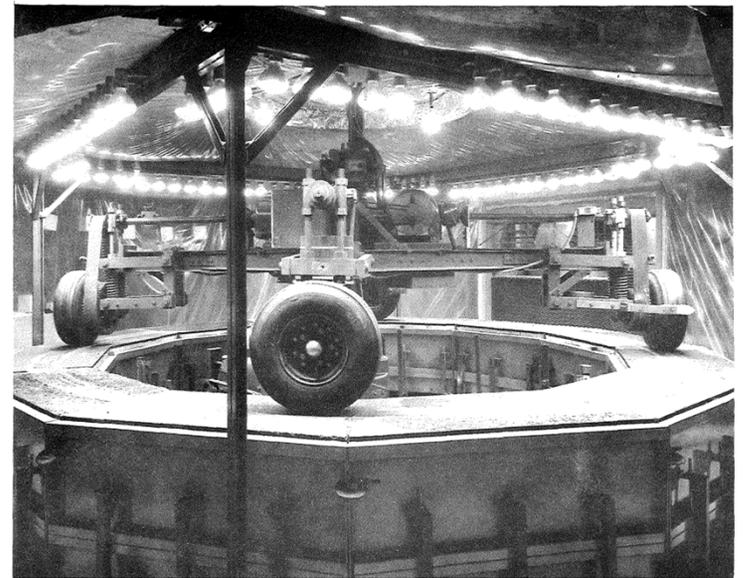


The Michigan Aggregate Wear Index (AWI) and Brief History of Road Friction Evaluations

Christopher R. Byrum, PhD, PE
MDOT Concrete/Materials Engineer
MDOT Aggregate Quality Team

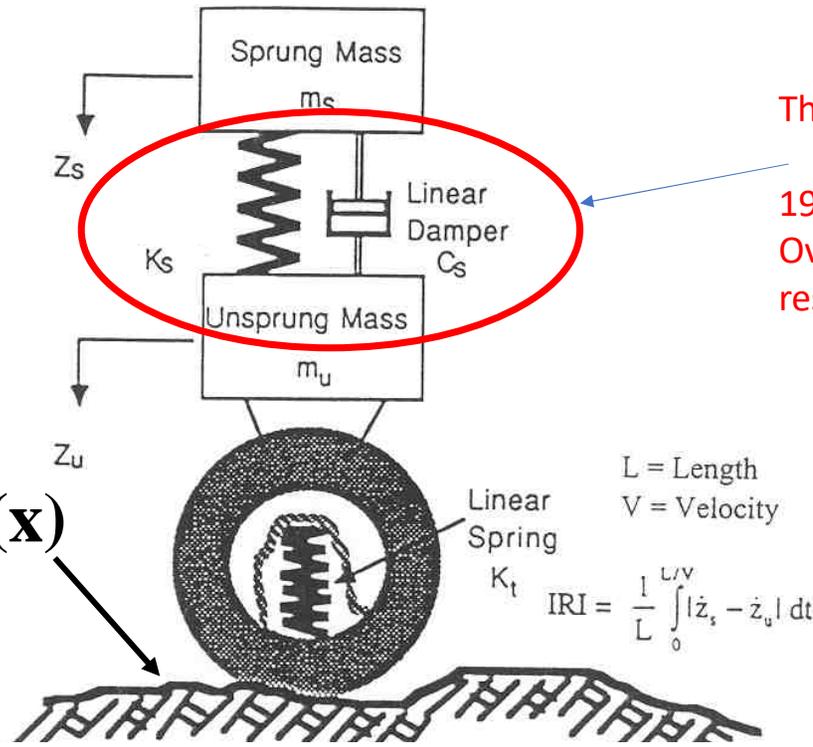
1960s American Oil Research Laboratories, Indiana



LABORATORY TEST MACHINE WITH MICHIGAN DESLICKING PAVEMENTS

Most Common “Ride Quality Index”

IRI



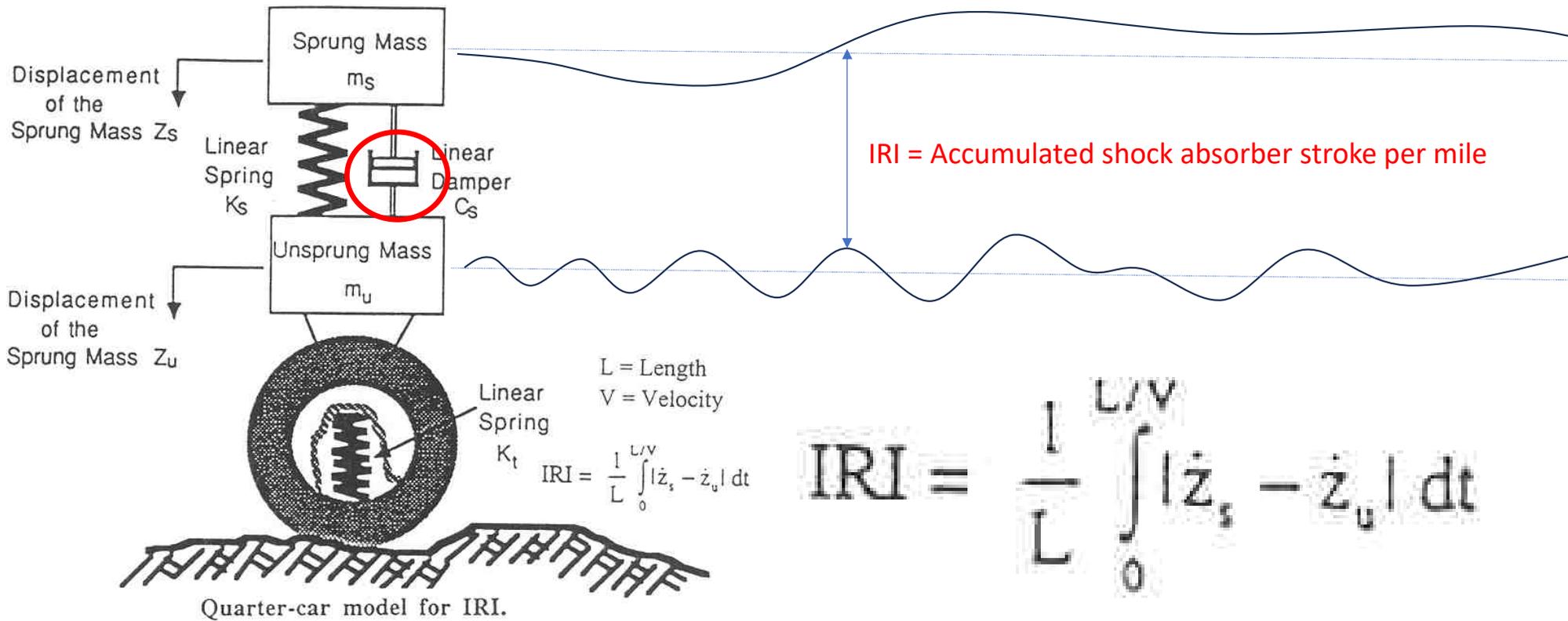
The “Golden Car” Settings:
1980’s Chevy Sedan,
Over-damped to limit
response length

Profile $z = f(x)$

L = Length
V = Velocity

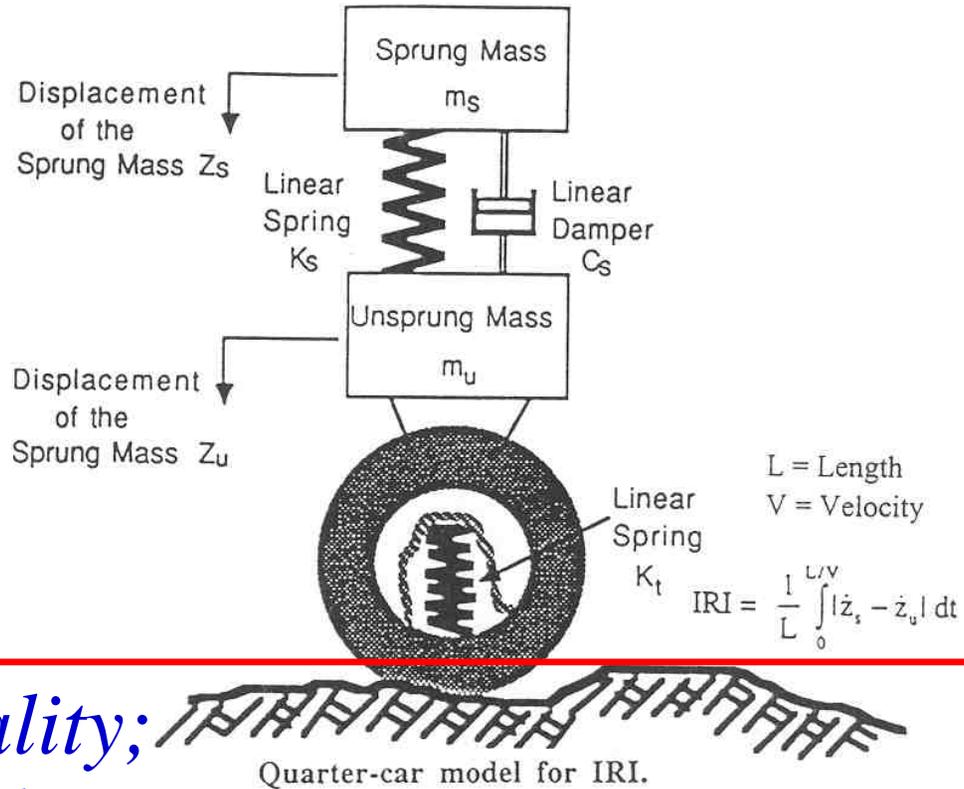
$$IRI = \frac{1}{L} \int_0^{L/V} |\dot{z}_s - \dot{z}_u| dt$$

IRI Units = L/L → Suspension Movement per Mile



$$IRI = \frac{1}{L} \int_0^{L/V} |\dot{z}_s - \dot{z}_u| dt$$

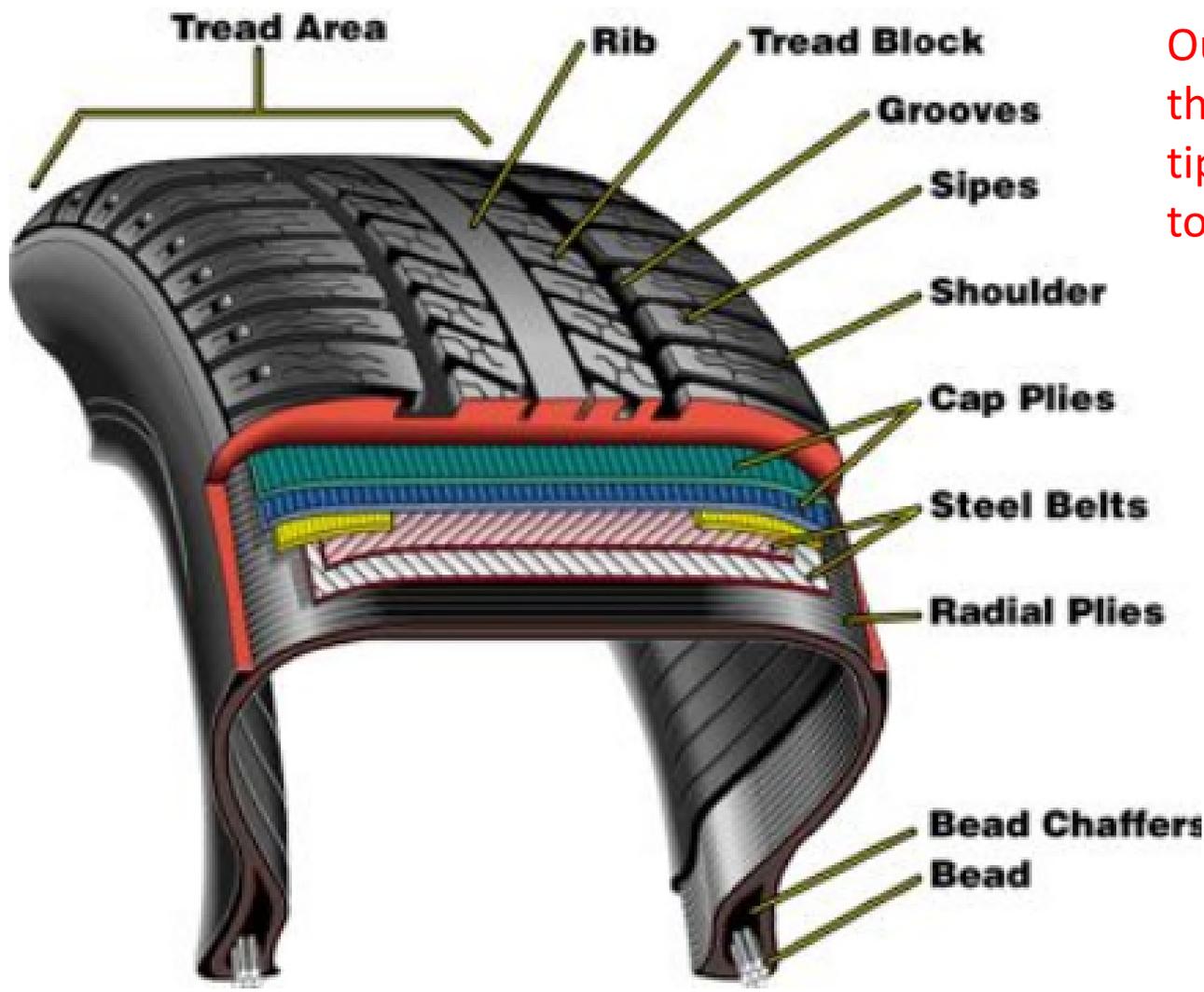
Tire-Pavement Interaction – the fine red line



Response = Ride Quality

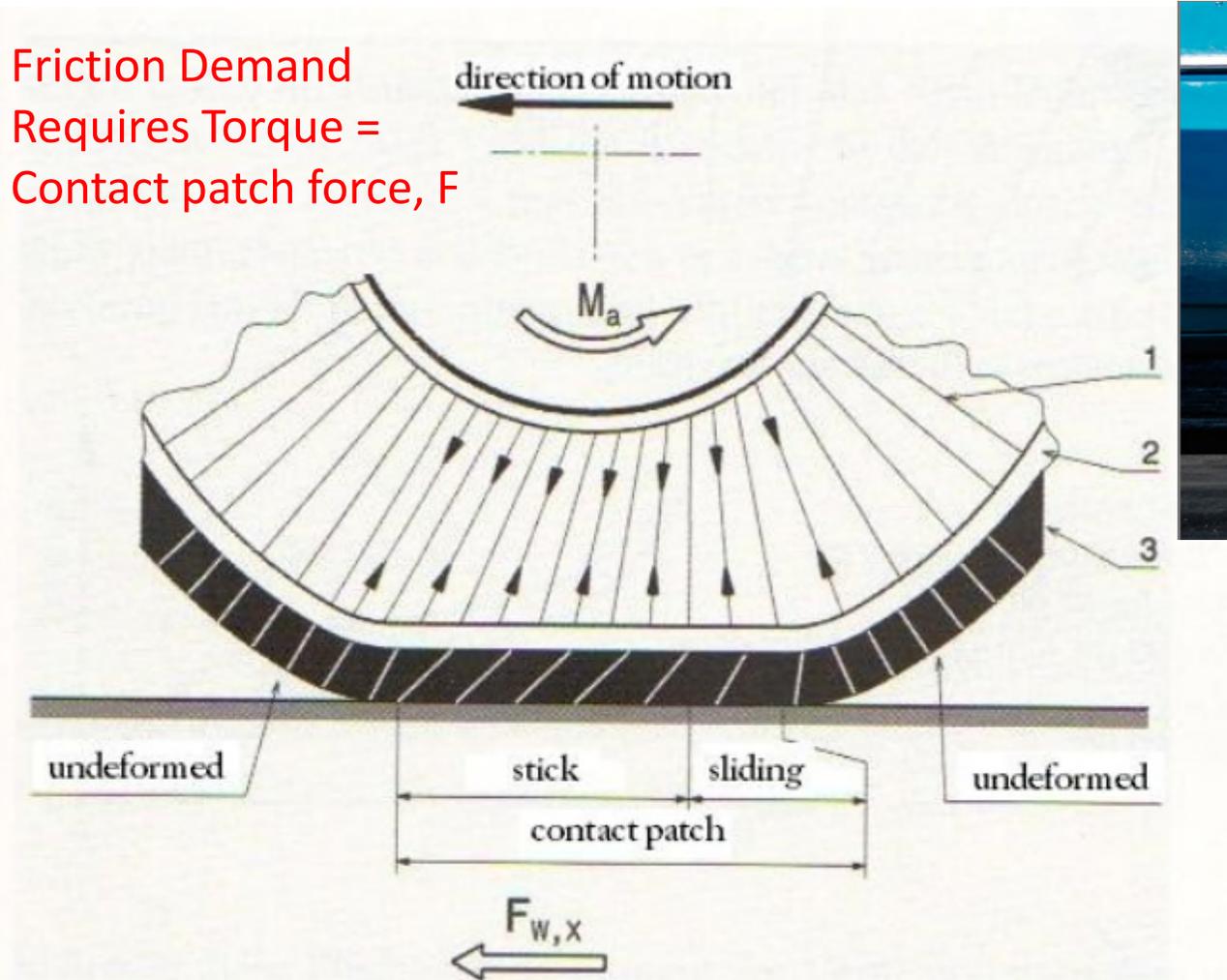
Inputs = Pavement Quality;

*Texture, smoothness, faulting,
curvature, waves, tenting, dips,
humps, cross-slope, rutting,
pumping rate...*



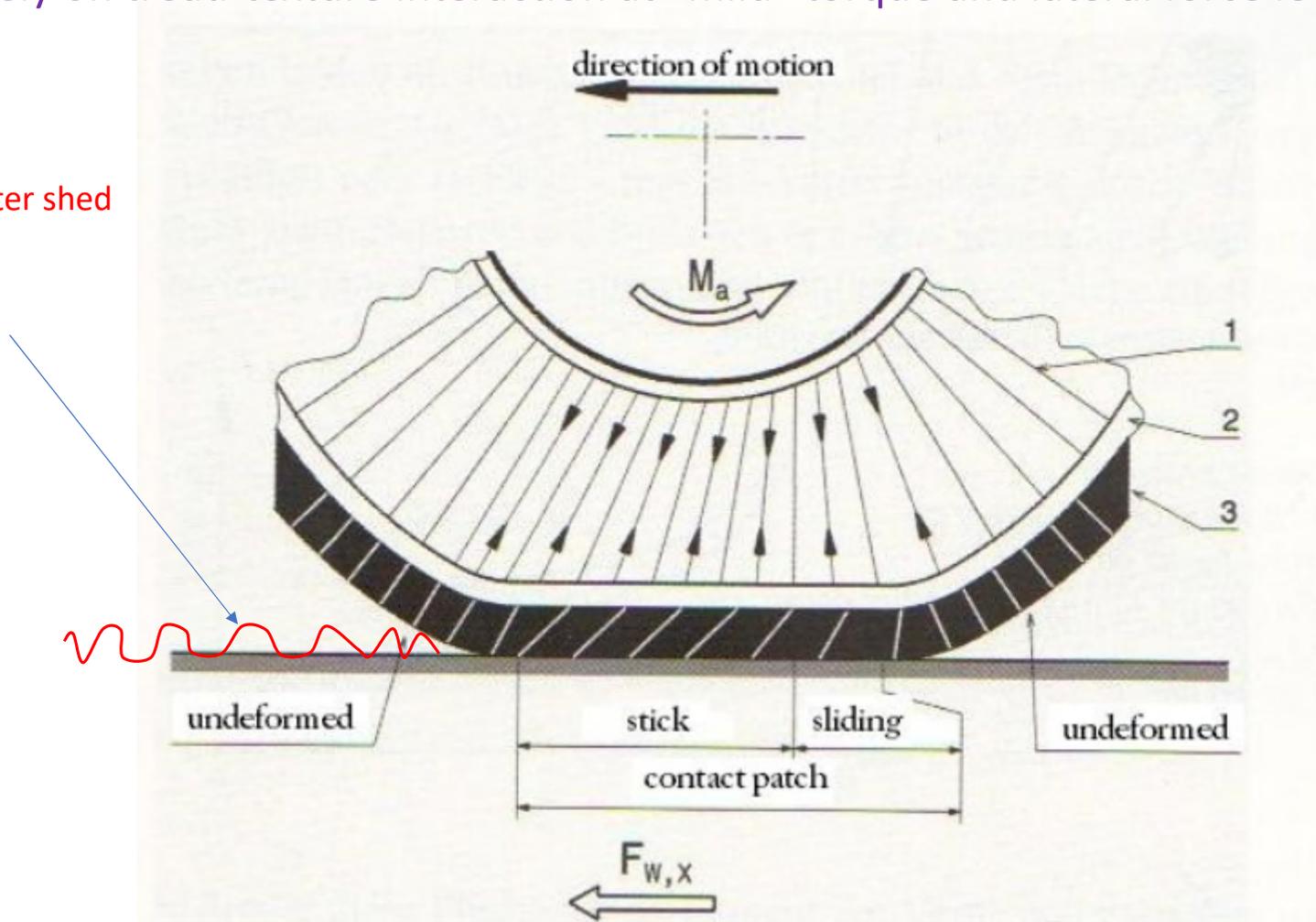
Our tires interact with the exposed aggregate tips and texture grooves to mobilize friction

Friction Demand
Requires Torque =
Contact patch force, F



Highway Drivers rely on tread-texture interaction at “mild” torque and lateral force levels.

