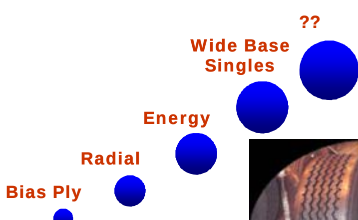
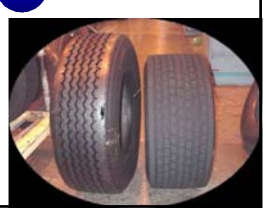
State-of-the-Art and State-of-the-Practice on the Impact of Wide-Base Tires on Pavements

Imad L. Al-Qadi
Illinois Center for Transportation
Dept. of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

ILLINOIS

Tire Development





ILLINOIS

Tire Characteristics

EUROPE

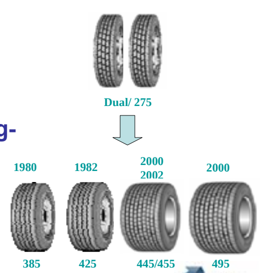
Tire Type	Tire Size	Contact Width (mm)	Overall-Diameter (mm)
Dual	11R22.5	184	1050
Conventional	385/65R22.5	285	1071
Conventional	425/65R22.5	308	1126
First Generation	445/65R22.5	340	1155
EU	495/45R22.5	427	1013

North America

Tire Type	Tire Size	Tire Pressure (kPa)	Contact Width (mm)	Overall-Diameter (mm)
Dual	275/80R22.5	720	212.13	1044
Second Generation	445/50R22.5	720	373.02	1028
Second Generation	455/55R22.5	720	387.86	1079

Wide-base Tire Characteristics

- Introduced to North America in 1982
- Low Profile Design
- Relatively Uniform Contact Pressure
- Design for High-Speed Long-Distance Carrier
- Relatively Reduced Empty Weight
- Efficient Fuel Consumption

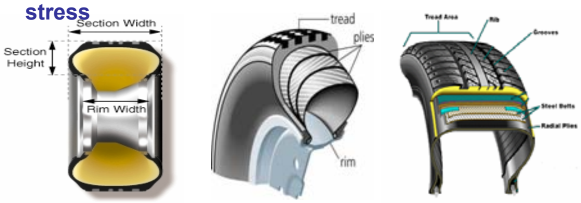


Tire Design Code

- Dual Tire:
  - Nominal tire width range from 250~305mm
  - 12-22.5; 12R22.5; 275/80R22.5
  - High Profile
- Wide-Base Tire
  - Nominal tire width range from 400~460 mm
  - 385/65R22.5; 425/65R22.5; 455/55R22.5
  - Low Profile
- Code
  - Tire width (mm)/ tire aspect ratio (%)/ radial ply (R)/ rim diameter code (in)

Cross-section of Tire

- Aspect Ratio: the ratio of section height to width
- Bias Ply: High tire profile - High rolling dynamic stress
- Radial Ply: Low tire profile - low rolling dynamic stress



ILLINOIS

Dual vs. Wide-Base Tires

- Wide-base tires have been used in Europe since the early 1980s
- In some countries more than 80% of trailers used wide-base tires
- Earlier generation of wide-base tires were proven more detrimental to flexible pavement systems than regular dual tires

ILLINOIS

Impact of Early Wide-Base Tire

- Early generations are 385/65R22.5, 425/65R22.5, and 445/65R22.5:
  - Required high inflation pressure (790 to 890kPa – smaller contact area).
  - Significantly increased pavement damage compared to dual tires:
    - Damage ratios ranged between 1.31 and 4.30.

ILLINOIS

Christison et al. (1980)

– In-field measured pavement responses

– Conventional wide-base tire induces more damage than dual tire

→1.2~1.8 times more fatigue damage

Akram et al. (1992)

- Multi-Depth Deflectometer at a speed of 90 km/h
- Conventional wide-base tire

→Pavement life reduced by a factor of 2.5~2.8 when wide-base tire is used

ILLINOIS

Penn State (1989)

- Comparison between Dual and Wide-base Tires:
  - 11R22.5, 245/75R22.5
  - 385/65R22.5, 425/65R22.5
  - Testing speed: 58 km/hr
- Pavement Damage Evaluation:
  - 10 and 45% fatigue damage model (Finn et al.1986)
  - Wide-base tire induces significantly more damage than dual tire (1.5 times more fatigue damage)

ILLINOIS

Huhtala et al. (1992)

- Comparison between Dual and Wide-base Tires
  - 11R22.5, 265/70R19.5
  - 355/75R22.5, 385/65R22.5, 425/65R22.5
  - Test speed: 76 km/hr
- Pavement Damage Evaluation
  - Steering axle is the most detrimental
  - A drive axle equipped with wide-base tires is more damaging than dual-tires by a factor of 2.3 ~ 4.0.

ILLINOIS

FHWA (1993)

- Comparison between dual and wide-base tires
  - 11R22.5
  - 425/65R22.5
- Pavement Damage Evaluation:
  - Wide-base tire induces significantly more damage than dual tire:
  - ➔3.5 times more fatigue damage
  - ➔1.9 times more rutting damage

ILLINOIS

Dual vs. Wide-Base Tires

- *Earlier generation of wide-base tires were detrimental to flexible pavement*
- A new generation of wide-base tires has recently been introduced:
  - Legalized in all states for 355.8kN GVW trucks
  - 16-18% wider than the first generation:
    - Makes use of a new crown architecture that allows wider widths at low aspect ratios
    - Designed based on inch/width principle
  - More uniform tire-pavement contact stress:
    - Reduced tire pressure (690kPa) at high loads (151kN)
  - Potential economic advantages

ILLINOIS

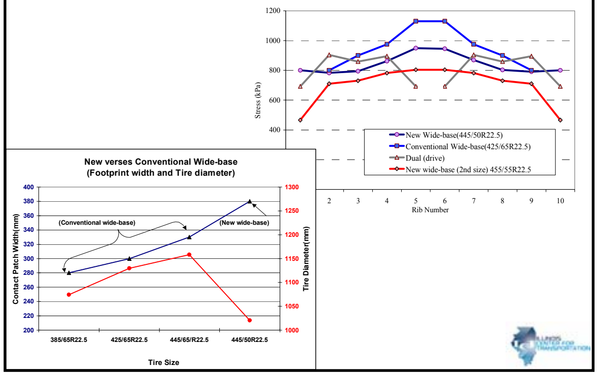
New vs. Old - Design

Unique Infini-Coil™ technology.
¼ mile of continuous steel cable to help eliminate casing growth

425/65R22.5 XZY

ILLINOIS

New Generation of Wide-Base Tires

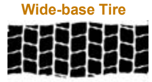


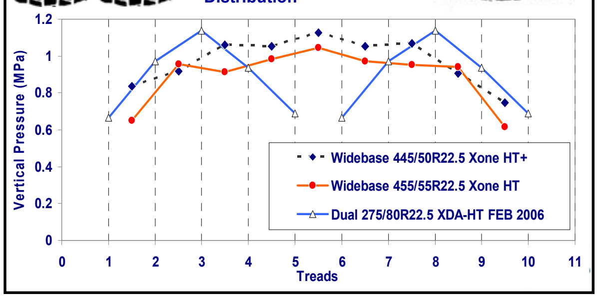
Vertical Peak-Pressure Distribution

Dual-Tire Assembly

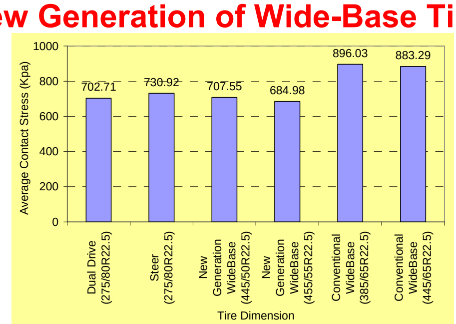
Actual Tire Imprints and Maximum Vertical Contact Pressure Distribution

Wide-base Tire





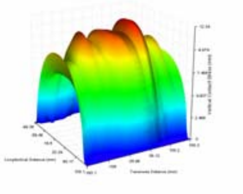
New Generation of Wide-Base Tires



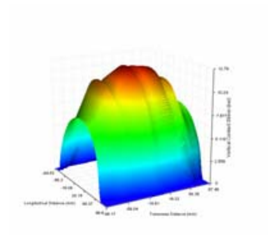
Average Contact Stress at Pavement Surface

ILLINOIS

New Generation of Wide-Base Tires



Measured Contact Stress at Pavement Surface – 275/80R22.5

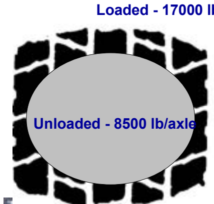


Measured Contact Stress at Pavement Surface – 445/50R22.5

ILLINOIS

Loaded - 17000 lb/axle

All footprints done exactly to 0.4 : 1 Scale.



Loaded - 17000 lb/axle

Loaded - 17000 lb/axle

Why Wide-Base Tires NOW?

