



TOWARDS STANDARDIZED PAVEMENT SURFACE TEXTURE SPECTRAL ANALYSIS AND EVALUATION

AHMAD ALHASAN¹, PH.D., P.E. AND DAVID WHITE², PH.D., P.E.

¹ VICE PRESIDENT OF ENGINEERING SERVICES

² FOUNDER AND CEO

INGIOS GEOTECHNICS



HONORING THE PAST. PAVING THE FUTURE.

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OUTLINE

- **BACKGROUND**
- TEXTURE MEASUREMENTS, SMART WAVE, AND SPECTRAL ANALYSIS
- CONCLUDING REMARKS AND FUTURE WORK



Pavement Friction Management

- Great progress has been achieved in standardizing continuous friction measurements and their use in safety assessment.
- Still challenged with the physical systems need for water and tires, and the inconsistency between different systems.



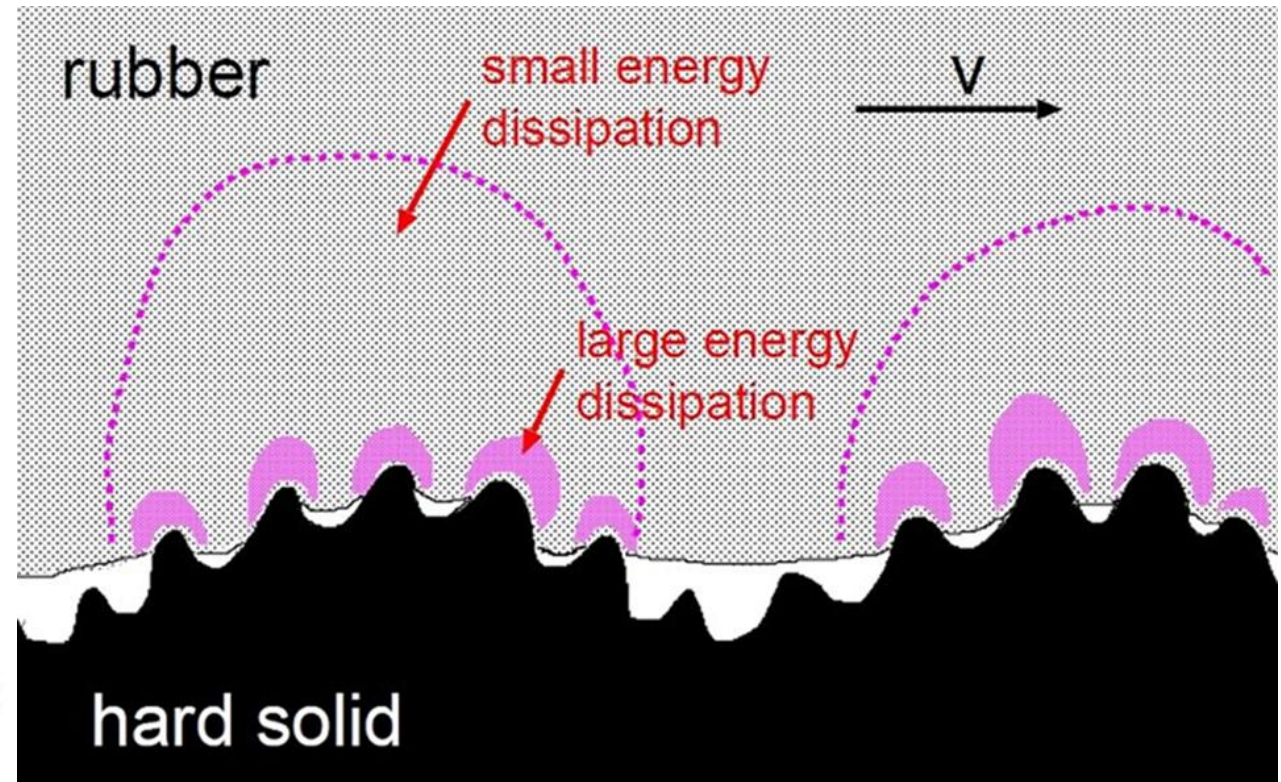
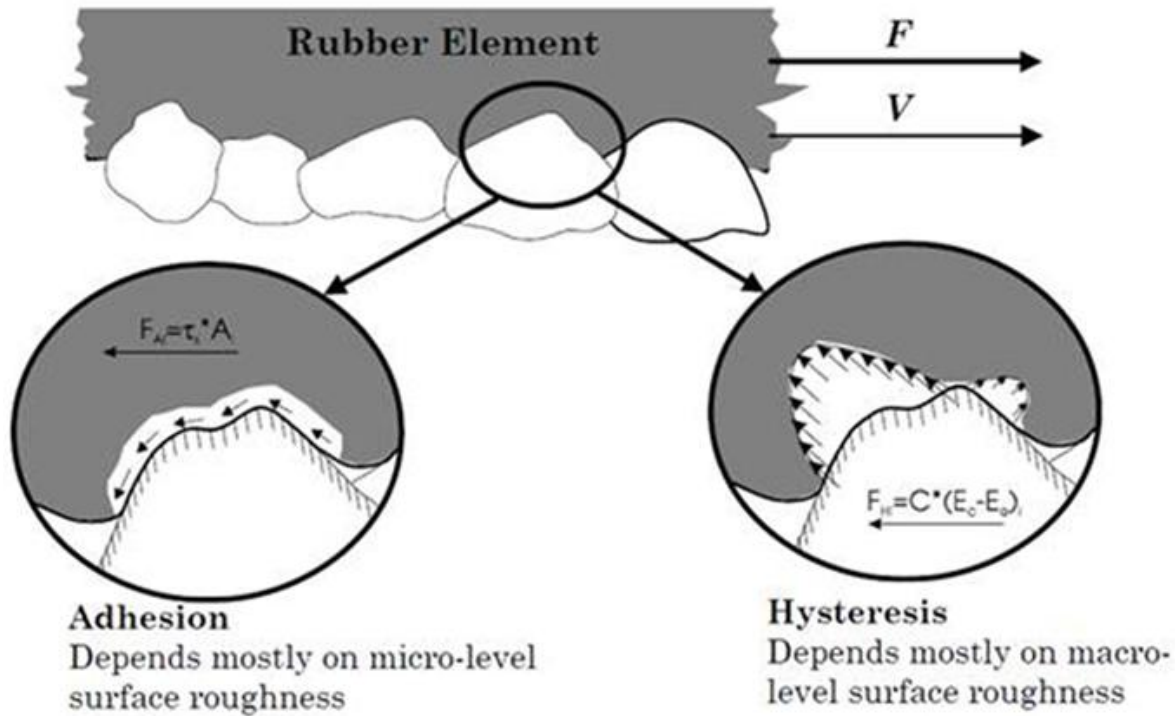
SCRIM, WDM USA



LWST, Iowa DOT

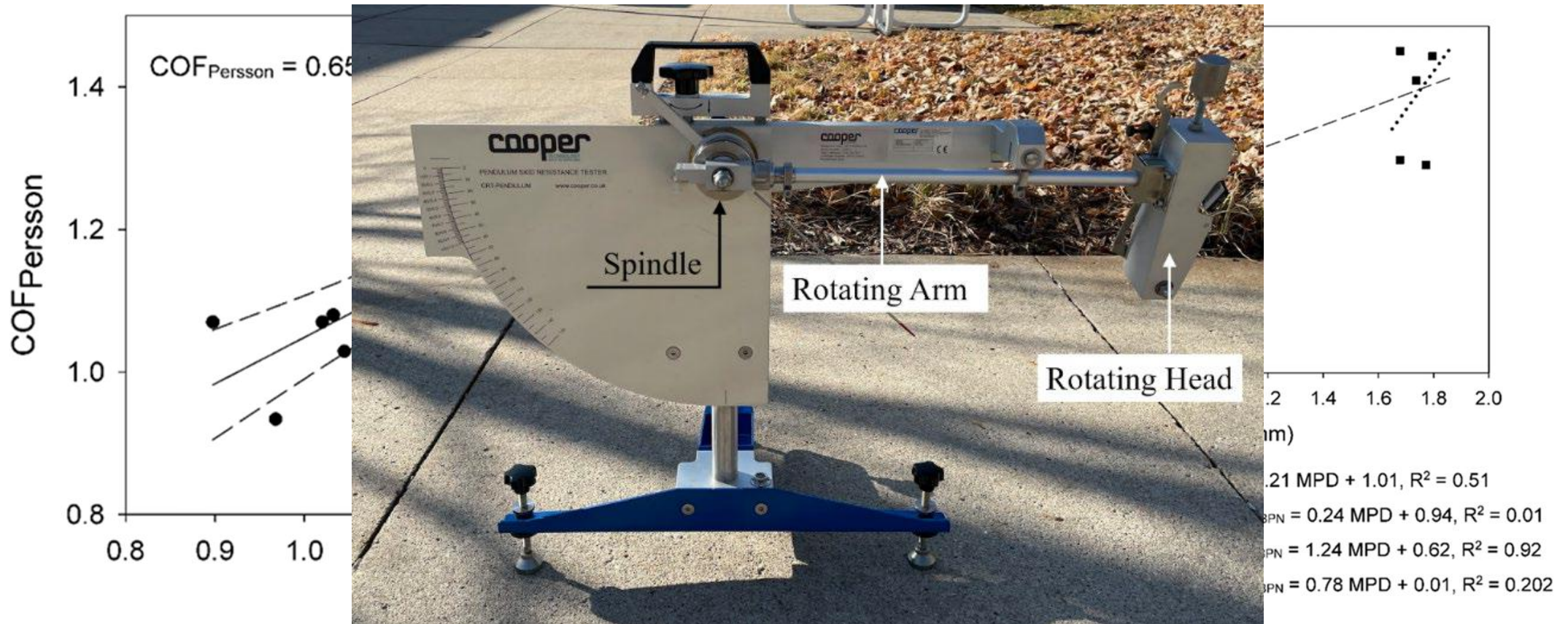
Pavement Texture Scanning

- ⦿ Persson's friction model provided a robust physical and analytical solutions for a simple rubber block.

