Impacts of Research, Practice, and Teaching on Pavement Engineering

Michael I. Darter, PE, PhD
Applied Research Associates, Inc. and
Emeritus Professor of Civil Engineering
University of Illinois

National Road Research Alliance Pavement Conference

18 February 2016

Research, Practice, and Teaching Has Had Big Impact on “Pavement Design”

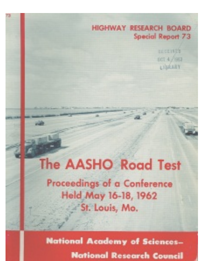
Lets take a journey………

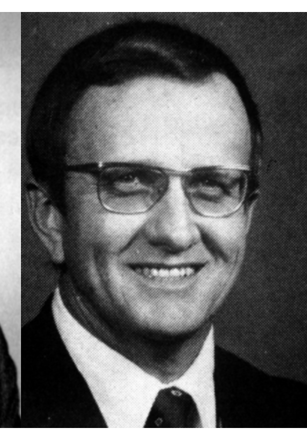
- Before the AASHTO Road Test
- After the AASHTO Road Test
- Evolution from Empirical design to the Mechanistic-Empirical procedures and what it means

Early Sources

- **Principles of Pavement Design**, Eldon J. Yoder, Purdue University, 1959.
  - Prof. Yoder: “There is no rational method of structural design of pavements, yet!”

- **AASHTO Road Test Reports**. Highway Research Board, 1960’s.





Early Sources

- **Application of AASHO road test results to design of flexible pavements in Minnesota (United States. Bureau of Public Roads. R & D report)** – 1966
- by Eugene L Skok (Author)

Pavement Design Before AASHO

- **Major Road tests before AASHO**
  - **Several early road tests (IL, CA, MN, MI, etc.)**
  - **WASHO flexible pavement:** 1952-54 Heavier loads cause higher fatigue cracking, edge effects significant, thickness of HMA significant, many more.
  - **Maryland JRCP:** 1950-51 Heavier loads cause much higher fatigue cracking and pumping.
  - **Vandalia CRCP:** 1947-67 Thickness and reinforcement critical to performance. Also crack opening.

Pavement Design Before AASHO

- **Key theoretical developments Flexible Pavement**
  - One layered system (Boussinesq)
  - Layered systems analysis (Burmister, 1940s, Corps of Engineers)
  - Materials characterization: fatigue, permanent damage, layer modulus
  - Limiting stress and deflection in subgrade, base, subbase

D. M. Burmister

Carl Monismith

Pavement Design Before AASHO

- **Key theoretical developments Rigid Pavement**
  - Load stress and deformation calculation procedure for slab on grade & impact on fatigue cracking (Westergaard)
  - Temperature & moisture curling/warping of slabs & impact on cracking (Westergaard, Bradbury)
  - Materials characterization: strength, modulus, fatigue, CTE, shrinkage
  - Fatigue damage: M. A. Miner
  - Joint load transfer (Southerland)
  - Crack openings & load transfer (CRCP)

Pavement Design Before AASHO

- **Procedures for Flexible Design**
  - "Principles for flexible pavements consists of testing subgrade soil and then, from correlation data or theory, determining the thickness of pavement required to protect the subgrade (same for subbase and base)." Yoder
  - Map of USA for flexible design: soil class, soil strength, deflection, etc.

Francis Hveem

Flexible Design Procedures 1959

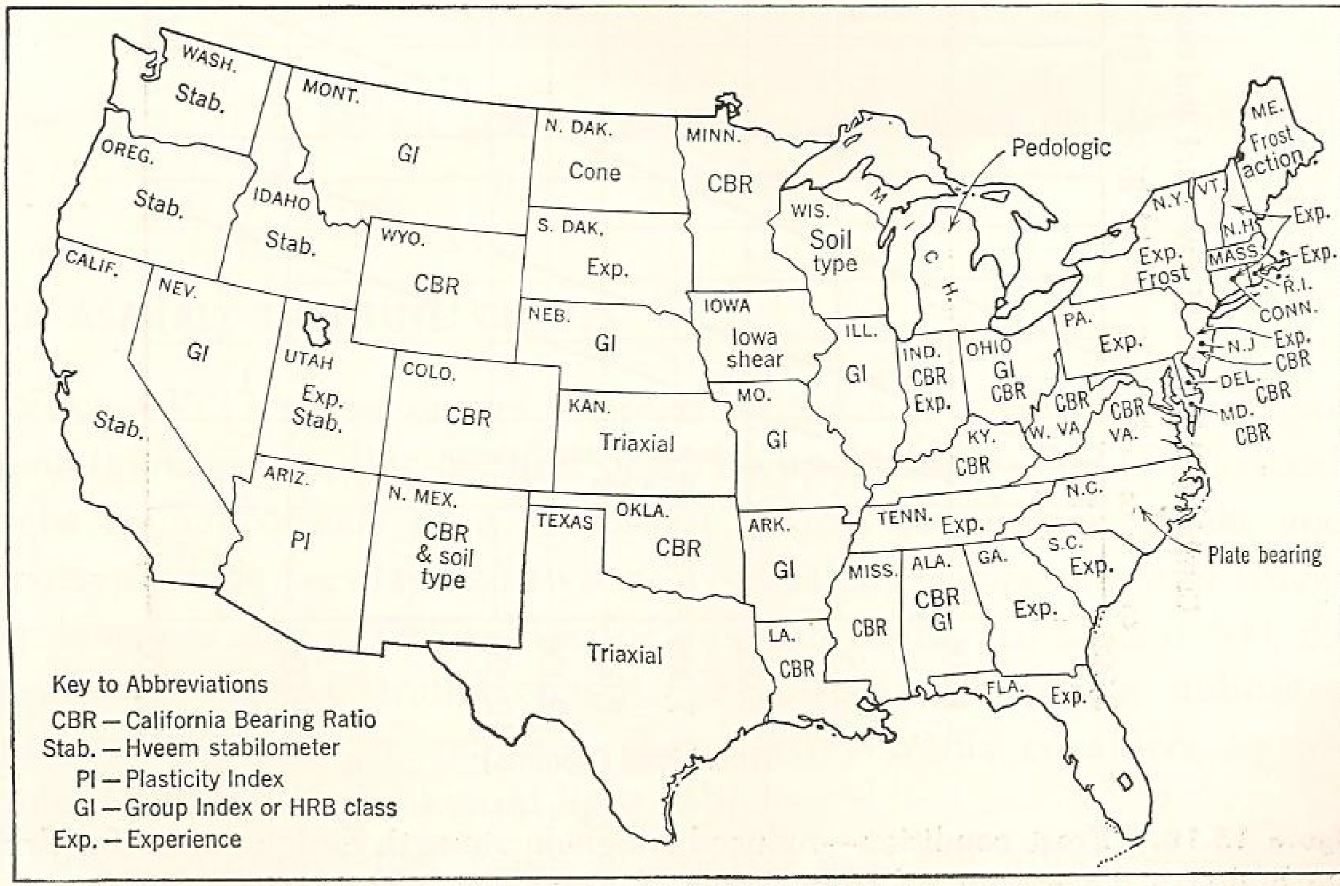
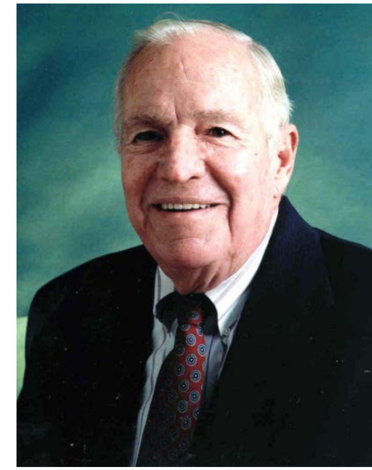


Figure 15.19. Design practices for thickness of flexible pavements.

Pavement Design Prior AASHO

- **Procedures for Rigid Design**
  - "Design criteria for rigid pavements are based upon allowable tensile stress of the concrete. Base courses for control of pumping are generally used at arbitrary depths determined by field performance." Yoder
  - PCA design procedure: thickness, joints, base.



Robert Packard

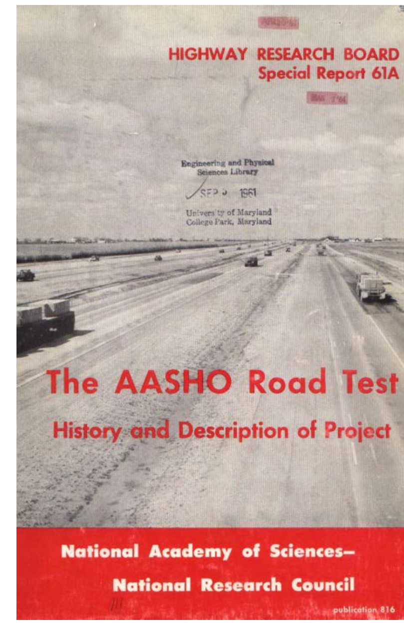
Gordon Ray

AASHO Road Test 1958-60

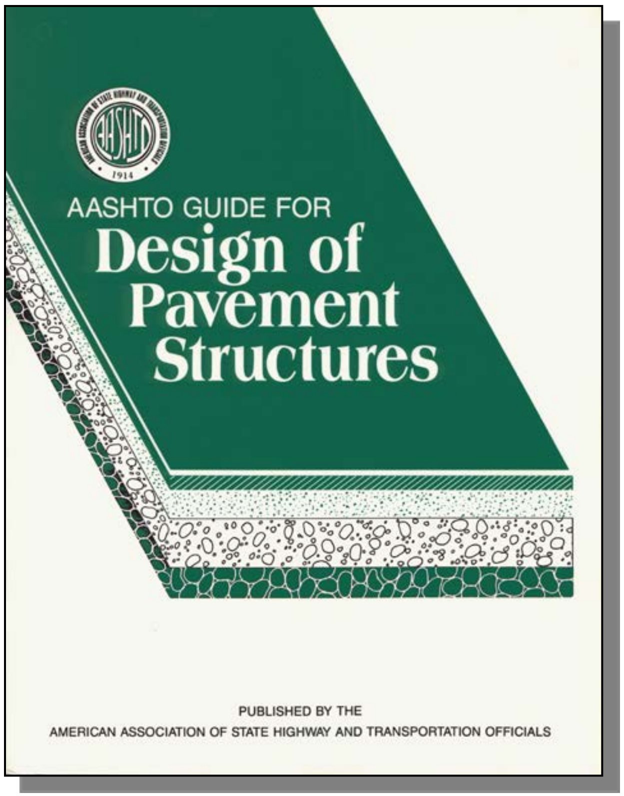
- US faced a huge need for an adequate pavement design procedure in late 1950's. Why?
  - Interstate Highway System and other major highway construction.
- AASHO primary purpose was to determine the relationship between axle loading and pavement structure on pavement performance (Taxes).
  - Use to design pavements to provide an engineering basis for establishing maximum axle load limits, and to provide a basis for the allocation of highway user taxation.

AASHO Based Procedure

- **AASHO Road Test Design Concept: Empirical**
  - The design procedures are based on regression equations that relate the loss in pavement serviceability to the pavement structural section (SN or slab) and ESALs.
  - The overall concept of the AASHO pavement design procedure is to provide a pavement structure that is adequate in thickness, composition, and quality to ensure the pavement section does not reach a terminal serviceability level during its design life.
    - Terminal serviceability defines a pavement that is considered unacceptable by the highway user.
    - **No focus at all on fatigue cracking of HMA/PCC, rutting, joint faulting, etc.**

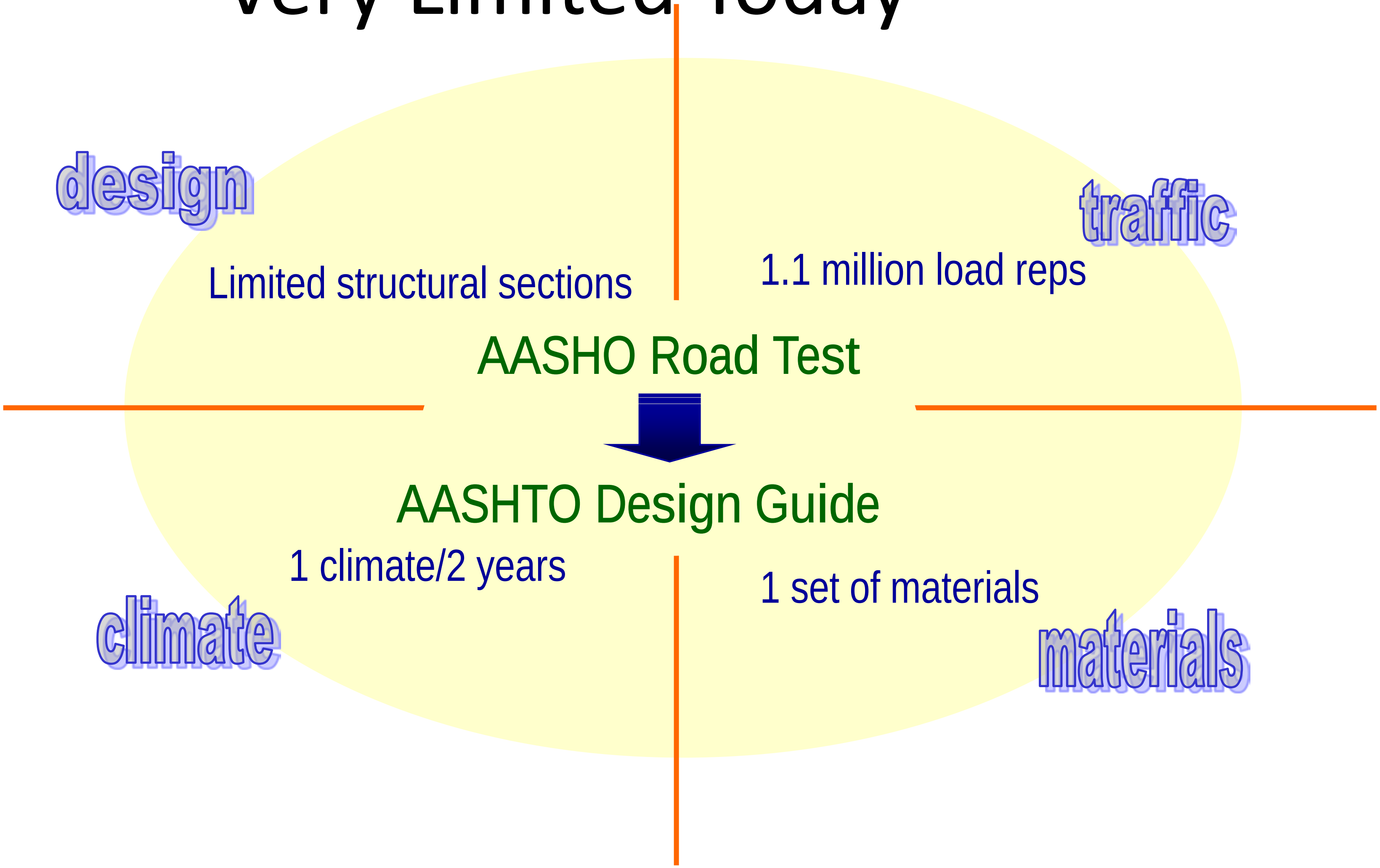


AASHTO Pavement Design Guide



- Empirical methodology based on AASHO Road Test in the late 1950's
- Several versions:
  - 1961, 1972, 1986, 1993 (Empirical)
  - Many limitations

AASHTO Design Procedure ---Great For 1961, But … Very Limited Today---



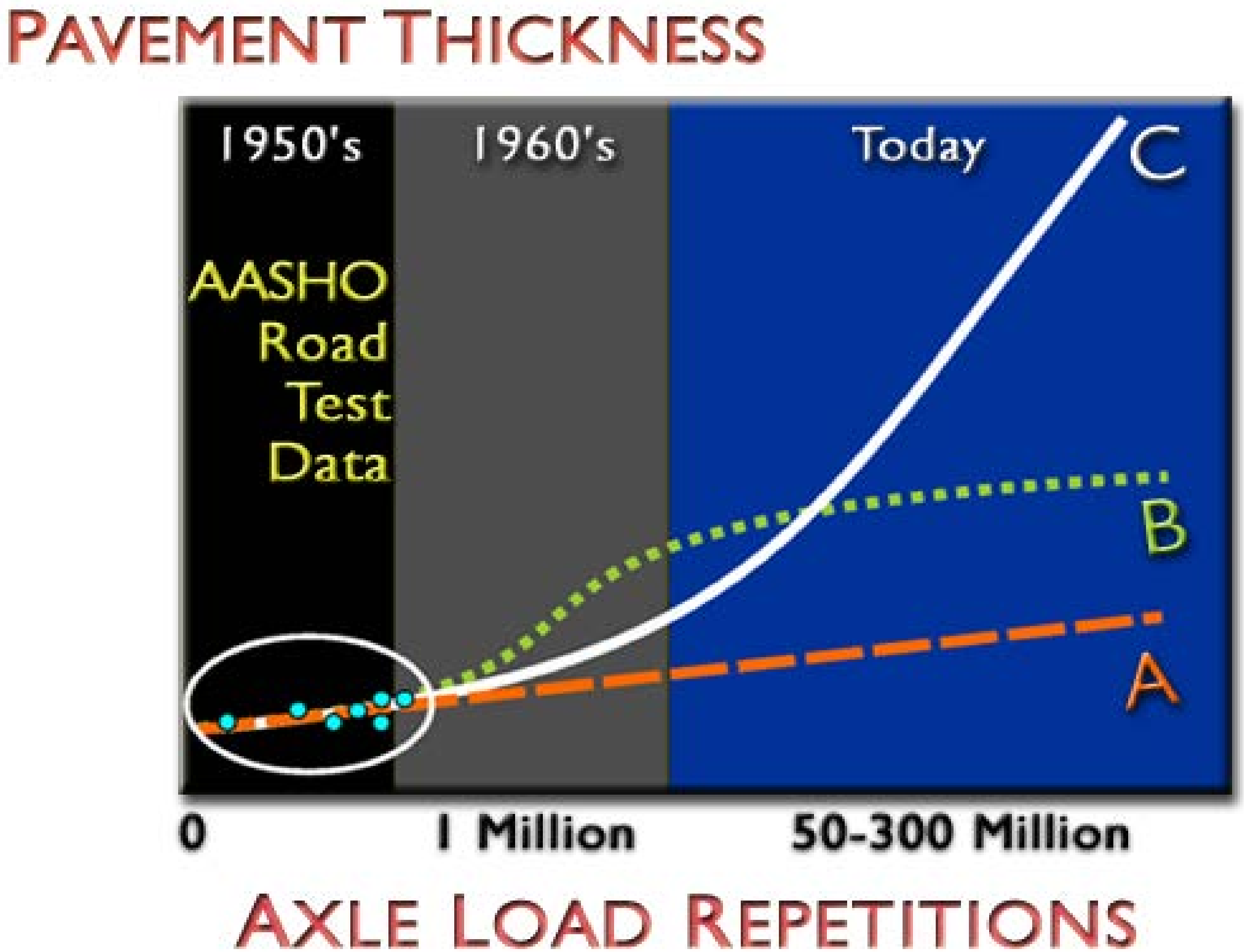
After the AASHO Road Test…..

