Revision of the South African Pavement Design Method Phase 3

Road Pavements Forum – May 2013

Overview of the SAPDM Pavement Design Research Outcomes and System Integration

H Theyse

Aim of the presentation

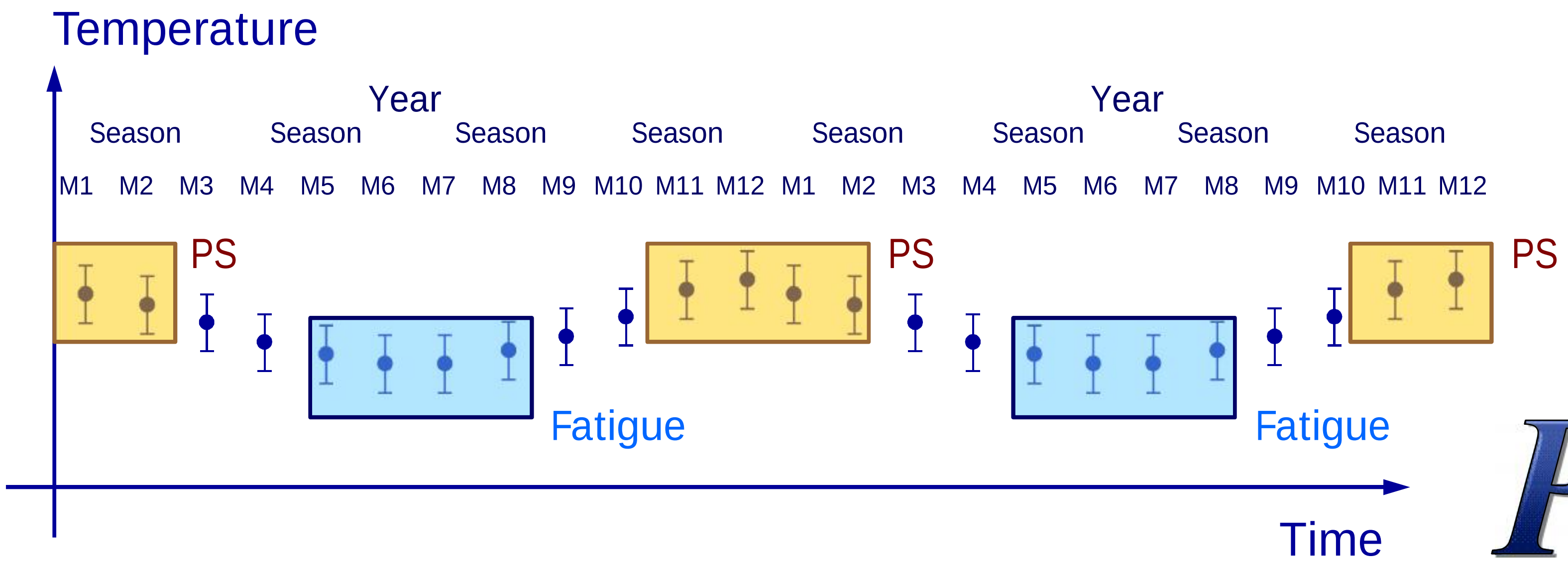
- Highlight
  - Change in mechanistic-empirical design approach
  - Integration
    - Pavement design
      - Mix design and structural design
    - Pavement design delivery system
  - Research outcomes
- Project made possible by ...
  - SANRAL’s commitment and funding
  - The hard work of research teams and individuals

Design approach mind-shift

- Mechanistic-empirical design of flexible pavements
  - Past approach
    - Pavement structural capacity is determined by stress/strain associated with wheel-loads
    - Focus on stress/strain analysis
    - What is the stiffness of the material?
  - Future approach
    - Pavement structural capacity is determined by imposed stress/strain <u>relative to material strength</u>
    - Material characteristics changes daily and seasonally with the environment
    - Focus on material stiffness and strength under changing environmental conditions

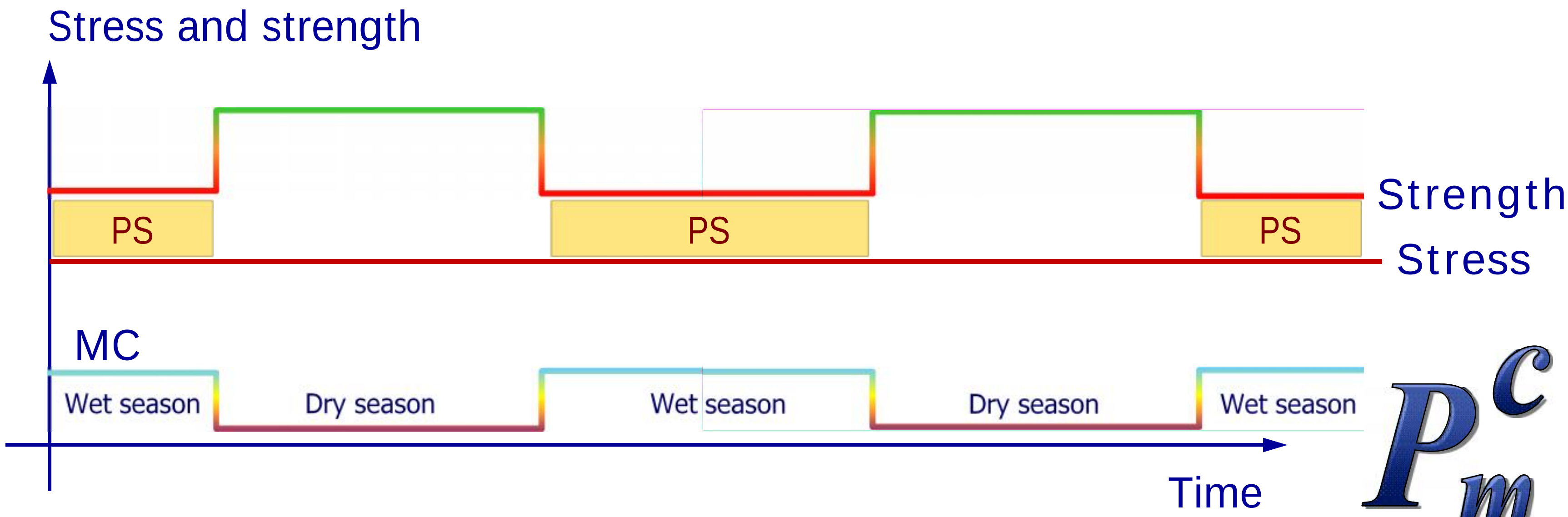
Example – Asphalt

- Fatigue and plastic strain highly dependent on temperature conditions
  - Past approach
    - 20° C reference temperature
  - Future approach
    - Seasonal and diurnal temperature changes



Example – Unbound

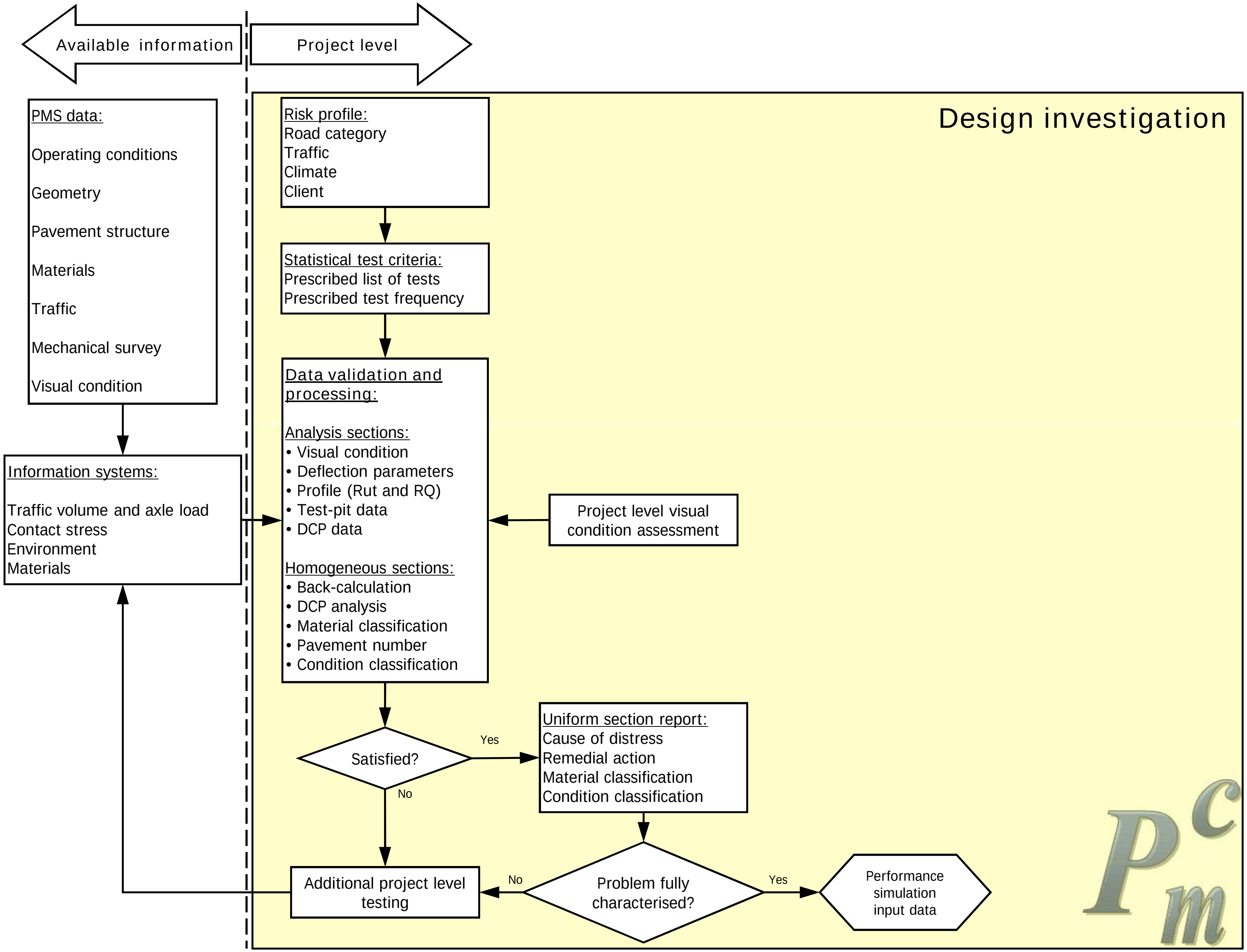
- Plastic strain highly dependent on layer moisture conditions
  - Past approach
    - Dry, intermediate or wet conditions for duration of structural analysis period
  - Future approach
    - Seasonal moisture content changes



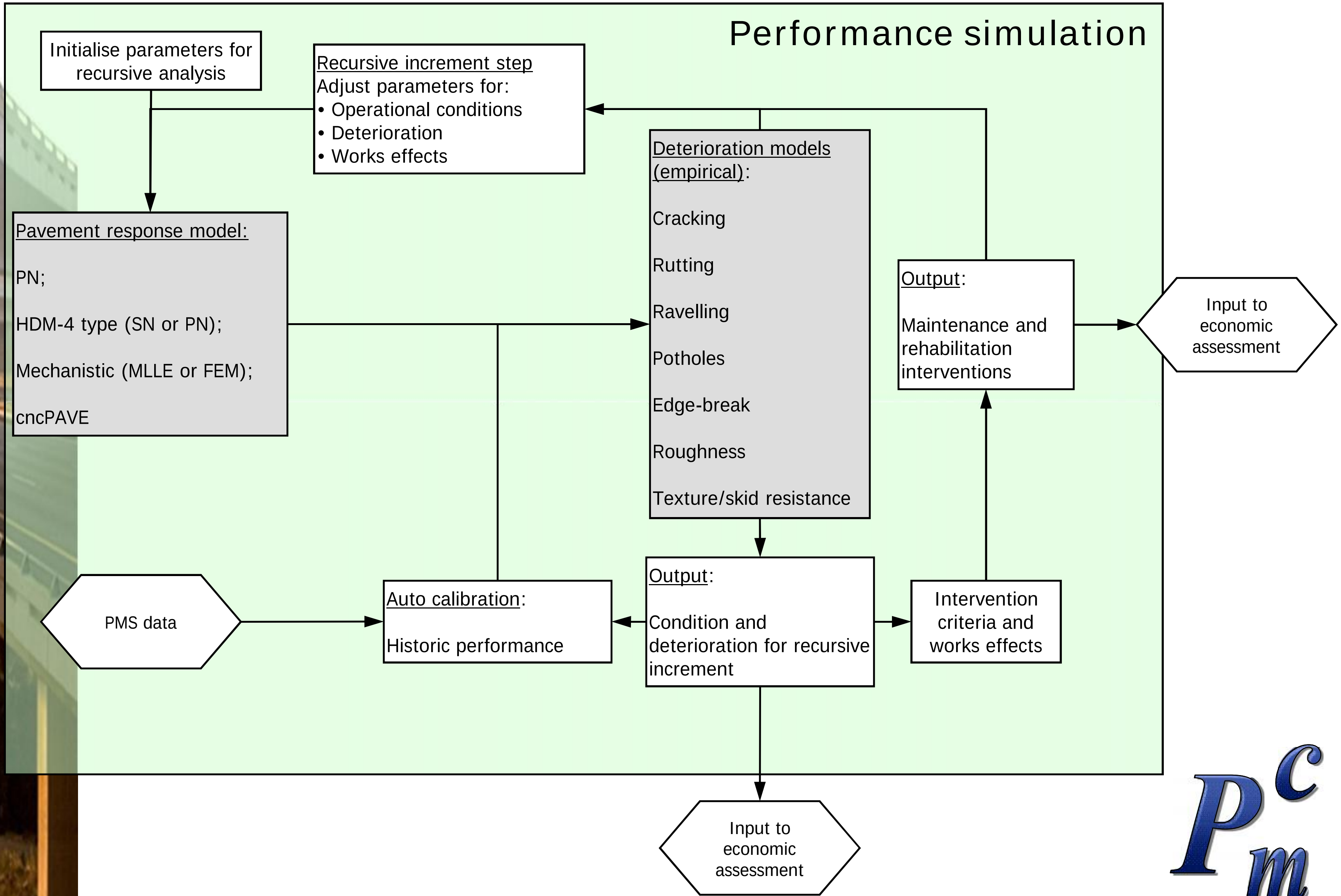
Integrated pavement design delivery process

Project phase	Responsible party				
	Road authority	Design office	Central laboratory	Service providers	Site laboratory
Project initiation	Create and activate project				
Design investigation		Preliminary investigation and analysis			
			Project level surveys		
		Detail analysis			
Recursive performance simulation		Historic analysis with auto-calibration			
		Future performance with economic assessment			
Final design specification		Select final design and develop specification			
Construction					Q/A testing and approval of work
		Approval of payment certificate			
	Payment				

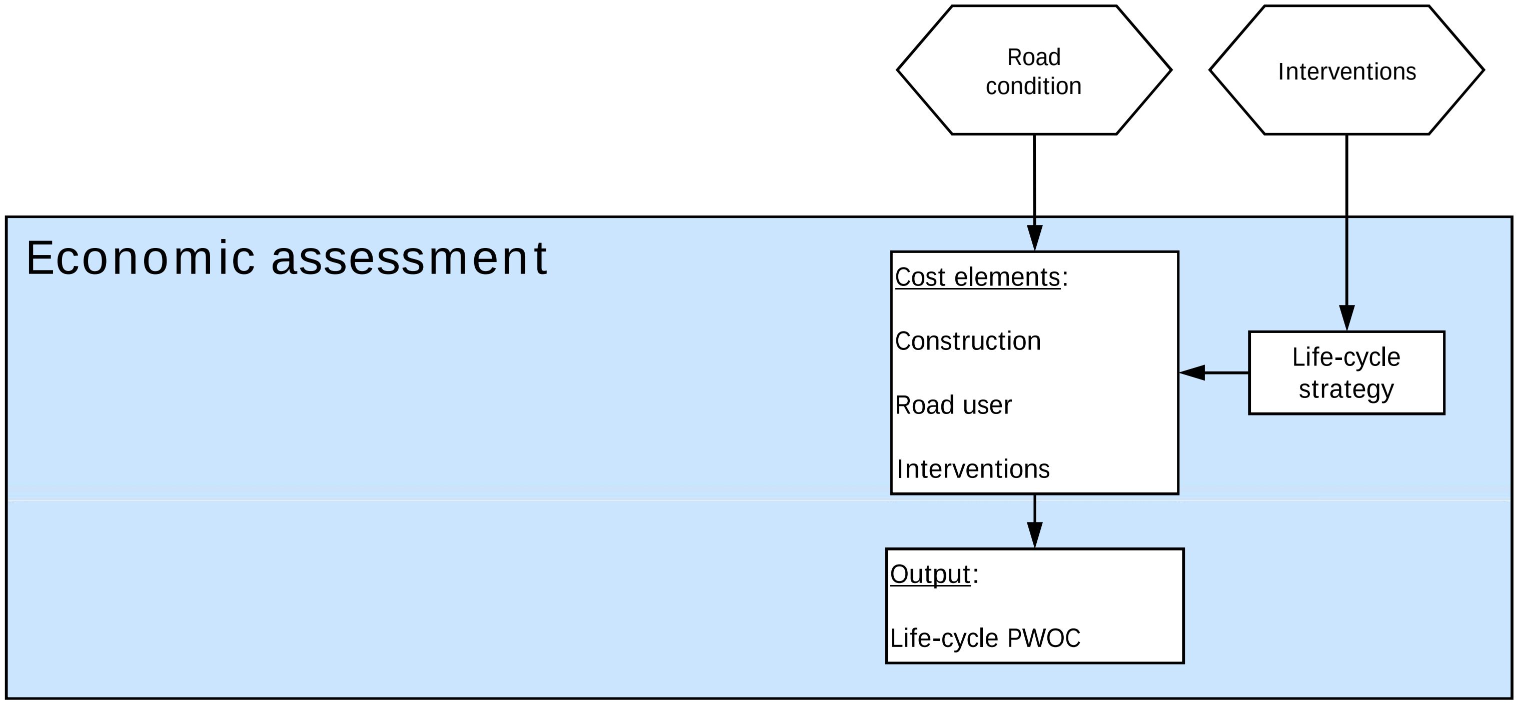
Design investigation system



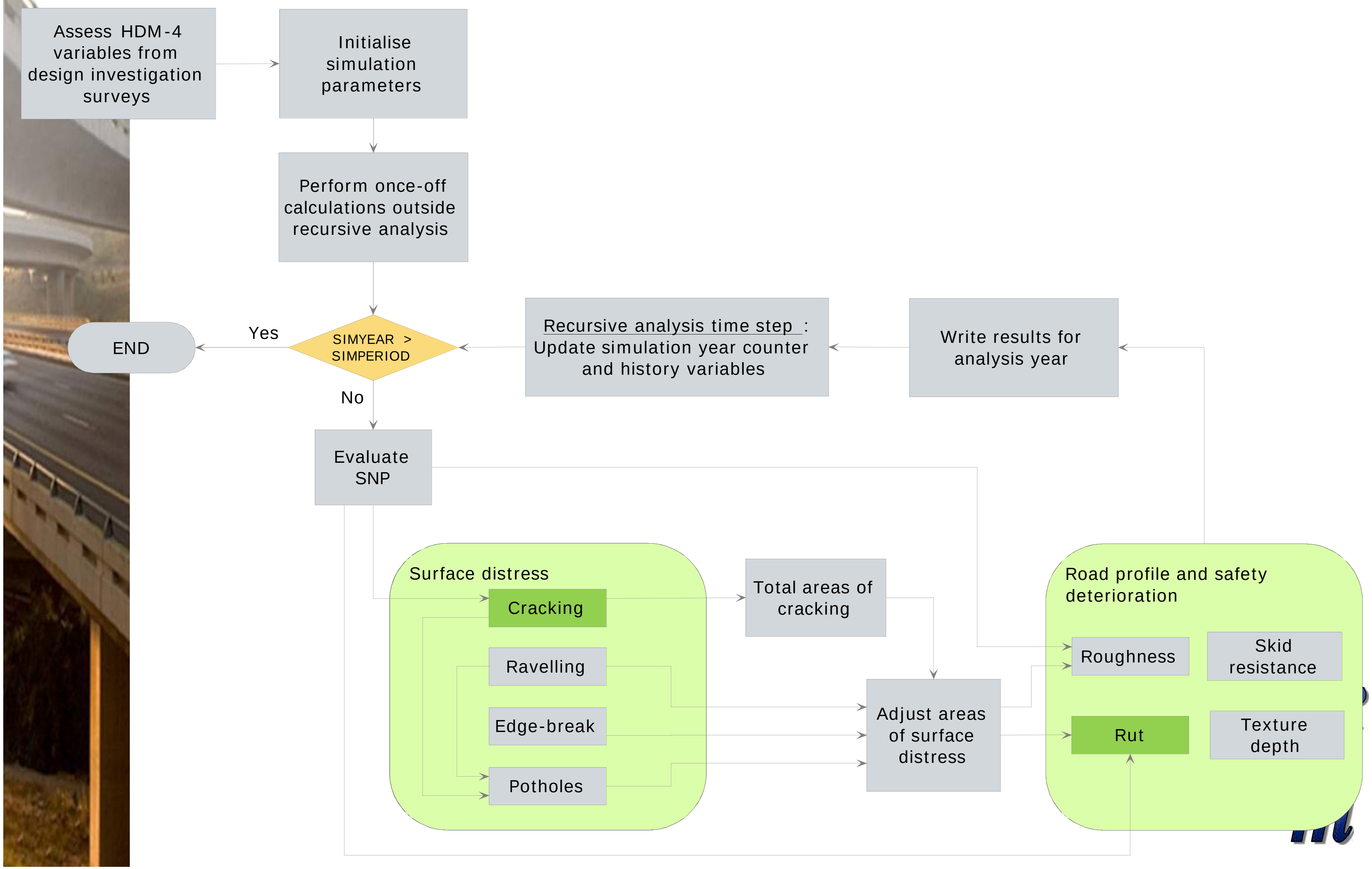
Performance simulation system



Economic assessment system



HDM-4 performance simulation



Research areas

- Design investigation
- Traffic
- Materials
- Pavement Analysis
- Stochastic recursive simulation
- Environmental effects

