Model Validation Using Accelerated Facility Measurements

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Drawbacks of Current Flexible Pavement Analysis

- Vehicular Loading:
  - Stationary Circular
- Pressure Distribution:
  - Uniform Vertical Contact Stress
  - No Surface Tangential Contact Stresses
- Effect of Vehicle Speed & Loading:
  - Pavement Response to Loading Is Time-Independent
  - No Transient Local Loading

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Transient Local Load

- Total wheel loads:
  - Static portion + Time-dependent dynamic load changes
  - Coupled with the continuous amplitude
  - Nonuniform distribution
- Mass inertia forces in dynamic analyses
  - Mass inertia forces are exerted by the dynamic changes of loads within tire imprint

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Outline

- Proper Instrumentation
- Modeling
- Field Validation

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Benefits of Instrumentation

- Measurement of response
- Prediction of performance/ failure
- Life estimation
- Pavement configuration comparisons
- Modification of designs
- Construction/ maintenance evaluation

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Pavement Instrumentation

- Selection
- Calibration
- Installation
- Protection
- Data Collection
- Data Analysis

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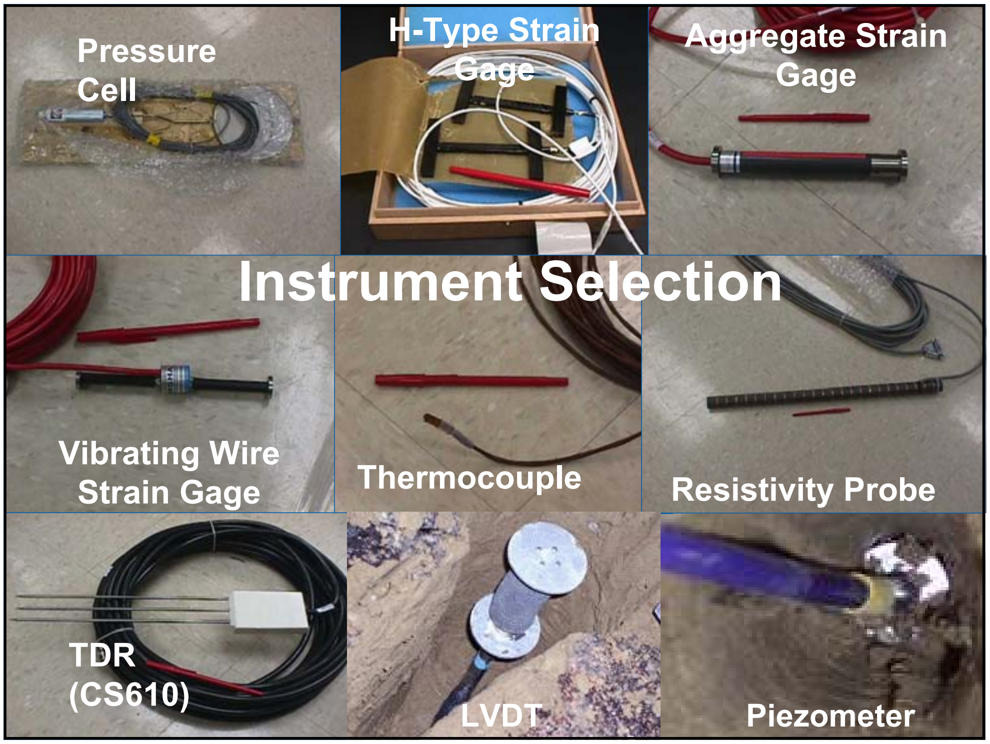
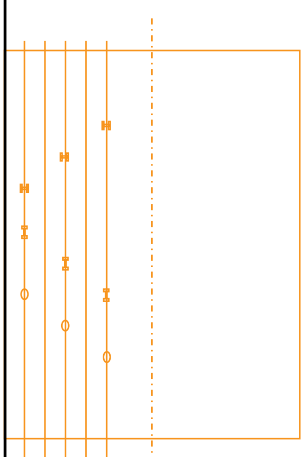
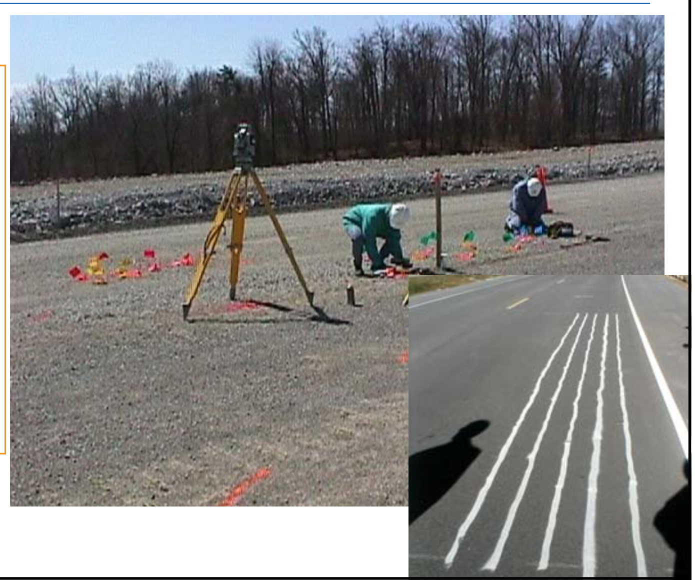

Pressure Cell
H-Type Strain Gage
Aggregate Strain Gage
Instrument Selection
Vibrating Wire Strain Gage
Thermocouple
Resistivity Probe
TDR (CS610)
LVDT
Piezometer


Instrument Modification (LVDT)

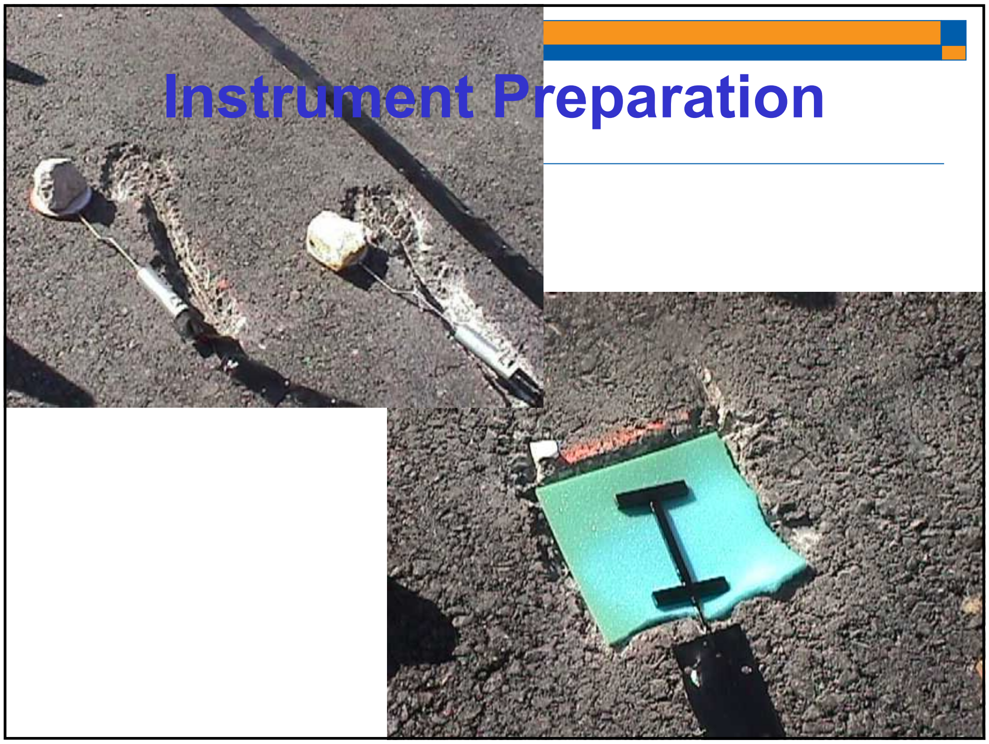
Instrument Calibration (TDR)