- **Everything changed!**
  - Truck axle loadings increased, number of trucks greatly increased, tire pressure increased, …
  - Materials changed for both flexible and rigid pavements….
  - Designs changed as well in terms of layered systems, joint designs, thicker HMA layers, ….
  - Longer and longer design lives demanded.
  - Rehabilitation became much more prevalent than new design and construction.
  - Performance characteristics more demanding.
  - Lane closures became more risky and costly and unsafe.

Note in AASHTO Guide 1962

- "A traffic analysis period of 20 years has been used for the sake of convenience. It must not be confused with pavement life, which is affected by many factors in addition to traffic factors."

Limitations: Huge Traffic Extrapolation



AASHO Road Test Based Procedure

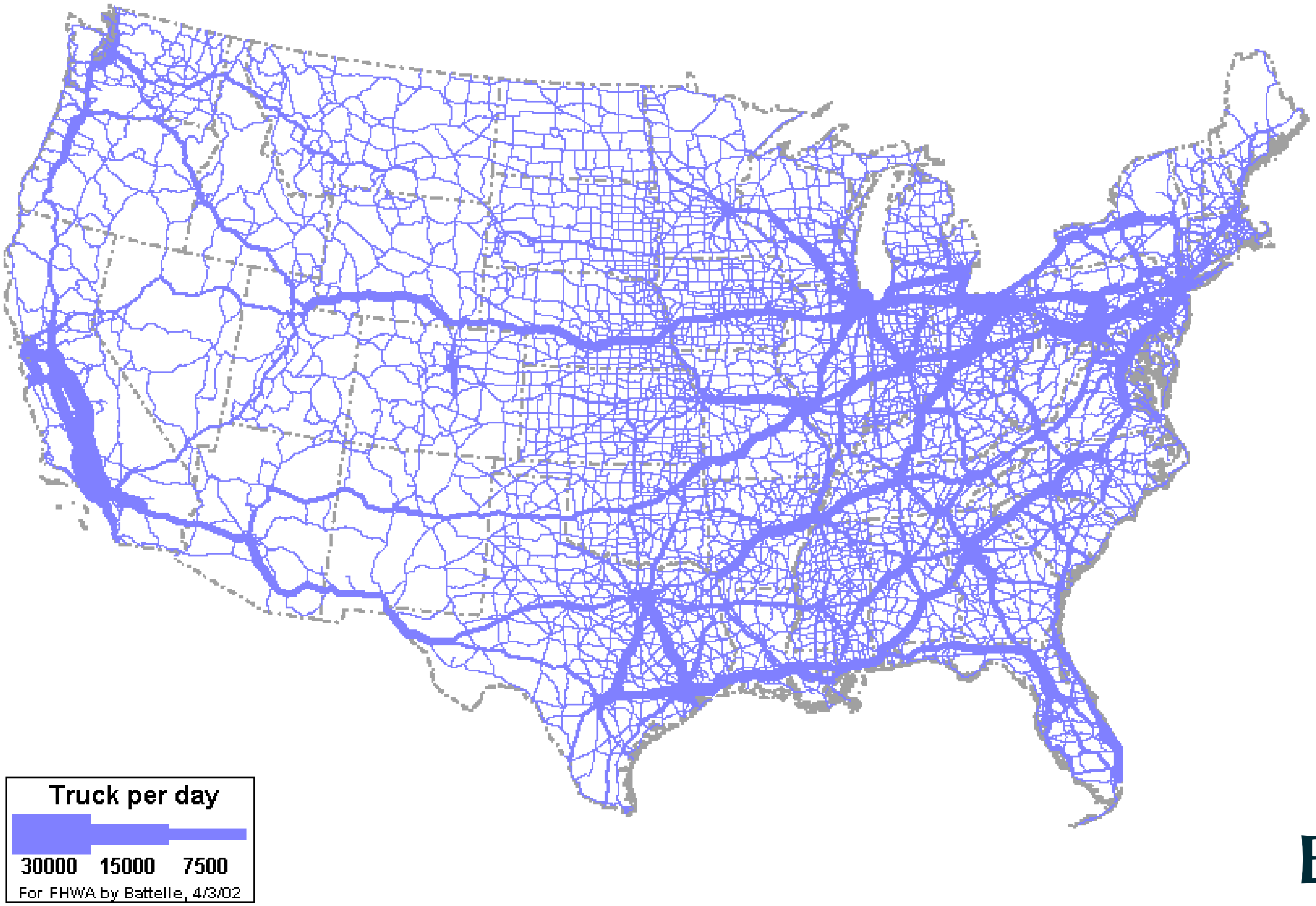
- **Flexible pavement: Empirical basis**
  - Provide SN to protect subgrade: CBR, R-Value
  - Layer coefficients: HMA, base, subbase
  - Regional factor: Used to adjust thickness by States to provide desired thickness
  - Design procedure major limitations
    - Layer coefficients not measurable, regression coefficients
    - Not able to design to control fatigue cracking or permanent deformation
    - No basis for design reliability
    - Simplistic nomograph: **One Minute Pavement Designer**

AASHO Road Test Based Procedure

- **Rigid pavement: Empirical + Limited Mechanistic basis**
  - Mechanistic aspects: Corner stress model, k-value, Ec.
  - Calibration using ART data
  - Design procedure major limitations
    - No consideration of joint faulting (adjust thickness which did not work)
    - No consideration for joint spacing
    - Poor consideration for base course effect
    - No basis for design reliability
    - Simplistic nomograph: **One Minute Pavement Designer**

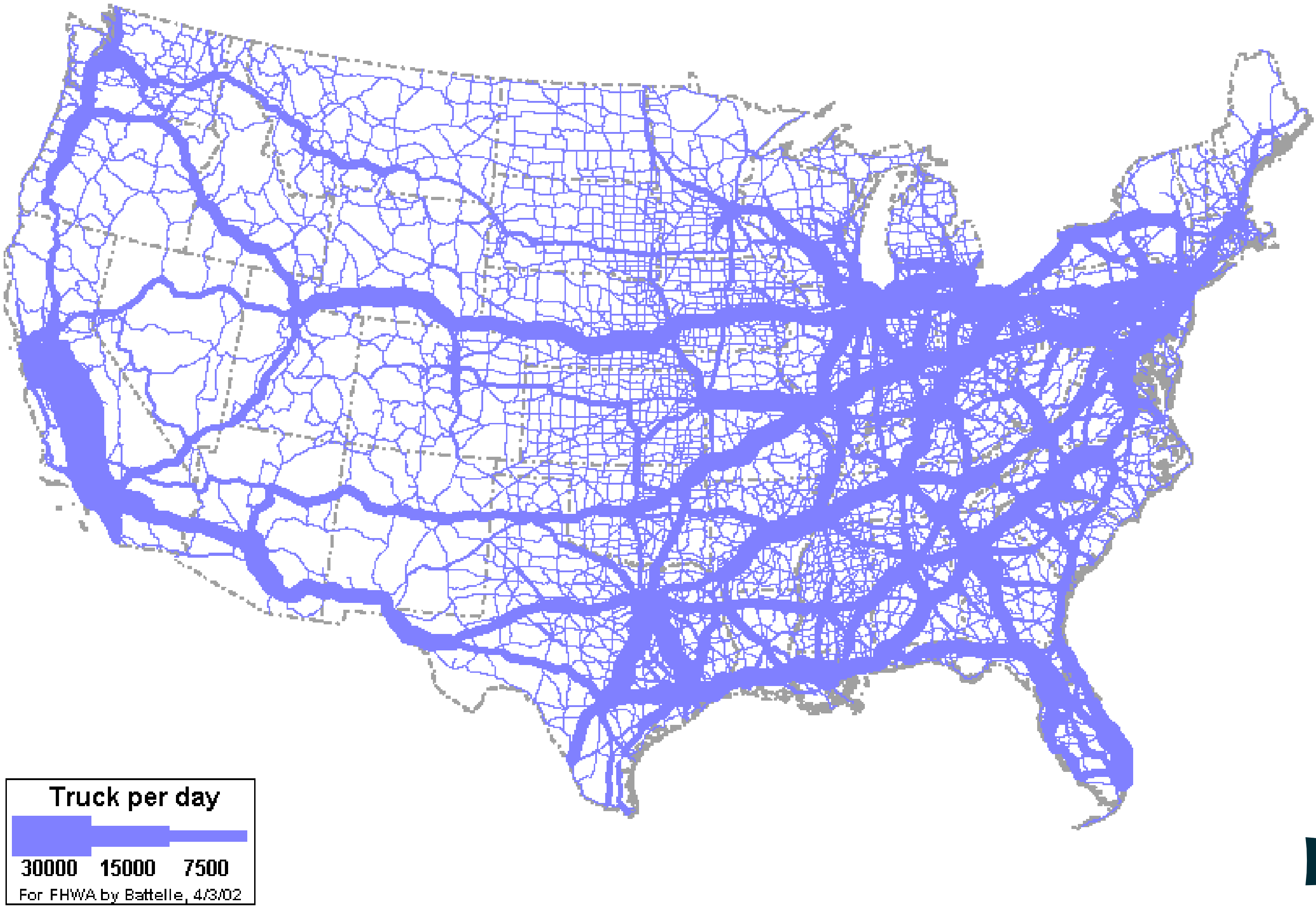
Let's not kid ourselves, Over the decades since the AASHO Road Test, there have been many pavement problems and failures associated with design and material deficiencies and under-estimating truck traffic.

1998 Truck Flow



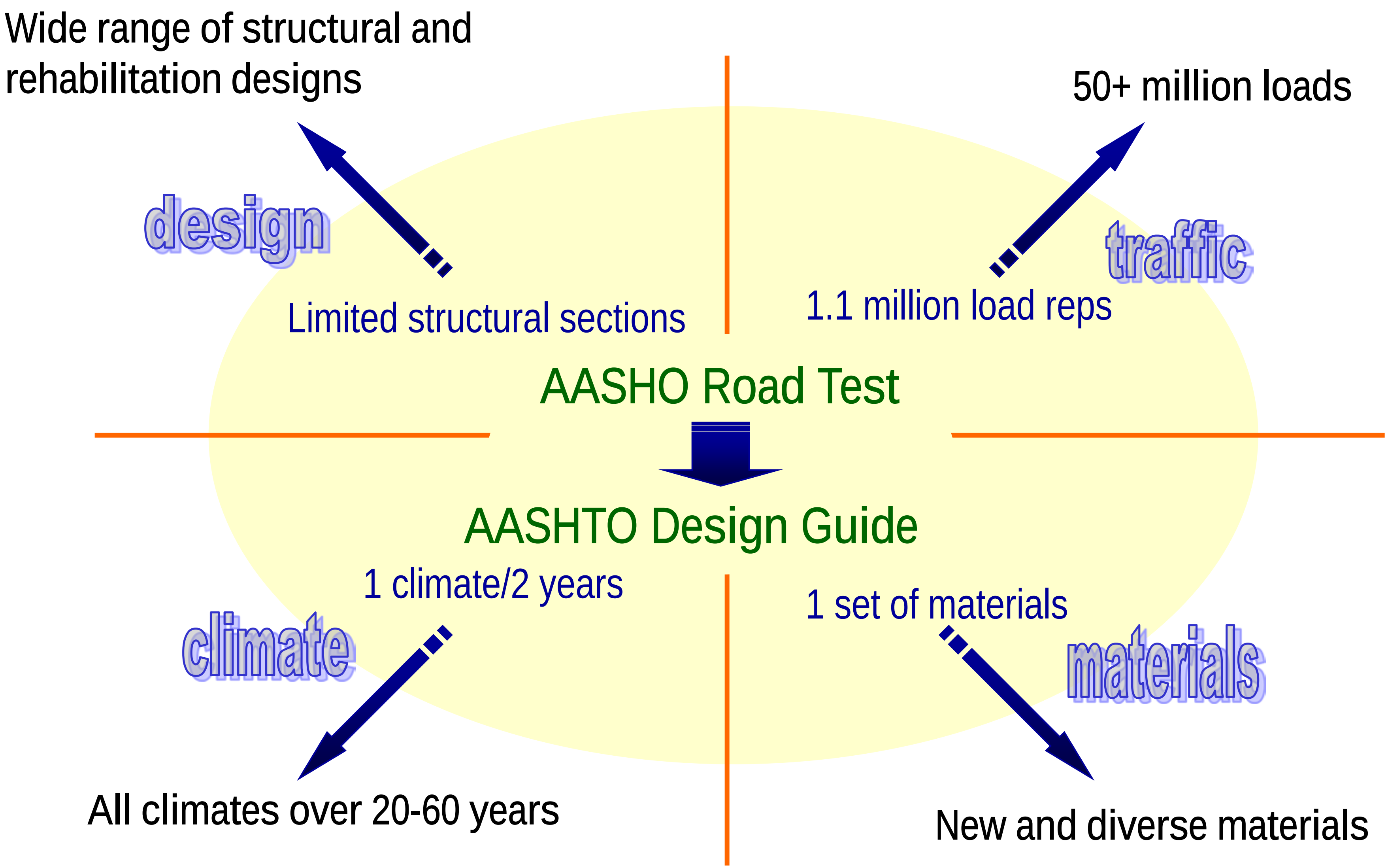
Battelle

2020 Forecast Truck Flow



Battelle

Current AASHTO vs. Current Needs



Initiation of "Mechanistic-Empirical" Design

- As a result of these limitations, several attempts were made to develop a "rational" or "mechanistic" based design procedure starting actually in the 1960s.
  - Skok, E.L., and F.N. Finn. "Theoretical Concepts Applied to Asphalt Concrete Pavement Design," *Proceedings,* International Conference on the Structural Design of Asphalt Pavements, University of Michigan, 1962.
- The various industries did develop their own mechanistic based procedures (asphalt, concrete, aggregate) and a few States (MN, IL, KY, VA, others).
- On a national level, TRB/NCHRP made major effort in the 1980s but a big industry fight killed it for a decade!

Recent TRB Paper

WHAT PAVEMENT RESEARCH WAS DONE FOLLOWING THE ROAD TEST
AND WHAT SHOULD HAVE BEEN DONE BUT WAS NOT

Carl L. Monismith, Dr. Eng. (hon.), P.E.
W. R. Hudson, Ph.D., P.E.
Fred N. Finn, M.S. P.E.
Eugene. L. Skok, Jr., Ph.D., P.E.
James. F. Shook, M.S., P.E.

