Equivalent Loading Frequencies to Simulate Asphalt Layer Pavement Responses Under Dynamic Traffic Loading

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Introduction

- ***Dynamic response*** **of AC pavements under moving load is a key component for accurate prediction of** ***flexible pavement performance.***
- ***Reliable determination*** **of pavement responses to** ***moving load*** **is essential for a successful mechanistic design procedure.**
- ***Time and temperature dependency*** **of asphalt must be considered in the mechanistic analysis response model.**

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AASHTO MEPDG Approach

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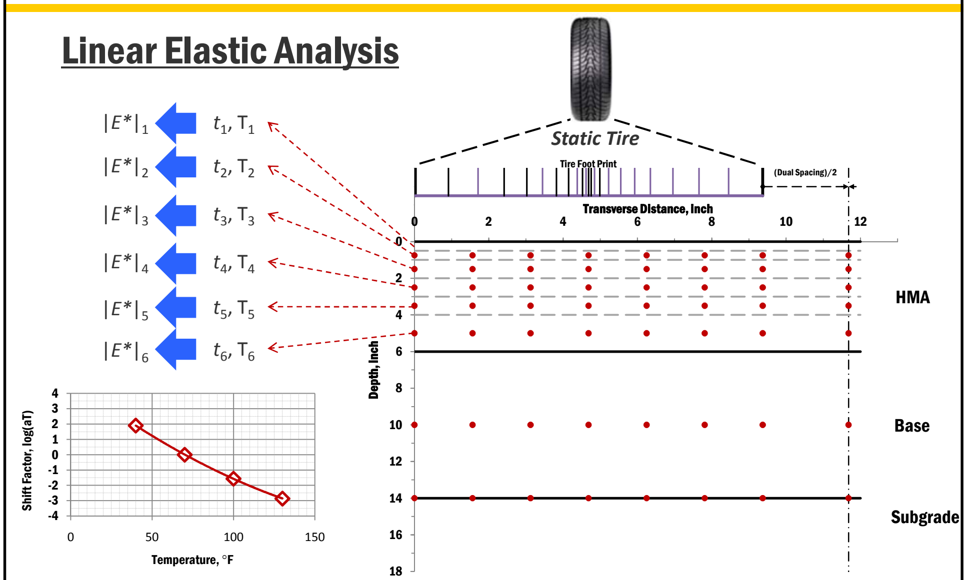
Linear Elastic Analysis



AASHTO MEPDG

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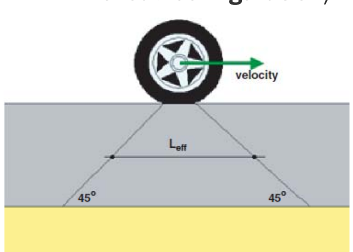
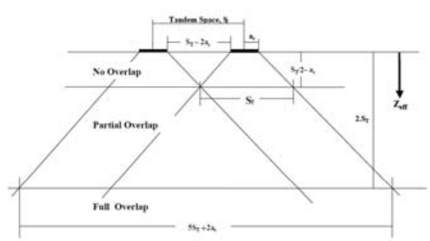
- **Vertical stress distribution used to estimate traffic-induced loading time.**
  - **Axle load configuration, Vehicle speed & Pavement structure**





$$t = \frac{L_{eff}}{17.6\,V_s} \;\Rightarrow\; f = \frac{1}{t}$$

$$Z_{eff} = \sum_{i=1}^{n-1}\left(h_i \sqrt[3]{\frac{E_i}{E_{SG}}}\right) + h_n \sqrt[3]{\frac{E_n}{E_{SG}}}$$

Literature Review

- Dongre, R. N., Myers, L. A., and D'Angelo, J. A., "Conversion of Testing Frequency to Loading Time: Impact on Performance Predictions Obtained from the Mechanistic–Empirical Pavement Design Guide", Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C., 2006.
- Al-Qadi, I. L., W. Xie, and Elseifi, M. A., "Frequency Determination from Vehicular Loading Time Pulse to Predict Appropriate Complex Modulus in MEPDG", Journal of the Association of Asphalt Paving Technologists, Vol. 77, 2008, pp. 739-772.
- Katicha, S., Flintsch, G.W., Loulizi, A., and Wang L. "Conversion of Testing Frequency to Loading Time Applied to Mechanistic-Empirical Pavement Design Guide," Transportation Research Record No. 2087, TRB, Washington D.C., 2008, pp. 99-109.
- …

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Appropriate Representative Elastic Modulus

B. S. Underwood and Y. R. Kim

- "Determination of the Appropriate Representative Elastic Modulus for Asphalt Concrete," IJPE, Vol. 10, Iss. 2, 2009, pp. 77-86
  - Evaluated several approximation methods for calculation of stresses & strains in linear viscoelastic materials.
  - MEPDG method is biased towards overestimating the appropriate stiffness by up to a 31% error.
  - Representative modulus to use for LEA is average of
    - dynamic modulus at a frequency equal to $1/t_p$ and
    - relaxation modulus evaluated at a time equal to ½ t_p.
  - Proposed Method resulted in 2 - 6% error