INSTRUMENT LOCATION AND DRIVING PATHS

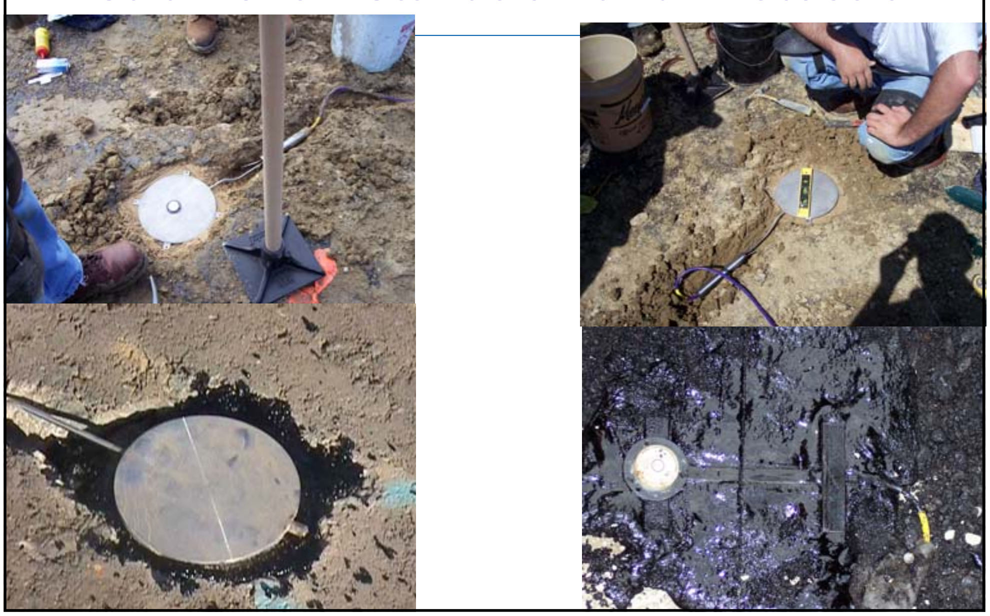




Instrument Preparation



Instrument Installation and Protection



LVDT Installation

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Instrument Protection

Instrument Protection

WIRE SPLICING

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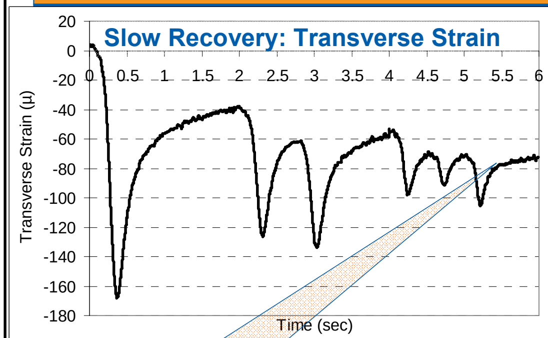
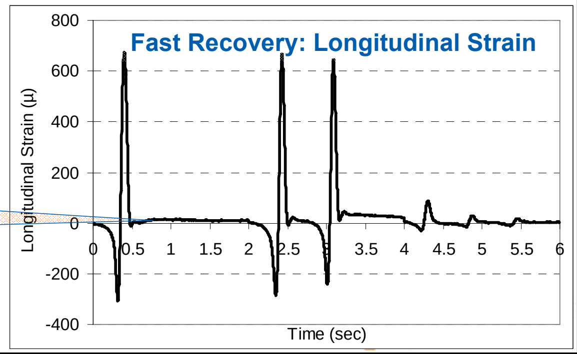
Field Responses



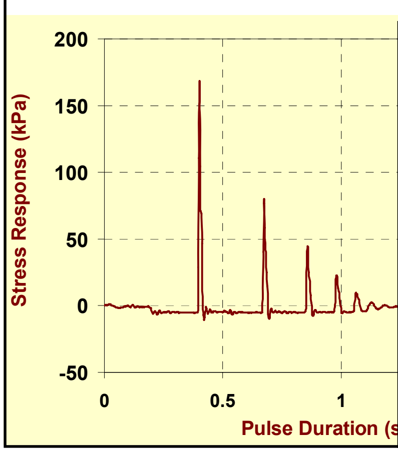
Residual strain condition: 5 mph and 34 ºC HMA

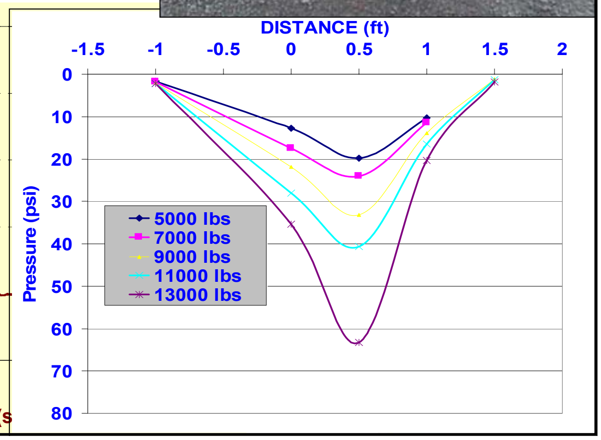
Greater residual strain in transverse direction

Smaller residual strain

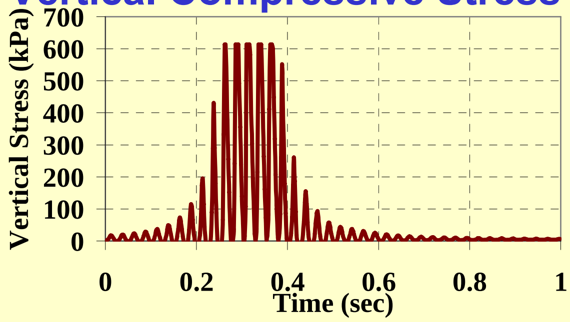


Instrument Response under FWD Loading

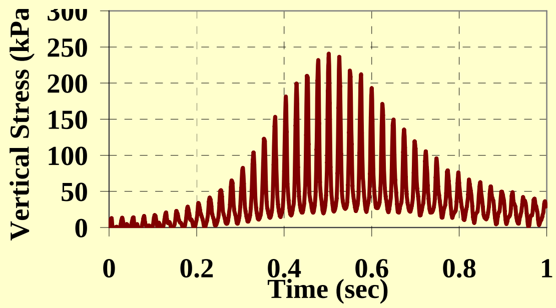




Vertical Compressive Stress during Compaction

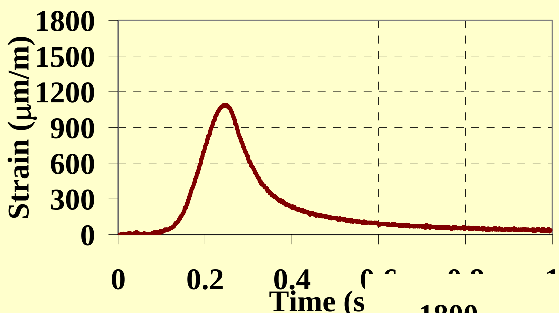


138mm

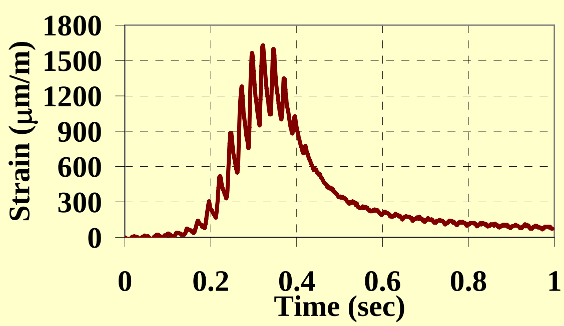


263mm

Horizontal Transverse Strain under HMA

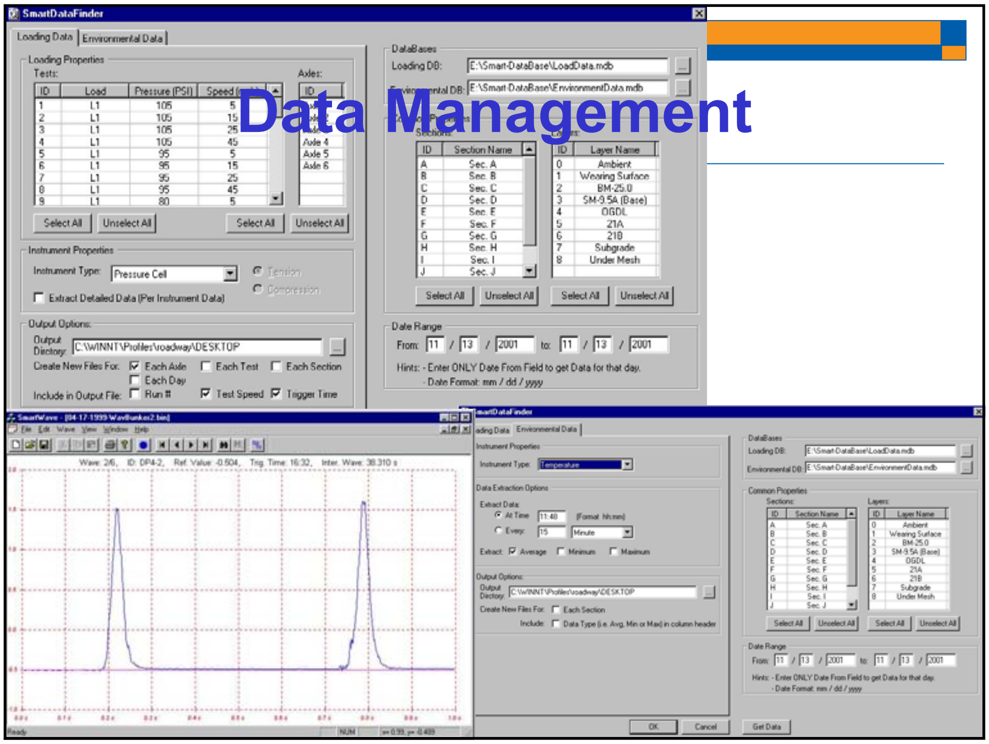


No Vibrations

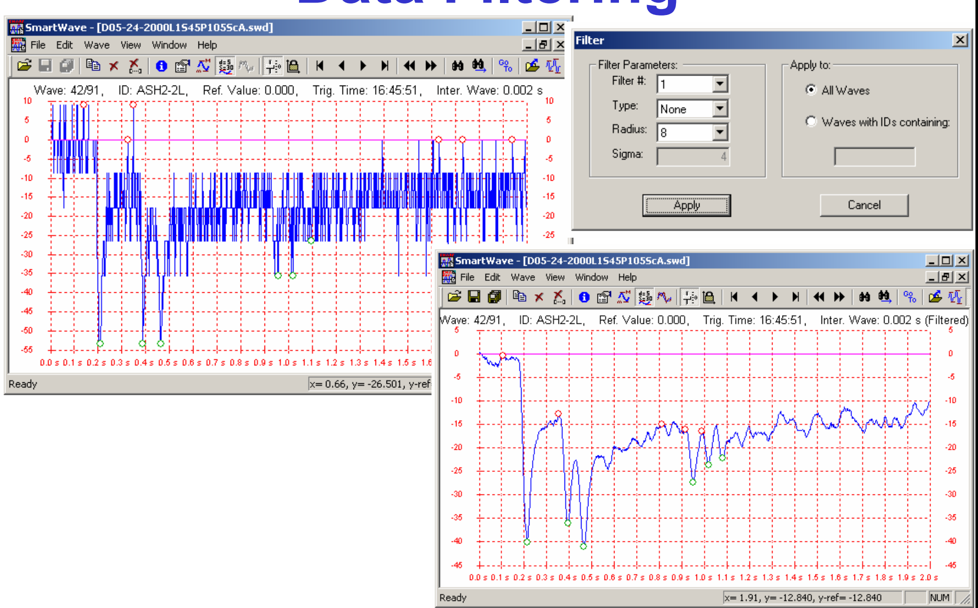


Vibrations: 40 Hz
(2400 VPM)

Data Management



Data Filtering



TYPES OF DATA

Static Data (Environmental)
- Frost depth (6 hours)
- Moisture (1 hour)
- Temperature (15 minutes)

Dynamic Data (Truck Loading)
- Stress (2-second wave)
- Strain (2-second wave)

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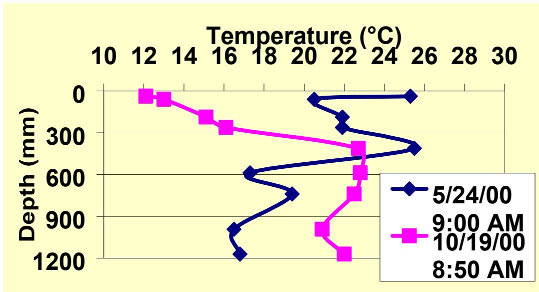
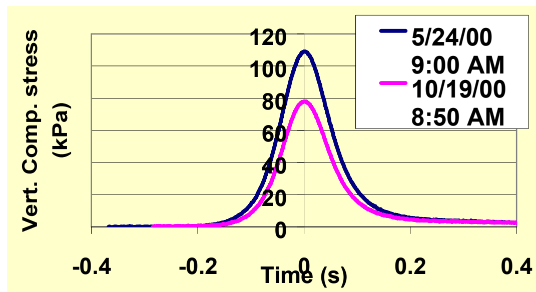
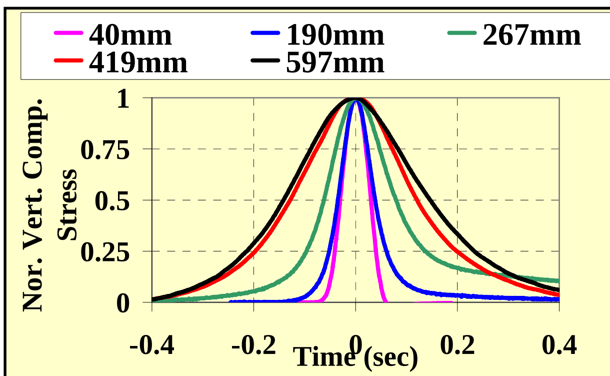
Pavement Response

TEMPERATURE EFFECT



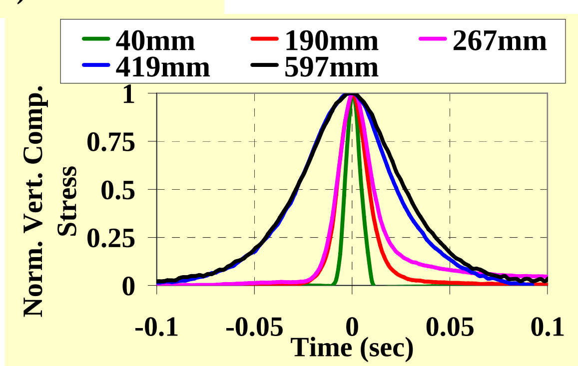
8 km/h, 190mm

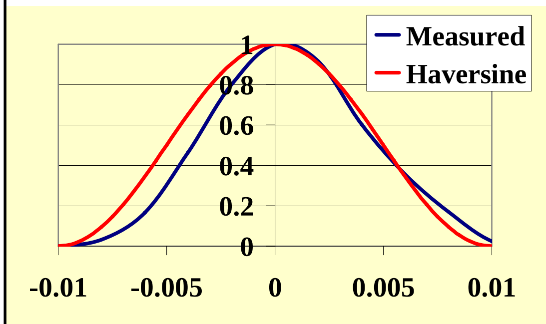




8km/h

72km/h

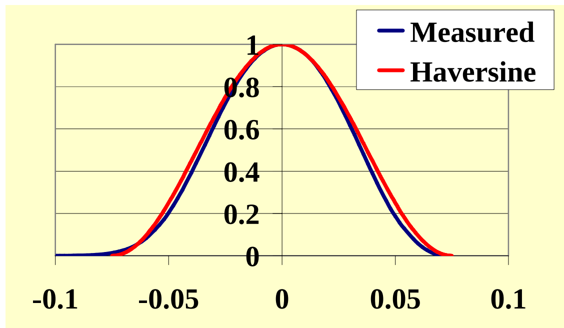




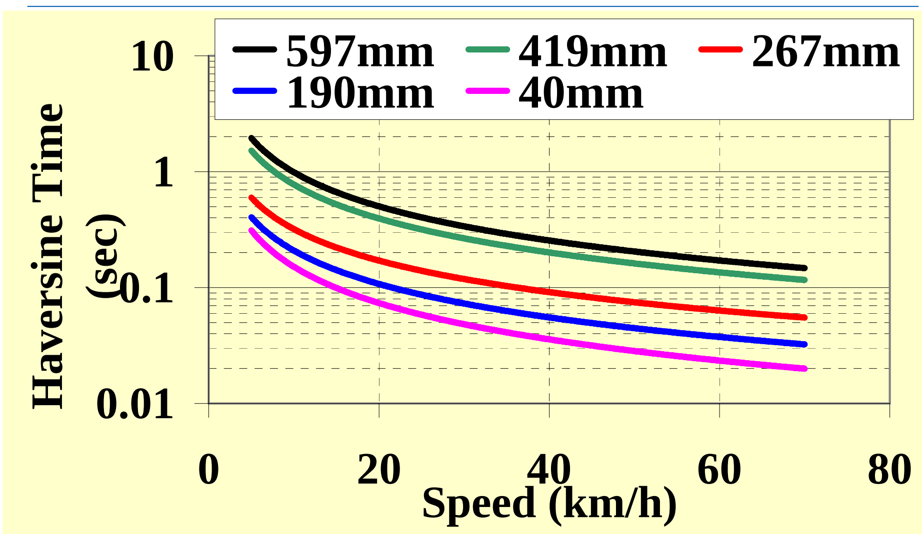
$$y(t) = \sin^2\left(\frac{\pi}{2} + \pi * \frac{t}{d}\right)$$

72km/h, 40mm, d=0.02s

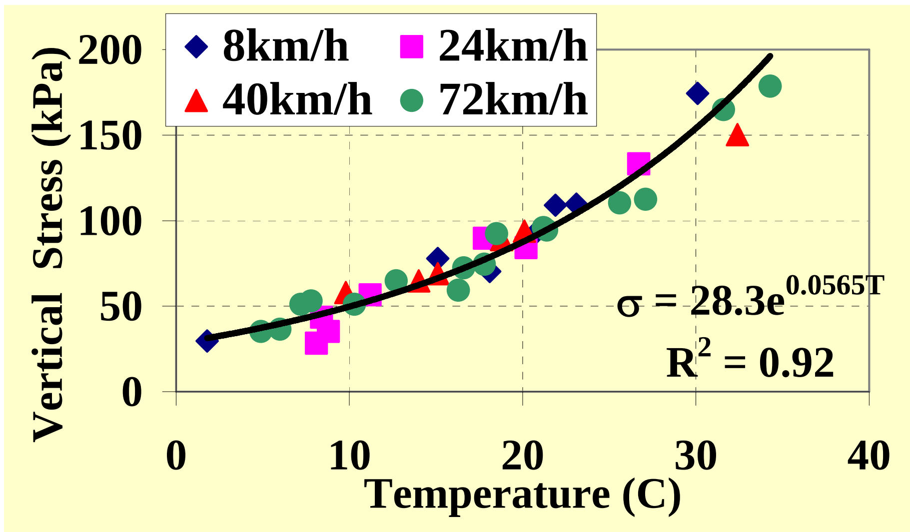
8km/h, 40mm, d=0.15s



Haversine Duration vs. Depth and Speed



Vertical Stress vs. Speed



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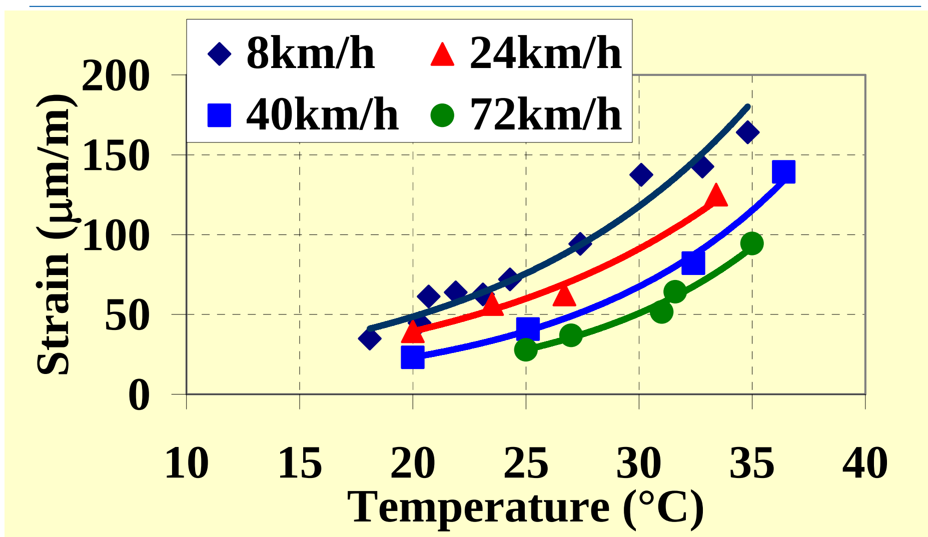
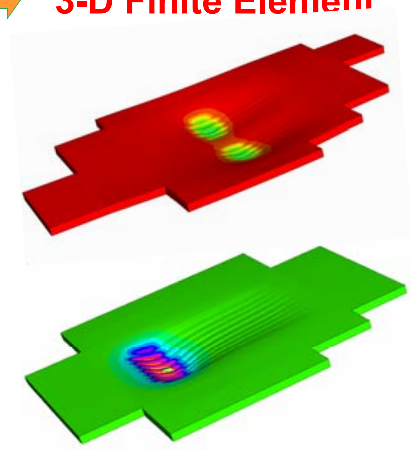
Transverse Strain vs. Speed



