



# RPUG 2018 CONFERENCE - SOUTH DAKOTA

*30 Years On The Road To Progressively Better Data*

**Rapid City September 18-21**

# Characterizing the Impact of Curling and Warping on Ride Quality

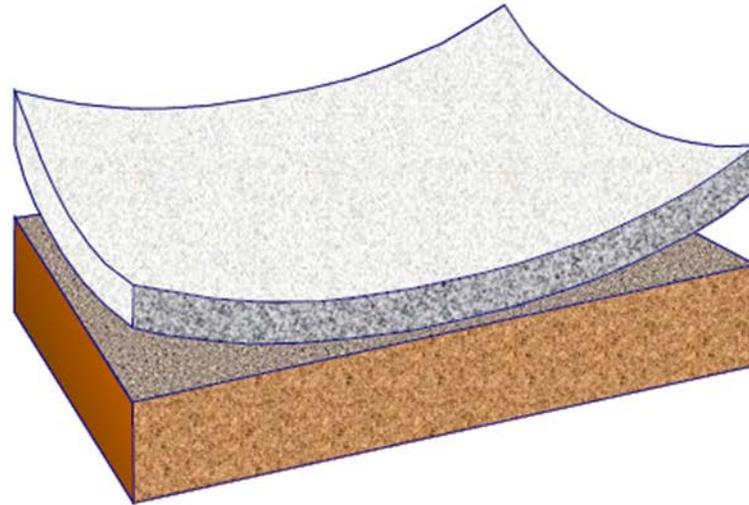
By

Ahmad Alhasan

# Acknowledgments

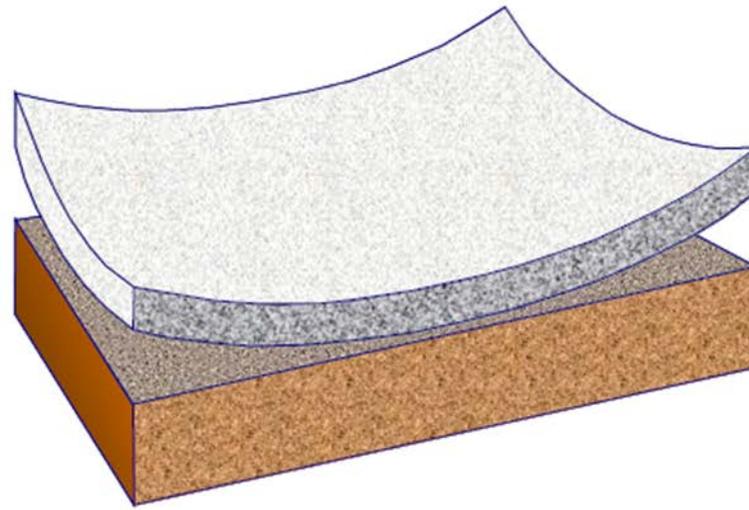
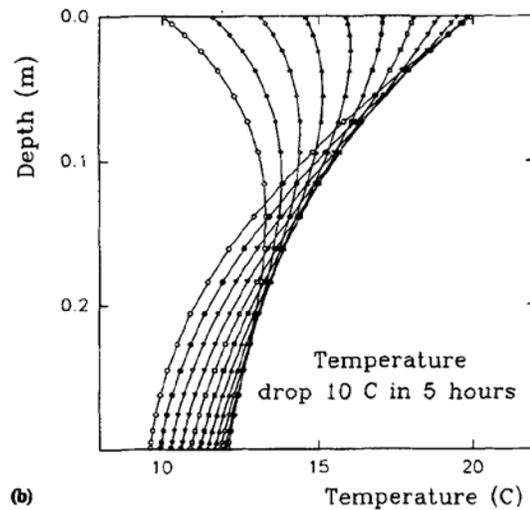
- Coauthors:
  - Shuo Yang, Halil Ceylan, Sunghwan Kim, and Yang Zhang.
- Iowa DOT, Iowa Highway Research Board, and FHWA

Curling and warping is a simple behavior affected by many variables.



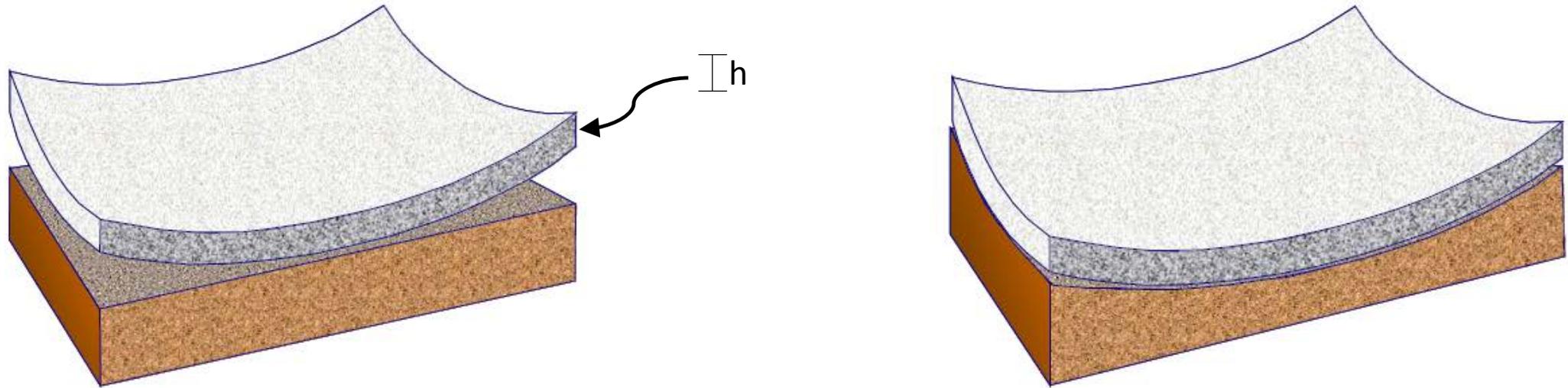
Liang and Niu (1989)  
Yu et al. (2004)

