Determination of In-Place Elastic Layer Modulus: Backcalculation Methodology and Procedures

Panelists

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Organizing Committee

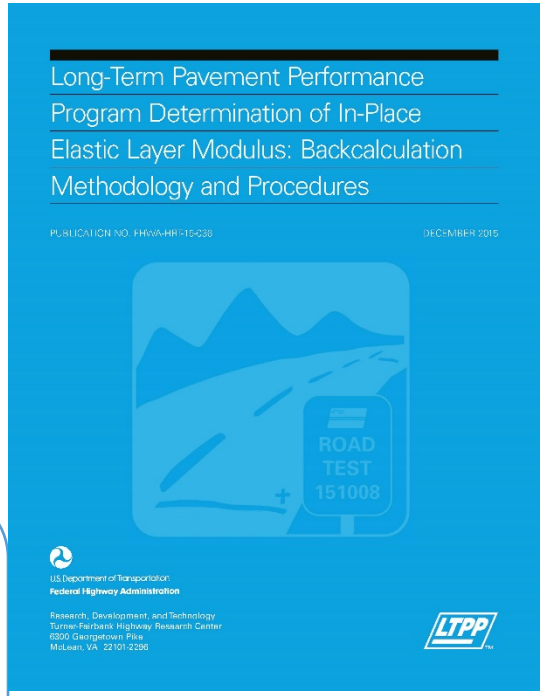
TRB Committee on Pavement Structural Modeling and Evaluation

October 25, 2016

Outline

- Introduction to backcalculation
  - Tools/programs available
- Guidelines for backcalculation
  - Dealing with anomalies and unreasonable values
- Procedures adopted in the LTPP project
  - Results and lessons learned
- Backcalculated modulus in mechanistic-empirical (M-E) design
  - Use of backcalculation results in M-E rehabilitation design
- Questions and answers

Acknowledgements



Determination of In Place Elastic Layer Modulus: Backcalculation Methodology and Procedures

- Long-Term Pavement Performance Data Analysis Project DTFH61-11-C-00051
- Publication Number: FHWA-HRT-15-036

Learning Objectives

- Understand the process and the tools available to backcalculate elastic layer moduli from deflection basin data
- Describe the backcalculated layer modulus values integrated into the computed parameter tables in LTPP
- Use of backcalculated modulus in M-E design

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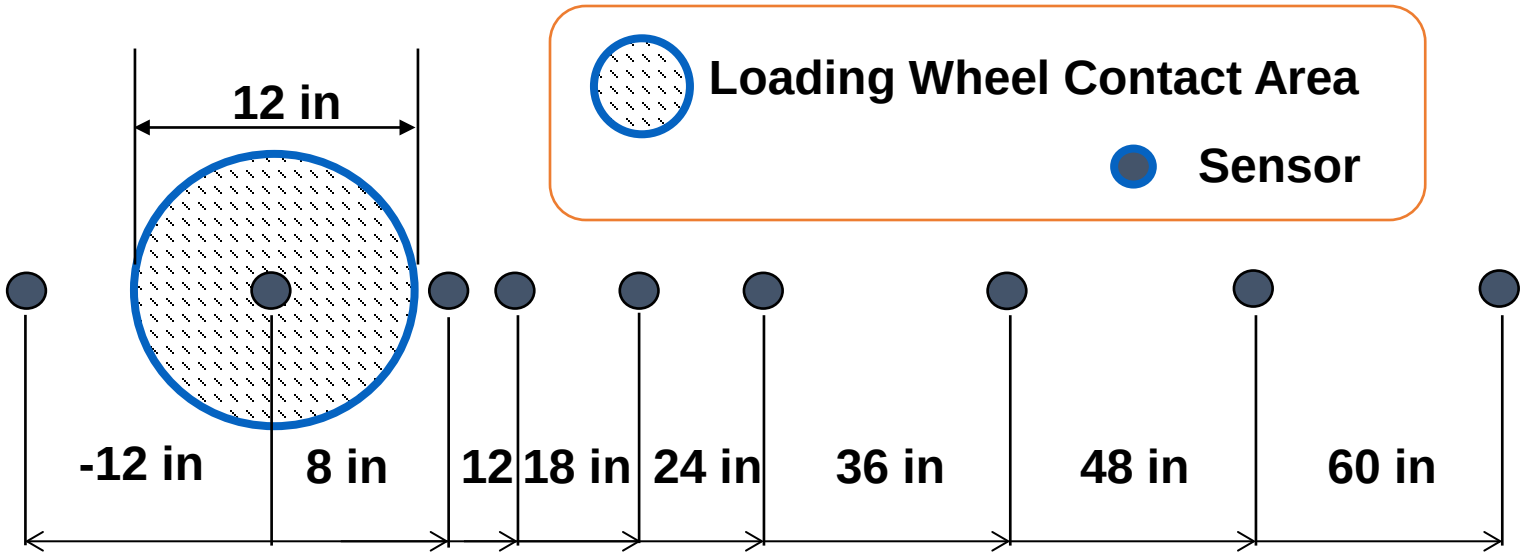
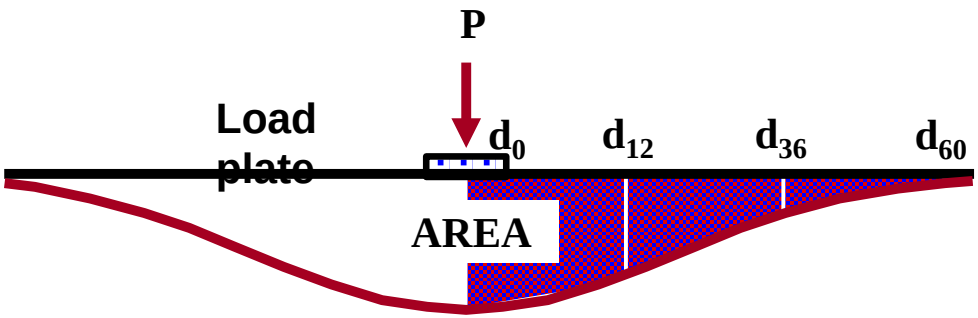
Falling Weight Deflectometer (FWD) Testing

- NDT procedure
- Impact load device
  - Simulate a moving wheel load
  - Measure pavement response-deflection basin
  - Require no fixed reference
  - Relatively fast
- Several applications
  - Backcalculation of layer properties – most common

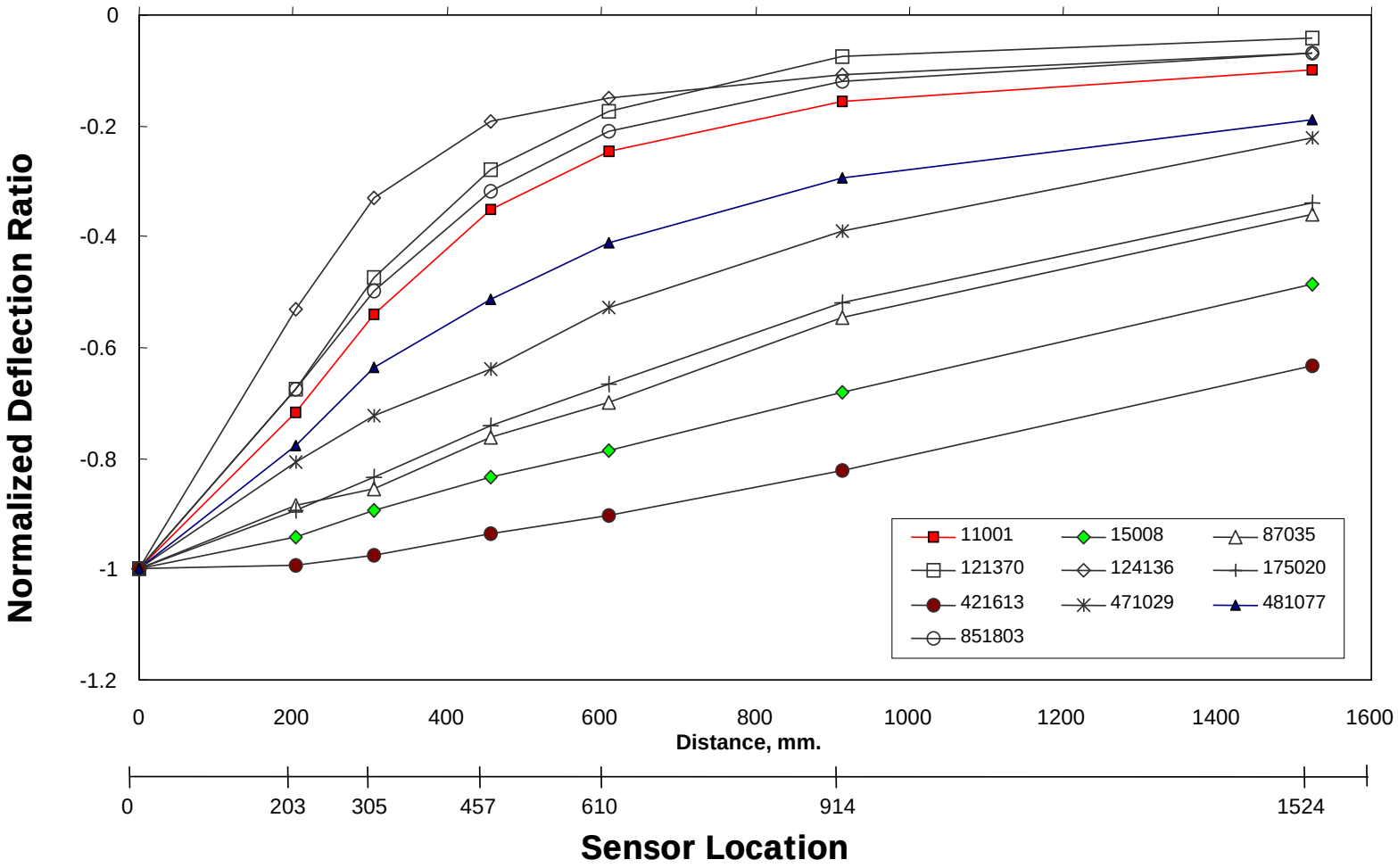
Typical Sensor Configuration & Deflection Basin



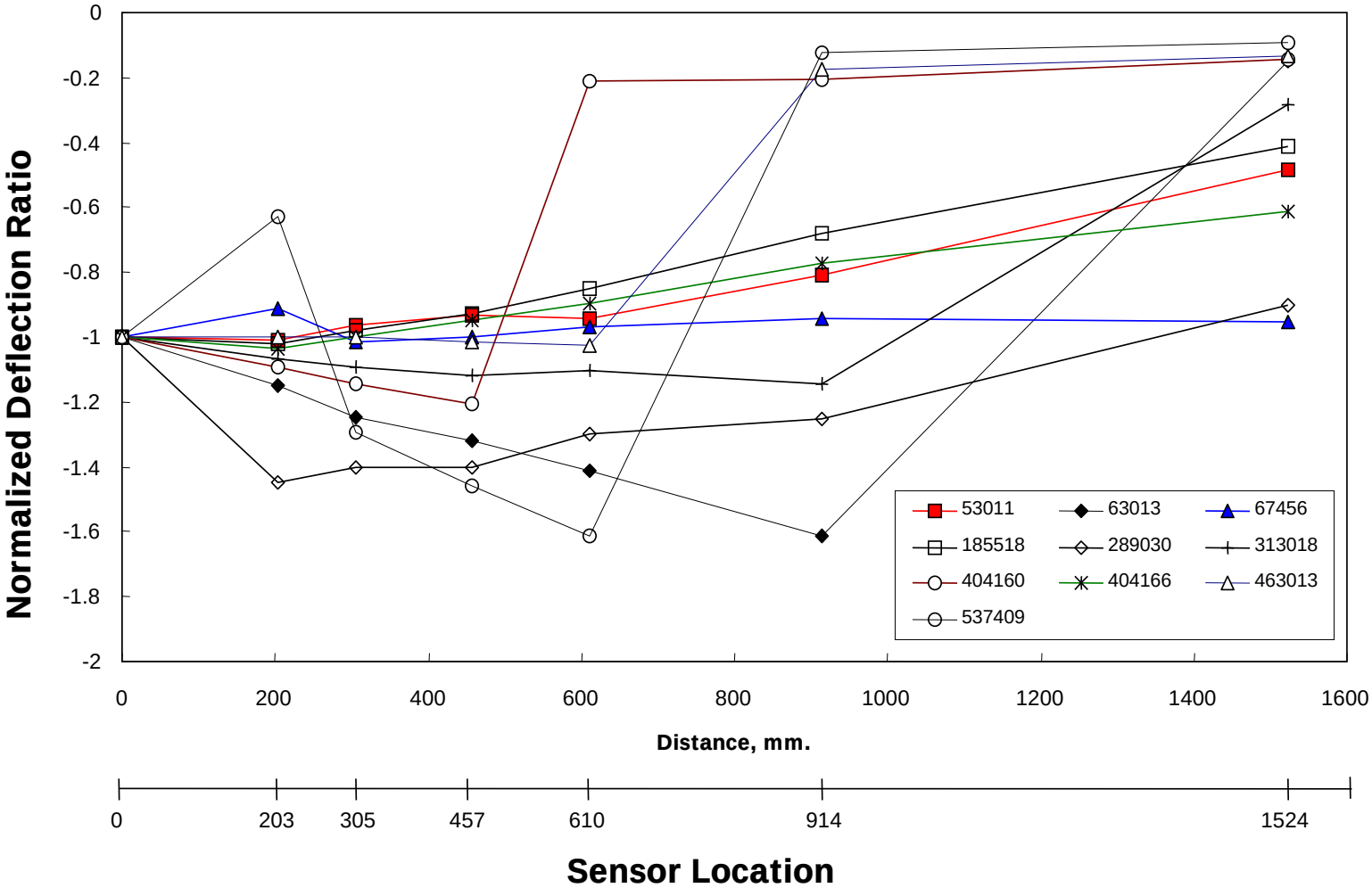
Deflection Basin



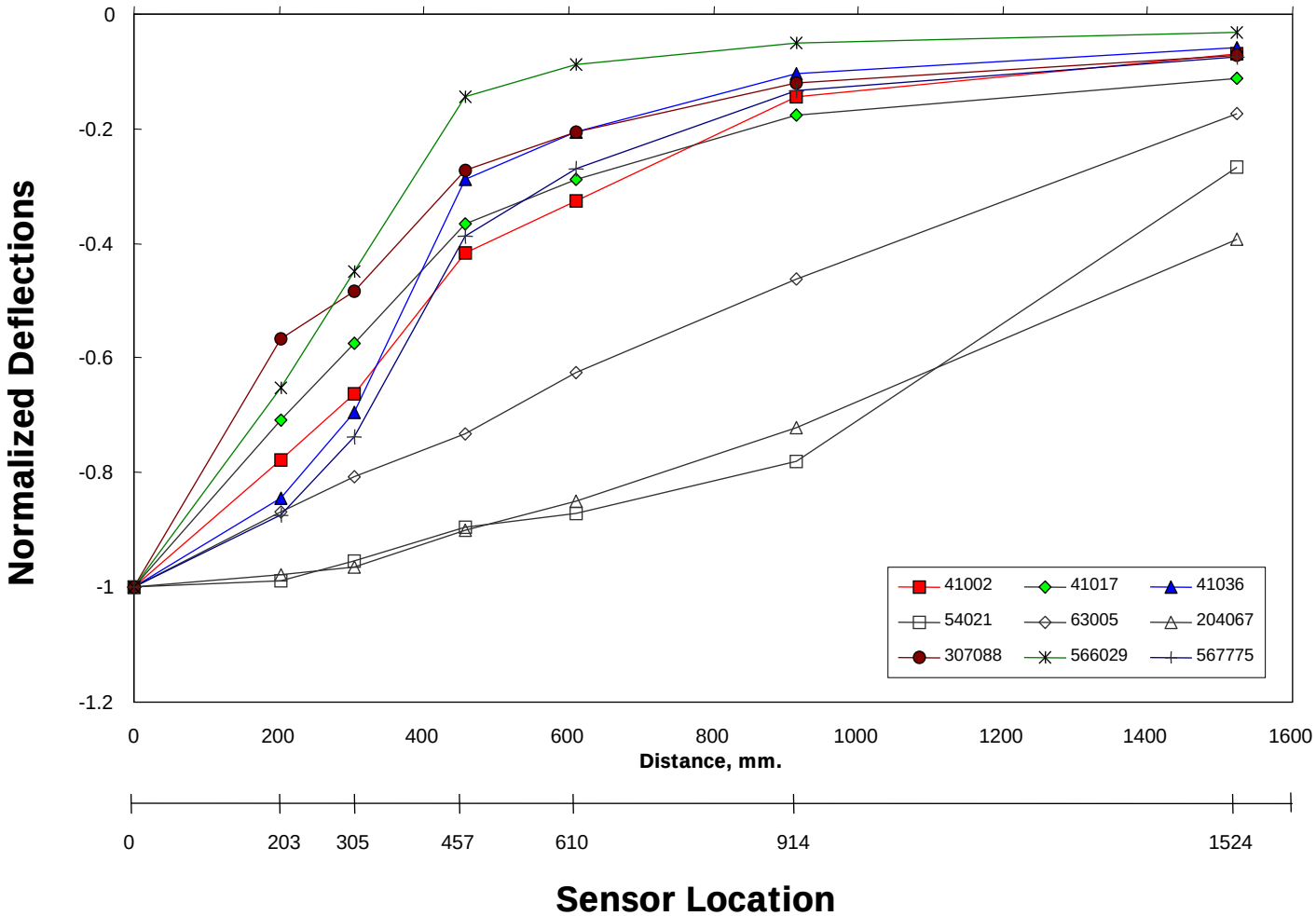
Typical Normalized Deflection Basin



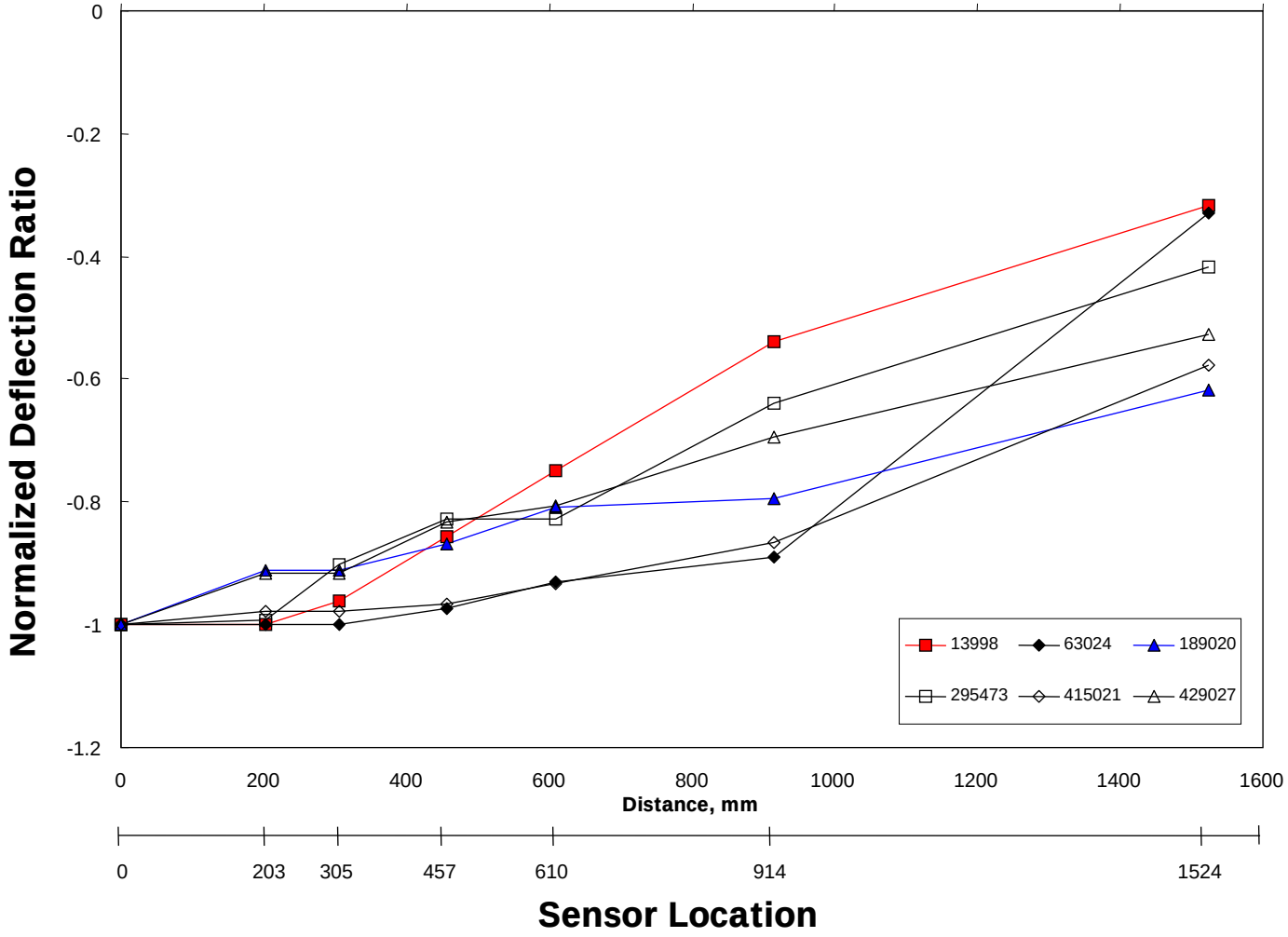
Typical Normalized Deflection Basin—Type I



Typical Normalized Deflection Basin—Type II

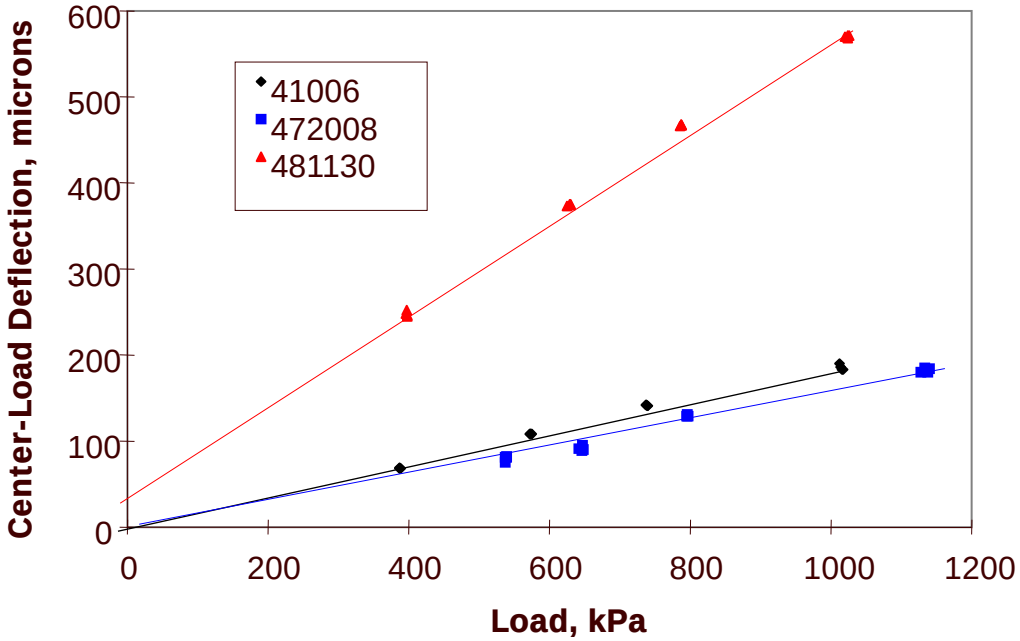


Typical Normalized Deflection Basin—Type III



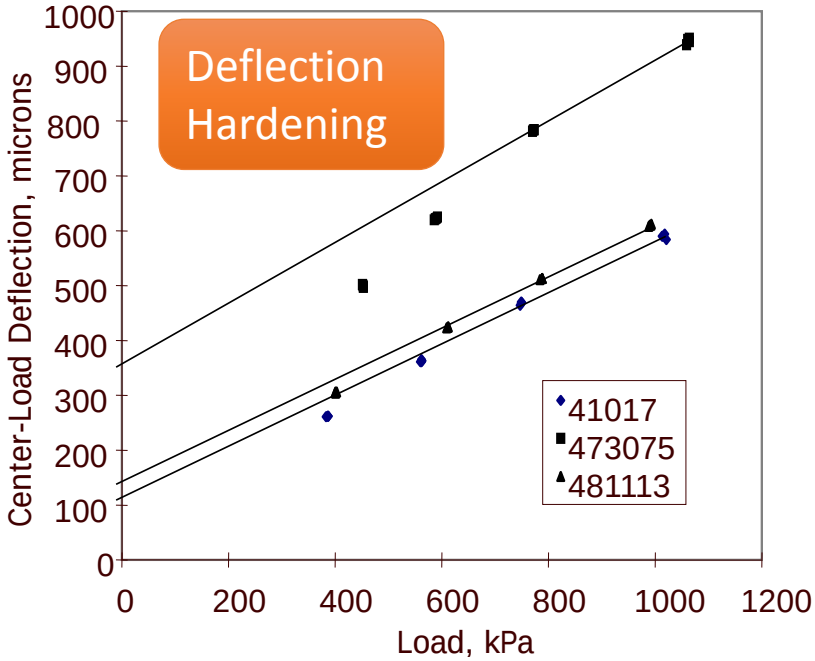
Deflection Testing at Different Load Levels
Linear Response

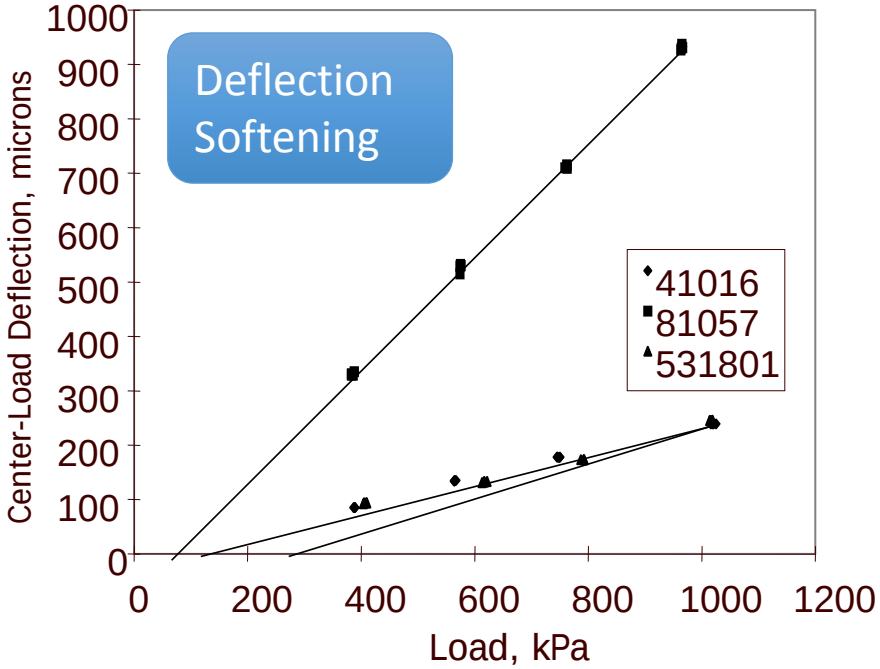
- Four drop heights
  - 6,000 lb. (378 kPa)
  - 9,000 lb. (566 kPa)
  - 12,000 lb. (755 kPa)
  - 16,000 lb. (1007 kPa)



Deflection Response

An Indicator of Material Behavior





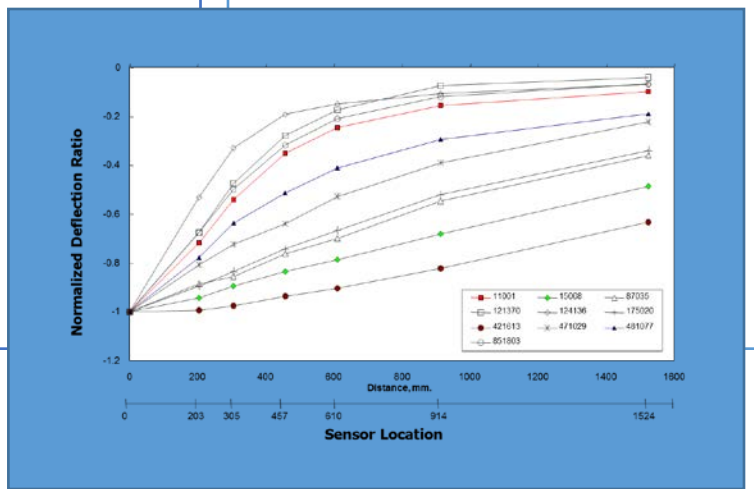
Backcalculation Methods and Software

Methods

- Iterative Search Methods
- Database Search Methods
- Equivalent Thickness Methods
- Forward Calculation Methods/ Closed form solutions
- Other/Evolving