Modeling

Instrumentation → **Field Test** → **3-D Finite Element**



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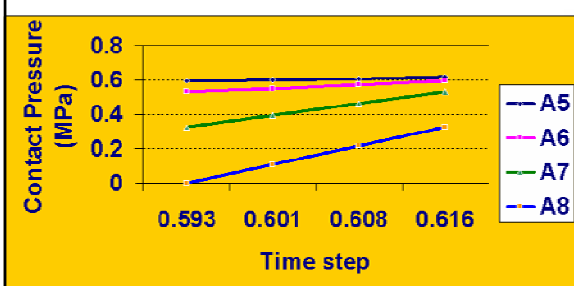
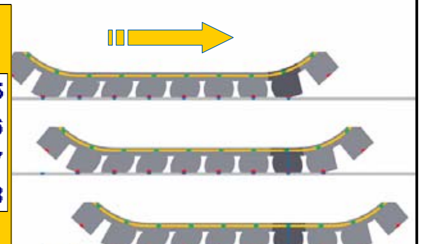
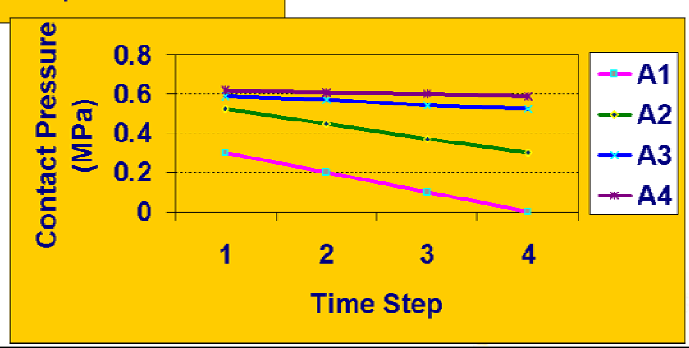
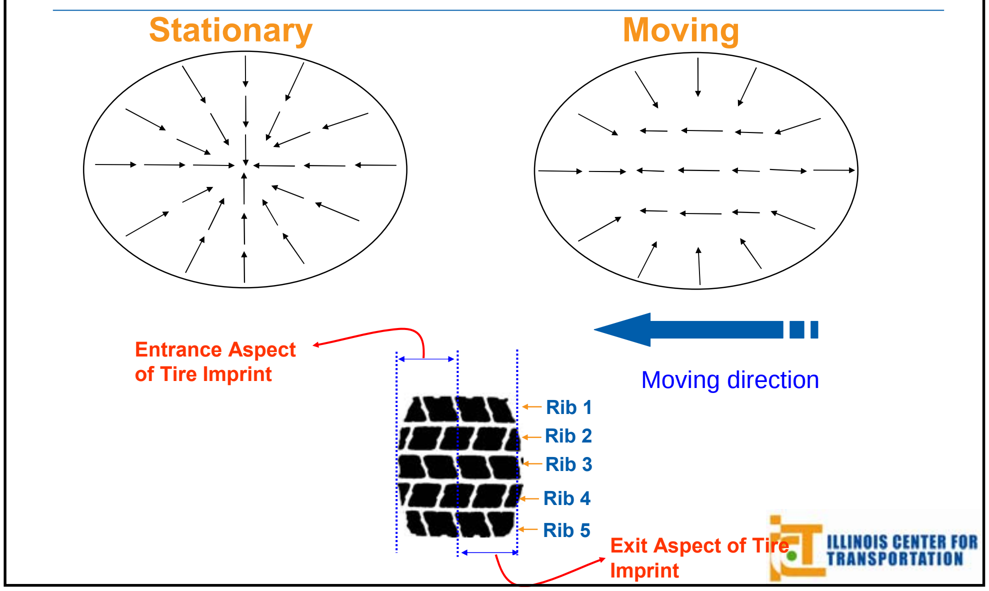
Loading Amplitude: Continuous (Entrance/ Exit)



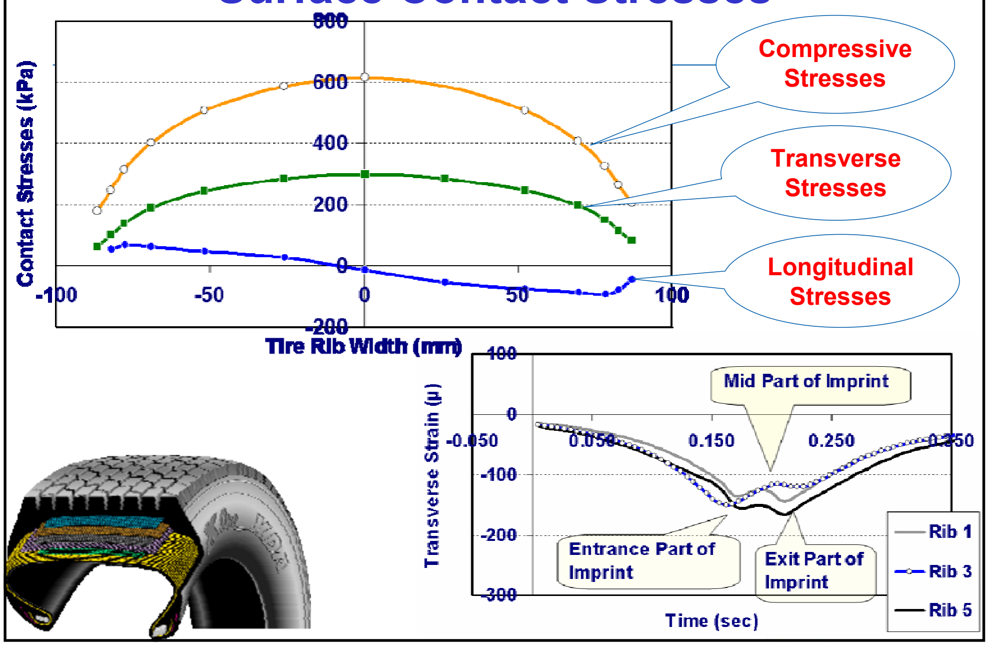




Surface Tangential Contact Stresses

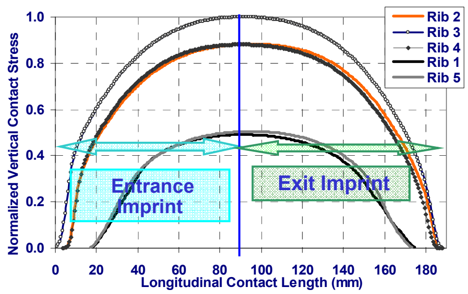


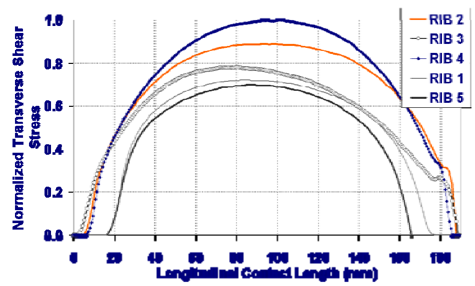
Surface Contact Stresses



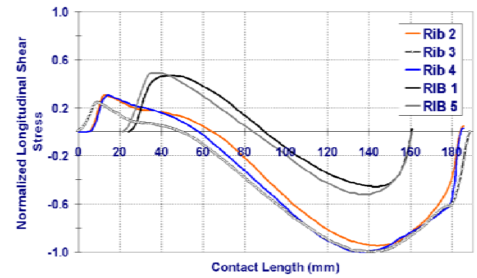
Nonuniform Stresses of Each Rib

- Ribs 1 and 5 (Outer ribs): Shorter contact length and smaller contact stress
- Ribs 2, 3, and 4 (Inner ribs): Longer contact length and higher contact stress

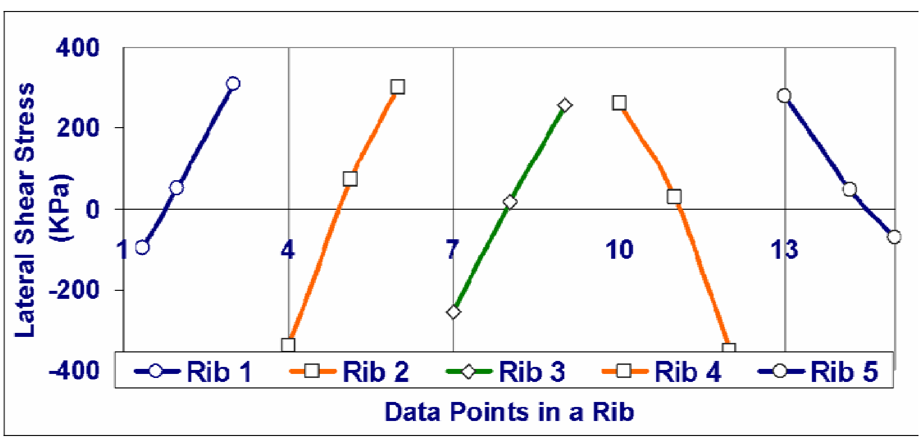




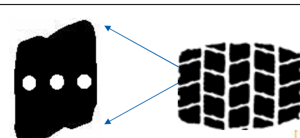
- Vertical Contact Stress
- Transverse Shear Stress
- Longitudinal Shear Stress



Measured Surface Tangential Stress



Stress Measuring Locations



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Analysis Approach

3D Finite Element Modeling

Analysis Considerations
- Material Constitutive Models
- Loading Amplitude
- Surface Tangential Stresses
- Layer Interface Condition

Implicit Dynamic Analysis

Validation of FE Models
(w/ Field Measurements)