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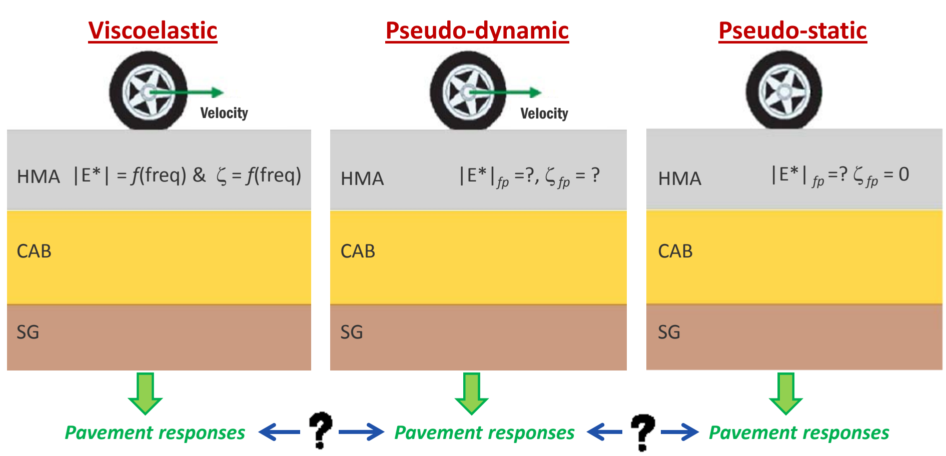
Research Objective

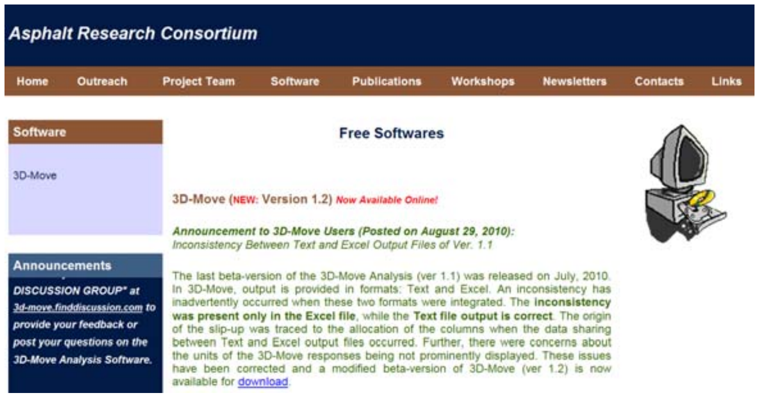
- Investigate the existence of one or more ***predominant frequencies*** (f_p) associated with the AC layer that controls the dynamic response of pavements.

- ***AC Critical Reponses***:
  - Longitudinal & transverse tensile strains
  - Vertical compressive strains

Viscoelastic vs. Pseudo Analysis



Pavement Analysis
3D-Move Analysis Software



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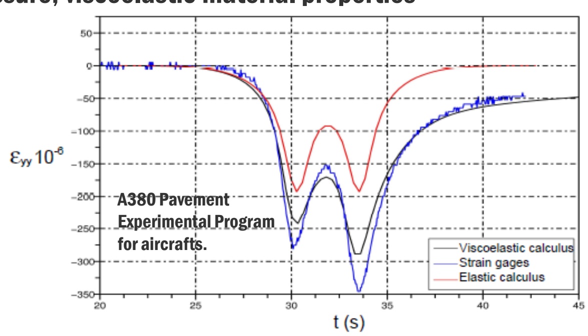
Freeware Download at:
http://www.arc.unr.edu/Software.html

Pavement Analysis
3D-Move Analysis Software - Validation

1. **3D-Move vs. ViscoRoute (2010)**
   – ViscoRoute (IFFSTAR – LCPC): moving circular loaded areas with uniform contact pressure, viscoelastic material properties

Reference:
Chabot, A., Chupin, O., Deloffre, L., and Duhamel, D., "Viscoroute 2.0: a tool for the simulation of moving load effects on asphalt pavement," Road Materials and Pavement Design an International Journal, Volume 11/2, 2010, pp. 227-250.

Loft A., "Evaluation de Viscoroute-v1 pour l'étude de quelques chaussées souples", Msc. Dissertation, Dresden University of Technology speciality Urban and Road construction, 2005.



Comparison between elastic computations, ViscoRoute1.0 simulations and transversal strain measurements at the bottom of bituminous layers for a 4-wheels moving load

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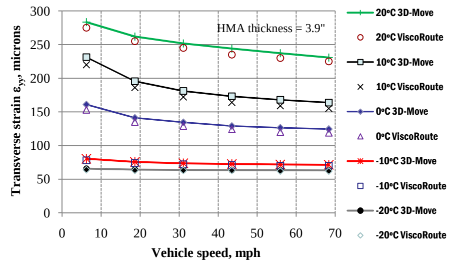
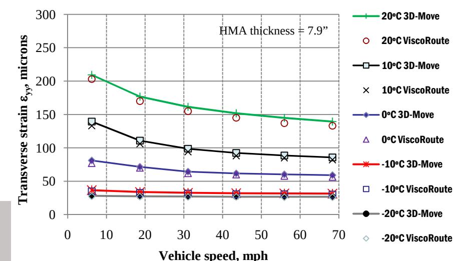
Pavement Analysis

3D-Move Analysis Software - Validation



3D-Move vs. ViscoRoute
Vehicle speed = 6 to 70 mph
Pavement temperature = -20°C to 20°C



ViscoRoute Test Results Refer to:
Chabot, A., Chupin, O., Deloffre, L., and Duhamel, D., "Viscoroute 2.0: a tool for the simulation of moving load effects on asphalt pavement," Road Materials and Pavement Design an International Journal, Volume 11/2, 2010, pp. 227-250.