By Pavement Type

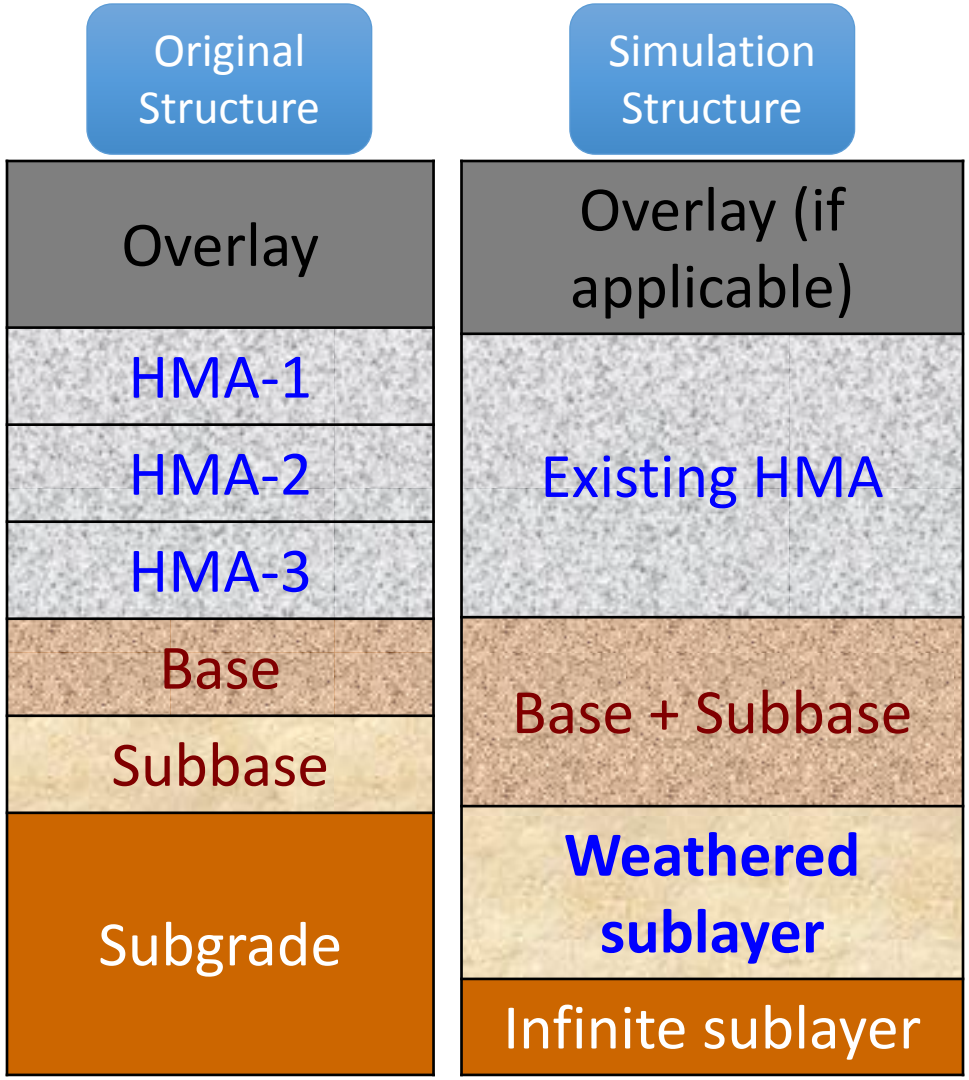
- Flexible pavements
  - EVERCALC, MODCOMP/MODTAG, MODULUS, ELMOD, and others
- Rigid pavements
  - Best-fit method, Area Method, EVERCALC, etc



Simulation of Structure for Backcalculation

Mapping Layers

- EVERCALC – 5 layers
- MODTAG – 7 layers
- MODULUS – 4 layers

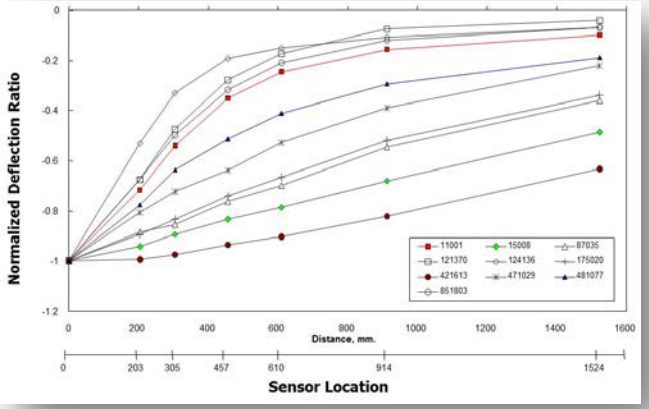


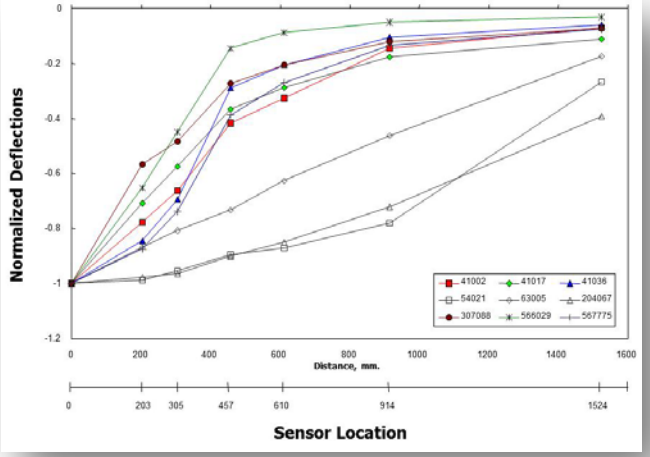
Selection of Backcalculation Program
Depends on User's Needs

- Underlying theory (same as that used in design procedure?)
- Number of layers permitted in the analyses
- Convergence criterion
  - RMSE, absolute error, error term accounting for specific sensors
- Accuracy of the program
- Operational characteristics
- Ease of use of the program
- Stability of the program

LTPP Data Analyses Project
Hypotheses & Findings

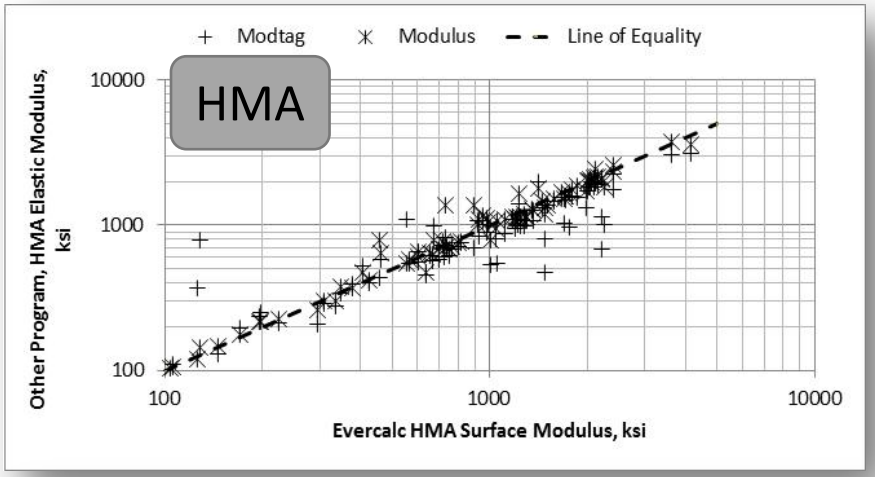
- **Hypotheses:**
  - Backcalculation packages result in the same set of elastic layer modulus values.
  - Backcalculated elastic layer modulus values are correlated to but have a bias related to laboratory measured modulus values.
- **Findings:**
  - For deflection basins consistent with elastic layer theory:
    - Hypotheses accepted.
  - For deflection basins diverging from elastic layer theory:
    - Hypotheses rejected.

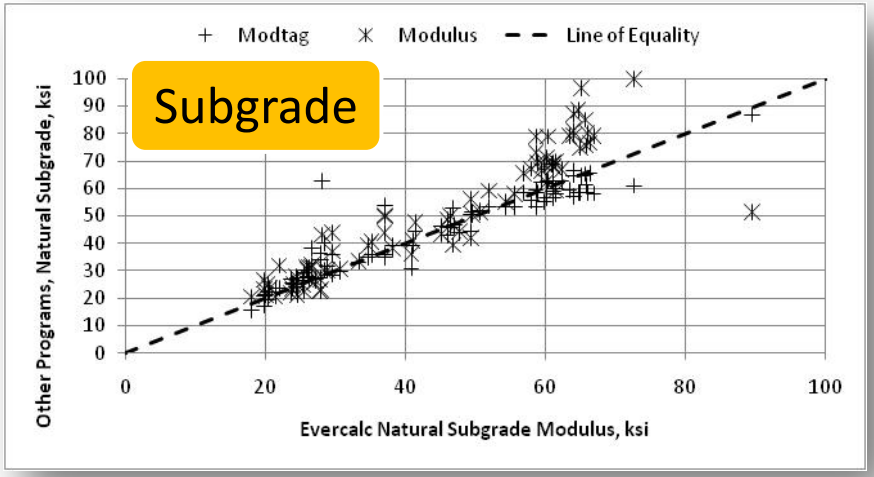


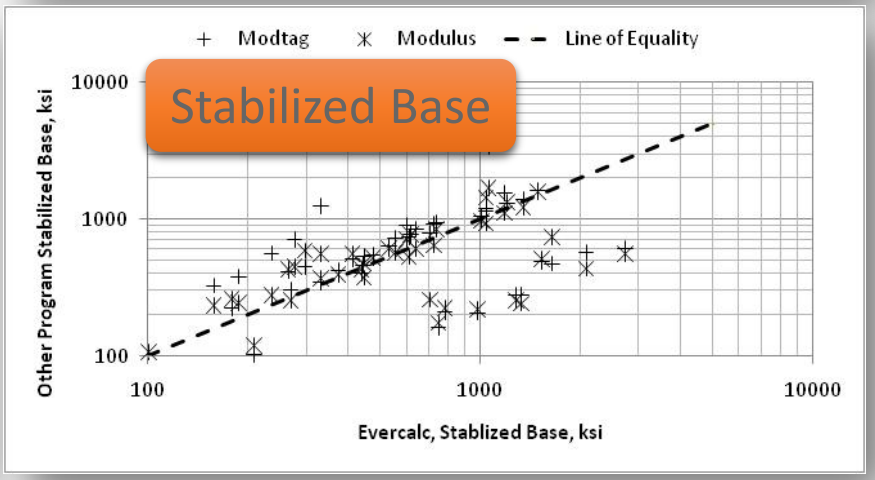


Findings

Programs resulted in similar elastic layer modulus values for many case study sites.







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Backcalculation of E Values

In place elastic layer moduli from deflection basins for forensic investigations or rehabilitation design.

1. Limited to a specific number of layers:
   a) Structure simulation is important.
   b) Results are a composite E value for individual layers.
2. Most procedures, based on elastic layer theory:
   a) E values do not vary vertically or horizontally for an individual layer .
   b) Layer is intact and continuous in the horizontal plane.

Reality versus Simulation?

Backcalculation Challenges

Assessment of Results, Categories:

- Errors between measured & calculated values.
- Compensating adjacent layer E-values.
- Inappropriate E-values.

Overcoming the Issues:

- First – try to identify what is causing the issue.
- Do not make random changes to structure.

How does one know that the results are good/poor?

How does one Identify the cause of bad results?

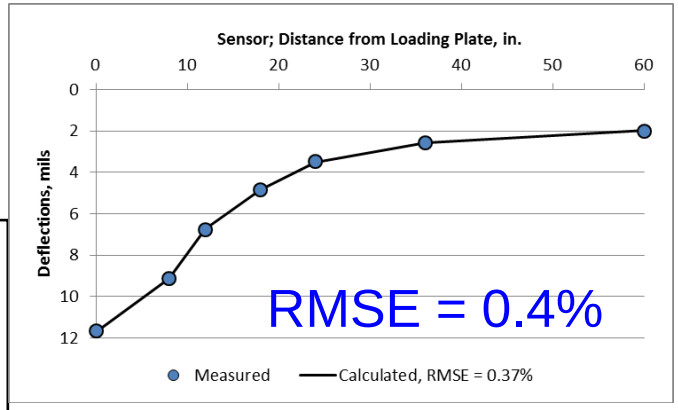
Assessment of Results

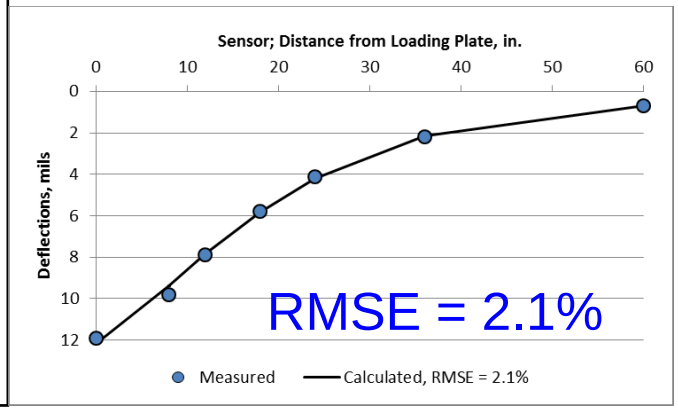
Error Term

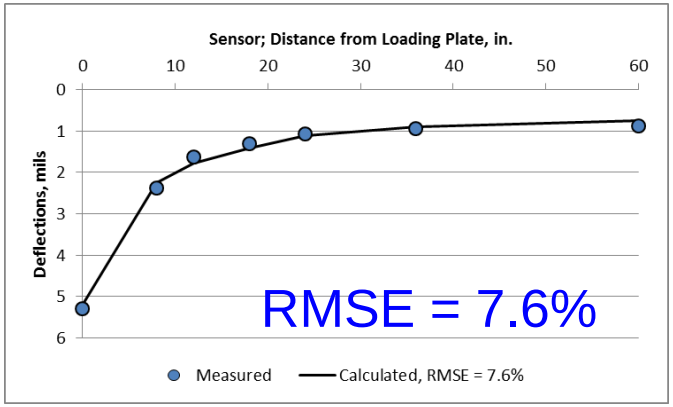
Error between the measured and calculated deflection basins.

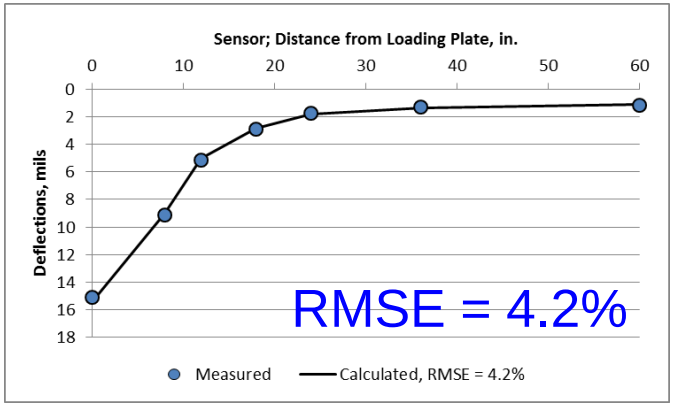
1. Absolute error per sensor—MODULUS.
2. Root mean squared error—EVERCALC, MODCOMP

Make error as small as possible. (RMSE<5%)









Assessment of Results
RMSE

- Error between the measured and calculated deflection basins
- BUT:

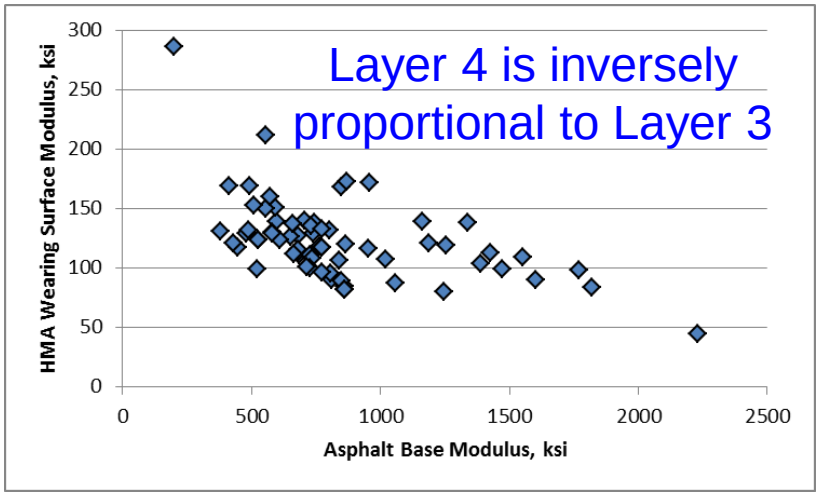
- Low RMSE—does not mean you have accurate values for in place layers.
- High RMSE—does not mean you have inaccurate values for the in place layers.