Model Verification

Pavement Response Analysis

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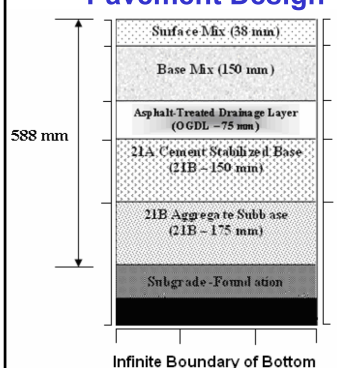
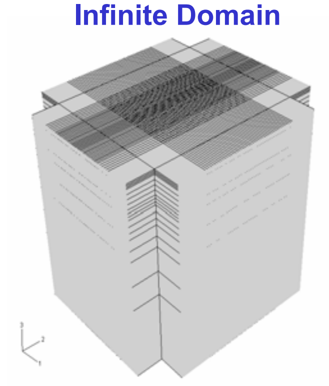
3D FE Model

Pavement Design



Infinite Domain



Interface Friction Model: Elastic Slip Model

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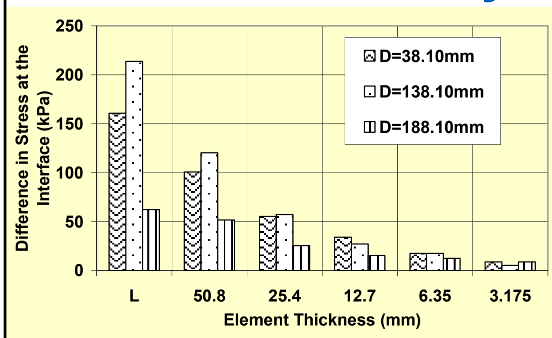
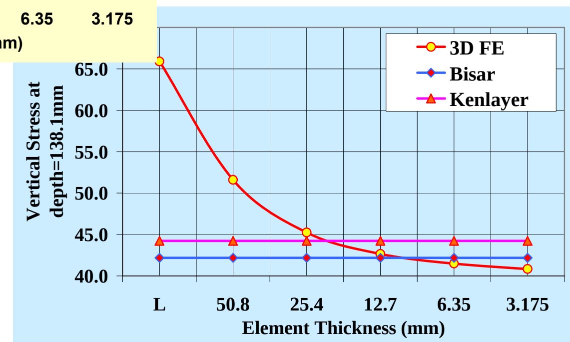
Sensitivity Analysis



Jump in Vertical Stress at the Interfaces

Convergence of the Vertical Stress

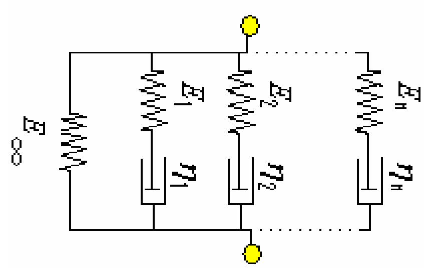


HMA Viscoelastic Properties

- Generalized Maxwell Solid Model: Consists of one spring and n Maxwell elements connected in parallel

- Relaxation modulus was converted from creep compliance and expressed as Prony Series

$$E(t) = E_0(1 - \sum_{i=1}^{N} E_i(1 - e^{-t/\tau_i}))$$



- where,
  - $E(t)$ = Relaxation Modulus,
  - E_0 = Instantaneous Modulus,
  - E_i = Material Constants Referred to as
  - Relaxed Strengths, and
  - τ = Relaxation Time.

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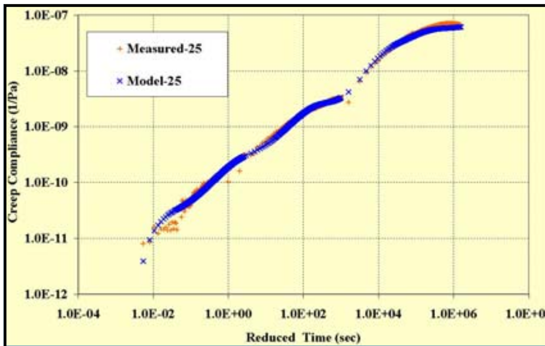
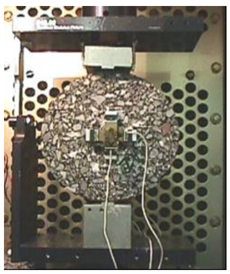
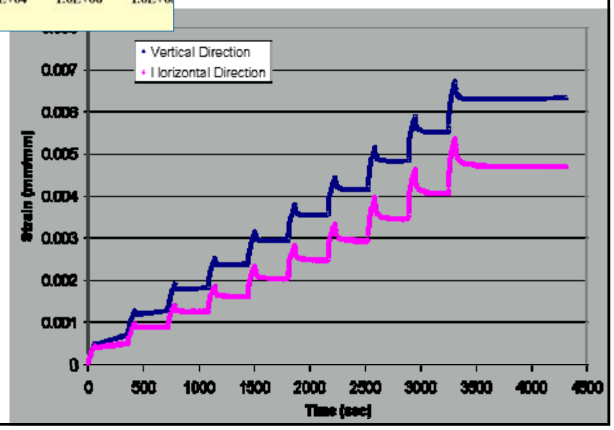


Creep Compliance Test at Various Loading Levels





Dynamic Analysis

- Dynamic Loading:
  - Vehicle suspension excited by surface irregularities; assumes a flat tire-pavement surface contact area
- Dynamic Analysis:
  - Dynamic structure response depends on load frequency to structure natural frequency ratio
  - Dynamic resonance may occur at some circumstances
- Implicit dynamic analysis was used
  - Unconditionally Stable/ Very Small Residual

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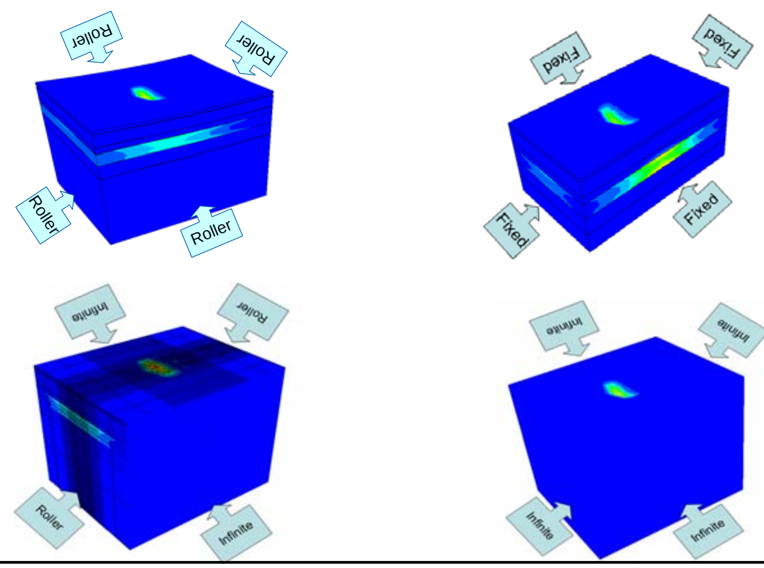
Boundary Effect Check for Dynamic Analysis



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MODEL VALIDATION

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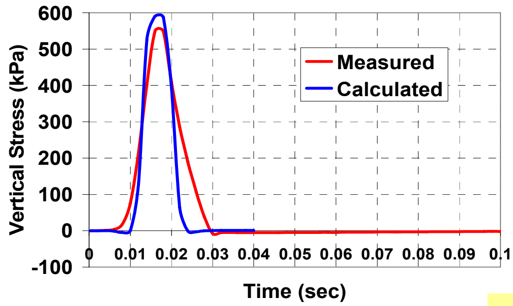
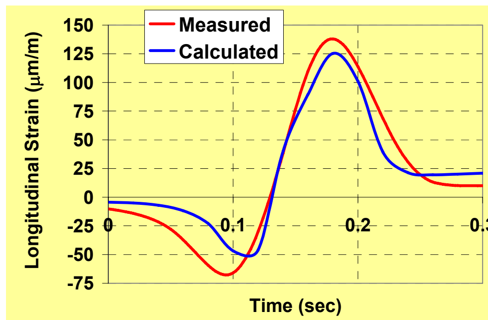
Model Validation