# Curling and warping is a simple behavior affected by many variables.



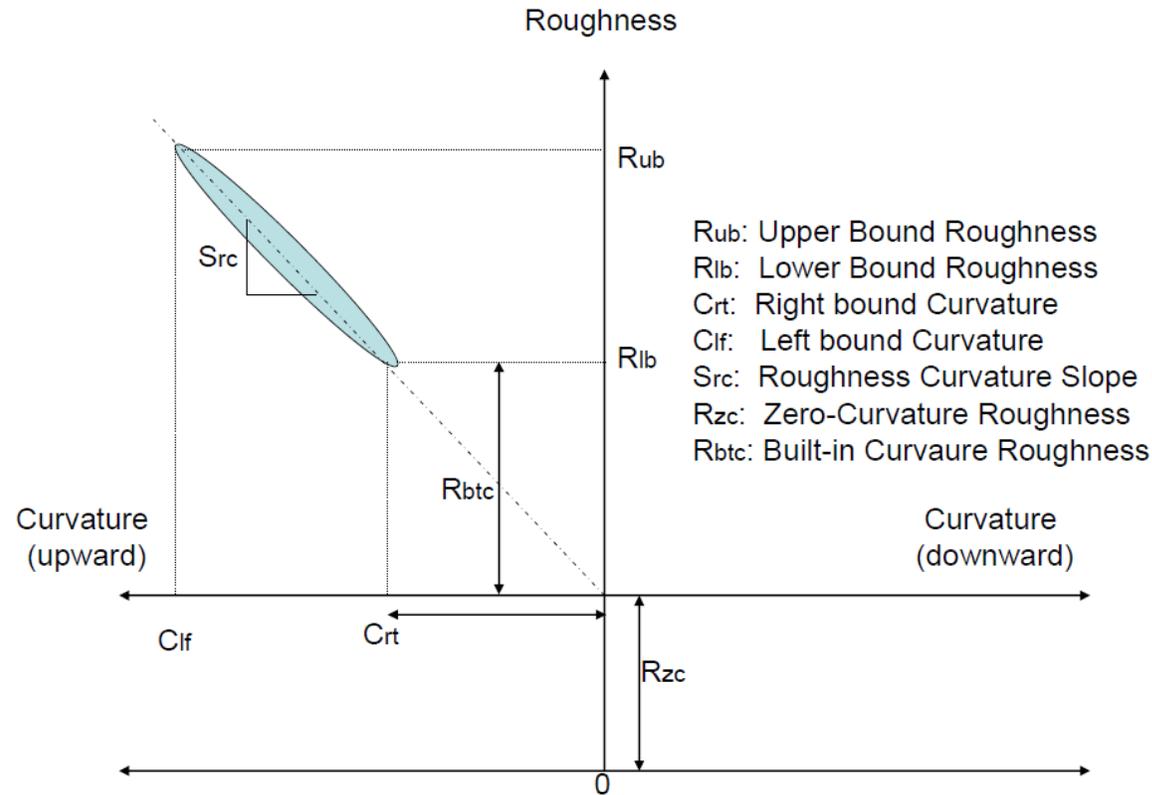
Liang and Niu (1989)  
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Curling and warping is a simple behavior affected by many variables.



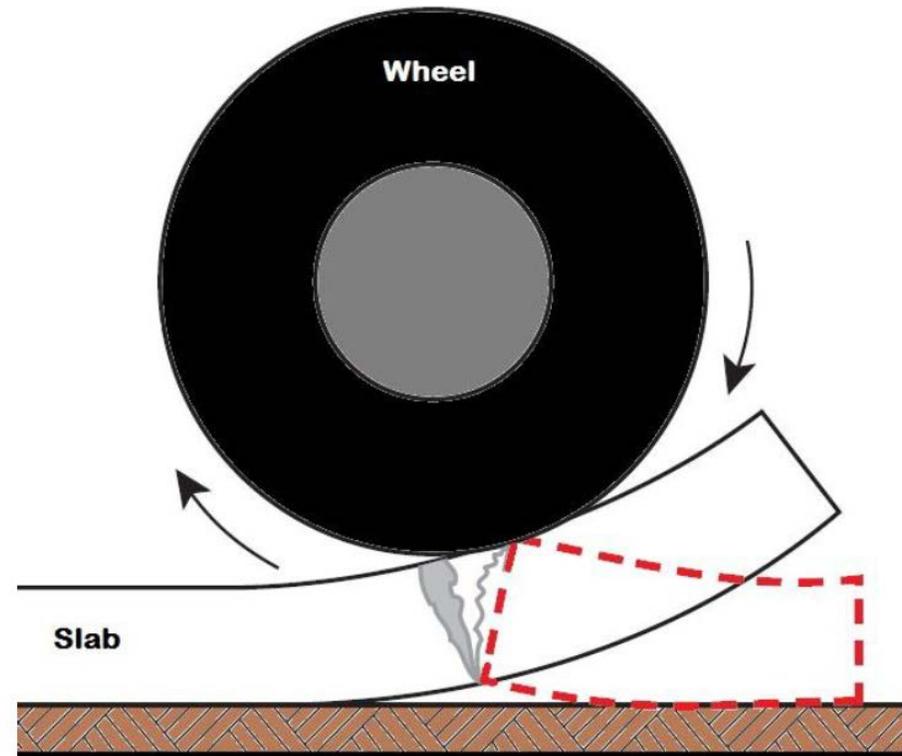
Liang and Niu (1989)  
Yu et al. (2004)

# Curling and warping affects pavement performance and structural integrity.



Chang et al. (2008)  
Kosmatka (2003)

# Curling and warping affects pavement performance and structural integrity.



Chang et al. (2008)  
Kosmatka (2003)

# The state of Iowa has one of the highest percentages of PCC pavements in the nation.



## Impact of Curling, Warping, and Other Early-Age Behavior on Concrete Pavement Smoothness: Early, Frequent, and Detailed (EFD) Study

National Concrete Pavement Technology Center



Phase II Final Report  
January 2007

Sponsored by  
the Federal Highway Administration (Project 16)