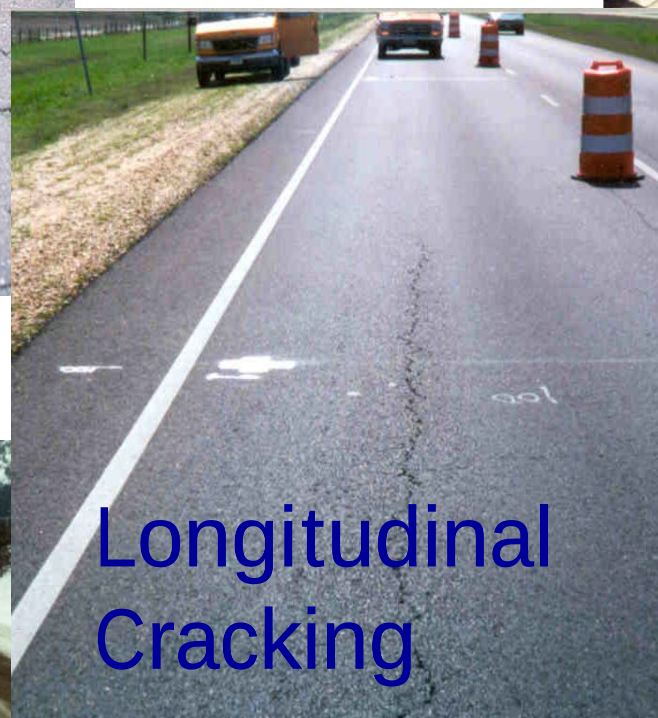
AAHSTO: Major Improvement Needed

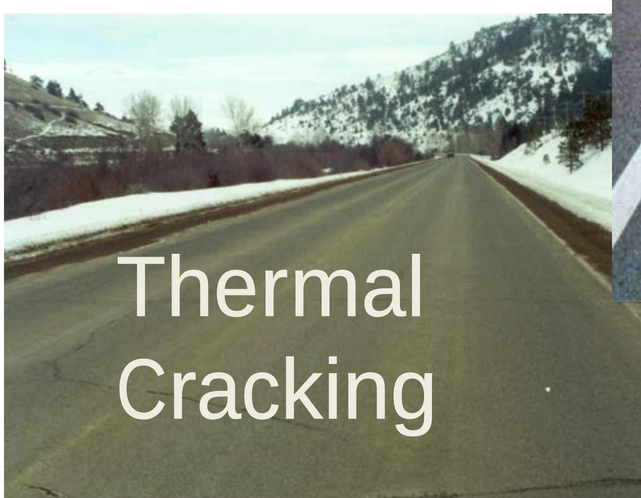
- **1996:** National meeting recommended Mechanistic based design procedure calibrated to field data.
- **1997:** AASHTO made decision to proceed
- **1998-2004: NCHRP Project 1-37A**, developed procedure (completed by Applied Research Associates, Inc. & Arizona State University): Mechanistic-Empirical Pavement Design Guide (MEPDG or just ME) [Dr. Khazanovich, UM]
- **2004 Onward:** A number of States began implementation including Missouri, Indiana, Arizona, Colorado, Utah, California, etc.
- **2008 Onward:** AASHTO adopted design procedure and States continued implementation and training.
  - Universities began teaching, States, and consultants began training in the AASHTO ME.

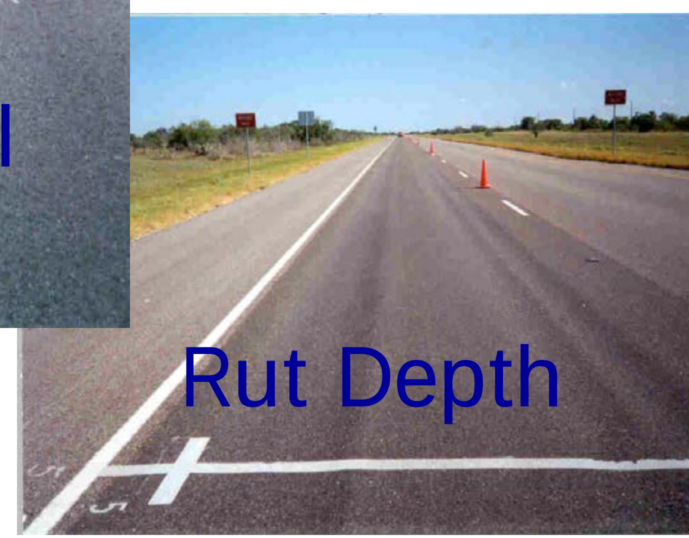
AASHTO MEPDG

- Development of the MEPDG
  - The MEPDG is based on mechanistic empirical design concepts.
    - **Mechanistic:** Design procedure calculates pavement responses such as stresses, strains, and deflections under axle loads (plus climate related) and then accumulates the "damage" over time.
    - **Empirical:** Theoretically calculated "Damage" is correlated with actual performance of pavements.
    - *This is a BIG advantage, the distress prediction models actually predict field performance!*

HMA Pavement Performance



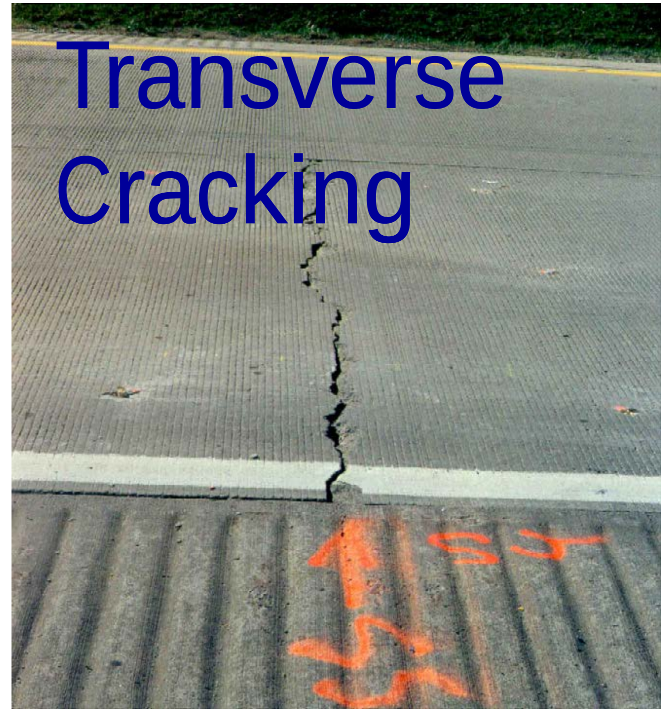




Some Specific Advantages: HMA

Old AASHTO 1960-93	New AASHTO ME Design
• Structural design provides only SN, not HMA thickness!	• Directly provides HMA thickness to prevent fatigue cracking & rut
• No connection between asphalt binder grade to performance	• Asphalt binder grade directly related to fatigue cracking, rutting, and low temp cracking
• HMA & base layer coefficients complete garbage	• HMA dynamic modulus & creep compliance measures
• ESALs used for traffic	• Actual axle loads & types
• Climate not considered	• Climate directly considered
• Rehab does not consider reflection cracking	• Rehab directly considers reflection cracking (NEW)

JPCP Pavement Performance



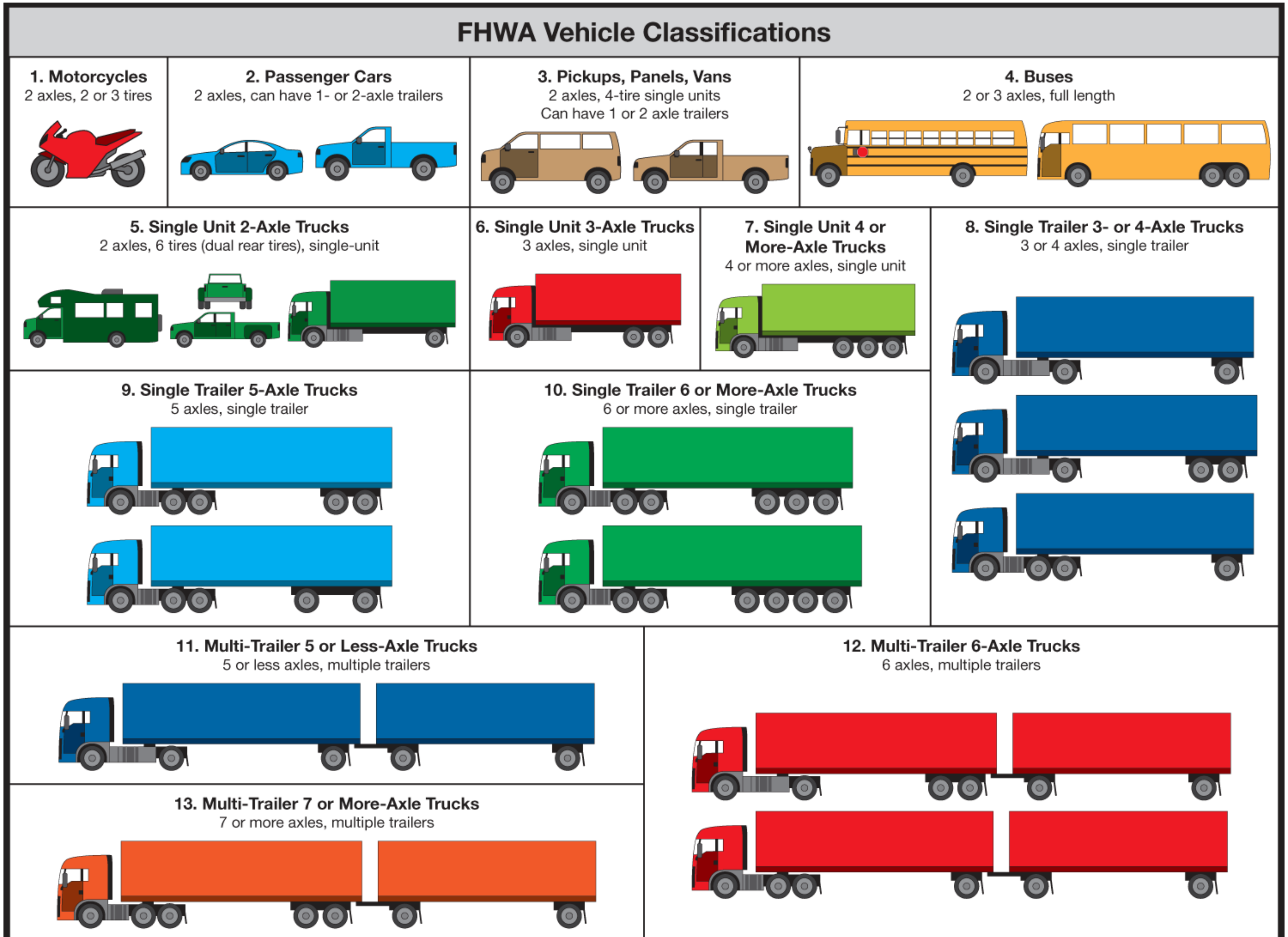
Some Specific Advantages: PCC

Old AASHTO 1960-93	New AASHTO ME Design
• No direct consideration of base support and slab/base friction!	• Directly considers base modulus & slab/base friction to prevent cracking.
• No consideration of PCC shrinkage, slab curling & warping, joint opening/closing.	• Direct consideration of PCC shrinkage, slab curling & warping temperature & moisture gradients
• No direct consideration of joint dowels, tied PCC shoulders, spacing, width.	• Direct consideration of joint dowel bar diameter, tied PCC shoulders, spacing, slab width.
• ESALs used for traffic.	• Actual axle loads & types.
• Climate not considered.	• Climate directly considered.
• Rehab does not consider reflection cracking at all.	• Rehab directly considers reflection cracking. (NEW)
• Rehab does not consider past damage of existing pavement.	• Rehab directly considers past damage of existing pavement.

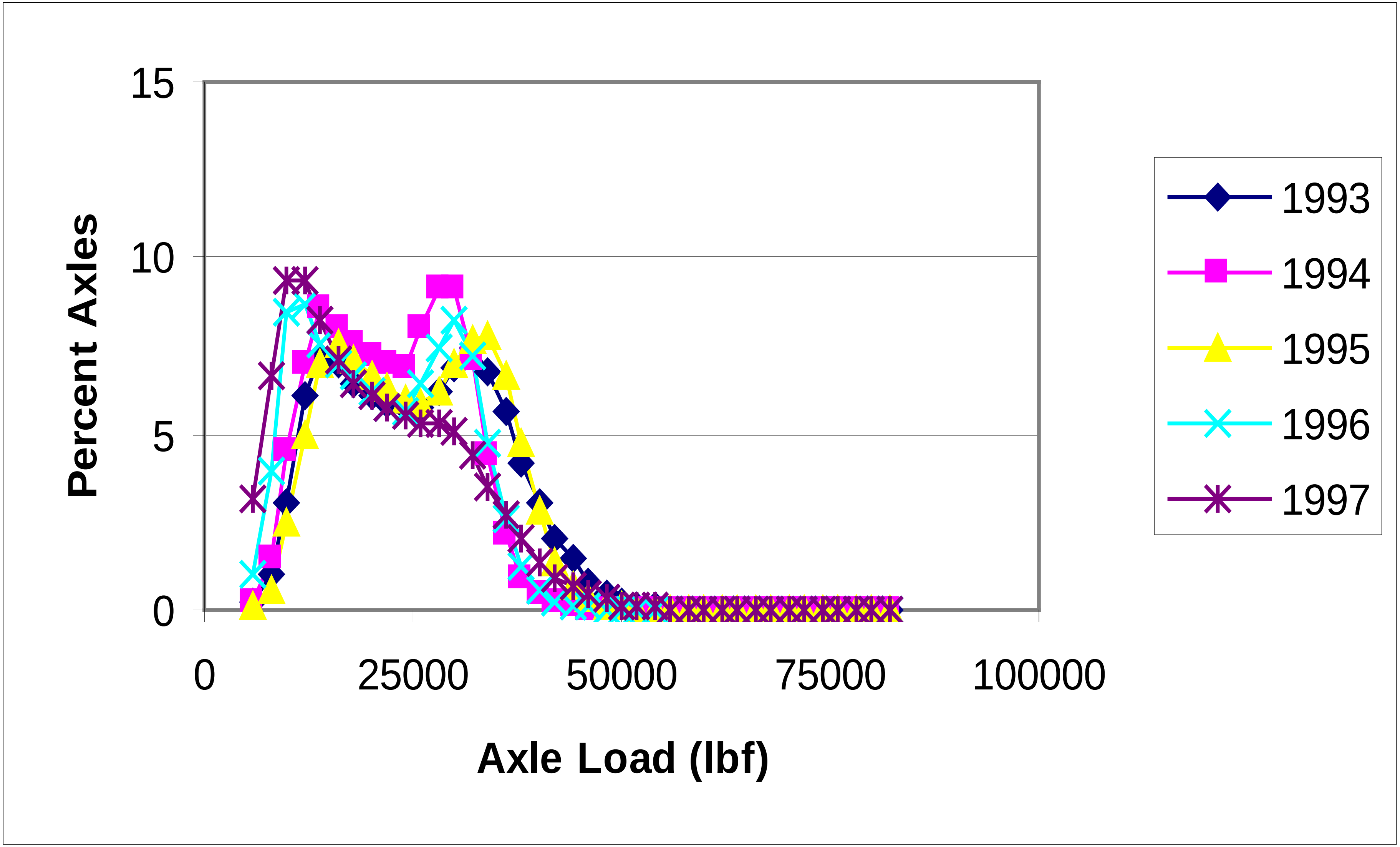
AASHTO MEPDG Overview

- MEPDG Basics
  - An overview to the Design Guide procedure.
  - *Inputs:*
    - *Traffic*
    - *Climate*
    - *Pavement materials & Subgrade*
    - *Layer design factors*
    - *Design Performance criteria & Reliability*
  - *Outputs & selection of acceptable design*

