The Impact of Wide-Base Tires on Pavements - A National Study

Transportation Pooled Fund Study TPF-5(197)

TRB Webinar October 19, 2015

Sponsored by TRB Committees AFD60, AFD80 and AFK50

AGENDA

- TPF-5(197)Introduction and Background: Eric Weaver, FHWA
- Introduction to NG-WBT: Imad Al-Qadi, UIUC
- Impact of NG-WBT on pavement responses: Imad Al-Qadi, UIUC
- Designing pavement structures considering NG-WBT: Imad Al-Qadi, Jaime Hernandez
- Environmental impact of NG-WBT – Life-cycle assessment: Imad Al-Qadi, UIUC
- Q&A
- Final remarks: Imad Al-Qadi, UIUC and Eric Weaver, FHWA

TPF-5(197) Background

- International Workshop in October 2007
  - Concluded that past research not relevant to current tire designs and not applicable to a range of pavement structures
  - Recommended a National Research Program with International Collaboration
  - EPA promoting use as part of SmartWay Transport Partnership http://www.epa.gov/smartwaytransport/index.htm
  - Minutes available here: http://www.arc.unr.edu/Workshops.html
- Illinois DOT initiated a pooled fund solicitation in 2008;
- Requested FHWA lead in 2009
  http://www.pooledfund.org/projectdetails.asp?id=423&status=4

TPF-5(197) Scope and Objectives

- Tires in US market with width > 425mm
- Flexible pavement structures only
- Encourage Industry and International Partnerships
- Couple analytic modeling and experimental testing to quantify damage to pavements
- Deliver a tool and method to assess damage to their networks based on tire configuration
- Provide highway agencies a tool for determining appropriate tire load limits considering the trade-off between potential pavement damage relative to potential environmental and economic benefits

TPF-5(197) Status

- Seven State Participants; IL, MN, MT, NY, OK, TX, VA
- Industry representation and investment by RMA
- In-Kind contribution from OH DOT
- Coordination with ATA, EPA, NHTSA, DOE and RMA
- 3 Face-to-Face TAC meetings; 1 virtual
- 2 TRB Webinars
- Draft final deliverables received

TPF-5(197) Next Steps

- Gather the technical evaluation panel for a final meeting to evaluate products and make final recommendations – November 4-5, 2015 @TFHRC
- Disseminate products and publications through FHWA
- Publish articles in relevant media to further spread the word....

Effect of Wide-Base Tires on Pavement Damage – A National Study Part II

Imad L. Al-Qadi, PhD, PE, Dist.M.ASCE
Jaime Hernandez, PhD Candidate
Eric Weaver, PE

October 19th, 2015

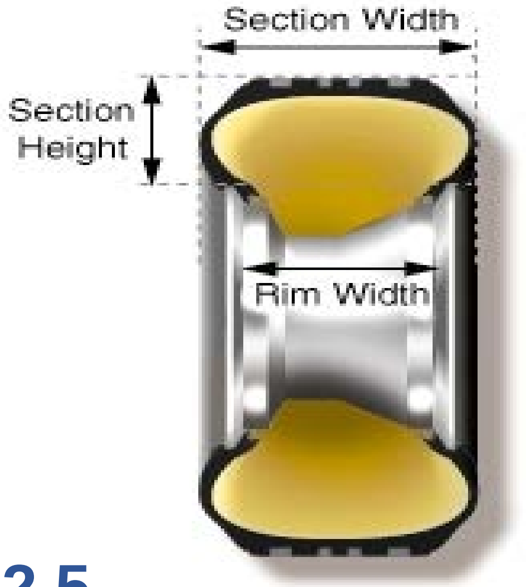
Introduction to NG-WBT

New-Generation Wide-Base Tire

WBT 445/50R22.5
New-Generation Wide-Base Tire

DTA 275/80R22.5

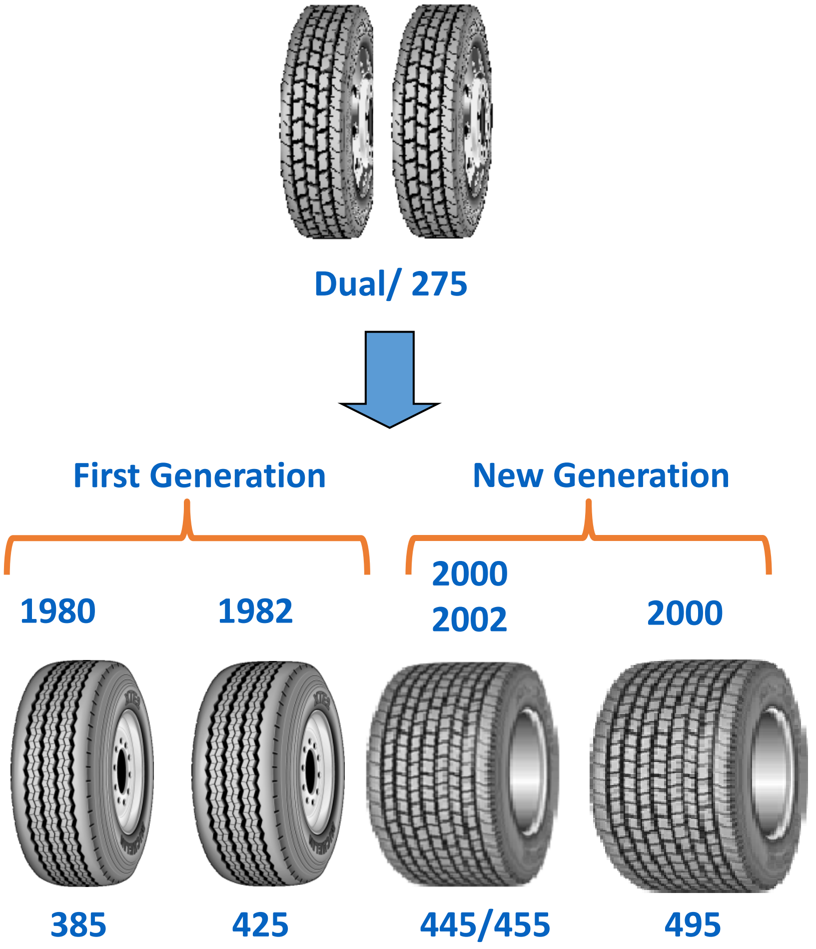
New-Generation Wide-Base Tire



- **Dual Tire**
  - Nominal tire width 250~305mm
  - High Profile
  - 12-22.5; 12R22.5; 275/80R22.5
- **Wide-Base Tire**
  - Nominal tire width 400~460 mm
  - Low Profile
  - 385/65R22.5, 425/65R22.5, 445/50R22.5, 455/55R22.5
- **Code**
  - Tire width (mm); tire aspect ratio (ratio of section height to width in %); radial ply (R); rim diameter code (in)

New-Generation Wide-Base Tire

- Introduced to North America in **1982**
- Earlier design was for **on- and off-road**
- **Low profile** design
- Relatively reduced **empty weight**
- Efficient **fuel** consumption/ low **emission**



New-Generation Wide-Base Tire

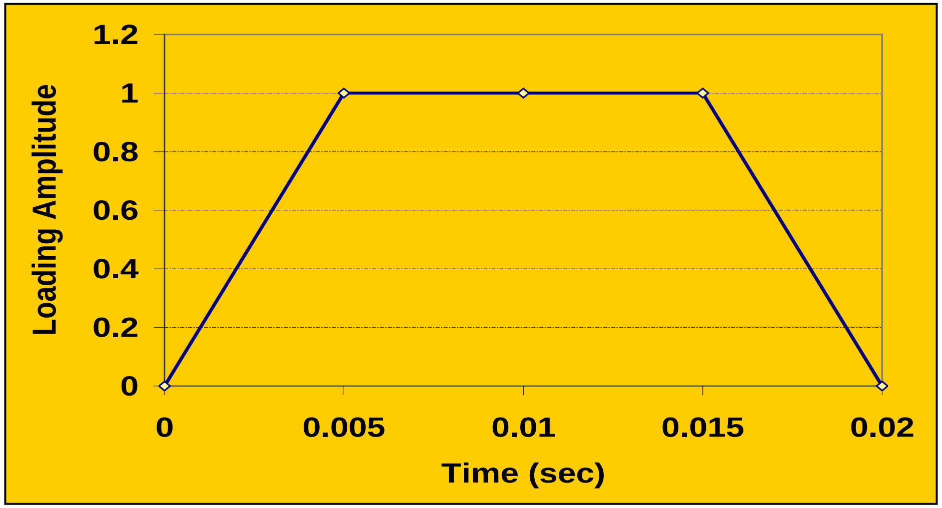
- Wide-base tires have been used in Europe since **early 1980s**
- In some countries more than **80%** of trailers use wide-base tires
- **FG-WBT** was proven **more detrimental to flexible pavements** than dual tires; **NG-WBT** is **less damaging** than **FG-WBT**

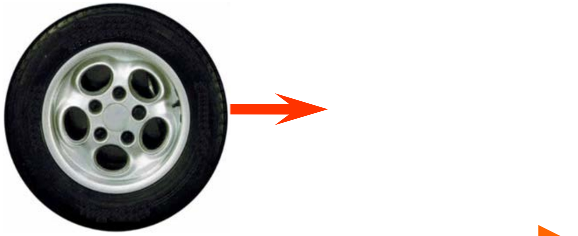
Impact of NG-WBT on Pavement Responses

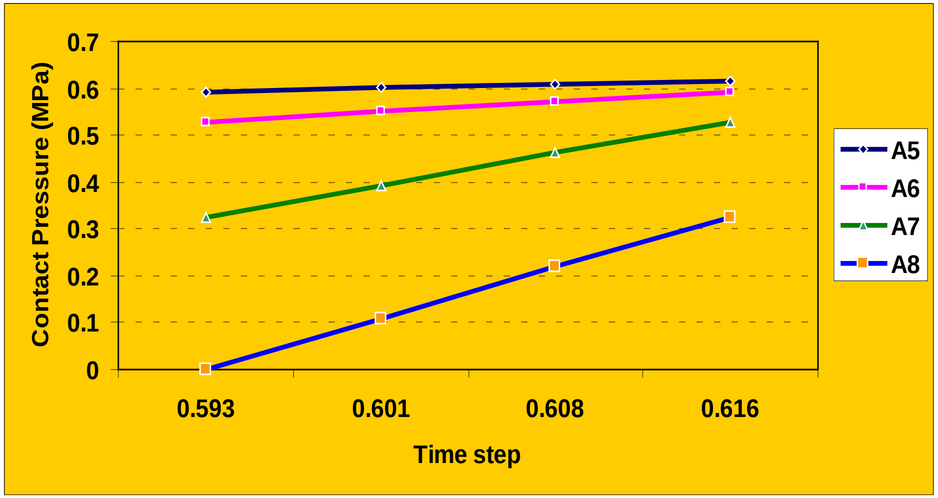
Finite Element Model

- Three-dimensional **dynamic analysis** with **moving load**
- Measured **3D contact** stresses
- **Viscoelastic** asphalt materials (AC)
- **Nonlinear** granular materials (thin pavement)
- **Layer interaction**
- **AC temperature**

Continuous Moving Loading



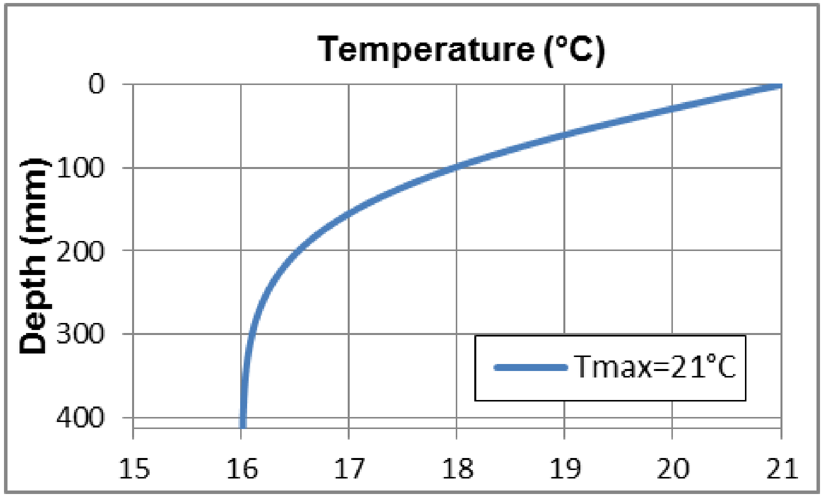




Continuous Moving Loading

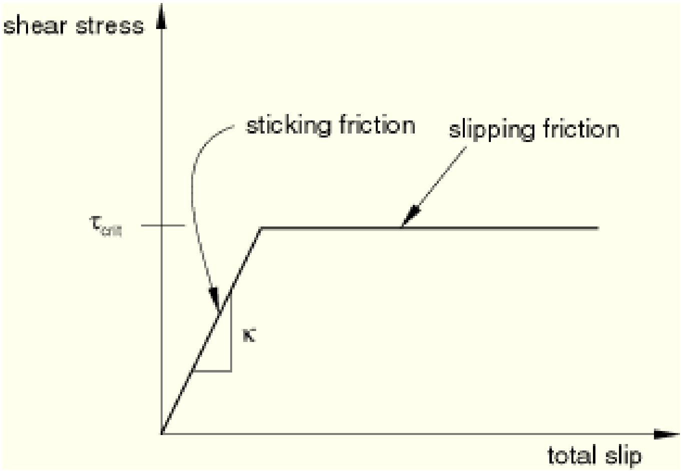
Temperature and Layer Interaction

- Temperature profile in AC layer



Sample: AC = 412.5mm

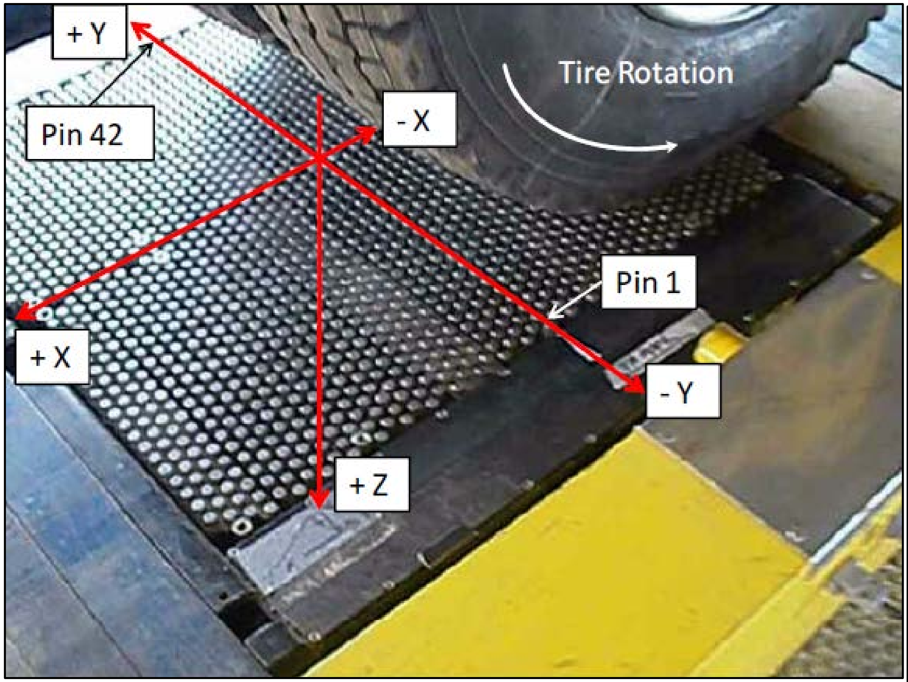
- Layer Interaction
  - Fully bonded AC layers
  - Coulomb Friction Model for AC to base and base to subgrade interfaces