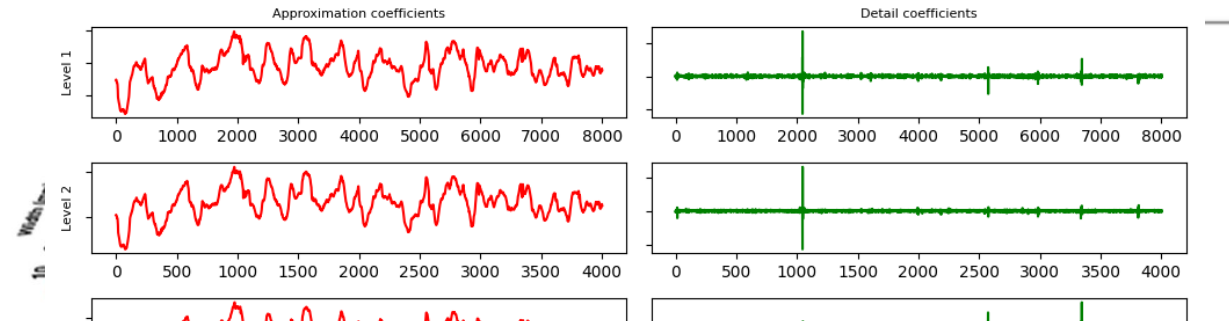


Testing the Theory

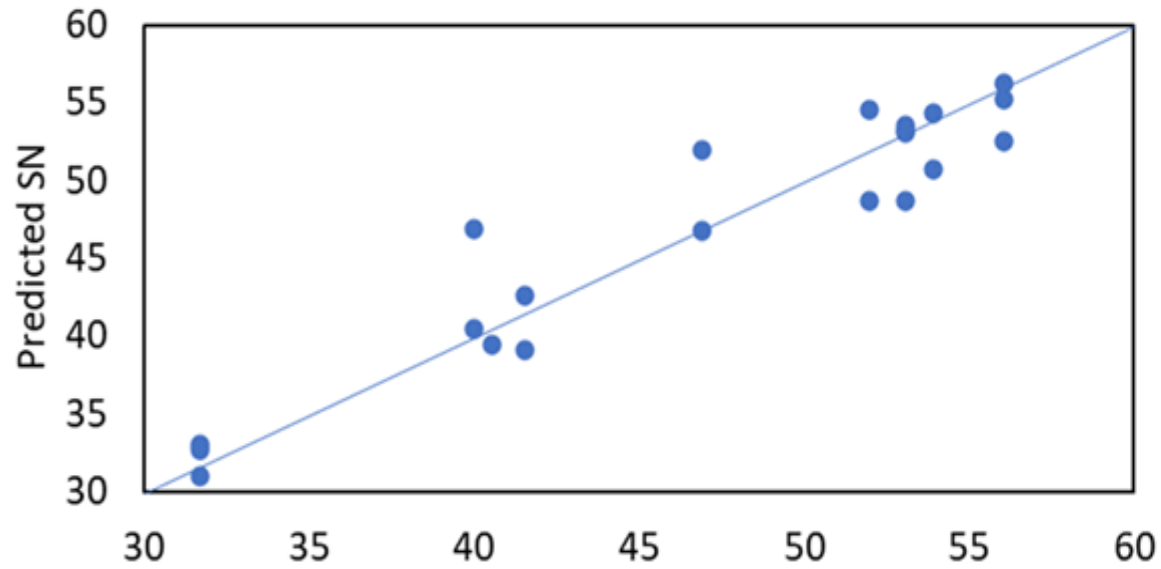
- Persson's friction model provided a robust physical and analytical solutions for a simple rubber block (British Pendulum).



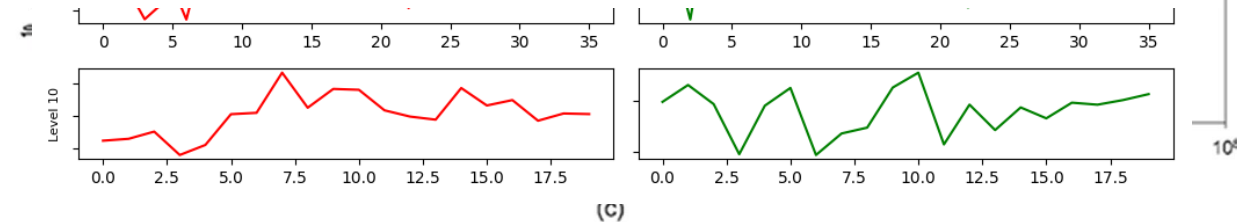
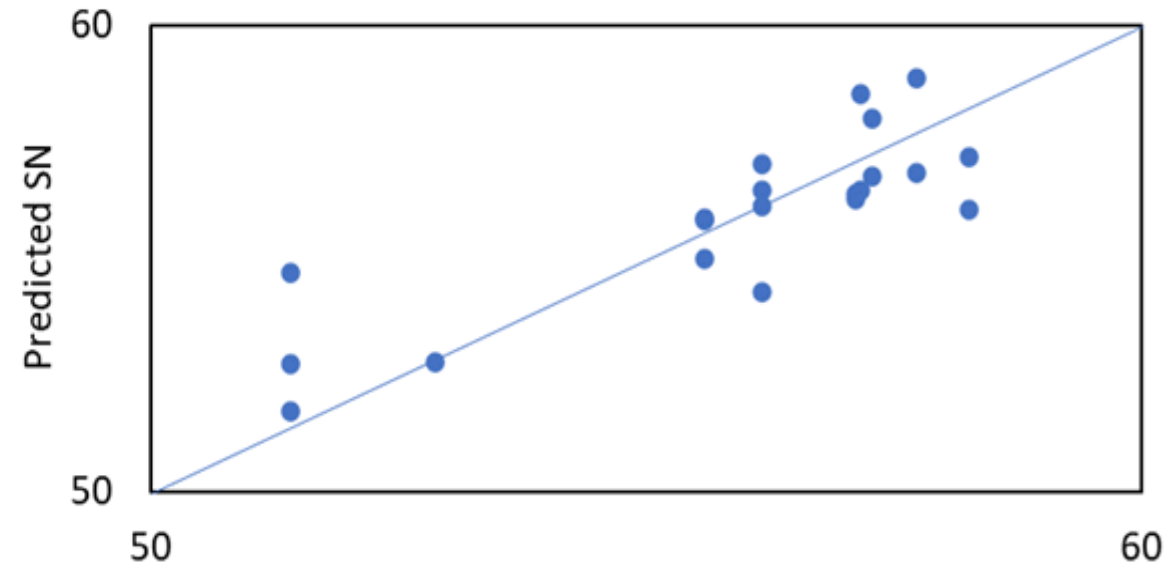
Implementing A Concept



Predicted vs Measured (Average, Smooth, 40 mph)



Predicted vs Measured (Average, Ribbed, 40 mph)



