The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

How rough is your pavement?

Tuesday, March 17, 2020
2:00-3:30 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Learning Objectives

At the end of this webinar, you will be able to:

- Develop a plan for characterizing and reporting roughness on urban and low-speed roadways
- Apply the IRI algorithm to urban and low-speed roadways that improves correlation to objective measurements of ride quality
- Analyze assess the accuracy of road profile measurements collected under adverse conditions
- Measure profile more accurately on urban and low-speed roadways

NCHRP
Research Report 914

Measuring, Characterizing, and Reporting
Pavement Roughness
of Low-Speed and Urban Roads

Moderator: Brian L. Schleppi OH DOT

Background

- Most all inertial profilers to date are unable to collect valid road profile data at very low speeds and in stop and go operation
- Even if (and when) we are able to collect valid road profiles in such conditions, we may be over stating the perceived roughness as the International Roughness Index uses a 50 mph simulated travel speed
  - Since our actual travel speeds are much lower, these roads don’t “feel” as rough
  - Arguably, comparing IRI from urban and low speed roads to say interstates and expressways, is not legitimate

Background

- The type or spectrum of roughness events in urban and low speed environments can be quite different from high speed facilities
  - Crowned intersections
  - Bus pads
  - Man hole covers
  - Curb drains
  - Etc.
- An alternative to the current IRI is needed to improve quantification of road roughness on the low-speed and urban highway networks

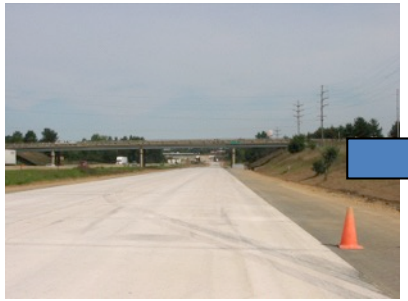
TRB Seminar

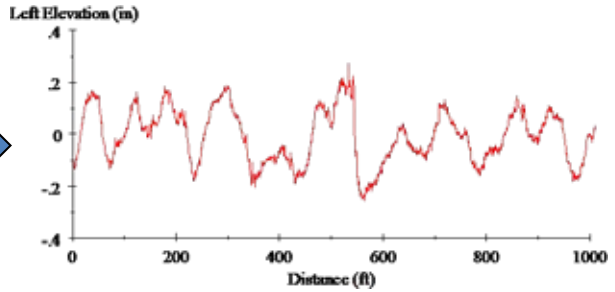
Measuring, Characterizing, and Reporting Pavement Roughness of Low-Speed and Urban Roads

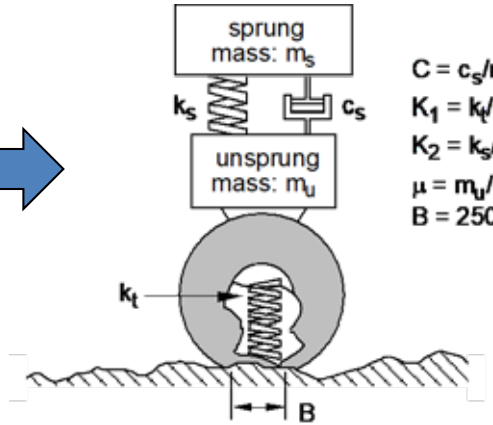
March 17, 2020

Steven M. Karamihas, Brian L. Schleppi

Road Profiles and International Roughness Index







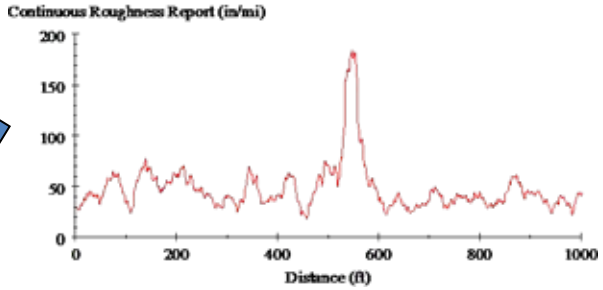
$C = c_s/m_s = 6.0\ sec^{-1}$

$K_1 = k_t/m_s = 653\ sec^{-2}$

$K_2 = k_s/m_s = 63.3\ sec^{-2}$

$\mu = m_u/m_s = 0.15$

$B = 250\ mm$



IRI

NCHRP Report 914

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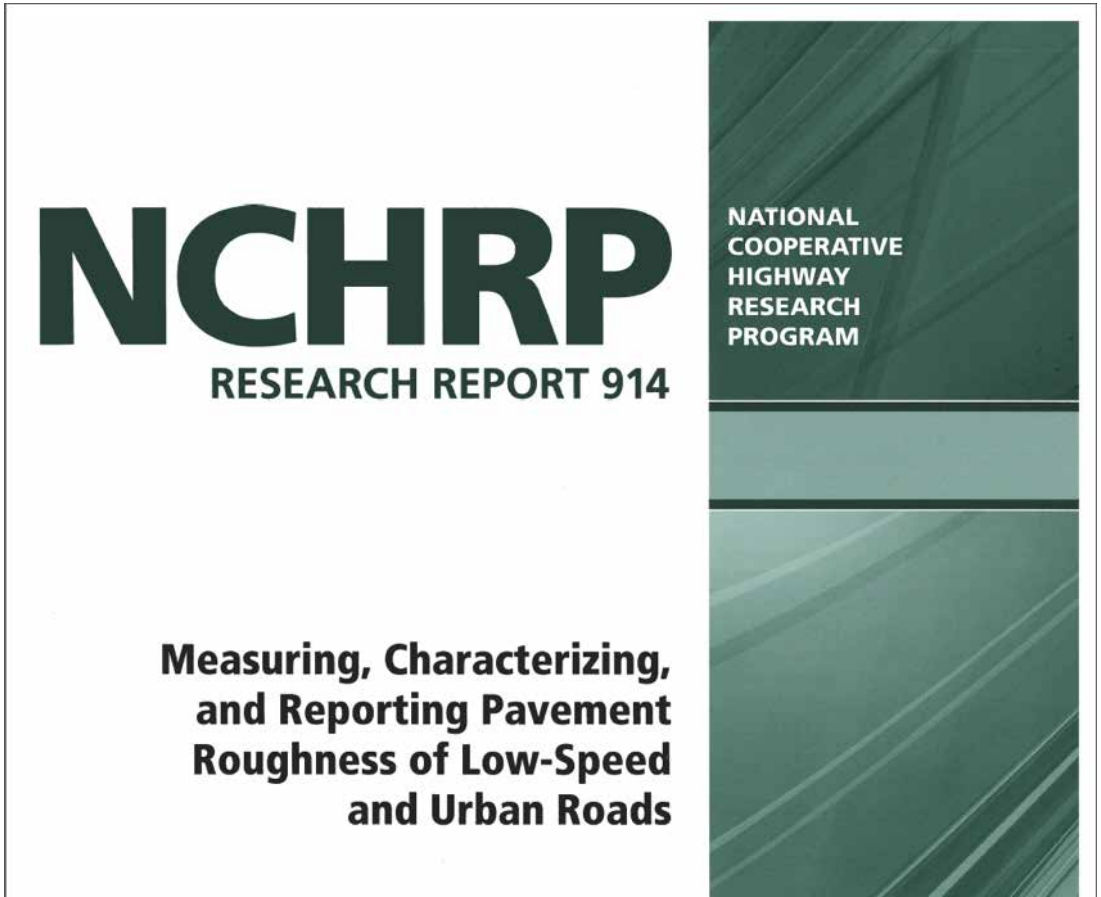

Outline

- Urban and Low-Speed Road Profile Content
- Incorporation of Additional Data
- Theory of Inertial Profiling
- Road Profiler Operation at Low Speed and with Stops
- Automatic Detection of Profile Measurement Errors
- IRI and Ride Quality Primer
- Low-Speed Roughness Index
- Recommendations (as we go along…)

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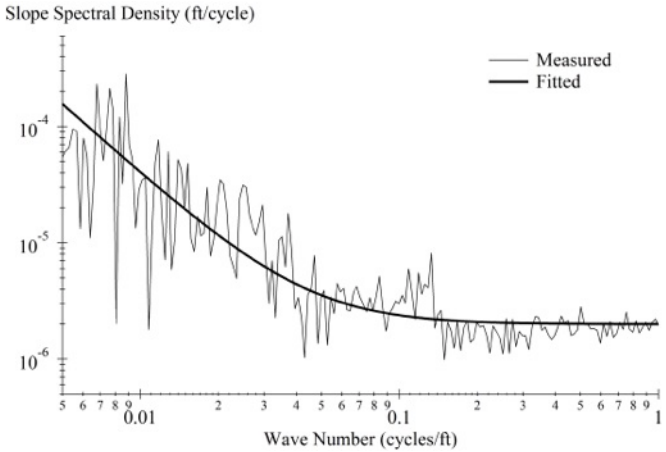
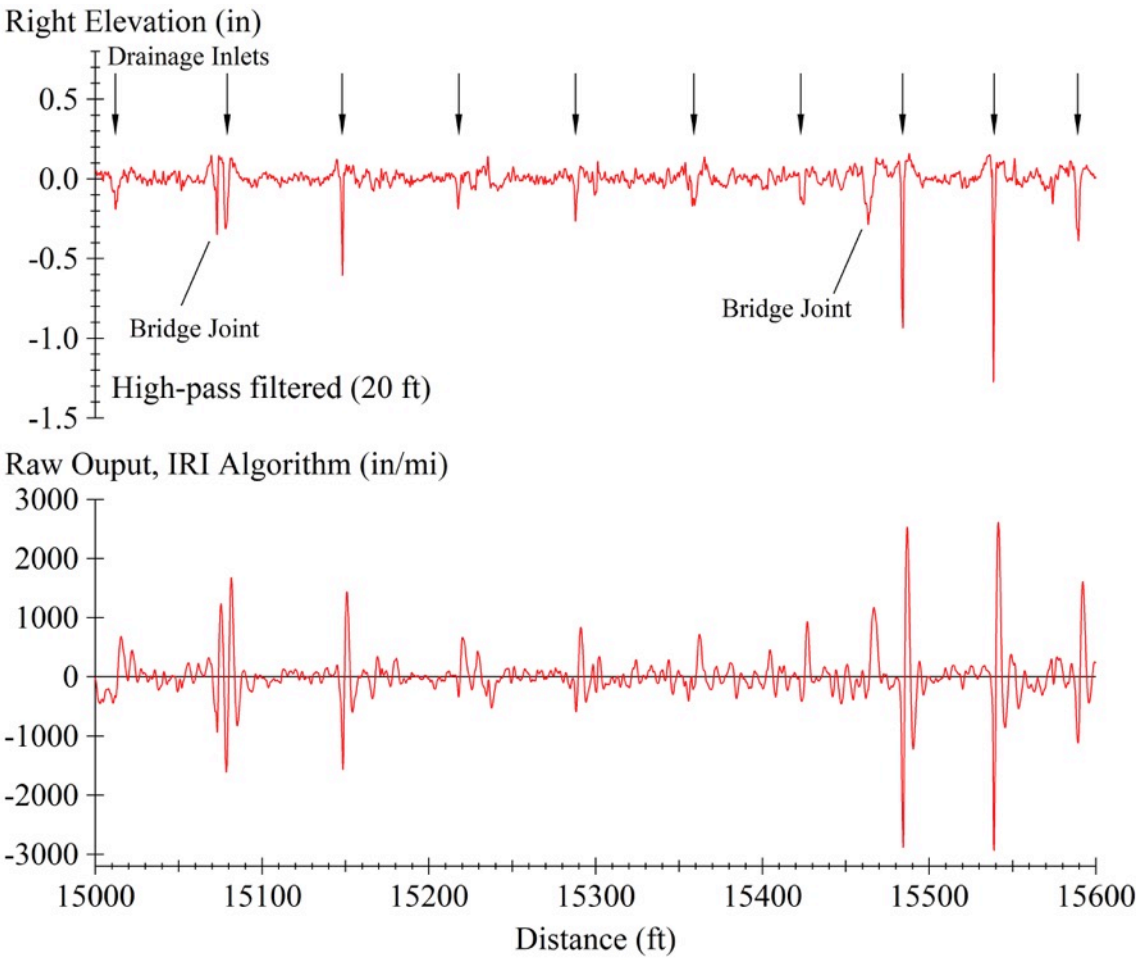
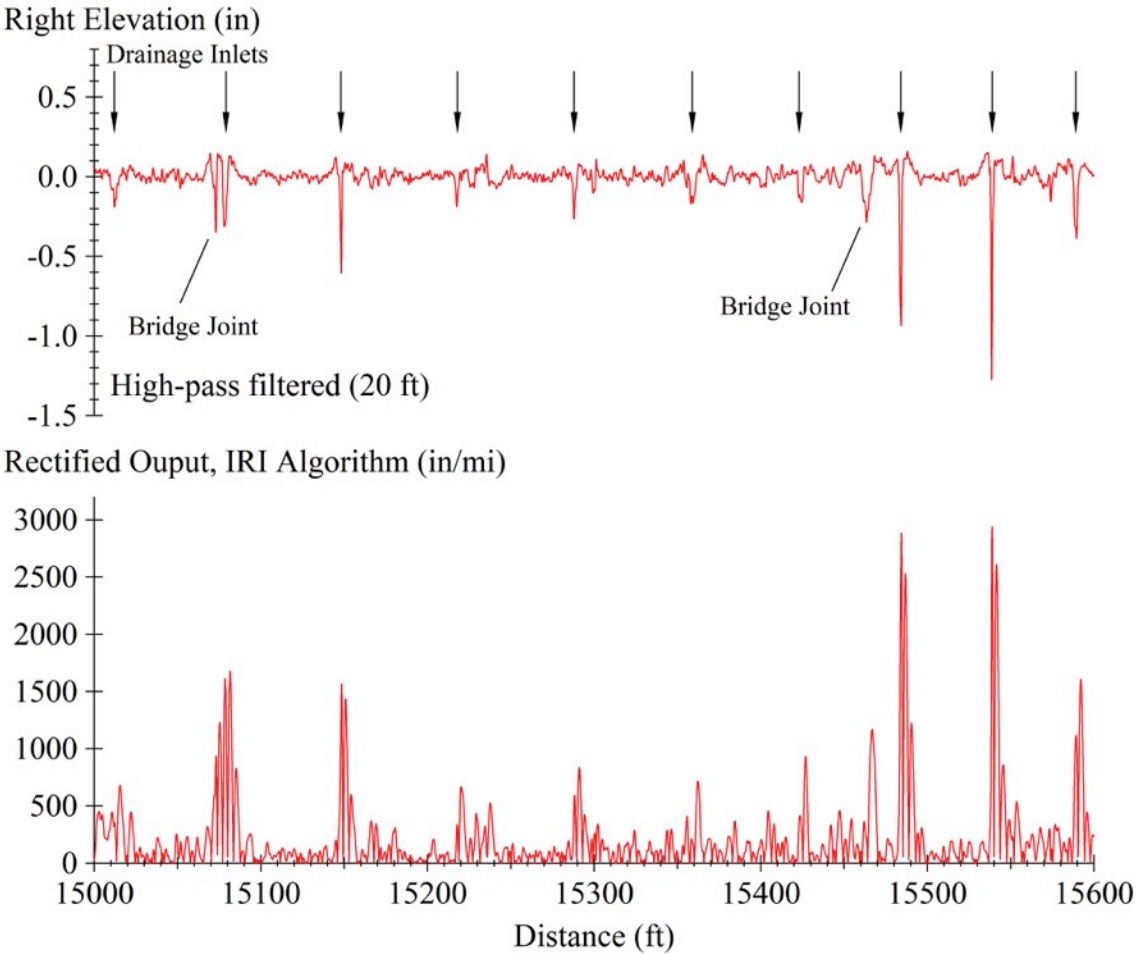
Low-Speed Road Profile Content