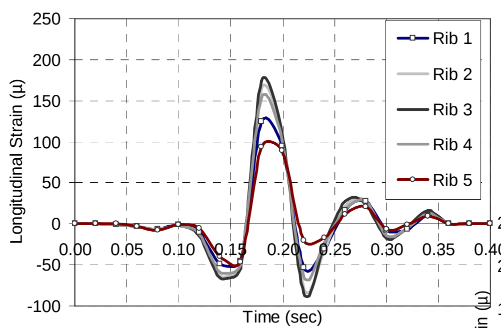


Vertical stress

Strain at bottom of HMA wearing surface

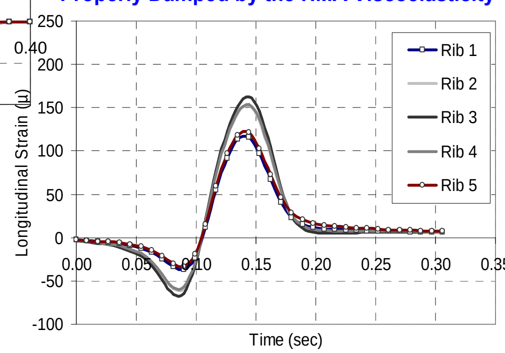


Difference in Loading Amplitude



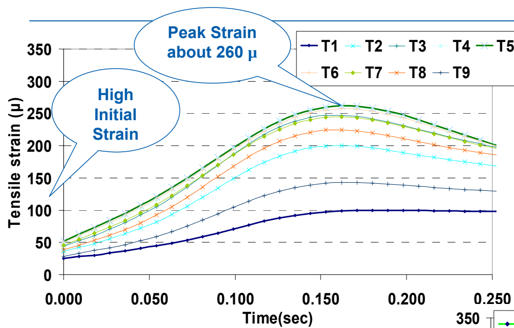
Strain-oscillation at the bottom of HMA

No oscillation at the bottom of HMA: Properly Damped by the HMA Viscoelasticity



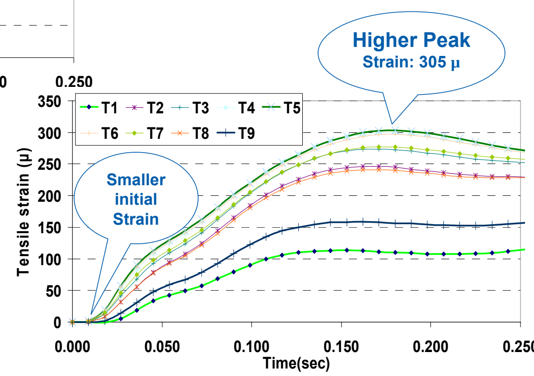
Quasi Static vs. Dynamic Analysis

Interstate Pavement Design: 25°C @ 5 mph



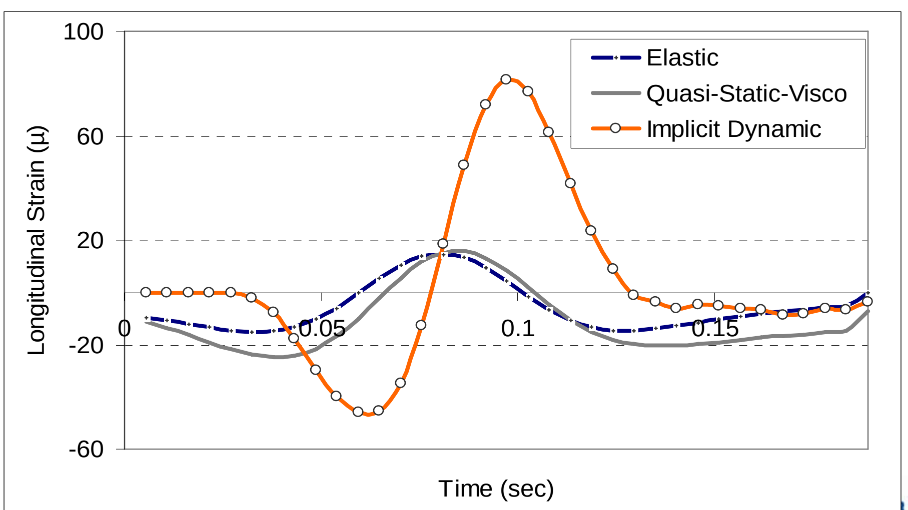
▪ Quasi-Static Visco Analysis

▪Implicit Dynamic Analysis

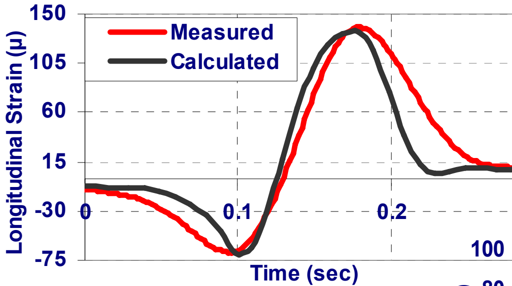


Quasi Static vs. Dynamic Analysis

Extreme Case

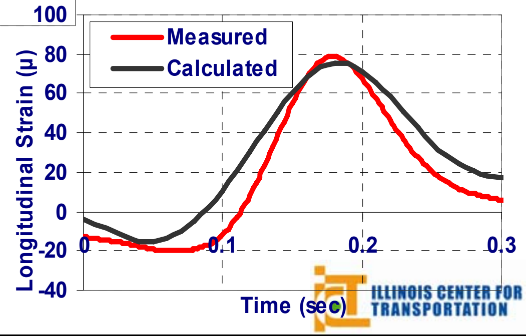


Pavement Response Validation (Dynamic Analysis)



Bottom of the wearing surface (38.1mm)

Bottom of the HMA (188 mm)



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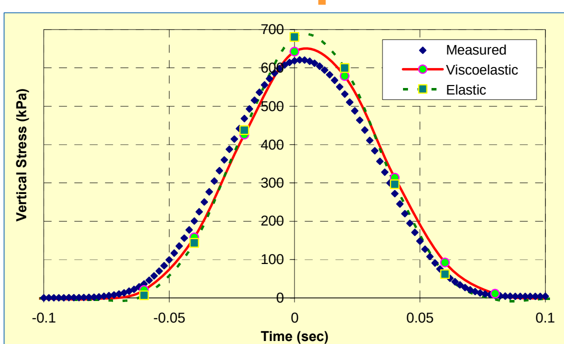
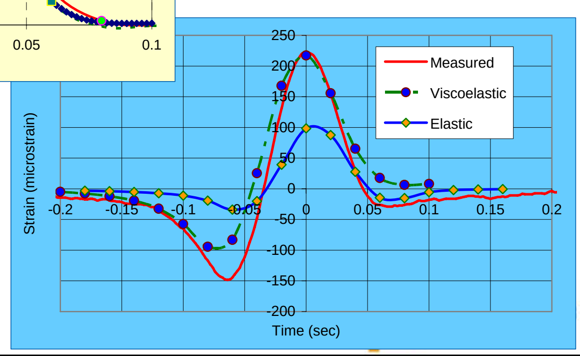
Response Validation

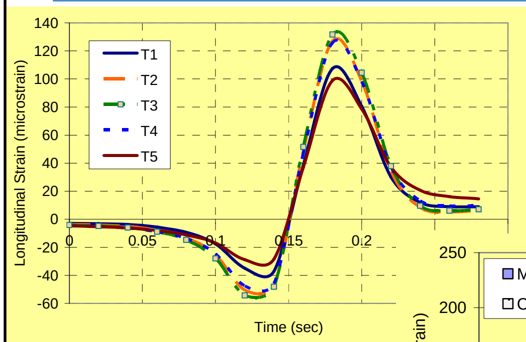


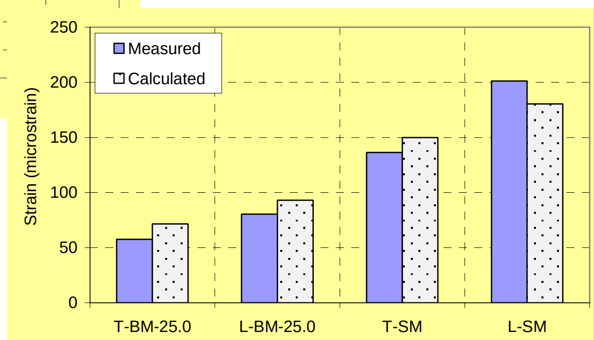
Under Wearing Surface

Under Wearing Surface



Dual Tires Configuration (T=25°C)





Longitudinal Strain (Wearing Surface)

After Validation!

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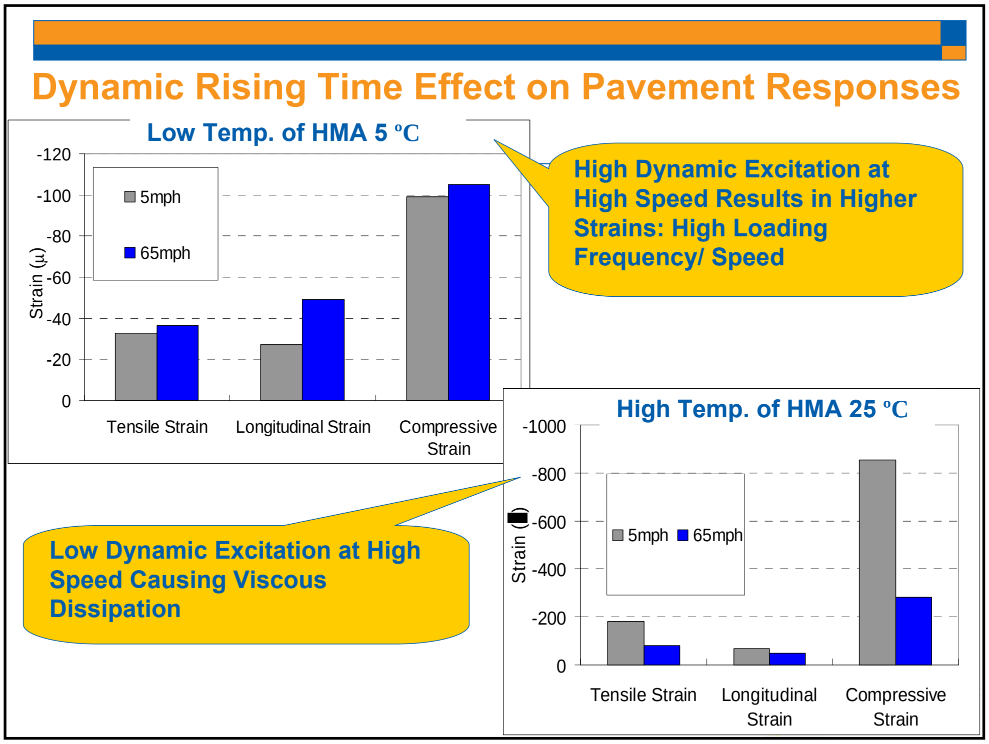
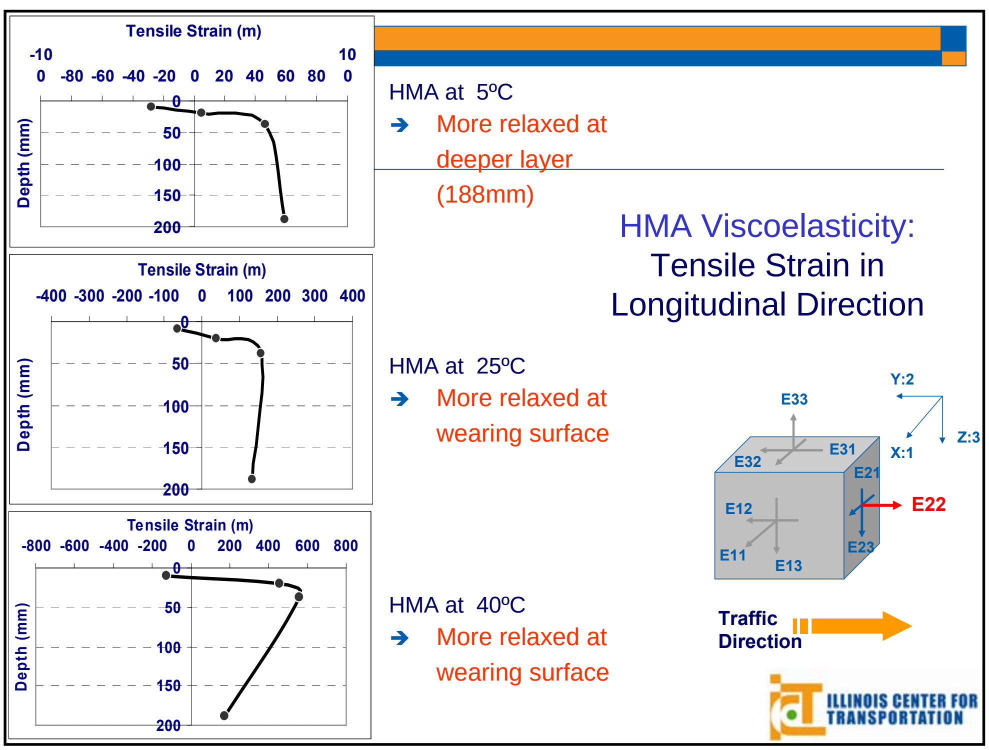

