Department of
Civil, Environmental,
and Geo- Engineering

COLLEGE OF
Science & Engineering
UNIVERSITY OF MINNESOTA

Mechanistic-Empirical Design in USA

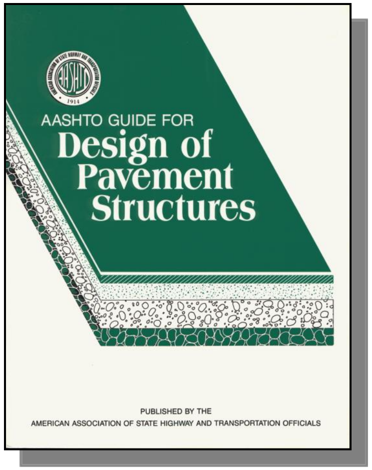
Lev Khazanovich, Ph.D.
Professor
University of Minnesota

Presentation Outline

1. Why mechanistic-empirical (ME) design?
2. Overview of AASHTOWare ME
    1. Required input parameters (material properties, climate, traffic)
    2. Performance models
    3. Benefits

History of Empirical Design Guide

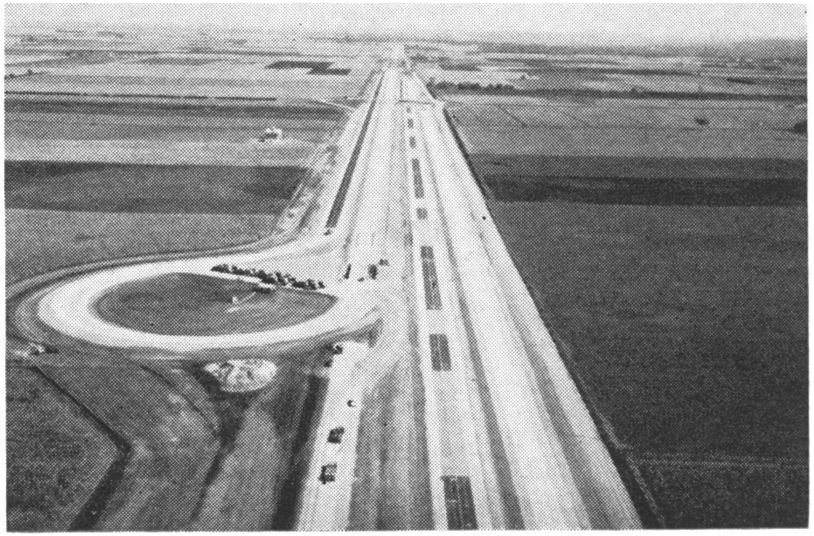
- Empirical design methodology based on AASHO Road Test in the late 1950’s
- Several versions:
  - 1961 (Interim Guide), 1972, 1986
  - 1986 version included refined material characterization
  - 1993 revised version
    - More on rehabilitation
    - More consistency between flexible, rigid designs
    - Current version for flexible design procedures

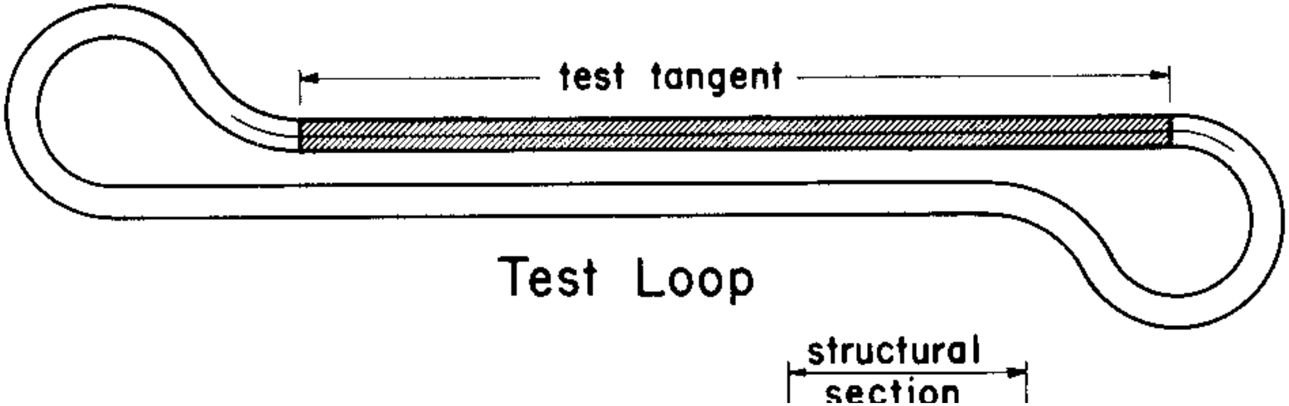


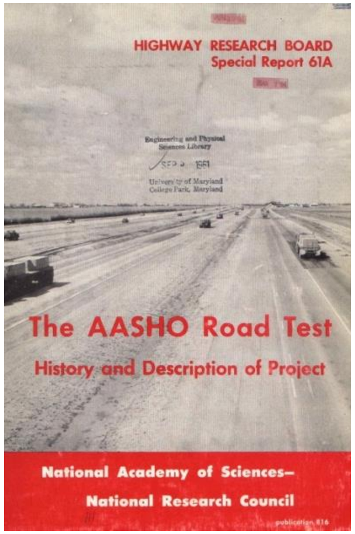
AASHTO GUIDE FOR
Design of Pavement Structures

PUBLISHED BY THE
AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS

AASHO Road Test (late 1950’s)







HIGHWAY RESEARCH BOARD
Special Report 61A

Engineering and Physical Sciences Library
SEP 9 1961
University of Maryland
College Park, Maryland

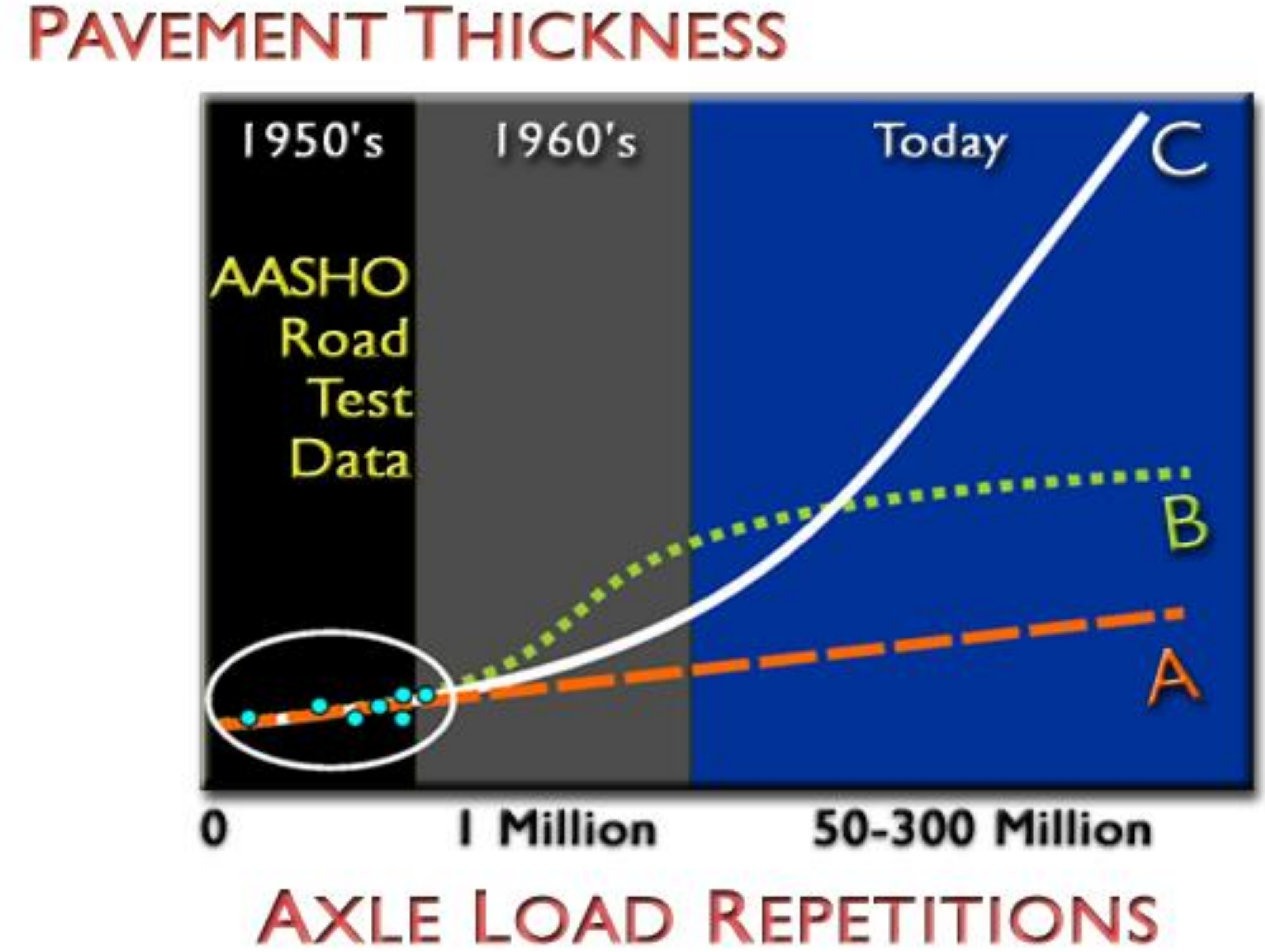
The AASHO Road Test
History and Description of Project

National Academy of Sciences–
National Research Council

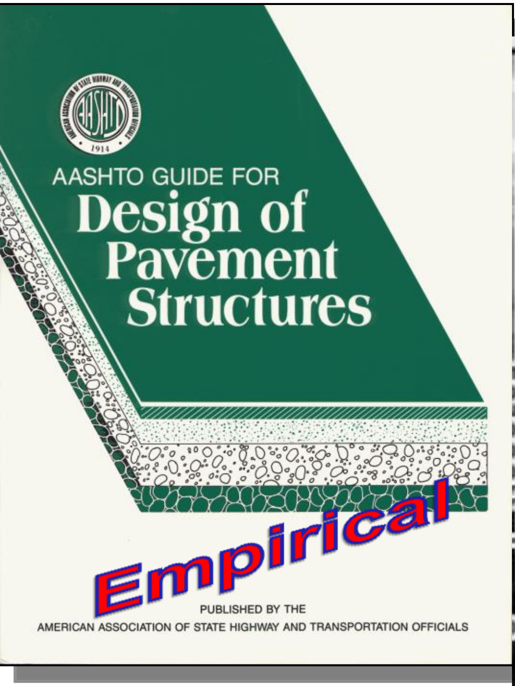
publication 816

(AASHO, 1961)

Low Traffic Level



Evolution of Pavement Design in USA

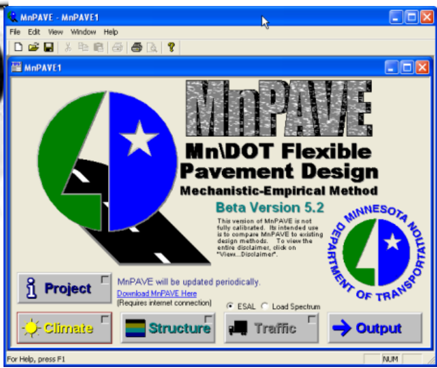


AASHTO GUIDE FOR
Design of Pavement Structures

Empirical

PUBLISHED BY THE
AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS

http://www.jantoo.com/cartoon/11800597



MnPAVE - MnPAVE1

MnPAVE1

MnPAVE
Mn\DOT Flexible Pavement Design
Mechanistic-Empirical Method
Beta Version 5.2

This version of MnPAVE is not fully calibrated. Its intended use is to compare MnPAVE to existing design methods. To view the entire disclaimer, click on "View...Disclaimer".