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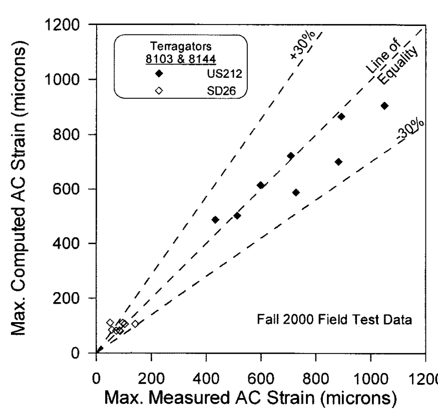
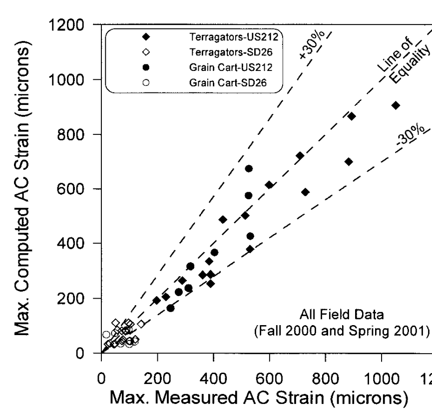
3D-Move Analysis Software - Validation

2. SD Heavy Off-Road Vehicle Field Sections (2000)





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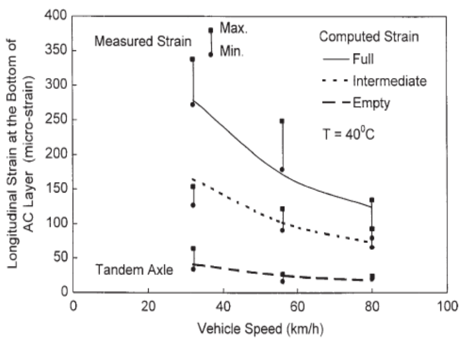
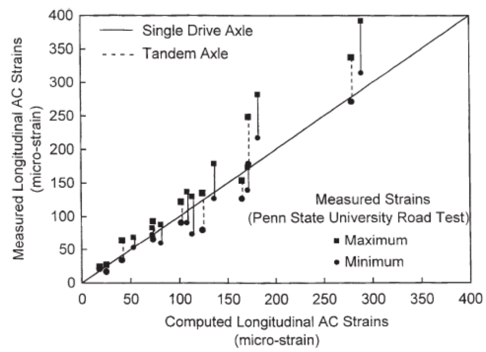
3D-Move Analysis Software - Validation

3. PennState University Test Track (1999)





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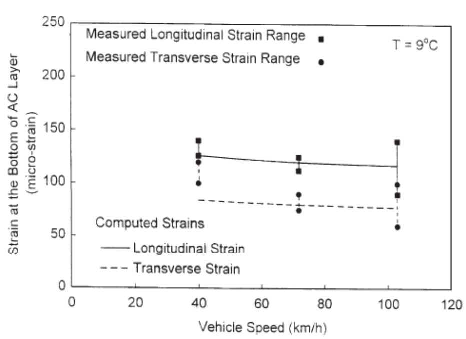
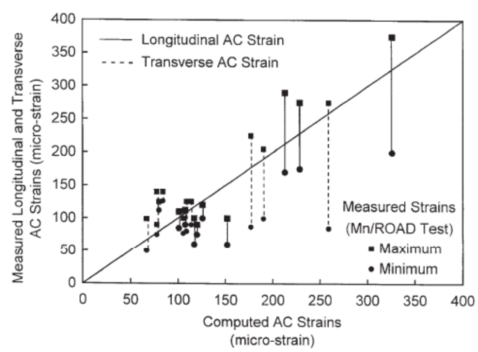
3D-Move Analysis Software - Validation

4. MnRoad (1997)





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Database of pavement responses

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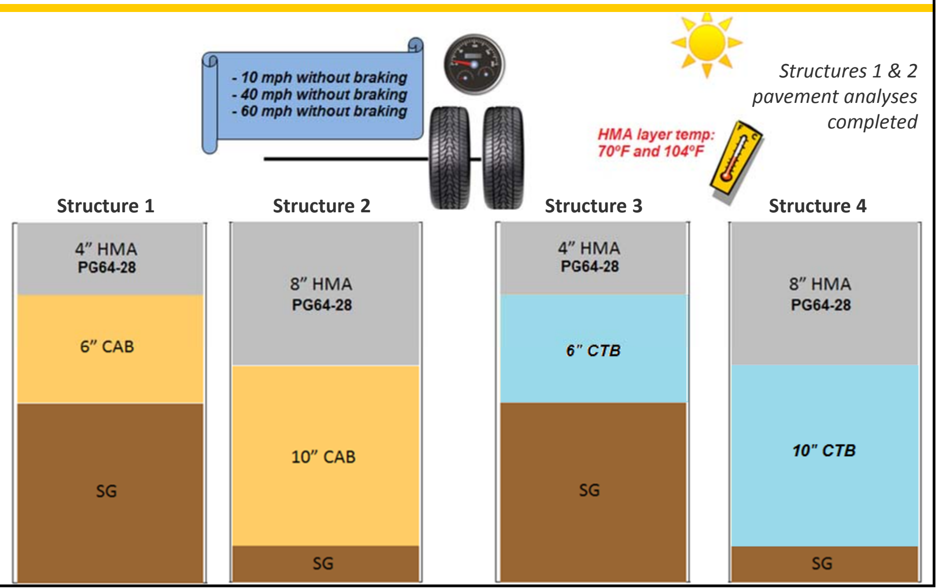

