Pavement Surface Safety Analysis with Data From Different Devices

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Outline

- Introduction
- Field Data Collection: Friction & Texture
- Preliminary Results
- Wavelet based Analysis for Macro-texture Data
- Novel 3D Texture Parameters
- Conclusions

Background

- Pavement friction: the force resisting the relative motion between vehicle tire and pavement surface
    - Important for roadway safety
    - Static devices: British pendulum tester (BPT), dynamic friction tester (DFT)
    - High speed instruments: locked wheel skid trailer, grip tester - consuming water & tire with limited contact area

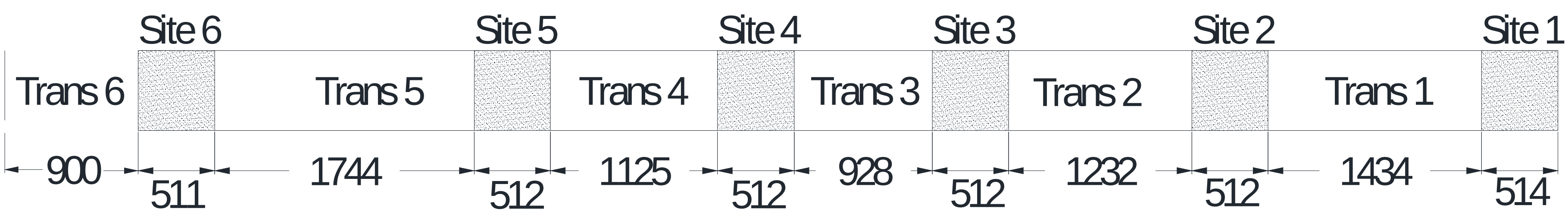
Background

- Pavement texture: the deviations of pavement surface from a true planar surface
  - Macrotexture: sand patch, circular track meter (CTM), high speed profiler (0.5 mm ~ 50 mm)
  - Widely used indicators: MPD (2D) and MTD (3D)
  - No consistent relationships between traditional texture indicators and friction
  - Microtexture: primarily in laboratory (<0.5 mm)

Objectives

- Investigate the suitability of novel texture indicators for friction analysis using data from different devices
  - Grip tester: continuous friction measurements
  - Dynamic friction tester: portable device to measure the speed dependency of pavement friction
  - AMES high speed profiler: MPD (macro-texture)
  - LS-40 surface scanner: 0.01 mm resolution (macro- & micro-texture)

Data Sources



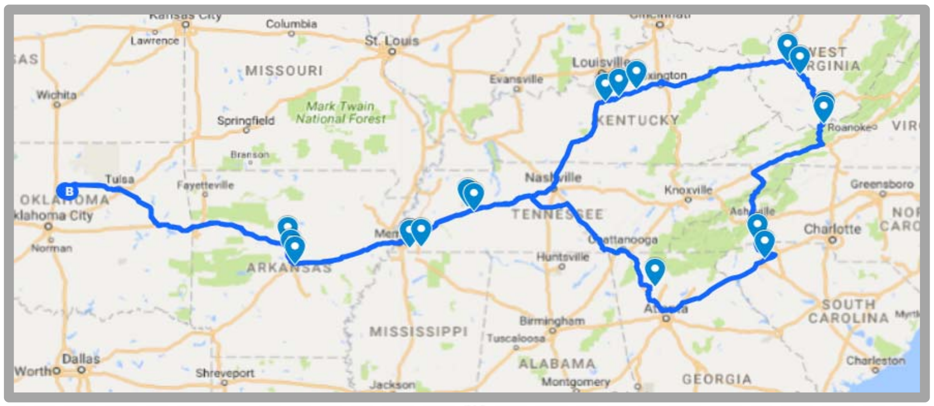
OKLAHOMA DOT SPR 2115, *LONG TERM PAVEMENT PERFORMANCE MONITORING OF SIX LTPP SPS-10 SECTIONS IN OKLAHOMA WITH 3D LASER IMAGING*

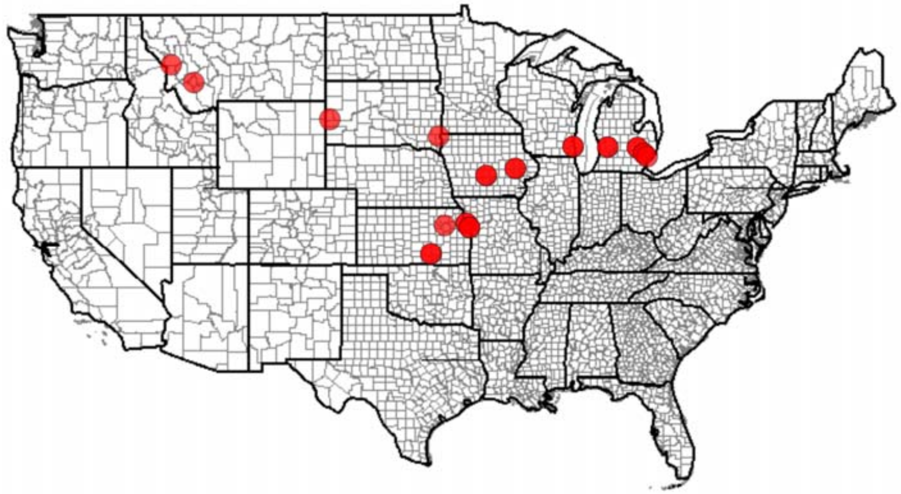
LTPP SPS-10 in Oklahoma

Section ID	Binder	Comment	Agg Combination	Insoluble Residue
1	PG 70-28	HMA with RAP + RAS	1	56.3
2	PG 70-28	WMA Foaming with RAP + RAS	1	56.3
3	PG 70-28	WMA Chemical with RAP + RAS	1	56.3
4	PG 64-22	WMA Chemical with RAP + RAS	1	56.3
5	PG 58-28	WMA Chemical with RAP + RAS	1	56.3
6	PG70-28	WMA Stone mix with mineral filler	2	43.6
Mainline	PG70-28	HMA with RAP	3	60.8

Aggregate Combination 1 contains 38% 5/8 Chips + 35% Stone Sand + 12% Sand + 12% RAP + 3% RAS;
Aggregate Combination 2 contains 90% 5/8 Chips + 10 Mineral Filler;
Aggregate Combination 3 contains 34% 5/8 Chips + 13% Scrns. + 30% Stone Sand + 13% Sand + 10% RAP.

Data Sources





FHWA, *LONG TERM PERFORMANCE MONITORING OF HIGH FRICTION SURFACING TREATMENTS (HFST) SITES* (3 YR)

Data Sources

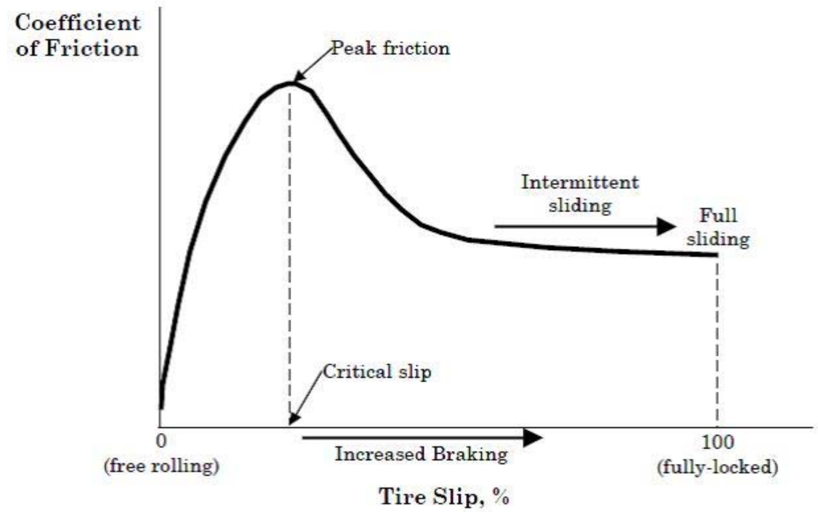
- Oklahoma DOT SPR 2775, *Development of Aggregate Characteristics-Based Preventive Maintenance Treatments Using 3D Laser Imaging and Aggregate Imaging Technology for Optimized Skid Resistance of Pavements*
- Investigate & quantify the impacts of aggregate characteristics on pavement skid resistance of preventive maintenance treatments

Typical Aggregate Sources

Preventive Maintenance Test Sections

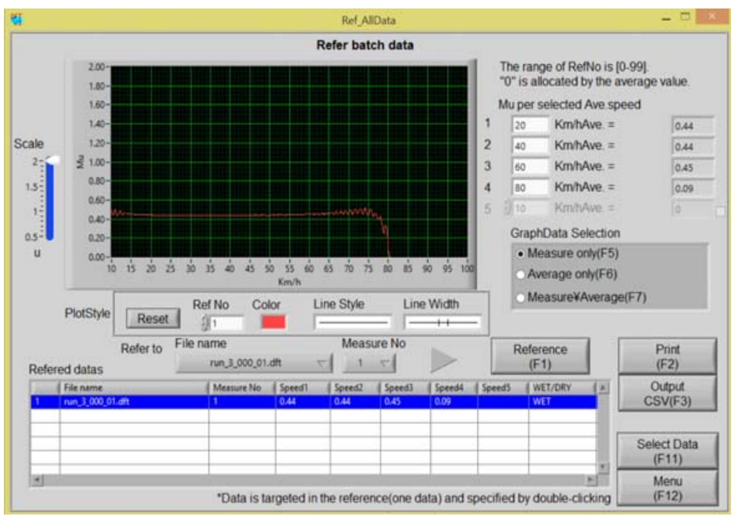
Data Collection Instruments

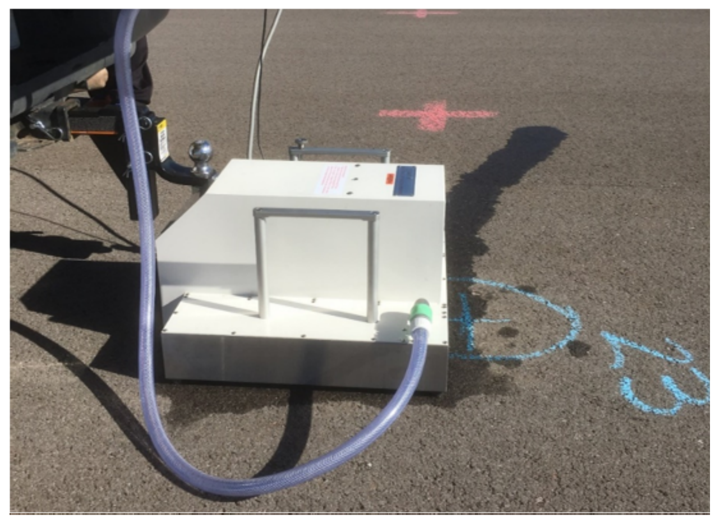
- Grip Tester
  - Continuous surface friction measuring device
  - Operating at the critical slip to simulate modern vehicle ABS technology with much lower water consumption
  - Much shorter testing section length requirement
  - Airports and highways safety management



Data Collection Instruments

- Dynamic Friction Tester (DFT)
  - Portable device to measure the speed dependency of pavement friction
  - Acquiring friction at testing speed from 10 to 80 km/h



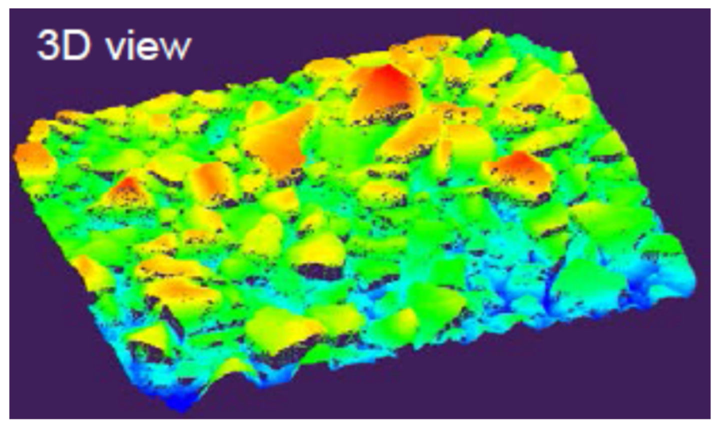


Data Collection Instruments

- AMES 8300 High Speed Profiler
  - Measurement speeds: 25 ~ 65 mph
  - Laser height sensor: 0.045 mm resolution
  - Horizontal resolution: 1.2 mm
  - Sampling rate: 62,500 per second
  - Profile wavelength: 0.5 mm

Data Collection Instruments

- LS-40 Surface Analyzer
  - Data Pixel: 2048 x2448
  - Resolution: 0.01mm (0.0004'')
  - Pavement surface micro- & macro-texture



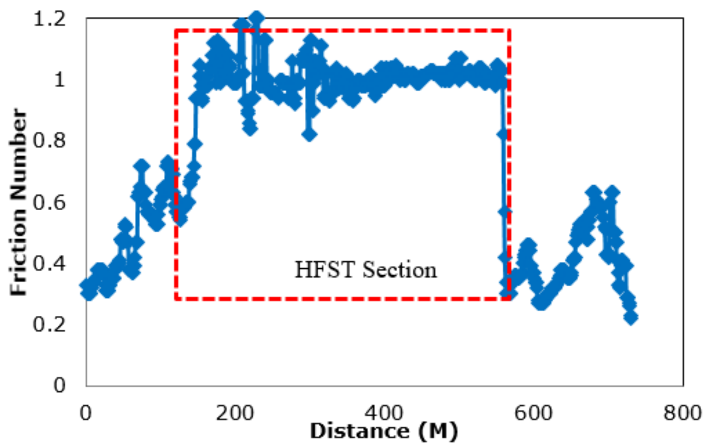
Data Collection Instruments

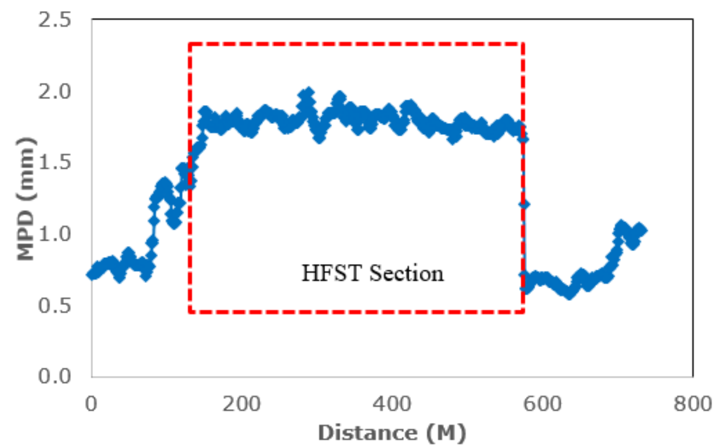
- 3D laser imaging technology (OSU)
  - 1mm 3D surface data with full lane coverage at 60 mph (no traffic control required)
  - Macro-texture profile data (MPD)
  - Provide pavement surface condition data to support the analysis

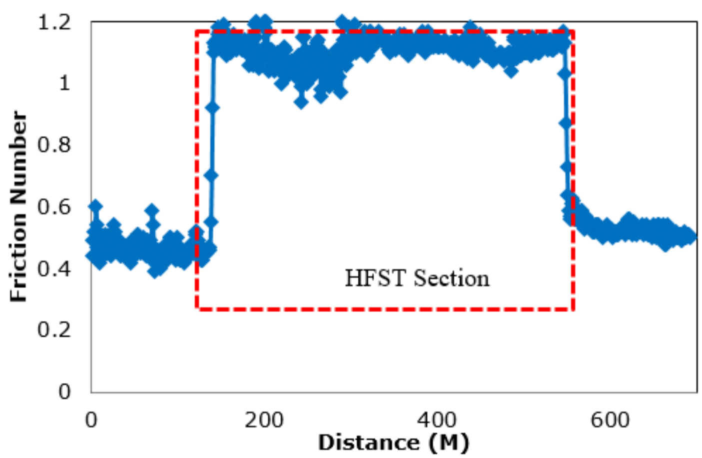
Methodology

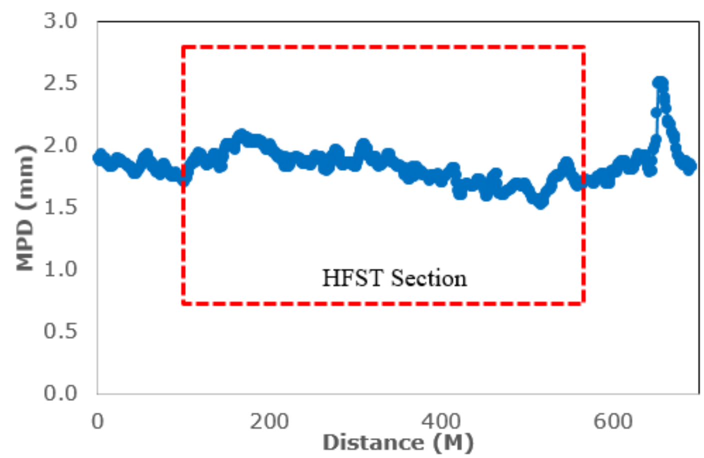
- Wavelet based Analysis
  - To decompose pavement macro-texture data into multi-scale characteristics
  - To investigate the suitability of wavelet based indicators for pavement friction prediction
  - AMES data vs. grip tester data
- Novel Texture Parameters
  - Five categories: height, volume, hybrid, spatial, and feature based parameters from various disciplines (24 indicators in total)
  - To examine the relationship between them and friction
  - LS-40 data vs. DFT data

Preliminary Results









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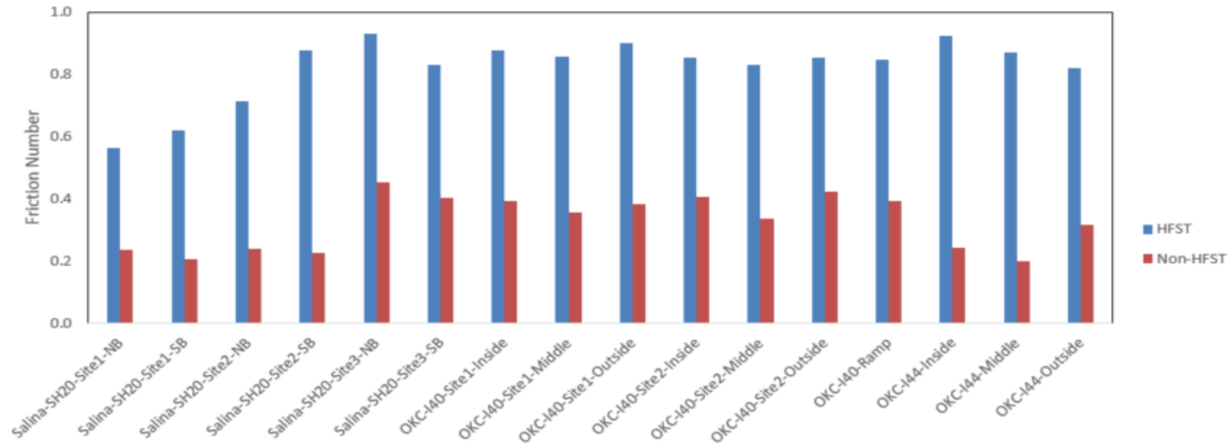
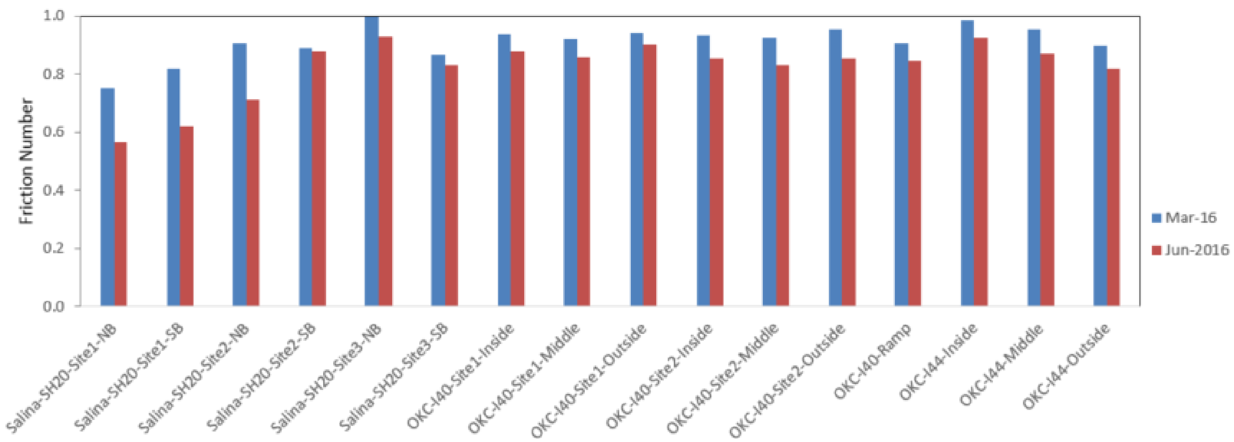
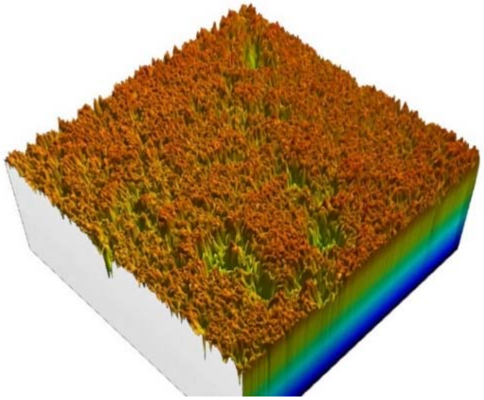
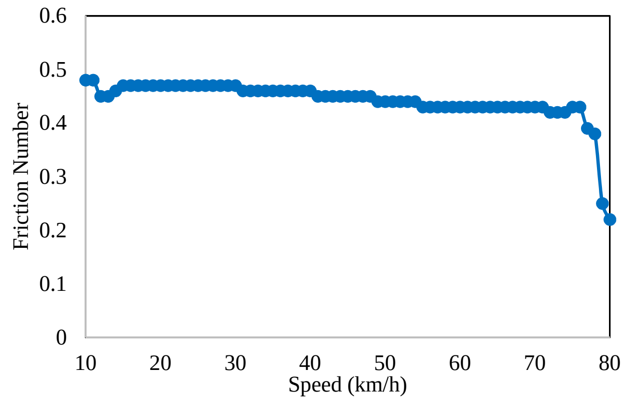


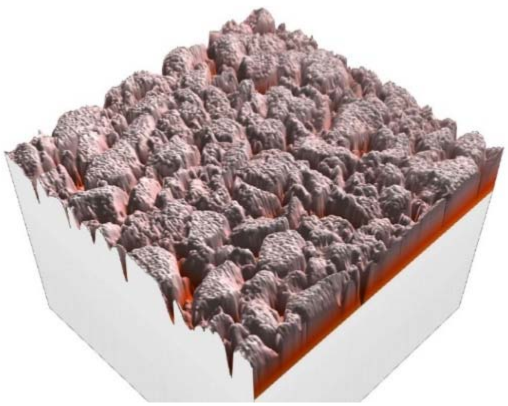


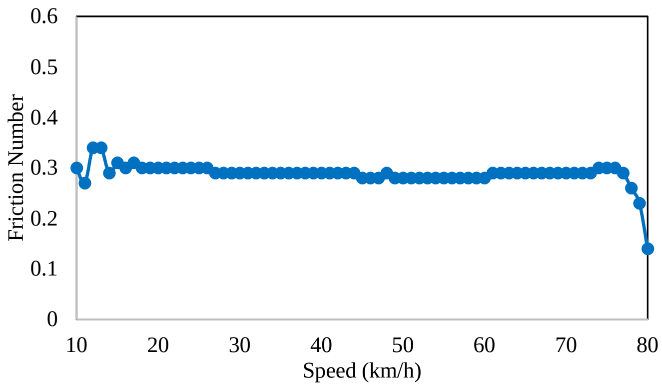
Preliminary Results





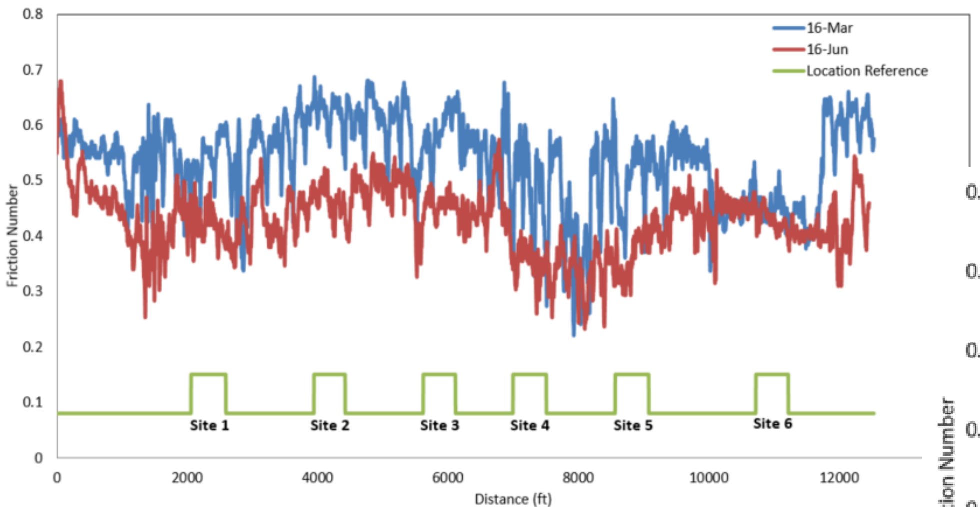
LTPP SPS-10 WMA Foaming with RAP + RAS

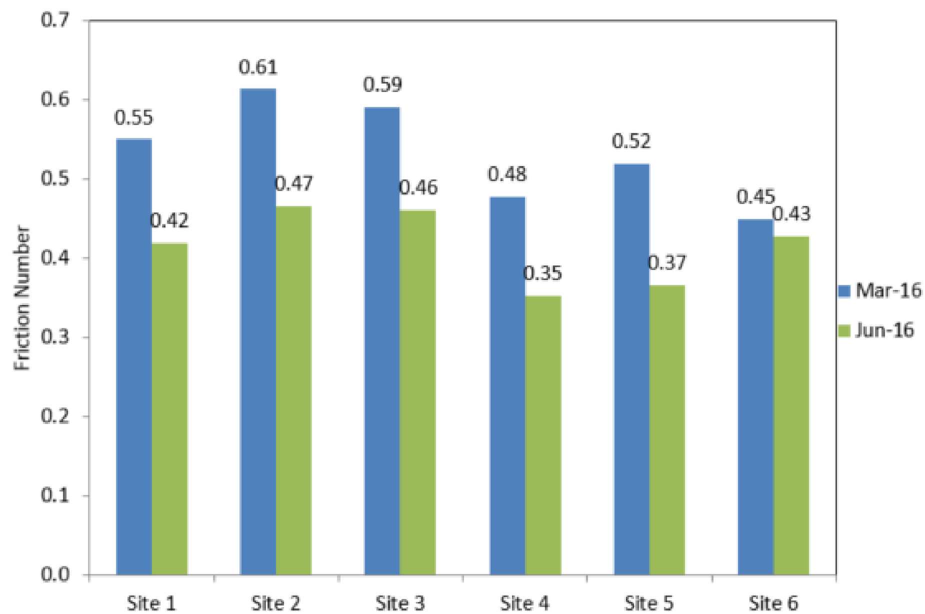




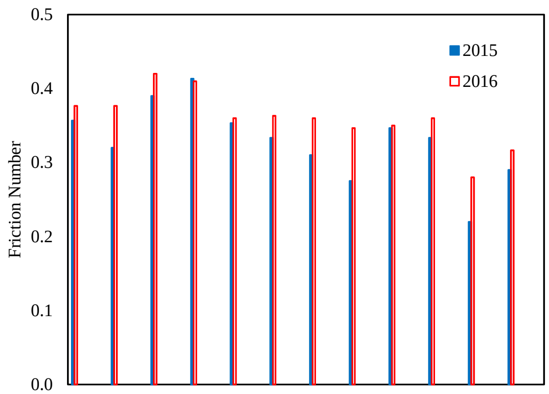
LTPP SPS-10 SMA with Mineral Filler

Preliminary Results

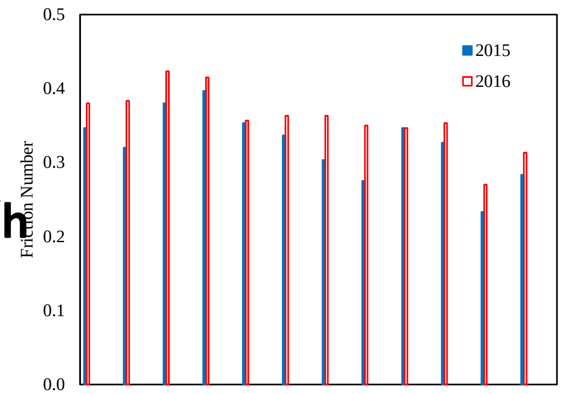




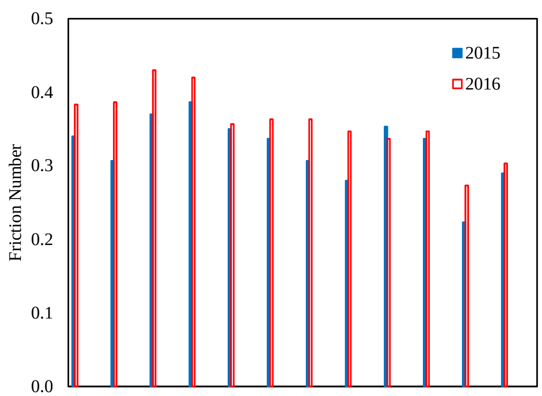
Preliminary Results



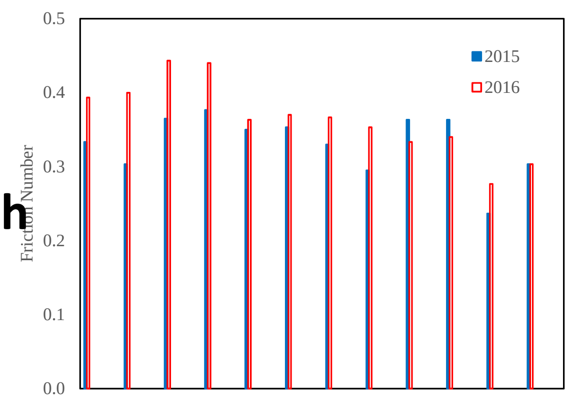
70 km/h



60 km/h



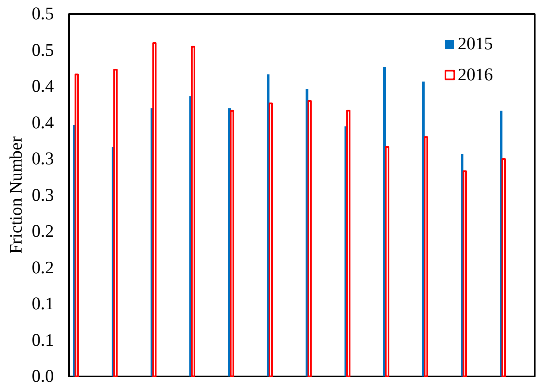
50 km/h



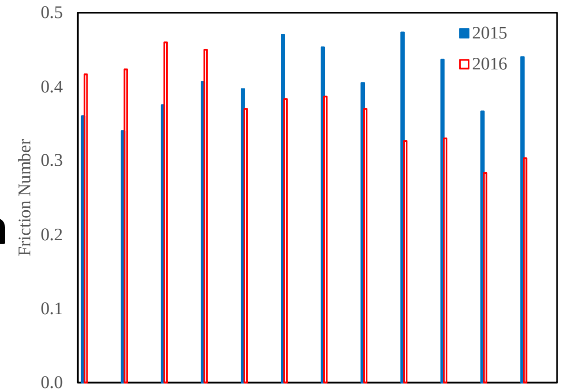
40 km/h

Increased DFT Values

Preliminary Results

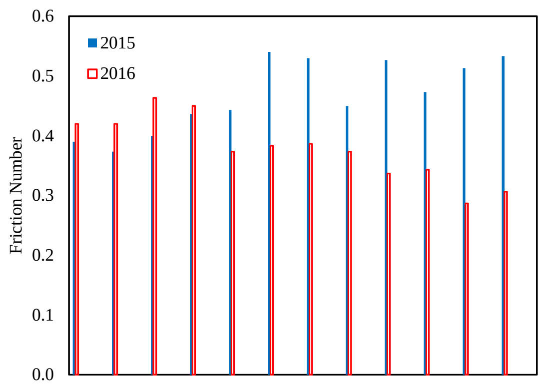


25 km/h

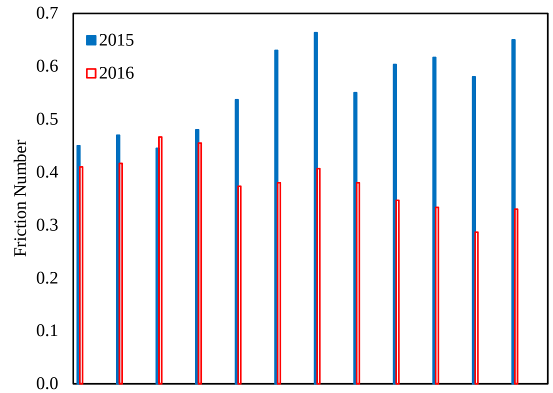


20 km/h

Decreased DFT Values

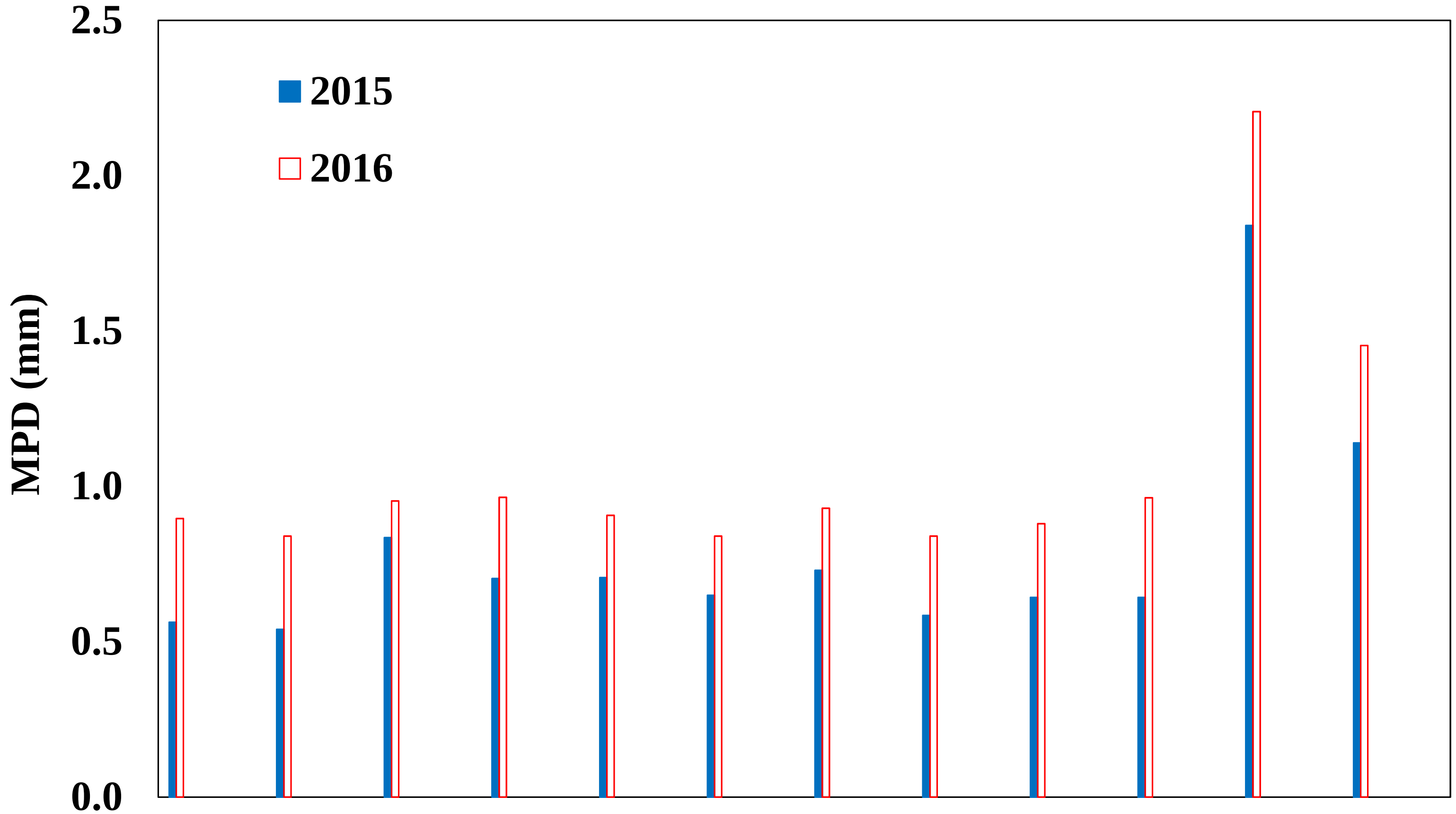


15 km/h

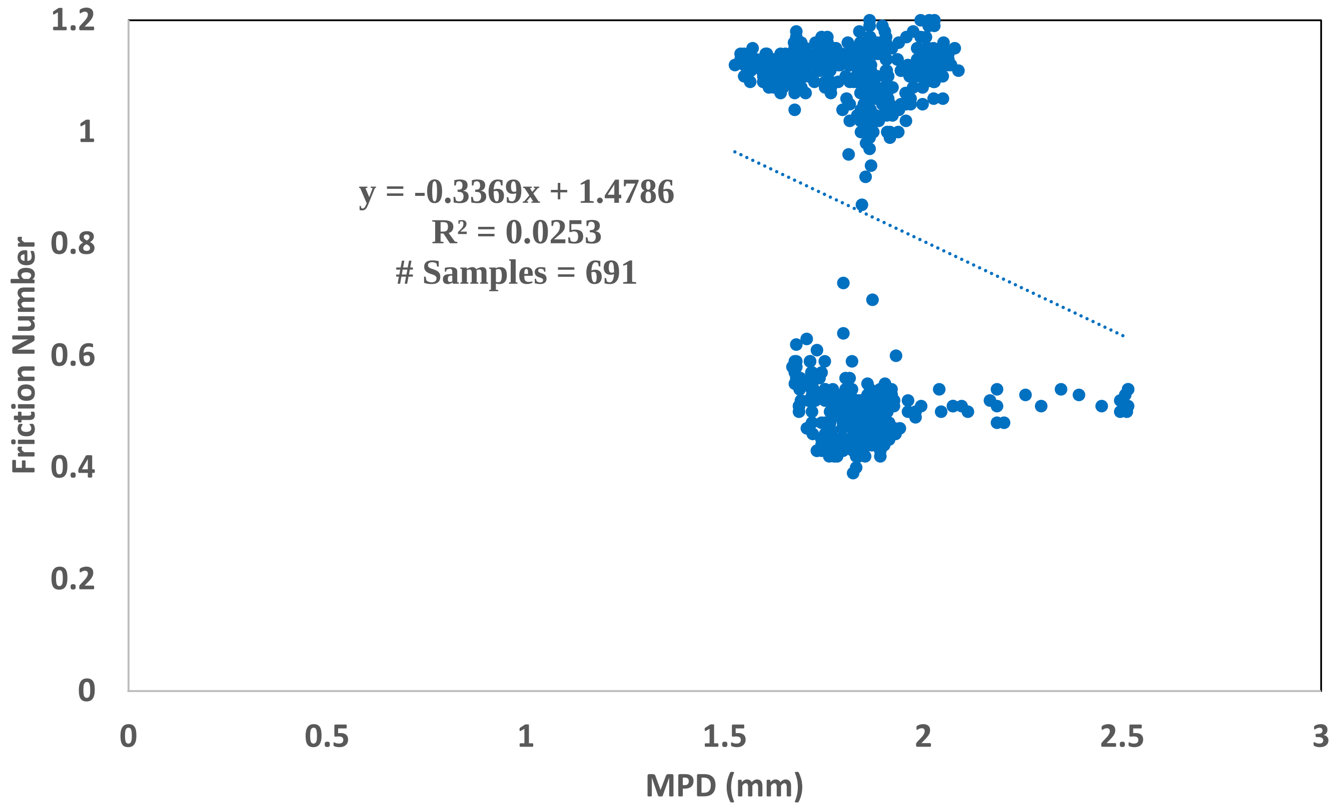


10 km/h

Preliminary Results



Preliminary Results



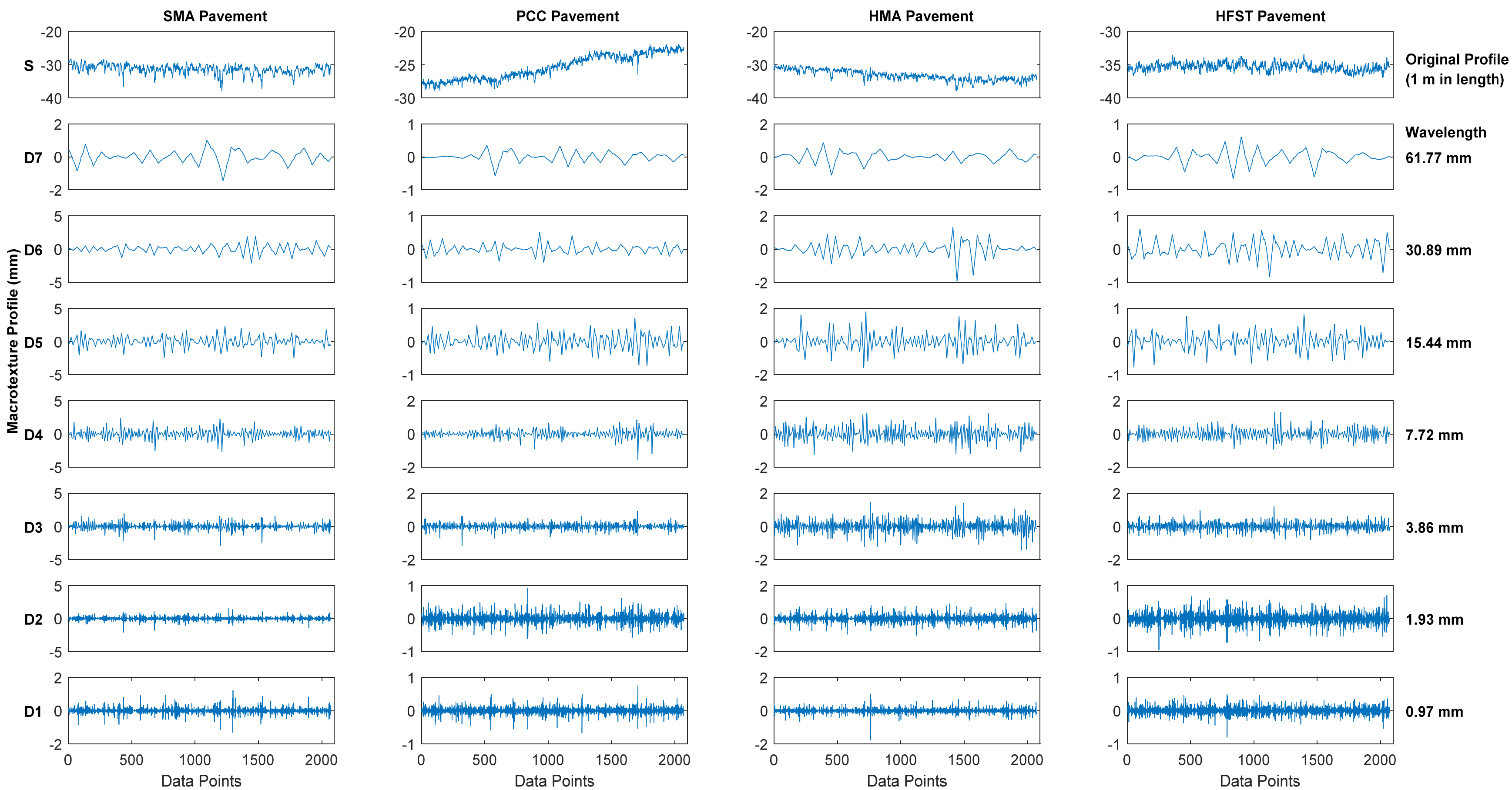