Dynamic Rising Time Effect on Pavement Responses
Low Temp. of HMA 5 °C
-120
-100
-80
-60
-40
-20
0
Strain (µ)
5mph
65mph
Tensile Strain
Longitudinal Strain
Compressive Strain
High Dynamic Excitation at High Speed Results in Higher Strains: High Loading Frequency/ Speed
High Temp. of HMA 25 °C
-1000
-800
-600
-400
-200
0
5mph
65mph
Tensile Strain
Longitudinal Strain
Compressive Strain
Low Dynamic Excitation at High Speed Causing Viscous Dissipation


Tensile Strain (m)
Depth (mm)
HMA at 5ºC
➔ More relaxed at deeper layer (188mm)
HMA Viscoelasticity: Tensile Strain in Longitudinal Direction
HMA at 25ºC
➔ More relaxed at wearing surface
HMA at 40ºC
➔ More relaxed at wearing surface
E33
E31
E32
E21
E22
E12
E11
E13
E23
Y:2
X:1
Z:3
Traffic Direction
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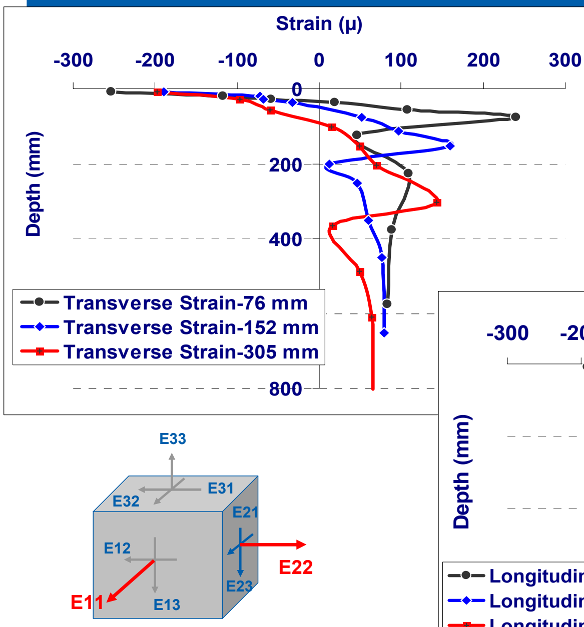
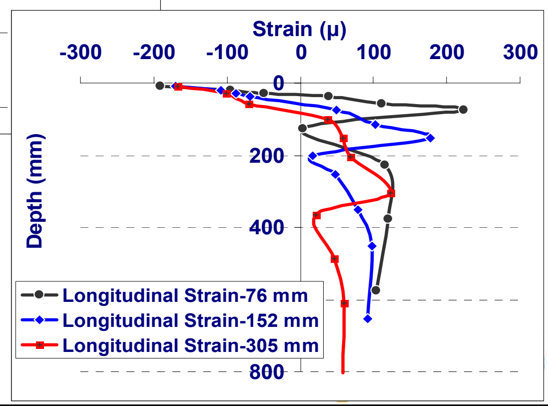
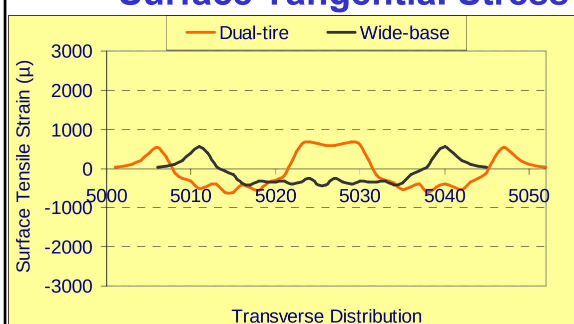
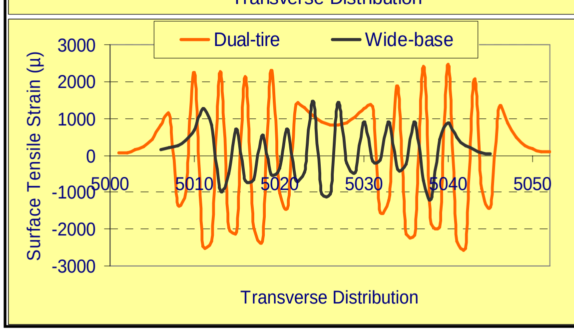


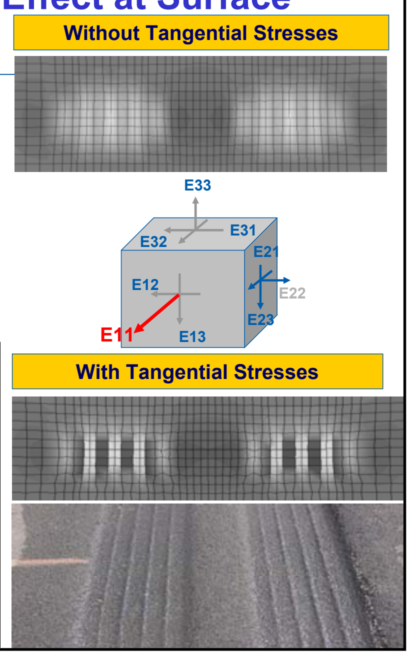
HMA Thickness Dependency
(Vertical distribution)



Surface Tangential Stress Effect at Surface

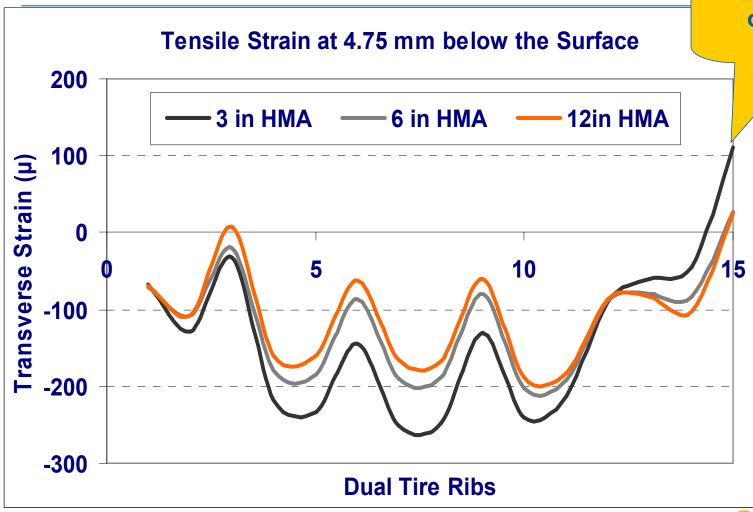




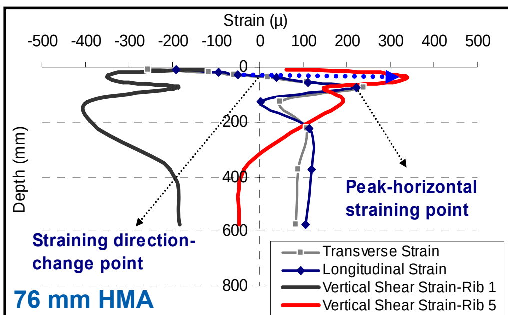


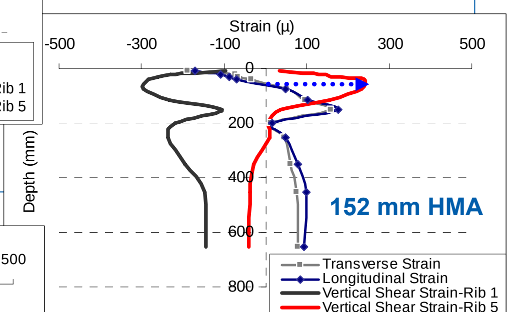
HMA Thickness Dependency at Shallow Depth
(Transverse Distribution)

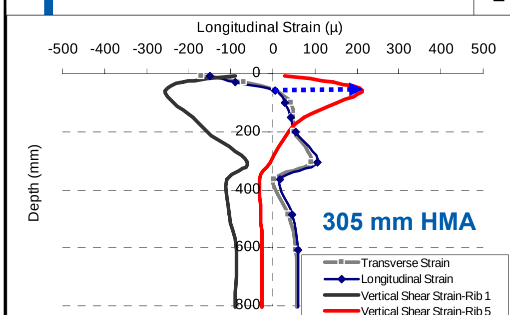
Between Two Tires of a Dual-Tire Assembly

