Mechanistic-Empirical Pavement Design Using CalME and PavementME

John Harvey, PE

University of California Pavement Research Center

City and County Pavement Improvement Center

UC Davis

GEO-INSTITUTE
Los Angeles Chapter

7 October 2020
"Next year on the Queen Mary!"

UCPRC
UNIVERSITY of CALIFORNIA Davis • Berkeley | PAVEMENT RESEARCH CENTER

Outline

- What are UCPRC and CCPIC?
- Overview of empirical and mechanistic-empirical (ME) pavement design
- CalME design for asphalt surfaced pavements
  - Calibration for California conditions
- Pavement ME design for concrete surfaced pavements
  - Calibration for California conditions
- Summary

Who and What is the University of California Pavement Research Center?

- Mission
  - *Research, development and implementation of economically and environmentally sustainable, equitably distributed, multi-functional pavement systems*
- Who we are
  - 2 campuses (Davis, Berkeley), materials laboratories, 2 Heavy Vehicle Simulators
  - 8 Professional Researchers
  - 8 Research and development engineers
  - 13 graduate students
  - 6 Technical and admin support staff
  - Partner research organizations
- 3 to 5-year contracts with Caltrans since 1995
  - Partnered Pavement Research Center
  - Full arc: conceptual studies, basic research, development, support and evaluation of implementation, continuous improvement

UCPRC
UNIVERSITY of CALIFORNIA | PAVEMENT RESEARCH
Davis • Berkeley | CENTER

Some Current and Recent UCPRC Areas of Work

- Caltrans (90% of our work) and other work
  - Pavement management
  - Life Cycle Cost Analysis (LCCA)
  - Mechanistic-Empirical design methods
    - Long life rehabilitation, concrete and asphalt
  - Environmental Life Cycle Assessment (LCA)
  - New materials
  - Performance related specifications and construction quality
  - Rehabilitation construction productivity and work zone traffic
  - Recycling (asphalt, concrete, asphalt rubber, in-place recycling)
    - Existing pavement materials, other waste, forest and agriculture biomass feedstocks
  - Multi-functional pavement and quality of life
    - Permeable for stormwater quality, flood control
    - Pavement for thermal conditions (heat island, human thermal comfort) and noise
- Other partners
  - FHWA, Calrecycle, National Center for Sustainable Transportation, FAA, Air Resources Board, state and national pavement industries, legislature, agencies, universities, NGOs

UCPRC | City and County Pavement Improvement Center

Welcome To CCPIC

- Chartered in September 2018 by League of California Cities, County Engineers Association of California, and California State Association of Counties
- Funded by Institute of Transportation Studies at UC Davis and UC Berkeley, Mineta Transportation Institute at San Jose State University
- Governance board: city and county public works officials
- Technical content partners:
  - UC Davis and UC Berkeley
  - CSU Chico Preservation Center, CSU Long Beach, Cal Poly San Luis Obispo

CCPIC Website

www.ucprc.ucdavis.edu/ccpic

- Best practices technical briefs
- Training class information
- Outreach presentations
- Sample specifications
- Guidance
- Tools
- Unpaved roads
- Pavement contact list

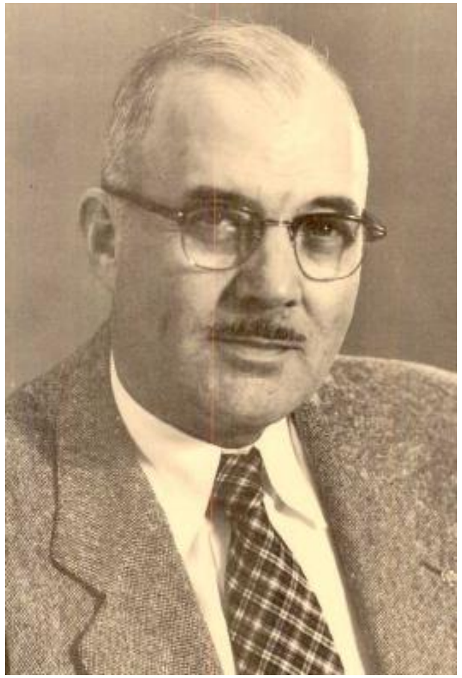
Overview of empirical and mechanistic-empirical (ME) pavement design