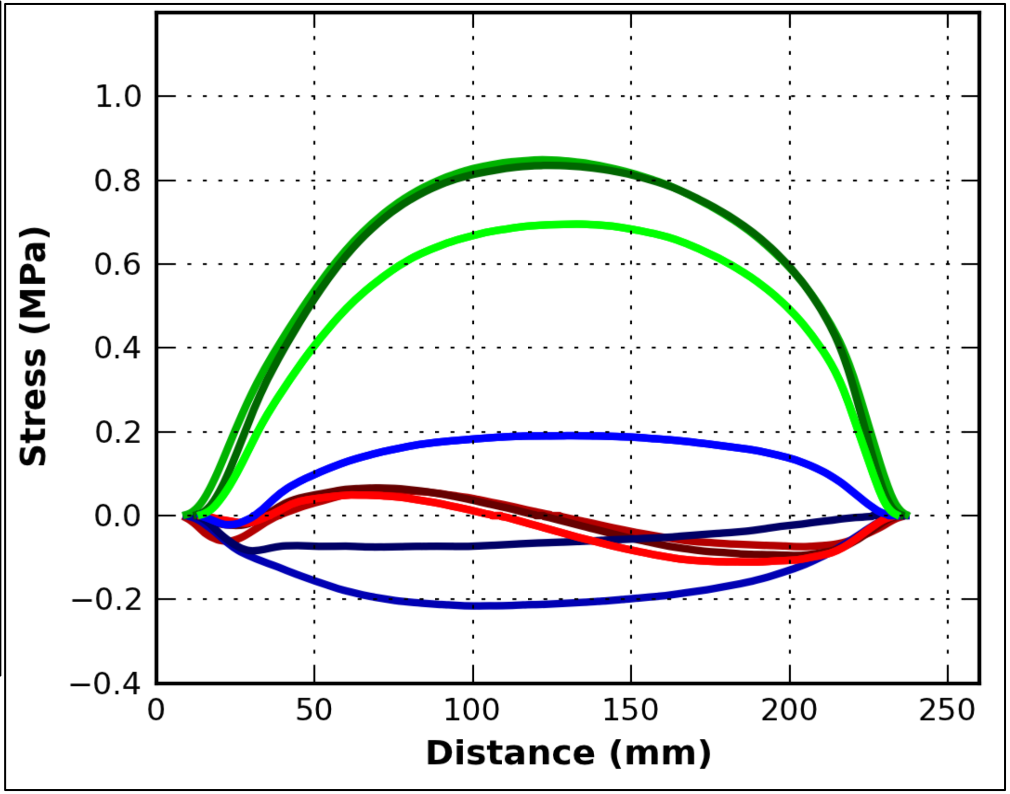


Abaqus documentation

Measured 3D contact stresses

- Three-dimensional, non-uniform

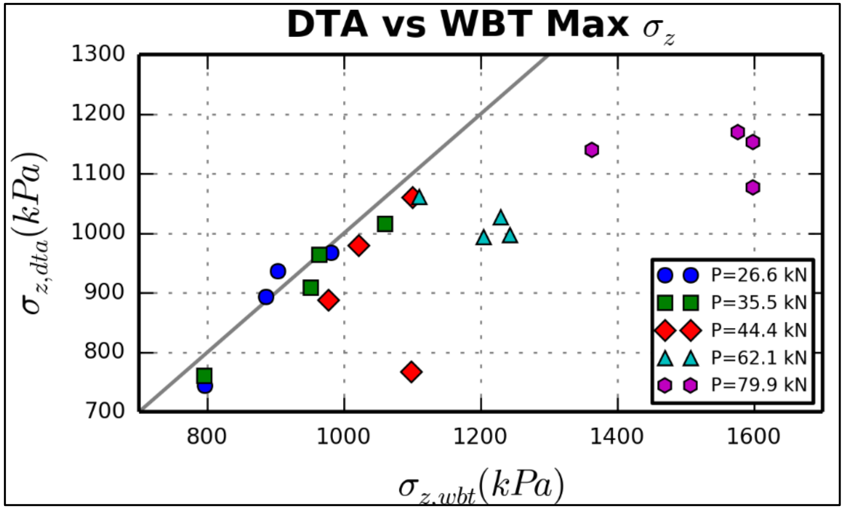




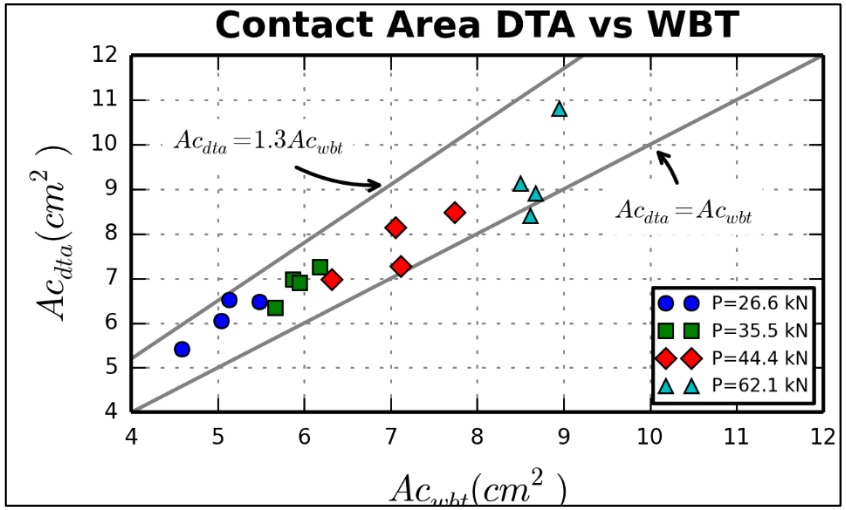
Typical Stress Distribution

Measured 3D Contact Stresses

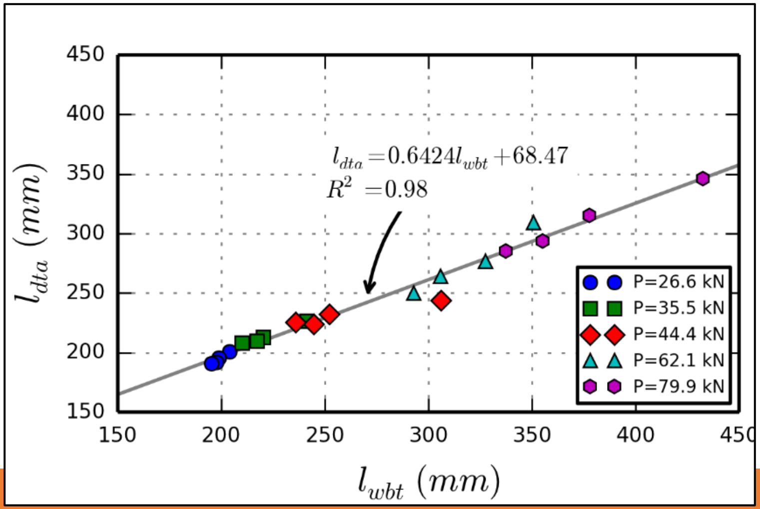
Vertical Contact Stresses



Contact Area

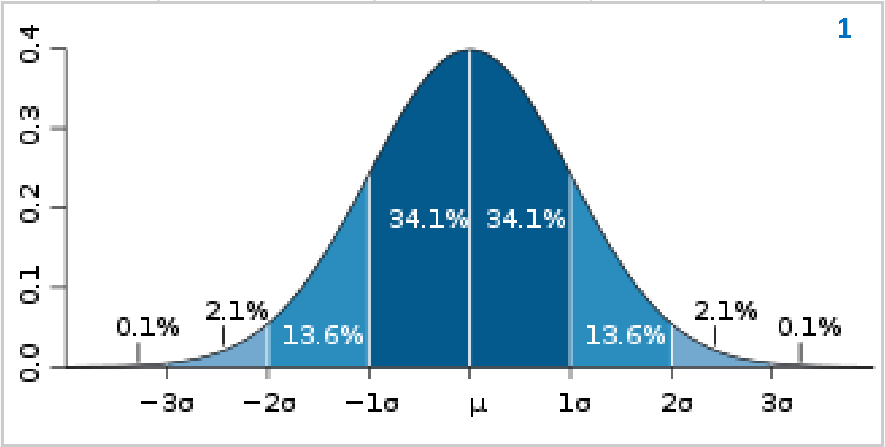


Maximum Contact Length



Viscoelastic AC

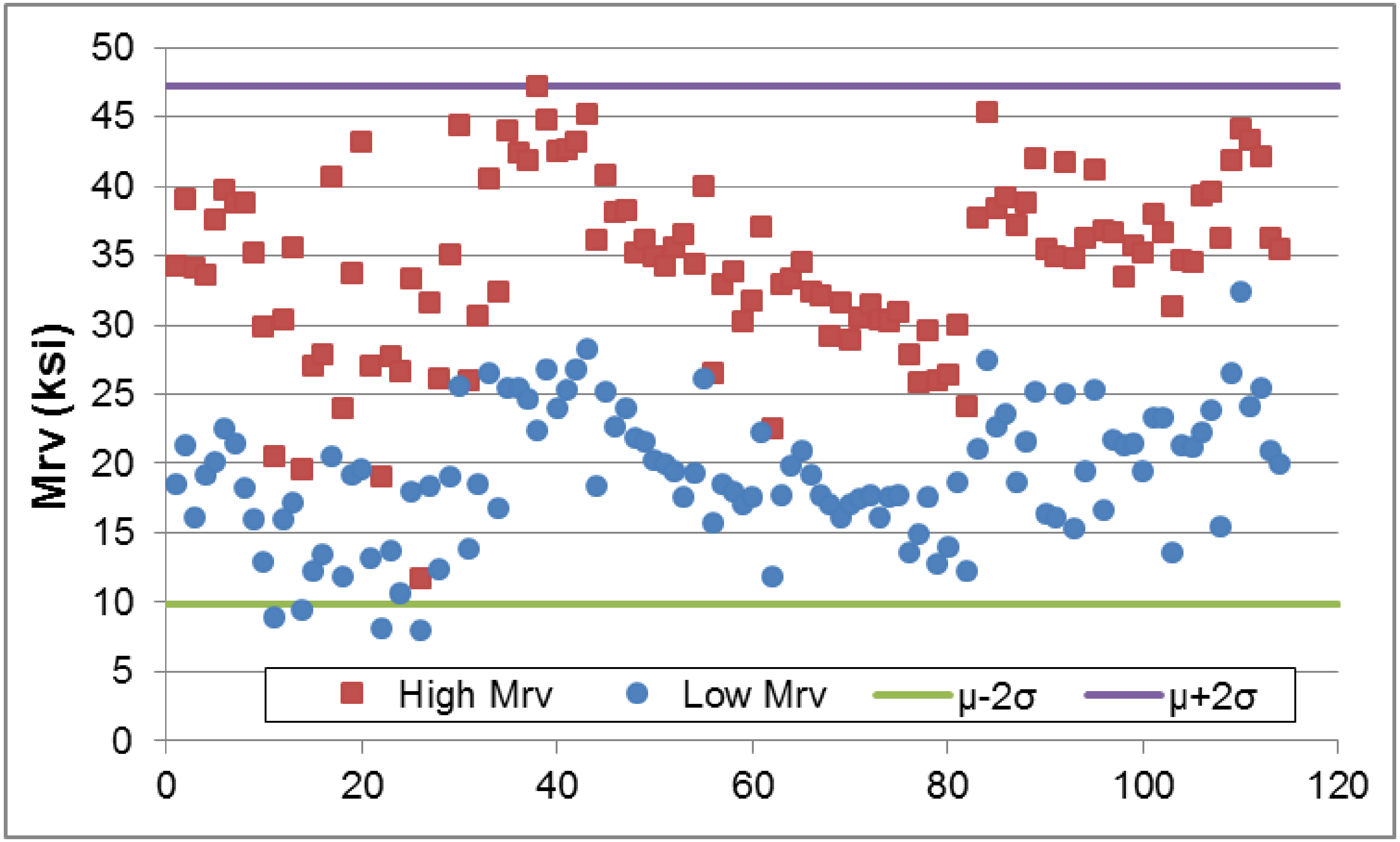
- Layer Properties: **NMAS**
  - Wearing Surface (WS) 9.5 or 12.5mm
  - Intermediate Layer (IS) 25 or 19.5mm
  - Base Layer (BS) 25 or 37.5mm
- Based on more than **1000 data sets from LTPP**



2σ ≈ 95.4%,
2.5σ ≈ 97.5%
and 3σ ≈ 99.8%

Nonlinear Granular Materials

- Vertical resilient modulus of 114 base materials at two stress levels



FEM Simulation Matrix – Thin

Thin Pavement Structure		
	Materials	Thicknesses (mm)
AC Layer	W, S*	75 and 125
Base**	W, S*	150 and 600
Subgrade	35 and 140 MPa	--
Possible combination	32	
With load cases (12)	384	

*W = Weak; S = Strong

**Considered with nonlinear mat

FEM Simulation Matrix – Thick

Thick Pavement Structure		
	Materials	Thicknesses (mm)
Wearing Surface	W1, S1*	25 and 62.5
Intermediate Layer	W2, S2*	37.5 and 100
Binder Layer	W3, S3*	62.5 and 250
Base and Subbase	140 and 415 MPa	150 and 600
Subgrade	70 MPa	--
Possible Combination	16	
With Load cases (12)	192	

*W = Weak; S = Strong

Loading Conditions

Load Case	Tire Type	Applied Load (kN)	Tire Inflation Pressure (kPa)
L1	WBT	26.6	552
L2	WBT	26.6	862
L3	WBT	79.9	552
L4	WBT	79.9	862
L5	DTA	26.6	552
L6	DTA	26.6	862
L7	DTA	26.6	552/758
L8	DTA	79.9	552
L9	DTA	79.9	862
L10	DTA	79.9	552/758
L11	WBT	44.4	758
L12	DTA	44.4	758

Model Validation: Database

ILLINOIS

U.S. Department of Transportation
Federal Highway Administration

ILLINOIS CENTER FOR TRANSPORTATION

Impact of Wide-Base Tires on Pavements - Database

Main Menu | Edit Profile | Administration → | Logout

Select a Project

This database provides data and reports for some of the projects that used wide-base tires as part of the research. The database is developed by research group at Illinois Center for Transportation (ICT) of University of Illinois at Urbana-Champaign and mainly includes the data from sections built under FHWA project DTFH61-11-C-00025 to study the effect of wide-base tires on pavement as well as some existing databases from past studies.