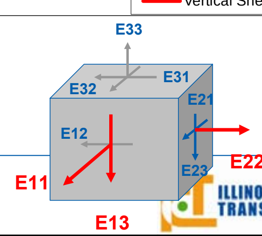


Strain Trade-off Phenomenon

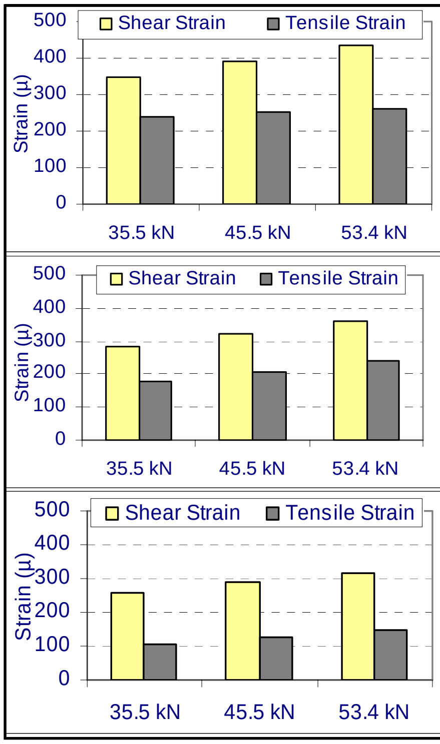








Vertical Shear Strain vs. Tensile Strain 25ºC

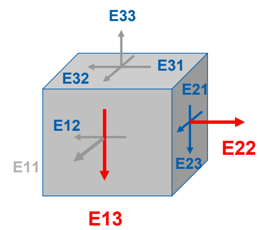


HMA ➔ 76 mm

HMA ➔ 152mm

HMA ➔ 305mm

- **Shear Strain: Critical value within HMA**
- **Maximum Tensile strain at the bottom of HMA**



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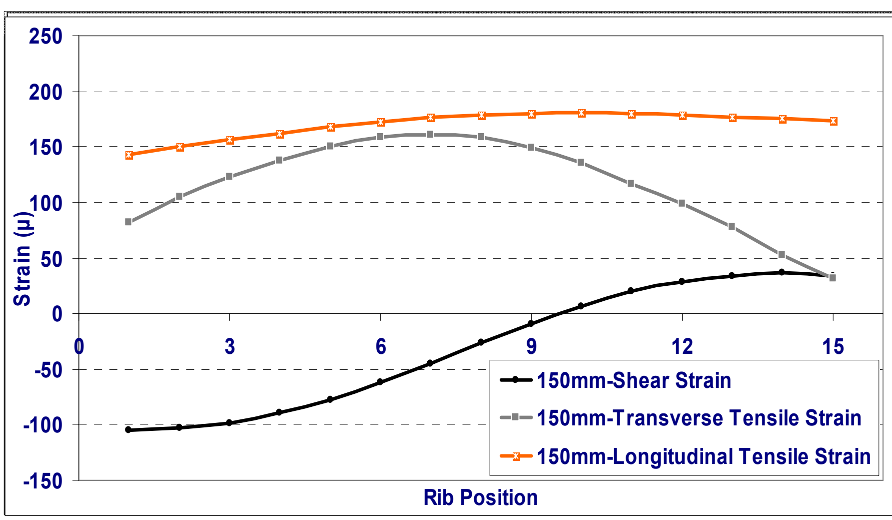
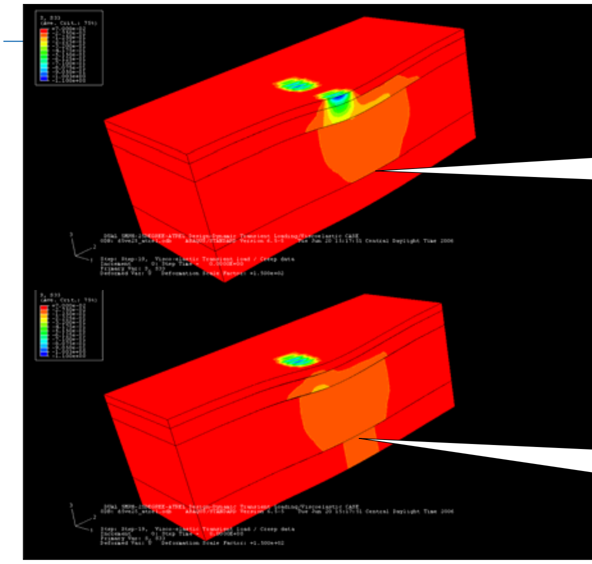
Strain Distribution with Depth

- ❑ **Critical strain within HMA (One Tire of a Dual-Tire Assembly Loading)**
- ❑ **Strains from 4.75mm to bottom of 150mm HMA**



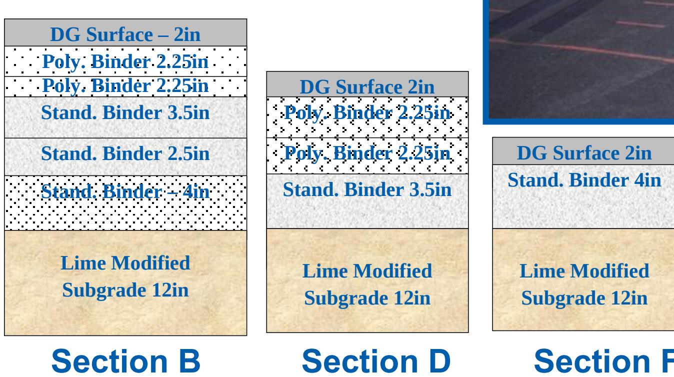
Stress Overlap in Dual Tire Loading



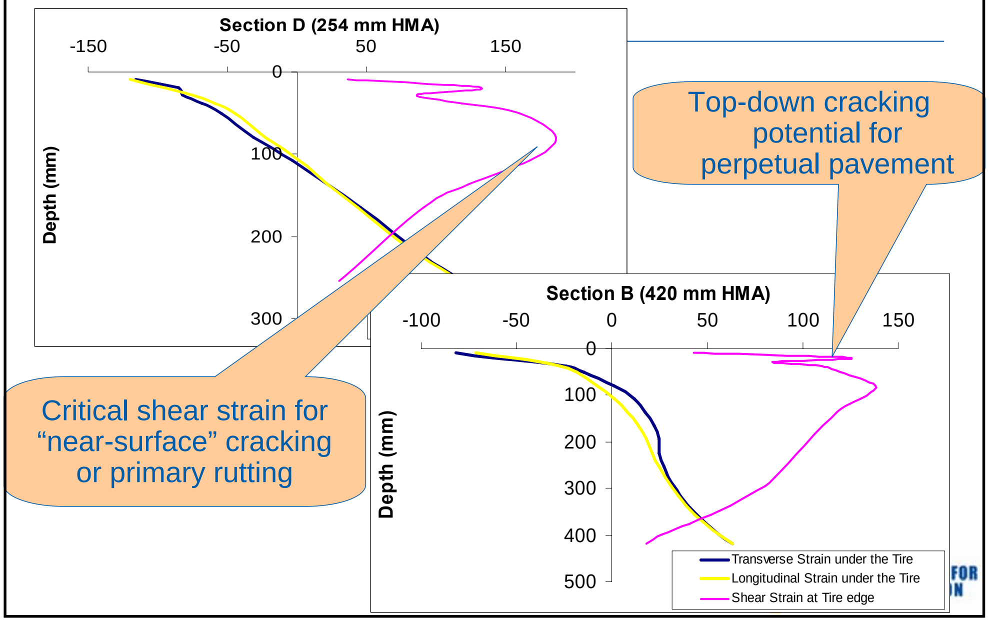
Underneath Dual-tire Assembly: Low Compressive Stress underneath Tire

In the middle of Dual-Tire Assembly: High Compressive Stress in the Middle of Tire

Model Validation



Strain Distribution with HMA Depth



Summary

- Accurate pavement response prediction requires realistic loading assumptions and appropriate constitutive modeling
- Pavement mechanism can be better understood through accelerated pavement testing and validated modeling
- Pavement performance monitoring and damage quantification data are needed

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What Did We Learn from Model Validation

- Dynamic analysis resulted in greater flexible pavement responses than quasi-static analysis
- Critical shear strains at shallow depth are significantly higher than the tensile strain at the bottom of HMA
- Tangential surface stresses affect the prediction of top-down cracking, primary rutting, and occasionally fatigue damage
- The extent of surface tangential stresses' impact is affected by pavement structure, HMA, tire characteristics, applied load, temperature, and rib-groove structure

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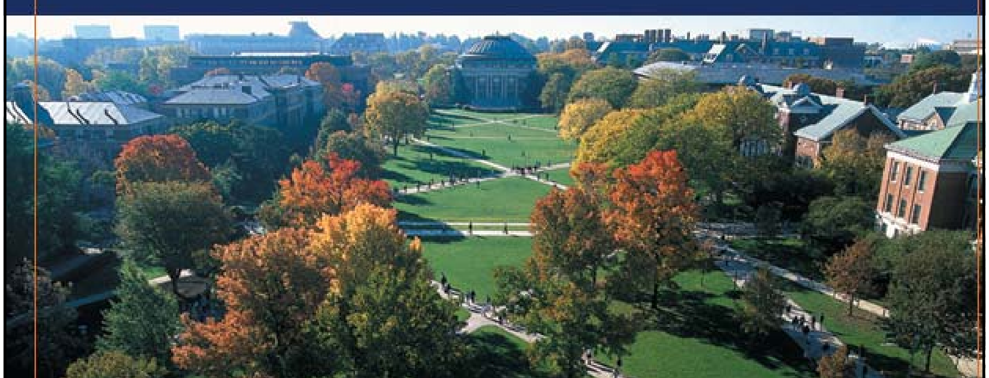
Thank You



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