Deeper texture can better shed hydroplaning water



Advanced texture scanning laser by MDOT
year 2000

- 0.04 mm elevation sample spacing
- 200 mm sample length



Digital "Sieve Analysis"

I-69 Tex F

9-Jul-03

12:34:09

Dirt

Texture

=

=

20 mm

MEGA

+

+

1 mm

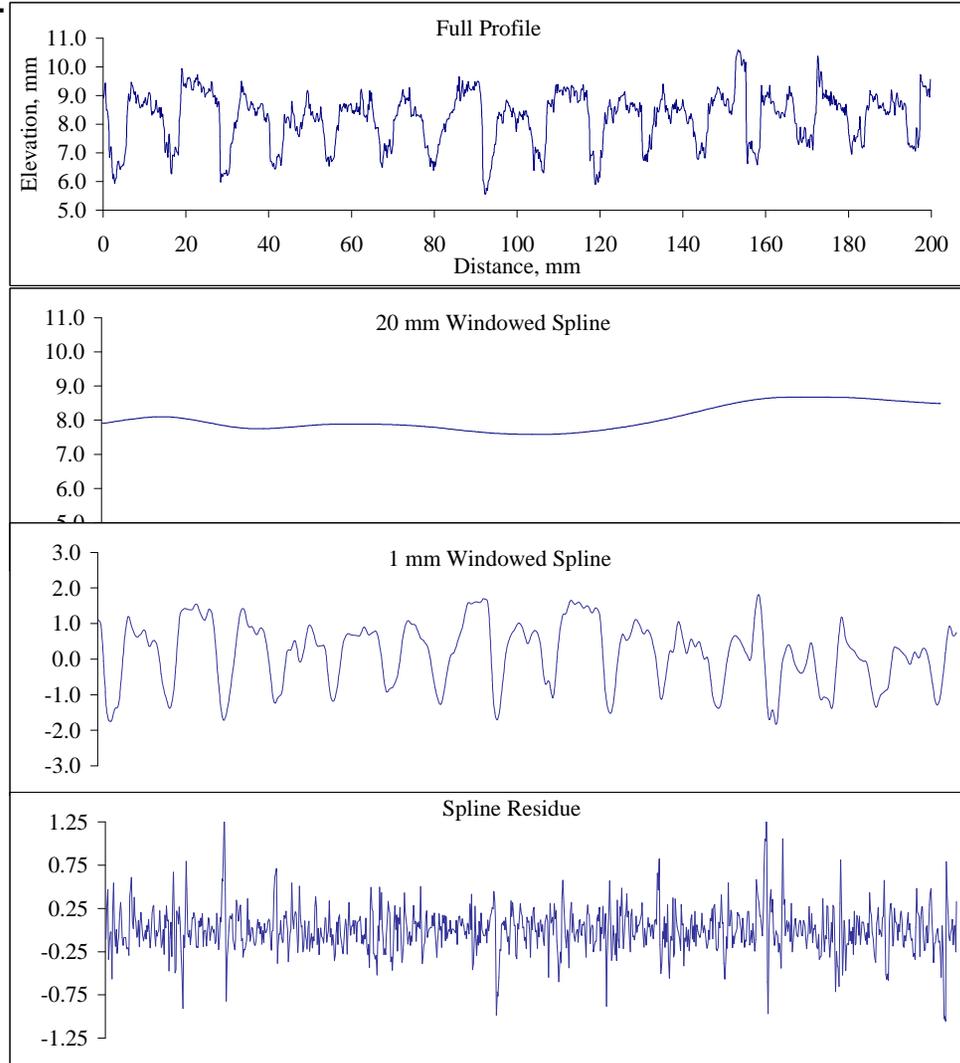
MACRO

+

+

Pan

MICRO



Dynamic Hydroplaning



Digital "Sieve Analysis"

I-69 Tex F

9-Jul-03

12:34:09

Dirt **Texture**

= **=**

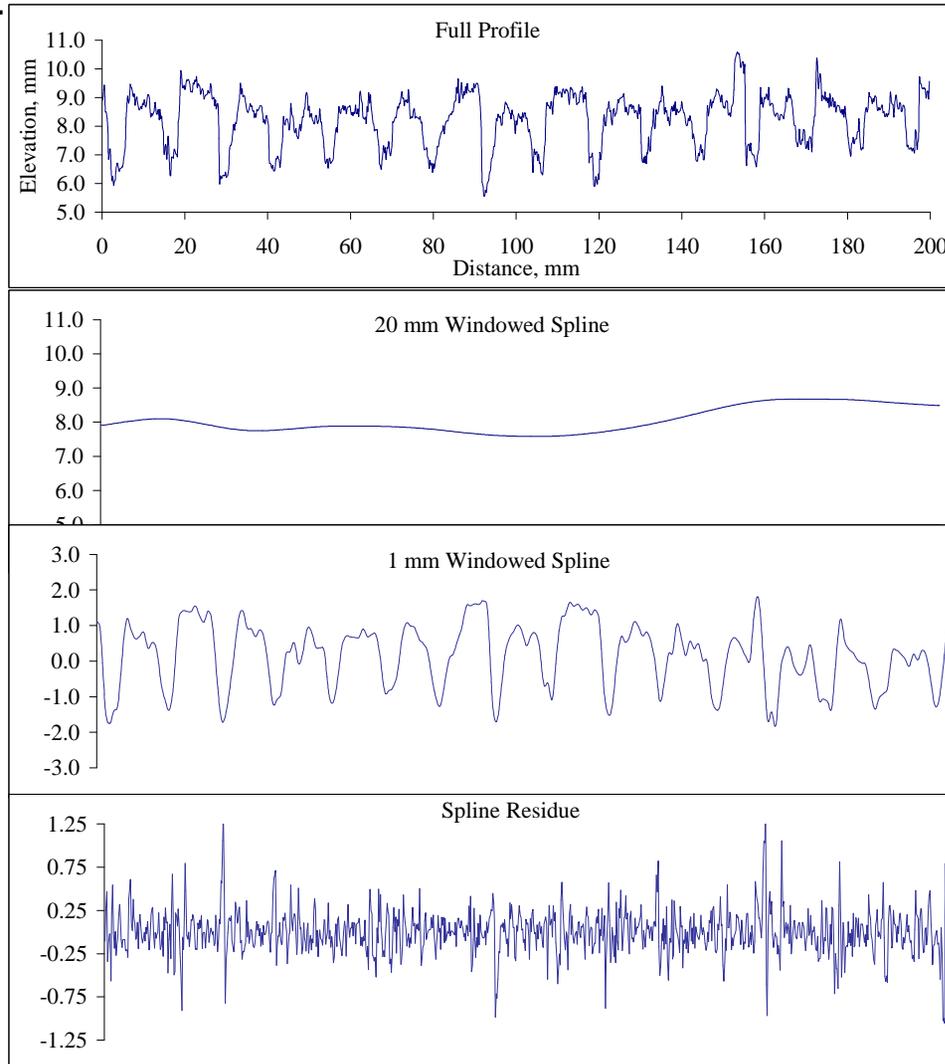
20 mm **MEGA**

+ **+**

1 mm **MACRO**

+ **+**

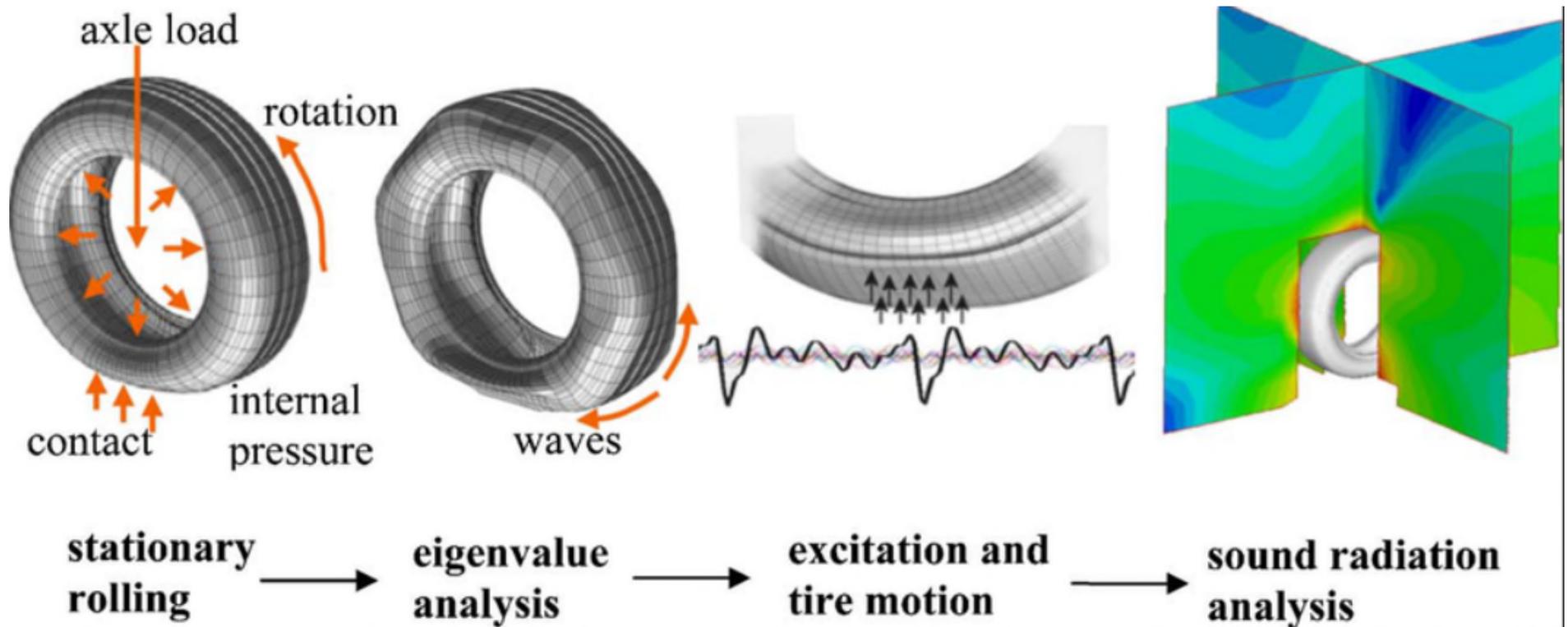
Pan **MICRO**



We don't want any waves here

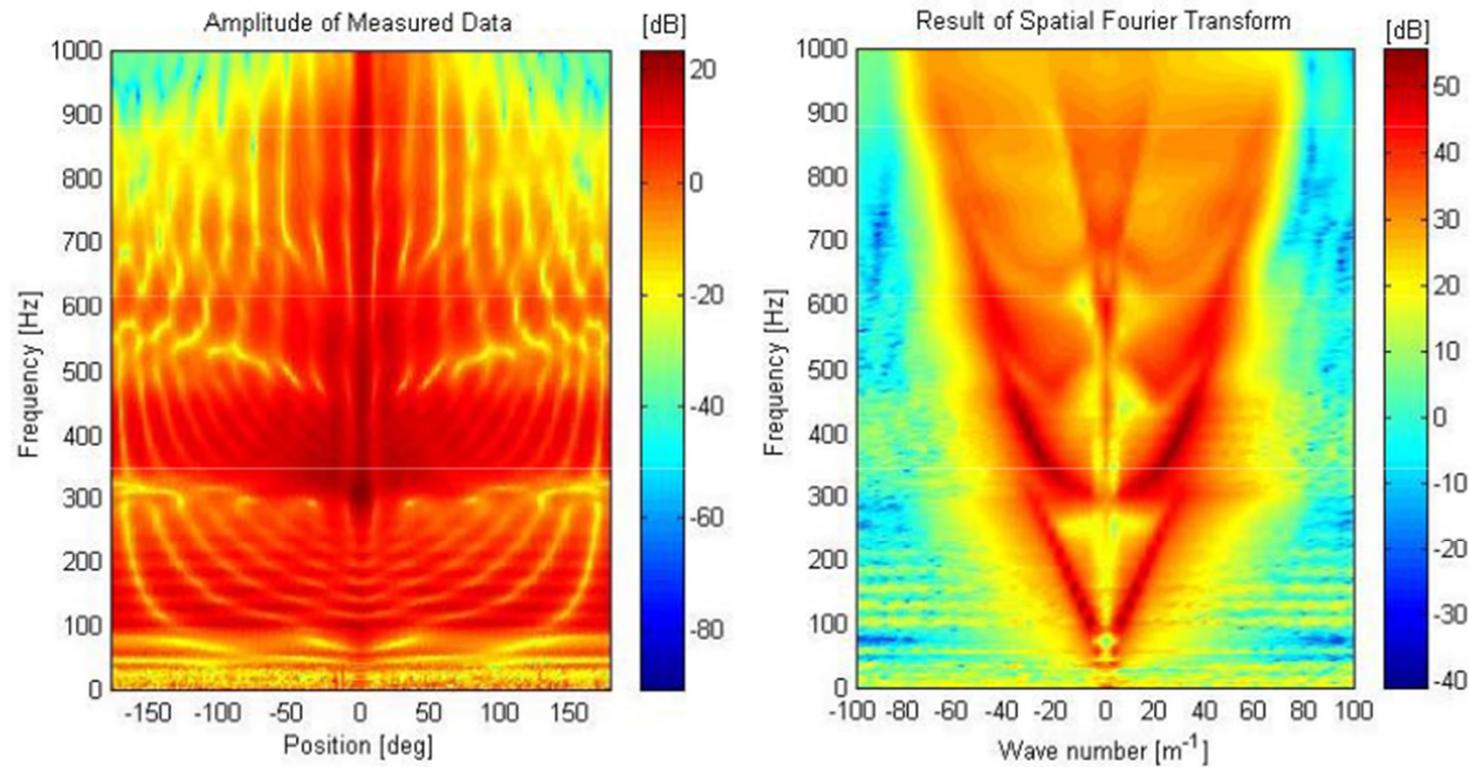
Need proper macro-texture for hydroplaning resistance and to get up between tread blocks

Need proper micro-texture for rubber friction interaction on the macro texture



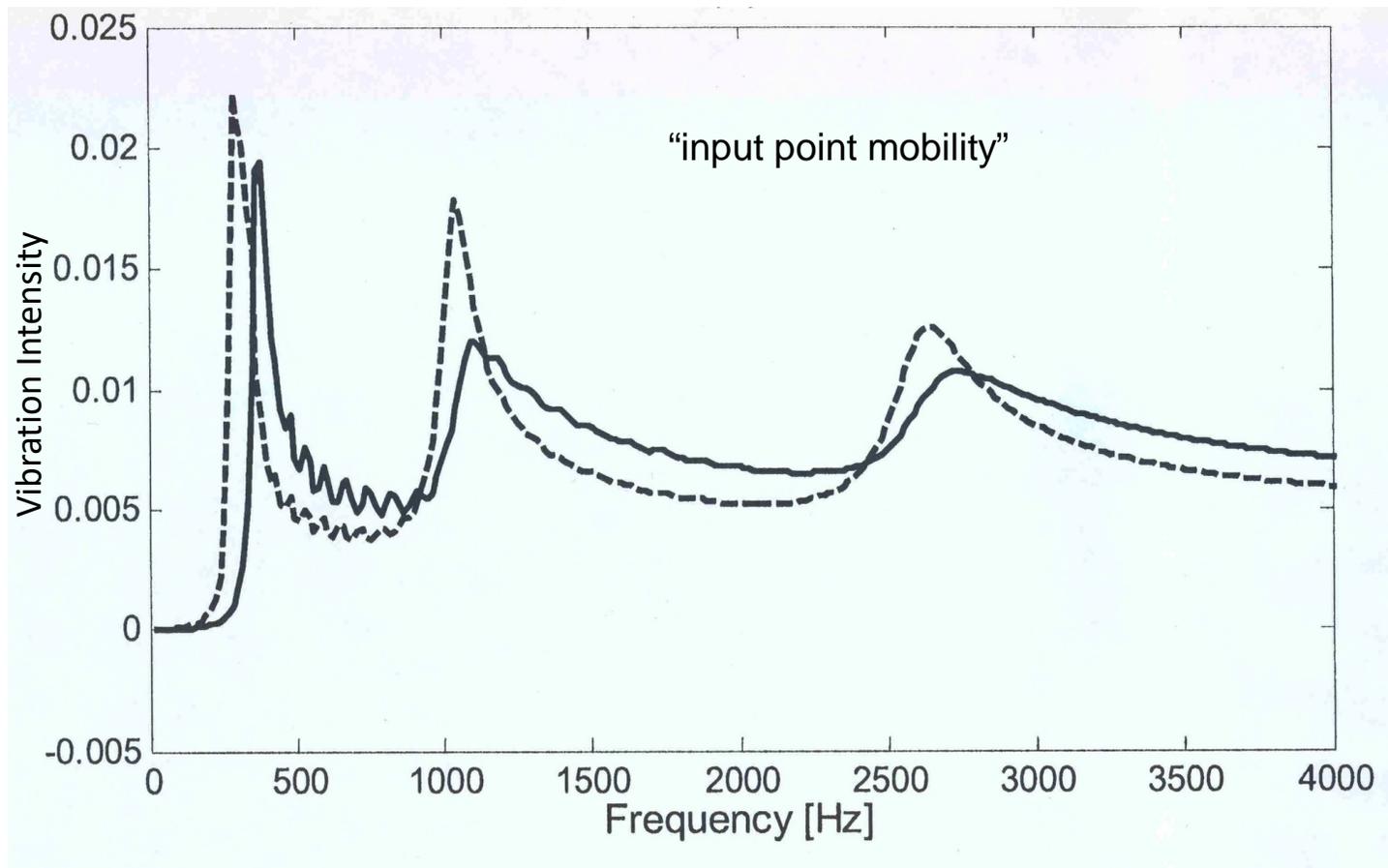
The Tire Engineer

Near-Field Acoustic Holography (NAH) Really Cool Stuff!