**IOWA STATE UNIVERSITY**

Iowa State University Center for Transportation Research and Education is the umbrella organization for the following centers and programs: Bridge Engineering Center • Center for Worker Impacts on Mobility and Safety • Construction Management & Technology • Iowa Local Cultural Systems Program • Iowa Traffic Safety Data Center • Midwest Transportation Consortium • National Concrete Pavement Technology Center • Partnership for Geotechnical Advancement • Roadway Administration Management and Operations System • Statewide Urban Design and Specifications • Traffic Safety and Operations

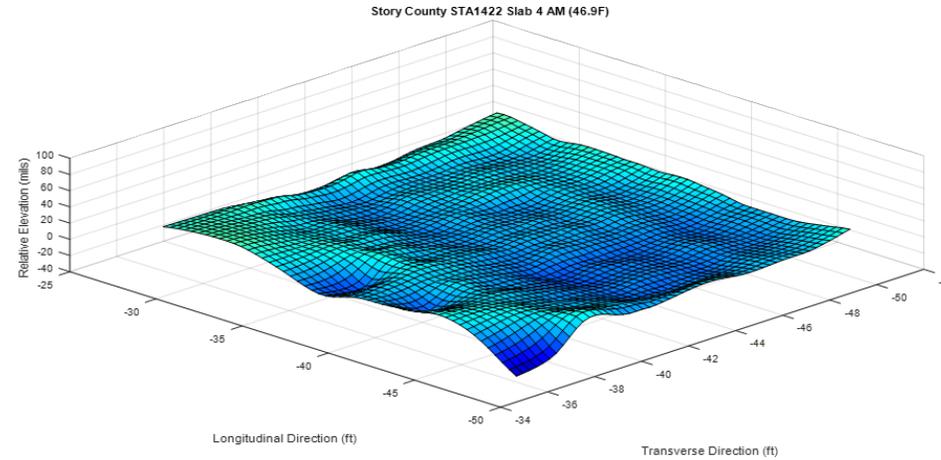


Curling and warping characterization can be done using different tools.

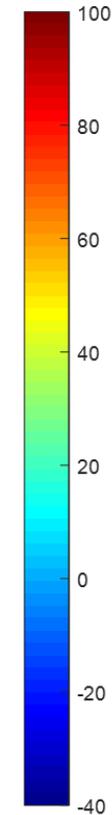
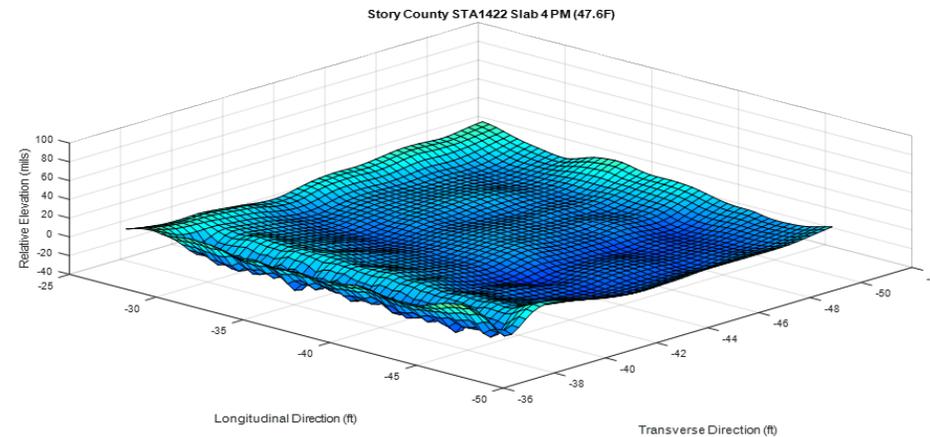


# Curling and warping characterization can be done using different tools.

Morning



Afternoon



Curling and warping characterization can be done using different tools.



# Curling and warping characterization can be done using different tools.



Westergaard equations represent an idealized model of the reality!

$$z = -z_0 \frac{2 \cos \lambda \cosh \lambda}{\sin 2 \lambda - \sinh 2 \lambda} \left[ (-\tan \lambda + \tanh \lambda) \cos \frac{x}{l\sqrt{2}} \cosh \frac{x}{l\sqrt{2}} + (\tan \lambda + \tanh \lambda) \sin \frac{x}{l\sqrt{2}} \sinh \frac{x}{l\sqrt{2}} \right]$$

Westergaard (1927)

Westergaard equations represent an idealized model of the reality!

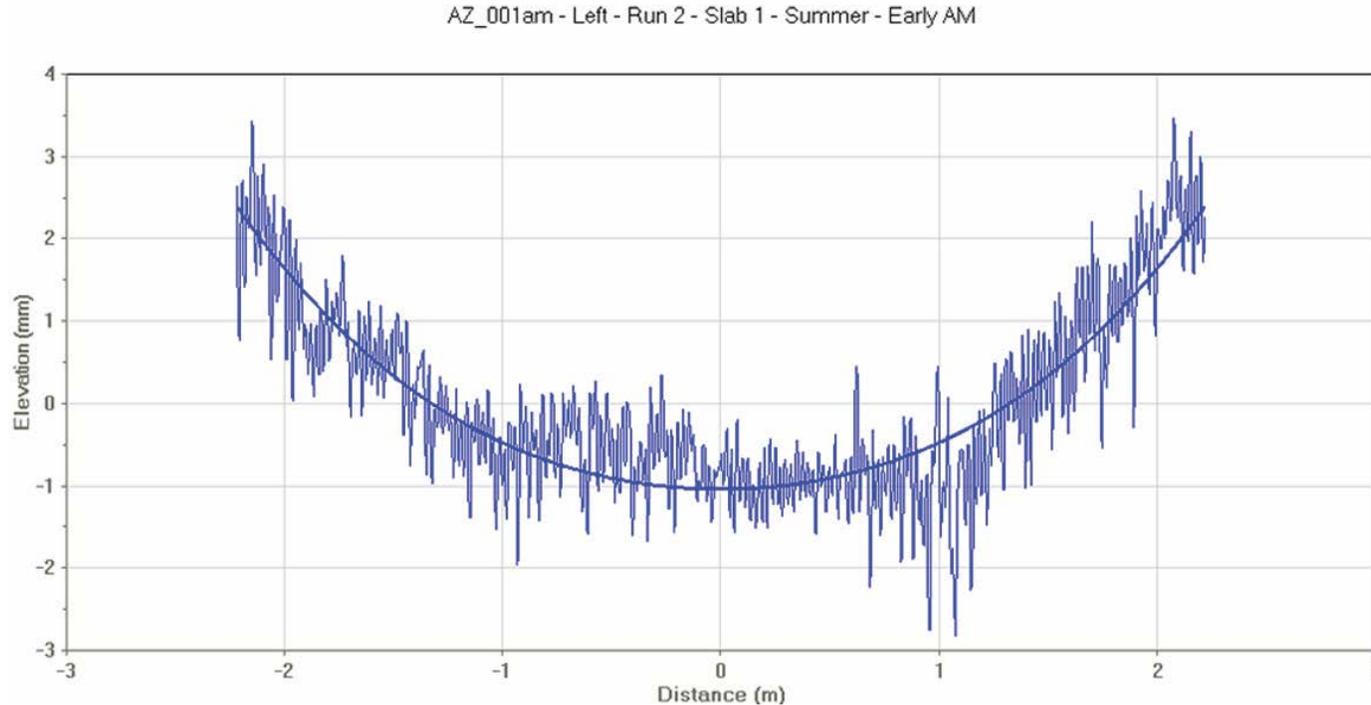
Westergaard (1927)

