NCHRP 1-41

Calibration of Fracture Predictions to Observed Reflection Cracking in HMA Overlays

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Rong Luo, Sheng Hu, Fujie Zhou

Pavement Performance Prediction Symposium
July 16, 2009, Laramie, Wyoming
MEPDG vs. NCHRP 1-41

MEPDG

- Traffic
- Material Properties
- Climate-EICM
- Pavement Structure

Pavement Response ($\sigma$, $\epsilon$) Model: Multi-layer elastic system

Pavement Distress Models

Pavement Performance Predictions

NCHRP 1-41

- Interlayer
- Existing Pavement Conditions

Pavement Response Model
- Stress Intensity Factor (SIF)
- Artificial Neural Network (ANN)

Pavement Distress Model Reflection Cracking (Thermal, Shearing, Bending)

Pavement Performance Prediction: Reflection Cracking Extent and Severity
Reflection Cracking Modeling

- Traffic input
- New temperature model
  (Model source: Dr. C. J. Glover, Department of Chemical Engineering, Texas A&M Univ.)
- Load transfer efficiency
- Fracture property of asphalt mixtures (A and n)
- Artificial neural network (ANN) models
  - Stress intensity factor (SIF) model
  - Mixture modulus
- Reflection cracking models
- Model calibration
Mechanisms of Reflection Cracking

- Traffic loading
  - Bending
  - Shearing

- Daily temperature change
  - Thermal stress
Field Data for Calibration and Validation of Reflection Cracking Models

- Long-Term Pavement Performance (LTPP) database

- Reflection cracking projects for Texas Department of Transportation (TxDOT)

- Reflection cracking study at Applied Research Associates (ARA), New York City
Expected Model

- Fast
- Based on current MEPDG parameter
- Accounts for three cracking mechanisms
- Easy to calibrate locally
- Easy to use in design
Reflection Cracking in HMA Overlay

Temperature ($\Delta T$)

Thermal Stress

Bending Load Stress

Shearing Load Stress

Overlay

Existing Asphalt Layer

Subgrade

Base Course

Subbase

$H_{\text{overlay}}$, $E_{\text{overlay}}$, $\alpha_{\text{overlay}}$

$H_{\text{Existing}}$, $E_{\text{Existing}}$, $\alpha_{\text{Existing}}$
Flow Chart of NCHRP 1-41

Selected Test Sections
- 10 models

Field Data Collection
- Distress
- Traffic
- Pavement
- Weather

Field Data Analysis
- Distress
- Traffic
- Axle load distribution

Temperature Model
- Weather data
- Modeling temperature with depth
- New temperature model

Pavement Data
- Layers
- Material properties
- Non-destructive testing

Calibration Process
- Asphalt modulus
  - Falling weight deflectometer
  - Artificial neural network
- Calculated number of days
  - Thermal (2)
  - Shear (2)
  - Bending (1)
- Calibration to field distress
  - Five calibration coefficients
  - Three levels of damage

Crack Propagation Model
- Temperature
- Traffic shear
- Traffic bending
- Artificial neural network models
  - Modulus
  - Stress intensity factors
- Viscoelastic thermal stress
- Crack growth

Final Model of Reflection Cracking
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Climate Zone</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC/AC</td>
<td>AC, then AC OL</td>
<td>59 16 33</td>
<td>108</td>
</tr>
<tr>
<td>AC/Mill/AC</td>
<td>AC, then Mill+AC OL</td>
<td>62 47 16</td>
<td>125</td>
</tr>
<tr>
<td>AC/SC/AC</td>
<td>AC w/ Interlayer, then AC OL</td>
<td>26 12</td>
<td>38</td>
</tr>
<tr>
<td>AC/FC/AC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRC/AC</td>
<td>CRC, then AC OL</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>JPC/AC</td>
<td>PCC, then AC OL</td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td>JRC/AC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>237 16 92 16</td>
<td>361</td>
</tr>
</tbody>
</table>
NYC Sections with Interlayer

- Twelve test sections for each joint spacing
  - 15 ft
  - 20 ft
- Measured cracking ratio
- Various reinforcing interlayers
Texas Sections with Interlayer

- Investigation of reflection cracking control treatment
- Selection of 3 test locations in Texas
- Evaluation of tested pavement in each spring

<table>
<thead>
<tr>
<th>District</th>
<th>Pavement Overlay</th>
<th>Type</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amarillo</td>
<td>AC/Interlayer/AC</td>
<td>Jun. 2002</td>
<td></td>
</tr>
<tr>
<td>Pharr</td>
<td>AC/Interlayer/AC</td>
<td>Apr. 2001</td>
<td></td>
</tr>
<tr>
<td>Waco</td>
<td>AC/Interlayer/JPC</td>
<td>Oct. 2002</td>
<td></td>
</tr>
</tbody>
</table>
Flow Chart of NCHRP 1-41

Selected Test Sections

Field Data Collection
- Distress
- Traffic
- Pavement
- Weather

Field Data Collection

Field Data Analysis
- Distress
- Traffic
- Axle load distribution

Temperature Model

Pavement Data Analysis

Crack Propagation Model

Calibration Process

Final Model
Data Collected from LTPP Sections

- Section 340503 (WF zone in New Jersey)
  - AC/AC overlay rehabilitation: July 27th, 1992
  - Transverse crack length before overlay: 88.2m