How to Develop an Empirical Design Method

- Build pavements with different thicknesses and structures
- Traffic the pavements
    - Accelerated Pavement Testing
        - Test tracks (like WASHO and AASHO Road Tests, Westrack, MnROAD, NCAT track)
        - APT machines (like Heavy Vehicle Simulators)
    - Field sections
        - Test sections (selected sections in the network as test sections
        - Pavement management system (the whole network)
- Observe how many traffic repetitions to reach failure
- Fit a curve to the results considering:
    - Structures
    - Materials
    - Traffic
    - Climate

Caltrans Empirical Design Method for New Pavement

- **O. J. Porter**
  - California State Pavement Engineer (1928-40)
  - Identified failures in terms of subgrade shear (rutting), excessive deflections (fatigue)
    - California Bearing Ratio (CBR) test for subgrade shear strength
  - Developed design curves based on field observations
  - Went to Army Corps of Engineers in 1940
    - Extended Caltrans highway curves to airfields with more accelerated pavement testing; which became the basis for military and FAA empirical design
- **Francis Hveem**
  - State Bituminous Engineer in 1941, then State Pavement Engineer 1945 to 1971
  - Developed R-value test
  - New thickness design equation in terms of gravel equivalent (GE) and gravel factors (Gf) from observations, R-value tests



Development and Calibration of Caltrans Empirical Flexible Pavement Design Method

Porter, Casagrande, Westergaard at Stockton

- Stockton road test (1937)
  - 3 inches DGAC, up to 0 to 5 ft of gravel subbase (ASB)
    - Where the gravel factor comes from, Gf ASB = 1.0
  - Tested with B-19 bomber load
- WASHO Road Test (1953-54)
  - Closed circuit track in Pocatello, Idaho
    - Thickest asphalt was 3 inches (0.25 ft)
  - Different flexible designs (mostly, wheel load factors to relate different wheel loads to a standard wheel load
- AASHO Road Test (1958-60)
  - Closed circuit tracks in Ottawa, Illinois
  - Different axle loads, conversion of all truck traffic to ESALs
    - 1,114,000 axle repetitions applied (less than TI=9, accounting for loads)
- <u>Last calibration around 1964</u> of Caltrans method added 0.2 DGAC safety factor based on premature fatigue cracking, AASHTO data

Caltrans Overlay Design Method

- Based on Benkelman Beam
  - Invented at WASHO Road Test
- Design method developed 1951-1955
  - Hveem compared deflections on small set of pavements (<u>maximum TI=9</u>) and related to fatigue cracking
  - Overlay design method, published in 1960, based on “deflection reduction” to a “tolerable deflection”
  - Calibrated 1961-1966, on 80 projects (state, counties, cities)
- Later developments
  - Adopted as CT 356 in 1969, max DGAC = 0.5 ft
  - Updated in 1974 based on observed performance of overlays
  - Extrapolated to higher TIs
  - Checked against performance in 1980
    - Average life to 30 percent cracking = 11.6 years
  - Correlation of Benkelman Beam/Traveling Deflectometer to Dynatest to FWD deflections in late 1980s