Vehicle Class Distribution

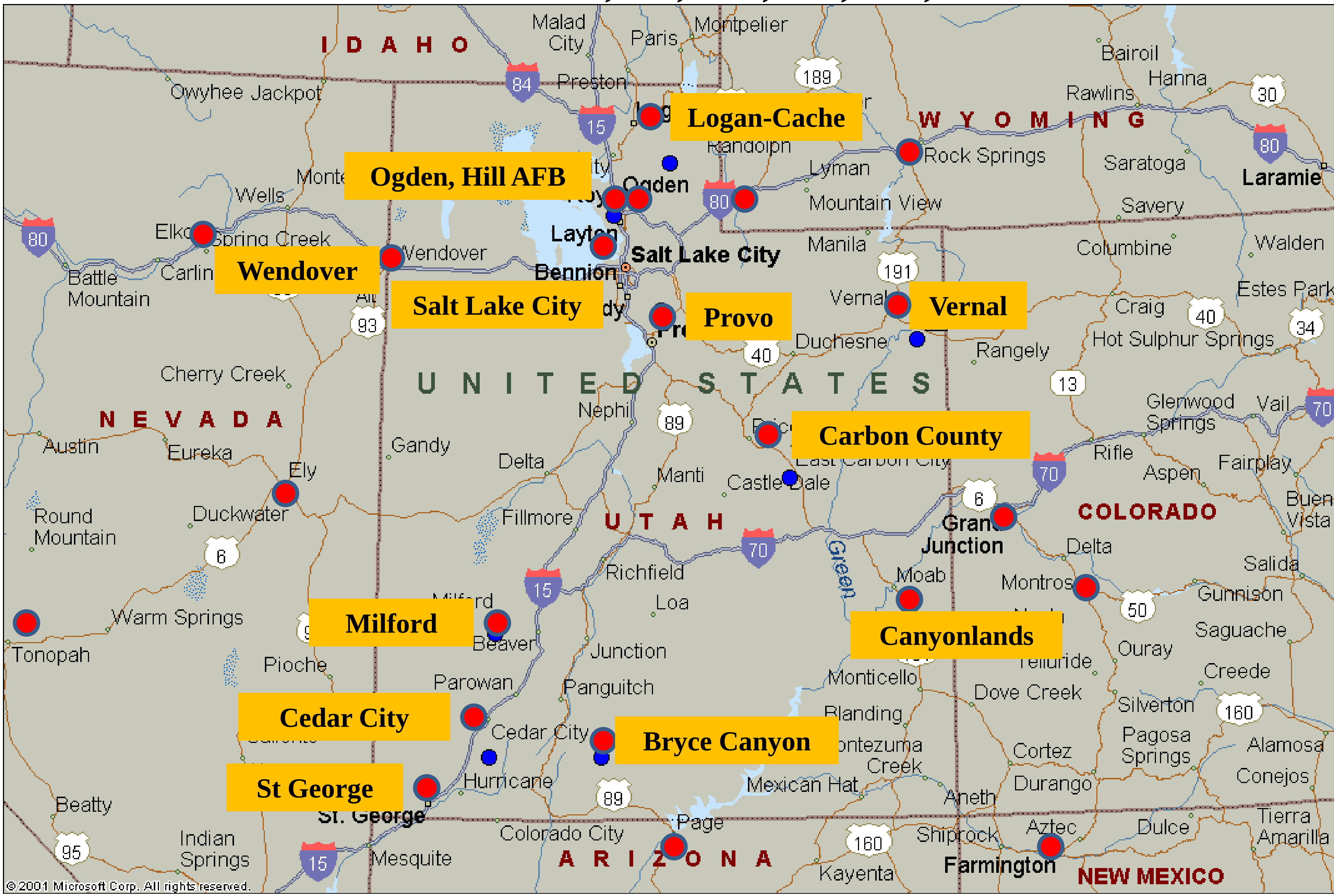


Tandem Axle Load Distribution



Utah Weather Stations

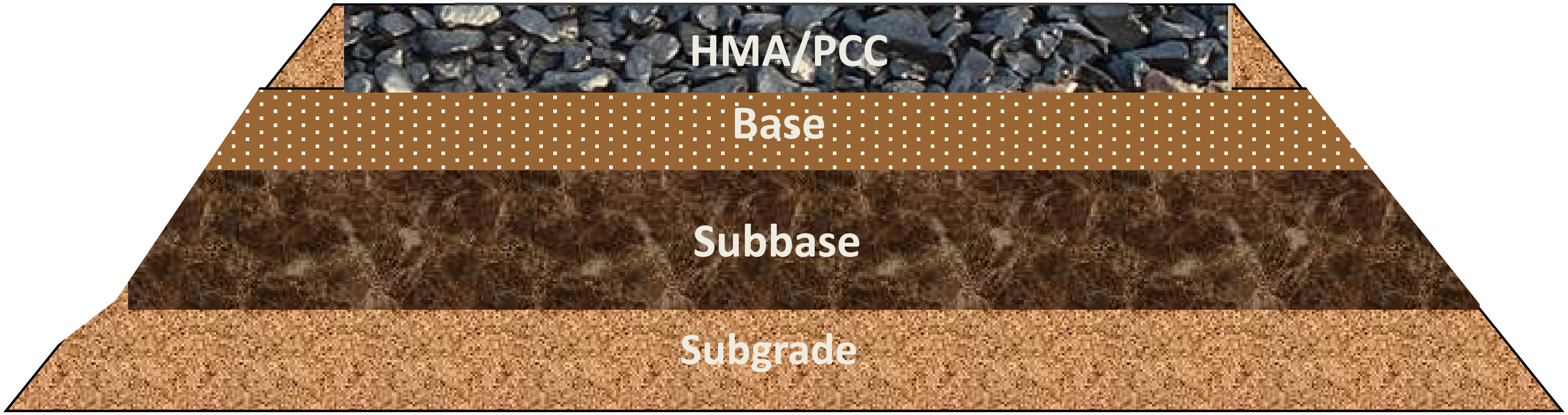
See also: NV, AZ, NM, CO, WY, ID



Pavement Layer Inputs

For Each Layer:

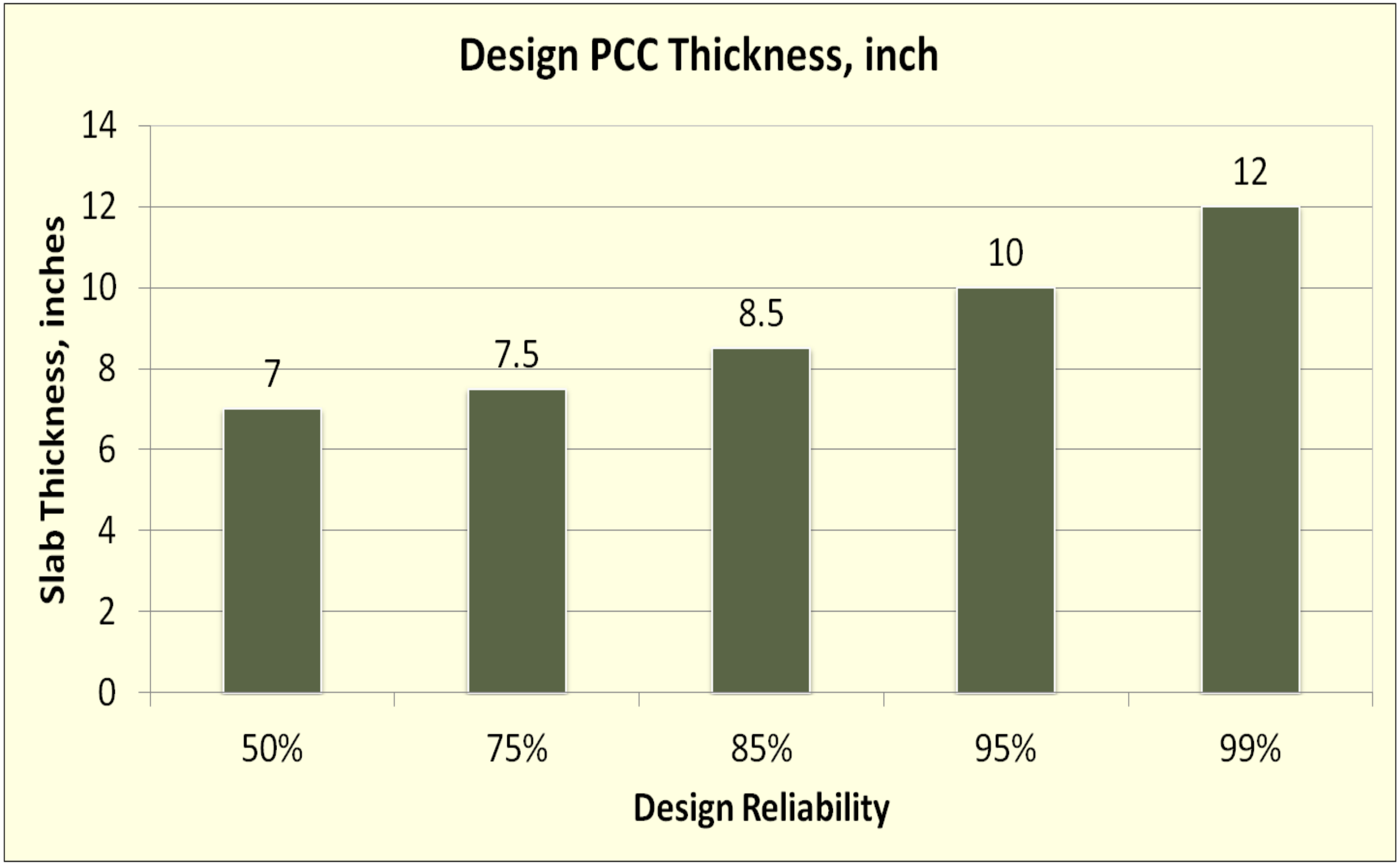
- **Physical properties** (Modulus of elasticity, unit weight, …)
- **Thermal properties** (Coef. of thermal expansion, …)
- **Hydraulic** properties (Moist. content, hyd. conductivity, …)



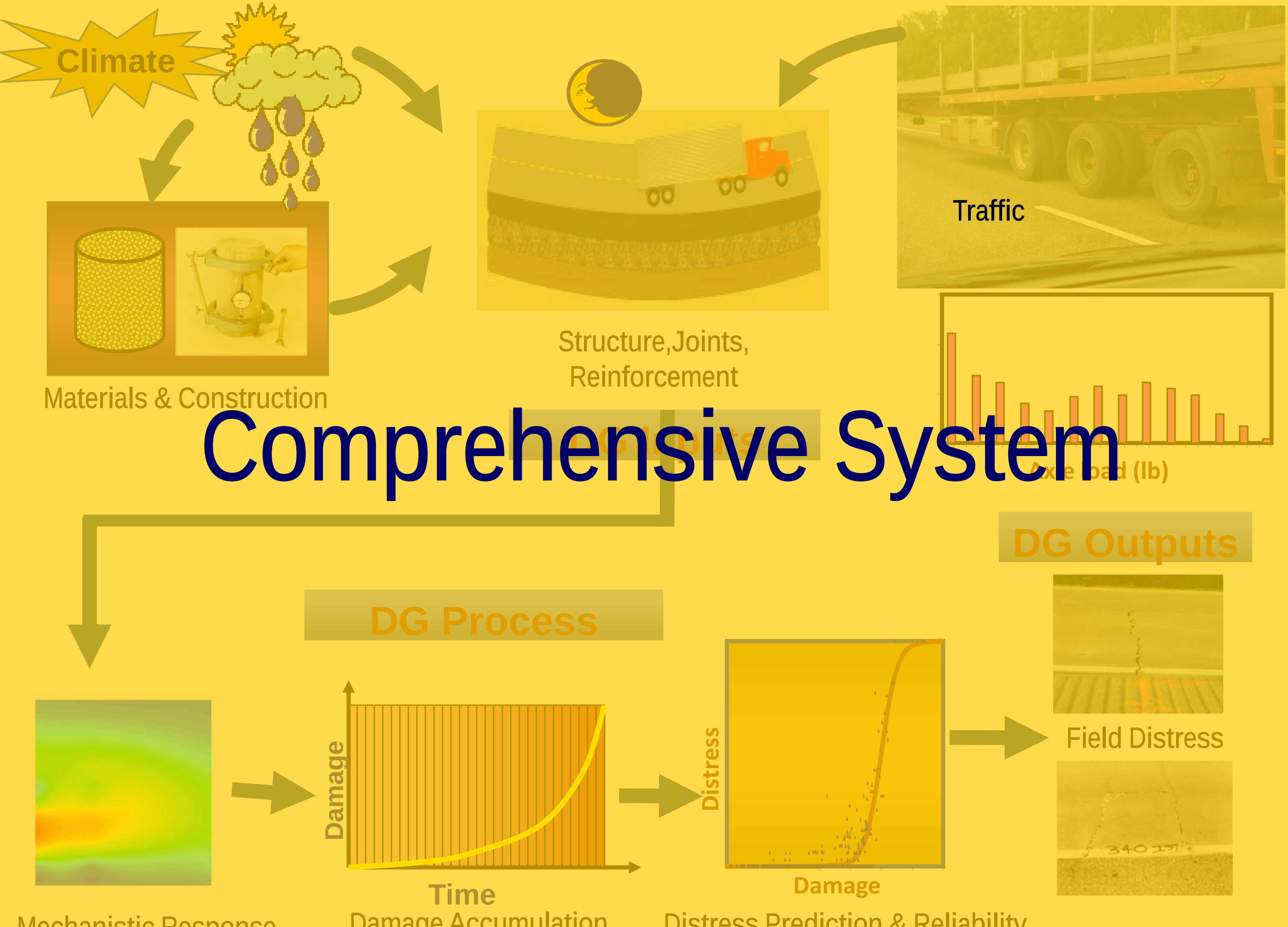
Design Reliability & Performance

- AASHTO 93: Reliability (ESALs and PSI)
- AASHTO ME: Reliability (Rutting, Cracking, Faulting, Smoothness IRI)
  - Must specify design Reliability each distress at end of design life:
    - R = Prob (Cracking < 10 percent lane area)
    - R = Prob (Rutting < 0.5 inches)
    - R = Prob (IRI Smoothness < 172 inches/mile)
  - Must specify maximum rutting, cracking, faulting, IRI, etc.