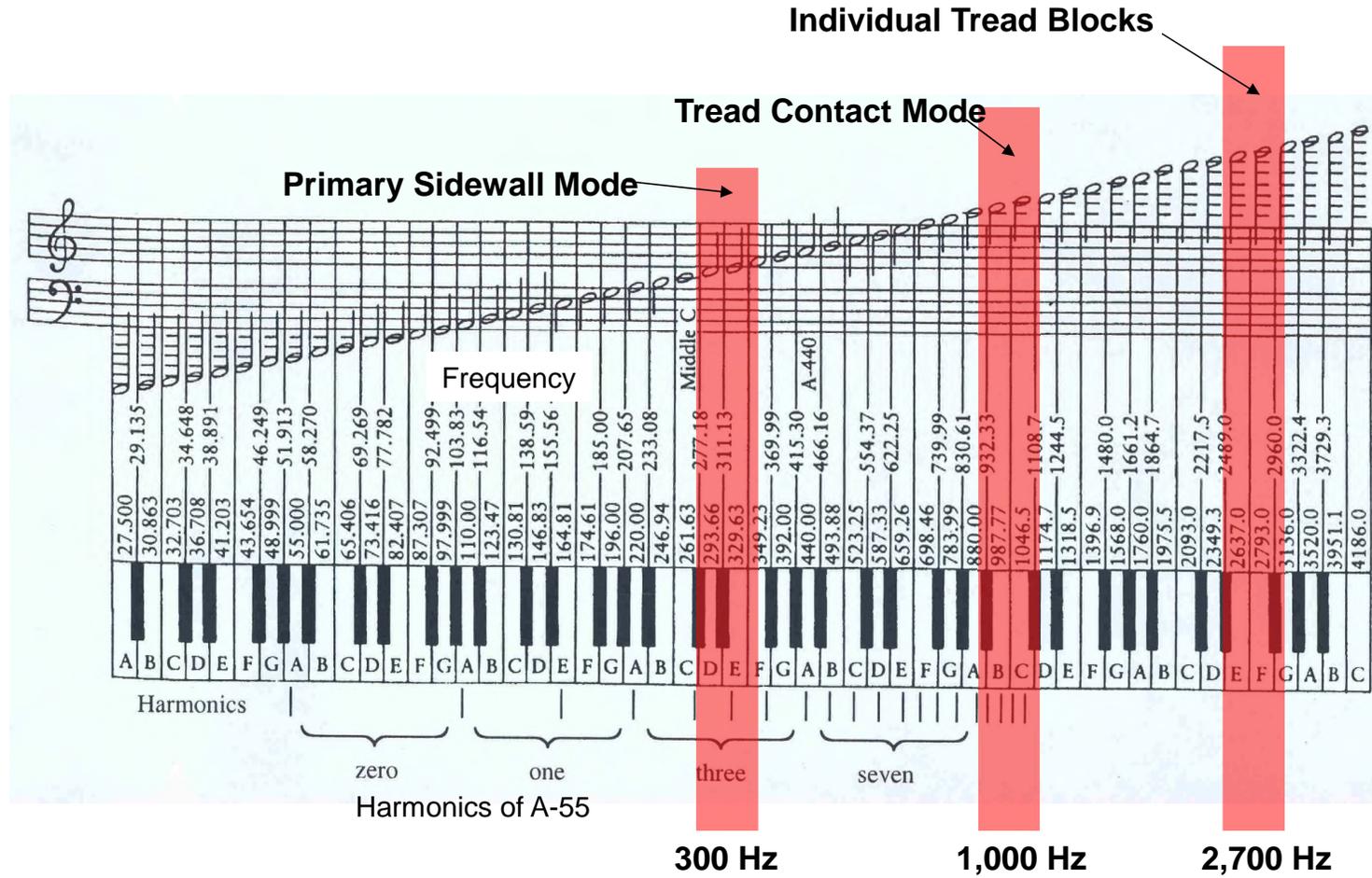
Bolton (Purdue Univ.) plot of data for a Passenger Car Tire

FEM Back-calculated Tire Properties from NAH



Bolton (Purdue Univ.) plot of data for a Passenger Car Tire

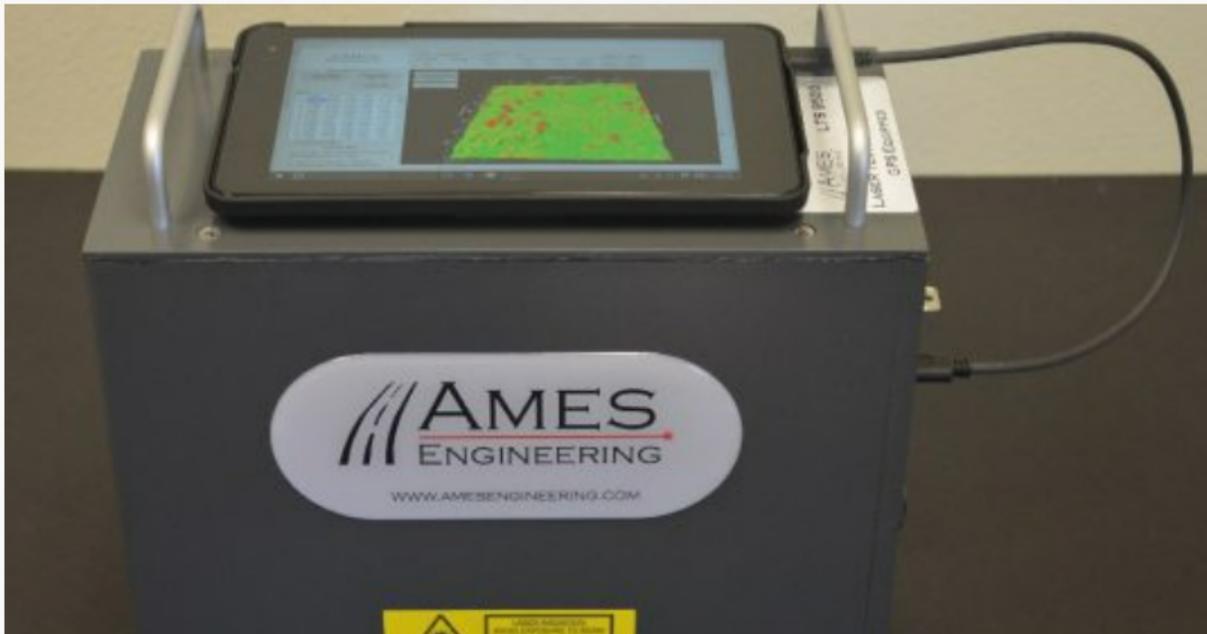
Byrum, 10-18-2006



What do these Tire-Modes sound like???

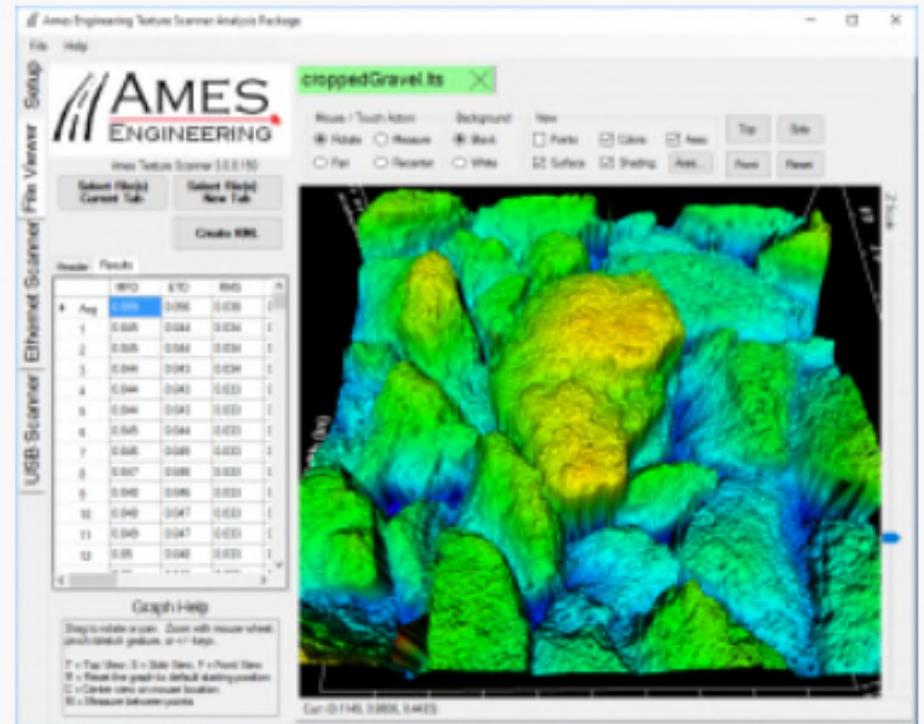
Rapid Laser Texture Scanner 9500

[Home](#) → [Rapid Laser Texture Scanner 9500](#)

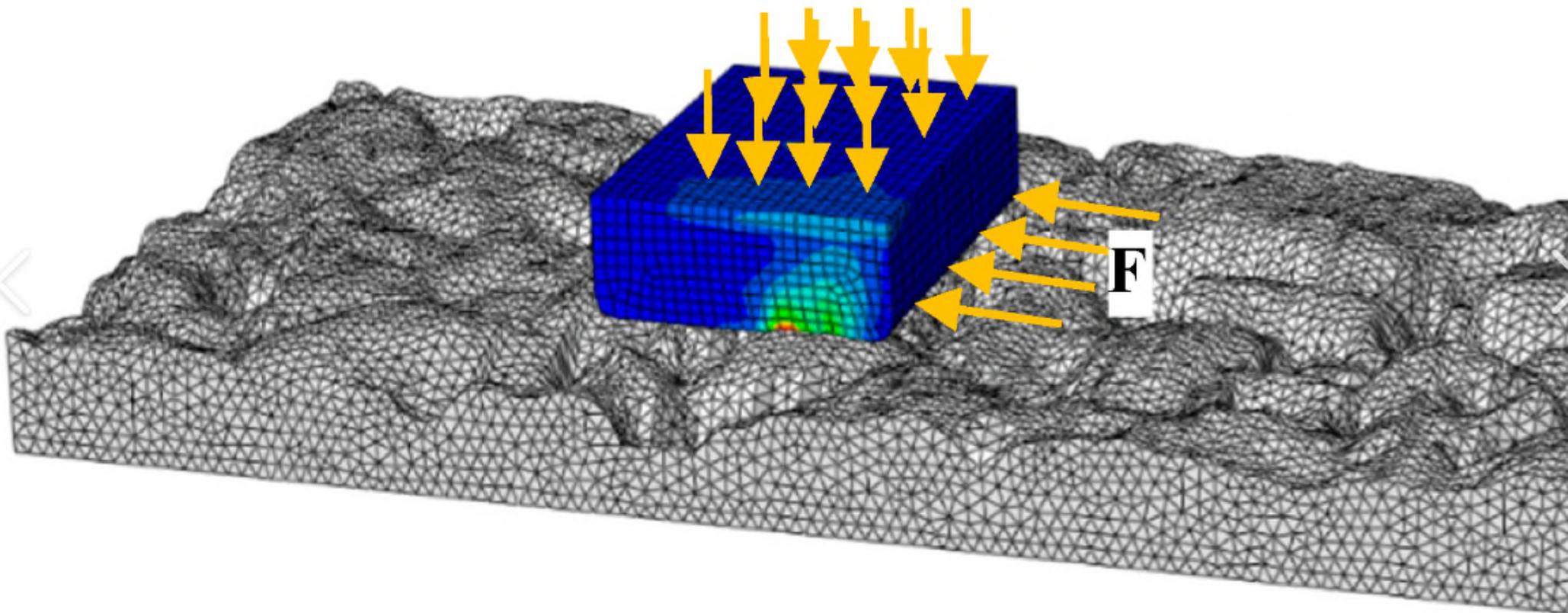


3D Analysis Suite

- A comprehensive Windows based 3D analysis suite is provided for in-depth viewing and analyzing of scan data
- Point-to-point measurement, surface model, point model, and black & white



Pressure



Our Focus Here-

Wheel path abrasion
loss of texture/polish





INVESTIGATION OF SLIPPERY CONDITION OF STONE SAND
CONCRETE PAVEMENT

Late 1940s
First friction studies

At the request of the Maintenance Division, and with their cooperation, an investigation has been made to determine the extent and cause of the unusually slippery-when-wet condition of certain concrete pavement projects located on US-2 and US-41 in the Upper Peninsula.

Project F 52-25, C6 on US-41 at Carp River Hill in Marquette was reported to be very slippery when wet. In July, 1948 steps were taken by the Maintenance Division to correct the condition by surface treatments.

On July 23, 1948, E. S. Anderson, Acting District Maintenance Engineer, reported to the Department that accidents due to skidding on wet concrete pavement were beginning to occur at an alarming rate on US-2, especially in the vicinity of Isabella, Manistique and Gulliver.

Friction

coefficients ranging from 0.35 to 0.20 with an average of 0.28. This is below the minimum value of 0.4 recommended by the American Association of State Highway officials for safe driving under all conditions. This point is fully discussed further on in the text. No definite correlation between pavement age, construction procedure or brand of cement is indicated. Tests on concrete using natural sand gave results ranging from 0.77 to 0.35, or an average of 0.50. A more complete account of each skidding test area follows:

AASHO had "recommended friction limits" by the late 1940's $\mu \geq 0.40$ lb/lb



Figure 8. View showing water truck, skidding car and measurement of stopping distance.

Determination of Coefficient of Sliding Friction

The skid resistance of a pavement surface can be readily determined by the principle that the work done by the external forces acting on a rigid body in any displacement is equal to the change in the kinetic energy of the body in the same displacement. This principle may be expressed by the equation:

$$F \cdot S = 1/2 \frac{W}{g} v^2 \quad (1)$$

where $F \cdot S$ equals work and $1/2 \frac{W}{g} v^2$ equals the kinetic energy of a body when

F = frictional resistance force in pounds,

S = displacement of body in feet,

W = weight of body in pounds,

g = 32.2 acceleration of gravity, and

v = velocity of body in feet per second.

by changing (v) in feet per second to miles per hour, substituting 32.3 for g, and cancelling the weight (w), the formula becomes

$$f = \frac{V^2}{30S}$$

where

f = coefficient of sliding friction,

V = velocity of vehicle in miles per hour, and

S = stopping distance in feet

Late 1940s AASHO Standard Method

Late 1940s

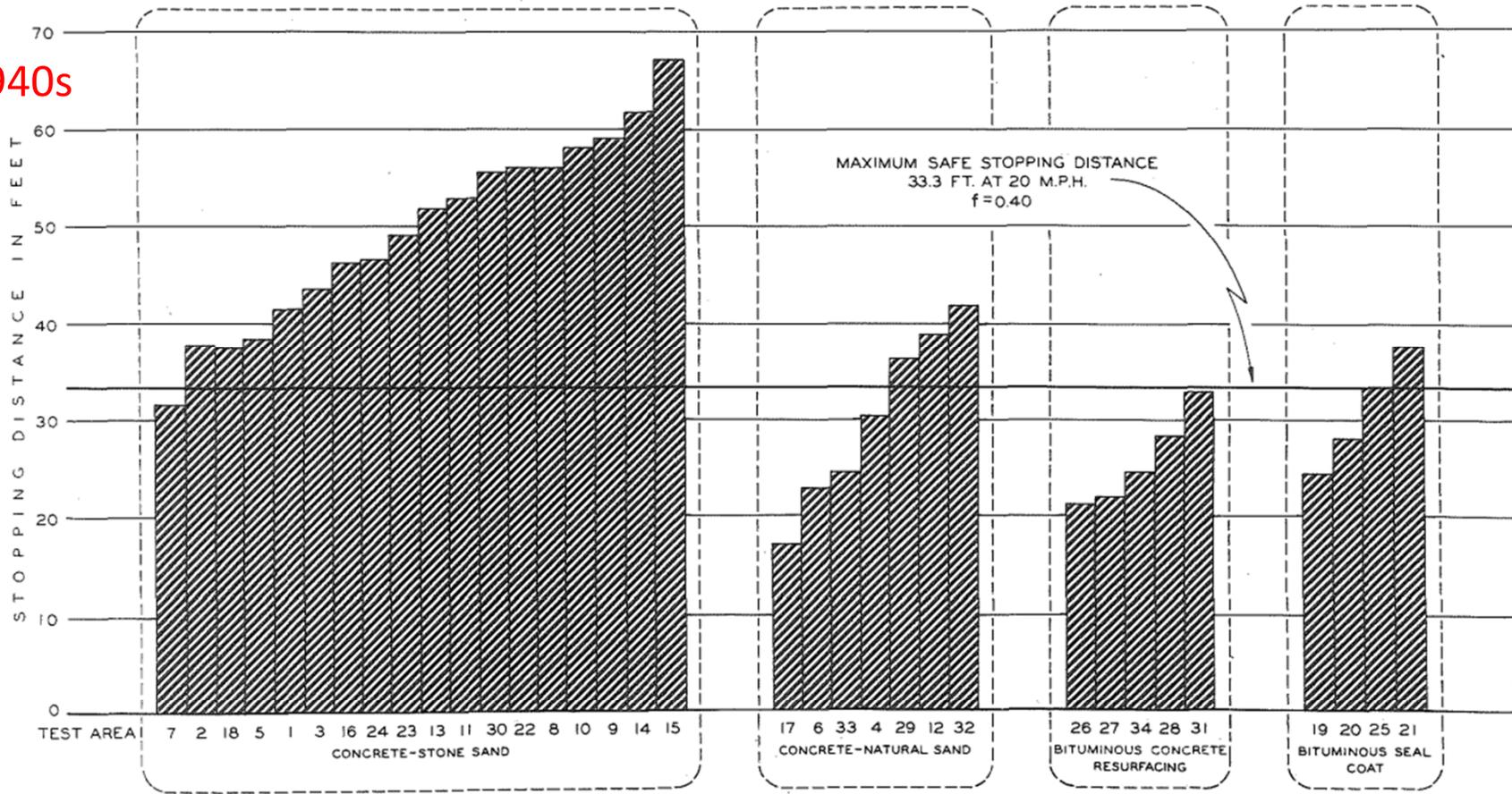
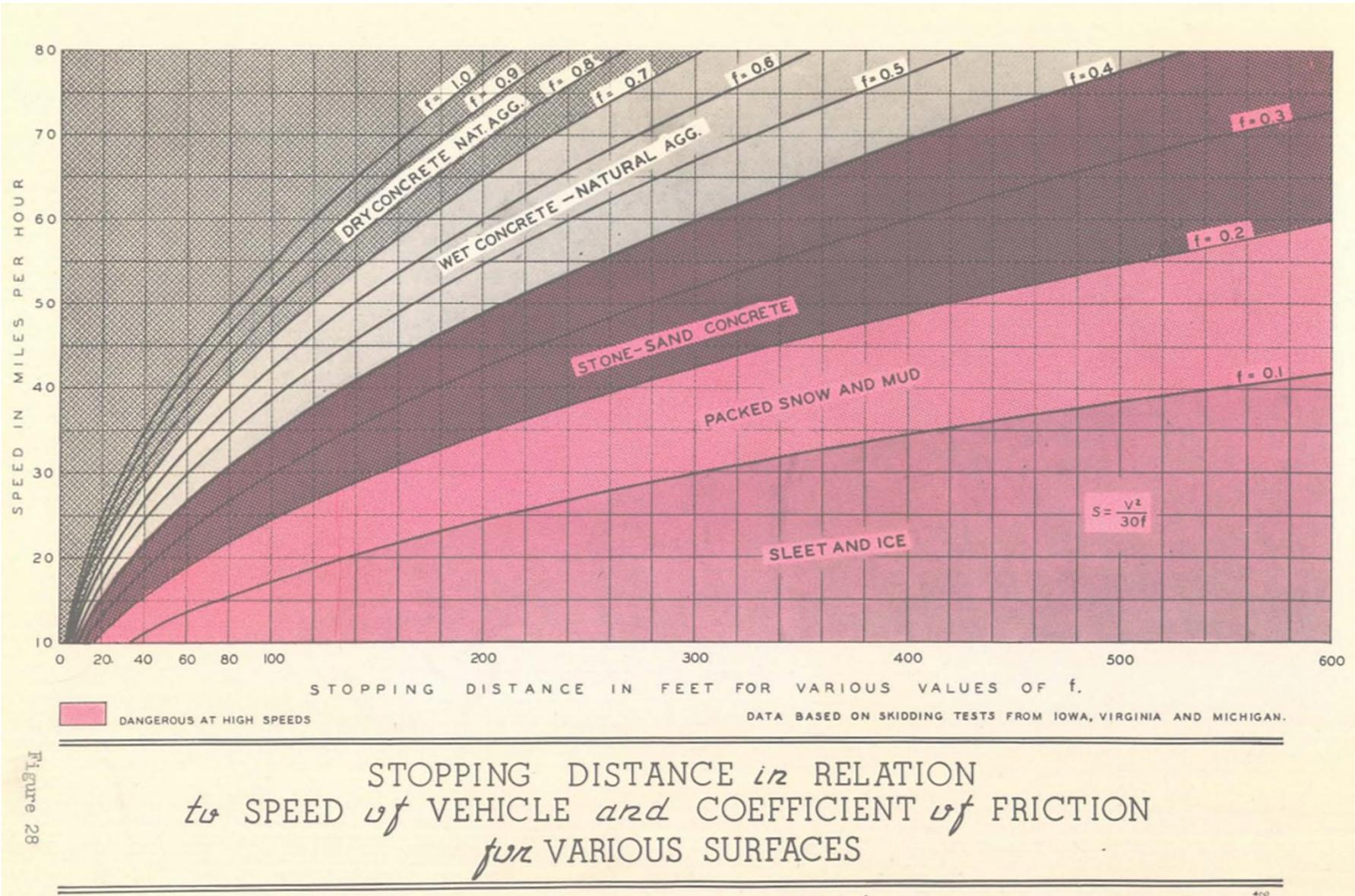


Figure 27

SKID RESISTANCE MEASUREMENTS ON VARIOUS PAVEMENT SURFACES
CONTAINING INLAND LIMESTONE AGGREGATES

BASED ON DATA IN TABLES 3 AND 4 — VEHICLE SPEED, 20 M.P.H.—WET PAVEMENT

Late 1940s



ROAD SURFACE FRICTION
FROM THE STANDPOINT OF
AUTOMOTIVE AND HIGHWAY ENGINEERS

Forward to 1956

Cars are getting Faster!

GM/MDOT Team

For Presentation at the Meeting of the
Association of Paving Technologists
Cleveland, Ohio

February 13 - 15, 1956

LAST COPY
DO NOT REMOVE FROM LIBRARY

P. C. Skeels, Head
Experimental Engineering Department
K. A. Stonex, Head
Technical Data Department
General Motors Proving Ground
and
E. A. Finney, Research Engineer
Michigan State Highway Department

ROAD SURFACE FRICTION FROM THE STANDPOINT OF AUTOMOTIVE AND HIGHWAY ENGINEERS

Engineers in the automotive industry are as much concerned as the highway engineers in the problem of maintaining high and consistent road surface friction characteristics on our highways. Nothing is so important for the safe, effective use of our highway system, and it is the opinion of the authors that a joint effort to determine the reasons for poor friction characteristics and to develop solutions is a matter of paramount importance.

 In the discussion, we are concerned primarily with the decrease in wet friction characteristics which results from a polishing action of the components of the pavement surface as a fundamental cause. The problem related to contamination of the surface by traffic slick or other factors is considered supplementary, however important it may be.

It is evident to the eye and by feel that the aggregate in pavement surfaces does develop a high degree of polish in many instances. This is almost certainly the result of inherent characteristics of the pneumatic tires as successive segments pass through the contact area.



Figure 3—Test car being towed by tank truck with water control valve.