Wavelet Analysis

- Decompose signal into combination of different wavelets
- Energy $$E_j^d = \sum_{i=1}^{N} |d_j(x)|^2$$
- Total Energy (TE) $$\mathrm{TE} = \sum_{j=1}^{L} E_j^d.$$
- Relative Energy (RE) $$RE_j = \frac{E_j^d}{TE} \times 100\%$$

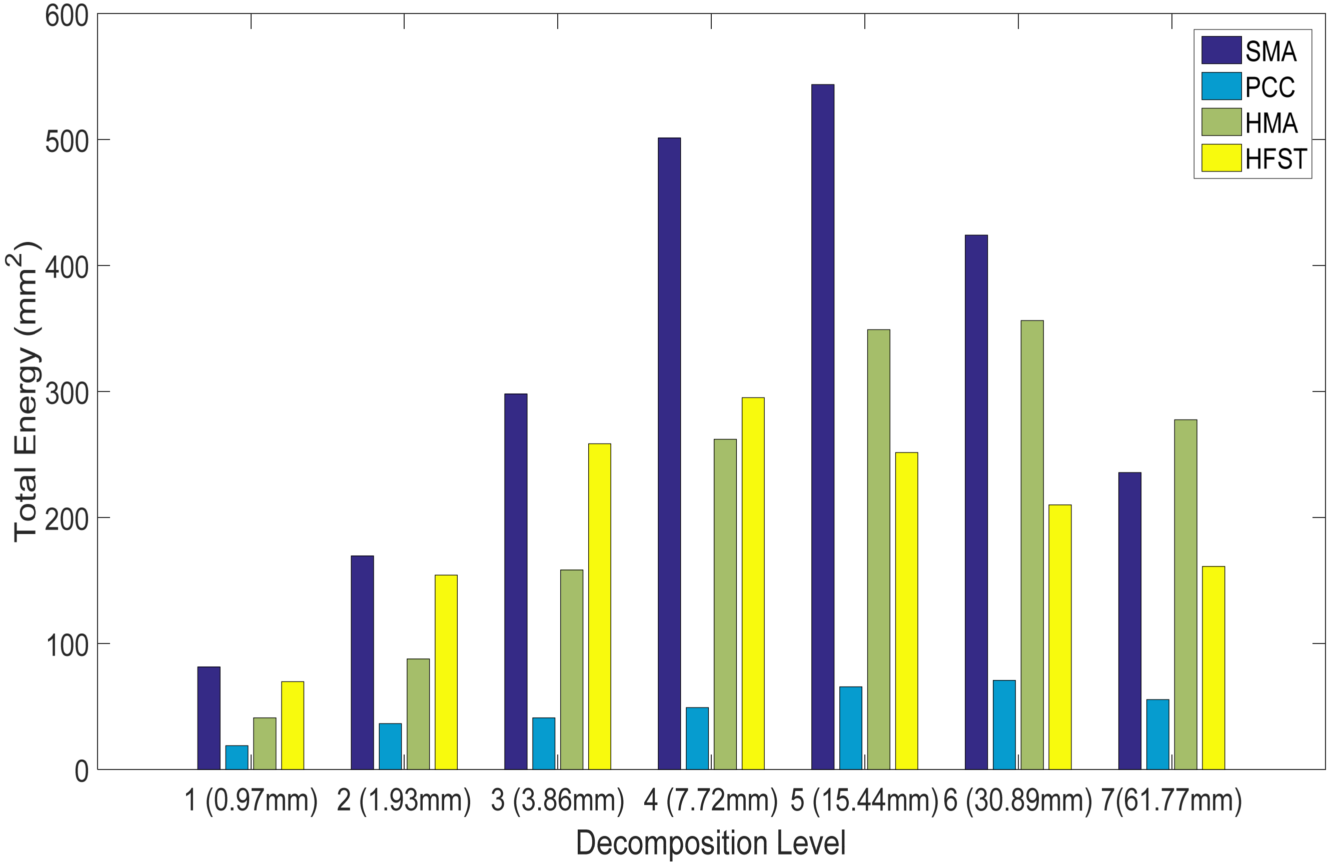
Wavelet Analysis of Macrotexture Profiles

- Mother wavelet: db3
- TE & RE: reported every 1 meter
  - 2072 data points
  - 7 decomposition levels
- Compare the energy indicators among four pavement types