- Ohio Sections
- UC-Davis Sections
- Florida Sections
- UIUC Thin Pavement Sections (2006)
- Smart Road (2000-2002)

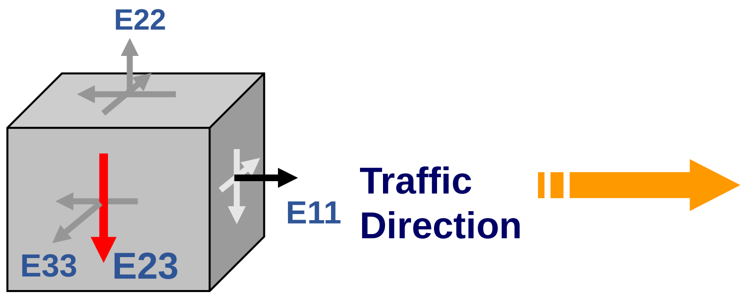
Source: [http://www.[illegible].com/]

Model Validation

- Measurements from low-volume roads and interstate highways
- Difference in vertical pressure on top of subgrade is 2.4% to 17.7%
- Difference in horizontal strains at the bottom of AC is 2.1% to 28.7%

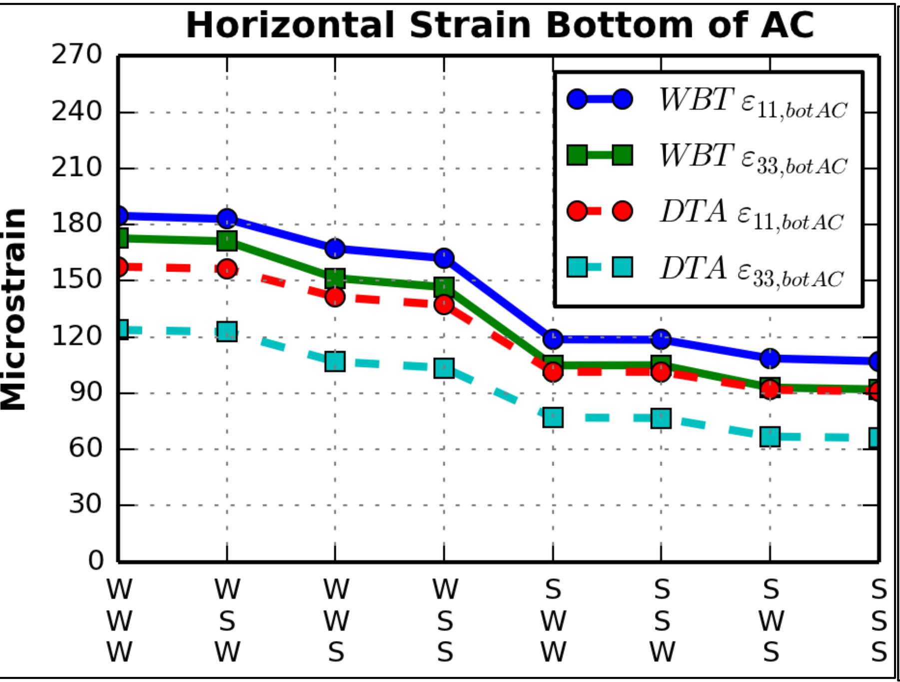
Critical Pavement Responses

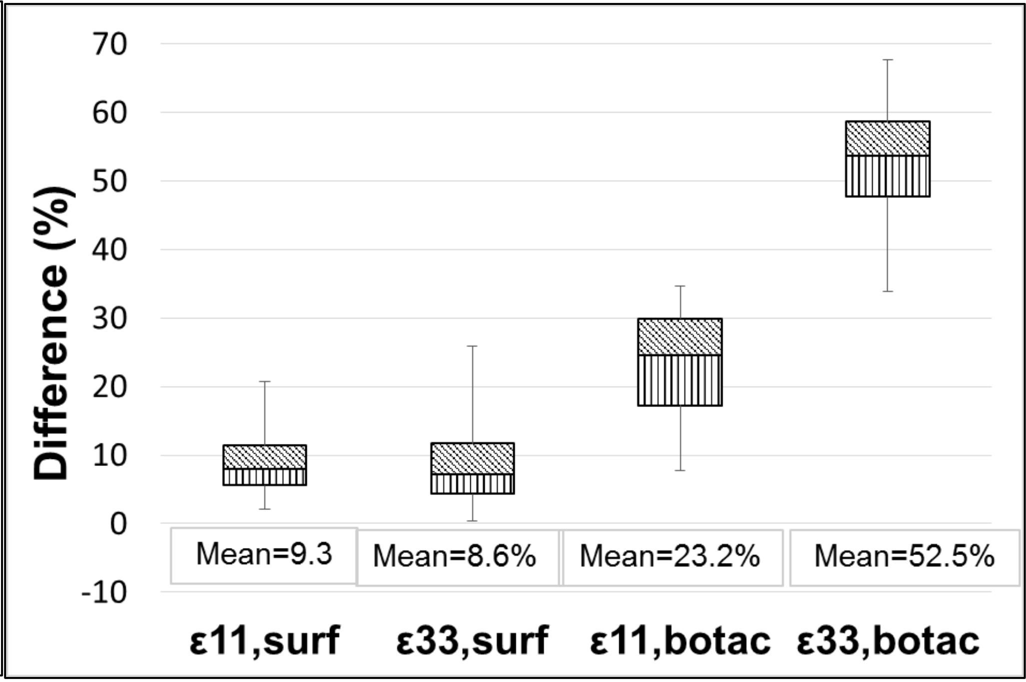
Distress	Pavement Response
Bottom-up fatigue cracking	Longitudinal and tensile strains at bottom of AC ($\varepsilon_{11,ac}$ and $\varepsilon_{33,ac}$)
Near-surface cracking	Transverse surface strain ($\varepsilon_{33,sf}$) and shear strain in AC ($\varepsilon_{23,ac}$)
Permanent deformation	Shear strain ($\varepsilon_{23,ac}$, $\varepsilon_{23,bs}$, and $\varepsilon_{23,sg}$) and vertical strain ($\varepsilon_{22,ac}$, $\varepsilon_{22,bs}$, and $\varepsilon_{22,sg}$) in each layer and

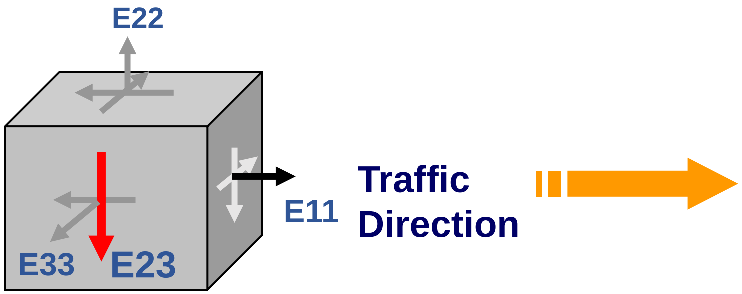


Pavement Responses

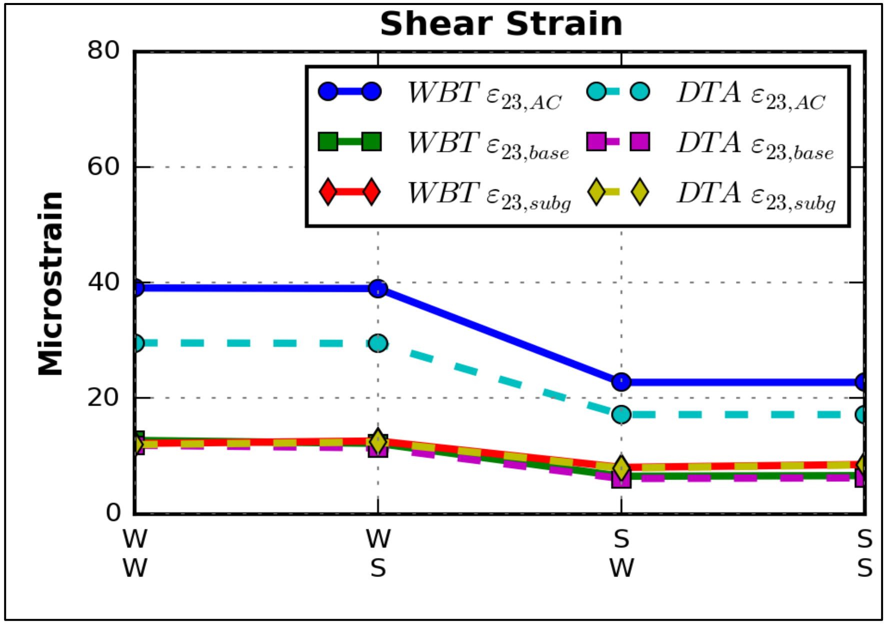
Tire type effect on critical responses

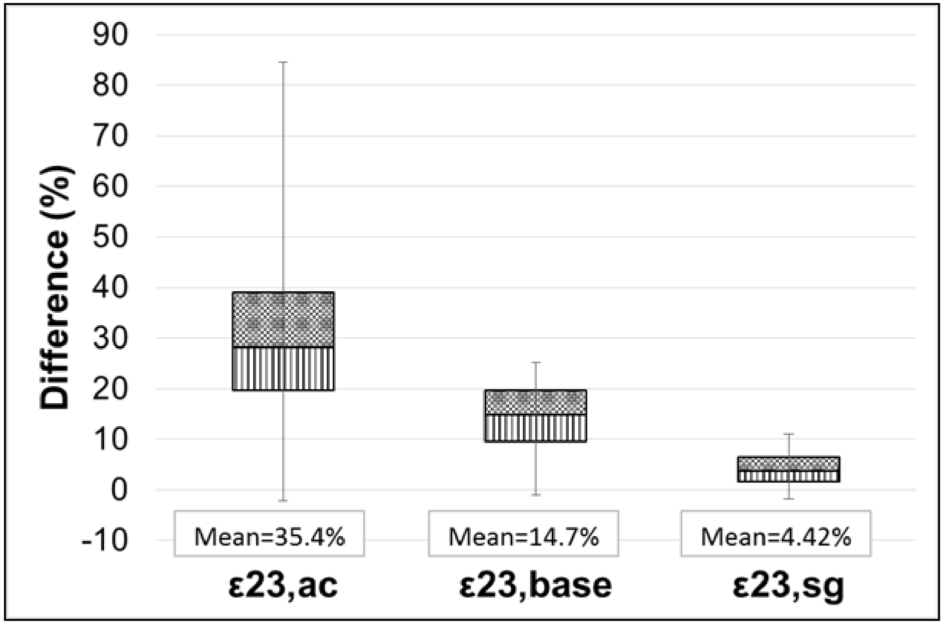






Thick Pavement Responses





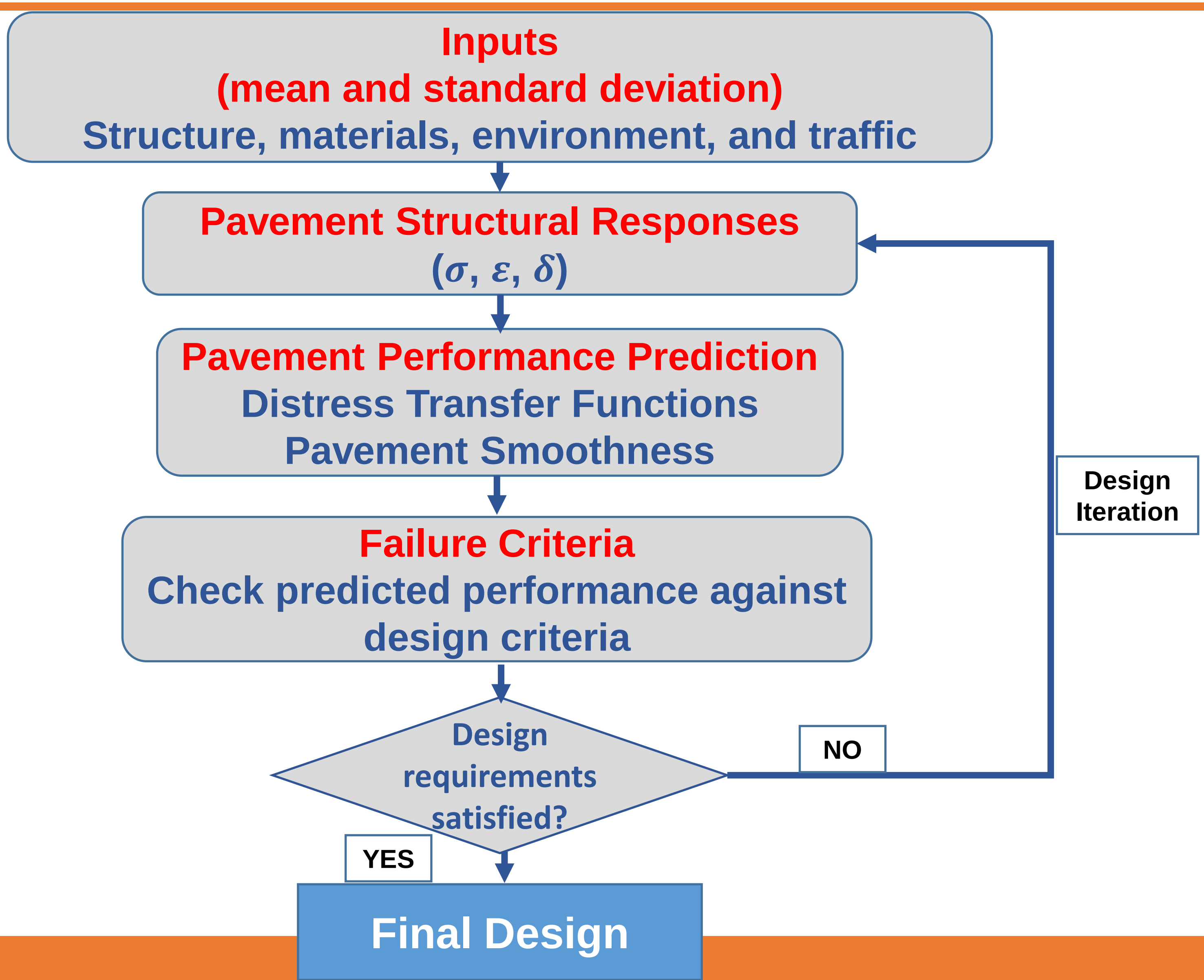
- **Altering AC material property has greater influence on responses than altering base material**
- **Near-surface impact: significantly greater difference for shear strain within AC than granular layers**

Pavement Responses

- **NG-WBT** generated **greater** pavement responses than DTA
- **Response difference** between NG-WBT and DTA is **reduced** with **depth**
- **Thin pavement:**
  - Highest difference in $\varepsilon_{33,ac}$: average was 52.5%
  - Average difference in $\varepsilon_{11,ac}$ was 23.2%
  - $\varepsilon_{23,sg}$ least difference (in some cases, higher for DTA)
- **Thick pavement:**
  - Greatest difference for thinnest/weakest
  - Near-surface impact is the highest

Designing Pavement Structures Considering NG-WBT

MEPDG



Inputs
(mean and standard deviation)
Structure, materials, environment, and traffic
Pavement Structural Responses
(σ, ε, δ)
Pavement Performance Prediction
Distress Transfer Functions
Pavement Smoothness
Failure Criteria
Check predicted performance against design criteria
Design requirements satisfied?
NO
Design Iteration
YES
Final Design

Limitations of MEPDG

	MEPDG	FEA
Analysis Type	Linear elastic analysis	Dynamic analysis considering moving tire and viscoelastic asphalt
Tire Type	Only DTA is considered	Both WBT and DTA can be simulated
Contact Stress	2D uniform vertical pressure	Non-uniform measured 3D contact stresses
Contact Area	Circular	True measured tire contact area
Friction between layers	Distributed spring model (user input)	Elastic stick model, defined by $\tau_{\max}$ and d_{max}
AC Layer Material Properties	Dynamic modulus obtained from master curve	Viscoelastic characterization using prony series

Adjustment Factors

- Main limitations of MEPDG:
  - Material characterization and loading condition
  - Incapability of simulating WBT
- Develop factors to adjust MEPDG pavement responses to that of FEA

Adjustment Factor Approach

WBT *FEA*

DTA *FEA*

DTA *MEPDG Procedure*

$$AF1 = \frac{WBT\ FEA}{DTA\ FEA}$$

$$AF2 = \frac{DTA\ FEA}{DTA\ ME\ Design}$$

$$WBT\ Full\ FEA = AF1 \times AF2 \times DTA\ MEPDG$$

Fatigue cracking $N_f = f(E, \varepsilon_t'); \varepsilon_t' = AF1_t \times AF2_t \times \varepsilon_t'$

