CalME Design and Analysis Software for Pavement Design and Analysis, and Analysis of HVS Results

Presented by D Jones, UCPRC
Prepared by J Harvey, UCPRC
On behalf of many at UCPRC, Dynatest, CSIR and other collaborators around the world

UCPRC
UNIVERSITY of CALIFORNIA Davis • Berkeley | PAVEMENT RESEARCH CENTER

Purposes of CalME

- Design and Analysis of Asphalt Surfaced Pavement
  - Flexible, composite and semi-rigid pavements
  - Emphasis on rehabilitation and preservation
- Analysis of HVS data
  - Interfaces for analysis of HVS instrumentation
  - Models set up for HVS and other APT data calibration
- Flexibility to add new materials, models, and additional calibration

Analysis approaches in CalME

- Caltrans R-value
- Asphalt Institute type equations
- Incremental-Recursive approach
  - Models the entire damage and distress development process from start to finish
  - Permits calibration using instrumentation and non-destructive testing (FWD etc) from entire HVS, track APT or field instrumented section loading history
  - Developed by Per Ullidtz, Dynatest
  - Focus of rest of presentation

Overview – How does it work

- Incremental-recursive approach
  - Incremental – simulation runs at one increment at a time
  - Recursive – output from one increment as input for the next increment
- In each increment:
  - Pavement response calculated from wheel loads
  - Damage and permanent deformation accumulated
- Outputs surface cracking, IRI, and rut depth

Overview – HMA Stiffness

- Same format as MEPDG but some parameters are identified differently

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

$$tr = lt \times \left(\frac{\eta_{ref}}{\eta} \right)^{aT}$$

$$\log \log \eta = A + VTS \cdot \log(T_{Rankine})$$

δ, α, β, γ, aT, A, VTS = model parameters
tr = reduced loading time
lt = actual loading time
η= viscosity
T= loading temperature

Overview – HMA Stiffness considerations

- Aging model
  - Basic approach implemented to account for asphalt aging and traffic compaction
  - Needs local calibration
- Rest Periods: Thixotropic hardening
  - Temporary stiffness decrease when small rest periods, stiffness recovers more as rest periods increase (di Benedetto)
  - Considered in shift factor based on average time between traffic repetitions
  - May include some healing effects

Overview – Unbound Layer Stiffness

- Two types of nonlinearities

$$E_P = \left(\frac{P}{40kN}\right)^{\alpha} \times E_{40kN}$$

First type of nonlinearity, classic stress harden or soften

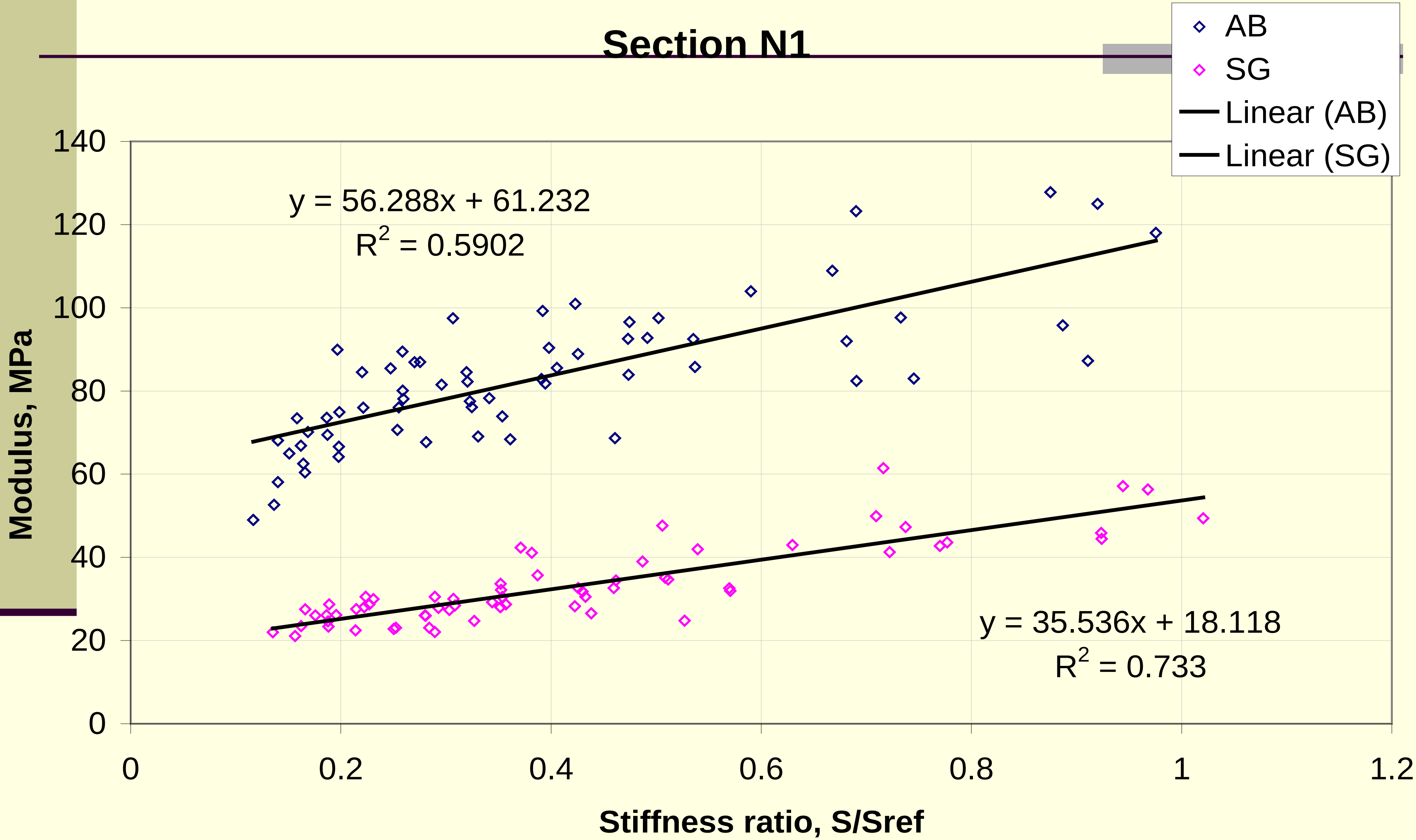
α, *StiffnessFactor*
= model param.
S_{ref} = normalizing constant
E = stiffness
P = Wheel load
S = Combined bending stiffness
h = Layer thickness

$$S = \sum_{1}^{n-1} h_i \times \sqrt[3]{E_i}$$

$$E_n = E_{n,ref} \times \left[1 - \left(1 - \frac{S^3}{S_{ref}^3}\right) \times StiffnessFactor\right]$$

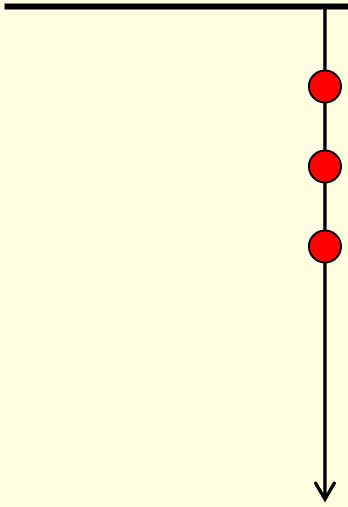
Second type of nonlinearity from confinement effect of overlying layers

Example: confinement effect on unbound layers NCAT calibration section



Overview – Pavement Temperature

- Currently has 6 California climates, others can be added
- 30-year hourly surface temperature database developed based on EICM runs
- In-depth temperature calculated with 1-D FEM on the fly (very fast!)



Traffic characterization

- Pavement design and analysis
  - Axle load spectra in database based on axle types, currently based on California WIM data
  - Includes extrapolation to all locations on state network based on simple truck traffic parameters and shape analysis (Lu et al)
  - Spectra and extrapolation approach can be applied to other networks
- HVS analysis
  - Simulates HVS loading

Overview – Pavement Response

- Stress and strain: layer elastic theory
  - Odemark-Bousinesq
  - OpenPave Layer Elastic Analysis program (open source, JD Lea)
- Reflective cracking strain:
  - Regression equation based on FEM analysis
  - 2-d to develop sensitivity to parameters
  - 3-d to get realistic values

Materials and Layer Thickness Characterization

- CalME designed to work with layer stiffness back-calculation program CalBack
  - Recommend FWD testing repeated two times of the day: characterization of HMA master stiffness curve
- Database of typical new materials in software
  - Updated with each new project
- Lab testing protocols for new materials
- Stiffness variability for Monte Carlo from back-calculation within project

Model Parameter Determination

- Parameters
  - Asphalt and asphalt stabilized recycled materials: master curve, rutting, fatigue
  - Aggregate base, subbase and subgrade stiffness and rutting
  - Cement/asphalt stabilized stiffness, cracking, crushing
- Software to create parameters from lab tests
- All parameters and addition of new materials editable in software

Performance Models

- Rutting
- Fatigue cracking
- Reflective cracking
- Cement treated base cracking and crushing
- Freeze/thaw
- IRI
- Reliability

Critical Zone for Rutting - HVS Tests

Upper 75 to 100 mm
high temperatures
high shear stresses

Rutting Model - HMA

- Based on J.A. Deacon's approach
- Rut depth is related to inelastic shear strain and thickness, and occurs in the top 100 mm only:

$$rd_{HMA}\ mm = K \times \gamma^{i} \times h$$

- And inelastic strain is related to loading, shear stress and elastic shear strain

$$\gamma^{i} = f(N, \tau, \gamma^{e})$$

Rutting – Unbound material

- Related to vertical strain at the top of the subgrade and stiffness

$$d_p = A \times MN^{\alpha} \times \left(\frac{\varepsilon}{\varepsilon_{ref}}\right)^{\beta} \times \left(\frac{E}{E_{ref}}\right)^{\gamma}$$

A, α, β, γ = model parameters
ε_{ref} , E_{ref} = normalizing constant
d_p = permanent deformation
MN = number of load repetitions in million
ε = vertical strain at the top of the unbound layer
E = Layer stiffness

Fatigue cracking – HMA – 1/3

- First calculate fatigue damage ω

$$\omega = \left(\frac{MN}{SF_{FAT} \cdot MN_p} \right)^{\alpha} \qquad \alpha = \exp\left(\alpha_0 + \alpha_1 \times \frac{t}{1°C} \right)$$

$$MN_p = A \times \left(\frac{\varepsilon}{\varepsilon_{ref}} \right)^{\beta} \times \left(\frac{E}{E_{ref}} \right)^{\gamma} \times \left(\frac{E_i}{E_{ref}} \right)^{\delta}$$

- Damaged master curve:

$$\log(E) = \delta + \frac{\alpha \times (1 - \omega)}{1 + \exp(\beta + \gamma \log(tr))}$$

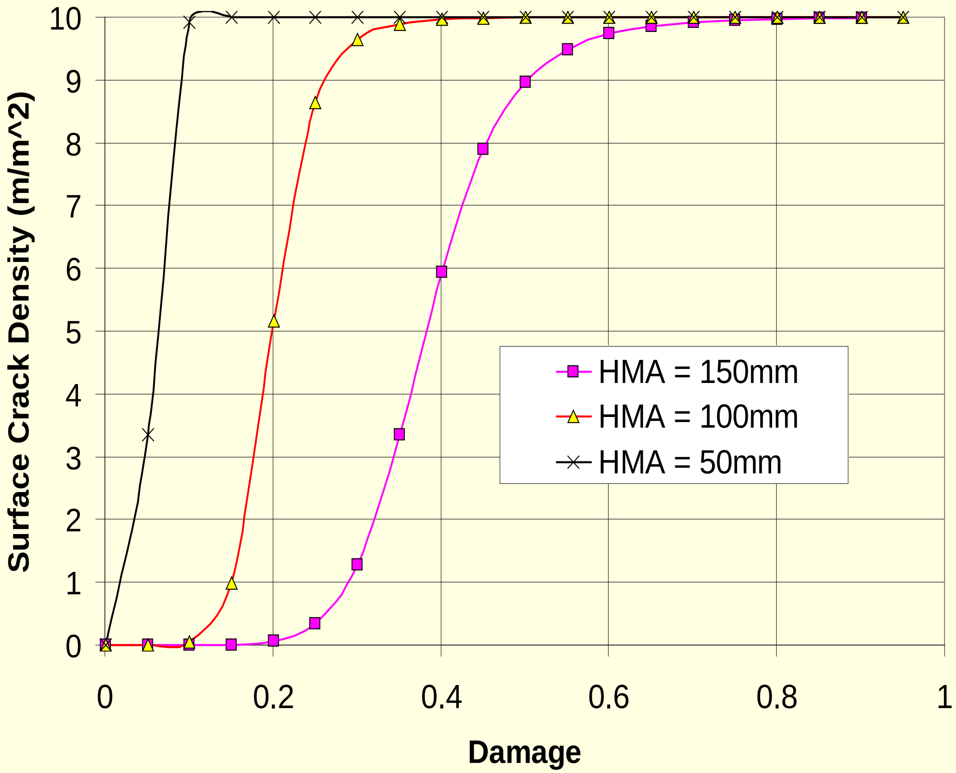
$A, \alpha_0, \alpha_1, \beta, \gamma, \delta$ = model parameters
ε_{ref}, E_{ref} = normalizing constant
MN = N in millions
MN_p = Allowable N
ε = bending strain
E = Damaged stiffness
E_i = Intact stiffness

Fatigue Cracking – HMA – 2/3

- Surface crack density is related to damage in deterministic analysis:

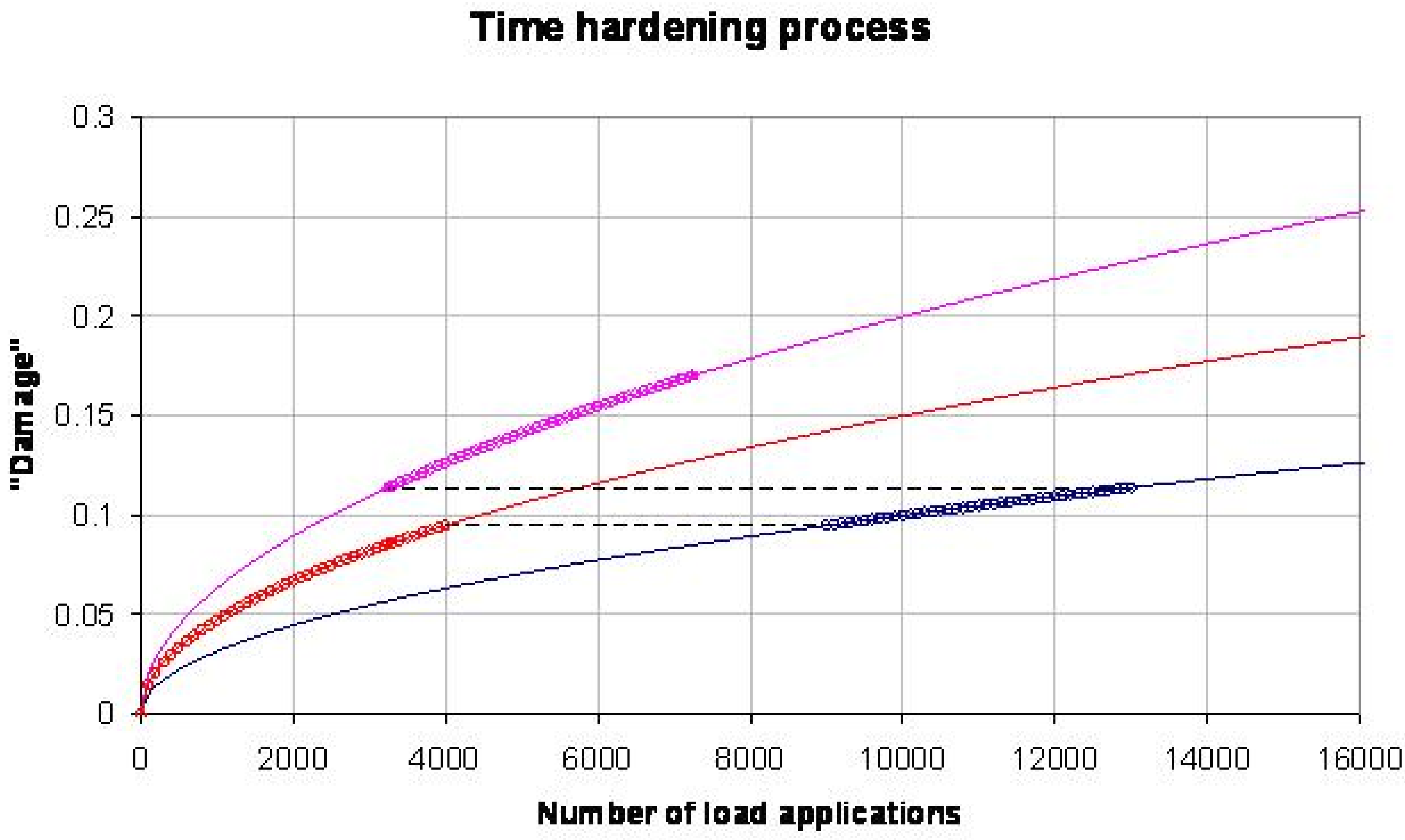
$$CR = \frac{10.0\ \mathrm{m/m^2}}{1+\left(\frac{\omega}{\omega_0}\right)^{\alpha}}$$

$$\omega_{initiation} = \frac{1}{1+\left(\frac{h_{HMA}}{h_{ref}}\right)^{a}}$$



α, a = calibration parameters
h_{HMA} = HMA thickness, h_{ref} = normalizing const.
$\omega_{initiation}$ = damage at crack initiation

Time Hardening Models Damage/Rut Accumulation Incrementally



Reflective Cracking - 1/2

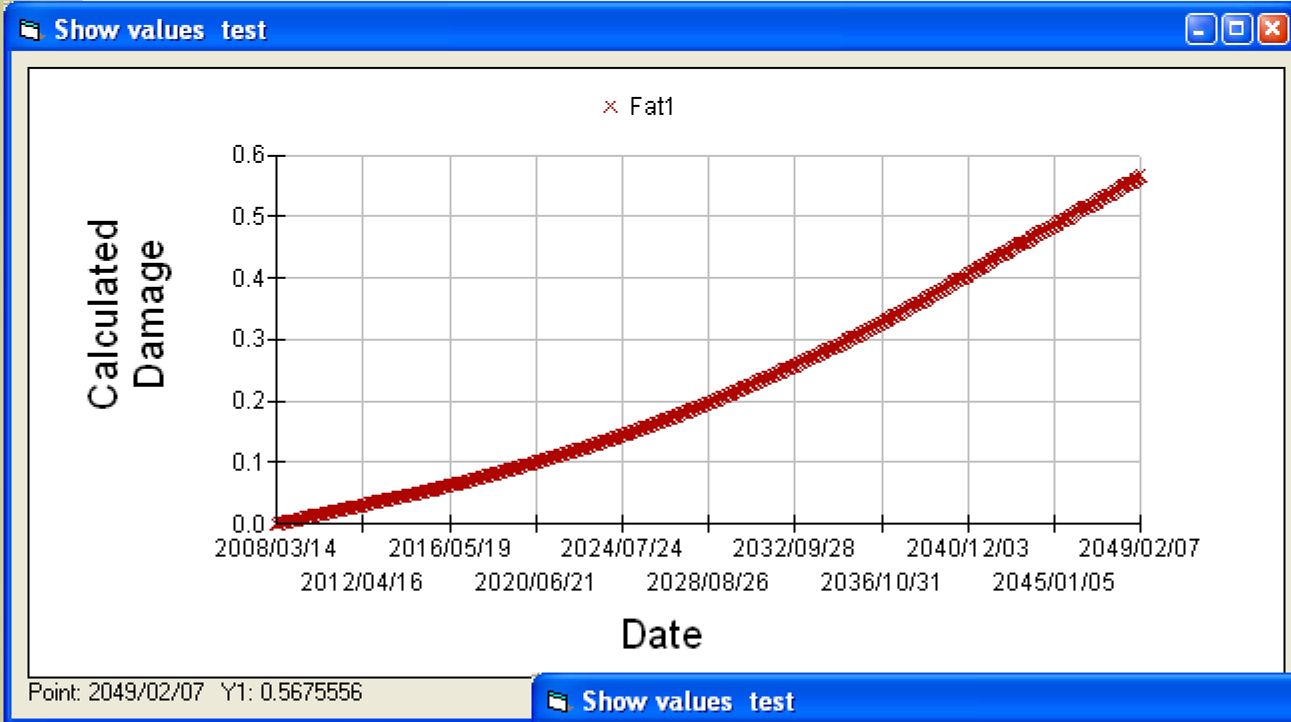
- Traffic induced: same approach as fatigue cracking except that HMA bottom strain is different:
  - HMA/HMA overlay: average maximum tensile strain at the crack tip
  - HMA/PCC overlay: bending strain at the crack tip assuming local debonding
  - Two damages are calculated, one for fatigue another for reflective cracking
- Thermal induced: models from U. of Minnesota (Khazanovich et al)

Consideration of Variability and Reliability

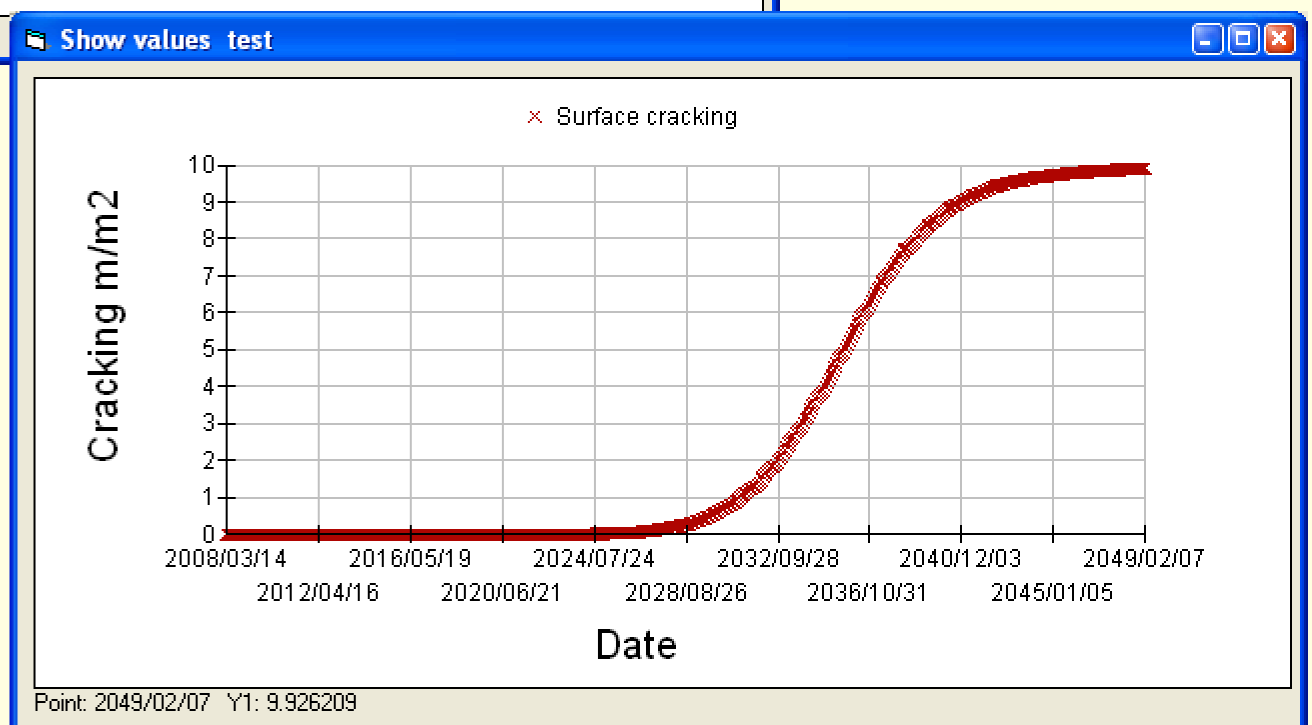
- Variation of thickness, stiffness, calibration coefficients
  - Deterministic
  - Within project variability (Monte Carlo simulation)
  - Between projects variability (sensitivity analysis)
- Traffic projection error
  - sensitivity analysis if warranted
- Climate variability
  - Random selection of initial year and day used to characterize each month (Monte Carlo simulation)

Single run of CalME predicts:

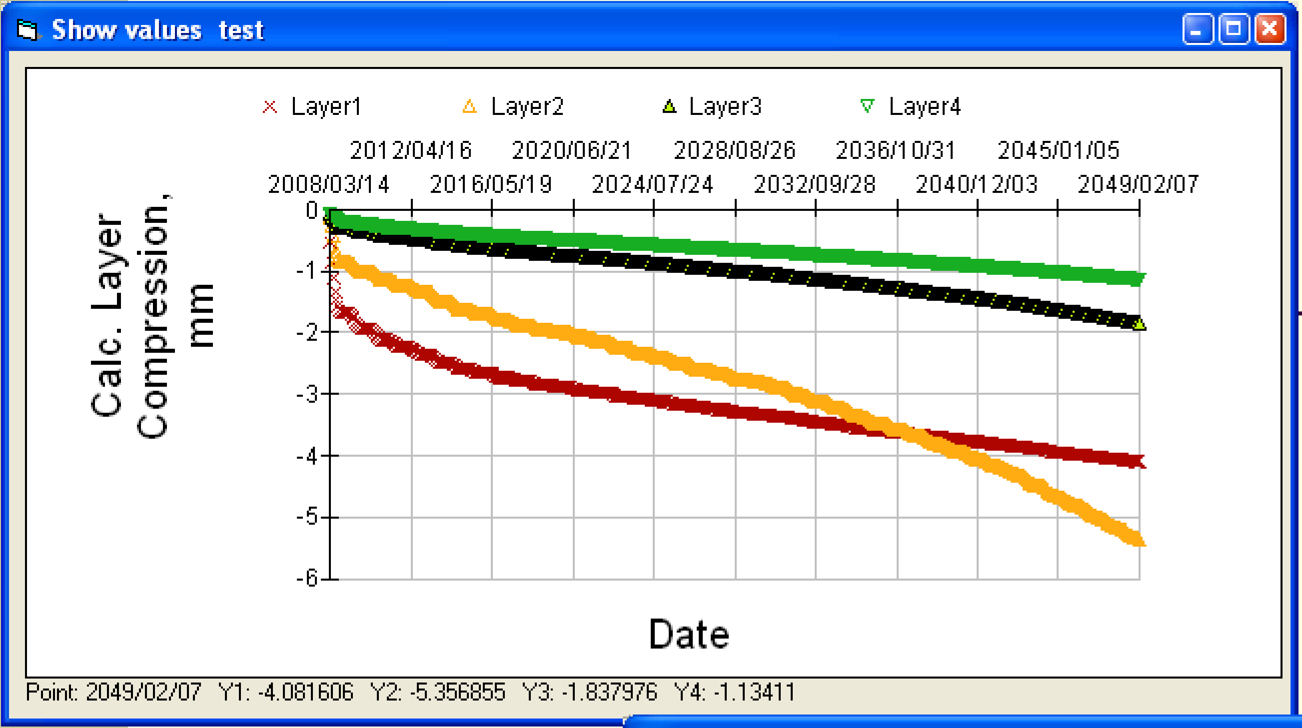
Damage to surface layer



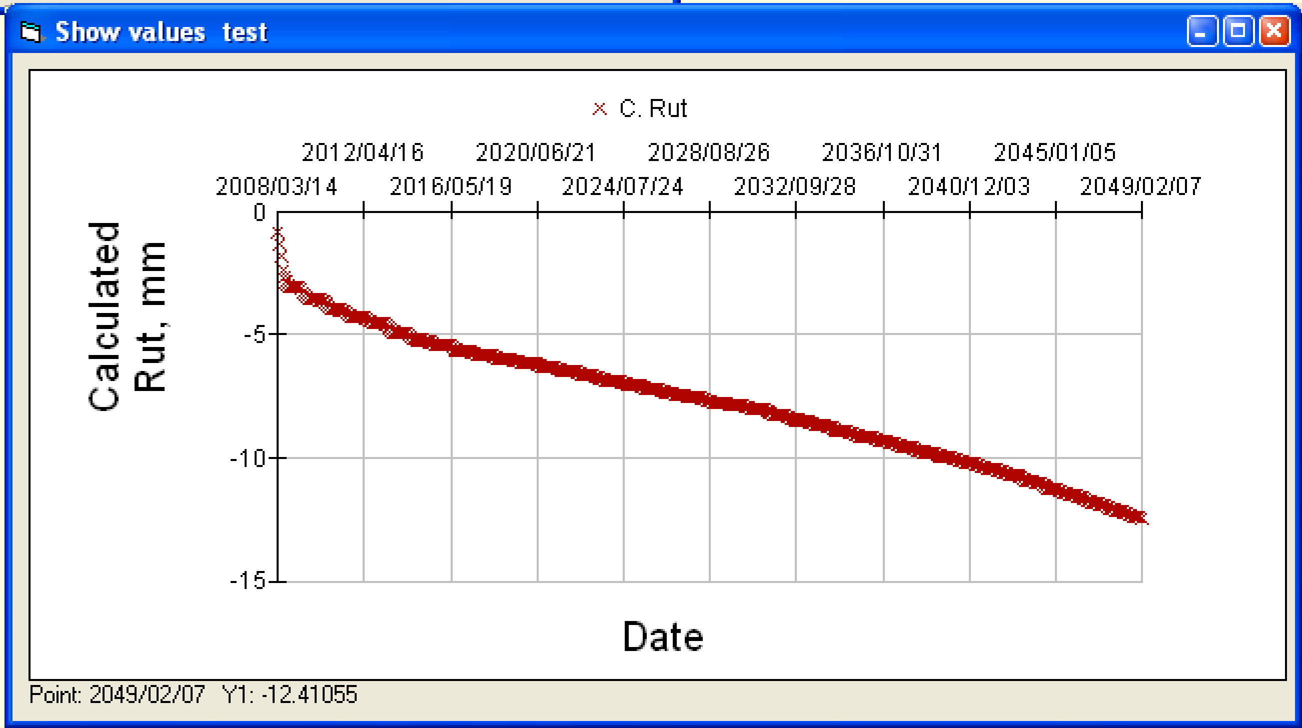
Cracking of surface layer, m/m²



Permanent deformation of each layer



Down rut on surface



For Reliability: Monte Carlo simulation using within project values

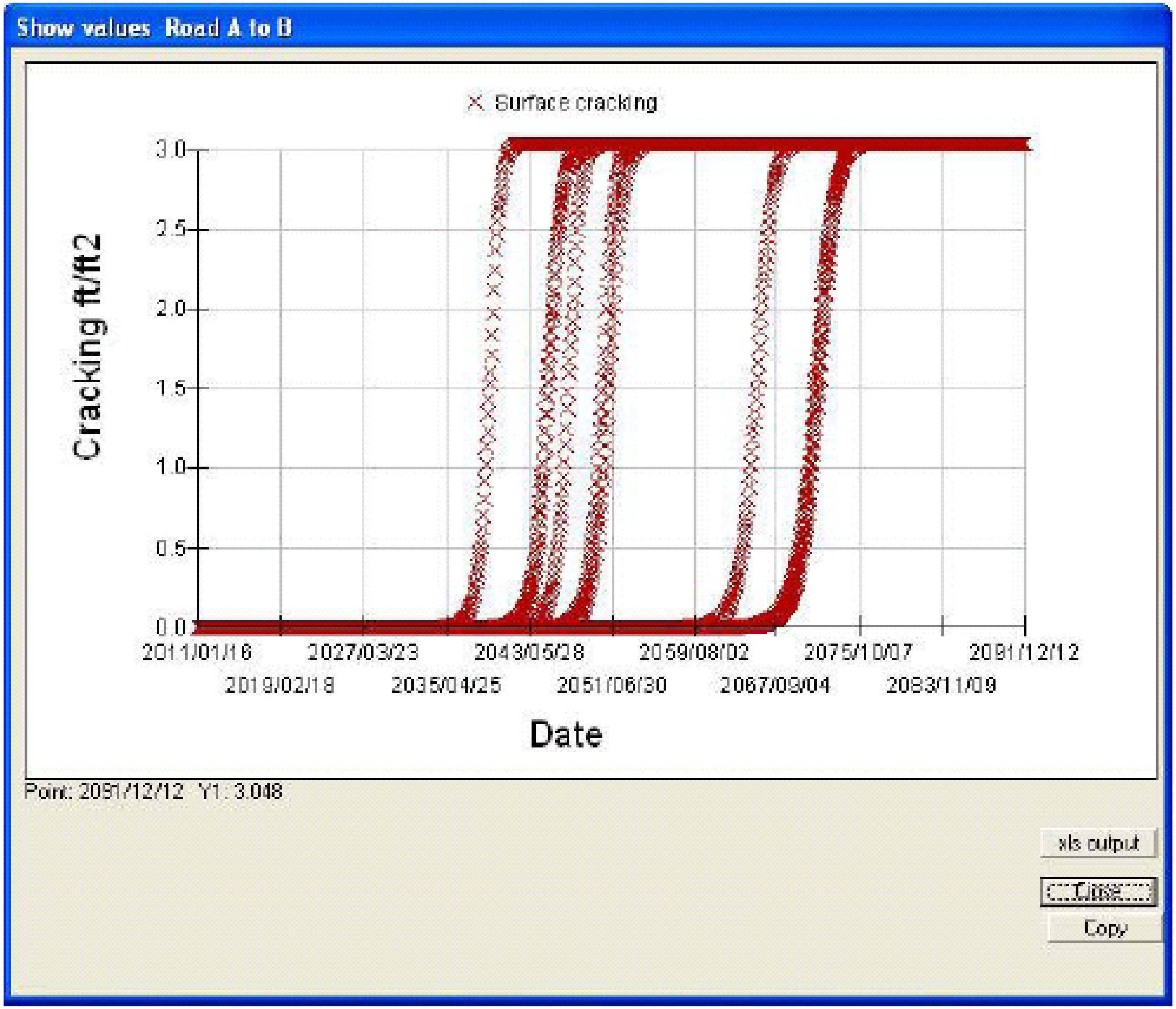
- Considers variability of all layers
  - Thicknesses
  - Stiffnesses (default or from back-calculation)
  - Materials constants for permanent deformation, fatigue and cracking
- Monte Carlo is fast!

Enter variability

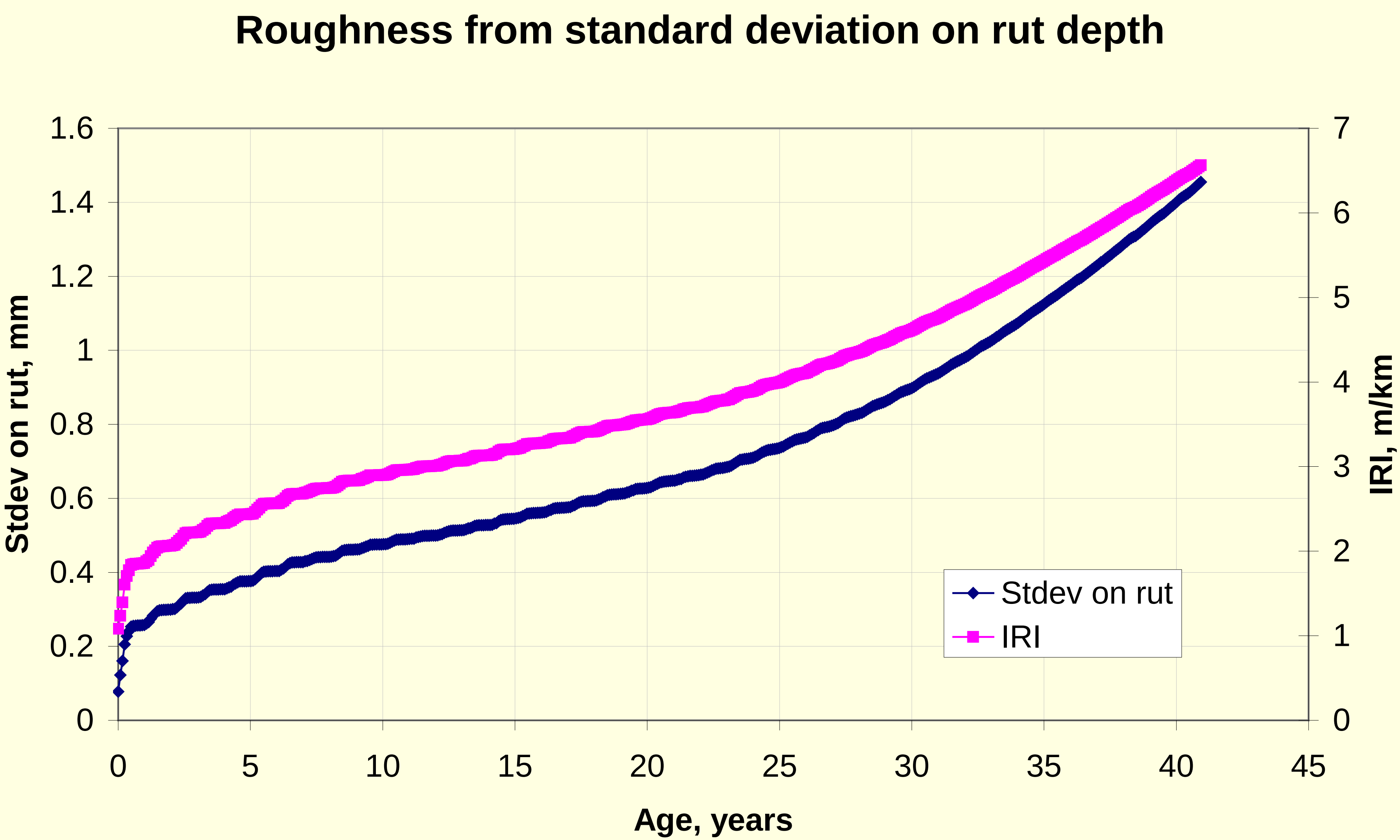
Store

Layer	CoV Thickness	sdf Modulus	sdf PdA	sdf FtA	sdf CrA
1	0.07	1.218	1.2	1.15	1.15
2	0.1	1.057	1.2	1.15	1.15
3	0	1.041	1.2	1.15	1.15

Monte Carlo runs of cracking



IRI calculated from rutted profile



Consideration of Pavement Preservation

- CalME simulates pavement preservation
  - M&R strategies designated by designer, or
  - Other strategies can be implemented
- Three types of M&R strategies:
  - Rehabilitation only (RRR)
  - Rehabilitation, 2 preservations, then rehab (RPPR)
  - Rehabilitation and then perpetual pavement preservation (RPPP)

CalME Calibration

- Can be calibrated using both accelerated pavement testing and field data, currently:
  - 27 Heavy Vehicle Simulator (HVS) test sections
  - 26 Westrack sections; NCAT, MnROAD validation

- Miner's Law (linear damage process) used in MEPDG, other methods only uses initial condition
- Incremental-recursive method calibration process
  - Calibrate damage models with deflections, strains, back-calculated stiffness
  - Once damage process through entire life of pavement is match, calibrate cracking and rutting

Key Differences between Field and HVS/Track Calibration

	Field	HVS/Track
Simulation Interval	1 month	1 hour
Typical Responses	FWD stiffness	Elastic and plastic deformation, stress, strain, FWD stiffness
Typical performance	Cracking history	Cracking, and rutting

CalME Features for HVS Testing Simulation

- Storage of pavement response and performance history
- Plots to compare calculated and measured response and performance history

Storage of Pavement Response History Example – MDD Elastic Deflections

Microsoft Access - [ProjectMDDResilient : Table]

File Edit View Insert Format Records Tools Window Help

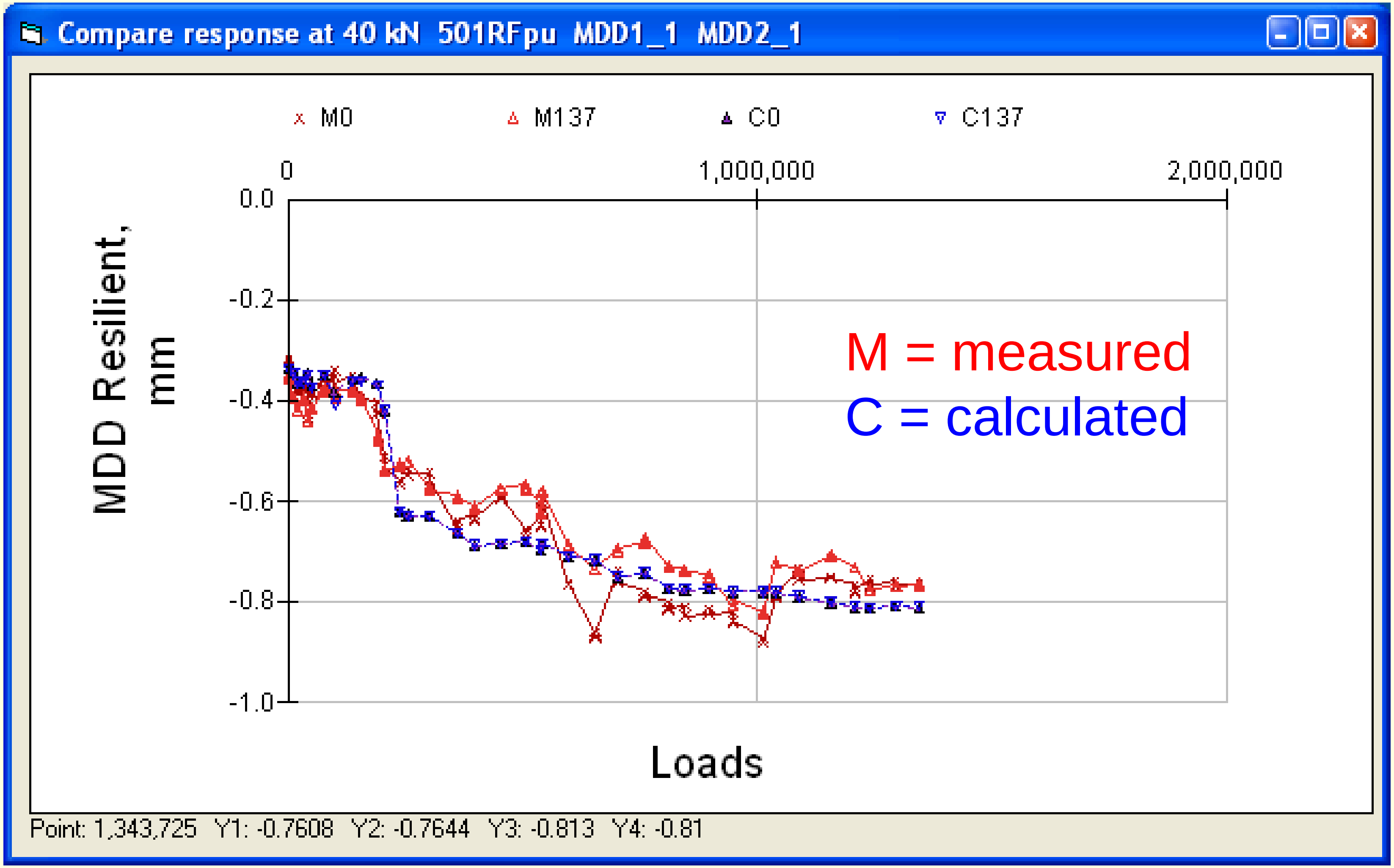
Type a question for help

ProjectName	DateNow	MDD	D1	D2	D3	D4	D5
500RF	5/22/1995 3:15:12 PM	1	-0.2805	-0.2647	-0.1956	-0.1581	-0.0775
500RF	5/22/1995 3:16:34 PM	1	-0.2816	-0.2752	-0.2074	-0.1622	-0.0768
500RF	5/22/1995 3:17:46 PM	1	-0.2898	-0.27	-0.2087	-0.1613	-0.0854
500RF	5/28/1995 3:03:36 PM	2	-0.6897	-0.5249	-0.4275	-0.293	-0.1659
500RF	5/28/1995 3:04:38 PM	2	-0.6807	-0.5125	-0.4242	-0.291	-0.1662
500RF	5/28/1995 3:05:12 PM	2	-0.4249	-0.2902	-0.2394	-0.1702	-0.0737
500RF	5/28/1995 3:06:12 PM	2	-0.4318	-0.2984	-0.2464	-0.1706	-0.0778
500RF	5/28/1995 3:06:40 PM	2	-0.6782	-0.5205	-0.4225	-0.2859	-0.1638
500RF	5/28/1995 3:07:12 PM	2	-0.429	-0.294	-0.2444	-0.1686	-0.0714
500RF	5/28/1995 3:10:30 PM	2	-0.9285	-0.7413	-0.5997	-0.4134	-0.2522
500RF	5/28/1995 3:10:45 PM	2	-0.9298	-0.7389	-0.6065	-0.4092	-0.249
500RF	5/28/1995 3:11:12 PM	2	-0.9318	-0.7412	-0.6046	-0.4164	-0.2457
500RF	5/28/1995 3:15:12 PM	1	-0.3167	-0.2918	-0.2219	-0.1849	-0.095
500RF	5/28/1995 3:16:34 PM	1	-0.3156	-0.289	-0.2263	-0.1747	-0.0904
500RF	5/28/1995 3:17:46 PM	1	-0.3142	-0.2893	-0.2196	-0.1776	-0.0914
500RF	5/28/1995 3:25:12 PM	1	-0.6034	-0.5651	-0.4712	-0.3749	-0.1816
500RF	5/28/1995 3:26:12 PM	1	-0.5978	-0.5624	-0.4733	-0.3672	-0.1837
500RF	5/28/1995 3:27:12 PM	1	-0.5901	-0.5603	-0.4705	-0.378	-0.196
500RF	5/28/1995 3:35:12 PM	1	-0.7471	-0.7062	-0.6019	-0.4854	-0.2417
500RF	5/28/1995 3:38:12 PM	1	-0.7572	-0.7229	-0.614	-0.4857	-0.2433
500RF	5/28/1995 3:40:12 PM	1	-0.7607	-0.7195	-0.6124	-0.4954	-0.2458
500RF	6/1/1995 9:37:41 AM	1	-0.2752	-0.217	-0.1904	-0.1489	-0.0813
500RF	6/1/1995 9:39:39 AM	1	-0.2755	-0.2171	-0.1872	-0.1475	-0.0824
500RF	6/1/1995 9:40:54 AM	1	-0.2774	-0.2194	-0.1828	-0.1446	-0.0817
500RF	6/1/1995 9:43:59 AM	2	-0.4012	-0.2834	-0.2226	-0.1424	-0.1052
500RF	6/1/1995 9:44:55 AM	2	-0.4015	-0.28	-0.2224	-0.1437	-0.1066

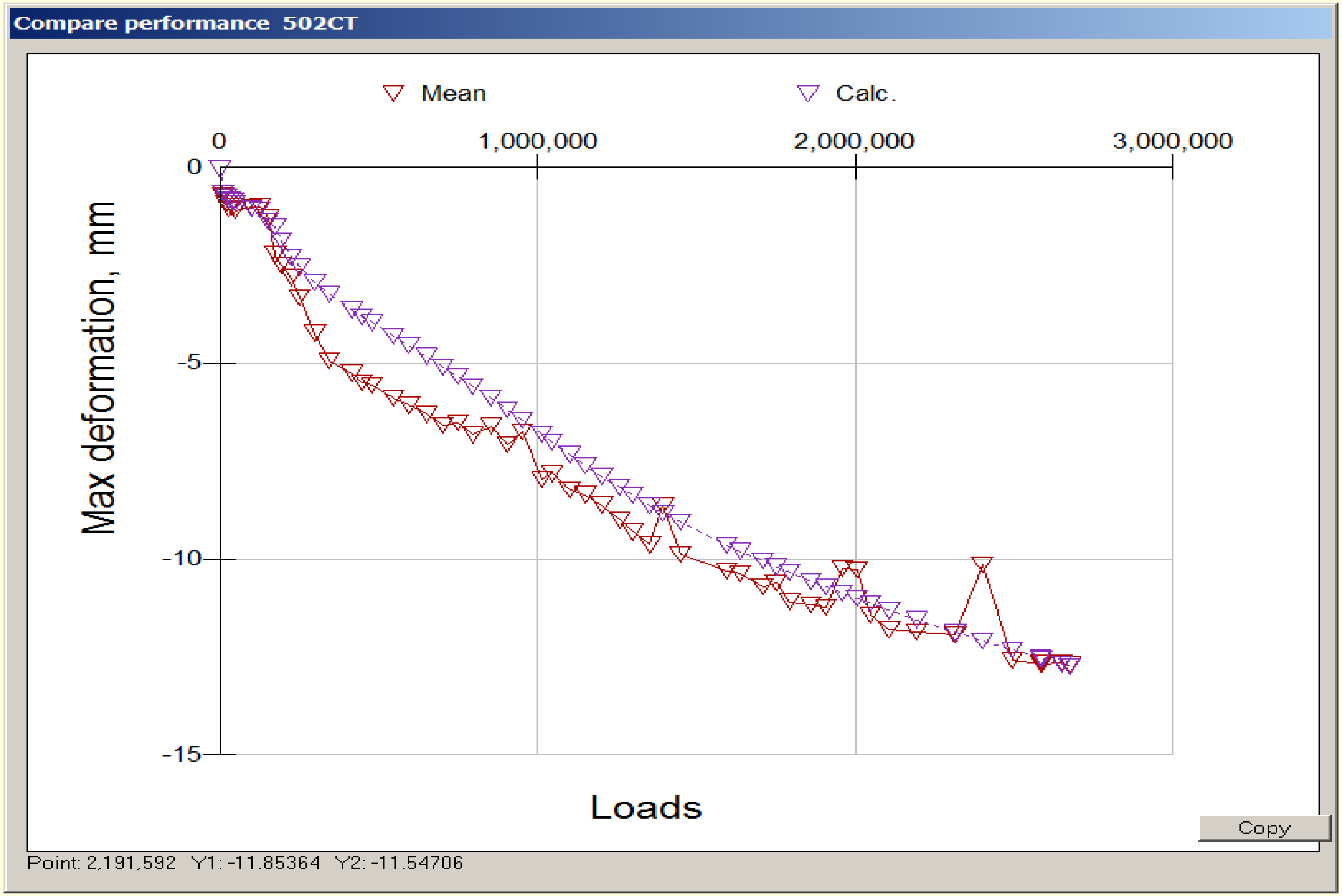
Record: 1 of 600 (Filtered)

Datasheet View FLTR NUM

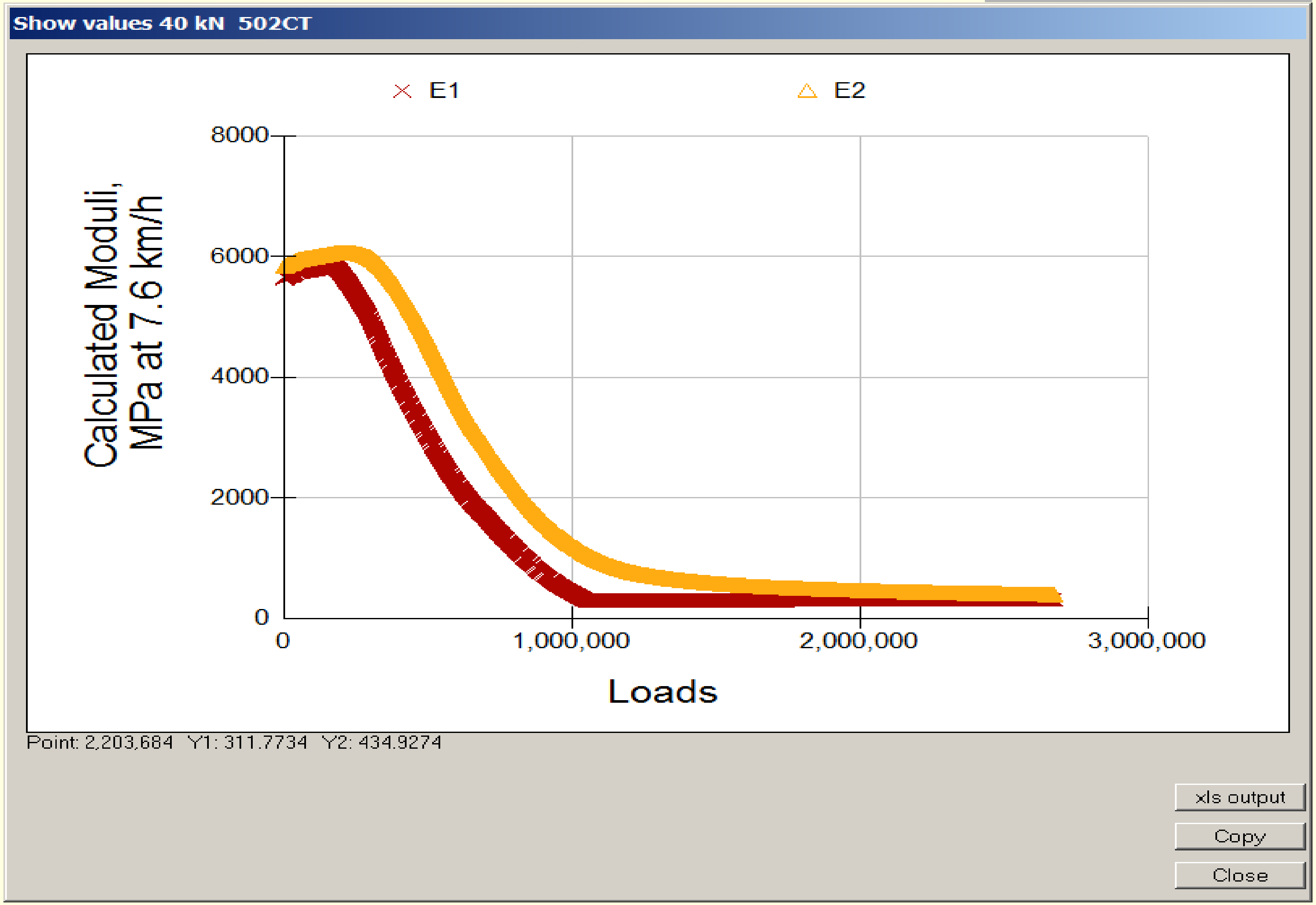
Plots for Response Comparison Example – MDD Elastic Deflections



Plots for Performance Comparison Example – Max Surface Deformation from Profilometer



Stiffness Reduction During HVS Testing Example – Top 2 HMA Layers



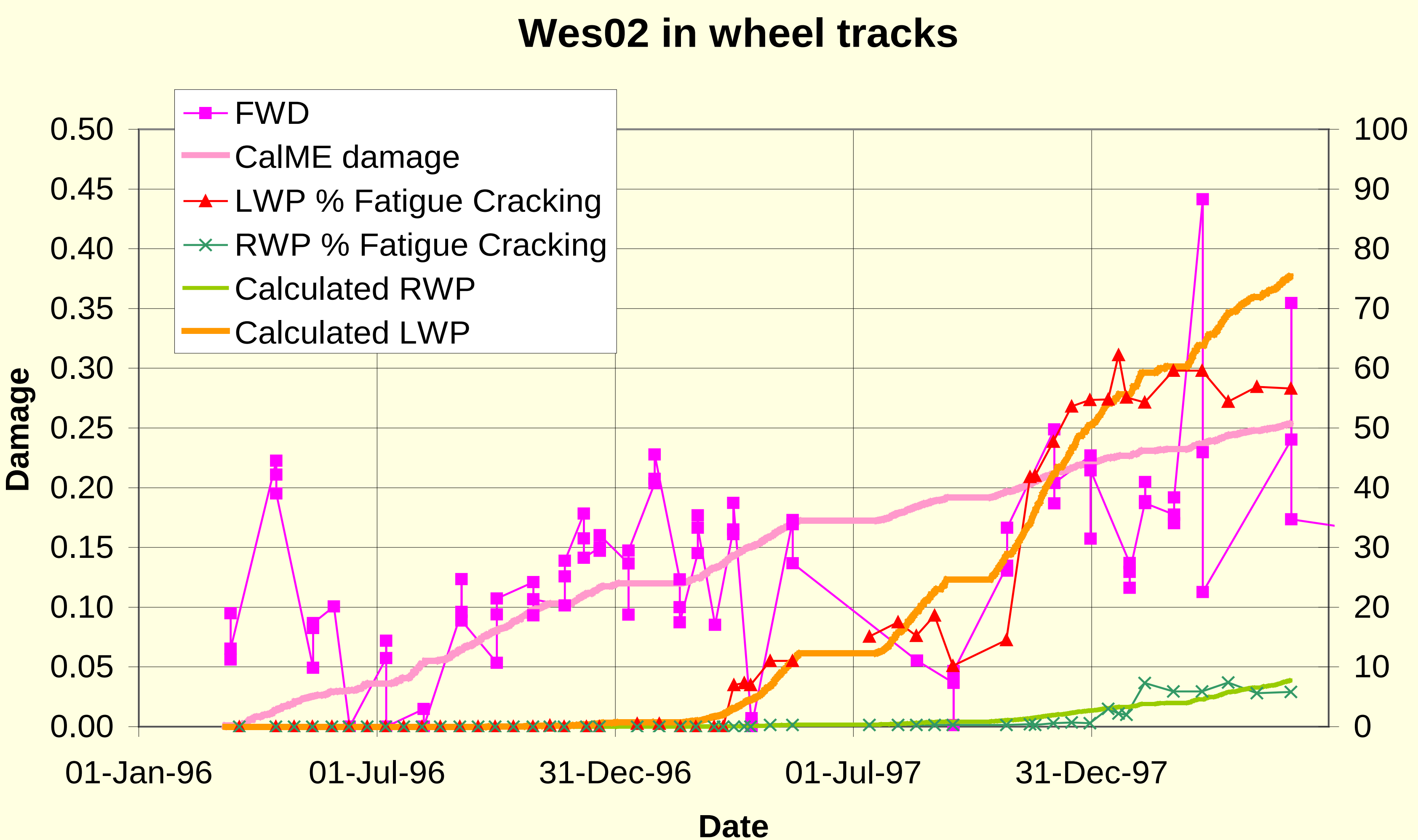
Calibration of Empirical Model Parameters

- Empirical parameters include:
  - Shift factor, *SF*, for damage evolution
  - All parameters for relating damage to surface crack density deterministically
- Data sources
  - WesTrack: beam frequency sweep and fatigue, FWD, crack density
  - HVS tests from UCPRC: beam frequency sweep and fatigue, deflections, crack density
  - NCAT, MnROAD sections used for validation
  - Further calibration with other HVS, APT and field data possible

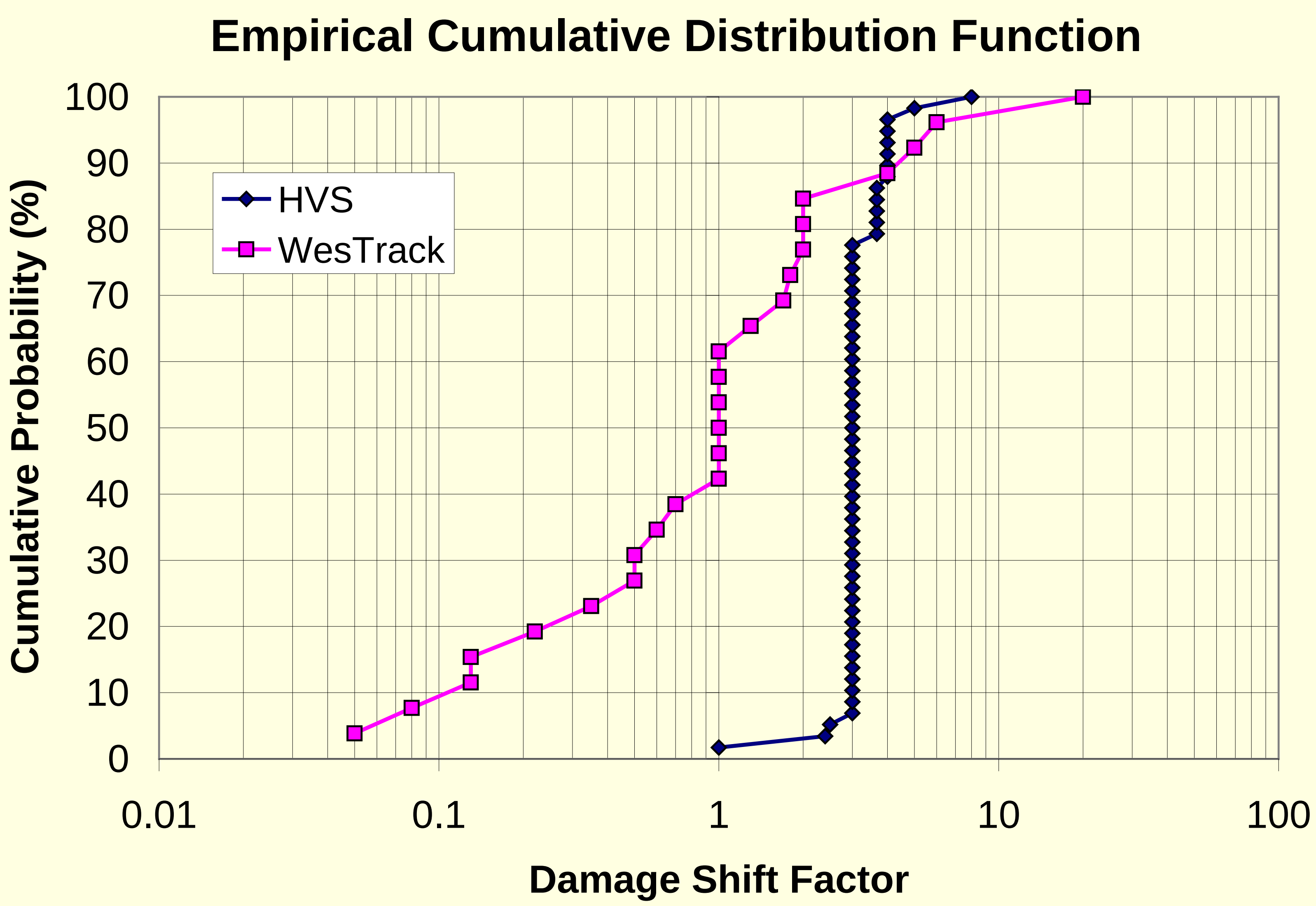
Calibration Procedure

- Step 1: Shift Factor for damage
  - Back-calculate AC stiffness from FWD => stiffness history
  - Back-calculate AC damage history
  - Predict AC damage history with CalME
  - Adjust shift factor to match
- Step 2: Damage to surface crack density correlation
  - Back-calculated damage history
  - Measured surface crack density history
  - Adjust parameters to match
- Final shift factors:
  - Fatigue and reflection cracking 1.0
  - HMA rutting 1.0, other asphalt mixes 0.5

Westrack Example



Distribution of Shift Factor for Fatigue Damage: HVS mean = 3; Westrack mean = 1



CalME status

- Version 1.0 complete, with documentation, user's guide
- Currently being used by:
  - Caltrans to design long-life rehab projects (about $75 million to date)
  - UCPRC for HVS section analysis (adding new materials, models with each experiment)
- Evaluation licenses available for free
  - Email jtharvey@ucdavis.edu
  - Requirements: give us your feedback

CalME next steps

- Upgrade code and improve interfaces
  - for HVS and design
  - Languages other than English
- Continue to add models, materials, improve reliability approach
- Looking for partners to do these steps, offer:
  - Assistance with updating databases with local materials and models
  - Perpetual license to source code of improved version for local use

Questions?

Reports downloadable at:
www.ucprc.ucdavis.edu