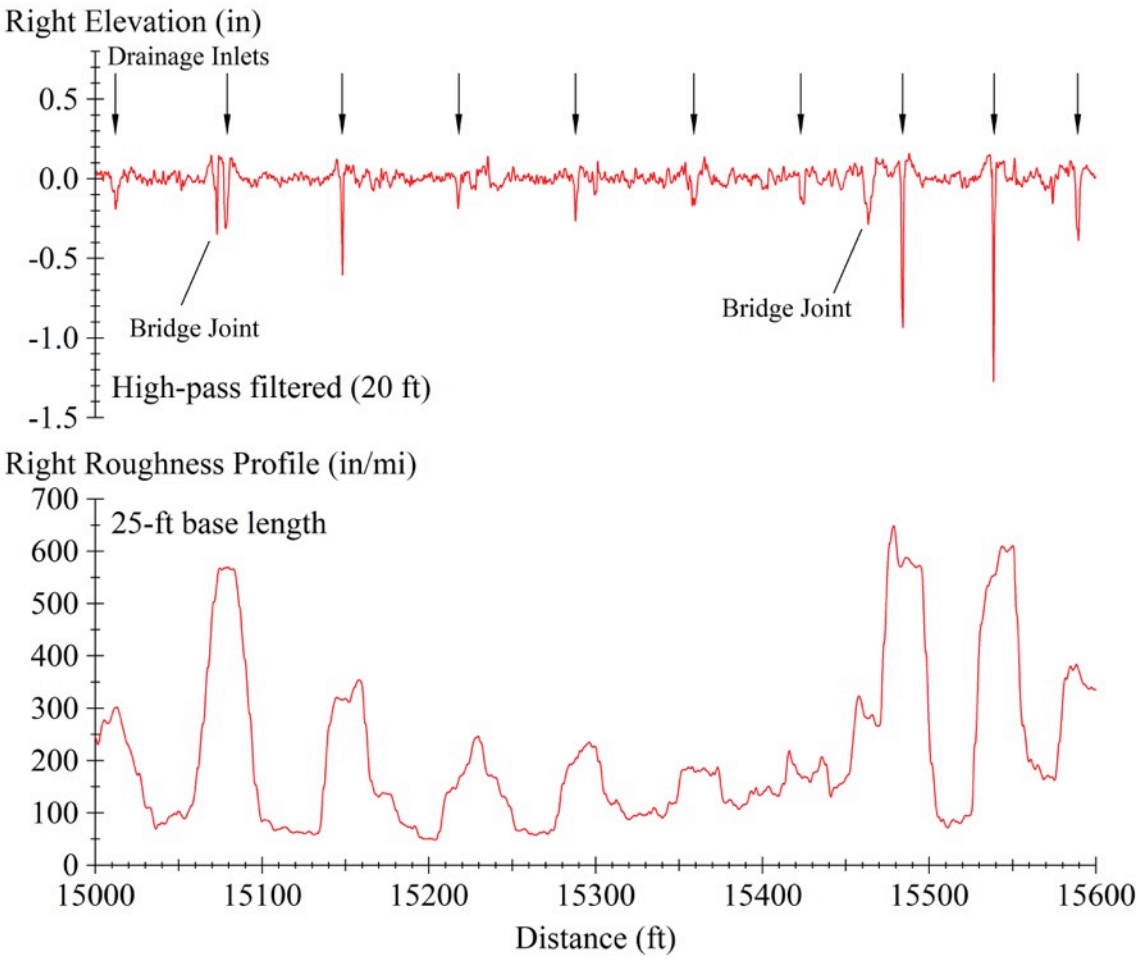
Drainage Inlets



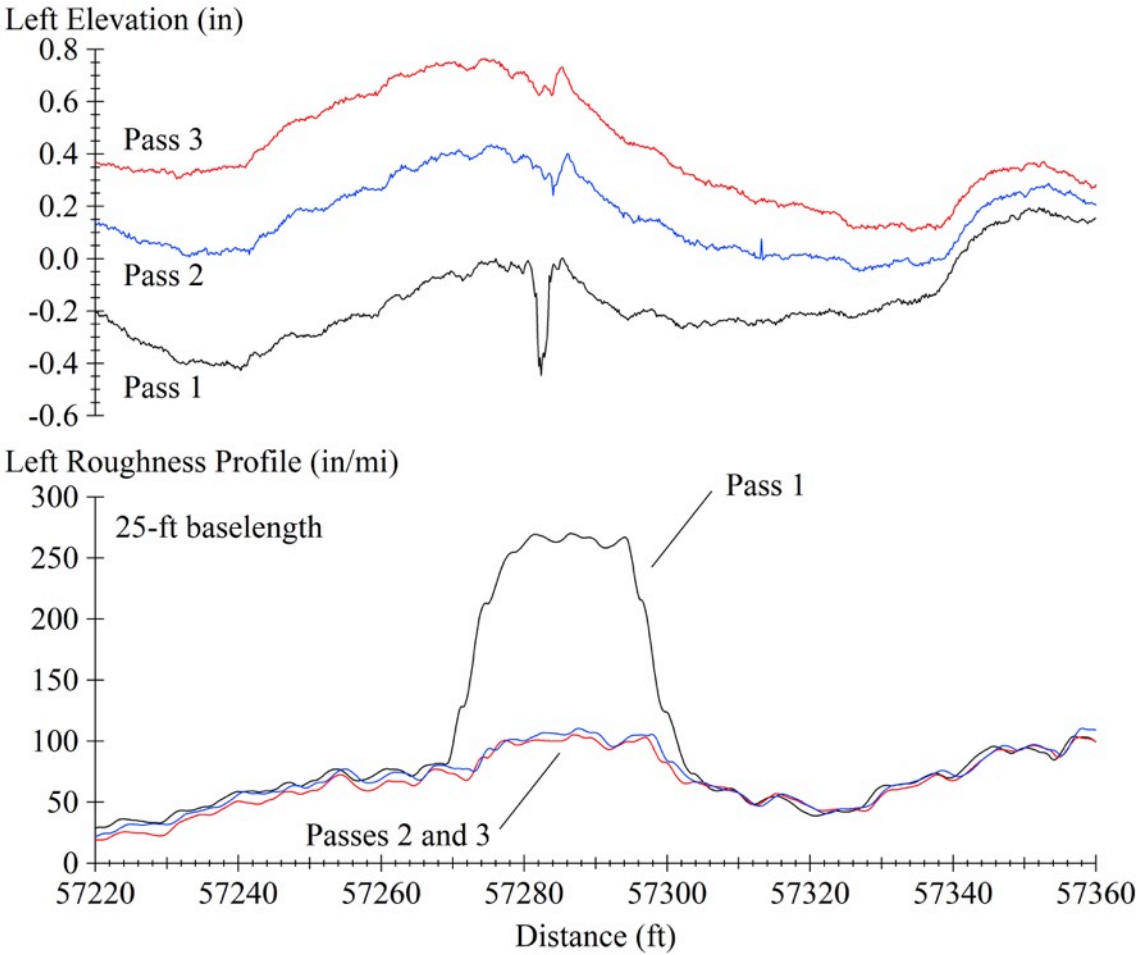
Drainage Inlets



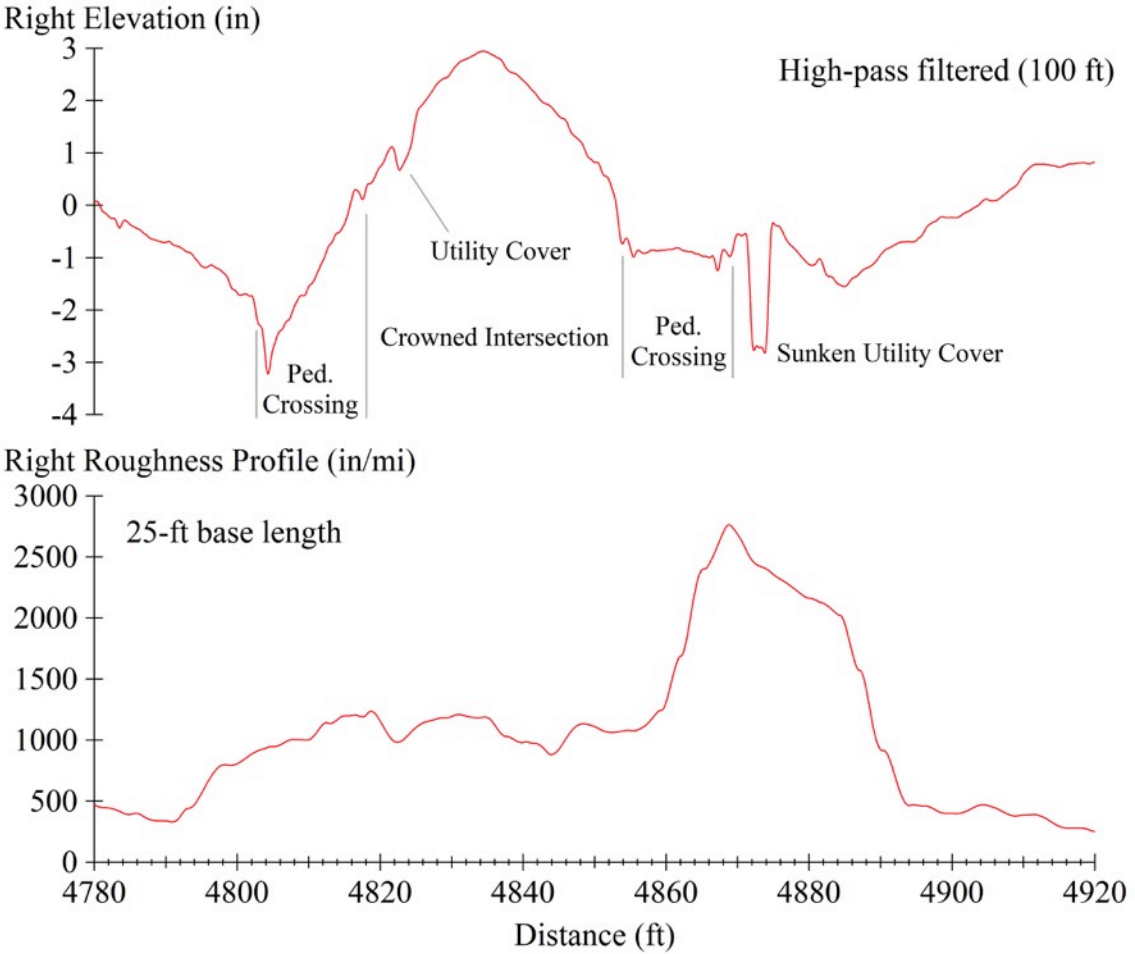
Drainage Inlets



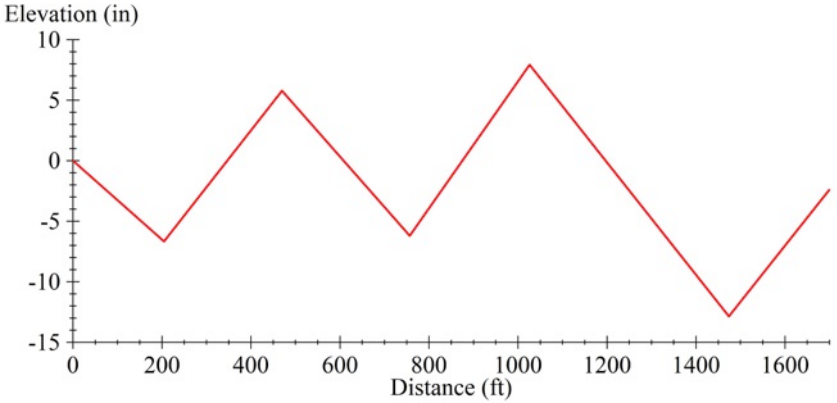
Hit or Miss Utility Cover

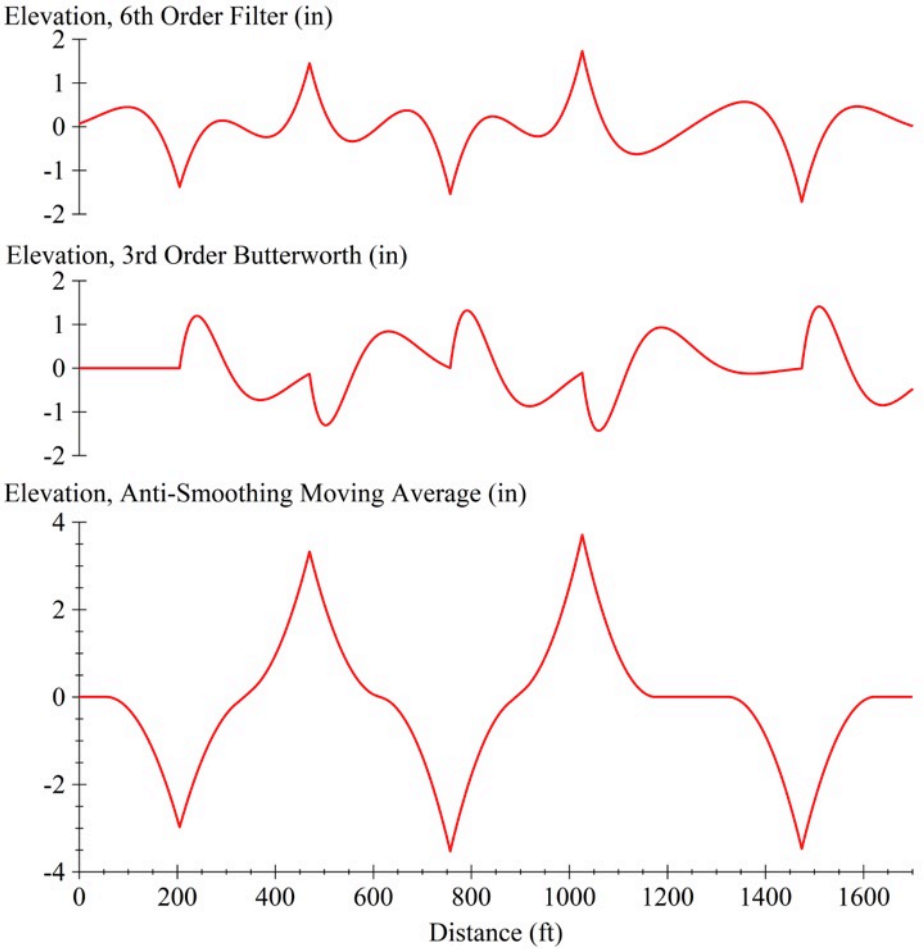


Compound Event



High-Pass Filtering: Grade Breaks



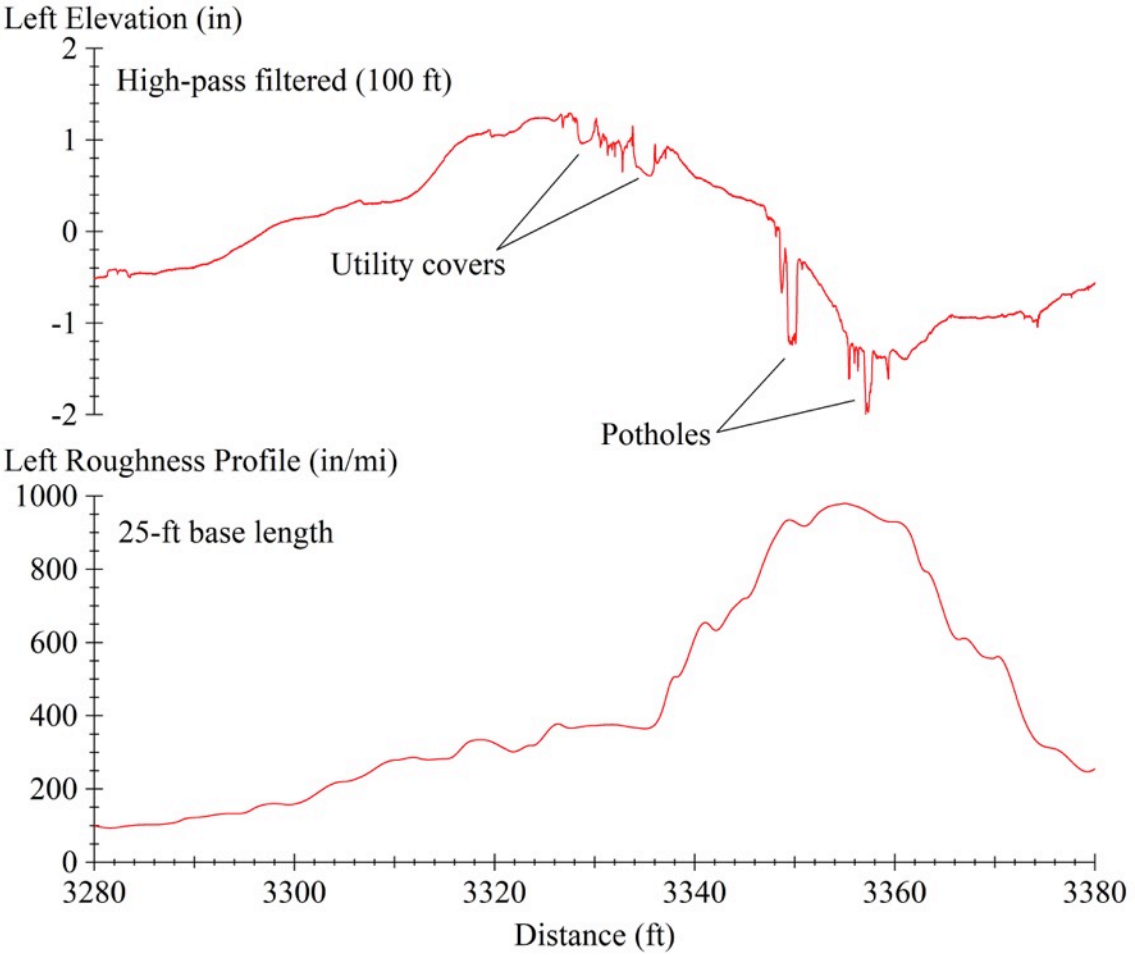


Reggin, A, et al.. 2008. “Urban considerations for Using Road Roughness To Manage Road Networks.” 7th International Conference on Managing Pavement Assets, Calgary, Alberta.

Recommendations

- Quantify localized roughness using a roughness profile.
- Set the standard base length to 25 ft.
- Record severe areas of localized roughness (ALR).
- Investigate severe ALR using profile.
- Know and understand your high-pass filter.
- Specify high-pass filtering with minimal distortion.
- Modifications to AASHTO M 328 and R 54 are recommended.

Feature Identification



Incorporation of Additional Data

- Distinguish between built-in features and pavement deterioration.
- Incorporate images into project-level analysis.
- Specify storage of profile with GPS.
