Update on Experiment to Model and Calibrate Pavement Structural Effects on Vehicle Fuel Economy and GHG Emissions

Participants:
University of California Pavement Research Center
Michigan State University
Massachusetts Institute of Technology Concrete Sustainability Hub
Oregon State University
University of Minnesota
Symplectic Engineering Corporation

Sponsored by:
California Department of Transportation
with assistance from Minnesota Department of Transportation
Phase I Tasks

• **I:1** Identify participating modelers, review models.
  – Completed

• **I:2** Identify test sections, measure pavement characteristics needed by modelers, and other characteristics affecting fuel economy.
  – 22 sections identified
  – Field deflection, IRI and MPD measurements completed twice (cool, hot conditions)
  – Laboratory shear frequency sweep tests as cross-check on viscoelastic high temp properties
  – Completed
Phase I Tasks

• I:3 Compare modeling results for test sections
  – Initial comparison of deflections, energy dissipation, fuel use for example pavements, completed
  – Back-calculation of elastic and viscoelastic properties for test sections (MSU), completed
  – Calculations of deflections, energy dissipation, differences in vehicle fuel economy for structural response, roughness, MPD, currently underway, expected completion 1 Dec 2014

• I:4 Prepare experimental plan for validation of modeling results: December 2014

• I:5 Communicate results of Phase I: January 2015

• I:6 Summarize results of Phase I: January 2015
Model Approaches

• UCPRC (implementation of Lyon)
  – Viscoelastic energy dissipation in asphalt on elastic underlying layers
  – 3-D finite element implementation

• Massachusetts Institute of Technology
  – Energy consumption in vehicle due to viscoelastic top layer (wheel rolling up hill calculated with gradient at wheel location in a moving coordinate system)
  – Viscoelastic beam implementation and elastic subgrade
  – Intended primarily for network use after calibration with finite element solutions

• Michigan State University
  – Energy consumption in vehicle due to viscoelastic top layer on elastic underlying layers (wheel rolling up hill calculated with average gradient of bowl)
  – Axisymmetric finite element implementation
Outside review of models and implementation by L. Khazanovich and S. Weissman, funded by MnDOT

Review of
assumptions,
implementation,
recommendations,

- for improving
  - implementation
  - for future
  - improvements
  - to models

The University of Minnesota research team reviewed the "Model information and implementation details" documents from MSU, MIT, and UCRC (see Appendix B) and provided recommendations on the modification of the evaluation.

1. Pervent detection models
2. Required inputs for detection models
3. Dissipation energy calculation
4. Other factors
5. Fuel consumption determination

The research team also evaluated the simple pavement sections for initial evaluation of models (see Appendix A) and provided recommendations on the modification of the evaluation.

Three modeling tools used to evaluate excess vehicle fuel consumption due to pavement deformations are evaluated. The three models are labeled as:

1. MIT
2. UCRC
3. Michigan
<table>
<thead>
<tr>
<th>Parameters for comparison</th>
<th>Max deflection at the bottom of the basin</th>
<th>Average slope under contact area</th>
<th>Dissipated energy in pavement (stress and strain)</th>
<th>Power from gradient compared to no gradient from HDM-4</th>
<th>Excess fuel consumption</th>
<th>Energy from profile or IRI</th>
<th>Energy from macrotexture</th>
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</thead>
<tbody>
<tr>
<td>Michigan State University</td>
<td>X (calibrate elastic cases w/LET)</td>
<td>X</td>
<td>X</td>
<td>X using Col. 2, 4 results</td>
<td>X</td>
<td>X NCHRP 720 eqtn + simulation model</td>
<td>X NCHRP 720 eqtn</td>
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<tr>
<td>MIT</td>
<td>X (not calibrated)</td>
<td>X</td>
<td>X</td>
<td>X from Gen II model</td>
<td>X</td>
<td>X approach using profile</td>
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<td>UCPRC</td>
<td>X (calibrate elastic cases w/LET)</td>
<td>X</td>
<td>X</td>
<td>X using Col. 3 results</td>
<td>X</td>
<td>X NCHRP 720 eqtn</td>
<td>NCHRP 720 eqtn</td>
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<tr>
<td>Section</td>
<td>Structure and Surface Type</td>
<td>Approx $H_{\text{top}}$ (mm)</td>
<td>Subgrade</td>
<td>Length (km)</td>
<td>Slope</td>
<td>avg IRI</td>
<td>MPD</td>
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<tr>
<td>---------</td>
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<td>PD-01</td>
<td>Concrete (JPCP)</td>
<td>222</td>
<td>Clay</td>
<td>0.94</td>
<td>-0.04%</td>
<td>1.16</td>
<td>0.29</td>
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<tr>
<td>PD-02</td>
<td>Concrete (JPCP) (Dowelled)</td>
<td>208</td>
<td>sand</td>
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<td>PD-03</td>
<td>Concrete (JPCP)</td>
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<td>1.17</td>
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<td>PD-04</td>
<td>Concrete (JPCP)</td>
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<td>0.17%</td>
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<tr>
<td>PD-05</td>
<td>Concrete (CRC)</td>
<td>TBD</td>
<td>Any</td>
<td>0.75</td>
<td>0.06%</td>
<td>1.15</td>
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<td>PD-06</td>
<td>HMA-O HMA</td>
<td>36 268</td>
<td>Sand</td>
<td>1.19</td>
<td>-0.09%</td>
<td>1.56</td>
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<td>PD-07</td>
<td>RHMA-G PCC</td>
<td>146 224</td>
<td>Sand</td>
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<tr>
<td>PD-08</td>
<td>HMA-O HMA PCC</td>
<td>35 117 278</td>
<td>Clay</td>
<td>0.38</td>
<td>-0.10%</td>
<td>1.54</td>
<td>1.37</td>
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<tr>
<td>PD-10</td>
<td>RHMA-G HMA PCC</td>
<td>86 196 233</td>
<td>Sand</td>
<td>0.81</td>
<td>-0.06%</td>
<td>0.97</td>
<td>1.67</td>
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<td>PD-11</td>
<td>HMA-O HMA</td>
<td>41 244</td>
<td>Clay</td>
<td>0.63</td>
<td>0.05%</td>
<td>1.22</td>
<td>2.06</td>
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<td>PD-12</td>
<td>HMA-O HMA</td>
<td>37 139</td>
<td>Clay</td>
<td>0.63</td>
<td>-0.02%</td>
<td>1.32</td>
<td>1.01</td>
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<tr>
<td>Section</td>
<td>Structure and Surface Type</td>
<td>Approx H&lt;sub&gt;top&lt;/sub&gt; (mm) GPR/coring</td>
<td>Sub grade</td>
<td>Length (km)</td>
<td>Slope</td>
<td>avg IRI</td>
<td>MPD</td>
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<tr>
<td>---------</td>
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<td>391</td>
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<td>0.13%</td>
<td>1.37</td>
<td>0.73</td>
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<td>PD-14</td>
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<td>233</td>
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<td>3.57</td>
<td>0.70</td>
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<td>PD-15</td>
<td>RHMA-O HMA</td>
<td>31 193</td>
<td>Sand</td>
<td>1.13</td>
<td>0.08%</td>
<td>0.95</td>
<td>2.05</td>
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<td>PD-16</td>
<td>HMA-G HMA</td>
<td>41 231</td>
<td>Sand</td>
<td>0.63</td>
<td>0.12%</td>
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<td>PD-17</td>
<td>HMA</td>
<td>210</td>
<td>Any</td>
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<td>-0.01%</td>
<td>1.37</td>
<td>0.66</td>
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<td>PD-18</td>
<td>RHMA-G HMA</td>
<td>29 226</td>
<td>Sand</td>
<td>0.63</td>
<td>-0.08%</td>
<td>0.65</td>
<td>0.85</td>
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<tr>
<td>PD-19</td>
<td>RHMA-G HMA</td>
<td>65 168</td>
<td>Any</td>
<td>0.75</td>
<td>0.01%</td>
<td>0.95</td>
<td>0.84</td>
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<td>PD-20</td>
<td>RHMA-G HMA CTB</td>
<td>43 115 217</td>
<td>Clay</td>
<td>0.50</td>
<td>-0.02%</td>
<td>1.72</td>
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<td>PD-21</td>
<td>HMA-O HMA CTB</td>
<td>30 124 235</td>
<td>Clay</td>
<td>0.38</td>
<td>1.01%</td>
<td>1.51</td>
<td>1.84</td>
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<tr>
<td>PD-22</td>
<td>RHMA-G HMA CTB</td>
<td>43 246 124</td>
<td>Clay</td>
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<td>0.25%</td>
<td>1.20</td>
<td>0.74</td>
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<td>PD-23</td>
<td>HMA CTB</td>
<td>274 146</td>
<td>Sand</td>
<td>0.63</td>
<td>-0.11%</td>
<td>0.88</td>
<td>0.80</td>
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</tbody>
</table>
Day and night FWD testing

- Temperature measured to 200 mm depth in AC for back-calculations
Lab Testing

• Shear frequency sweeps on upper layers of AC sections for comparison with back-calculated values
Field Testing

• MPD and MTD from Laser Texture Scanner
IRI from inertial profiler day and night

- RoLine laser used on PCC for IRI
- Spot laser used on AC for IRI
- High speed spot laser on AC for MPD

The MPD values measured along the section are shown in Figure 8.
Dynamic back-calculations by Michigan State University