Pavement Responses Locations

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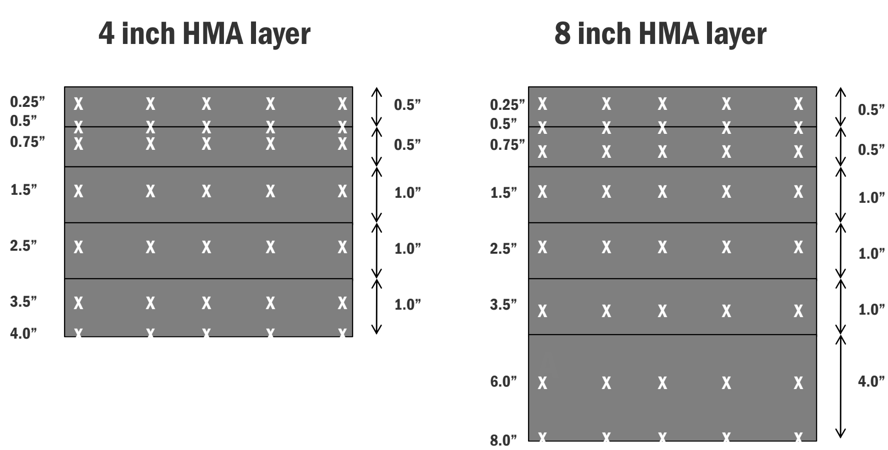

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Data analysis completed for responses at center line of the load

Proposed approach to determine f_p

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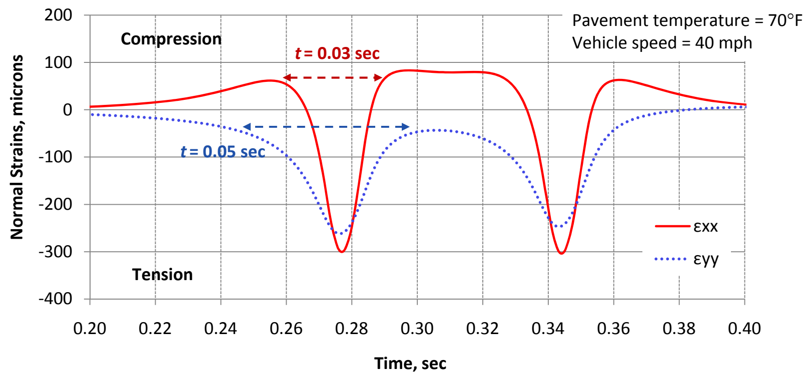
- **Example: Bottom of the 4-inch HMA layer:**



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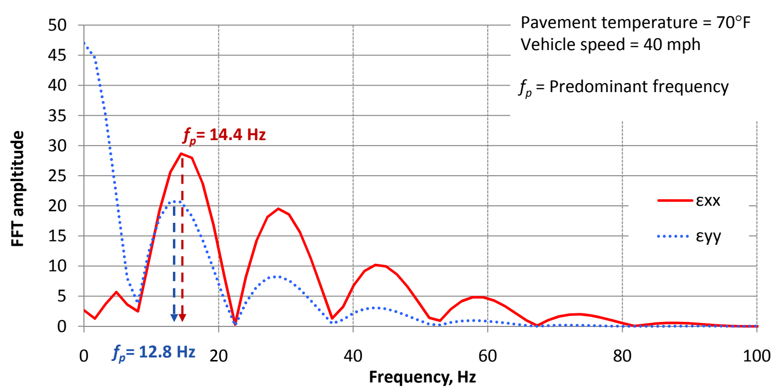
Proposed approach to determine f_p

WRSC Western Regional Superpave Center

- **FFT amplitudes of the normal strains of the 4-inch HMA**



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f_p for the 4-inch HMA layer

Case Study	Depth (in)	Predominant frequency, (Hz)							
		ε_{xx}		ε_{yy}		ε_{zz}		σ_{zz}	
		f_p	f_{pseudo}	f_p	f_{pseudo}	f_p	f_{pseudo}	f_p	f_{pseudo}
Case 1: 70ºF and 40 mph	0.25	14.4	14.4	12.8	14.4	14.4	14.4	14.4	14.4
	0.5	14.4		12.8		14.4		14.4	
	0.75	14.4		12.8		14.4		14.4	
	1.5	14.4		12.8		14.4		14.4	
	2.5	14.4		12.8		14.4		14.4	
	3.5	14.4		12.8		14.4		14.4	
	4	14.4		12.8		14.4		14.4	
Case 2: 104ºF and 40 mph	0.25	14.4	14.4	14.4	14.4	14.4	30.4	14.4	14.4
	0.5	14.4		12.8		30.4		14.4	
	0.75	14.4		14.4		30.4		14.4	
	1.5	12.8		14.4		30.4		14.4	
	2.5	30.4	30.4	14.4		14.4	14.4	14.4	
	3.5	30.4		14.4		14.4		14.4	
	4	28.8		14.4		14.4		14.4	
Case 3: 70ºF and 60 mph	0.25	21.6	21.6	19.4	21.6	21.6	21.6	21.6	21.6
	0.5	21.6		19.4		21.6		21.6	
	0.75	21.6		19.4		19.4		21.6	
	1.5	21.6		16.8		21.6		21.6	
	2.5	21.6		21.6		21.6		21.6	
	3.5	21.6		19.4		21.6		21.6	
	4	21.6		19.4		21.6		21.6	
Case 4: 104ºF and 60 mph	0.25	21.6	21.6	21.6	21.6	43.3	43.3	21.6	21.6
	0.5	21.6		19.2		43.3		21.6	
	0.75	21.6		19.2		43.3		21.6	
	1.5	21.6		21.6		43.3		21.6	
	2.5	43.3	43.3	21.6		21.6	21.6	21.6	
	3.5	43.3		21.6		21.6		21.6	
	4	43.3		21.6		21.6		21.6	
Case 5: 70ºF and 10 mph	0.25	3.6	7.6	3.2	3.6	3.6	7.6	3.6	3.6
	0.5	3.6		3.2		3.6		3.6	
	0.75	3.6		3.2		3.6		3.6	
	1.5	3.2		3.2		7.6		3.6	
	2.5	7.6		3.6		7.6		3.6	
	3.5	4		3.6		3.6	3.6	3.6	
	4	4		3.6		3.6		3.6	
Case 6: 104ºF and 10 mph	0.25	7.6	7.6	3.2	3.6	7.6	7.6	3.6	3.6
	0.5	7.6		3.2		7.6		3.6	
	0.75	7.6		3.2		7.6		3.6	
	1.5	11.2	11.2	3.6		3.6	3.6	3.6	
	2.5	11.2		3.6		3.6		3.6	
	3.5	11.2		3.6		3.6		3.6	
	4	11.2		3.6		3.6		3.6	