# The Mechanistic-Empirical mindset wins again!

$$z = -z_0 \frac{2 \cos \lambda \cosh \lambda}{\sin 2\lambda - \sinh 2\lambda} \left[ (-\tan \lambda + \tanh \lambda) \cos \frac{x}{l\sqrt{2}} \cosh \frac{x}{l\sqrt{2}} + (\tan \lambda + \tanh \lambda) \sin \frac{x}{l\sqrt{2}} \sinh \frac{x}{l\sqrt{2}} \right]$$

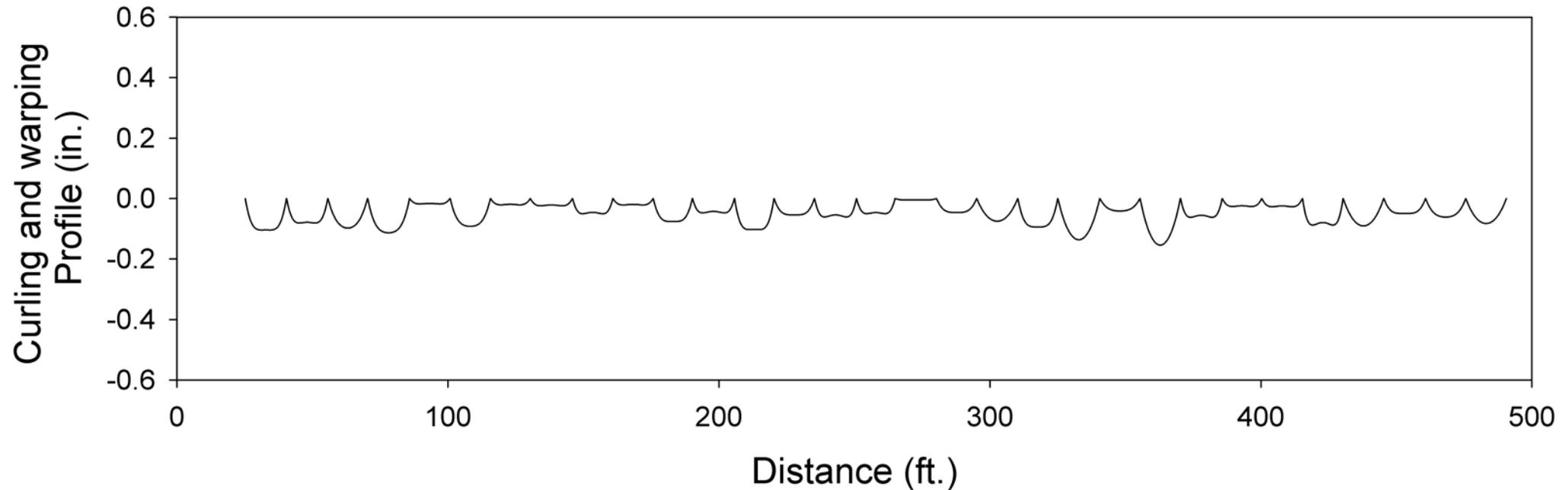
$$PSG = \frac{\alpha \Delta T + \Delta \varepsilon_{sh}}{h}$$

$$l = \sqrt[4]{\frac{Eh^3}{12(1 - \mu^2)k}}$$

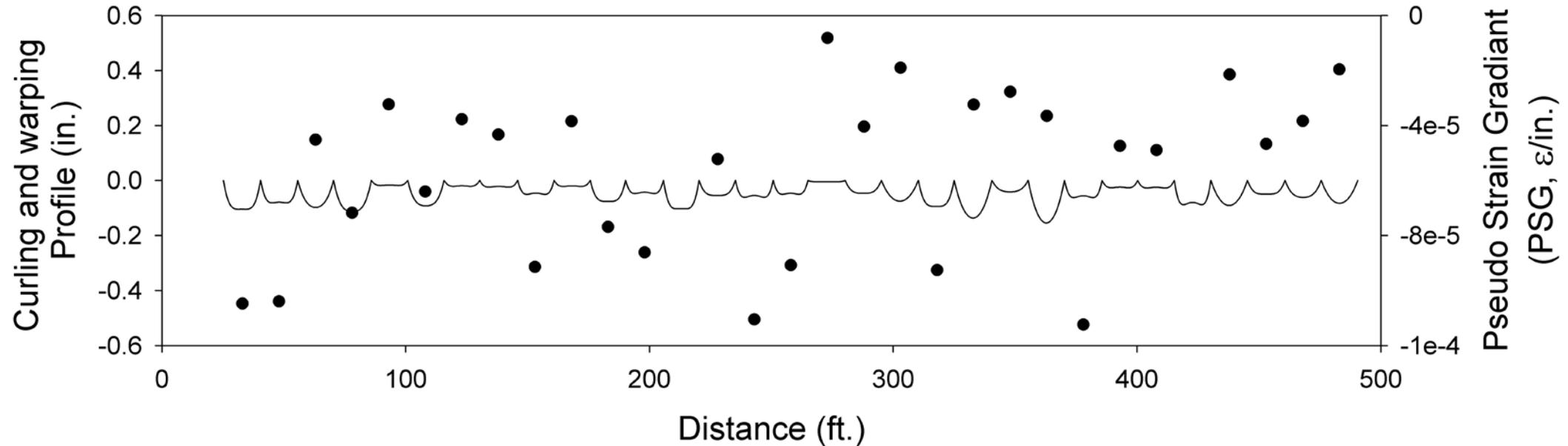


Chang et al. (2008)

Iowa's LTPP section was analyzed in-house following the 2GCI approach.

