

Perpetual Pavements

Dr. David Timm, PE



What is a Perpetual Pavement?

- 35+ Years of Service
- Minimal structural improvements
- No deep structural distresses
 - Only surface remedies needed



Perpetual Pavements in the U.S.



<http://www.asphaltmagazine.com/dotAsset/4af55c62-42dd-4bbe-a6cc-8f647455eb22.jpg>



Goal of Perpetual Pavement Design

- Design against deep structural distresses
Bottom up fatigue cracking

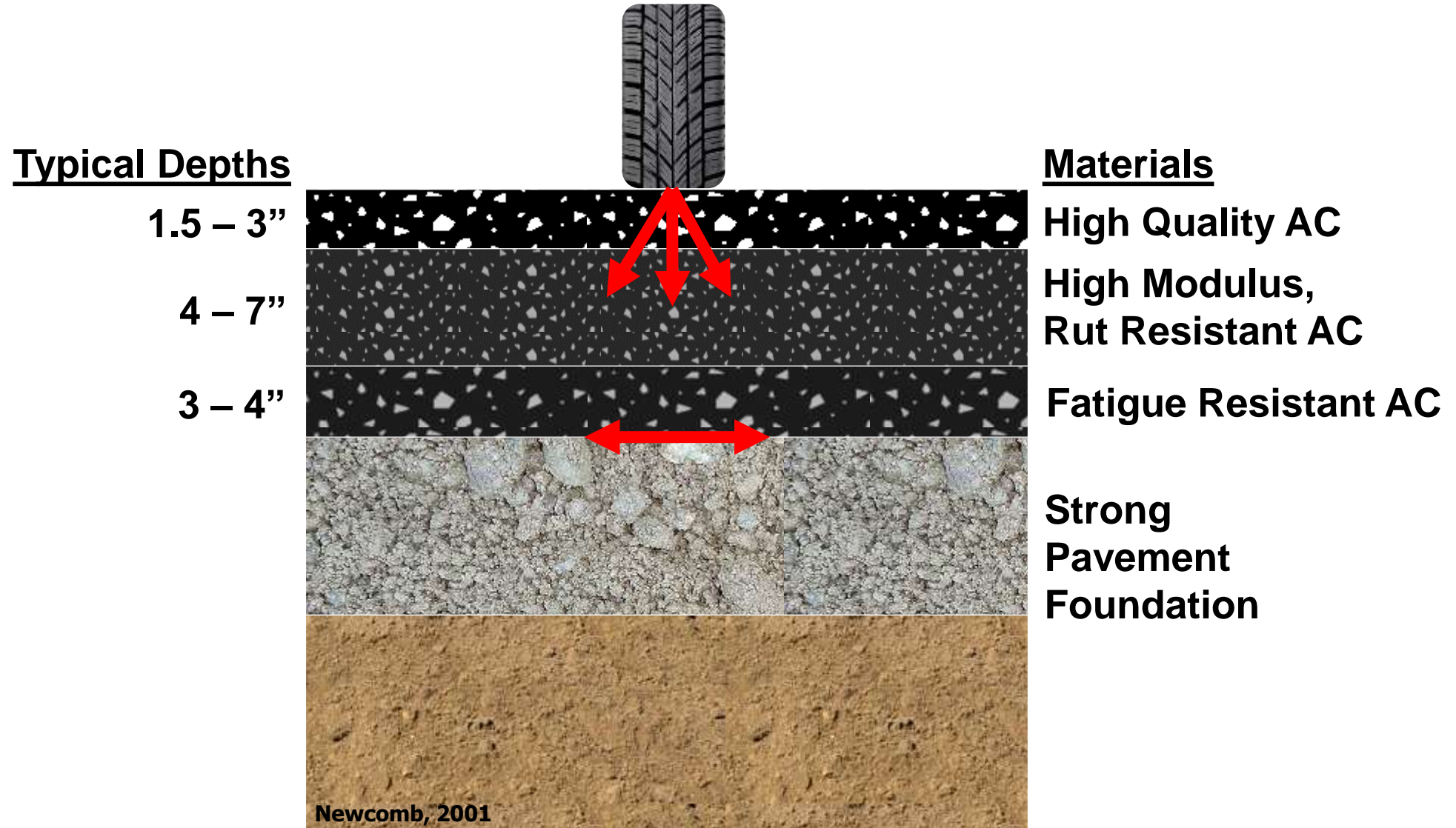


Structural Rutting

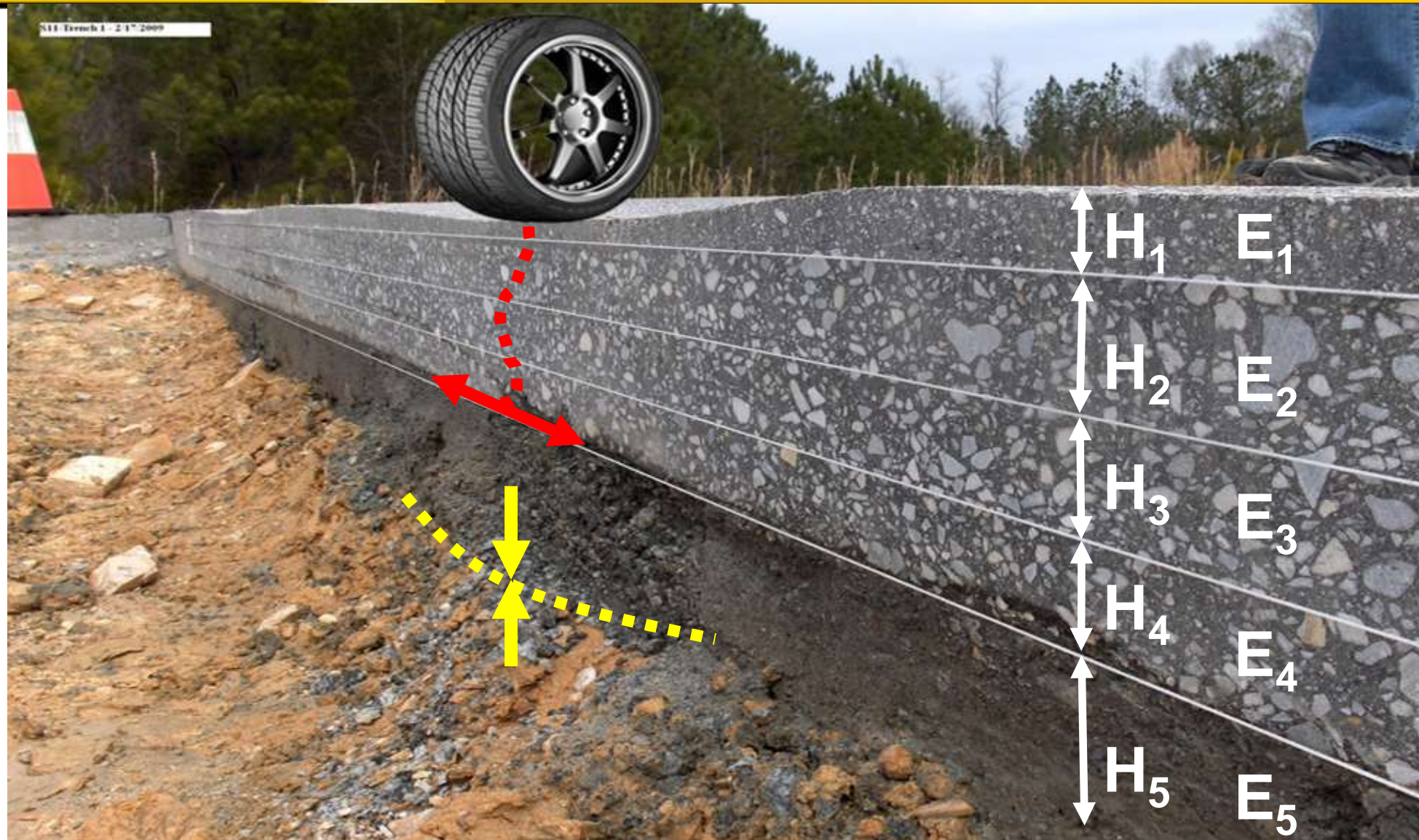