- Back-calculated multiple points in each section
- Some divided into sub-sections
- Relaxation modulus $E_t$, complex modulus $E^*$, shift factor
- No major differences day vs night
Analysis of initial two simple pavement sections for initial comparisons and for calibration of MIT model

- Back-calculations to develop master curve from day and night FWD tests
- Pavements
  - 3 layers all linear elastic, poisson = 0.35
  - 3 layers visco elastic surface, poisson = 0.35 one asphalt material master curve
- Two temperatures (20, 50 C) x two speeds (5, 60 mph)
- Vehicle information:
  - Single wheel, circular or square load, contact pressure = 700 kPa
  - Load = 5 kN, 20 kN, 40 kN
- Outcome to report: shape of deflection basin and dissipated energy for each case
  - Total cases: three elastic cases and twelve viscoelastic cases
Initial DISPLACEMENT COMPARISONS – ELASTIC
UCPRC shallow subgrade

Comparison slides prepared by E. Coleri
Initial DISPLACEMENT COMPARISONS – VISCOELASTIC – 50C – 5 mph
UCPRC shallow subgrade

UCPRC-5kN-5mph-50C
MSU-5kN-5mph-50C
MIT-5kN-5mph-50C

UCPRC-20kN-5mph-50C
MSU-20kN-5mph-50C
MIT-20kN-5mph-50C

UCPRC-40kN-5mph-50C
MSU-40kN-5mph-50C
MIT-40kN-5mph-50C
UCPRC change in subgrade thickness

• Changed from shallow subgrade used by Pouget to 5 m thick subgrade to better match semi-infinite subgrades of Michigan State and Layer Elastic Theory

• MIT using Winkler foundation
DISPLACEMENT COMPARISONS - ELASTIC

- UCPRC-5kN-5mph
- MSU-5kN-5mph
- MIT-5kN-5mph

- UCPRC-20kN-5mph
- MSU-20kN-5mph
- MIT-20kN-5mph

- UCPRC-40kN-5mph
- MSU-40kN-5mph
- MIT-40kN-5mph
DISPLACEMENT COMPARISONS – VISCOELASTIC – 50C – 5 mph

Graph 1: UCPRC-5kN-5mph-50C, MSU-5kN-5mph-50C, MIT-5kN-5mph-50C

Graph 2: UCPRC-20kN-5mph-50C, MSU-20kN-5mph-50C, MIT-20kN-5mph-50C

Graph 3: UCPRC-40kN-5mph-50C, MSU-40kN-5mph-50C, MIT-40kN-5mph-50C
Excess fuel consumption measurements

• MIT and MSU are using equivalent gradient to calculate excess fuel consumption:

\[ GR = 100 \times \sum_{i=0}^{n-1} \left( \frac{d_{i+1} - d_i}{Dx} \right) \]

- \( GR \) = Equivalent Gradient in %
- \( d_i \) = The deflection at position \( x_i \) (m)
- \( Dx \) = Incremental \( (x_{i+1} - x_i) \) (m)
- \( n \) = The number of data points under the contact area \( (x_{\text{dmax}}, x_{(\text{dmax}+\text{radius})}) \)

• UCPRC is using strain-stress and phase angle:

(Pouget et al)

\[ W = \iiint (\pi \cdot \sin(\phi_E) \cdot \sigma_{0z} \cdot \varepsilon_{0z}) \cdot dV \]
EXCESS FUEL CONSUMPTION COMPARISONS – Diesel

Excess fuel for Diesel (mL/km)

MSU
MIT
UCPRC

Excess fuel for Diesel (mL/km)

5 mph 60 mph 5 mph 60 mph 5 mph 60 mph 5 mph 60 mph 5 mph 60 mph

5 kN 20 kN 40 kN 5 kN 20 kN 40 kN

20 C 50 C
Factorial for analysis of results from field test sections

• **Speeds**
  - 50 km/hr (31.3 mph), 100 km/hr (61.5 mph)

• **Temperatures**
  - One temperature at 1/3 depth in the total asphalt layers: 30 C and 45 C

• **Factorial**
  - 3 vehicles x 2 speeds x 2 temperatures x Z structures
    (Z up to 22, start with 10)

• **Vehicles (use from NCHRP 720 study)**
  - Medium car, SUV, Heavy truck
Phase II: assessment of importance and potential empirical calibration

• Phase II will begin in December 2014
• Objectives
  – A: Using the calibrated models, calculate net annual excess fuel consumption for vehicles, traffic speeds, temperatures, pavement types (flexible, composite, semi-rigid, jointed concrete, continuously reinforced concrete) for California conditions
  – If results warrant, then:
  – B: Verify the same models using the results of field measurements on the same sections with instrumented vehicles
    • General approach used by Michigan State for calibration of HDM4 models for fuel use for macrotecture and roughness (NCHRP 1-45)