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.
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

Typical Depths

- 1.5 – 3”
- 4 – 7”
- 3 – 4”

Materials

- High Quality AC
- High Modulus, Rut Resistant AC
- Fatigue Resistant AC
- Strong Pavement Foundation

Newcomb, 2001
Mechanistic-Empirical Pavement Design
Mechanistic-Empirical \textbf{Perpetual} Pavement Design
Mechanistic-Empirical Perpetual Pavement Design

- Contact Area
- Log N
- Log $\varepsilon$
- Endurance Limit
- No Damage Accumulation

- $H_1$, $E_1$
- $H_2$, $E_2$
- $H_3$, $E_3$
- $H_4$, $E_4$
- $E_5$

$P$, $\varepsilon_t$, $\varepsilon_v$
What is the **Endurance Limit** for AC?

An endurance limit is a threshold response below which damage does not occur.
History of Endurance Limits

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

[Graph showing percentile of microstrain against microstrain with N3 and N4 lines indicating lab-measured endurance limit]
Horizontal Strain Distributions at NCAT Test Track

![Graph showing horizontal strain distributions with labeled axes: Percentile on the y-axis ranging from 0% to 100% and Microstrain on the x-axis ranging from 0 to 1200. The graph indicates a transition from 'No Fatigue' to 'Fatigue' with various data points and lines for different years (2003, 2006).]
Evaluation of Perpetual Pavement Winners
# Award Winner Metrics

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

![Bar chart showing microstrain at 50th percentile for different locations: IA (76), MT (146), OK (128), OK 2 (153), VA (169), KY (188), MS (164), TN (162). The horizontal line at 200 represents the 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 με compressive strain at the 50th percentile for rutting
Perpetual Pavement Design Tools

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

https://goo.gl/i3FMej
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
### Structural Inputs

#### Material Type

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material Type</th>
<th>AC</th>
<th>Cracked AC</th>
<th>PCC</th>
<th>Rubb PCC</th>
<th>C and S PCC</th>
<th>B and S PCC</th>
<th>Gran Base</th>
<th>Soil</th>
<th>Rock</th>
<th>Other</th>
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<tr>
<td>1</td>
<td>AC</td>
<td>76</td>
<td>-22</td>
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<td>4</td>
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#### Performance Criteria

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<th>Variability</th>
<th>Performance Criteria</th>
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<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
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</tbody>
</table>

#### Structural Information

- **Season:** Summer
- **Duration (weeks):** 52
- **Mean Air Temperature (°F):**
  - Summer: 70
  - Winter: 70
  - Spring: 70
  - Spring 2: 70
- **Temperature Correction:** Yes

#### Modulus Properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>Min Modulus (psi)</th>
<th>Modulus (psi)</th>
<th>Max Modulus (psi)</th>
<th>Poisson's Ratio</th>
<th>Min - Max</th>
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<tr>
<td>1</td>
<td>50000</td>
<td>493720</td>
<td>4000000</td>
<td>0.35</td>
<td>0.15 - 0.4</td>
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<td>351642</td>
<td>-4000000</td>
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<td>3</td>
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<td>25000</td>
<td>50000</td>
<td>0.4</td>
<td>0.35 - 0.45</td>
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<td>4</td>
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<td>10000</td>
<td>40000</td>
<td>0.45</td>
<td>0.2 - 0.5</td>
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<tr>
<td>5</td>
<td>3000</td>
<td>10000</td>
<td>40000</td>
<td>0.45</td>
<td>0.2 - 0.5</td>
</tr>
</tbody>
</table>

#### Thickness

| Layer | Thickness (in) |
|-------|----------------|---------------|
| 1     | 3              |
| 2     | 4              |
| 3     | 6              |
| 4     | 9              |
| 5     | Infinite       |

#### Accept Changes

- Cancel Changes
- Accept Changes
Input Variability

Layer: AC

- Modulus Variability
  - Distribution Type: Log-normal
  - Coefficient of Variation: 30%

- Thickness Variability
  - Distribution Type: Normal
  - Coefficient of Variation: 5%

The diagrams show the frequency distribution of Modulus (psi) and Thickness (in).
Performance Criteria – Fatigue Cracking

Layer Performance Criteria (Press F1 for Help)

Layer: [Input Field]

Position
- Top
- Middle
- Bottom

Criteria
Threshold
Target Percentile
Transfer Function
k1
k2

Note: The transfer functions are for strain only.