![Graphs showing observed crack length and ratio of reflection crack length to max. length over time.](Graphs.png)

- Observed crack length
- Ratio of reflection crack length to max. length
Portland Cement Concrete (PCC) with 20 ft joint spacing

- Interlayer material: composite
- PCC joint crack length: 240 ft (10 joints × 24 ft)

Data Collected from NYC Sections

- Observed crack length
- Ratio of reflection crack length to max. length
Data Collected from Texas Sections

- Amarillo District
  - Interlayer material: composite
  - Transverse crack length before overlay: 46 m

![Observed crack length](image1)

![Ratio of reflection crack length to max. length](image2)
Development of Reflection Cracking

- The amount and severity of reflection cracking follows a sigmoidal curve (S-shape)
Modified Reflection Cracking Model

- Length of transverse crack after overlay
- Observed by time

\[
D(N_i) = e^{\left(\frac{\rho}{N_i}\right)^\beta}
\]

where

- \(D(N_i)\) = Measured crack length at \(N_i\)
- \(N_i\) = number of days after overlay
- \(i\) = \(i^{th}\) crack observation
- \(\rho\) and \(\beta\) = calibration coefficients
Calibration of Reflection Cracking Model

- Given severity levels
  - $\rho_H$ and $\beta_H$ for high severity level
  - $\rho_M$ and $\beta_M$ for medium/high severity levels
  - $\rho_L$ and $\beta_L$ for low/medium/high severity levels

- For specific types of pavement
  - HMA overlay on HMA surface
  - HMA overlay on PCC surface, etc
Calibrated Models for LTPP Sections

- LTPP section 340503 (WF zone in New Jersey)
  - AC/AC overlay

Calibrated Parameters Values

<table>
<thead>
<tr>
<th>Severity</th>
<th>Parameter  $\beta$</th>
<th>Parameter $\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+M+L</td>
<td>2.365</td>
<td>3617.12</td>
</tr>
<tr>
<td>H+M</td>
<td>4.107</td>
<td>4761.25</td>
</tr>
<tr>
<td>H</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Calibration Model for NYC Sections

- NYC test section with 20 ft joint spacing
  - AC/PCC overlay with composite interlayer

Calibrated Parameters Values

<table>
<thead>
<tr>
<th>Severity</th>
<th>Parameter</th>
<th>β</th>
<th>ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+M+L</td>
<td>β</td>
<td>0.731</td>
<td>1402.14</td>
</tr>
<tr>
<td></td>
<td>ρ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H+M</td>
<td>β</td>
<td>0.711</td>
<td>2799.96</td>
</tr>
<tr>
<td></td>
<td>ρ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>β</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>ρ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Calibration Model for Texas Sections

- Texas test sections (Amarillo District)
  - AC/AC overlay with composite interlayer

![Graph showing reflective crack length ratio over time for different severities.]

<table>
<thead>
<tr>
<th>Severeity</th>
<th>Parameter</th>
<th>$\beta$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+M+L</td>
<td></td>
<td>0.667</td>
<td>1619.74</td>
</tr>
<tr>
<td>H+M</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Traffic Data

- Overview of traffic data for AC Overlay Design
  - Axle Load Distribution
- Classification of Traffic Load
- Modeling Cumulative Axle Load Distribution (CALD)
- Determination of CALD of LTPP Test Sections
  - CALD curve
  - Calculated parameters
  - Result of LTPP section (example of 180901)
Axle Load Distribution Factor (1/2)

- Percentage of total axles in each load interval for a specific axle type and vehicle class
- Axle type and load interval

<table>
<thead>
<tr>
<th>Axle Type</th>
<th>Axle Load Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>3,000 ~ 40,000 lb. at 1,000 lb. intervals</td>
</tr>
<tr>
<td>Tandem</td>
<td>6,000 ~ 80,000 lb. at 2,000 lb. intervals</td>
</tr>
<tr>
<td>Tridem &amp; Quad</td>
<td>12,000 ~ 102,000 lb. at 3,000 lb. intervals</td>
</tr>
</tbody>
</table>

- Vehicle class: Class 4 to 13
- Tires: single and dual
Axle Load Distribution Factor (2/2)

- Weigh-In-Motion (WIM) data

- Distribution of axle loads in a vehicle class
  \[ \text{Number of axles measured in each load interval} = \frac{\text{Total number of axles in all load intervals}}{\text{Number of axles measured in each load interval}} \]

- Normalized Axle Load Distribution Factor (ALDF)
  \[ = 100 \text{ for each axle type of each vehicle class} \]
Categorization of Traffic Load

- Eight categories on axle type and number of tires

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Single Axle</th>
<th>Tandem Axle</th>
<th>Tridem Axle</th>
<th>Quad Axle</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>No. 1</td>
<td>No. 3</td>
<td>Single Tire</td>
<td>No. 7</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>No. 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>No. 2</td>
<td>Dual Tires</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>No. 4</td>
<td>No. 6</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>No. 6</td>
<td>No. 8</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
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</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Model Tire Load