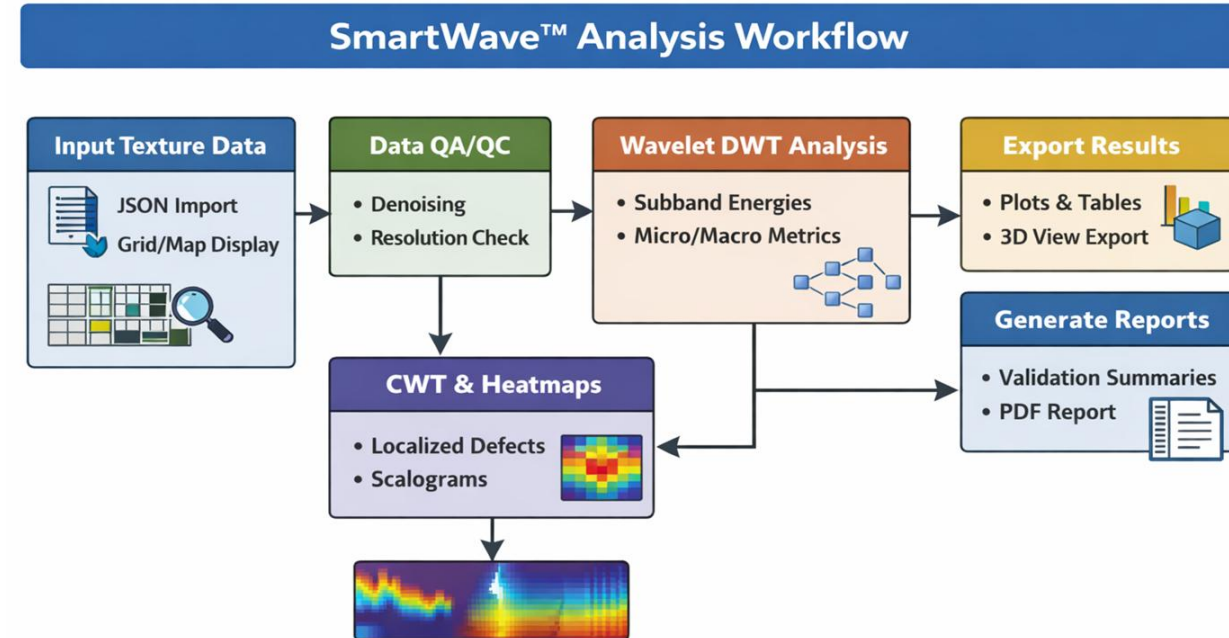
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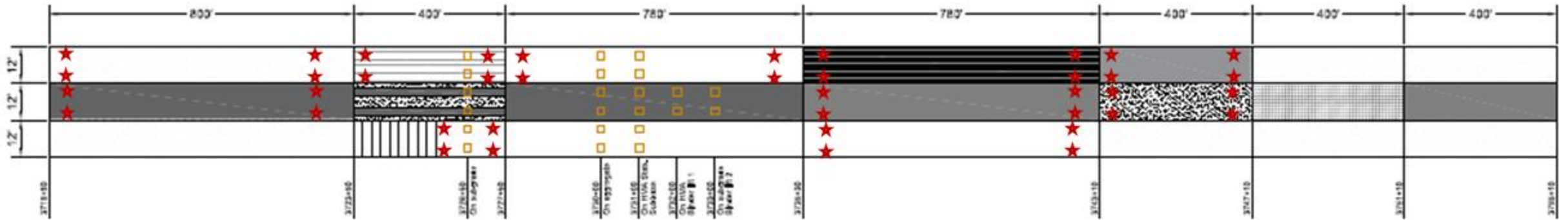


Pavement Texture Data Standardization

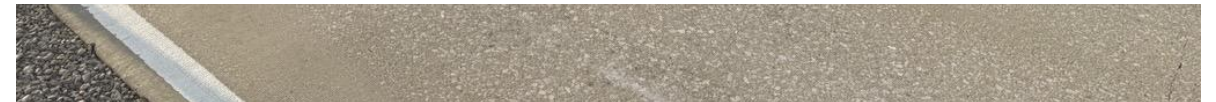
- To move towards contactless tire-pavement friction we need improved standards for texture data and analysis.
- Smart Wave™ is a proprietary platform capable of supporting analysis and friction of texture and friction data.



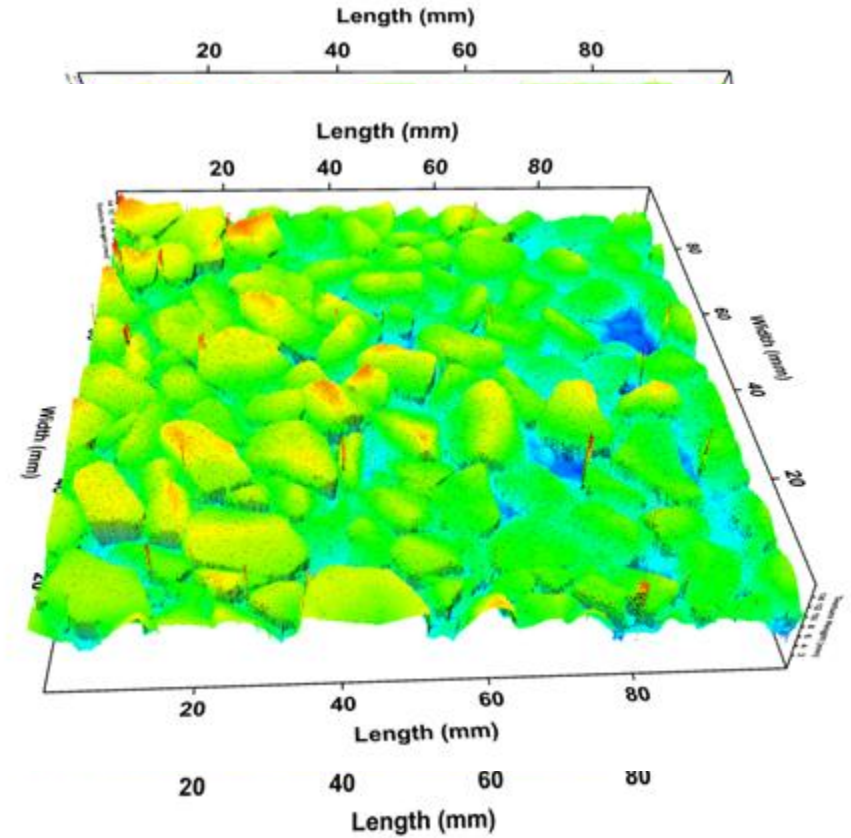
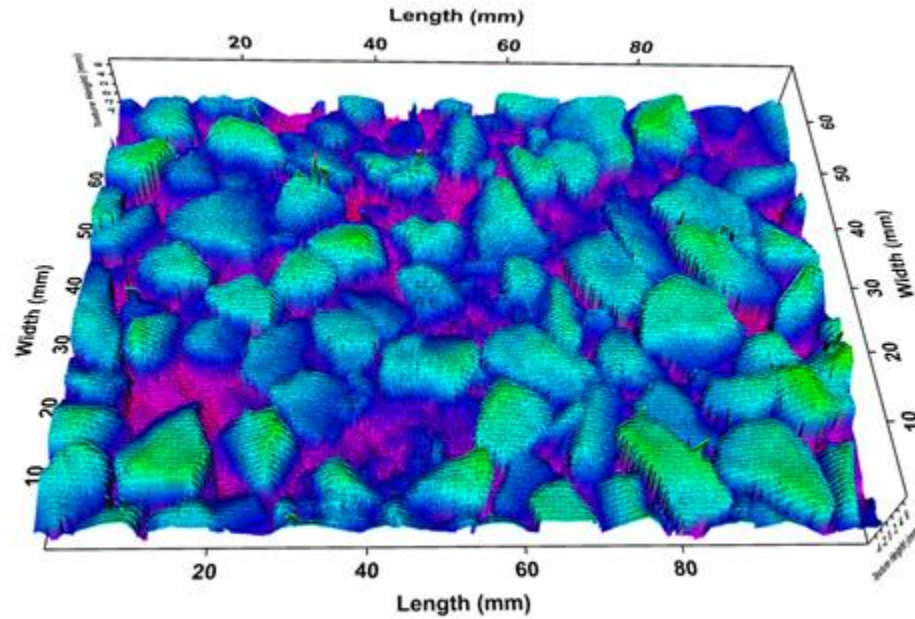
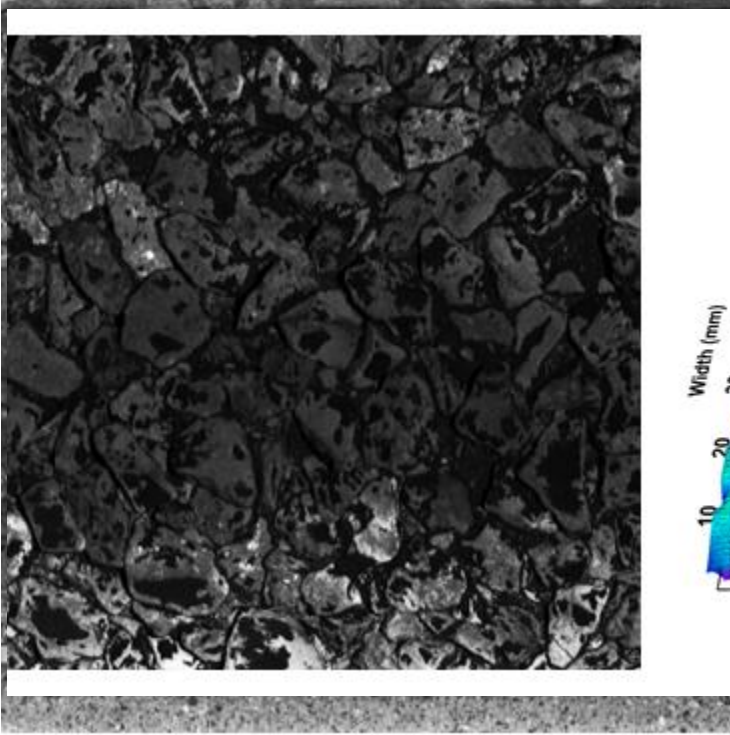
ICART Data Collection



8.5" CRCP - Turf Drag Finish	Smooth Finish with General Grooving	Turf Drag Finish w/ Diamond Grooving	Smooth Finish with Diamond Grinding	Smooth Finish	Turf Drag Finish	Turf Drag Finish
11.5" 12.5 mm SMA	Artificial Rutting	12.5 mm SMA	9.5 mm Dense Graded HMA	Mix surfaced with 30% Colloidal Smoke & 70% Silica	Single Chip Seal	1.5" min Dense Graded HMA
8.5" JPCP - Turf Drag Finish	Artificial Faulting	Longitudinal Tining	Transverse Tining	Turf Drag Finish	Turf Drag Finish	Turf Drag Finish



