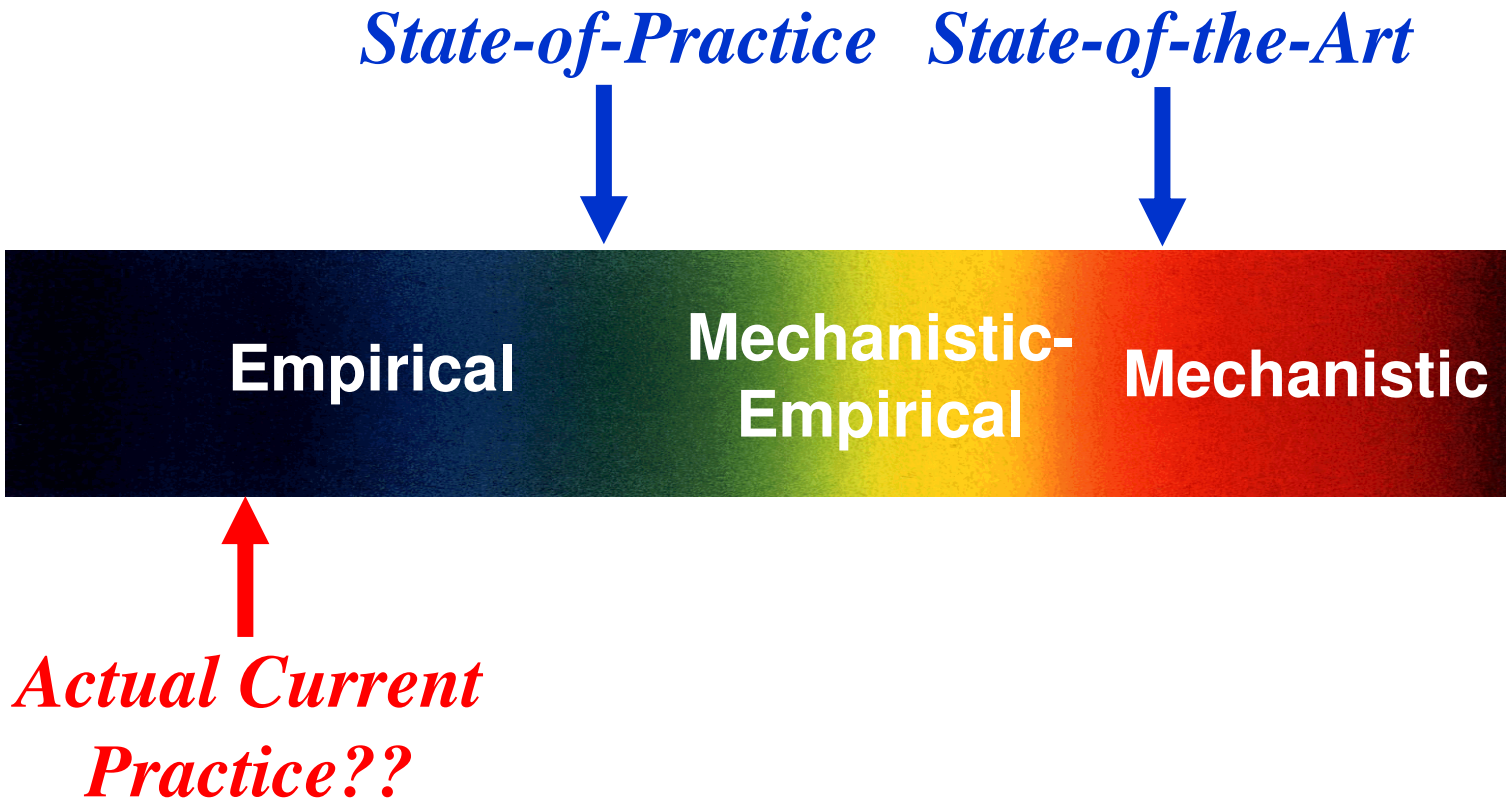
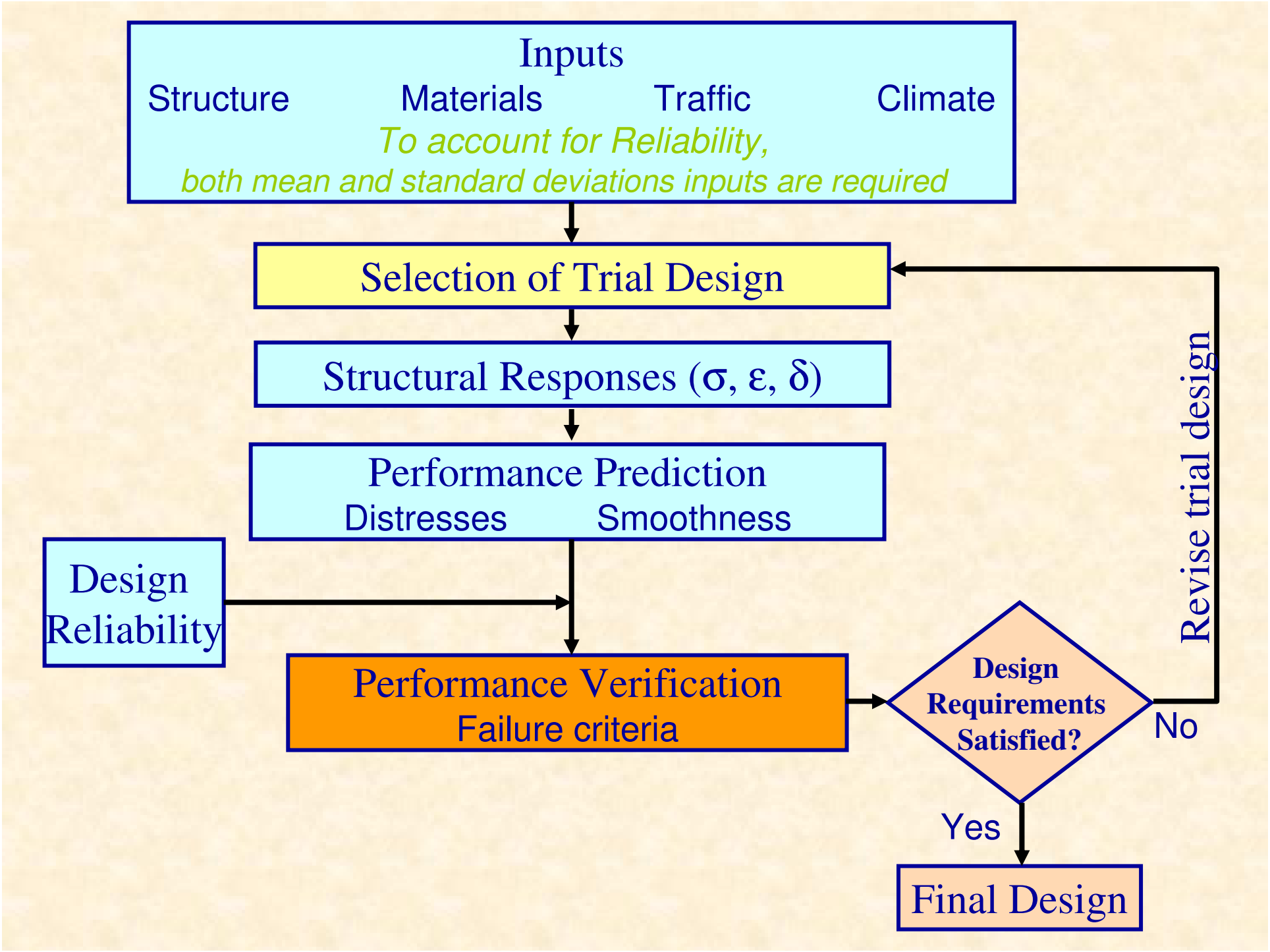
Pavement Design—
Where are We?

By

Dr. Mofreh F. Saleh

Pavement Design—Where are We??




Inputs
Structure
Materials
Traffic
Climate
To account for Reliability,
both mean and standard deviations inputs are required
Selection of Trial Design
Structural Responses (σ, ε, δ)
Performance Prediction
Distresses
Smoothness
Design Reliability
Performance Verification
Failure criteria
Design Requirements Satisfied?
No
Revise trial design
Yes
Final Design

PERMANENT DEFORMATION IN FLEXIBLE PAVEMENTS

LOAD RELATED - Rutting

Rutting -
Permanent deformation in
all layers.
Wide versus narrow rut depths.

Shoving & Corrugations

Rutting

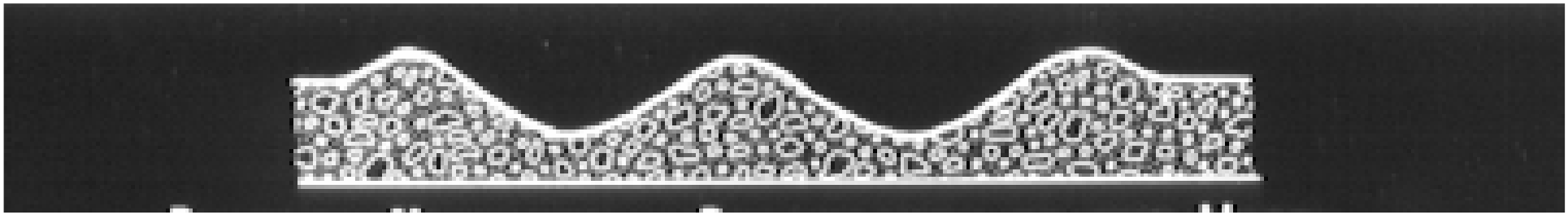
- Vertical and/or horizontal permanent deformation of one or more layers in the pavement system.

Rutting Mechanisms

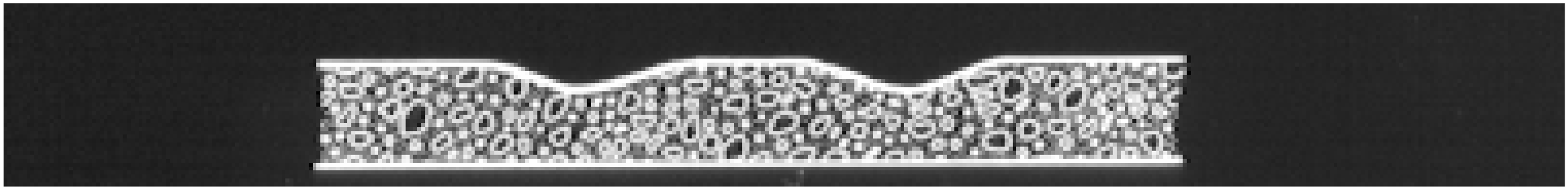
- Densification – Vertical movements
  - Compression –
  - Consolidation –
- Shear deformation – Lateral movements

Rutting Mechanisms

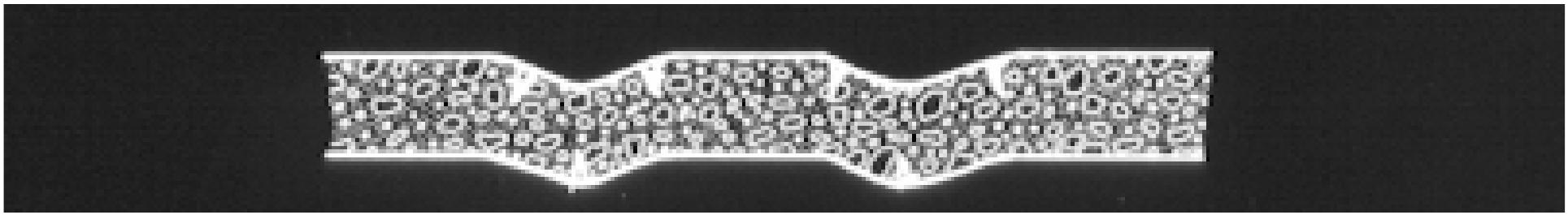
- Potential Primary Causes:
  - Plastic movement of HMA in hot weather
  - Inadequate compaction of HMA during construction
- Potential Secondary Causes:
  - Plastic movement in other layers
  - Inadequate compaction in other layers



Plastic movement - Depression in the Wheel Path with Humps in Either Side

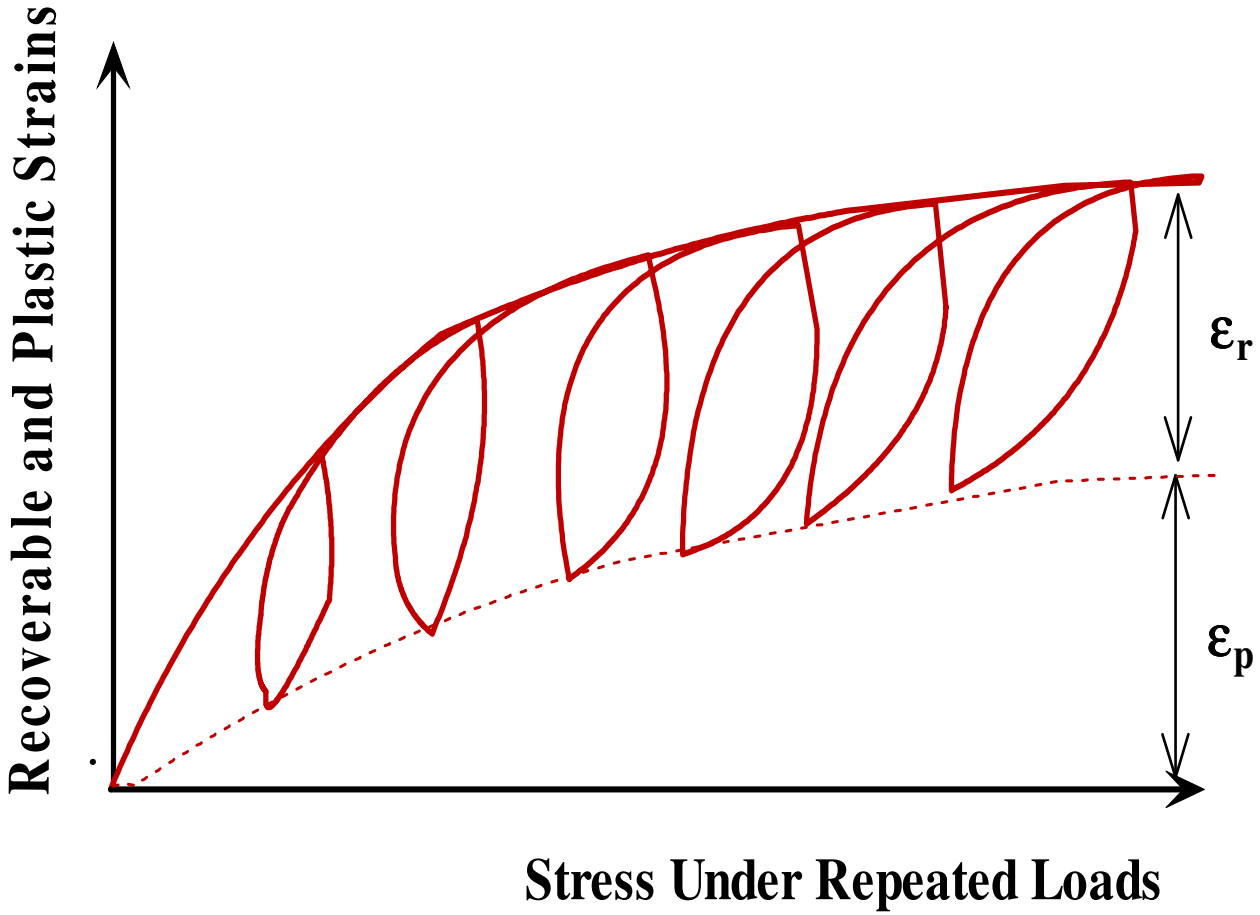


Consolidation/Densification -Depression in the Wheel Path Without Any Humps



Mechanical Deformation - Subsidence or Densification in the Unbound Base or Subgrade and Accompanied by a Cracking Pattern

Permanent or Plastic Deformations



Rutting Models

- **Subgrade compressive strain models:** determine the cover requirements to protect the subgrade or embankment soil.

- **Permanent deformation/strain models:** these models accumulate all permanent strain values to estimate the total rutting at the surface of the pavement structure.

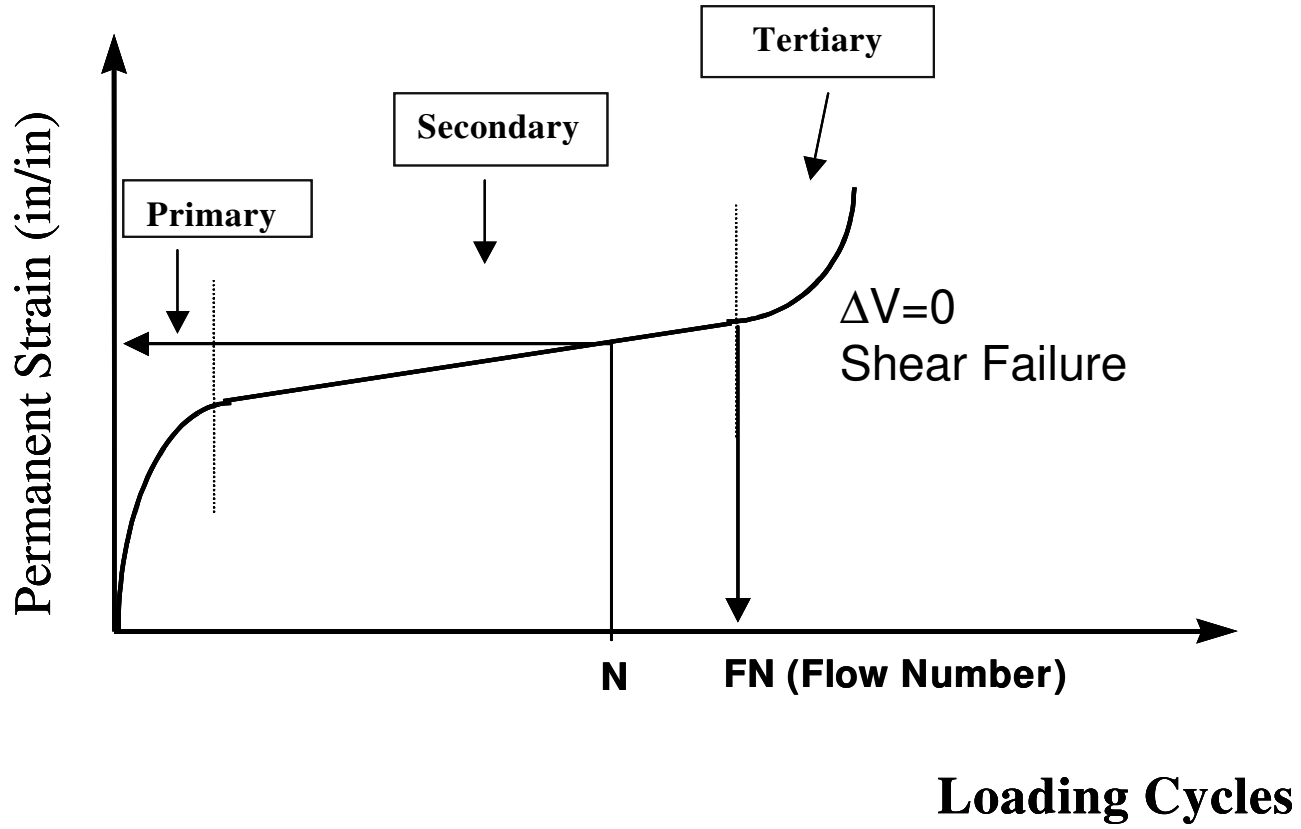
Subgrade Strain Models

$$N_f = f_1 \left(\varepsilon_V \right)^{-f_2}$$

- Austroad
- Asphalt Institute
- Shell
- Transport and Road Research Lab (TRRL)
- Belgian Road Research Center (BRRC)

Organization	f_1	f_2	Allowable Rut Depth, mm (in)
Asphalt Institute	1.365×10^{-9}	4.477	13 (0.5)
Shell (revised 1985)			
50% Reliability	6.15×10^{-7}	4	
85% Reliability	1.94×10^{-7}	4	13 (0.5)
95% Reliability	1.05×10^{-7}	4	
U.K. Transport and Road Research			
Laboratory C (85% Reliability)	6.18×10^{-8}	3.95	10 (0.4)
Belgian Road Research Center	3.05×10^{-9}	4.35	10 (0.4)
AUSTROADS (Old)	$1.66*10^{-15}$	7.14	?
AUSTROADS (New)	$6.017*10^{-15}$	7	?

Material Properties Dictate The Maximum Allowable Permanent Deformation

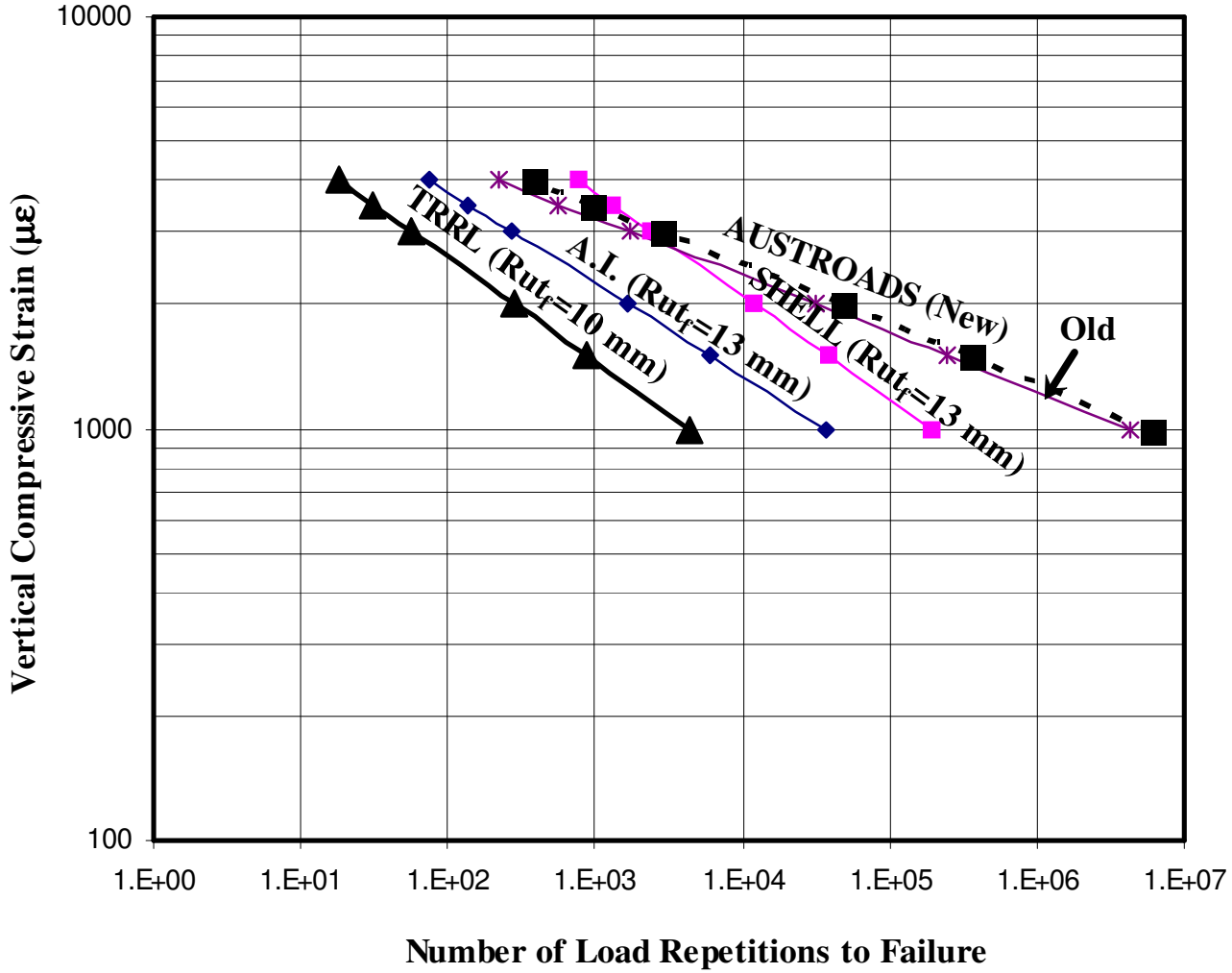


Austroad Rutting Model

$$N_f = \left(\frac{9300}{\mu\varepsilon} \right)^{7.0}$$

F1 =6.017*10-8, f2= -7

Comparison between different compressive strain models



Subgrade Strain Models

- Based on:
  - Specific design conditions
  - Material properties
  - Environmental conditions
- Limitations
  - Can't accurately be extended beyond inference space
  - Models suggest that allowable rut depth will not be exceeded if ε_v is limited
  - Assume that all permanent deformations occur in the subgrade.

Permanent Deformations in all Pavement Layers

$$F = a * S^{b} - p - p_{t} = 0$$

$$p = \frac{1}{3} * (\sigma_1 + \sigma_2 + \sigma_3)$$

$$S = \sigma_1 - \sigma_3$$

where:

a,b = material parameters that are independent of plastic deformation.

p_t= the hardening parameter that represents the hydrostatic tensile strength of the material.

σ_1, σ_2,and σ_3 = major, intermediate and minor principal stresses, respectively.

X-Section of FEM

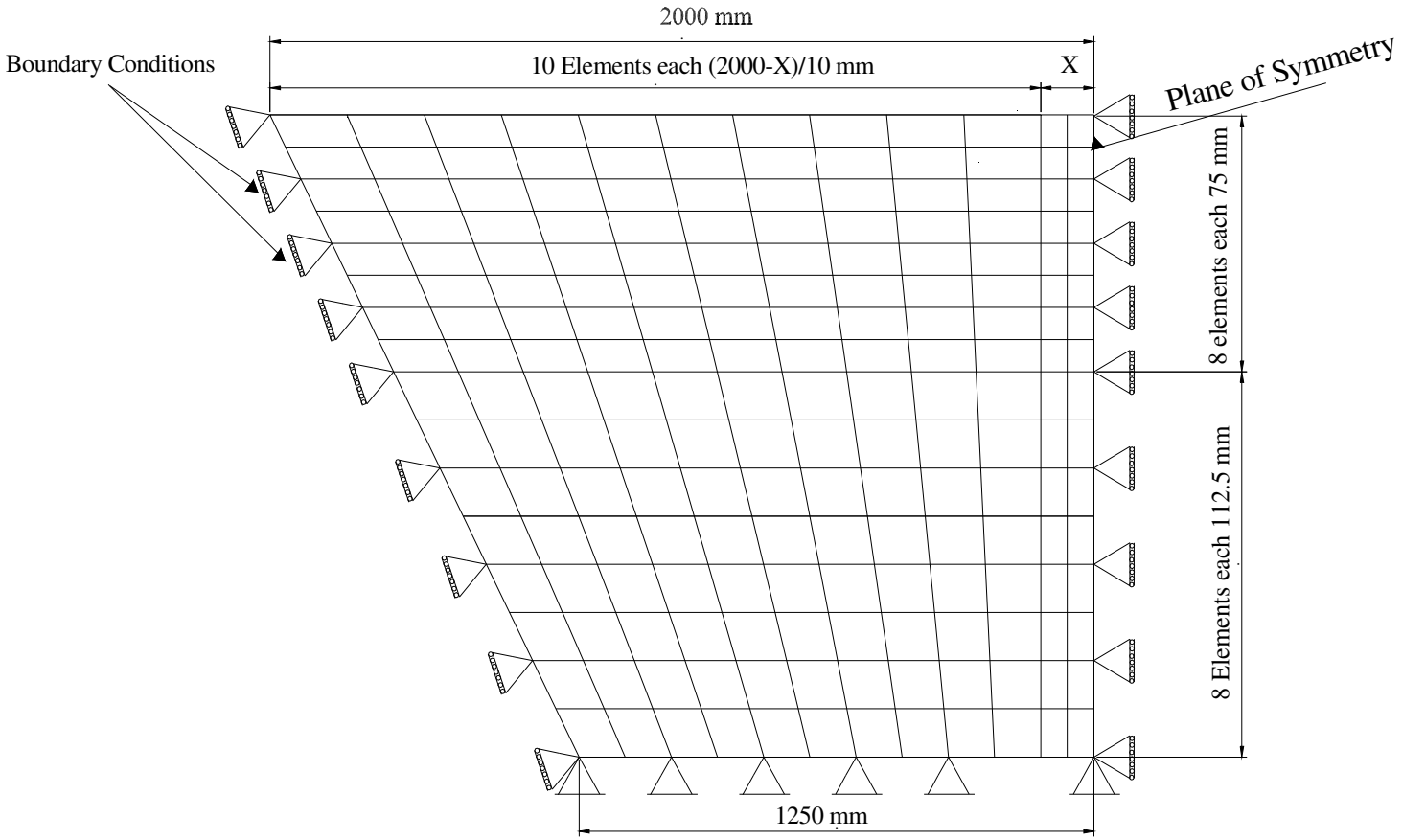


FIGURE 5 Cross Section of the Finite Element Model

Longitudinal Section in the FEM

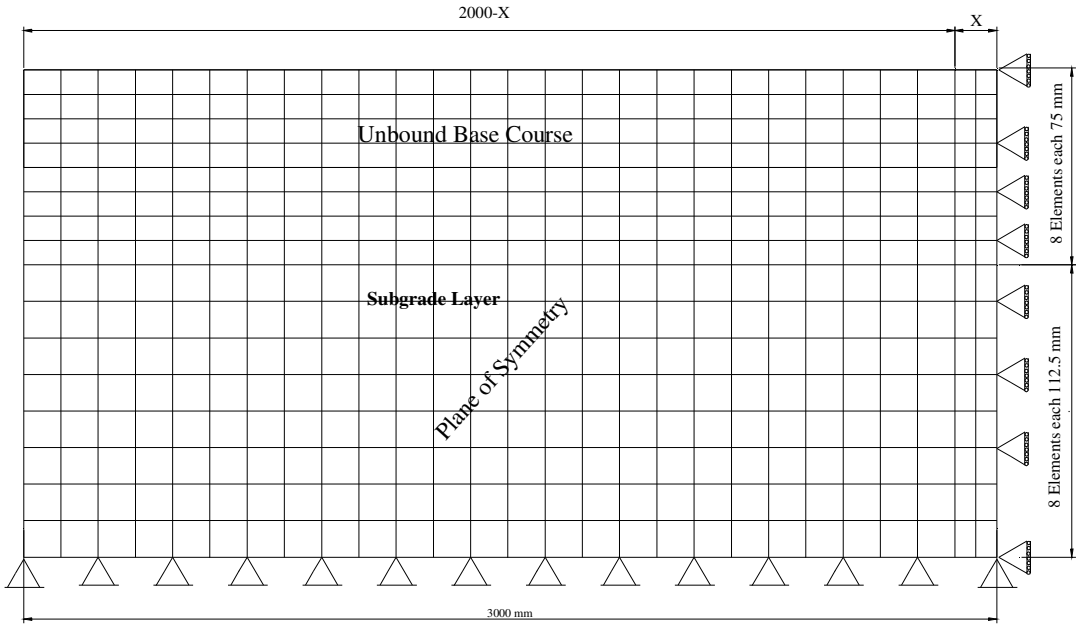
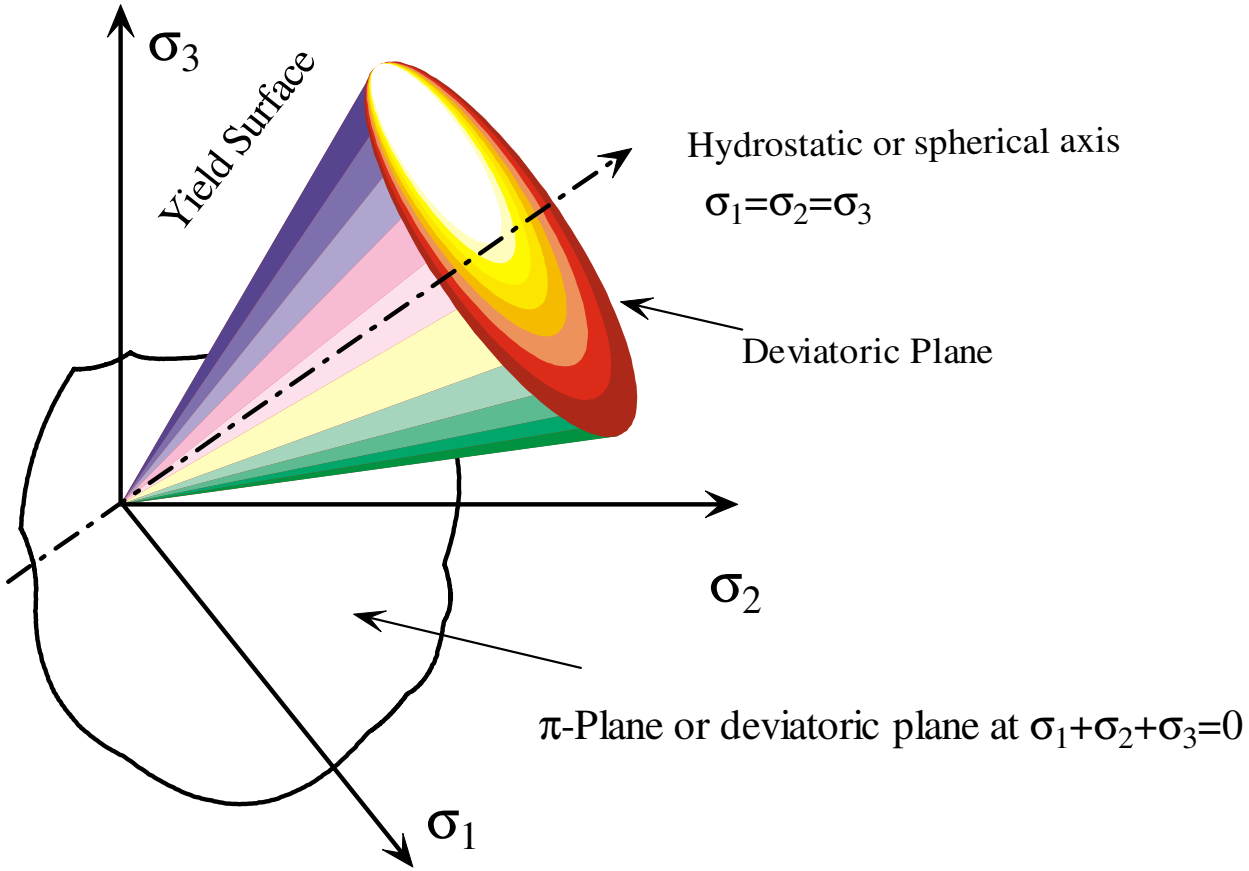
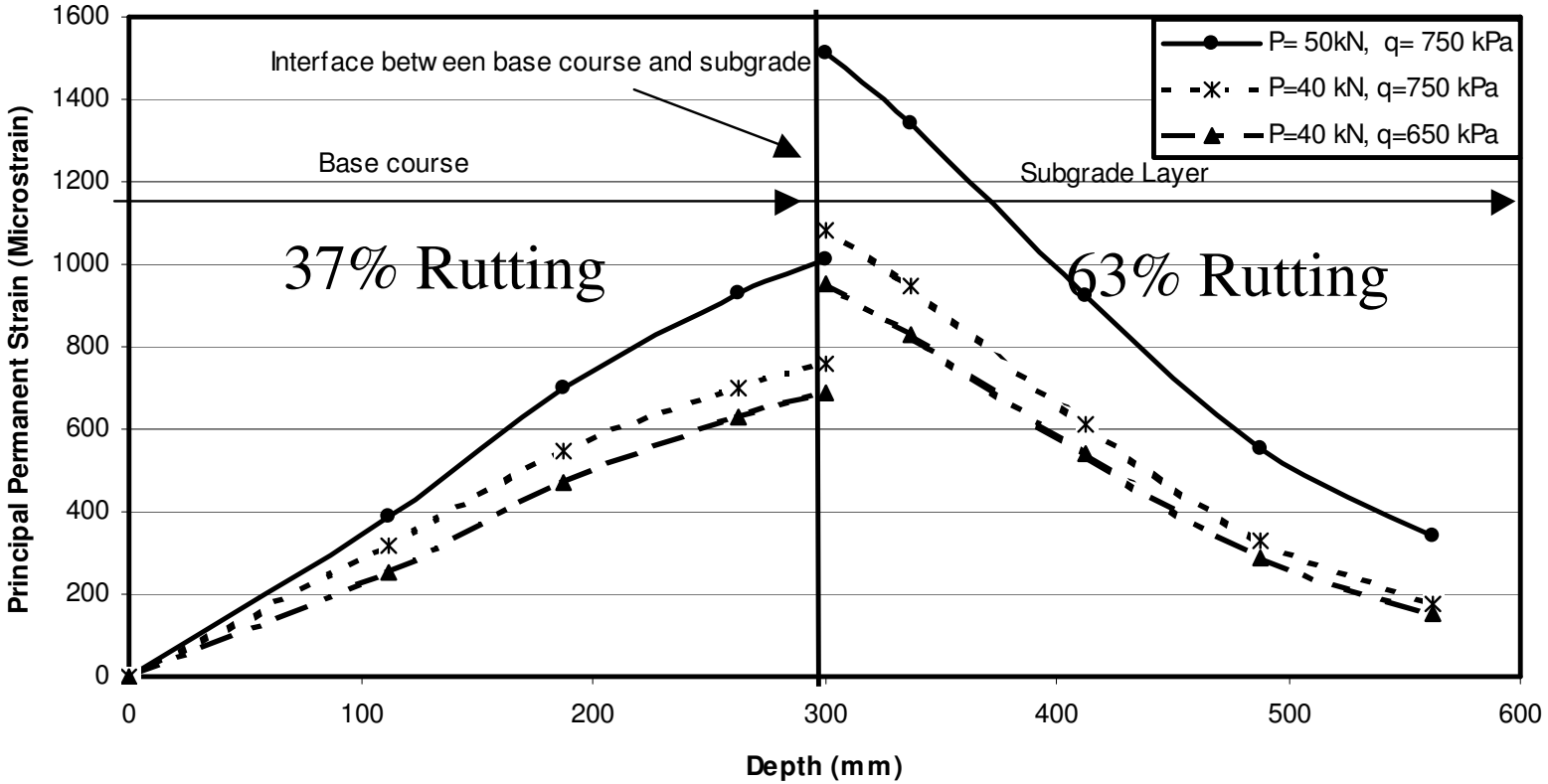


FIGURE 4 Elevation View of the Finite Element Model

Drucker-Prager Model



Permanent Vertical Strain& Rutting Calculations



Permanent Deformation Prediction Models

- Considers permanent deformation of each layer individually
- General form of models:

$$Log\varepsilon_p = a + b(LogN)$$

- Deformation (rutting) is calculated:

$$Total \quad Rutting = \sum_{i=1}^{n} (\varepsilon_p)_i * h_i$$

Ohio State Model

- Permanent Strain Accumulation Model (rutting rate)

$$\frac{\varepsilon_p}{N} = A\,(N)^{-m}$$

- "A" and "m" are constants based on material type and stress state

Typical values of A and m in the Ohio State model (Barenberg and Thompson, 1990).

Moisture	Unconfined Strength, kPa (psi)	Repeated Deviator Stress, kPa (psi)	m	A x 10^{-4}
Optimum	159 (23)	34 (5)	0.86	12.4
		69 (10)	0.86	18.2
		103 (15)	0.86	43.7
Optimum + 4%	90 (13)	34 (5)	0.83	17.0
		69 (10)	0.83	42.5
		103 (15)	0.83	138.0

Asphalt Institute Model

$$Log(\varepsilon_p) = -14.97 + 0.408 * Log(N) + 6.865 * Log(T)$$
$$+1.107 * Log(\sigma_d) - 0.117 * Log(V) + 1.908 * Log(P_{be})$$
$$+0.971 * Log(Vv)$$

ε_p	=	Permanent strain (axial).
N	=	Number of load repetitions to failure.
T	=	Temperature, oF.
σ_d	=	Deviator stress, psi.
V	=	Viscosity at 21 ^oC (70^{o}F), Ps x 10^6.
Pbe	=	Percent by volume of effective bitument.
Vv	=	Percent volume of air voids.

Kaloush-Witczak Model

$$Log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = -3.74938 + 2.02755\left(LogT\right)$$

$$+ 0.4262\left(LogN\right)$$

Allen and Dean Model

$$Log\varepsilon_p = C_o + C_1[Log(N)] + C_2[Log(N)]^2 + C_3[Log(N)]^3$$

εp	=	Permanent strain (axial).
N	=	Number of stress or wheel load repetitions.
C0-3	=	Regression coefficients that are factors of the temperature and the deviator stress, as shown in Table below.

Coefficient	HMA	Dense-Graded Aggregate Base	Subgrade
C_o	$- 0.000663\ T^2 + 0.1521\ T - 13.304 + (1.46 - 0.00572\ T) * \log \sigma_1$	$- 4.41 + (0.173 + 0.003\ w) * \sigma_1 - (0.00075 + 0.0029\ w) * \sigma_3$	$- 6.5 + 0.38w - 1.1 (\log \sigma_3) + 1.86 (\log \sigma_1)$
C_1	0.63974	0.72	$10^{(-1.1 + 0.1\ w)}$
C_2	- 0.10392	$- 0.142 + 0.092 (\log w)$	$0.018\ w$
C_3	0.00938	$0.0066 - 0.004 (\log w)$.	$0.007 - 0.001\ w$

where,

T	=	Temperature, °F.
σ_1	=	Deviator stress, lbf/in2.
w	=	Moisture content, percent.
σ_1	=	Deviator stress, lbf/in2.
σ_3	=	Confining pressure, lbf/in2

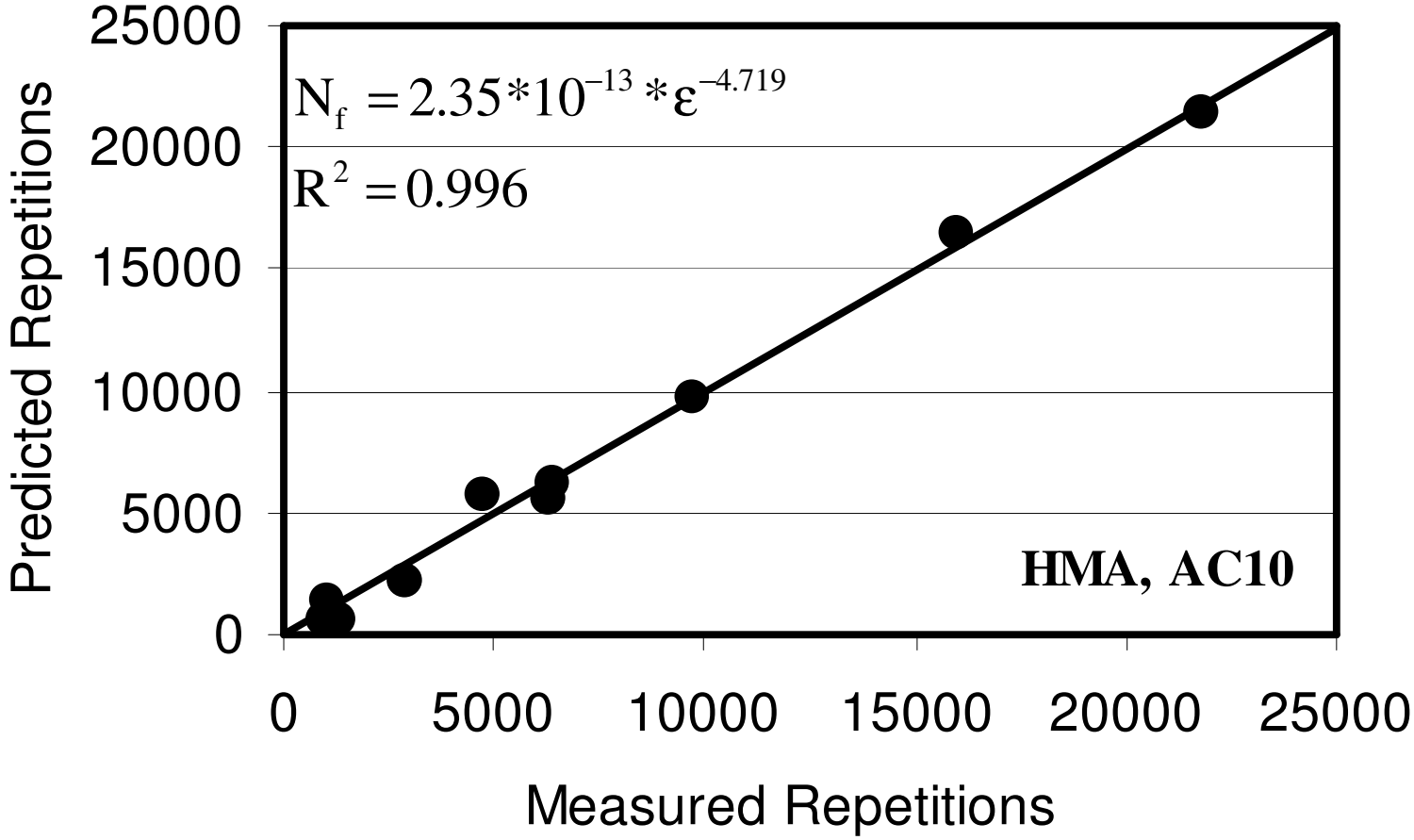
Fatigue Criteria

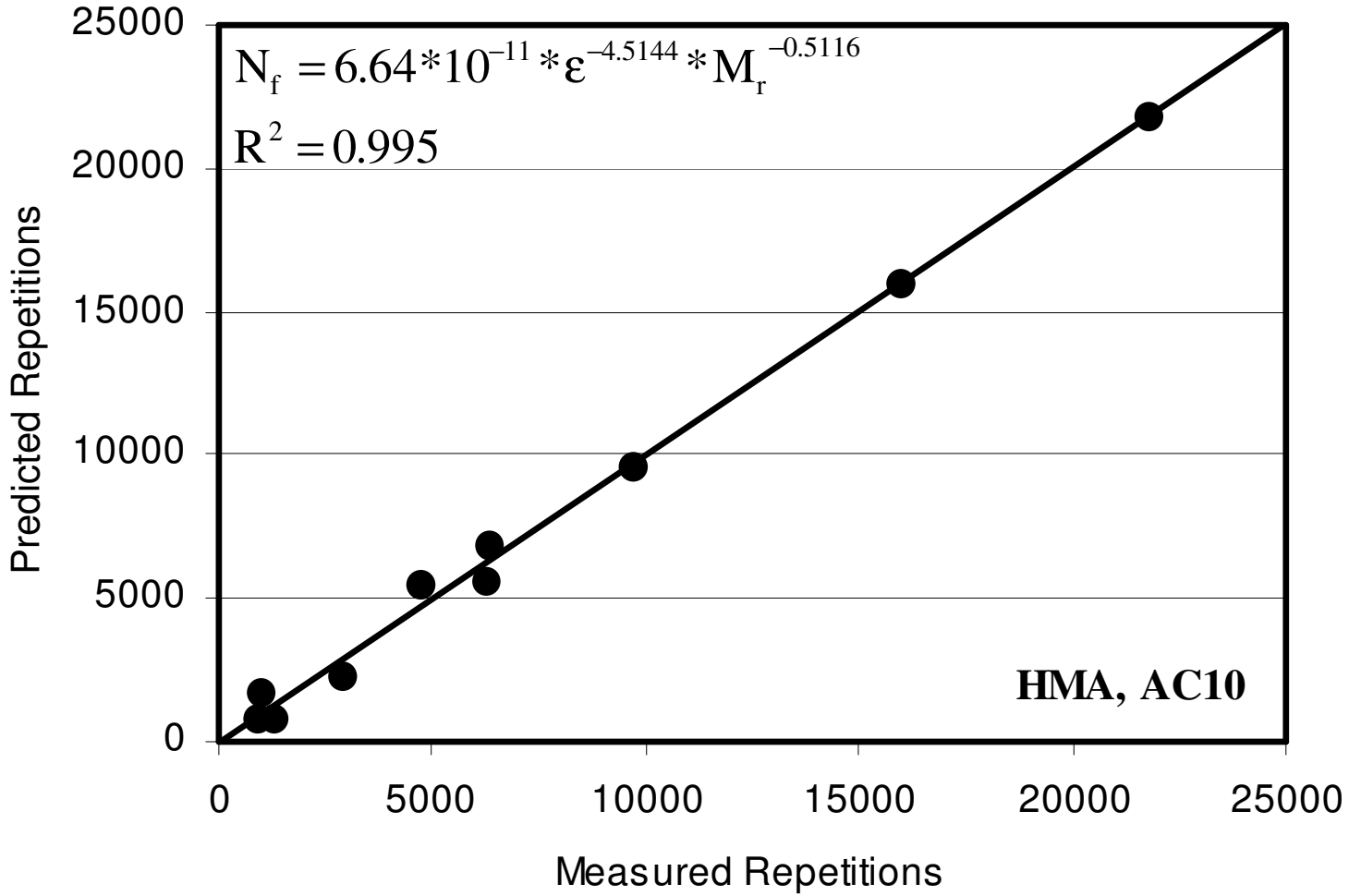
$$N_f = K_1 \left(\varepsilon_t\right)^{K_2} \left(E\right)^{K_3}$$

University of Canterbury Fatigue Models for AC-10

$$N_f = 2.35 * 10^{-13} * \varepsilon^{-4.719} \qquad R^2 = 0.996$$

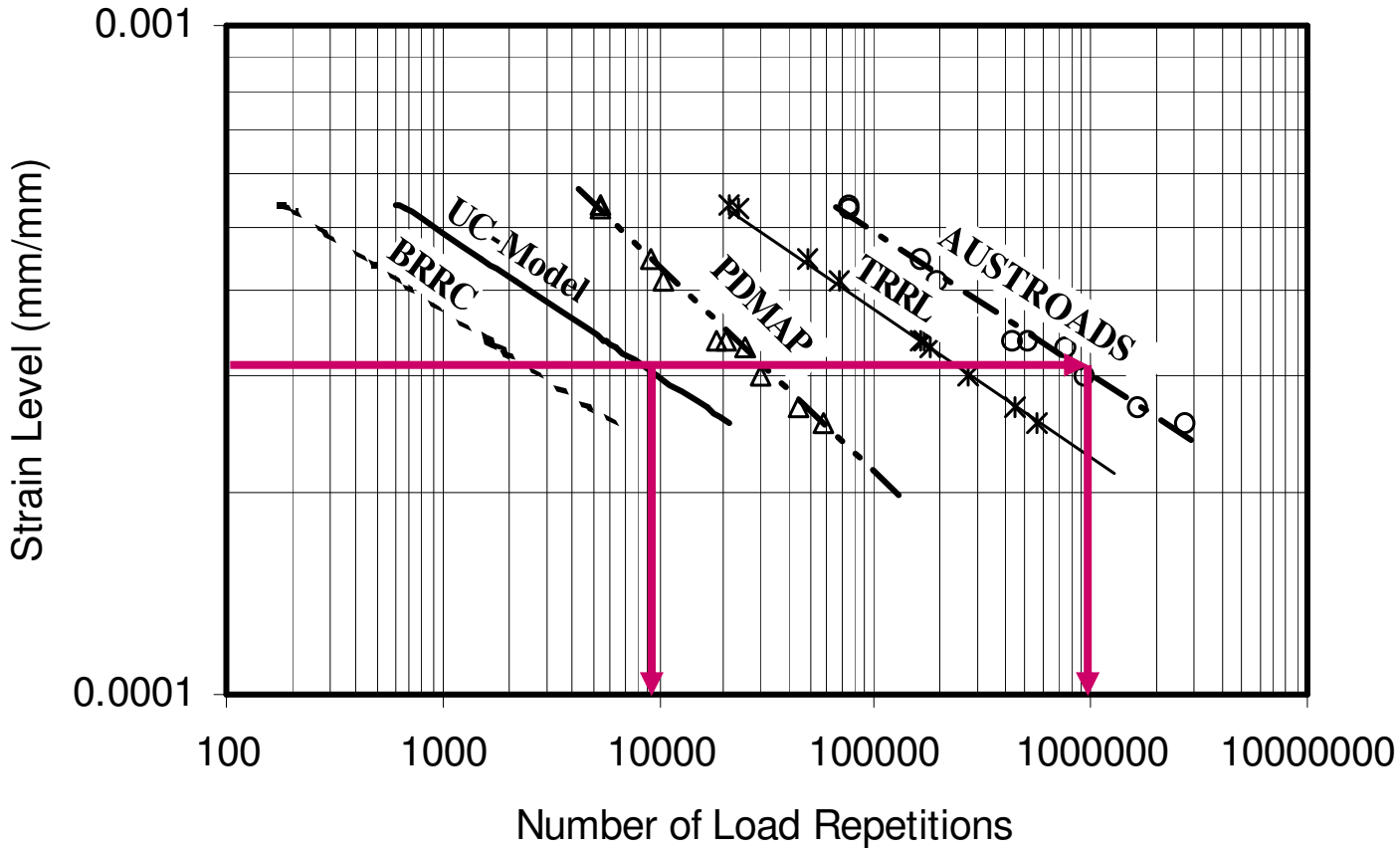
$$N_f = 6.64 * 10^{-11} * \varepsilon^{-4.514} * M_r{}^{-0.5116} \qquad R^2 = 0.995$$


$N_f = 2.35*10^{-13}*\varepsilon^{-4.719}$
$R^2 = 0.996$
HMA, AC10
Predicted Repetitions
Measured Repetitions
0
5000
10000
15000
20000
25000


$N_f = 6.64*10^{-11}*\varepsilon^{-4.5144}*M_r^{-0.5116}$
$R^2 = 0.995$
HMA, AC10
Predicted Repetitions
Measured Repetitions
0
5000
10000
15000
20000
25000

Fatigue Equation	Response Parameter	Fatigue Constants			Other Parameters in Equation	Definition of Failure, % Cracking
		Coefficient, K_1	Response Exponent, K_2	HMA Modulus Exponent, K_3		
Asphalt Institute	$\varepsilon_{\square}$	0.0796	-3.291	-0.854	Dynamic Modulus Percent Air Voids Percent Asphalt by Volume	50
Shell	$\varepsilon_{\square}$	0.0685	-5.671	-2.363	Dynamic Modulus	20
PDMAP	$\varepsilon_{\square}$	6.601×10^{14}	-3.291	-0.854	Flexure Modulus	Lab, Crack Initiation
	$\varepsilon_{\square}$	8.851×10^{15}	-3.291	-0.854	Flexure Modulus	10
	$\varepsilon_{\square}$	1.219×10^{16}	-3.291	-0.854	Flexure Modulus	45
TRRL	$\varepsilon_{\square}$	1.66×10^{-10}	-4.32	0		---
Belgian	$\varepsilon_{\square}$	4.92×10^{-14}	-4.76	0		---
Ontario	$\varepsilon_{\square}$	8.86×10^{-14}	-5.12	0	Dynamic Modulus	20
Canterbury	$\varepsilon_{\square}$	2.35*10-13	-4.719	0		Lab Model
	$\varepsilon_{\square}$	6.64*10-11	-4.5144	-0.5116	Resilient Modulus	Lab Model

Fatigue Criteria



Factors to be considered

- Definitions of Failure (10%, 20% or 50%)
- Developing a set of models relevant to the different mix (AC-10, AC-14, or AC-20)
- and bitumen types (conventional bitumen versus polymer modified bitumen)