MnPAVE will be updated periodically.
Download MnPAVE Here
(Requires internet connection)

● ESAL ○ Load Spectrum

For Help, press F1

NUM

PvD
AASHTOWare
Pavement™
ME Design
AASHTO

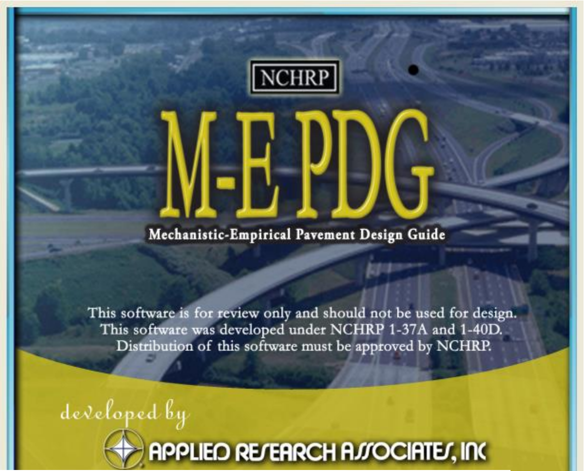
History of AASHTO ME Design

- 2004: NCHRP Project 1-37A: Development of the Guide for Design of New and Rehabilitated Pavement Structures
  - 2002 Design Guide
  - MEPDG
- 2007: NCHRP Project 1-40B – Manual of Practice
- 2007: NCHRP Project 1-40D – Local Calibration Guide
- 2008: Balloted by AASHTO
  - AASHTO ME design procedure

MEPDG Software

Software

- NCHRP
  - MEPDG versions 0.7, 0.8, 0.9, 1.0, 1.1
- AASHTOWare
  - DARWin-ME (2011-2013)
  - Pavement ME (since 2013)



NCHRP

M-E PDG

Mechanistic-Empirical Pavement Design Guide

This software is for review only and should not be used for design.
This software was developed under NCHRP 1-37A and 1-40D.
Distribution of this software must be approved by NCHRP.

developed by

APPLIED RESEARCH ASSOCIATES, INC

DARWin ME™

chanistic Empirical Pavement Design

PvD AASHTOWare Pavement™ ME Design

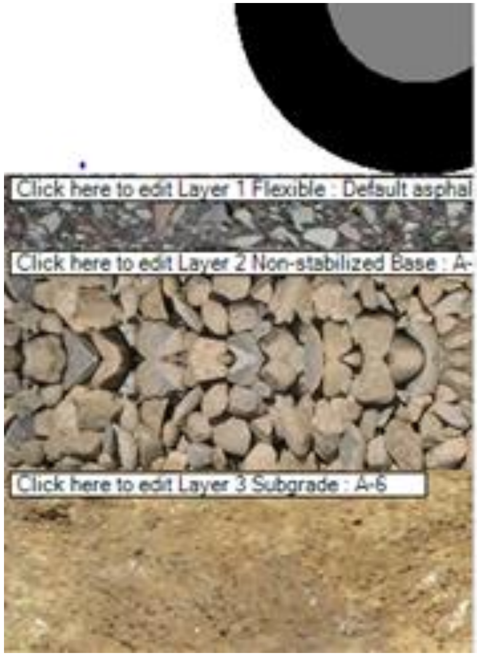
AASHTO

Licensing

- MEDPG v 1.1
  - Public domain, but installation file is not distributed
  - Requires connection to the TRB server
  - Can be disconnected at any time
- Pavement ME
  - Individual license: $5,000/year
  - Site license for up to 9 users: US$20,000/year
  - Site license for up to 14 users: US$30,000/year
  - Site license for unlimited users: US$40,000/year

Design Inputs – 4 Main Categories

- Traffic
  - Volume
  - Axle load distribution
  - Axle configuration
- Climate
  - Latitude, longitude, elevation, etc.
- Structure
  - Layers, thicknesses, and material properties
- Performance thresholds and reliability level



Input Levels

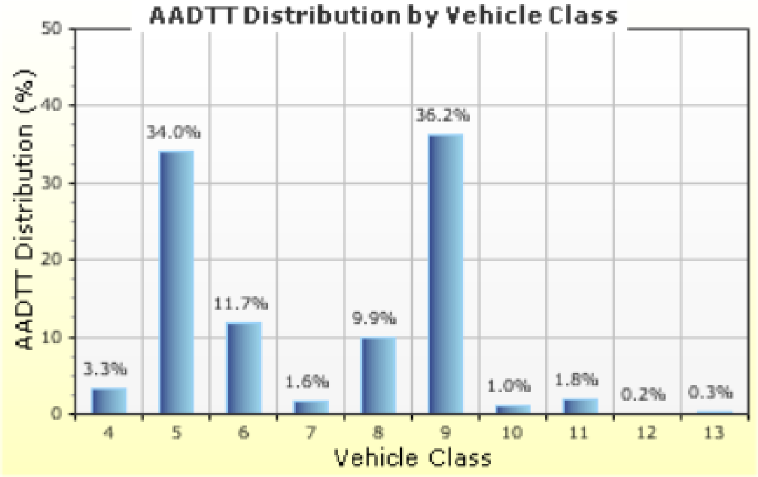
The Design Guide includes three levels of specification for inputs.

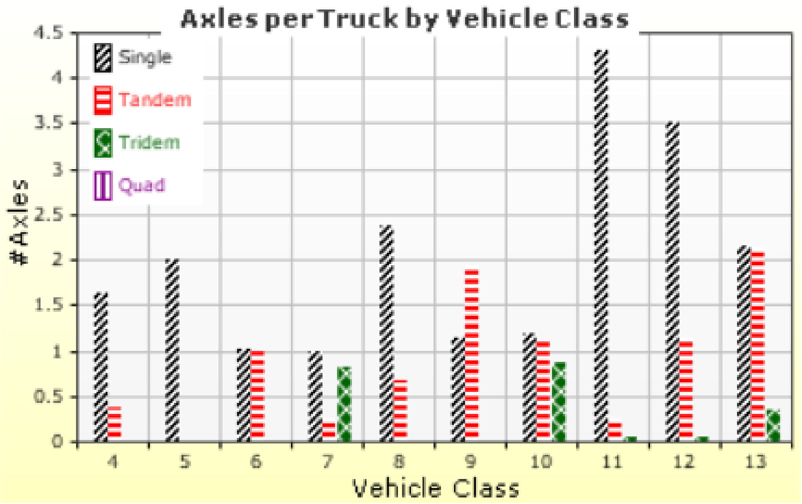
Input Level	Determination of Input Values	Knowledge of Input Parameter
1	Project/Segment Specific Measurements—Lab, WIM, FWD	Good
2	Correlations/Regression Equations, Regional Values—CBR, R-Value, Dynamic Cone Penetrometer	Fair
3	Soil Classifications, Typical values	Fair - Poor

Traffic Loading Inputs

- Vehicle volume, growth & classification
- Single, tandem, tridem, quad axle load distributions
- Monthly vehicle distribution
- Lateral lane distribution and traffic wander
- Tire pressure
- Tractor wheelbase
- Truck speed

Traffic Loading Inputs Examples





Axle Configuration

Traffic Wander	
Mean wheel location (in.)	18
Traffic wander standard deviation (in.)	10
Design lane width (ft)	12

Axle Configuration	
Average axle width (ft)	8.5
Dual tire spacing (in.)	12
Tire pressure (psi)	120

Average Axle Spacing	
Tandem axle spacing (in.)	51.6
Tridem axle spacing (in.)	49.2
Quad axle spacing (in.)	49.2

Wheelbase does not apply

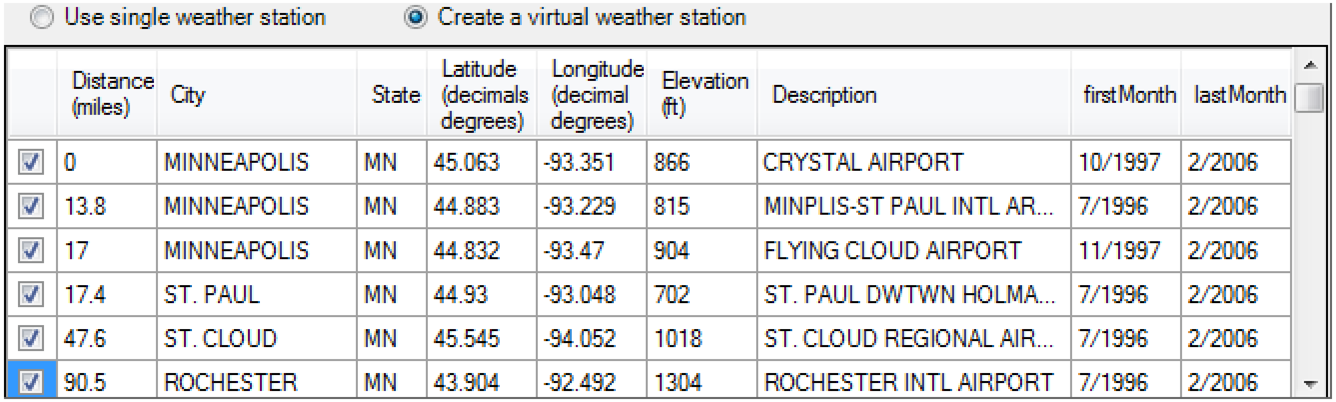
Number of Axles per Truck

Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

Climate Inputs

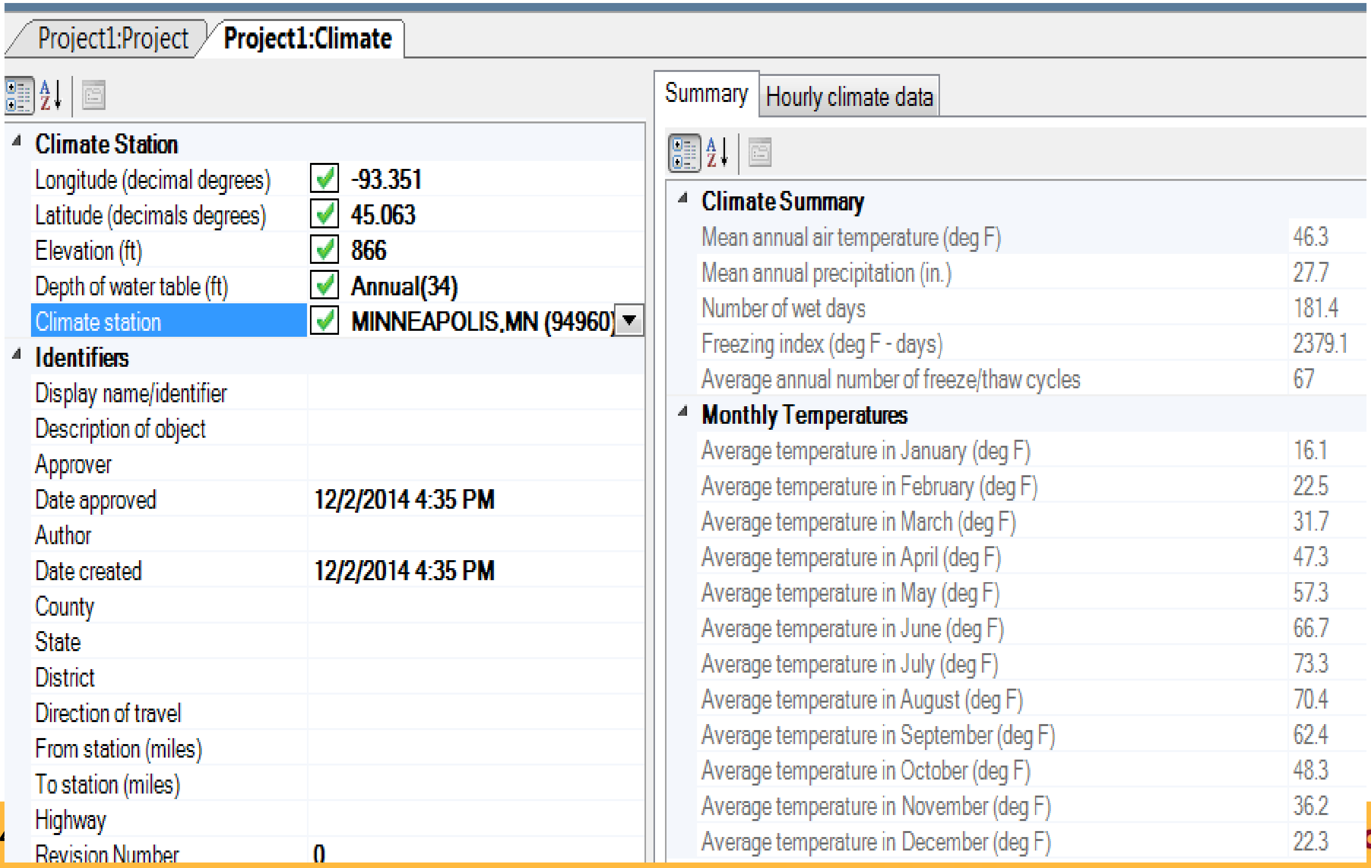
- Hourly climatic data: Weather Stations
  - – Temperature
  - – Precipitation
  - – Wind speed
  - – Cloud cover
  - – Relative ambient humidity
- Water table level