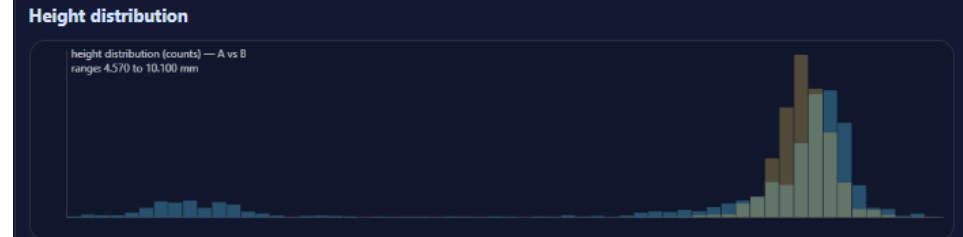
Included a Wide Range of Surfaces



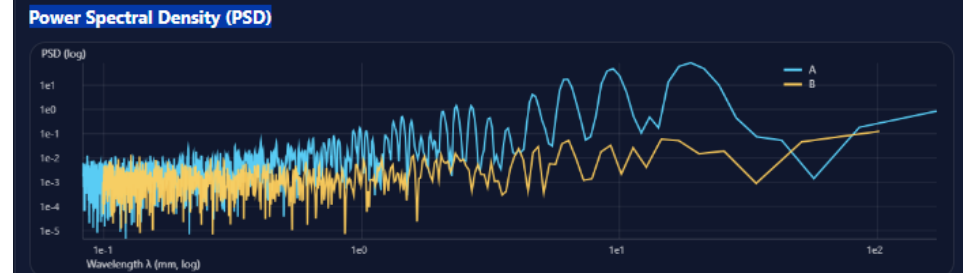
Smart Wave is a Comprehensive Platform

The screenshot displays the Smart Wave software interface with the following components:

- Target grid:** Original (may be slow)
- Aggregation:** Mean (bin average)
- Swap X/Y:** No
- ASPECT:** CSVs may contain a header block (key=value) followed by x, (x), y, (y), z, (z) records. Large files are opened using streaming (no full-file load). The import will bin/average to the selected target grid.
- Import progress:** Import complete. Output grids: 816x1024 - dx=0.09942mm - dy=0.12656mm
- Buttons:** Load bundled demo JSON, Export metrics JSON, Export current tab PNGs, Export all PNGs
- Export notes:** Exports each scenario as a PNG. Tables are rendered to an efficient canvas first, then exported as PNG. File names include the tab and element id (e.g., viz_01.png, compare_3DComp.png). Expected scheme: grid_x is a 2D array (height x width) of texture heights (mm) with grid_dx_mm and grid_dy_mm. This demo also supports optional paired_functional_measurements (Std Number, Peak Slice).
- 2) Analysis settings:**
 - Wavelet family:** Daubechies 3 (db3)
 - Levels (2D DWT):** 4
 - Denoise:** None
 - Threshold scale:** Universal (sigma*sqrt(2 ln 2))
 - Buttons:** Run analysis, Reset
 - Status:** Analysis complete. Wavelet=db3, levels=4, denoise=None, thr=0.000000
 - Notes:** For multi-level analysis, SmartWave(TM) pads to the next power-of-two size (reflect padding) to avoid edge artifacts. Band "leakage" is reported using a conservative mapping: lambda = 2 * (level+1) * dx (or dy).
- Cross-section settings:**
 - Direction:** Along X (row)
 - Index:** 0
 - Window avg (profiles):** 1
 - Zoom start (mm):** 0
 - Zoom length (mm):** 80
 - Update cross-section:**
 - Ra:** 0.1104
 - Rq (RMS):** 0.1347
 - Rz:** 0.7817
 - Rpk:** 0.633
 - Rku:** 2.722
- Profile cross-section:** A line graph showing height (mm) scaled by 1000 vs distance (mm) from 0.0 to 80.0.
- Height distribution:** A histogram showing height distribution (counts) vs height (mm) scaled by 1000.
- 3D surface viewer (color + contrast shading):** Interactive 3D visualization of the texture map using WebGL. Uses height-based color with Lambert shading from a directional light (similar to contrast-shaded 3D models). Recommended for large grids: use downsample 8~32x for responsive viewing.
- Viewer controls:**
 - Downsample:** 4x
 - Vertical exaggeration:** 1
 - Contrast:** 1.8
 - Colormap:** Heat
 - Light azimuth (deg):** 315
 - Light elevation (deg):** 45
 - Buttons:** Build / Update 3D, Reset view, Export 3D PNG
 - Mouse drag to rotate - Wheel zoom - Shift drag pan**
 - Status:** Mesh ready (756x204 points)
- 3D display:** A 3D perspective view of the surface texture, color-coded by height.

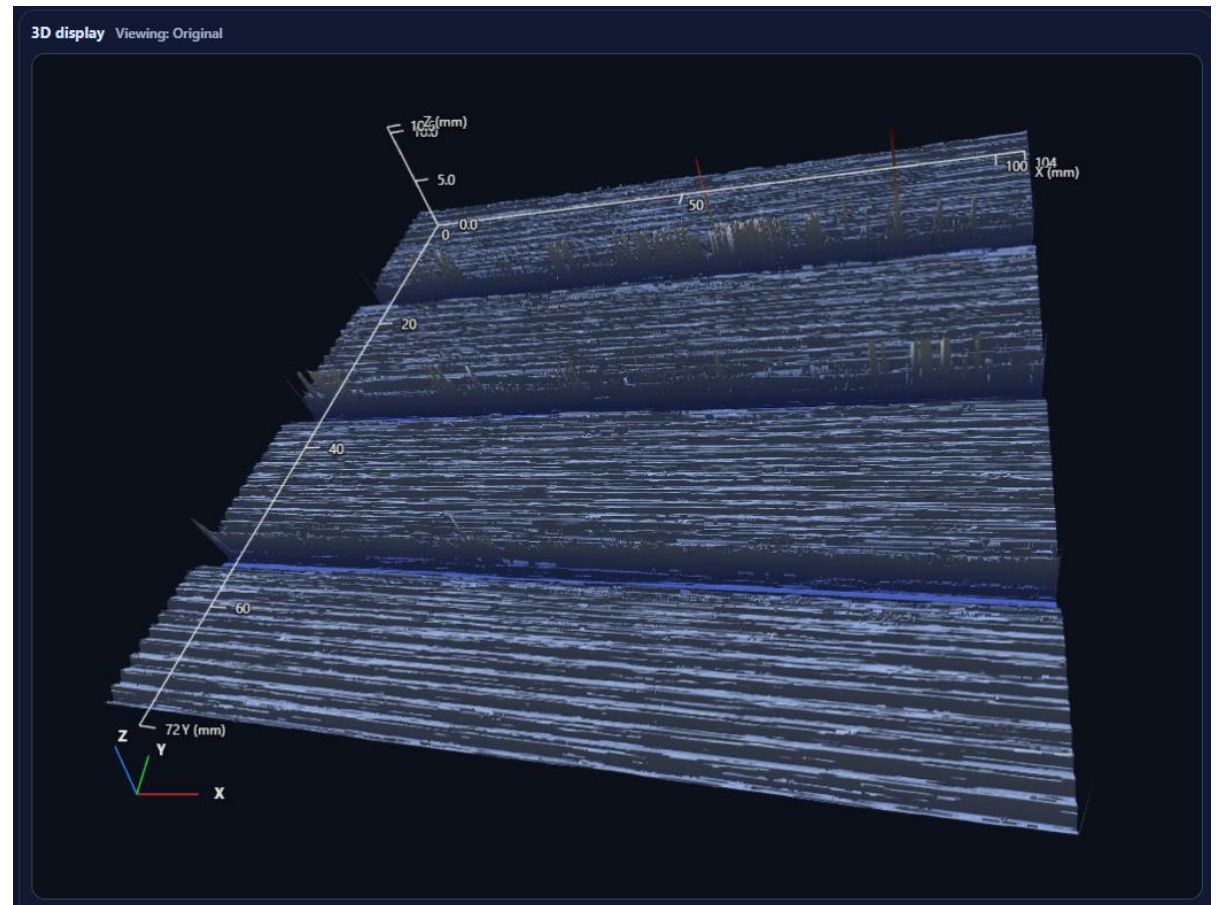
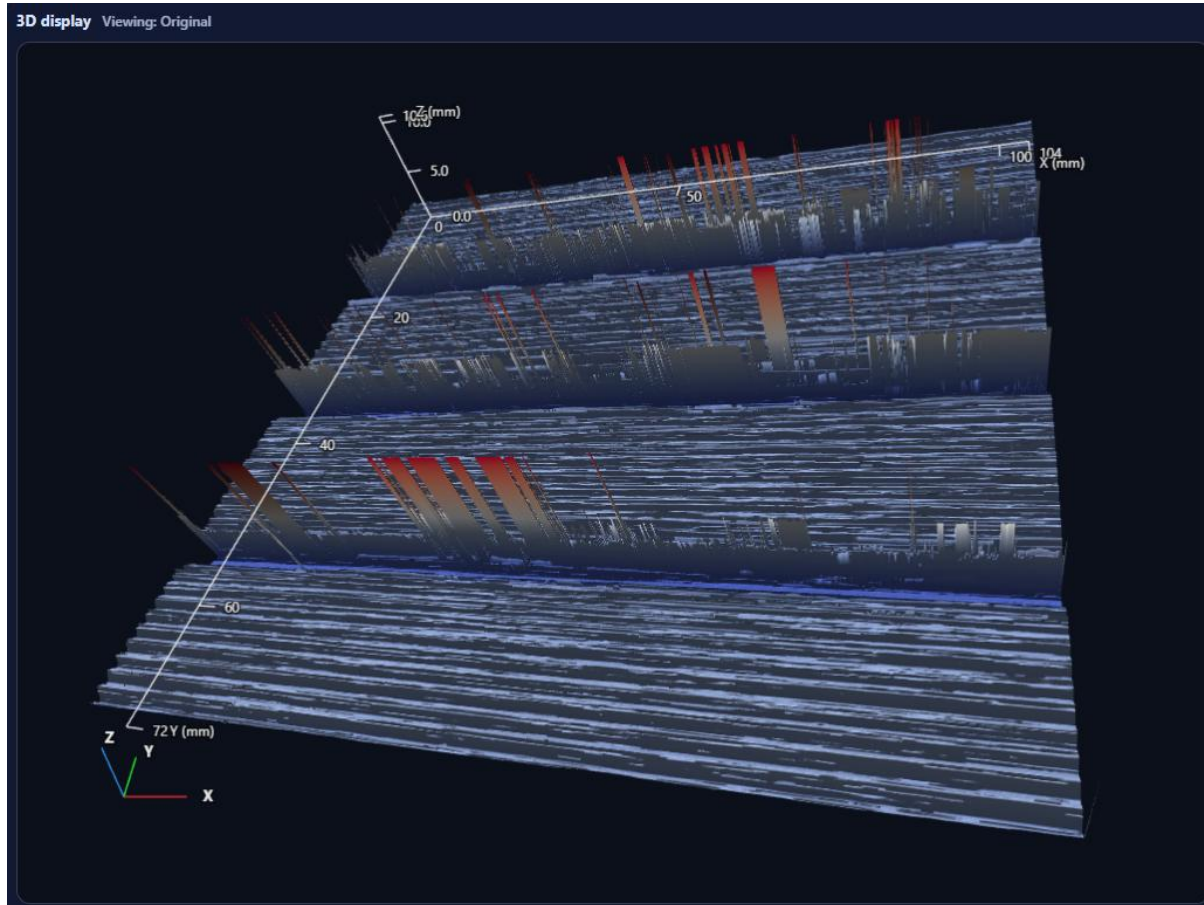