Permanent Deformation $N_f = f(T, \varepsilon_v'); \varepsilon_v' = AF1_v \times AF2_v \times \varepsilon_v$

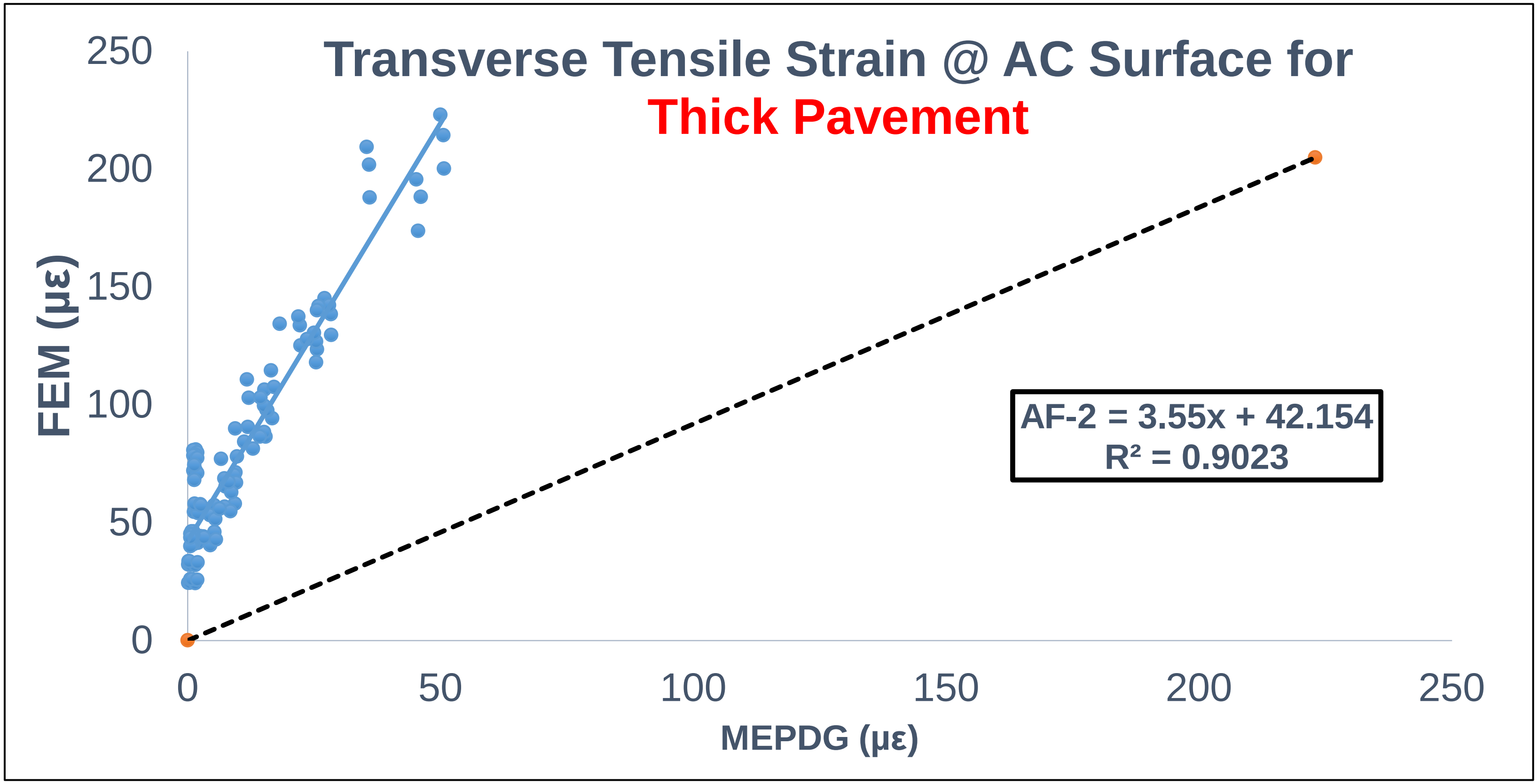
AF-2: MEPDG to FEA

- Since MEPDG cannot **simulate WBT**, only **DTA cases** are considered for AF-2
- A total **of 336 cases** were run in **ABAQUS** for DTA
- Same cases were simulated in **MEDPG**

AF-2: MEPDG to FEA

	FEA (Reference)	MEPDG
Axle load	Same	
Contact stresses	Measure 3D	Tire pressure
Contact area	Measured	Circular
Motion of tire (speed)	5 mph	From E*
Temperature	Calculated	Sublayers
Friction between layers	Elastic stick model	Spring model
AC	Viscoelastic	E*/Elastic analysis
Base	Linear (Thick)/ Nonlinear (Thin)	Linear elastic
Subgrade	Linear elastic	Linear elastic

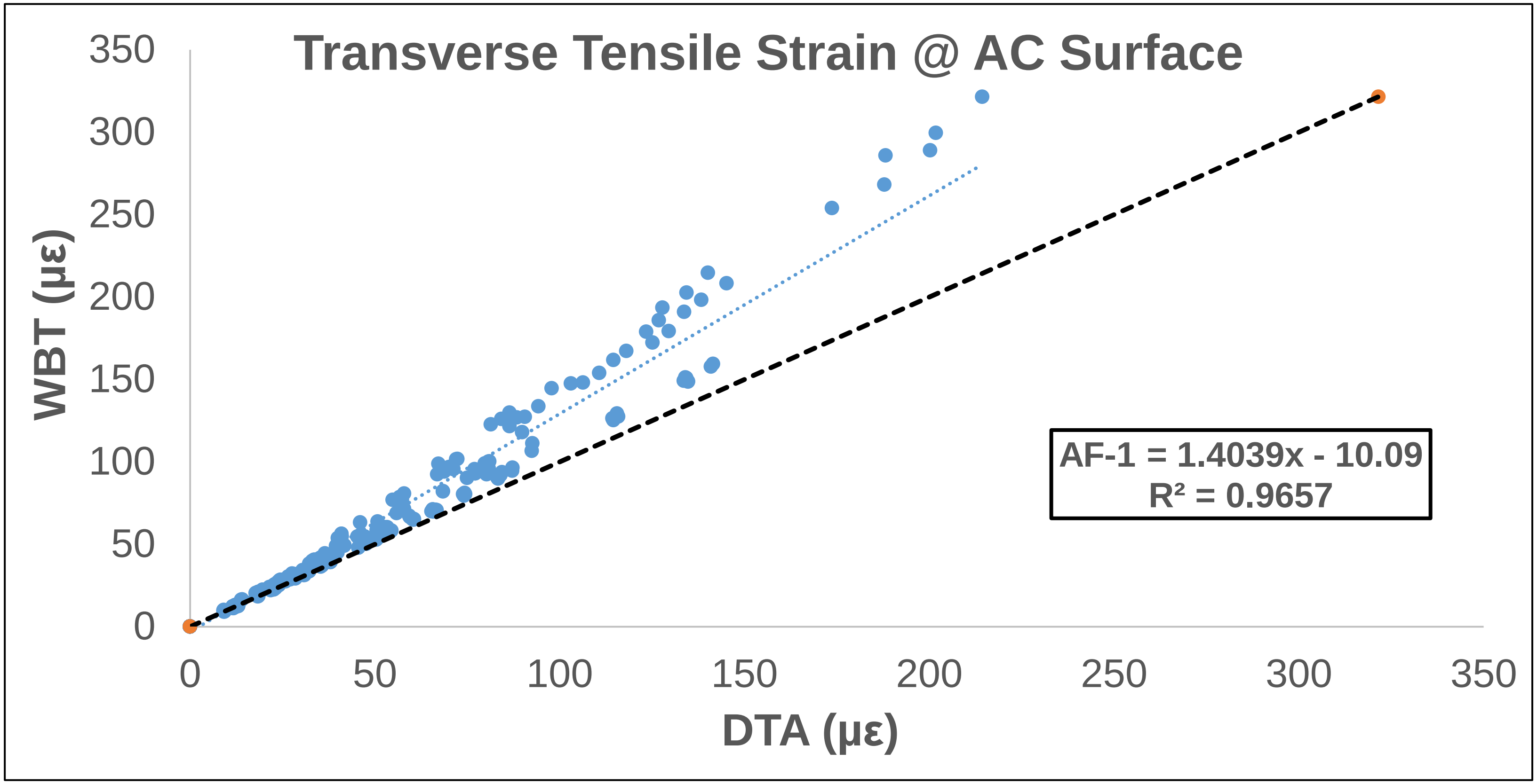
AF-2: MEPDG to FEA



AF-1: DTA to NG-WBT

- Total of 240 cases for WBT and 240 cases for DTA were run in ABAQUS considering same material properties and pavement structures
- Only differences were contact stresses and contact areas (measured under same axle load for WBT and DTA)

AF-1: DTA to NG-WBT



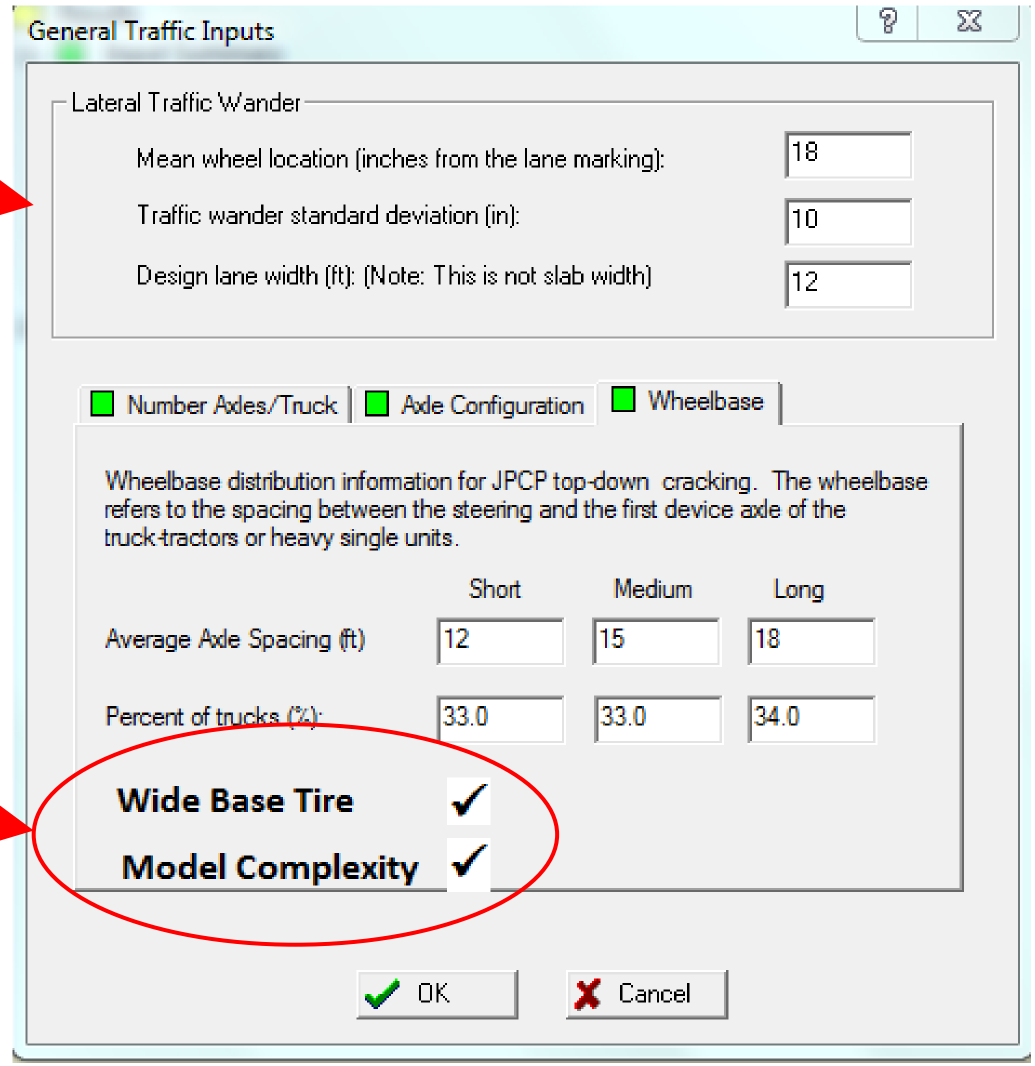
Numerical Example

- Case: AC=125 mm, Base=150 mm, P=44 kN, ρ=758 kPa
- MEPDG Response: $\varepsilon_{22,subg}$=557.0 με
- $\epsilon_{22,subg}$= subgrade max. vertical strain (secondary rutting)
- $AF2$ (Model Complexity) = 0.7433×MEDPG − 10.163
- $AF1$ (DTA to WBT) = 1.1615×DTA – 4.5571

Response	MEPDG	Adjusted MEPDG	NG-WBT
$\varepsilon_{22,subg}(\mu\varepsilon)$	557.0	403.9	464.5

Adjustment Factor Implementation

Current MEPDG Window



Proposed addition

Artificial Neural Networks

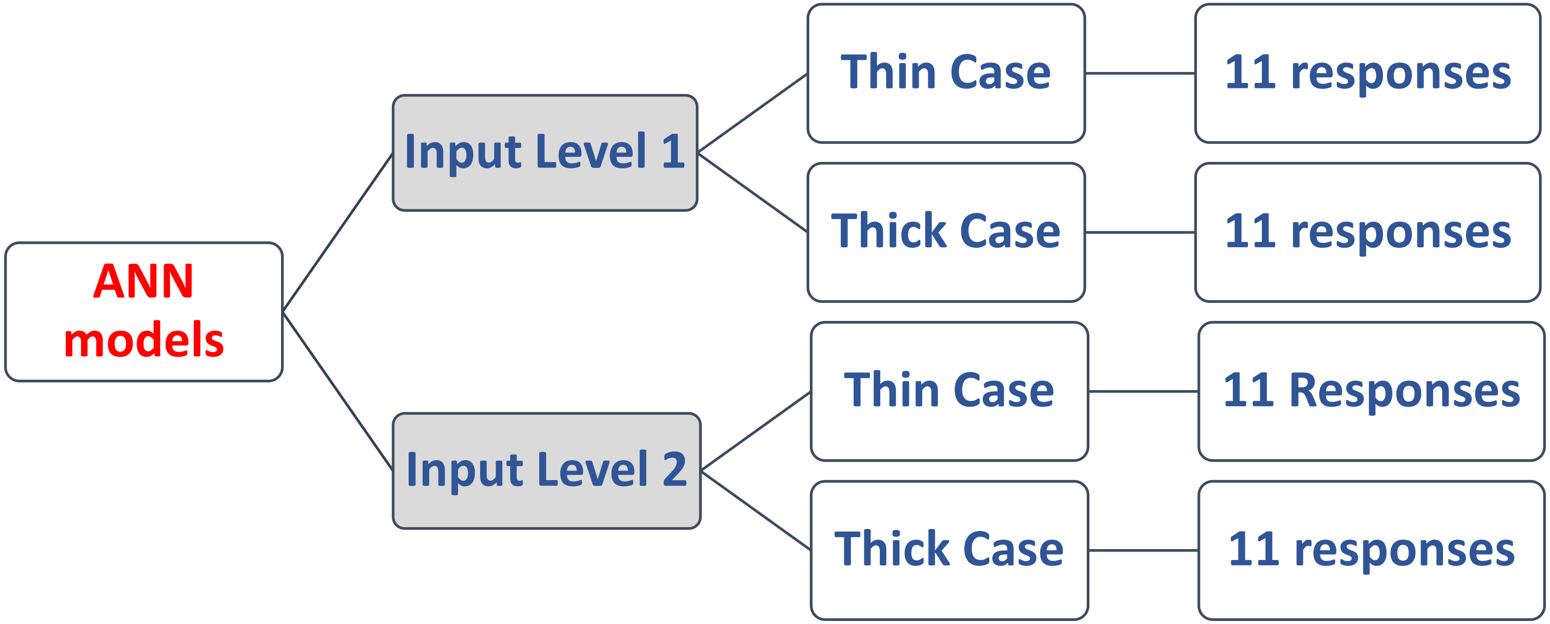
- FE is a powerful analytical method for pavement analysis, but:
  - Requires **highly technical knowledge**
  - **Not user friendly**
  - **Time consuming**
  - **Not a prediction tool**
- A simple tool to evaluate the effect of parameters on pavement response is needed