- Link to available databases:
  - Available: Railroad crossings, intersections, bridges
  - Much Less Available: Utility cuts

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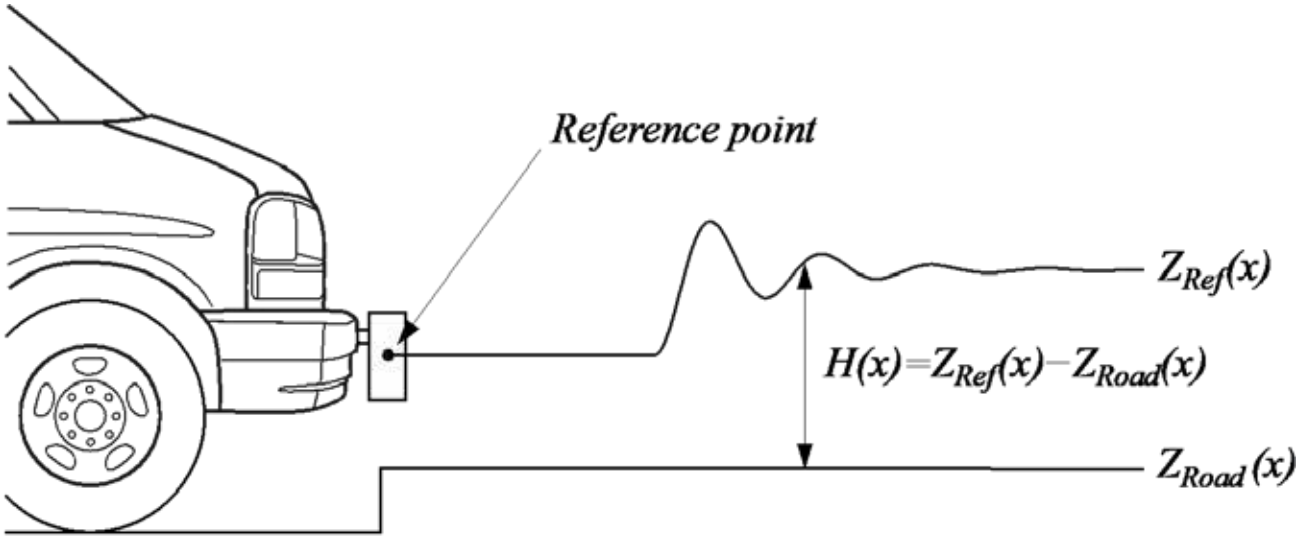
Inertial Profiler, Theory of Operation



$$Z_{Road}(x) = Z_{Ref}(x) - \left(Z_{Ref}(x) - Z_{Road}(x)\right)$$

$$Z_{Road}(t) = \iint A_{Ref}(t)\,dt\,dt - H(t)$$

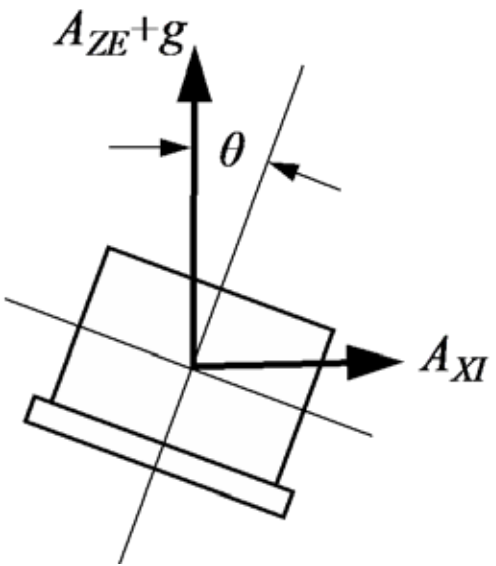
$$Z_{Road}(x) = \iint \left(A_{Ref}(x)/V^2(x)\right)dx\,dx - H(x)$$

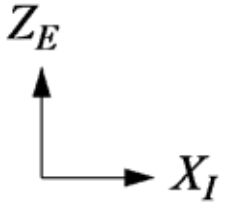
A_{Ref} – vertical acceleration

V – vehicle forward speed (often assumed constant)

Reproduced from: Huft, D. L., "South Dakota Profilometer." *Transportation Research Record 1000* (1984) p. 1-8.

Accelerometer Alignment, Servo Type





$$A_{ZV} = A_{XI}\sin(\theta) + (A_{ZE}+g)\cos(\theta) - g$$

$$A_{ZV} - A_{ZE} = A_{XI}\sin(\theta) + (A_{ZE}+g)(\cos(\theta) - 1)$$

Tilted due to longitudinal deceleration

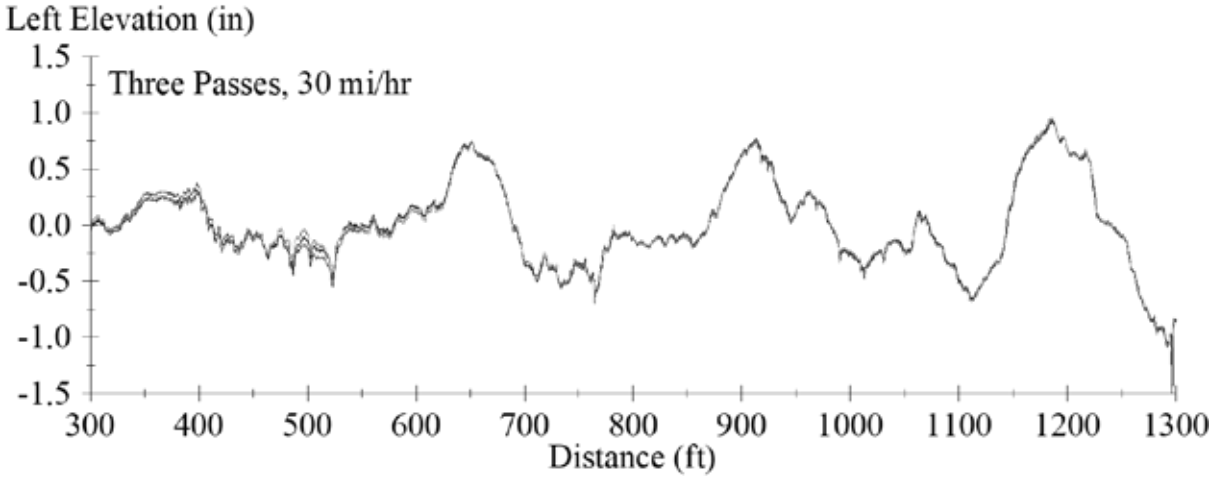
Reproduced from: Sayers, M. W. and S. M. Karamihas, *The Little Book of Profiling.* University of Michigan Transportation Research Institute (1998) 100 p.