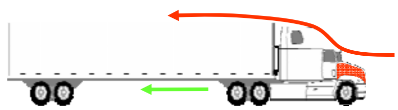
- **Substantial savings to truck freight transportation:**
  - **Fuel economy**
  - **Increase hauling capacity (increase payload)**
  - **Reduced tire cost and repair**
  - **Ride and comfort**
  - **Reduced emission and noise**
  - **Reduced recycling impact of scrap tires**
  - **Better handling, braking, and safety**

ILLINOIS

Impact on Road Infrastructure?

Where Does the Fuel Go?

- **aerodynamic drag** — At 60 mph (100 kmh), aerodynamic drag consumes approximately 40% of the fuel.
- **mechanical losses** — Mechanical losses consume approximately 25% of the fuel.
- **rolling resistance** — Rolling resistance accounts for approximately 35% of the fuel consumed.



ILLINOIS

Fuel Economy/ Hauling Capacity

- Tire rolling resistance accounts for 35% of truck energy consumption
- Using the new generation of wide-base tires reduces rolling by 12%:
  - Reduction fuel consumption by an average of 4%
  - Savings of 400 gallons of fuel per year
    - A truck that uses 6.5 mpg on duals will be at 6.76 mpg or better with new wide-base generation
    - At 120,000 miles/year, the saving is 710 gallons (3230 liters) per vehicle per year
- Reduces truck weight by 410kg:
  - Increases haling capacity by 2%

ILLINOIS

Tire Cost and Repair, Truck Safety, and Ride Comfort

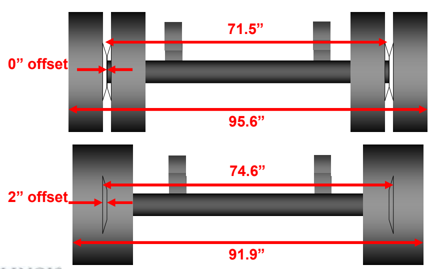
- Requires only one rim compared to two for dual tires
- Requires half the repair time needed for dual tires
- Handling is maintained even when two tires blow out
  - Requires regular monitoring of tire pressure (good practice for all tire types)
- Ride quality is improved by 12% compared to dual tires

ILLINOIS

Environment Impact

- Reduced gas emission: Reduction of 1.1 million metric tons of carbon equivalent by 2010 (assuming current market share, 5%)
- Reduce recycling impact of scrap tires:
  - 72.5kg of residual materials for dual tires vs. 53.6kg for a wide-base tire assembly.

Effect of Tires on Track Width



Areas of Research

- Dynamic impact of the tire (25% less than dual tires).
- Recapping of wide-base tires vs. dual tires
- Impact on road Infrastructure

Cost 334 Action in Europe (1997~2001)

- APT and instrumented pavement (17 tire assemblies)
- Intensive research on the effect of wide-base tires
  - Tire type, axle load, tire pressure, and pavement design
- Pavement Damage Evaluation:
  - Developed Tire Configuration Factor (TCF) by stepwise regression analysis
  - Suggested the use of wide-base tires on the steering axle
  - Top down crack was not considered

The COST Action (2001)

- Introduced the concept of tire configuration factor (TCF):

$$TCF = (width/470)^{-1.68}(length/198)^{-0.85}(pres.\ ratio)^{0.81}$$

Tire Type	W mm	D mm	TCF	Primary Roads Wide-base vs. dual
Dual (275/80R22.5)	368	1054	1.52	----
Wide (445/50R22.5)	380	947	1.56	2.7%
Wide (455/55R22.5)	380	998	1.47	-3.1%

Al-Qadi et al. (2002)

- Heavily Instrumented Virginia Smart Road
- Comparison between dual and wide-base tires
  - 445/50R22.5, 455/55R22.5
  - Test parameters: speed, axle load, tire pressure
- Pavement Damage Evaluation:
  - Various transfer functions
  - Steering axle is the most detrimental
  - Wide-base is more fatigue damaging by a factor of 1.35.
  - Equivalent rutting damage
  - Wide-base is less damaging than dual in surface initiated top-down cracking by a factor of 0.45

Prophète et al. (2003)

- Instrumented Pavement: Laval University
- Comparison between dual and wide-base tires
  - 385/65R22.5, 455/55R22.5
  - 50 km/hr, axle load, tire pressure
  - Wide-base (455) is more fatigue damaging by a factor of 1.54
  - Wide-base (455) is less rutting damaging by a factor of 0.17
  - Surface initiated top-down cracking is less damaging by 0.87 times

ILLINOIS

NCAT Experimental Study (2005)

- Compared field responses of new generation of wide-base tires to dual tires
- Measurements conducted at 72.4km/h
- Used measured strains at the bottom of HMA and vertical stress on top of subgrade
- Both Dual and wide-base tires configurations causes the same pavement damage

ILLINOIS

Impacts on Road Infrastructure

- Only a few studies on new wide-base tire
- What do we know:
  - The steering axle is the most damaging of all axles
  - Significantly less damage than the first wide-base tire generations
  - Impact on the subgrade is similar to dual tires

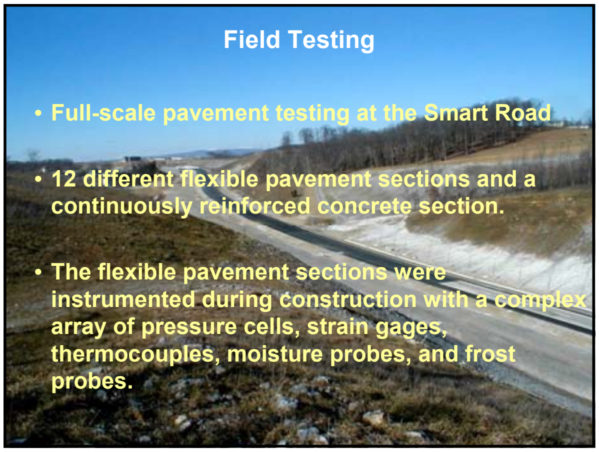
ILLINOIS

Impacts on Road Infrastructure

- What do we know :
  - The 455/50R22.5 tire is less damaging than the 445/50R22.5 tire
  - The layered theory can not be used to quantify tire damage
  - Focus has been given to primary roads

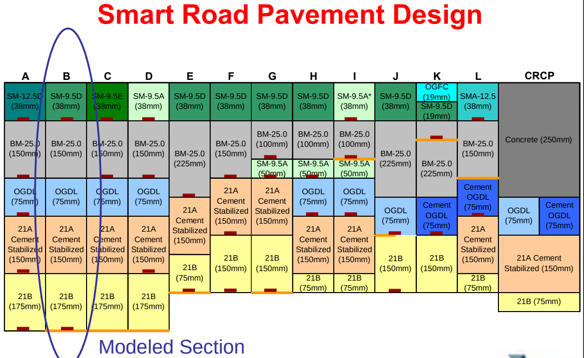
ILLINOIS

Field Testing



- Full-scale pavement testing at the Smart Road
- 12 different flexible pavement sections and a continuously reinforced concrete section.
- The flexible pavement sections were instrumented during construction with a complex array of pressure cells, strain gages, thermocouples, moisture probes, and frost probes.

Smart Road Pavement Design



ILLINOIS

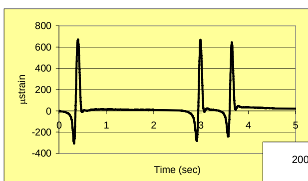
Al-Qadi and Co-Workers

- Testing at the Virginia Smart Road (2000-2002):



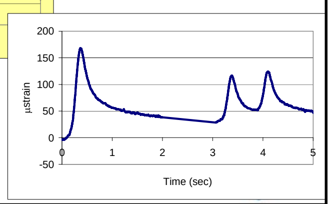
ILLINOIS

Four speeds – 2 Load levels – 4 Tire Pressures



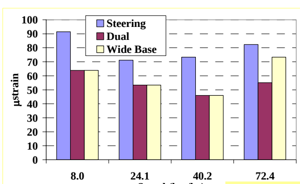
Longitudinal Strain

Transverse Strain



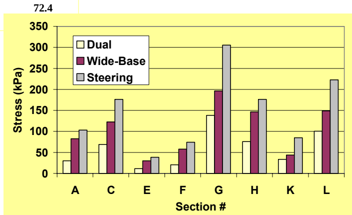
ILLINOIS

Field Evaluation



Tensile Strain under HMA

Vertical Stress under HMA



ILLINOIS

Conclusions of the Exp. Program

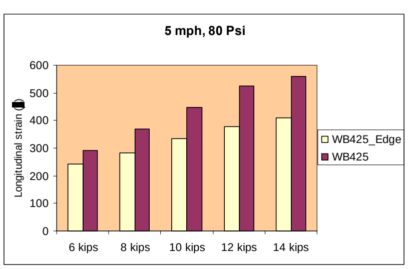
- The steering axle is the most detrimental of all tire configurations (small contact area with respect to the carried load)
  - Fatigue failure: slightly greater for the wide-base tire configuration
  - Subgrade Rutting: approximately equal for the wide-base and dual tires configurations
- Recommendation: Address a broader range of failure mechanisms (i.e., HMA rutting, top-down cracking) using FEM.