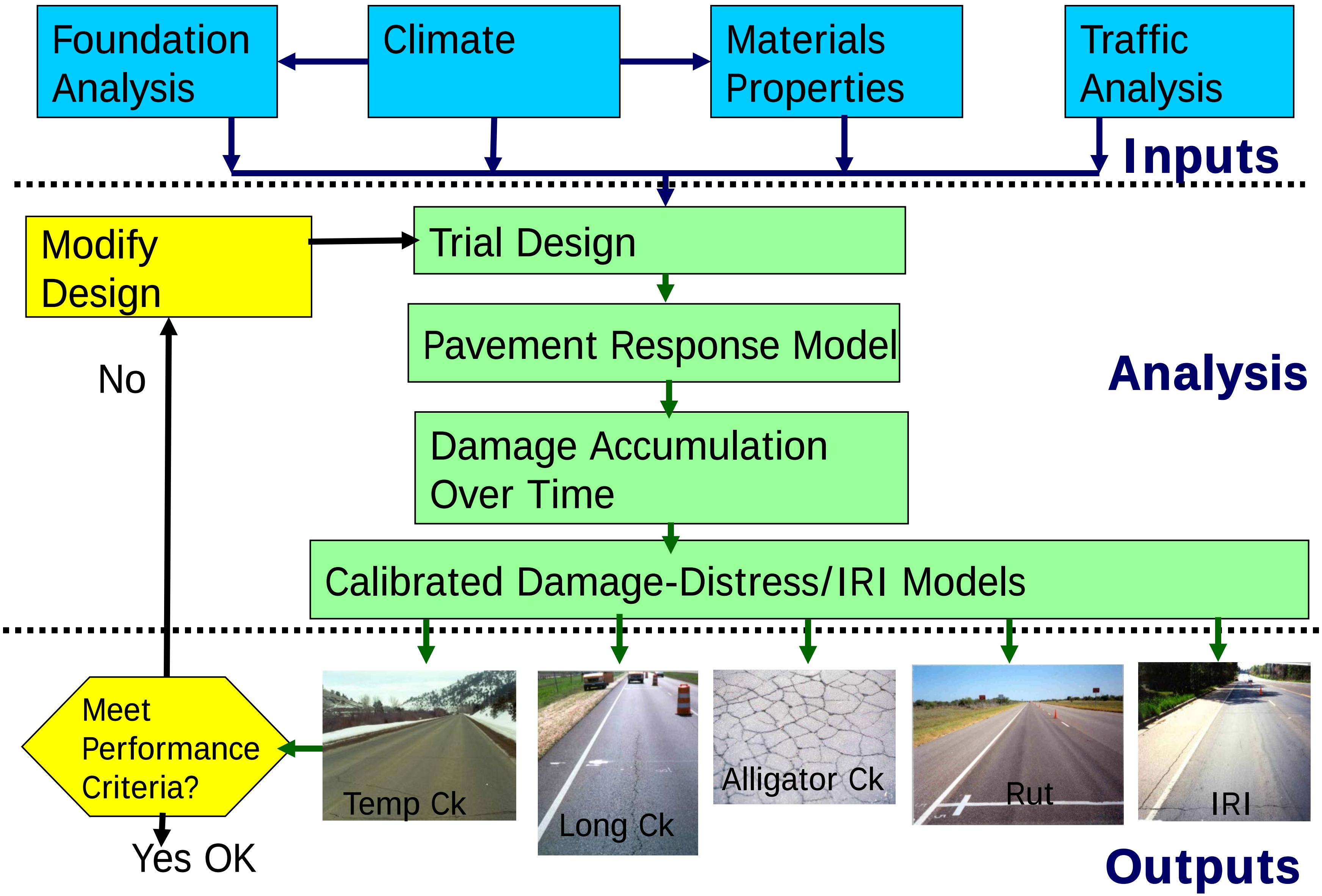
Impact of Design Reliability



Comprehensive System

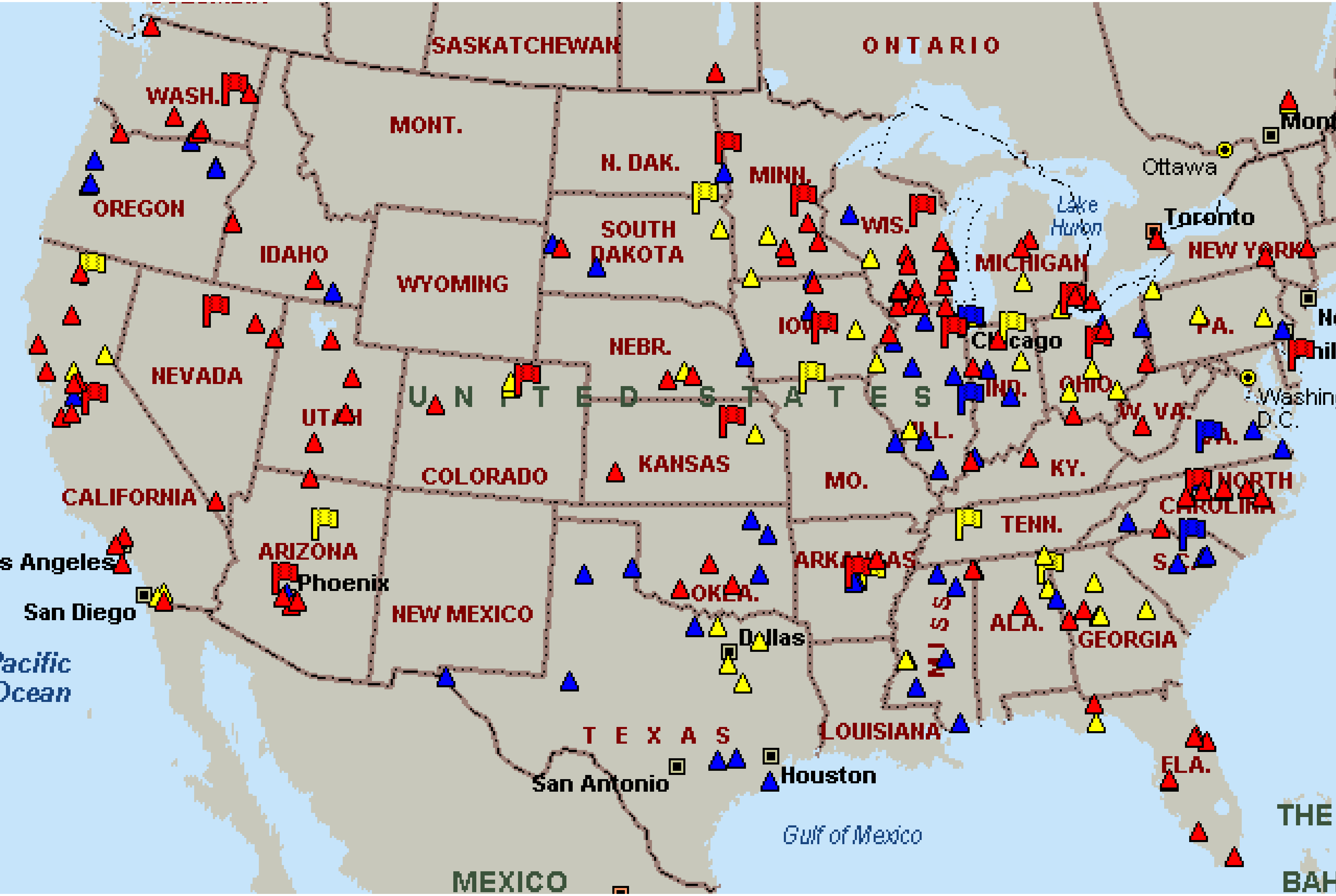


M-E Design Process



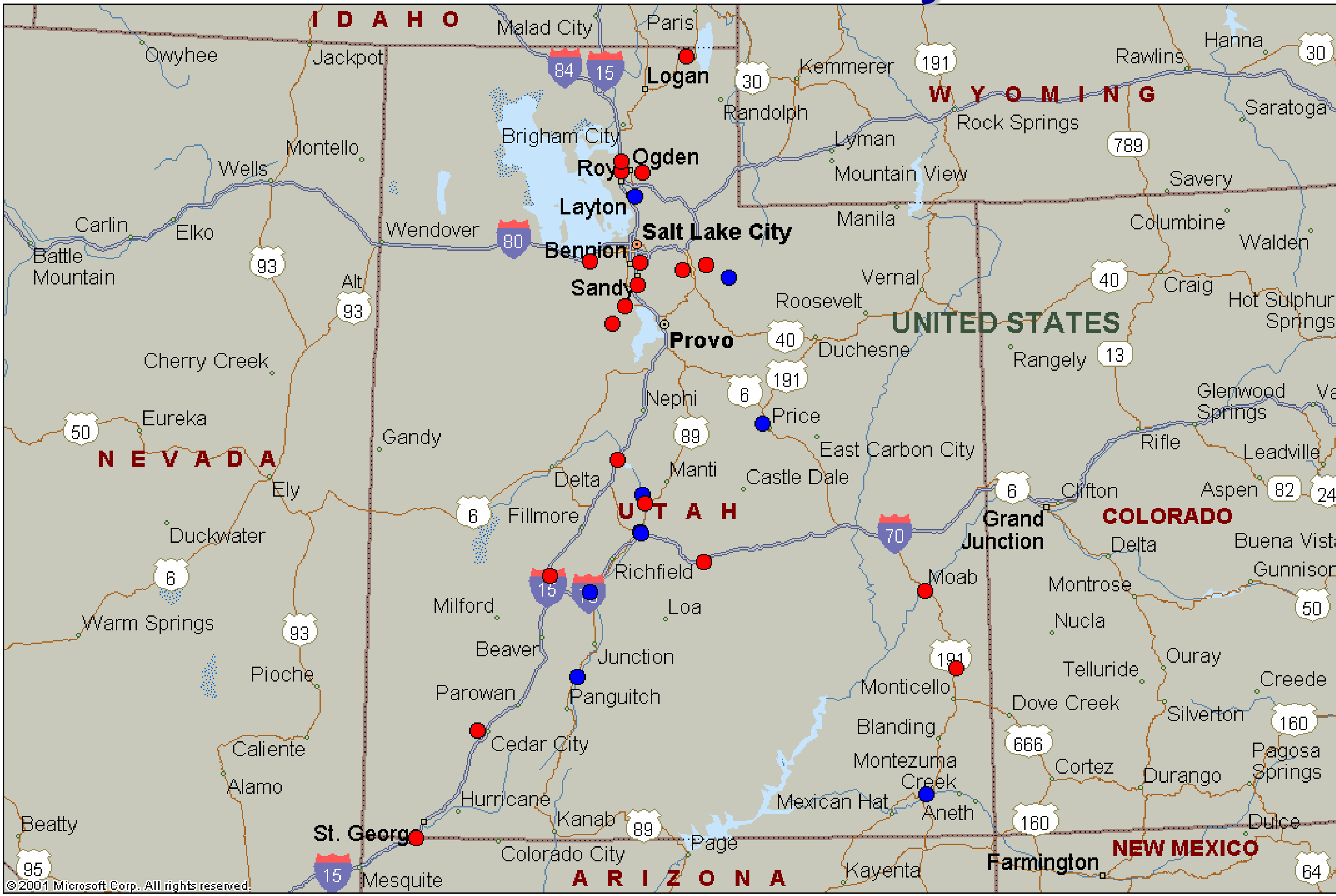
State Local Calibration of Distress/IRI

- A comprehensive effort was made to "calibrate" and validate the MEPDG to local conditions.
- Field data from around the State were collected and utilized to validate distress and smoothness equations.
- Results showed that all equations but rutting followed National calibrations well. Rutting was recalibrated!
- No bias in distress/IRI predictions!