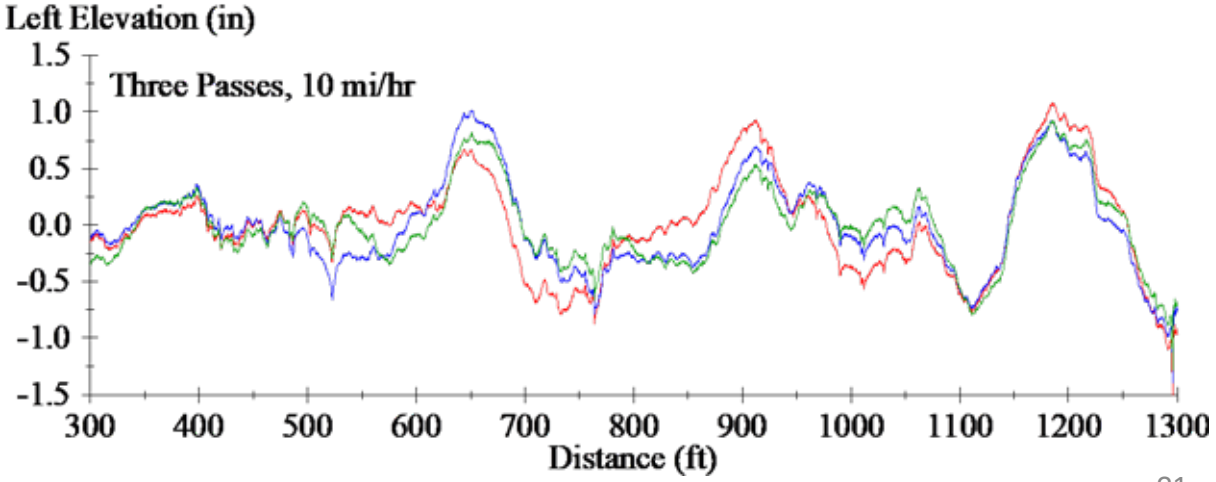
“Speed” Experiment

- Included ~30 staged reproductions of common disturbances.
- Tested 6 commercial inertial profilers.
- Examined effects on profile and IRI.

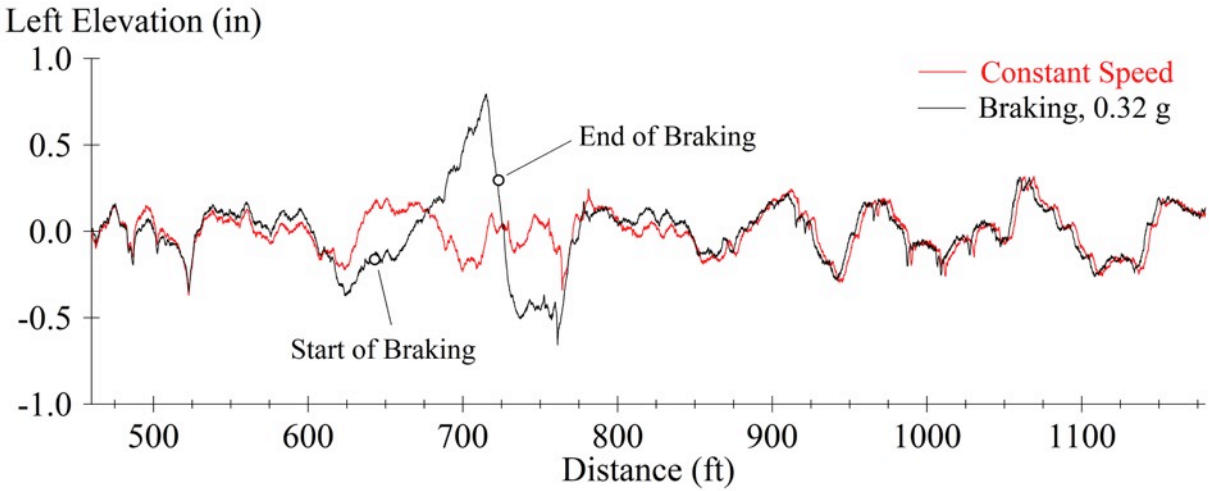
“Speed” Experiment: Test Profilers

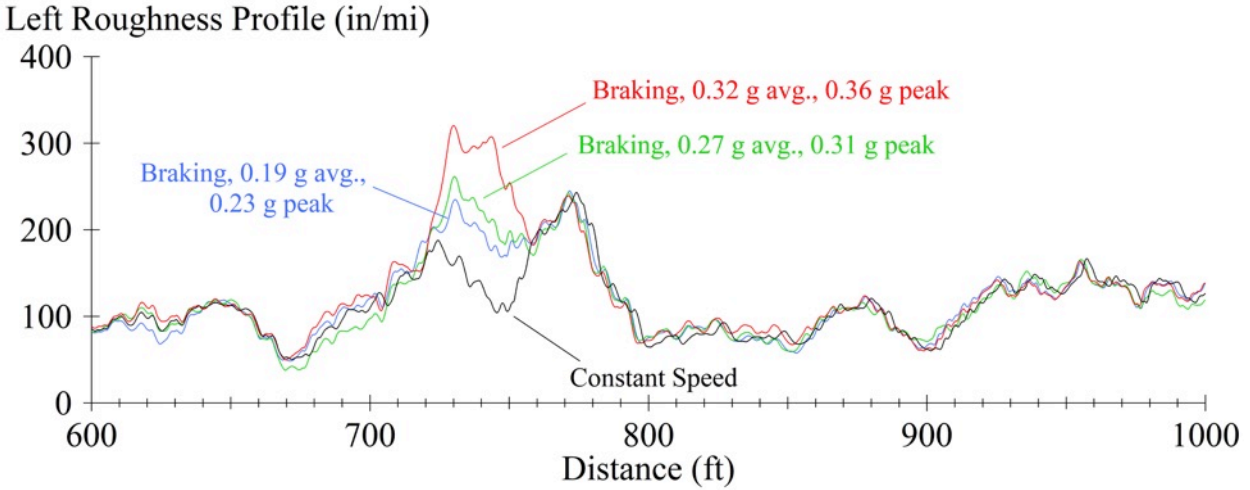
Low Speed Operation



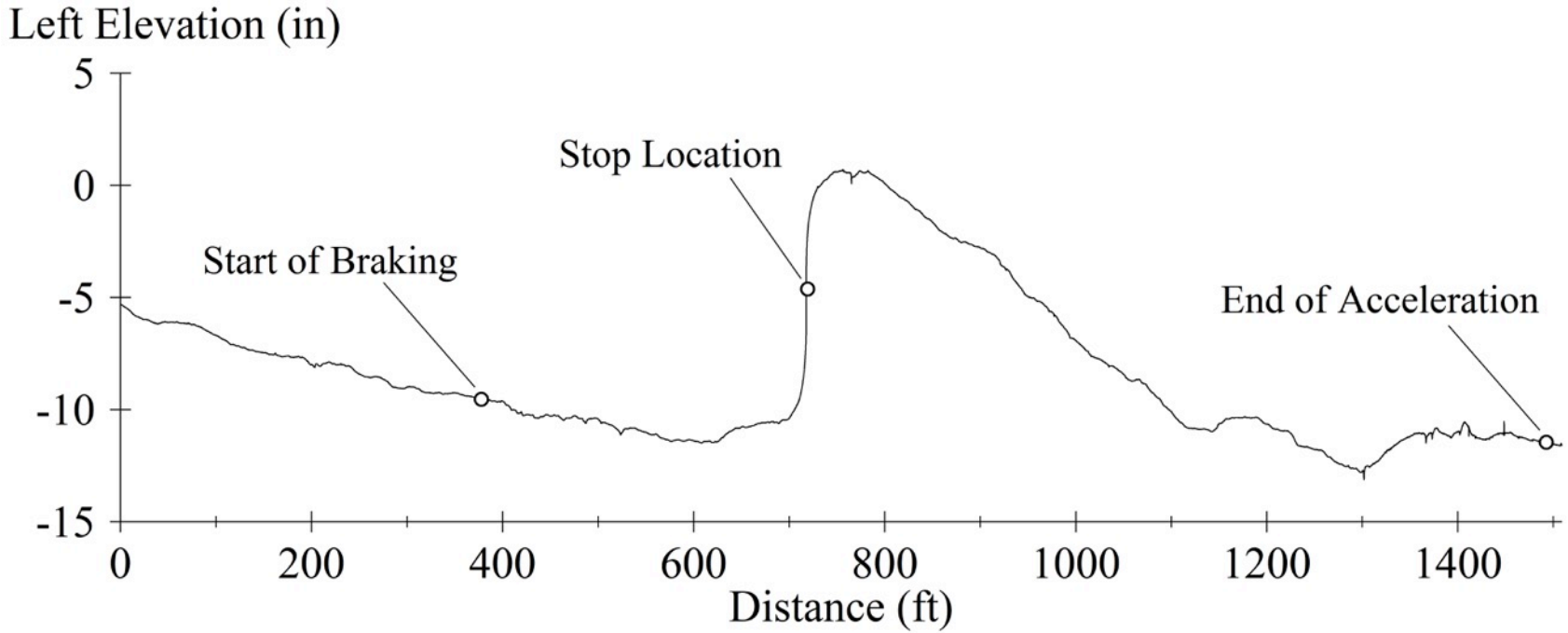


Braking

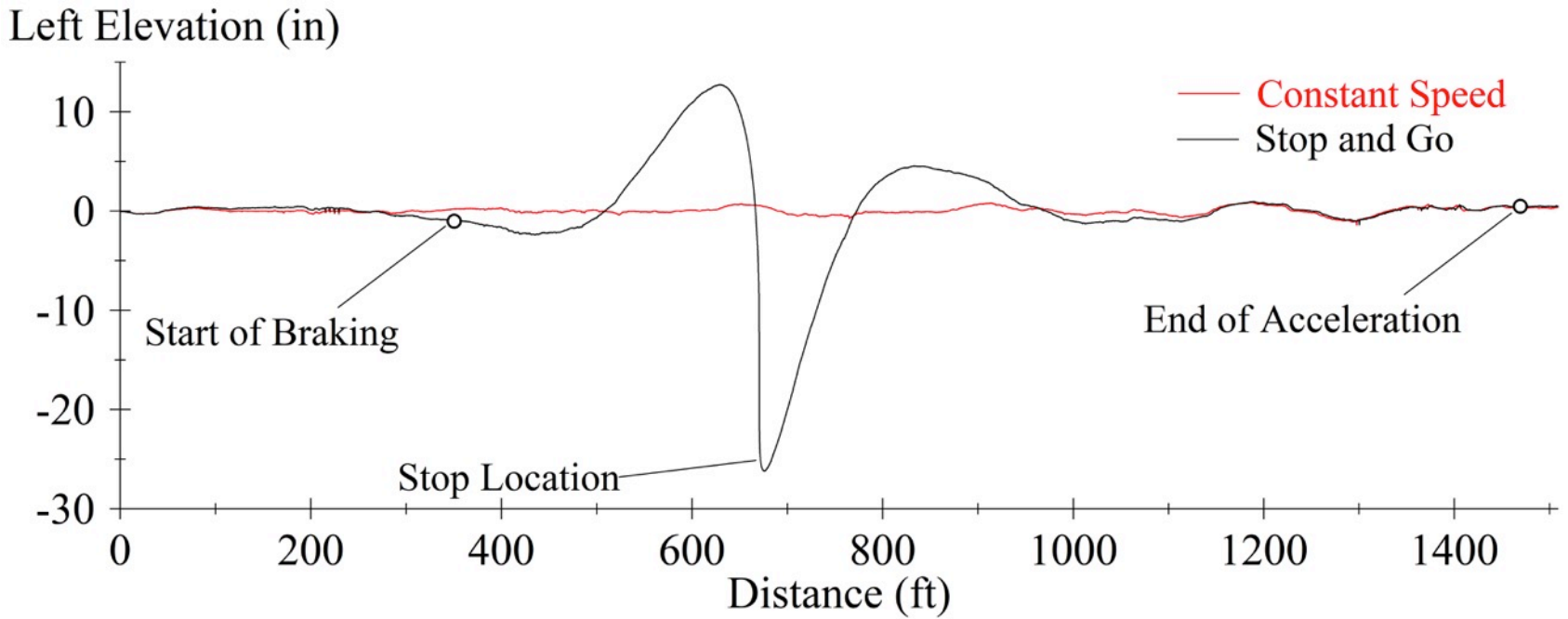

Left Elevation (in)
1.0
0.5
0.0
-0.5
-1.0
Constant Speed
Braking, 0.32 g
End of Braking
Start of Braking
500
600
700
800
900
1000
1100
Distance (ft)


Left Roughness Profile (in/mi)
400
300
200
100
0
Braking, 0.32 g avg., 0.36 g peak
Braking, 0.27 g avg., 0.31 g peak
Braking, 0.19 g avg.,
0.23 g peak
Constant Speed
600
700
800
900
1000
Distance (ft)