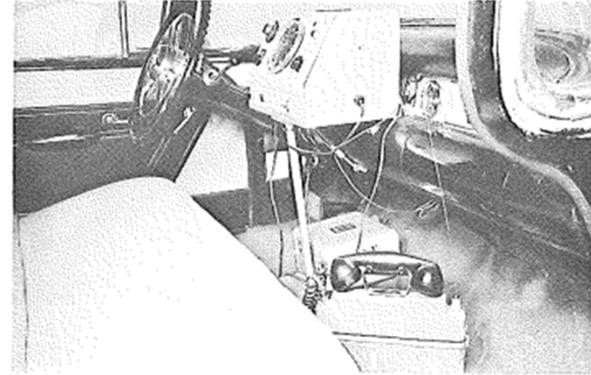


Figure 4—Strain indicating meter mounted in the front seat compartment and portable radio used for communication with the test operators in the tow truck.

Buick Torque Tube Driveshaft

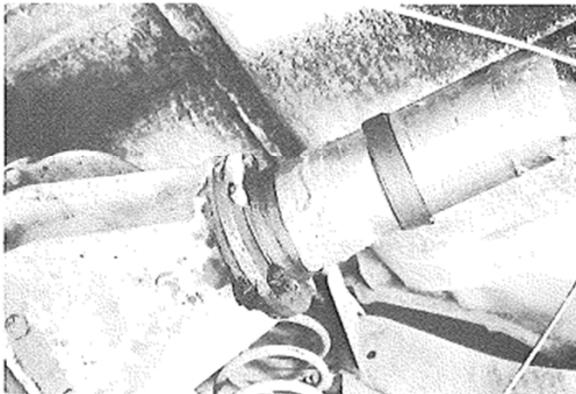


Figure 5—Buick torque tube with strain gauges installed under protective cover.

good repeatability

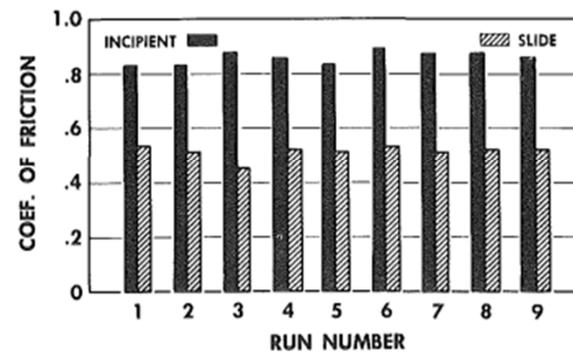


Figure 6—Incipient and sliding coefficients of friction observed on the 40 mph lane of the Proving Ground Test Track—Bituminous concrete surface.

Coefficient of friction is defined as: **Mid 1950s Standard:**

$$\mu = \frac{F_6}{F_5} = \frac{F_6}{F_3 - \frac{H_1}{L_w} F_6}$$

Buick Torque-Tube in a towed instrumented car

With known constant values of F_3 , H_1 , and L_w with this vehicle, the coefficient of friction is calculated for values of tractive force (F_6) indicated by stress observations. Figure 28 shows the coefficient of friction as a function of the tractive force.

AWI is also a "Tractive Force"

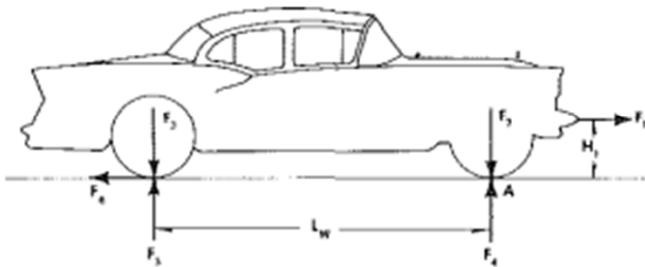


Figure 27—Force diagram of car.

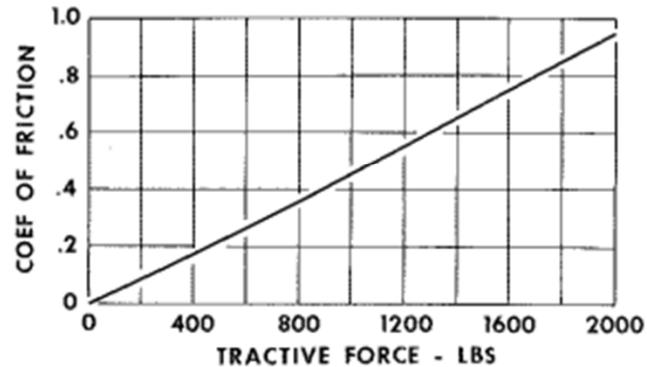


Figure 28—Calibration curve for coefficient of friction from tractive force readings.



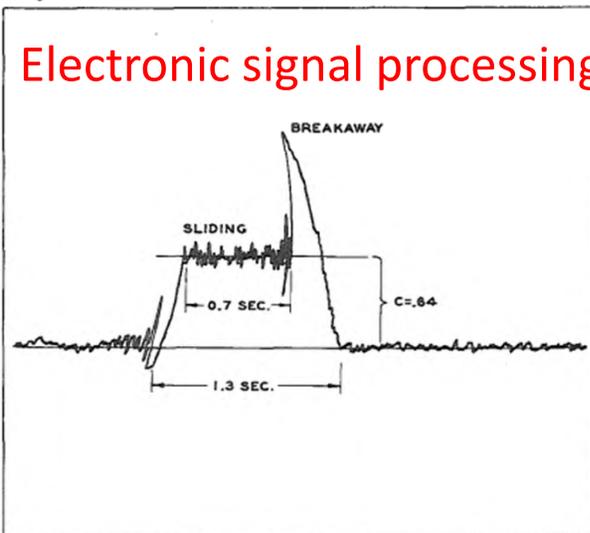
Figure 1. MSHD skid testing equipment.



Figure 2. Skid testing trailer.

Late 1950's – First "Skid Trailer" set-up

Figure 3. Typical skidding trace on wet bituminous concrete. 30 m.p.h.



Electronic signal processing

Figure 4. Skid cycle control panel, oscillograph, and strain analyzer.

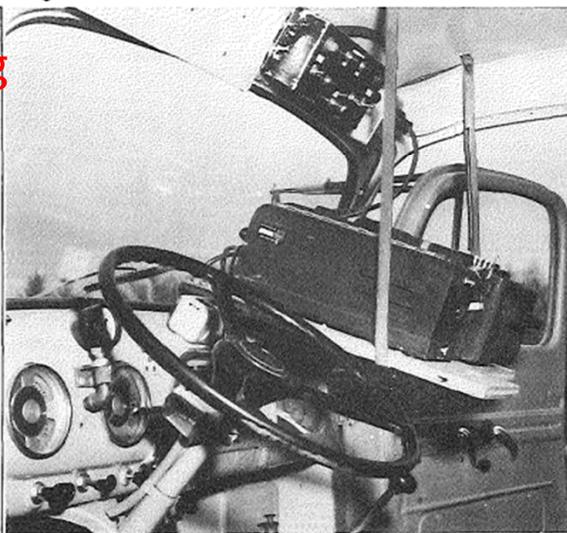
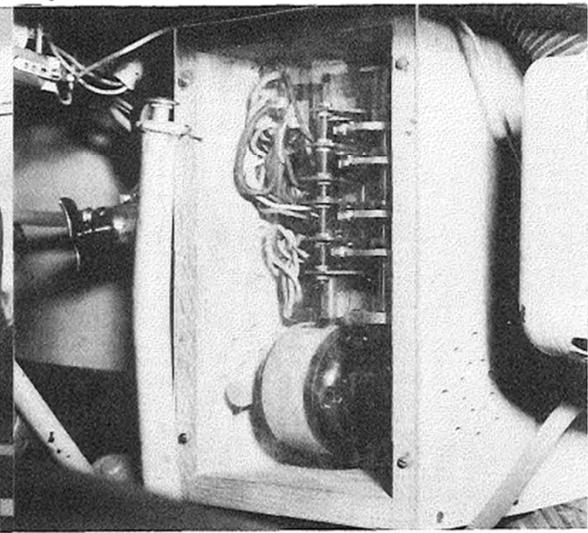
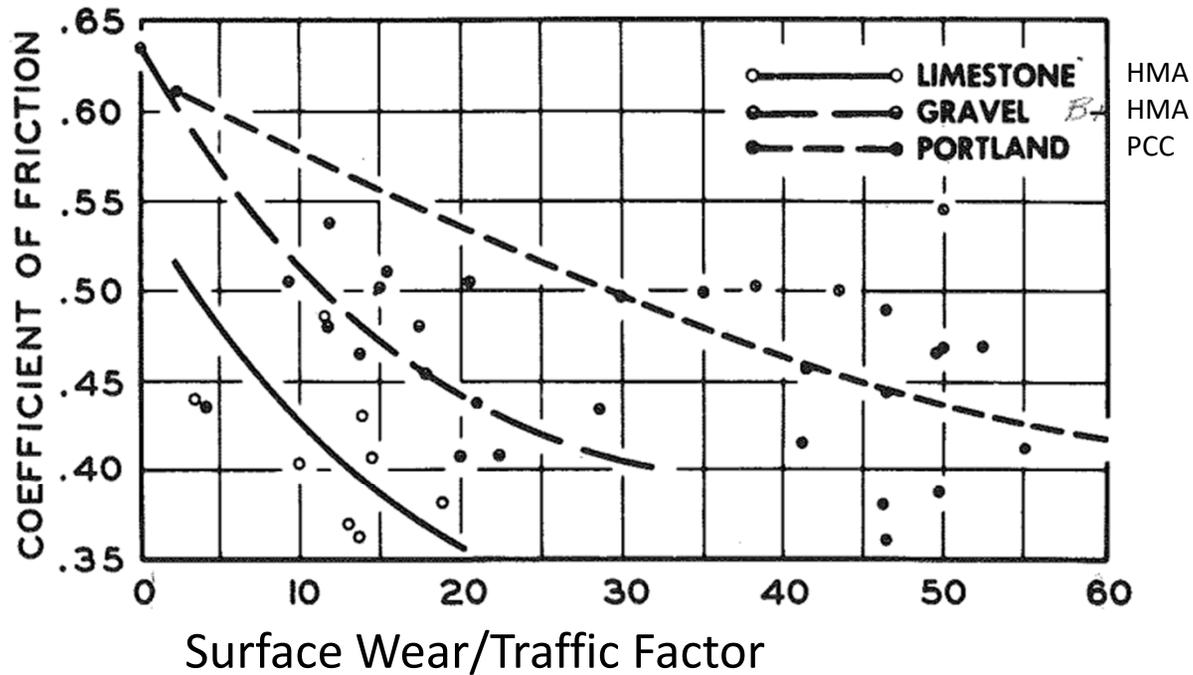


Figure 5. Cycle control cams and motor drive.





Late 1950's – First Texture/Friction Loss Studies
 early “polishing curves” with “wear/traffic” factor

RELATIVE SKID RESISTANCE OF PAVEMENT SURFACES
BASED ON MICHIGAN'S EXPERIENCE

E. A. Finney and M. G. Brown

L

G.R

E. 1

7

The World wakes up



A paper to be presented at the
First International Skid Prevention Conference
September 8-12, 1958
University of Virginia
Charlottesville, Virginia

Report No. 295
Research Laboratory Division
Office of Testing and Research
Research Project 54 G-74

Comparing the old method to the new – the correlation equations

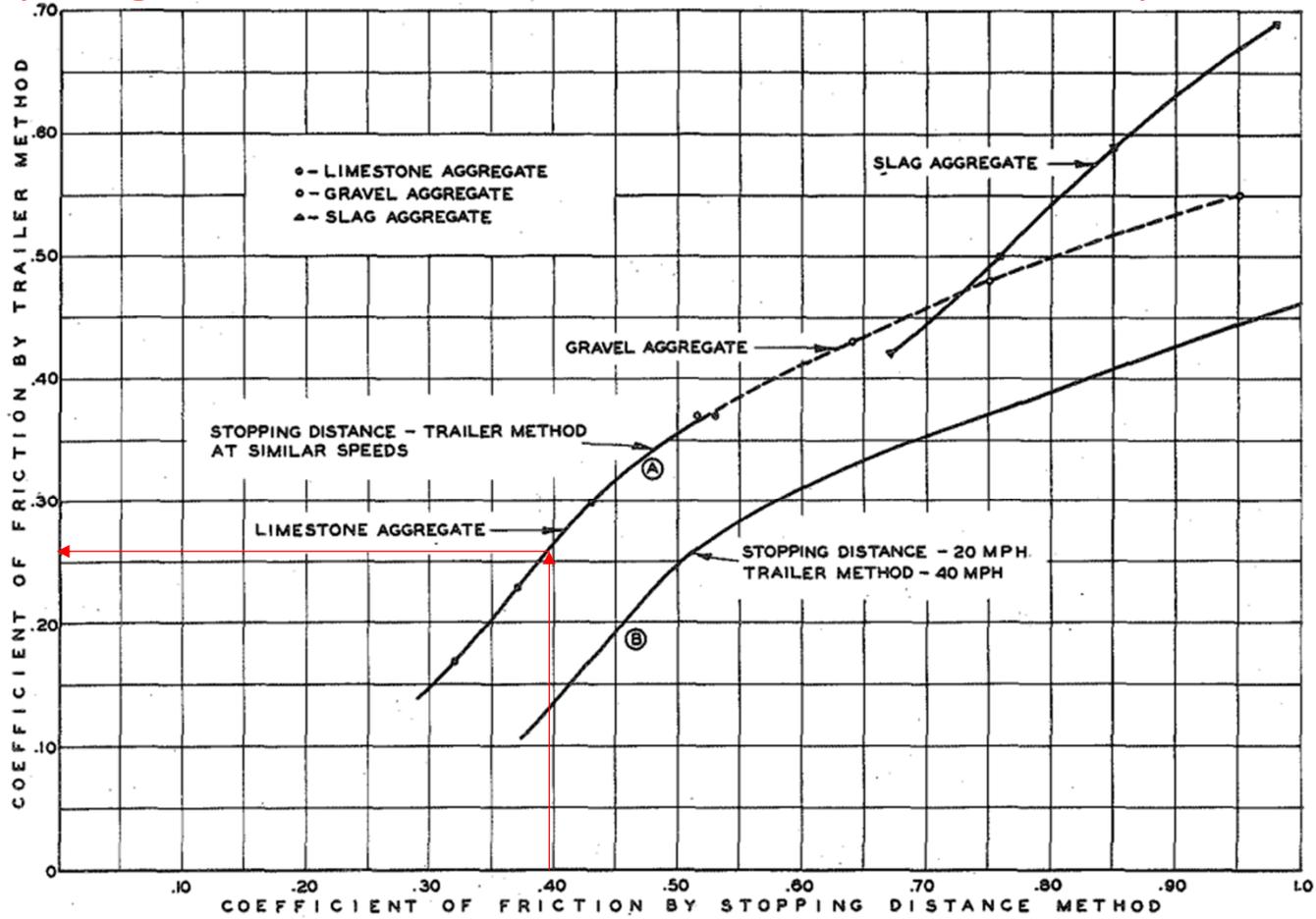
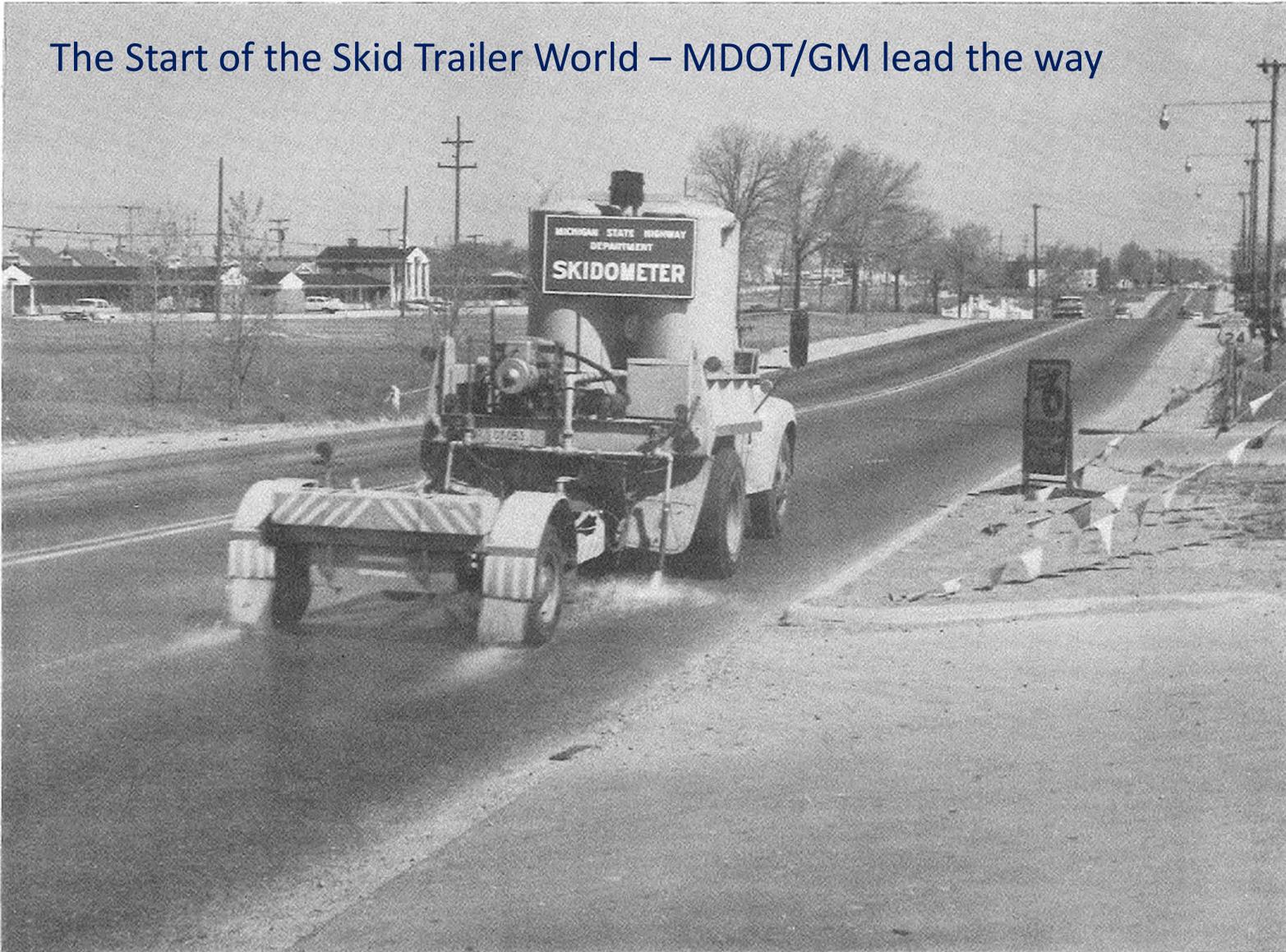


Figure 21. Friction relationships: Trailer and stopping distance methods at different speeds.

The Start of the Skid Trailer World – MDOT/GM lead the way



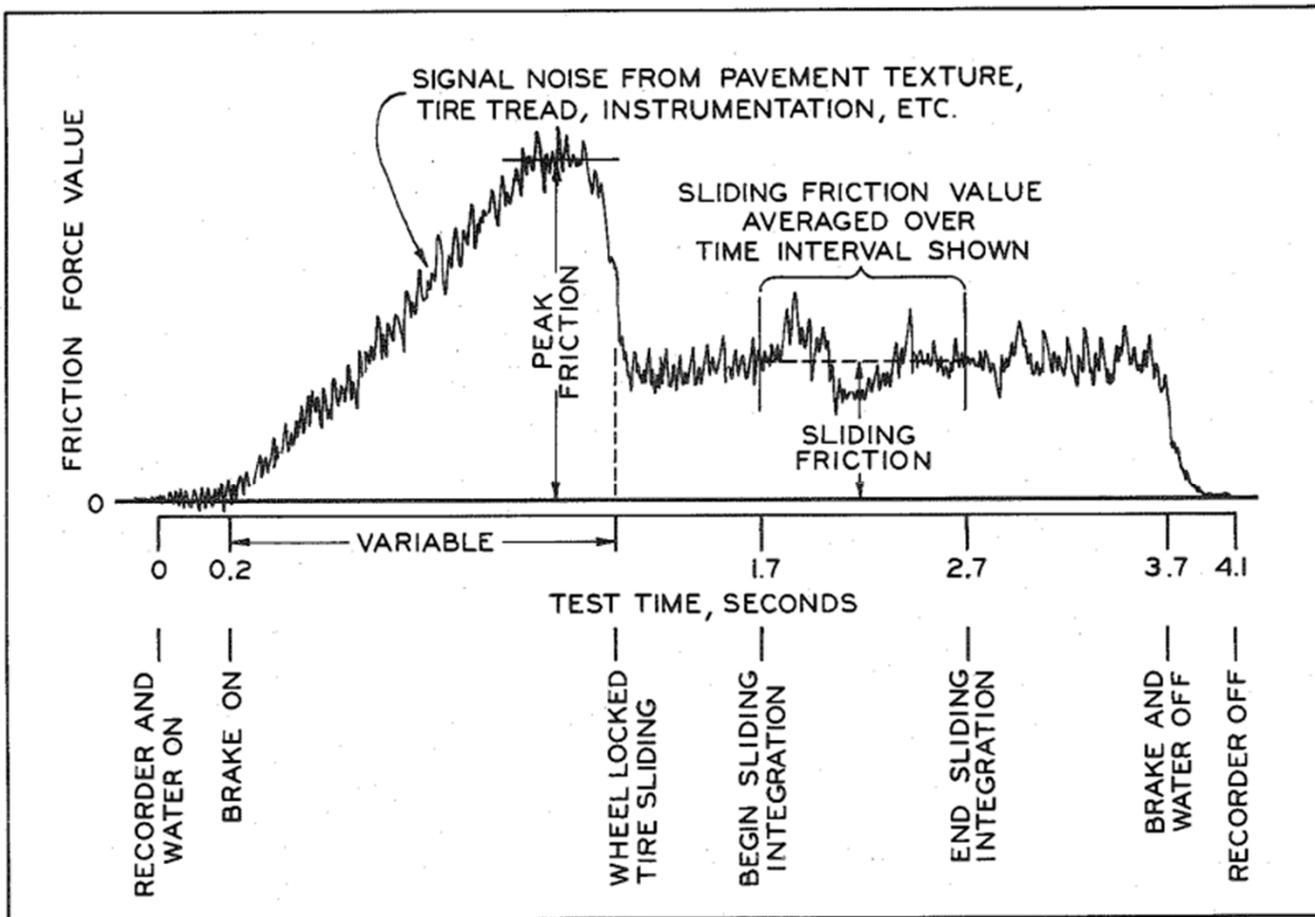


Figure 10. Typical record of skid test cycle (controlled lock mode, maximum rate of braking).