ANN Inputs/Outputs

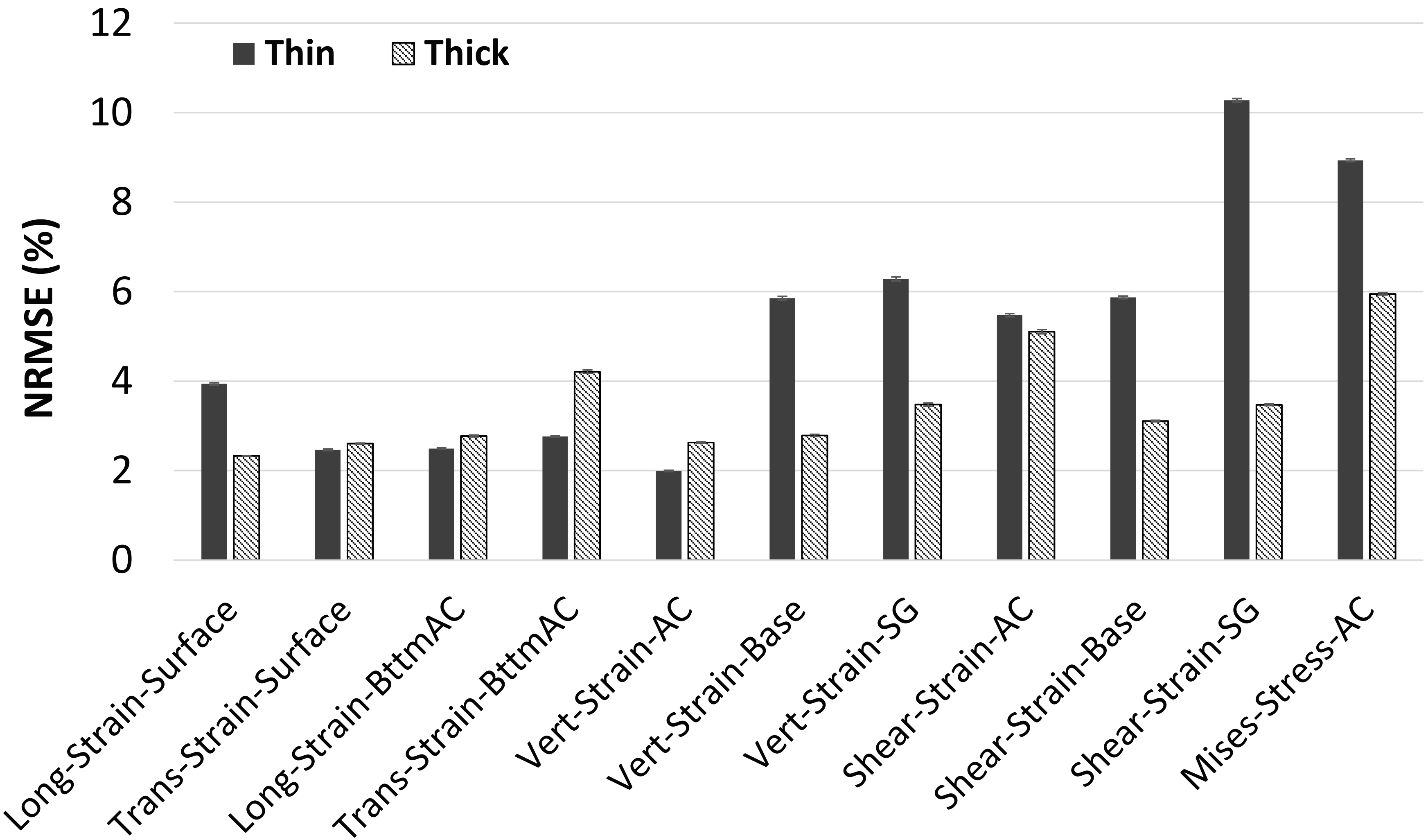
Inputs	Outputs
Loading information • Axle Load • Tire Type • Tire Pressure **Pavement Structure** • High Volume/Low Volume • Layer Thicknesses • Material Properties	**Critical pavement responses** • Long./Trans Strain Surface • Long./Trans Bottom of AC • Vertical Strain in AC • Shear Strain in AC • Mises Stress in AC • Vertical Strain in Base • Shear Strain in Base • Vertical Strain in SG • Shear Strain in SG

ANN Development

- 11 ANN models for **each response**, pavement **structure**, and **input level**

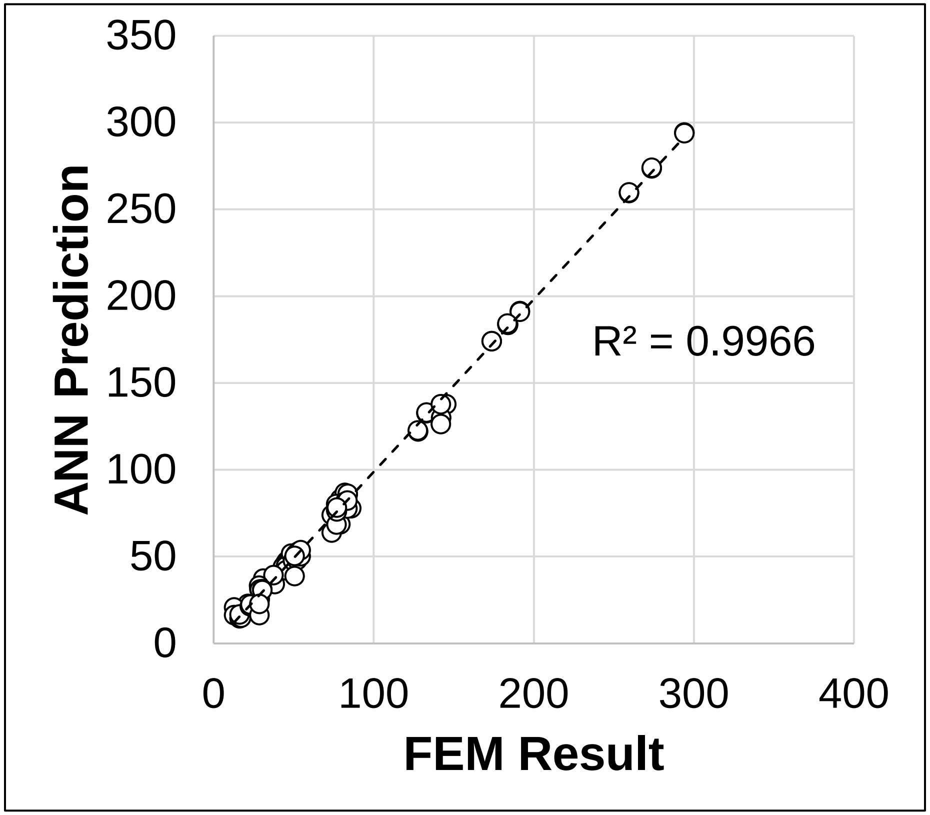


Results – Example Performance

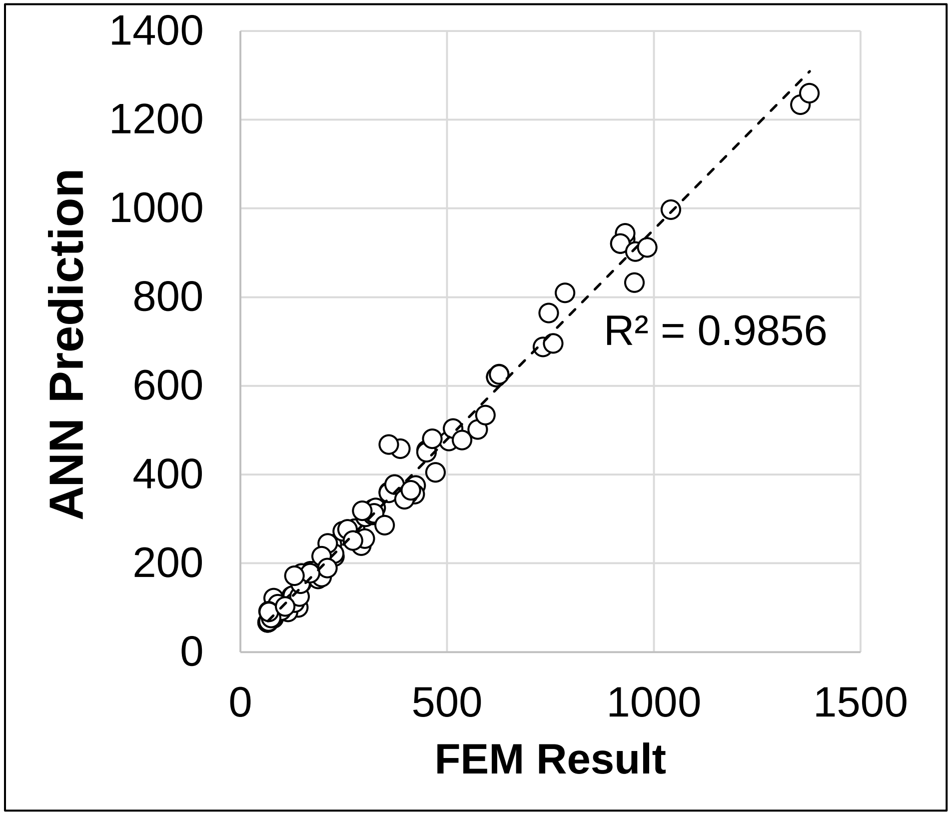


Example of Correlation Results

Longitudinal Strains Surface



Vertical Strain Subgrade



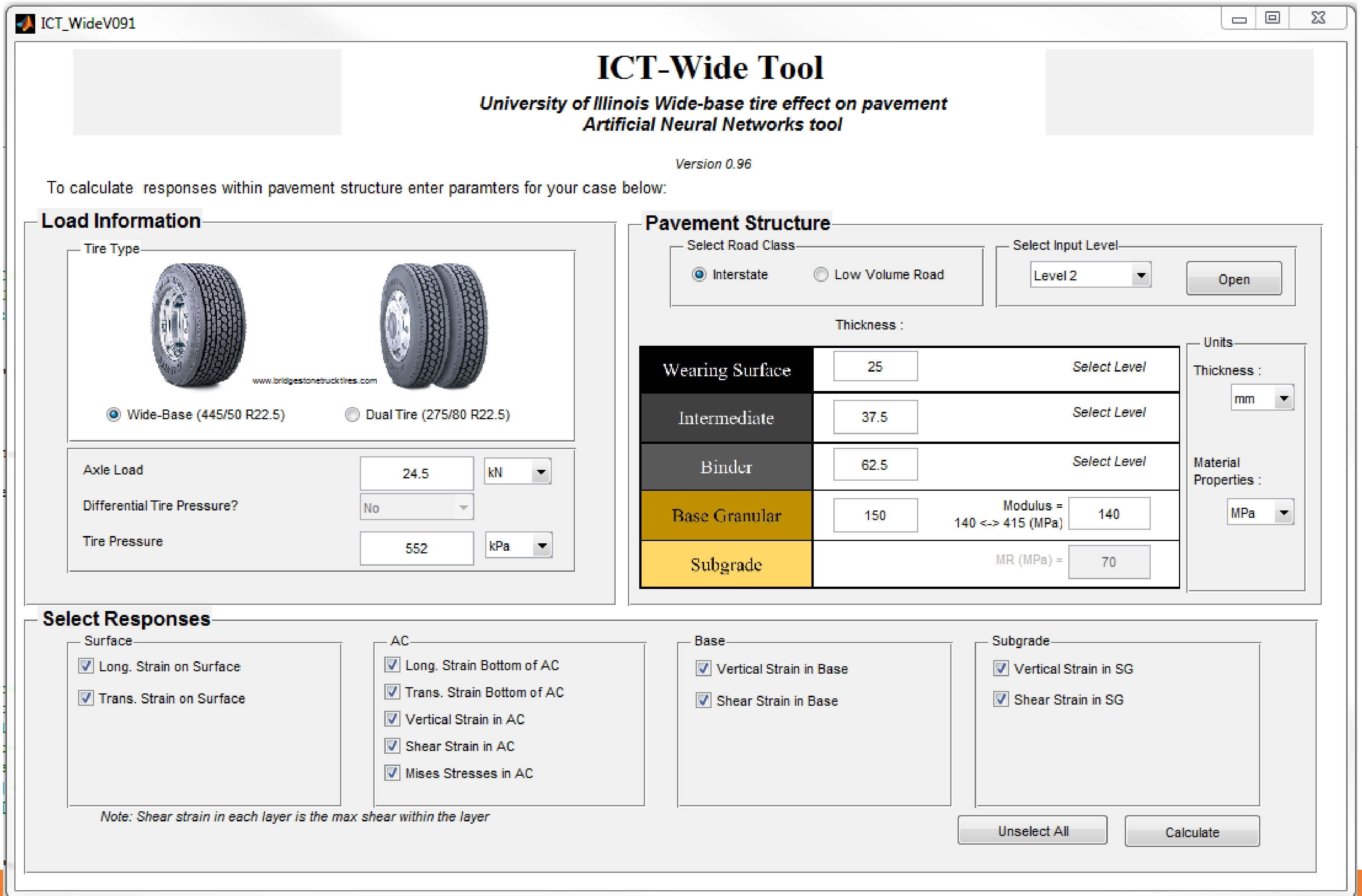
Average Performance

	Thick				Thin			
	Level 1		Level 2		Level 1		Level 2	
	R^2	%NRMSE	R^2	%NRMSE	R^2	%NRMSE	R^2	%NRMSE
Average	0.983	3.07	0.993	3.92	0.992	5.55	0.991	3.73
STD	0.018	1.29	0.008	1.08	0.008	2.94	0.010	1.48