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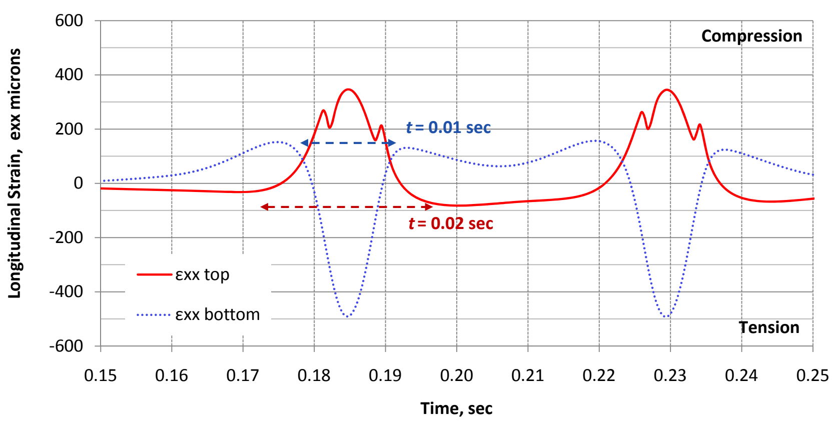
Case 4 Predominant Frequencies

Temp = 104°F, V = 60 mph, Tensile Strain ε_{xx}



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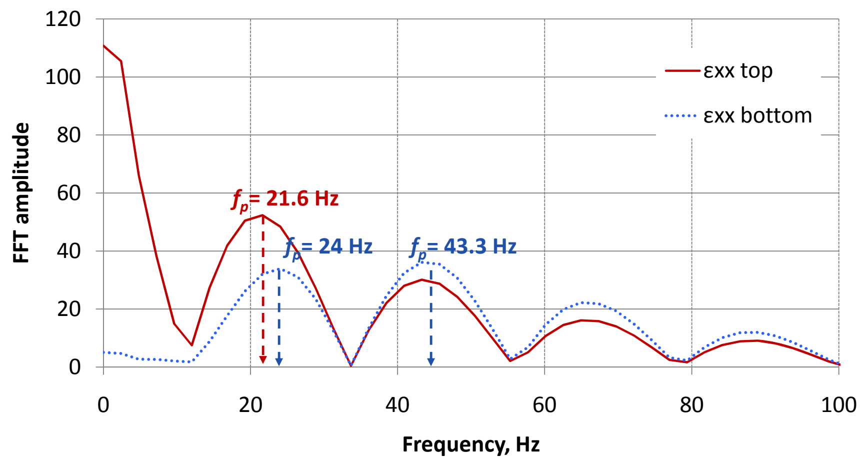
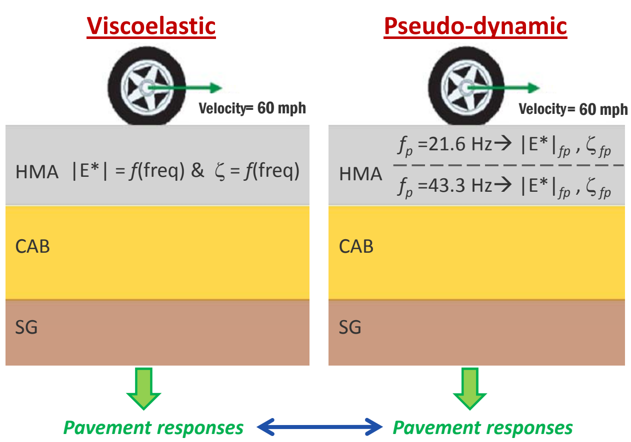
Case 4 Predominant Frequencies