1295 PAVEMENT FRICTION TESTER (PFT)



The Dynatest 1295 Pavement Friction Tester (PFT) measures the average locked wheel (skid) and peak (slip) friction characteristics on dry or self-wetted paved surfaces. It is designed for maintenance testing to evaluate the alteration of pavement friction resulting from traffic, aging and weathering.

TE
450
.86
1965
c.2



AMERICAN OIL COMPANY

**RESEARCH AND DEVELOPMENT
DEPARTMENT**



**LABORATORY TEST TRACK INVESTIGATION OF THE
SKID RESISTANCE OF BITUMINOUS PAVEMENTS
COMPOSED OF HARD TYPE FINE AGGREGATES**

T. L. SPEER

FINAL REPORT

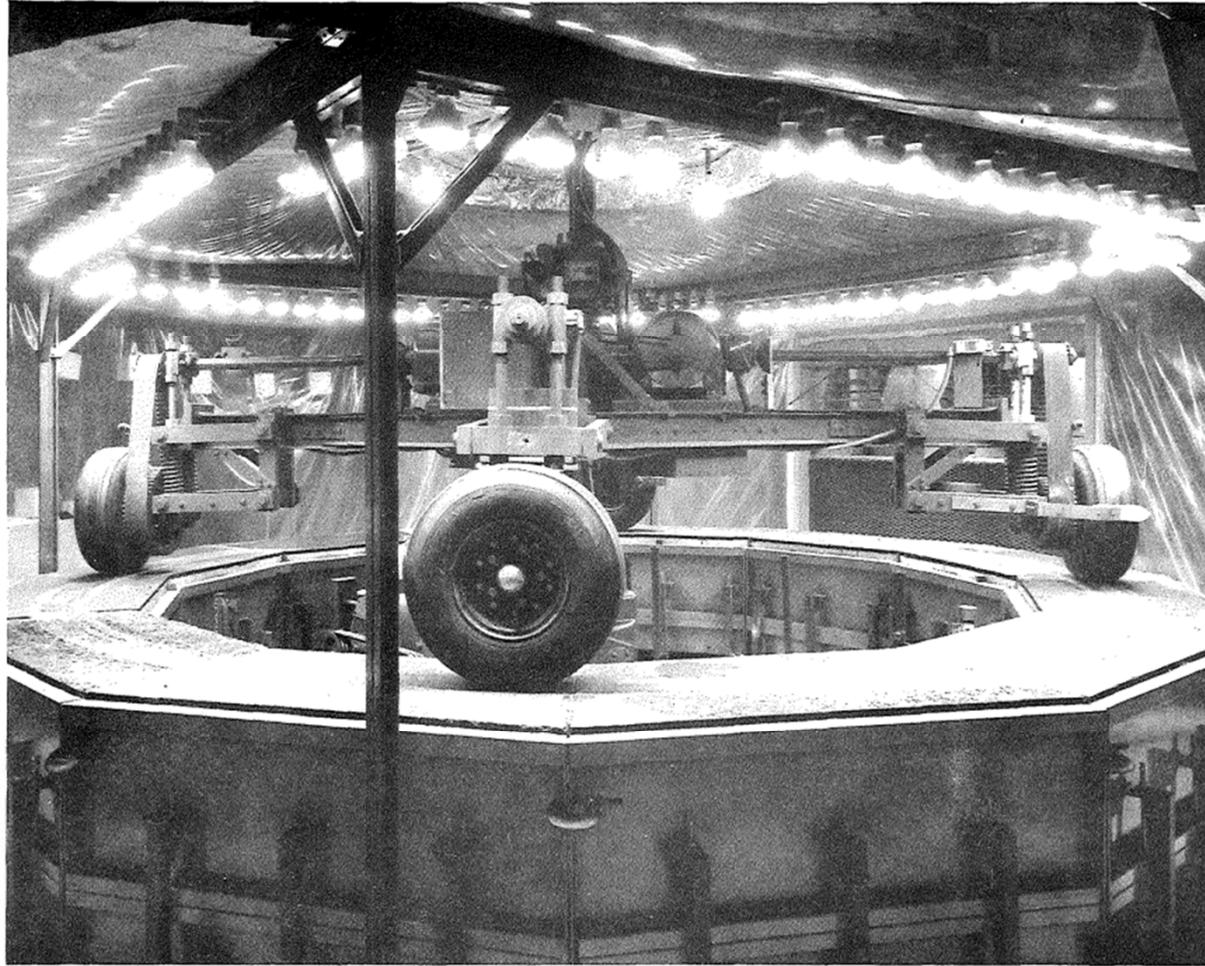
**RESEARCH PROJECT FOR MICHIGAN STATE HIGHWAY DEPARTMENT,
OFFICE OF TESTING AND RESEARCH**

JULY, 1965

The genius inspiration
seed for the MDOT wear
track and AWI procedure

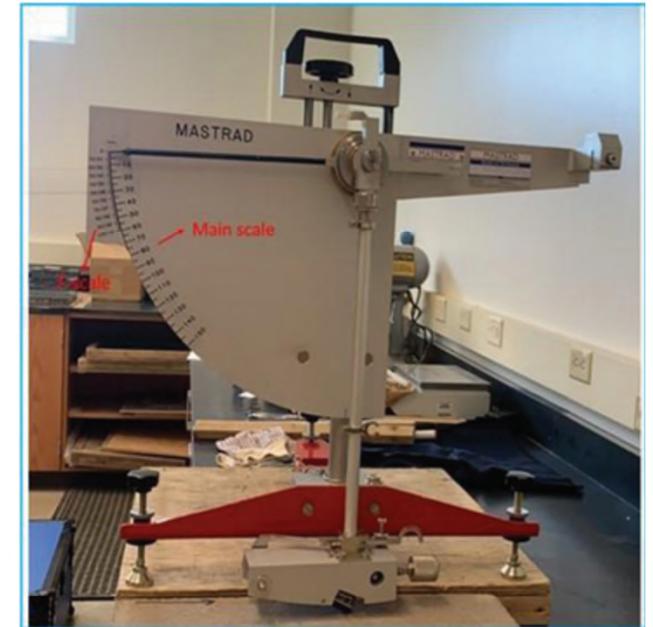
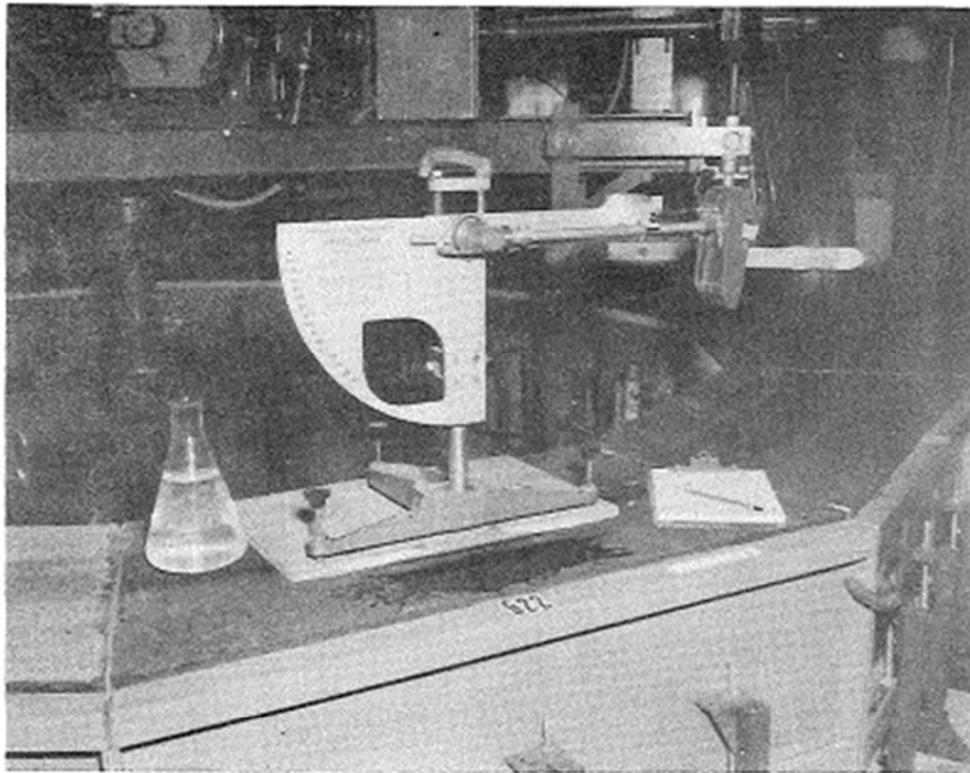
Big Oil - 1965

Mid 1960s



LABORATORY TEST MACHINE WITH MICHIGAN DESLICKING PAVEMENTS

Mid 1960s



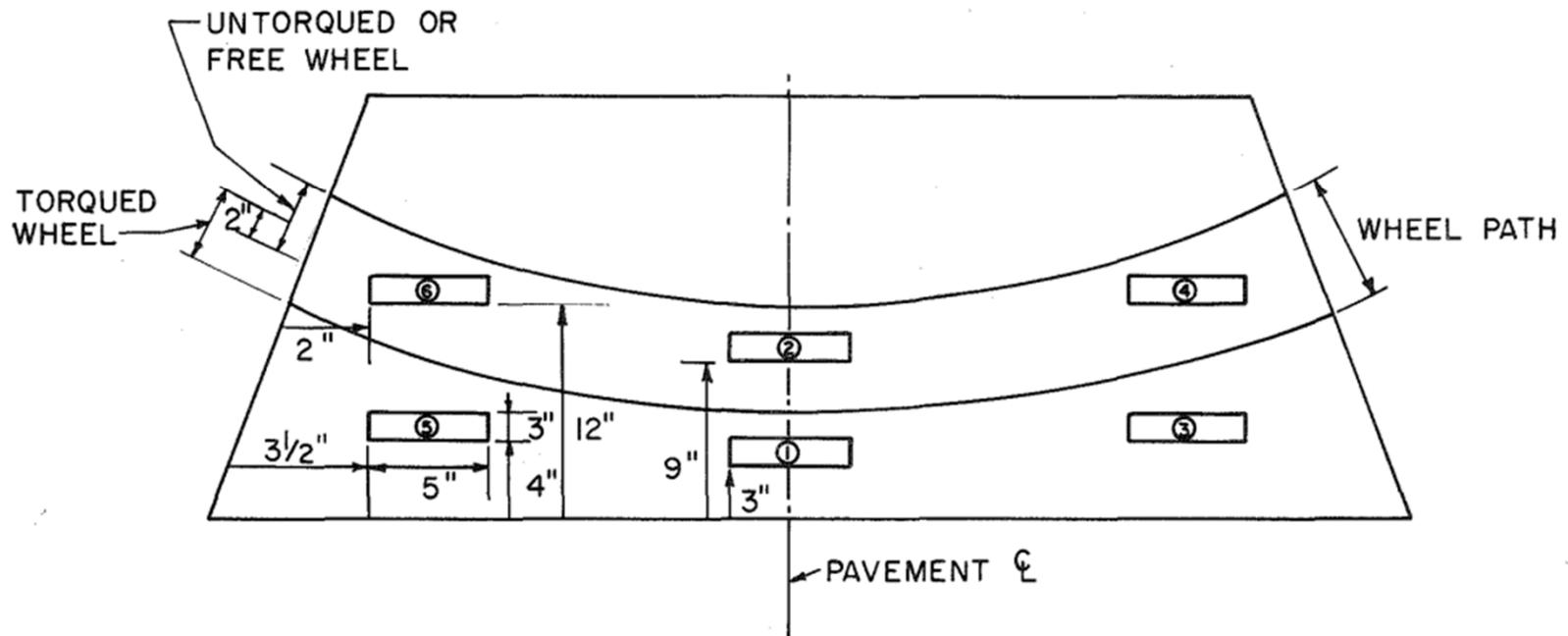
The "British Pendulum"

STANDARD PORTABLE SKID
RESISTANCE TESTER INSTRUMENT

American Oil Test Pads and Locations

FIGURE 13

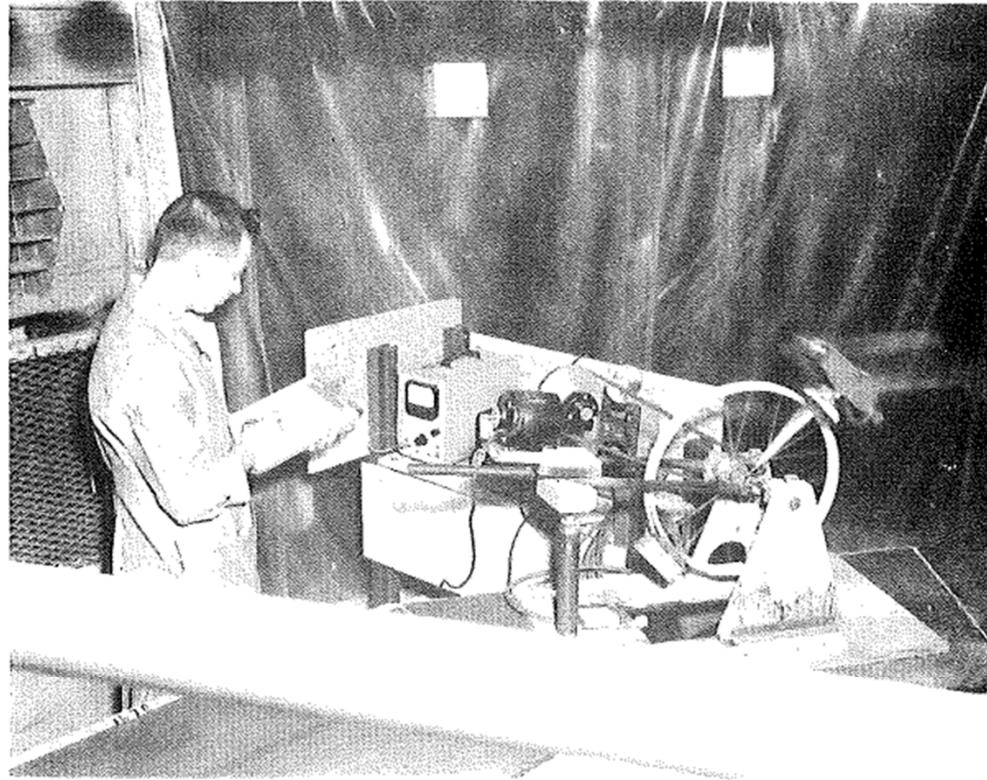
AWI uses the 2-4-6 pattern like this



SKID TEST SITES ARE NUMBERED ① TO ⑥
PERIODIC TRAFFIC EFFECTS MEASURED AT ①, ②, ④ AND ⑥

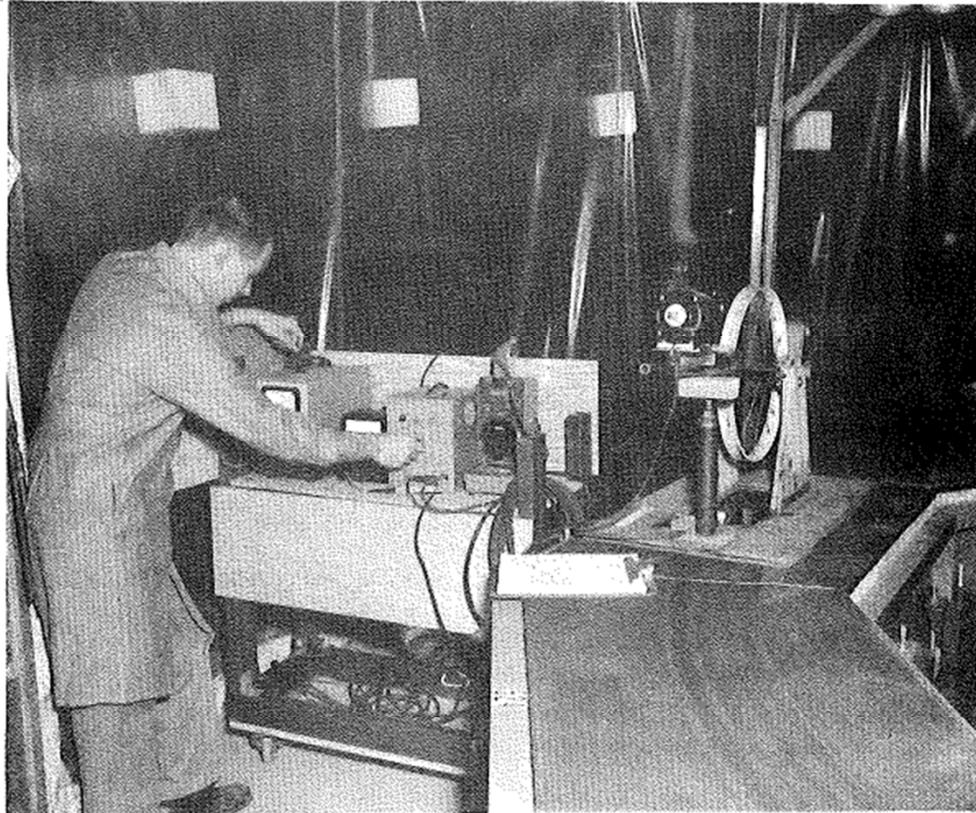
PAVEMENT LOCATIONS FOR PORTABLE SKID TESTER MEASUREMENTS

Mid 1960s



PORTABLE HIGH SPEED SKID
RESISTANCE TESTER INSTRUMENT /

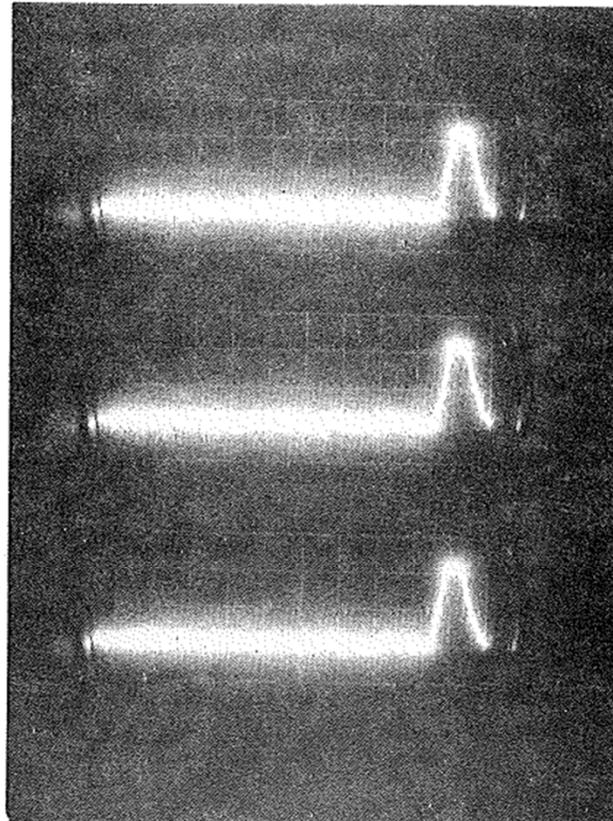
Mid 1960s



The MDOT AWI lab friction tester is obviously based on this early bicycle tire testing system concept