ILLINOIS

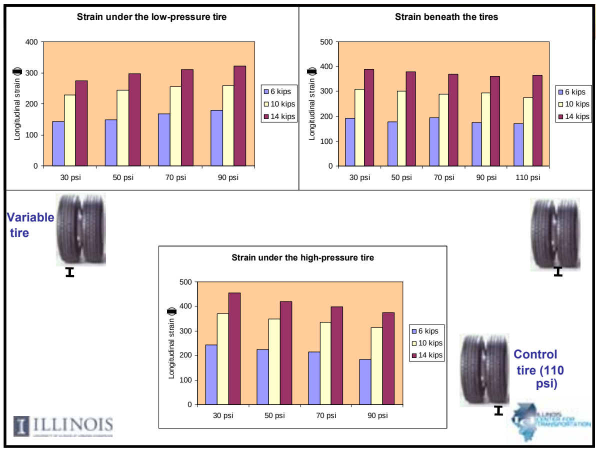
Accelerated Loading Facility

ILLINOIS

Tire position effect



ILLINOIS



Analytical Model

- Uniform Pressure Distribution model:
  - Original models developed by Boussinesq (1885) and Burmister (1954),
  - Uniform vertical pressure distribution
  - Circular areas
- Non-uniform Pressure Distribution Model
  - Nonuniform tire contact pressure model (Scharpery, 1980)
  - Distributions are actually non-uniform (Tielking, 1980)
  - Depended on the size and tire types (Roberts, 1987)
    - Tensile strain at the bottom of HMA results in excess of 100% higher than those for uniform pressure

Limitations of the Layered Theory

- Can not differentiate between wide-base tires or dual tires (i.e., 385/65R22.5 = 455/55R22.5 and 11R22.5 = 12R22.5).
- Improvement in pressure distribution in the new generation of wide-base tire may not be quantified.
- Vehicle speed has no effects on pavement damage.

Theoretical Approaches

	Layered Theory	Finite Element
Dimension	2D-Plane Stress	2D, 3D
Loading Area	Circular	Versatile
Stress	Uniform	Unif. or Nonunif.
Bonding	Fully Bonded	Bonded/Friction
Dynamic	No	Yes
Material	Elastic	Elastic/ Visco-elastic etc…

ILLINOIS

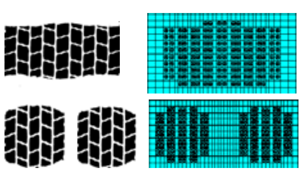
Finite Element Approaches

	Axisymmetric	2D-Plane Strain	3D FE
Loading	Static	Static	Static/Dynamic
Loading Area	Circular Single	Line Load	Versatile
Computation Time and memory	Lowest	Middle	Highest Intensity
Interface Modeling	No	Partial	Yes
Discontinuity Modeling	No	Partial	Yes

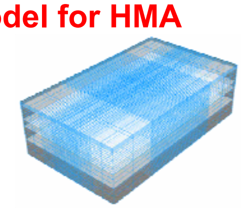
Major Disadvantage (green cells: Circular Single, Line Load, Highest Intensity)

ILLINOIS

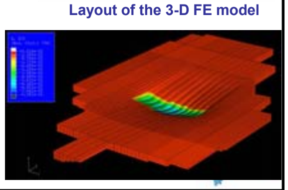
Proposed FE Model for HMA



Real and FE simulated tire foot prints for wide-base tire and dual tire assembly



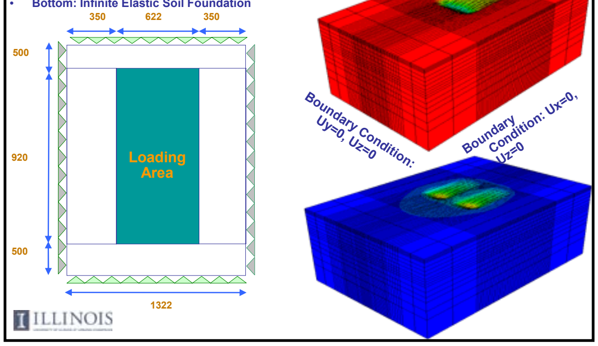
Layout of the 3-D FE model



ILLINOIS

Finite Element Model

- C3D8R (Solid: Eight Nodes Linear Brick Reduced Integration)
- One Integration Point in the Middle of the Element
- Bottom: Infinite Elastic Soil Foundation



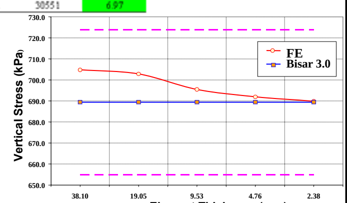
ILLINOIS

Mesh Size Sensitivity Check

- Level of Accuracy : +/- 5% of Vertical Contact Stress at Surface
- Stress Jumping Check at the Interface
- Element Thickness for HMA

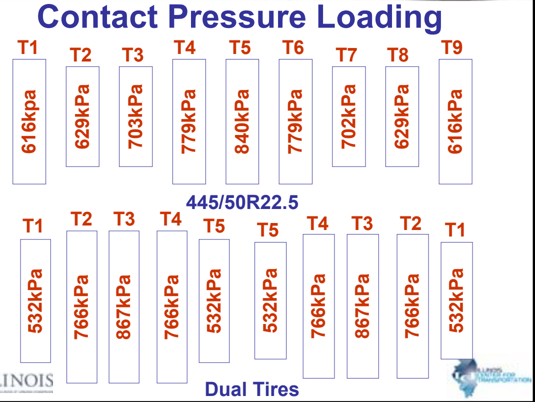
Case ID	Element Thickness (mm)	Model Size (dof)	Number of Elements	Data Storage (Gbytes)	Computational Time (sec)	Jump at WS – BM Interface (kPa)
A	38.10	172,476	42,916	2.35	3145	93.2
B	19.05	212,226	55,656	3.09	4871	52.2
C	9.53	291,726	81,136	4.19	6599	25.6
D	4.76	450,726	132,096	7.26	18565	9.90
E	2.38	760,776	231,468	12.91	30551	6.97

- BISAR: Pavement Response Analysis Software Based on Layered Theory
- FE: Finite Element Method



ILLINOIS

Contact Pressure Loading



ILLINOIS

Material Characterization

- HMA materials: Linear viscoelastic constitutive model
  - Indirect resilient modulus and creep compliance
  - Prony Series Expansion
- Granular materials: Linear elastic constitutive model
  - Nondestructive testing (FWD)

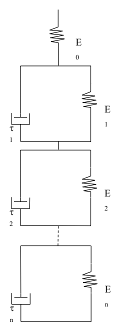
ILLINOIS

Prony Series

- The Prony Series model consists of one spring and K Voigt elements connected in series

$$D(t) = D_0 + \sum_{i=1}^{K} D_i (1 - e^{-t/\tau_i})$$

- where
  - $D(t)$ = creep compliance (MPa) at time t;
  - D_0 = glassy creep compliance (MPa);
  - D_i = material constants referred to as retardation strengths; and
  - τ = relaxation time.



ILLINOIS

LVE Model of HMA

Creep Compliance from Lab

$$E(t)D(t) = \frac{\sin(n\pi)}{n\pi} \qquad D(t) = D_0 + \sum D_i (1 - e^{-t/\tau}), i = 1,9$$

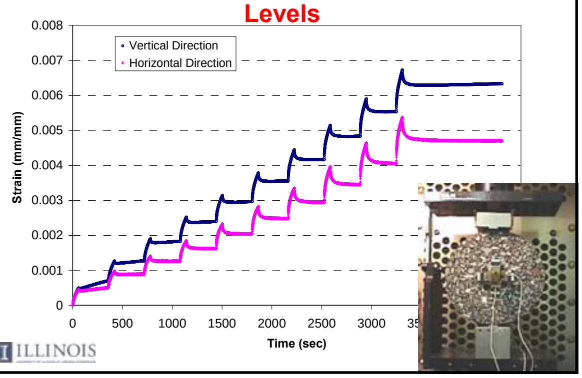
Log(time), E(t), K(t), and G(t) – Curve Fitting

Finding Prony Series Coefficients

Bulk and Shear Moduli → ABAQUS

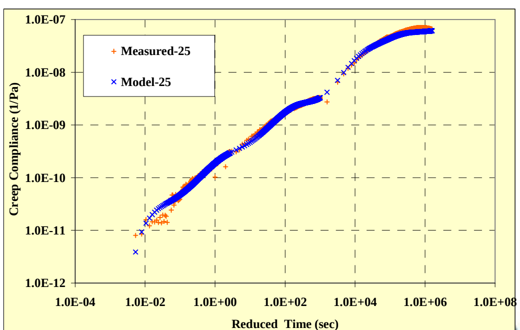
ILLINOIS

Creep Compliance Test at Different Loading Levels



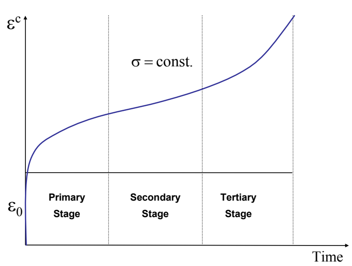
ILLINOIS

Creep Compliance Master Curve @ 25 ° C



ILLINOIS

Time-Hardening Creep Model



$$\varepsilon^c = A\sigma^m t^n$$

$$\dot{\varepsilon}^c = \frac{\partial \varepsilon^c}{\partial t} = An\sigma^m t^{n-1}$$