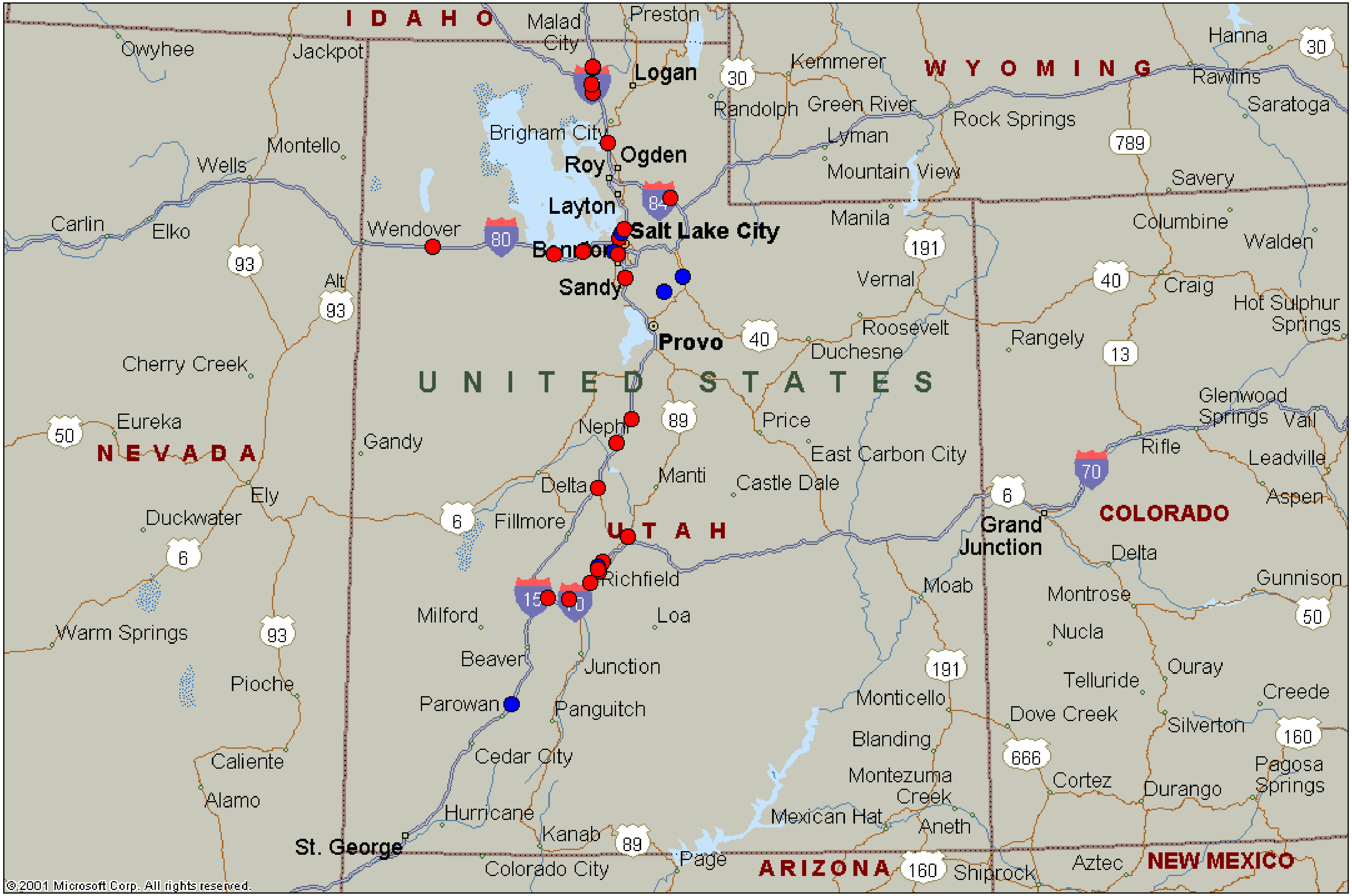
All JPCP/CRCP Sections

28 Utah HMA Projects



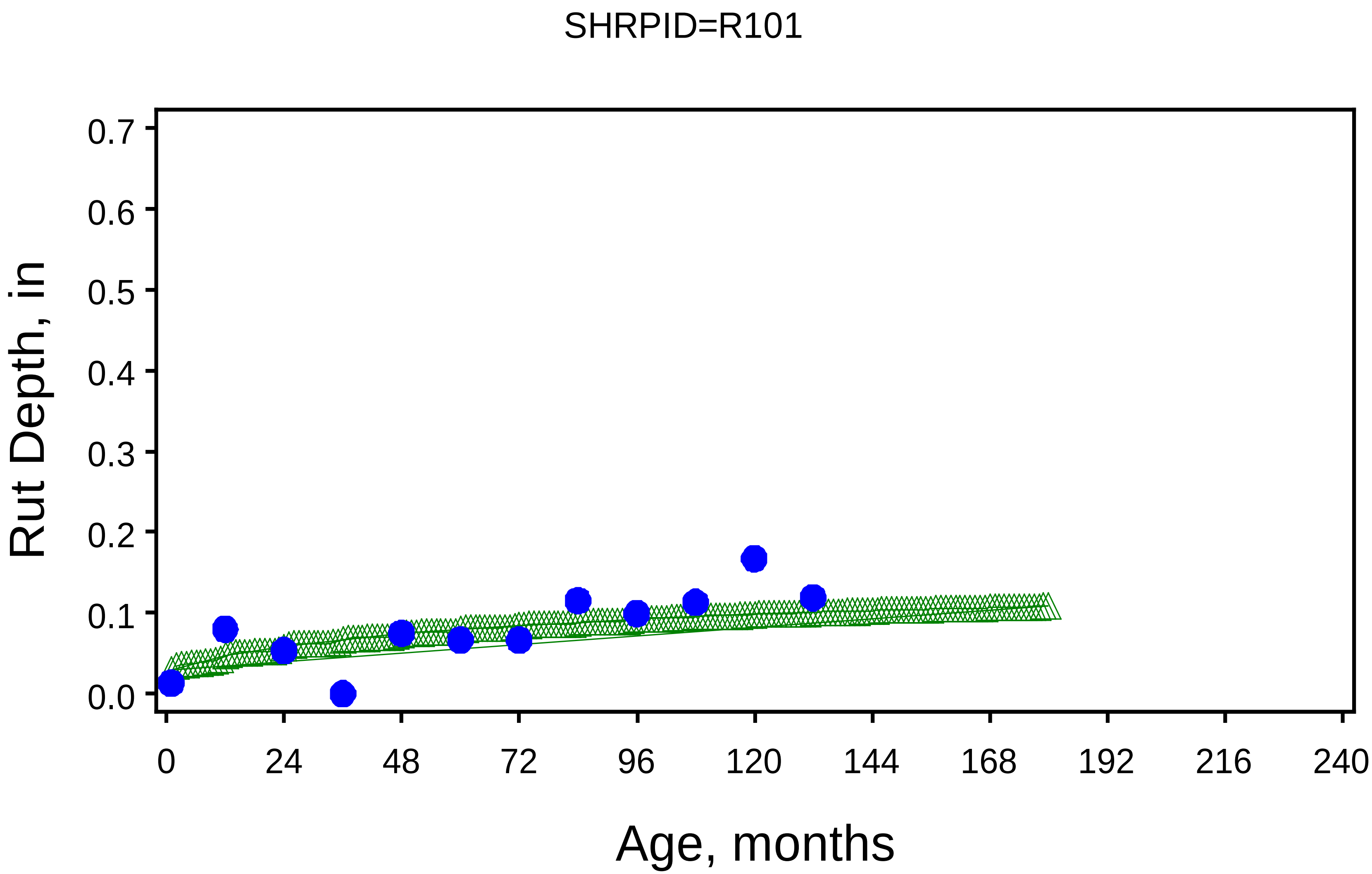
● PMS ● LTPP

23 Utah JPCP Projects

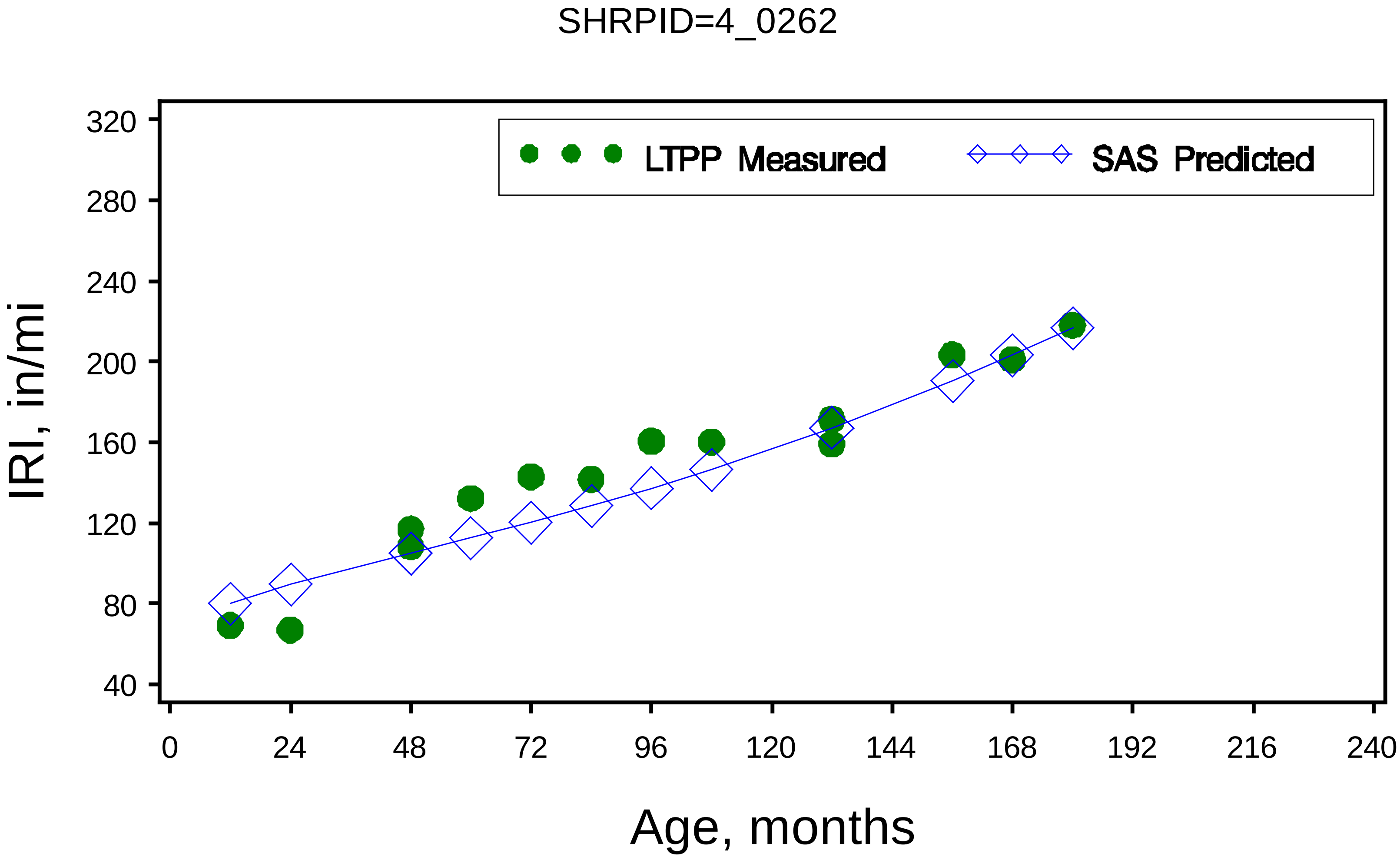


● PMS ● LTPP

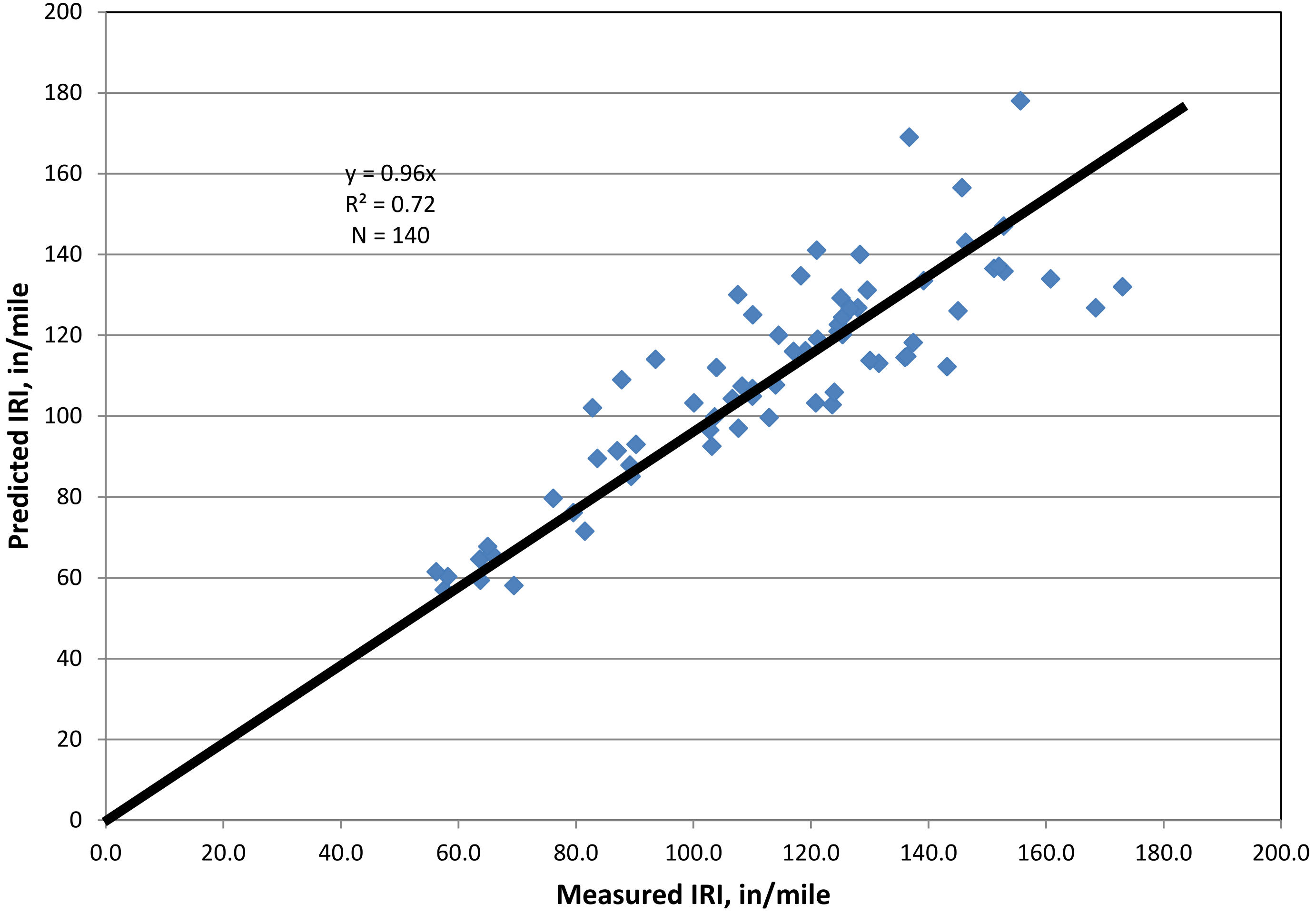
SR 226 Weber Co.