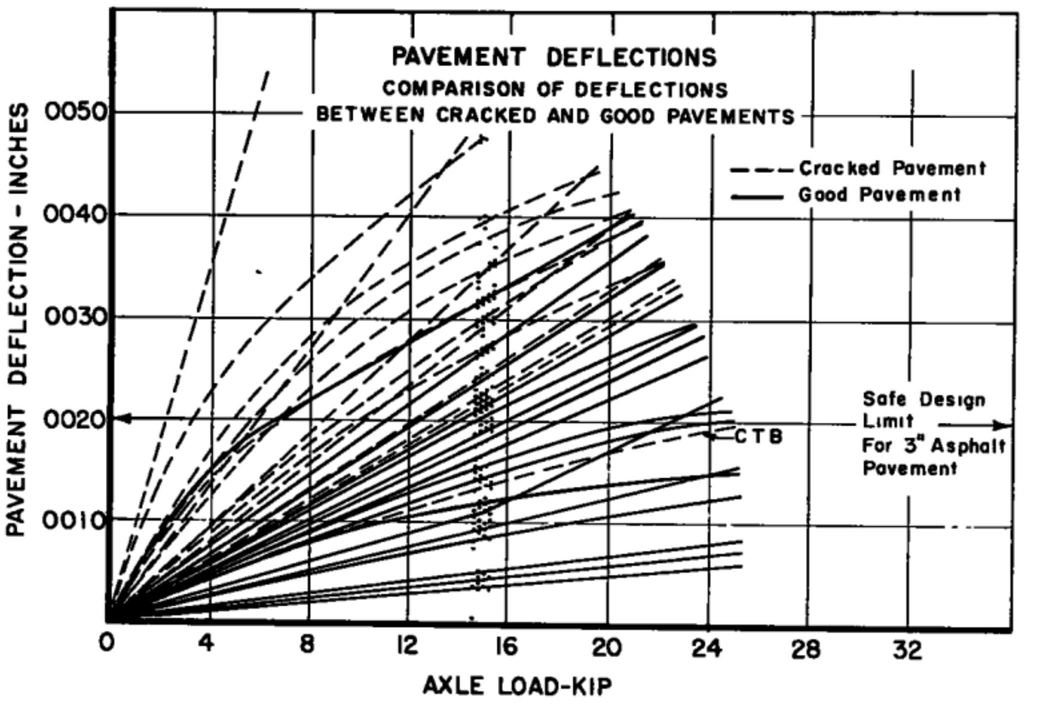


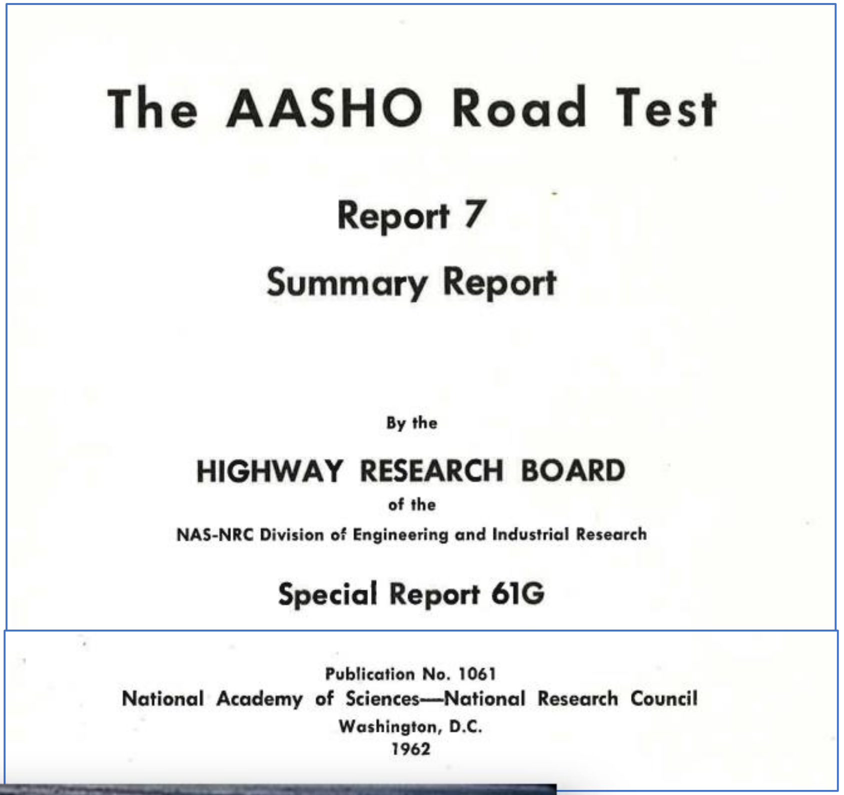
Figure 25.

Traffic and Climate in Empirical Approaches

- Traffic: Convert all traffic into one type
  - Highway Traffic into equivalent 80 kN (18 kip) single axle repetitions (Equivalent Single Axle Loads)
  - Airfield Traffic in terms of equivalent load on design aircraft wheel (Equivalent Single Wheel Load)
  - Why do this?
    - Lack of empirical data, and less calculation
  - Need new observations if traffic changes
- Climate: Usually not considered
  - Lack of empirical data

Example Empirical Design Methods

- Army Corps of Engineers/FAA empirical methods
  - Originally based on CBR test (Caltrans 1920s)
  - Accelerated pavement testing to extend highway design curves until 1960s, continued use of APT today
  - Replaced by LEDFAA mechanistic-empirical method with B777
- Caltrans R-value and deflection reduction overlay empirical methods
- AASHTO 1993 Design Method
  - Concrete pavement and asphalt new pavement designs
  - Based on AASHTO Road Test performance
- All these methods are relatively rapid and easy to perform pavement designs
  - Why not use them?