Nonlinear Creep Parameters (A, n, and m)

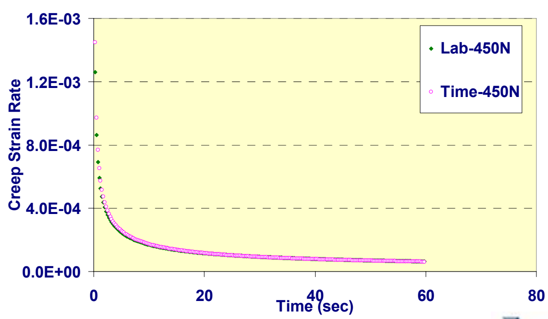
ILLINOIS

Fitted Time Hardening Creep Model Parameters

MATERIALS	TIME HARDENING PARAMETERS			COEFFICIENT OF DETERMINATION			
	A	n	m	SSE	Ssy	MSE	RMSE
WS 20 deg	3.2800E-04	1.1301	-0.4189	2.969E-09	1.491E-07	5.620E-12	2.37065E-06
BM 20 deg	2.2500E-03	0.5566	-0.5979	6.385E-06	8.900E-05	2.668E-09	5.16527E-05
WS 30 deg	2.4800E-03	0.6961	-0.6134	4.594E-06	8.500E-05	1.920E-09	4.38178E-05
BM 30 deg	7.1200E-04	0.0292	-0.5756	1.800E-05	1.130E-04	7.588E-09	8.71091E-05
WS 40 deg	7.4500E-04	0.765	-0.4289	1.358E-08	9.307E-07	2.310E-11	4.80625E-06
BM 40 deg	1.6200E-04	0.0826	-0.307	2.902E-07	2.091E-06	4.940E-10	2.22261E-05

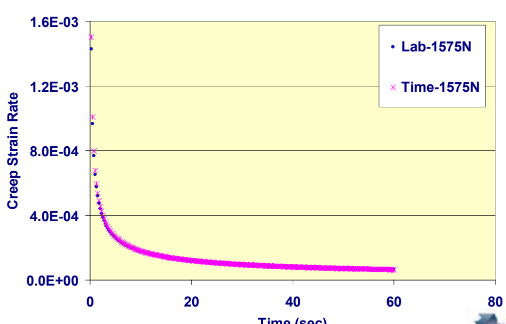
ILLINOIS

Lab Test vs. Fitted Creep Model (450 N/ 30 °C)



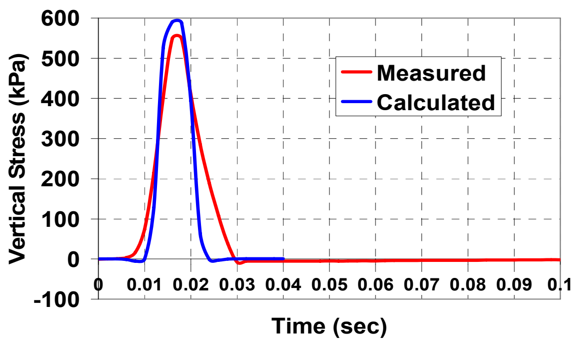
ILLINOIS

Lab Test vs. Fitted Creep Model (1575 N/ 30 °C)

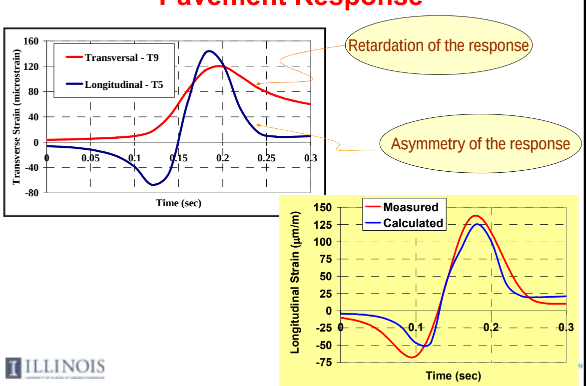


ILLINOIS

Model Calibration and Validation

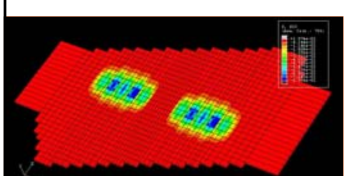


Pavement Response

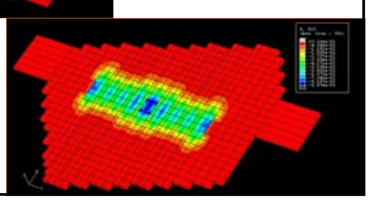


Surface Vertical Stress (T=25°C)

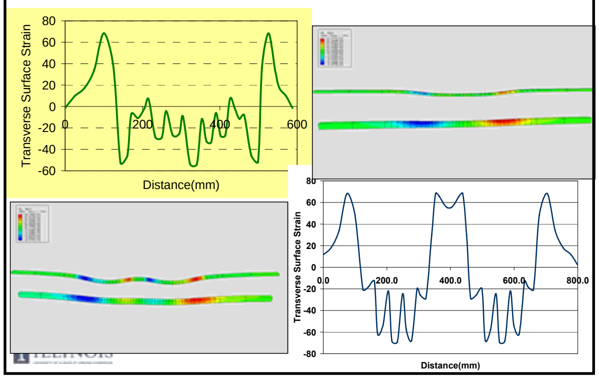
Vertical Stress (Dual Tires)



Vertical Stress (Wide-Base)



Surface Strain (T=25°C)



ILLINOIS

Combined Relative Damage

- Number of cycles till failure spread over several orders of magnitude:
  - Rutting of HMA and top-down cracking are the most critical distresses since they directly affect the pavement surface condition

$$\text{CombinedDR} = a_1 DR_{rutting-HMA} + a_2 DR_{top-down} + a_3 DR_{fatigue} + a_4 DR_{rutting-subgrade}$$

$$a_1 = \frac{1/\log(N_{rutting-HMA})}{1/\log(N_{rutting-HMA}) + 1/\log(N_{top-down}) + 1/\log(N_{rutting-subgrade}) + 1/\log(N_{fatigue})}$$

$$a_2 = ..., a_3 = ..., a_4 = ...$$

ILLINOIS

Al-Qadi and Co-Workers

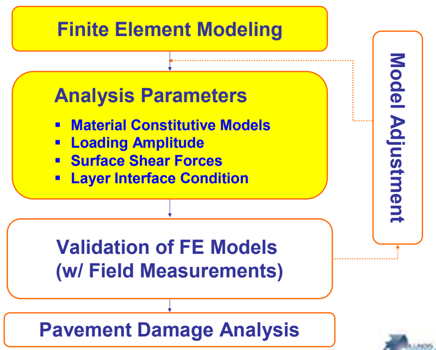
- Combined Damage Ratios:

Distress Tire	A	B	C	D	CDR
445/50R22.5	2.25	1.43	1.13	0.76	1.19
455/55R22.5	1.83	1.34	0.97	0.25	1.07

A: Fatigue Cracking, B: Subgrade Rutting, C: HMA Rutting, D: Top-down

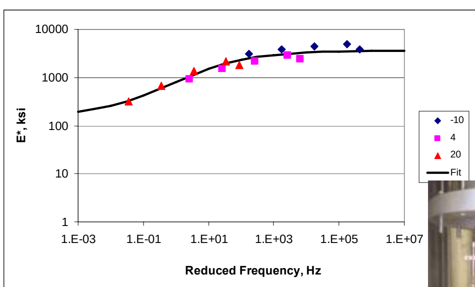
ILLINOIS

New Analysis Approach



ILLINOIS

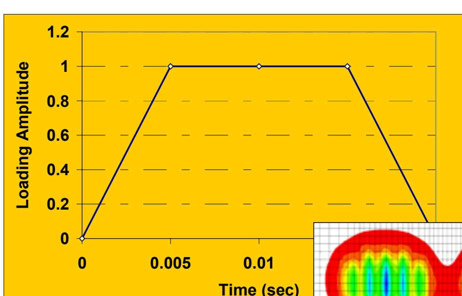
Master curve for section "F"

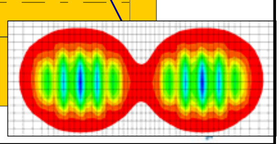


ILLINOIS

Trapezoidal Loading (Traditional)

- All tire imprints have the same loading amplitude



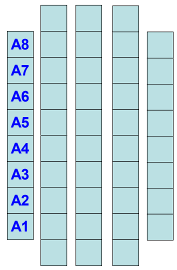


ILLINOIS

Discretization of Tire Imprint

One of the dual tire imprint

Discretization into FE

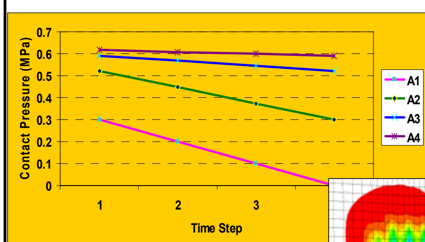


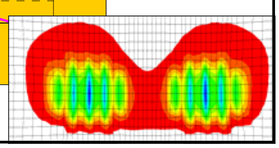
Finite elements

ILLINOIS

Continuous Loading (Exit Part)