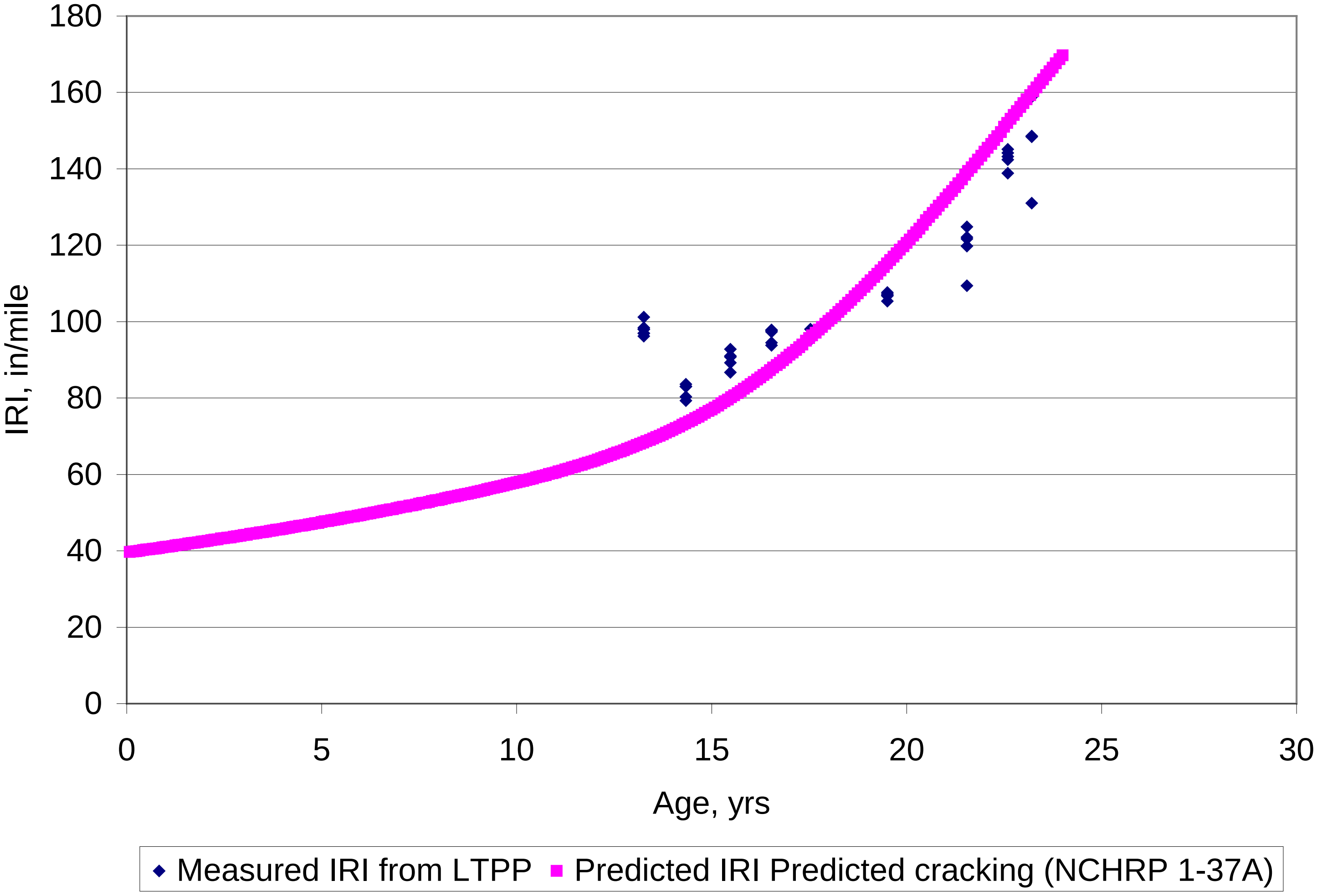
Example Measured & Predicted IRI

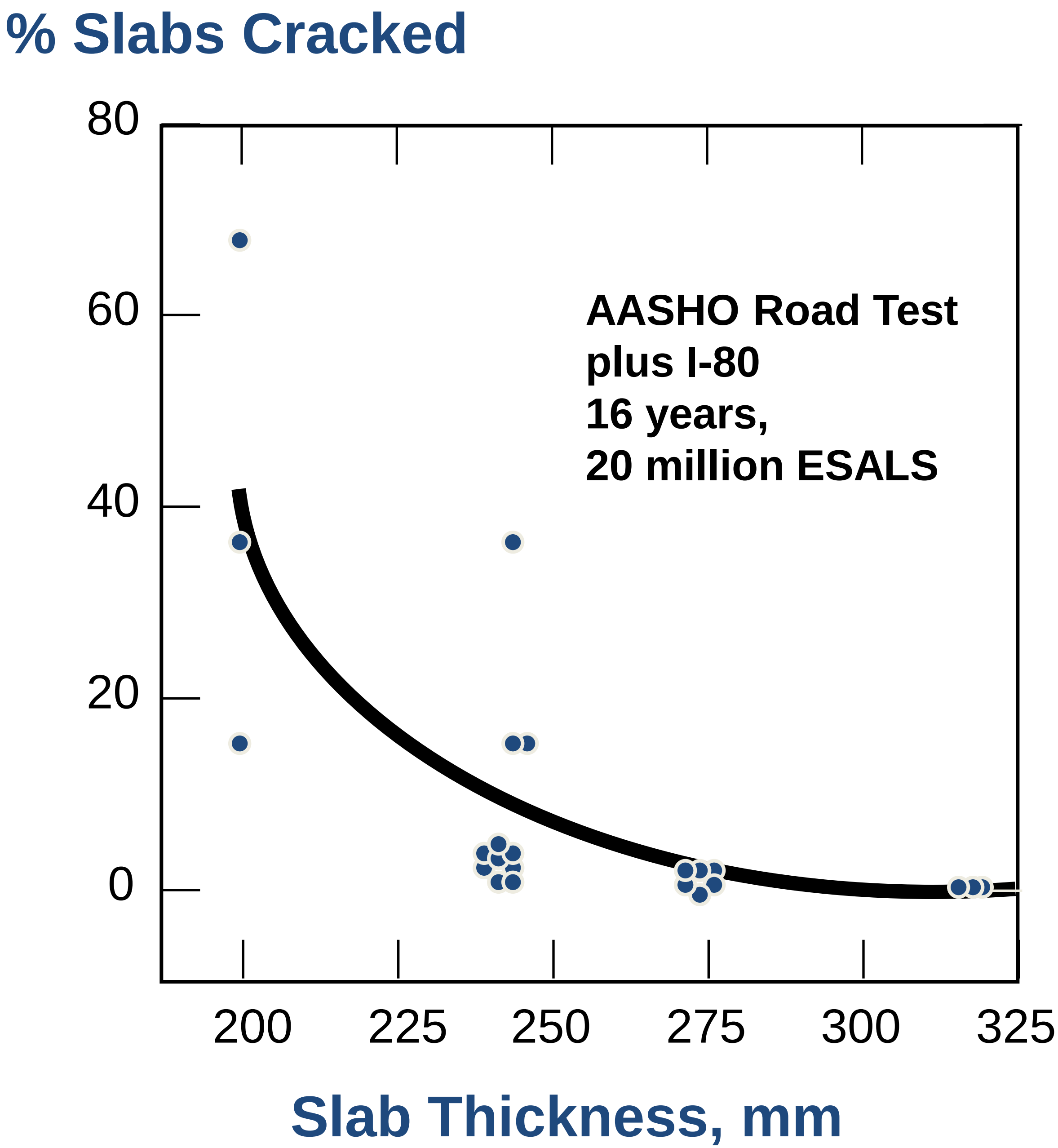


Utah JPCP Predicted Vs Measured IRI

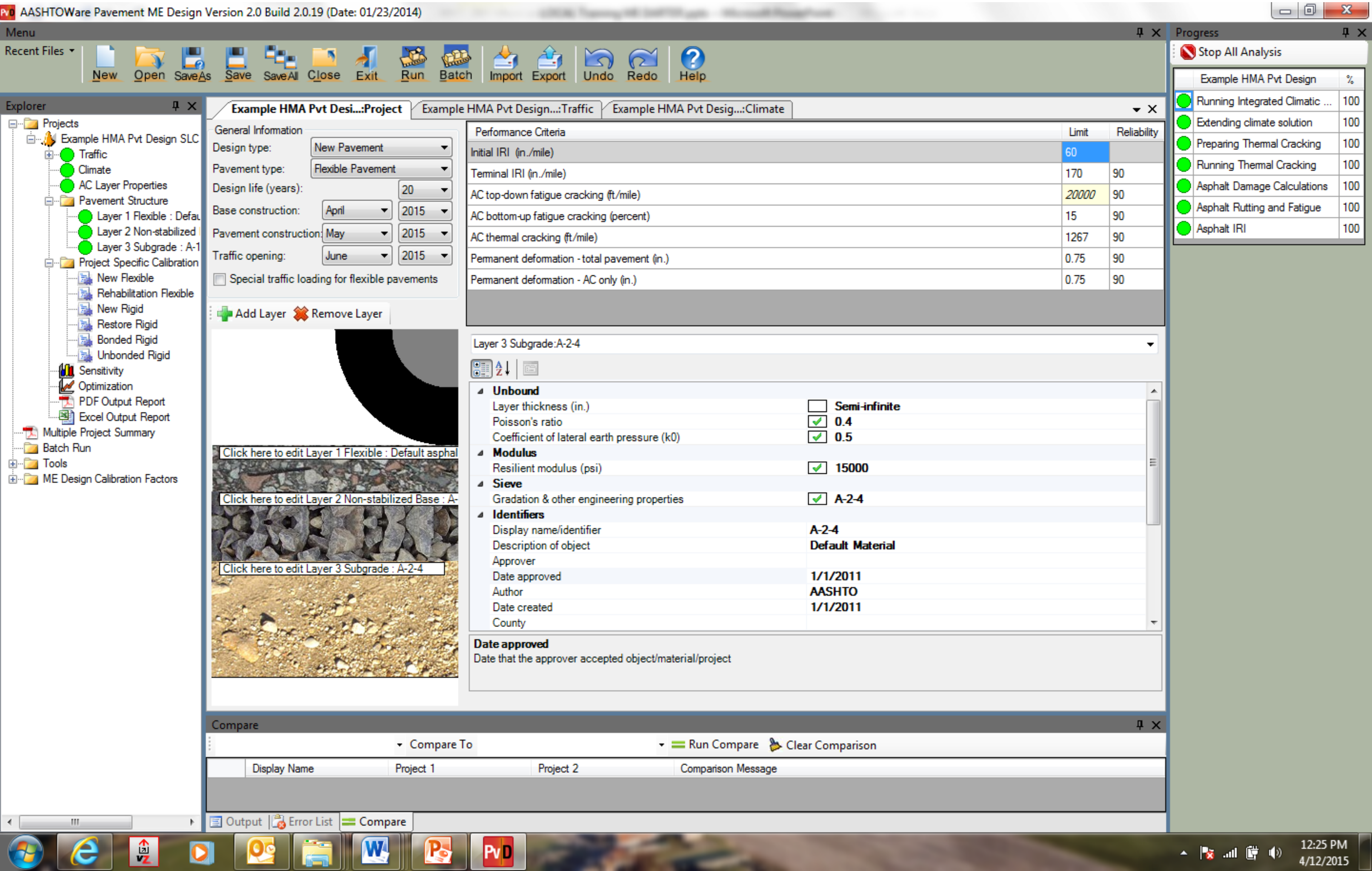


Utah HMA Case Study
—IRI Smoothness—

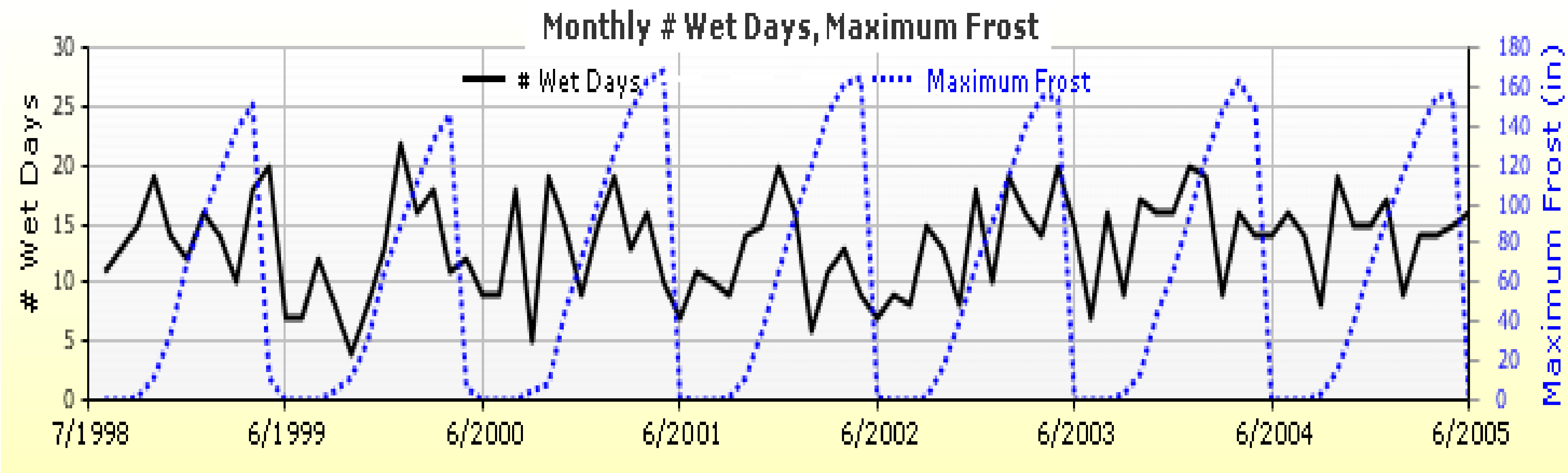



% Slabs Cracked
80
60
40
20
0
AASHO Road Test
plus I-80
16 years,
20 million ESALS
200
225
250
275
300
325
Slab Thickness, mm

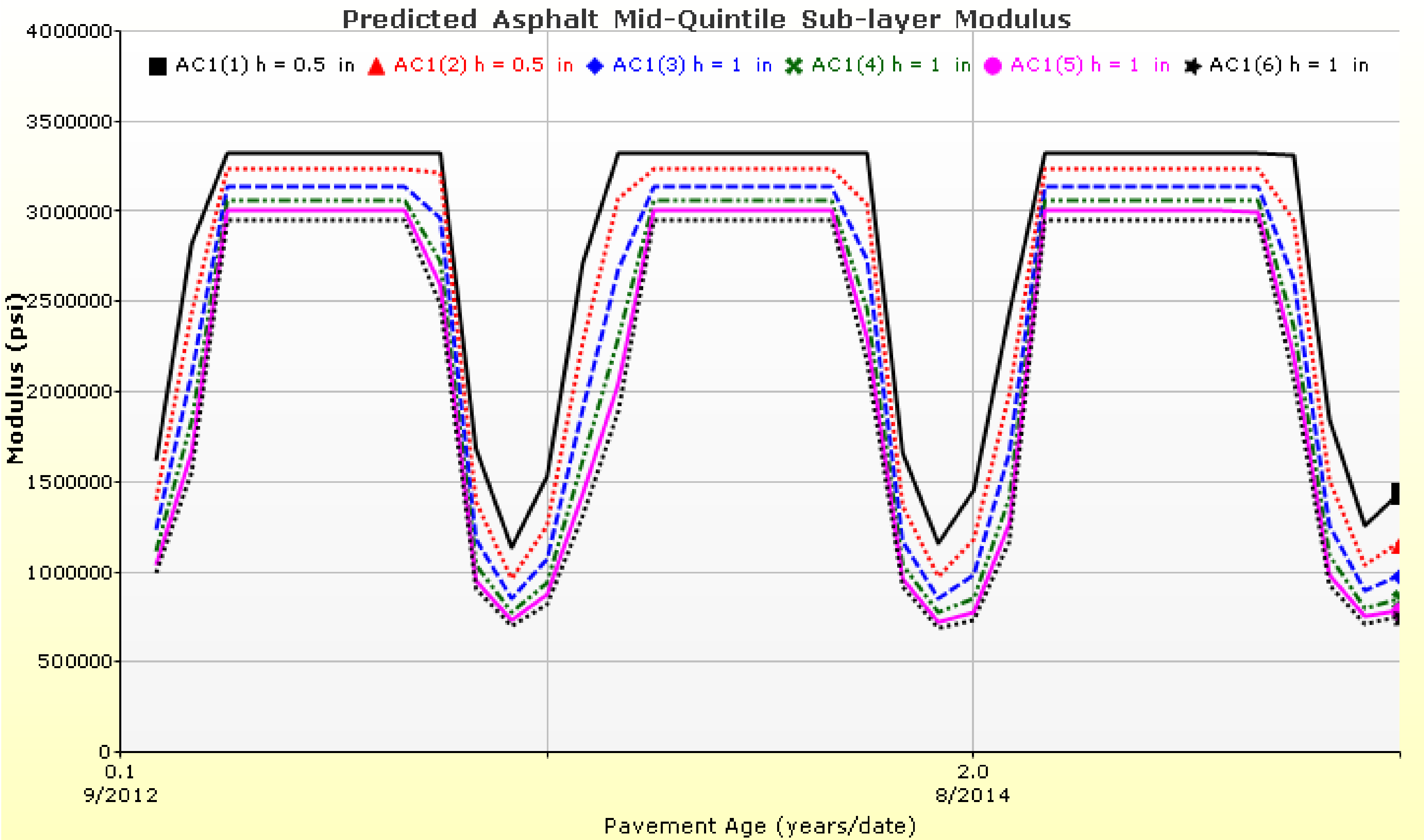
AASHTO ME Input Screen



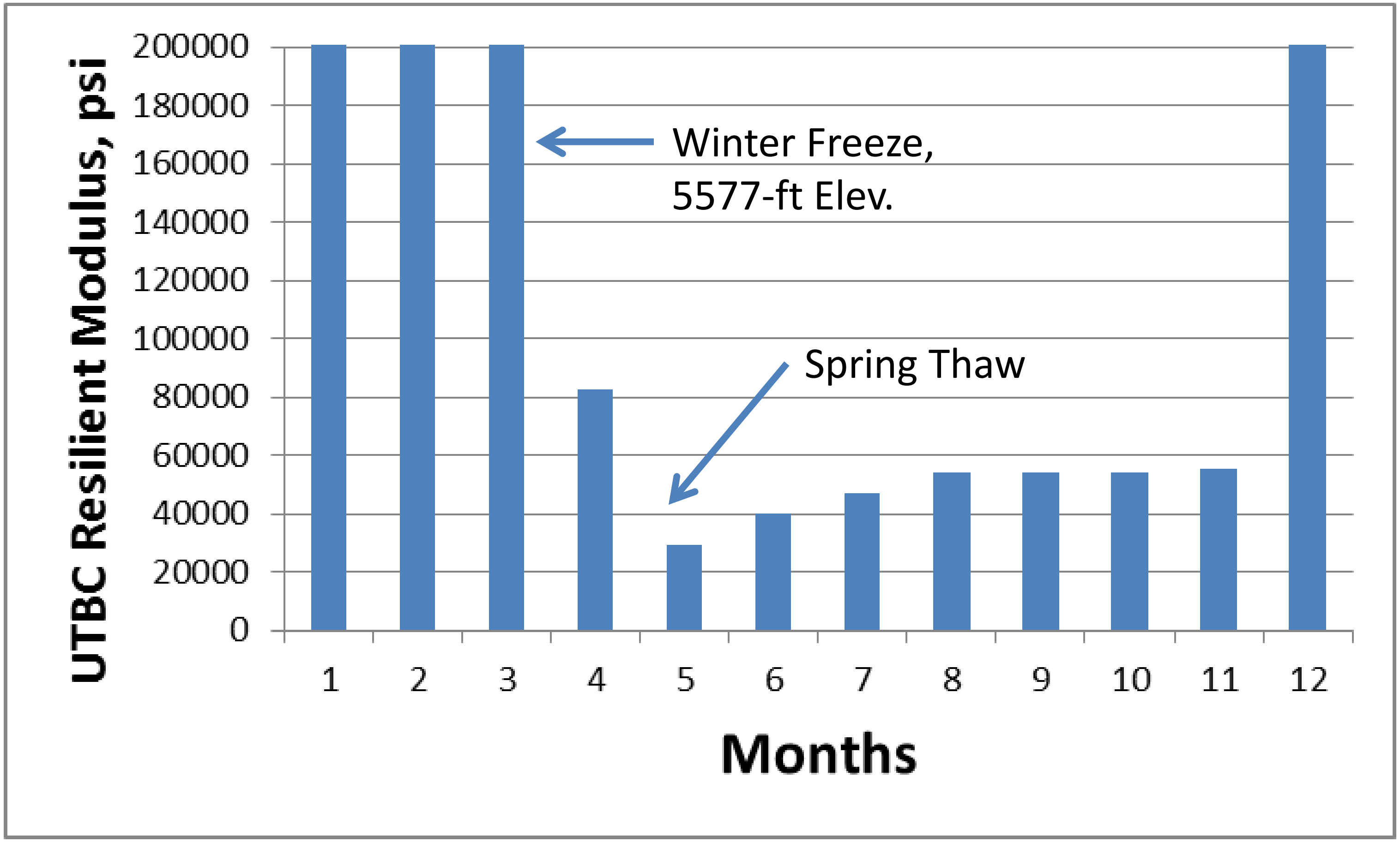
Example Output: Climate



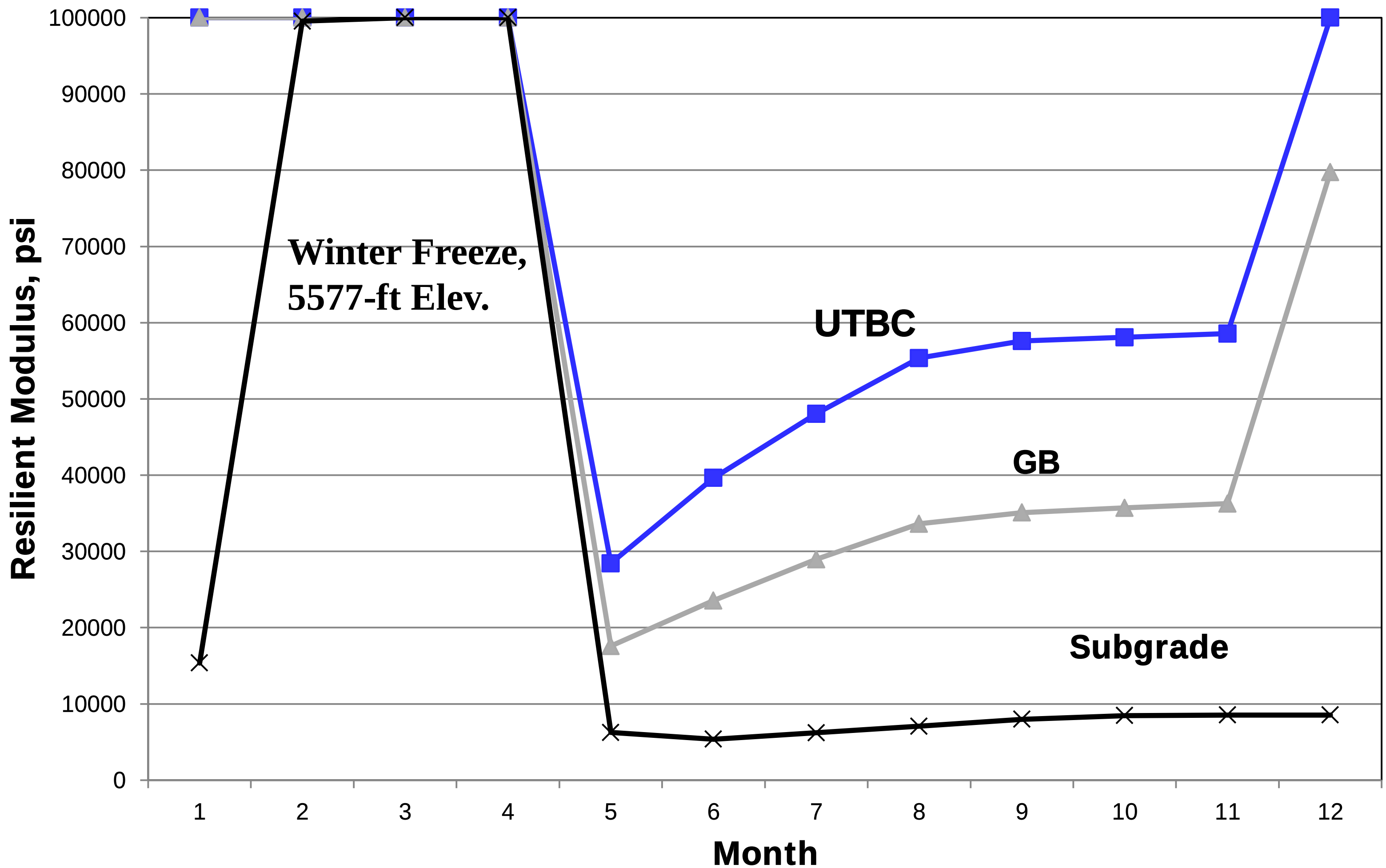
HMA Modulus E* Over Time



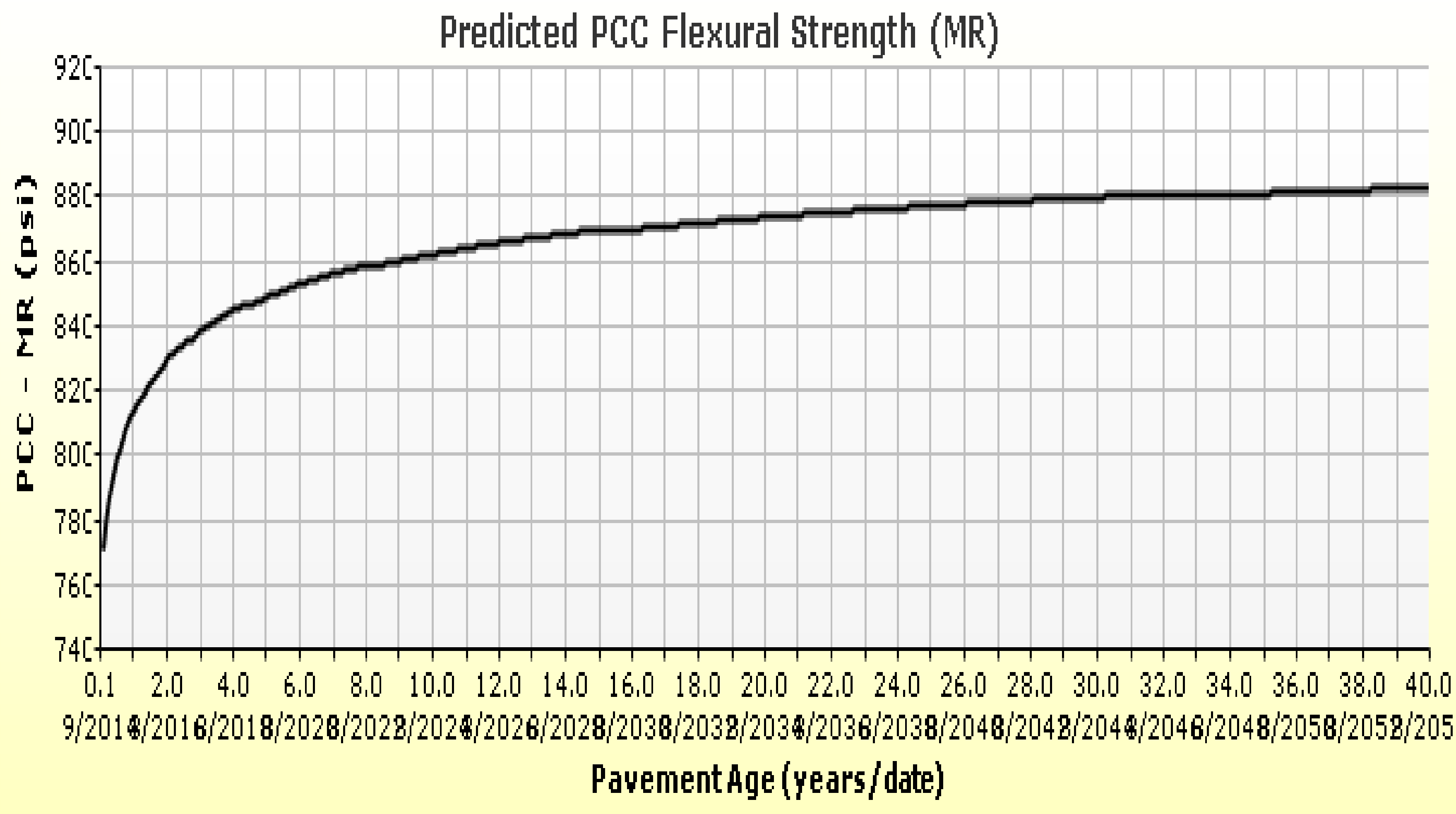
UTBC Modulus Over Year



UTBC, GB & Subgrade Modulus Over Year



PCC Flexural Strength Over Time



MEPDG Output Summary HMA

Design Inputs

Design Life: 20 years
Design Type: Flexible Pavement

Base construction: July, 2015
Pavement construction: August, 2015
Traffic opening: September, 2015

