Global Roadway Infrastructure

• Nearly 40 million miles of roads on Earth (2013)
  • Enough roads to circle Earth 1,600 times

[Image of satellite view of Earth with glowing road networks]
Global Roadway Mileage – Top 5 Countries

- **Russia**: 797,458
- **Canada**: 4,092,722
- **China**: 2,551,586
- **Brazil**: 982,634
- **Australia**: 2,914,127
U.S. Roadway Infrastructure

- 2,674,821 miles paved
- 1,417,901 miles unpaved
HOW MANY OF OUR U.S. ROADS ARE PAVED WITH ASPHALT?

93.99%

93.79% 89.34%
Roads

estimated $101 billion in wasted time and fuel annually.

long term. Currently, the Federal Highway Administration estimates that $170 billion in capital investment would be needed on an annual basis to significantly improve conditions and performance.

Forty-two percent of America’s major urban highways remain congested, costing the economy an estimated $101 billion in wasted time and fuel annually. While the conditions have improved in the near term, and Federal, state, and local capital investments increased to $91 billion annually, that level of investment is insufficient and still projected to result in a decline in conditions and performance in the long term. Currently, the Federal Highway Administration estimates that $170 billion in capital investment would be needed on an annual basis to significantly improve conditions and performance.
Dakota Report Cards (2013)

North Dakota:
- 87,128 miles of public roads, with 9% in poor condition
- $407 million is needed for drinking water wastewater, not reported
- 720 structurally deficient bridges
- $261/yr costing motorists
- $400 per motorist per year in costs from driving on roads in need of repair

South Dakota:
- 82,576 miles of public roads, with 17% in poor condition
- $540 million is needed for drinking water
- $106 million is needed for wastewater
- 1,210 structurally deficient bridges
- $339/yr
- $528 per motorist per year in costs from driving on roads in need of repair
Road Construction Economics

• Estimates according to ARTBA
  • Construct new 2-lane undivided road
    • $2-$3 million per mile in rural areas
    • $3-$5 million in urban areas
  • Construct a new 4-lane highway
    • $4-$6 million per mile in rural and suburban areas
    • $8-$10 million per mile in urban areas
  • Construct a new 6-lane Interstate highway
    • $7 million per mile in rural areas
    • $11 million or more per mile in urban areas
  • Expand an Interstate Highway from 4 lanes to 6 lanes – about $4 million per mile
  • Mill and resurface a 4-lane road – about $1.25 million per mile

http://www.artba.org/about/transportation-faqs/
Evolution of Pavement Thickness Design

Pre 1950’s Experience

1960’s Development of Empirical Methods

1980’s Initial Mechanistic-Empirical Methods

1990’s NCRHP 1-37A M-E Design

2000’s Implementation of M-E Methods

Flexible Pavement Design in the U.S. - State of the Practice

Pavement Design Methods

- **Empirical**: 28
- **Empirical & MEPDG**: 11
- **MEPDG Only**: 1
- **Empirical & Other ME**: 7
- **Other ME**: 3

Pierce and McGovern, 2013
NCHRP Project 20-05, Topic 44-06
AASHTO Empirical Flexible Pavement Design Method

\[
\log W_{18} = Z_R S_0 + 9.36 \log (SN + 1) - 0.20 + \frac{\log \left[ \frac{\Delta PSI}{4.2 - 1.5} \right]}{0.4 + \frac{1094}{(SN + 1)^{5.19}}} + 2.32 \log M_R - 8.07
\]
Empirical Method Based on AASHO Road Test

Figure 1. Looking east, Loops 5 and 2 in foreground.

Figure 92. Automatic batch-type plant used to produce binder course mixture; dryers in tandem.
Specific Traffic and Climate

Figure 23. Test vehicles, showing typical axle arrangements and loadings.

Figure 26. During periods of adverse weather traffic operations were governed by safety considerations. Snow and ice conditions usually resulted in operating at reduced speeds.
Flexible Pavement Design Curves

Figure 23. Main factorial experiment, relationship between design and axle load applications at $p = 1.5$ (from Road Test equations).
AASHTO M-E Design Software
Major Limitations of M-E Design

• Pavement performance prediction
  • Evaluation
  • Calibration
  • Verification

• Pavements are still designed to fail
Long-Life (Perpetual) Pavements

- 35+ Year Service
- Minimal Improvements
- No deep distress
  - Problems only at surface
Perpetual Pavements Avoid Deep Structural Problems
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 Perpetual Pavement Design

No Damage Accumulation

Log $N$

Threshold Strain

No Damage Accumulation

Log $\varepsilon$

$D_1$, $E_1$

$D_2$, $E_2$

$D_3$, $E_3$

$D_4$, $E_4$

$E_5$

Contact Area

$P$

$\varepsilon_t$

$\varepsilon_v$
What is the endurance limit for asphalt concrete?

• 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 higher strains
Measured Strains & Endurance Limit

Lab-measured endurance limit
Strain Distributions NCAT Test Track

No Fatigue

Fatigue
Further Evaluation of Criteria – Perpetual Pavement Award Winners
## Perpetual Pavement 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>
</tr>
</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>
</tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>Kentucky</td>
<td>I-65, Hart County</td>
<td>2009</td>
<td>44</td>
<td>76,000,000 ESAL</td>
</tr>
<tr>
<td>Mississippi</td>
<td>I-22, Desoto County</td>
<td>2007</td>
<td>39</td>
<td>60,000,000 ESAL</td>
</tr>
<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>
</tr>
</tbody>
</table>
Further Evaluation Results – Fatigue Cracking
Further Valuation Results – Rutting

The chart illustrates the microstrain at the 50th percentile for different states, measured in microstrain. The states are IA, MT, OK, OK 2, VA, KY, MS, and TN, with respective values of 76, 146, 128, 153, 169, 188, 164, and 162. A horizontal red line indicates a threshold for comparison.
## Example Designs with New Criteria

<table>
<thead>
<tr>
<th>Subgrade Mr (ksi)</th>
<th>Base Mr (ksi)</th>
<th>Calculated AC Thickness (in.)</th>
<th>Range of Maximum Thicknesses (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minneapolis (PG 64-34)</td>
<td>Phoenix (PG 70-22)</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>12.5</td>
<td>15.5</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>10.5</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>10.5</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>10</td>
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<td>9</td>
<td>12.5</td>
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<tr>
<td>20</td>
<td>50</td>
<td>8.5</td>
<td>12.5</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>
Design Comparison – M-E vs Perpetual
Minneapolis – 6” 30 ksi Agg Base – 5 ksi Soil
Need for Distribution-Based Design

• Pavements experience wide range of loading and environmental conditions
  • Results in wide range of strain responses

• Traditional M-E design uses transfer functions and Miner’s Hypothesis to sum damage over time
  • Fatigue transfer functions difficult to develop and may not provide sufficient accuracy
  • 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
Long-Life Pavement Design Software

Software Available @

https://goo.gl/r1yiwQ
http://www.eng.auburn.edu/users/timmdav/Software.html
Cold Central Plant Recycled Perpetual Pavements

- RAP usage common
  - 81.8 million tons used in 2016
  - Majority used as HMA or WMA
- Opportunity to use RAP with cold recycling techniques
  - Fewer virgin materials
  - Less fuel consumption
  - Fewer emissions
  - Faster construction time
- Cold RAP usage in 2016 = 0.2 million tons
Cold Central Plant Recycling

Milling

Fractionation

CCPR Mixing (RAP+recycling agents)

Conventional Paving
Virginia DOT CCPR Experience

• 2011: I-81
  • CIR, FDR & CCPR
  • 6000 trucks/day

• 2012: NCAT Test Track
  • CCPR and Stabilized Base Sections
  • 10 million ESALs/test cycle

• 2016: I-64
  • CCPR and Stabilized Base
VDOT Sections at the NCAT Test Track
VDOT Test Sections

N3-6"AC

S12-4"AC SB

N4-4"AC

CCPR-100% RAP with 2% Foamed 67-22 and 1% Type II Cement

6" Crushed granite aggregate base and 2" subgrade stabilized in-place with 4% Type II cement

Depth, in.

SMA

Superpave

CCPR

Stabilized Base

Aggregate Base

Subgrade

Asphalt Strain Gauges

Temperature Probe

Earth Pressure Cell
Cracking Performance after 20 Million ESALs

N3-6”AC

N4-4”AC

S12-4”AC SB
Rutting Performance After 20 Million ESALs
Ride Quality after 20 Million ESALs
In-Place AC Modulus @ 68F
Tensile Strain @ 68F
Perpetual Pavement Analysis
Additional Perpetual Analysis
Stabilized Base? Use Caution!
VDOT Implementation

- I-64 Williamsburg, VA
- 7.08 miles
- 200,000 tons of RAP
- $10,000,000 savings

$88/\text{yd}^2$ vs. $42/\text{yd}^2$
Future Challenges

SMA

RAS

RAP

WMA

GTR

CIR
U.S. Asphalt Concrete Industry

Estimated WMA Tons (Million)

<table>
<thead>
<tr>
<th>Year</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial &amp; Residential</td>
<td>4.55</td>
<td>11.31</td>
<td>17.81</td>
<td>21.35</td>
<td>22.78</td>
</tr>
<tr>
<td>Other Agency</td>
<td>3.60</td>
<td>9.84</td>
<td>16.29</td>
<td>18.86</td>
<td>27.85</td>
</tr>
<tr>
<td>DOT</td>
<td>8.55</td>
<td>19.99</td>
<td>34.60</td>
<td>46.41</td>
<td>55.68</td>
</tr>
</tbody>
</table>

Tons Used, Million

<table>
<thead>
<tr>
<th>Year</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA/WMA</td>
<td>0.70</td>
<td>1.10</td>
<td>1.19</td>
<td>1.86</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Tons Used, Million

<table>
<thead>
<tr>
<th>Year</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA/WMA</td>
<td>56.0</td>
<td>62.1</td>
<td>66.7</td>
<td>68.3</td>
<td>67.8</td>
</tr>
</tbody>
</table>

WMA

RAS

RAP
Concluding Remarks

• Pavement thickness design in transition
  • From empirical to mechanistic-empirical
• M-E design much more robust
  • Better traffic/climate/materials/performance characterization
  • Capable of adapting to new conditions
• Perpetual pavements are key to sustainable future
  • Incorporation of sustainable materials is critical
• Innovative materials can achieve long-life
Thank you!

Reach me at
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