Note: The following sign convention is used:
Negative - Tension
Positive - Compression
Deflection is Positive Downward

Cancel Changes
Accept Changes
### Performance Criteria – Fatigue Cracking

#### Layer Performance Criteria (Press F1 for Help)

<table>
<thead>
<tr>
<th>Layer:</th>
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<tbody>
<tr>
<td>Position</td>
<td>Criteria</td>
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<tr>
<td>Top</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td></td>
</tr>
<tr>
<td>Bottom</td>
<td>Horizontal Strain</td>
</tr>
</tbody>
</table>

**Note:** The transfer functions are for strain only.

- **Horizontal Strain Distribution**
- **Vertical Strain**
- **Principal Strain**
- **Horizontal Strain**
- **Vertical Deflection**
- **Principal Strain**

Deflection is Positive Downward

[Accept Changes] [Cancel Changes]
Performance Criteria – Fatigue Cracking

Layer Performance Criteria (Press F1 for Help)

Layer: 2

<table>
<thead>
<tr>
<th>Position</th>
<th>Criteria</th>
<th>Threshold</th>
<th>Target Percentile</th>
<th>Transfer Function</th>
<th>k1</th>
<th>k2</th>
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<tr>
<td>Middle</td>
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<td>Bottom</td>
<td>Horizontal Strain Distribution</td>
<td>Percentile</td>
<td>Microstrain</td>
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<td>55th</td>
<td>-110</td>
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</table>

Note: The following sign convention is used...
Negative - Tension
Positive - Compression
Deflection is Positive Downward

Load Default Distribution
## Performance Criteria – Rutting

![Layer Performance Criteria (Press F1 for Help)](image)

<table>
<thead>
<tr>
<th>Position</th>
<th>Criteria</th>
<th>Threshold</th>
<th>Target Percentile</th>
<th>Transfer Function</th>
<th>k1</th>
<th>k2</th>
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<tbody>
<tr>
<td>Top</td>
<td>Vertical Strain</td>
<td>200 microstrain</td>
<td>50</td>
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</table>

Note: The transfer functions are for strain only.

Note: The following sign convention is used:
- Negative - Tension
- Positive - Compression
- Deflection is Positive Downward

[Accept Changes] [Cancel Changes]
Traffic Inputs
Vehicle Type Distribution

Roadway Functional Classification

<table>
<thead>
<tr>
<th>Vehicle Classification</th>
<th>%AADT</th>
<th>Rural Interstate</th>
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<tr>
<td>4</td>
<td>1.2</td>
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<td>9.4</td>
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<td>8</td>
<td>7.4</td>
<td>2.36</td>
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<td>68.5</td>
<td>1.13</td>
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<td>1.2</td>
<td>1.19</td>
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<td>11</td>
<td>8.1</td>
<td>4.25</td>
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<td>12</td>
<td>0.8</td>
<td>3.52</td>
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<td>13</td>
<td>1.2</td>
<td>2.15</td>
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</table>

Average Number of Axles Per Vehicle

<table>
<thead>
<tr>
<th></th>
<th>Single</th>
<th>Tandem</th>
<th>Tridem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>2</td>
<td>0.39</td>
<td>0</td>
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<td>Tandem</td>
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<td>Tridem</td>
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<td>0.99</td>
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<td>Single</td>
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<td>Tandem</td>
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<td>0</td>
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<tr>
<td>Tridem</td>
<td>1</td>
<td>0</td>
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</table>
Axle Types & Load Spectra
PerRoad Thickness Design Module
Simulation Results

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

<table>
<thead>
<tr>
<th>Layer</th>
<th>Location</th>
<th>Criteria</th>
<th>Units</th>
<th>Target Value</th>
<th>Target Percentile</th>
<th>Actual Percentile</th>
<th>Pass/Fail?</th>
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<tbody>
<tr>
<td>2</td>
<td>Bottom</td>
<td>Tensile Strain</td>
<td>microns</td>
<td>-257.</td>
<td>95</td>
<td>96.2</td>
<td>Pass</td>
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<td>-194.</td>
<td>85</td>
<td>85.4</td>
<td>Pass</td>
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<td>-158.</td>
<td>75</td>
<td>68.</td>
<td>Fail</td>
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<td>-131.</td>
<td>65</td>
<td>53.4</td>
<td>Fail</td>
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<td>-110</td>
<td>55</td>
<td>41</td>
<td>Fail</td>
</tr>
<tr>
<td>4</td>
<td>Top</td>
<td>Vertical Strain</td>
<td>microns</td>
<td>200.</td>
<td>50.</td>
<td>31.6</td>
<td>Fail</td>
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</tbody>
</table>
2nd Design Iteration

Output & Design Module

Thickness Design:
- Number of Pavement Layers: 4
- Layer 1: AC
- Layer 2: AC
- Layer 3: Gravel Base
- Layer 4: Soil
- Layer 5: Infinite