- Continuous Loading Amplitude: Decrease
  - Half of the longitudinal pressure distribution (exit side)

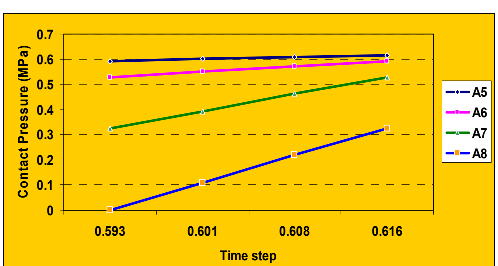




ILLINOIS

Continuous Loading (Entrance Part)

- Continuous Loading Amplitude: Increase
  - Half of longitudinal pressure distribution (entrance side)



ILLINOIS

Assigning pressure data to the FE of tire imprint

- **Dual tire**

8kph XDA2- dual 6.9b_6.9b

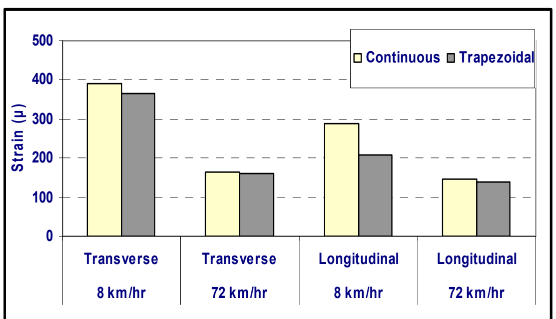
	ELEMENT	Weight F for EL 6	Weight F for EL 8	Tread A	B	C	D	E	F	G	H	I	J
				0.641	0.872	0.988	0.858	0.641	0.641	0.872	0.988	0.858	0.641
	10		0.425		0.371	0.420	0.365			0.371	0.420	0.365	
	9	0.488	0.752	0.313	0.656	0.743	0.645	0.313	0.313	0.656	0.743	0.645	0.313
entrance	8	0.850	0.935	0.545	0.815	0.924	0.802	0.545	0.545	0.815	0.924	0.802	0.545
	7	0.975	0.985	0.625	0.859	0.973	0.845	0.625	0.625	0.859	0.973	0.845	0.625
	6	0.960	0.970	0.615	0.846	0.958	0.832	0.615	0.615	0.846	0.958	0.832	0.615
	5	0.805	0.898	0.516	0.783	0.887	0.770	0.516	0.516	0.783	0.887	0.770	0.516
	4	0.405	0.700	0.260	0.610	0.692	0.601	0.260	0.260	0.610	0.692	0.601	0.260
exit	3		0.327		0.285	0.323	0.281			0.285	0.323	0.281	
	2												
	1												

- **Wide-base 455**

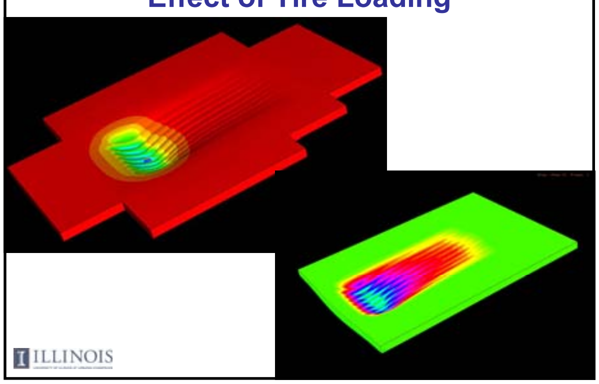
455_new (7.2bar)_Final

	ELEMENT	Weight F for EL 7	Weight F for EL 8	Weight F for EL 9	Tread A	B	C	D	E	F	G	H	I	
					0.500	0.830	0.884	0.940	0.956	0.940	0.884	0.830	0.500	
	10		0.500	0.476		0.415	0.442	0.447	0.455	0.447	0.442	0.415		
	9	0.530	0.820	0.790	0.265	0.681	0.725	0.743	0.755	0.743	0.725	0.681	0.265	
entrance	8	0.858	0.940	0.915	0.429	0.780	0.831	0.860	0.875	0.860	0.831	0.780	0.429	
	7	0.962	0.990	0.978	0.481	0.822	0.875	0.919	0.935	0.919	0.875	0.822	0.481	
	6	1.000	0.990	1.000	0.500	0.822	0.875	0.940	0.956	0.940	0.875	0.822	0.500	
	5	0.960	0.935	0.975	0.480	0.776	0.827	0.917	0.932	0.917	0.827	0.776	0.480	
	4	0.845	0.810	0.910	0.423	0.672	0.716	0.855	0.870	0.855	0.716	0.672	0.423	
exit	3	0.485	0.450	0.770	0.243	0.374	0.398	0.724	0.736	0.724	0.398	0.374	0.243	
	2			0.420				0.395	0.402	0.395				
	1													

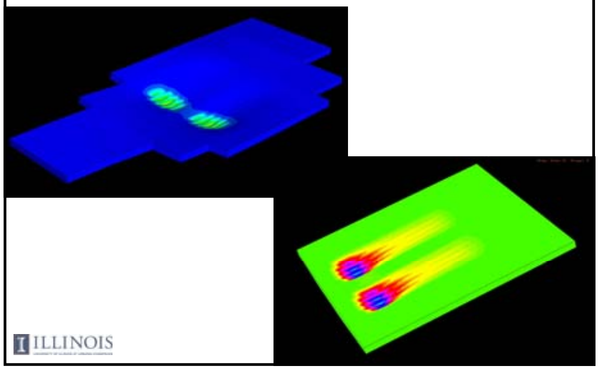
Pavement Response (40°C)



Effect of Tire Loading

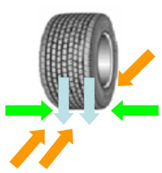


Trapezoidal vs. Continuous Loading



ILLINOIS

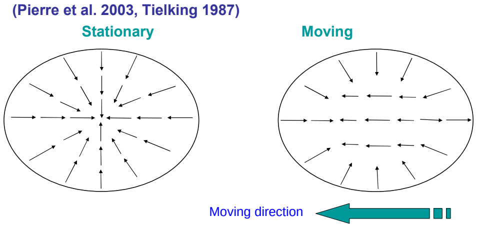
Incorporation of Lateral Loading



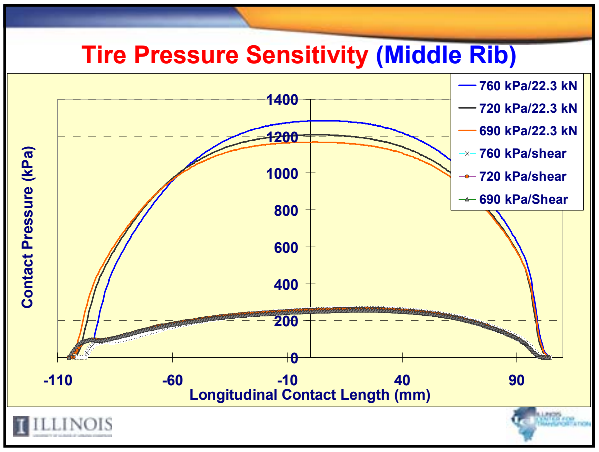
ILLINOIS

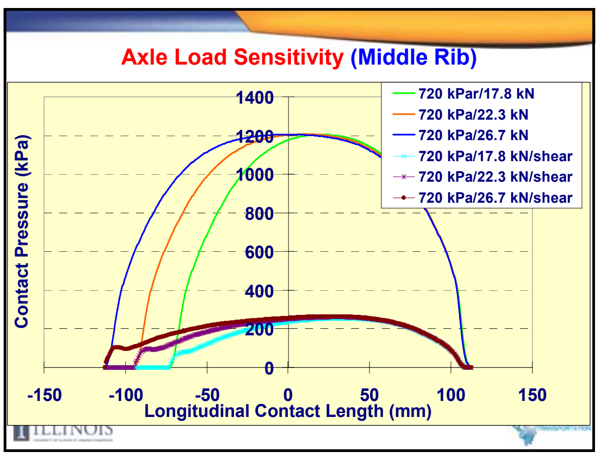
Surface Tangential Contact Pressures

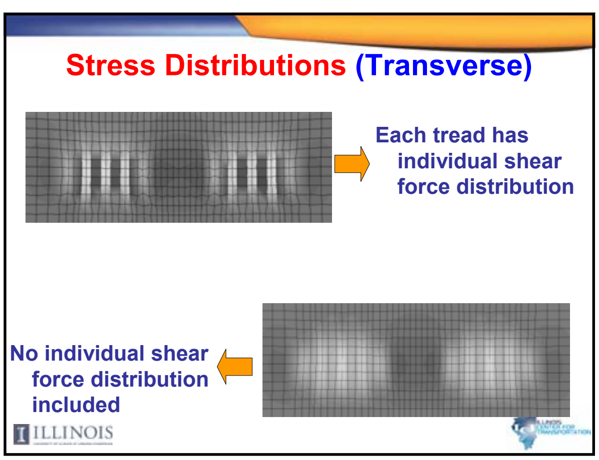
- Conventional surface tangential pressure distributions (Pierre et al. 2003, Tielking 1987)