The AASHO Road Test

Report 7

Summary Report

By the

HIGHWAY RESEARCH BOARD

of the

NAS-NRC Division of Engineering and Industrial Research

Special Report 61G

Publication No. 1061

National Academy of Sciences—National Research Council

Washington, D.C.

1962

Limitations of Empirical Methods

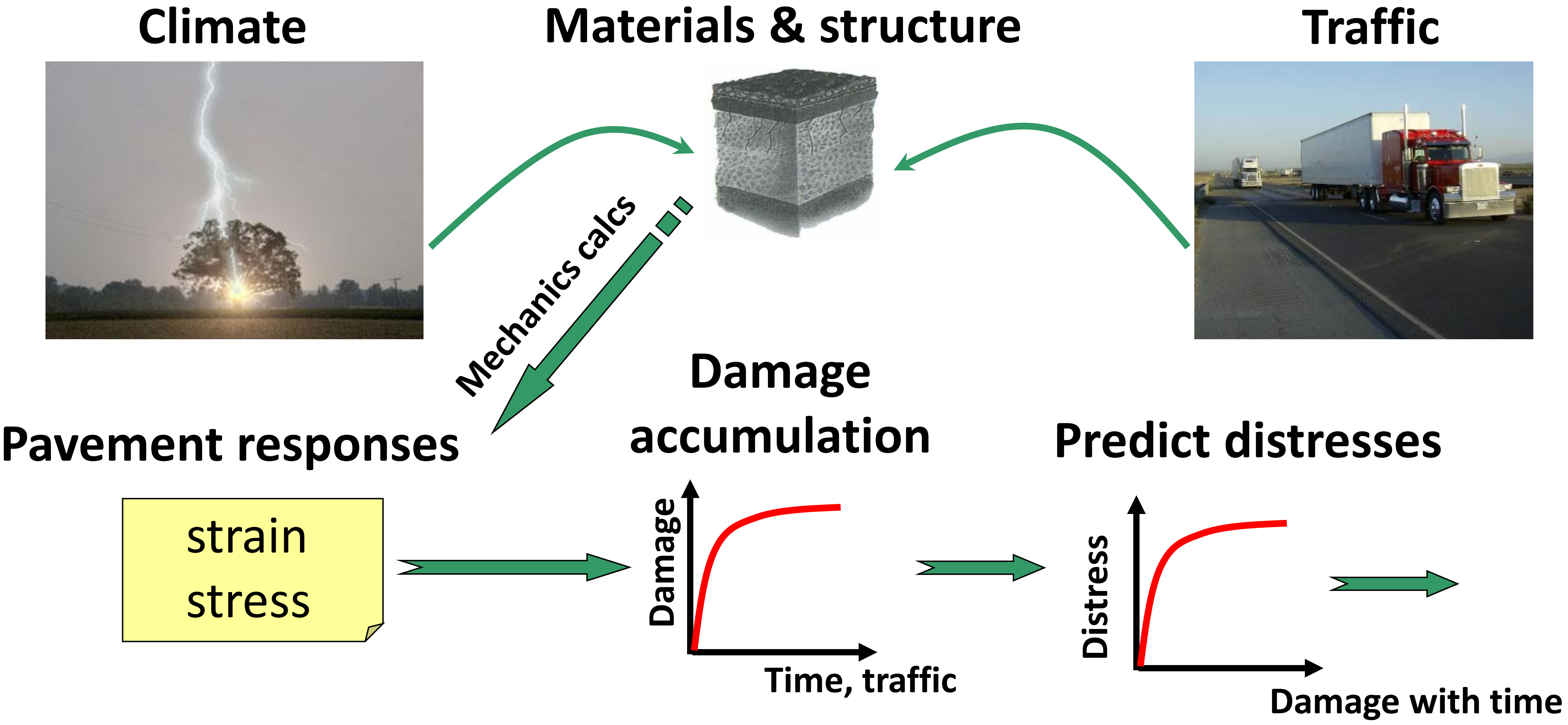
- Most important:
- 1. to consider anything new takes a long time and difficult to include in the method
  - New materials
  - New pavement structures
  - Changes in materials, such as mix design, new components
  - New construction quality specs
  - Changes in traffic
  - Climate
- 2. Mode of failure not explicitly considered
- 3. Variables require great simplification or are ignored
  - Materials
  - Traffic
  - Construction quality
  - Climate
- 3. Reliability hard to consider