Simplified Climate Inputs



○ Use single weather station ● Create a virtual weather station

	Distance (miles)	City	State	Latitude (decimals degrees)	Longitude (decimal degrees)	Elevation (ft)	Description	firstMonth	lastMonth
☑	0	MINNEAPOLIS	MN	45.063	-93.351	866	CRYSTAL AIRPORT	10/1997	2/2006
☑	13.8	MINNEAPOLIS	MN	44.883	-93.229	815	MINPLIS-ST PAUL INTL AR...	7/1996	2/2006
☑	17	MINNEAPOLIS	MN	44.832	-93.47	904	FLYING CLOUD AIRPORT	11/1997	2/2006
☑	17.4	ST. PAUL	MN	44.93	-93.048	702	ST. PAUL DWTWN HOLMA...	7/1996	2/2006
☑	47.6	ST. CLOUD	MN	45.545	-94.052	1018	ST. CLOUD REGIONAL AIR...	7/1996	2/2006
☑	90.5	ROCHESTER	MN	43.904	-92.492	1304	ROCHESTER INTL AIRPORT	7/1996	2/2006



Climate Station

Longitude (decimal degrees)	✓	-93.351
Latitude (decimals degrees)	✓	45.063
Elevation (ft)	✓	866
Depth of water table (ft)	✓	Annual(34)
Climate station	✓	MINNEAPOLIS,MN (94960)

Identifiers

Display name/identifier	
Description of object	
Approver	
Date approved	12/2/2014 4:35 PM
Author	
Date created	12/2/2014 4:35 PM
County	
State	
District	
Direction of travel	
From station (miles)	
To station (miles)	
Highway	
Revision Number	0

Climate Summary

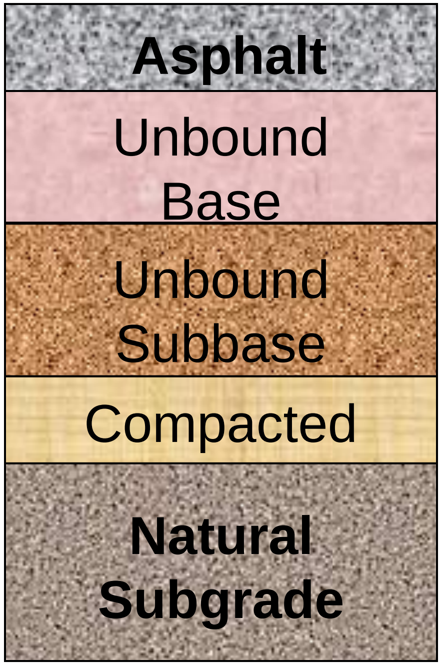
Mean annual air temperature (deg F)	46.3
Mean annual precipitation (in.)	27.7
Number of wet days	181.4
Freezing index (deg F - days)	2379.1
Average annual number of freeze/thaw cycles	67

Monthly Temperatures

Average temperature in January (deg F)	16.1
Average temperature in February (deg F)	22.5
Average temperature in March (deg F)	31.7
Average temperature in April (deg F)	47.3
Average temperature in May (deg F)	57.3
Average temperature in June (deg F)	66.7
Average temperature in July (deg F)	73.3
Average temperature in August (deg F)	70.4
Average temperature in September (deg F)	62.4
Average temperature in October (deg F)	48.3
Average temperature in November (deg F)	36.2
Average temperature in December (deg F)	22.3

Structure Inputs - Layers

Conventional



Asphalt

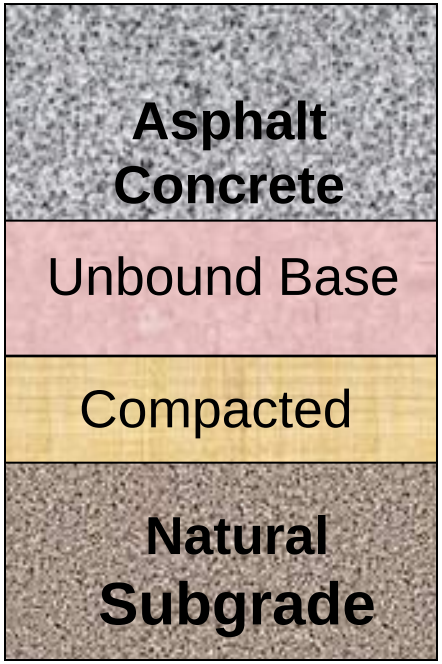
Unbound Base

Unbound Subbase

Compacted

Natural Subgrade

Deep Strength



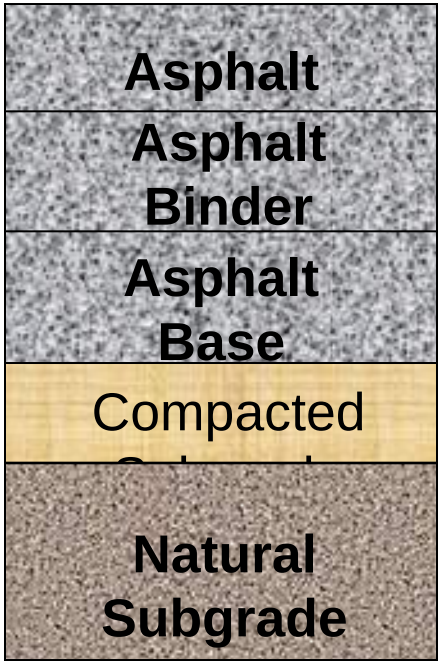
Asphalt Concrete

Unbound Base

Compacted

Natural Subgrade

Full-Depth



Asphalt

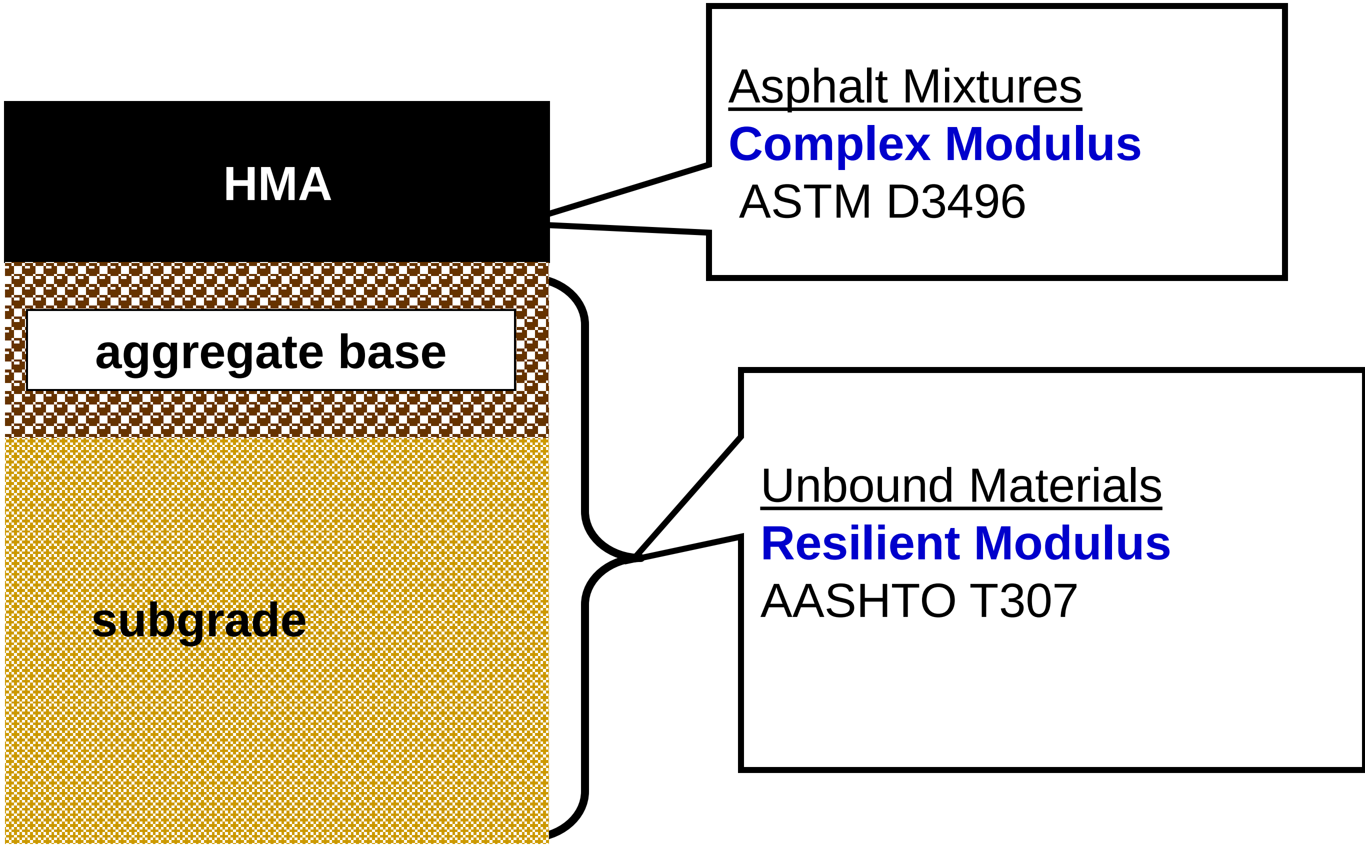
Asphalt Binder

Asphalt Base

Compacted

Natural Subgrade

Structure Inputs: Materials Properties



Asphalt Mixtures
Complex Modulus
ASTM D3496

Unbound Materials
Resilient Modulus
AASHTO T307

Empirical Relation for |E*|

$$\log E = -1.249937 + 0.29232\,\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\,\rho_4 - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff} + V_a}\right) + \frac{3.871977 - 0.0021\,\rho_4 + 0.003958\,\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\,\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log(f) - 0.393532\log(\eta))}} \tag{2.3}$$

where:

E = Dynamic modulus, 10^5 psi

η = Bitumen viscosity, 10^6 Poise

f = Loading frequency, Hz

V_a = Air void content, %

V_{beff} = Effective bitumen content, % by volume

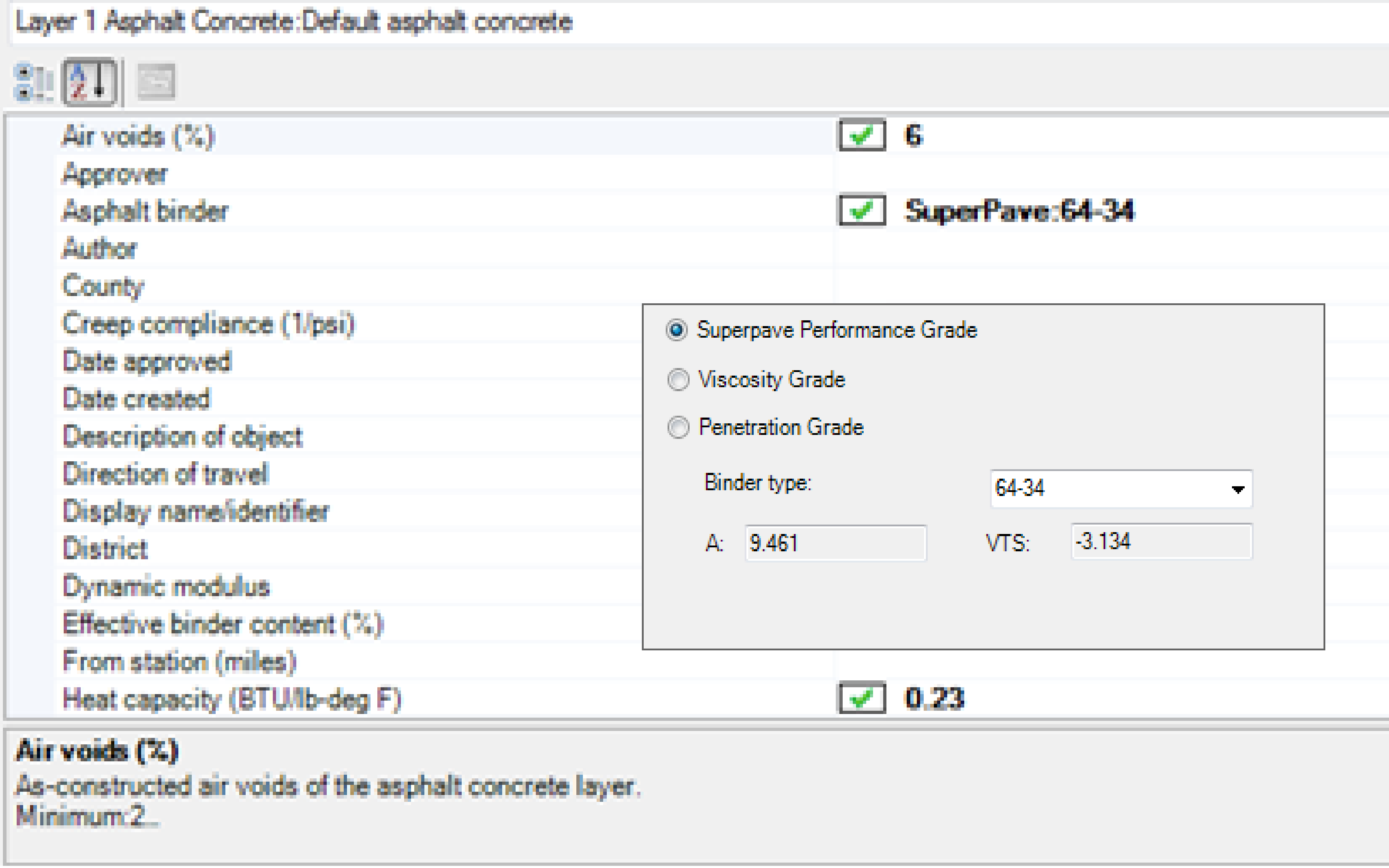
ρ_{34} = Cumulative % retained on the 19-mm sieve

ρ_{38} = Cumulative % retained on the 9.5-mm sieve

ρ_4 = Cumulative % retained on the 4.76-mm sieve

ρ_{200} = % passing the 0.075-mm sieve

Simplified Asphalt Materials Inputs (Level 3)



Layer 1 Asphalt Concrete:Default asphalt concrete

Air voids (%)	✓ 6
Approver	
Asphalt binder	✓ SuperPave:64-34
Author	
County	
Creep compliance (1/psi)	
Date approved	
Date created	
Description of object	
Direction of travel	
Display name/identifier	
District	
Dynamic modulus	
Effective binder content (%)	
From station (miles)	
Heat capacity (BTU/lb-deg F)	✓ 0.23

● Superpave Performance Grade

○ Viscosity Grade

○ Penetration Grade

Binder type: 64-34

A: 9.461

VTS: -3.134

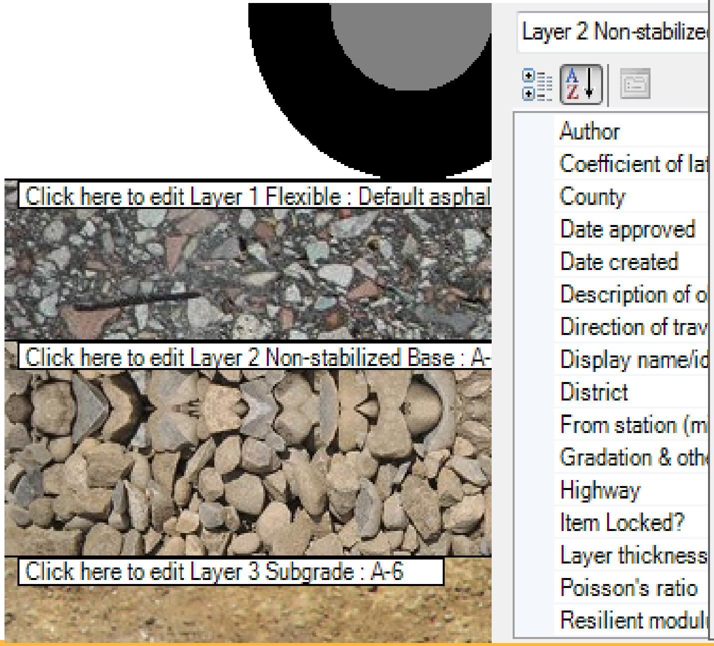
Air voids (%)

As-constructed air voids of the asphalt concrete layer.
Minimum:2...

Simplified Unbound Base/ Soil Inputs

Estimate resilient

- CBR,
- R-Value, or
- Dynamic Cone
- **Soil Classifica**



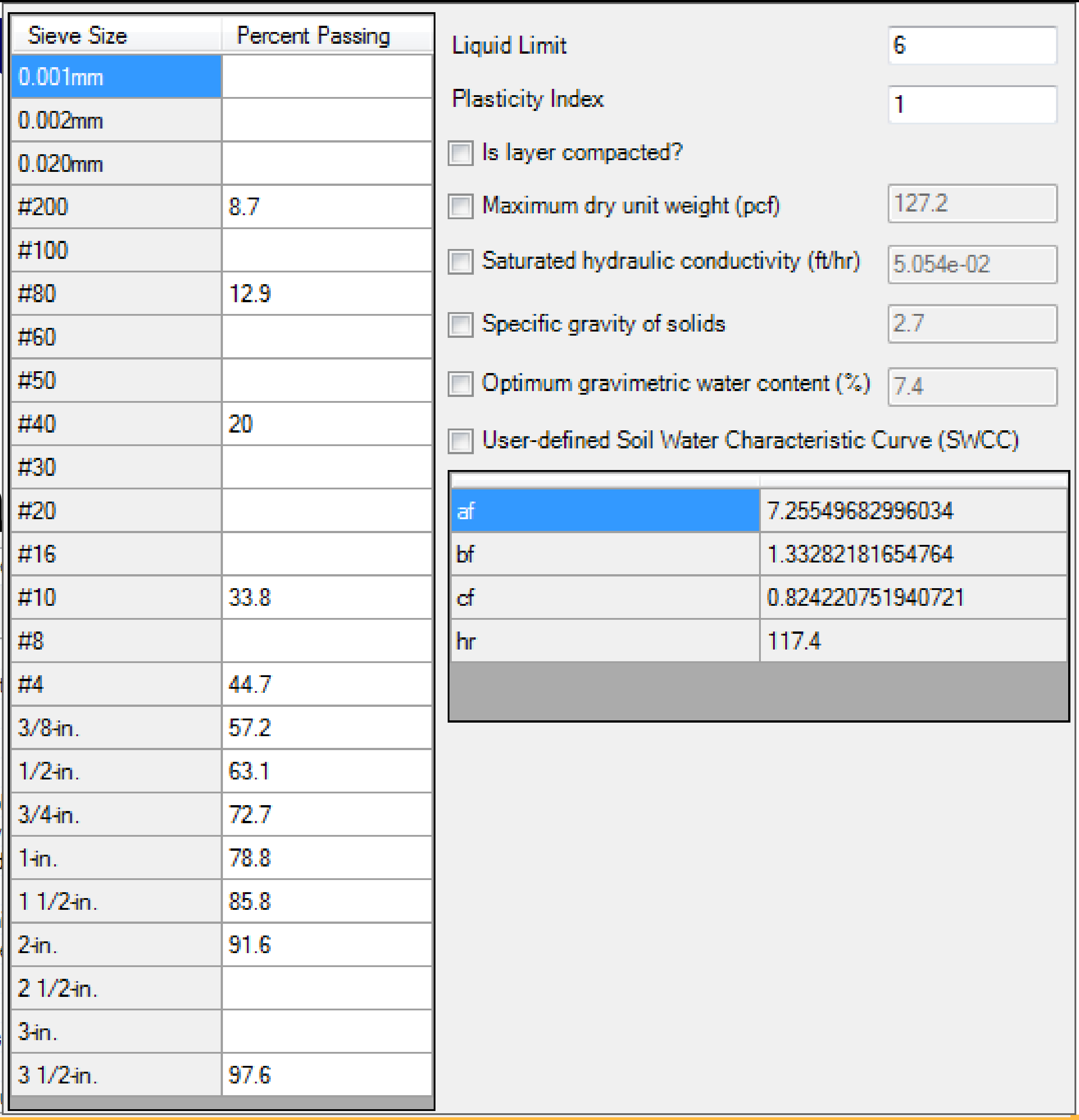
Click here to edit Layer 1 Flexible : Default asphal

Click here to edit Layer 2 Non-stabilized Base : A-

Click here to edit Layer 3 Subgrade : A-6

Layer 2 Non-stabilize

- Author
- Coefficient of lat
- County
- Date approved
- Date created
- Description of o
- Direction of trav
- Display name/id
- District
- From station (m
- Gradation & othe
- Highway
- Item Locked?
- Layer thickness
- Poisson's ratio
- Resilient moduli



Sieve Size	Percent Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20
#30	
#20	
#16	
#10	33.8
#8	
#4	44.7
3/8-in.	57.2
1/2-in.	63.1
3/4-in.	72.7
1-in.	78.8
1 1/2-in.	85.8
2-in.	91.6
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Liquid Limit: 6

Plasticity Index: 1

☐ Is layer compacted?