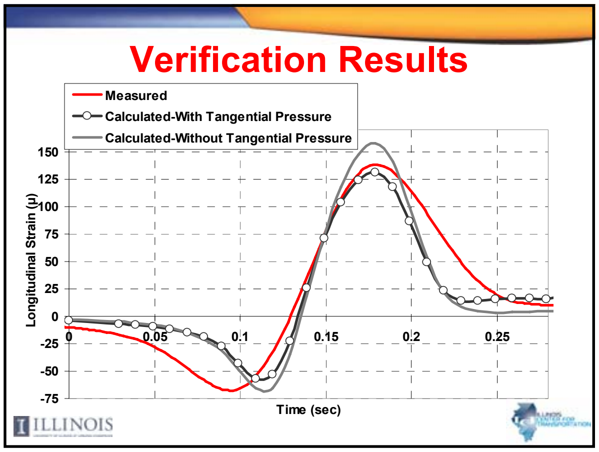


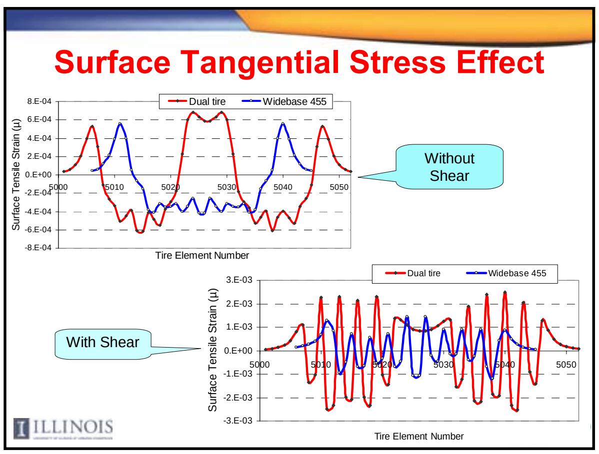
ILLINOIS

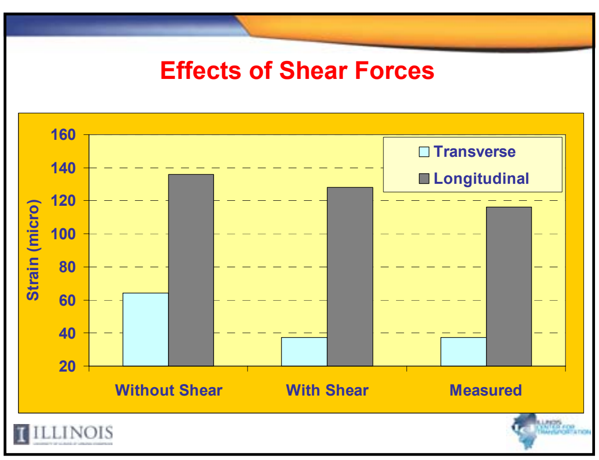

Tire Pressure Sensitivity (Middle Rib)
760 kPa/22.3 kN
720 kPa/22.3 kN
690 kPa/22.3 kN
760 kPa/shear
720 kPa/shear
690 kPa/Shear
Contact Pressure (kPa)
1400
1200
1000
800
600
400
200
0
-110
-60
-10
40
90
Longitudinal Contact Length (mm)
ILLINOIS


Axle Load Sensitivity (Middle Rib)
720 kPar/17.8 kN
720 kPa/22.3 kN
720 kPa/26.7 kN
720 kPa/17.8 kN/shear
720 kPa/22.3 kN/shear
720 kPa/26.7 kN/shear
Contact Pressure (kPa)
1400
1200
1000
800
600
400
200
0
-150
-100
-50
0
50
100
150
Longitudinal Contact Length (mm)


Stress Distributions (Transverse)
Each tread has individual shear force distribution
No individual shear force distribution included
ILLINOIS


Verification Results
Measured
Calculated-With Tangential Pressure
Calculated-Without Tangential Pressure
Longitudinal Strain (μ)
Time (sec)
ILLINOIS


Surface Tangential Stress Effect
Dual tire
Widebase 455
Surface Tensile Strain (μ)
Tire Element Number
Without Shear
With Shear
ILLINOIS


Effects of Shear Forces
Transverse
Longitudinal
Strain (micro)
Without Shear
With Shear
Measured
ILLINOIS

Surface Shear Forces

- Transverse Shear Forces
  - Induce higher stresses than longitudinal shear forces at the pavement surface
- Longitudinal Shear Forces
  - Balance their responses due to force-direction changes (compression to tension)

ILLINOIS

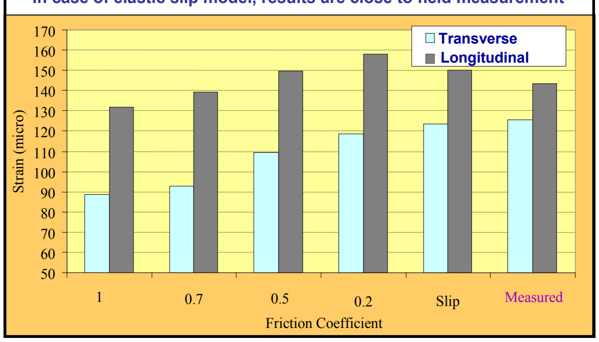
Interface Friction

- Simple Friction Model: Friction Coefficient Control
  - Model characterized by the Coulomb friction coefficient, μ
  - Resistance to movement is proportional to normal pressure at interface
- Elastic Slip Model: Max. Shear Stress Control
  - Shear stress and displacement are linearly dependent until shear stress equals shear strength; then converted to the Coulomb friction condition

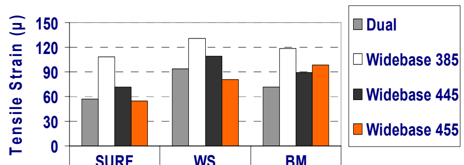
ILLINOIS

Measured vs. Calculated

- Variation in interface friction coefficients
- In case of elastic slip model, results are close to field measurement



Critical Tensile Strain Using LVE

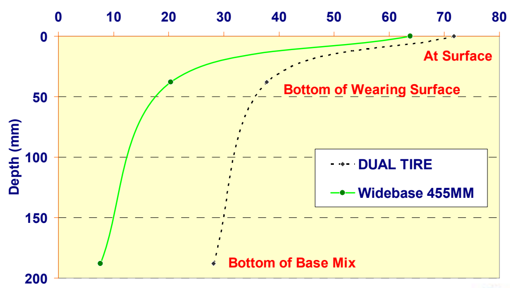


	SURF	WS	BM
Dual	56.93	93.59	71.40
Widebase 385	108.45	130.64	118.15
Widebase 445	71.71	109.13	89.09
Widebase 455	54.99	80.52	98.57