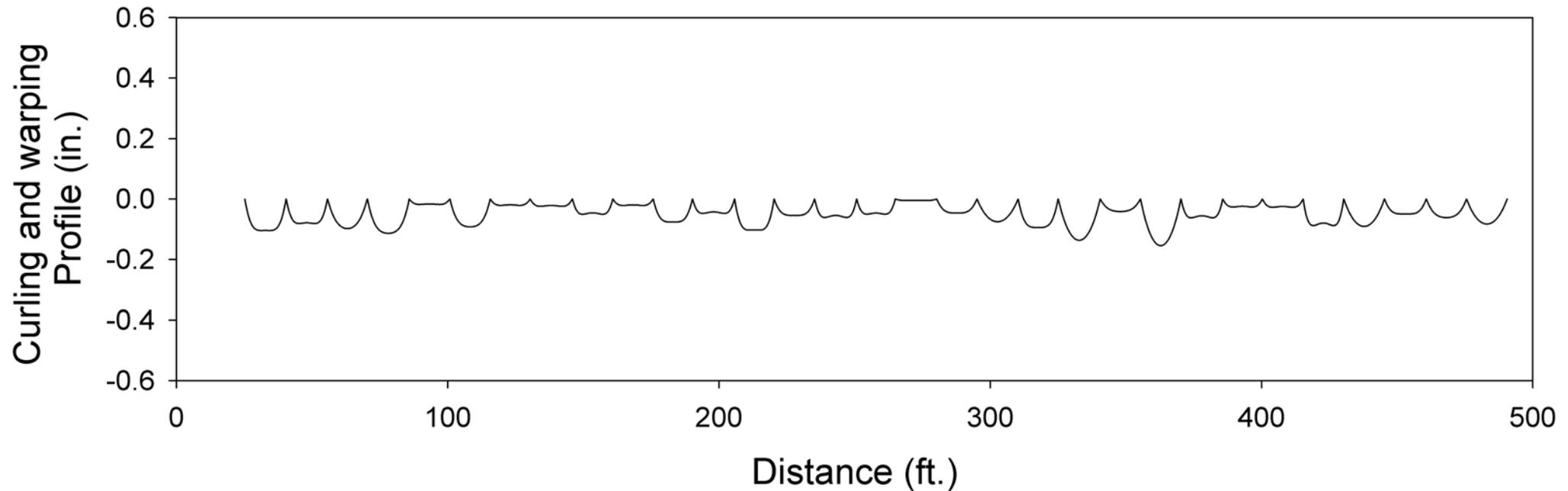


Iowa's LTPP section was analyzed in-house following the 2GCI approach.

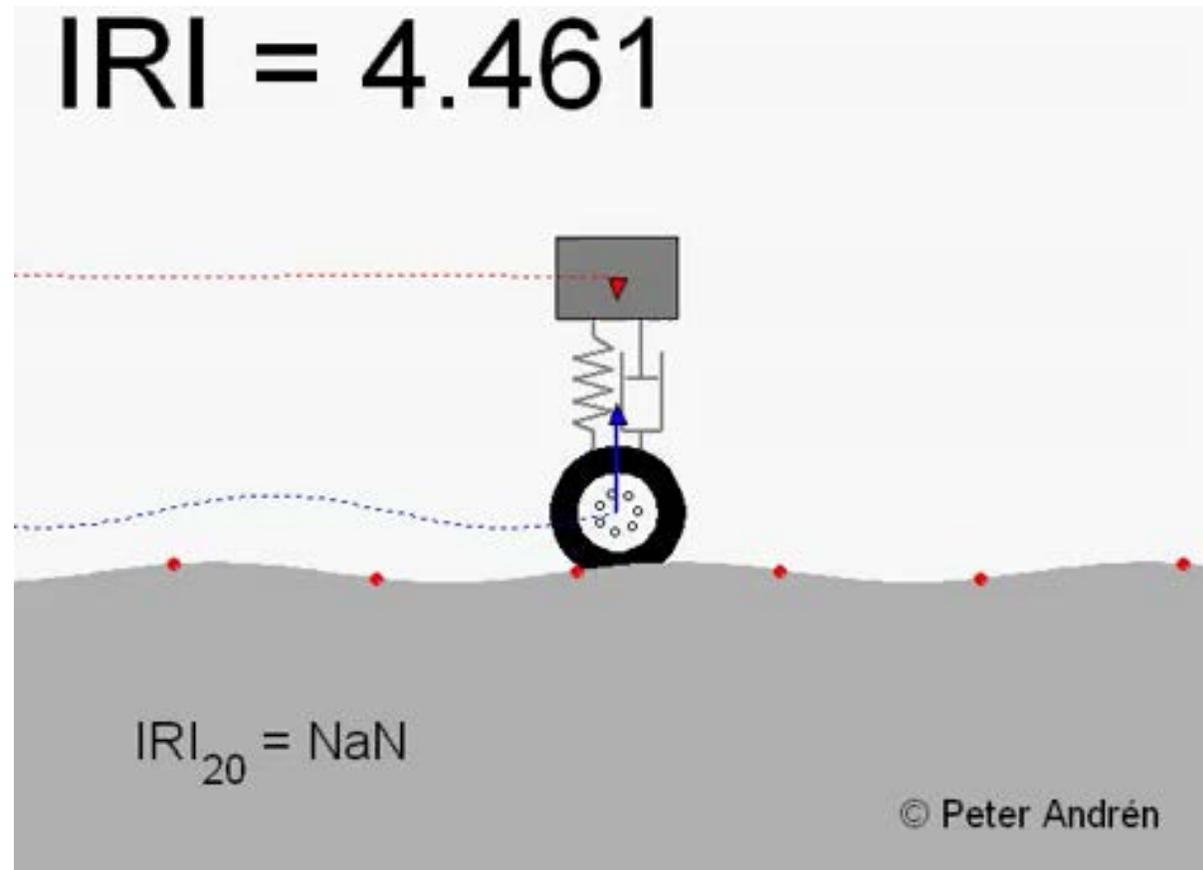


# IRI is not a linearly separable statistic.

IRI = ~~80.09~~ in./mi

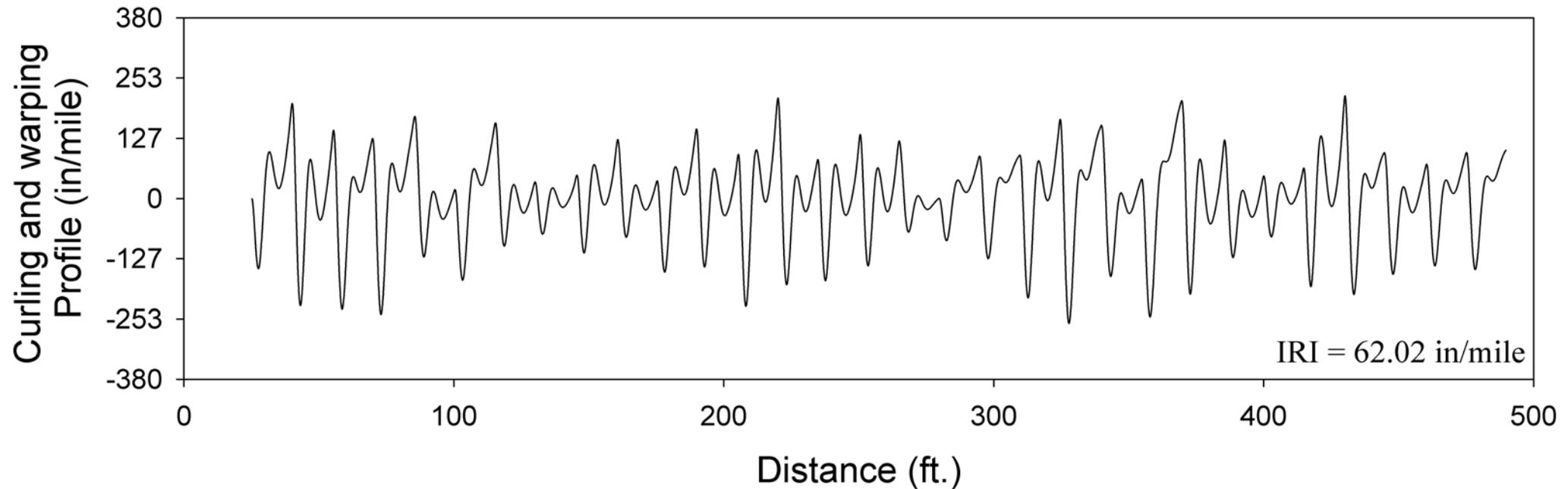


IRI is the average value of the absolute suspension strokes of a quarter-car model simulations.

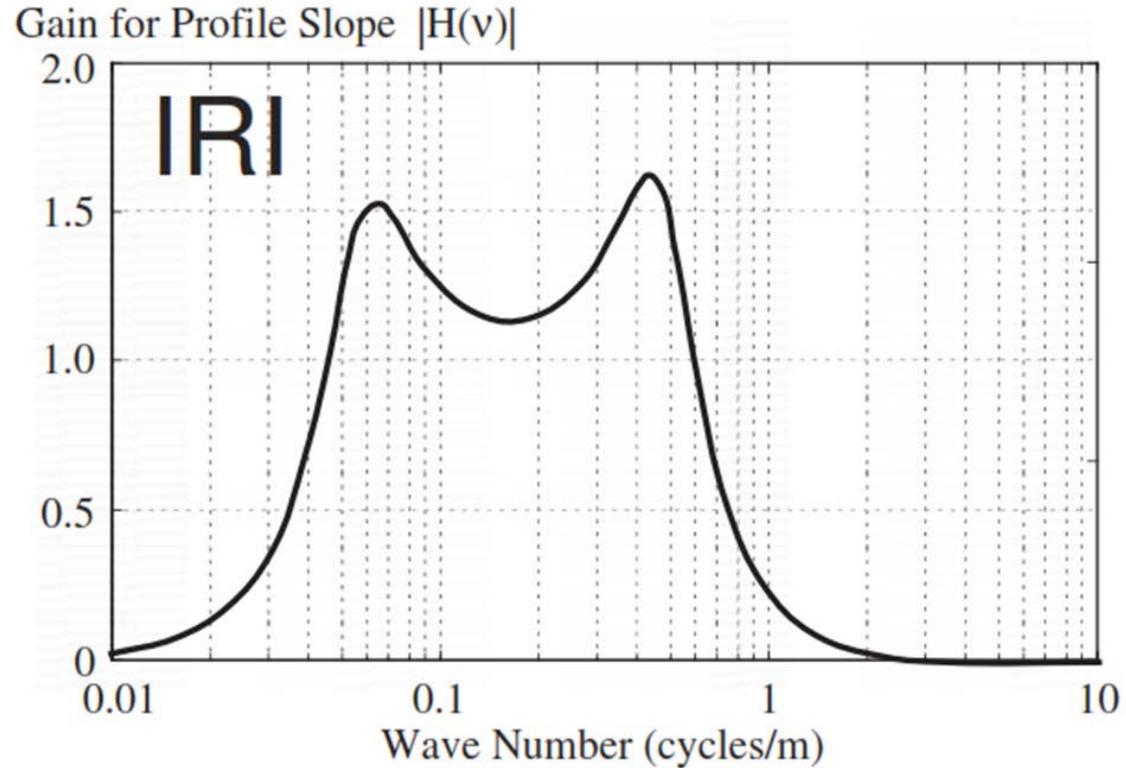
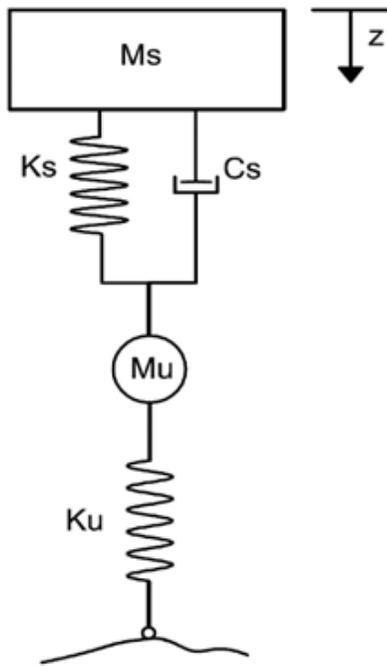


ASTM E1926-08 (2015)

IRI is the average value of the absolute suspension strokes of a quarter-car model simulations.



IRI is a non-linear function of a linear filter.

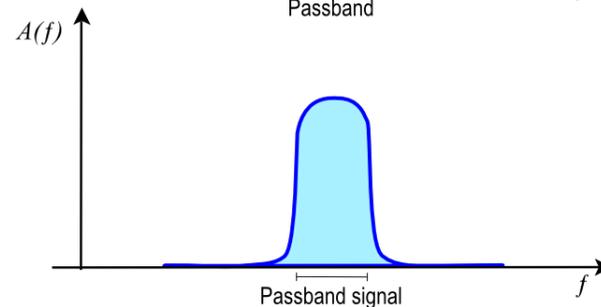
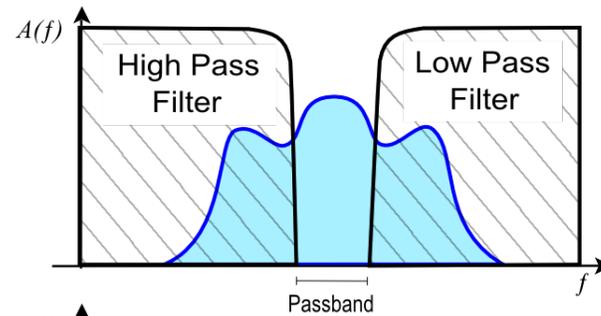
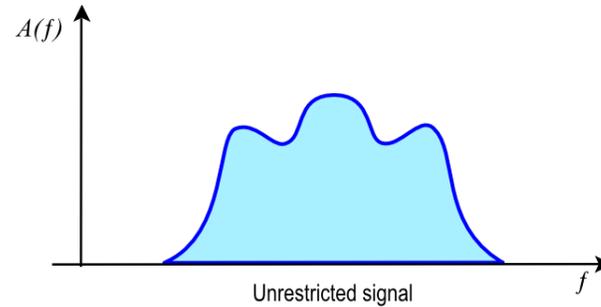


Fourier transform decomposes a profile into sinusoidal waves.