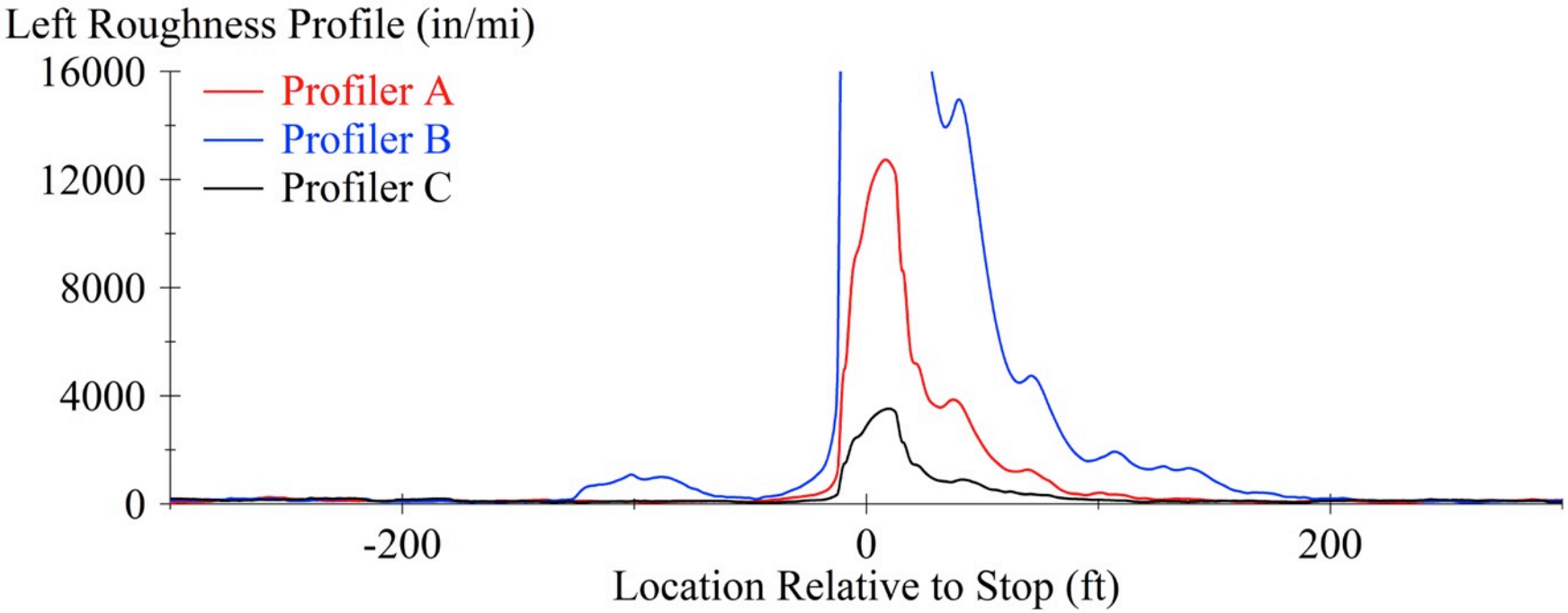
Stop and Go, Profile with Minimal Filtering



Stop and Go, Profile with Filtering



Stop and Go, Roughness Profiles



The severity and range were not consistent among the test profilers.

Stop and Go, Contaminated Region

Profiler	Side	Passes	Peak Localized Roughness (in/mi)	Contaminated Area (ft)	
				Upstream	Downstream
Profiler 1	Left	14	570-1,265	-44	77
	Right	14	380-635	-44	137
Profiler 2	Left	12	3,040-6,275	-46	160
	Right	12	0-2,220	-34	123
Profiler 3	Left	13	0-190	-33	96
	Right	13	30-190	-59	93
Profiler 4	Left	13	6,526-41,247	-78	171
	Right	13	4,055-37,000	-46	156
Profiler 5	Left	13	26,930-170,945	-152	248
	Right	13	10,330-256,610	-155	245
Profiler 6	Right	12	1,900-10,075	-74	153

Major Results

- Each profiler had a low-speed limit.
- Errors caused by horizontal acceleration depended on vehicle properties.
- Misalignment and drift at zero speed caused localized roughness in all cases.
- Filtering affected the area contaminated by a disturbance.
- Each profiler performed differently.

Recommendations

- Learn you profiler’s limits as a supplemental aspect of profiler certification.
- Use repeated runs if reference profiles are not available.
- Communicate these limits to your drivers.
- Safety is a much higher priority than data quality.

Automatic Detection of Errors

- Specify profilers that identify adverse conditions automatically:

  Low speed, excessive deceleration, stops, sensors out of range
- Specify processing software that can remove contaminated areas from IRI calculations.
- Modifications to AASHTO M 328, R 56, and R 57 are recommended.

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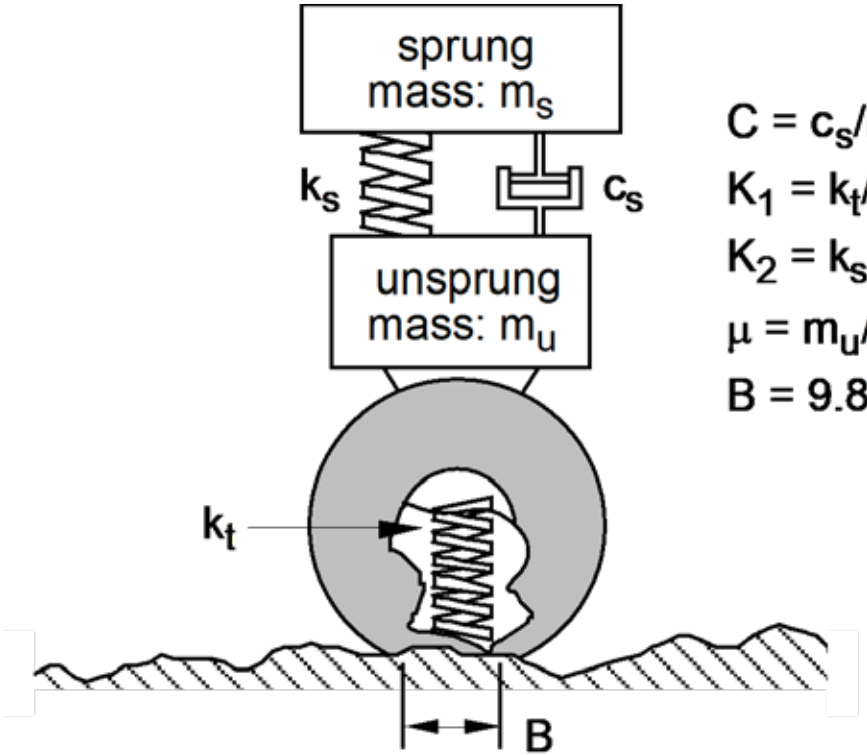
International Roughness Index (IRI)



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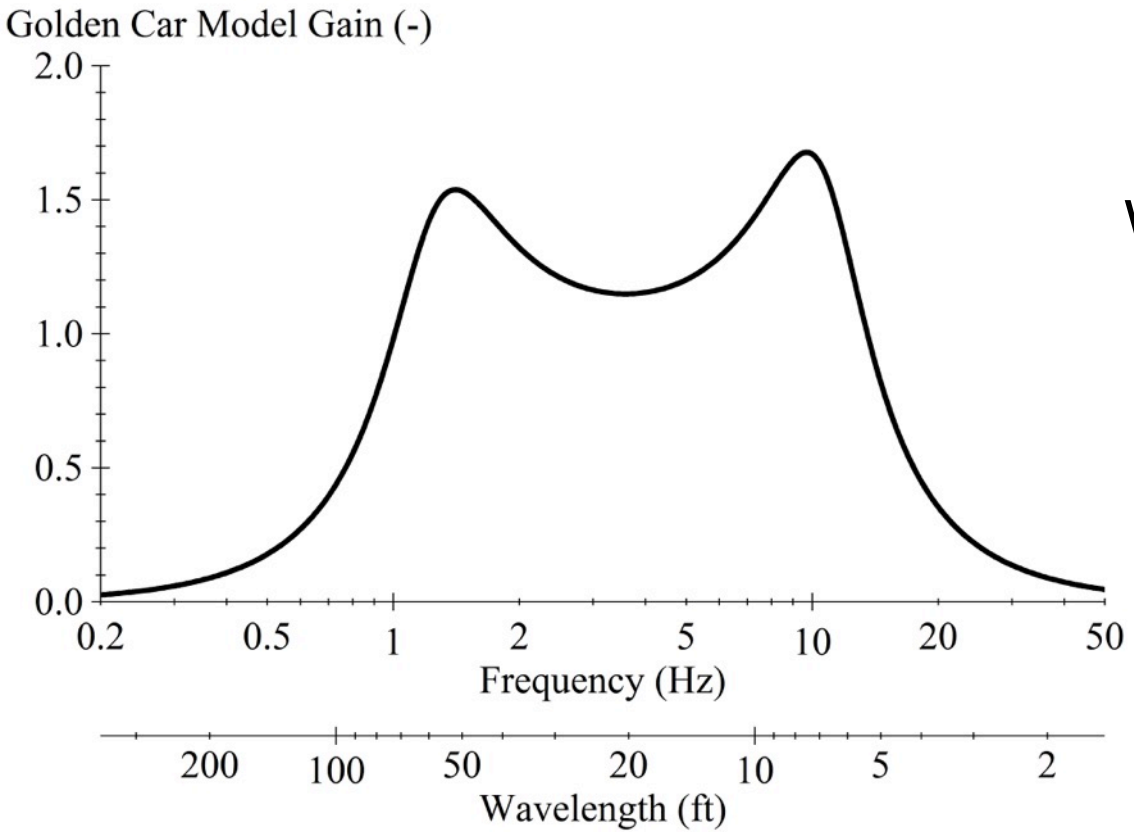
$K_2 = k_s/m_s = 63.3\ sec^{-2}$

$\mu = m_u/m_s = 0.15$

$B = 9.84\ in$

Sayers, M. W., "On the Calculation of International Roughness Index from Longitudinal Road Profile." *Transportation Research Record 1501* (1995) pp. 1-12.

Golden-Car Model Response



Wavelength
= Speed/Frequency

Karamihas, S. M., "Golden-Car Simulation Speed and Its Implications to the Relevance of the IRI." *ASTM STP 1555* (2011).
AASHTO M328-14, "Standard Specification for Inertial Profiler."

Ride Experiment

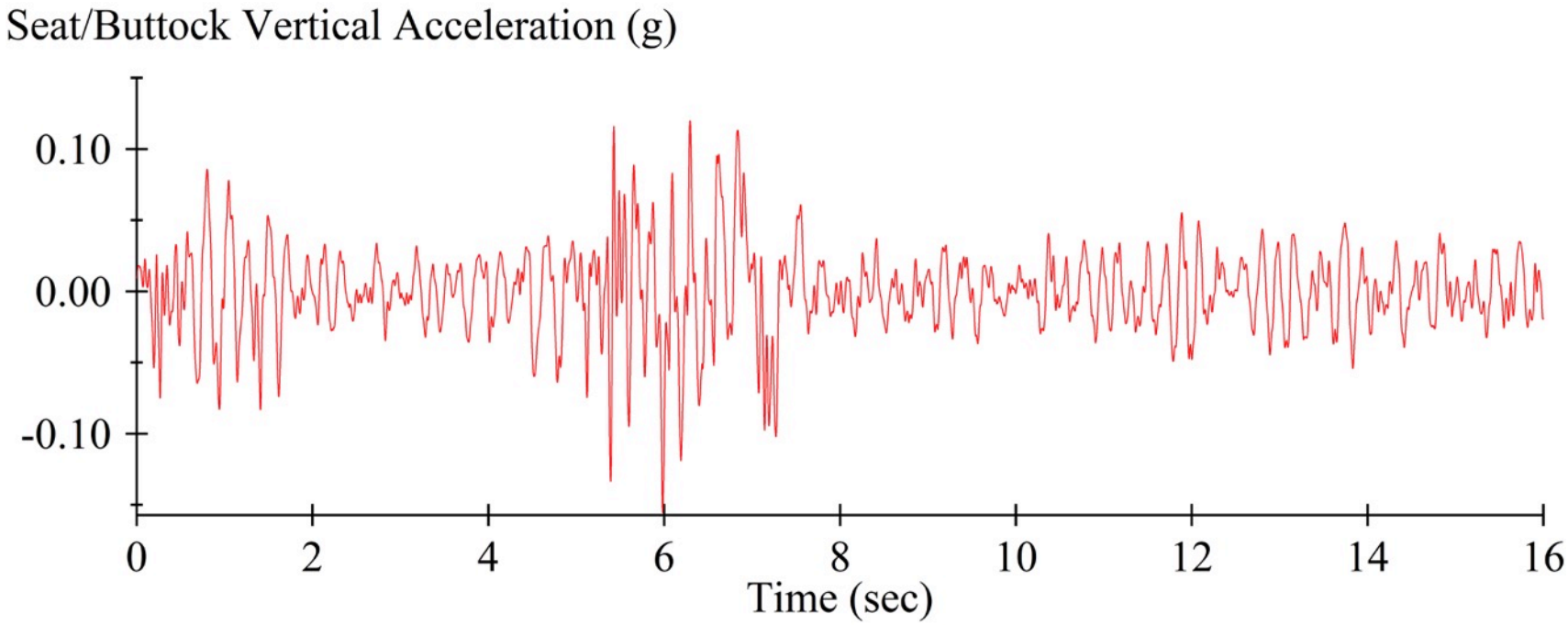
- Related objective measurement of ride vibration on urban and low-speed roads to roughness.
- Used standard measures of “discomfort” caused by vibration.
- Seeking correlation to roughness.
- 29 test sections: 6 routes, functional class 3, speed limit 30-55 mph