Model Tire Load: \( P = p \cdot L \cdot W \)
Cumulative Axle Load Distribution

Cumulative Load Distribution

$P_3 = 1$

$P_2$

$P_1$

Maximum load

Upper load limit*

Lower load limit

$L_1$

$L_2$

$L_3$

$P_i = f(L_i)$

*Tire Length

Legal axle load

Illegal axle load

*Upper load limit:
Federal Regulation for maximum allowable axle weight
### Models for Cumulative Axle Load Distribution

- **Gompertz model**

\[ y = \alpha \exp[-\exp(\beta - \gamma x)] \]

- \( \alpha \) is the **upper asymptote**
- \( \beta \) indicates the **width**
- \( \gamma \) indicates the **slope**

- **Modified model for Cumulative Axle Load Distribution (CALD)**

\[ P(L_i) = \exp[-\exp(\beta - \gamma L_i)] \]
# Characteristics of Axle Load Distribution

<table>
<thead>
<tr>
<th>Axle Type</th>
<th>Tires</th>
<th>Tire width (in.)</th>
<th>Tire Pressure (PSI)</th>
<th>Axle Load (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum ($L_1$)</td>
<td>Max. Allowable* ($L_2$)</td>
</tr>
<tr>
<td>Single</td>
<td>Single</td>
<td>7.874</td>
<td>40 (&lt; 6000 lb)</td>
<td>3,000</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>8.740</td>
<td>120 (&gt; 6000 lb)</td>
<td></td>
</tr>
<tr>
<td>Tandem</td>
<td>Single</td>
<td>7.874</td>
<td>120</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>8.740</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Tridem</td>
<td>Single</td>
<td>7.874</td>
<td>120</td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>8.740</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Quad</td>
<td>Single</td>
<td>7.874</td>
<td>120</td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>8.740</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

*Federal regulation for maximum allowable axle weight
CALD for LTPP Test Section (Single Axle)

- LTPP test section 180901 (Indiana)

![Cumulative Axle Load Distribution Curve](image)

### CALD on tire length

<table>
<thead>
<tr>
<th>Tire Length (in.)</th>
<th>CALD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>3.44</td>
</tr>
<tr>
<td>$L_2$</td>
<td>10.32</td>
</tr>
<tr>
<td>$L_3$</td>
<td>16.67</td>
</tr>
</tbody>
</table>

### Model parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>4.301</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.967</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.982</td>
</tr>
</tbody>
</table>
CALD for LTPP Test Section (Quad Axle)

- LTPP test section 180901 (Indiana)
  - Quad axle/dual tires(2004)

<table>
<thead>
<tr>
<th>Tire Length (in.)</th>
<th>CALD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>0.63</td>
</tr>
<tr>
<td>$P_1$</td>
<td>0.001</td>
</tr>
<tr>
<td>$L_2$</td>
<td>2.41</td>
</tr>
<tr>
<td>$P_2$</td>
<td>0.283</td>
</tr>
<tr>
<td>$L_3$</td>
<td>5.81</td>
</tr>
<tr>
<td>$P_3$</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Model parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>8.384</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>3.377</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.989</td>
</tr>
</tbody>
</table>
All CALD on Tire Length

- LTPP test section 180901 (Indiana)
## Calculated Model Parameters

<table>
<thead>
<tr>
<th>Axle</th>
<th>Tire</th>
<th>Model Parameter</th>
<th>Tire Length (in.)</th>
<th>CALD*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\beta$</td>
<td>$\gamma$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Single</td>
<td>Single</td>
<td>4.301</td>
<td>0.967</td>
<td>0.982</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>4.781</td>
<td>2.302</td>
<td>0.977</td>
</tr>
<tr>
<td>Tandem</td>
<td>Single</td>
<td>4.057</td>
<td>1.096</td>
<td>0.948</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>2.627</td>
<td>1.789</td>
<td>0.934</td>
</tr>
<tr>
<td>Tridem</td>
<td>Single</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>2.140</td>
<td>1.215</td>
<td>0.943</td>
</tr>
<tr>
<td>Quad</td>
<td>Single</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Dual</td>
<td>8.384</td>
<td>3.377</td>
<td>0.989</td>
</tr>
</tbody>
</table>

*Cumulative Axle Load Distribution*
Flow Chart of NCHRP 1-41

1. Selected Test Sections
2. Field Data Collection
   - Field Data Analysis
   - Temperature Model
   - Pavement Data
     - Layers
     - Material properties
     - Non-destructive testing
3. Crack Propagation Model
4. Calibration Process
5. Final Model
Pavement Data Analysis

- Pavement layer structure
- Falling Weight Deflectometer (FWD) data (including temperature)
- Backcalculation of layer moduli (using MODULUS)
Relaxation Modulus by FWD

\[ E(t) \text{ and } T \text{ are measured from FWD} \]

\[ \log E_1 = \log E(t, T) + m_{mix} \log \left( \frac{t}{a_T} \right) \]

\[ E(t, T) = E_\infty + E_1 \left( \frac{t}{a_T} \right)^{-m_{mix}} \]

\[ E(t) = \sum_{i=1}^{n} E_i e^{\frac{-t}{T_i}} \]