Bars are normalized within each statistic using $|value|$ so A and B can be compared side-by-side even though the units differ by metric. Raw values are printed above the bars.

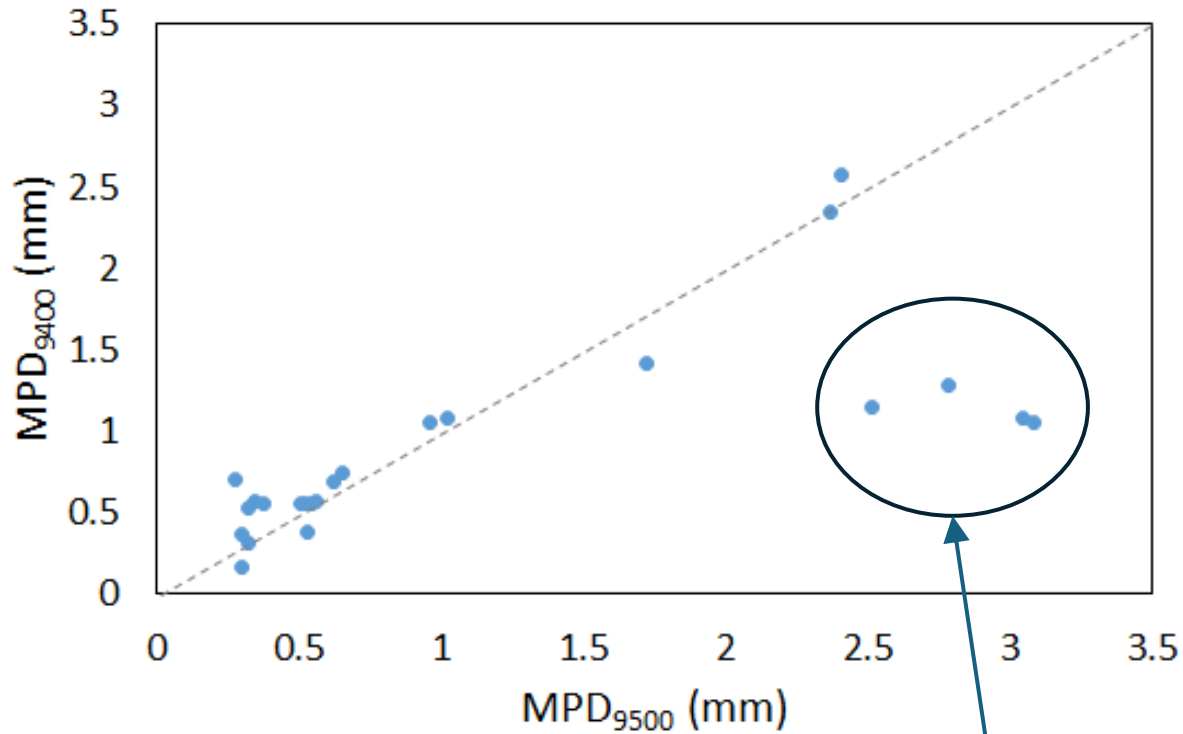


PSD is computed on the detrended profile (linear regression removed) using a Hann window and an FFT-based periodogram. X-axis is wavelength (mm, log), Y-axis is PSD (log; units are $mm^2 \cdot mm^{-1}$ for the periodogram scaling).

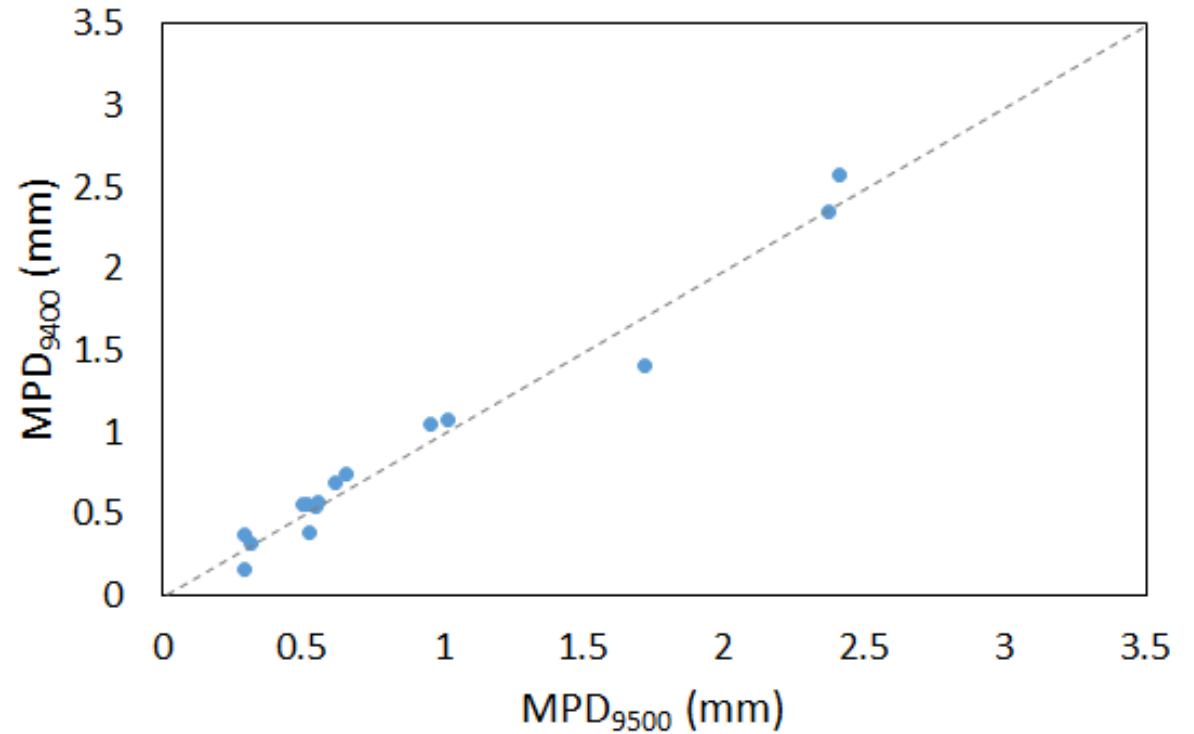
Filtering Varies Based on Laser Type and Surface Texture