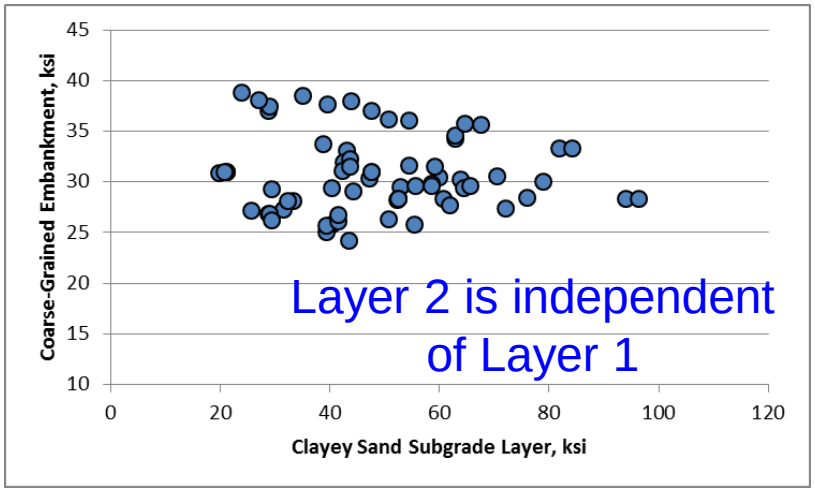
RMSE is not an indicator of accuracy in backcalculation!

Assessment of Results
Compensating Layer

Compensating adjacent layer E values

1. Layer E is inversely proportional to an adjacent layer E value.
2. The resulting E values for adjacent layer can be:
   a) Independent of one another.
   b) Proportional to one another.





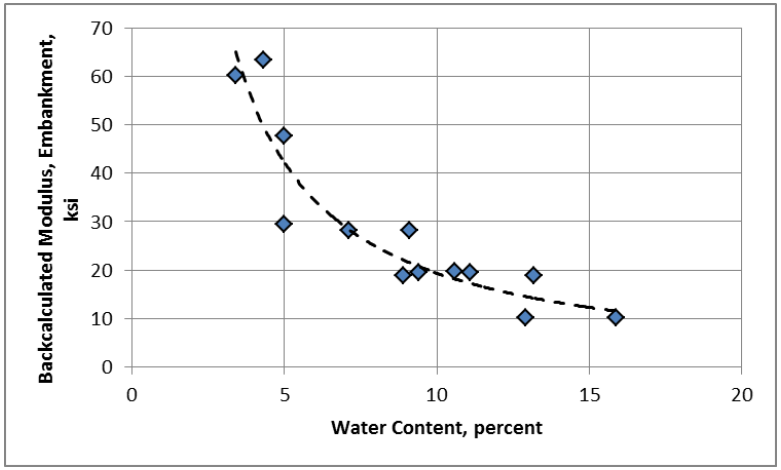
Assessment of Results

Inappropriate E Values for a Material

Thick. = 6 in.;	E = 878,000 psi
Thick. = 12 in.;	E = 215,343 psi
Thick. = 24 in.;	E = 48,655 psi
Thick. = Inf.;	E = 33,359 psi

Assessment of Results
Inappropriate E Values for a Material

- BUT, for unbound layers:
- E decreases as layer becomes wetter; near saturation E values can be low.
- E increases as layer becomes drier; for some materials/soils layer can respond as a bound layer.



Overcoming Backcalculation Issues

The more information you have, the fewer backcalculation challenges you have.

In other words:

Bad assumptions in Invalid values out!

or

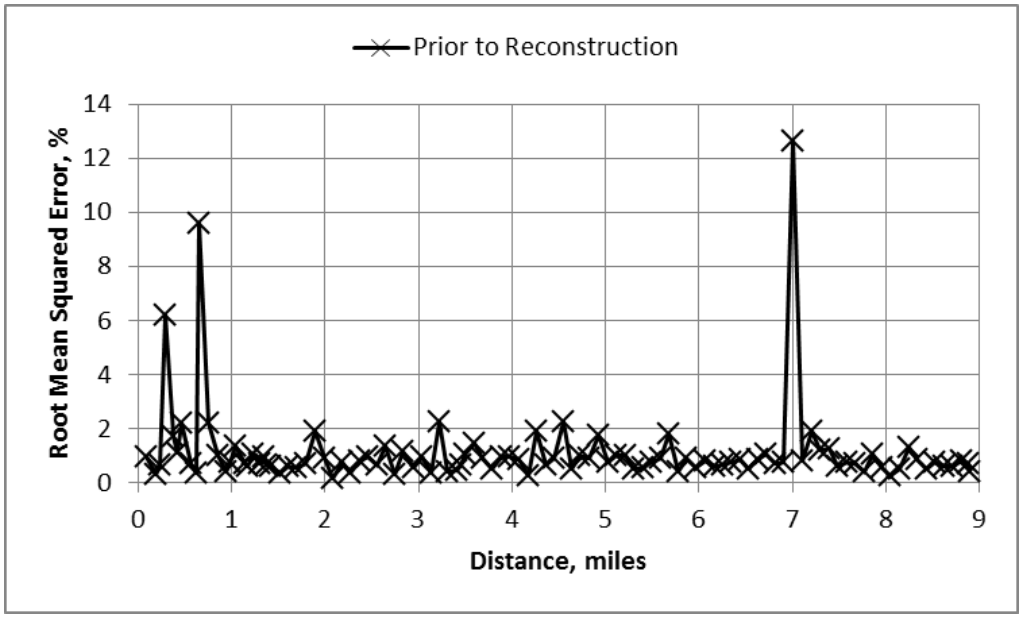
Garbage in

Garbage out!

Overcoming Backcalculation Issues

Quantify or understand the issue:

- Scattered across the entire project length?
- Common to a specific site feature?
- Confined to specific areas of the project?



Types of Errors or Issues

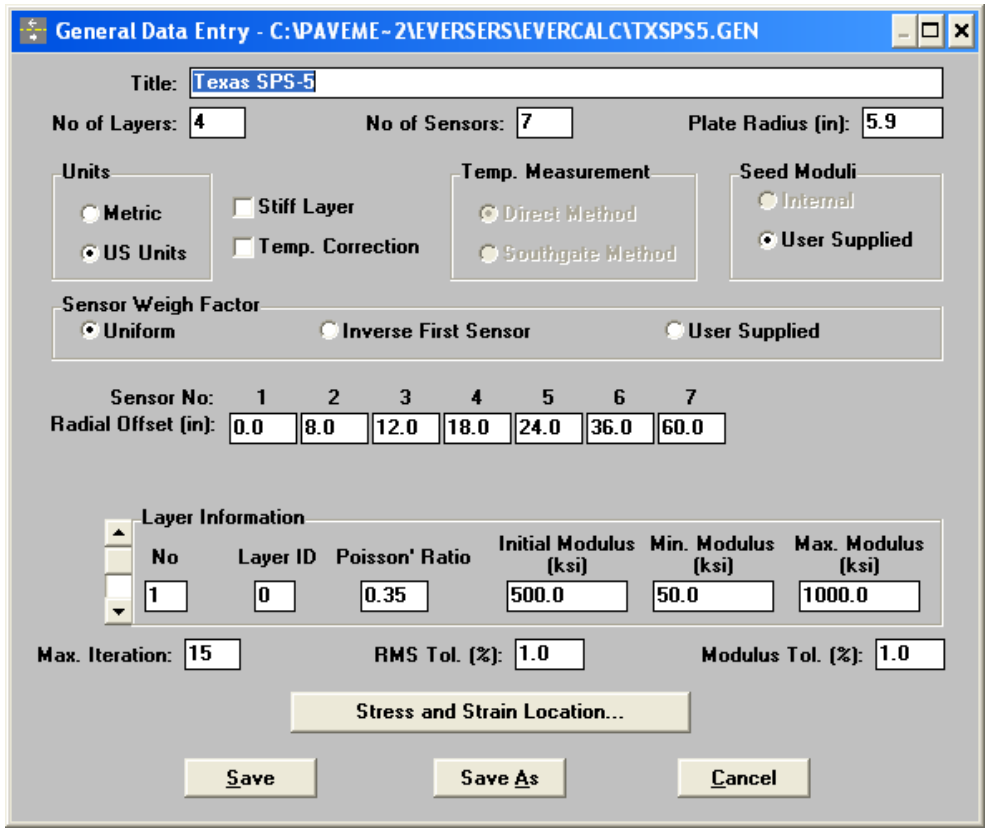
- Input Errors
- Measurement Issues
- Simulation Issues
  - No discontinuities
  - Homogeneous layers
  - Uniform contact pressures under the loading plate

Types of Errors or Issues

Input Errors

Typos (sometime blunders) in selected inputs

- Layer Thickness
- Sensor spacing
- Plate size
- Units



Types of Errors or Issues
Measurement Errors

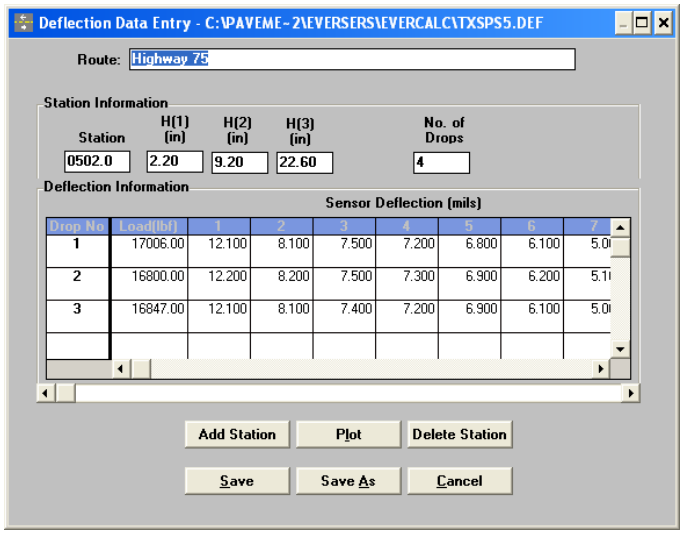
- Sensor spacing relative to layer structure
- FWD Calibration Issues
- Condition of Surface
  - Loose surface material
  - Cracks, discontinuities
  - Severe distortions

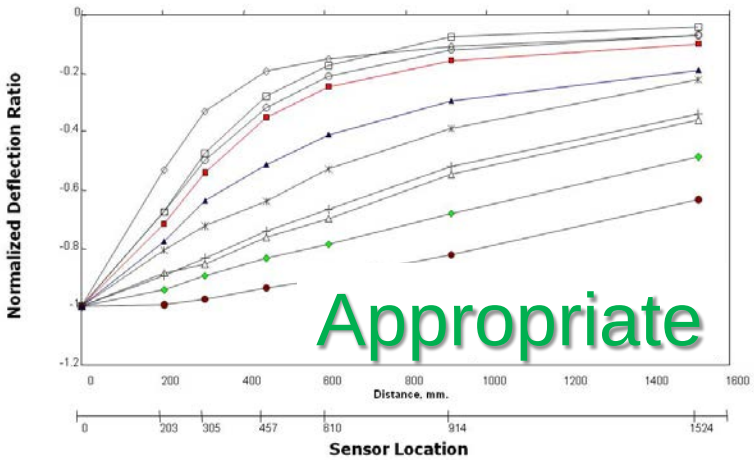
Types of Errors or Issues
Errors in Simulation of Structures

- Combining “like” layers, that may not be “like” layers.
- Number of layers
- Variability of layer thickness
- Thin layers
- Rigid layers
- Stripping
- Voids
- Water table depth

Identify Error or Issue

- When issues are identified, what should be done?
- Do the easier steps first:
- Review and check inputs to make sure they are correct – Check for Blunders.

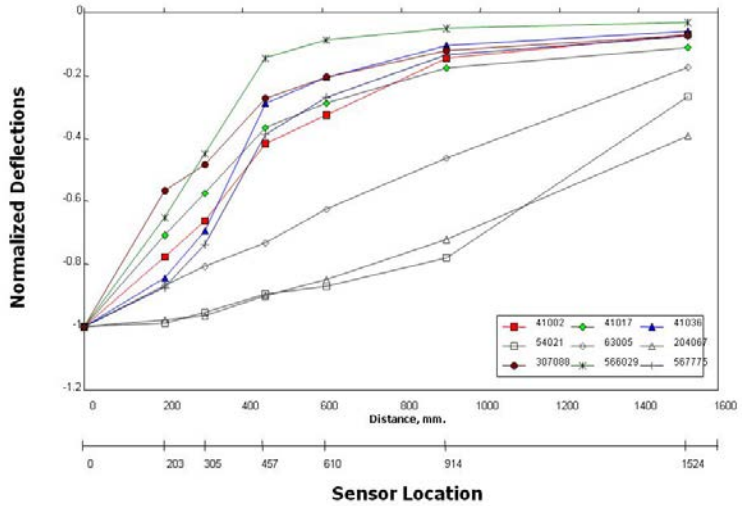


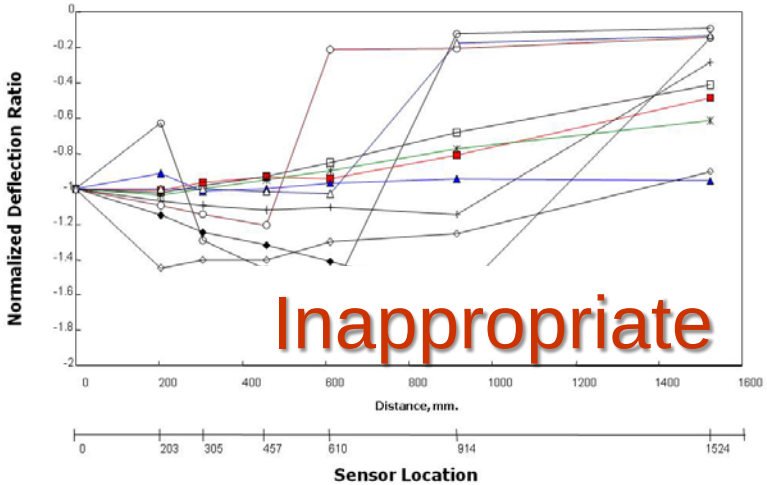


Identify Error or Issue

Evaluate Basins

- Evaluate basins to determine applicability to elastic layered solutions for backcalculation.