**Viscoelastic Thermal Stress**
Flow Chart of NCHRP 1-41

1. Selected Test Sections

2. Field Data Collection

   - Field Data Analysis
   - Temperature Model
   - Pavement Data Analysis

   **Temperature Model**
   - Weather data
   - Modeling temperature with depth
   - New temperature model

3. Crack Propagation Model

4. Calibration Process

5. Final Model
Reflection Cracking in HMA Overlay

- Temperature ($\Delta T$)
- Thermal Stress
- Shearing Load Stress
- Bending Load Stress

Overlay
- $H_{overlay}$, $E_{overlay}$, $\alpha_{overlay}$

Existing Asphalt Layer
- $H_{Existing}$, $E_{Existing}$, $\alpha_{Existing}$

Subgrade

Base Course

Subbase
Flow Chart of Predicting Thermal Crack Growth

Weather Data
- Hourly Solar Radiation
- Daily Wind Speed
- Daily Air Temperature
- Hourly Wind Speed
- Hourly Air Temperature
- Emissivity Coefficient
- Absorption Coefficient
- Albedo

Pavement Temperature ($\Delta T$)

Binder Properties
- 1999 Model? 2006 Model?

Viscoelastic Thermal Stress $\sigma(T)$

Thermal Stress Intensity Factor (SIF) (Artificial Neural Network Model)

Crack Growth $\Delta C = A[J]^n \Delta N$

Relaxation Modulus at Crack Tip (Artificial Neural Network Model)

Fracture Properties $A,n$

Is $\sum \Delta C \geq$ Overlay Thickness

Yes: No. of Days $N_{fT1}, N_{fT2}$

No.

Gradation Volumetric Composition
Frequency ($f_c$)
Viscosity ($\eta$)

Gradation Volumetric Composition
Phase Angle ($\delta_b$)
Shear Modulus of Asphalt ($G^*$)
Pavement Temperature Model

- Enhanced Integrated Climate Model (EICM)
- Model developed by Dr. Charles Glover’s research group, Department of Chemical Engineering, Texas A&M.

\[ \begin{align*}
\alpha &: \text{Albedo} \\
T_a &: \text{Air temperature} \\
q_s &: \text{Solar radiation} \\
\varepsilon &: \text{emissivity coefficient} \\
\varepsilon_a &: \text{absorption coefficient} \\
\kappa &: \text{Thermal conductivity}
\end{align*} \]

(Model source: Xin Jin, Rongbin Han, and Dr. Charles Glover, Department of Chemical Engineering, Texas A&M University)
Typical daily pavement temperature prediction using EICM model
Ahmed et. al (Transportation Research Record 1913, 2005)

Typical daily pavement temperature prediction using Glover model
Pavement Temperature Prediction

- Hourly Solar Radiation
- Hourly Air Temperature
- Hourly Wind Speed
- Emissivity Coefficient
- Absorption Coefficient
- Albedo
- Thermal conductivity coefficients $a$ and $d$

Pavement temperature at different depths
Climate Data Collection

  - Solar radiation (Wh/m²)

- *Daily climate data (1984 - 2002)*
  - Air temperature (°C): mean, maximum & minimum
  - Wind speed (m/s)
Modeled Hourly Air Temperature

Location of pavement section: Mills County, Texas.
Albedo Distribution in Winter

- 0.15-0.2
- 0.3-0.35
Albedo Distribution in Summer

- 0.3-0.35
- 0.15-0.2
Calculated Pavement Temperature

Location of pavement section: Mills County, Texas.
Flow Chart of NCHRP 1-41

Selected Test Sections

Field Data Collection

Field Data Analysis
Temperature Model
Pavement Data Analysis

Crack Propagation Model

Crack Propagation Model

Calibration Process
Final Model of Reflection Cracking

Crack Propagation Model
• Temperature
• Traffic shear
• Traffic bending
• Artificial neural network models
  ➢ Modulus
  ➢ Stress intensity factors
• Viscoelastic thermal stress
• Crack growth
Flow Chart of Predicting Thermal Crack Growth

Weather Data
- Hourly Solar Radiation
- Daily Wind Speed
- Hourly Wind Speed
- Daily Air Temperature
- Hourly Air Temperature
- Emissivity Coefficient
- Absorption Coefficient
- Albedo

Pavement Temperature (ΔT)
- Viscoelastic Thermal Stress $\sigma(T)$
- Thermal Stress Intensity Factor (SIF) (Artificial Neural Network Model)

Binder Properties
- 1999 Model? 2006 Model?
  - 1999 Model
    - Gradation
    - Volumetric Composition
    - Frequency ($f_c$)
    - Viscosity ($\eta$)
  - 2006 Model
    - Gradation
    - Volumetric Composition
    - Phase Angle ($\delta_b$)
    - Shear Modulus of Asphalt ($G^*$)

Relaxation Modulus at Crack Tip (Artificial Neural Network Model)