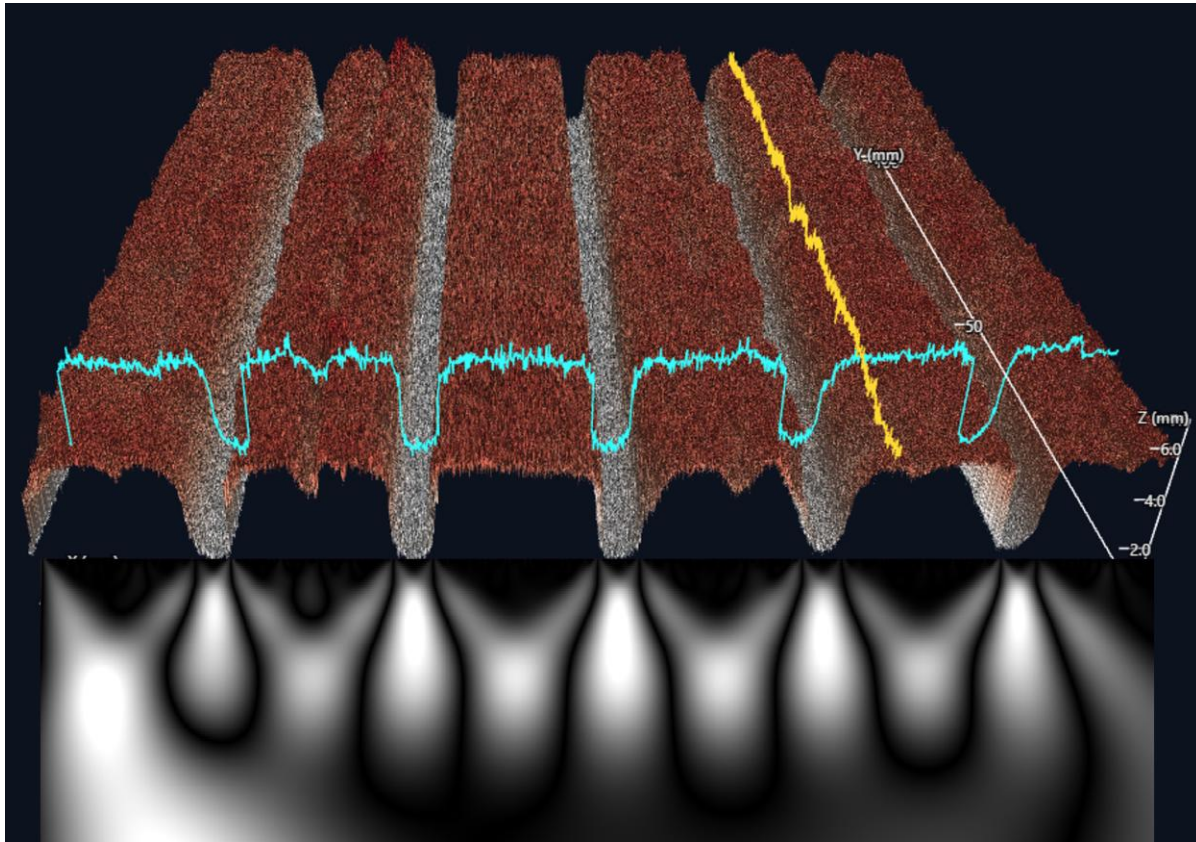
MPD is Highly Sensitive to Different Laser Measurements



Transverse Grooving



Wavelets Decompose Macro and Micro Texture



SmartWave(TM) — 2D Wavelet Texture Analysis

Alpha demo (offline HTML) Haar / db2 / db3 / sym2 / sym3 / coif1

1) Load data

JSON input: Choose File 2026-04-09...-11.P1

CSV import: Auto-detect (AE9500)

Target grid: Original (may be slow)

Aggregation: Mean (bin average)

Swap XY: No

AE9500 CDO may contain a header block (key=value) followed by x (mm), y (mm), z (mm) records. Large files are parsed using streaming (no full-file load). The import will bin/average to the selected target grid.

Import progress: Import complete. Output grid=216x1024 dx=0.00942mm dy=0.12456mm

Load bundled demo JSON | Export metrics JSON

Export current tab PNGs | Export all PNGs

Exports each <canvas> as a PNG. Tables are rendered to an offscreen canvas first, then exported as PNG. File names include the tab and element id (e.g., viz_01.png, compare_binComp.png).

Expected schema: grid_x is a 2D array (height x width) of texture heights (mm), with grid_dx, dy, and grid_dz, mm. This demo also supports optional $dx/dy/dz$ measurements (Skid Number, Peak Skid).

2) Analysis settings

Wavelet family: Daubechies 3 (db3)

Levels (2D DWT): 4

Denoise: None

Threshold scale: Universal ($\sigma \sqrt{2}$ in)

Run analysis | Reset

Status: Analysis complete. Wavelet=db3, levels=4, denoise=none, thr=0.00000.

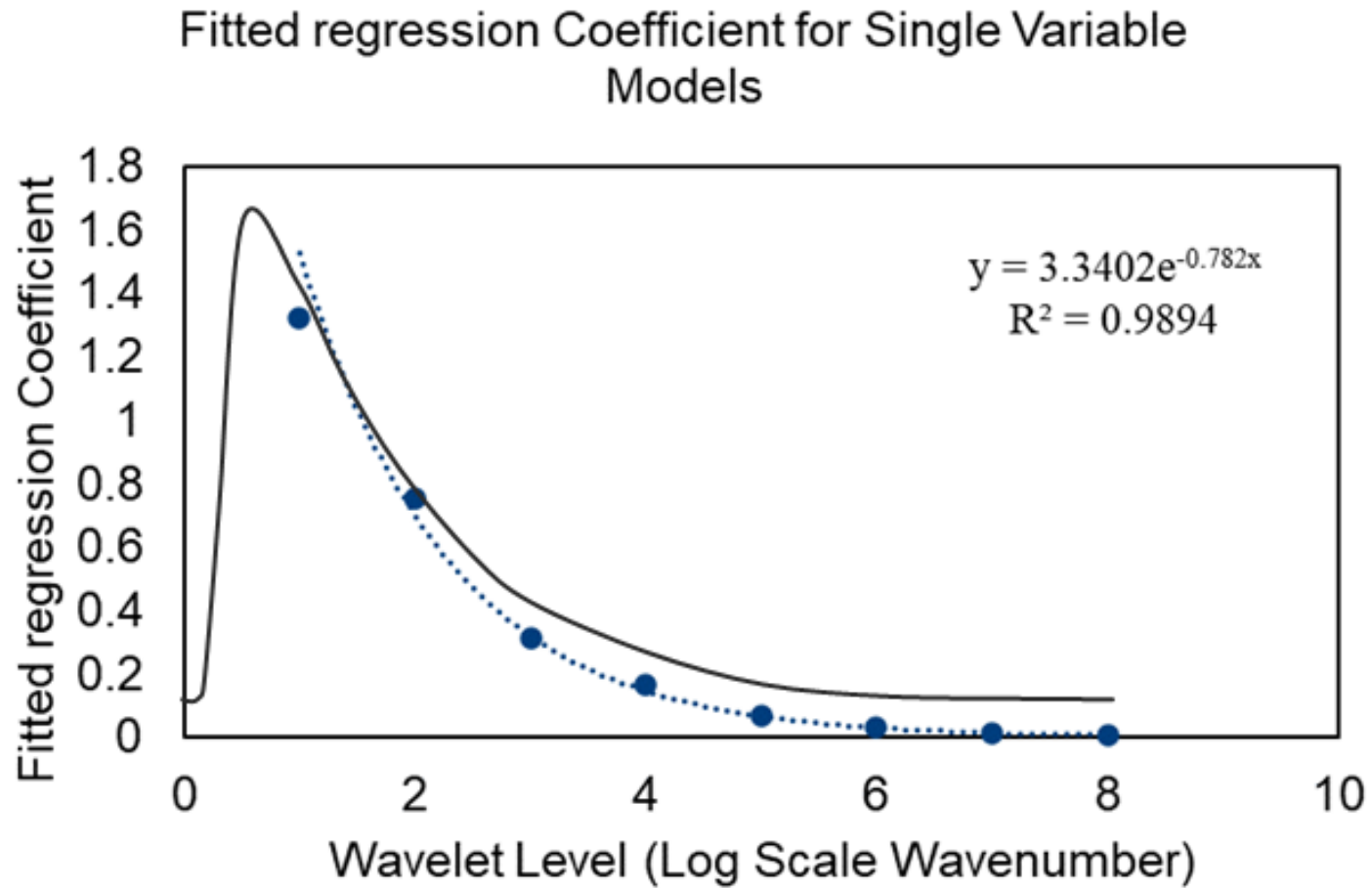
Notes: For multi-level analysis, SmartWave(TM) pads to the next power-of-two size (reflect padding) to avoid edge artifacts. Basic "waveletgrid" is reported using a compressive mapping: $16000 \times 2^{(levels+1)}$ dx (or dy).

