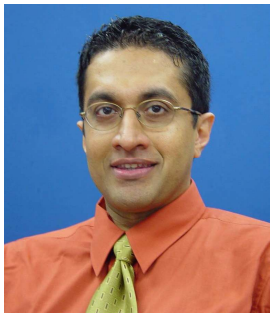
About the Presenter

- **Shree Rao** is the Group Leader for ARA's Transportation Research and Technology Deployment Group.
- He received his PhD from the University of Illinois, is a registered professional engineer in AR, CO, and NC.
- Over the past 21 years, Dr. Rao has led a wide variety of projects related to pavements, construction, design, performance, and materials including several related to dowel alignment and performance.



INNOVATIVE SOLUTIONS TO COMPLEX PROBLEMS

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Dowel Alignment and Joint Score – Implications for Specifications and Performance

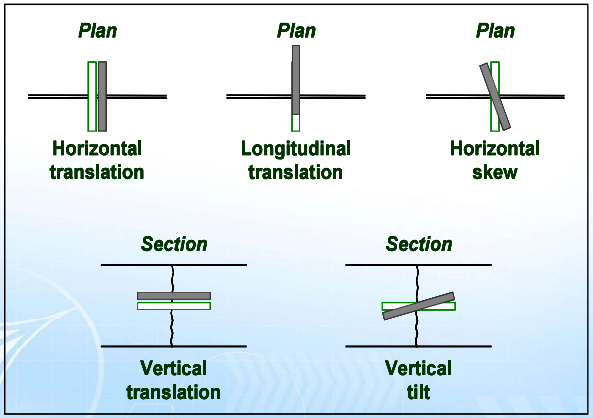
Shree Rao, PhD, PE
National Concrete Consortium
Fall 2020

NATIONAL SECURITY | ENERGY & ENVIRONMENT | INFRASTRUCTURE | HEALTH SOLUTIONS

Information and opinion based on…

- **LTPP sections across the U.S. (120+ sections, 3,800+ joints, 44,000+ dowel bars)**
- NCHRP 10-69 (Report 637) sections across the U.S. (60+ sections, 2,300+ joints, 28,000+ dowel bars)
- Thousands of joints for quality assurance on new construction and forensic analysis evaluation of existing pavements (contractors and State DOTs)
- Literature (lab studies) and communications with contractors/DOT personnel

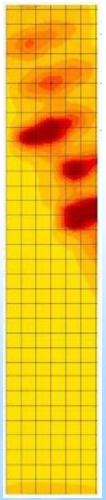
Dowel Alignment



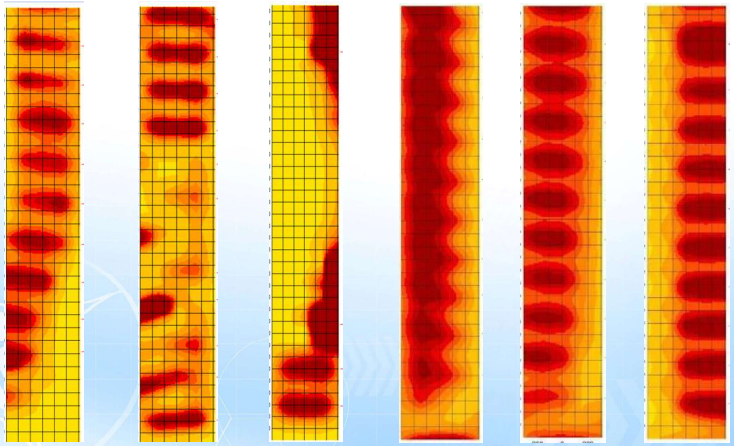
Source: Shree Rao (adapted from Tayabji 1986)

Poor Alignment

Source: ARA



Poor Alignment



Source: Shree Rao

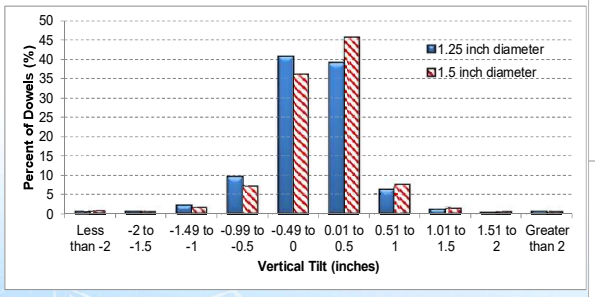
Scope of Presentation

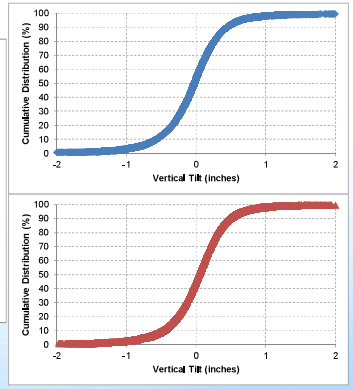
Long-Term Pavement Performance (LTPP) Test Sections

Location	Experiment Type	Number of LTPP Sections
Arizona	SPS-2	12
Arkansas	SPS-2/GPS-3	13
California	SPS-2	12
Colorado	SPS-2	12
Delaware	SPS-2	14
Iowa	SPS-2	13
Kansas	SPS-2	12
Kentucky	GPS-3	1
North Carolina	SPS-2	8
North Dakota	SPS-2	14
South Dakota	GPS-3	1
Wisconsin	SPS-2	12

- LTPP database: 181 doweled jointed concrete sections
- 6.4 to 13.2 inches
- 500 feet in length
- Approximately 33 joints
- 121 SPS-2 sections, and 3 GPS-3 sections were included in this study

Vertical Tilt





21,240 1.25-in dowel bars from 1,824 joints
23,300 1.5-in dowel bars from 1,997 joints

Source: FHWA

Two* Methodologies to Combine Bars at a Joint

Joint Score*

Yu and Khazanovich (2005)
Empirical

Range of Misalignment*	Weighting Factor
0.4 in < d < 0.6 in	0
0.6 in < d < 0.8 in	2
0.8 in < d < 1.0 in	4
1.0 in < d < 1.5 in	5
d >1.5 in	10

Resultant of vertical skew and horizontal tilt only

*Some variations of this methods exist

Effective Dowel Diameter

Khazanovich et al. (2009)
Based on lab tests and limited field data
NCHRP 637

$$d_{eq} = r_{emb} \times r_{cc} \times r_{vt} \times r_{hs} \times d_0$$

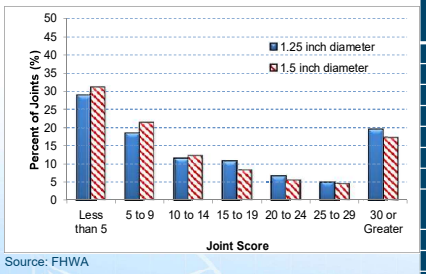
d_0 = actual dowel diameter
r = adjustment factors for embedment, concrete cover, vertical tilt, and horizontal skew.

$$r_{emb} = -0.010 L_{emb}^2 + 0.167 L_{emb} + 0.324$$

Why combine bars at a joint ???

Because we can only know or quantify the performance of the whole joint…
…and not of individual bars.

Joint Score



Source: FHWA

Location	Average Joint Score	Joint Score Standard Deviation	Number of 1.25-in Dowel Bar Joints	Number of 1.50-in Dowel Bar Joints
Arizona	11	12	197	195
Arkansas	19	17	169	202
California	27	20	196	194
Colorado	11	17	199	198
Delaware	19	22	228	219
Iowa	14	17	198	200
Kansas	18	19	198	203
North Carolina	11	15	26	232
North Dakota	11	13	190	194
South Dakota	18	8	25	0
Wisconsin	21	21	198	160

21,240 1.25-in dowel bars from 1,824 joints
23,300 1.5-in dowel bars from 1,997 joints

Joint Score and Cracking

Joint Score	Category
<=12	Low
12<JS<=30	Medium
>30	High

Chi-Squared Test for Independence

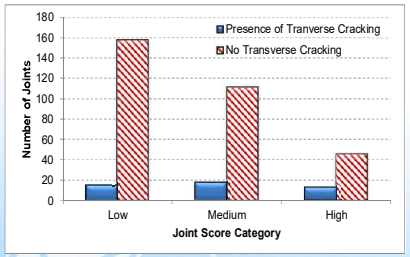
H_o: joint score and cracking/spalling are independent

H_A: joint score and cracking/spalling are dependent

Location	Number of Joints for Analysis	p-value Cracking
Arkansas	357	0.035
Arizona	390	0.015
California	388	0.769
Colorado	386	0.128
Delaware	449	0.425
Iowa	387	0.782
Kansas	390	0.126
North Carolina	248	N/A
North Dakota	383	0.653
South Dakota	25	N/A
Wisconsin	346	N/A

Joint Score and Cracking Arkansas

Joint Score	Category
<=12	Low
12<JS<=30	Medium
>30	High



Source: FHWA

	Yes	No	Total
Low	14	157	171
Medium	17	111	128
High	12	46	58
Total	43	314	357

	Yes	No	Total
Low	20.6	150.4	171
Medium	15.4	112.6	128
High	7.0	51.0	58
Total	43	314	357
p	**0.035468**		

Joint Score and Cracking

Joint Score	Category
<=12	Low
12<JS<=30	Medium
>30	High

Chi-Squared Test for Independence

H_o: joint score and cracking/spalling are independent

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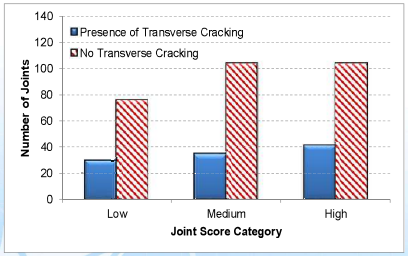
Wisconsin	346	N/A

Joint Score and Cracking California

Joint Score	Category
<=12	Low
12<JS<=30	Medium
>30	High



Source: FHWA

	Yes	No	Total
Low	29	76	105
Medium	34	104	138
High	41	104	145
Total	104	284	388

	Yes	No	Total
Low	28.1	76.9	105
Medium	37.0	101.0	138
High	38.9	106.1	145
Total	104	284	388
p	**0.768837**		

Joint Score

Source: Shutterstock

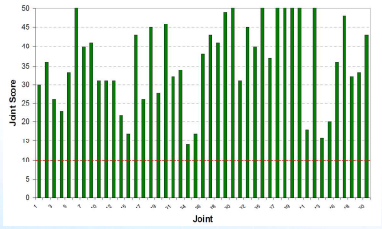
"Further research is needed to refine and verify Joint Score, but the weighting factors listed may be used as an interim measure."

"In the interim, the information provided in this technical brief may be utilized to develop practical, interim specifications."

"…occasional locked joints have no adverse effects on pavement performance."

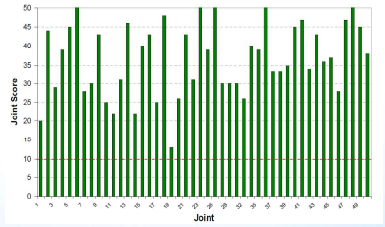
"...high potential for joint locking from dowel misalignment is a necessary but not a sufficient condition for pavement distress."

Joint Score (Georgia I-20, Yu 2005)



Source: ACPA

GA-2 (53% cracking)



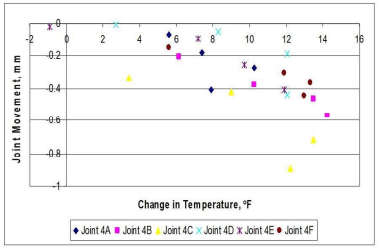
Source: ACPA

GA-3 (6% cracking)

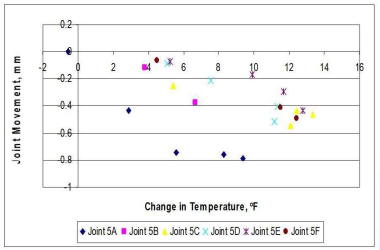
"Despite the prevalence of significantly misaligned dowel bars, the pavement performed very well for over 25 years"

"Although GA2 and GA3 exhibit drastically different pavement performance, there are no significant differences in dowel alignment between the two pavement sections"

Joint Score (Florida I-95, Mallela et al.)



Source: Mallela et al. 2012 Category 4 – JS ~ 30 to 40, none or only one bar with horizontal misalignment greater than 0.8 in.



Source: Mallela et al. 2012 Category 4 – JS ~ 30 to 40, equal contribution to JS from horizontally and vertically misaligned bars

"All the joints tested including those in category 5 (with the highest number and degree of dowel misalignment) experienced joint movements as a function of temperature change"

"The magnitudes of the joint movements in categories 2 through 5 appear to be relatively in the same order of magnitude when compared to the control category (category 1) which had perfectly aligned joints"

NCHRP 637, Khazanovich et al. 2009

"Dowel misalignment is not a primary cause or contributor to the development of transverse cracking. …smaller effect in cracking than variability in other parameters (concrete slab thickness, concrete strength, joint spacing, dowel-concrete friction, etc.)."

"…PCC-dowel friction and/or bond strength due to lack of proper bond breaker or dowel corrosion may cause more restrain to joint opening and closing than dowel rotational misalignment of typical levels."

NCHRP 637 App B, Rao, 2009

"Within the normal levels of misalignments there apparently is no difference in the amount of transverse cracking between joints with low and high average misalignments."

Lab Tests, Analytical Modeling, Field Evaluation (60 projects, 17 States, 2,300 joints, 28,000 dowel bars)

Scope of Presentation

Joint Score

FACTS

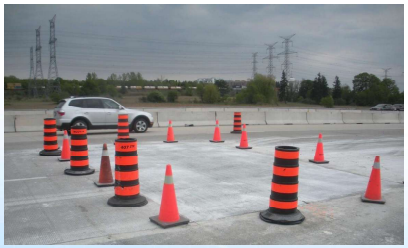
- Weights and limits were speculative and not validated
- Vertical skew and horizontal tilt only, does not consider location of bar
- Developed as a screening tool toward identifying joints for further investigation
- Even with high joint scores, joints may not lock up
- Occasional locked joints have no adverse effects on pavement performance
- Even with high joint scores, risk of increase in transverse cracking is small (but may not be zero)

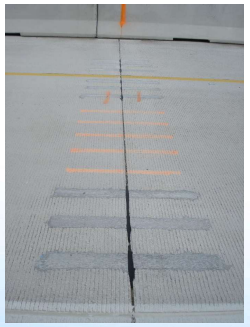
OPINION

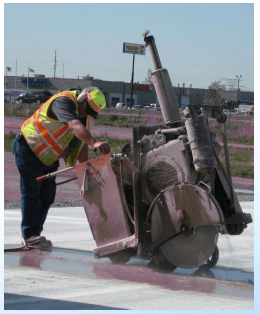
- Easy to calculate, comprehend, and use
- Next general Joint Score should be developed

- Greatest cracking risk likely in the early age particularly when dowel/concrete friction is high + misalignment is high (cracks are closer to the dowels)
- Other sources of transverse cracking stresses (curling/warping, slab weight, slab/base friction) are more significant that those due to dowel misalignment
- Effect is secondary as there are many other primary factors that control cracking (durability, strength, curling/warping, mix design, etc.)

Is the small risk worth …


Source: Dave Hein


Source: Dave Hein


Source: Shree Rao

Two* Methodologies to Combine Bars at a Joint

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Resultant of vertical skew and horizontal tilt only

*Some variations of this methods exist

Effective Dowel Diameter

Khazanovich et al. (2009)
Based on lab tests and limited field data
NCHRP 637

$$d_{eq} = r_{emb} \times r_{cc} \times r_{vt} \times r_{hs} \times d_0$$

d_0 = actual dowel diameter
r = adjustment factors for embedment, concrete cover, vertical tilt, and horizontal skew.

$$r_{emb} = -0.010 L_{emb}^2 + 0.167 L_{emb} + 0.324$$

NCHRP 637 App C, Hoegh and Khazanovich, 2009

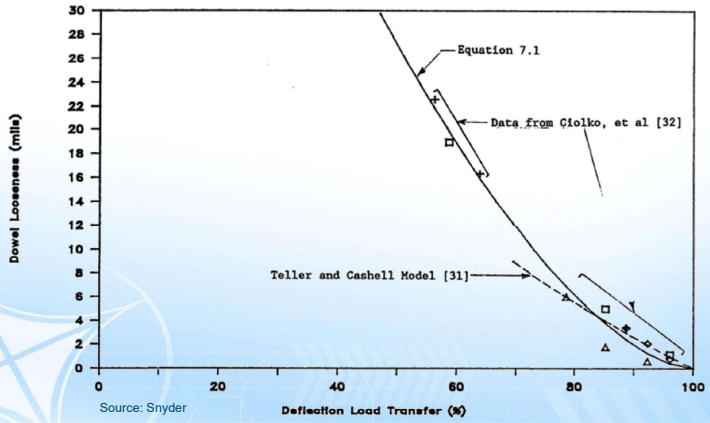
"Dowel rotation does not affect dowel shear capacity unless the rotation is as extreme as 2 in. per 9-in. embedment"

"Reduction in dowel embedment length of up to 6 in. does not affect dowel performance, while reduction in embedment length to 3 in. and lower significantly affects shear capacity"

"Reduction in concrete cover from 3.25 in. to 1.25 in. causes severe reduction in ultimate shear force"

"Combinations of misalignments have a compounding effect on shear performance"

Snyder, 1988



Source: Snyder

Effective Dowel Diameter

Location	Number of Joints	Dowel Diameter (in.)	Average Effective Dowel Diameter (in.)	Average Effective Dowel Diameter Standard Deviation (in)	Average Effective Reduction in Dowel Diameter (%)
Arizona	197	1.25	1.20	0.05	4.2
	195	1.5	1.40	0.09	6.4
Arkansas	169	1.25	1.13	0.18	9.3
	202	1.5	1.42	0.11	5.5
California	196	1.25	0.94	0.26	25.0
	194	1.5	1.25	0.24	17.8
Colorado	199	1.25	1.18	0.27	8.3
	198	1.5	1.44	0.13	4.1
Delaware	228	1.25	1.05	0.36	16.8
	219	1.5	1.46	0.11	2.7
Iowa	198	1.25	1.17	0.18	6.4
	200	1.5	1.43	0.15	4.4
Kansas	198	1.25	1.14	0.20	8.9
	203	1.5	1.44	0.11	4.3
North Carolina	26	1.25	1.20	0.14	3.8
	232	1.5	1.42	0.24	6.1
North Dakota	190	1.25	1.23	0.06	1.8
	194	1.5	1.46	0.07	2.7
South Dakota	25	1.25	1.21	0.03	3.5
Wisconsin	198	1.25	1.15	0.17	8.1
	160	1.5	1.39	0.21	7.2

Effective Dowel Diameter

Created Pavement ME files for all sections

Extracted performance (cracking, faulting, IRI, joint LTE, etc. data from LTPP database)

Ran Pavement ME with two dowel diameters (actual and effective) for all sections to the date of latest performance data

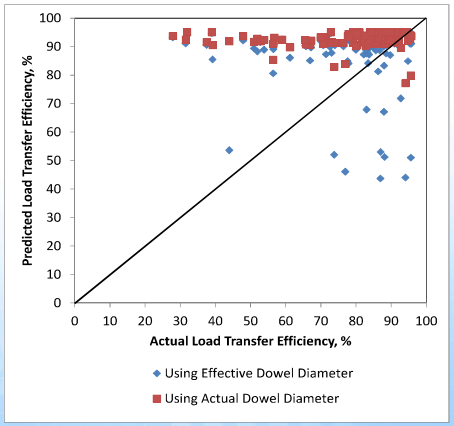
This analysis cannot be performed with Joint Score

Effective Dowel Diameter

Use EDD in Pavement ME

Use Actual DD in Pavement ME

Predicted vs. Actual Load Transfer Efficiency (LTE)



Effective Dowel Diameter

FACTS
- Developed based on laboratory and analytical modeling
- Considers all types of misalignment, considers location of bars
- Only impacts faulting, joint LTE, and IRI (not transverse cracking)

OPINION
- Needs to be calibrated with real field data to improve fit
- Dowel misalignment has the potential to increase dowel looseness over time
- This reduces load transfer across the joint and can result in increased faulting and roughness
- Affected by factors such as mix characteristics (concrete strength, gradation, aggregate type, etc.) and design characteristics (base, subgrade, layer thicknesses, etc.)
- **Potential to include in a performance specification**
  - **lower EDD, higher faulting/IRI as modeled in Pavement ME → disincentives**
  - **higher EDD, lower faulting/IRI as modeled in Pavement ME → incentives**

Impact on Specifications

Good	Moderate	Poor
No direct impact on performance because it is what is expected by most agencies Incentives to encourage quality	Increased risk (but no certainty) of reduced performance Disincentives to discourage frequency of occurrences	Further investigation (extent, severity, design, local experience, options)	Very high to high risk of poor performance Remove/replace or other mitigation measures

PERFORMANCE SPECIFICATIONS or PERCENT WITHIN LIMITS

Performance Specifications

Dowel Placement Specifications

- Stringent, but constructible, requirements should be specified, and allowance should be made for tolerable errors
- Performance specifications or percent-within-limit specifications (incentive / disincentives) may be a good approach

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Thank You!