Results in a structure with Perpetual or Long-Life

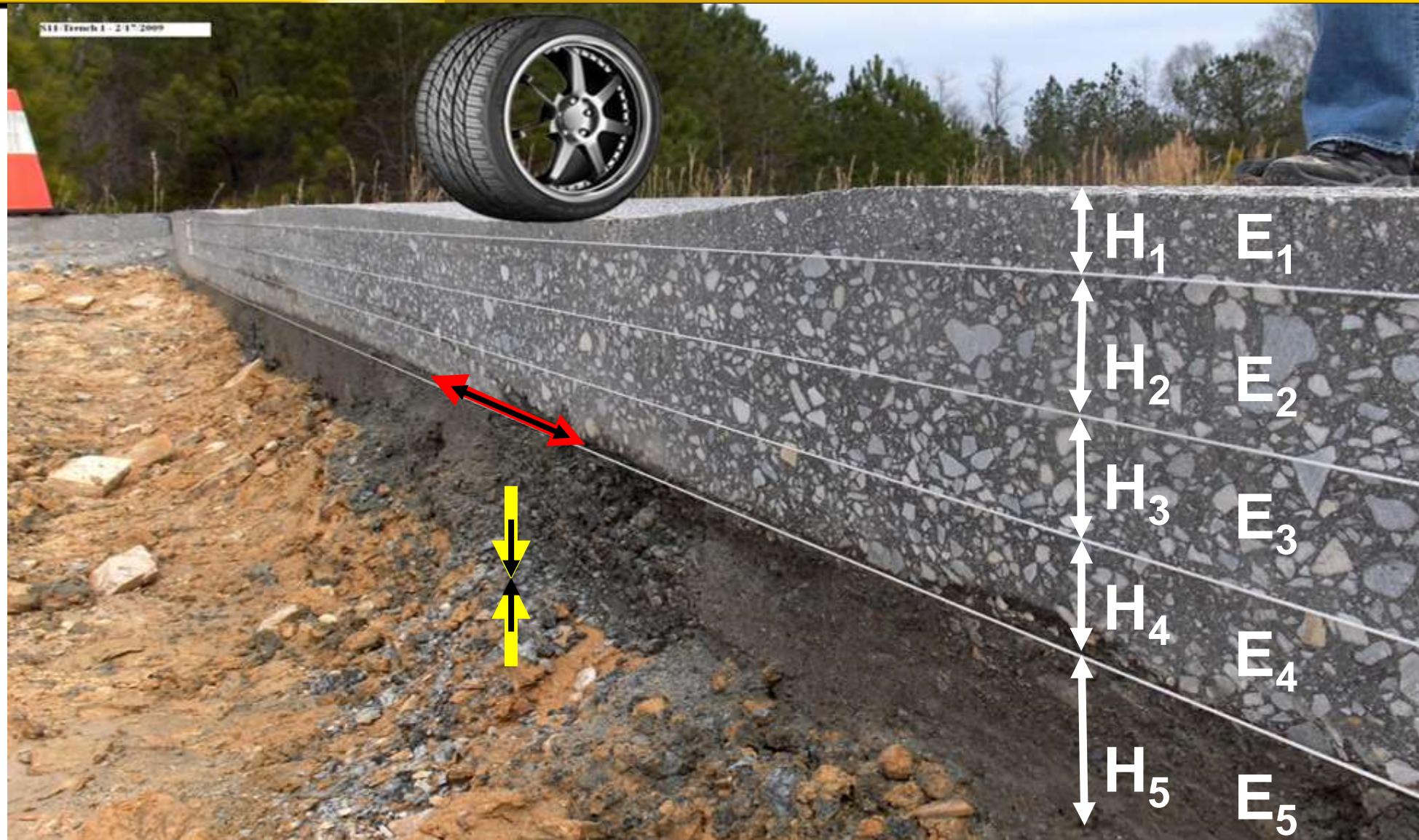
Perpetual Pavement Cross-Section



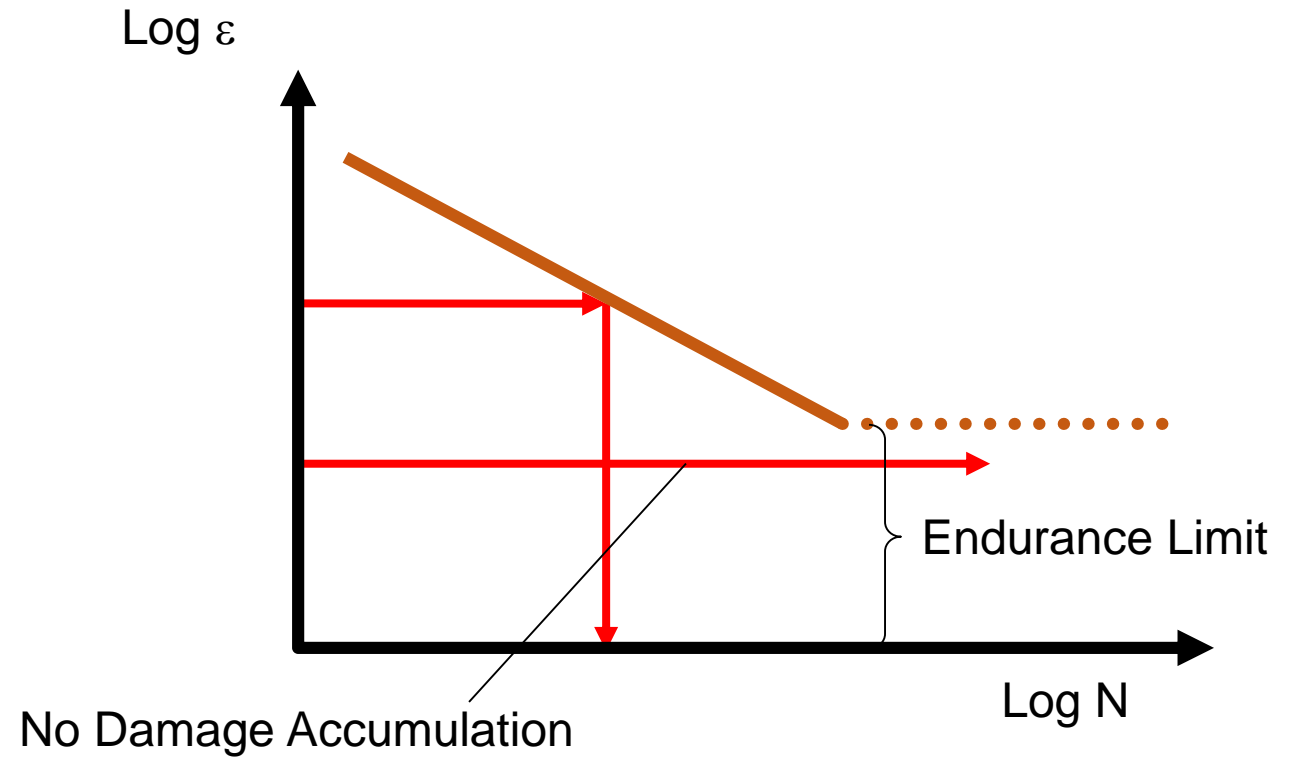
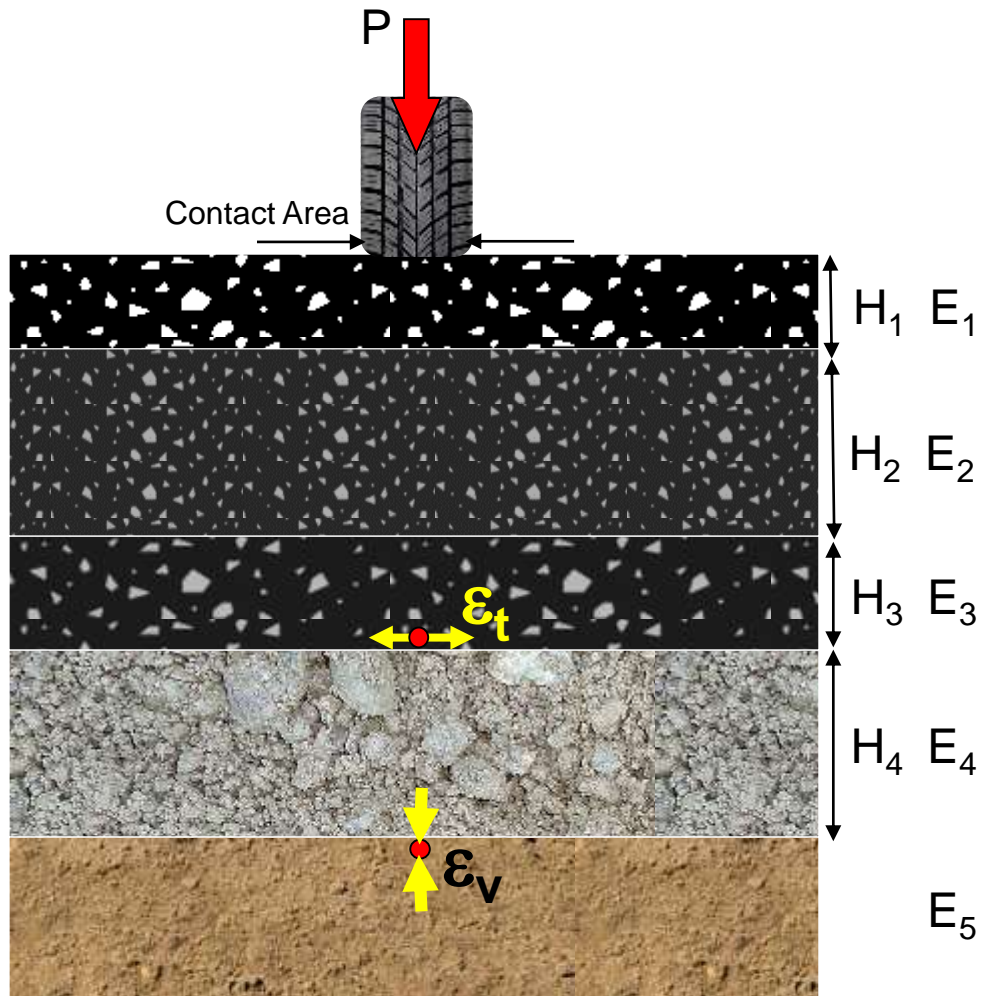
Mechanistic-Empirical Pavement Design



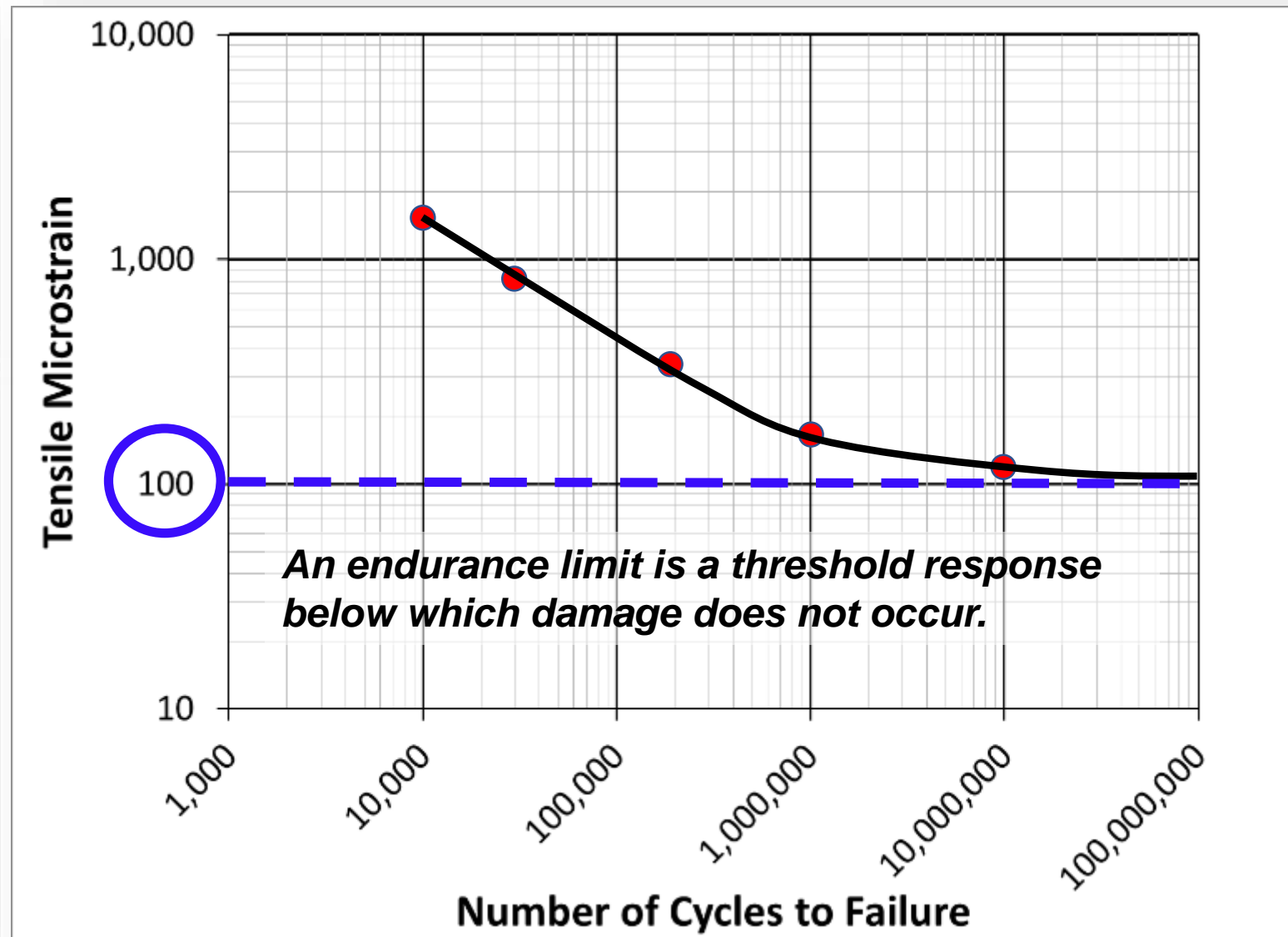
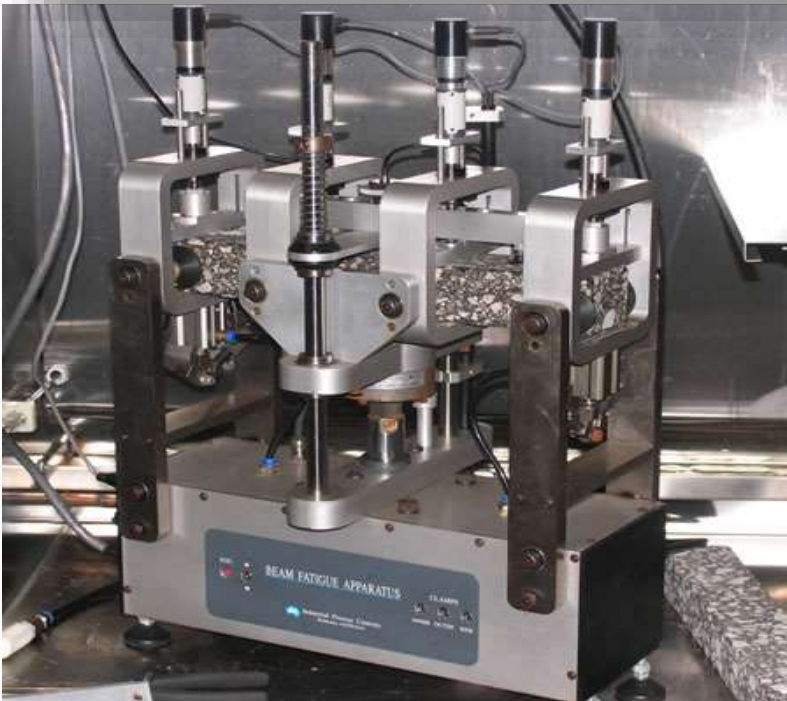
Mechanistic-Empirical **Perpetual** Pavement Design



Mechanistic-Empirical **Perpetual** Pavement Design



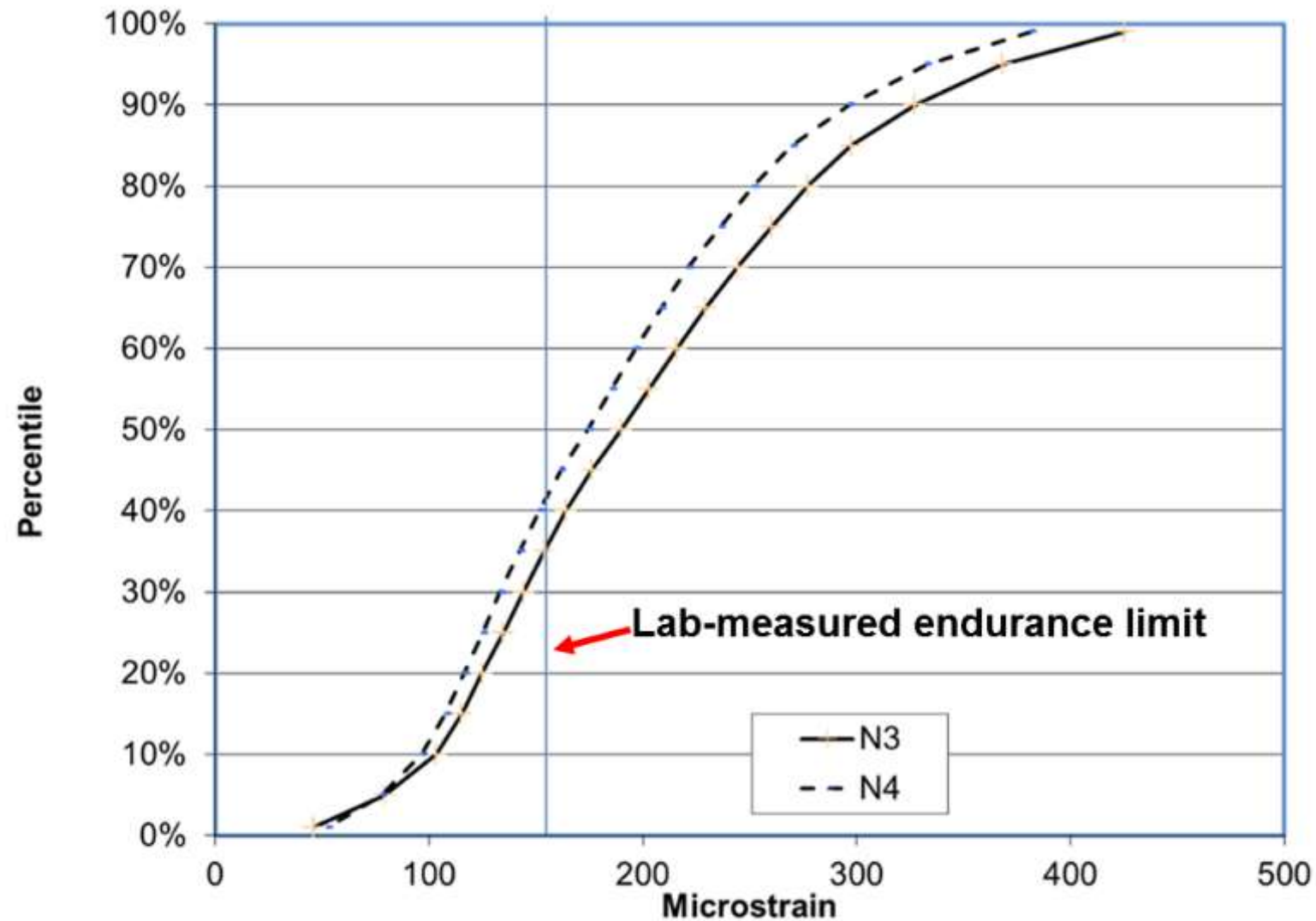
What is the **Endurance Limit** for AC?