Climate Data Sources: 40.787, -111.968

Design Structure

Layer type	Material Type	Thickness (in.):
Flexible	Default asphalt concrete	5.0
NonStabilized	A-1-a	6.0
Subgrade	A-2-4	Semi-infinite

Volumetric at Construction:

Effective binder content (%)	11.0
Air voids (%)	6.5

Traffic

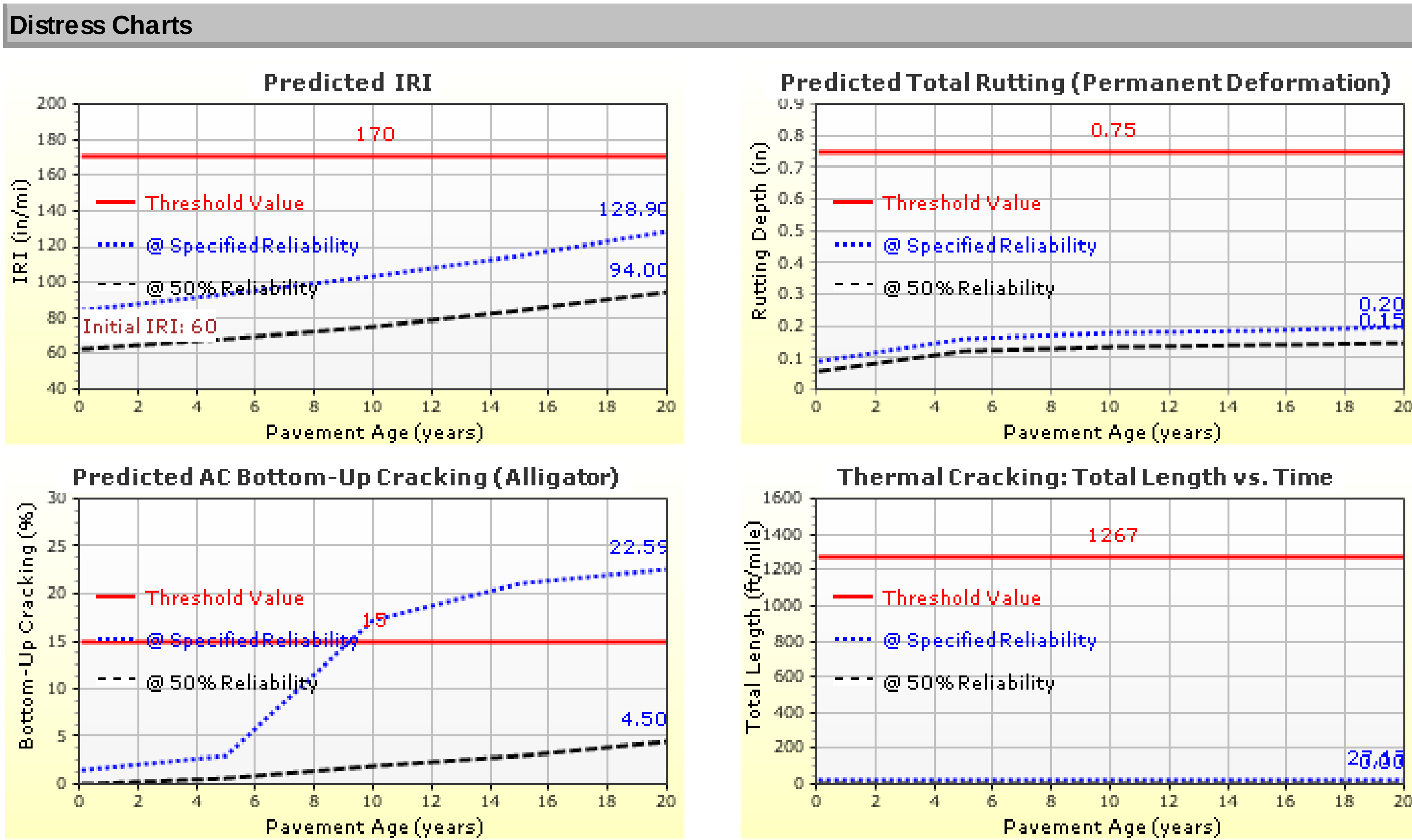
Age (year)	Heavy Trucks (cumulative)
2015 (initial)	1,440
2025 (10 years)	2,578,150
2035 (20 years)	5,629,360

Design Outputs

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	170.00	128.87	90.00	99.74	Pass
Permanent deformation - total pavement (in.)	0.75	0.20	90.00	100.00	Pass
AC bottom-up fatigue cracking (percent)	15.00	22.59	90.00	77.16	Fail
AC thermal cracking (ft/mile)	1267.00	27.17	90.00	100.00	Pass
AC top-down fatigue cracking (ft/mile)	20000.00	3089.32	90.00	100.00	Pass
Permanent deformation - AC only (in.)	0.75	0.05	90.00	100.00	Pass

MEPDG Output Graph: 4 in HMA



MEPDG Output: 5 in HMA

Design Inputs

Design Life: 20 years
Design Type: Flexible Pavement

Base construction: July, 2015
Pavement construction: August, 2015
Traffic opening: September, 2015

Climate Data Sources: 40.787, -111.968

Design Structure

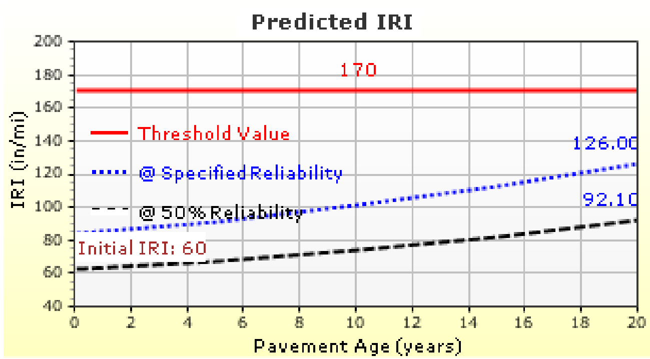
Layer type	Material Type	Thickness (in.):
Flexible	Default asphalt concrete	5.0
NonStabilized	A-1-a	6.0
Subgrade	A-2-4	Semi-infinite

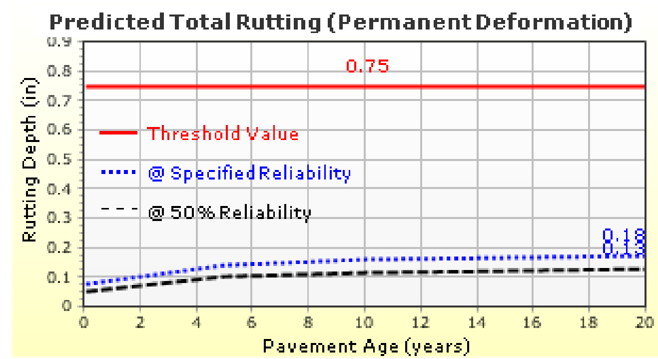
Volumetric at Construction:	
Effective binder content (%)	11.0
Air voids (%)	6.5

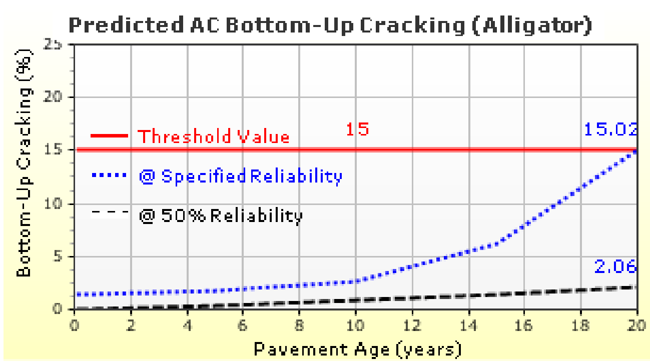
Traffic

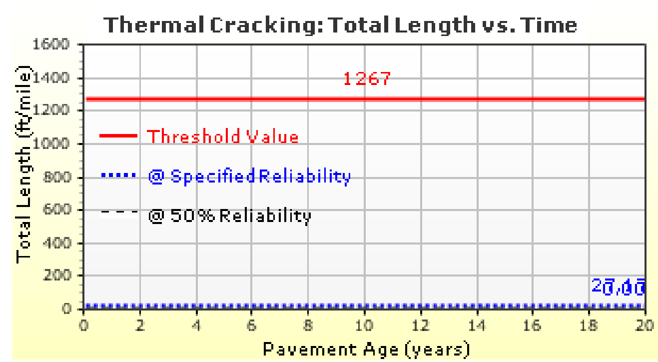
Age (year)	Heavy Trucks (cumulative)
2015 (initial)	1,440
2025 (10 years)	2,578,150
2035 (20 years)	5,629,360

Distress Charts









Summary

- Many States have made very significant efforts to properly implement the new AASHTO ME Design Guide since 2005.
- Continued training will be needed for States, local governments, consultants, university students, and others to properly use the procedure.
- Significant savings in construction costs and potentially maintenance and rehab costs!

6x6 ft Joints, Pan American Highway, Chile

Utah Examples of Designs

- HMA: Wanship to Coalville (high traffic)
- PCC: I-15 Point Project (high)
- HMA: Local Collector (lower)

Comparison With Old & New
AASHTO Design Results: I-84 Wanship-Coalville
Heavy Traffic: 24 Million Trucks

Old AASHTO 1993

- 9.5-in HMA
- 11-in UTBC
- 22-in Granular Borrow
- Subgrade (CBR=3)

New AASHTO ME DESIGN

- 8-in HMA
- 11-in UTBC
- 22-in Granular Borrow
- Subgrade (A6 Class)

Often there is a savings
in construction cost for
higher traffic!

Example: PCC Thickness (High Traffic)

- I-15 Point Rehabilitation Project (2014)
  - Mainline: 92 M trucks design lane (capacity)
- Design of UBOL using AASHTO ME:
  - 11 in JPCP
  - 2 in HMA / 9 in Existing JPCP
- Design of UBOL using AASHTO 93:
  - 13 in JPCP
  - 2 in HMA / 9 in Existing JPCP

Comparison With Old & New AASHTO Design Results: Local Collector

Medium Traffic: 3 Million Trucks

Old AASHTO 1993

- 6-in HMA*
- 6-in UTBC
- 21-in Granular Borrow
- Subgrade (CBR=3)

New AASHTO ME DESIGN

- 4.5-in HMA
- 6-in UTBC
- 12-in Granular Borrow
- Subgrade (A7 Class)

HMA Thickness by Layered Analysis

Forensic Capabilities

- Impact of construction variances on service life and costs
- Determining causes of various types of deterioration

Forensic Example

- HMA overlay placed, lots of fatigue cracking after 9 years
- Coring indicated 2-inch HMA Overlay has debonded
- MEPDG prediction, assuming debonding, predicts 6 year fatigue life!

9 Years after placement: Debonding AC OL

Lots of fatigue cracking, due to debonding of AC layers.

Bogotá, Columbia
Major Freeway– A Very Complex Pavement Structure...

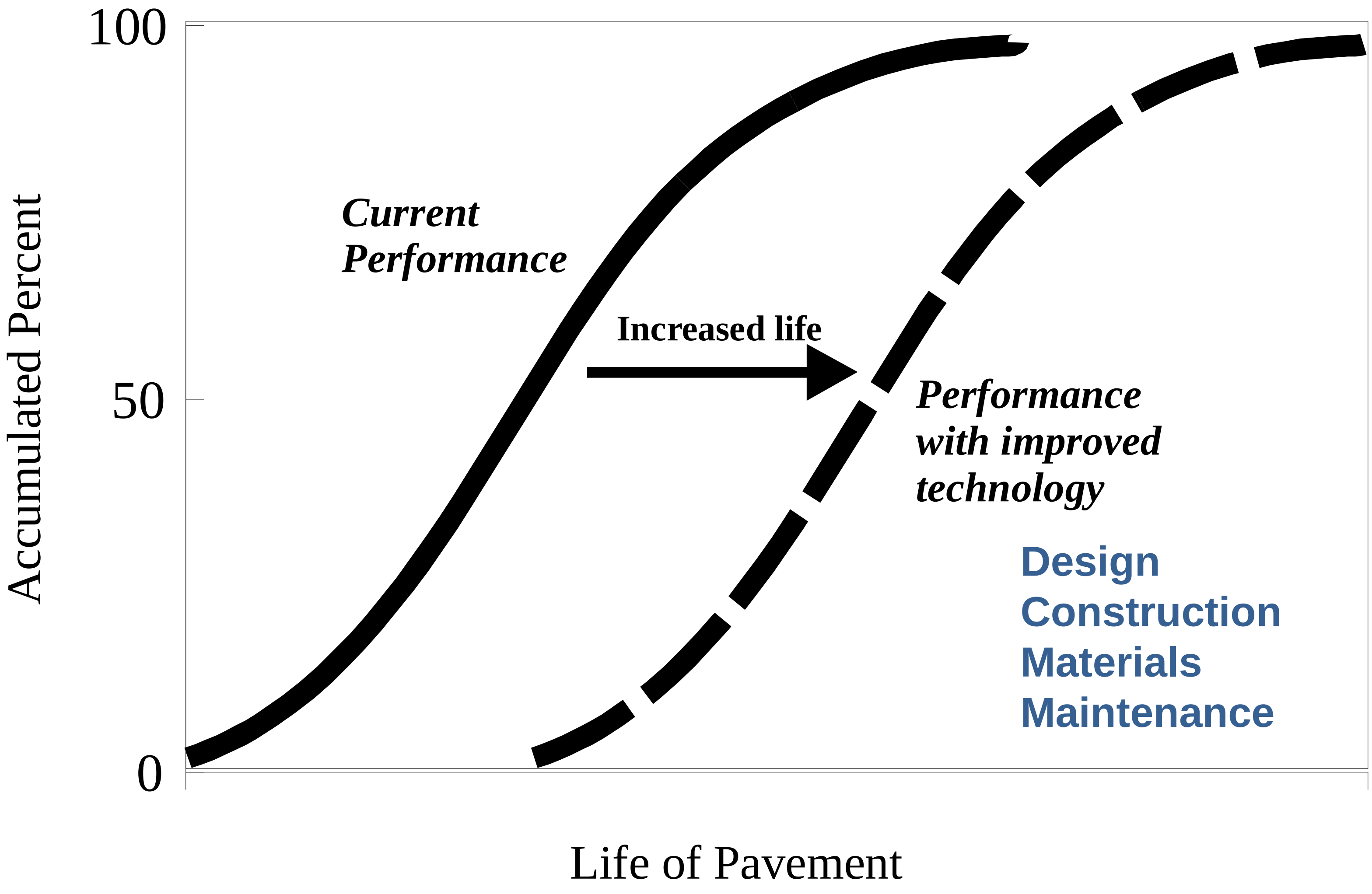
Pavement Design Benefits

- Recognition of Optimized Designs
- Long-Term Performance Predictions
- VE of Pavement Issues
- Reduced Construction Time
- Appropriate Use of Materials
- Reduced Construction Cost
- Forensic Capabilities

Future Need for Test Tracks

- "Mechanistic-Empirical" design makes it clear that having actual field pavement sections is critical to the validity and accuracy of the ME procedure.
- While we can obtain many good sections to use in local/national calibration from the highway network, these are limited in designs and materials.
- Test tracks like MnRoad and NCAT are invaluable to testing innovative designs and materials. Then, their performance can be used in further calibration of M-E distress and smoothness models.
- MnRoad is INVALUABLE in this process!
  - Current Example: Use of "short" jointed concrete design calibration

Future: Improved Pavement Longevity?



Impact of pavements

driving comfort, safety, delays from lane closures, timely movement of products, economic development, defense, communication, ……

Challenging times…

Some highways now designed
to carry 400 million heavy axles
Over 40 years of climate conditions!