stress effect similar to that of an external wheel-load
  - Thermal cracking and fatigue become two fracture mechanisms explained by the same basic model

Effective stress in asphalt

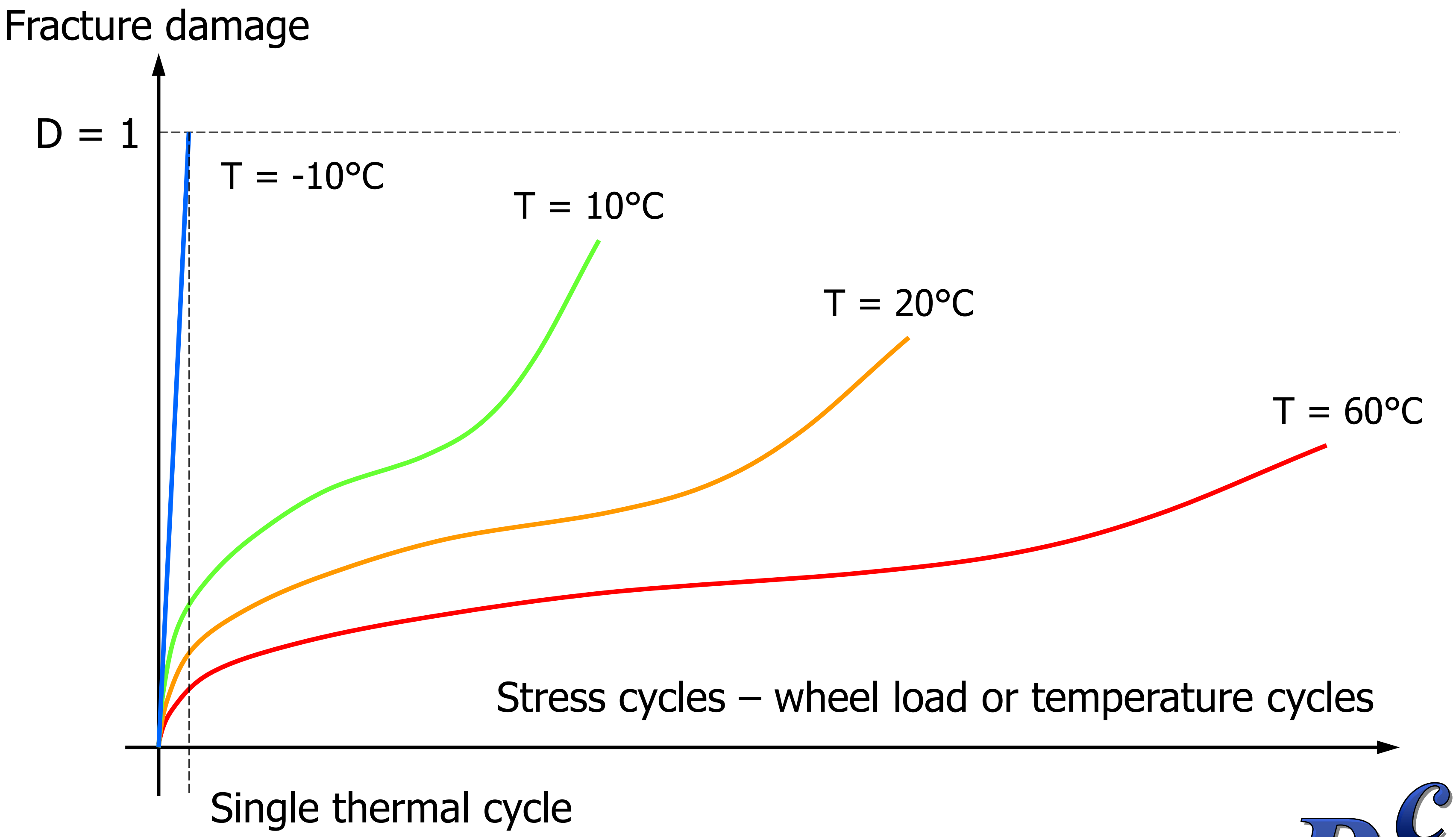


$$\begin{pmatrix} S'_{xx} \\ S'_{yy} \\ S'_{zz} \\ S_{xy} \\ S_{yz} \\ S_{zx} \end{pmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & 0 & 0 & 0 \\ K_{21} & K_{22} & K_{23} & 0 & 0 & 0 \\ K_{31} & K_{32} & K_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & K_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{66} \end{bmatrix} \begin{pmatrix} e_{xx} \\ e_{yy} \\ e_{zz} \\ e_{xy} \\ e_{yz} \\ e_{zx} \end{pmatrix} - \begin{bmatrix} K_{11} & K_{12} & K_{13} & 0 & 0 & 0 \\ K_{21} & K_{22} & K_{23} & 0 & 0 & 0 \\ K_{31} & K_{32} & K_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & K_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{66} \end{bmatrix} \begin{pmatrix} \alpha\Delta T \\ \alpha\Delta T \\ \alpha\Delta T \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Effective stress - asphalt



Stress based fatigue including thermal stress



Memory-less fatigue damage model

- Stress based model

$$\frac{\partial D}{\partial N} = \frac{b}{e^{D}}\left(k + \frac{(D+s)^{2}}{a^{2}}\right)^{\frac{1}{c}}$$

$$a = \alpha_1 T^{\alpha_2} \sigma_t^{\alpha_3} \sigma_t^{\alpha_4 \ln(T)}$$

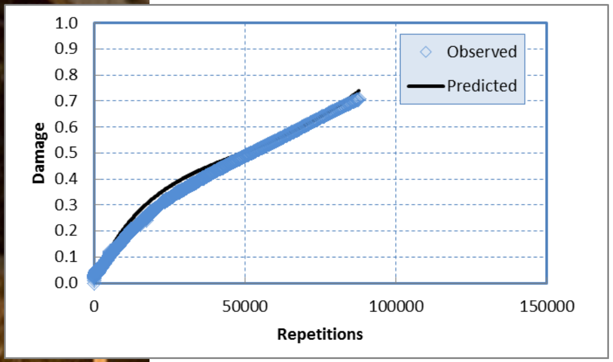
$$b = \beta_1$$

$$k = \kappa_1 T^{\kappa_2} \sigma_t^{\kappa_3 T^{\kappa_4}}$$

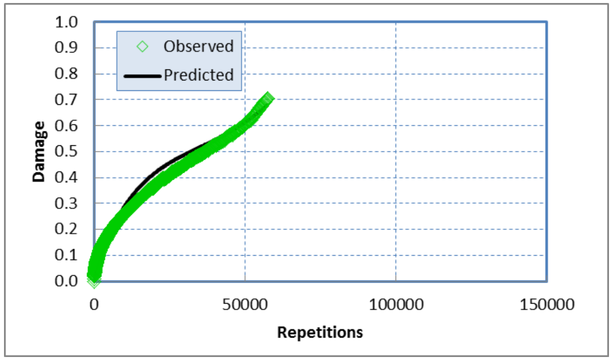
$$c = \chi$$

$$s = \gamma_1 + \gamma_2(T) + \gamma_3 \ln(\sigma_t) + \gamma_4(T)\ln(\sigma_t)$$

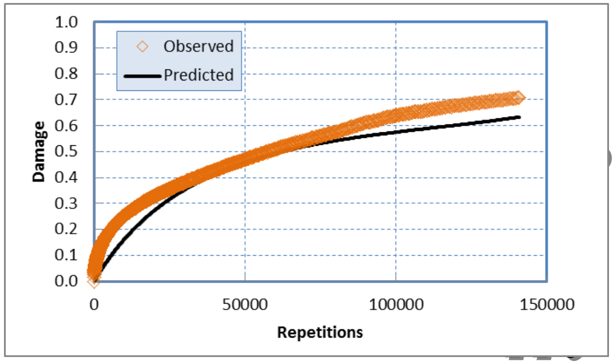
5019 kPa at 5°C



4355 kPa at 10°C

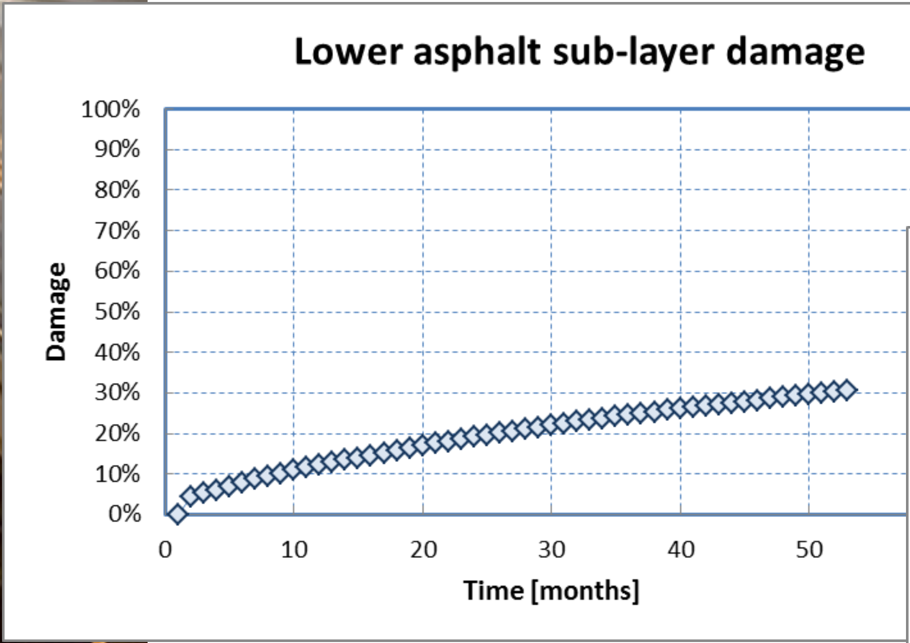


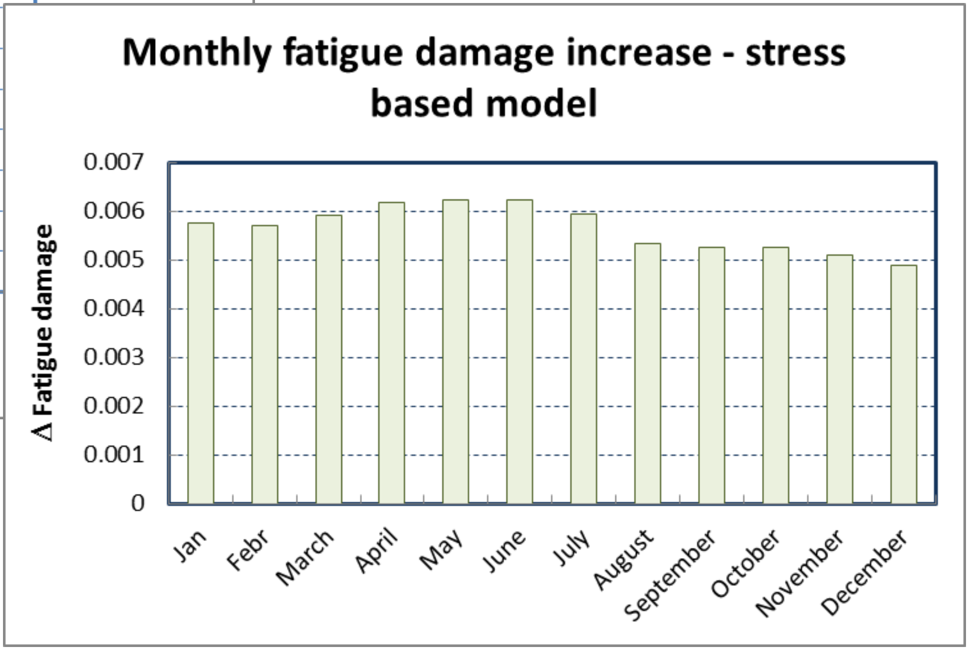
1350 kPa at 20°C



Recursive simulation results – Stiffness reduction

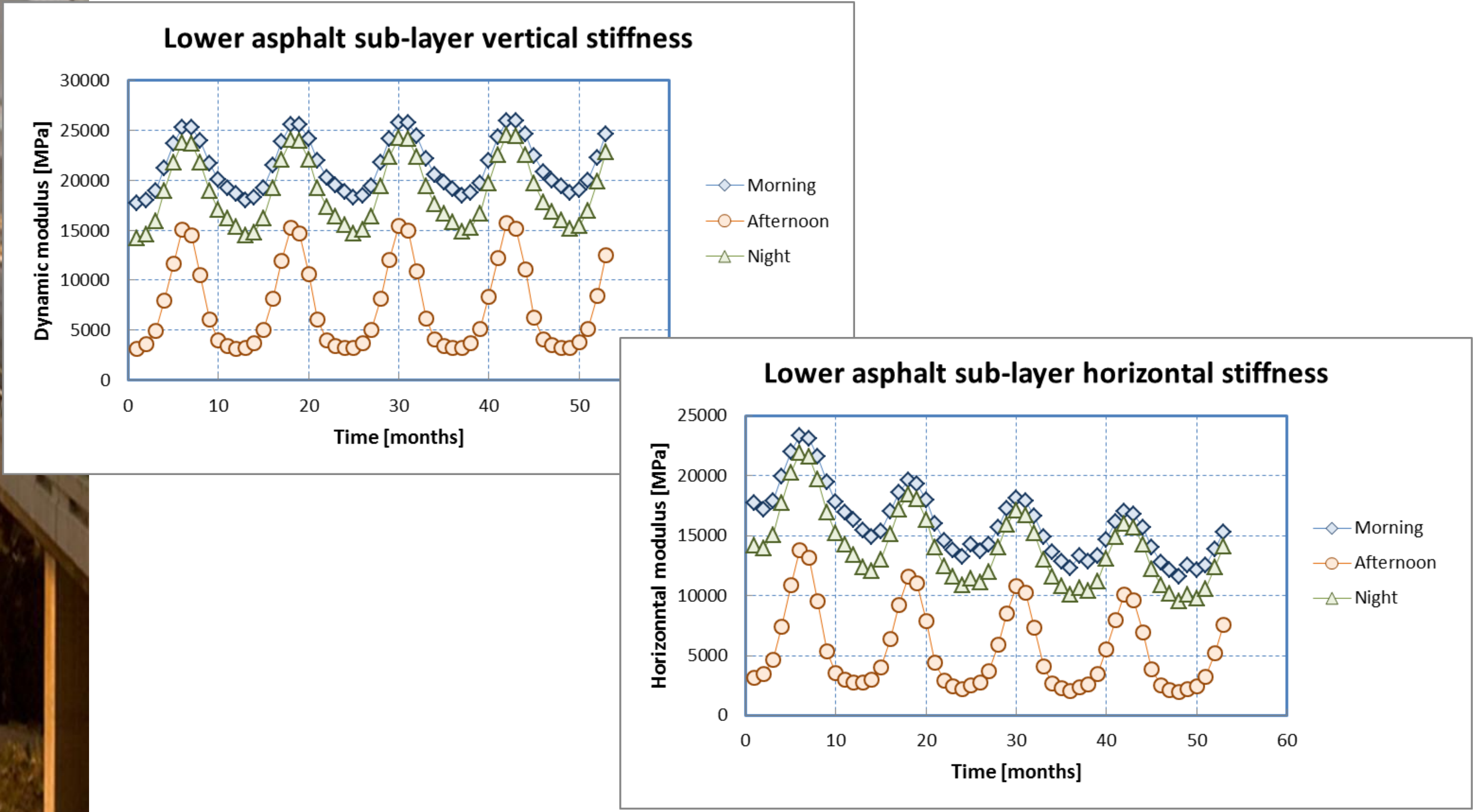
- Asphalt stress based fatigue (Ver. 23)
  - Still excludes thermal stress


Lower asphalt sub-layer damage


Monthly fatigue damage increase - stress based model

Recursive simulation results – Stiffness reduction

- Asphalt stress based fatigue (Ver. 23)



Recursive simulation – Closing statements

- The models cannot be used without sophisticated software
  - Unfortunately pavement behaviour and performance is not simple
- Role of the design engineer
  - Proper design investigation and material characterisation
  - Not models and calculations
  - Inputs are really simple except for advanced input level