INSTRUMENTATION FOR HIGH SPEED
POWER CONSUMPTION DETERMINATIONS

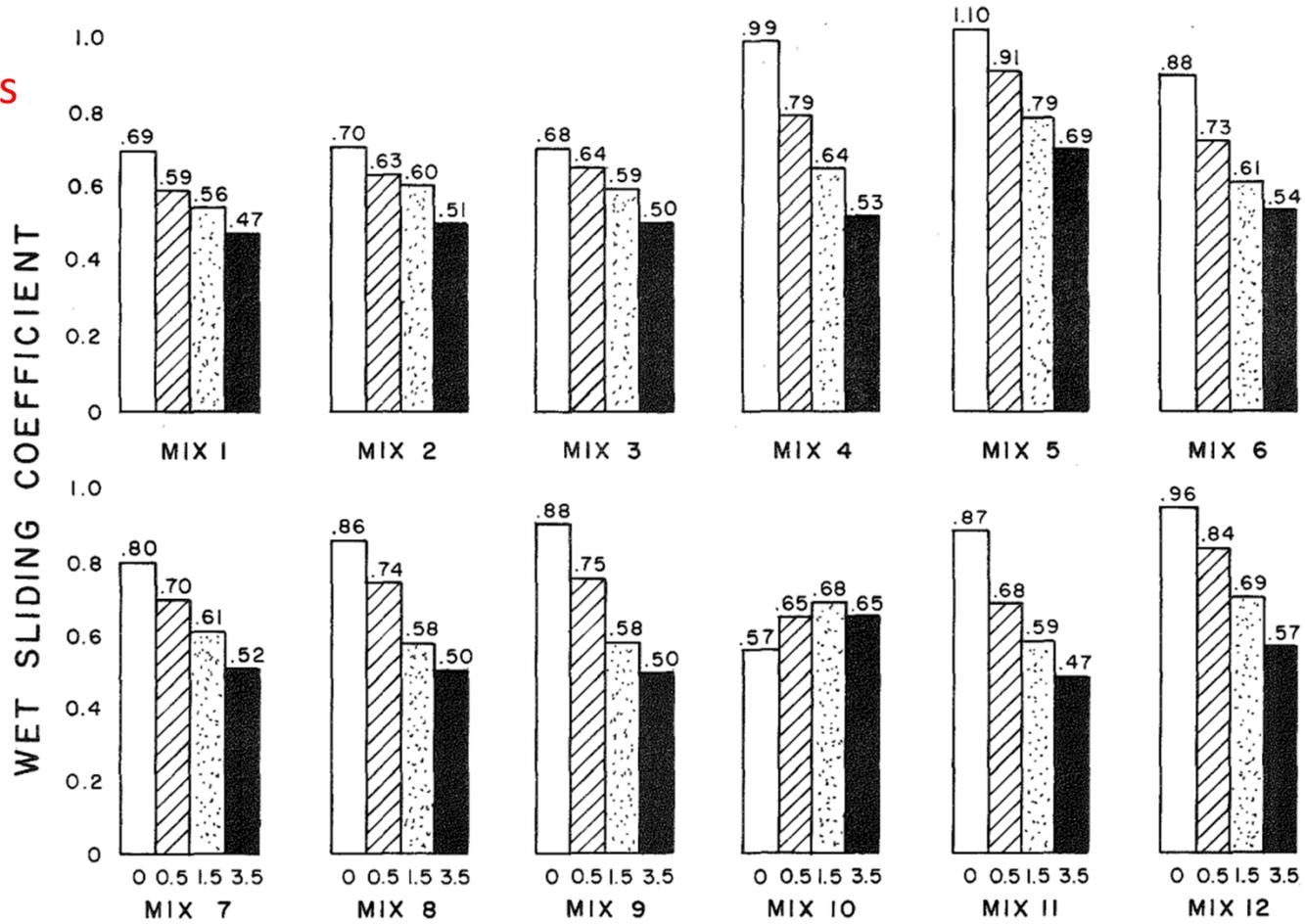
Mid 1960s



The MDOT AWI uses a similar slider-rack and electronic signal from a horizontal load cell

SLIDER LOAD OSCILLOGRAMS
FOR 30 MPH TESTER SPEED

Mid 1960s



Early Polishing "Curves"
3,500,000 passes

WHEEL COVERAGES - MILLIONS
DESLICKING MIXTURE PERFORMANCE

1970s

THE MICHIGAN DEPARTMENT OF TRANSPORTATION
CIRCULAR WEAR TRACK—RESULTS OF
PRELIMINARY AGGREGATE POLISHING TESTS

First Progress Report

R. W. Muethel

Research Laboratory Section
Testing and Research Division
Research Project 71 C-13
(Phase 2)
Research Report No. R-1098

The First MDOT Wear Track AWI Study Report

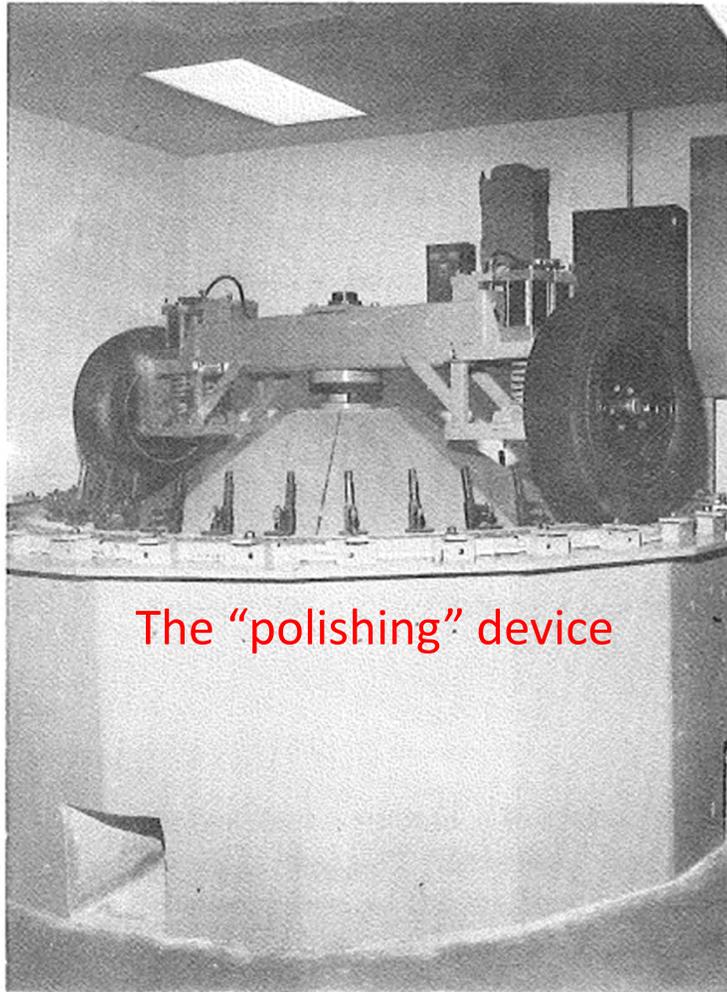
The Official Justification for the AWI System and Wear Track Procedure

In 1965 the Department's Standard Specifications for Road and Bridge Construction were revised to include a ban on the use of crushed limestone in the wearing course of bituminous concrete (4.12) mixes, and a 70 percent carbonate limit on crushed gravel for these mixes. These restrictions, however, resulted in severe aggregate supply problems, particularly in the northern lower peninsula where local aggregates are primarily high-carbonate gravels and quarried carbonates.

In 1971 the Department initiated a study at the request of the gravel producers to evaluate the ban on using crushed limestone in the wearing course of bituminous concrete (4.12) mixes, and the 70 percent carbonate limit on crushed gravel for these mixes. The study, titled "Study of Aggregate and Mix Requirements for Durable and Skid Resistant Bituminous Mixtures" (Research Project 71 C-13), included the design and construction of a circular wear track under Phase 2, for the study of the effect of simulated traffic polish on various aggregates for use in bituminous pavements.

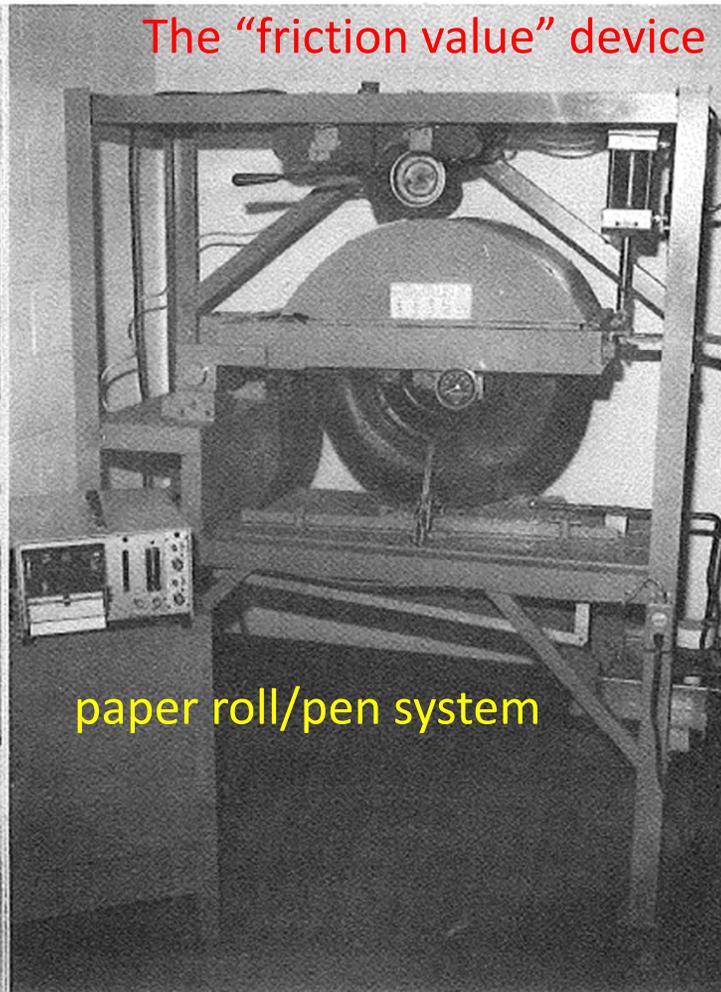
Construction of the wear track was completed in 1974 and the first experimental polishing tests were scheduled. A total of eight series of tests were completed between 1974 and 1977 at which time the wear track was dismantled for relocation in the Department's new Testing and Research Laboratory building. Reconstruction of the wear track at the new laboratory location was completed in 1978.

1970s



The "polishing" device

Figure B-2. MDOT wear track.



The "friction value" device

paper roll/pen system

Figure B-3. MDOT static skid tester.

1970s

L. T. Oehler

- 2 -

October 14, 1977

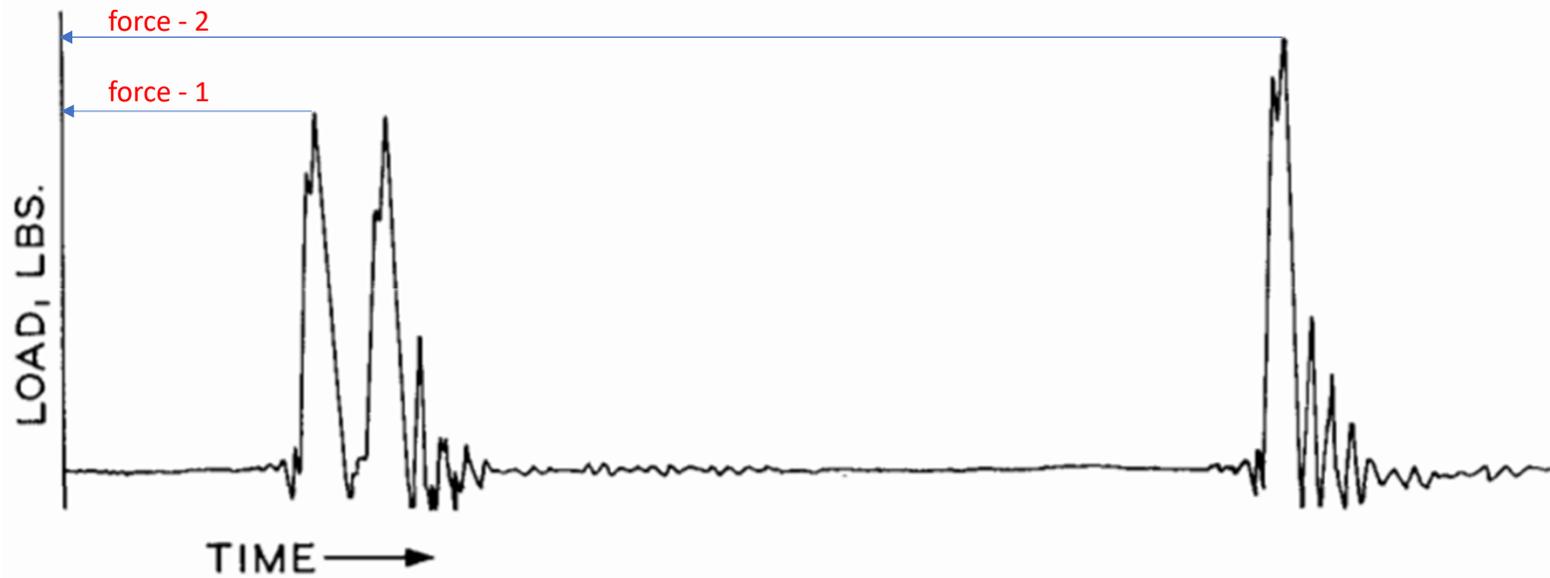


Figure 1. Typical wheel stopping forces obtained from static skid tester.

Load cell traces recorded using paper roll/pen system





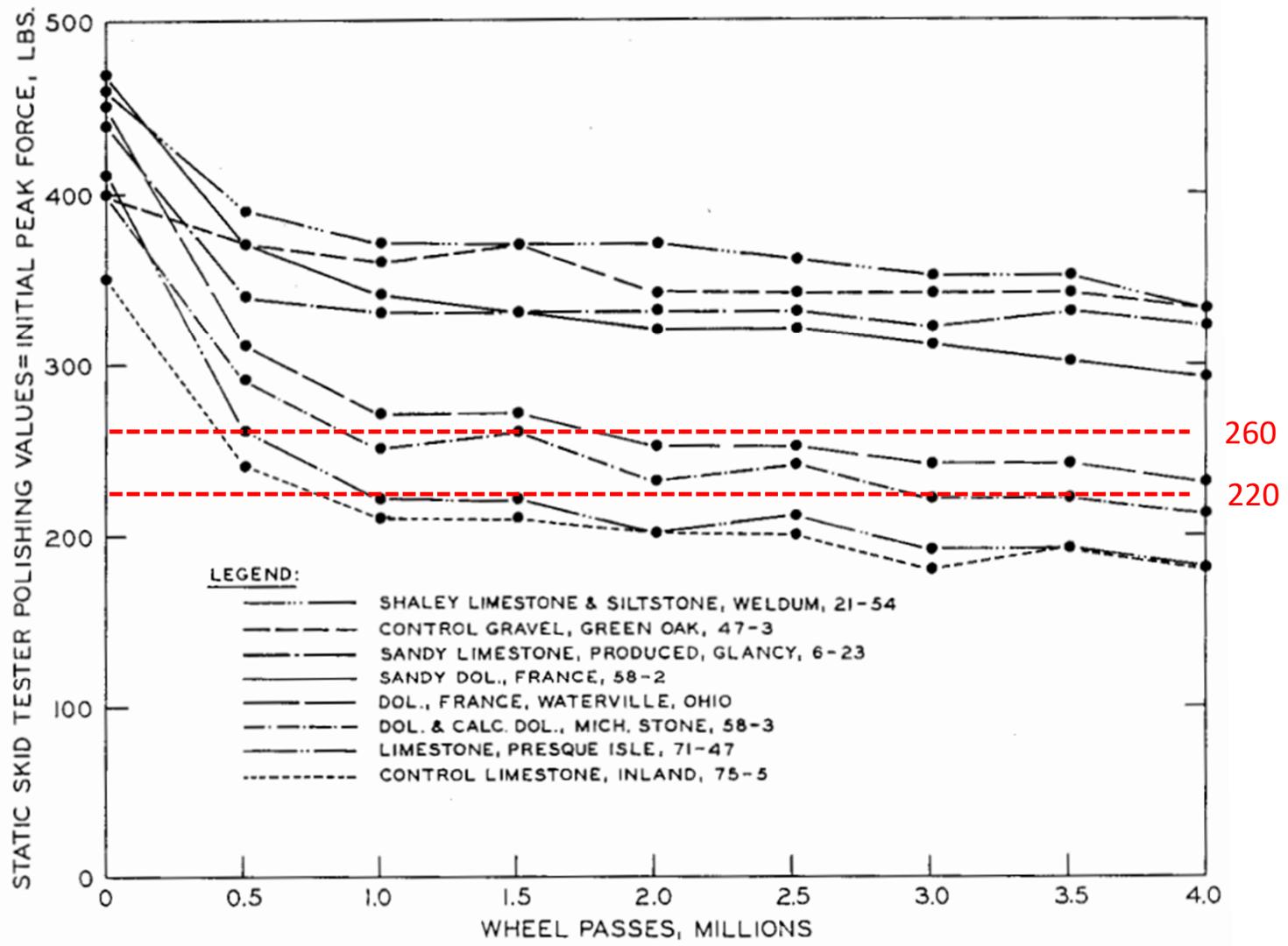


Figure A-4. Wear track test series No. 4.

SN40

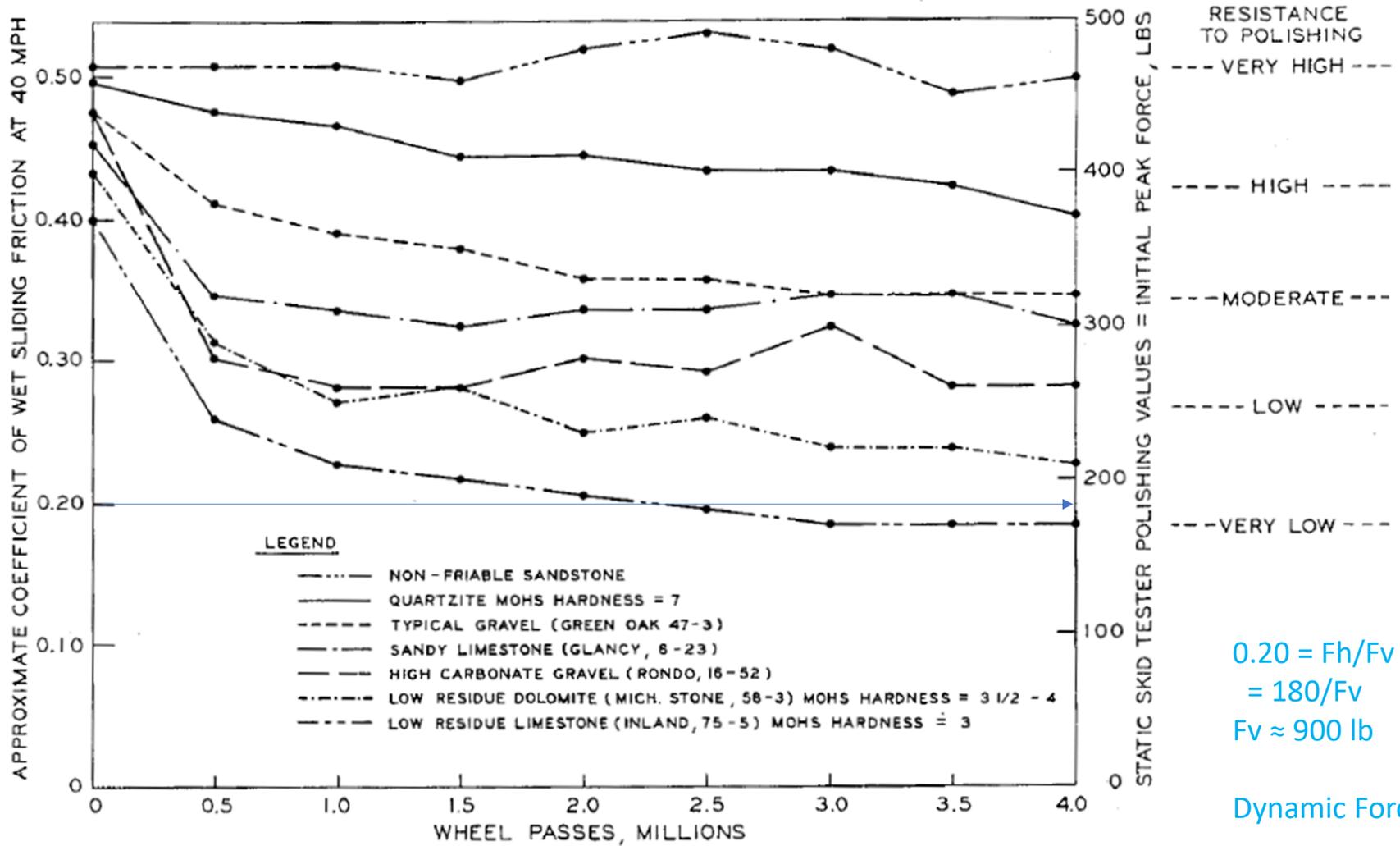
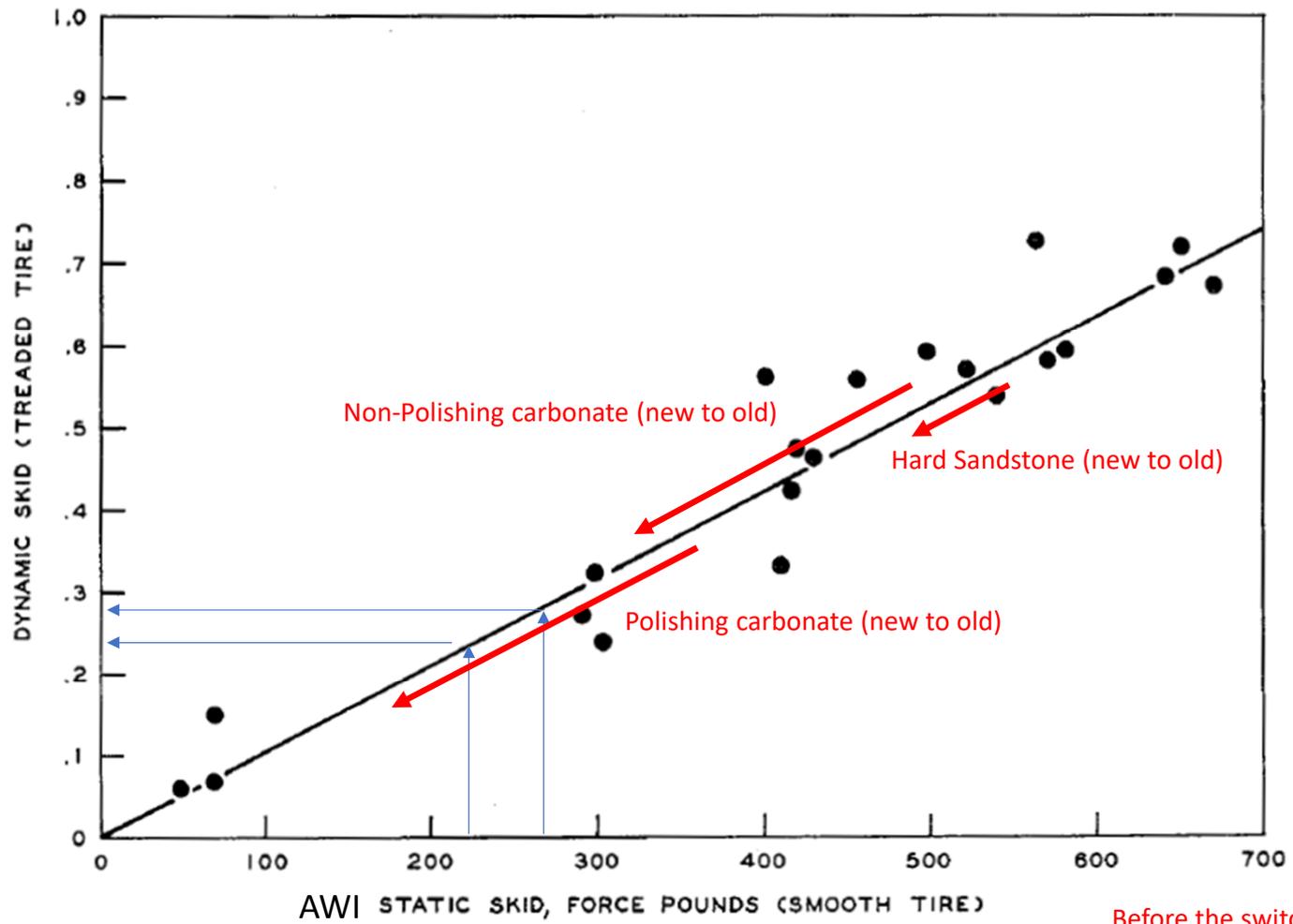