Temp = 104°F, V = 60 mph, Tensile Strain ε_{xx}

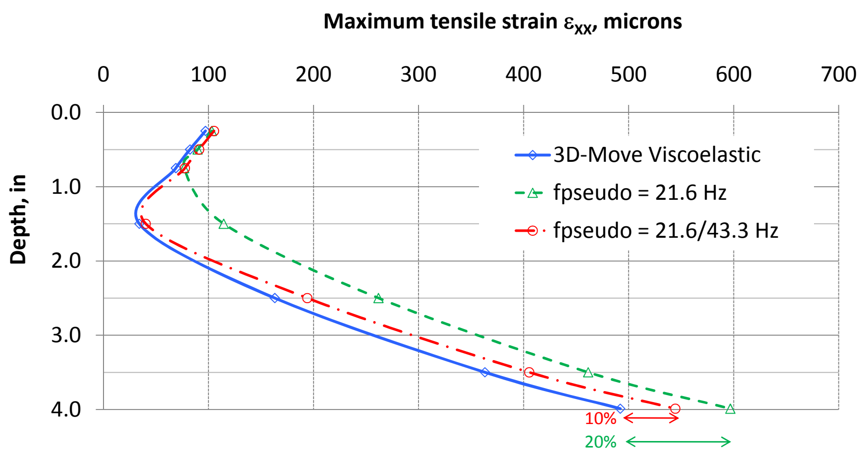


Pseudo-Dynamic Analysis



Case 4 Pseudo-Dynamic Analysis

Temp = 104°F, V = 60 mph, Tensile Strain ε_{xx}



f_p for the 8-inch HMA layer

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Case Study	Depth* (in)	Predominant frequency, (Hz)							
		ε_{xx}		ε_{yy}		ε_{zz}		σ_{zz}	
		f_p	f_{pseudo}	f_p	f_{pseudo}	f_p	f_{pseudo}	f_p	f_{pseudo}
	0.25	12.8		16		30.4		14.4	
	0.5	12.8		11.2		30.4		14.4	
	0.75	12.8	12.8	9.6		30.4	30.4	14.4	
Case 7: 70ºF and 40 mph	1.5	12.8		14.4	12.8	30.4		14.4	14.4
	2.5	12.8		14.4		30.4		14.4	
	3.5	30.4		14.4		14.4		14.4	
	6	30.4	30.4	12.8		12.8	12.8	14.4	
	8	14.4		12.8		12.8		14.4	
	0.25	14.4		12.8		30.4		14.4	
	0.5	14.4	14.4	12.8		30.4	30.4	14.4	
	0.75	14.4		11.2		30.4		14.4	
Case 8: 104ºF and 40 mph	1.5	12.8		12.8	14.4	30.4		14.4	14.4
	2.5	30.4		12.8		14.4		14.4	
	3.5	30.4	30.4	12.8		14.4	14.4	14.4	
	6	30.4		12.8		14.4		14.4	
	8	30.4		12.8		14.4		14.4	
	0.25	19.2		19.2		19.2		21.6	
	0.5	19.2		16.8		40.8		21.6	
	0.75	19.2	19.2	16.8		45.7	45.7	21.6	
Case 9: 70ºF and 60 mph	1.5	19.2		19.2	19.2	45.7		21.6	21.6
	2.5	19.2		19.2		43.2		21.6	
	3.5	45.7		21.6		21.6		21.6	
	6	45.7	45.7	19.2		19.2	19.2	21.6	
	8	45.7		19.2		19.2		21.6	
	0.25	21.6		19.2		45.7		21.6	
	0.5	21.6	21.6	19.2		45.7	45.7	21.6	
	0.75	19.2		16.8		45.7		21.6	
Case 10: 104ºF and 60 mph	1.5	45.7		21.6	21.6	21.6		21.6	21.6
	2.5	45.7		21.6		21.6		21.6	
	3.5	43.3	45.7	21.6		21.6	21.6	21.6	
	6	43.3		21.6		21.6		21.6	
	8	43.3		19.2		21.6		21.6	
	0.25	3.6		3.2		7.6		3.6	
	0.5	3.6		3.2		7.6		3.6	
	0.75	3.6	3.6	3.2		7.6	7.6	3.6	
Case 11: 70ºF and 10 mph	1.5	3.6		3.6	3.6	7.6		3.6	3.6
	2.5	3.6		3.6		7.6		3.6	
	3.5	7.6		3.6		7.6		3.6	
	6	3.6	7.6	3.2		3.6	3.6	3.6	
	8	3.6		3.2		3.6		3.2	
	0.25	3.6		3.2		7.6		3.6	
	0.5	3.6		3.2		7.6	7.6	3.6	
	0.75	3.2		3.6		7.6		3.6	
Case 12: 104ºF and 10 mph	1.5	11.2	11.2	3.6	3.6	3.6		3.6	3.6
	2.5	11.2		3.6		3.6		3.6	
	3.5	11.2		3.6		3.6	3.6	3.6	
	6	4		3.2		3.6		3.6	
	8	3.6		3.2		3.6		3.2	

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Viscoelastic vs. Pseudo-Dynamic analysis

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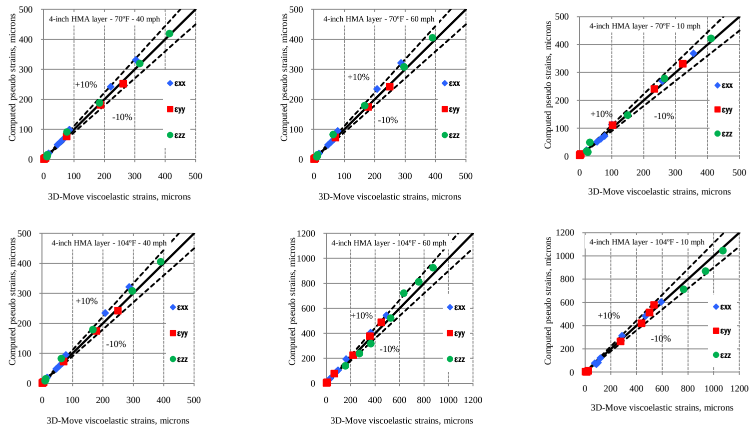
4-inch HMA layer



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N

Viscoelastic vs. Pseudo-Dynamic analysis

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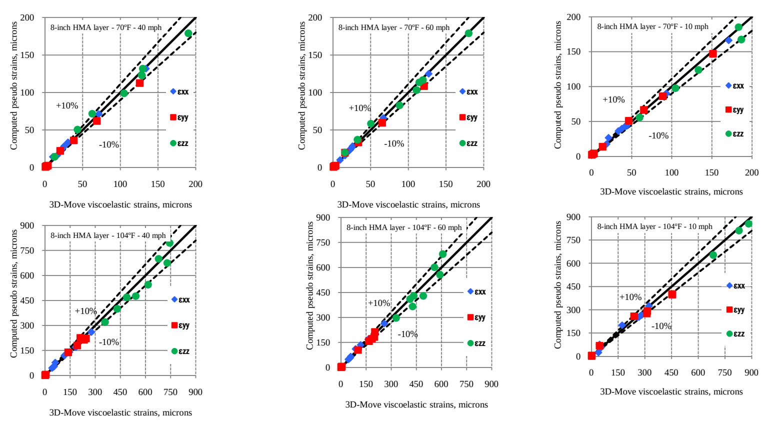
8-inch HMA layer