SAPDM Pavement Design Research Outcomes

Design Investigation

Design Investigation: Research Outcomes

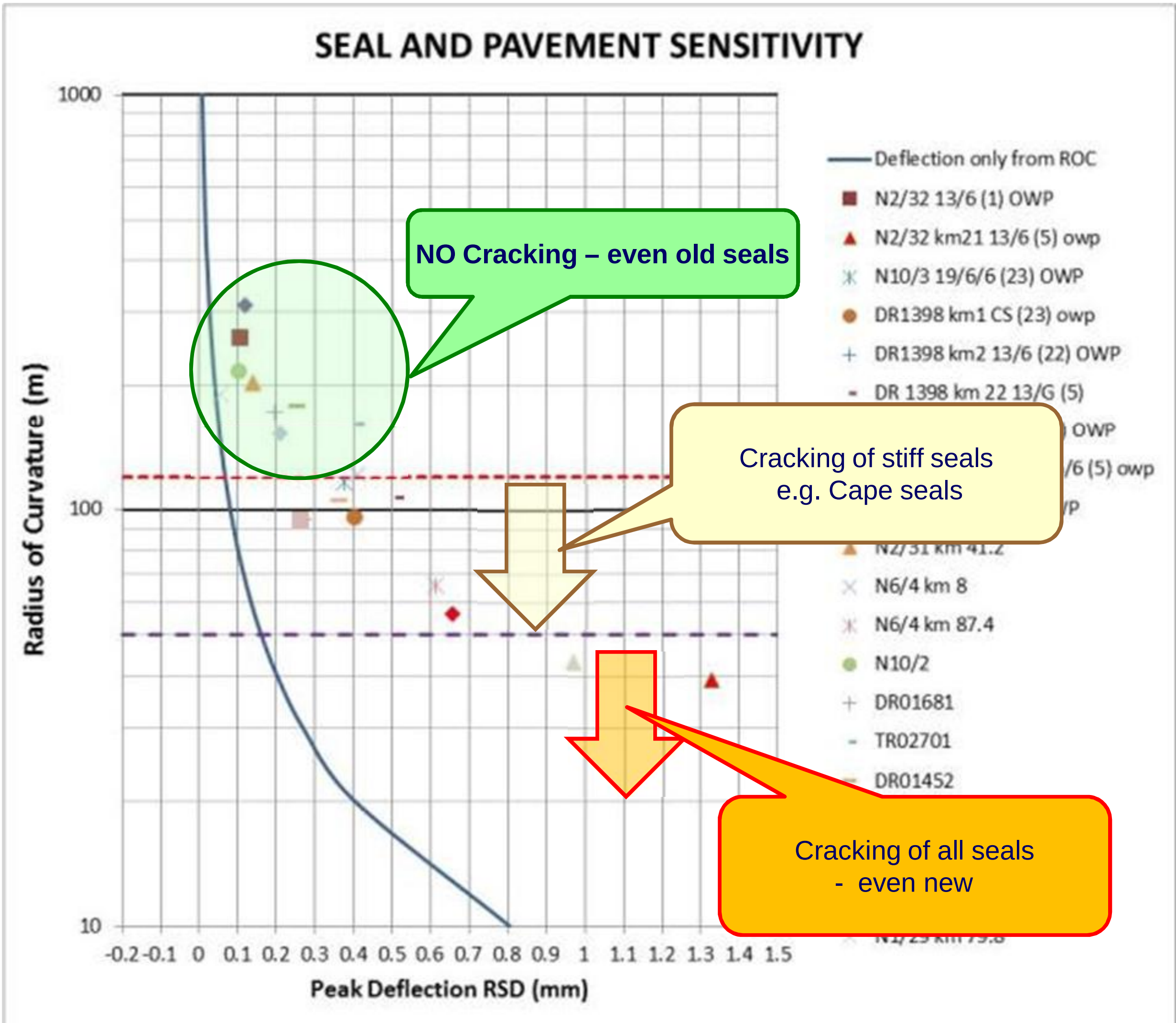
- Deflection bowl parameters
- Back-calculation
- Change detection

Deflection bowl parameters

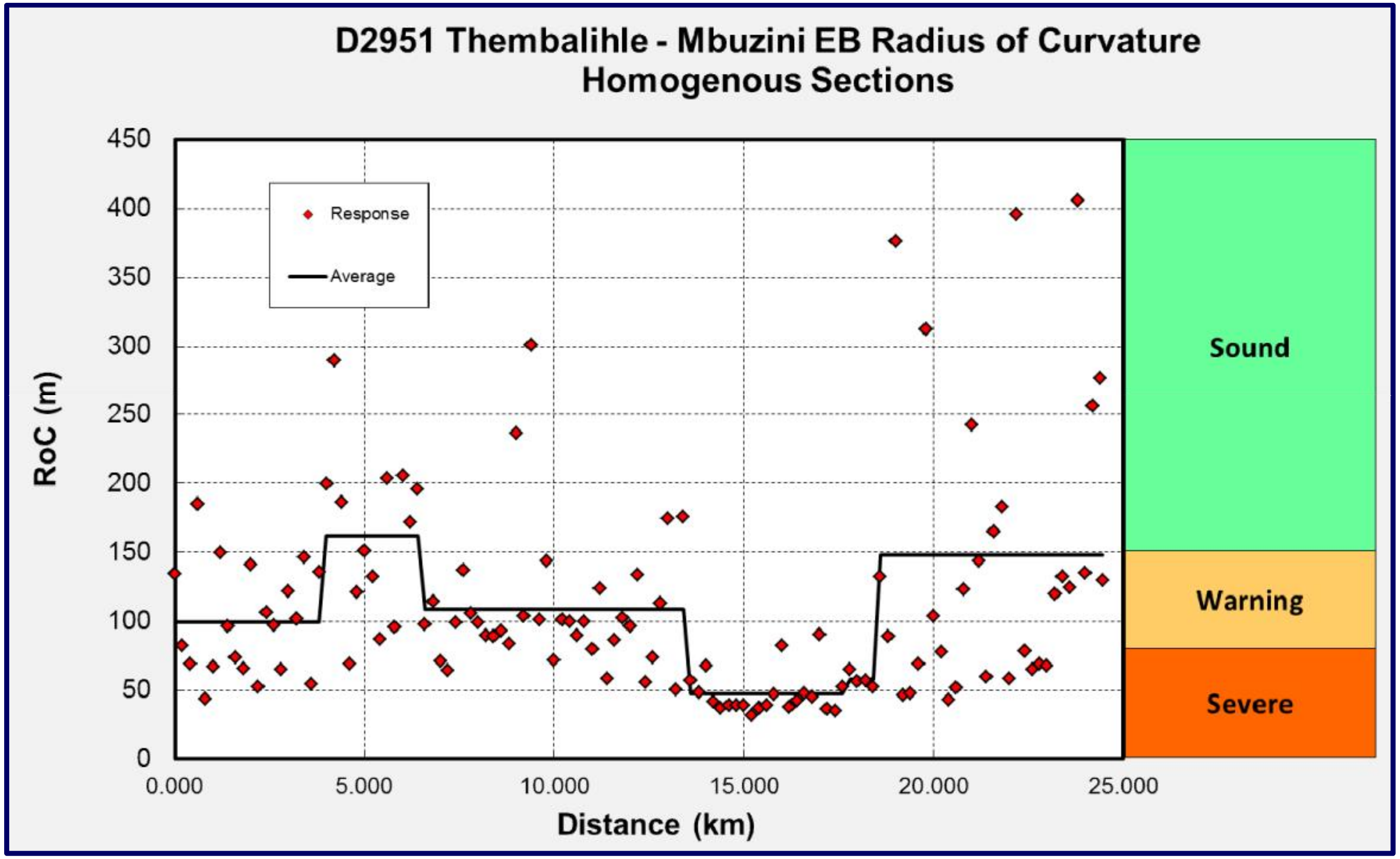
- Usual suspects
  - Base layer index
  - Middle layer index
  - Lower layer index
- Better utilisation of ....
  - Radius of curvature
  - Far sensor deflection

Stabilised base layers		
Stiffness	**FWD deflection (Horak, 2008)**	
	Peak deflection (mm)	**Base Layer Index**
Stiff	< 0.400	< 0.200
Firm	0.400 – 0.600	0.200 – 0.400
Soft	> 0.600	> 0.400

Radius of Curvature (van Zyl, 2012)

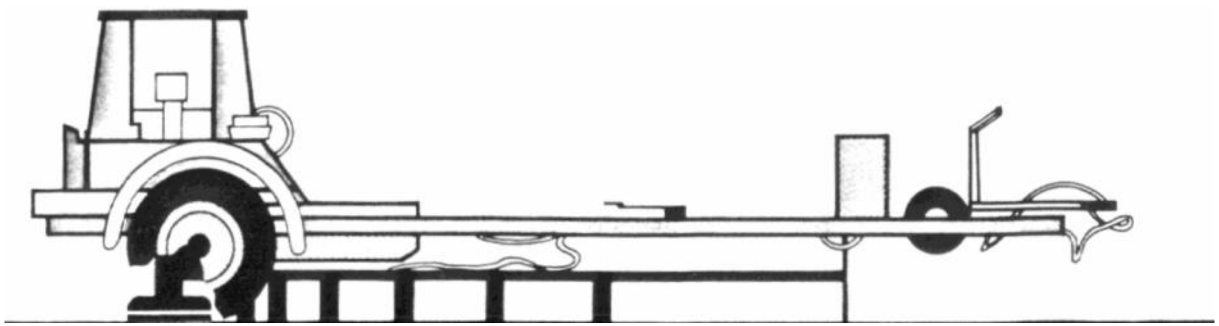


Radius of Curvature



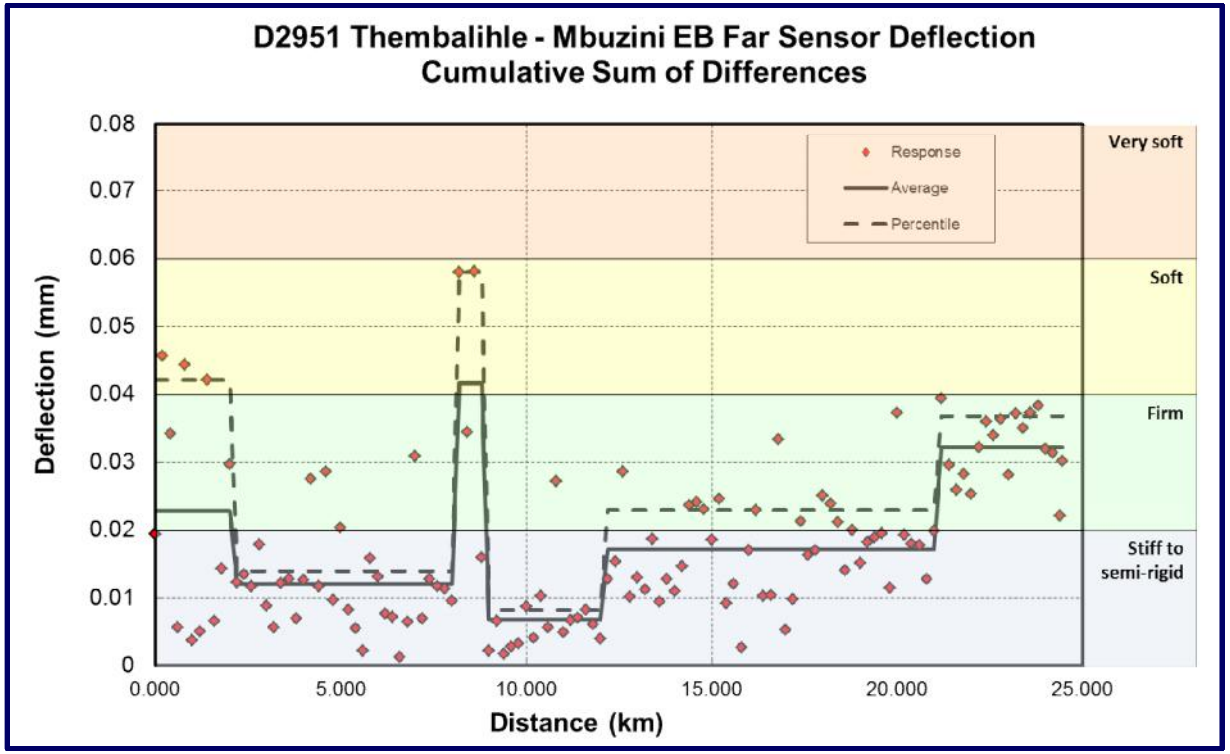
Far sensor deflection (Theyse, 2012)

- FWD deflection at 1800 mm offset
  - Indicator of deep subgrade conditions
    - $\delta_{1800} \leq 20$ micron – Stiff to semi-rigid
    - $20 < \delta_{1800} \leq 40$ micron – Firm subgrade
    - $40 < \delta_{1800} \leq 60$ micron – Soft subgrade
    - $60 < \delta_{1800} \leq 80$ micron – Very soft subgrade



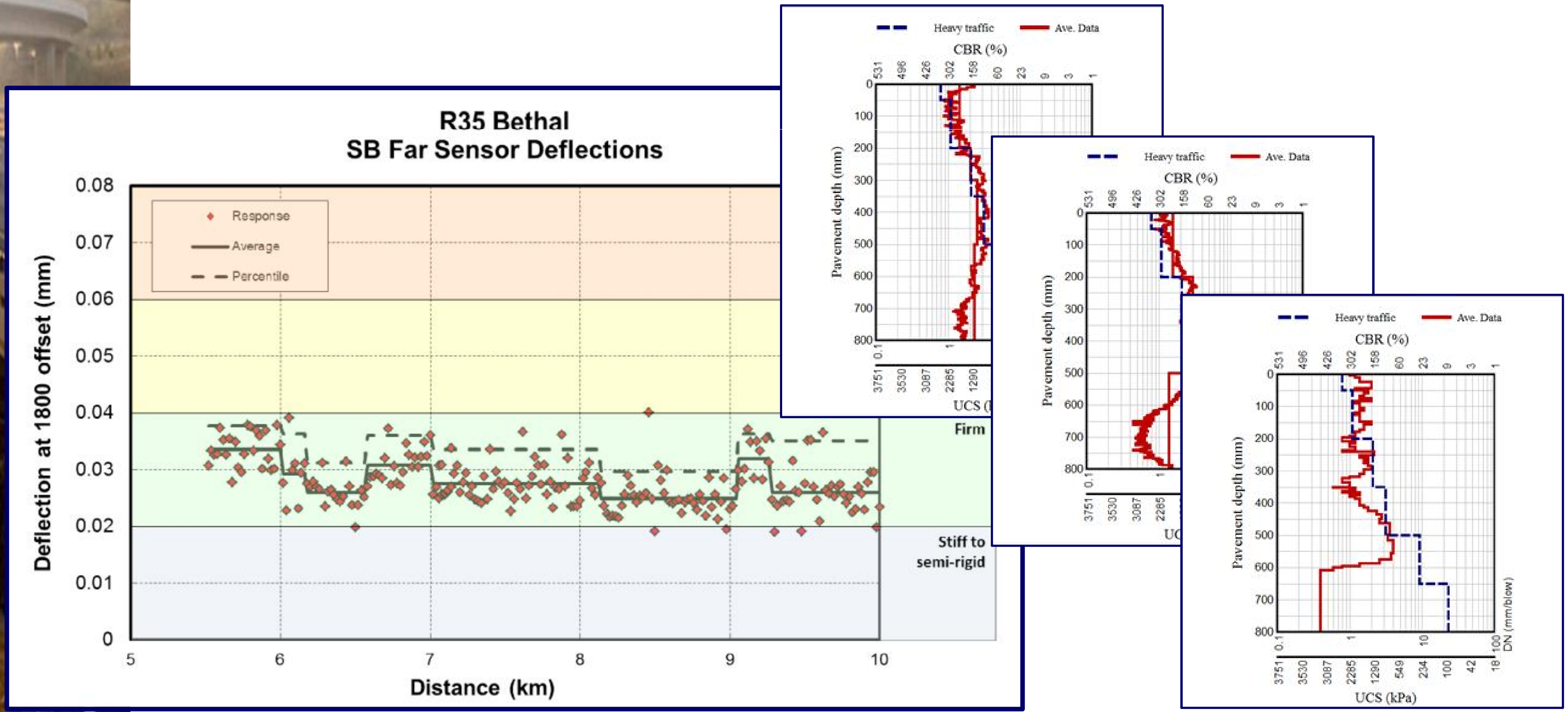
Far sensor deflection (Theyse, 2012)

- Mountainous area with bed-rock found in some test-pits



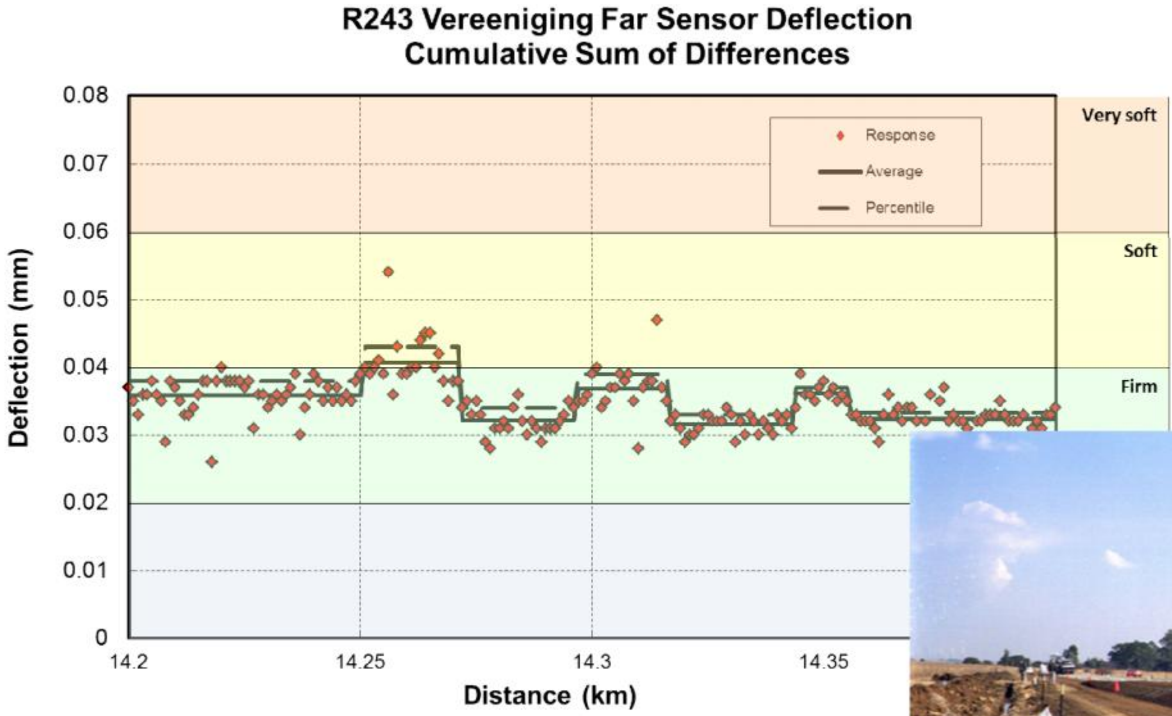
Far sensor deflection (Theyse, 2012)