Visualization: 3D Viewer | Metrics | Compare to baseline | CWT (localized defects)

Original texture map | Denoised / reconstructed (LL + details)

Detail magnitude (HH at last level)

Wavelets Decomposition Can Estimate the Impact of Texturing



Towards a Global Friction Model

$$F = F[S, V, A, W, T, F_s]$$

F_s is the base friction measurement (used LWST at 40 MPH for now)

S tire slip ratio operator

V nominal vehicle speed impact ratio operator

A tire angle impact

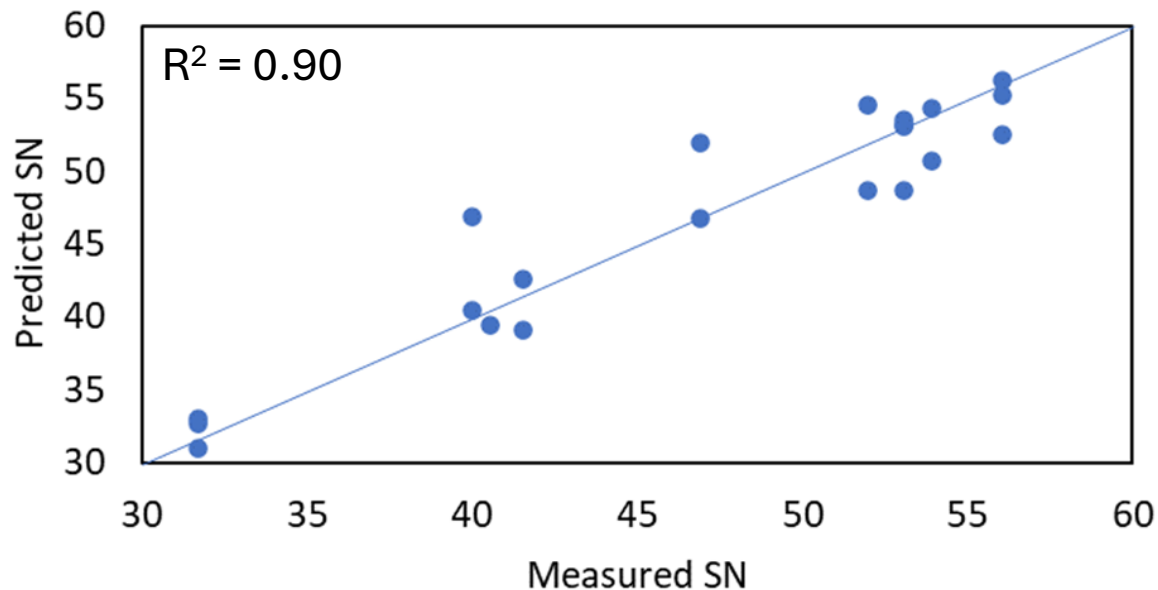
W wet conditions operator

T tire characteristics operator

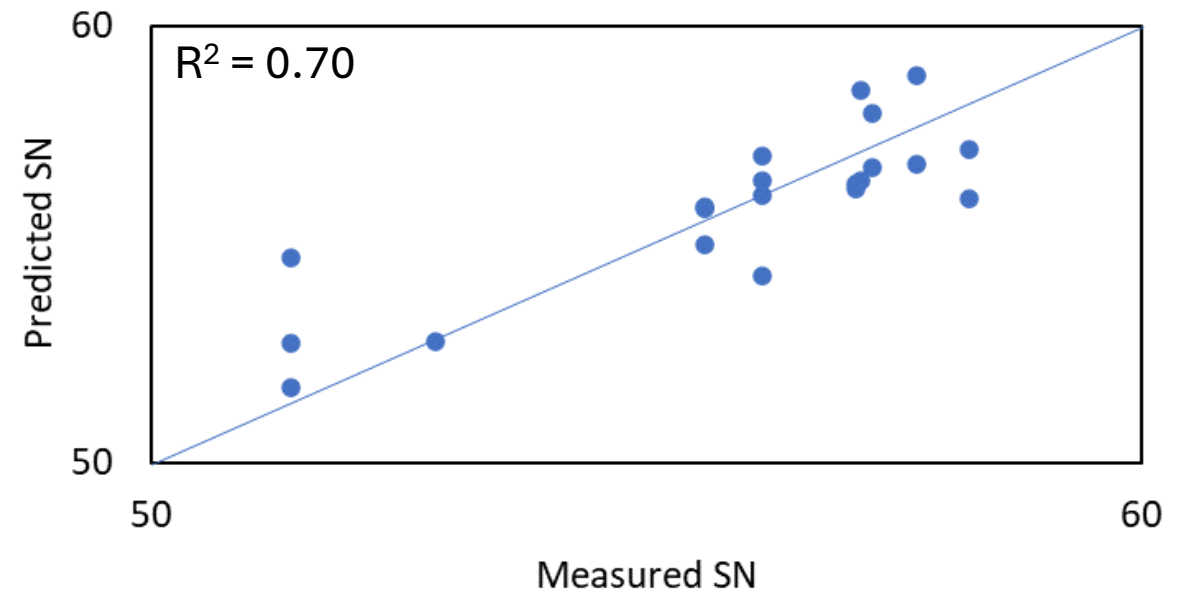
Base Friction Measurements

- Wavelets energy showed a strong to very strong correlations with LWST measurements.

Predicted vs Measured (Average, Smooth, 40 mph)



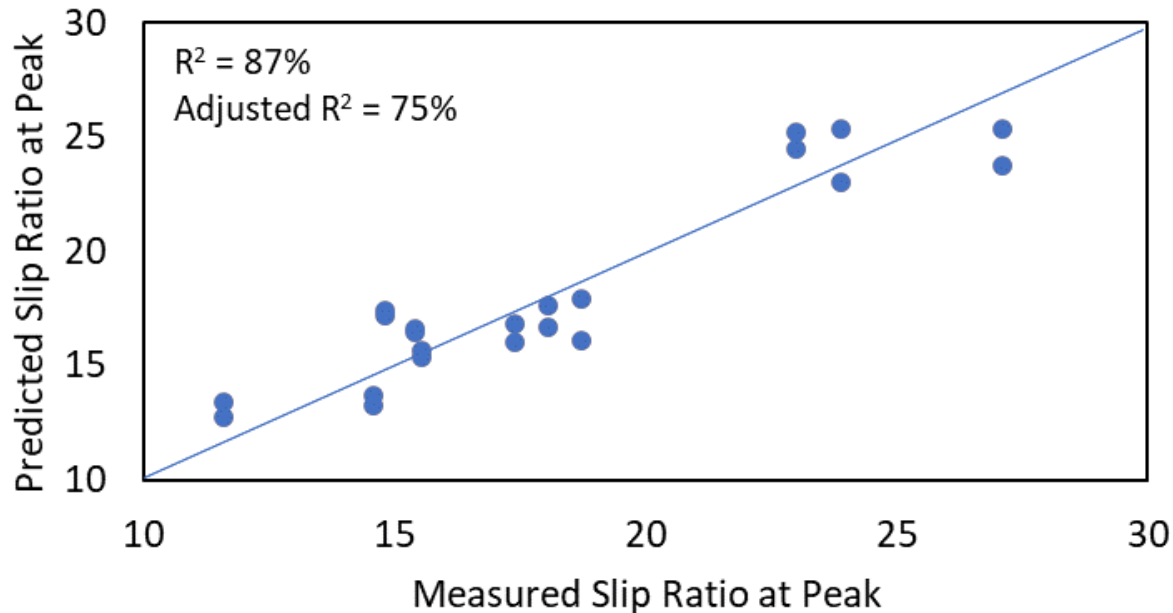
Predicted vs Measured (Average, Ribbed, 40 mph)



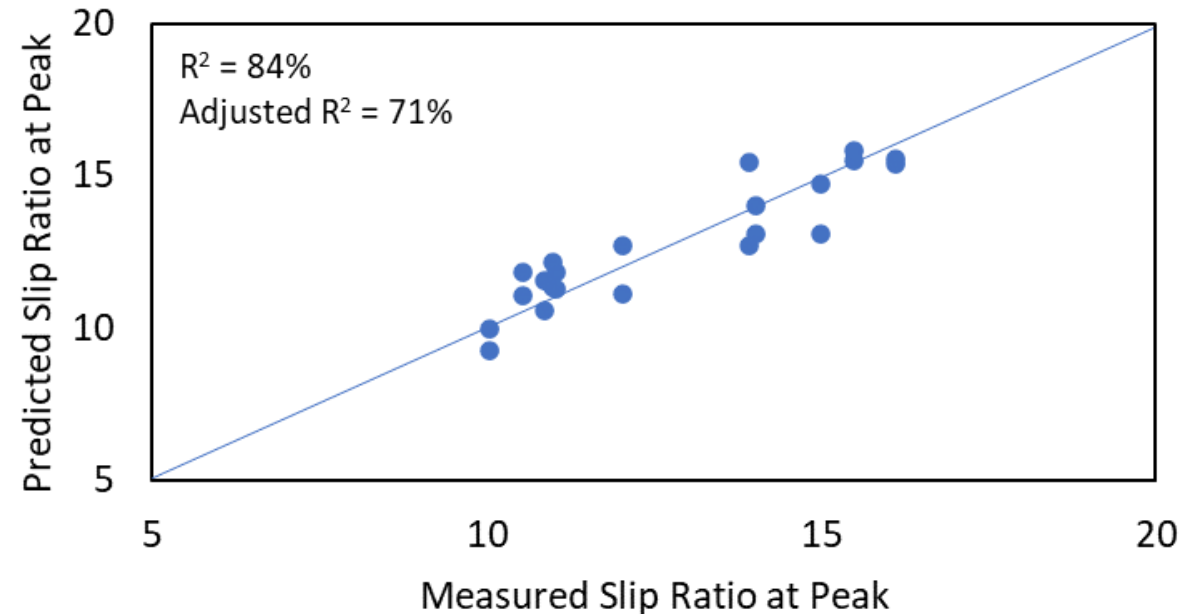
Slip Ratio Impact

- $SR_{Peak} = \sum_{i=1}^n a_{SR,i} E_i$

Predicted vs Measured (Slip Ratio, Ribbed)