☐ Maximum dry unit weight (pcf): 127.2

☐ Saturated hydraulic conductivity (ft/hr): 5.054e-02

☐ Specific gravity of solids: 2.7

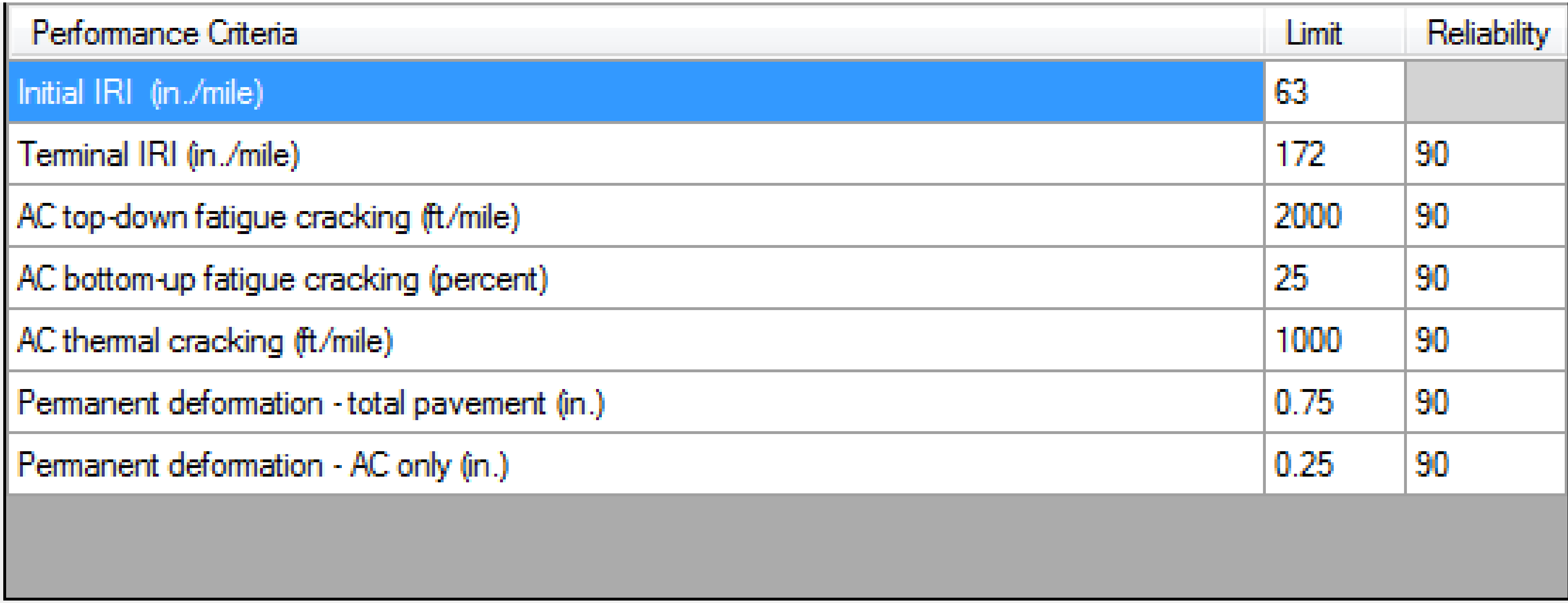
☐ Optimum gravimetric water content (%): 7.4

☐ User-defined Soil Water Characteristic Curve (SWCC)

af	7.25549682996034
bf	1.33282181654764
cf	0.824220751940721
hr	117.4

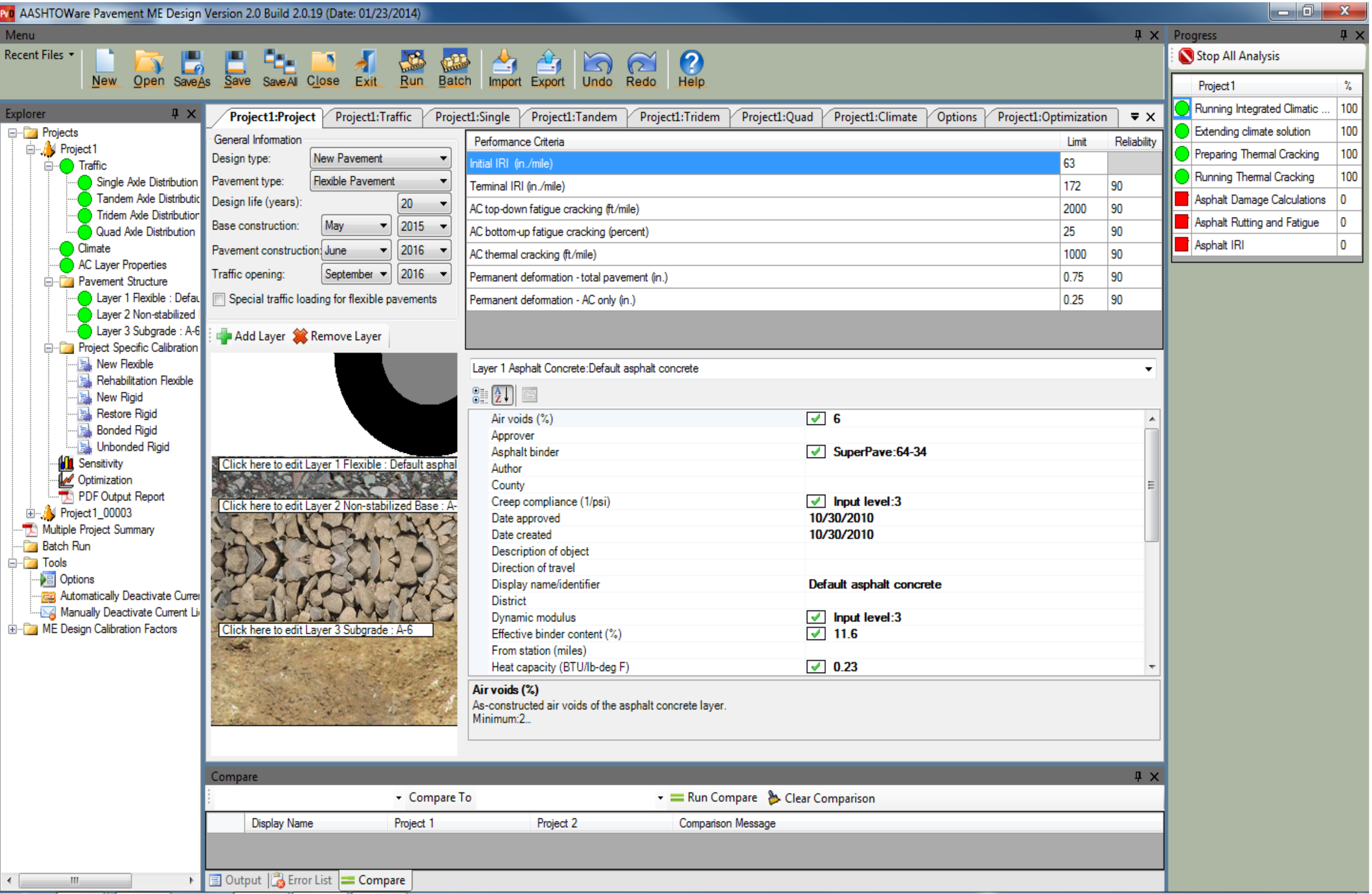
Performance Criteria

- Threshold Levels
- Reliability Levels



Performance Criteria	Limit	Reliability
Initial IRI (in./mile)	63	
Terminal IRI (in./mile)	172	90
AC top-down fatigue cracking (ft/mile)	2000	90
AC bottom-up fatigue cracking (percent)	25	90
AC thermal cracking (ft/mile)	1000	90
Permanent deformation - total pavement (in.)	0.75	90
Permanent deformation - AC only (in.)	0.25	90

AASHTOWare Pavement ME Design Software



AASHTOWare Pavement ME Design Version 2.0 Build 2.0.19 (Date: 01/23/2014)

General Information

Design type:	New Pavement
Pavement type:	Flexible Pavement
Design life (years):	20
Base construction:	May 2015
Pavement construction:	June 2016
Traffic opening:	September 2016

☐ Special traffic loading for flexible pavements

Performance Criteria	Limit	Reliability
Initial IRI (in./mile)	63	
Terminal IRI (in./mile)	172	90
AC top-down fatigue cracking (ft/mile)	2000	90
AC bottom-up fatigue cracking (percent)	25	90
AC thermal cracking (ft/mile)	1000	90
Permanent deformation - total pavement (in.)	0.75	90
Permanent deformation - AC only (in.)	0.25	90

Layer 1 Asphalt Concrete:Default asphalt concrete

Air voids (%)	☑ 6
Approver	
Asphalt binder	☑ SuperPave:64-34
Author	
County	
Creep compliance (1/psi)	☑ Input level:3
Date approved	10/30/2010
Date created	10/30/2010
Description of object	
Direction of travel	
Display name/identifier	Default asphalt concrete
District	
Dynamic modulus	☑ Input level:3
Effective binder content (%)	☑ 11.6
From station (miles)	
Heat capacity (BTU/lb-deg F)	☑ 0.23

Air voids (%)
As-constructed air voids of the asphalt concrete layer.
Minimum:2...

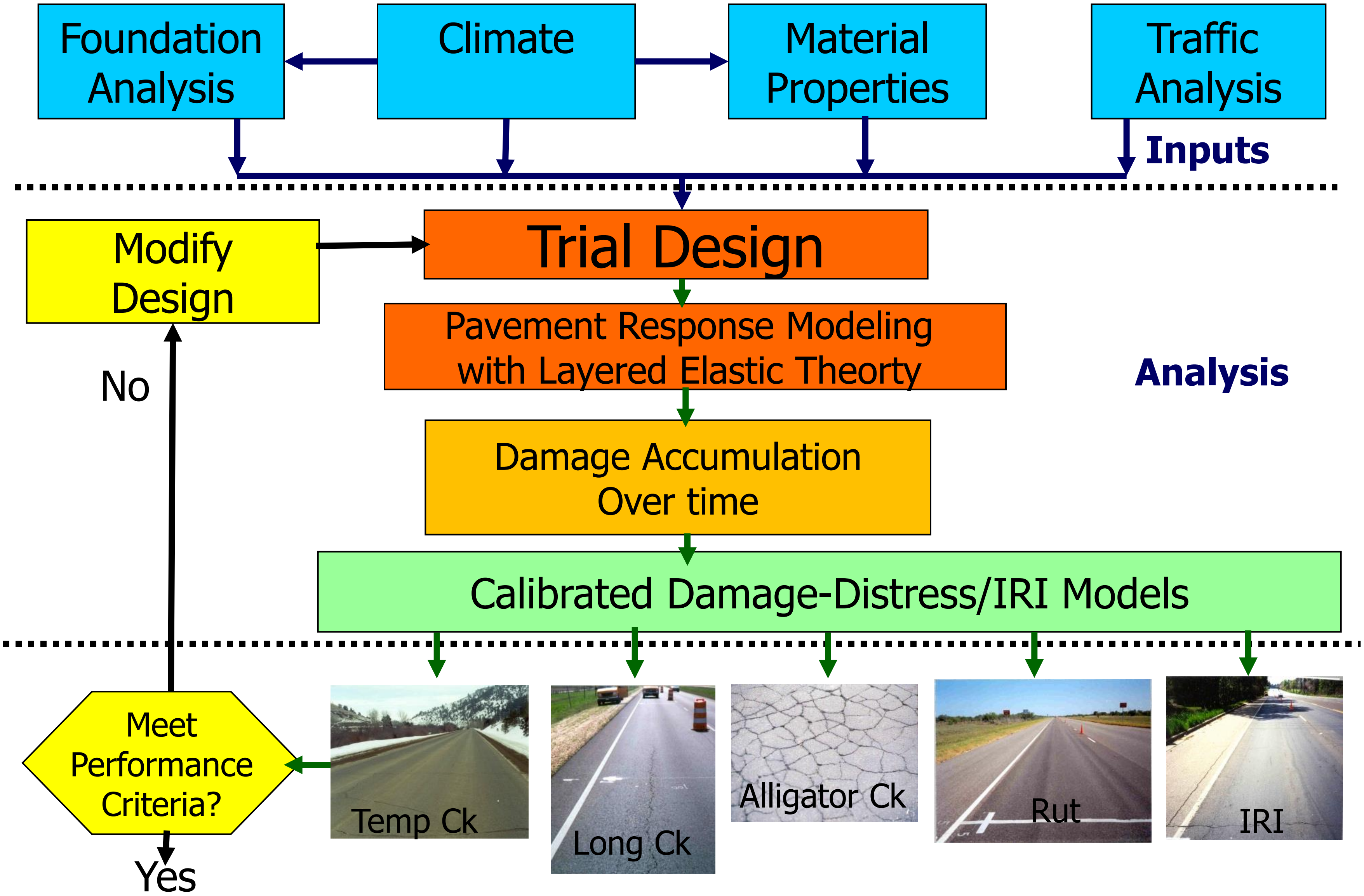
Display Name	Project 1	Project 2	Comparison Message

Progress

Stop All Analysis

Project1	%
● Running Integrated Climatic ...	100
● Extending climate solution	100
● Preparing Thermal Cracking	100
● Running Thermal Cracking	100
🟥 Asphalt Damage Calculations	0
🟥 Asphalt Rutting and Fatigue	0
🟥 Asphalt IRI	0

Design Process



Foundation Analysis

Climate

Material Properties

Traffic Analysis

Inputs

Trial Design

Modify Design

Pavement Response Modeling with Layered Elastic Theorty

Analysis

Damage Accumulation Over time

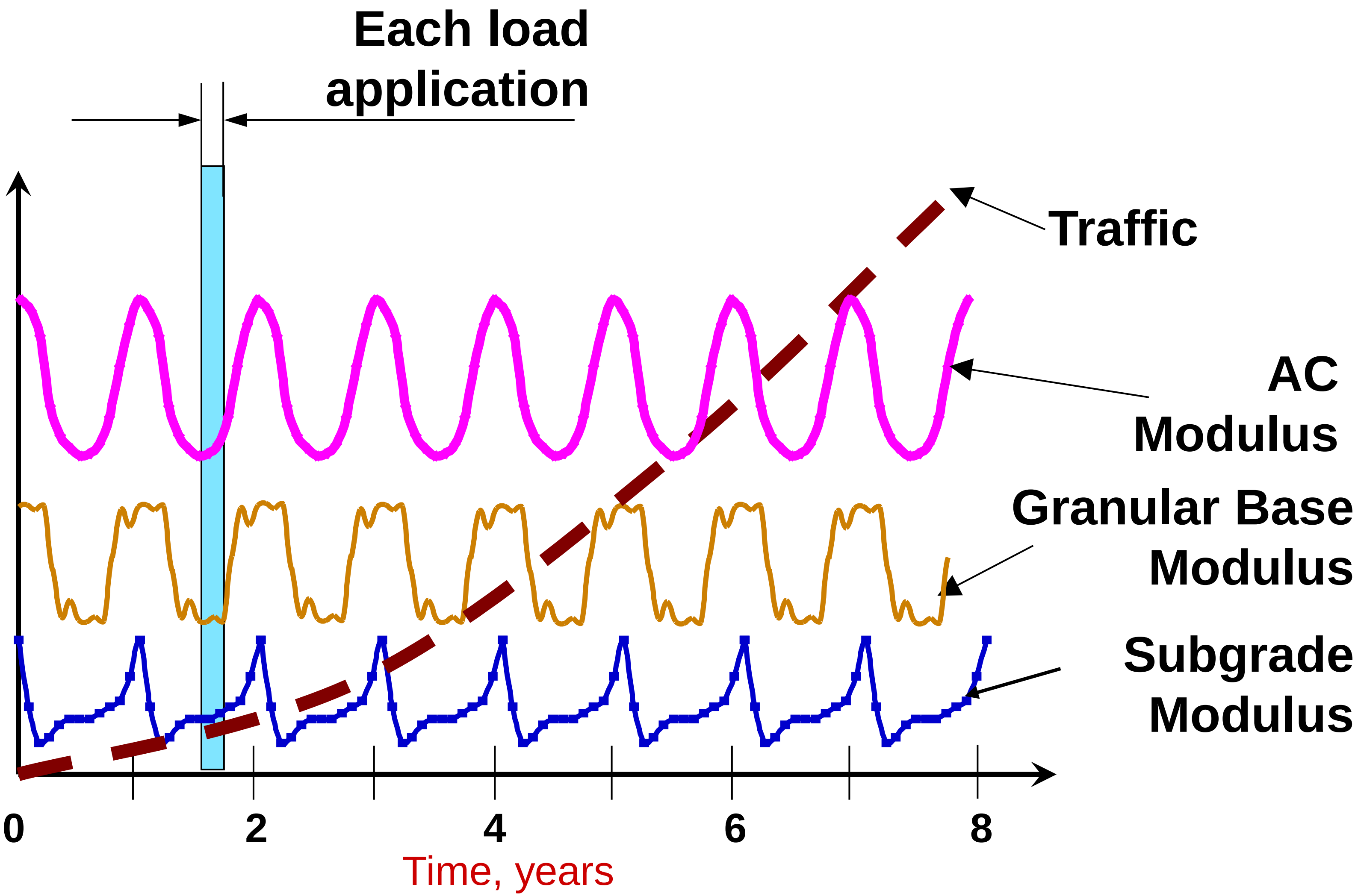
Calibrated Damage-Distress/IRI Models

No

Meet Performance Criteria?