Test Vehicles

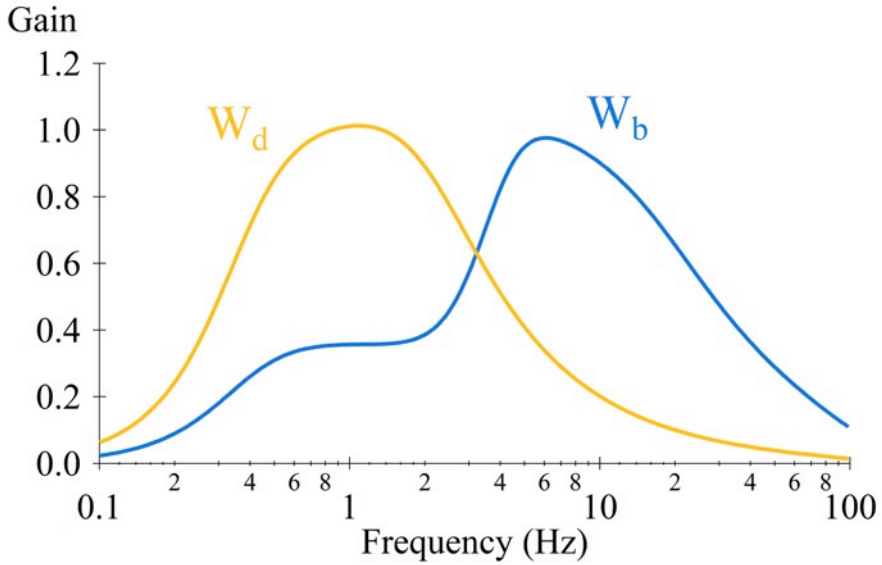
Instrumentation: Ride Sensors

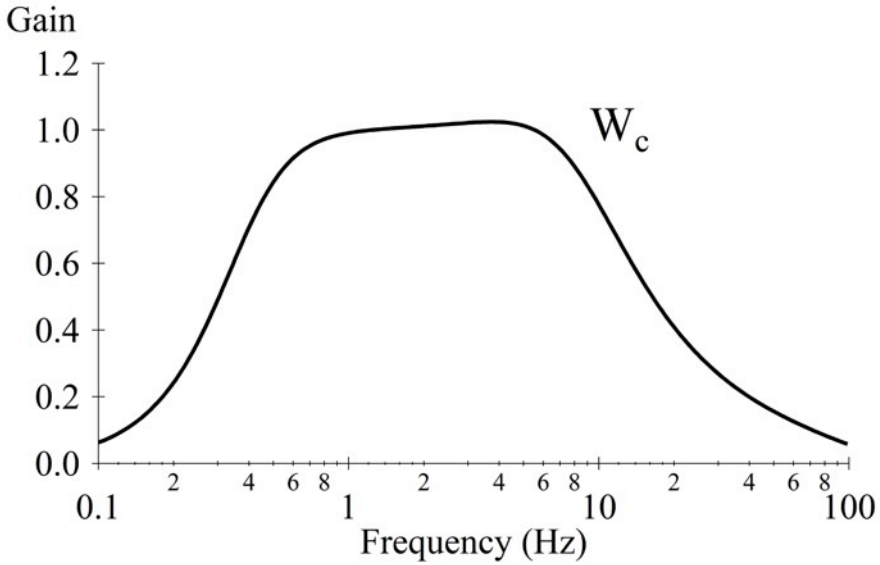
Instrumentation:Profiler

Accelerometer Output



SAE 2834/ISO 2631 Frequency Weighting





“Rough” Ride Metrics

Root Mean Square Weighted Acceleration: $$rmsa_w = \left[\frac{1}{N} \sum_{i=1}^{N} a^2{}_w(i) \right]^{\frac{1}{2}}$$

Point Vibration Total:

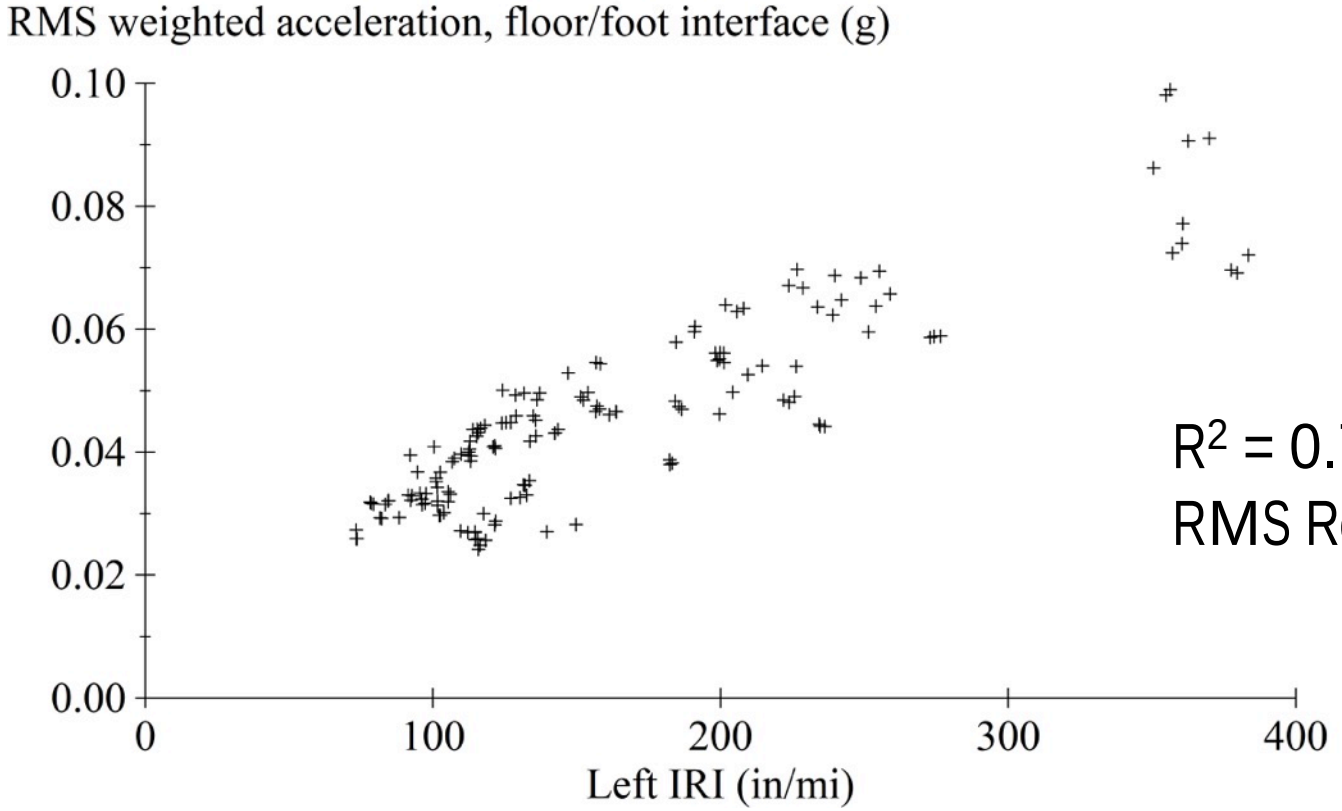
$$PV = \left(k^2{}_x rmsa^2{}_{wx} + k^2{}_y rmsa^2{}_{wy} + k^2{}_z rmsa^2{}_{wz} \right)^{1/2}$$

Overall Vibration Total: $$OVT = \left(PV^2{}_{ff} + PV^2{}_{sbk} + PV^2{}_{sbt} \right)^{1/2}$$

* Stay tuned for “Transient” metrics.

Source: ISO 2631/SAE J2834

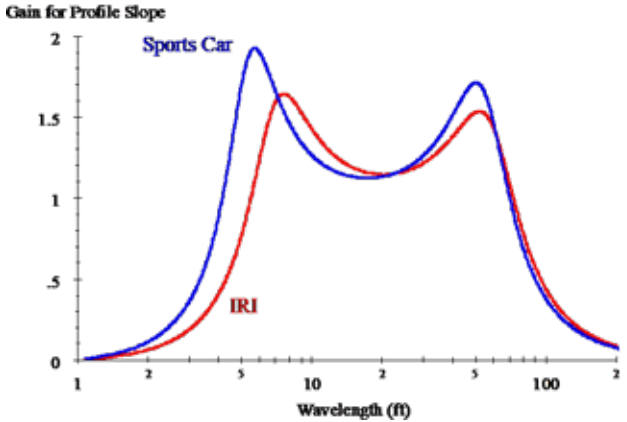
Floor/Foot Vibration v. IRI: Sedan

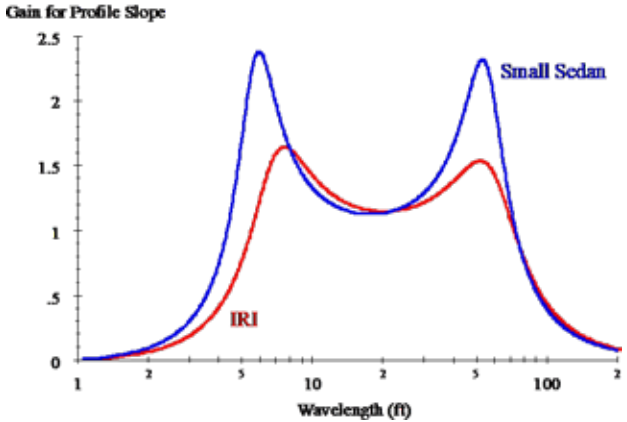


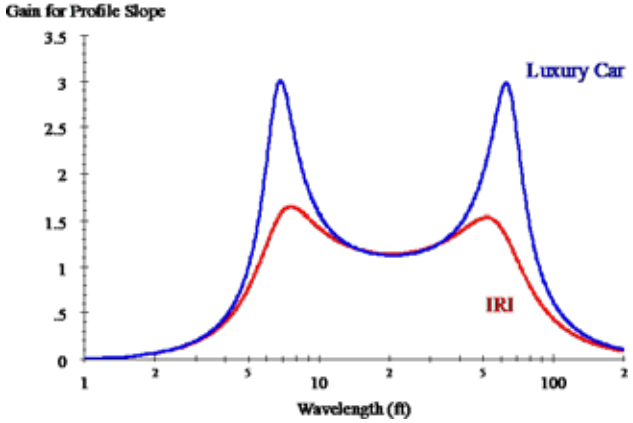
$R^2 = 0.796$

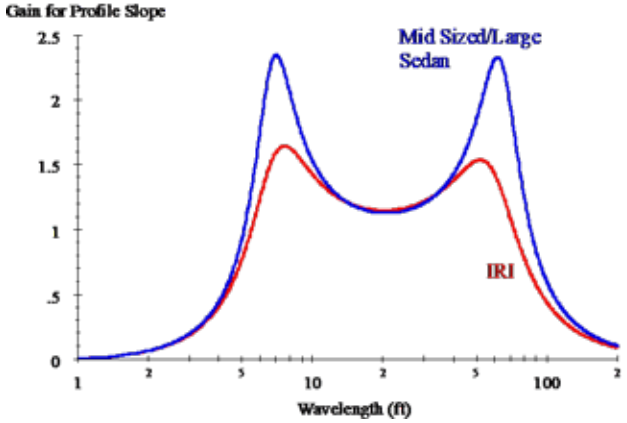
RMS Residual
= 0.0065 g

IRI Generality



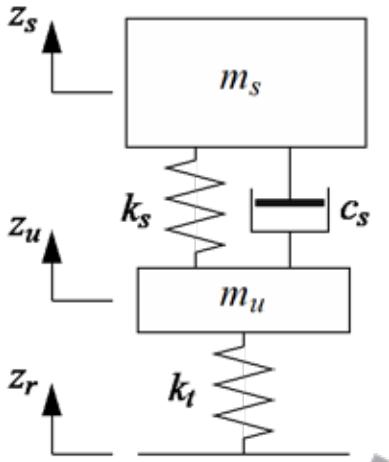


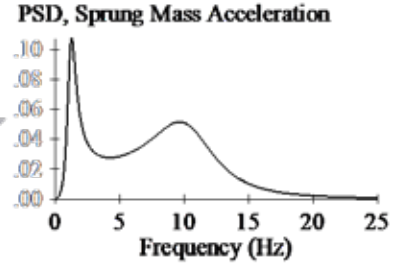


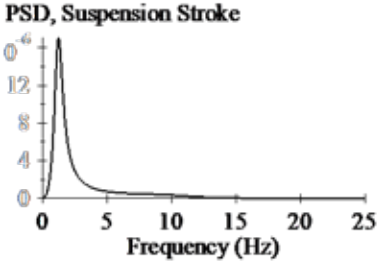


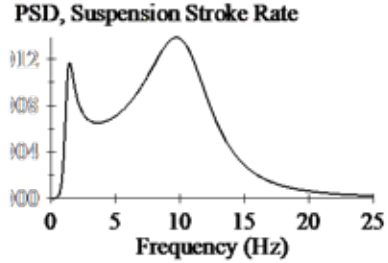
Source: Training Materials, University of Michigan