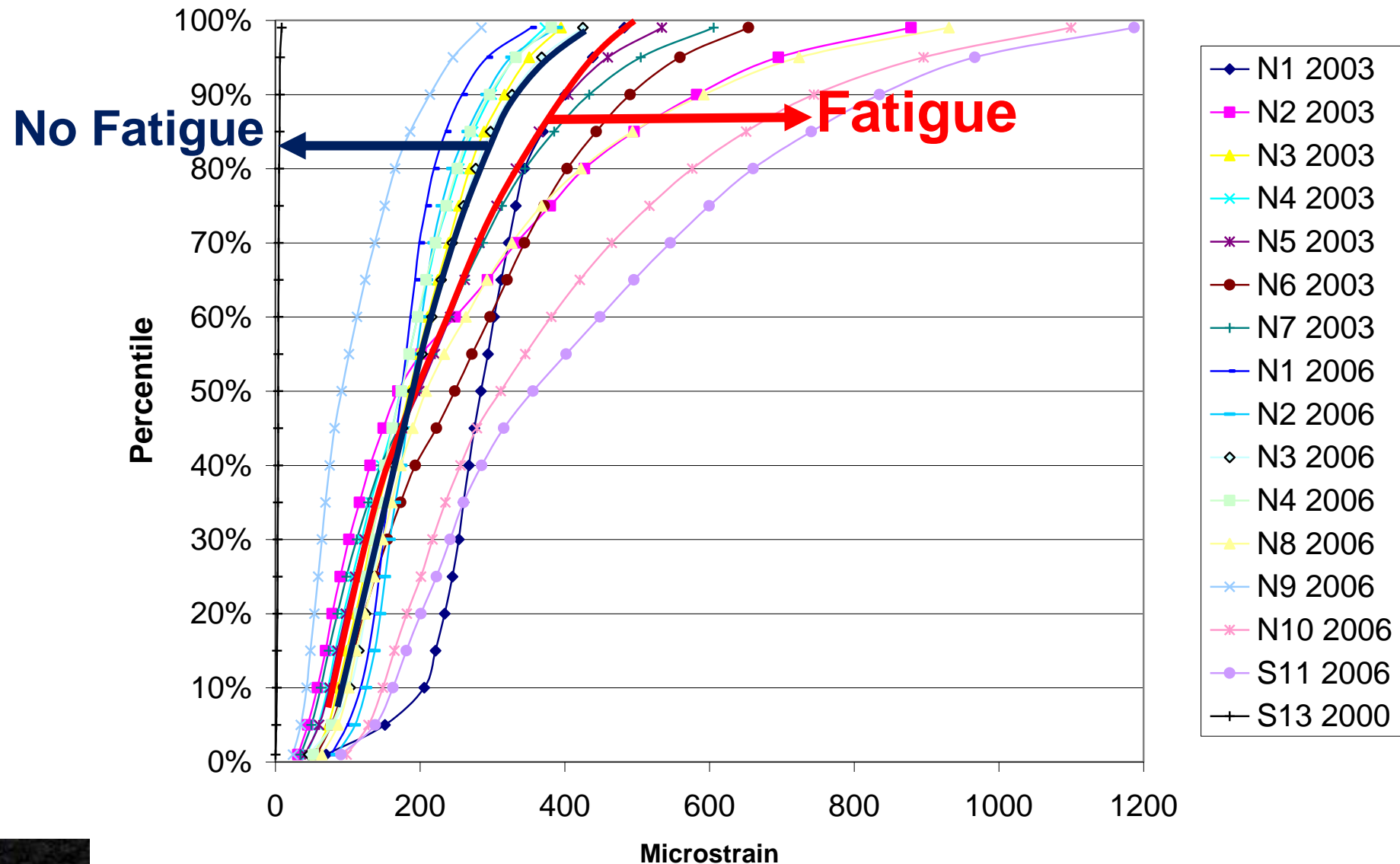
History of Endurance Limits

- 1972 – Monismith estimates about 70 $\mu\epsilon$
- 2001 – I-710 designed at 70 $\mu\epsilon$
- 2002 – 70 $\mu\epsilon$ used by APA
- 2007 – NCHRP 9-38 Lab Study
 - 100 $\mu\epsilon$ for unmodified binders
 - 250 $\mu\epsilon$ for modified binders
 - Lab conditions more severe than field
- 2007 – MEPDG uses 100 to 250 $\mu\epsilon$
- 2008 – Measurements at NCAT Test Track show strains in perpetual pavements well exceeding laboratory values

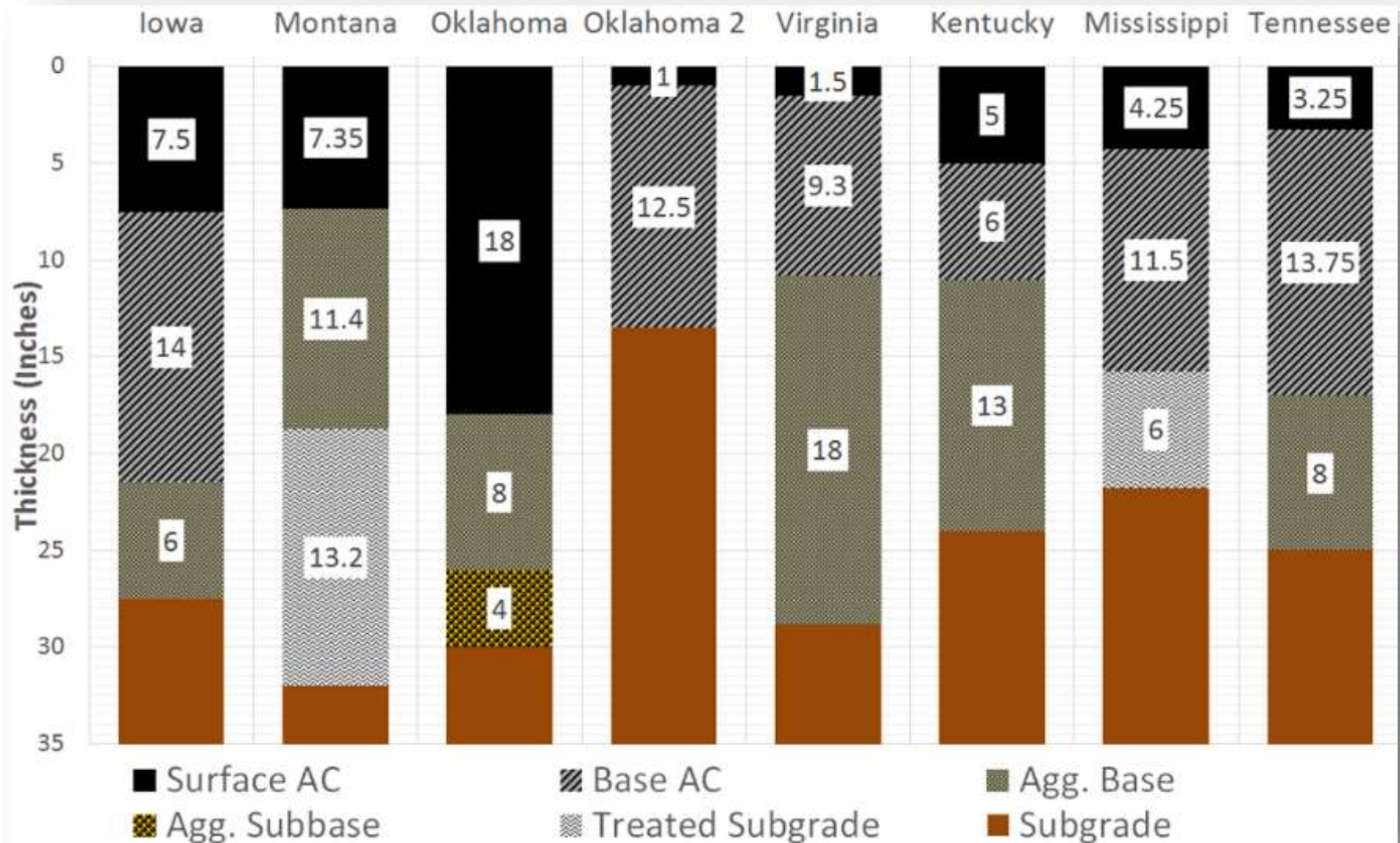
Measured Horizontal Strains and Endurance Limits



Horizontal Strain Distributions at NCAT Test Track



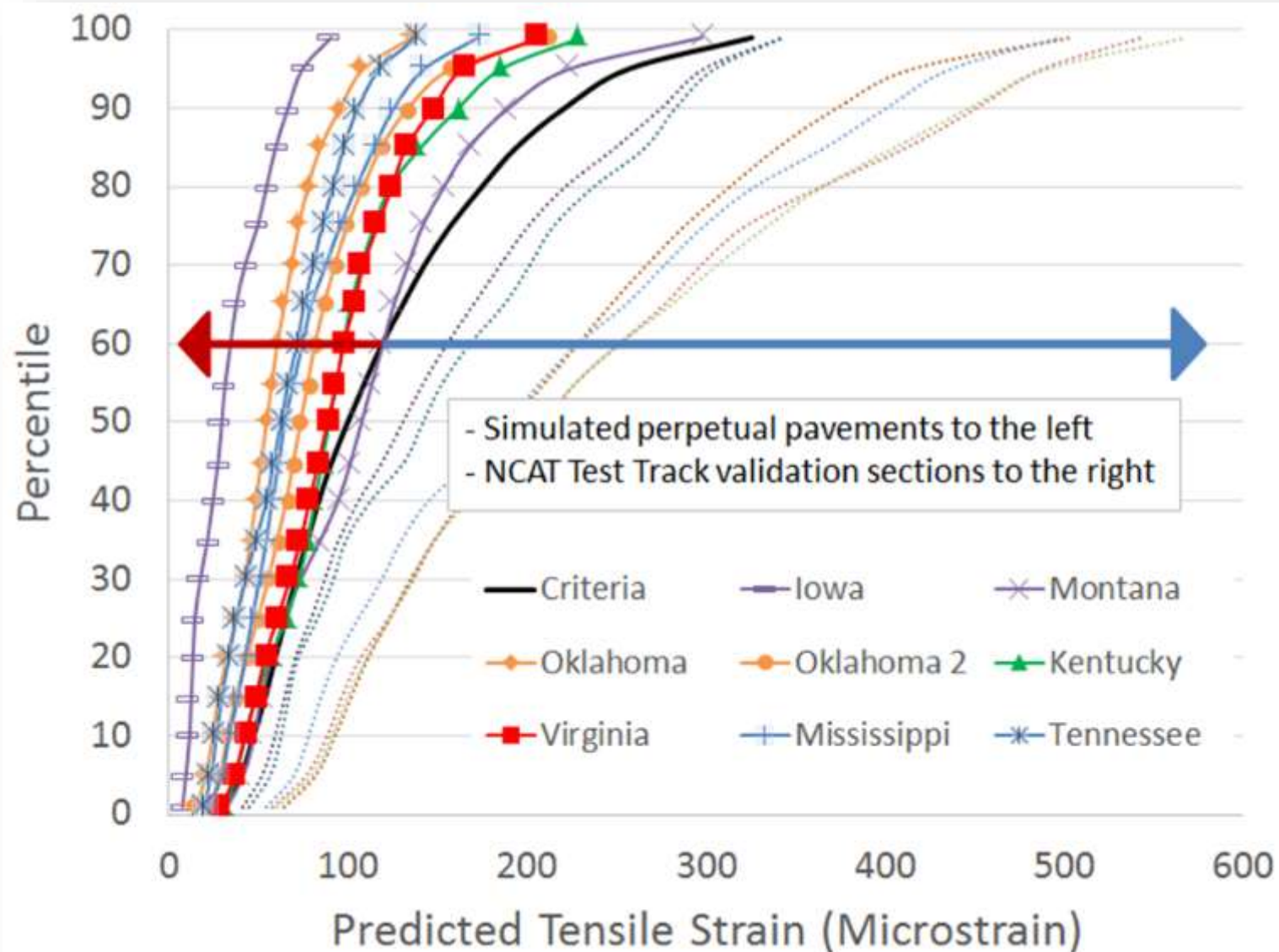
Evaluation of Perpetual Pavement Winners



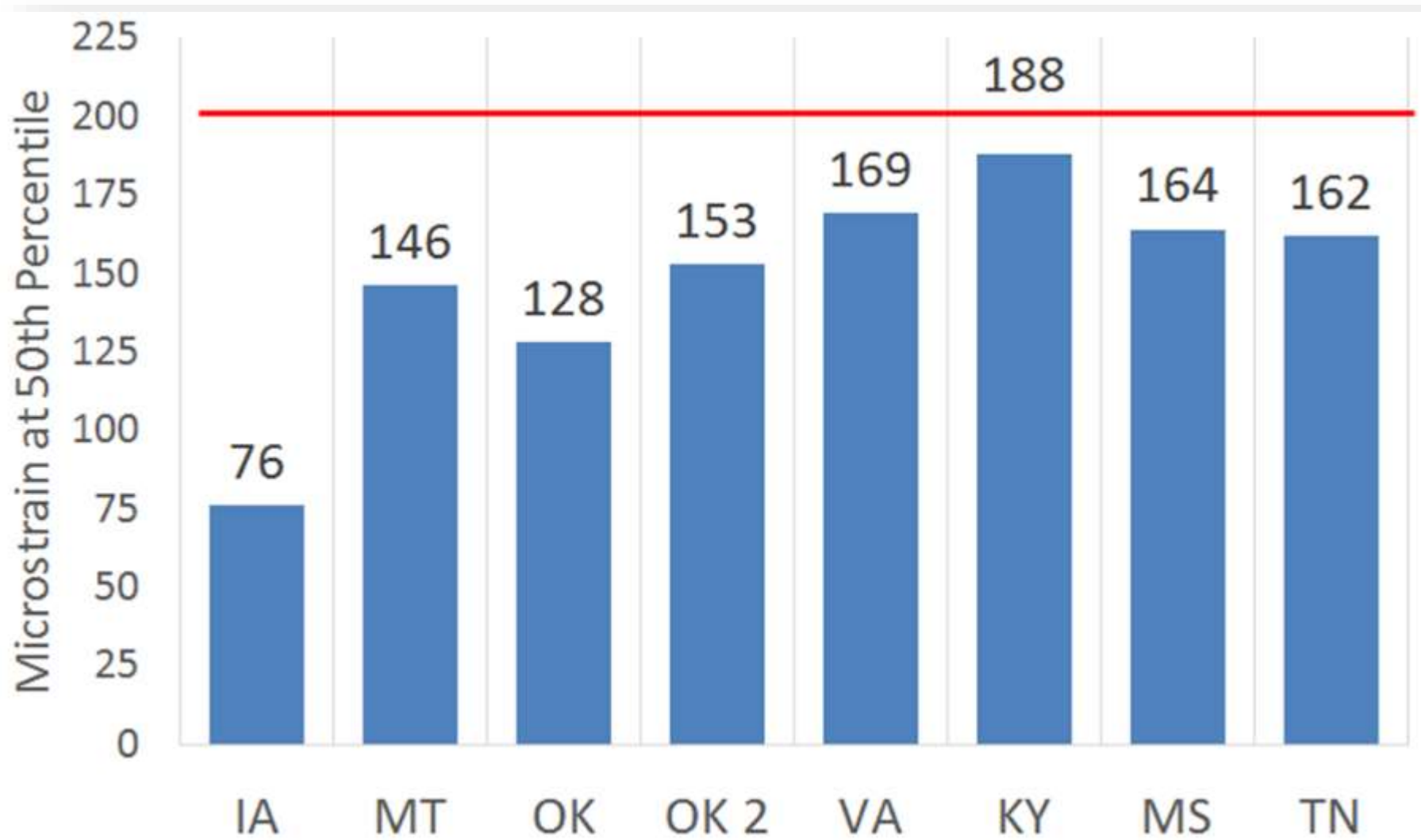
Award Winner Metrics

State	Project	Year Honored	Service Years (Time of award)	Cumulative Traffic (Time of award)
Iowa	I-80, MP 225.9 to 239.9	2002	38	32,000,000 ESAL
Montana	I-90 MP 439.33 to 445.4	2005	44	15,000,000 ESAL
Oklahoma	I-35, MP 185.6 to 192.6	2003	40	61,000,000 ESAL
Oklahoma	I-40, MP 160.2 to 165.5	2002	40	60,000,000 ESAL
Virginia	I-81, MP 318.4 to 324.9	2006	41	29,000,000 ESAL
Kentucky	I-65, Hart County	2009	44	76,000,000 ESAL
Mississippi	I-22, Desoto County	2007	39	60,000,000 ESAL
Tennessee	I-65, MP 22.4 to 32.56	2002	35	25,800,000 ESAL