- SURF: Surface
- WS: Bottom of Wearing Surface
- BM: Bottom of HMA

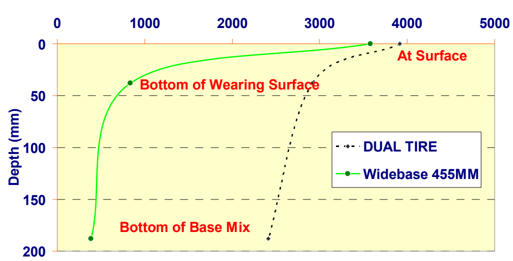
Max Shear Creep Strain @ 40°C and 5mph

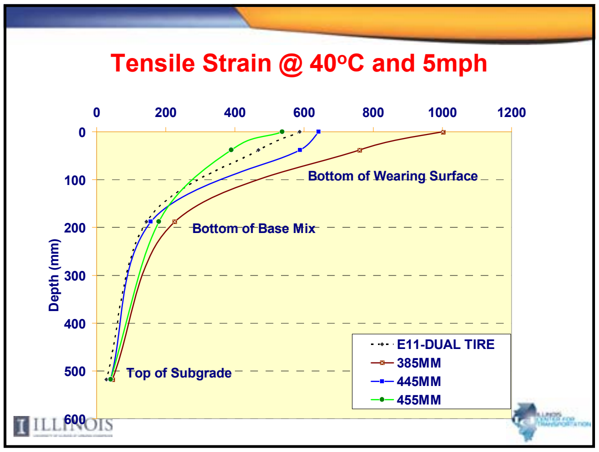
One Loading Cycle

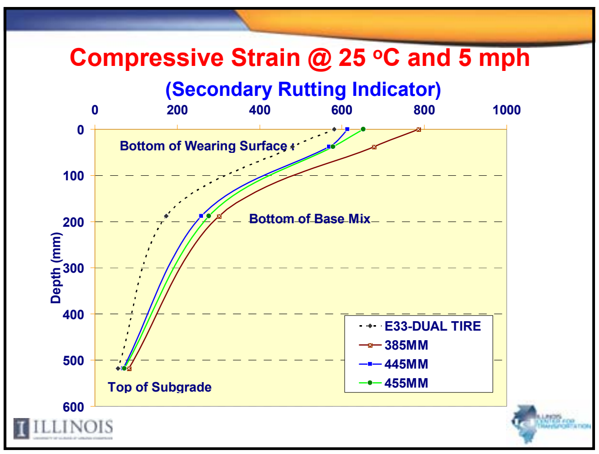


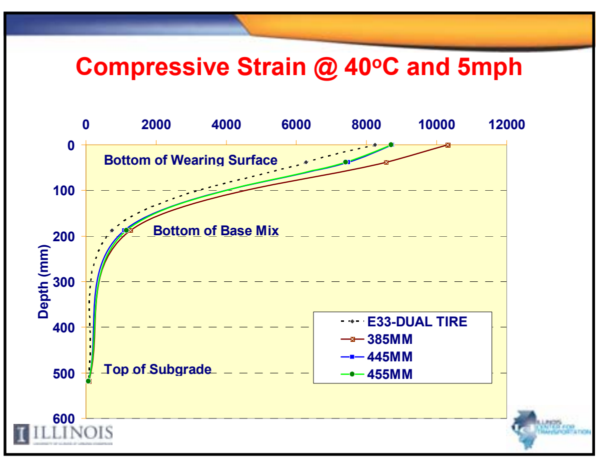
Shear Creep Strain @ 40°C and 5mph

1000 Loading Cycles




Tensile Strain @ 40oC and 5mph
Bottom of Wearing Surface
Bottom of Base Mix
Top of Subgrade
Depth (mm)
E11-DUAL TIRE
385MM
445MM
455MM
ILLINOIS


Compressive Strain @ 25 oC and 5 mph
(Secondary Rutting Indicator)
Bottom of Wearing Surface
Bottom of Base Mix
Top of Subgrade
Depth (mm)
E33-DUAL TIRE
385MM
445MM
455MM
ILLINOIS


Compressive Strain @ 40oC and 5mph
Bottom of Wearing Surface
Bottom of Base Mix
Top of Subgrade
Depth (mm)
E33-DUAL TIRE
385MM
445MM
455MM
ILLINOIS

Dynamic Analysis

When a heavy vehicle travels on a pavement, its axle load does not maintain steady state; but varies even on a smooth road (dynamic oscillation varies by +/-15%)

ILLINOIS

Why Dynamic Analysis Is Needed?

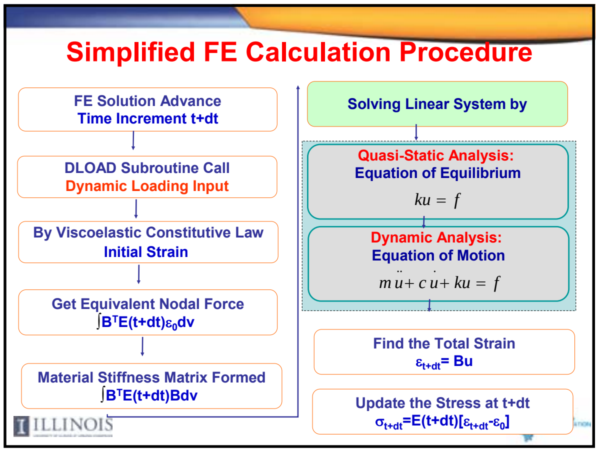
- Quasi-static visco analysis:
  - ✓ Does not consider the mass inertia and damping forces
- Dynamic analysis
  - ✓ Considers mass inertia and damping forces effect on pavement responses
  - ✓ Different contact areas of tire imprint can affect the magnitude of inertia forces
  - ✓ Pavement response is affected by loading amplitude
- Need proper energy dissipation algorithm such as, structural damping, mass damping, friction and visco-elastic material property

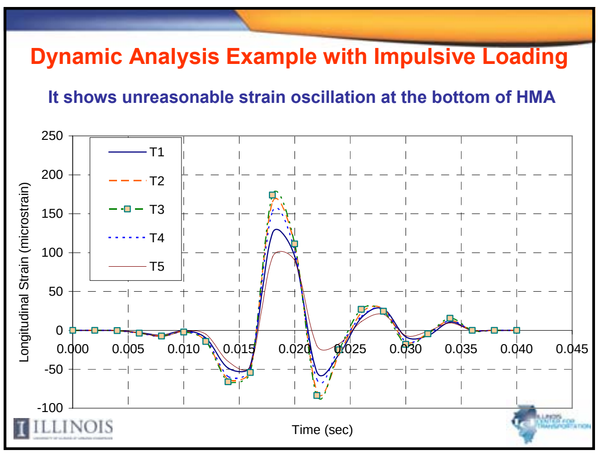
ILLINOIS

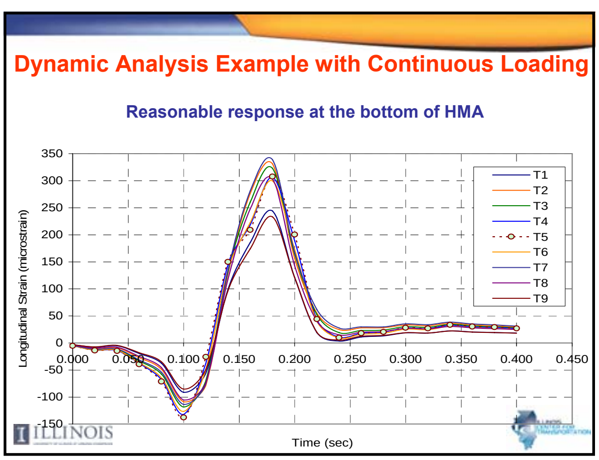
Various Dynamic Analysis Approaches

- Implicit Dynamic Analysis
  - ✓Advantage: Unconditionally Stable/ Very Small Error
  - ✓Disadvantage: Long Analysis Time
- Explicit Dynamic Analysis
  - ✓Advantage: Short Analysis Time
  - ✓Disadvantage: Conditionally Stable/ High Error
- Modal/Subspace Dynamic Analysis
  - ✓ Only Applicable to the Linear System

ILLINOIS

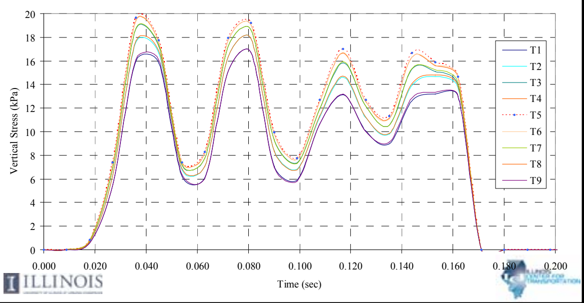

Simplified FE Calculation Procedure
FE Solution Advance
Time Increment t+dt
DLOAD Subroutine Call
Dynamic Loading Input
By Viscoelastic Constitutive Law
Initial Strain
Get Equivalent Nodal Force
$\int B^T E(t+dt)\varepsilon_0 dv$
Material Stiffness Matrix Formed
$\int B^T E(t+dt) B dv$
Solving Linear System by
Quasi-Static Analysis:
Equation of Equilibrium
$ku = f$
Dynamic Analysis:
Equation of Motion
$m\ddot{u} + c\dot{u} + ku = f$
Find the Total Strain
$\varepsilon_{t+dt} = Bu$
Update the Stress at t+dt
$\sigma_{t+dt} = E(t+dt)[\varepsilon_{t+dt} - \varepsilon_0]$
ILLINOIS


Dynamic Analysis Example with Impulsive Loading
It shows unreasonable strain oscillation at the bottom of HMA
Longitudinal Strain (microstrain)
250
200
150
100
50
0
-50
-100
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Time (sec)
T1
T2
T3
T4
T5
ILLINOIS


Dynamic Analysis Example with Continuous Loading
Reasonable response at the bottom of HMA
Longitudinal Strain (microstrain)
350
300
250
200
150
100
50
0
-50
-100
-150
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.350
0.400
0.450
Time (sec)
T1
T2
T3
T4
T5
T6
T7
T8
T9
ILLINOIS

Dynamic Analysis Example without Damping

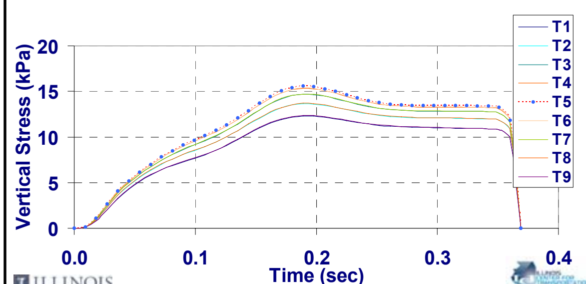
- ✓ It shows unreasonable stress oscillation at the top of subgrade
- ✓ The excitation is much higher than that at shallow depths
- ✓ A proper energy dissipation rule needs to be incorporated