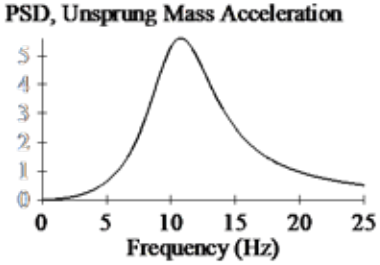
IRI Generality

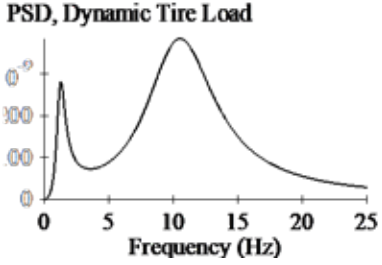




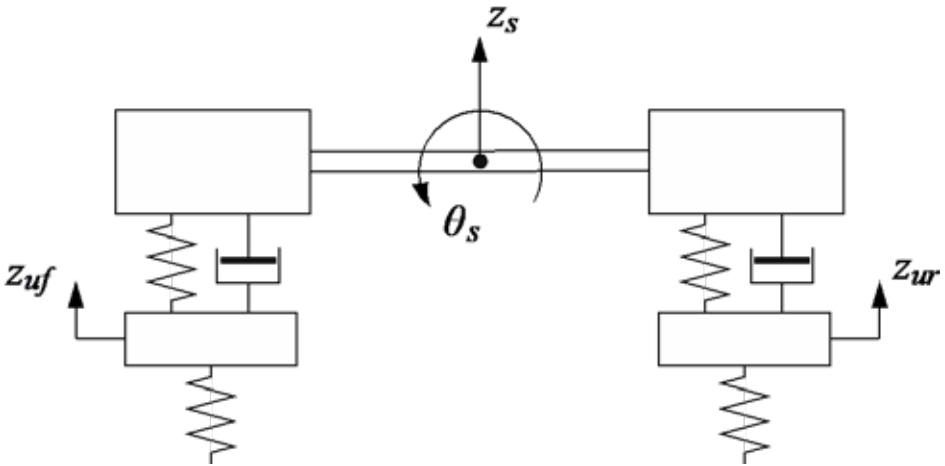




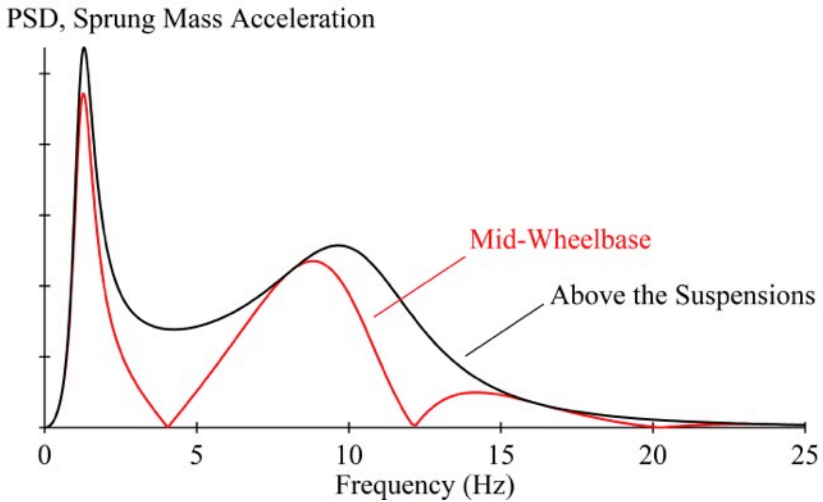




Wheelbase Filtering

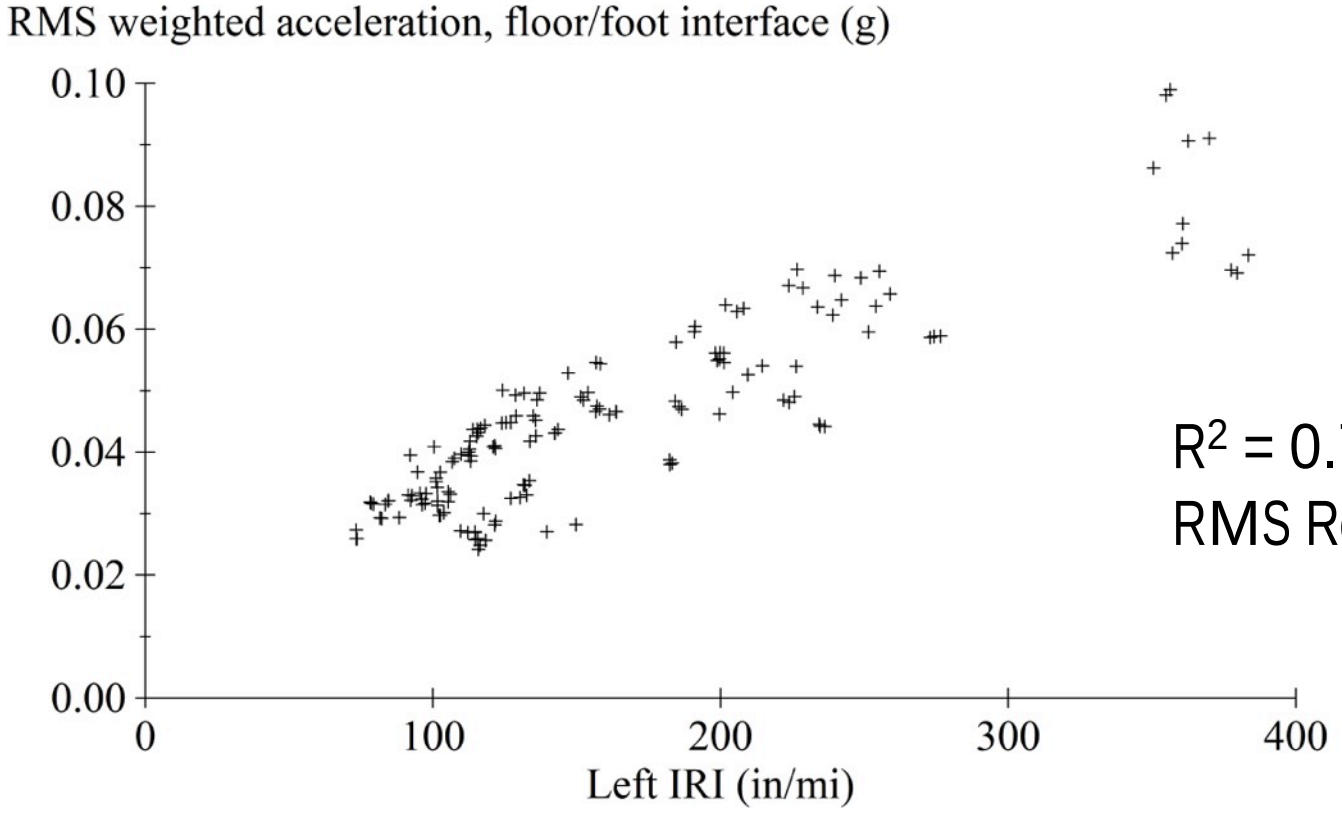


Pitch Plane Model



Acceleration Response

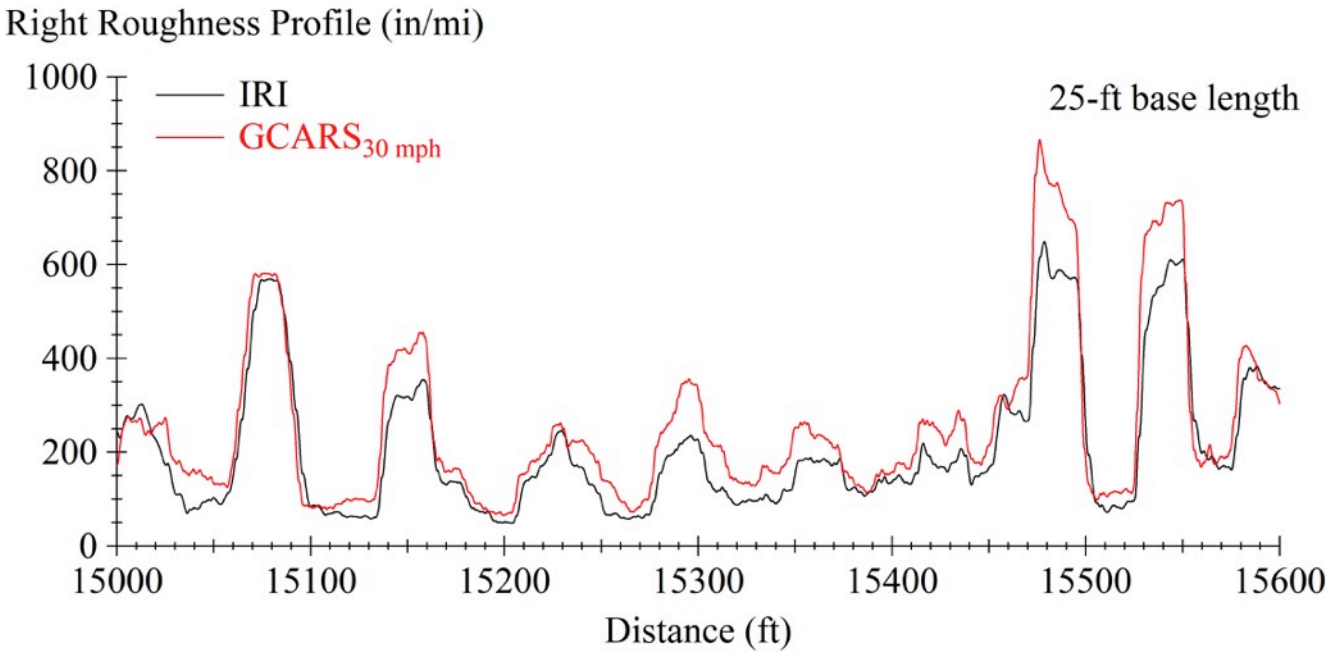
Floor/Foot Vibration v. IRI: Sedan



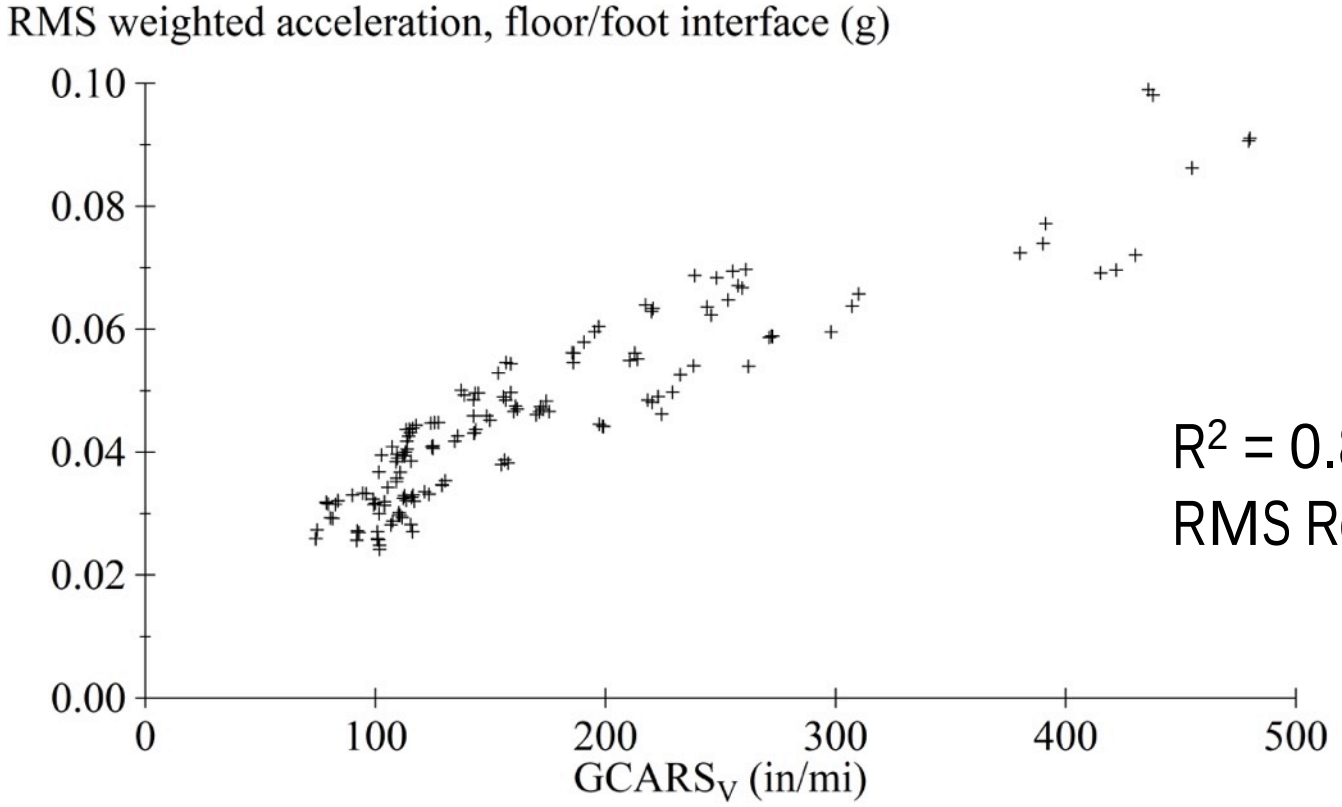
$R^2 = 0.796$

RMS Residual
= 0.0065 g

Golden Car Average Rectified Slope (GCARS)



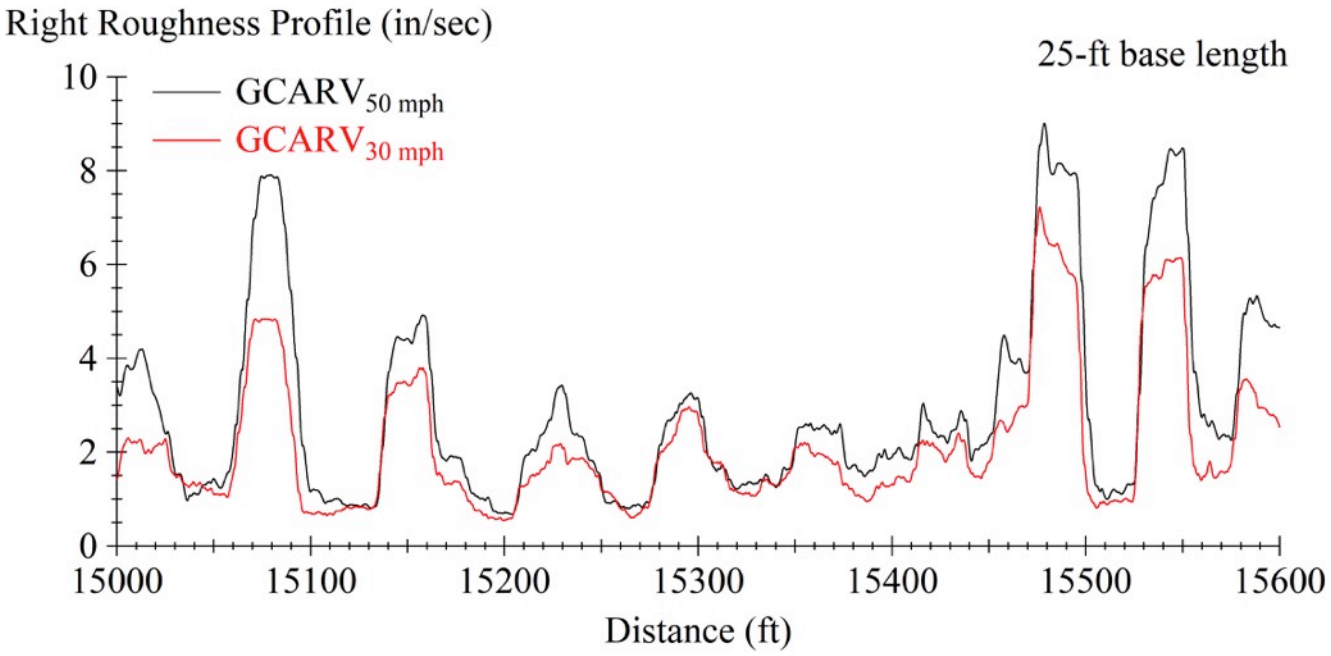
Floor/Foot Vibration v. $GCARS_V$: Sedan