Wavelet Decomposition Analysis



Energy Distribution



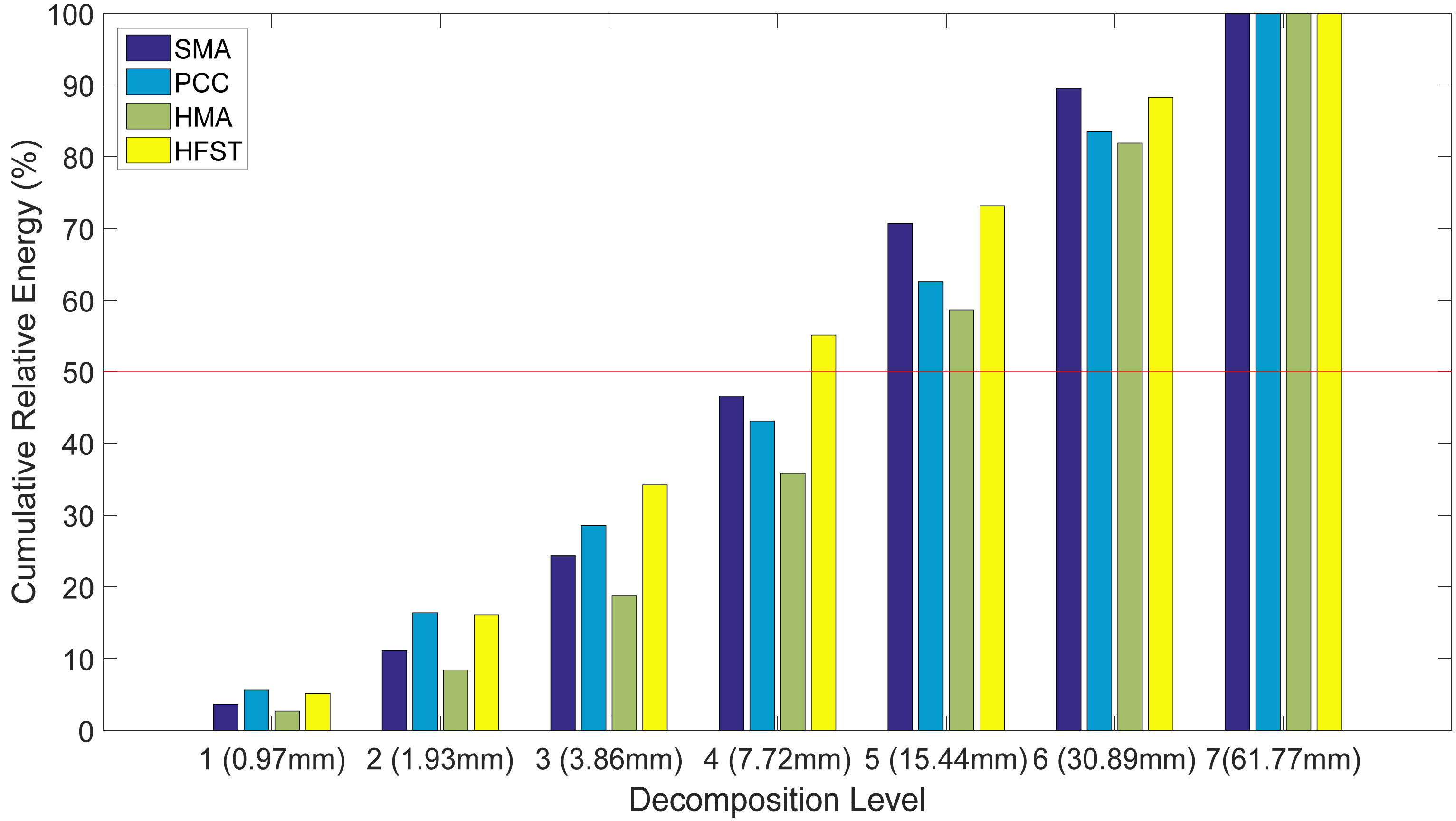
Total Energy Distribution

- Variation of macro-texture
  - SMA > HMA > HFST > PCC
- TE distribution
  - SMA > HMA > HFST > PCC
- TE could reflect macro-texture variation, but not friction #
  - HFST (1.0) > HMA (0.56) > SMA (0.50) > PCC (0.40)

Relative Energy

- Wavelength for macrotexture: 0.5~50 mm
- Macrotexture at various wavelengths: may contribute differently to pavement friction performance
- Relative energy: to investigate its distribution for various pavement types

Cumulative Relative Energy



Correlation Analysis

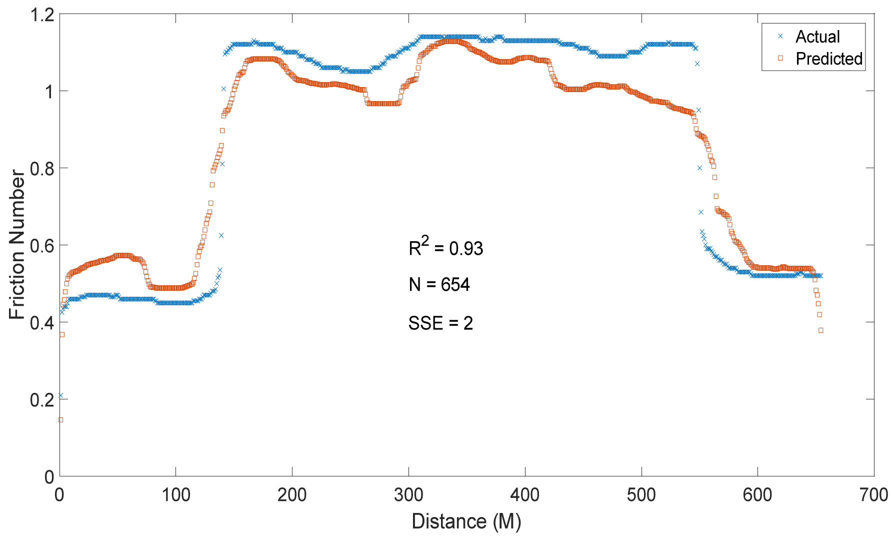
- Correlation coefficients between RE and friction number
  - RE at D1 to D3: positive
  - RE at D5 to D7: negative
  - RE at D4: transition

Site ID	Correlation Coefficients						
	D1	D2	D3	D4	D5	D6	D7
1	0.93	0.95	0.94	-0.21	-0.86	-0.74	-0.02
2	0.06	0.35	0.76	0.58	-0.34	-0.33	-0.37
3	-0.39	0.12	0.79	0.86	0.26	-0.57	-0.45
4	0.29	0.52	0.83	0.79	-0.39	-0.77	-0.55
5	0.58	0.68	0.76	0.50	-0.65	-0.63	-0.47
6	0.81	0.84	0.73	-0.19	-0.75	-0.62	-0.05

Friction Prediction Model

- Relate friction to macro-texture using TE & RE
- Friction contribution by different wavelengths in energy

$$\boldsymbol{Friction\ Number} = \boldsymbol{a + TE * b + \sum_{j=1}^{7} RE_j * c_j}$$



3D Areal Parameters

- Five categories of 3D areal texture parameters
  - Calculated using all the data points
    - Height parameters
    - Volume parameters
    - Hybrid parameters
    - Spatial parameters
  - Calculated based upon the features
    - Feature parameters

Height Parameters

- ISO Standard
  - Arithmetic mean height (Sa)
  - Root mean square height (Sq)
  - Skewness (Ssk) & Kurtosis (Sku)
  - Maximum height of the surface (Sp, Sv, and Sz)
- ASTM Standard
  - MPD: average height of the two highest peaks of two 50cm profile segments

$$S_a = \frac{1}{A}\iint_A |z(x,y)|\,dx\,dy$$

$$S_q = \sqrt{\frac{1}{A}\iint_A z(x,y)\,dx\,dy}$$

$$S_{sk} = \frac{1}{{S_q}^3}\frac{1}{A}\iint_A z^3(x,y)\,dx\,dy$$

$$Sk_u = \frac{1}{{S_q}^4}\frac{1}{A}\iint_A z^4(x,y)\,dx\,dy$$

Volume Parameters

- Void volume (Vv)
- Material volume (Vm)
- Peak material volume (Vmp)
- Core material volume (Vmc)
- Core void volume (Vvc)
- Dales void volume (Vvv)

$$V_{vc} = V_v(mr1) - V_v(mr2)$$

$$V_{mc} = V_m(mr2) - V_m(mr1)$$

$$V_{vv} = V_v(mr2)$$

$$V_{mp} = V_m(mr1)$$

Hybrid Parameters

- Consider both the height and spacing information of a 3D surface simultaneously
- Differentiate the surface with similar degree of roughness
  - Root mean square gradient (Sdq)
  - Interfacial area ratio (Sdr)

$$S_{dq} = \sqrt{\frac{1}{A}\iint \left(\frac{\partial z^2}{\partial x} + \frac{\partial z^2}{\partial y}\right) dxdy}$$

$$S_{dr} = \frac{(Texture\_Surface\_Area)-(Cross\_Sectional\_Area)}{Cross\_Sectional\_Area}$$

Spatial Parameters

- Autocorrelation length (Sal): the distance over the surface such that the new location has minimal correlation with the original
- Texture aspect ratio (Str): the division of Sal and the length of slowest decay of the autocorrelation function in any direction
- Texture direction (Std): the angular direction of the dominant lay comprising a surface

Feature Parameters

- Peak density (Spd)

$$S_{pd} = \frac{Number\ of\ peaks}{Area}$$

- Peak curvature (Spc)

$$S_{pc} = \frac{1}{N} \iint_{Peak-Area} \left(\frac{\partial^2 z(x,y)}{\partial x^2}\right) + \left(\frac{\partial^2 z(x,y)}{\partial y^2}\right) dx\, dy$$

- S5p (S5v): the arithmetic mean height of the five highest peaks (lowest valleys)
- S10z: the sum of S5p and S5v

Correlation Within Category

Height	Sq	Ssk	Sku	Sp	Sv	Sz	Sa	MPD
Sq	1.00	-0.17	0.26	0.95	0.93	0.99	0.99	0.94
Ssk	-0.17	1.00	-0.96	-0.26	-0.16	-0.05	-0.05	-0.22
Sku	0.26	-0.96	1.00	0.36	0.27	0.16	0.16	0.29
Sp	0.95	-0.26	0.36	1.00	0.97	0.94	0.94	0.92
Sv	0.93	-0.16	0.27	0.97	1.00	0.94	0.94	0.90
Sz	0.99	-0.05	0.16	0.94	0.94	1.00	1.00	0.92
Sa	0.99	-0.05	0.16	0.94	0.94	1.00	1.00	0.92
MPD	0.94	-0.22	0.29	0.92	0.90	0.92	0.92	1.00

Height Parameters

Correlation Within Category

Parameter		Volume						Hybrid	
		Vm	Vv	Vmp	Vmc	Vvc	Vvv	Sdq	Sdr
Volume	Vm	1.00	0.70	1.00	0.65	0.71	0.64	-	-
	Vv	0.70	1.00	0.70	0.99	1.00	0.96	-	-
	Vmp	1.00	0.70	1.00	0.65	0.71	0.64	-	-
	Vmc	0.65	0.99	0.65	1.00	0.99	0.94	-	-
	Vvc	0.71	1.00	0.71	0.99	1.00	0.93	-	-
	Vvv	0.64	0.96	0.64	0.94	0.93	1.00	-	-
Hybrid	Sdq	-	-	-	-	-	-	1.00	0.77
	Sdr	-	-	-	-	-	-	0.77	1.00