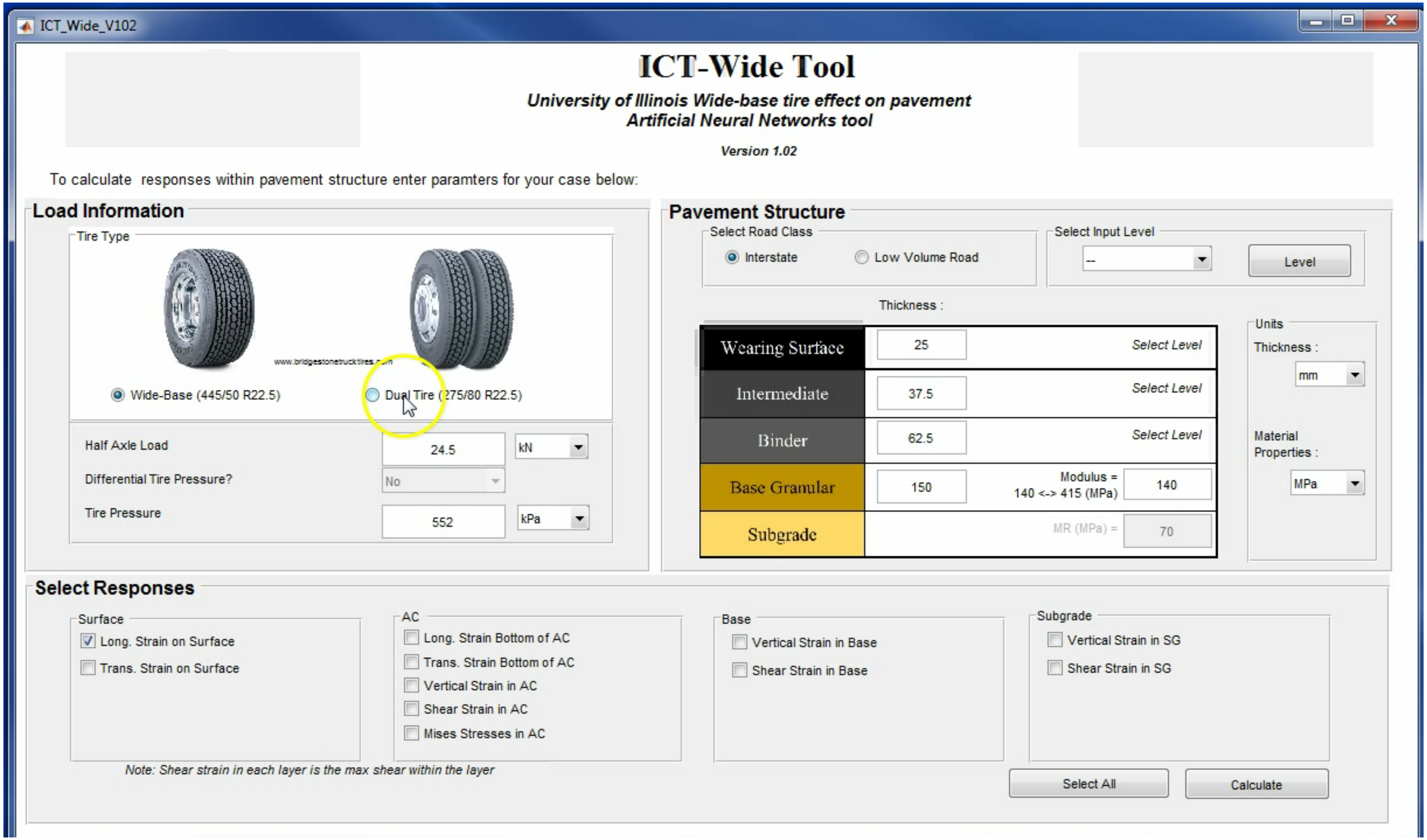
Level 1: Detailed (sigmoidal coefficients)

Level 2: Simplified (modulus at 25^{o}C)

ANN TOOL

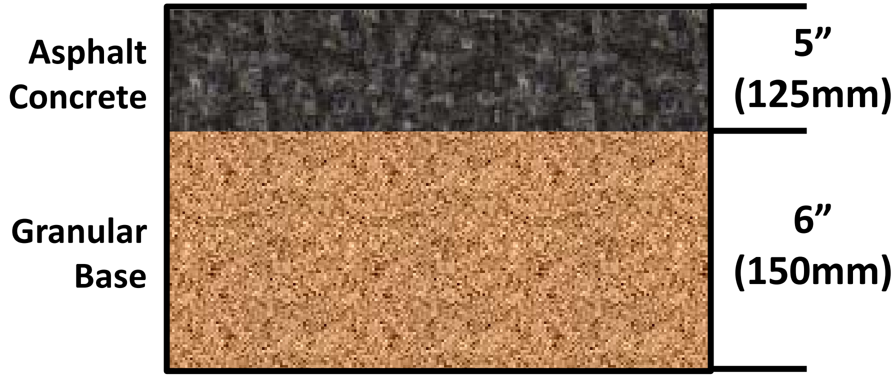

ICT_WideV091
ICT-Wide Tool
University of Illinois Wide-base tire effect on pavement
Artificial Neural Networks tool
Version 0.96
To calculate responses within pavement structure enter paramters for your case below:
Load Information
Tire Type
www.bridgestonetrucktires.com
Wide-Base (445/50 R22.5)
Dual Tire (275/80 R22.5)
Axle Load
24.5
kN
Differential Tire Pressure?
No
Tire Pressure
552
kPa
Pavement Structure
Select Road Class
Interstate
Low Volume Road
Select Input Level
Level 2
Open
Thickness :
Wearing Surface
25
Select Level
Intermediate
37.5
Select Level
Binder
62.5
Select Level
Base Granular
150
Modulus =
140 <-> 415 (MPa)
140
Subgrade
MR (MPa) =
70
Units
Thickness :
mm
Material Properties :
MPa
Select Responses
Surface
Long. Strain on Surface
Trans. Strain on Surface
AC
Long. Strain Bottom of AC
Trans. Strain Bottom of AC
Vertical Strain in AC
Shear Strain in AC
Mises Stresses in AC
Base
Vertical Strain in Base
Shear Strain in Base
Subgrade
Vertical Strain in SG
Shear Strain in SG
Note: Shear strain in each layer is the max shear within the layer
Unselect All
Calculate

ANN TOOL


ICT_Wide_V102
ICT-Wide Tool
University of Illinois Wide-base tire effect on pavement
Artificial Neural Networks tool
Version 1.02
To calculate responses within pavement structure enter paramters for your case below:
Load Information
Tire Type
www.bridgestonetrucktires.com
Wide-Base (445/50 R22.5)
Dual Tire (275/80 R22.5)
Half Axle Load
24.5
kN
Differential Tire Pressure?
No
Tire Pressure
552
kPa
Pavement Structure
Select Road Class
Interstate
Low Volume Road
Select Input Level
--
Level
Thickness :
Wearing Surface
25
Select Level
Intermediate
37.5
Select Level
Binder
62.5
Select Level
Base Granular
150
Modulus = 140 <-> 415 (MPa)
140
Subgrade
MR (MPa) =
70
Units
Thickness :
mm
Material Properties :
MPa
Select Responses
Surface
Long. Strain on Surface
Trans. Strain on Surface
AC
Long. Strain Bottom of AC
Trans. Strain Bottom of AC
Vertical Strain in AC
Shear Strain in AC
Mises Stresses in AC
Base
Vertical Strain in Base
Shear Strain in Base
Subgrade
Vertical Strain in SG
Shear Strain in SG
Note: Shear strain in each layer is the max shear within the layer
Select All
Calculate

EXAMPLE: ANN AND AF

- Thin Pavement
- Material Property
  - "Weak" AC
  - "Strong" Subgrade (E=140 MPa)



Direction	Strong Base		
Vertical	k_1=453.3	k_2=0.8858	k_3=-0.5713
Horizontal	k_4=282.4	k_5=0.6701	k_6=-1.1341
Shear	k_7=310.3	k_8=1.0297	k_9=-1.1036

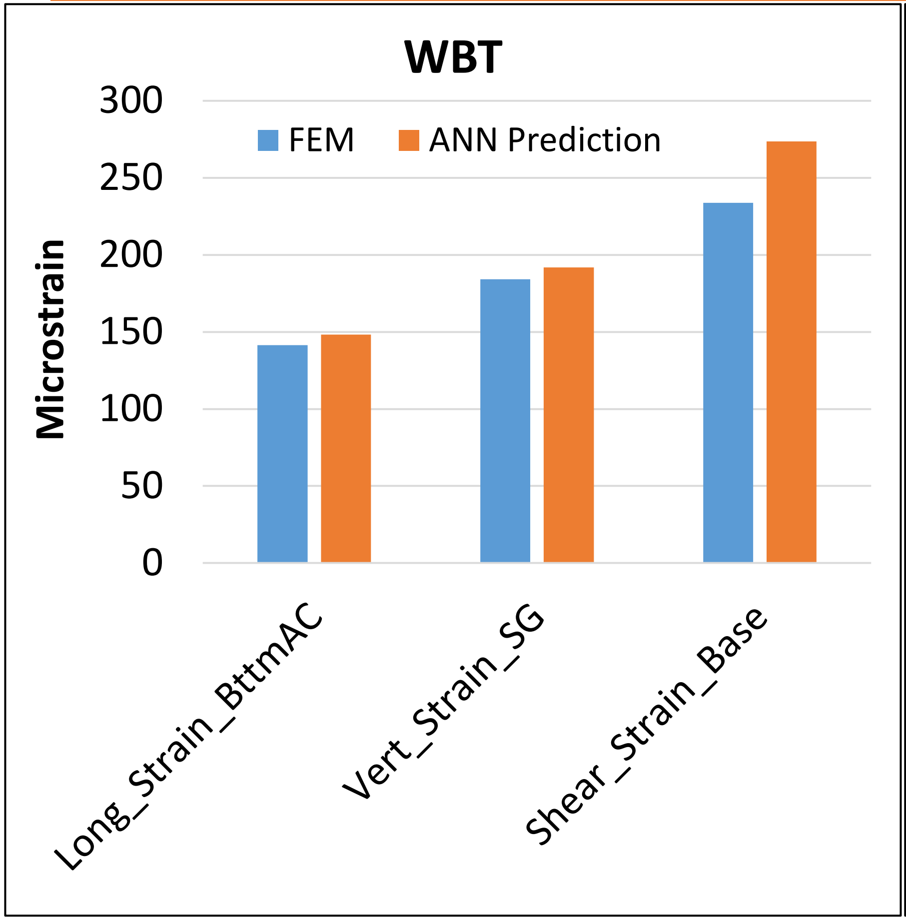
- Loading Condition (measured)
  - Load: WBT=43.7 kN, DTA=39.3 kN
  - Tire Inflation Pressure = 758 kPa

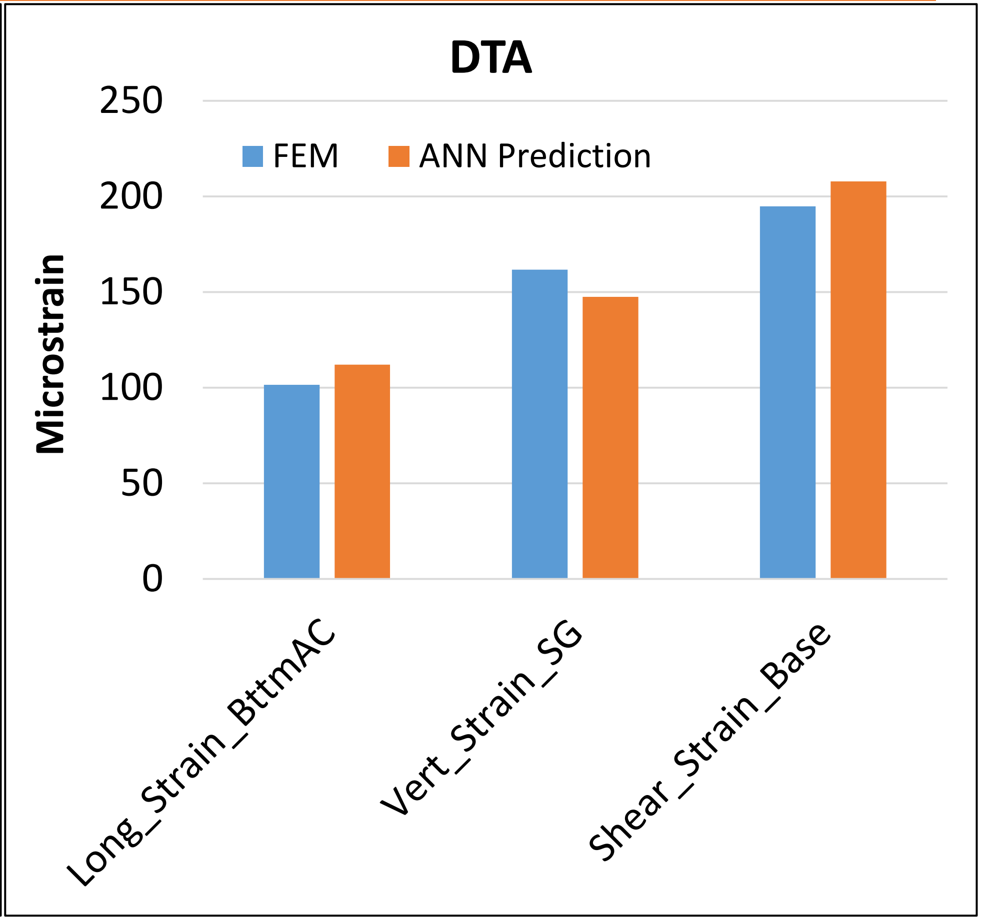
FEM Responses

Tire Type	$\epsilon_{11,botAC}$	$\epsilon_{22,subg}$	$\gamma_{23,base}$
WBT	148.2	191.9	273.6
DTA	112.1	147.5	207.8

- $\epsilon_{11,botAC}$ = longitudinal and transverse tensile strains at bottom of AC (**fatigue cracking**)
- $\epsilon_{22,subg}$ = maximum vertical strain on subgrade (**rutting**)
- $\gamma_{23,base}$ = shear strain in granular base layer

ANN Prediction





Average difference: WBT=DTA=8.6%

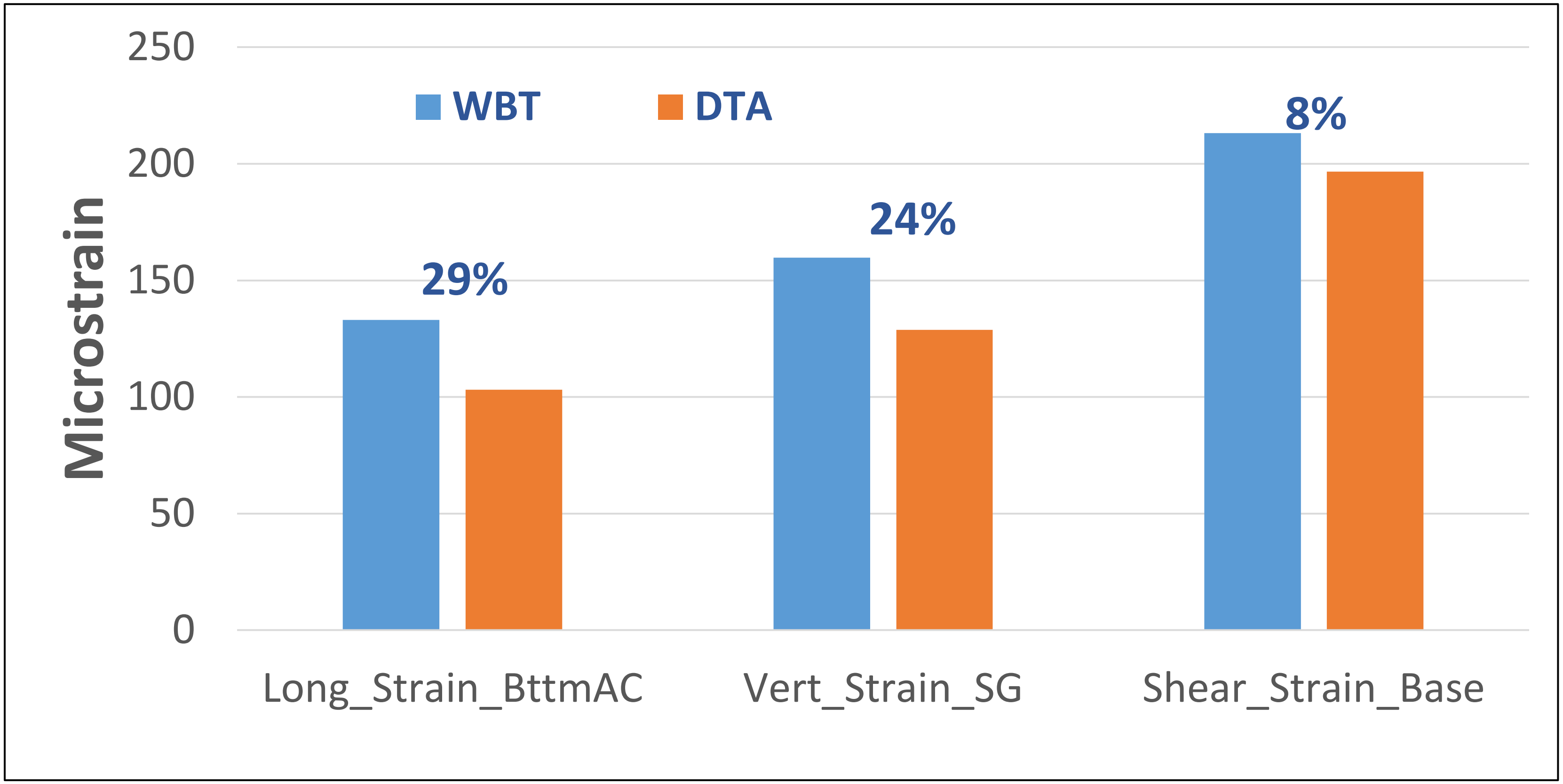
ANN Interpolation

- **Typical Case:**
  - Load = 8.5 kips; Tire Pressure = 690 kPa
  - Typical thin pavement structure
  - Same material properties as previous example