Identify Error or Issue
Check Sensor Spacing

- Make sure sensor spacing inputs match what was used to collect deflection basin data.

Identify Error or Issue
Surface Condition

- Cracks
- Loose material, raveling
- Severe distortions

Notes on surface condition during FWD testing can prove very valuable!

Identify Error or Issue
Structural Layer Information

- Good quality pavement structural layer information.
- Ensure sufficient destructive tests to define layer thicknesses and subsurface features.

Drill cores & borings in areas with significantly different basin shapes.

Identify Error or Issue
Layer Insensitive to Load

- Thin layers under thicker layers.
- Change in modulus values have little effect on the deflection basin.

Assume a typical E value for the layer or combine with a "like" adjacent layer.

Thin layer?

Identify Error or Issue
Subsurface Features

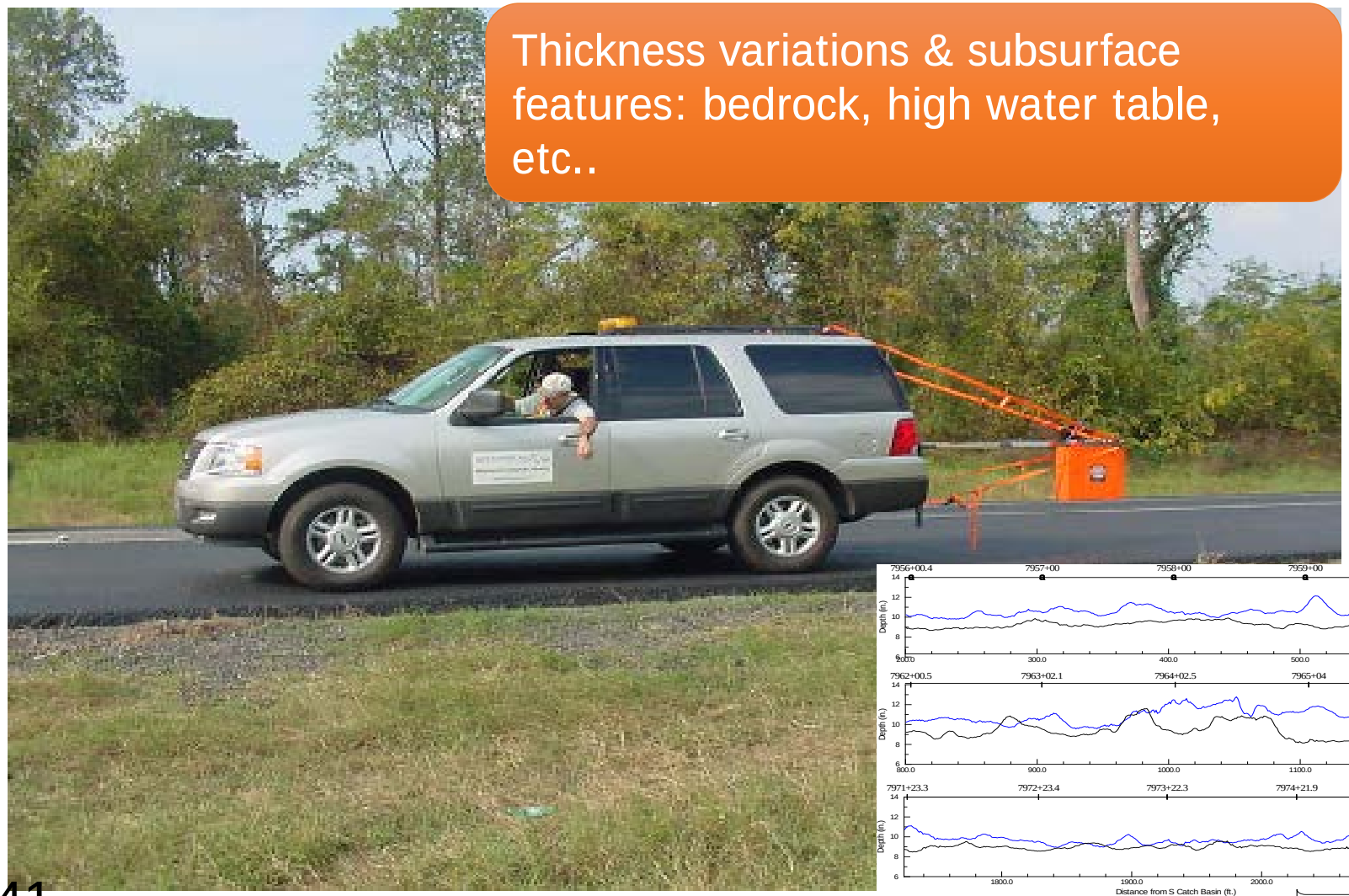
- Stripping in HMA mixtures between layers.
- “Like” unbound layers with opposite stress sensitivity.

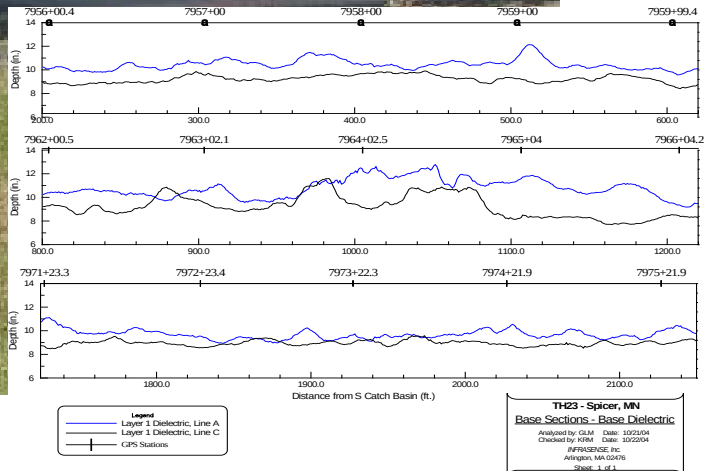
Identify Error or Issue
Subsurface Features

- Loss of bond or horizontal cracks near surface.
- Vertical cracks below surface.

Identify Error or Issue

Thickness variations & subsurface features: bedrock, high water table, etc..





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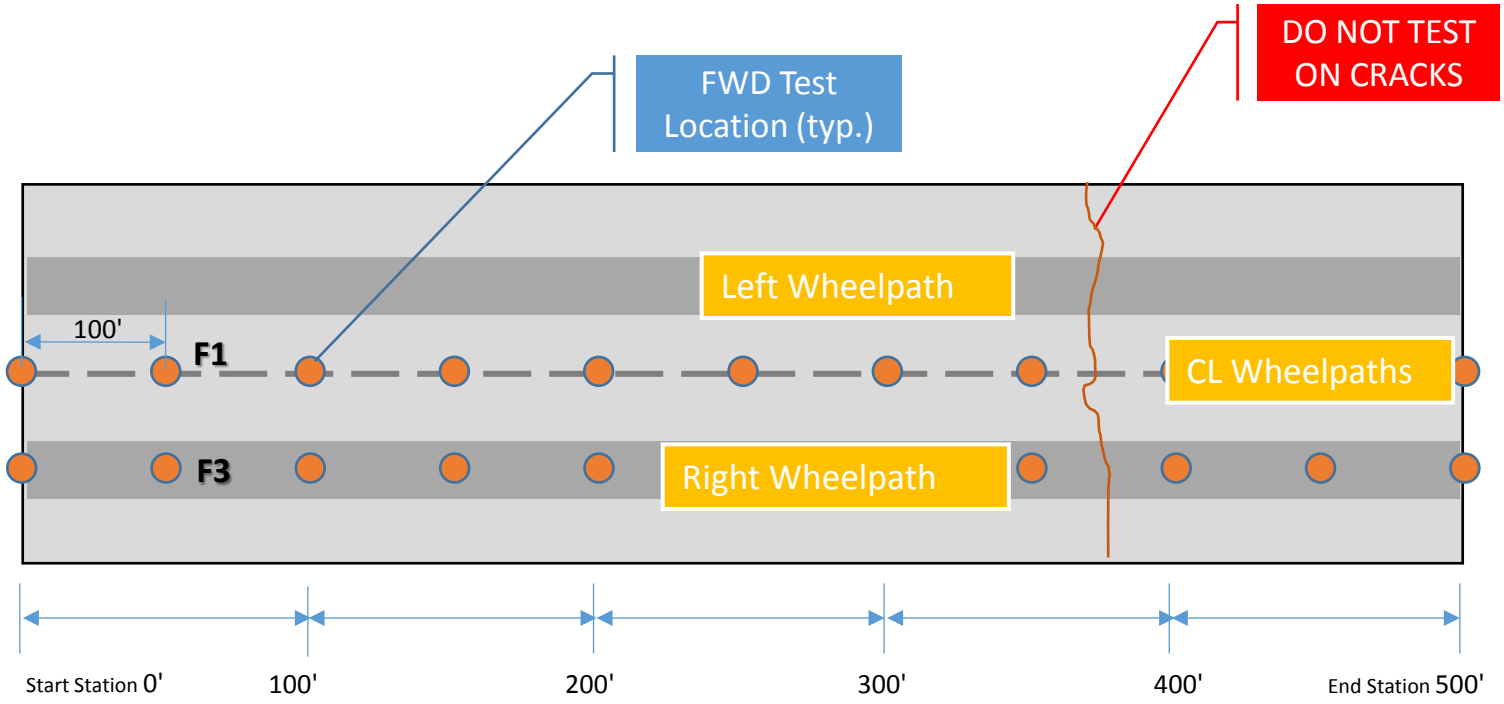
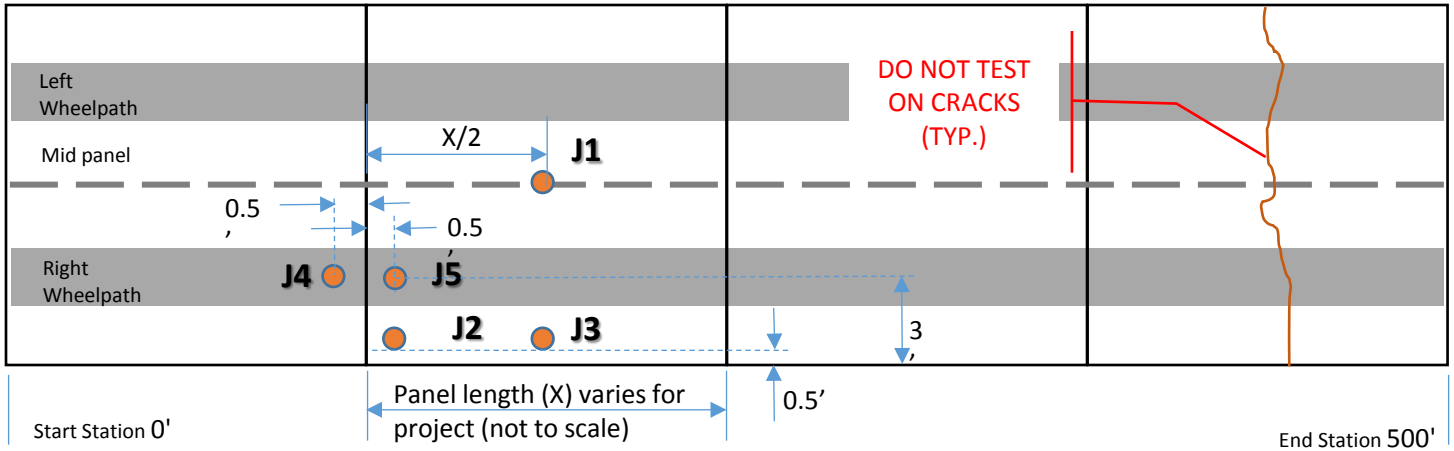
LTPP FWD Test Plan for Flexible Pavement



- 4 Drop Heights (6, 9, 12, and 16 kips)
- No. of drops = 4 per drop height
- Total Drops per test point = 16

LTPP FWD Test Plan for Rigid Pavement



- 3 Drop Heights (9, 12, and 16 kips)
- No. of drops = 4 per drop height
- Total Drops per test point = 12

LTPP FWD Deflection Test Data
A Snapshot

- Number of sections
  - 1,744 HMA surface + 1,008 PCC surface
  - 381 sections under HMA and PCC
  - 3,133 unique sections in all States
- Automate97 percent deflection basins fell under Type 2/Typical categories
- Requirements
  - Automated backcalculation procedure
  - Less dependency on user
  - Recreate the results by others not involved in the development process
- Backcalculation Procedures
  - EVERCALC
  - MODTAG (MODCOMP)
  - Best Fit for all RIGID Sections

5,847,770 deflection basins (typical and type 2)