- Homogenous subgrade with old pavement at about 600 mm depth



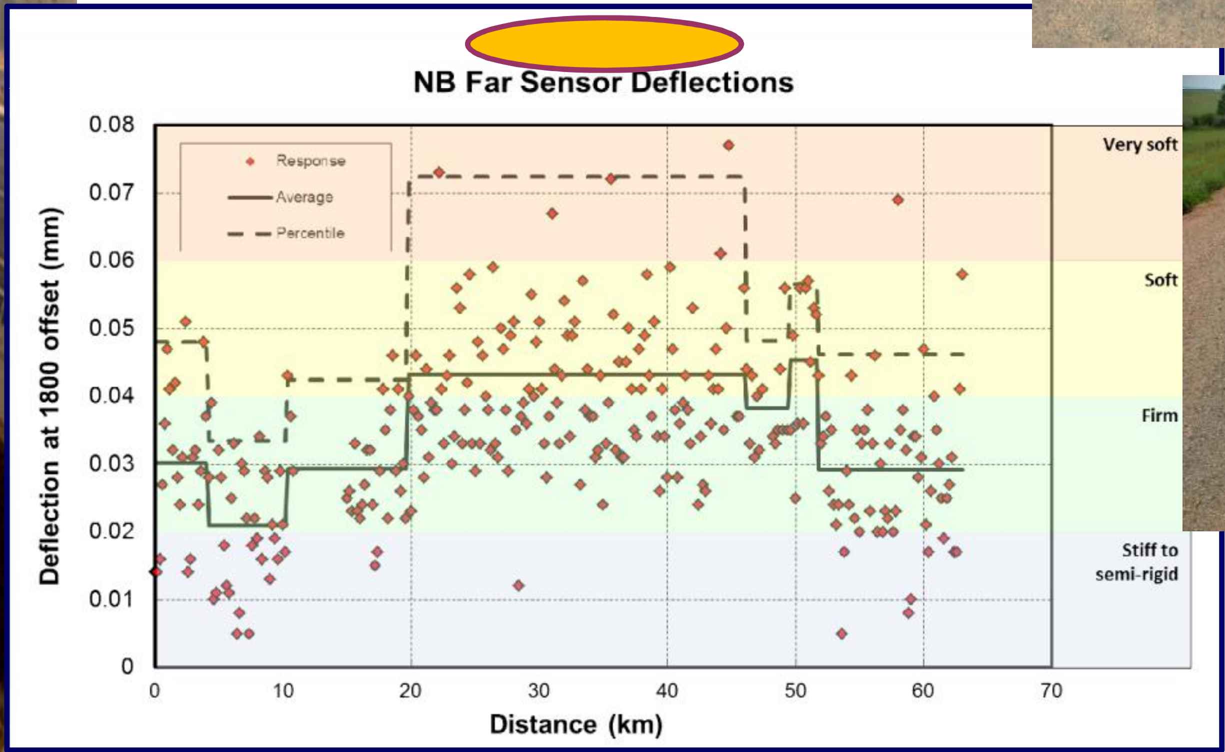
Far sensor deflection (Theyse, 2012)

- Moist subgrade



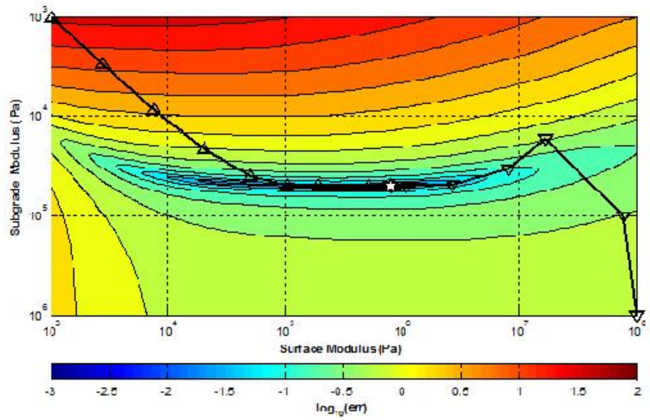
Far sensor deflection (Theyse, 2012)

- Wet subgrade

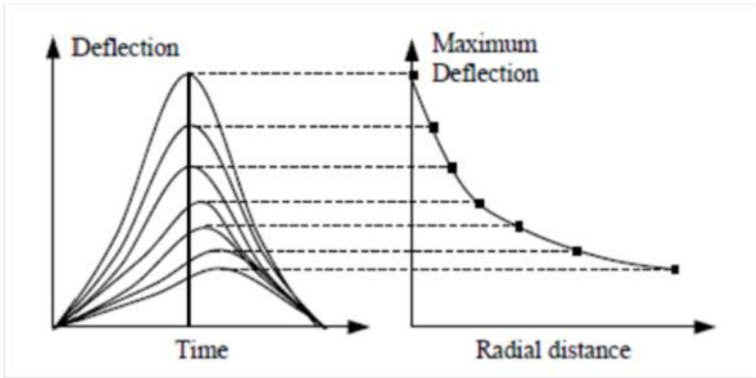


Back-calculation

- *Back*-PADS (Lea and Theyse, 2006)
    - Robust minimisation algorithm
        - Solution independent of seed moduli
    - Surface bowl and depth deflection profiles
    - Fast

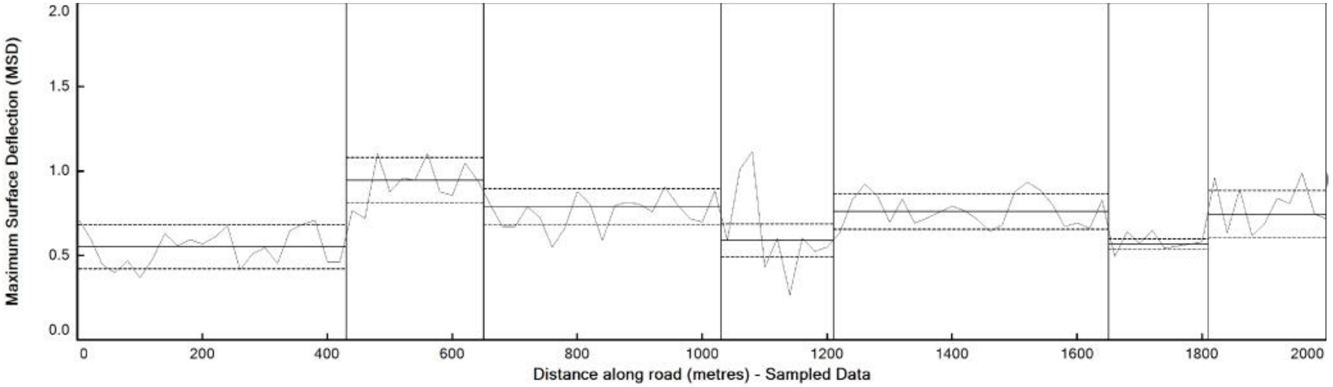


- *Back*-GAMES (Maina, 2012)
    - Static and dynamic back-calculation
    - Global solution
    - Very fast and automatic



Change detection

- Past
  - Cumulative sum of differences method
    - Sensitive to outliers
    - Manual change detection by visual inspection
- Future (van As, 2013)
  - Exponentially weighted moving average
    - Outlier detection
  - Maximum likelihood method
    - Change point detection
  - Fully automatic



SAPDM Pavement Design Research Outcomes

Traffic

Traffic Research Areas: Completed Reports (1/3)

- SANRAL/SAPDM/A2/2009/01

  Correction of Systematic Error in WIM Data

  DPG De Wet (with M Slavik)
- SANRAL/SAPDM/A2/2009/02

  Research Traffic Data Preparation

  SC van As & AJ Papenfus
- SANRAL/SAPDM/A2/2009/03

  Traffic Data Verification and Replacement

  SC van As

Traffic Research Areas: Completed Reports (2/3)

- SANRAL/SAPDM/A2/2009/04
  - WIM Dynamic Load Correction
  - SC van As
- SANRAL/SAPDM/A2/2012/01
  - Heavy Vehicle Classification
  - SC van As
- SANRAL/SAPDM/A2/2012/02
  - Traffic Stratification System
  - AJ Papenfus & SC van As

Traffic Research Areas: Completed Reports (3/3)

- SANRAL/SAPDM/A2/2012/03
  Loading Classes and Axle Load Distributions
  SC van As
- SANRAL/SAPDM/A2/2012/04
  Payment Factors for Traffic and WIM Monitoring
  SC van As
- SANRAL/SAPDM/A2/2012/05
  Vehicle Free-Flow Speed Prediction Model
  SC van As

Traffic Research Areas: Current Research

- Traffic Growth Estimation
  - SC van As
  - Waiting for Data
- Homogeneous Sections
  - Research completed
  - Report to be completed

Traffic Research Areas: Manuals

- TMH 14 South African Standard Automatic Traffic Data Collection Format
- TMH 3 Specifications for the Provision of Traffic and WIM Monitoring Service
- TMH8 Traffic Monitoring Procedures (In Process)
- TRH16 Traffic Loading (Cancelled)
- Statistical methods (In Process)

SC van As & Z Kimmie

Traffic Research Areas: Technical Reference Manuals

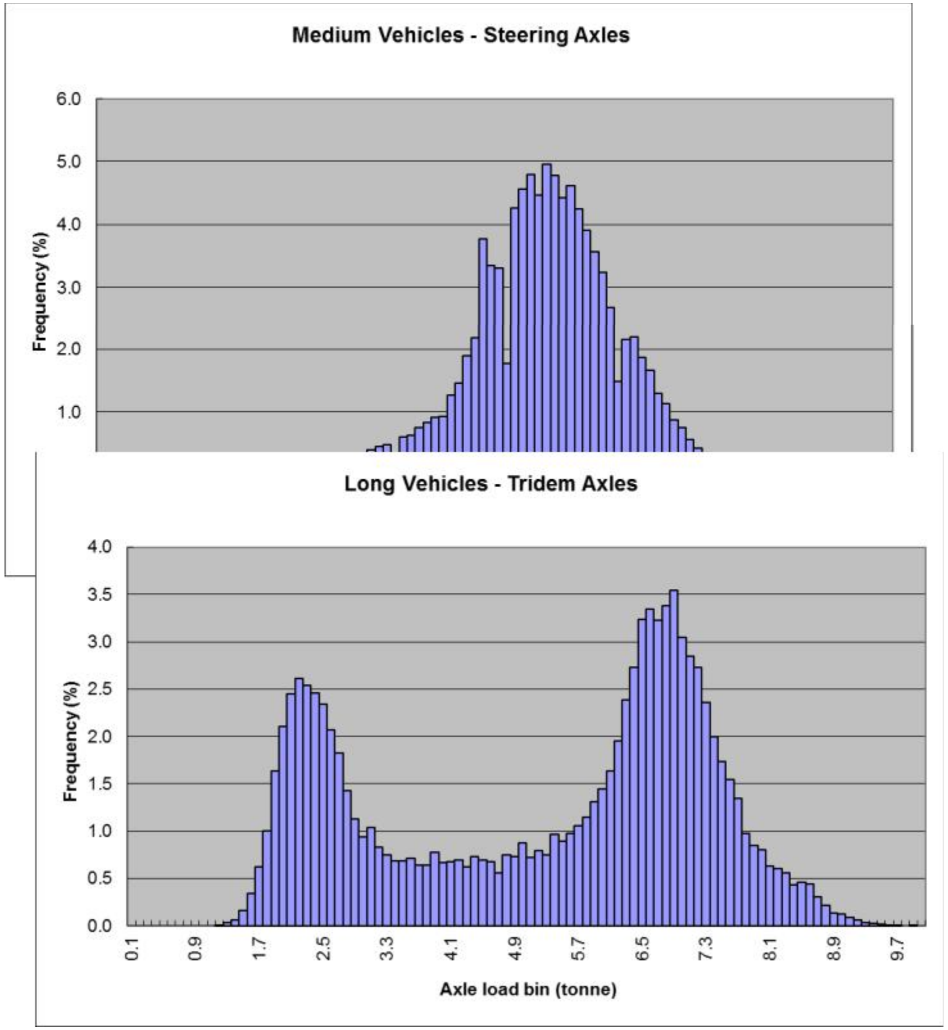
- HTM2 Highway Traffic Model
  - Volume 1: Traffic Flow Model (SAPDM-A3-2013-01)
  - Volume 2: Free-Flow Speed Model (SAPDM-A3-2013-02)
  - Volume 3: Capacity Analysis Model (In Process)
- Vehicle Operating Cost Model (In Process)
- NetSafe Highway Safety Model (In Process)
- TMS Traffic Monitoring System (Not Commenced)

Traffic Research Outcomes

- Axle load histogram design
- WIM data validation and post-calibration
- Dynamic loading
- Contact stress

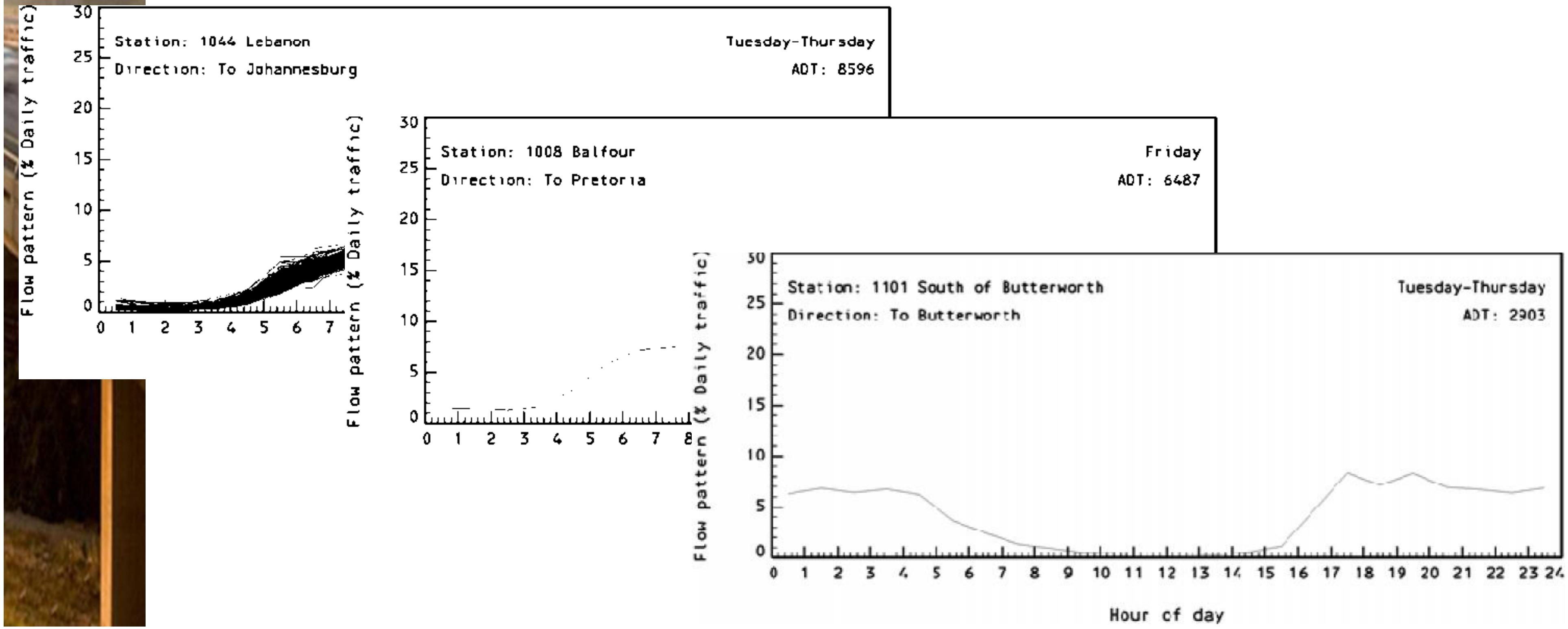
Axle load histogram design

- Heavy vehicle classes
  - Short
  - Medium
  - Long
- Axle configurations
  - Steer
  - Single
  - Tandem
  - Tridem



Traffic Data Verification

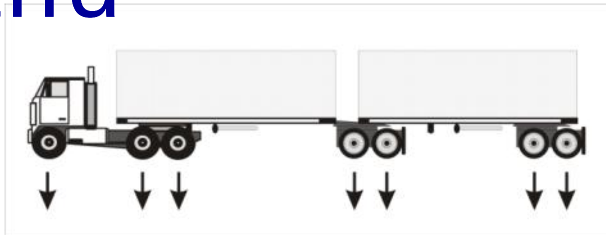
- Pattern tests
  - Cluster Analysis (van As)
  - Neural Networks



WIM data validation and post-calibration

- WIM data validation filters (Slavik & van As, 2009)
  - Remove vehicle entry if
    - Lane number less than 1 or more than 4
    - Vehicle length less than 2.5 m or more than 25 m
    - Number of axles less than 2 or more than 15
    - Any axle weigh less than 1 t or more than 20 t
    - 1st two axles both weigh less than 2 t
    - Front axle weigh less than 1 t or more than 10 t
    - Axle spacing between 1st and 2nd axle less than 2.1 m
    - Any axle spacing less than 1.1 or more than 10 m
    - More than 3 axles in an axle group

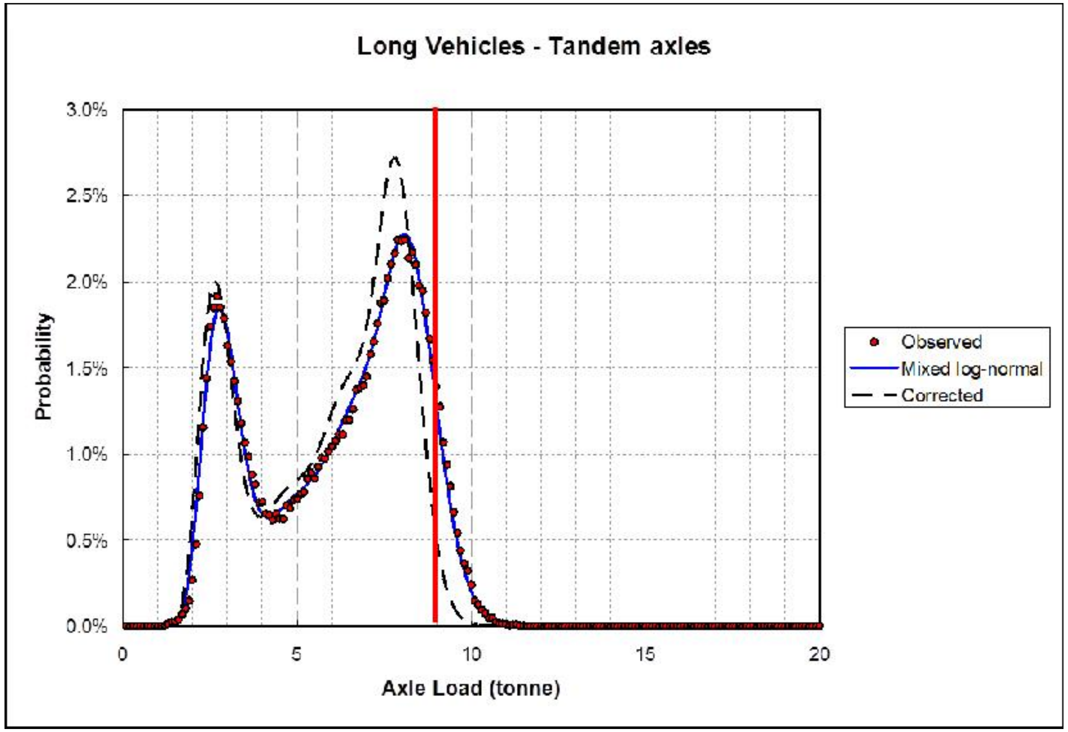
WIM data validation and post-calibration



- WIM post-calibration (De Wet & Slavik, 2009)
  - TT method – Truck selection
    - 6-7 Axle articulated heavy vehicles (tandem rear axles on tractor)
    - Average “calibrated” axle load 6.5 to 8.5 tons per axle
  - TT method – Calibration
    - Calibrate for target tractor load of 21.8 ton
  - TT method – Conditions
    - Calibration factor within limits (0.7 to 1.3)
    - Front axle load standard deviation within limits
    - Tractor load standard deviation within limits

WIM data validation and post-calibration

- WIM post-calibration (De Wet & Slavik, 2009)
  - 5 % random and 5 % systematic error

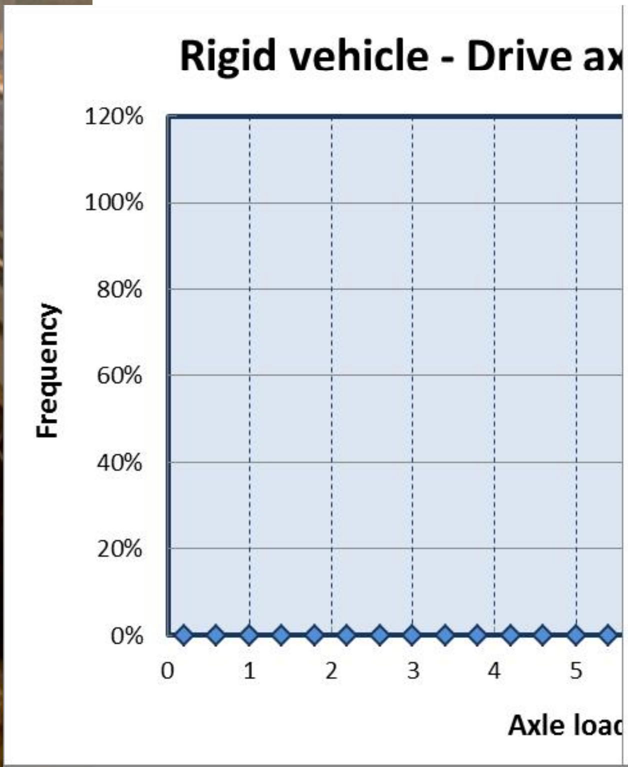


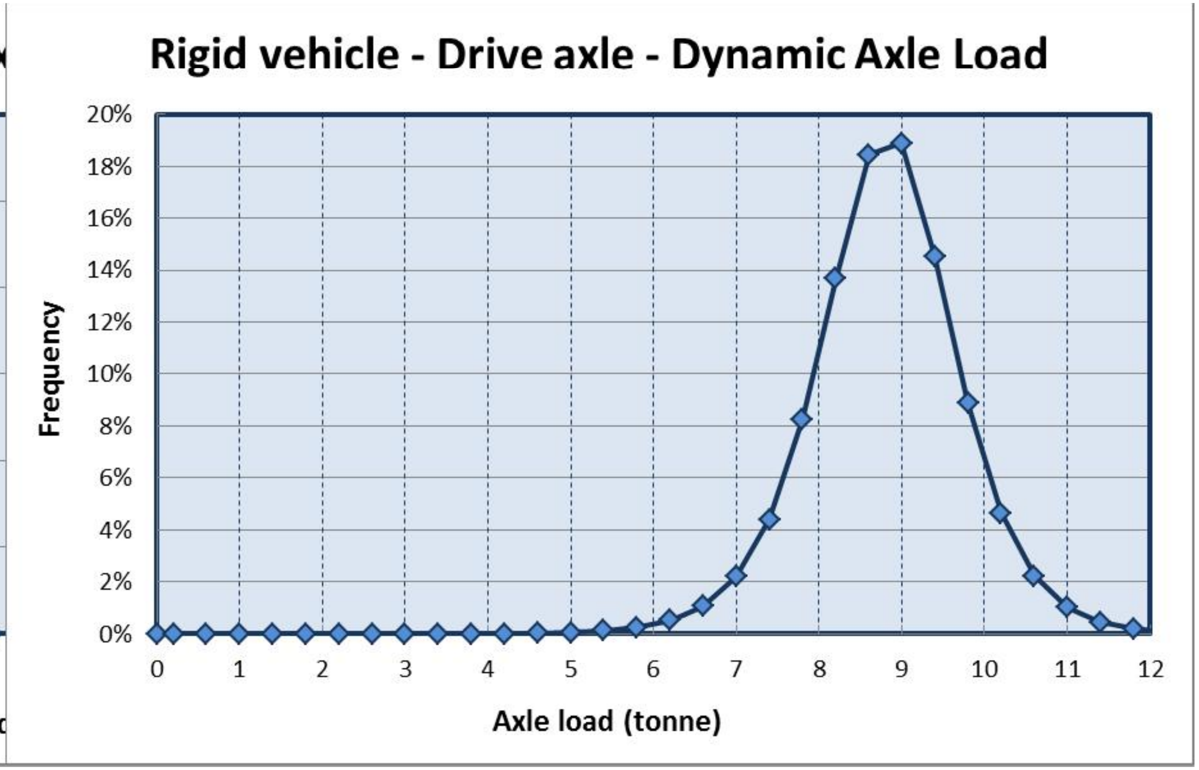
Dynamic loading

- Truck-SIM simulations and calibration of empirical dynamic loading model (Steyn, 2011)
  - Vehicle type
  - Static load
  - Speed
  - Road profile

Dynamic loading

- Example
  - Rigid vehicle driving at 80 km/h on road with IRI of 2.7 mm/m
  - Drive axle at legal load limit



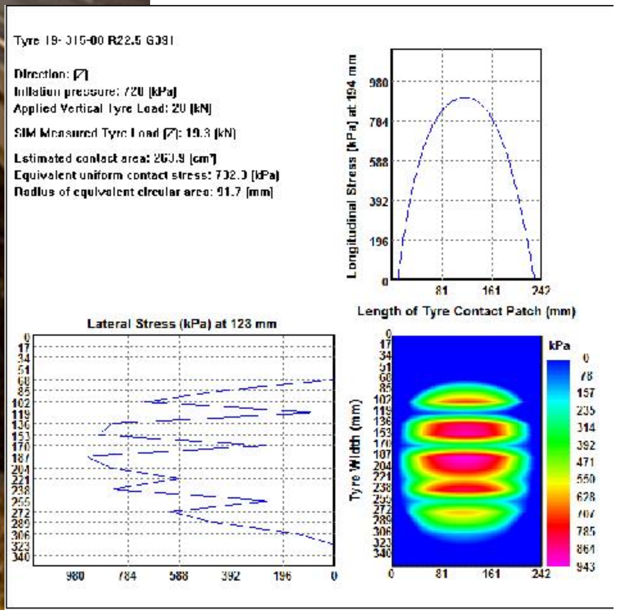


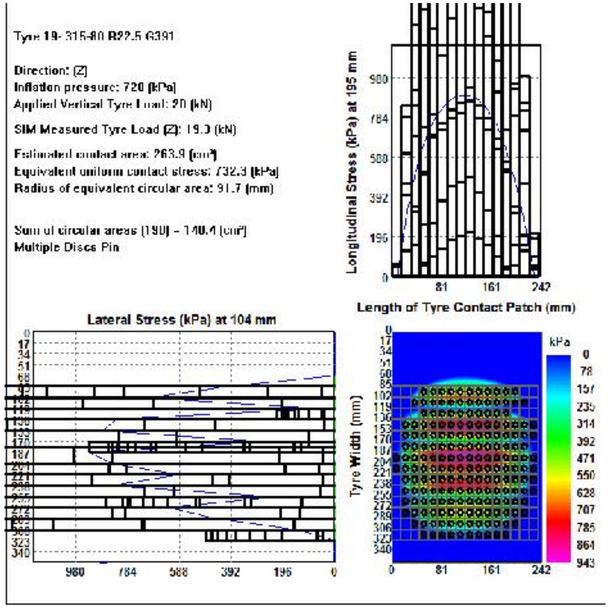
Contact stress

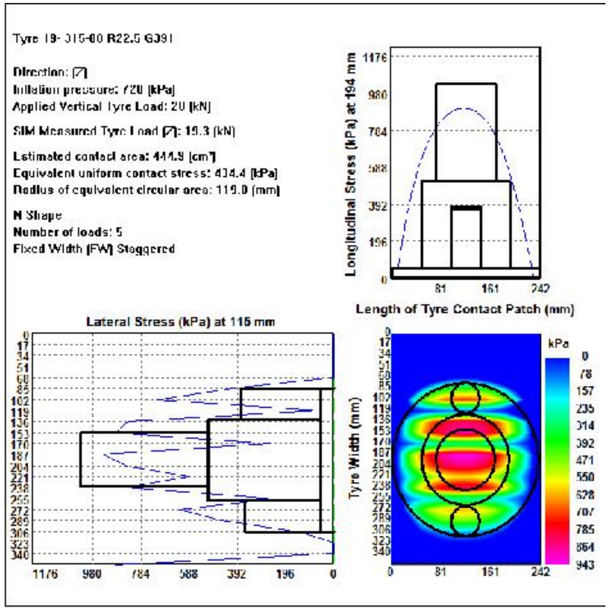
- Tyre-Stress software (de Beer & Maina)
  - Initial work (2011)
    - Develop and populate tyre-pavement contact stress information system
    - Modelling complex 3D tyre-pavement contact stress
  - Additional work (2012 - 2013)
    - Rectangular loading (Maina, 2012)
    - Simplify contact patch geometry to reduce analysis time

Contact stress – Initial phase

- Measured contact stress
  - Complex, irregular pattern
- Multiple circular loads
  - Accurate but not practical
- Reduced circular loads
  - Almost there but not quite yet ….

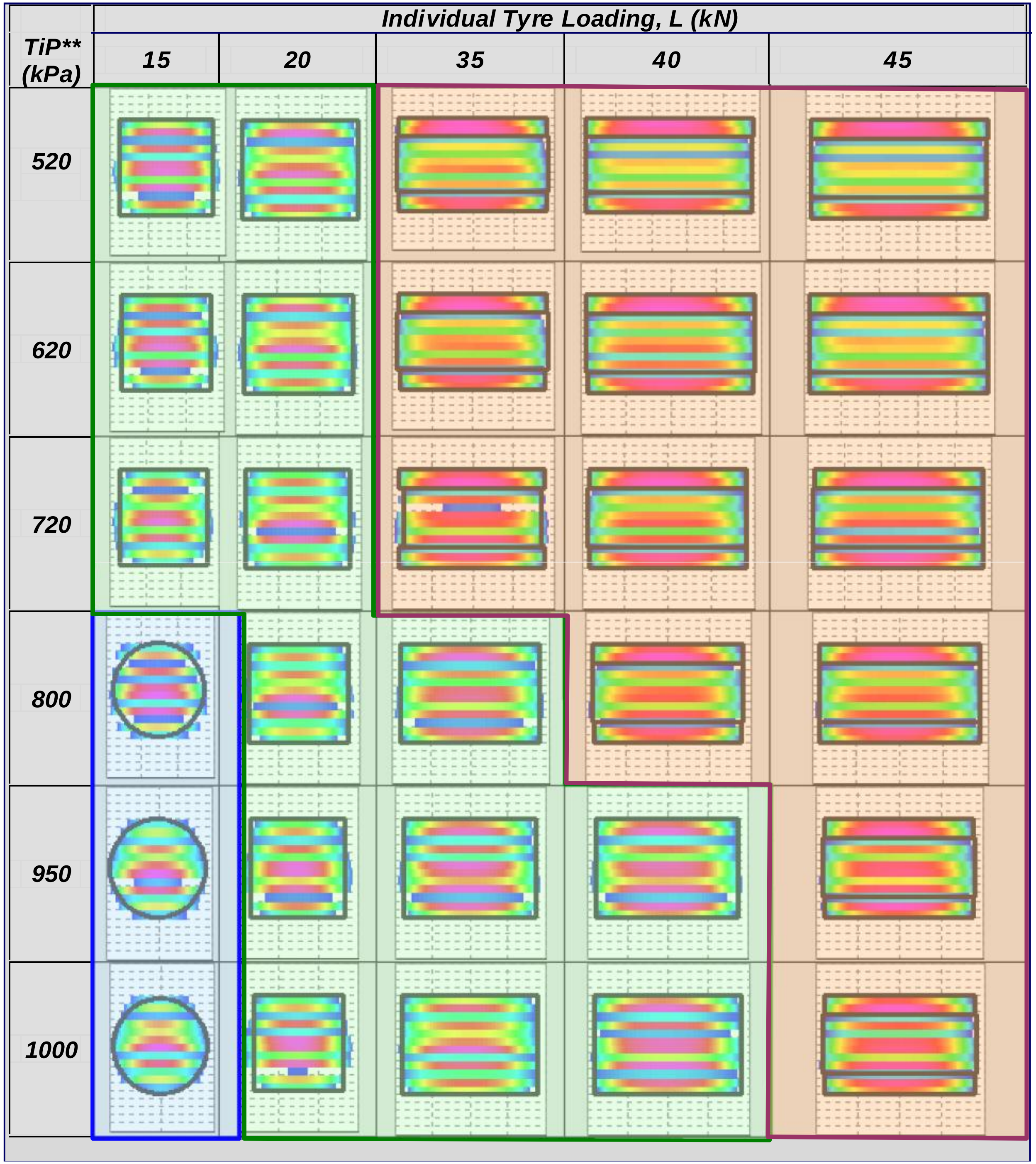






Contact stress – Final phase

- Limit contact patch geometry
    - n-shape
        - Single circular
        - Single rectangular
    - m-shape
        - Triple rectangular


Individual Tyre Loading, L (kN)
TiP**
(kPa)
15
20
35
40
45
520
620
720
800
950
1000

(Not to scale)

SAPDM Pavement Design Research Outcomes

Materials

Materials Research Areas

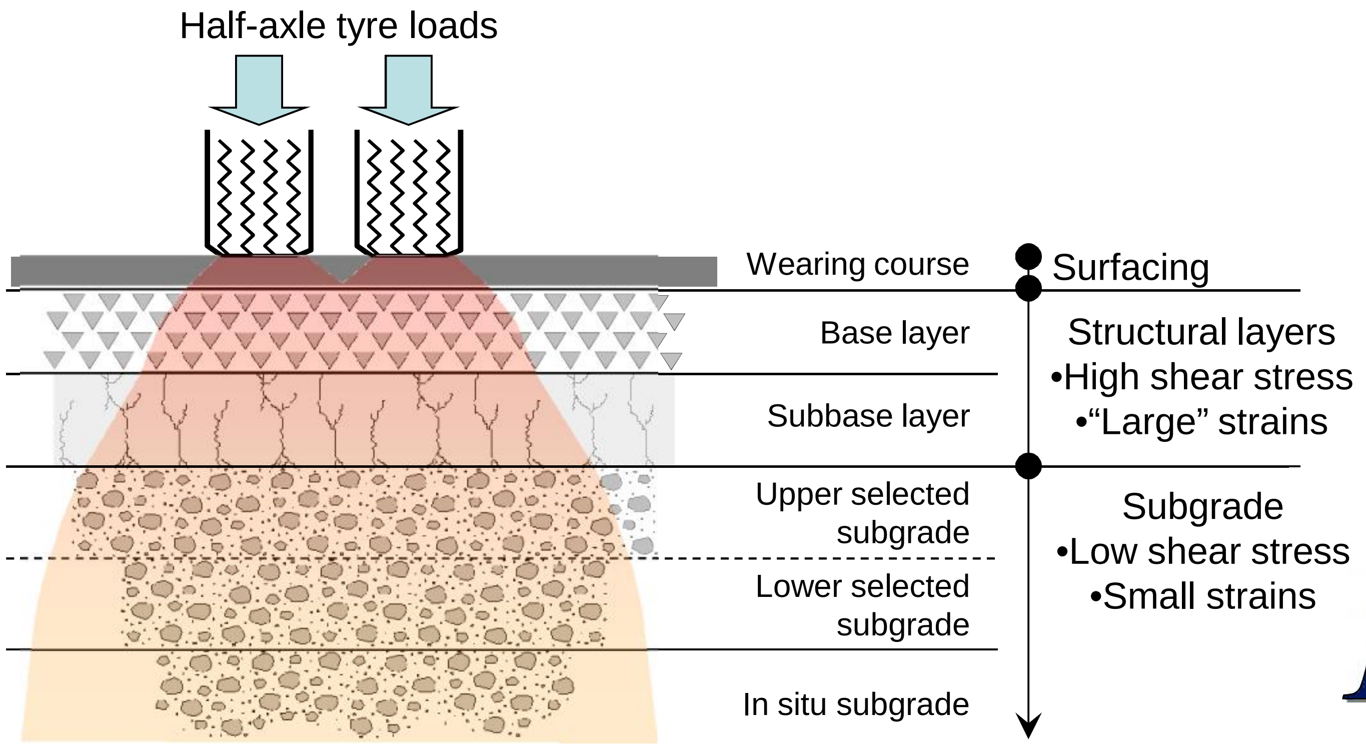
- Unbound material (Theyse & van Aswegen)
  - Subgrade
  - Structural layers
- Stabilized material (Mgangira & Theyse + CSIR/US support)
- Hot-mix asphalt (Verhaeghe, Denneman, Anochie-Boateng, O’Connel)
- Concrete and paving blocks (Strauss & Slavik)
- Surface seals (Milne, Visser, Jenkins, Steyn, van Zyl, Gerber, Mukandile)

SAPDM Pavement Design Research Outcomes – Unbound material

Subgrade and structural layer models

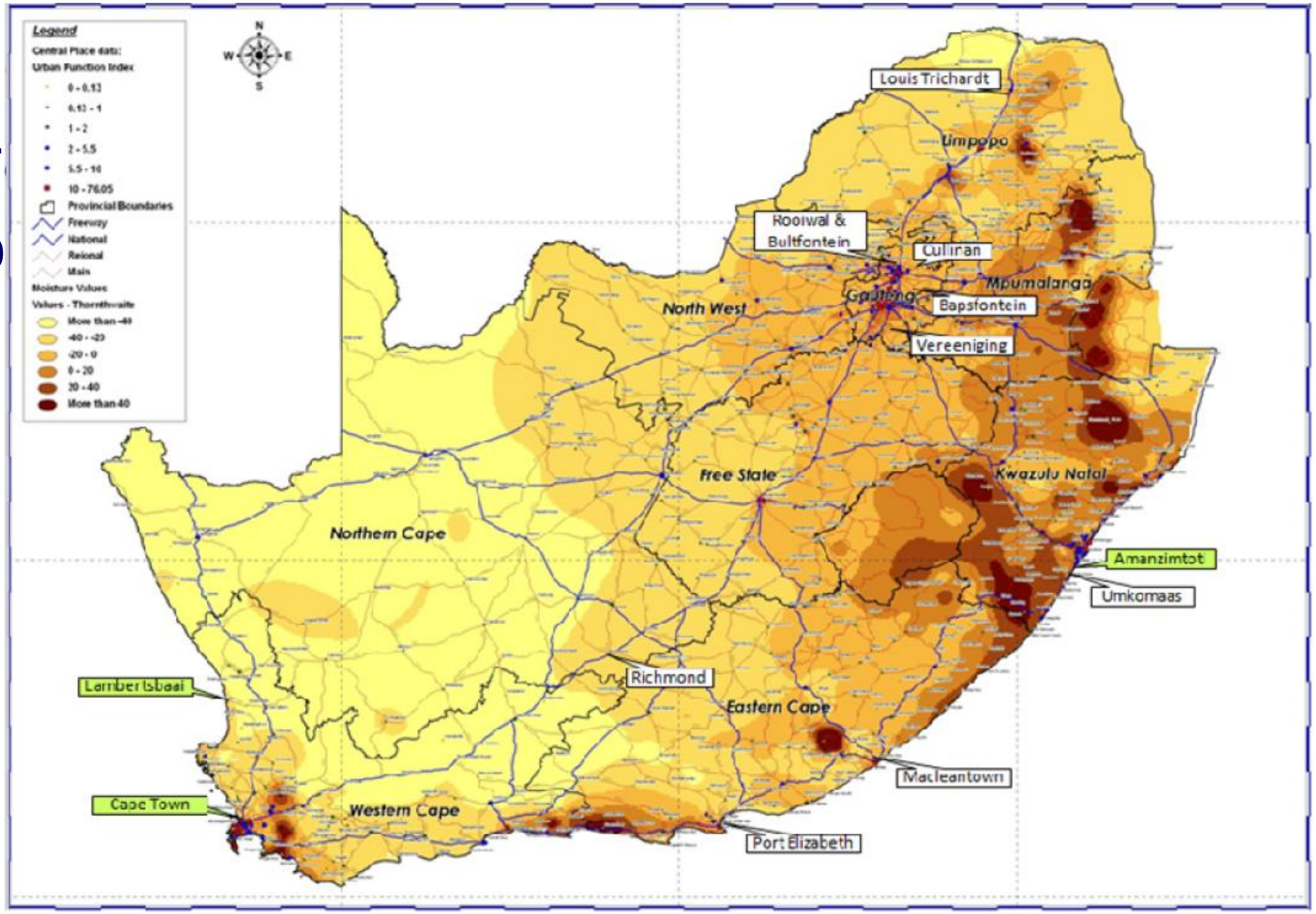
Unbound material – Design approach

- Structural layers
  - High shear stress – counter with shear strength
  - Stress ratio approach
- Subgrade
  - Low shear stress
  - Critical response parameter – elastic parameter



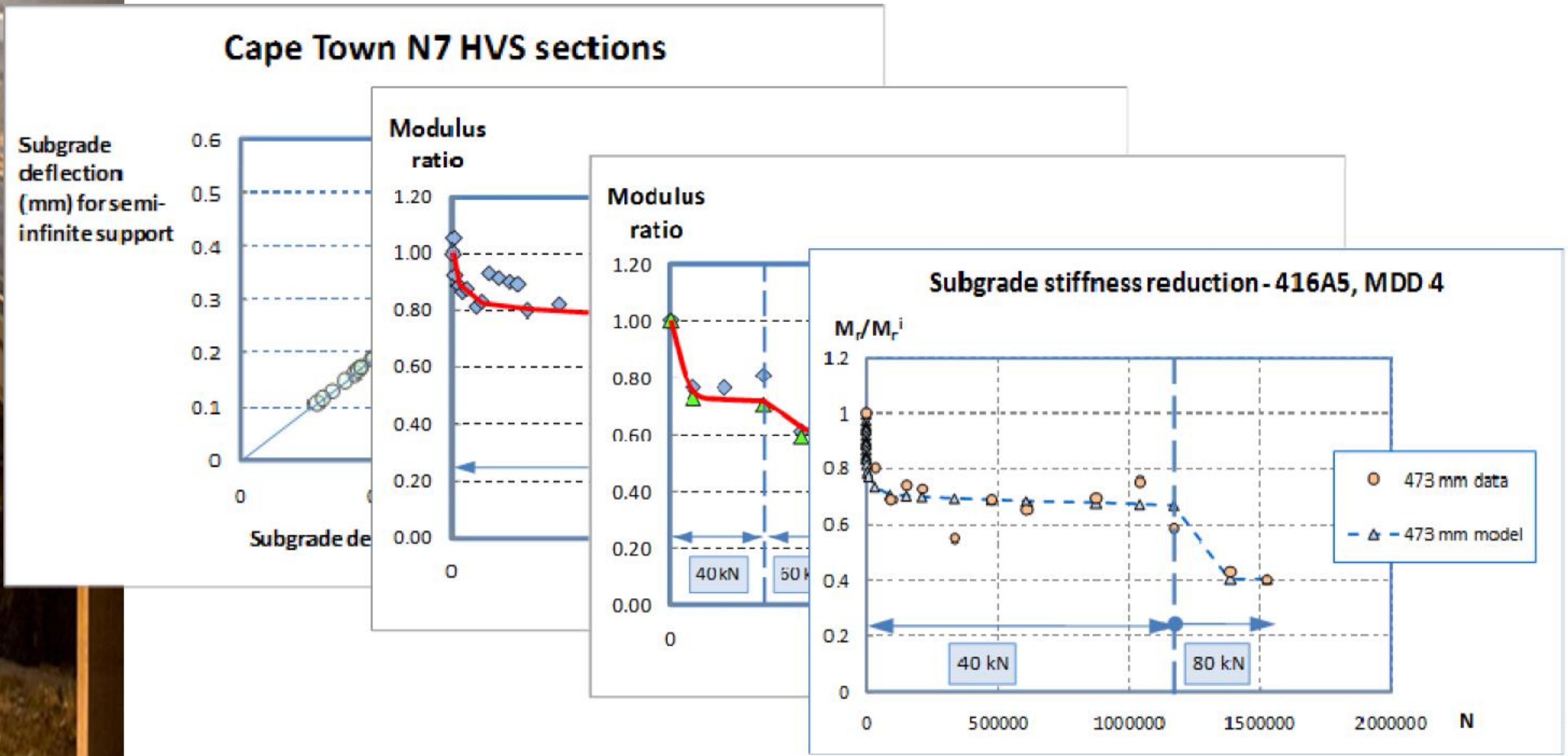
Subgrade models

- Elastic response
    - Semi-infinite subgrade
    - Stiffness reduction model
- Perman
    - Subgr
    - Do no



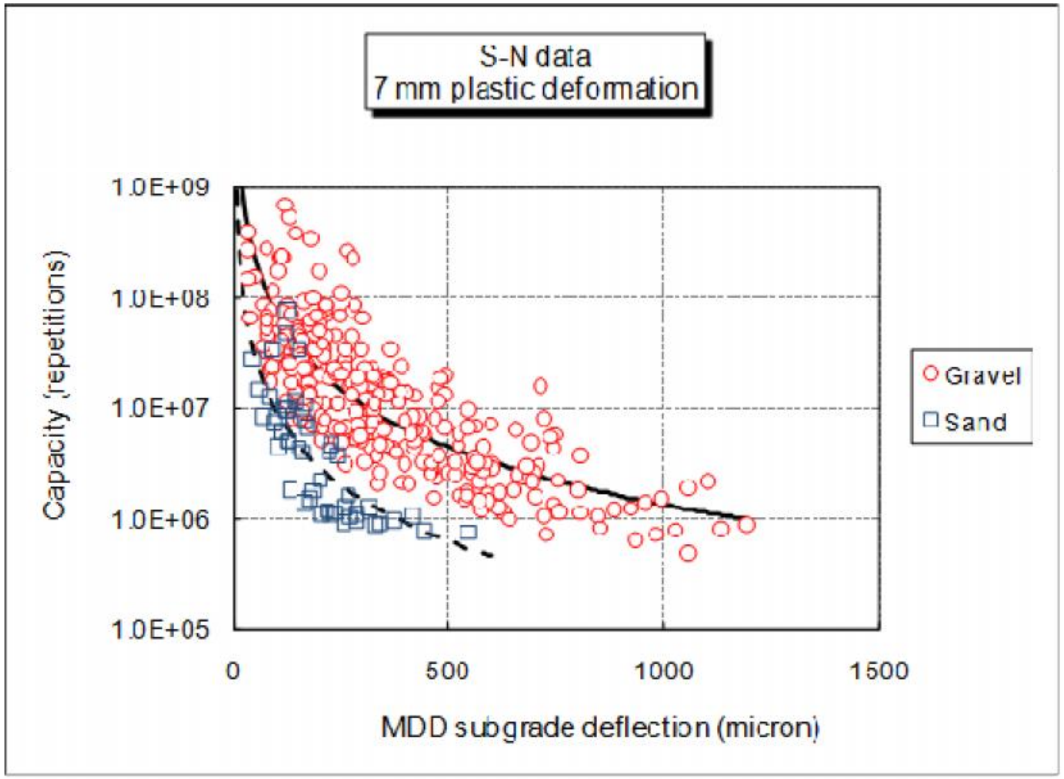
Subgrade Elastic Response Models

- Semi-infinite subgrade
- Stiffness reduction model



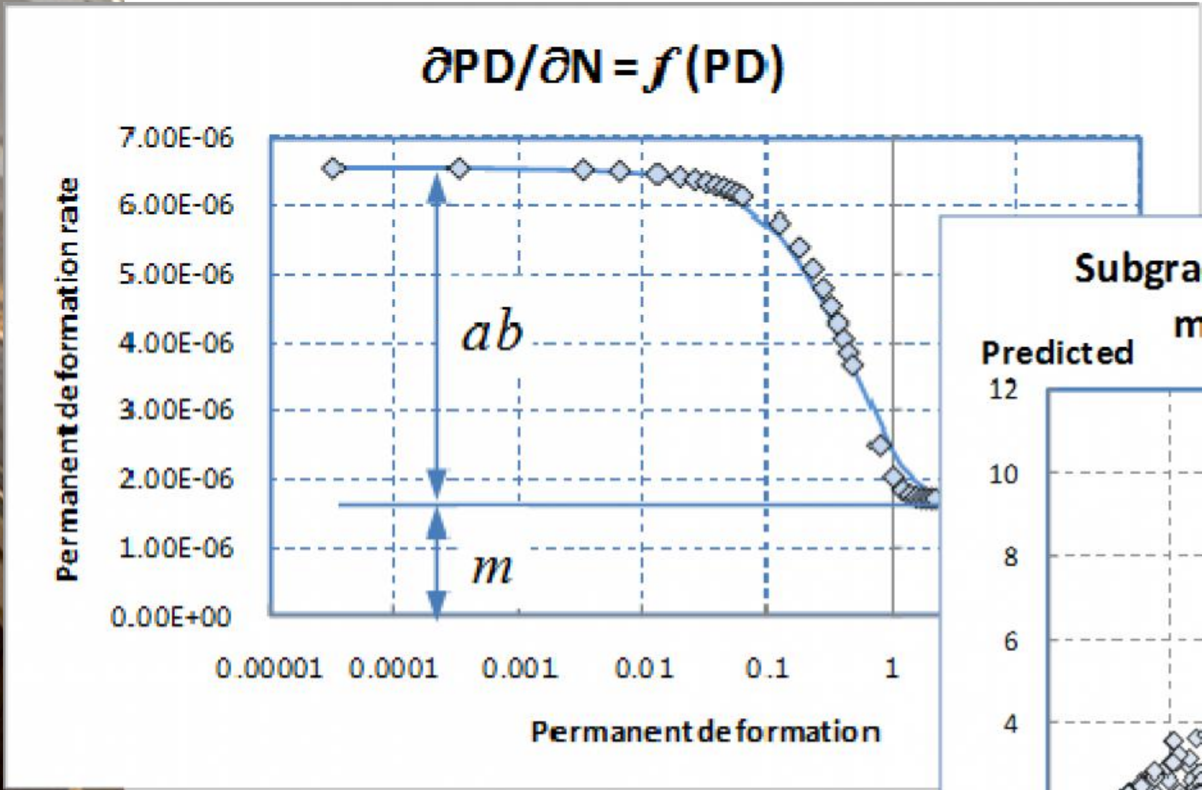
Subgrade Permanent Deformation Models

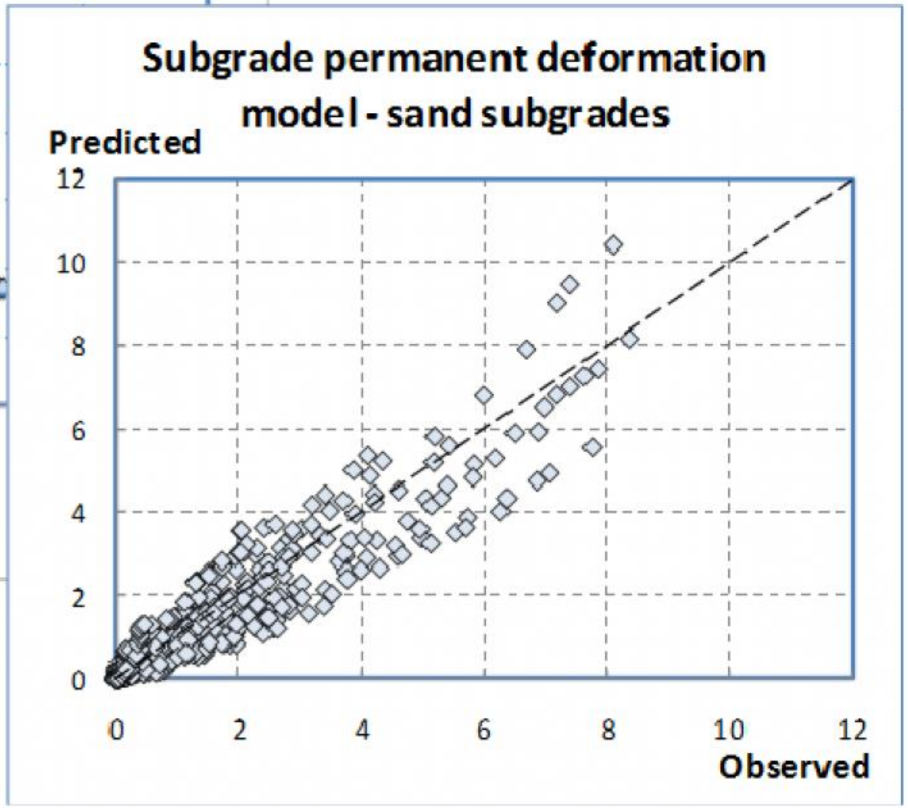
- Conventional S-N type models



Subgrade Permanent Deformation Models

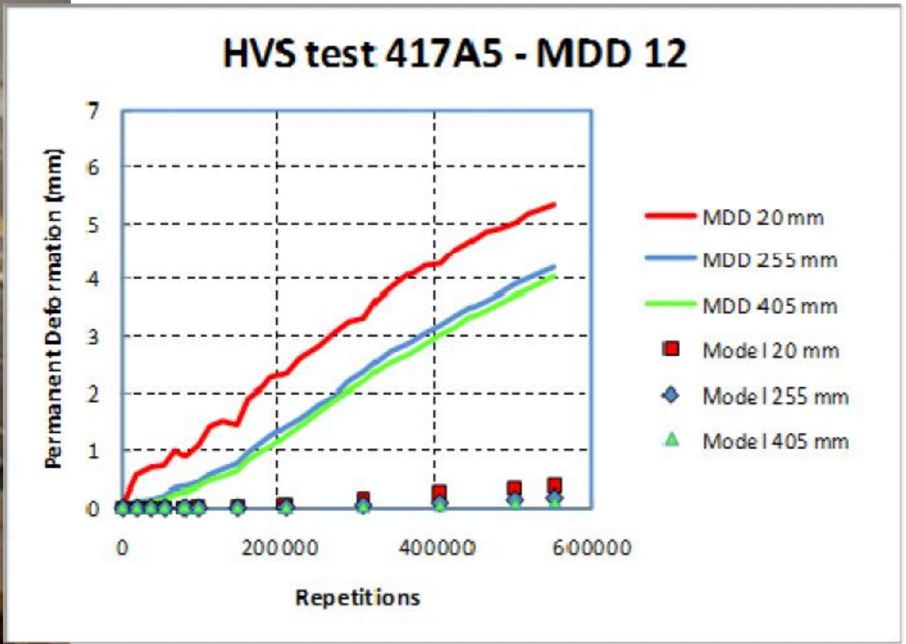
- “Memory-less” models

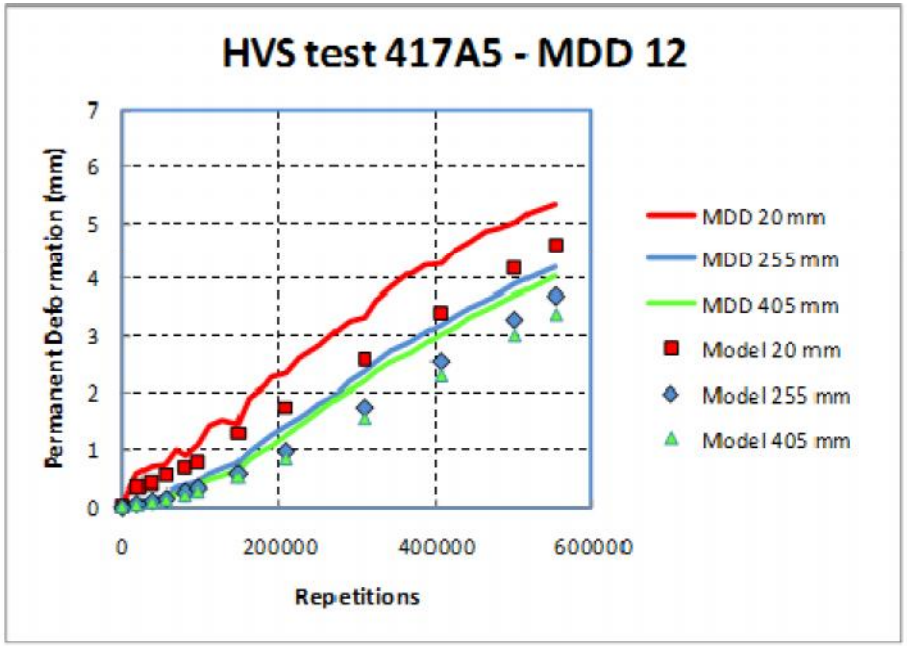




Subgrade Permanent Deformation Models

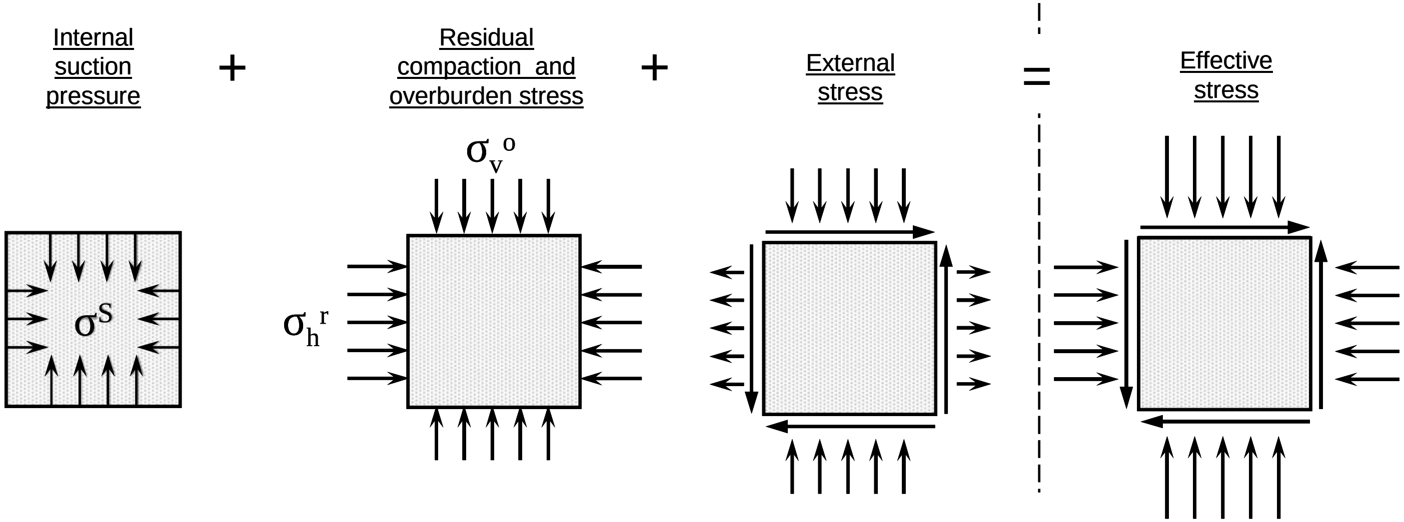
- SAMDM 1996 vs SAPDM 2013





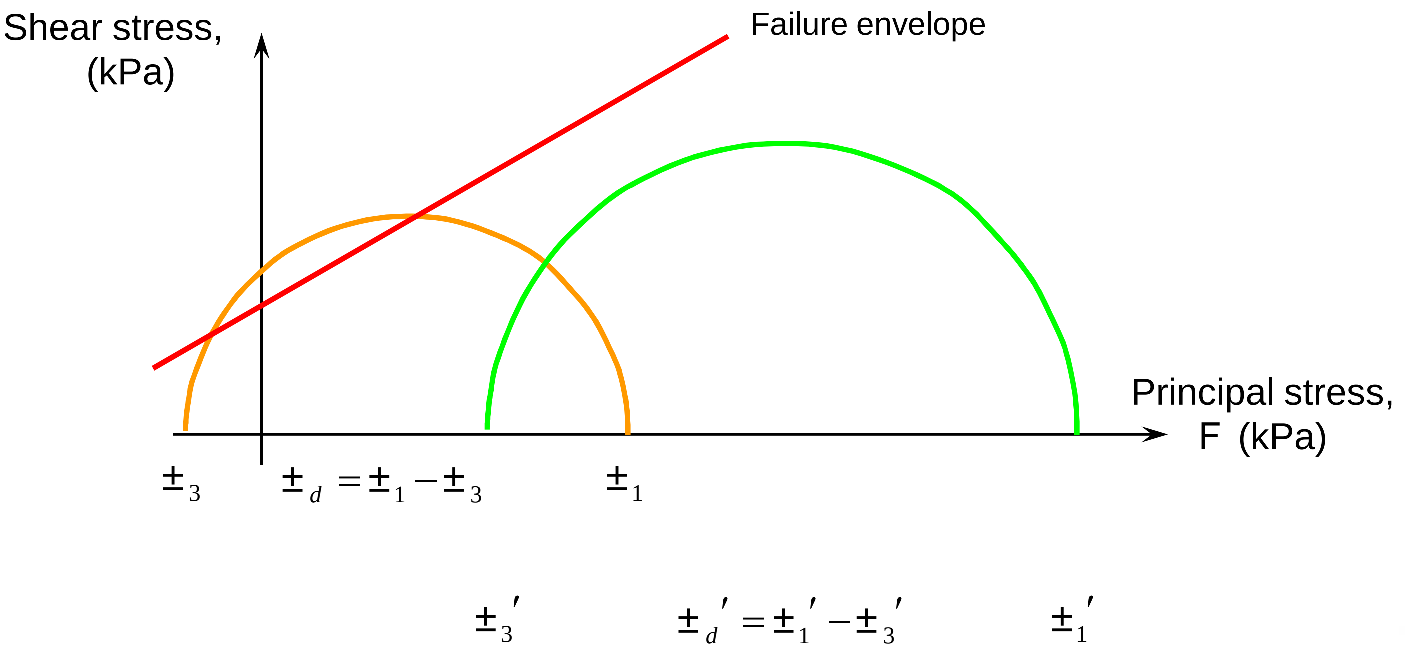
Structural layer models

- Elastic response
    - Stress-dependent stiffness if needed
- Permanent deformation
    - Stress Ratio approach similar to FoS
    - BUT ...... in terms of effective stress
        - Suction pressure
        - Residual compaction stress
        - External load stress



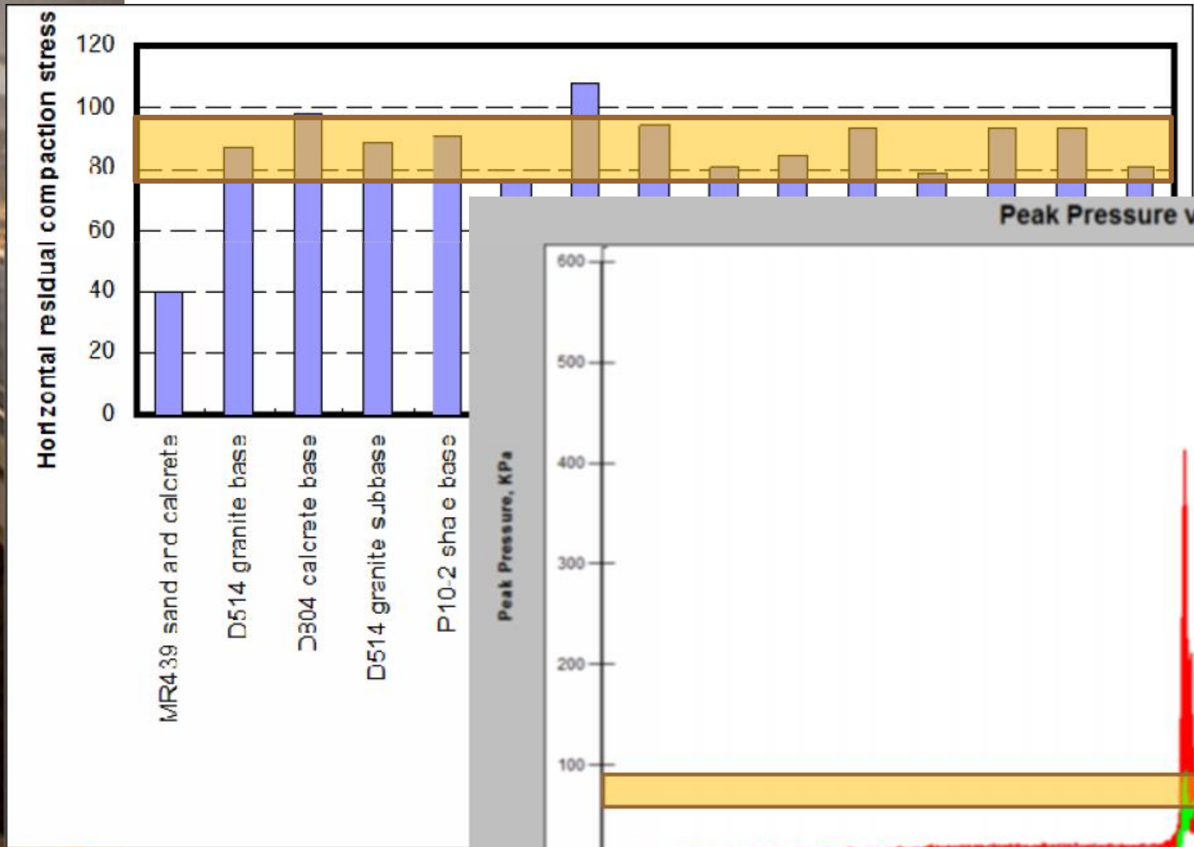
Effective stress

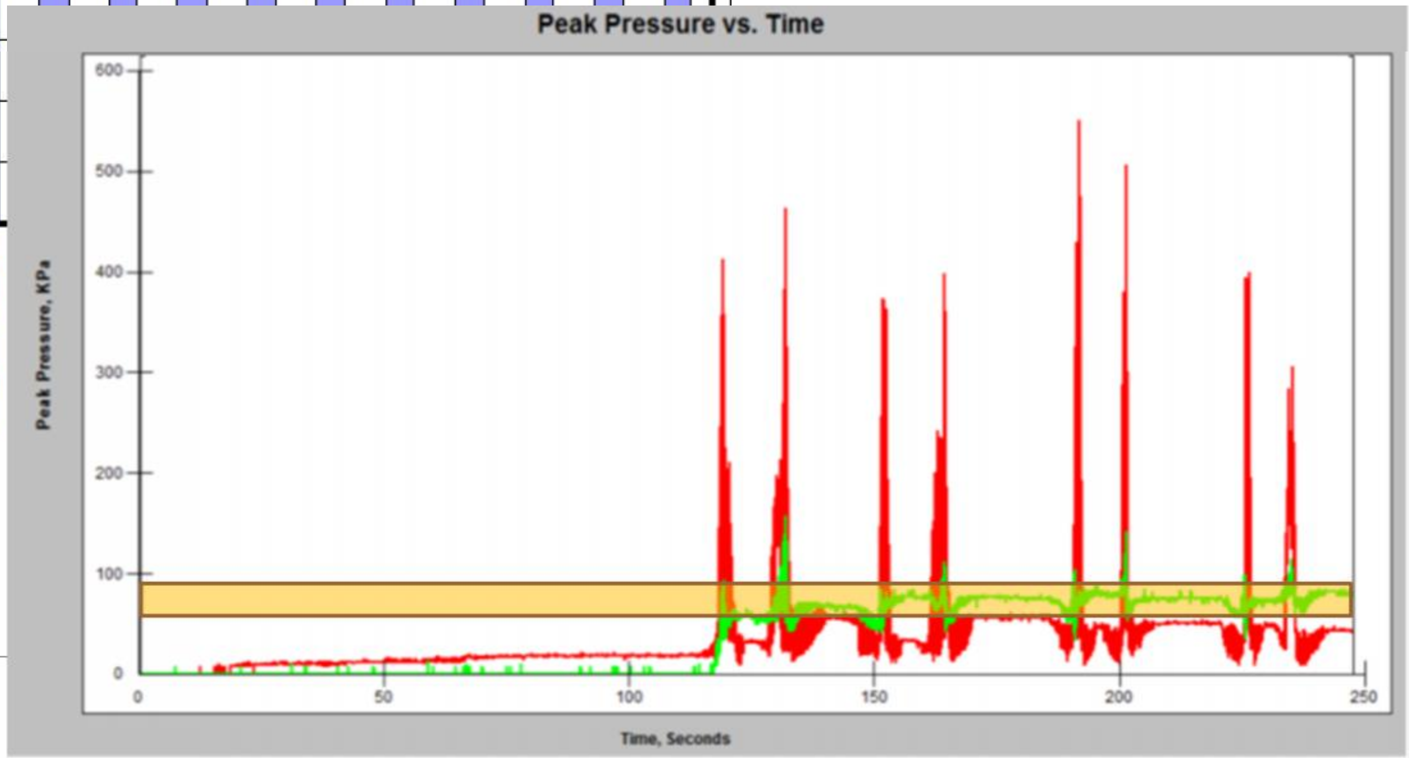
- No tensile stress in unbound material



Residual compaction stress

- Does it exist...?
    - Theory developed
    - Initial experimental confirmation



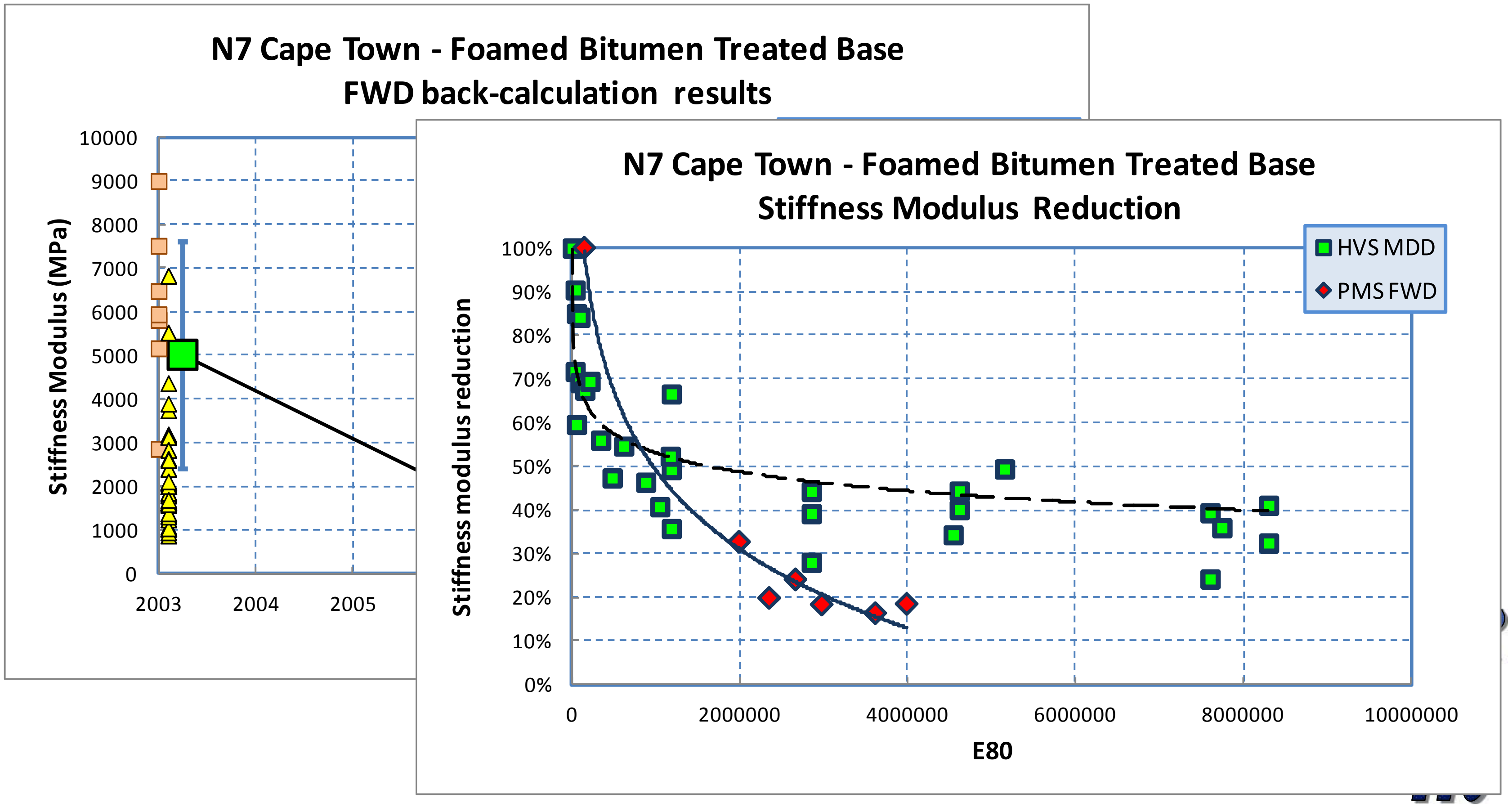


SAPDM Pavement Design Research Outcomes – Stabilised material

Elastic response and damage models

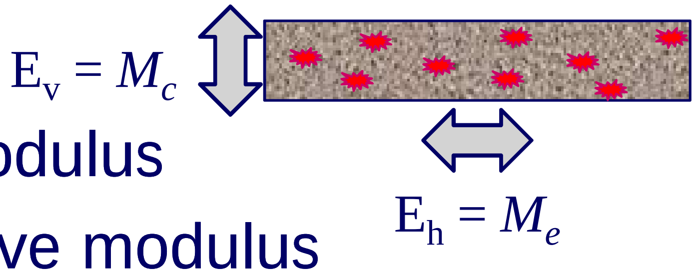
Elastic Response Models

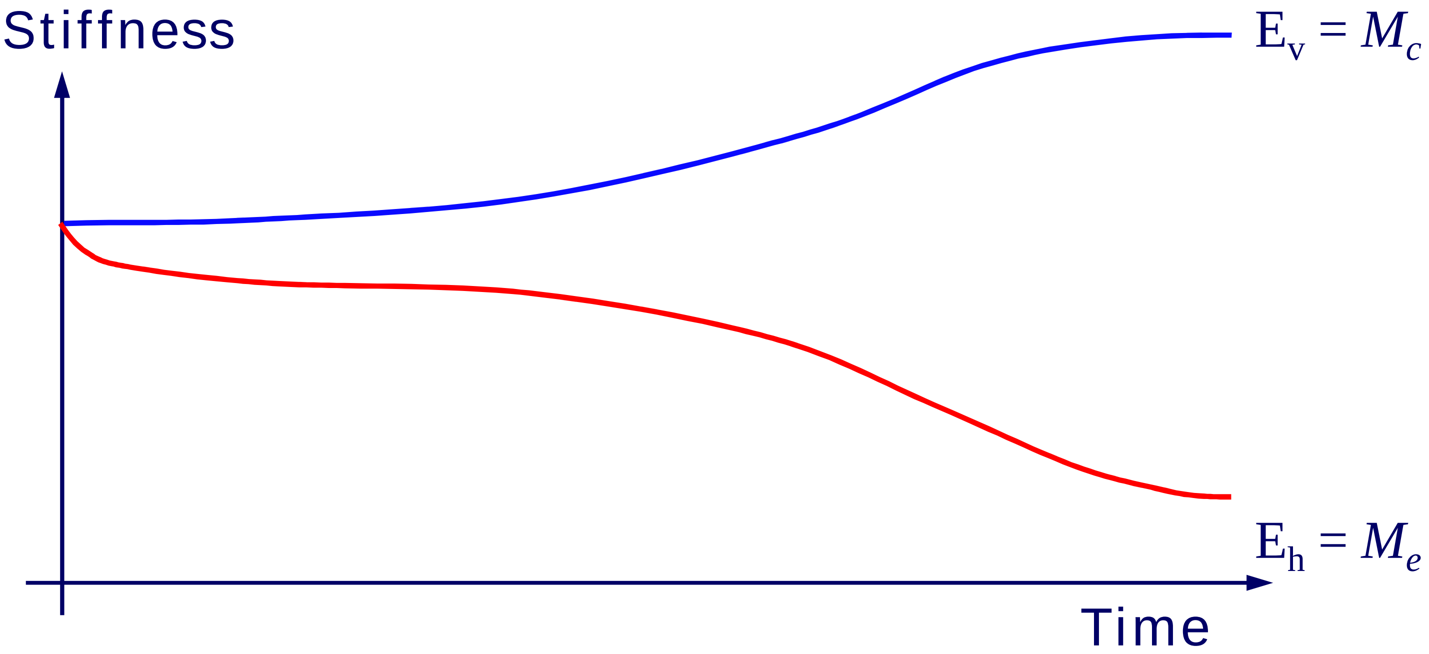
- Stiffness reduction confirmed
  - Cement and Bitumen Stabilized Material



Elastic response

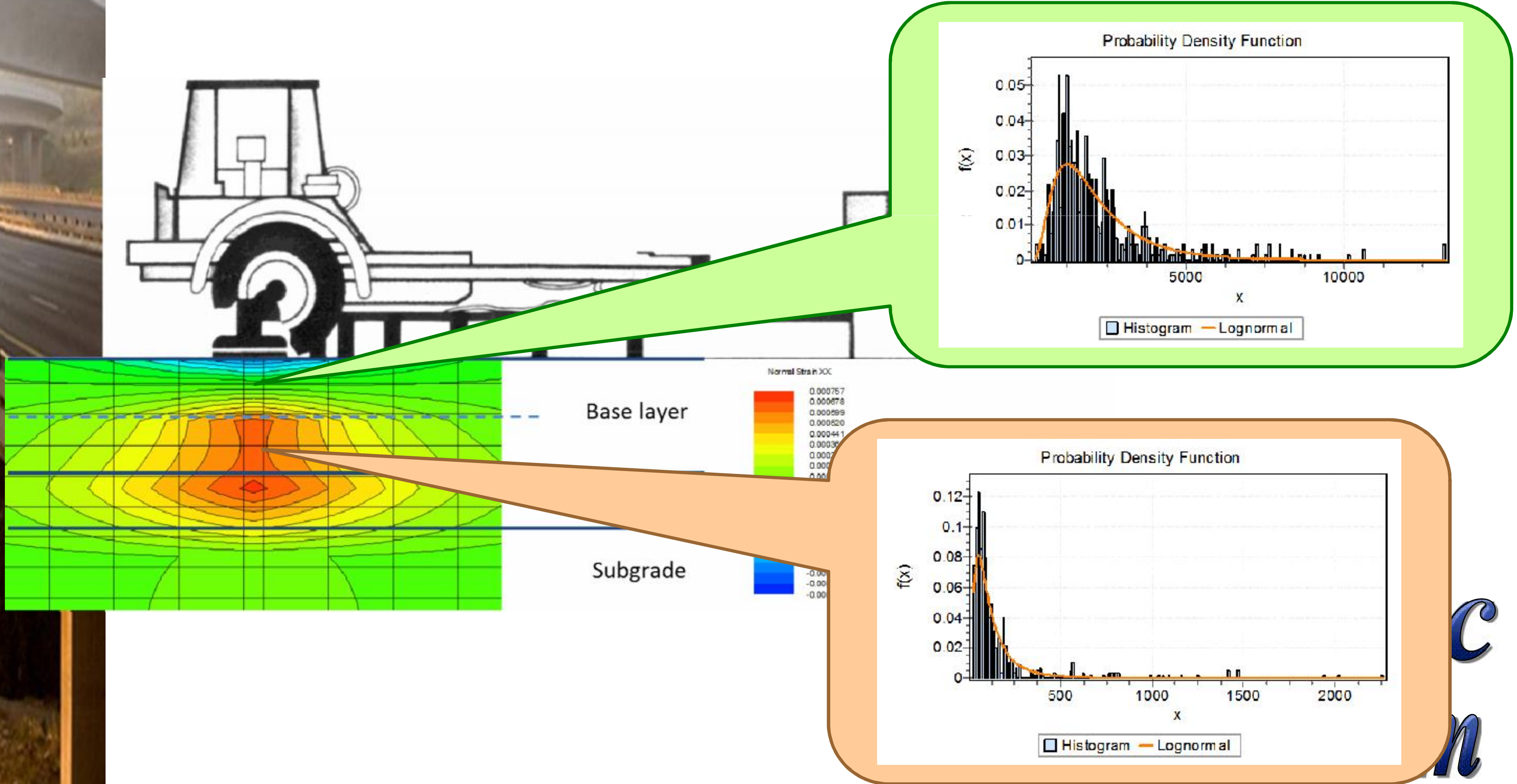
- Anisotropic approach
  - Vertical stiffness – chord modulus
  - Horizontal stiffness – effective modulus





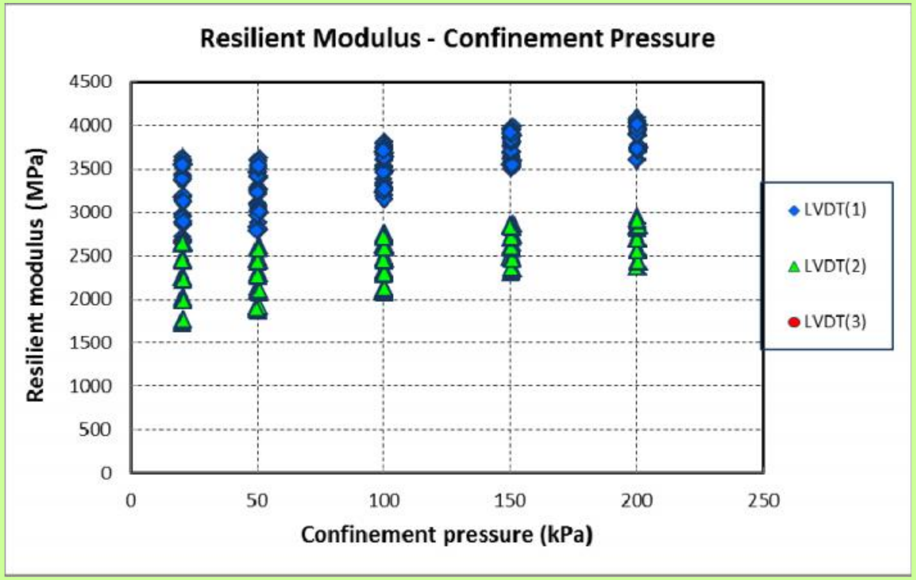
Elastic Response Models

- Anisotropic stiffness model
  - Effective horizontal stiffness



Elastic Response Models

- Anisotropic stiffness model
  - Vertical stiffness



SAPDM Pavement Design Research Outcomes – Asphalt material

Elastic response and damage models

Asphalt research outcomes

- Elastic response
  - Temperature dependent
  - Implicit visco-elastic model
    - Load-pulse duration = f (vehicle speed)
- Fatigue
- Permanent deformation
- Biggest gain is in the number of mixes tested

Asphalt mixes tested

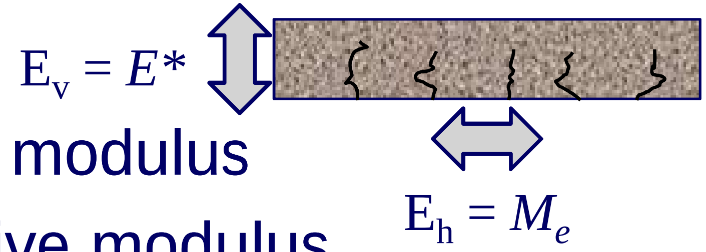
- SAPDM project
  - BTB with 40/50 PEN
  - Coarse continuous with AE2
  - Medium continuous with AE2
  - Bitumen rubber mix
  - Medium continuous with 60/70 PEN
  - HiMA

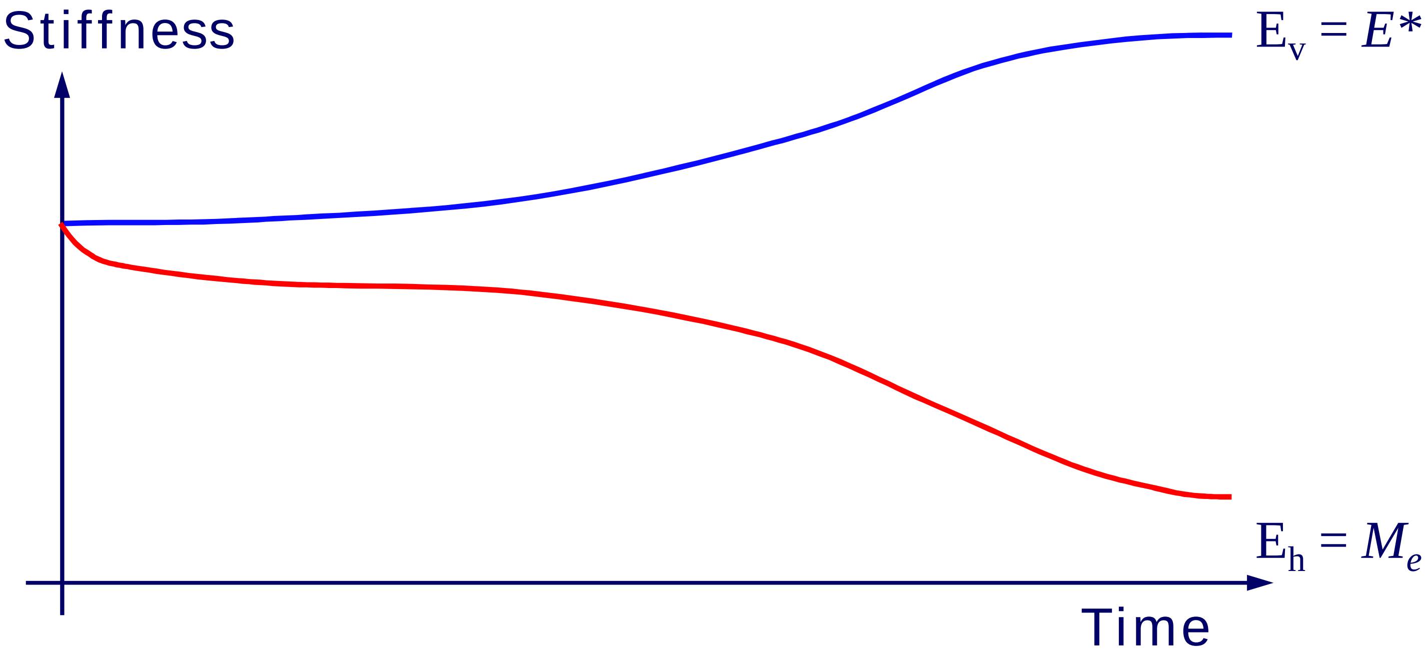
Asphalt mixes tested

- SABITA project
  - 8 new mixes to be tested
    - AP1 BTB (KZN)
    - 50/70 medium continuous (WC)
    - Durban Type-A; Type-D RA; Type-D WMA
    - AP1 coarse continuous (Gauteng)
    - Bitumen-rubber porous asphalt (Gauteng)
    - SMA (KZN)
  - additional testing on SAPDM mixes
    - Hamburg wheel tracking
    - Lottman moisture susceptibility
    - Dynamic modulus with confinement

Elastic response

- Anisotropic approach
  - Vertical stiffness – dynamic modulus
  - Horizontal stiffness – effective modulus



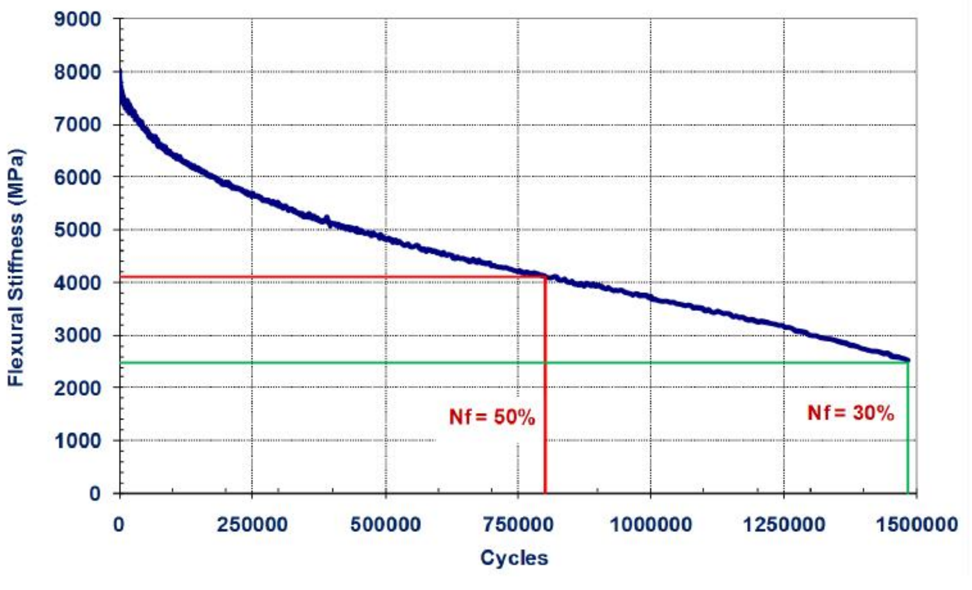


Elastic response

- Effect of ageing enters through binder properties
- Input level B (basic)
  - Pre-tested mixes (including binder properties); or
  - Predictive mix E^* and default binder properties
- Input level I (intermediate)
  - Tested binder properties
  - Predictive mix E^*
- Input level A (advanced)
  - Tested binder properties
  - Tested mix E^*

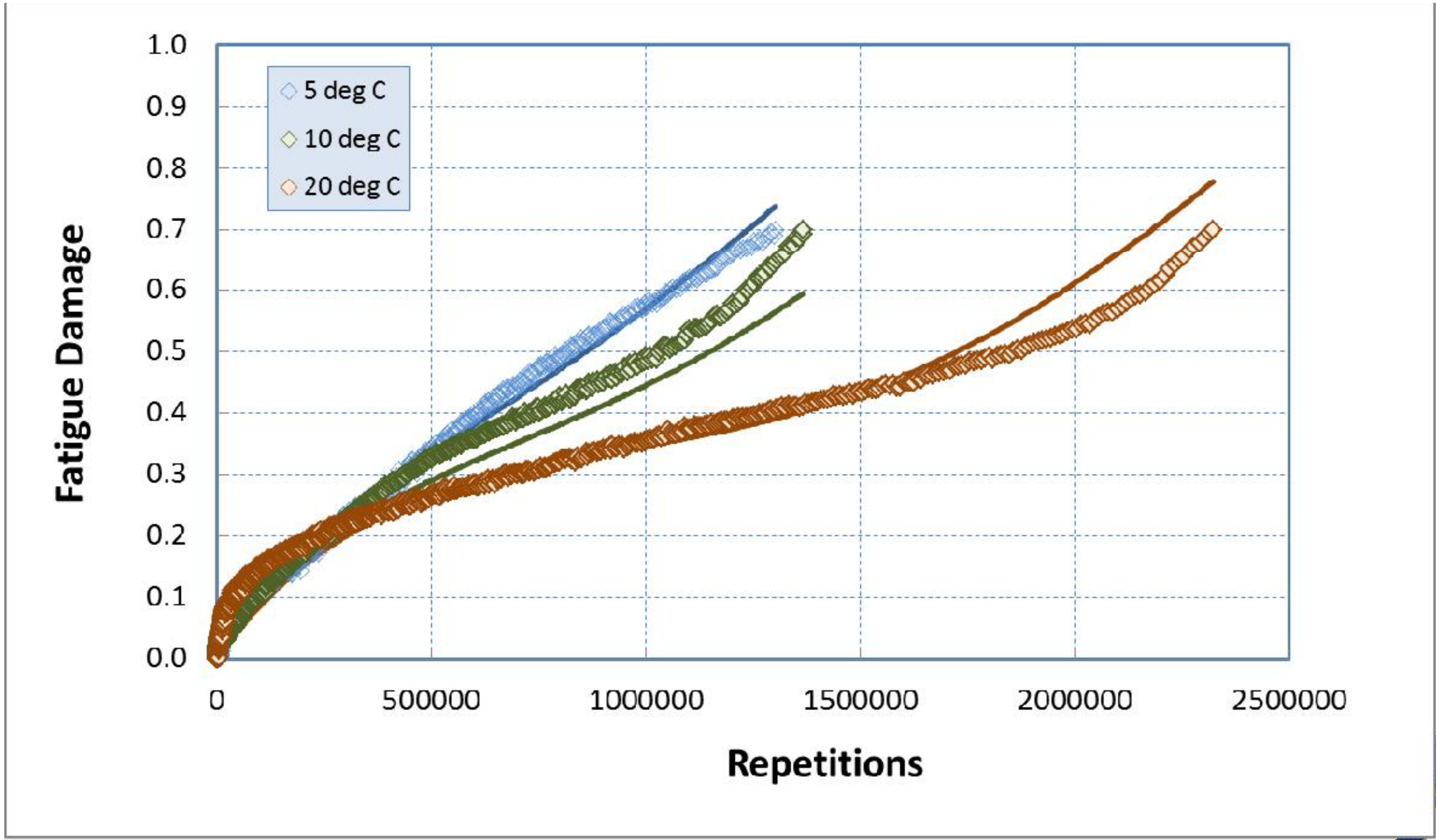
Damage models

- Fatigue
  - Past
    - Very limited calibration data set
      - 2 mixes tested in late 1960s
      - Fatigue models at single design temperature
    - Repetitions to 50 % of initial stiffness
    - S-N type models with a fixed terminal condition



Damage models

- Fatigue
  - Future

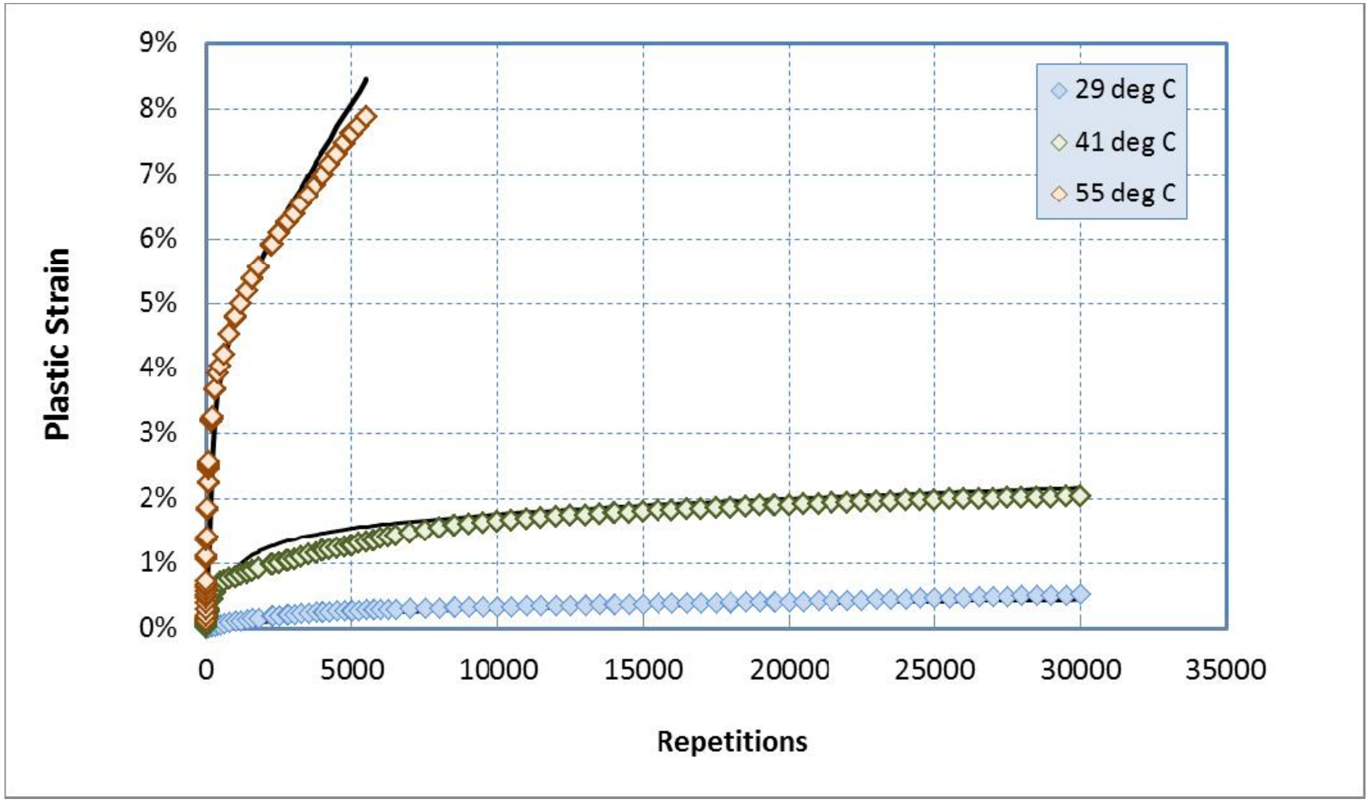


Damage models

- Permanent deformation
  - Past
    - No model

Damage models

- Permanent deformation
  - Future



SAPDM Pavement Design Research Outcomes – Concrete and paving blocks

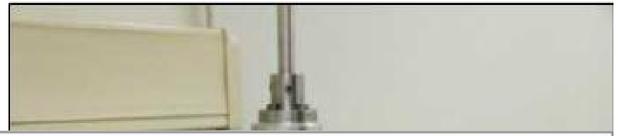
Damage models

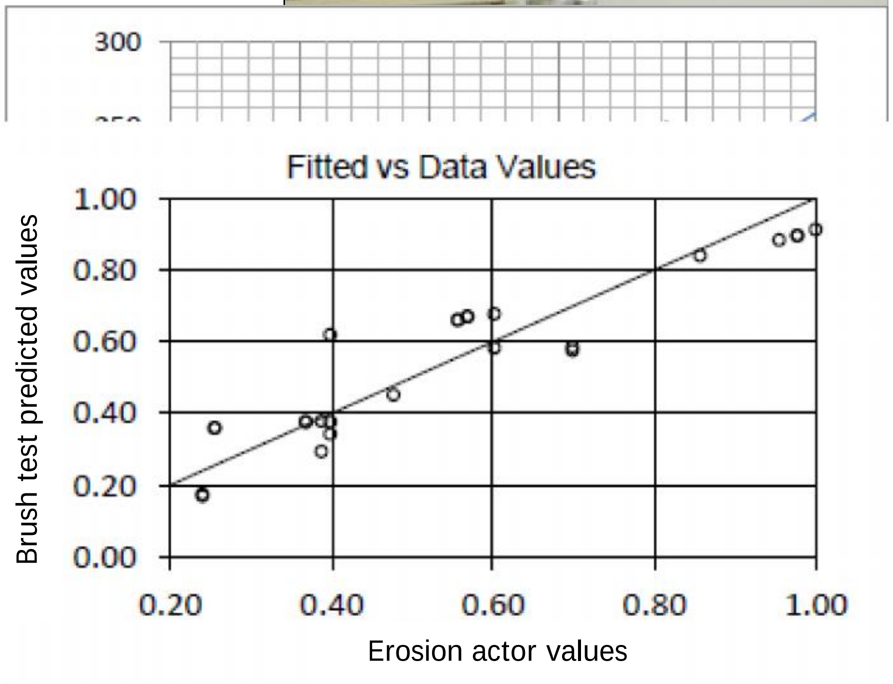
Concrete and block paving research areas

- Concrete pavements
  - cncPave used as a departure point
  - Additional work on
    - Erosion of subbase below concrete
    - Load-transfer at joints
- Block pavements
  - Critical design factors
  - Riding quality deterioration models
  - Introduction into cncPave

Damage models: Concrete pavements

- Subbase erosion
  - Past
    - Factor in cncPave based on user experience
  - Future
    - Erosion factor derived from
    - Level B (basic)
      - GM, PI and ITS
    - Level I (Intermediate)
      - Brush test
    - Level A (Advanced)
      - Rotational Shear Tes





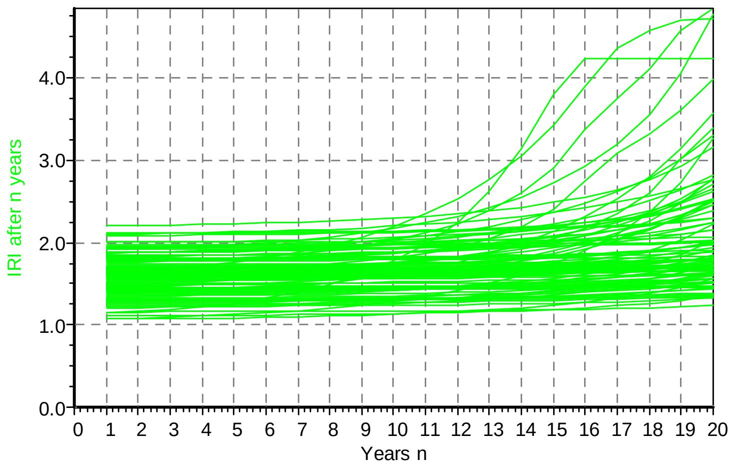
Critical design factors: Block pavements

- Joint width
    - Less than 2 mm
- Joint filling
    - High crushing strength sand
    - Low permeability grading
    - Fully filled
- Thicker, higher strength blocks in “lock-up” pattern
- Stabilized subbase

Damage models: Block pavements

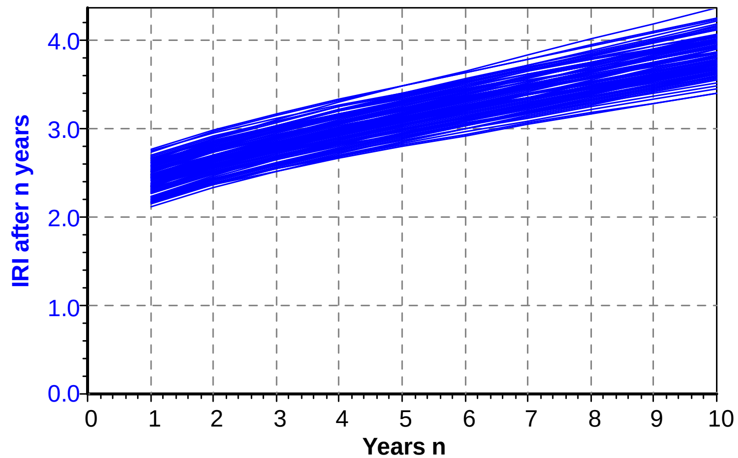
- Riding quality deterioration
  - Past
    - Not available in cncPave
  - Future
    - block-PAVE available in cncPave
    - Request for calibration data

Jointed concrete



Description of site, time and run v0.4 gu 30/4/13

Block paving



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SAPDM Pavement Design Research Outcomes

Pavement Analysis

Significant research outcomes

- Pavement analysis
  - Multi-layer, linear-elastic analysis
    - Anisotropic material models (Maina, 2012)
    - Rectangular loading (Maina, 2012)
  - Effective stress (Theyse, 2009)
  - Stress and temperature dependent material models (Theyse, 2009 & 2011)
  - Validation with
    - Finite element analysis (du Preez)
    - Measured stress and strain - R104 (Steyn)