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Pseudo-Static Analysis

- **Pseudo-Static:**
  - Vehicle speed = 0
  - Linear Elastic Analysis (LEA)
  - Use f_p to select $|E^*|_{fp}$
  - Damping $\zeta_{fp} = 0$
- **Also Compare pavement responses following**
  - MEPDG approach (f = 1/t)
  - Modified MEPDG (f = 1/(2t))
  - Ferry ($f = 1/(2\pi t)$)

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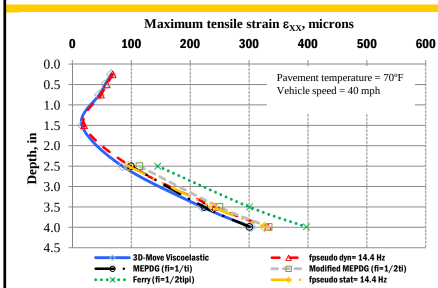
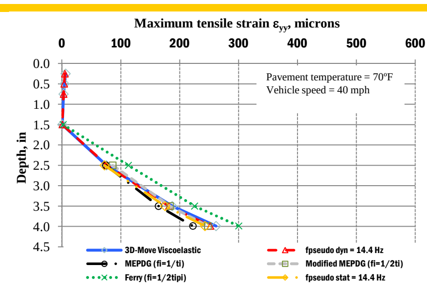
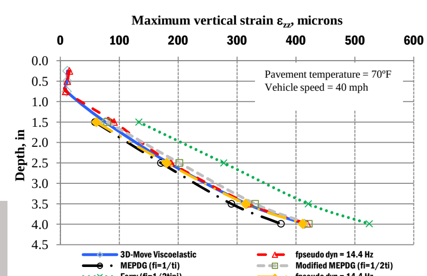
Pavement responses comparison





Pavement temperature = 70 °F
4-inch HMA layer
40 mph



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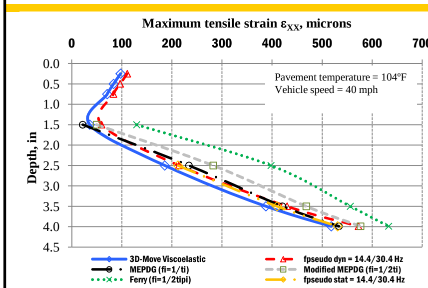
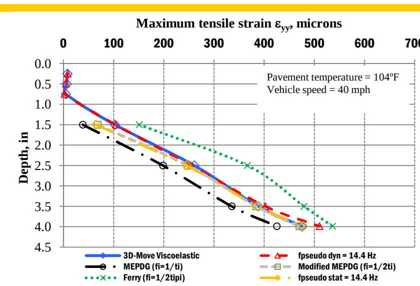
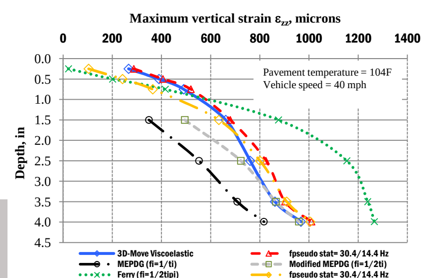
Pavement responses comparison

Western Regional Superpave Center





Pavement temperature = 104 °F
4-inch HMA layer
40 mph



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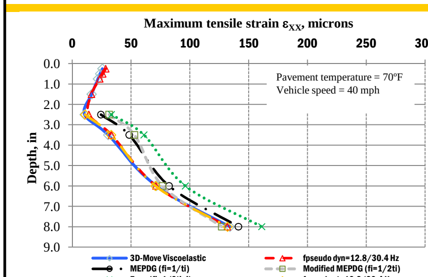
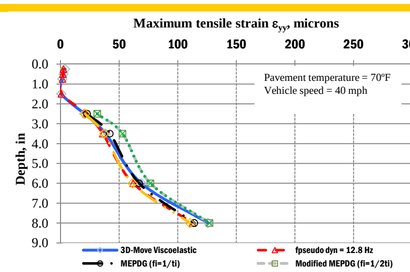
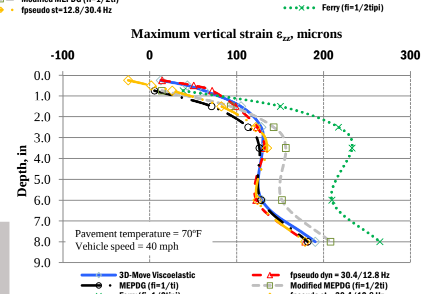
Pavement responses comparison

Western Regional Superpave Center





Pavement temperature = 70 °F
8-inch HMA layer
40 mph



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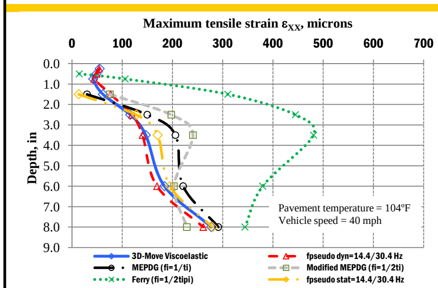
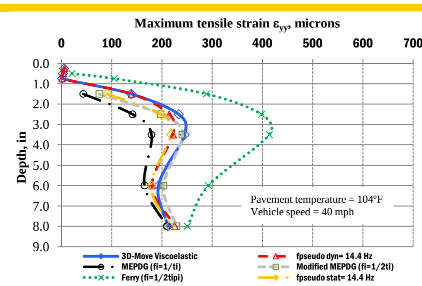
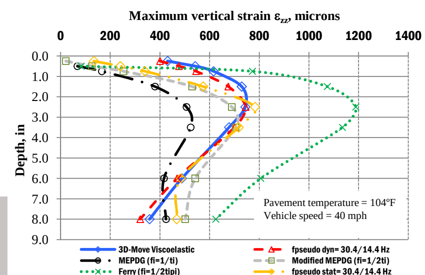
Pavement responses comparison