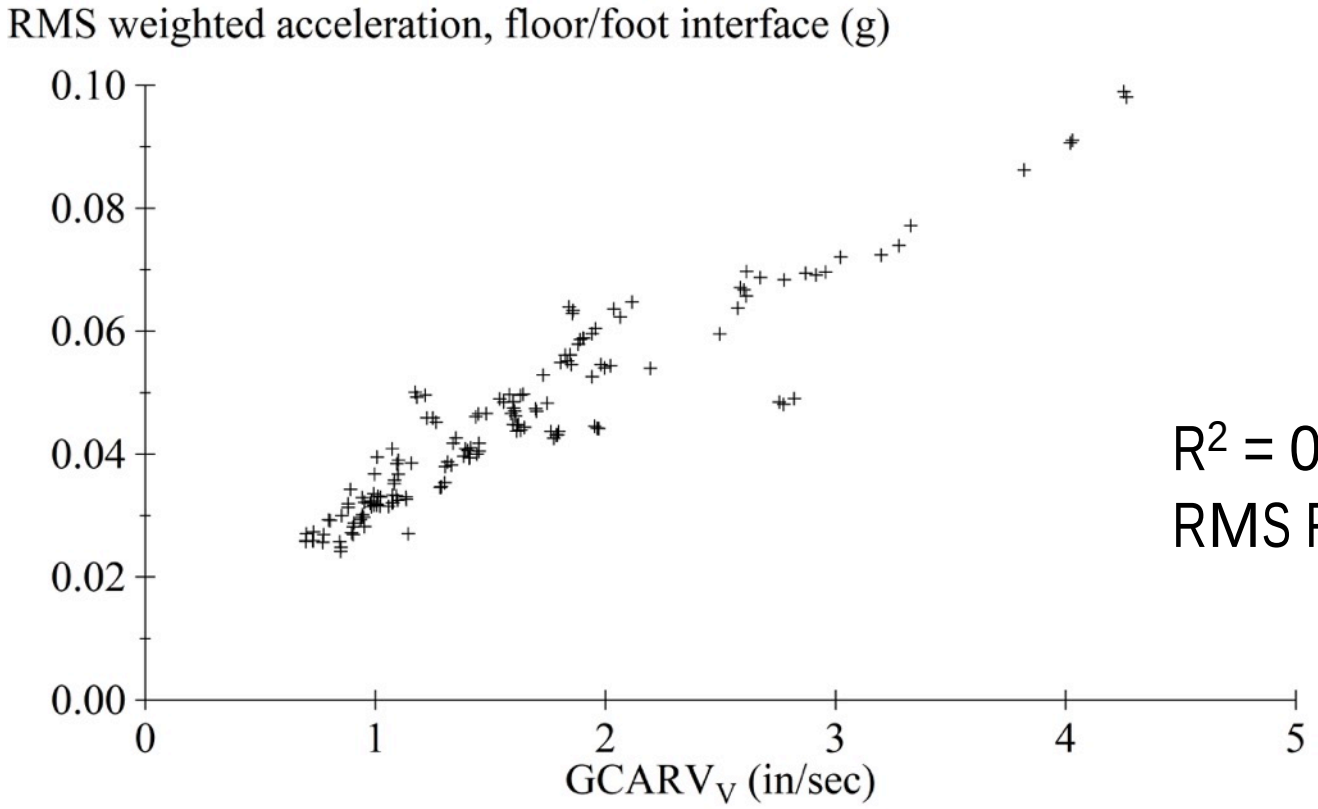
$R^2 = 0.867$

RMS Residual
= 0.0053 g

Golden Car Average Rectified Velocity (GCARV)



Floor/Foot Vibration v. $GCARV_V$: Sedan



$R^2 = 0.901$

RMS Residual
= 0.0045 g

Transient Ride Metrics

Root Mean Quad Weighted Acceleration: $$rmqa_w = \left[\frac{1}{N} \sum_{i=1}^{N} a_w^4(i) \right]^{\frac{1}{4}}$$

Maximum Transient Vibration (MTV): $$rmsa_{w,T}(j) = \left[\frac{1}{M} \sum_{i=j}^{j+M-1} a_w^2(i) \right]^{\frac{1}{2}}$$

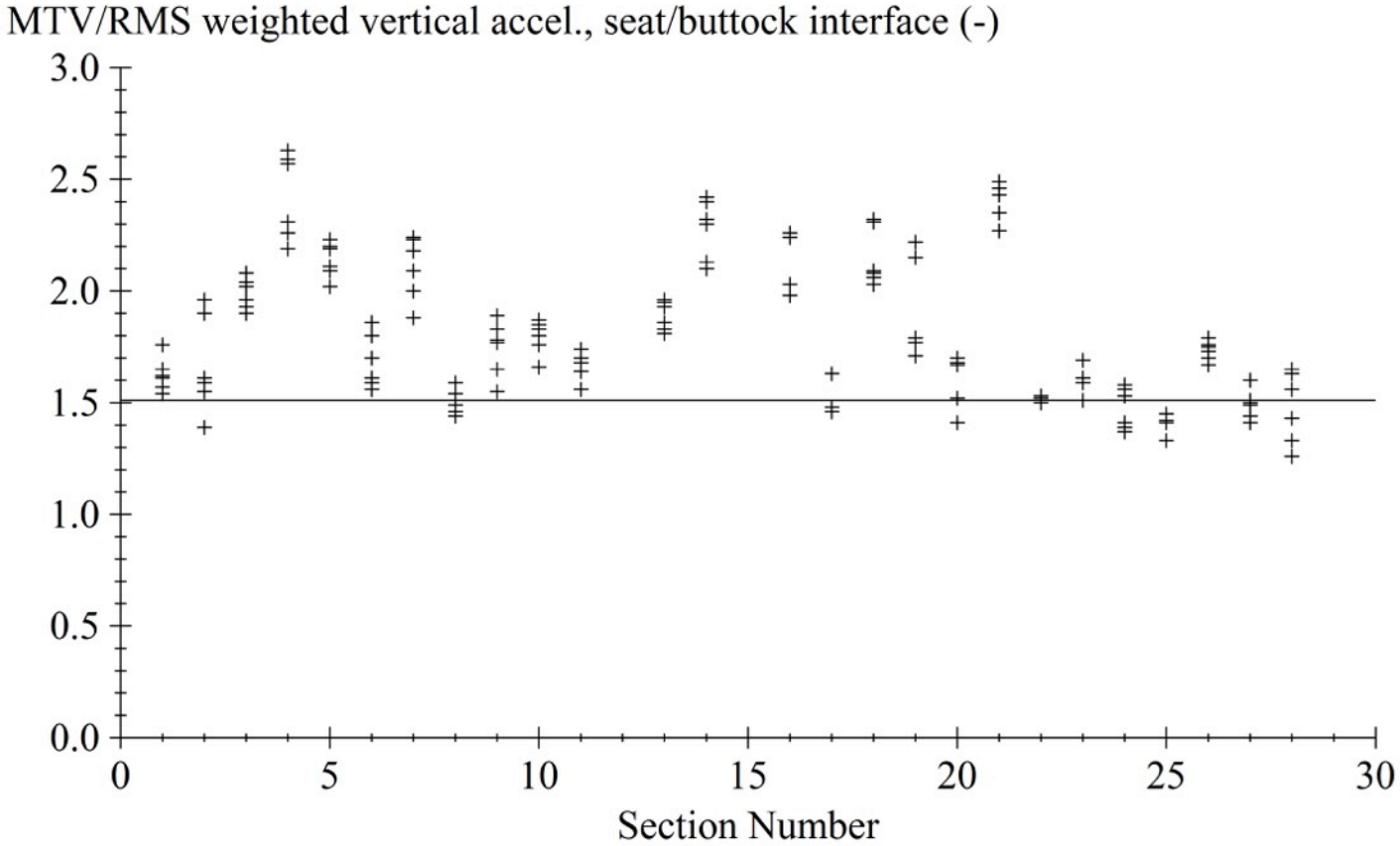
$$MTV = max\left(rmsa_{w,T}(j)\right), j = 1, N - M$$

Crest Factor: $$CF = \frac{\max\left(|a_w(j)|, j = 1, N\right)}{rmsa_w}$$

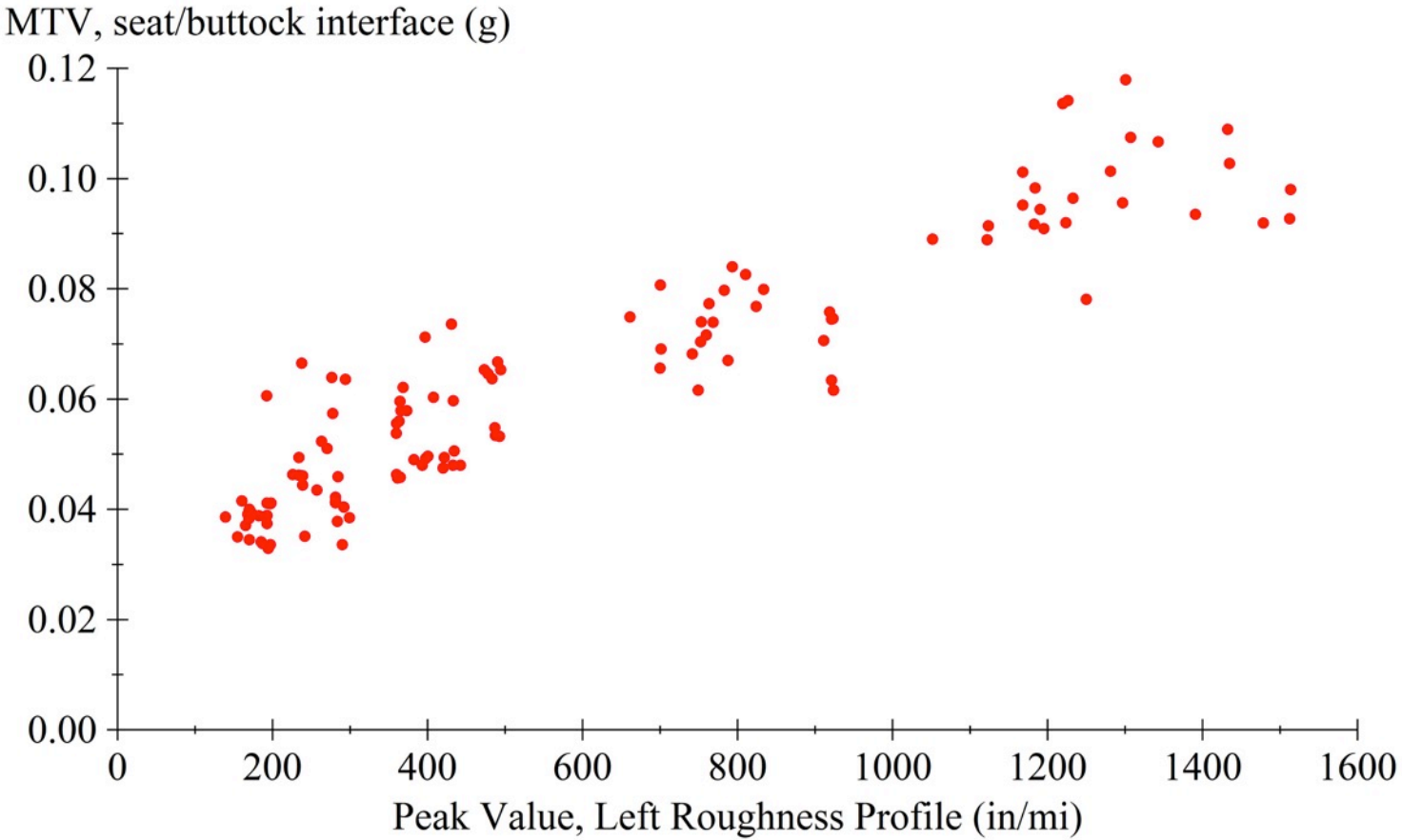
Transient vibration if: $$\frac{rmqa_w}{rmsa_w} > 1.5, \quad \frac{MTV}{rmsa_w} > 1.5, \quad CF > 9$$

Source: ISO 2631/SAE J2834

MTV/rmsa_w, Mid-Sized Sedan



MTV versus Peak Localized Roughness



Important Findings

- IRI and measured ride discomfort were correlated.
- Matching simulation speed to travel speed (i.e., $GCARS_V$) improved correlation.
- An intensity measure (i.e., $GCARV_V$) correlated to ride quality more successfully with changes in speed.
- On urban pavements, localized roughness must be included to quantify functional quality.

Recommendations

- Incorporate localized roughness into management of urban pavement systems.
- Consider the use of Golden Car Average Rectified Velocity ($GCARS_V$) for functional evaluation of low-speed pavements.
- Convene an expert task group to discuss practical implementation, AASHTO R 54.

Thank you!

Today's Speakers

- Brian Schleppi, Brian.Schleppi@dot.ohio.gov

- Steven Karamihas, stevemk@umich.edu

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