Definition of Error Status

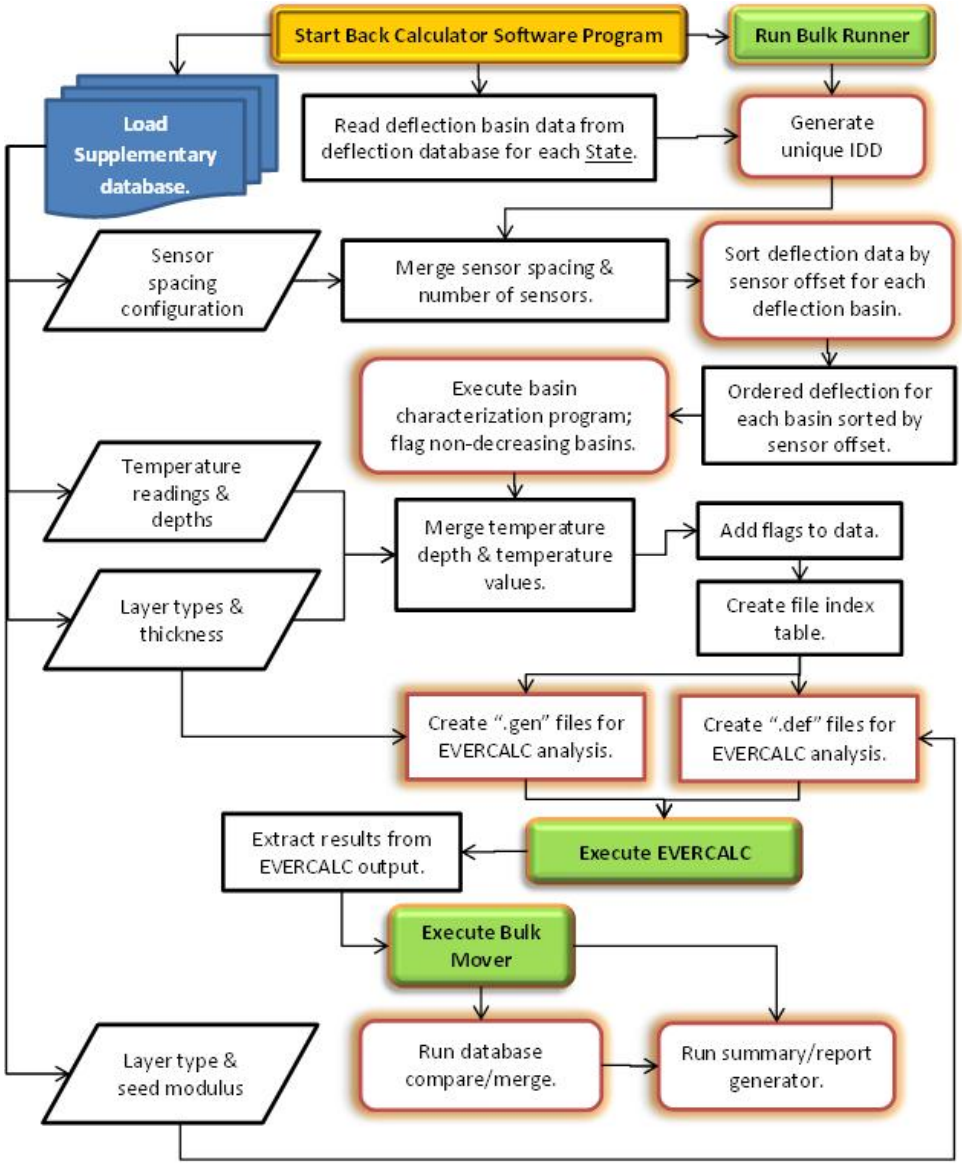
Based on RMSE and Backcalculated E Value

Criterion	Acceptable	Atypical	Error or Unacceptable
RMSE	≤3.0	≤3.0	>3.0
	and	and	or
Modulus value (by material type)	Within Acceptable range limits	Outside acceptable but within atypical limits	Outside Atypical range limits

Acceptable	Atypical	Error

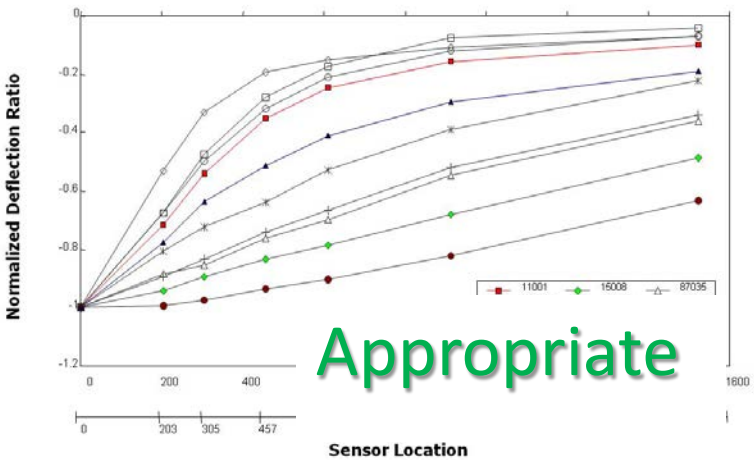
Automated Backcalculation Process

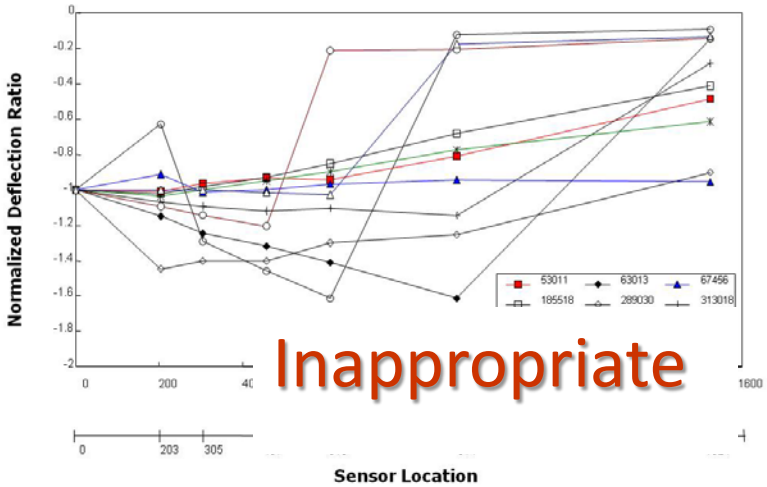
- Makes process less dependent on the users
- Users can use the tools and procedures to recreate the results.



Preprocess Data

- Issues with sensor or deflection data
- ModTag/Program Slic
- Deflection basin characterization
  - Unacceptable - Type I & Type III
  - Acceptable – Type II or Typical
- Load response characterization – post processing of backcalculation results
  - Deflection hardening
  - Deflection softening
  - Elastic/linear elastic

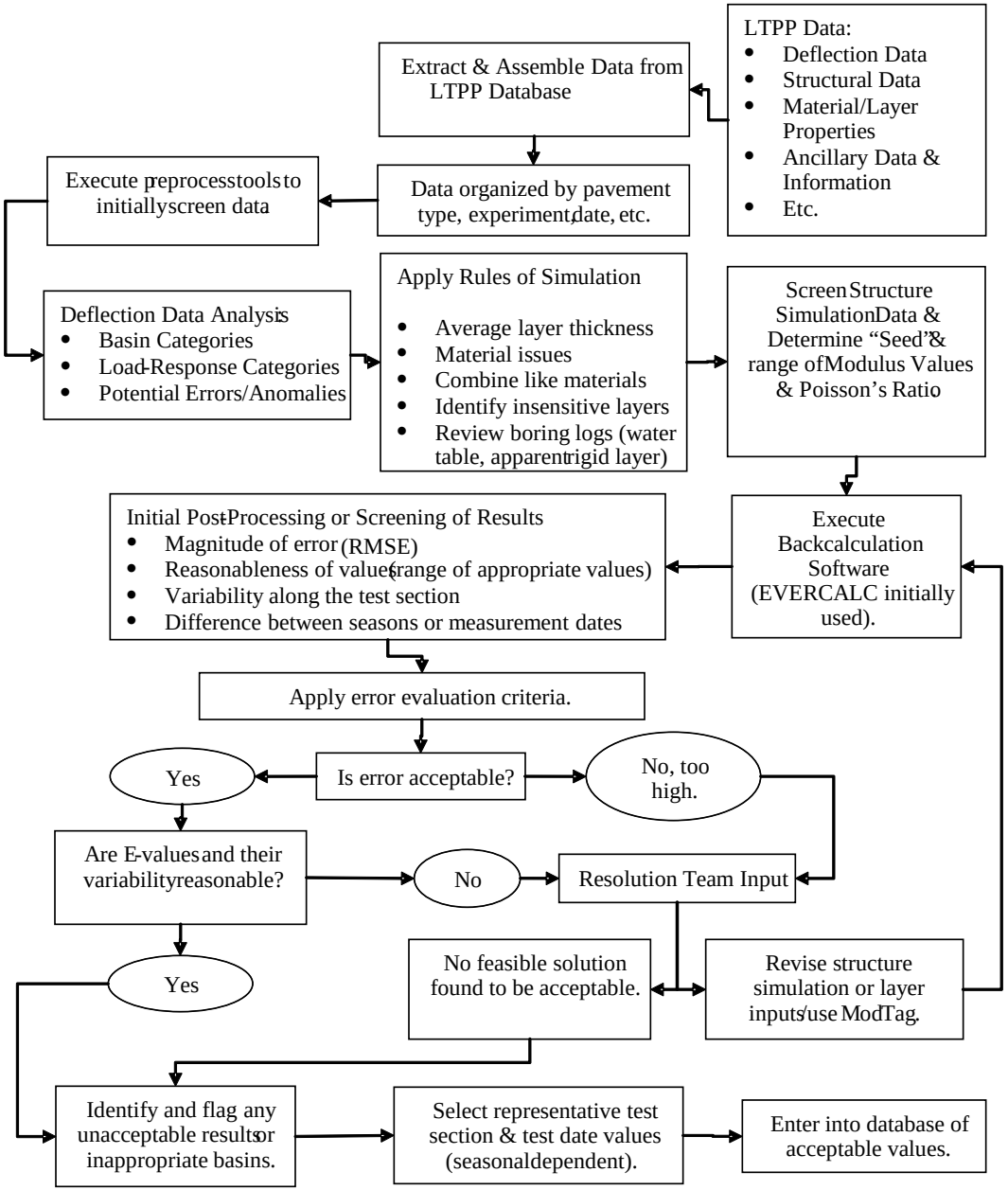




Decision Tree

1. Extract & assemble data
2. Preprocess data
3. Apply rules of simulation
4. Execute BC – program
5. Apply error evaluation criteria
6. Resolve/flag inappropriate results
7. Enter into CPT

Analyses performed by State to optimize computational needs



Computed Parameter Tables
LTPP Database

Layer Structure Information
1. Section Information
2. Structures, EVERCALC
3. Structures, BEST FIT

Backcalculated Modulus Values	
Individual Basins	**Summary for Test Day**
1. Elastic layer moduli from EVERCALC/MODCOMP	1. Elastic layer moduli from EVERCALC/MODCOMP
2. Elastic layer moduli from BEST FIT	2. Elastic layer moduli form BEST FIT
3. Load transfer efficiency from BEST FIT	3. Load transfer efficiency from BEST FIT

Mapped to LTPP Sections Layer information (L05B)	All results included in CPTs	Only results defined as acceptable and Atypical included in CPTs

Findings

- 97 percent of LTPP deflection data – good to use in backcalculation
- Over 76 percent of deflection basins resulted in elastic layer moduli considered acceptable or atypical
- Deflection testing provides valuable information & data
- Use of 4 drop heights not necessary for rehabilitation designs.

Result	Total Number of Drops	Percent of Total Drops
Drops	5,662,494	100
Unacceptable Results	1,350,680	23.9
Atypical Results	2,494,628	44.1
Acceptable Results	1,817,186	32.1
Total Acceptable & Atypical Results	4,311,814	76.1

Outline

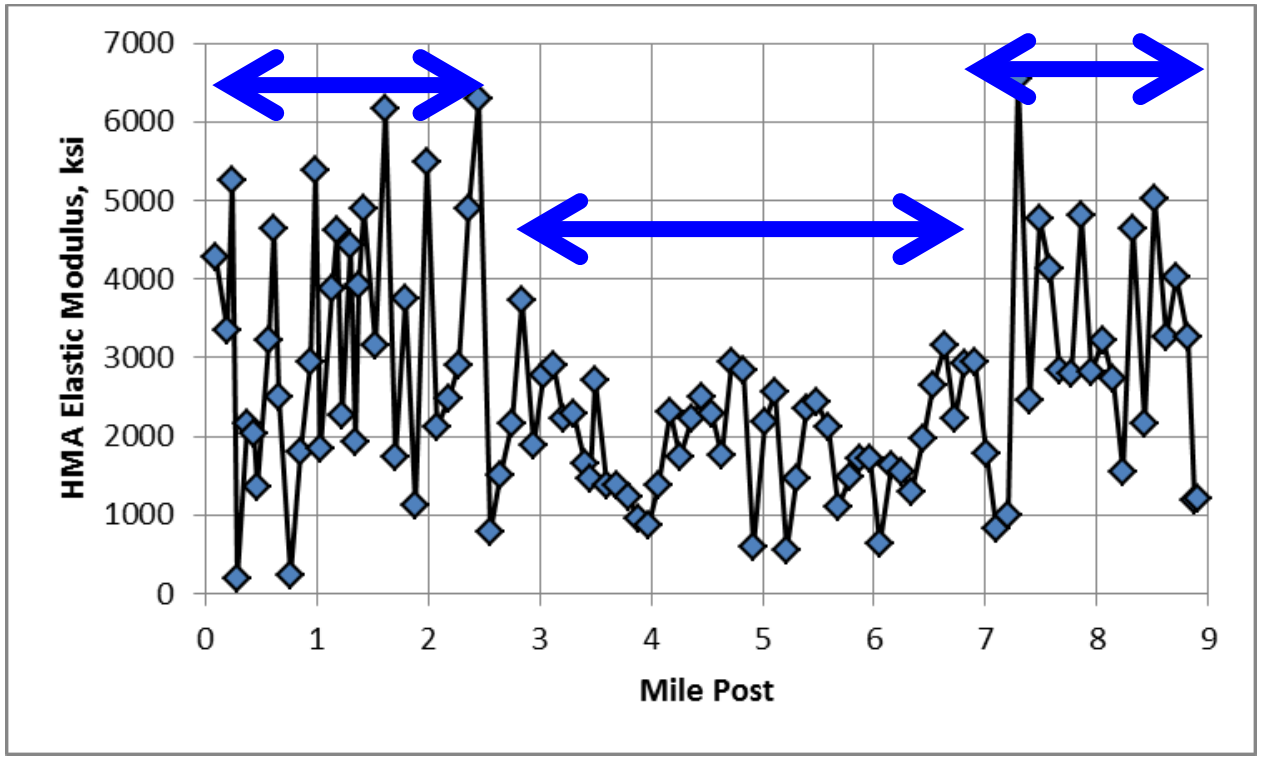
- Introduction to backcalculation
  - Tools/programs available
- Guidelines for backcalculation
  - Dealing with anomalies and unreasonable values
- Procedures adopted in the LTPP project
  - Results and lessons learned
- Backcalculated modulus in mechanistic-empirical (M-E) design
  - Application and use of backcalculation results
- Questions and answers

Application and Use

- Use of backcalculated data for rehabilitation design
  - Location for sampling.
  - Layer E values.
  - In place damage.
  - Schedule rehabilitation or preservation.
  - Load transfer efficiency.