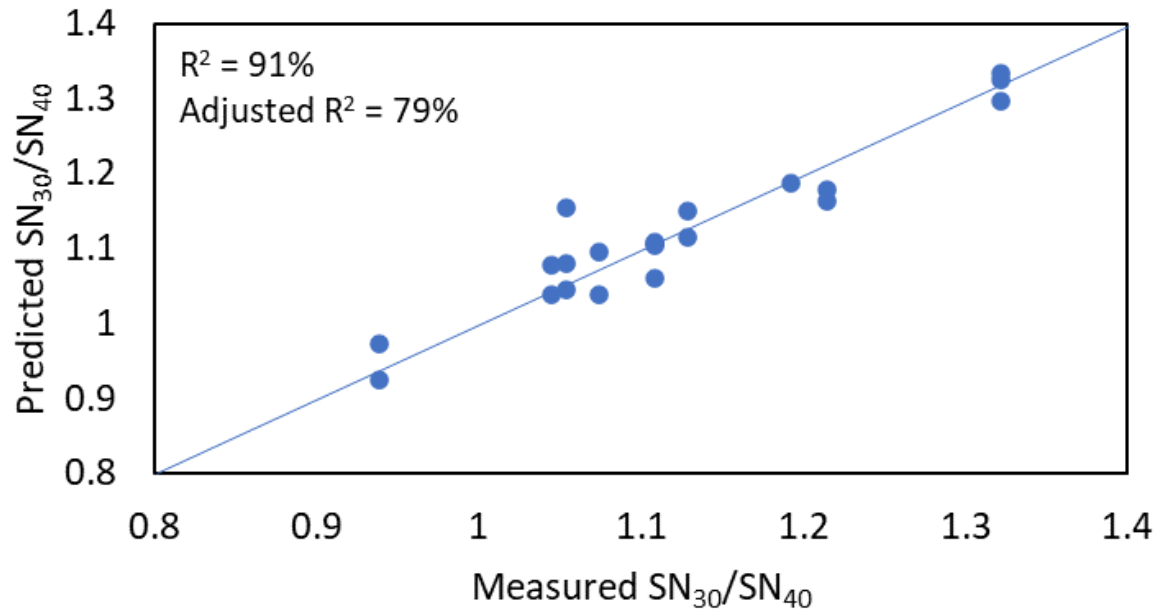
Predicted vs Measured (Slip Ratio, Smooth)



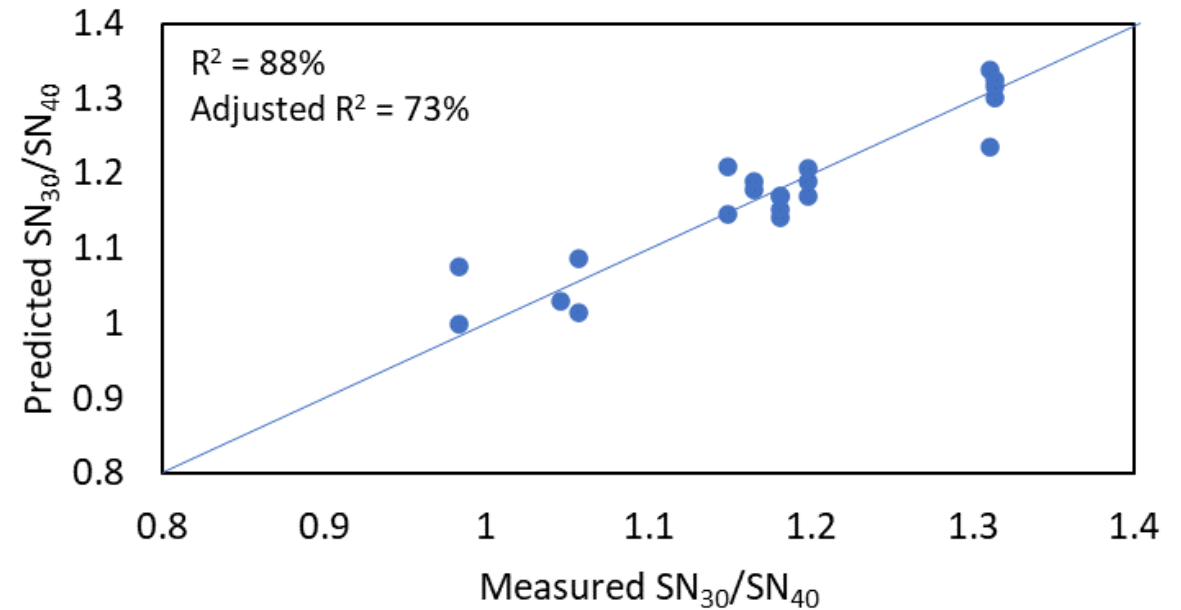
Speed Impact

- $SN_v = SN_v \sum_{i=1}^n a_{v,i} E_i$

Predicted vs Measured (SN_{30}/SN_{40} , Ribbed)



Predicted vs Measured (SN_{30}/SN_{40} , Smooth)



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Concluding Remarks

- Spectral analysis is crucial for filtering, decomposition, and advanced contactless friction models.
- Wavelets analysis allows for more stable and less sensitive analysis to outliers compared to traditional texture parameters.
- Defining ground truth is based on a combination of stable spectral content, measurements from engineered surfaces, and performance in relation to friction predictions.

Engineered Surfaces Provide Stable Ground Truth

Isolines Off

Isoline step (mm)

Isolines are computed in mesh coordinates from the height field (mm) and rendered as 3D line segments that rotate with the surface.

Colormap

Tip: Bent Cool Warm is a diverging colormap optimized for shaded 3D surfaces (keeps mid-tones from washing out).

Light azimuth (deg)

Light elevation (deg)

Axis triad On

Full axes (mm) On

Axes anchor

Y labels

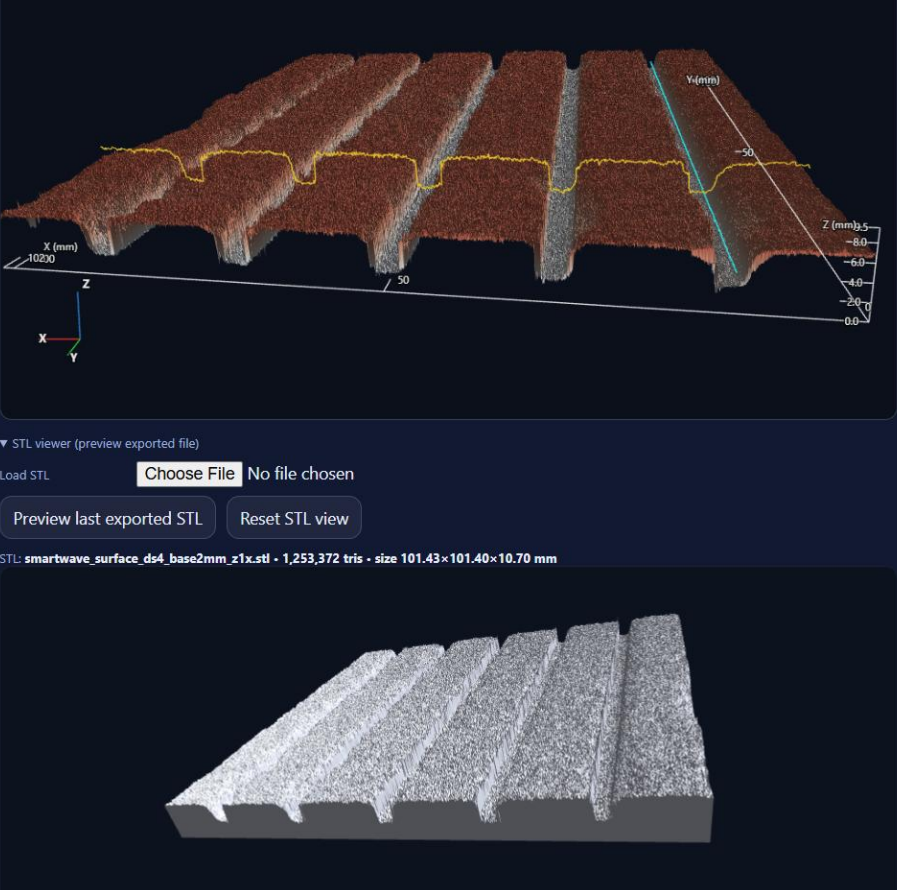
Y label direction controls whether tick values are referenced from the top (map-style) or from the bottom (Cartesian-style) of the scan.

Cross-section line On (single)

Cross-section line uses the current Cross-section settings (Visualization tab: direction + index). Click "Build / Update 3D" after changing the cross-section.

Mouse: drag to rotate • Wheel: zoom • Shift+drag: pan

3D print export (STL)



Future Work

- We are working on defining the tuning parameters for the various filters needed for different measuring systems.
- Need consistent definitions, yet flexible enough, to define the spectral and wavelets analysis parameters.
- Global models and procedures require a wider range of data from different texture and friction devices and collected from different locations.

QUESTIONS?

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