Horizontal Strain Distribution – Simulation Results



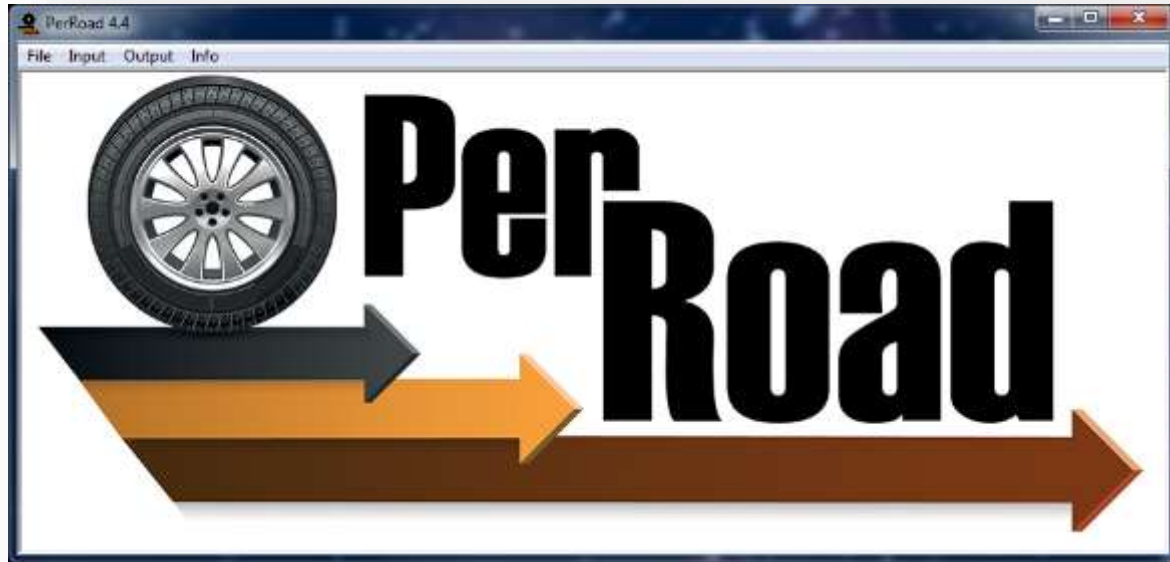
Award Winners – Vertical Strain Rutting Criteria



Need & Justification for Distribution-Based Design

- Pavements experience range of loading and environmental conditions
 - Results in wide range of strain responses
- Traditional M-E design uses transfer functions and sums damage vs. time
 - Fatigue transfer functions difficult to develop and may not be accurate
 - Transfer functions not needed with perpetual pavement design
- Designing with a strain distribution will limit fatigue cracking and avoid transfer functions
 - Also arrive at reasonable perpetual (maximum) pavement thicknesses
- Data from NCAT Test Track and validated with Perpetual Pavement Award Winners supports this approach
 - Horizontal tensile strain distribution for fatigue cracking
 - 200 $\mu\epsilon$ compressive strain at the 50th percentile for rutting

Perpetual Pavement Design Tools



<https://goo.gl/i3FMej>

<http://www.asphaltroads.org/perpetual-pavement/about-perpetual-pavements/>

The image shows the PerRoadXPress software interface. It is a form-based application for calculating pavement thickness. The interface includes the following fields and values:

- Functional Classification: Urban Collector (dropdown menu)
- Two-Way AADT: 1000 (range: 500 to 5000)
- %Trucks: 1 (range: 1 to 20)
- %Growth: 1 (range: 0 to 3)
- Design Trucks: 63482 (Total Trucks in 30 Years)
- Design ESALs: 18917 (Total ESALs in 30 Years)
- AASHTO Soil Classification: A-1-a (dropdown menu)
- Soil Modulus: 29500 (range: 10,000 to 30,000 psi)
- Aggregate Base Thickness: 4 (range: 0 to 10 in.)
- HMA Modulus: 800000 (range: 400,000 to 1,000,000 psi)

A "CALCULATE" button is located below the HMA Modulus field. Below the calculation fields, there are labels for "Calculated HMA" and "Design HMA" in inches, with a note that the calculated thickness is rounded up to the nearest 0.25". At the bottom, there are "Exit" and "Help" buttons.

Key Features of PerRoad 4.4

- Layered elastic analysis
- Up to 5 pavement layers
- User enters design criteria
 - Strain distributions
 - Single strain values and control percentiles
 - Conventional M-E criteria with transfer functions
- Many built-in default parameters
 - Material properties and variability
 - Traffic and load distributions
- Program uses Monte Carlo simulation to simulate uncertainty in design

Design Example with PerRoad 4.4

- Interstate pavement
- 4 layer structure
 - 76-22 AC
 - 64-22 AC
 - Granular Base
 - Subgrade Soil
- Moderate Climate



http://www.flexiblepavements.org/sites/www.flexiblepavements.org/files/imagecache/awards_interior/awards/project_16-_interstate_271_kokosing.jpg

Structural Inputs

3" 76-22

AC

AC

Cracked AC

PCC

Rubb PCC

C and S PCC

B and S PCC

Gran Base

Soil

Rock

Other

Structural and Seasonal Information (F1 for Help)

of Layers: ☐ 2 ☐ 3 ☒ 4 ☐ 5

Seasonal Information

Season: ☒ Summer ☐ Fall ☐ Winter ☐ Spring ☐ Spring2 Current Season: Summer

Duration (weeks): Summer: 52, Fall: 0, Winter: 0, Spring: 0, Spring2: 0

Mean Air Temperature, F: Summer: 70, Fall: 70, Winter: 70, Spring: 70, Spring2: 70

☒ Temperature Correction

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Material Type	AC	AC	Gran Base	Soil	Soil
PG Grade	76 -22	64 -22			
Min Modulus (psi)	50000	50000	5000	3000	3000
Modulus (psi)	483770	351642	25000	10000	10000
Max Modulus (psi)	4000000	4000000	50000	40000	40000
Poisson's Ratio	0.35	0.35	0.4	0.45	0.45
Min - Max	0.15 - 0.4	0.15 - 0.4	0.35 - 0.45	0.2 - 0.5	0.2 - 0.5
Thickness (in)	3	4	6	999	Infinite
	Variability	Variability	Variability	Variability	Variability
	Performance Criteria	Performance Criteria	Performance Criteria	Performance Criteria	Performance Criteria

Cancel Changes Accept Changes

Input Variability

Input Variability

Layer: AC

Modulus Variability

Distribution Type: Log-normal

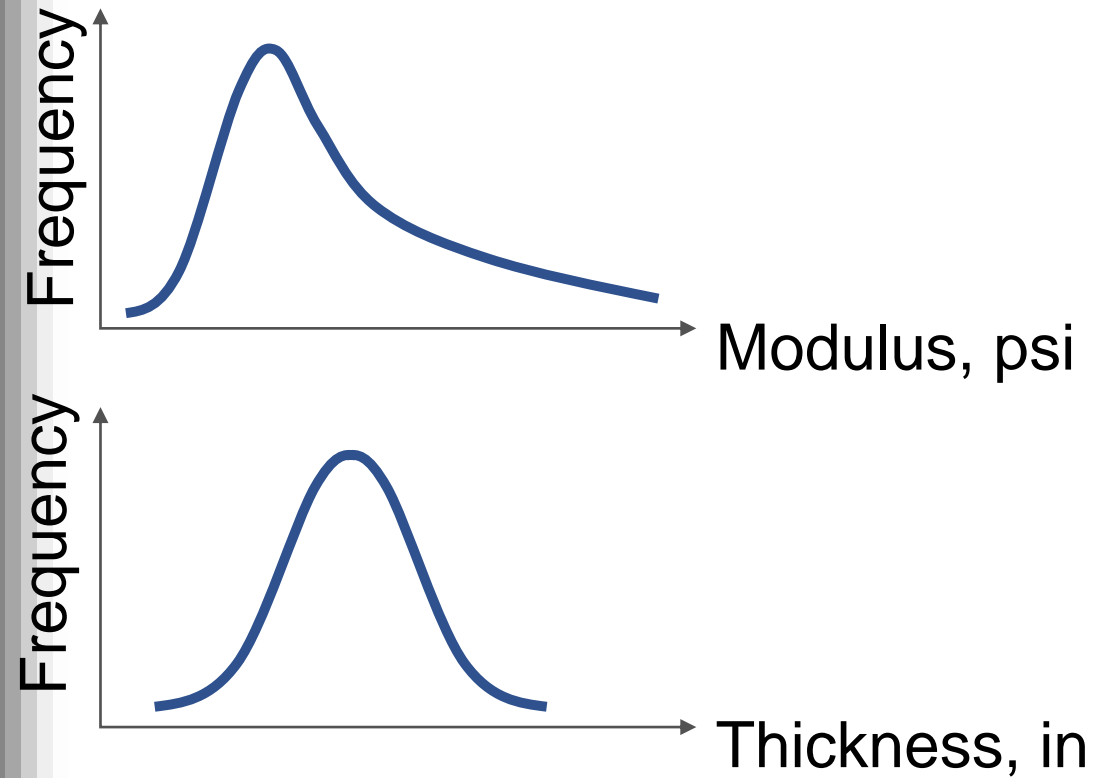
Coefficient of Variation: 30 %

Thickness Variability

Distribution Type: Normal

Coefficient of Variation: 5 %

Cancel Changes Accept Changes



Performance Criteria – Fatigue Cracking

Layer Performance Criteria (Press F1 for Help)

Layer:

Position	Criteria	Threshold	Target Percentile	Transfer Function	k1	k2
<input type="checkbox"/> Top						
<input type="checkbox"/> Middle						
<input type="checkbox"/> Bottom						

Note: The transfer functions are for strain only.

Note: The following sign convention is used...

Negative = Tension

Positive = Compression

Deflection is Positive Downward

Performance Criteria – Fatigue Cracking

Layer Performance Criteria (Press F1 for Help)

Layer:

Note: The transfer functions are for strain only.

Position	Criteria	Threshold	Target Percentile	Transfer Function	k1	k2
<input type="checkbox"/> Top						
<input type="checkbox"/> Middle						
<input checked="" type="checkbox"/> Bottom	<div><div>Horizontal Stress</div><div>Vertical Stress</div><div>Principal Stress</div><div>Horizontal Strain</div><div>Vertical Strain</div><div>Principal Strain</div><div>Vertical Deflection</div><div>Horizontal Strain Distribution</div></div>	<input type="text" value="0"/>	<input type="text" value="50"/>			

Note: The Negative = Compression
Positive = Tension
Deflection is Positive Downward

Performance Criteria – Fatigue Cracking

Layer Performance Criteria (Press F1 for Help)

Layer:

Note: The transfer functions are for strain only.

Position	Criteria	Threshold	Target Percentile	Transfer Function	k1	k2
<input type="checkbox"/> Top						
<input type="checkbox"/> Middle						
<input checked="" type="checkbox"/> Bottom	Horizontal Strain Distribution					
		Percentile	Microstrain			
		95th	-257			
		85th	-194			
		75th	-158			
		65th	-131			
		55th	-110			

Note: The following sign convention is used...

Negative = Tension

Positive = Compression

Deflection is Positive Downward

Performance Criteria – Rutting

Layer Performance Criteria (Press F1 for Help)

Layer:

Note: The transfer functions are for strain only.

Position	Criteria	Threshold	Target Percentile	Transfer Function	k1	k2
<input checked="" type="checkbox"/> Top	<input type="text" value="Vertical Strain"/>	<input type="text" value="200"/> microstrain	<input type="text" value="50"/>	<input type="checkbox"/>		

Note: The following sign convention is used...

Negative = Tension

Positive = Compression

Deflection is Positive Downward

Traffic Inputs

Loading Conditions (F1 for Help)





General Traffic Data

Two-Way AADT % Trucks % Trucks in Design Lane %

Axes Groups / Day % Truck Growth Directional Distribution %

Input Load Spectra by Vehicle Type

Loading Configurations (Check All That Apply)

 ☒ Single %  ☒ Tandem %  ☒ Tridem %  ☐ Steer %

Current Configuration:

Current Axle Load Distribution











Axle Wt kip	% Axles	Axle Wt kip	% Axles	Axle Wt kip	% Axles	Axle Wt kip	% Axles	Axle Wt kip	% Axles
0-2	<input type="text" value="0"/>	24-26	<input type="text" value="0.35"/>	48-50	<input type="text" value="0"/>	72-74	<input type="text" value="0"/>	96-98	<input type="text" value="0"/>
2-4	<input type="text" value="4.46"/>	26-28	<input type="text" value="0.2"/>	50-52	<input type="text" value="0"/>	74-76	<input type="text" value="0"/>	98-100	<input type="text" value="0"/>
4-6	<input type="text" value="9.13"/>	28-30	<input type="text" value="0.1"/>	52-54	<input type="text" value="0"/>	76-78	<input type="text" value="0"/>	100-102	<input type="text" value="0"/>
6-8	<input type="text" value="11.32"/>	30-32	<input type="text" value="0.05"/>	54-56	<input type="text" value="0"/>	78-80	<input type="text" value="0"/>	102-104	<input type="text" value="0"/>
8-10	<input type="text" value="19.55"/>	32-34	<input type="text" value="0.04"/>	56-58	<input type="text" value="0"/>	80-82	<input type="text" value="0"/>	104-106	<input type="text" value="0"/>
10-12	<input type="text" value="25.5"/>	34-36	<input type="text" value="0.02"/>	58-60	<input type="text" value="0"/>	82-84	<input type="text" value="0"/>	106-108	<input type="text" value="0"/>
12-14	<input type="text" value="14.57"/>	36-38	<input type="text" value="0.01"/>	60-62	<input type="text" value="0"/>	84-86	<input type="text" value="0"/>	108-110	<input type="text" value="0"/>
14-16	<input type="text" value="6.42"/>	38-40	<input type="text" value="0.01"/>	62-64	<input type="text" value="0"/>	86-88	<input type="text" value="0"/>	110+	<input type="text" value="0"/>
16-18	<input type="text" value="3.84"/>	40-42	<input type="text" value="0"/>	64-66	<input type="text" value="0"/>	88-90	<input type="text" value="0"/>		
18-20	<input type="text" value="2.39"/>	42-44	<input type="text" value="0"/>	66-68	<input type="text" value="0"/>	90-92	<input type="text" value="0"/>	Total	<input type="text" value="100"/>
20-22	<input type="text" value="1.37"/>	44-46	<input type="text" value="0"/>	68-70	<input type="text" value="0"/>	92-94	<input type="text" value="0"/>		
22-24	<input type="text" value="0.68"/>	46-48	<input type="text" value="0"/>	70-72	<input type="text" value="0"/>	94-96	<input type="text" value="0"/>		