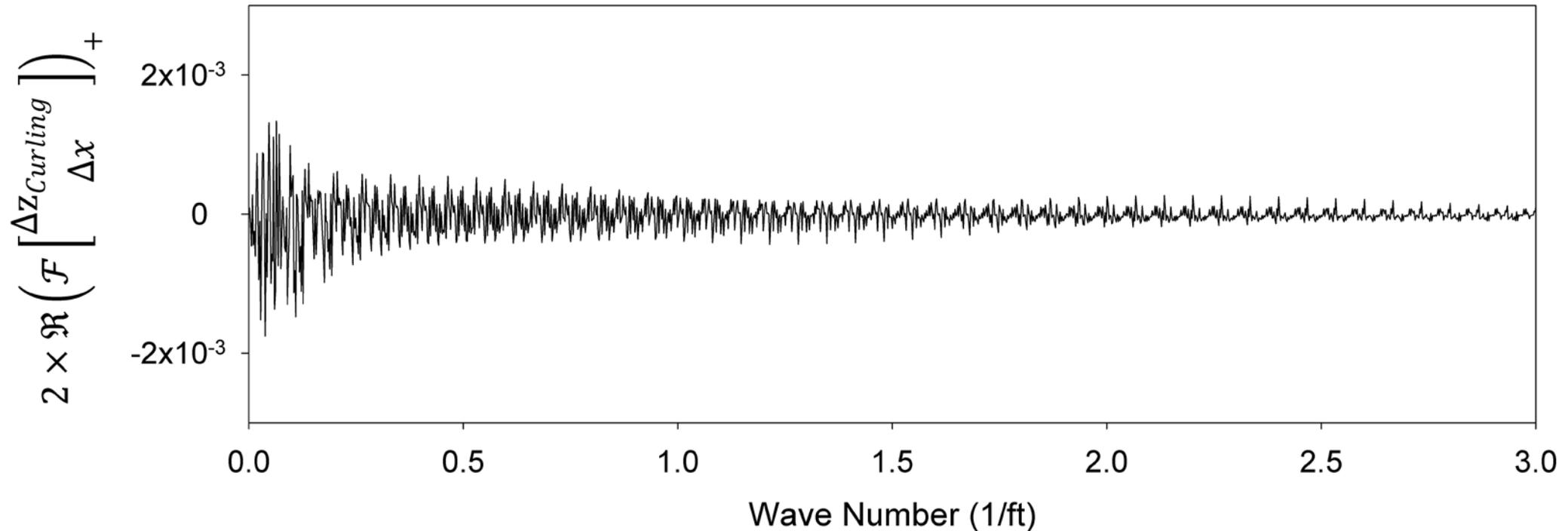


Wikipedia 2015

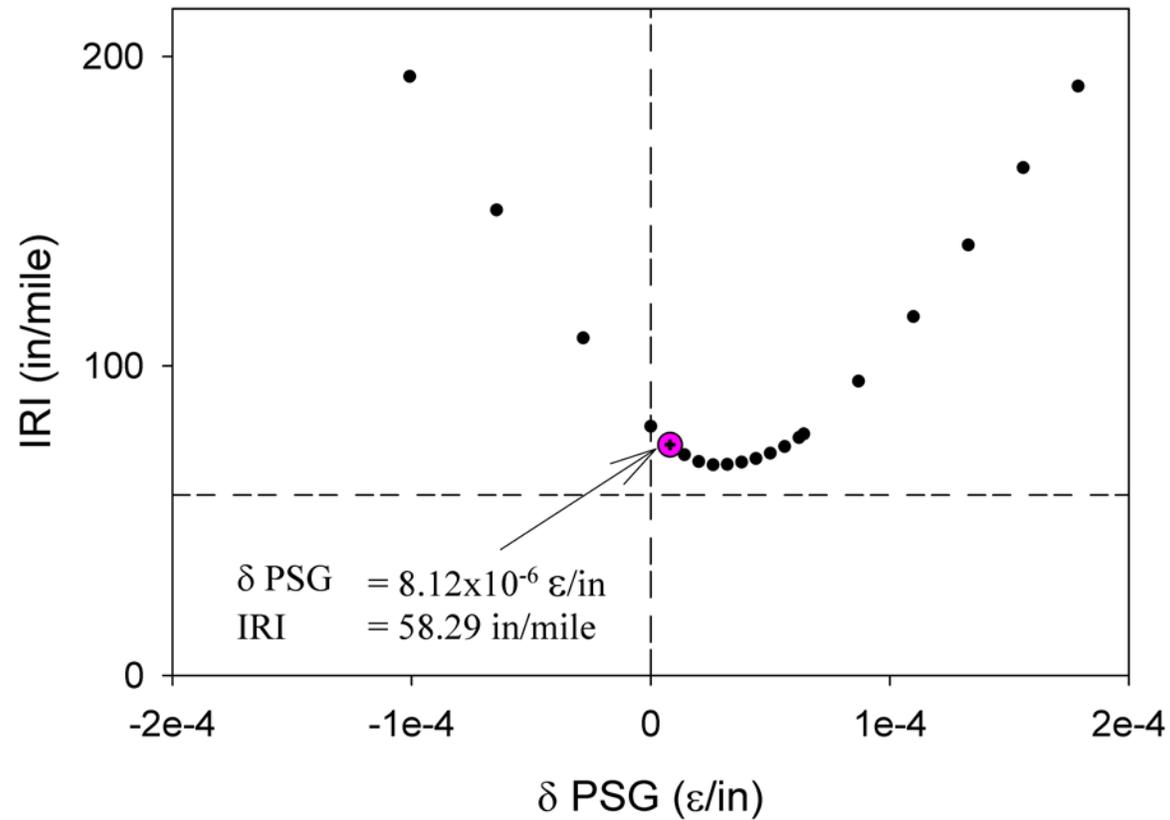
# Filters are products of multiplication in the frequency domain.



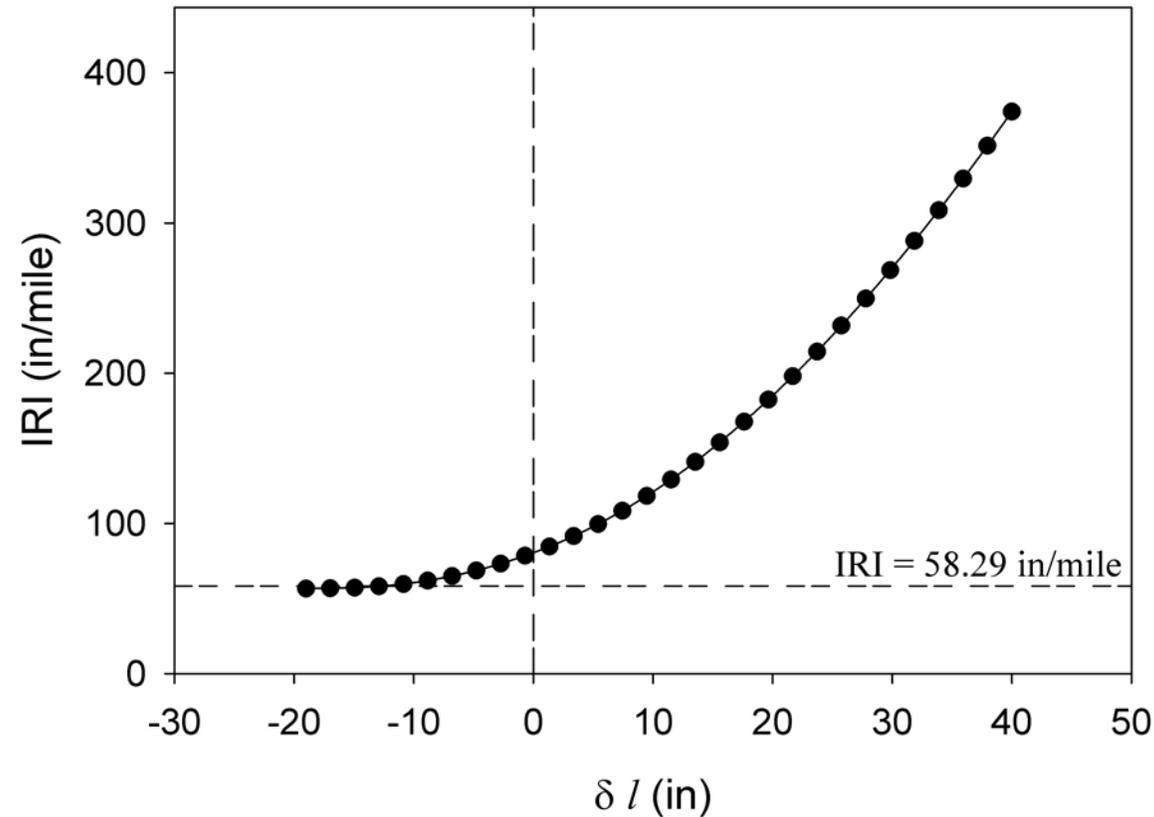
Profiles with curling and warping show unique signatures in the frequency domain.



# The Pseudo-Gradient can be manipulated to predict the change in IRI.



The impact of changing relative radius of stiffness can give estimates of the design impact.



# References

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