Volume & Hybrid Parameters

Correlation Within Category

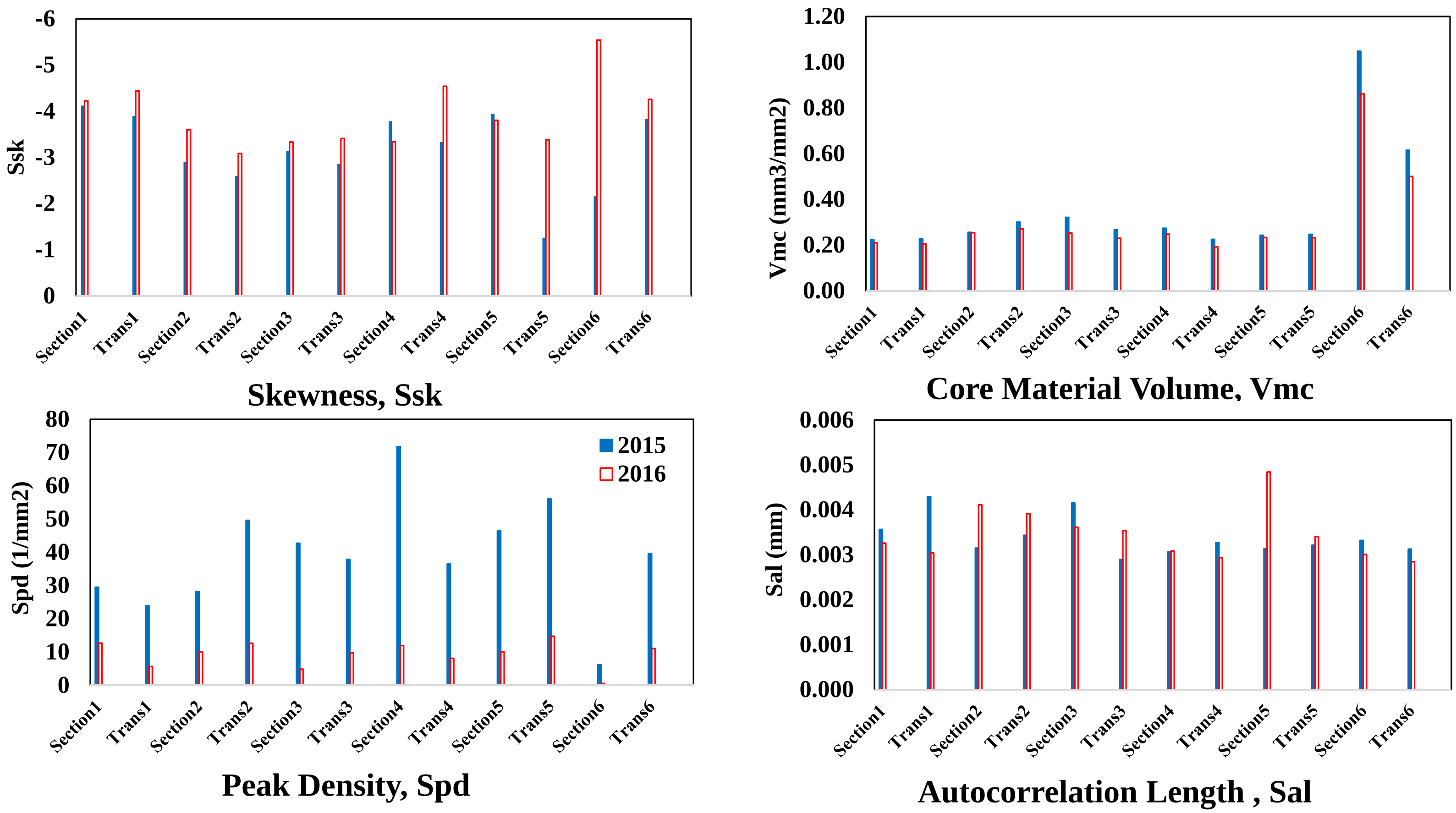
Parameter		Spatial			Feature				
		Sal	Str	Std	Spd	Spc	S10z	S5p	S5v
Spatial	Sal	1.00	-0.26	-0.07	-	-	-	-	-
	Str	-0.26	1.00	0.52	-	-	-	-	-
	Std	-0.07	0.52	1.00	-	-	-	-	-
Feature	Spd	-	-	-	1.00	-0.30	-0.34	-0.32	-0.30
	Spc	-	-	-	-0.30	1.00	0.93	0.81	0.86
	S10z	-	-	-	-0.34	0.93	1.00	0.85	0.94
	S5p	-	-	-	-0.32	0.81	0.85	1.00	0.61
	S5v	-	-	-	-0.30	0.86	0.94	0.61	1.00

Spatial & Feature Parameters

Correlation Among Categories

Parameter		Height		Volume	Hybrid	Spatial		Feature		
		Sq	Ssk	Vmc	Sdq	Sal	Str	Spd	Spc	S5v
Height	Sq	1.00	-0.17	0.97	0.66	-0.08	0.58	-0.30	0.77	0.83
	Ssk	-0.17	1.00	0.01	0.20	0.22	0.20	0.37	0.11	-0.02
Volume	Vmc	0.97	0.01	1.00	0.73	-0.07	0.58	-0.26	0.86	0.88
Hybrid	Sdq	0.66	0.20	0.73	1.00	-0.02	0.44	-0.11	0.79	0.68
Spatial	Sal	-0.08	0.22	-0.07	-0.02	1.00	-0.26	-0.08	-0.07	-0.12
	Str	0.58	0.20	0.58	0.44	-0.26	1.00	-0.08	0.48	0.48
Feature	Spd	-0.30	0.37	-0.26	-0.11	-0.08	-0.08	1.00	-0.30	-0.30
	Spc	0.77	0.11	0.86	0.79	-0.07	0.48	-0.30	1.00	0.86
	S5v	0.83	-0.02	0.88	0.68	-0.12	0.48	-0.30	0.86	1.00

Selected 3D Texture Parameters



Friction Model Development

- Multivariate regression analysis: identify the most significant 3D areal texture parameters for DFT friction at different speeds

3D Parameters	Friction Number								
	DFT70	DFT60	DFT50	DFT40	DFT30	DFT25	DFT20	DFT15	DFT10
Ssk	-	-	-	-	-	-	-	*	*
Vmc	**	**	**	**	**	*	-	-	*
Sal	-	-	-	-	-	-	-	-	-
Spd	-	-	-	-	-	-	*	**	***

Friction Model Development

- Vmc: significant for DFT friction at testing speeds over 25 km/h
- Spd: significant for DFT friction at testing speeds less than 20 km/h
- Ssk: significant for DFT friction at testing speed of 10 km/h
- Sal: not significant for friction at any speeds
- Friction models: based on only the significant 3D parameters

$$\boldsymbol{Friction\ Number = a + \sum_{1}^{3} T_i * b_i}$$

Friction Models (Based on 3D Parameters)

DFT Value @	P-value	R^2	SSE
70 km/h	8.07E-05	0.58	0.031
60 km/h	4.54E-05	0.57	0.034
50 km/h	7.63E-05	0.54	0.038
40 km/h	0.00018	0.48	0.044
30 km/h	0.001804	0.37	0.057
25 km/h	0.012268	0.29	0.066
20 km/h	0.003921	0.33	0.089
15 km/h	8.28E-05	0.38	0.131
10 km/h	0.002568	0.54	0.209

Friction Models (Based on MPD)

DFT Value @	P-value	R^2	SSE
70 km/h	5.52E-03	0.30	0.051
60 km/h	5.15E-03	0.29	0.055
50 km/h	5.76E-03	0.26	0.060
40 km/h	0.00832	0.25	0.063
30 km/h	0.01288	0.26	0.067
25 km/h	0.01302	0.26	0.069
20 km/h	0.02860	0.21	0.097
15 km/h	0.10751	0.10	0.192
10 km/h	0.18092	0.16	0.373

Conclusions

- Wavelet based energy distributions of macrotexture for different pavement surfaces: could vary significantly
- Wavelet based energy at different wavelengths: contribute differently to pavement friction (D1 ~ D3 positive, D5 ~ D7 negative)
- Discussions: how to help design better mixture?

Conclusions

- 3D areal texture parameters
  - Vmc (volume parameter): relate to pavement friction at higher speeds
  - Spd (feature parameter): relate to pavement friction at lower speeds
- Friction models based on new texture parameters
  - With moderate R-squared values (outperforms MPD based model)
  - Demonstrate the potential to use novel 3D areal parameters for friction correlation
- Discussion: Vmc as macro-texture, while Spd as micro-texture indicator?

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