Yes

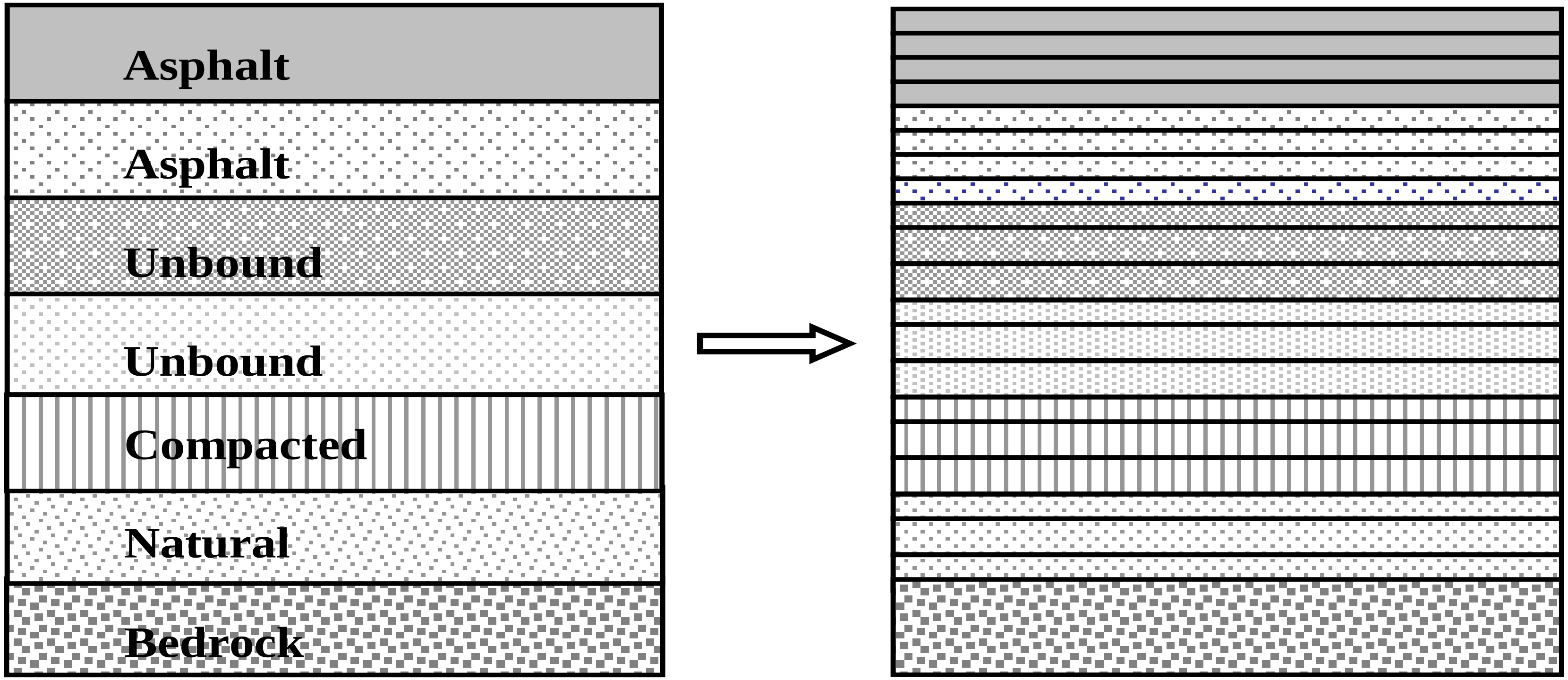
Annual Modulus Variability



Structural Analysis

Pavement Structure

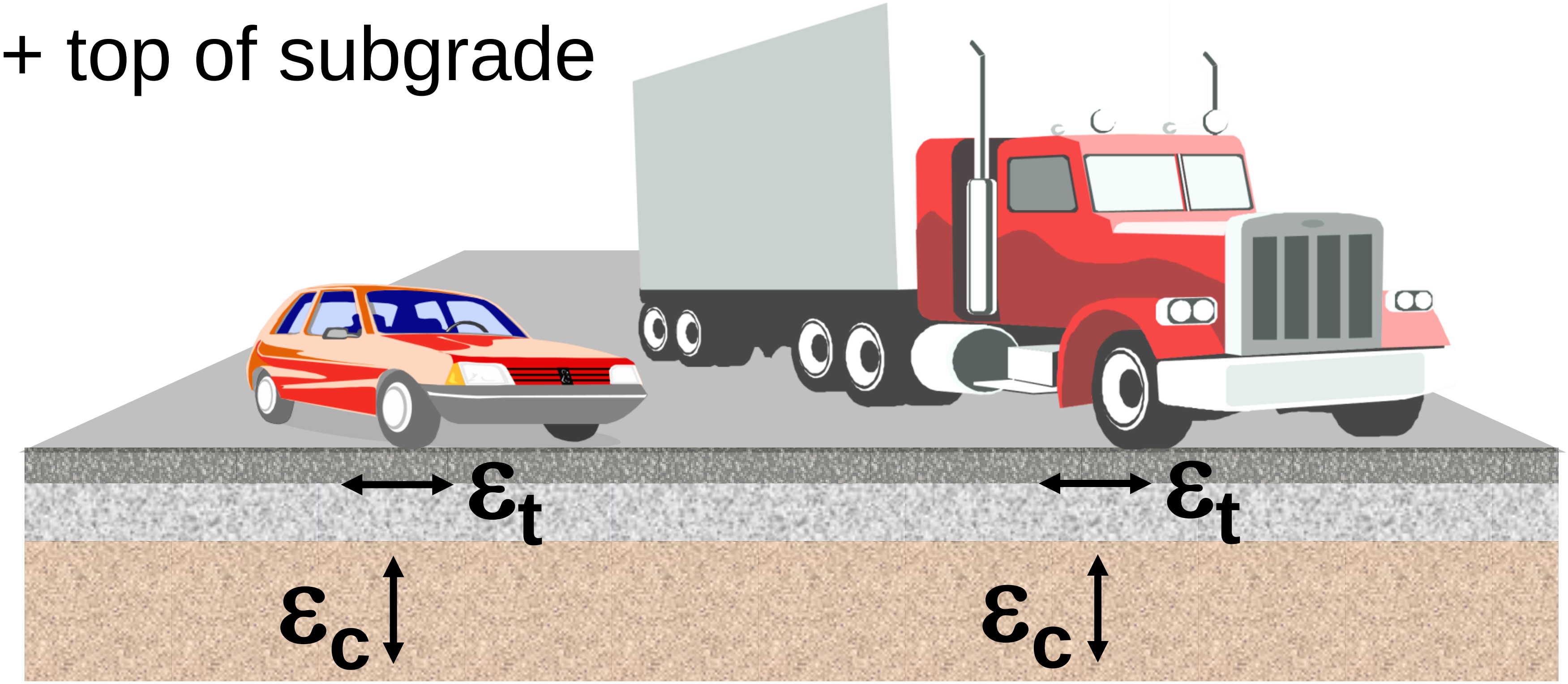
Layered Elastic Model



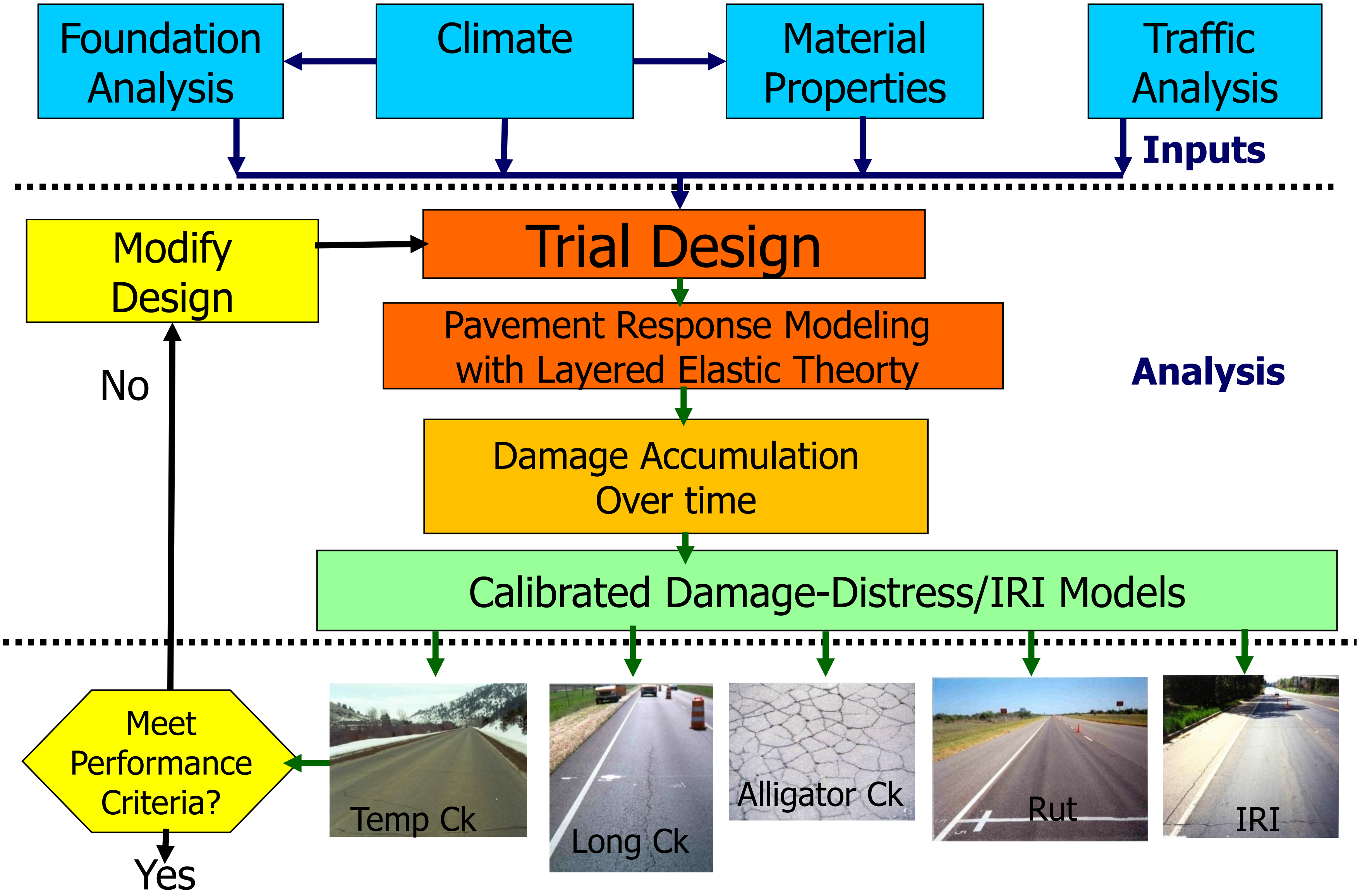
Structural Analysis (cont.)

- Critical structural response
- Cracking: ε_t at surface + bottom of all bound layers
- Rutting: ε_c at mid-thickness of all layers

+ top of subgrade



Design Process



Foundation Analysis

Climate

Material Properties

Traffic Analysis

Inputs

Trial Design

Modify Design

Pavement Response Modeling with Layered Elastic Theorty

Analysis

Damage Accumulation Over time

Calibrated Damage-Distress/IRI Models

No

Meet Performance Criteria?