Asphalt	125 mm	Weak
Base Granular	150 mm	Strong
Subgrade		Strong

- **Critical Responses:**
  - Trans./Long. Strain at bottom of AC
  - Shear Strain at Base
  - Vertical Strain at top of SG

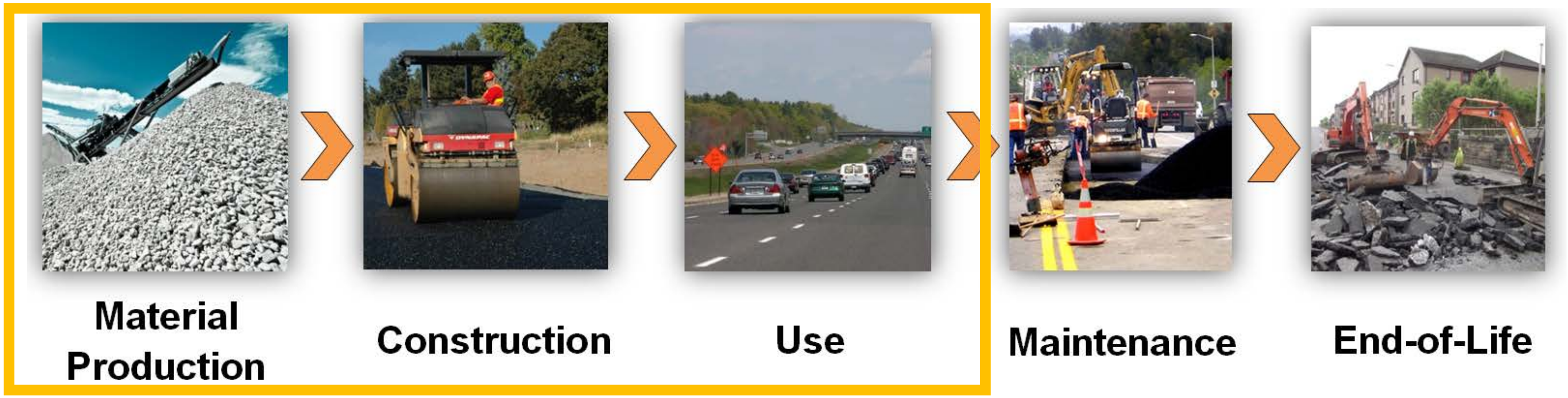
ANN Interpolation



Life-Cycle Assessment

LCA and LCCA

- Life cycle assessment (LCA)
  - Evaluates interactions of environment and product system (cradle to grave)
- Life cycle cost analysis (LCCA)
  - Evaluates total economic worth of a usable project by analyzing initial costs and discounted future costs



Life Cycle of Pavement

NG-WBT Impact Adoption

- **Energy:** includes **primary** and **secondary energy demand** in "MJ"
- **Global warming potential (GWP):** characterized by greenhouse gases (**GHGs**)
- **Costs:** Associated with **material** production, **equipment** operation, and **fuel** change in the Use phase

Scope

- Functional unit: **2-lane 2-mile-AC** pavement in one direction with annualized analysis period
- Life cycle phases: **material**, **construction**, and **use** phases
- Pavement structure: **surface AC overlay** (pavement structure below the surface overlay is out of scope)

Life Cycle Inventory

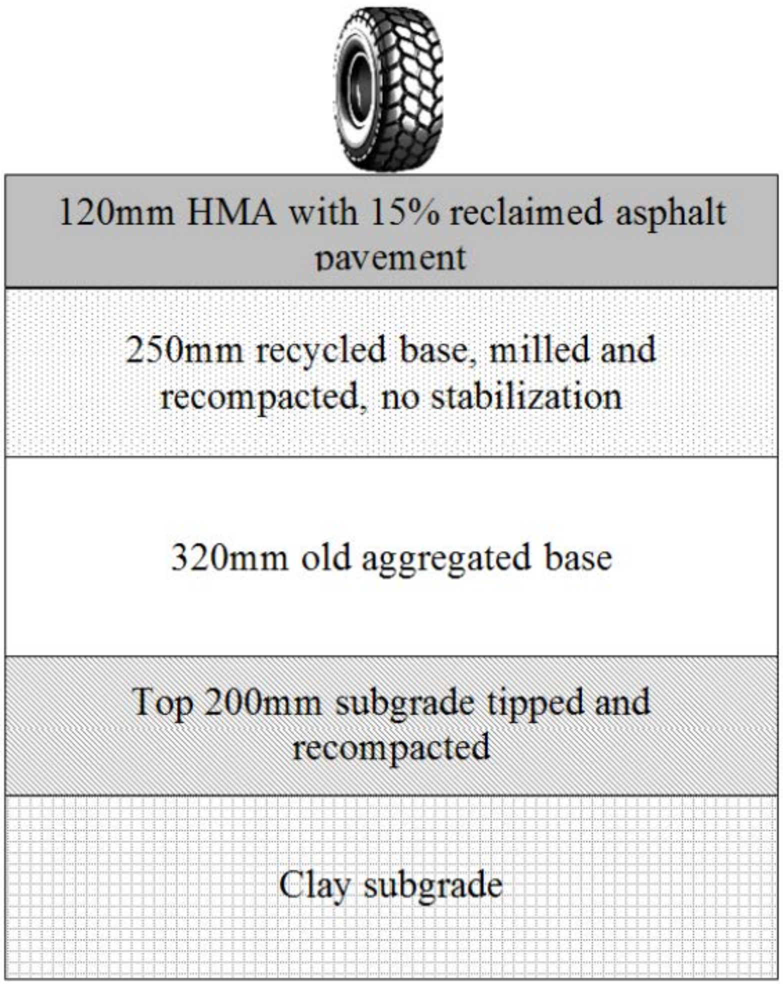
- **Material phase**
  - Aggregate, AC binder, electricity and hauling
  - UIUC LCI and cost database were modified to reflect general conditions of N. America
- **Construction phase**
  - Productivity and fuel use of equipment
  - Used NCHRP 744, NONROAD, Ecoinvent, etc.
  - Construction occurs during nine-hour nighttime closure (no construction delay)

Life Cycle Inventory - Use phase

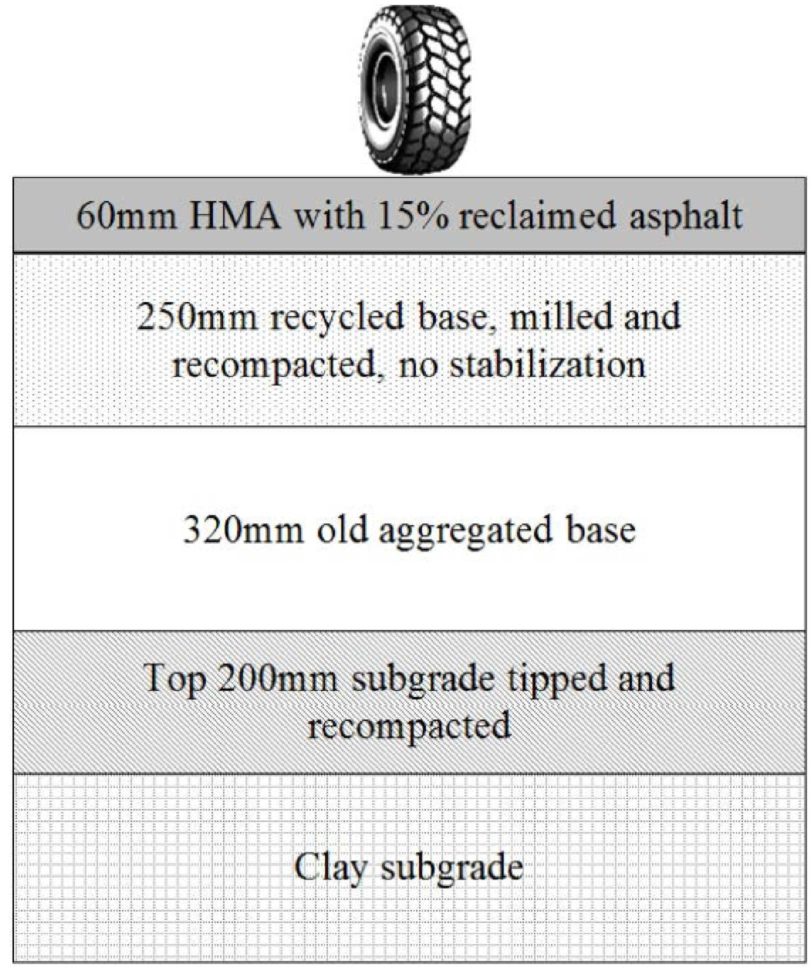
- Time progression of IRI and MPD
- Rolling resistance (RR) model used to update vehicle emission model
  - HDM-4 as a RR model
  - MOVES as a vehicle emission model
- Assumed 3.2% fuel economy improvement[1]
- Asphalt Institute transfer functions for rutting and fatigue cracking

1. Genivar (2005)

Pavement Sections



671 HC (thick) Section



670 HC (thin) Section

Pavement Information

Case Study	671HC (Thick asphalt)	670HC (Thin asphalt)
County	Nevada	Los Angeles
Route	I-80 Westbound	SR-213 Westbound
Surface	Asphalt concrete	Asphalt concrete
Section length	3,129 m (2 miles)	3,129 m (2 miles)
# of lanes in each direction	2	2
Lane width	3.66 m	3.66 m
AADT (One-way)	13,500	15,750
Truck percentage	19%	2%
Construction type	Mill and asphalt overlay	Mill and asphalt overlay
HMA layer thickness	120 mm	60 mm
Tire types analyzed	DTA and four levels of market penetration of NG-WBT	DTA and four levels of market penetration of NG-WBT

Maximum Strain and # of Repetition

- For 16 & 20 kips and 100 psi at 20ºC
  - Max. tensile strain (bottom of AC)
  - Max. compressive strain (top of subgrade)

Maximum number of repetitions

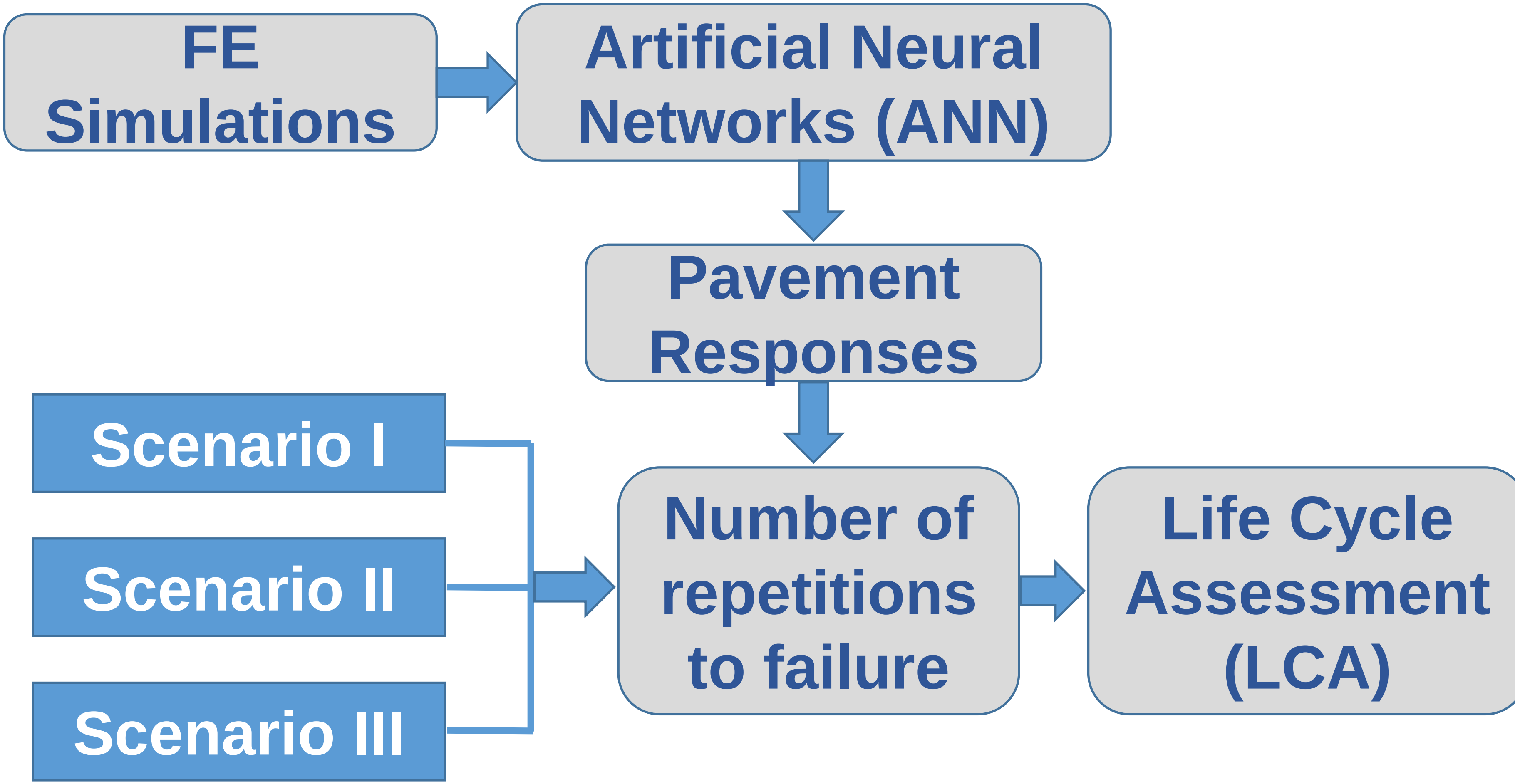
Tire type	Distress type	Case 670HC (Thin asphalt)	Case 671HC (Thick asphalt)
DTA	Fatigue cracking	282,405	3,042,203
	Rutting	714,044	1,700,743
NG-WBT	Fatigue cracking	128,638	2,007,418
	Rutting	395,690	2,125,011