Crack Growth
- $\Delta C = A[J]^n \Delta N$

Is $\Sigma \Delta C \geq$ Overlay Thickness

Yes
- No. of Days $N_{fT1}, N_{fT2}$

No
Flow Chart of Bending Crack Growth

**Weather Data**
- Hourly Solar Radiation
- Hourly Wind Speed
- Daily Air Temperature
- Emissivity Coefficient

**Pavement Temperature (ΔT)**

**Daily Traffic Vehicle Class Distribution**

**Each Vehicle Class (Axle and Tire Loads)**

**Bending Stress Intensity Factor (SIF) (Artificial Neural Network Model)**

**Crack Growth**
\[ ΔC = A[J]^n ΔN \]

**Layer Relaxation Modulus (Artificial Neural Network Model)**

**Binder Properties**

**Gradation Volumetric Composition**
- Frequency (\( f_i \))
- Viscosity (\( \eta \))

**Gradation Volumetric Composition**
- Phase Angle (\( \delta_a \))
- Shear Modulus of Asphalt (\( G^* \))

**Fracture Properties**

**Is \( ΣΔC ≥ \) Overlay Thickness?**

**No of Days**
\[ N_{IB} \]
Flow Chart of Shearing Crack Growth

Weather Data
- Hourly Solar Radiation
- Daily Wind Speed
- Daily Air Temperature
- Emissivity Coefficient
- Absorption Coefficient
- Albedo

Hourly Wind Speed

Hourly Air Temperature

Daily Wind Speed

Daily Air Temperature

Daily Traffic Vehicle Class Distribution

Pavement Temperature (ΔT)

Binder Properties

1999 Model? 2006 Model?

1999 Model
- Gradation Volumetric Composition Frequency (f_j)
- Viscosity (η)

2006 Model
- Gradation Volumetric Composition Phase Angle (δ_b)
- Shear Modulus of Asphalt (G*)

Layer Relaxation Modulus
(Artificial Neural Network Model)

Fracture Properties A,n

Each Vehicle Class (Axle and Tire Loads)

Shear Stress Intensity Factor (SIF) (Artificial Neural Network Model)

Crack Growth
ΔC = A[J]^n ΔN

Is ΣΔC ≥ Overlay Thickness?

No

Yes

Is ΣΔC ≥ Overlay Thickness?

No of Days
N_{IS1}, N_{IS2}
Witczak 1999 Model

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/4 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/8 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#200 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vₐ (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vₜₜ (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>η (10⁶ poise)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fₜ HZ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E* psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Witczak</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>ANN</td>
<td>0.98</td>
<td></td>
</tr>
</tbody>
</table>
Modeling of Relaxation Modulus by Artificial Neural Network (ANN) (2006 Model)

- Witczak 2006 Model

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradation</td>
<td></td>
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<tr>
<td>3/4 (%)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>#4 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#200 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V_a (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V_{beff} (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log</td>
<td>G*</td>
<td></td>
</tr>
<tr>
<td>10⁶ psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>δ_{c} deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E* psi</td>
<td></td>
<td>0.77</td>
</tr>
<tr>
<td>Witczak</td>
<td></td>
<td>0.96</td>
</tr>
<tr>
<td>ANN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing predicted vs observed IE*I (GPa)](image)

- Predicted IE*I (GPa)
- Observed IE*I (GPa)
Modeling of Stress Intensity Factor (SIF) by Artificial Neural Network (ANN) (1/9)

AC_InterLayer_LevelingCourse_AC_slip_L

- Optimized ANN Model Predictions
  - Independent Testing Set = 250 (Training Set = 2,990)

- Average Absolute Error (AAE) (%) = 1.42
- Root Mean Squared Error (RMSE) = 0.18
- Coefficient of Correlation, $R^2 = 0.9997$
- $Se / Sy = (0.16/9.44) = 0.017$

AC_InterLayer_LevelingCourse_AC_slip_M

- Optimized ANN Model Predictions
  - Independent Testing Set = 250 (Training Set = 2,990)

- Average Absolute Error (AAE) (%) = 2.00
- Root Mean Squared Error (RMSE) = 0.18
- Coefficient of Correlation, $R^2 = 0.9995$
- $Se / Sy = (0.16/7.90) = 0.020$

Inputs:
- Hoarealv, Eryalv, Hervalv, Hervalv, Eviralv, OAC, 
  Geenizing, C

Output: SIF (Stress Intensity Factor)
Modeling of Stress Intensity Factor (SIF) by Artificial Neural Network (ANN) (3/9)

**AC_AC**

- Optimized ANN Model Predictions
  - Independent Testing Set = 250 (Training Set = 1,370)
- Average Absolute Error (AAE) (%) = 1.50
- Root Mean Squared Error (RMSE) = 0.33
- Coefficient of Correlation, $R^2 = 0.9982$
- $S_e / S_y = (0.32 / 7.80) = 0.040$

**AC_PCC**

- Optimized ANN Model Predictions
  - Independent Testing Set = 500 (Training Set = 14,080)
- Average Absolute Error (AAE) (%) = 2.10
- Root Mean Squared Error (RMSE) = 1.32
- Coefficient of Correlation, $R^2 = 0.9998$
- $S_e / S_y = (1.23 / 99.60) = 0.012$
Modeling of Stress Intensity Factor (SIF) by Artificial Neural Network (ANN) (4/9)

Pure_Bending_AC_AC_Dual_Tire_Together

Pure_Bending_AC_AC_Dual_Tire_Together (Only Positive)
Modeling of Stress Intensity Factor (SIF) by Artificial Neural Network (ANN) (5/9)

Pure_Bending_AC_AC_Single_Tire_Together

Pure_Bending_AC_AC_Single_Tire_Together (Only Positive)

Optimized ANN Model Predictions
Independent Testing Set = 250 (Training Set = 1,509)

Average Absolute Error (AAE) (%) = 14.88
Root Mean Squared Error (RMSE) = 0.16
Coefficient of Correlation, $R^2 = 0.9993$
$Se / Sy = (0.15/5.73) = 0.025$

Optimized ANN Model Predictions
Independent Testing Set = 250 (Training Set = 871)

Average Absolute Error (AAE) (%) = 44.91
Root Mean Squared Error (RMSE) = 0.24
Coefficient of Correlation, $R^2 = 0.9965$
$Se / Sy = (0.24/3.99) = 0.059$

Inputs: $H_{rootly}$, $E_{rootly}$, $H_{olight}$, $E_{olight}$, $H_{base}$, $E_{base}$, $H_{sand}$, $L_{tire}$, $c$
Output: SIF (Stress Intensity Factor)
Modeling of Stress Intensity Factor (SIF) by Artificial Neural Network (ANN) (6/9)

Pure_Bending_AC_PCC_Single_Tire_Together

Pure_Bending_AC_PCC_Single_Tire_Together
(Only Positive)
Modeling of Stress Intensity Factor (SIF) by Artificial Neural Network (ANN) (7/9)

AC_AC_Shearing_BendPart_Dual_Tire

<table>
<thead>
<tr>
<th>Optimized ANN Model Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Testing Set = 250 (Training Set = 4,070)</td>
</tr>
<tr>
<td>Average Absolute Error (AAE) (%) = 8.05</td>
</tr>
<tr>
<td>Root Mean Squared Error (RMSE) = 0.15</td>
</tr>
<tr>
<td>Coefficient of Correlation, $R^2 = 0.9991$</td>
</tr>
<tr>
<td>$Se / Sy = (0.15/5.14) = 0.029$</td>
</tr>
</tbody>
</table>

AC_AC_Shearing_ShearPart_Dual_Tire

<table>
<thead>
<tr>
<th>Optimized ANN Model Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Testing Set = 500 (Training Set = 12,460)</td>
</tr>
<tr>
<td>Average Absolute Error (AAE) (%) = 1.47</td>
</tr>
<tr>
<td>Root Mean Squared Error (RMSE) = 0.03</td>
</tr>
<tr>
<td>Coefficient of Correlation, $R^2 = 0.9999$</td>
</tr>
<tr>
<td>$Se / Sy = (0.03/2.74) = 0.010$</td>
</tr>
</tbody>
</table>
Modeling of Stress Intensity Factor (SIF) by Artificial Neural Network (ANN) (9/9)

AC_PCC_Shearing_ ShearPart_Dual_Tire

- Optimized ANN Model Predictions:
  - Independent Testing Set = 500 (Training Set = 12,460)

- Average Absolute Error (AAE) (%) = 1.13
- Root Mean Squared Error (RMSE) = 0.02
- Coefficient of Correlation, $R^2 = 0.9998$
- $S_e / S_y = (0.01/0.62) = 0.010$

- Inputs: $H_{shear}$, $E_{shear}$, $H_{flange}$, $E_{flange}$, $H_{hole}$, $E_{hole}$, $Embrake$, $Log\ K_{flange,torque}$, $L_{tire, c}$
- Output: SIF (Stress Intensity Factor)

AC_PCC_Shearing_ ShearPart_Single_Tire

- Optimized ANN Model Predictions:
  - Independent Testing Set = 500 (Training Set = 12,460)

- Average Absolute Error (AAE) (%) = 0.77
- Root Mean Squared Error (RMSE) = 0.01
- Coefficient of Correlation, $R^2 = 0.9999$
- $S_e / S_y = (0.01/1.54) = 0.010$

- Inputs: $H_{shear}$, $E_{shear}$, $H_{flange}$, $E_{flange}$, $H_{hole}$, $E_{hole}$, $Embrake$, $Log\ K_{flange,torque}$, $L_{tire, c}$
- Output: SIF (Stress Intensity Factor)
Fracture Properties of Asphalt Mixtures

Paris’ Law – Traffic

\[
\frac{dc}{dN} = \frac{A[\Delta K_I + 2\Delta K_{II} ]^n \cdot a_k}{(\text{Healing Shift Factor})}
\]

c = Crack length

N = Load repetitions

\(K_I, K_{II}\) = Bending, shearing stress intensity factor

A, n = Fracture coefficients

\(a_k\) = Viscoelastic stress pulse effect
Fracture Properties of Asphalt Mixtures – SHRP Formulation (1/3)

\[ n = g_0 + \frac{g_1}{m_{mix}} \]

\[ \log A = g_2 + \frac{g_3}{m_{mix}} \log D_1 + \frac{g_4}{m_{mix}} \log \sigma_t \]

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Wet-Freeze</th>
<th>Wet-No Freeze</th>
<th>Dry-Freeze</th>
<th>Dry-No Freeze</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g_0)</td>
<td>-2.09</td>
<td>-1.429</td>
<td>-2.121</td>
<td>-2.024</td>
</tr>
<tr>
<td>(g_1)</td>
<td>1.952</td>
<td>1.971</td>
<td>1.677</td>
<td>1.952</td>
</tr>
<tr>
<td>(g_2)</td>
<td>-6.108</td>
<td>-6.174</td>
<td>-5.937</td>
<td>-6.107</td>
</tr>
<tr>
<td>(g_3)</td>
<td>0.154</td>
<td>0.19</td>
<td>0.192</td>
<td>1.53</td>
</tr>
<tr>
<td>(g_4)</td>
<td>-2.111</td>
<td>-2.079</td>
<td>-2.048</td>
<td>-2.113</td>
</tr>
<tr>
<td>(g_5)</td>
<td>0.037</td>
<td>0.128</td>
<td>0.071</td>
<td>0.057</td>
</tr>
<tr>
<td>(g_6)</td>
<td>0.261</td>
<td>1.075</td>
<td>0.762</td>
<td>0.492</td>
</tr>
</tbody>
</table>
Fracture Properties of Asphalt Mixtures – SHRP Formulation (2/3)

- Tensile Strength

\[ r = 0.005 \text{ in} / \text{mm}, \ T = 77^\circ F, \ \sigma_t = 6.895 \left[ \frac{E(t,T) \times 1000}{6.895 \times 21.3} \right]^{\frac{1}{1.95}} \rightarrow \text{Temperature} \]

\[ r = 0.5 \text{ in} / \text{mm}, \ T = 77^\circ F, \ \sigma_t = 6.895 \left[ \frac{E(t,T) \times 1000}{6.895 \times 45.5} \right]^{\frac{1}{1.56}} \rightarrow \text{Traffic} \]
### Fracture Properties of Asphalt Mixtures – SHRP Formulation (3/3)

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>$t_o$</th>
<th>$w_{rm}$</th>
<th>$R$</th>
<th>$T_d$ (°C)</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$G_g$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet-Freeze</td>
<td>285.506</td>
<td>0.0151552</td>
<td>1.935091</td>
<td>-5.8</td>
<td>-31.5684</td>
<td>199.212</td>
<td>0.86122</td>
</tr>
<tr>
<td>Wet-No Freeze</td>
<td>23673.4</td>
<td>7.057E-05</td>
<td>2.260818</td>
<td>-6.41</td>
<td>-42.4851</td>
<td>259.275</td>
<td>0.90583</td>
</tr>
<tr>
<td>Dry-Freeze</td>
<td>2548.37</td>
<td>0.0013974</td>
<td>2.286142</td>
<td>-6.22</td>
<td>-38.7678</td>
<td>239.04</td>
<td>1.57084</td>
</tr>
<tr>
<td>Dry-No Freeze</td>
<td>3831.11</td>
<td>0.0008449</td>
<td>2.031535</td>
<td>-6.07</td>
<td>-41.5477</td>
<td>266.889</td>
<td>0.53157</td>
</tr>
</tbody>
</table>
Binder Properties: CAM Model

Shear Modulus of Binder (Pa) vs. Frequency (rad/sec)

- Bryan Binder PP2+0Month (Measured)
- Bryan Binder PP2+0Month (Modeled)
- Bryan Binder PP2+3Month (Measured)
- Bryan Binder PP2+3Month (Modeled)
- Bryan Binder PP2+6Month (Measured)
- Bryan Binder PP2+6Month (Modeled)
Determination of $m_{\text{mix}}$ for Fracture Model

\[ \log[E_{\text{mix}}] \]

Calculated with ANN-Witczak Model

\[ E_{\text{mix}} = E_1 \left( \frac{t}{a_t} \right)^{-m_{\text{mix}}} \]
Determination of Compliance Coefficient for Fracture Model

\[ D_1 = \frac{E_1 \cdot \sin (m_{mix} \cdot \pi)}{\pi \cdot m_{mix}} \]
Viscoelastic Stress Pulse Effect

\[ W(t) \]
Load Wave Shape

\[ [W(t)]^n \]

\[(0.92)^n\]
\[(0.84)^n\]
\[(0.72)^n\]

\[ (18 + L_j) \text{ ft.} \]

\[ \Delta t \]
Viscoelastic Stress Pulse Effect

Overlay $L_j$

Old Surface

Crack or Joint

Load Wave Shape

$W(t)$

$[W(t)]^n$

$(1.11)^n$

$(14 + L_j)$ ft.