SAPDM Pavement Design Research Outcomes

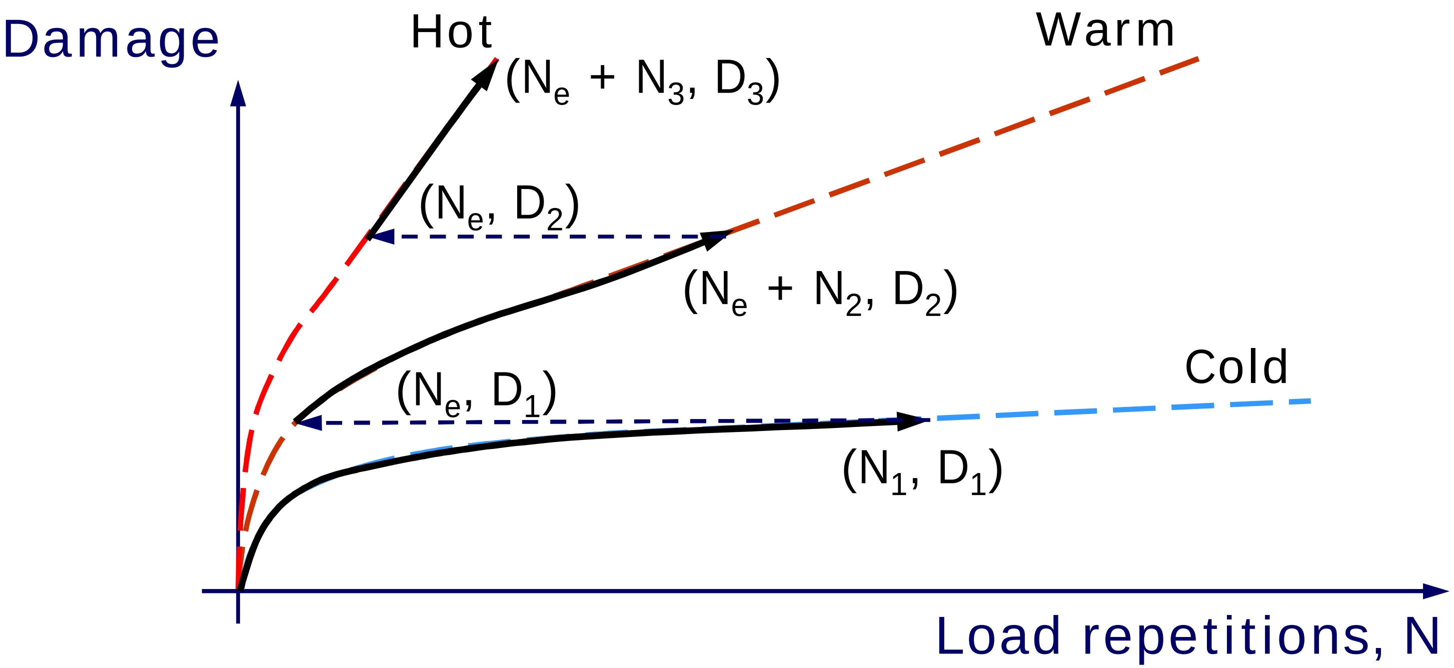
Stochastic, recursive simulation

Research areas

- Non-linear recursive simulation
  - Strain-hardening
  - Memory-less damage models (Theyse & van As, 2009)
    - Markov property
      - The evolution of future damage depends only on the current level of damage and future loading

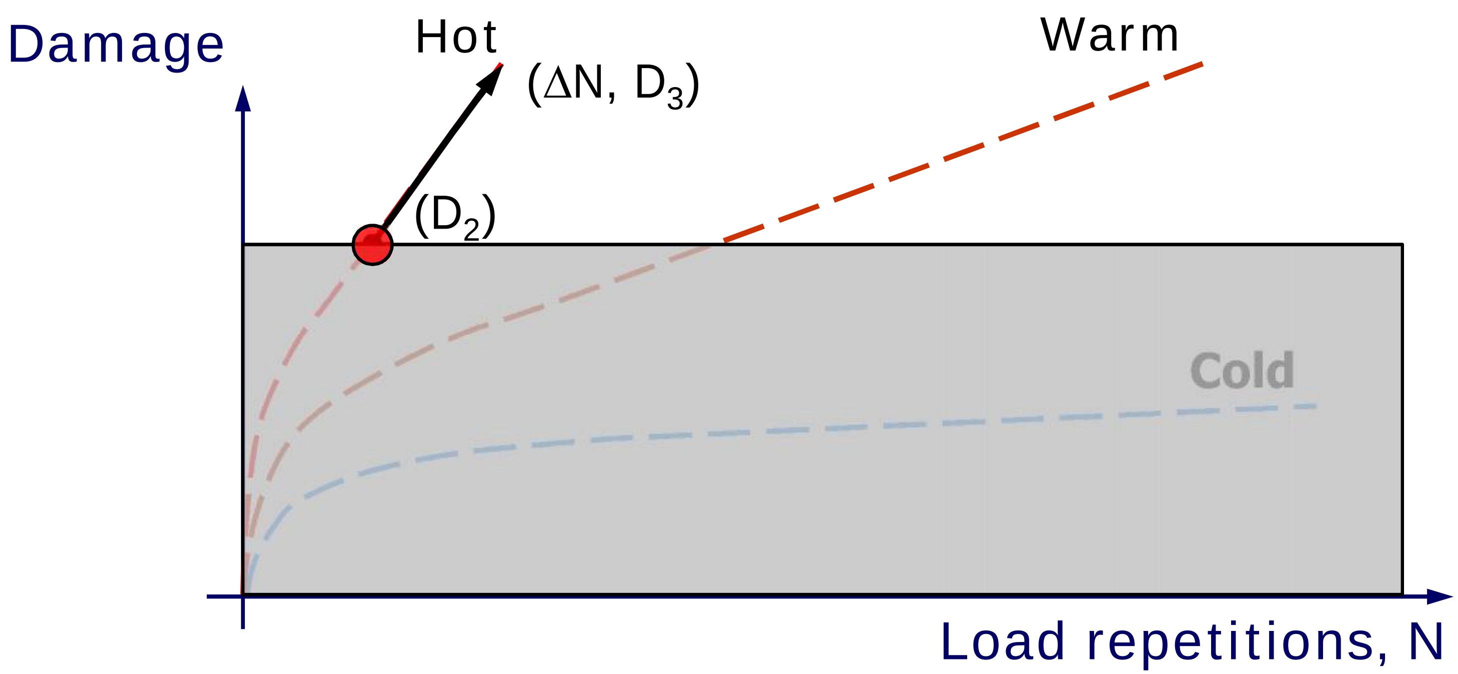
Research areas

- Non-linear recursive simulation
  - Strain-hardening



Research areas

- Non-linear recursive simulation
  - Memory-less model



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Significant research outcomes

- Memory-less model calibrated for
  - Subgrade stiffness reduction
  - Unbound plastic strain
    - Crushed stone bases
    - Subgrade
  - HMA
    - Plastic strain
    - Fatigue

SAPDM Pavement Design Research Outcomes

Environmental Effects

Research areas

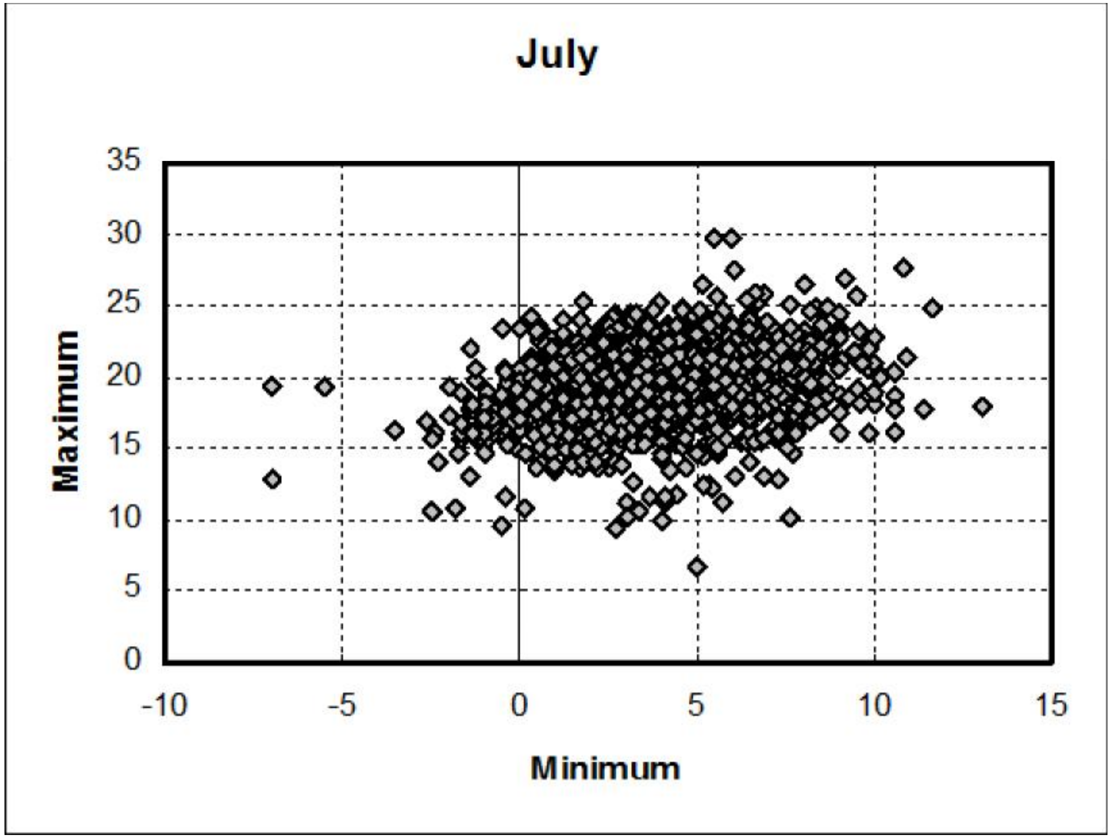
- Environmental effects
  - Climate zones and pavement moisture conditions
  - Ambient temperature zones and asphalt temperature depth profiles

Significant research outcomes

- Ambient temperature and asphalt temperature profiles
  - *Thermal*-PADS models (Viljoen & Denneman)
    - Daily minimum and maximum ambient temperature
    - AC surface temperature
    - AC depth temperature profile
    - AC diurnal temperature profile

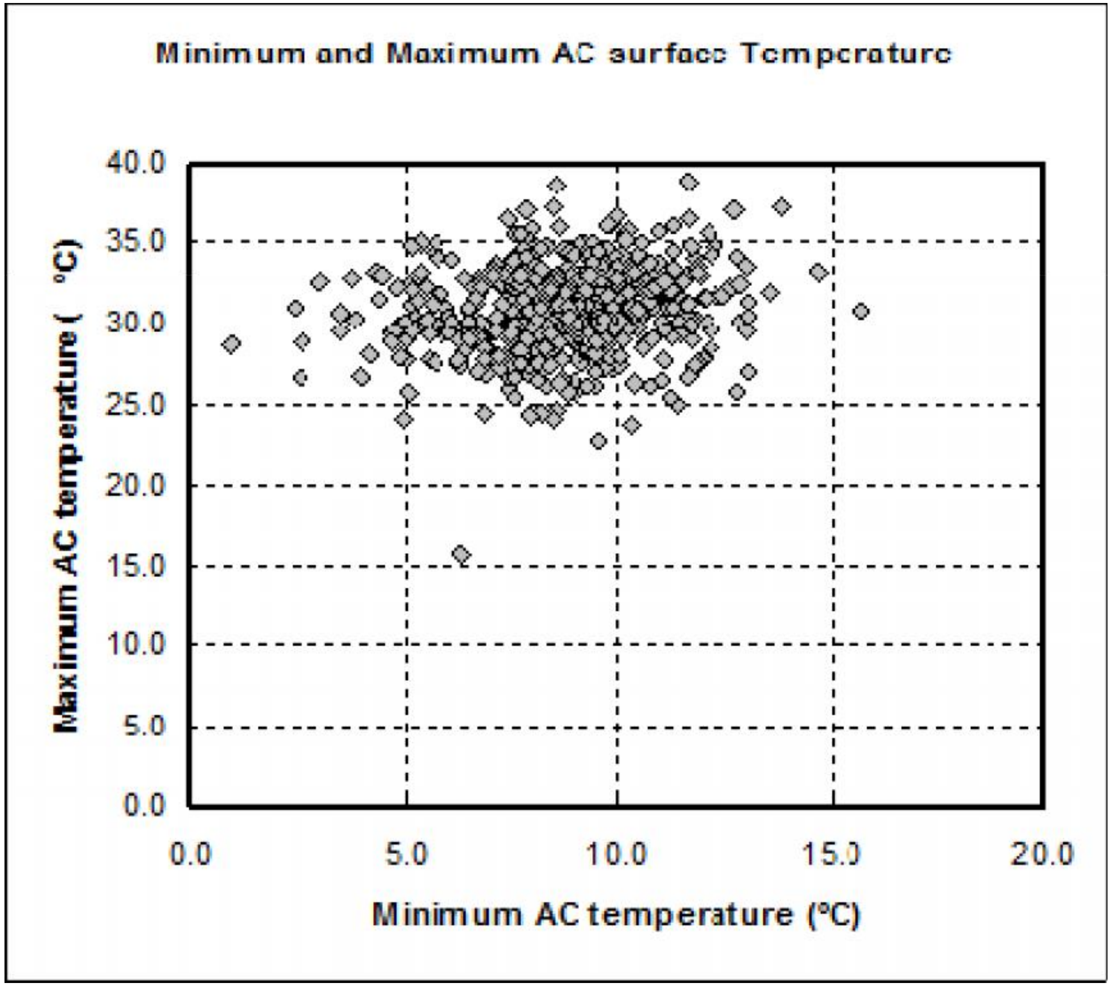
Significant research outcomes

- Daily minimum and maximum ambient temperature



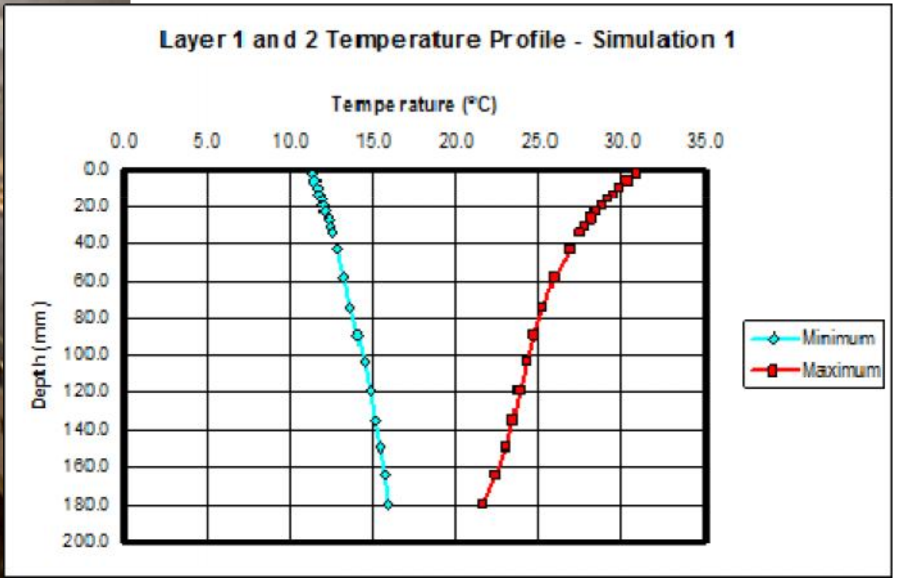
Significant research outcomes

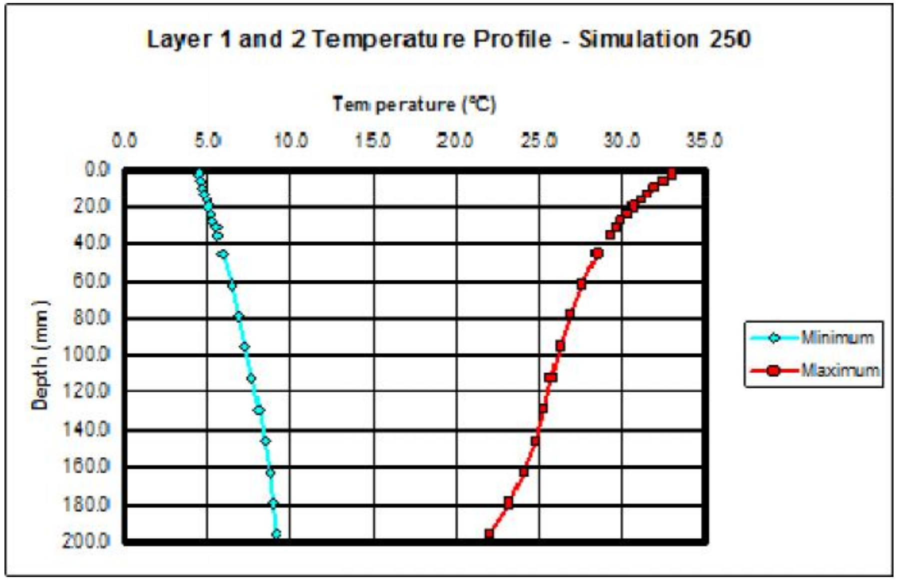
- AC surface temperature



Significant research outcomes

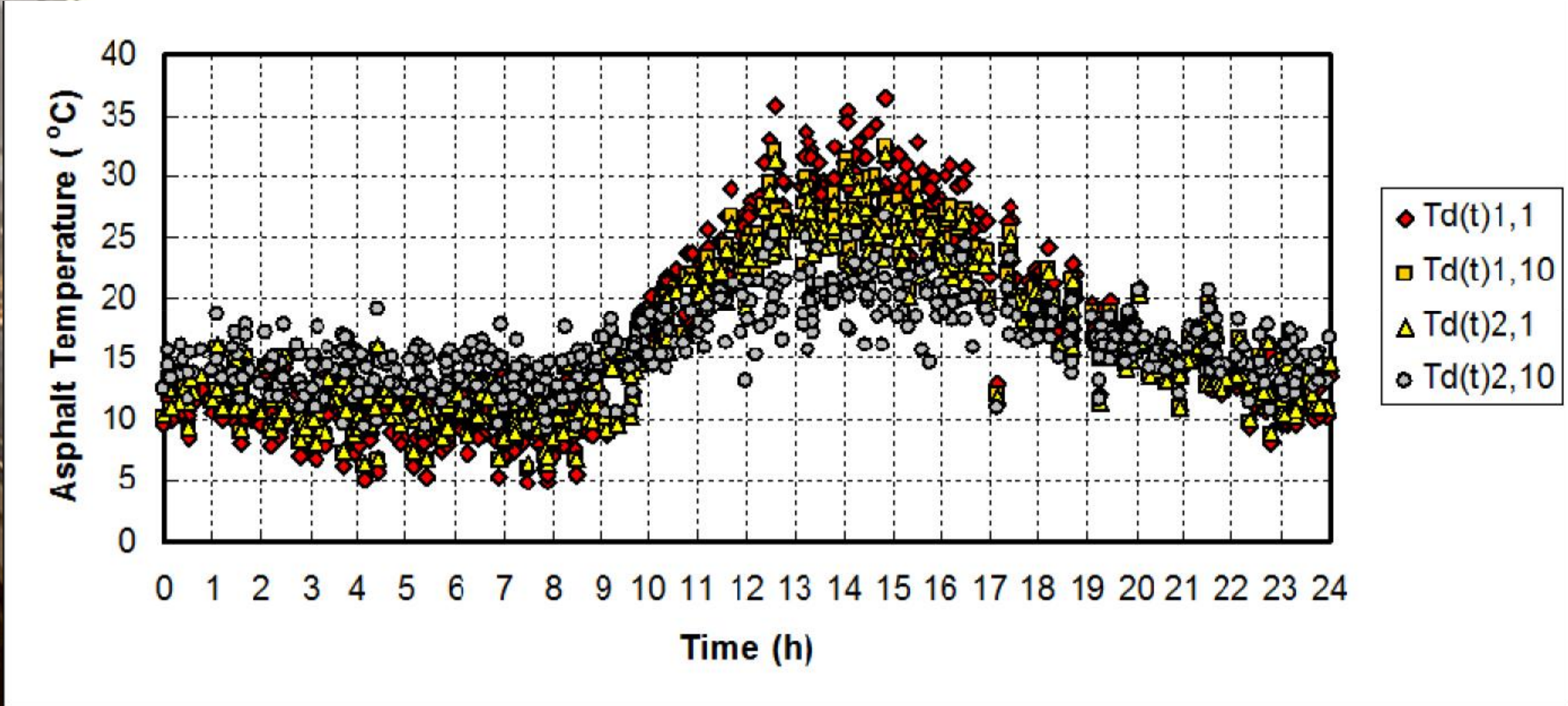
- AC depth temperature profile





Significant research outcomes

- AC diurnal temperature profile



Closure

- SAPDM related research in all areas of pavement design
  - Too many outcomes to list
  - Highlighted most significant outcomes
  - Started with implementation in software system