Scenario-Based Case Study

- Various NG-WBT market penetrations
- Two different AC pavement sections

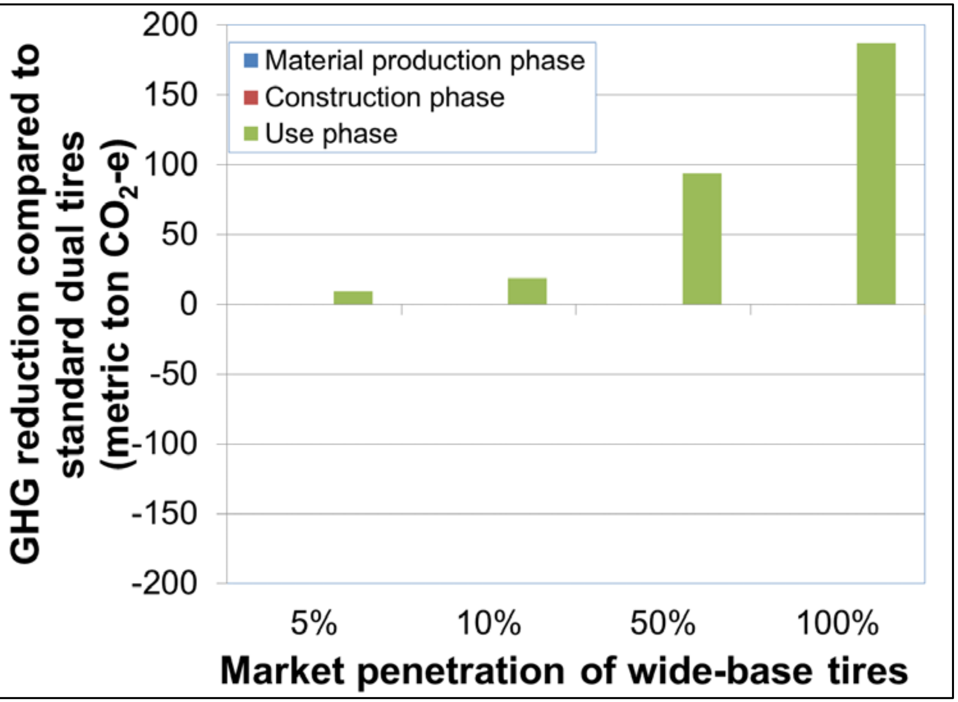
Scenario I	Dual and WBT have the **same impact** on **fatigue cracking & roughness**
Scenario II	Dual and WBT have **different impact** on **fatigue cracking**
Scenario III	Dual and WBT have **different impact** on **fatigue cracking & roughness**

Case Study Procedure

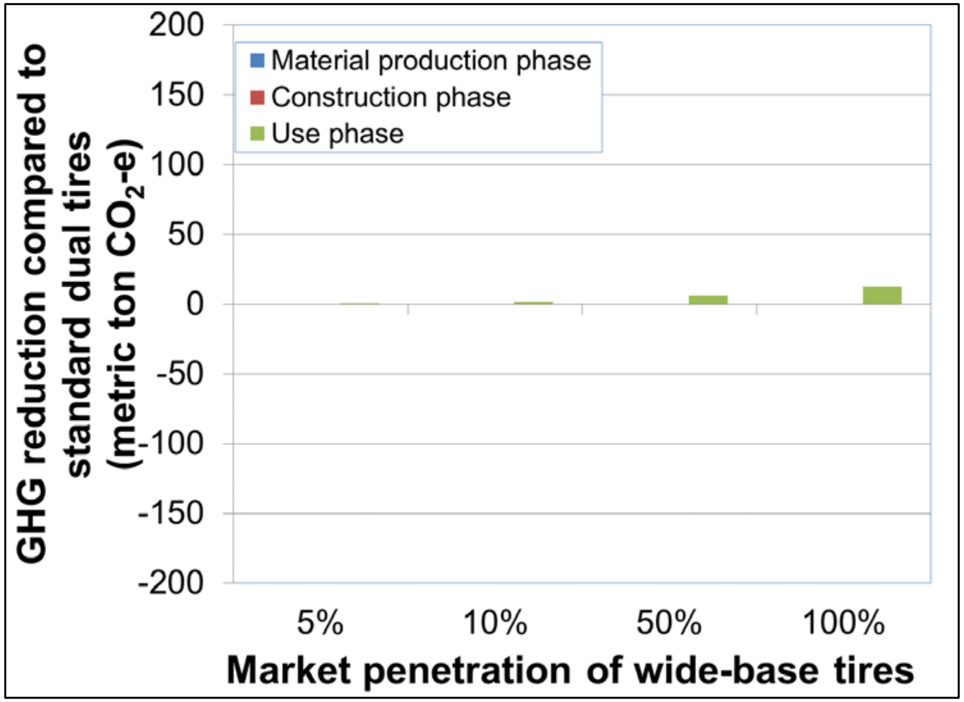


Scenario I: Reduction in GHG

- Difference comes from 3.2% fuel **consumption improvement**



671 HC (thick) Section



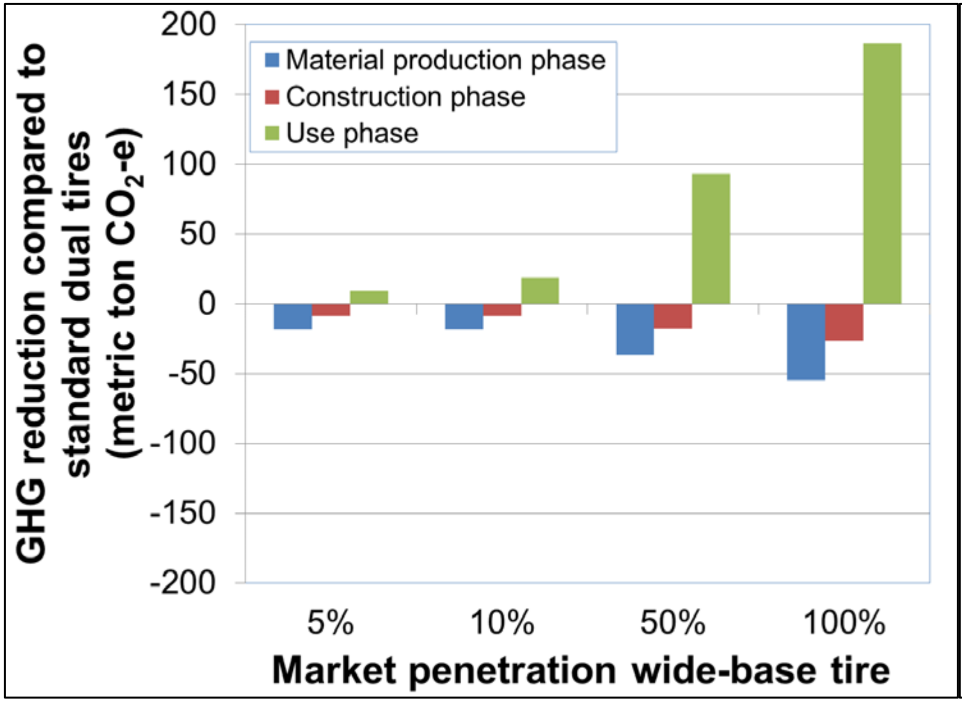
670 HC (thin) Section

Scenario I: Thick & Thin Cases

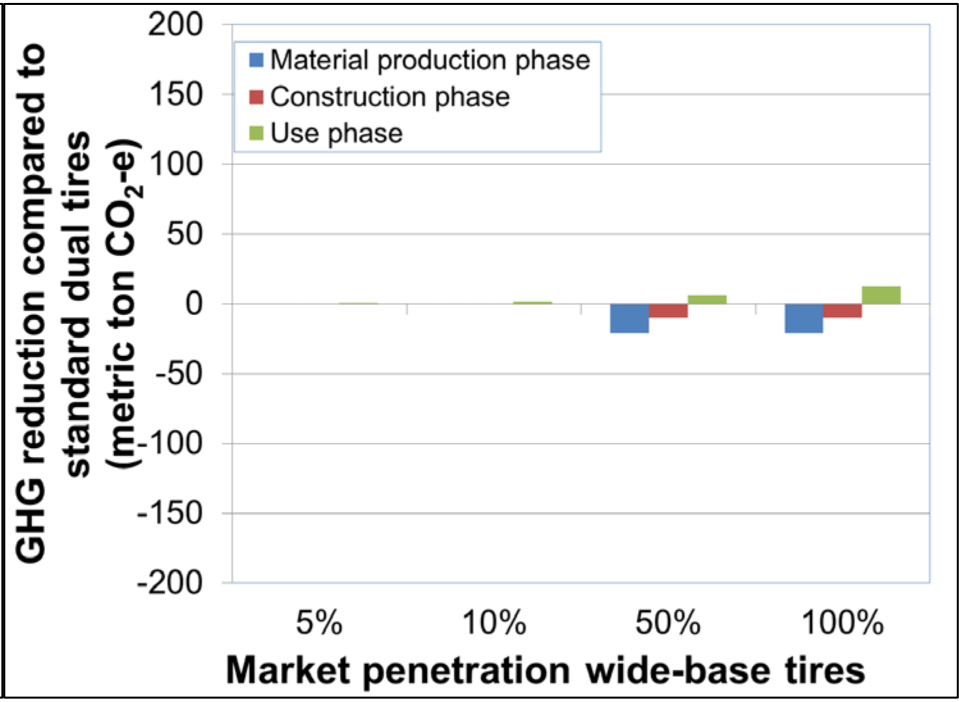
		Thick	Thin
	Market Penetration	Use Phase	Use
Energy saving compared to baseline (MJ)	5%	127,654	8,694
	10%	255,308	17,388
	50%	1,276,540	86,941
	100%	2,553,079	173,881
GHG reduction compared to baseline (metric ton CO_2e)	5%	9	1
	10%	19	1
	50%	94	6
	100%	187	13
Economic saving compared to baseline ($ Present)	5%	3,108	225
	10%	6,216	449
	50%	31,079	2,246
	100%	62,158	4,493

Scenario II: Thick & Thin Cases

Saving from fuel economy and loss due to increased pavement damage



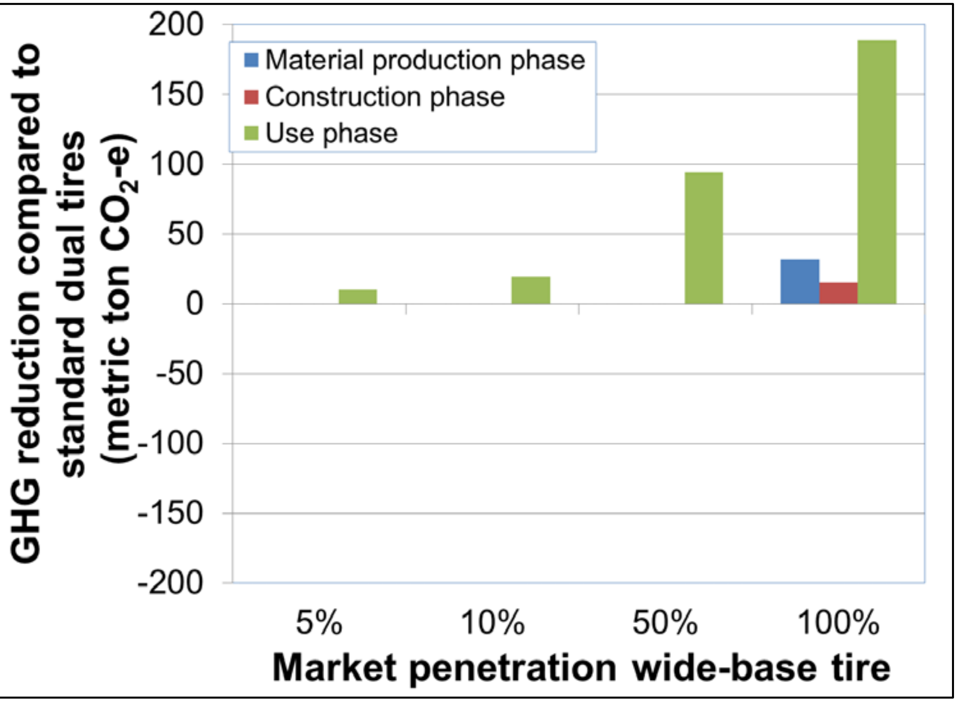
671 HC (thick) Section



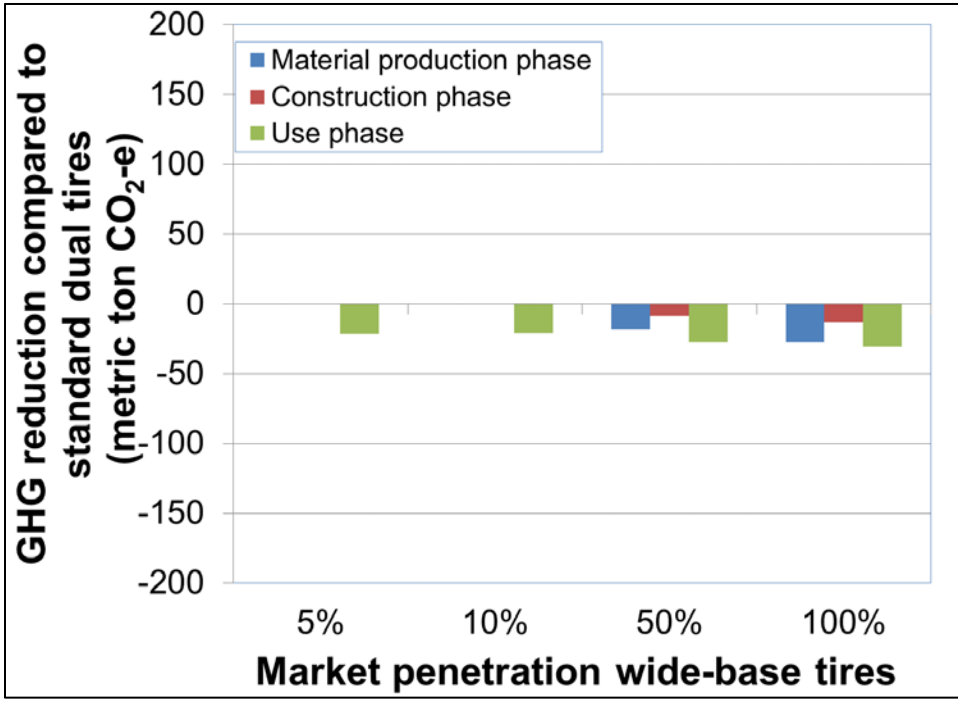
670 HC (thin) Section

Scenario III: Thick & Thin Cases

- **Thick case: Savings from fuel economy improvement and reduced pavement damage**
- **Thin case: Reduction from increased pavement damage and faster roughness deterioration**



671 HC (thick) Section



670 HC (thin) Section

Final Remarks

Remarks

- MEPDG is not appropriate to compare NG-WBT and DTA. Adding adjustment factors was proposed to address this issue
- NG-WBT demonstrates a significant improvement compared to first generation of wide-base tires
- NG-WBT results in greater pavement responses than DTA; the difference is reduced with pavement depth

Remarks

- DTA with differential tire inflation pressure develops higher pavement responses than DTA having same tire inflation pressure, but still lower than NG-WBT
- Benefits are sensitive to the method used to determine pavement performance
- NG-WBT can save energy and reduces GHG and emissions, depending on corresponding pavement performance
- A holistic approach is needed to quantify the impact of wide-base tires