Figure 4. Examples of wear track polishing.



Before the switch to K.J. Law skid trailers in the 1970s

Figure 2. Correlation study: GM Unit skid test vs. static wheel.

“Petrographic” AWI for
Mixed sand/gravel pits

Uses geologic pick
technique to separate
sample into groups, then an
equation to back-predict
AWI

<u>COMPOSITION OF SAMPLE</u>			
ROCK TYPE	PERCENT	WEAR TRACK AWI	CALCULATED AWI
IGNEOUS/METAMORPHIC	21.3	370	78.8
SEDIMENTARY			
Carbonates	73.2	250	183.0
Sandstone	3.4	490	16.7
Siltstone	0.0	475	0.0
Shale	0.0	335	0.0
Clay Ironstone	0.0	275	0.0
Chert	2.1	345	7.2
Weighted Sample AWI			285.7
Uncrushed Particles, %			34
AWI Reduction based on uncrushed			
Reduction in Percent . . . (0.26 X 34)			8.8
Adjusted AWI			260

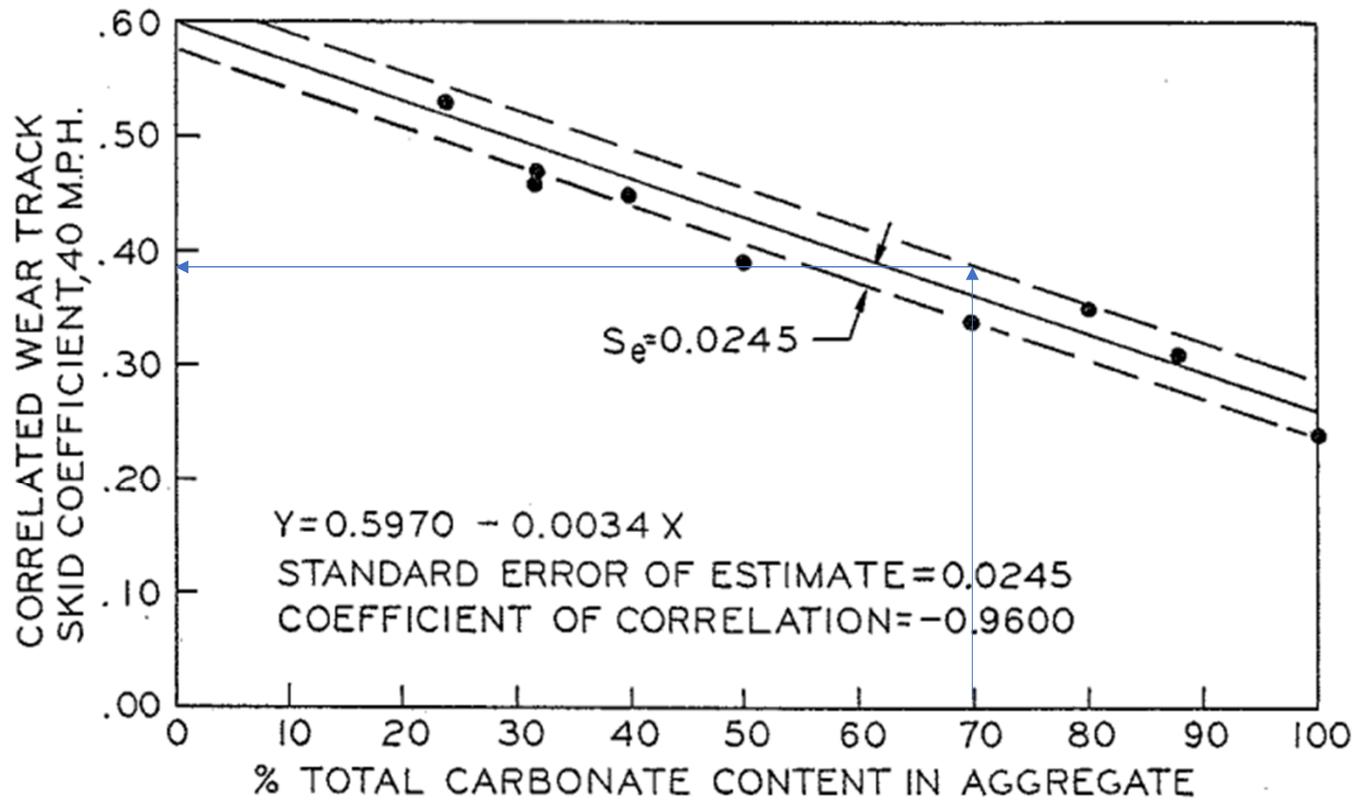
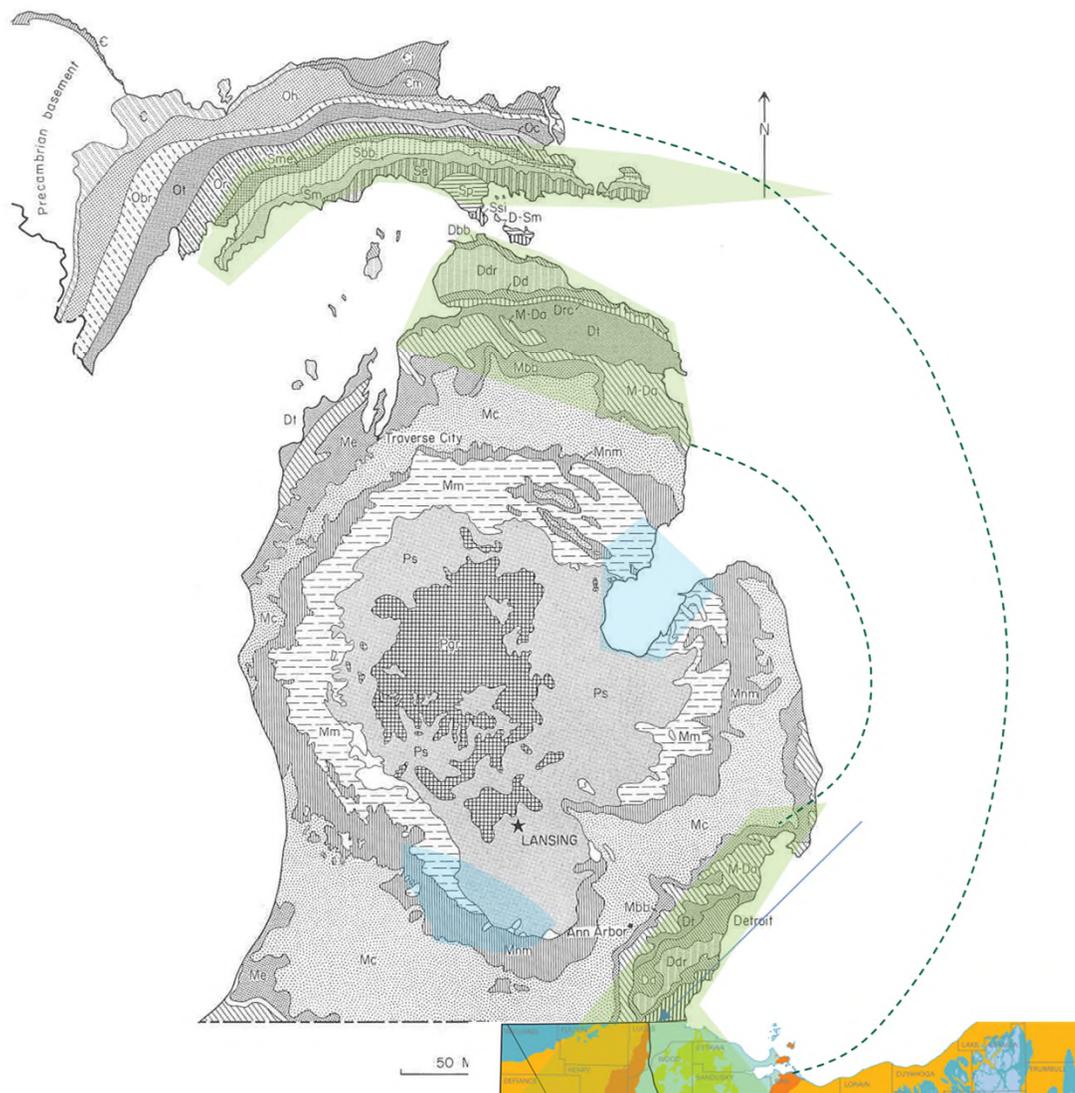


Figure 1. Least square linear regression line for carbonate rock content vs. correlated friction coefficients.

CARBONATES

	<i>Pennsylvanian</i>
Pgr	Grand River
Ps	Saginaw
	<i>Mississippian</i>
Mb	Bayport
Mm	Michigan
Mnm	Napoleon - Marshall
Mc	Coldwater
Mbb	Berea - Bedford
Mc	Ellsworth - Antrim
	<i>Mississippian Devonian</i>
M-Da	Antrim
	<i>Devonian</i>
Dt	Traverse
Drc	Rogers City
Dd	Dundee
Ddr	Detroit River
Dbb	Bois Blanc
	<i>Devonian Silurian</i>
D-Sm	Mackinac breccia
	<i>Silurian</i>
Sbi	Bass Island
Ssi	St. Ignace
Sp	Point Aux Chenes
Se	Engadine
Sm	Manistique
Sbb	Burnt Bluff
Sme	Mayville



from Dorr & Eschman 1970

Carbonate Percentages for
Select Mixed Glacial
Sand/Gravel Deposits

EXPLANATION



Wisconsin end moraines



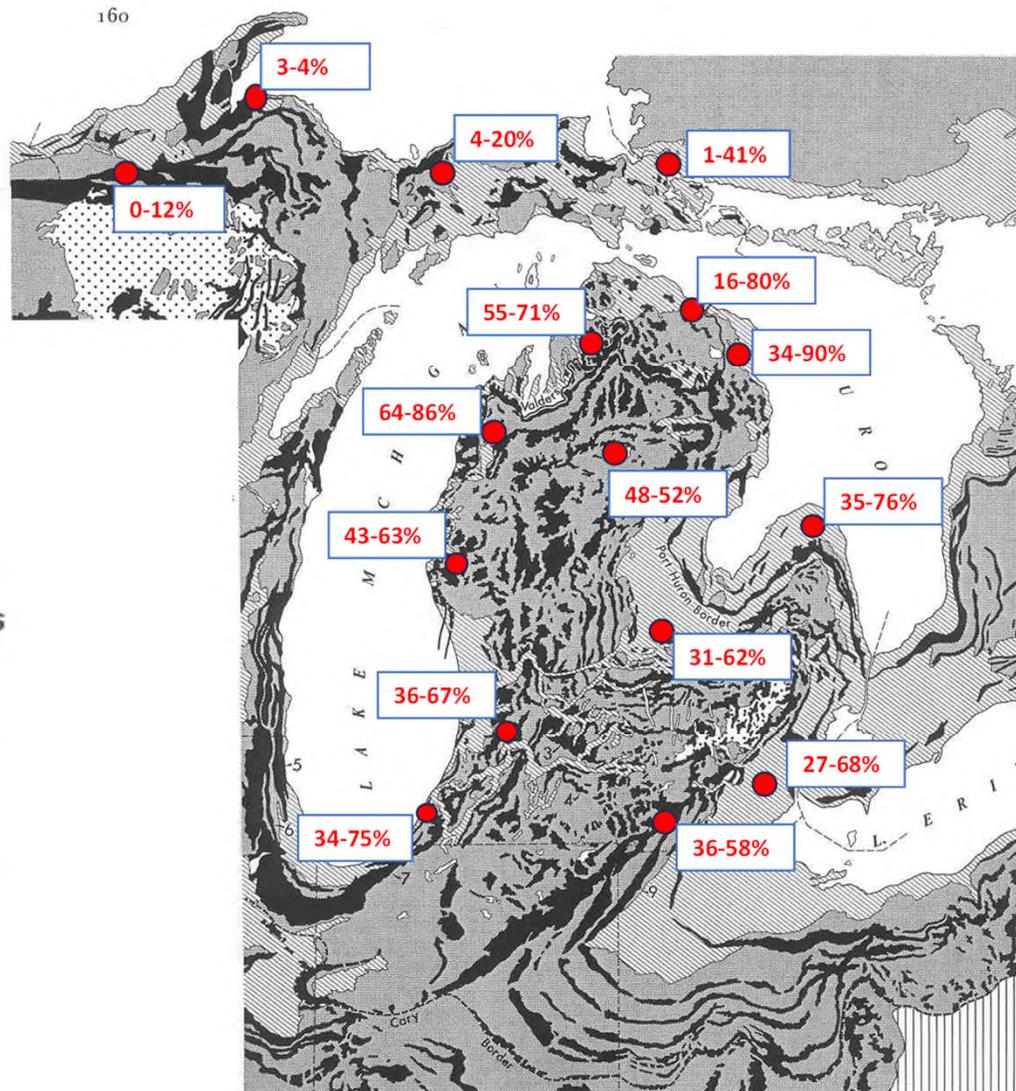
Ground moraines and outwash plains



Lake sediments



Ice-contact stratified drift



Geological Society of America, 1959

Earliest MDOT Aggregate Durability Spec I could find

The 1919 Standard Specifications, Bituminous Macadam Surface specified the same aggregate gradations as specified for Water-bound Macadam Surface as follows:

1919-1921 Bituminous Macadam Surface Course:

Physical Requirements:

Physical Property	Limestone (%)	Cobbles, Granite, Trap Rock (%)
French Coefficient of Wear, not less than	7	10
Toughness, not less than	9	10
Hardness, not less than	14	16

Engineers were already separating out "limestone" from other rock types

Rock	Toughness Drop Test in Cms.	Toughness Relative, Ls. = 1	Relative Wear Deval Test Ls. = 1
Diabase	25	2.8	2.28
Basalt	20	2.2	1.80
Feldspathic quartzite	20	2.2	1.73
Pyroxene quartzite	19	2.1	1.73
Amphibolite	19	2.1	1.80
Altered diabase	19	2.1	1.93
Rhyolite	19	2.1	1.35
Andesite	18	2.0	1.28
Altered basalt	18	2.0	1.66
Diorite	17	1.9	1.66
Slate	17	1.9	1.14
Quartzite	17	1.9	1.51
Hornblende schist	16	1.8	1.14
Augite syenite	15	1.7	1.51
Gabbro	14	1.6	1.66
Calcareous sandstone	14	1.6	1.20
Hornblende gneiss	14	1.6	1.35
Chlorite schist	14	1.6	1.16
Hornblende granite	13	1.4	1.31
Feldspathic sandstone	13	1.4	0.81
Granite	12	1.3	1.35
Chert	12	1.3	0.54
Peridotite	11	1.2	1.25
Biotite schist	11	1.2	1.09
Sandstone	10	1.1	0.81
Granite gneiss	10	1.1	1.10
Mica schist	10	1.1	0.93
Biotite granite	9	1.1	0.93
Limestone	9	1.0	1.00
Dolomite	9	1.0	0.91
Biotite gneiss	8	0.9	0.86
Marble	6	0.7	0.88

Rock	Hardness in Units of U. S. Dept. Agri.	Hardness Re-calculated to Moh Scale	Hardness from Table 1.
Chert	19.4	6.95	6.95
Quartzite	18.9	6.77	6.63
Hornblende granite	18.6	6.67	...
Feldspathic quartzite	18.5	6.63	6.10
Rhyolite	18.3	6.55	6.55
Granite	18.3	6.55	6.54
Fresh diabase	18.3	6.55	6.04
Augite syenite	18.3	6.55	...
Diorite	18.2	6.52	6.26
Trachyte	18.1	6.48	6.33
Syenite	18.0	6.45	6.30
Biotite granite	17.9	6.41	6.49
Basalt	17.8	6.38	6.09
Granite gneiss	17.7	6.34	6.51
Gabbro	17.7	6.34	6.14
Hornblende gneiss	17.6	6.30	5.80
Amphibolite	17.5	6.27	5.82
Andesite	17.0	6.09	6.17
Hornblende schist	17.0	6.09	5.60
Mica schist	16.9	6.05	5.20
Biotite gneiss	16.1	5.95	5.92
Biotite schist	16.1	5.77	5.50
Calcareous sandstone	15.8	5.66	5.41
Chlorite schist	15.4	5.52	...
Slate	15.0	5.38	...
Dolomite	14.9	5.34	...
Feldspathic sandstone	14.6	5.23	...
Sandstone	14.4	5.16	6.13
Peridotite	14.2	5.09	6.28
Limestone	14.1	5.05	3.70
Marble	13.1	4.69	3.20

A loose specification, just had to meet "typical values" and not be unusually soft or flaky

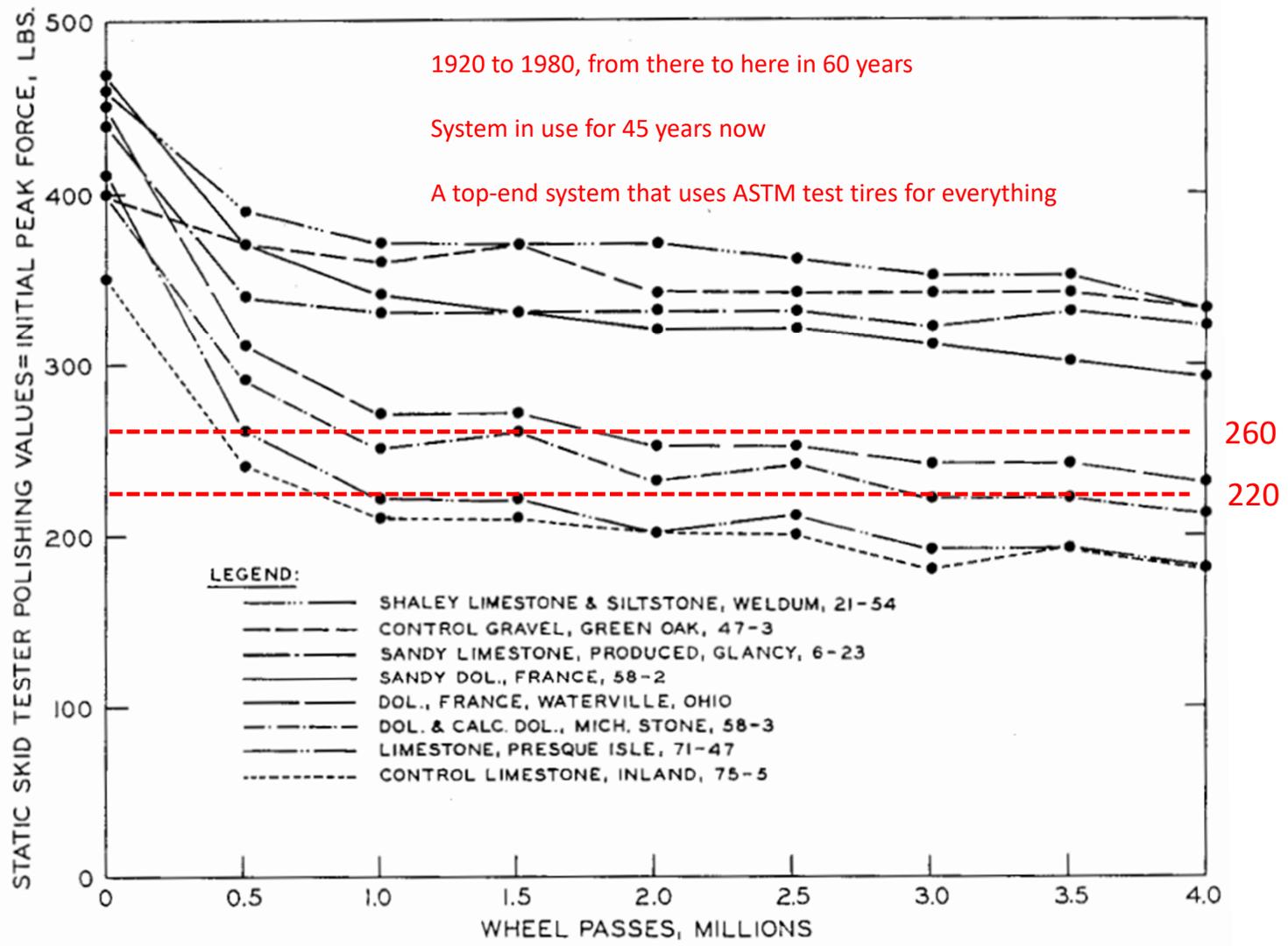


Figure A-4. Wear track test series No. 4.