ILLINOIS

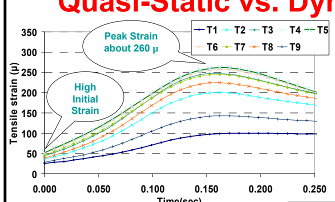
Dynamic Analysis Example with Damping

- ✓ Incorporates proper damping factors
- ✓ Damping controls excitation only, it does not affect stress output



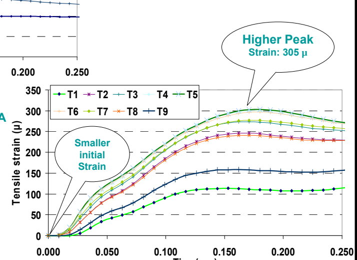
ILLINOIS

Quasi-Static vs. Dynamic Analysis



- Tensile Strain at the Bottom of HMA

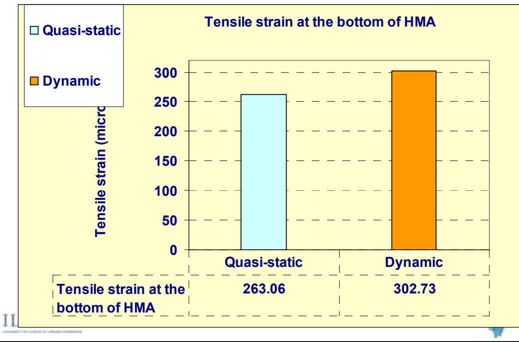
- Tensile Strain at the Bottom of HMA



ILLINOIS

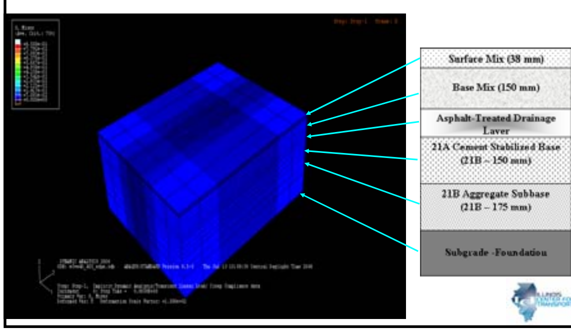
Quasi-static Response vs. Dynamic Response

Maximum dynamic strain is higher than that of quasi-static analysis (about 15%)



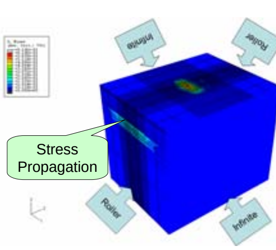
Boundary Effect Check

- Contact Stress at Surface: Max. 1.1MPa (160psi)
- Response Check by Mises Stress Range: 0.97MPa (150psi) ~ 0.01MPa (1.45psi)
- For Element Size, Need to Check Stress Concentration at the Boundary

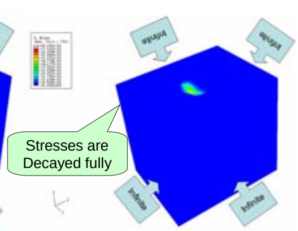


Boundary Effect Check for Dynamic Analysis

- Case 1

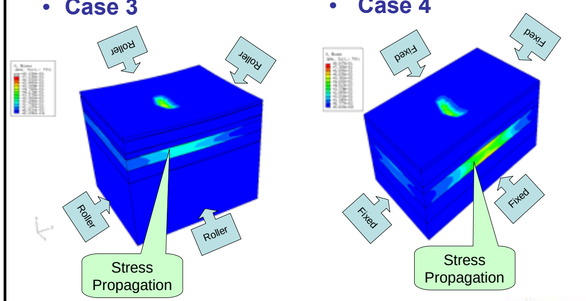


- Case 2



Boundary Effect Check for Dynamic Analysis

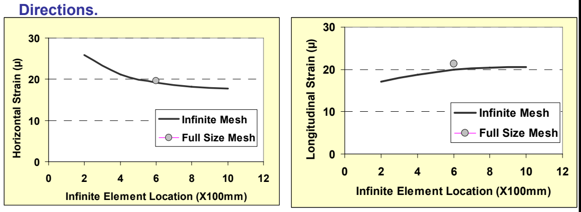
- Case 3
- Case 4



ILLINOIS

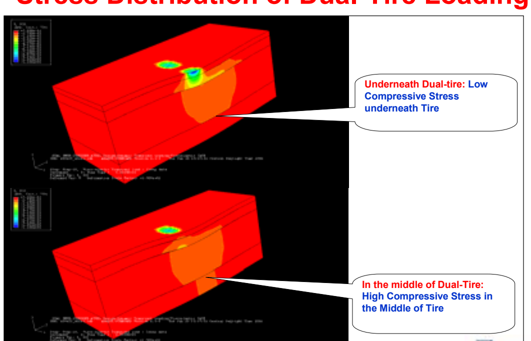
Boundary Effect Check

- After Element Size Selection and Use Infinite Elements at the Boundary, the Effective Location of the Infinite Boundary Is Defined
- Compare with Full Size of Mesh Design (3 X 3 X 5 m)
- Example: The Location of Infinite Element Start Converge after Six Times the Tire Loading Radius in Horizontal and Longitudinal Directions.



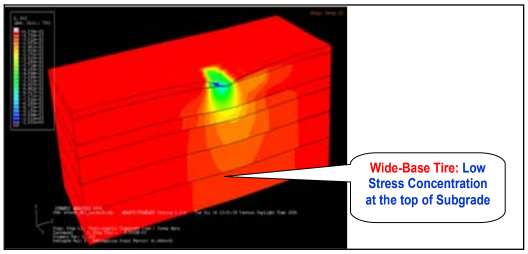
ILLINOIS

Stress Distribution of Dual-Tire Loading



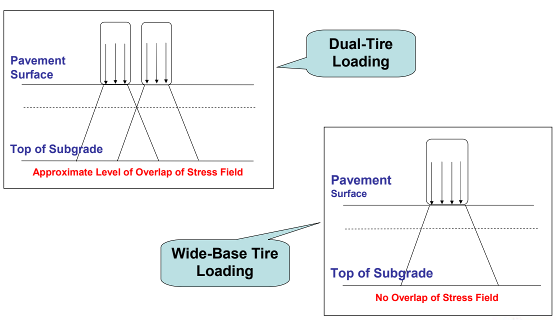
ILLINOIS

Stress Distribution of Wide-Base Tire Loading



ILLINOIS

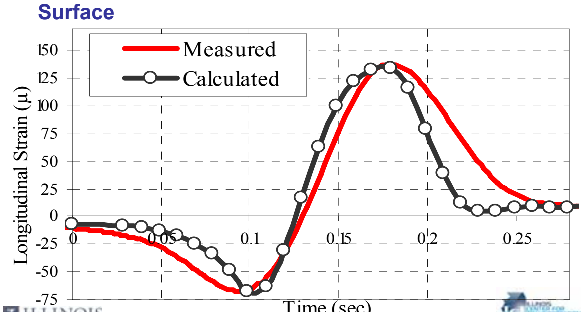
Distribution of Wheel Load



ILLINOIS

Pavement Response Validation

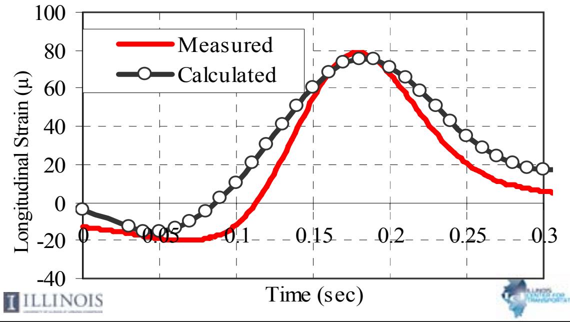
- Dynamic FE Analysis: Bottom of the Wearing Surface



ILLINOIS

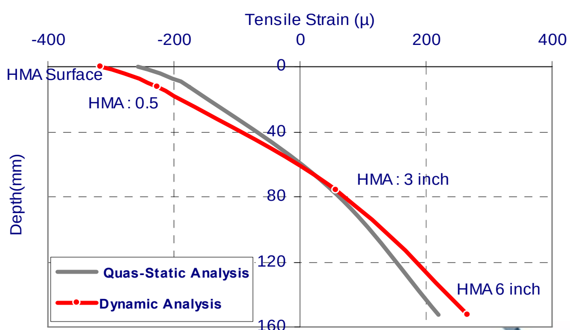
Pavement Response Validation

- Dynamic FE Analysis: Bottom of the HMA



ILLINOIS

Quasi-Static vs. Dynamic Analysis



ILLINOIS

Summary

- VE FE modeling should be used to quantify tire damage to pavements:
  - Continuous Loading Better Simulates Field Loading Conditions
  - Surface Shear Should Be Considered
  - Interface Stresses Should Be Appropriately Modeled
  - Dynamic Analysis Will Enhance The Model Prediction Capabilities
- Results of the developed FE models are in reasonable agreement with experimental measurements.
- Damage Comparison:
  - Fatigue
  - Primary Rutting
  - Secondary Rutting
  - Top Down Cracking
- Pavement damage of wide-base should be evaluated in the context of other benefits of pavements

ILLINOIS

Questions?

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN