Beta Testing and Validation of HMA PRS

NCHRP 9-22 WEBINAR

December 15, 2010

Introduction to Project

- Project Team
- Specification Developments
  - Materials and Method Specifications
  - Performance Based Specifications
  - Performance Related Specifications
- NCHRP 9-22
  - Project history
  - Objectives

Project Team

- **Fugro Consultants, Inc., Austin, TX**
  - Prime contractor and project management
  - Manual of Practice of the HMA PRS
  - Software de-bugging
- **Arizona State University**
  - Technical program development
  - Spreadsheet solution for the three MEPDG distresses
  - Software de-bugging
- **Transmetric America Inc.**
  - C++ Software Development lead
  - Users Manual

Specification Development

- **Materials and Method Specifications**
  - **Direct the contractor to use specified materials in definite proportions and specific types of equipment and methods to complete the work**
  - **Each step is usually directed by a representative of the agency**

Specification Development

- **Quality Assurance Specifications**
- **Materials and construction (M&C) variables used in process control and acceptance**
- **HMA volumetric properties (air voids, asphalt content, aggregate gradation, etc.) are assumed to relate to performance**
- **These properties referred to as Acceptance Quality Characteristics (AQCs)**
- **Primarily tied to performance through intuition, engineering judgment, or both**

Specification Development

- **Performance Based Specifications (PBS)**
  - The AQCs of the mixture and the pavement are defined in terms of performance using *measured* fundamental engineering properties and prediction models
  - Specifications describe how the finished product should perform over time
  - Has had limited acceptance in the industry because of timely acceptance testing issues and with no consensus as to the performance time period

Specification Development

▪Performance Related Specification (PRS)

- **Similar to Performance Based Specifications**
- **AQCs are *correlated* to fundamental engineering characteristics and in turn to performance through prediction models**
- **Connection to performance through valid empirical or mechanistic prediction models**
- **Relationships between material properties such as HMA layer thickness, strength, and pavement distresses to fundamental engineering properties**

Specification Development

▪Performance Related Specification (PRS) con't

- Performance of the pavement predicted based on the as-designed and the as-constructed properties.
- Difference in predicted performance between the as-designed and as-constructed pavement is the basis calculating incentive/disincentive for contractors.

Performance Related Specifications

- In 1994 the FHWA funded the design, construction, and application of loads on a test track project, Westrack, that provided the basis for the development of a prototype PRS
- Quantified the effects of variation in materials and construction (M&C) properties on overall pavement performance

Performance Related Specifications

- The project team developed empirical relationships and formed the basis for the performance prediction models used in the supporting software, HMA Spec
- Limitations were identified in the HMA Spec software and project NCHRP 9-22 was initiated

NCHRP 9-22 Project History

- Awarded to Fugro Consultants LP (Fugro), October 2000
- Project Scope
  - Evaluate and refine the HMA PRS and supporting HMA Spec software
  - Calibrate and validate the Level I and II performance models
  - Develop a training course to assist the implementation of the HMA Spec software

NCHRP 9-22 Project History

- Scope modified in April 2001 to include the MEPDG Prediction Models
- Use the Mechanistic-Empirical (M-E) Design Guide Software produced in NCHRP Project 1-37A as the “engine” for performance prediction models in the HMA PRS.

NCHRP 9-22 Project History

- **Project "on hold" awaiting development of the MEPDG models**
- **MEPDG software "run times" for specification simulation were unacceptable**
- **Project "on hold" to resolve run time problem**

NCHRP 9-22 Project History

- Scope revised in 2005 to develop spreadsheet solutions
- Excel® based distress prediction model simulation runs were instantaneous
- Since Excel® software is "version dependent", decision made in 2006 to convert to C++ software

NCHRP 9-22 Project Objectives

- **Development of Spreadsheet Solutions (rutting, fatigue, thermal cracking)**
- **Preliminary integration of spreadsheet solutions into HMA Spec**
- **Rename software to Quality Related Specification (QRSS)**

NCHRP 9-22 Project Objectives, con't

- **Prepare QRSS alpha version**
- **Prepare and test QRSS beta version**
- **Final Report and presentation of results to the NCHRP Panel**

Arizona State University Presentation

TRB Webinar Series

A Rational Methodology to Assess Performance Related Pay Factors for Asphalt Pavements

Introduction and Overview

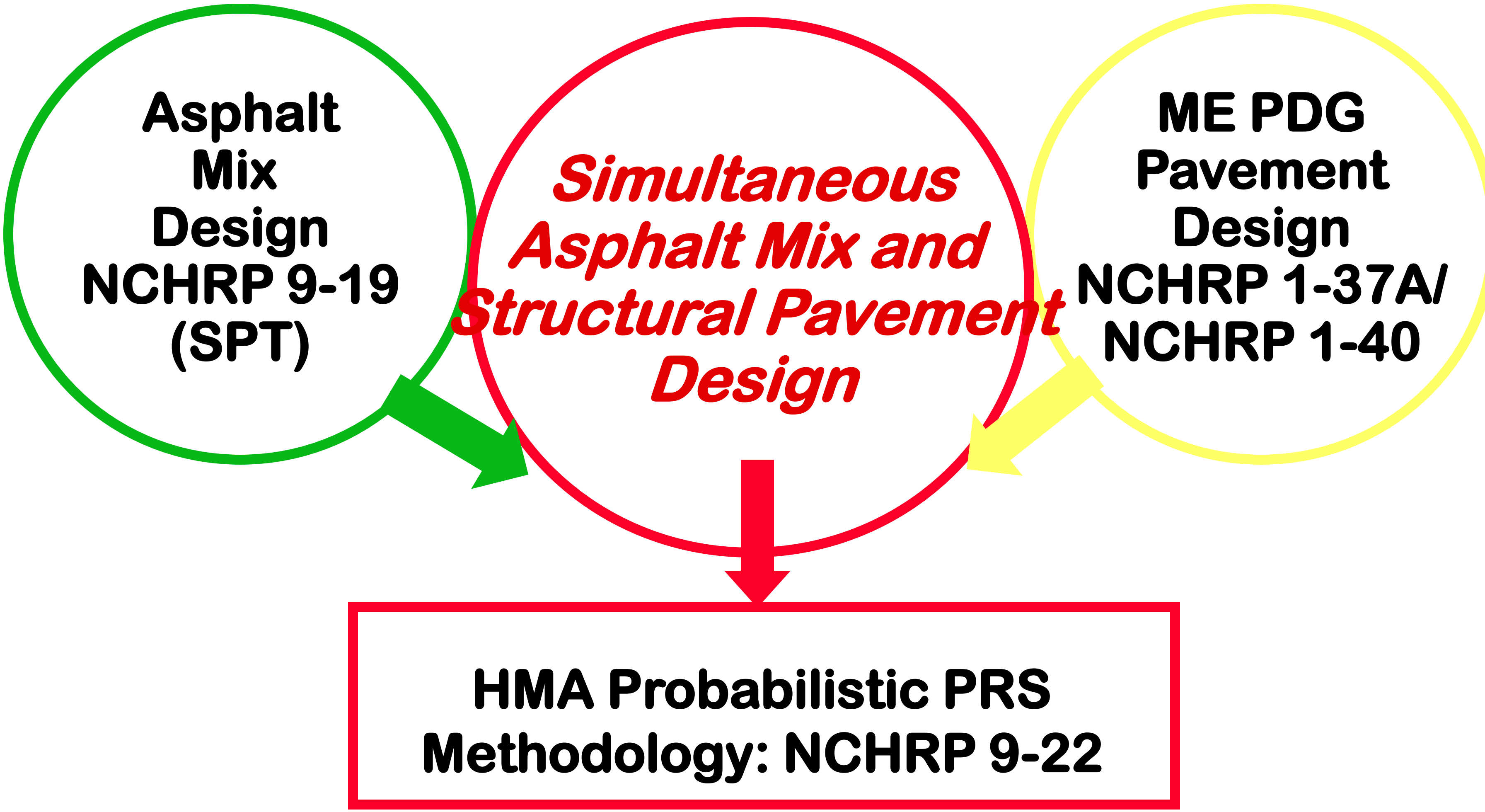
Dr. M. W. Witczak
Professor, Civil and Environmental Engineering

Program Demonstration

Dr. M. Jeong
Pavement Specialist
AMEC Earth and Environmentl, Inc.

STUDY PURPOSE

Ultimate Goal in Pavement Technology is…



ME-PDG Version 1.0 Solution-Necessity for Rapid Solution

No of Variables	Comp Hrs	Comp Days	Comp Yrs
6	32	1.33	-
10	512	21	.06
20	524,288	21,845	59.9
50	5.63xE^14	2.35xE^13	6.43xE^10
64	9.2xE^18	3.84xE^17	1.05xE^15

General Approach

- ***Develop Closed Form Solutions for Major M-E PDG HMAC Distress Types***
  - *HMAC Rutting*
  - *HMAC Fatigue (Alligator)*
  - *HMAC Thermal Fracture*
- ***Solutions Need to Be:***
  - *Rapid (Seconds or Minutes)*
  - *Highly Accurate When Compared to M-E PDG Solutions*
  - *Simple to Implement*
- ***Code Methodology***
  - *Spreadsheet to C++*

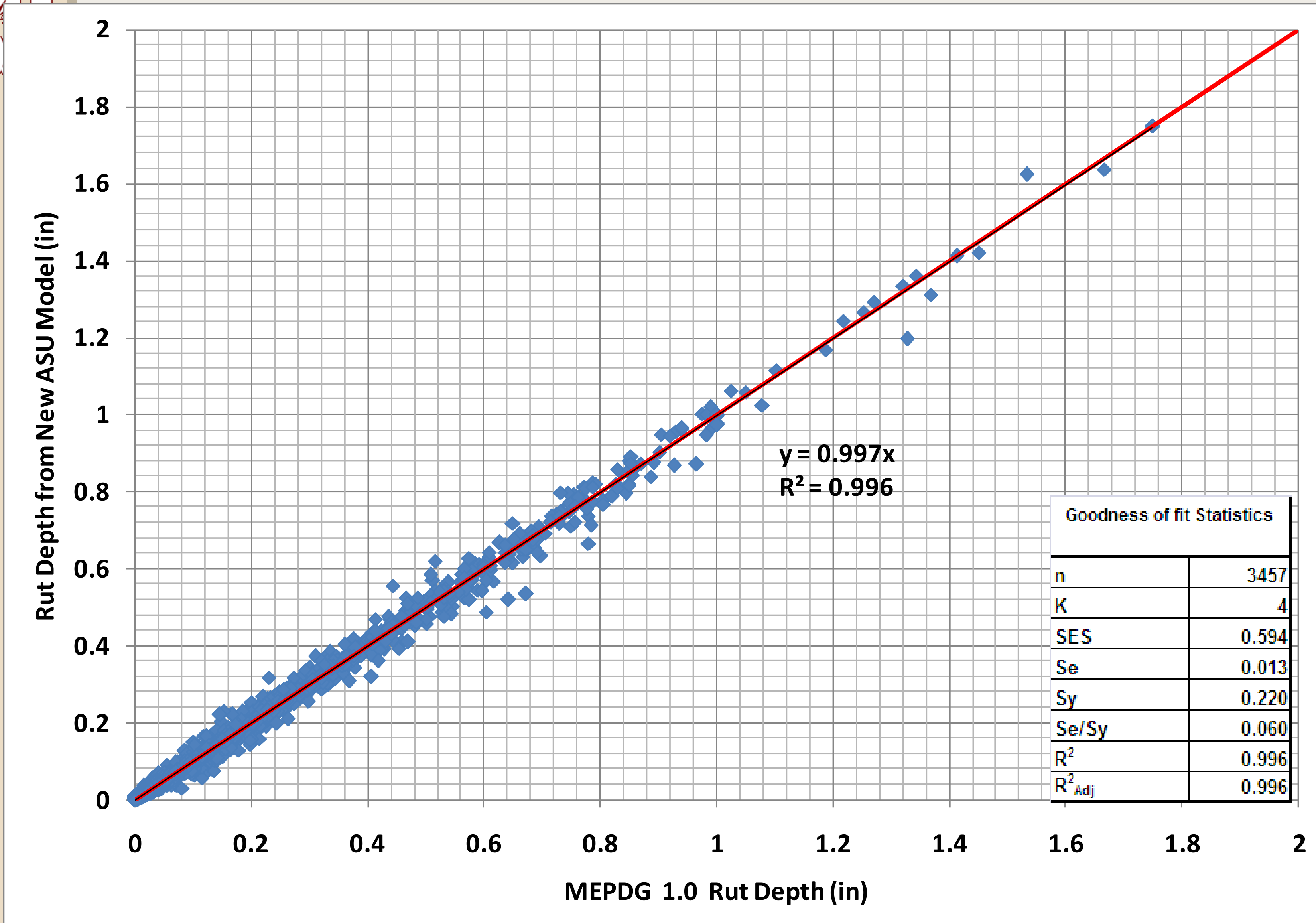
General Approach

- **Run simulation of M-E PDG**
  - Matrix of runs for all key variables
- **Develop accurate statistical closed form predicted model**
  - Damage M-E PDG ≈ Damage PM
- **Develop spreadsheet (Excel) system solution**
  - Deterministic Job Mix assessment vs. Plant Mix assessment.
- **Incorporate Probabilistic solution**
  - Probabilistic Job Mix assessment vs. Plant Mix assessment (Rosenblueth, Monte Carlo simulation, Taylor series).
- **Develop C++ user friendly program**
  - Insure that spreadsheet deterministic yields accurate solution to M-E PDG.

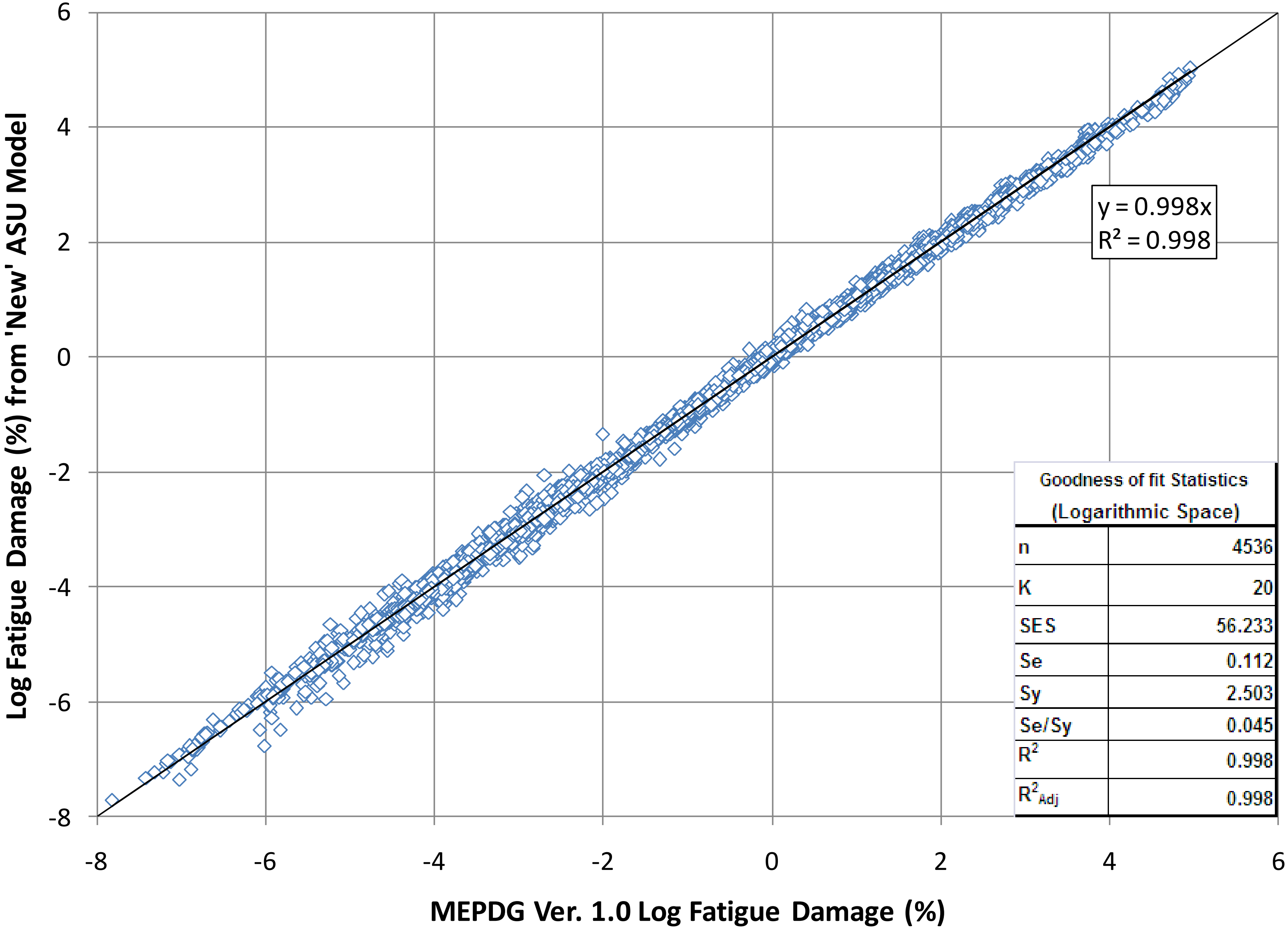
General Approach (Cont'd)

- Traffic is represented by ESALs.
- No Seasonal changes for unsaturated E (base/subbase/subgrade).
- PLD: Service Life Difference between Job Mix design (Lab) AC mix and Field (In-situ) AC mix
- Predicted Life Difference is the basis of the Pay Factors
- Deterministic and Probabilistic Analysis.
- Final Product :User Friendly C++ Code (Mimics AASHTO MEPDG)

Comparison of Rut Depth between MEPDG 1.0 and ASU Rutting Model

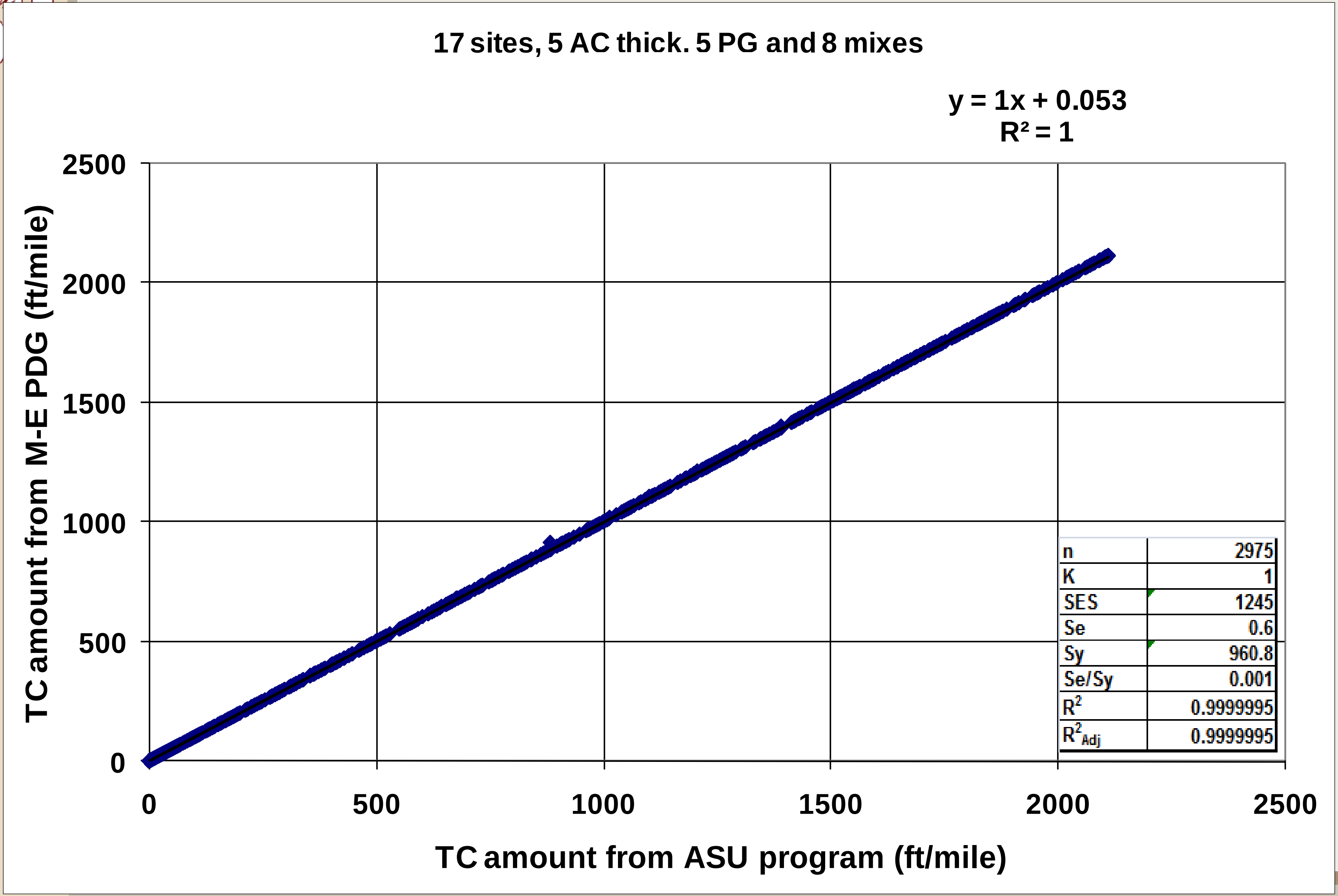


Comparison of Fatigue Damage between MEPDG 1.0 and ASU Fatigue Model



Goodness of fit Statistics (Logarithmic Space)	
n	4536
K	20
SES	56.233
Se	0.112
Sy	2.503
Se/Sy	0.045
R^2	0.998
R^2_{Adj}	0.998

Comparison of Thermal Cracking between MEPDG 1.0 and ASU Thermal Model



Effective Temperature for Fatigue Cracking (Cont'd)

$$T_{eff} = -1.016814\sqrt{f_{eff}} - 17.691387 + T'_f$$

→ *Based on 7776 M-E PDG Runs*

$$T'_f = 1.110(MAAT) + 1.254(\sigma_{MMAT}) - 1.132(Wind) + 0.337(Sunshine) + 0.071(Rainfall)$$

- ***T_{eff} = effective temperature for bottom-up fatigue cracking, °F***
- ***f_{eff} = effective frequency***
- ***T'_f = climatic factor***
- ***MAAT = mean annual air temperature, °F***
- ***σ_{MMAT} = standard deviation of the mean monthly air temperature within a given year, °F***
- ***Sunshine = mean annual sunshine, %***
- ***Wind = mean annual wind speed, mph***
- ***Rainfall = mean cumulative rainfall depth, inches***

Note that this climatic factor is the same for both AC rutting and Alligator Fatigue Cracking.

Effective AC Modulus (E^*_{eff})

$$\text{Log } E^*_{eff} = -1.249937 + 0.029232 \cdot p_{200} - 0.001767 \cdot (p_{200})^2 - 0.002841 \cdot p_4 - 0.058097 \cdot Va - 0.8022 \cdot \frac{Vb_{eff}}{(Vb_{eff} + Va)} + \frac{3.87197 - 0.0021 \cdot p_4 + 0.003958 \cdot p_{38} - 0.000017 \cdot (p_{38})^2 + 0.00547 \cdot p_{34}}{1 + e^{(-0.603313 - 0.31335 \cdot \log(f_{eff}) - 0.393532 \cdot \log(\eta_{T_{eff}}))}}$$

- E^*_{eff} = effective Asphalt Mix Dynamic Modulus, in 10^5 psi.
- η_{Teff} = bitumen viscosity in 10^6 poise (at effective temperature for fatigue).
- f_{eff} = effective loading frequency in Hz.
- Va = air voids in the mix, by volume
- Vbeff = % effective bitumen content, by volume
- p34 = % retained on the ¾ inch sieve, by total aggregate weight (cumulative)
- p38 = % retained on the 3/8-inch sieve, by total aggregate weight (cumulative)
- p4 = % retained on the No. 4 sieve, by total aggregate weight (cumulative)
- p200 = passing the No. 200 sieve, by total aggregate weight

Input Variables for Each Distress

- **Three INPUT parts**

1. **Initial User Input**
   - General and Basic information for the project

     (Project Info, Traffic, Climatic, Structure…)
2. **As-Design Job Mix Formula Input**
   - Mean and Standard Deviation of necessary variables for the Stochastic Analysis

     (Volumetric Properties, Gradation…)
3. **As-Constructed Data (each lot)**
   - Raw data collected from the field
   - From the raw data, the mean and standard deviation will be computed

Development of Probabilistic Based PRS Model Requirements

- ***As Built si^2 (Variance) of all Key Specific Mix and Pavement Cross Section Variables for a Unique Project in a Given Environment***
  - ***Mix Volumetrics (Va%, Vb%)***
  - ***Mix Gradation (P200, P4 etc..)***
  - ***PG Grade (Gb*, Viscosity, Pen)***
  - ***HMA Mass Density***
  - ***Pavement Cross Section (hac….)***

- ***Start Thinking of these Parameters for Two Conditions***
  - ***Lab or Job Mix Design (Demand Function)***
  - ***Actual Product Produced by Contractor in-Situ (Capacity Function)***

Job Mix Vs. Plant Produced Variability

Job Mix (Design) Formula – Demand Function	
$\mu_i = X_i$ X_i **(use Job Mix Formula)**	σ_i (use historical literature review for "typical" plant variability expected)

Plant Produced – Capacity Function	
$\mu_i = X_i$ X_i **(use Job Mix Formula)**	σ_i (use as produced variation of parameters from plant production)

Input Variables for Each Distress

❑ Critical Inputs for Probabilistic Analysis of JMF

Critical Inputs	Unit	Rutting		Fatigue .C.		Thermal C.	
		Mean	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
Target In-Situ Air Voids	**%**	T	H.V.	T	H.V.	T	H.V.
Effective Binder Content by Vol.	**%**	C	C	C	C	C	C
Cum. Retained 3/4	**%**	T	H.V.	T	H.V.		
Cum. Retained 3/8	**%**	T	H.V.	T	H.V.		
Cum. Retained #4	**%**	T	H.V.	T	H.V.		
Passing #200	**%**	T	H.V.	T	H.V.		
Gmm	**N/A**	D	H.V.	D	H.V.	D	H.V.
Gmb	**N/A**	D	H.V.	D	H.V.	D	H.V.
Gsb	**N/A**	D	H.V.	D	H.V.	D	H.V.

T = Transported from Initial Input

C = Computed by Other Variables

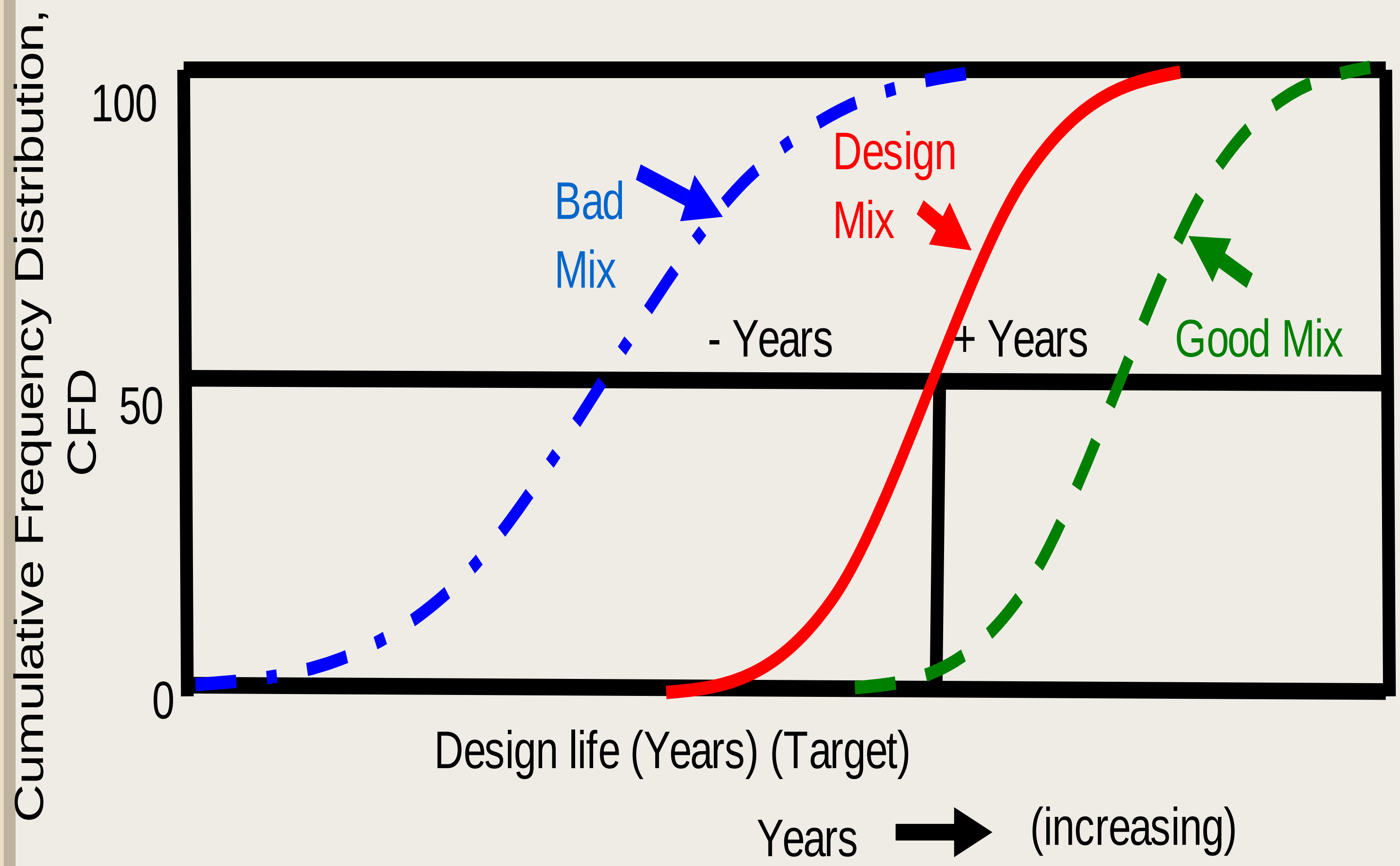
D = Direct User Input or Default Value

H.V. = Historical Value or User can input

Calculation of the Variance Associated with the Service Life

- *Up to 1000 Monte Carlo simulations are performed on the Witczak Dynamic Modulus Predictive equation.*
- *Each of the variables in the equation is treated as a random number following a Normal Probability distribution with a mean and standard deviation calculated from the statistical analysis of the field measured values for the as-constructed mix.*
- *For the JMF (JMD), historical (National or State) standard deviations of these variables are used.*
- *For the "As Produced" product, actual Lot-Project standard deviations of same key variables are used.*
- *The AC distress type mean and variance is then predicted based on these E* values from Monte Carlo simulation runs.*

Cumulative Frequency Distribution of the Service Life



Calculation of Predicted Life Difference (PLD)

- ***The program allows the user to select the PLD to be calculated using either one of the following methods:***

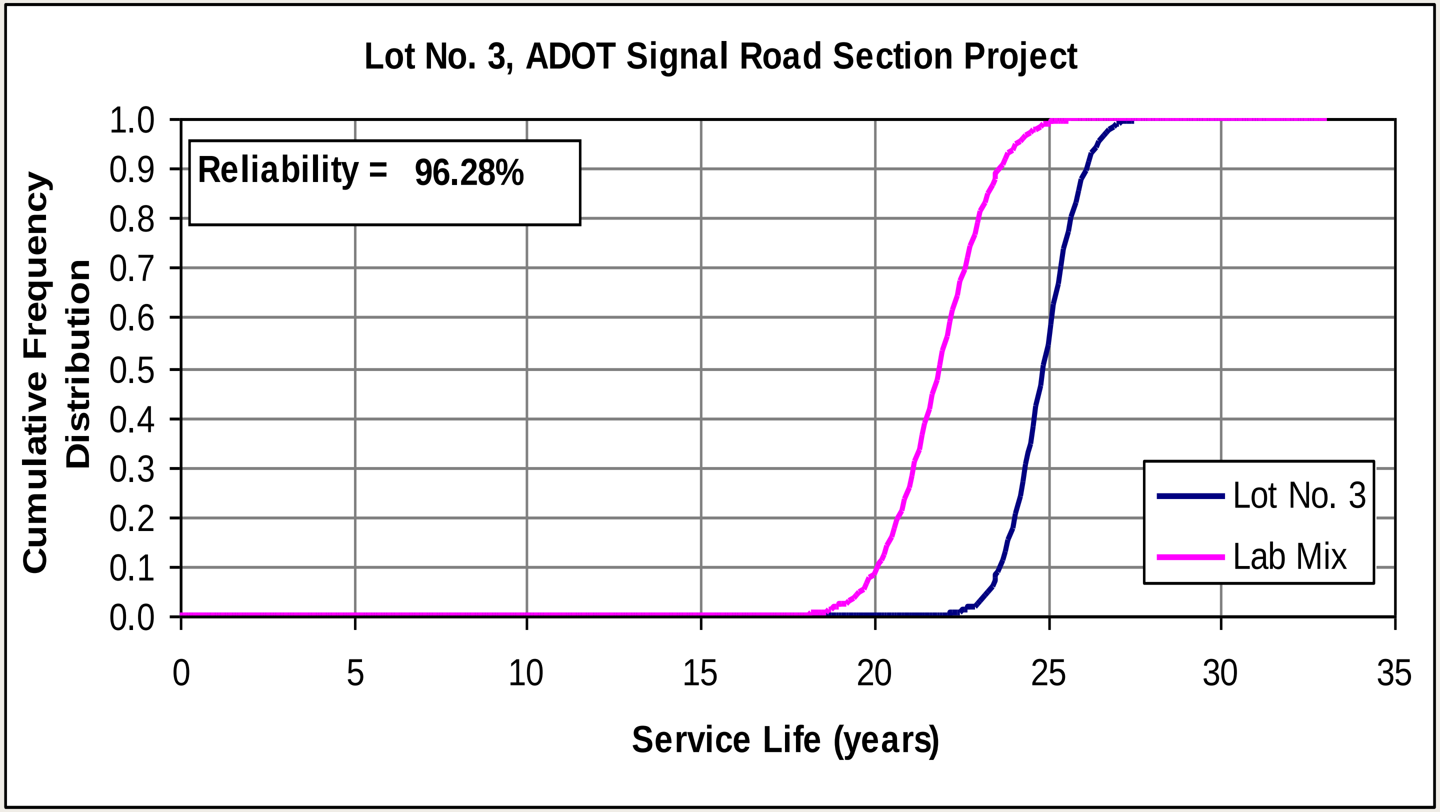
  a) PLD_T = (In Situ Mix Life - Target Life)

  In this case, the predicted life difference "PLD_T" is calculated as the average difference between the cumulative frequency distribution curve of the In Situ Mix Life and the constant Target Design Life.

  b) PLD_J = (In Situ Mix Life - JMF Life)

  In this case, the predicted life difference "PLD_J" is calculated as the average difference between the cumulative frequency distribution curves for the In Situ Mix Life and the Job Mix

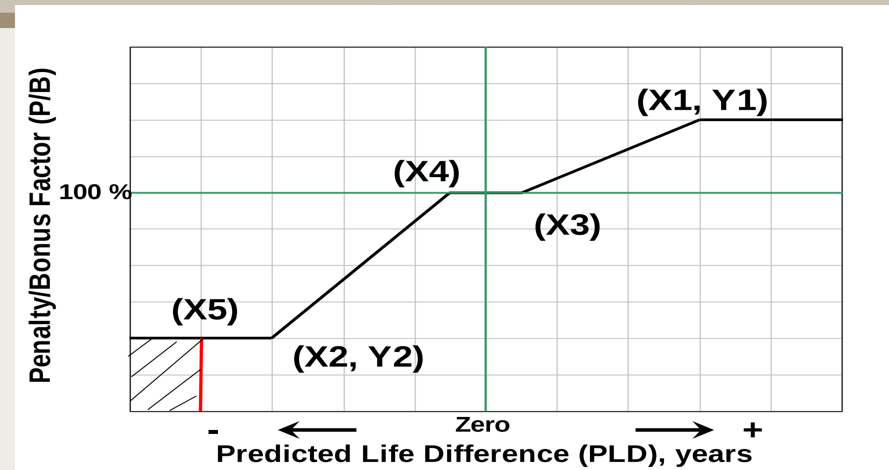
Example Comparison between Cumulative Distributions of Service Life Between Design and As Constructed Mix (Single Lot)

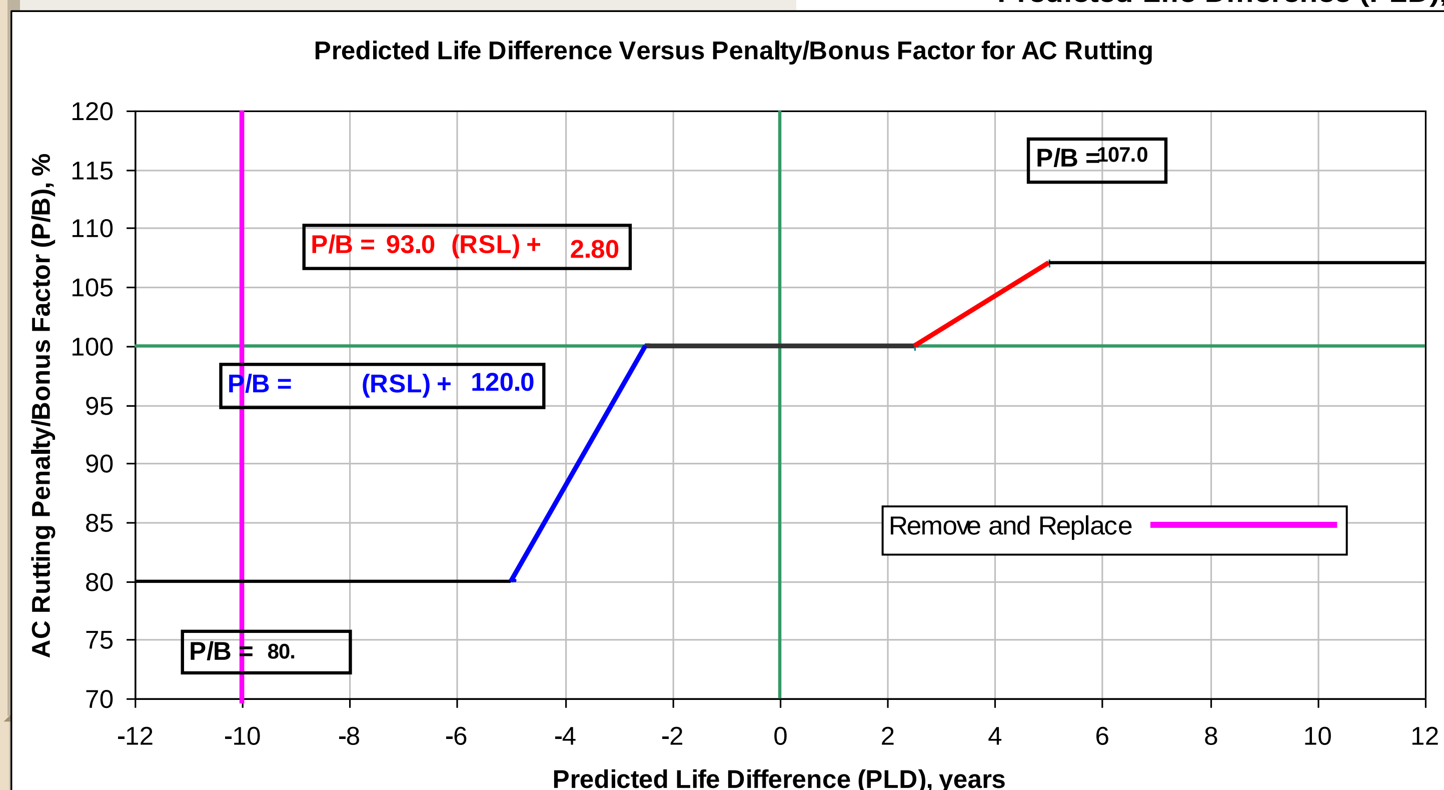


$$PLD_T = (\text{In Situ Mix Life} - \text{JMF Life})$$

Project Input Data (Cont's)

PAY ADJUSTMENT FACTOR (PF) DATA	
Max. Bonus (%), Y1	7
Max. Penalty (%), Y2	20
Max PLD (Years), X1	5
Min PLD (Years), X2	-5
PLD for no Bonus, X3	2.5
PLD for no Penalty, X4	-2.5
PLD for Remove and Replace, X5	-10





Revised Penalty Bonus Cost Equation

Final P/B Cost

P/B Cost for IRI

$$C_{PB} = C_{PB1} + C_{PB2}$$

P/B Cost for three distresses

$$C_{PB1} = \beta_r \left\{ P_{r\_s}\left(\frac{\sum n_k (P/B)_{rk}}{N_{t(AC\_s)}} - 1 \right) C_{AC\_s} + P_{r\_m}\left(\frac{\sum n_l (P/B)_{rl}}{N_{t(AC\_m)}} - 1 \right) C_{AC\_m} + P_{r\_b}\left(\frac{\sum n_m (P/B)_{rm}}{N_{t(AC\_b)}} - 1 \right) C_{AC\_b} \right\}$$

$$+ \beta_f \left(\frac{\sum n_m (P/B)_{fm}}{N_{t(AC\_b)}} - 1 \right) C_{AC\_b} + \beta_{tf} \left(\frac{\sum n_k (P/B)_{tfk}}{N_{t(AC\_s)}} - 1 \right) C_{AC\_s}$$

For Three Distresses (Three AC Layer System)

$$C_{PB2} = \sum_{i=1}^{L} \sum_{j=1}^{Lp/0.1} (P/B)_{IRIij}$$

For IRI

FUGRO

Mode I Output

MODE I : Simultaneous Asphalt Mix and Pavement Structural Design (M-E PDG Shortcut)

SUMMARY OF PROGRAM INPUT

PROJECT GENERAL INPUT DATA

Project ID	H492001C
Project Location	Signal Road Station
Date of Analysis	1/16/2007
Operator's Name	Ajatshatru Patni

PROJECT TRAFFIC AND CLIMATIC CONDITION

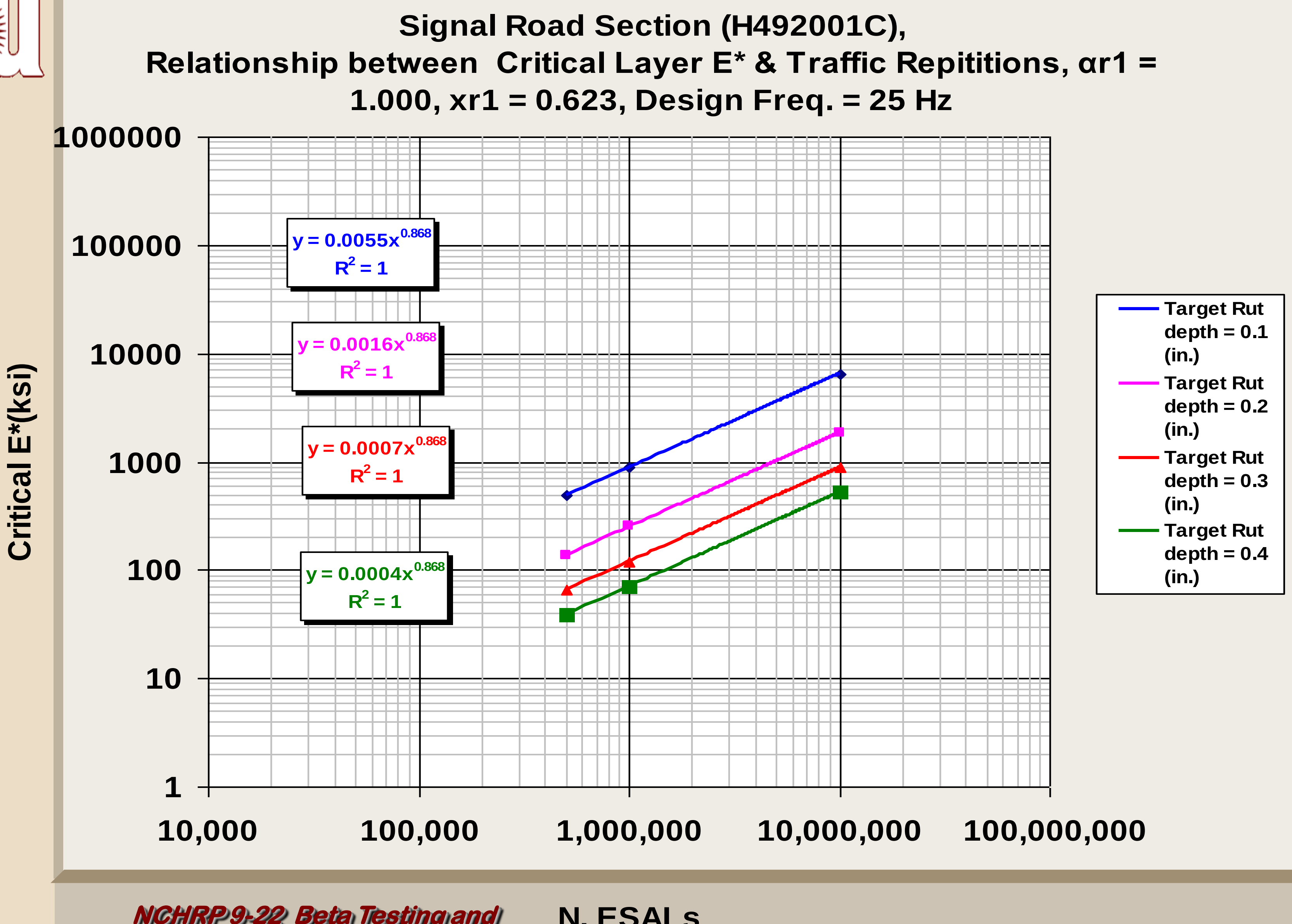
Desired Speed (mph)	65
Desired Traffic (ESALs)	5,900,000
Mean Annual Air Temperature (oF)	57.86
Mean Monthly Air Temp St. Dev. (oF)	18.80
Mean Annual Wind Speed (mph)	8.24
Mean Annual Sunshine (%)	89.41
Annual Cummulative Rainfall Depth (in)	8.23

SUMMARY OF PROGRAM OUTPUT **(Deterministic Solution Results)**

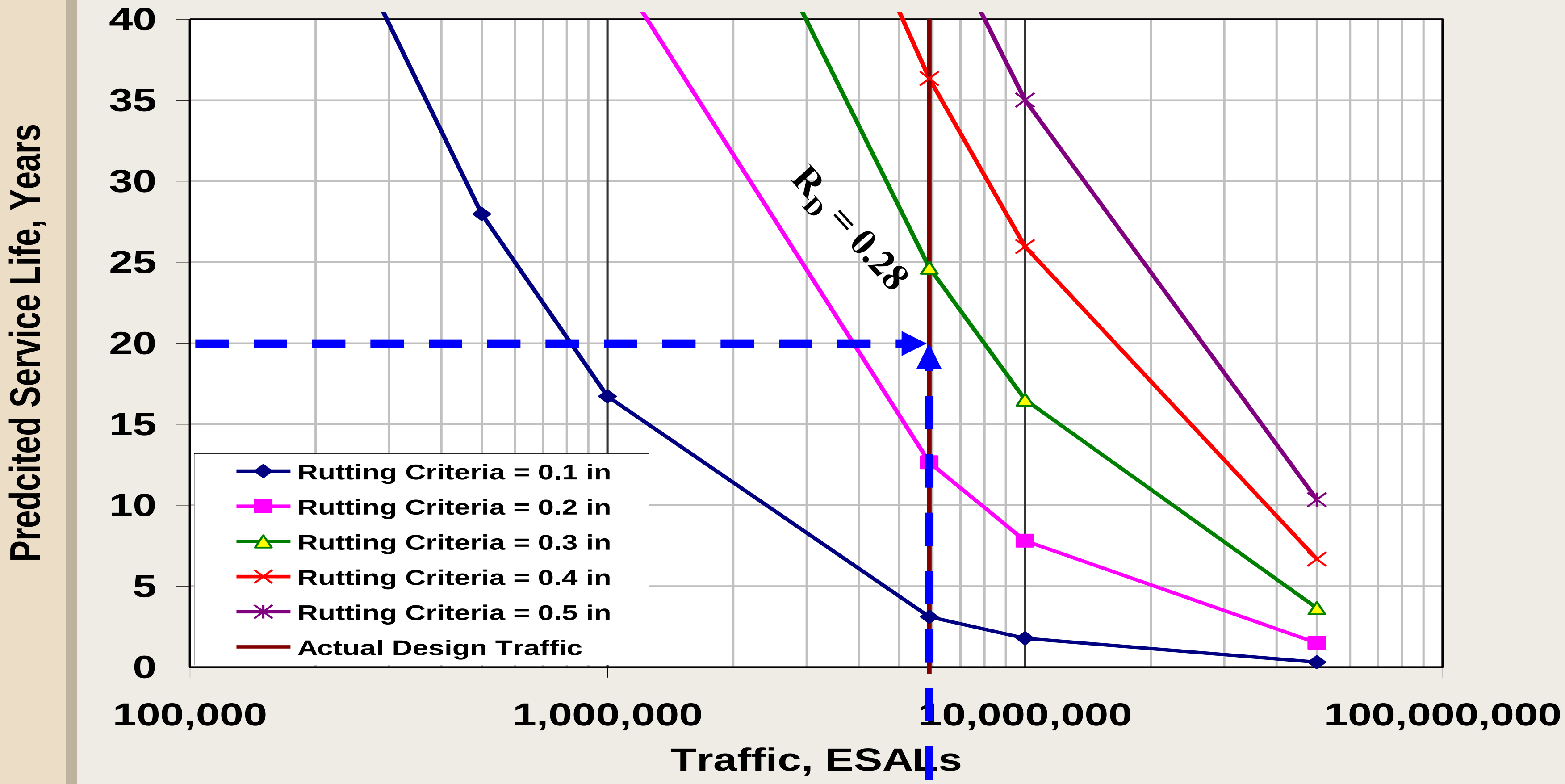
Layer Label ID	SHRP 3/4"		
Layer Thickness (in)	5		
Effective Frequency (Hz) **	33.74		
Effective Temperature (oF)	103.16		
SPT Recom. Frequency (Hz)	25	25	25
SPT Recom. Temperature (oF)	100.95		
Allowable Rut Depth (in)	0.30		
Allowable Layer E* (ksi)	557.178		
Predicted Rut Depth (in)	0.34		
Predicted Layer E* (ksi)	461.119		
Acceptable (Rut) ???	NO		
Acceptable (E*) ???	NO		

Please Go Back and Revise your Design!!!!

Influence of the Traffic Repetitions upon the Critical E* for Signal Road Section



Influence of Traffic Level upon Predicted Service Life (ADOT Signal Road Section Project – ADOT Traffic Known)



Simple Performance Test Procedure

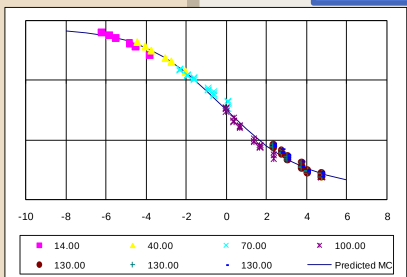
- The developed prediction models include Mix Characterization Property
  - Dynamic Modulus
    - For the analysis of rutting and fatigue cracking
  - Creep Compliance
    - For the analysis of thermal fracture
- Two options available to obtain the properties
  - 1: Use of Lab-measured data (Simple Performance Test)
    - Dynamic Modulus Test and Creep Compliance Test
  - 2: Use of Volumetric information
    - WPE for E* and a set of regression equations for D

Mix Design

ASU

Development of E* Master Curve

- **One (representative) master curve is developed based upon the multiple E* results.**
- Obtain optimized seven parameters of Sigmoidal Function



Calculation of effective temp. and freq.

- Two sets of a combination of effective temp. and freq. (rutting and fatigue cracking)

Rutting

$$F_{eff} = \frac{17.6v}{2(a + z_{eff})}$$

$$T_{eff} = 14.62 - 3.361Ln(Freq) - 10.940(z) + 1.121(MAAT) + 1.718(\sigma MMAT) - 0.431(Wind) + 0.333(Sunshine) + 0.08(Rain)$$

Fatigue

$$F_{eff} = \frac{17.6\,\upsilon}{2(a + h_{ac})}$$

$$T_{eff} = -13.995 - 2.332(Freq)^{0.5} + 1.006(MAAT) + 0.876(\sigma MMAT) - 1.186(Wind) + 0.549(Sunshine) + 0.071(Rain)$$

Calculation of Effective Dynamic Modulus.

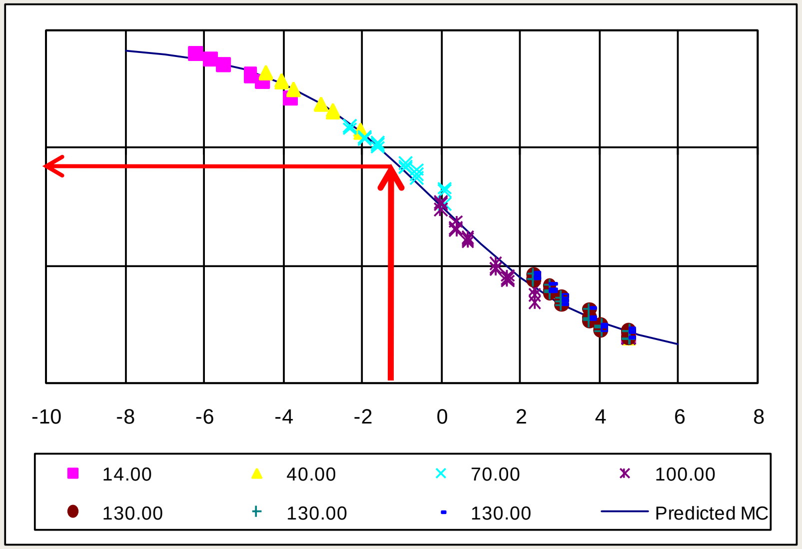
- Based upon the master curve as well as eff. Temp. and freq. , **E*eff** s are calculated for rutting and fatigue cracking

$$\log(E^*) = \delta + \frac{\alpha}{1 + \exp(\beta + \gamma \log t_r)}$$

$$aT_{eff}^2 + bT_{eff} + c = \log(a(T))$$

$$\log(a(T)) = \log\left(\frac{1}{f_{eff}}\right) - \log(t_r)$$

E*eff



Summary of the 9-22
Project Performance Related Specifications

- 9-22 represents the first true interaction of structural mix design and asphalt mix design methodologies
- Development of this methodology has been an enormous, enormous challenge to interact,link
  - Structural Design: 1-37A, 1-40D
  - Mix Design (Superpave / SPT): 9-19, 9-33 (A)
  - PRS (QRS): 9-22
- Recall that the process has been field calibrated to distress and pavement performance
- It is the FUTURE conceptual methodology that should be used to reward and/or penalize contractors for their product