Cancel Changes Import Load Spectra Save Load Spectra Accept Changes

Vehicle Type Distribution

Vehicle Type Distribution (Press F1 for Help)

Roadway Functional Classification: Rural Interstate

Vehicle Classification	% AADTT	Average Number of Axles Per Vehicle		
		Single	Tandem	Tridem
 4	1.2	1.62	0.39	0
 5	9.4	2	0	0
 6	3.3	1.02	0.99	0
 7	0.5	1	0.26	0.83
 8	7.4	2.38	0.67	0
 9	68.9	1.13	1.93	0
 10	1.2	1.19	1.09	0.89
 11	6.1	4.29	0.26	0.06
 12	0.8	3.52	1.14	0.06
 13	1.2	2.15	2.13	0.35
Total	100			

Cancel Changes Accept Changes

Axle Types & Load Spectra

Loading Conditions (F1 for Help)





General Traffic Data

Two-Way AADT: 1000 % Trucks: 10 % Trucks in Design Lane: 90 %

Axes Groups / Day: 136 % Truck Growth: 4 Directional Distribution: 50 %

Input Load Spectra by Vehicle Type

Loading Configurations (Check All That Apply)

 ☒ Single 50.43 %  ☒ Tandem 48.81 %  ☒ Tridem 0.76 %  ☐ Steer 0 %

Current Configuration: Single

Current Axle Load Distribution

Axle Wt kip	% Axles	Axle Wt kip	% Axles	Axle Wt kip	% Axles	Axle Wt kip	% Axles	Axle Wt kip	% Axles
0-2	0	24-26	0.35	48-50	0	72-74	0	96-98	0
2-4	4.46	26-28	0.2	50-52	0	74-76	0	98-100	0
4-6	9.13	28-30	0.1	52-54	0	76-78	0	100-102	0
6-8	11.32	30-32	0.05	54-56	0	78-80	0	102-104	0
8-10	19.55	32-34	0.04	56-58	0	80-82	0	104-106	0
10-12	25.5	34-36	0.02	58-60	0	82-84	0	106-108	0
12-14	14.57	36-38	0.01	60-62	0	84-86	0	108-110	0
14-16	6.42	38-40	0.01	62-64	0	86-88	0	110+	0
16-18	3.84	40-42	0	64-66	0	88-90	0		
18-20	2.39	42-44	0	66-68	0	90-92	0	Total	100
20-22	1.37	44-46	0	68-70	0	92-94	0		
22-24	0.68	46-48	0	70-72	0	94-96	0		

Cancel Changes Import Load Spectra Save Load Spectra Accept Changes

PerRoad Thickness Design Module

Output & Design Module (F1 for Help)

Thickness Design

Number of Pavement Layers:

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Material	<input type="text" value="AC"/>	<input type="text" value="AC"/>	<input type="text" value="Gran Base"/>	<input type="text" value="Soil"/>	<input type="text" value="Soil"/>
Thickness, in.	<input type="text" value="3"/>	<input type="text" value="4"/>	<input type="text" value="6"/>	<input type="text" value="999"/>	<input type="text" value="Infinite"/>

Reliability Analysis

Perpetual Pavement Design Results: Conventional Design with Transfer Functions

Disclaimer Cost Analysis Export Formatted Data to EXCEL Leave Module

Save As

Save in:

Name	Size	Item type	Date modified
Libraries			
David Timm			
Computer			
Network			
Adobe CS6 Design Standard		File folder	8/27/2014 4:32 PM
AFD60 2017		File folder	1/10/2017 11:08 AM

File name:

Save as type:

Monte Carlo Cycles

Number of Monte Carlo Cycles

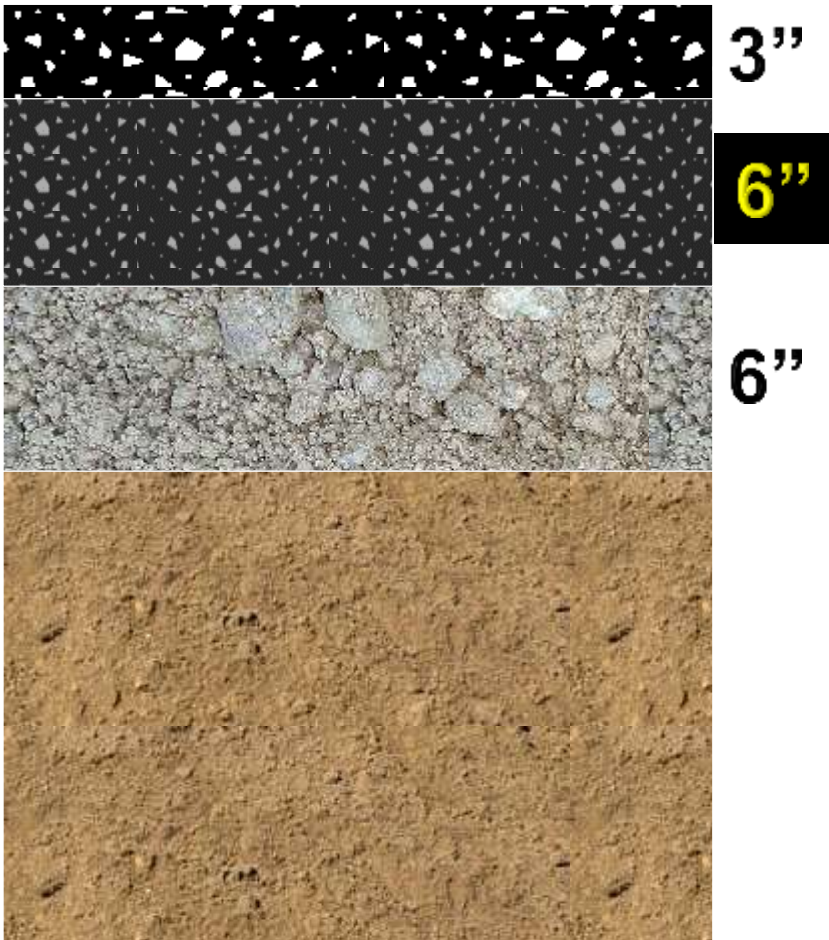
Simulation Results

Perpetual Pavement Design Results: Percentile Responses

Layer	Location	Criteria	Units	Target Value	Target Percentile	Actual Percentile	Pass/Fail?
2	Bottom	Tensile Strain	micr...	-257.	95	96.2	Pass
				-194.	85	85.4	Pass
				-158.	75	68.	Fail
				-131.	65	53.4	Fail
				-110	55	41	Fail
4	Top	Vertical Strain	micr...	200.	50.	31.6	Fail

- Pavement is NOT perpetual
 - Failing in both bottom-up fatigue and rutting
- Change design thicknesses and analyze again

2nd Design Iteration



Output & Design Module (F1 for Help)

Thickness Design

Number of Pavement Layers: 4

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Material	AC	AC	Gran Base	Soil	Soil
Thickness, in.	3	6	6	999	Infinite

Reliability Analysis

Set Monte Carlo Cycles

Perform Analysis

Perpetual Pavement Design Results: Conventional Design with Transfer Functions

Layer	Location	Criteria	Threshold	Units	Percent Below Critical	Damage/Million Axle	Years to D=0.1	Years to D=1.0
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Perpetual Pavement Design Results: Percentile Responses

Layer	Location	Criteria	Units	Target Value	Target Percentile	Actual Percentile	Pass/Fail?
2	Bottom	Tensile Strain	micr...	-257.	95	99.6	Pass
				-194.	85	96.	Pass
				-158.	75	91.6	Pass
				-131.	65	82.	Pass
				-110.	55	69.8	Pass
4	Top	Vertical Strain	micr...	200.	50.	55.2	Pass

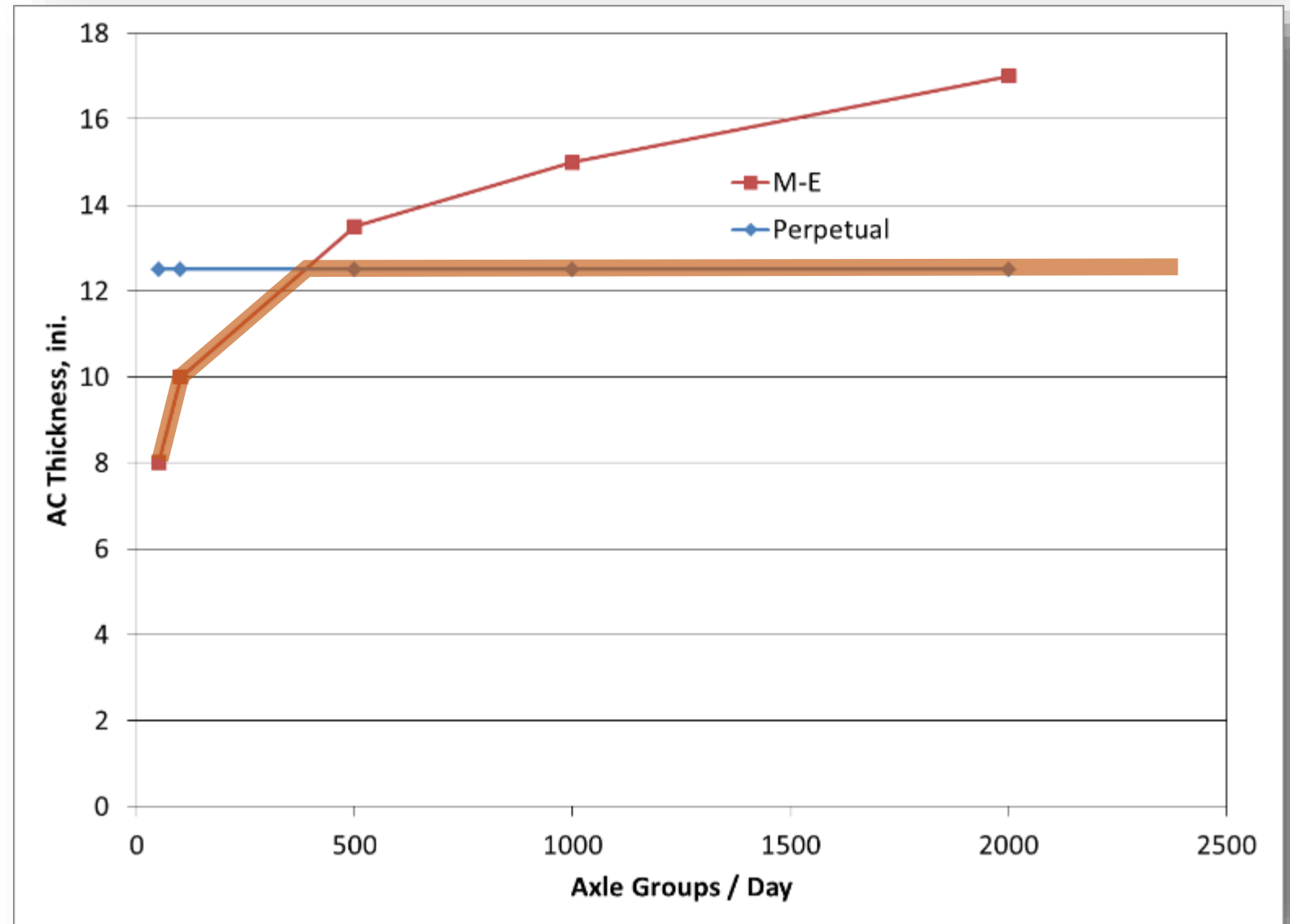
Disclaimer Cost Analysis Export Formatted Data to EXCEL Leave Module

Additional Design Examples

Subgrade Mr (ksi)	Base Mr (ksi)	Calculated AC Thickness (in.)				Range of Maximum Thicknesses (in.)
		Minneapolis (PG 64-34)	Phoenix (PG 70-22)	Baltimore (PG 64-22)	Average	
5	30	12.5	15.5	14	14.0	12.5-15.5
5	50	12	15	14	13.7	12-15
5	100	12	14	13.5	13.2	12-14
10	30	10.5	14	12	12.2	10.5-14
10	50	10.5	13	12	11.8	10.5-13
10	100	10	12	11	11.0	10-12
20	30	9	12.5	10	10.5	9-12.5
20	50	8.5	12.5	9.5	10.2	8.5-12.5
20	100	8	12	9	9.7	8-12

Design Comparison – Perpetual vs M-E

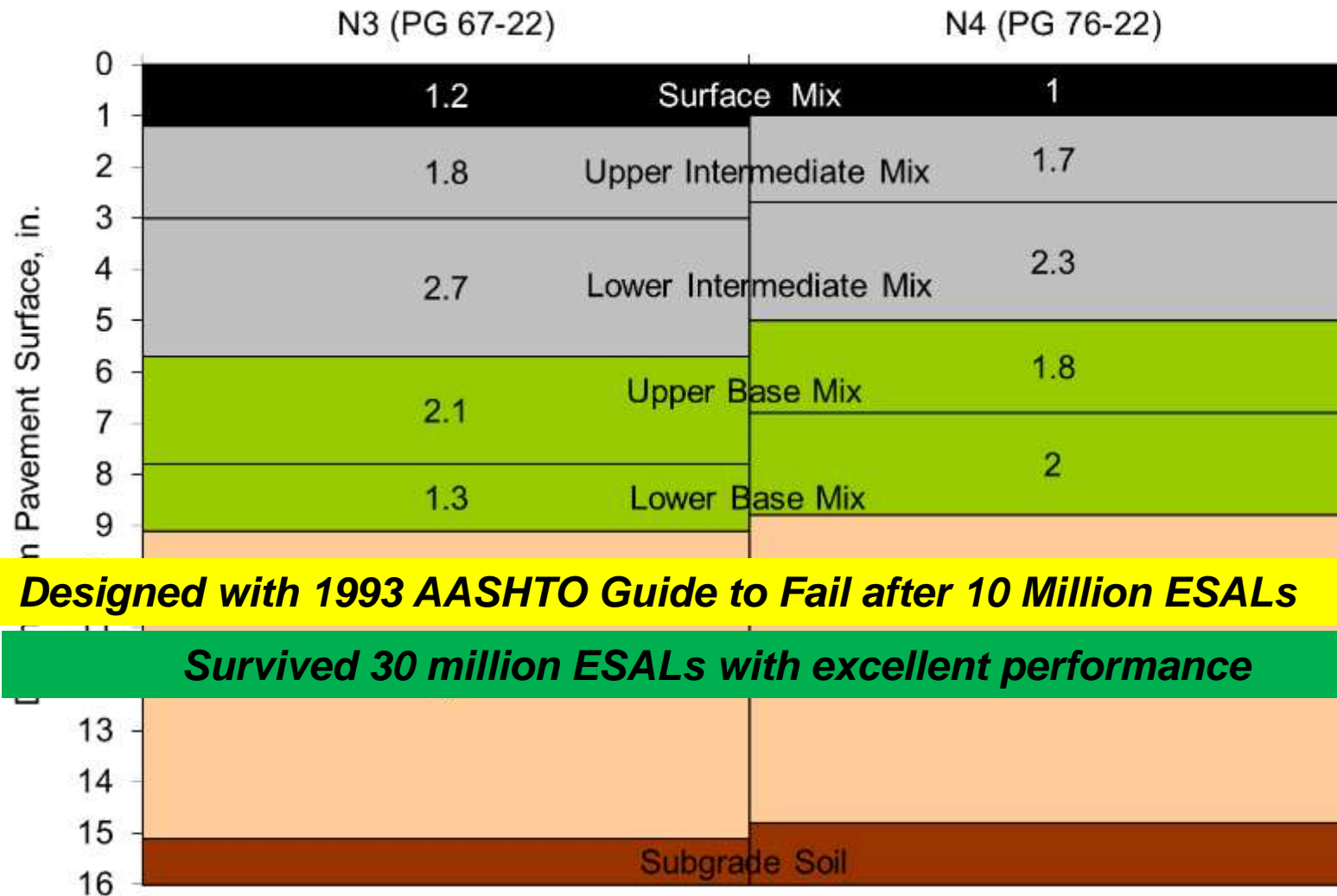
- Minneapolis
- 6" Aggregate Base
 - 30 ksi
- 5 ksi soil
- M-E 35 year analysis



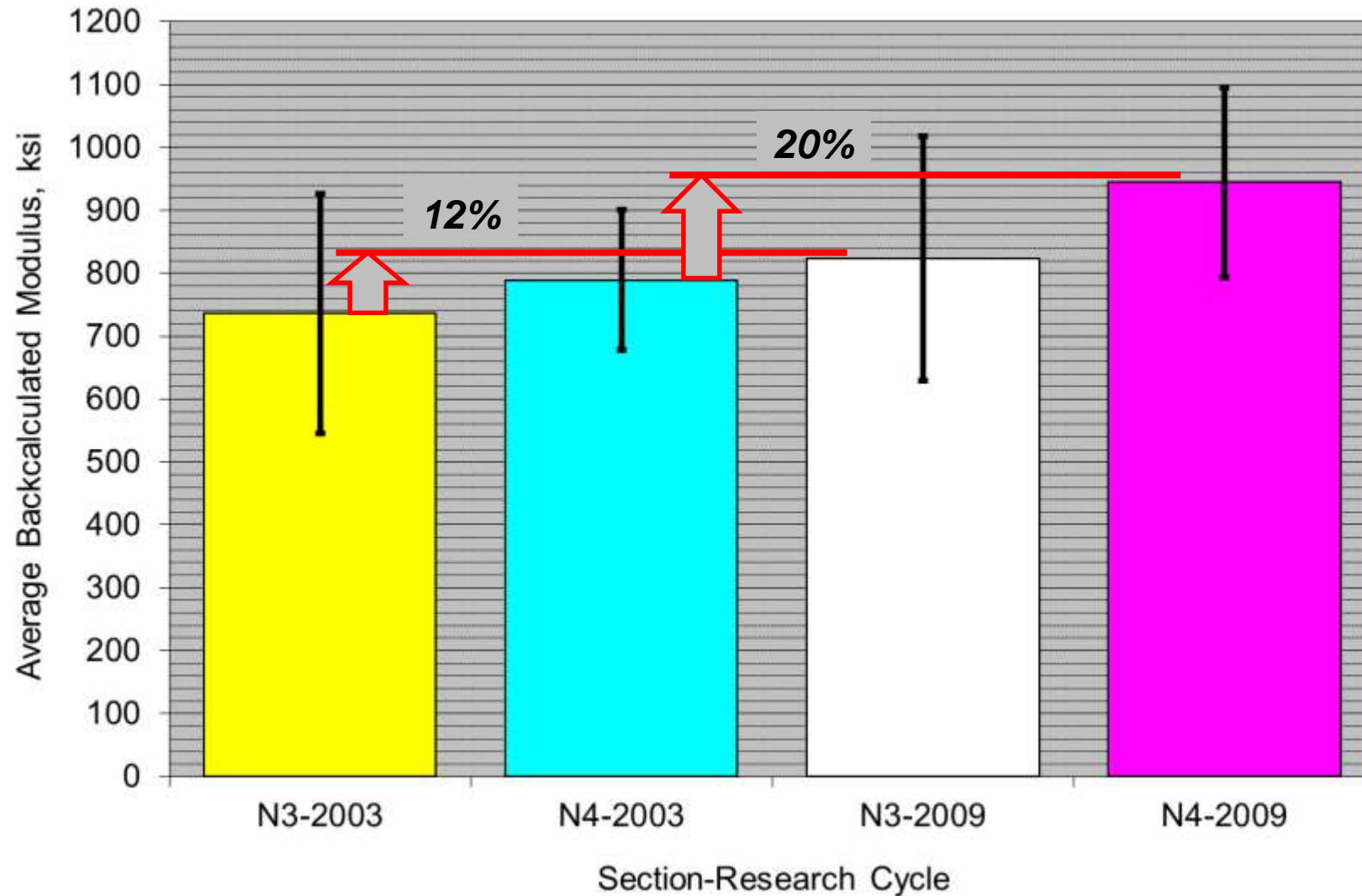
NCAT Test Track – Perpetual Experiments



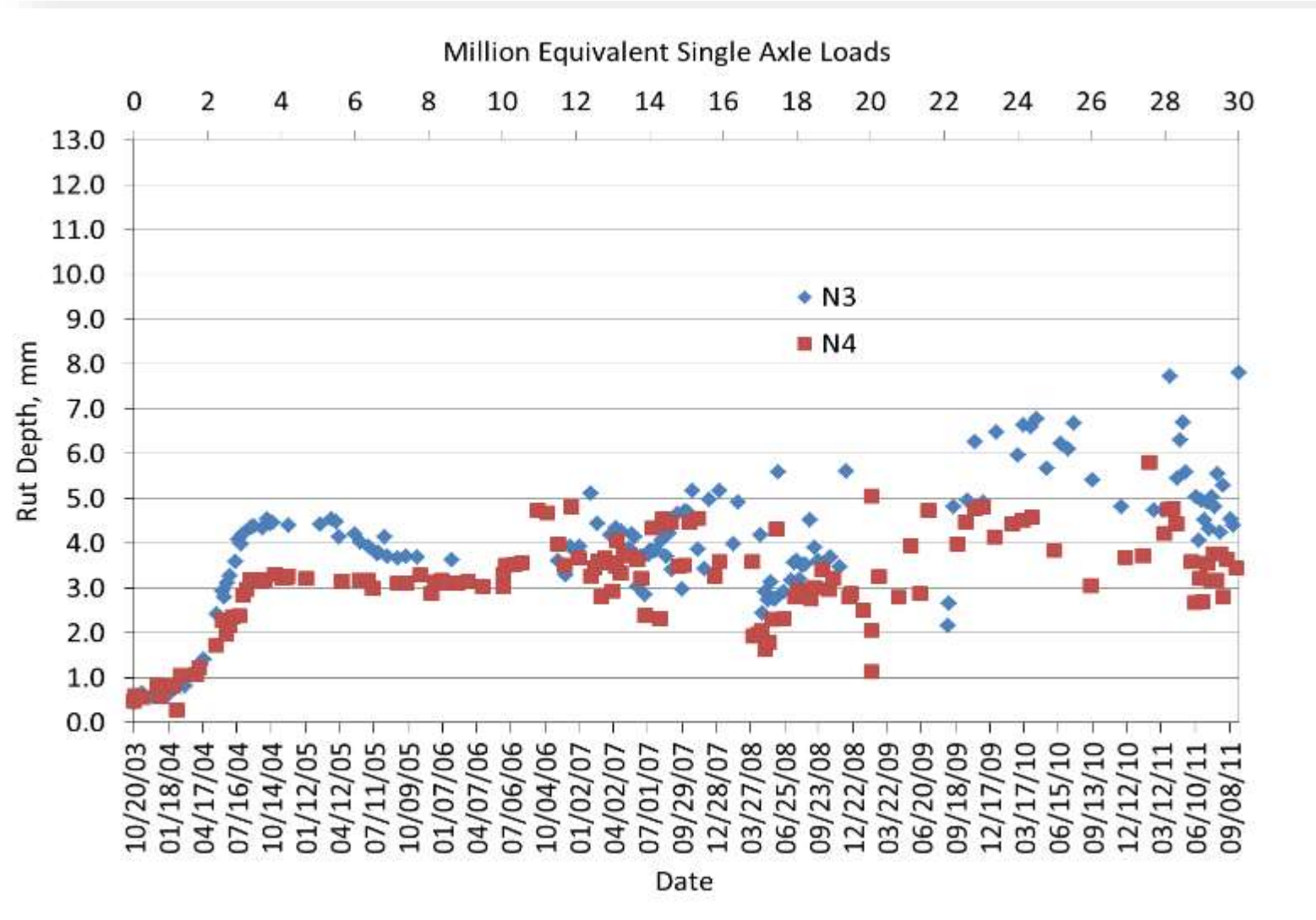
Test Sections – Experiment 1



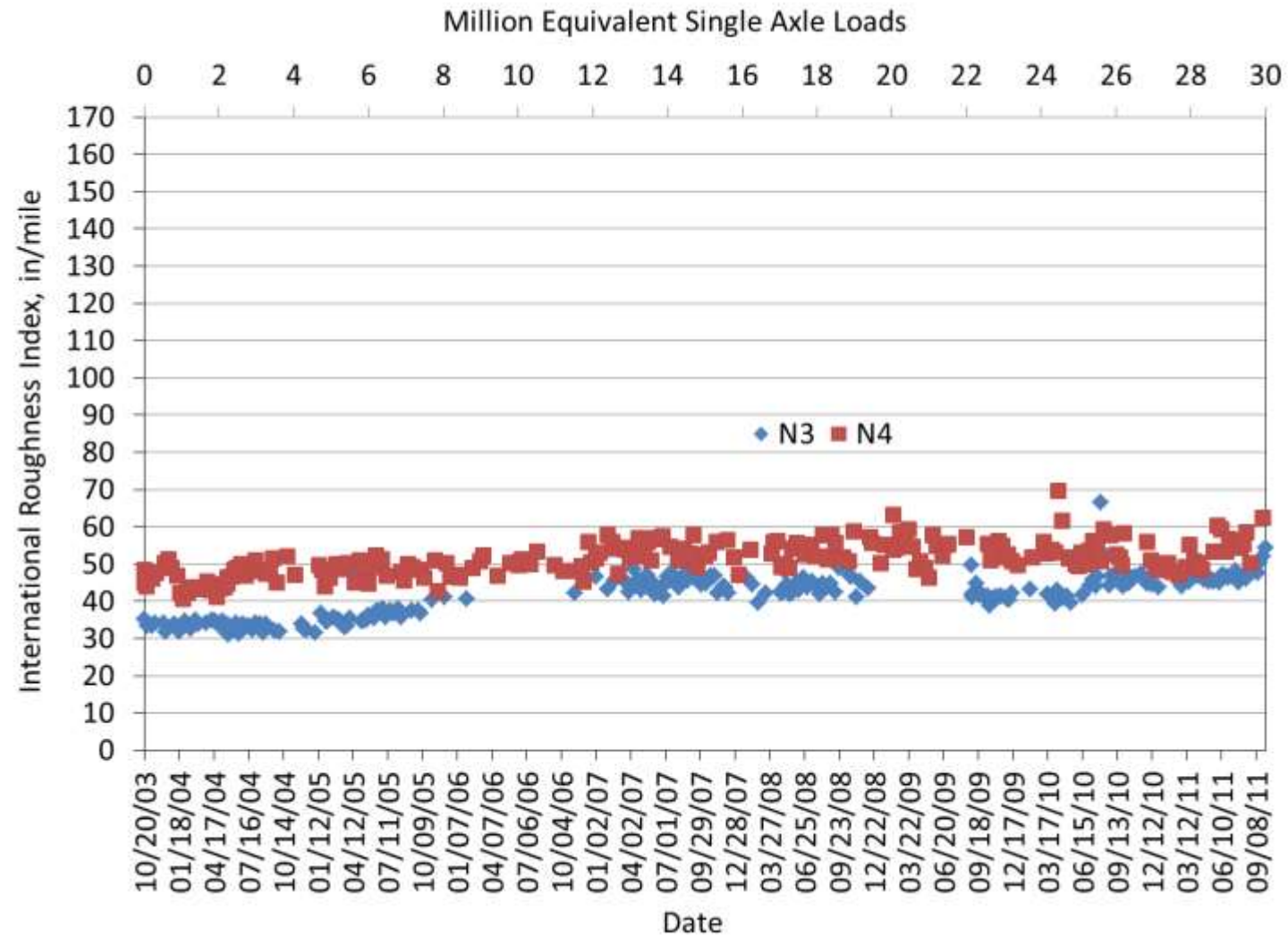
In-Place Modulus vs Time



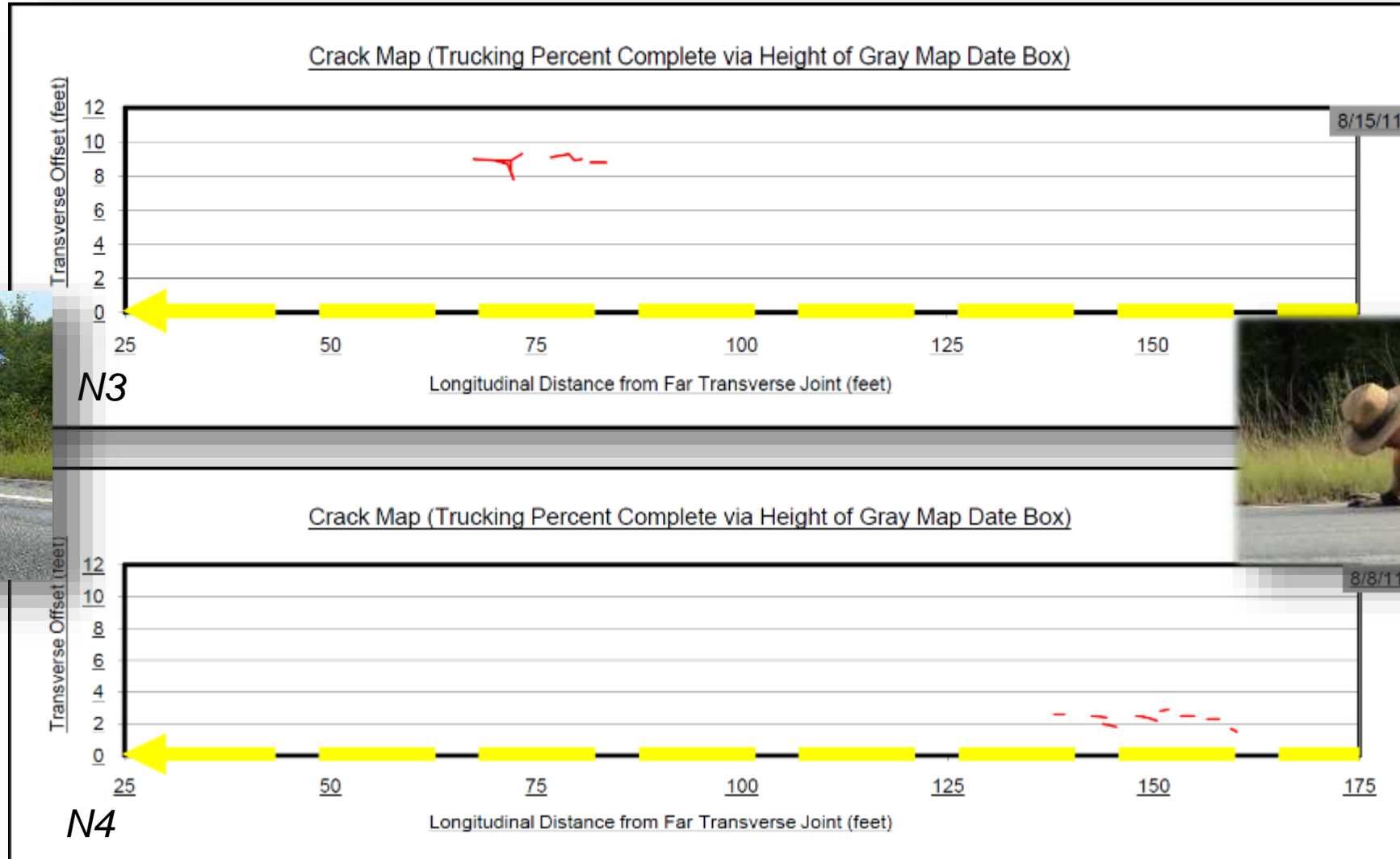
Rutting Performance



Ride Quality



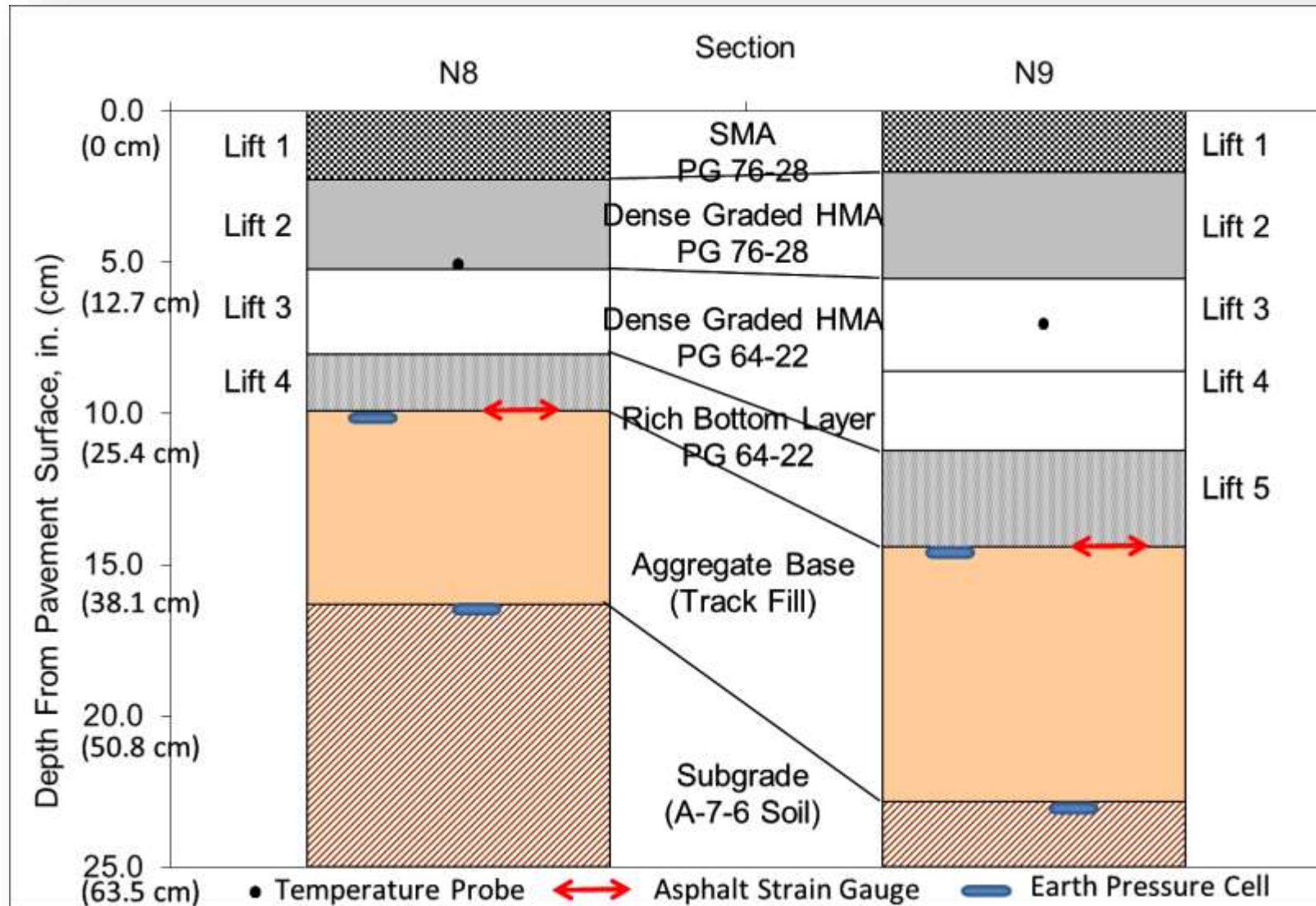
Cracking Performance



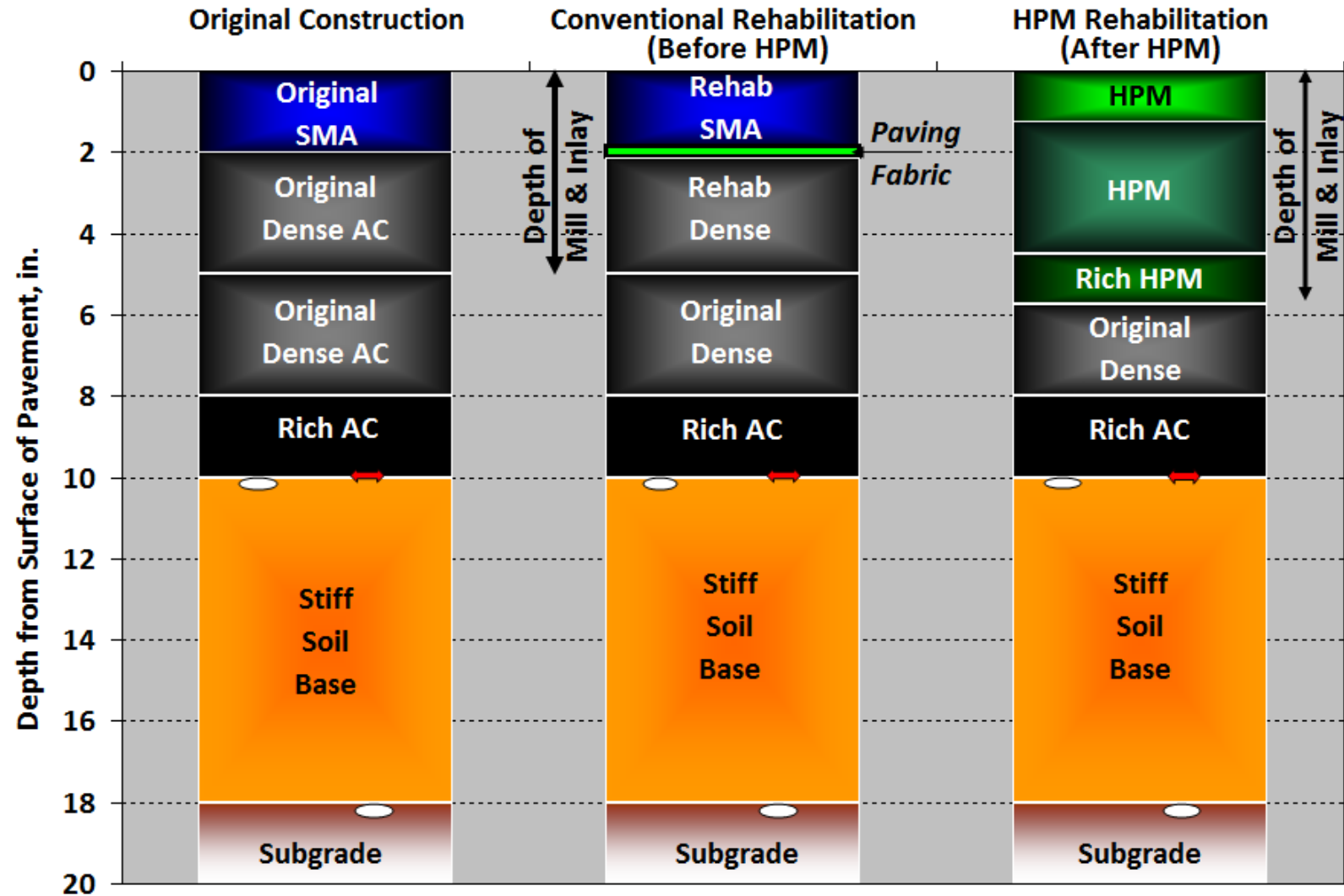
Forensic Trenching



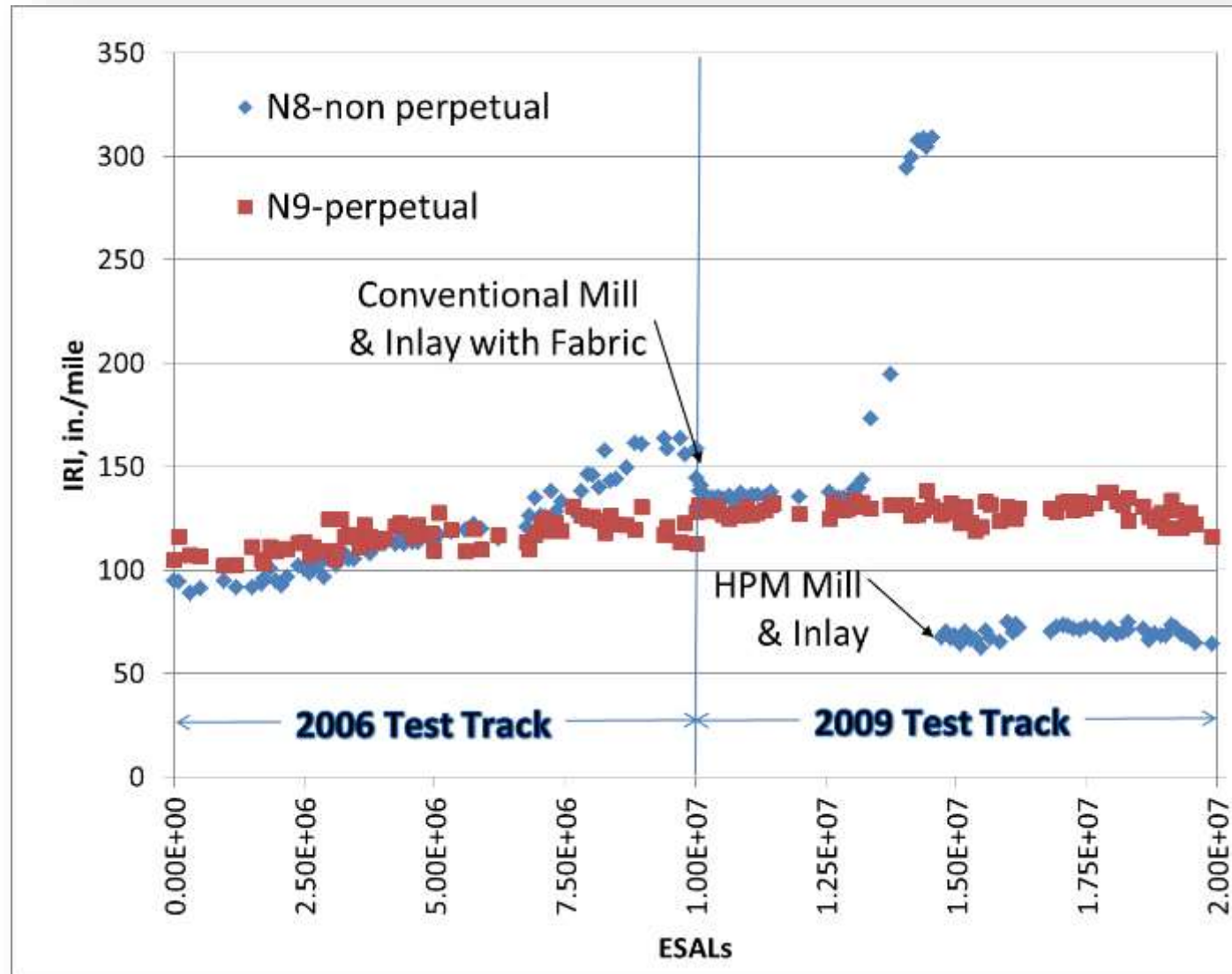
Test Sections – Experiment 2



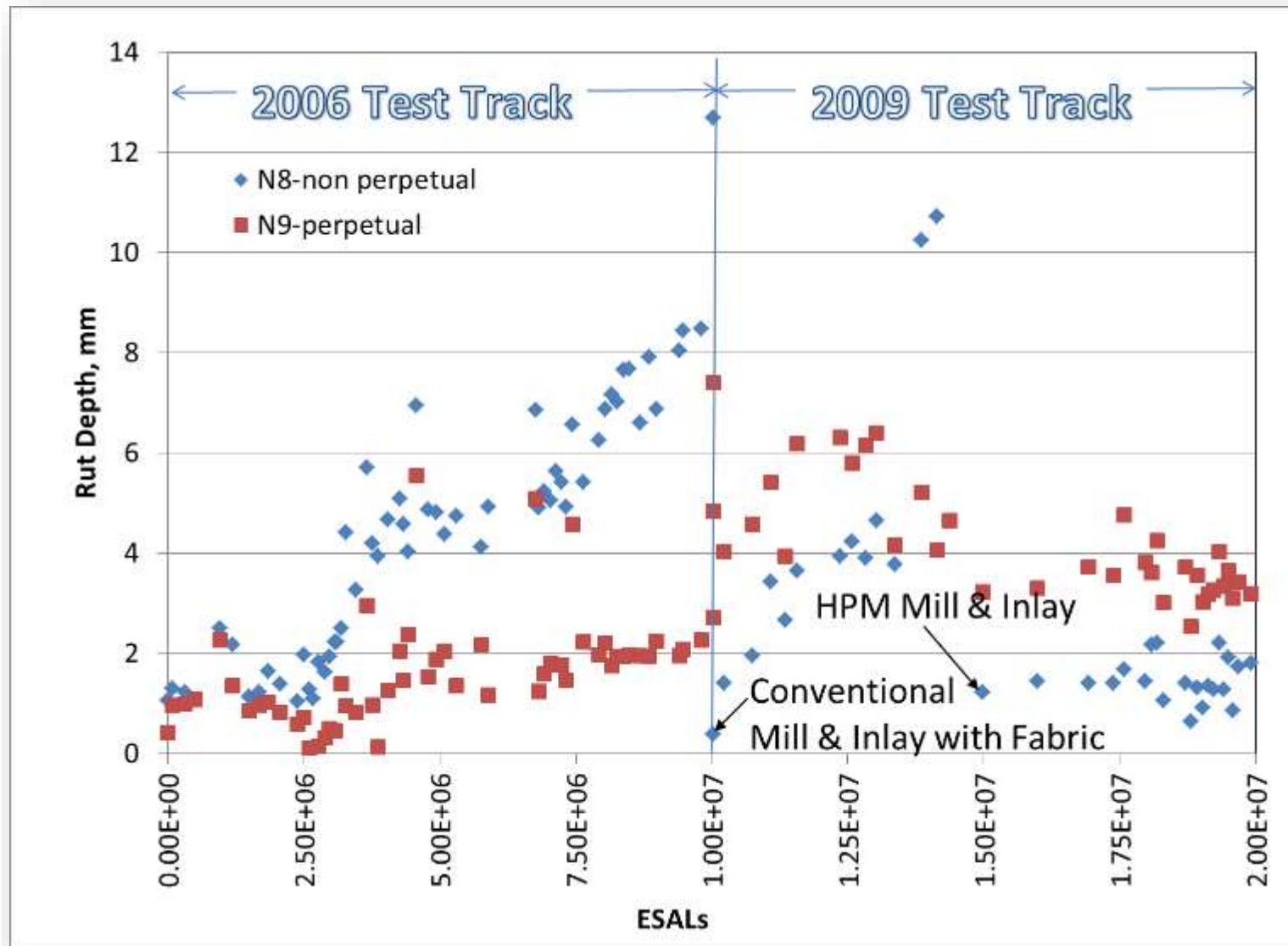
N8 Rehabilitation



Section Performance - IRI



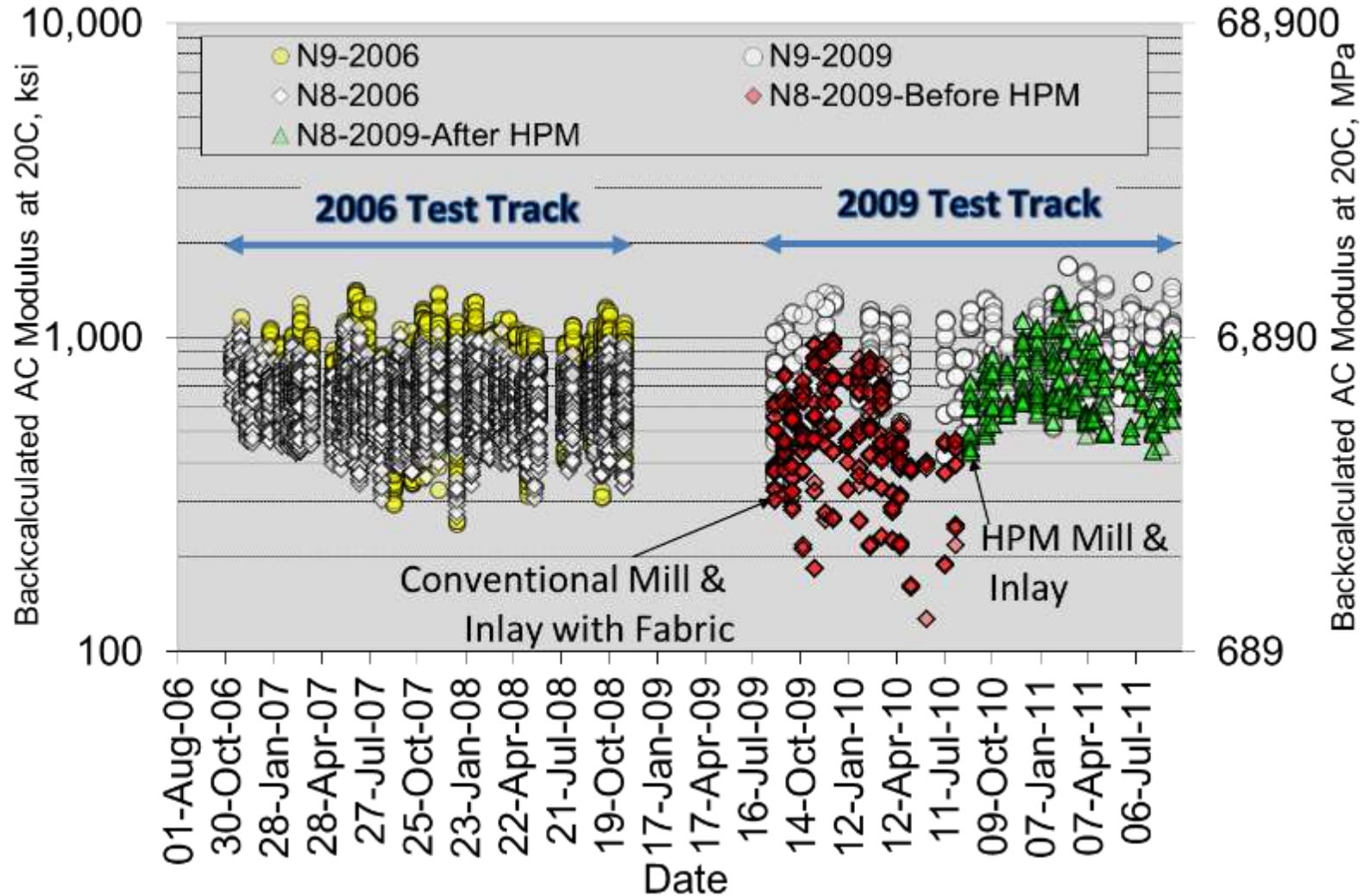
Section Performance - Rutting



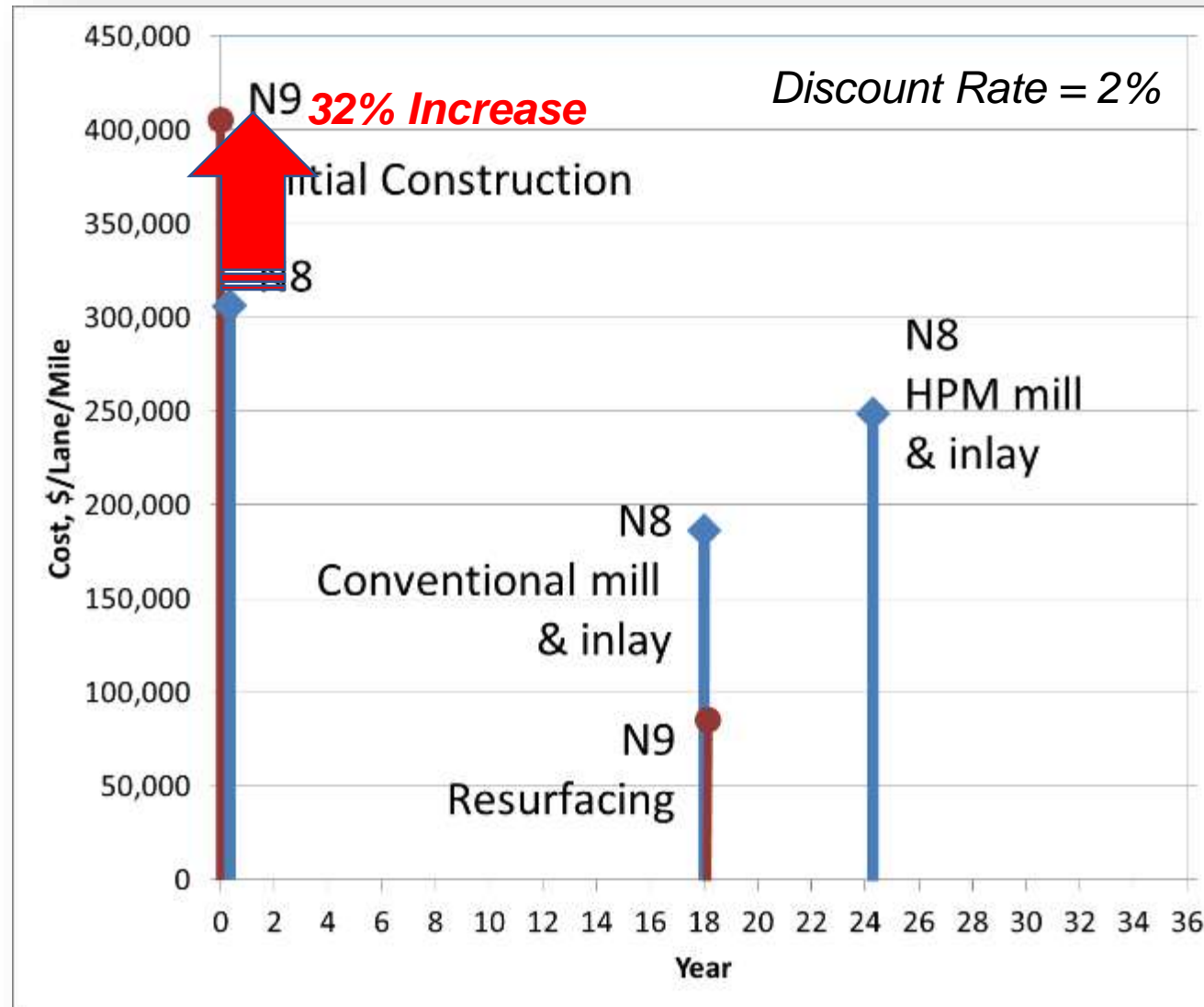
N8 After 1st Rehabilitation @ 3.5 MESAL



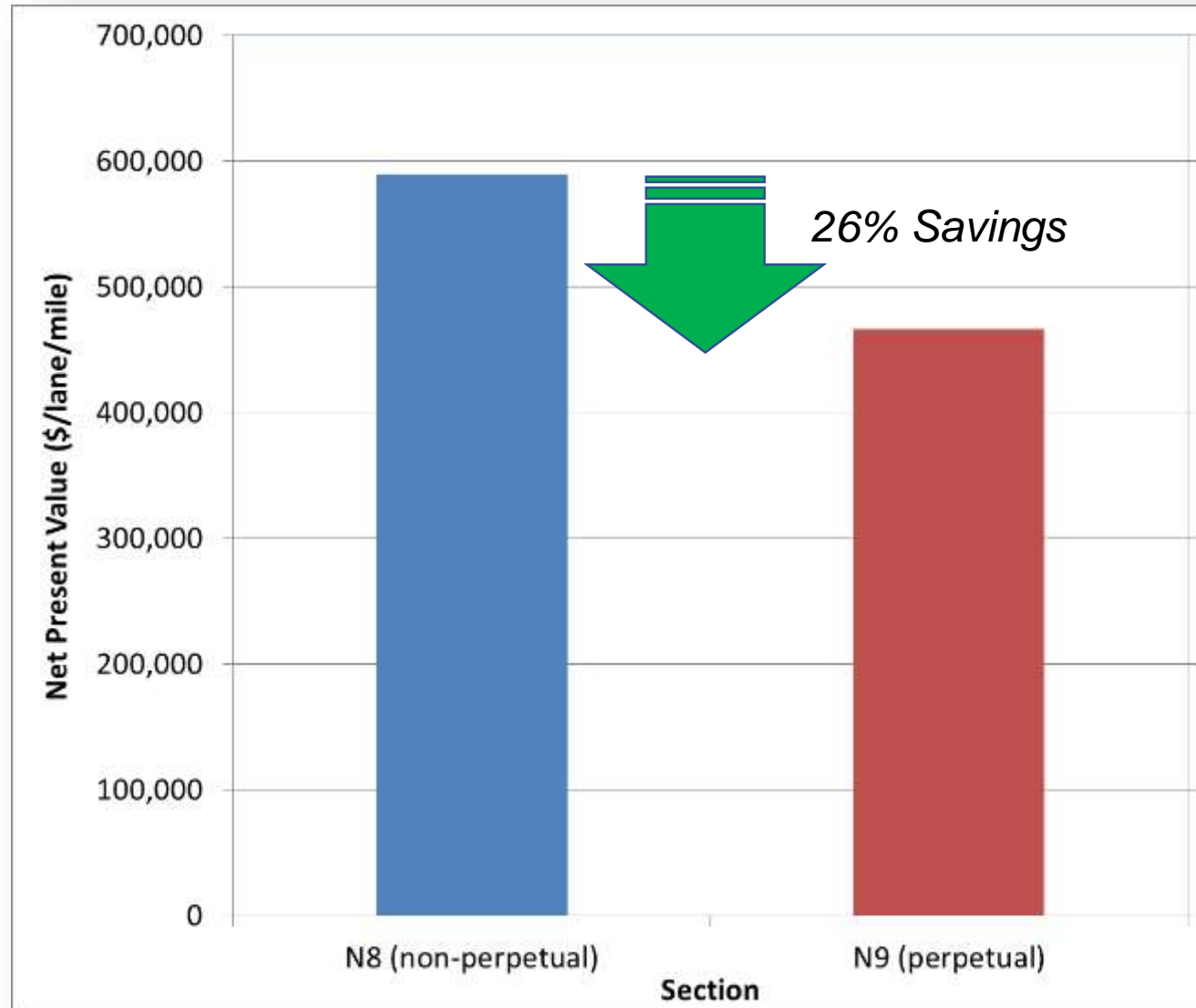
AC Modulus vs Date



Life Cycle Cost Analysis – Cash Flow Diagram



Life Cycle Cost Analysis – Net Present Value



Summary & Conclusions

- Perpetual pavements widely recognized across the U.S.
- Perpetual pavements don't have deep structural problems
 - Surface remedies make them an attractive option
- Perpetual pavements can be designed using mechanistic principles
 - Strain distributions developed at NCAT Test Track and validated with award winners
- PerRoad incorporates strain distribution design & Monte Carlo simulation to produce reasonable perpetual pavement cross-sections
 - Can be used to find maximum thicknesses
- Case studies from Test Track highlight key features of perpetual pavement
 - Tend to gain modulus over time
 - Exhibit excellent performance
 - Stable ride quality
 - Minimal rutting
 - No deep structural distresses
 - Cost effective

Thank you!