$\Delta t$

4.0 ft

5.0 ft

$4.0$ ft

$5.0$ ft

$5.0$ ft

$5.0$ ft

$4.0$ ft

$4.0$ ft

$4.0$ ft

$4.0$ ft

$4.0$ ft

$4.0$ ft
Flow Chart of NCHRP 1-41

Selected Test Sections

Field Data Collection

Field Data Analysis

Temperature Model

Pavement Data Analysis

Crack Propagation Model

Calibration Process
- Asphalt modulus
  - Falling weight deflectometer
  - Artificial neural network
- Calculated number of days
  - Thermal (2)
  - Shear (2)
  - Bending (1)
- Calibration to field distress
  - Five calibration coefficients
  - Three levels of damage

Final Model of Reflection Cracking
- $N_{fB1} = \text{Number of days for crack growth due to bending to reach Position I.}$
- $N_{fT1} = \text{Number of days for thermal crack growth to reach Position I.}$
- $N_{fS1} = \text{Number of days for crack growth due to shearing stress to reach Position I.}$
- $N_{fT2} = \text{Number of days for thermal crack growth to go from Position I to Position II.}$
- $N_{fS2} = \text{Number of days for crack growth due to shearing stress to go from Position I to Position II.}$
Calibration Quantities

\[ \rho_{LMH} = N_{JT1} \left( \alpha_0 + \alpha_1 \frac{N_{JT1}}{N_{JS1}} + \alpha_2 \frac{N_{JT1}}{N_{JB1}} \right) + N_{JT2} \left( \alpha_3 + \alpha_4 \frac{N_{JT2}}{N_{JS2}} \right) \]

Calibration Coefficients: \( \alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \beta_{LMH} \)
Another Set of Calibration Coefficients

\[ \rho_{MH} = N_{fT1} \left( \alpha_5 + \alpha_6 \frac{N_{fT1}}{N_{fS1}} + \alpha_7 \frac{N_{fT1}}{N_{fB1}} \right) + N_{fT2} \left( \alpha_8 + \alpha_9 \frac{N_{fT2}}{N_{fS2}} \right) \]

Calibration Coefficients: \( \alpha_5, \alpha_6, \alpha_7, \alpha_8, \alpha_9, \beta_{MH} \)

\[ \rho_H = N_{fT1} \left( \alpha_{10} + \alpha_{11} \frac{N_{fT1}}{N_{fS1}} + \alpha_{12} \frac{N_{fT1}}{N_{fB1}} \right) + N_{fT2} \left( \alpha_{13} + \alpha_{14} \frac{N_{fT2}}{N_{fS2}} \right) \]

Calibration Coefficients: \( \alpha_{10}, \alpha_{11}, \alpha_{12}, \alpha_{13}, \alpha_{14}, \beta_H \)
High severity Regression results of \( \rho \) and \( \beta \) for AC over JPC/JR pavement and Wet-Freeze climate zone beginning service during the winter.
High severity Regression results of $\rho$ and $\beta$ for AC over JPC/JRC pavement and Wet-Freeze climate zone beginning service during the summer.
Cracking Extent and Severity: AC over AC, WF

AC over AC Pavement at Anchorage, Alaska (WF)
Cracking Extent and Severity: AC over JRC, WF

AC over JRC Pavement at Champaign, Illinois (WF)
Cracking Extent and Severity: AC over FC over AC, WF

AC over FC over AC Pavement at Frederick, Maryland (WF)
Cracking Extent and Severity: AC over CRC, WF

AC over CRC Pavement at Tippecanoe, Indiana (WF)
Cracking Extent and Severity: AC over PetroGrid over PCC, WNF

AC over PetroGrid over PCC pavement at Waco, Texas (WNF)
Cracking Extent and Severity: AC over PetroGrid over AC, DF

AC over PetroGrid over AC pavement at Amarillo, Texas (DF)
Cracking Extent and Severity: AC over AC, WNF

AC over AC Pavement at Houston, Alabama (WNF)
Cracking Extent and Severity: AC over FC over AC, WNF

AC over FC over AC Pavement at Yazoo, Mississippi (WNF)
Cracking Extent and Severity: AC over AC, DF

AC over AC Pavement at Deaf Smith COUNTY, Texas (DF)
Cracking Extent and Severity: AC over AC, DNF

AC over AC Pavement in San Bernardino, California (DNF)
Cracking Extent and Severity: AC over GlasGrid over PC, WF

AC over GlasGrid over PC pavement at New York, New York (WF)
Flow Chart of NCHRP 1-41

Selected Test Sections
- 10 models

Field Data Collection
- Distress
- Traffic
- Pavement
- Weather

Field Data Analysis
- Distress
- Traffic
- Axle load distribution

Temperature Model
- Weather data
- Modeling temperature with depth
- New temperature model

Pavement Data
- Layers
- Material properties
- Non-destructive testing

Calibration Process
- Asphalt modulus
  - Falling weight deflectometer
  - Artificial neural network
- Calculated number of days
  - Thermal (2)
  - Shear (2)
  - Bending (1)
- Calibration to field distress
  - Five calibration coefficients
  - Three levels of damage

Crack Propagation Model
- Temperature
- Traffic shear
- Traffic bending
- Artificial neural network models
  - Modulus
  - Stress intensity factors
- Viscoelastic thermal stress
- Crack growth

Final Model of Reflection Cracking
Calibration of Fracture Predictions to Observed Reflection Cracking in HMA Overlays

Robert L. Lytton
Fang-Ling Tsai, Sang-Ick Lee
Rong Luo, Sheng Hu, Fujie Zhou

Pavement Performance Prediction Symposium
July 16, 2009, Laramie, Wyoming