Pavement temperature = 104 °F
8-inch HMA layer
40 mph



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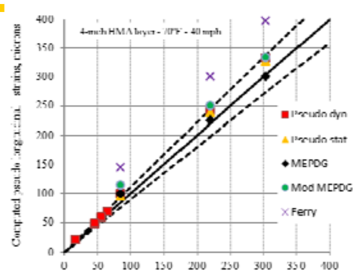
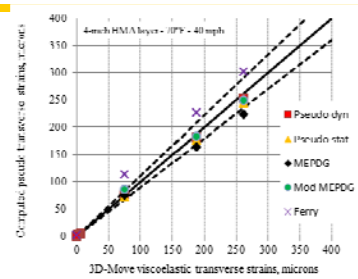
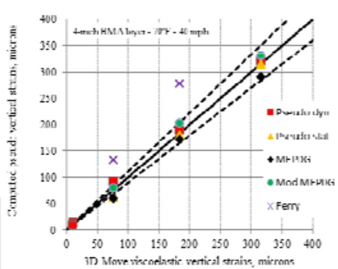
Pavement responses comparison





Pavement temperature = 70 °F
4-inch HMA layer



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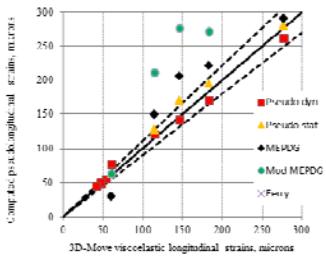
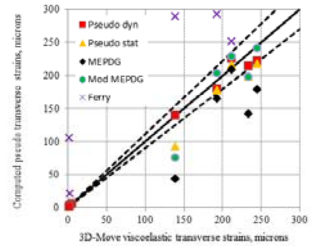
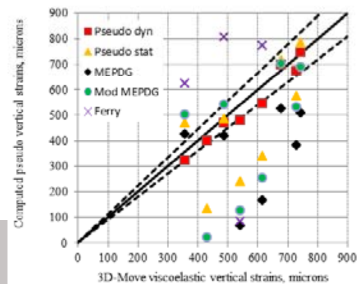
Pavement responses comparison

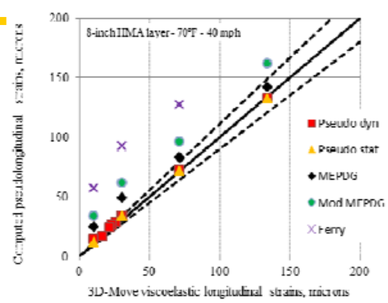


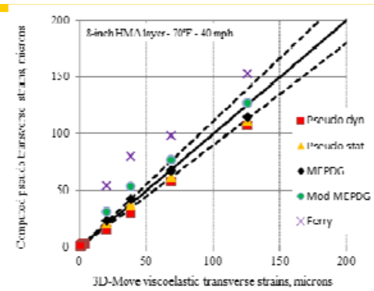


Pavement
temperature = 104 ˚F
4-inch HMA layer

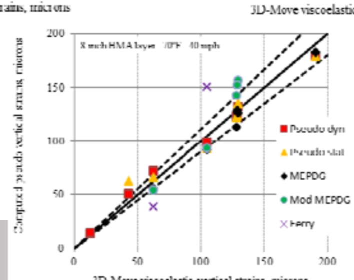


Pavement responses comparison

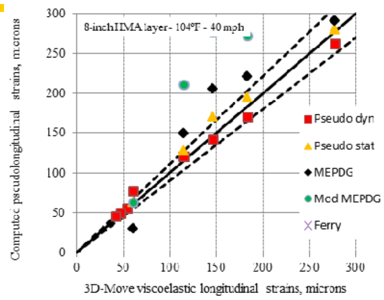


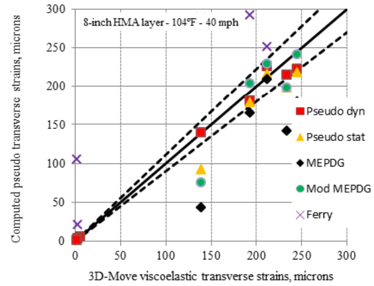


Pavement
temperature = 70 ˚F
8-inch HMA layer

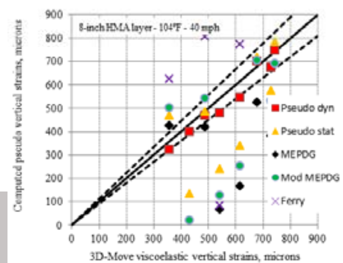


Pavement responses comparison





Pavement temperature = 104 °F
8-inch HMA layer



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Overall Findings

- Use of one single set of f_p cannot be assigned to the AC layer to study all responses.
- Pavement responses can be successfully predicted (within ±10%) by *Pseudo-Dynamic* equivalent approach.
- MEPDG approach derives in comparable pavement responses only when asphalt layer is stiff and there are no multiple f_p within the asphalt layer.

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Additional needed work…

- Investigate influence of axle load, response location and axle configuration on f_p.
- Investigate influence of CTB on f_p.
- Evaluate different time-frequency conversions.
- Other!

…Feedback…

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Acknowledgment

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– Contents reflect the views of the authors and do not necessarily reflect the official views & policies of FHWA.

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