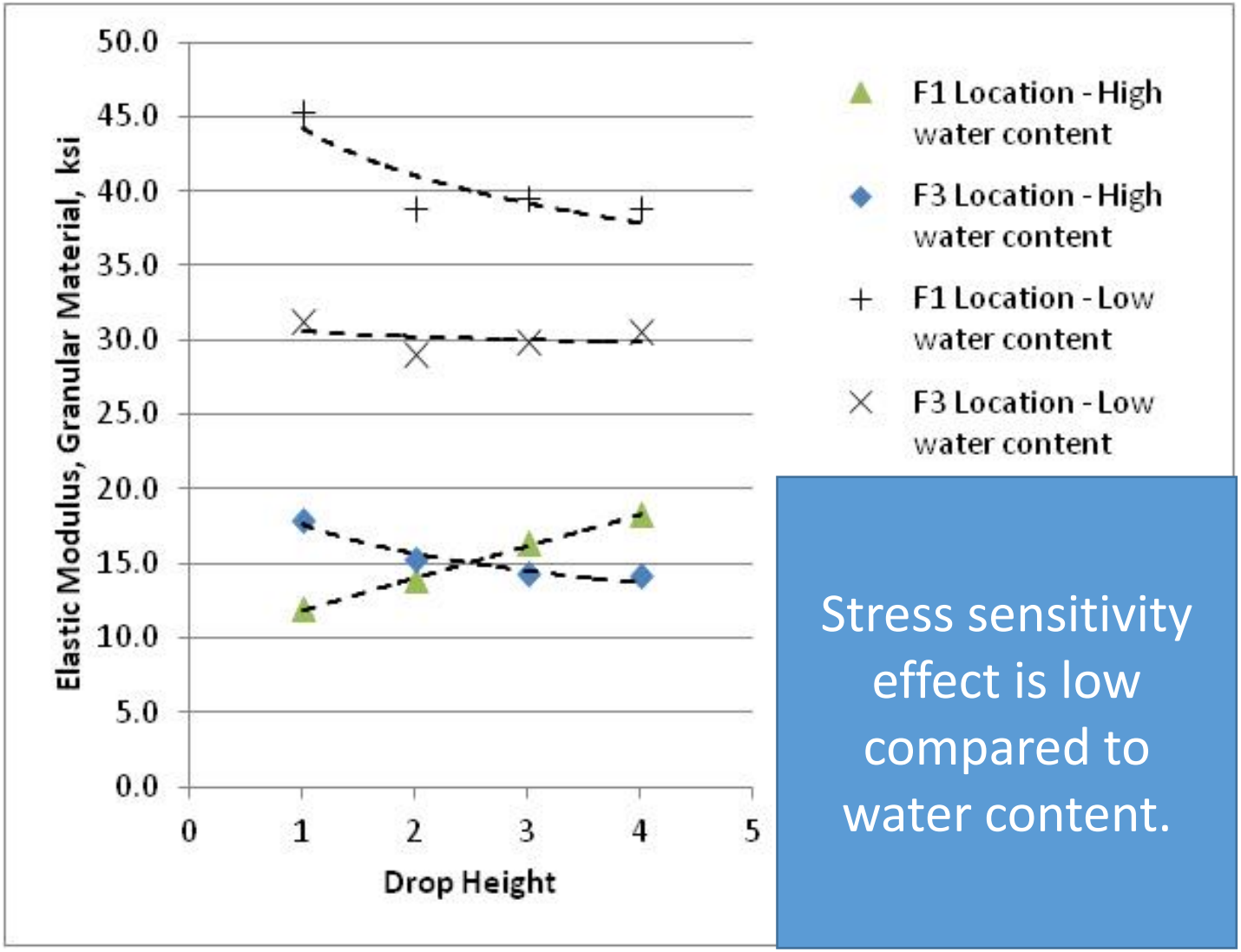
Location for Destructive Sampling

- Strategically identify areas with different pavement responses and stiffness.



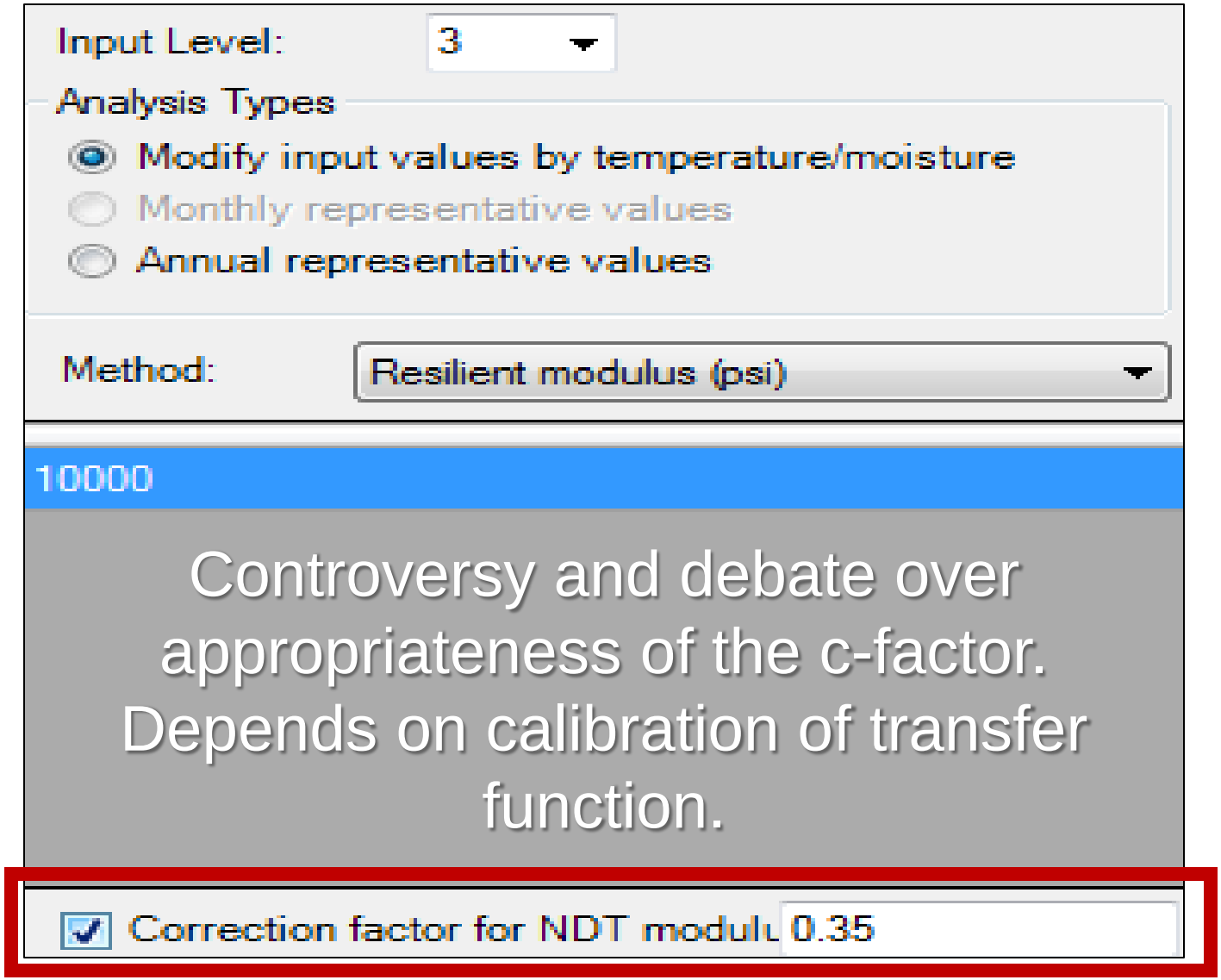
Allows better assumptions for simulation and identify anomalies.

Layer E Values as Inputs to Design



Stress sensitivity effect is low compared to water content.

Layer E Values as Inputs to Design



Controversy and debate over appropriateness of the c-factor. Depends on calibration of transfer function.

Layer E Values as Inputs to Design

Ratio between lab measured resilient modulus and backcalculated elastic modulus values for subgrade soils.

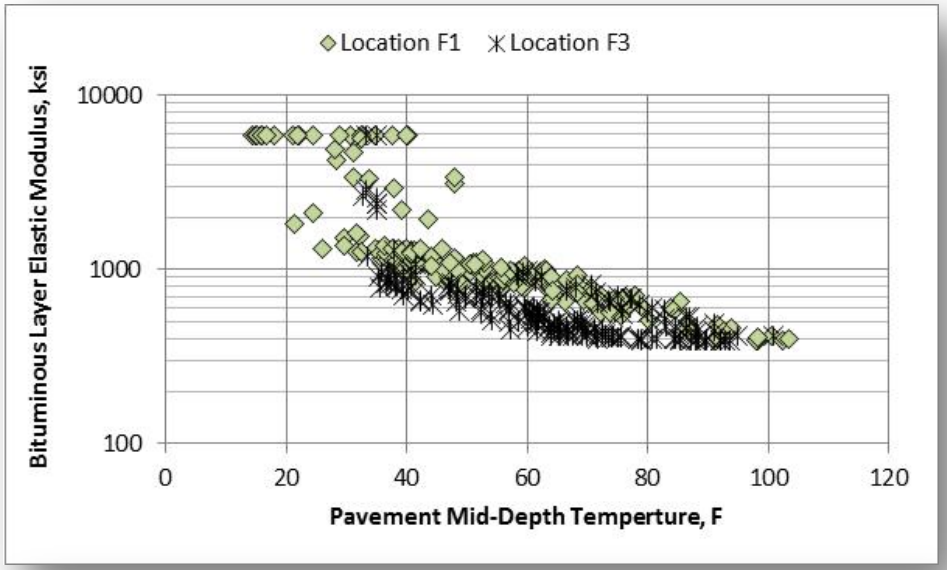
$$C = \frac{M_{R-Lab}}{E_{FWD}}$$

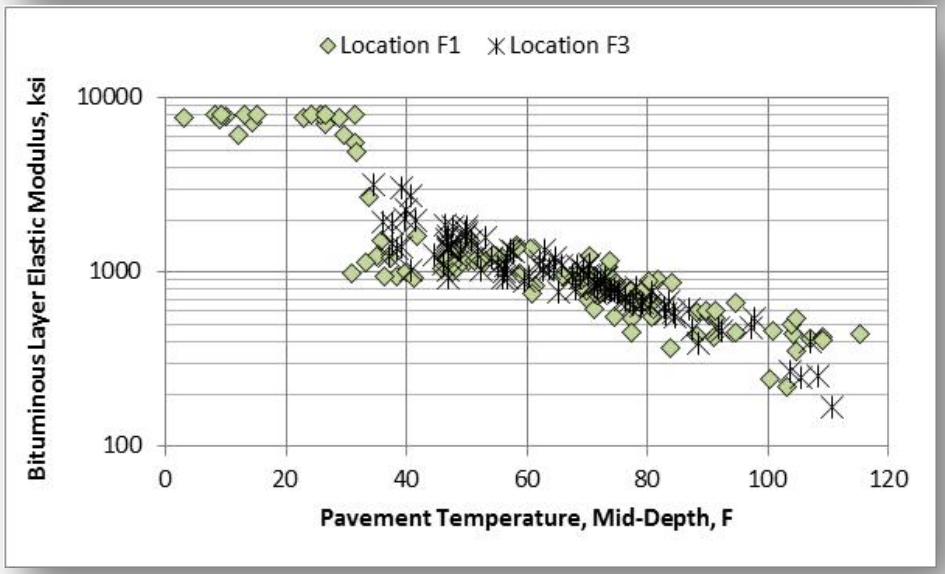
Backcalculation Program	Average c-Factor	Standard Deviation
Evercalc	0.35	0.136
Modcomp	0.36	0.146
Modulus	0.41	0.266

In Place Damage Assessment

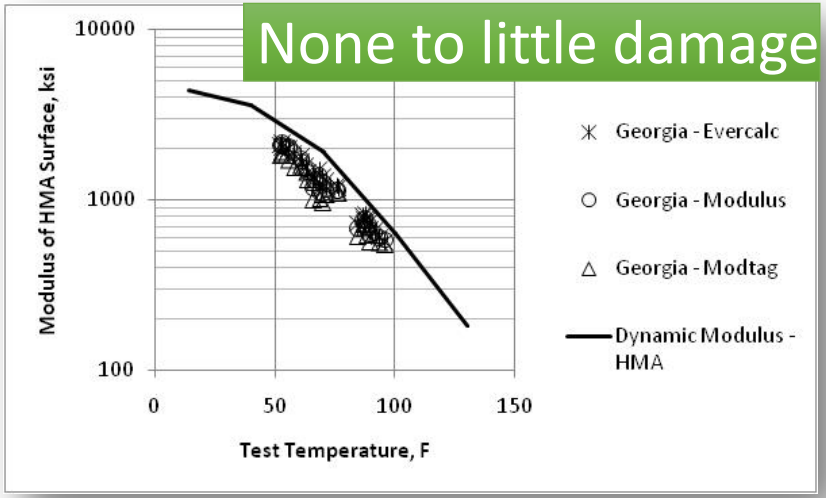
Within and between wheel path test locations can be different, probably related to the in place damage.

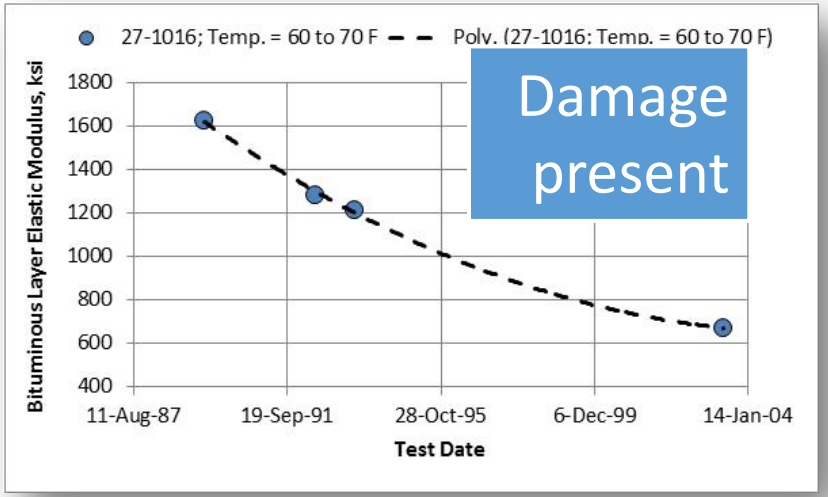
Result: if combined, it increases variability in modulus.