Yes

Temp Ck

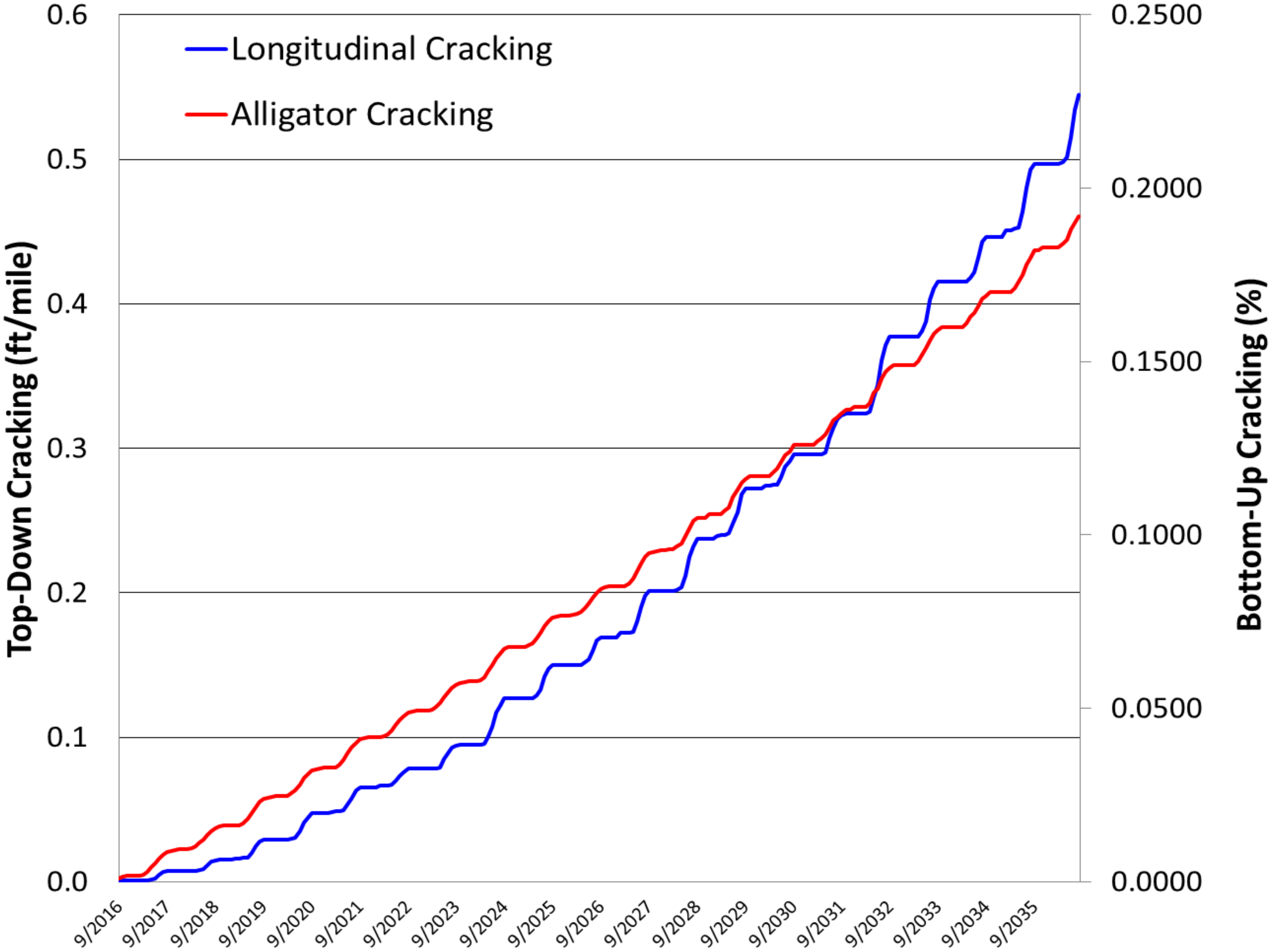
Long Ck

Alligator Ck

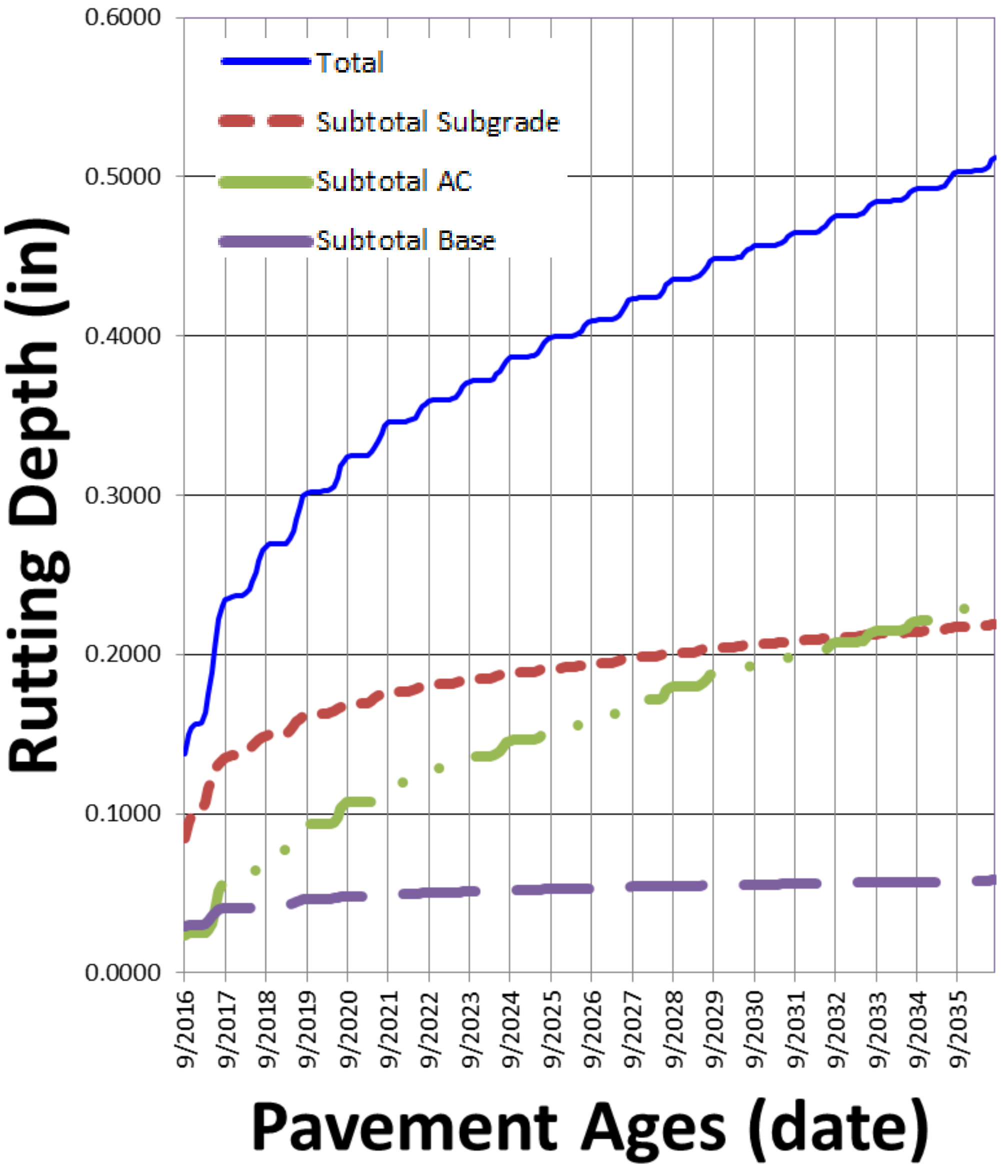
Rut

IRI

Example Fatigue Cracking Prediction

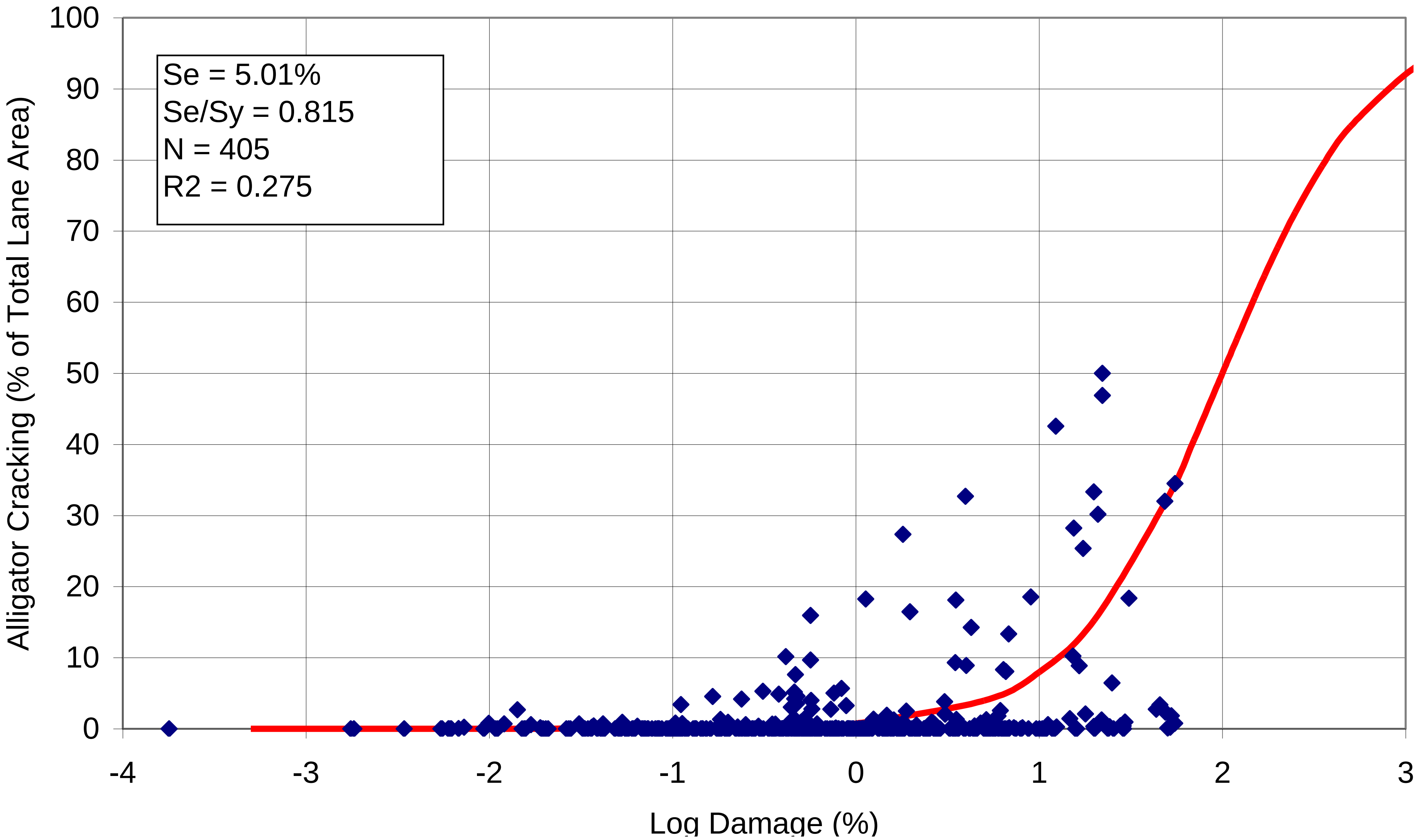


Rutting Model Prediction

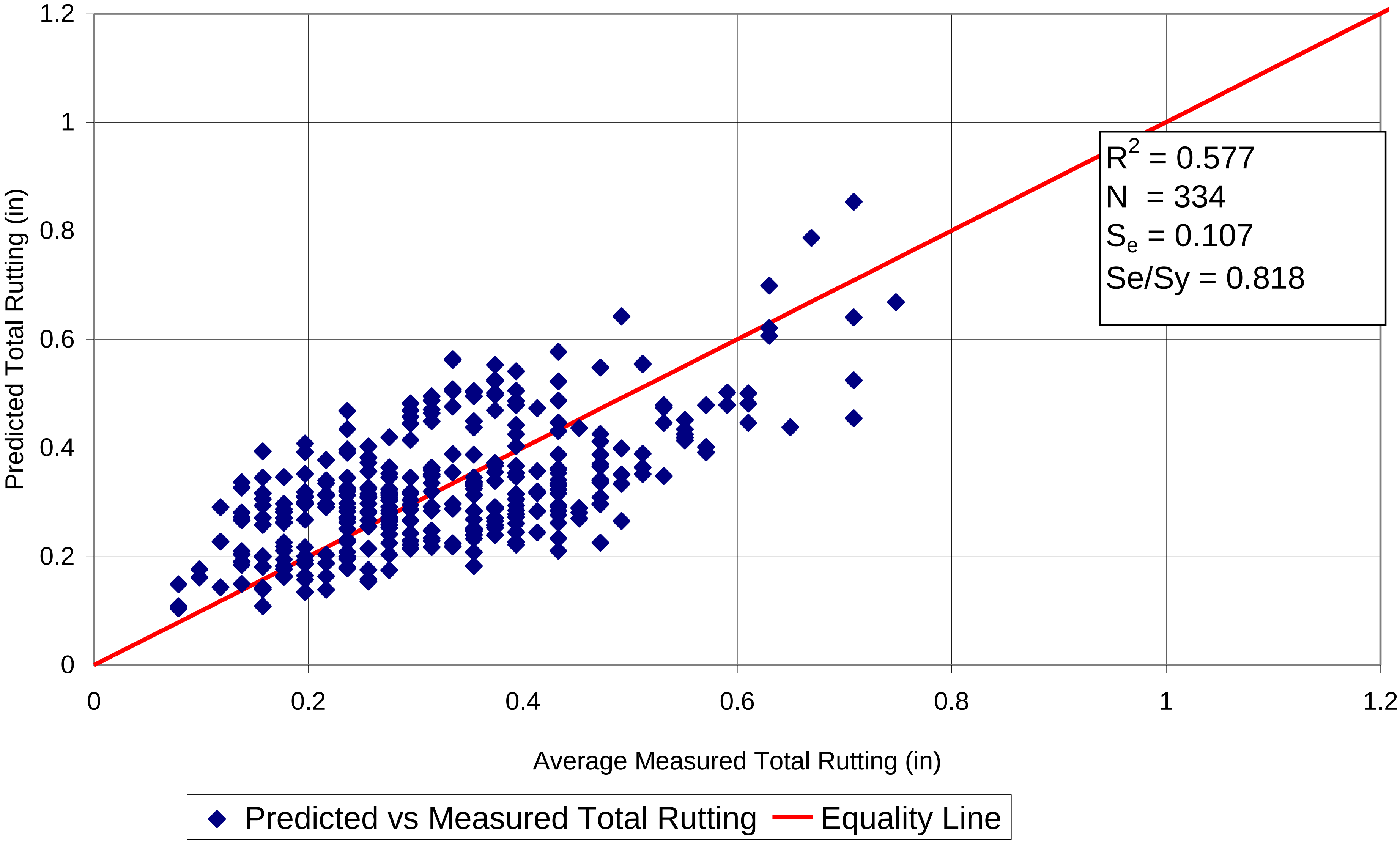


Model Calibration

Calibrated HMA Fatigue Model



Calibrated Rutting Model

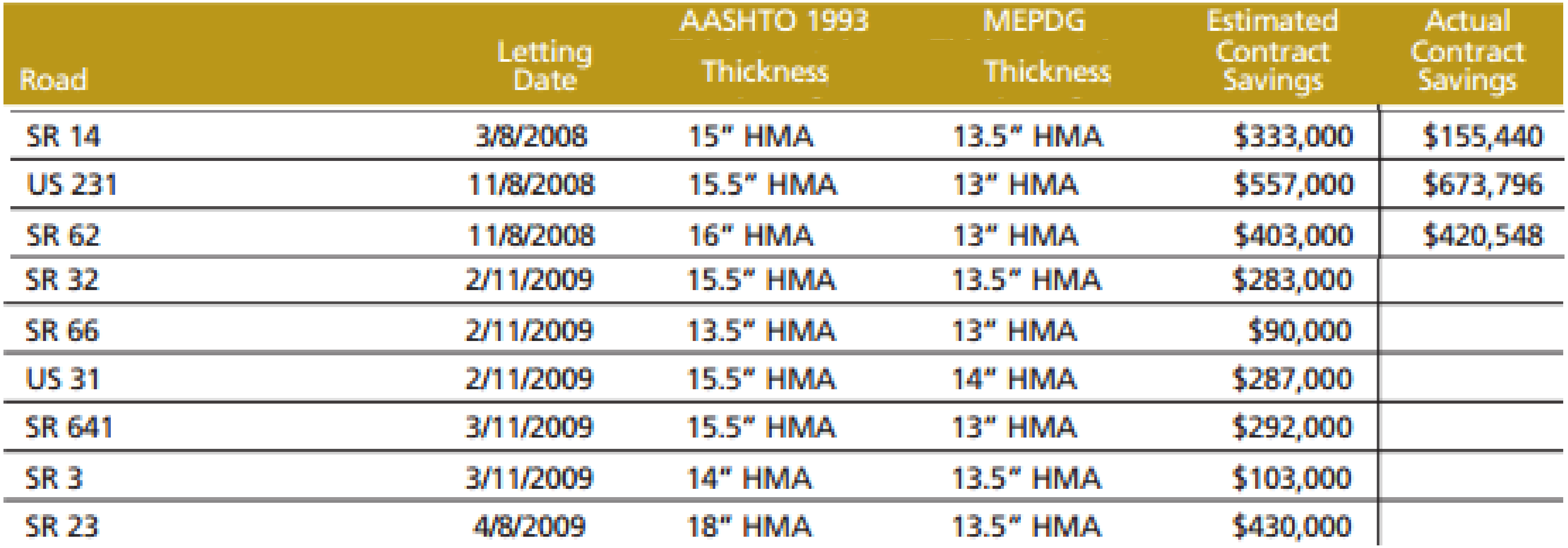


$R^2 = 0.577$
N = 334
$S_e = 0.107$
Se/Sy = 0.818

Benefits of MEPDG

- Accounts for many factors that change over time (traffic, climate, materials)
- Allows the prediction of key distress types as well as roughness over time
- Improved traffic characterization
- Improved structural modeling capabilities
- Improved materials characterization

Benefits of MEPDG – Indiana DOT



Road	Letting Date	AASHTO 1993 Thickness	MEPDG Thickness	Estimated Contract Savings	Actual Contract Savings
SR 14	3/8/2008	15" HMA	13.5" HMA	$333,000	$155,440
US 231	11/8/2008	15.5" HMA	13" HMA	$557,000	$673,796
SR 62	11/8/2008	16" HMA	13" HMA	$403,000	$420,548
SR 32	2/11/2009	15.5" HMA	13.5" HMA	$283,000	
SR 66	2/11/2009	13.5" HMA	13" HMA	$90,000	
US 31	2/11/2009	15.5" HMA	14" HMA	$287,000	
SR 641	3/11/2009	15.5" HMA	13" HMA	$292,000	
SR 3	3/11/2009	14" HMA	13.5" HMA	$103,000	
SR 23	4/8/2009	18" HMA	13.5" HMA	$430,000	

Asphalt thickness is reduced by 40 to 110 mm!

From Nantang (2010), http://onlinepubs.trb.org/onlinepubs/trnews/trnews271rpo.pdf

Conclusions

- **M-E design procedures are “Comprehensive” design procedures, or Not Just Thickness!**
- M-E models directly consider true effects and interactions of inputs on structural performance
- Design optimization possible where all distress types are minimized!
- **M-E design procedures are** more complex than empirical design
- Use of software and user training is required