EUROPE: MicroDeval Abrasion, LA Abrasion with Polished Stone Value (PSV)



EUROPE: Polished Stone Value (PSV)



Figure 3 The polishing machine ready for a PSV test



The “British Wheel” Polisher

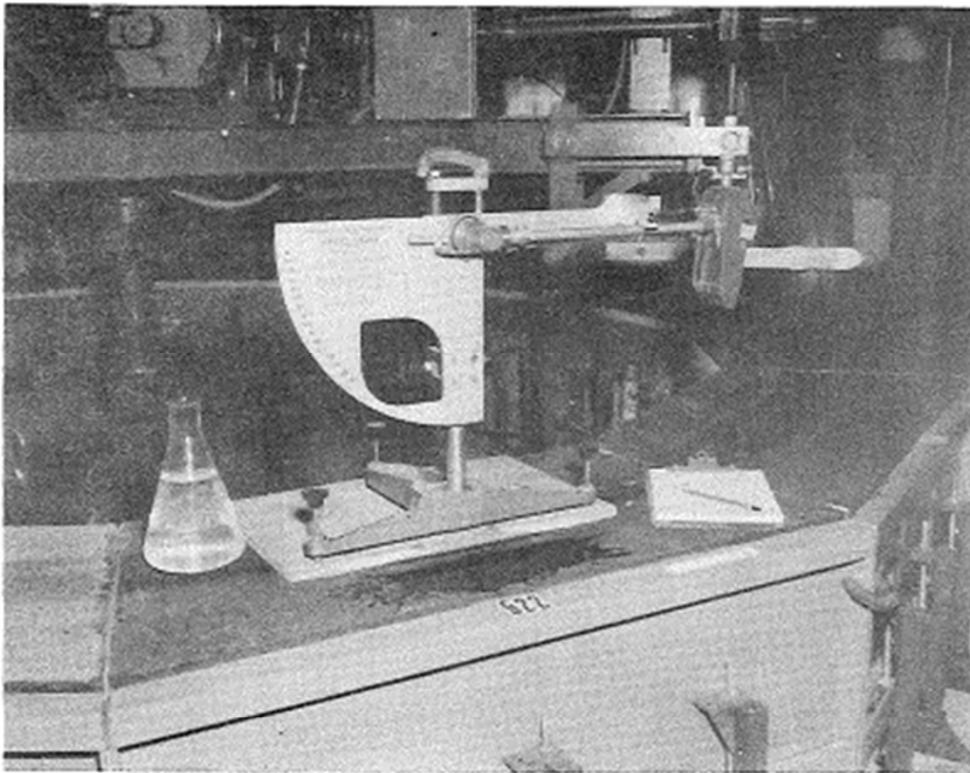


S882- ACCELERATED POLISHING MACHINE

DETERMINATION OF POLISHED STONE VALUE

- EN 1097-8:2009 (formerley BS812: Part 114: 1989)
- ASTM E303-93
- ASTM D3319-99

The Accelerated Polishing Machine is the industry standard device for the determination of the Polished Stone Value PSV



The "British Pendulum"

STANDARD PORTABLE SKID
RESISTANCE TESTER INSTRUMENT

Indiana DOT – Modified European Standard

TABLE 3.2
Specified Limits for Aggregate Properties

Property	Limit	Note
LAA	<30%	
MDA	<18%	
PSV-10	>28	
Magnesium (Mg) Content	>10.3% ¹	For Dolomite

¹(Magnesium)>10.3% is equal to (Magnesium Oxide)/0.60317
>17.1%

Laboratory Implementation of DFT

Maryland DOT Testing

- Circular Track Polishing Machine (3-Wheel Polisher)
- 100,000 revolutions (~36 hours)
- No water is used during polishing.

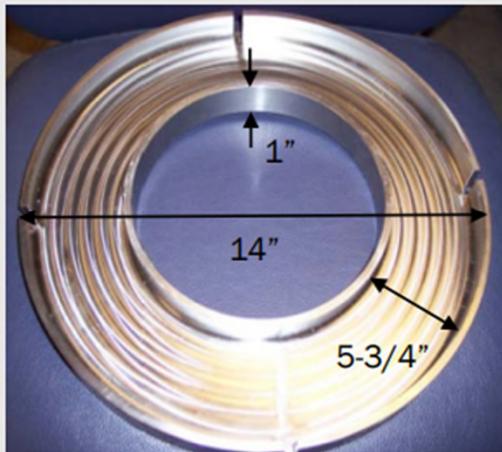


Laboratory Implementation of DFT



Maryland DOT Testing

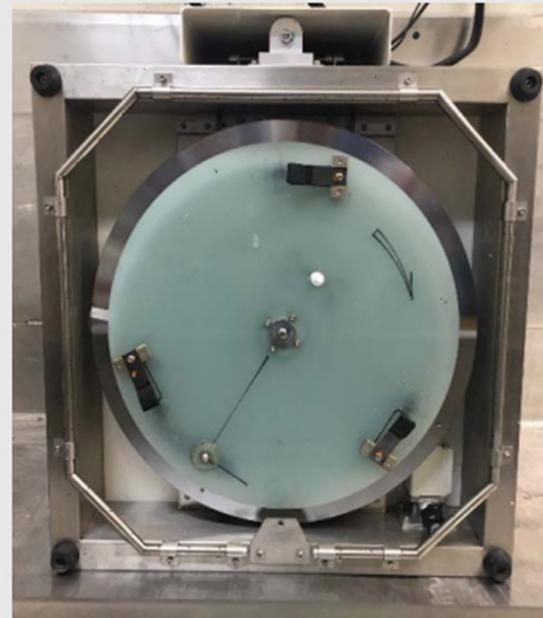
- Passing $\frac{1}{2}$ " and retained $\frac{3}{8}$ "
- ~ 24 hours with curing.



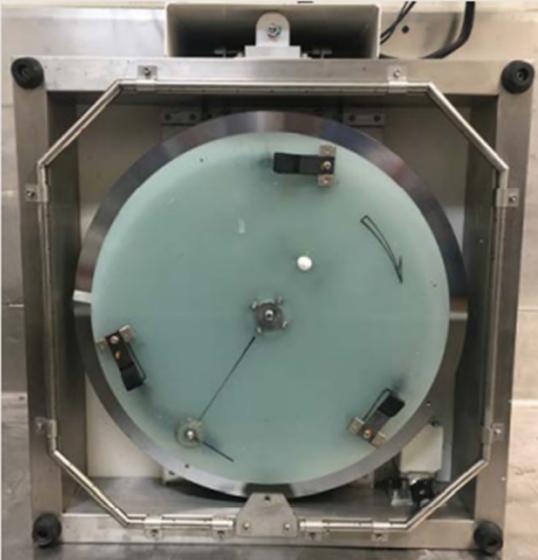
Dynamic Friction Tester (DFT)



- Dynamic Friction Test (DFT) measures a friction value on wet pavement surface (ASTM E1911).
- Spinning disk with 3 rubber sliders that contact the pavement surface as disk rotates.



Dynamic Friction Tester (DFT)

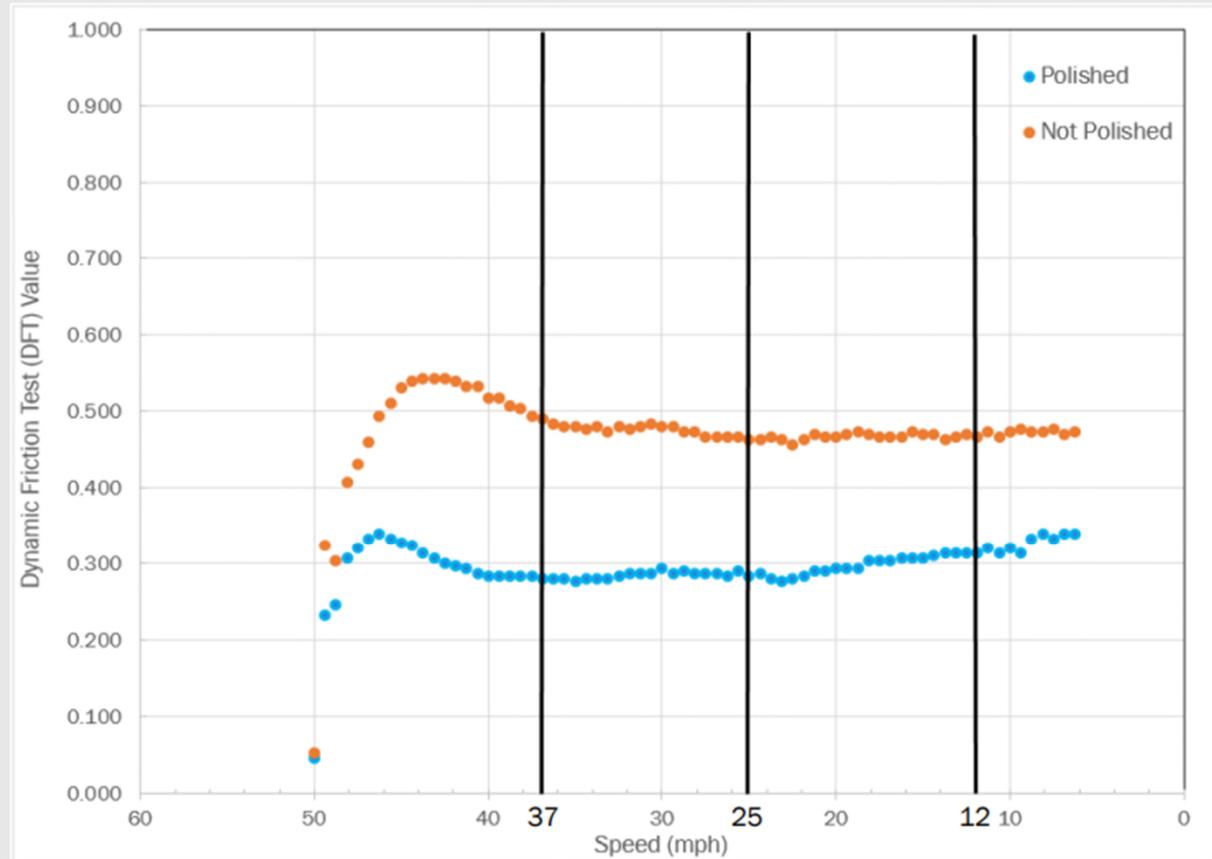


- Spinning disk with 3 rubber sliders
- L $\frac{3}{4}$ ", W $\frac{5}{8}$ ", H $\frac{1}{4}$ "
- Water is applied to pavement surface.
- Disk contacts the pavement surface at 50 mph.

Dynamic Friction Tester (DFT)



DFT value is an average of data collected at 37, 25, and 12 mph (60, 40, and 20 kph).

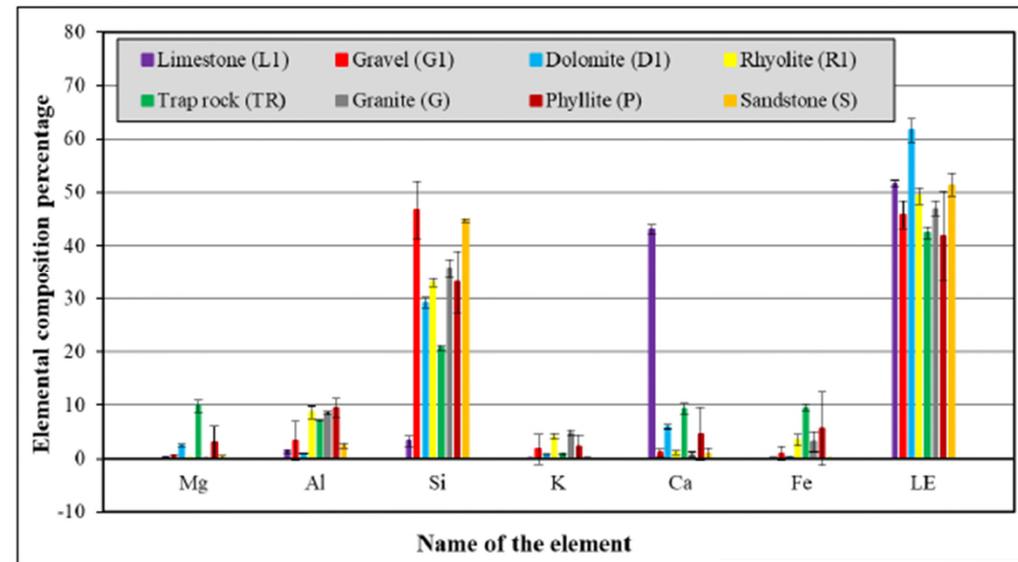
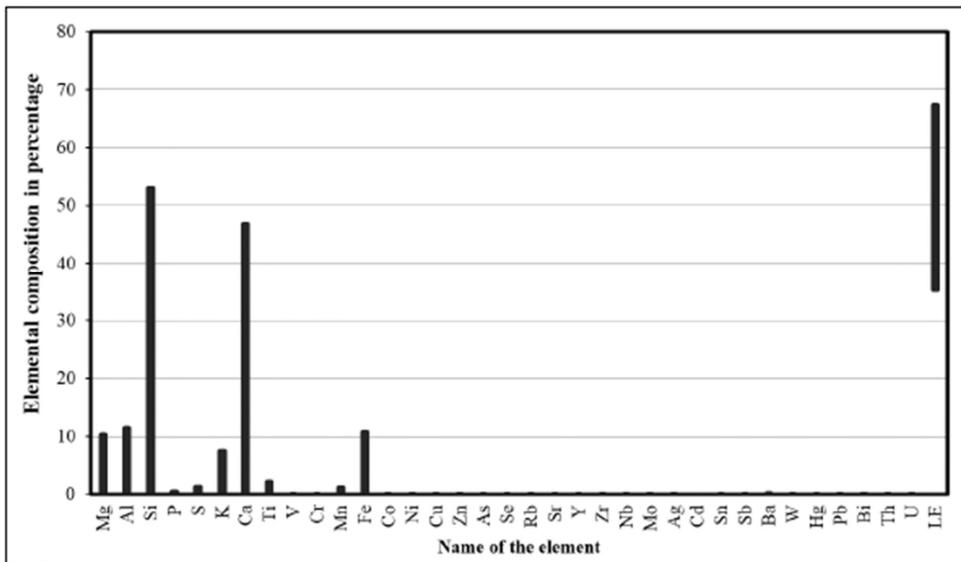


Portable XRF for Predicting Aggregate Frictional Resistance



❖ Commonly Observed Elements and Repeatability of XRF

- Eight limestones, Seven gravels, Four dolomites, Three rhyolite, One each of trap rock, granite, phyllite, and sandstone



→ Mg, Al, Si, K, Ca, Fe, and LE

Repeatability analysis

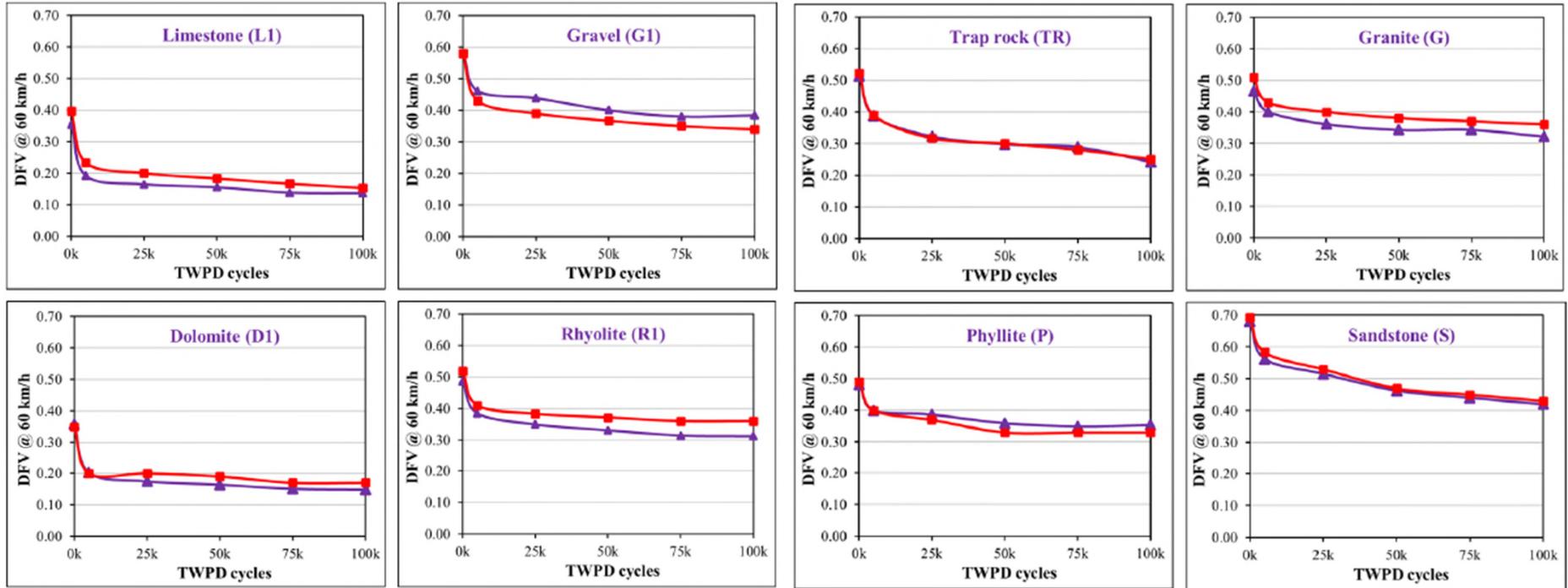
- G. Sandeep Reddy
- Imad N. Abdallah, PhD
- Soheil Nazarian, PhD

Portable XRF for Predicting Aggregate Frictional Resistance



❖ Measured and Predicted Friction Deterioration Curves for Selected Aggregates

- Eight limestones, Seven gravels, Four dolomites, Three rhyolite, One each of trap rock, granite, phyllite, and sandstone



Measured friction deterioration curve [40 hrs.]
 Predicted friction deterioration curve [0.5 hrs.]

Laboratory Implementation of DFT



Maryland DOT Specifications

- Blended DFT values based on aggregate bin %'s and gradations from HMA mixture designs.
- High DFV includes SMA, Open Graded Friction Course (PFC), & Surface Courses.
 - DFV greater than 40
- Standard DFV includes Surface Courses only.
 - DFV greater than 25
- RAP assigned a DFV of 30

DYNAMIC FRICTION VALUE (DFV)		
Category		DFV, minimum
HDFV I	High DFV	50
HDFV II		45
HDFV III		40
SDFV IV	Standard DFV	30
SDFV V		25
LDFV VI	Low DFV	20

Le manège de fatigue des structures routières



Un accélérateur de trafic exceptionnel dans le monde

*Roue
simple*



*Roues
jumelées*



*Tandem
à roues
jumelées*



Tridem