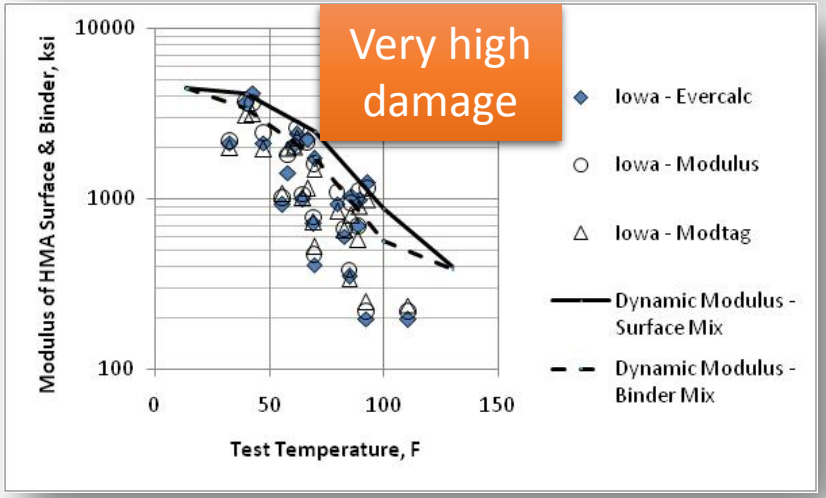


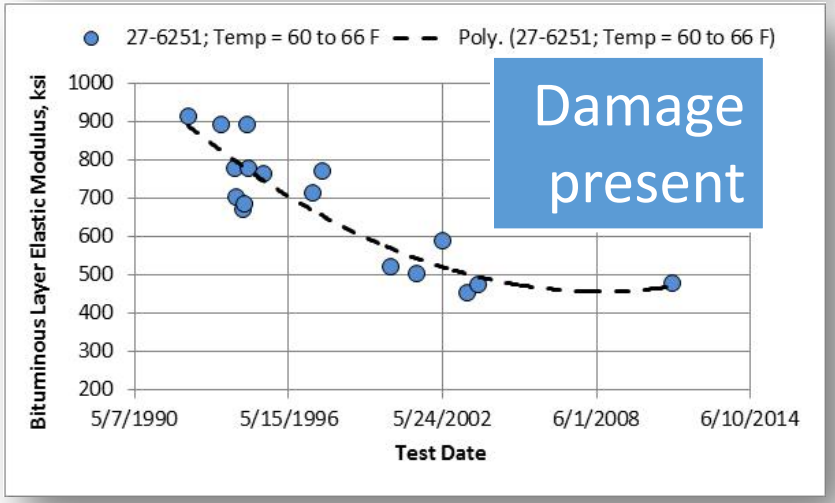


AC Damage Assessment









AC Damage Assessment
In-Place damage for Rehabilitation Design

Using backcalculated modulus data to estimate in place damage for rehabilitation design.

Dynamic modulus input level: 3

Gradation	Percent Passing
3/4-inch sieve	100
3/8-inch sieve	84
No.4 sieve	58
No.200 sieve	5.4

Modulus of existing AC layer obtained from NDT testing

NDT Modulus (psi)	Frequency (Hz)	Temperature (deg F)
885000	30	79
652000	30	86
459000	30	96

AC Damage Assessment

In-Place damage for rehabilitation design

$$\log(d_{AC}) = 0.2 \times \left[\ln\left(\frac{E_{PRED} - E_{FWD}}{E_{FWD} - 10^{\delta}} \right) + 0.3 \right]$$

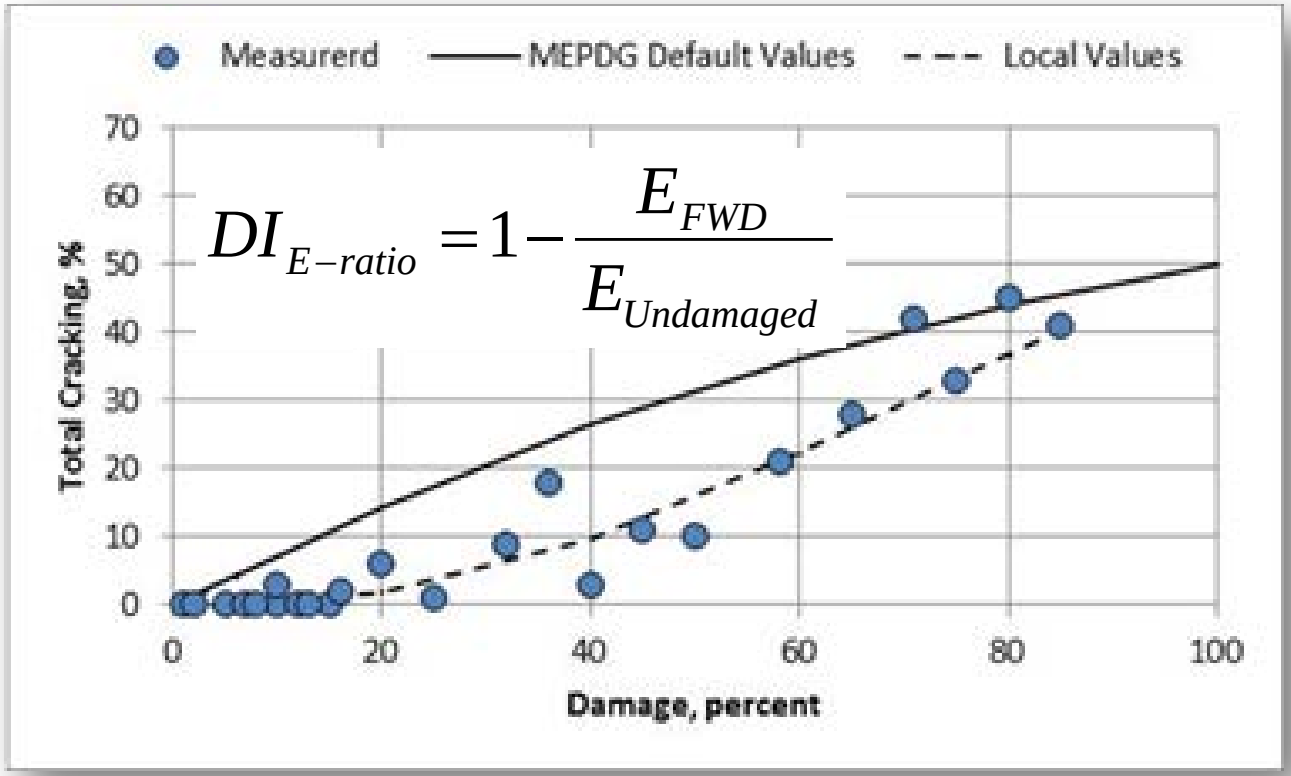
E_{PRED} = Laboratory dynamic modulus

Modulus of existing AC layer obtained from NDT testing

	NDT Modulus (psi)	Frequency (Hz)	Temperature (deg F)
▶	885000	30	79
	652000	30	86
	459000	30	96
*			

AC Damage Assessment

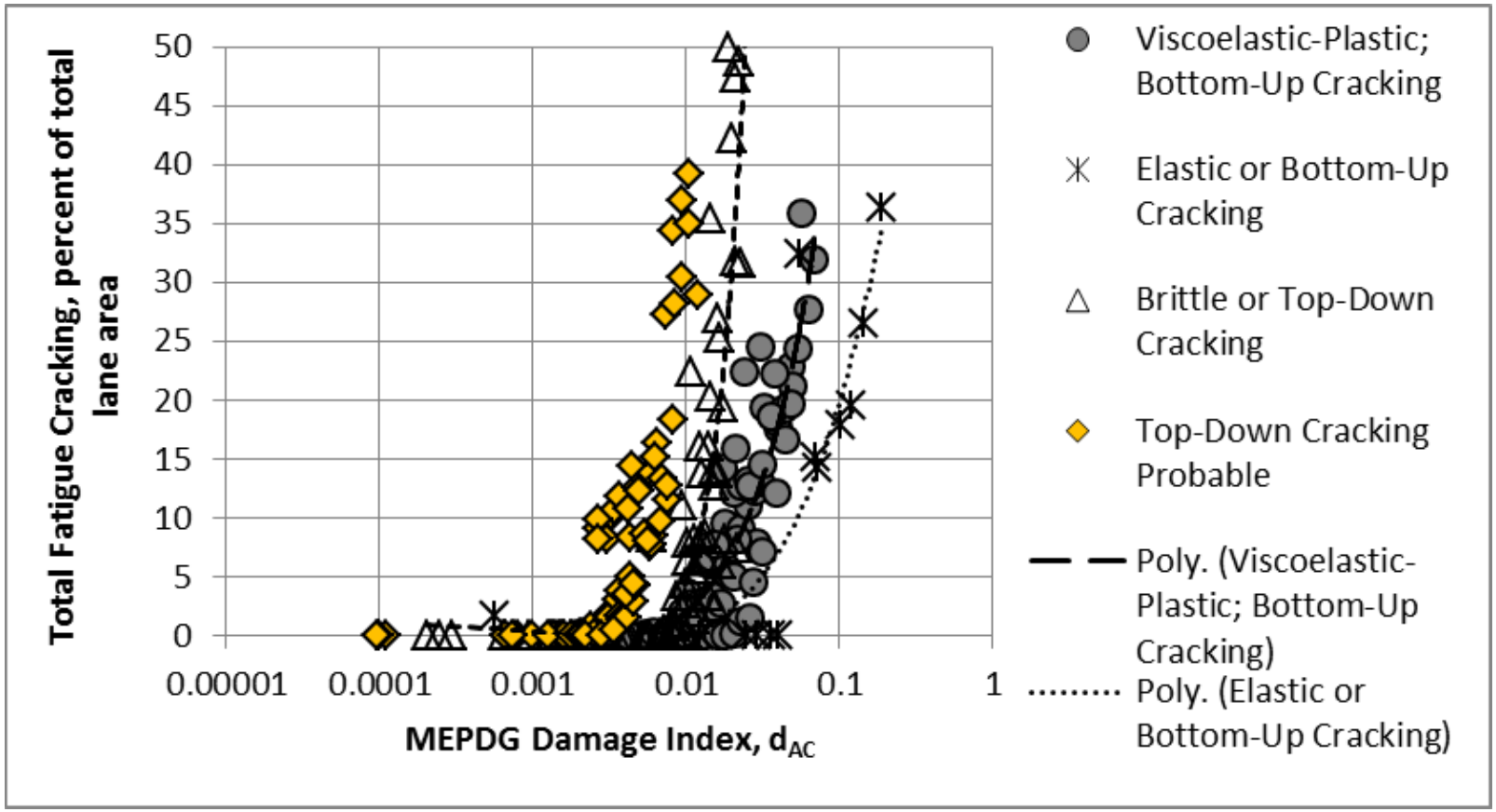
In place damage related to the amount of fatigue cracking for estimating the coefficients of the fatigue cracking transfer function.



$$DI_{E-ratio} = 1 - \frac{E_{FWD}}{E_{Undamaged}}$$

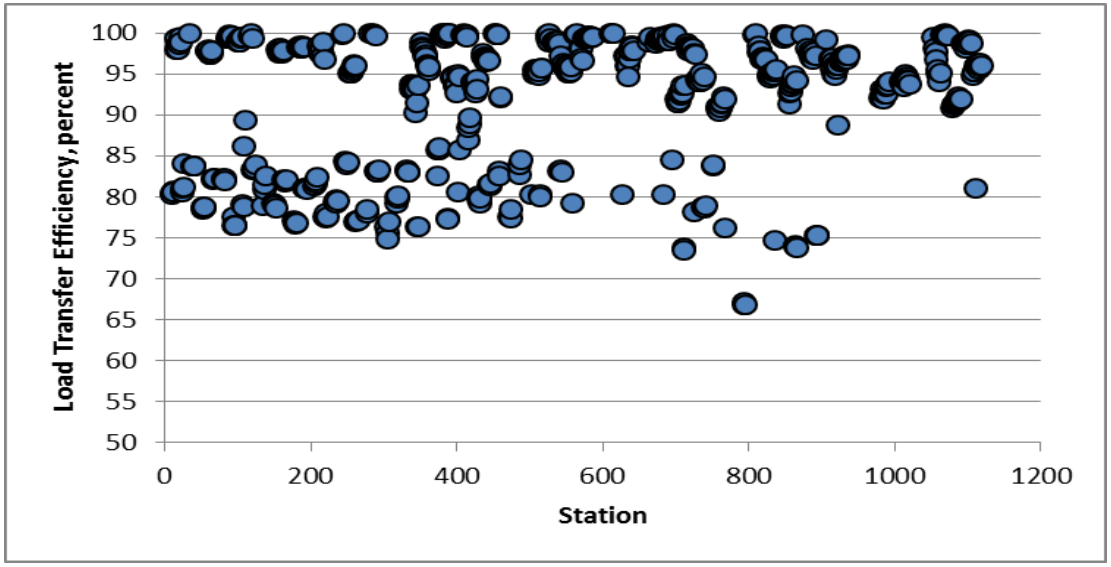
AC Damage Assessment

In-Place damage for rehabilitation design



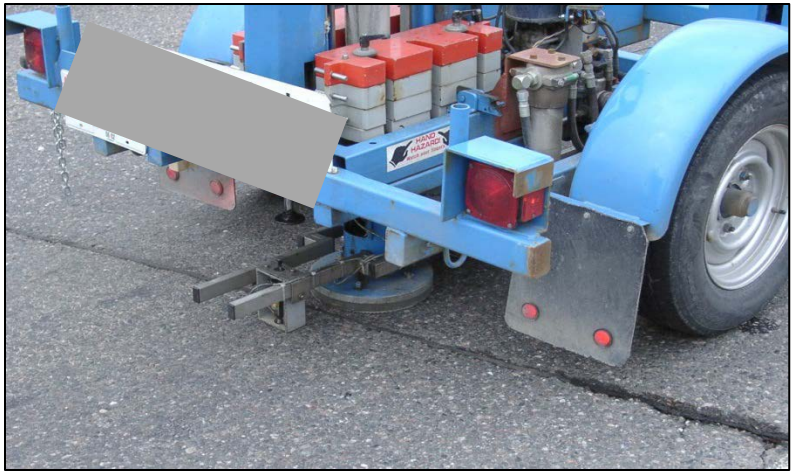
Load Transfer Efficiency for Rehabilitation Design

- Differential deflections across cracks in flexible and semi-rigid pavements is the more critical mechanism for cracking predictions for HMA overlay design.

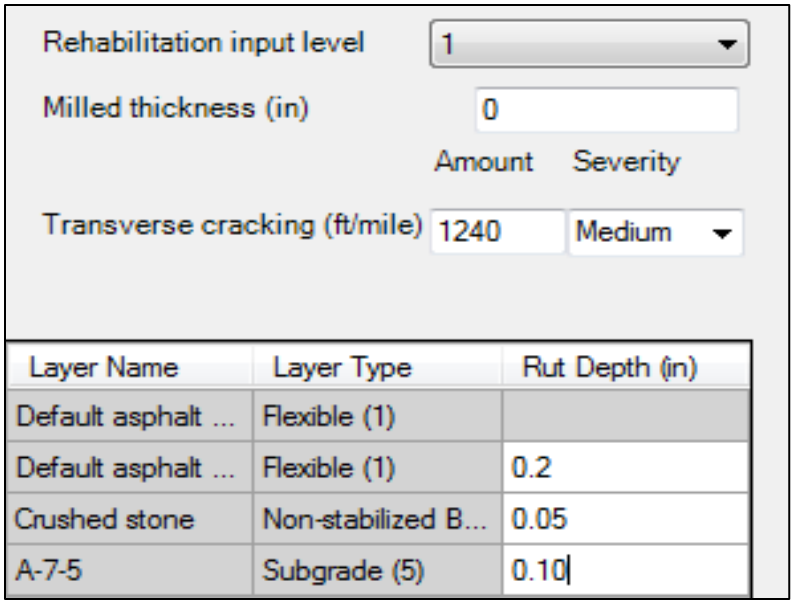


Load Transfer Efficiency for Rehabilitation Design

Differential deflections across cracks in flexible and semi-rigid pavements for cracking predictions.



Result: allows better assumptions for reflection cracking predictions.



Questions and Answers

Comments & suggestions for future webinars are welcomed.

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