Reliability Analysis:
- Set Monte Carlo Cycles
- Perform Analysis

Perpendicular Pavement Design Results:
- Conventional Design with Transfer Functions
  - Layer: 3" and 6"
  - Location: Top
  - Criteria: Tensile Strain
  - Units: microns
  - Target Value: 95
  - Percent Below Critical: 96
  - Damage/Million Axle: 96.8
  - Years to D=0.1: 82
  - Years to D=1.0: Pass

- Percentile Responses
  - Layer: Top
  - Criteria: Vertical Strain
  - Units: microns
  - Target Value: 50
  - Target Percentile: 55.2
  - Actual Percentile: Pass
### Additional Design Examples

<table>
<thead>
<tr>
<th>Subgrade Mr (ksi)</th>
<th>Base Mr (ksi)</th>
<th>Calculated AC Thickness (in.)</th>
<th>Average</th>
<th>Range of Maximum Thicknesses (in.)</th>
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</thead>
<tbody>
<tr>
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<td>Minneapolis (PG 64-34)</td>
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<td>Phoenix (PG 70-22)</td>
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<td>Baltimore (PG 64-22)</td>
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<td>Average</td>
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<td>14.0</td>
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<tr>
<td>20</td>
<td>100</td>
<td>8</td>
<td>9.7</td>
<td>8-12</td>
</tr>
</tbody>
</table>
• Minneapolis
• 6” Aggregate Base
  • 30 ksi
• 5 ksi soil
• M-E 35 year analysis
NCAT Test Track – Perpetual Experiments

- N9 14” AC
- N8 10” AC
- N4 PG 76-22
- N3 PG 67-22
Test Sections – Experiment 1

N3 (PG 67-22)

1.2 Surface Mix

1.8 Upper Intermediate Mix

2.7 Lower Intermediate Mix

2.1 Upper Base Mix

1.3 Lower Base Mix

N4 (PG 76-22)

1 Surface Mix

1.7 Upper Intermediate Mix

2.3 Lower Intermediate Mix

1.8 Upper Base Mix

2 Lower Base Mix

Subgrade Soil

Designed with 1993 AASHTO Guide to Fail after 10 Million ESALs

Survived 30 million ESALs with excellent performance
In-Place Modulus vs Time

- N3-2003: 700 ksi (12% increase)
- N4-2003: 900 ksi (20% increase)
- N3-2009
- N4-2009

Average Backcalculated Modulus, ksi

Section-Research Cycle
Rutting Performance

[Graph showing rut depth over time for Million Equivalent Single Axle Loads]
Ride Quality
Cracking Performance

Crack Map (Trucking Percent Complete via Height of Gray Map Date Box)

8/13/11

N3

Crack Map (Trucking Percent Complete via Height of Gray Map Date Box)

8/8/11

N4

Longitudinal Distance from Far Transverse Joint (feet)
Forensic Trenching
Test Sections – Experiment 2

Diagram showing depth from pavement surface in centimeters, with various layers labeled such as Lift 1, Lift 2, Lift 3, Lift 4, Lift 5, SMA PG 76-28, Dense Graded HMA PG 76-28, Dense Graded HMA PG 64-22, Rich Bottom Layer PG 64-22, Aggregate Base (Track Fill), Subgrade (A-7-6 Soil).
N8 Rehabilitation

- Original Construction
  - Original SMA
  - Original Dense AC
  - Rich AC

- Conventional Rehabilitation (Before HPM)
  - Rehab SMA
  - Rehab Dense
  - Rich AC

- HPM Rehabilitation (After HPM)
  - Paving Fabric
  - HPM
  - Rich HPM
  - Original Dense
  - Rich AC

Depth from Surface of Pavement, in.

Subgrade

Stiff Soil Base

Depth of Mill & Inlay
Section Performance - Rutting

![Graph showing rutting depth vs ESALs for 2006 and 2009 test tracks with data points for N8-non perpetual and N9-perpetual treatments. There are markers for HPM Mill & Inlay and Conventional Mill & Inlay with Fabric.]
N8 After 1\textsuperscript{st} Rehabilitation @ 3.5 MESAL
AC Modulus vs Date

Backcalculated AC Modulus at 20°C, ksl

2006 Test Track

2009 Test Track

Conventional Mill & Inlay with Fabric

HPM Mill & Inlay

Date


Backcalculated AC Modulus at 20°C, MPa

10,000
1,000
100
689
6,890
68,900

N9-2006
N8-2006
N9-2009
N8-2009-Before HPM
N8-2009-After HPM
Life Cycle Cost Analysis – Cash Flow Diagram

Discount Rate = 2%

Cost, $/Lane/Mile

Year

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36

Initial Construction

32% Increase

N9

Conventional mill & inlay

N8

Resurfacing

N9

HPM mill & inlay

N8
Life Cycle Cost Analysis – Net Present Value

26% Savings
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!

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