Many of these changes have uncalibrated design workarounds, limited data/ judgment solutions, or are not considered

Recent Changes

- Different climate regions
- Higher TIs, thicker pavement and overlays (ongoing)
- Asphalt QC/QA (1996)
  - Reduced average air-voids from 11 to 7%
- Rubberized asphalt on new pavement (2000s)
- Polymer modified asphalt (2000s)
- Full-depth reclamation (2000s)
- Long life asphalt pavement (2000s, 2010s)
  - Greater compaction, high RAP, Rich Bottom
- Cold In-place recycling
  - Partial depth (2000s)
  - Full-depth with cold central plant reclamation (now)
- Hveem to Superpave mix design (2016)
- Thin concrete overlays on asphalt (2018)
- High RAP/RAS mixes (now)

ME Simulation Process



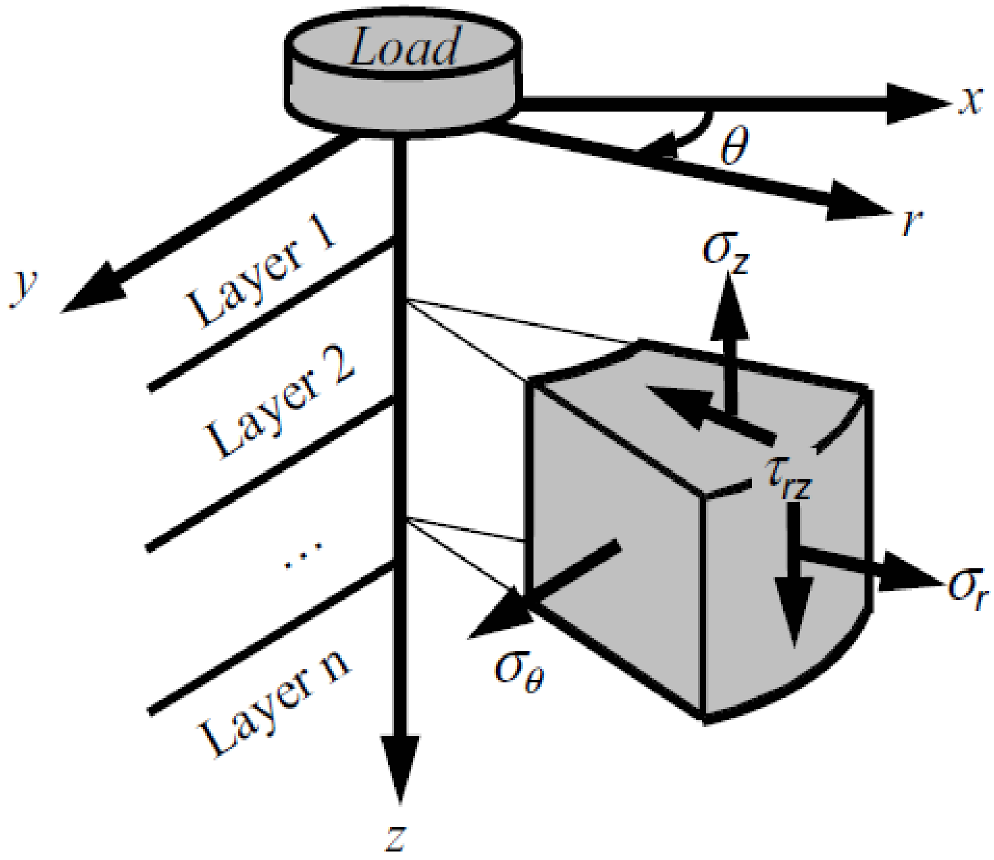
Simulated simultaneously for each distress

Mechanistic-Empirical Design Main Points

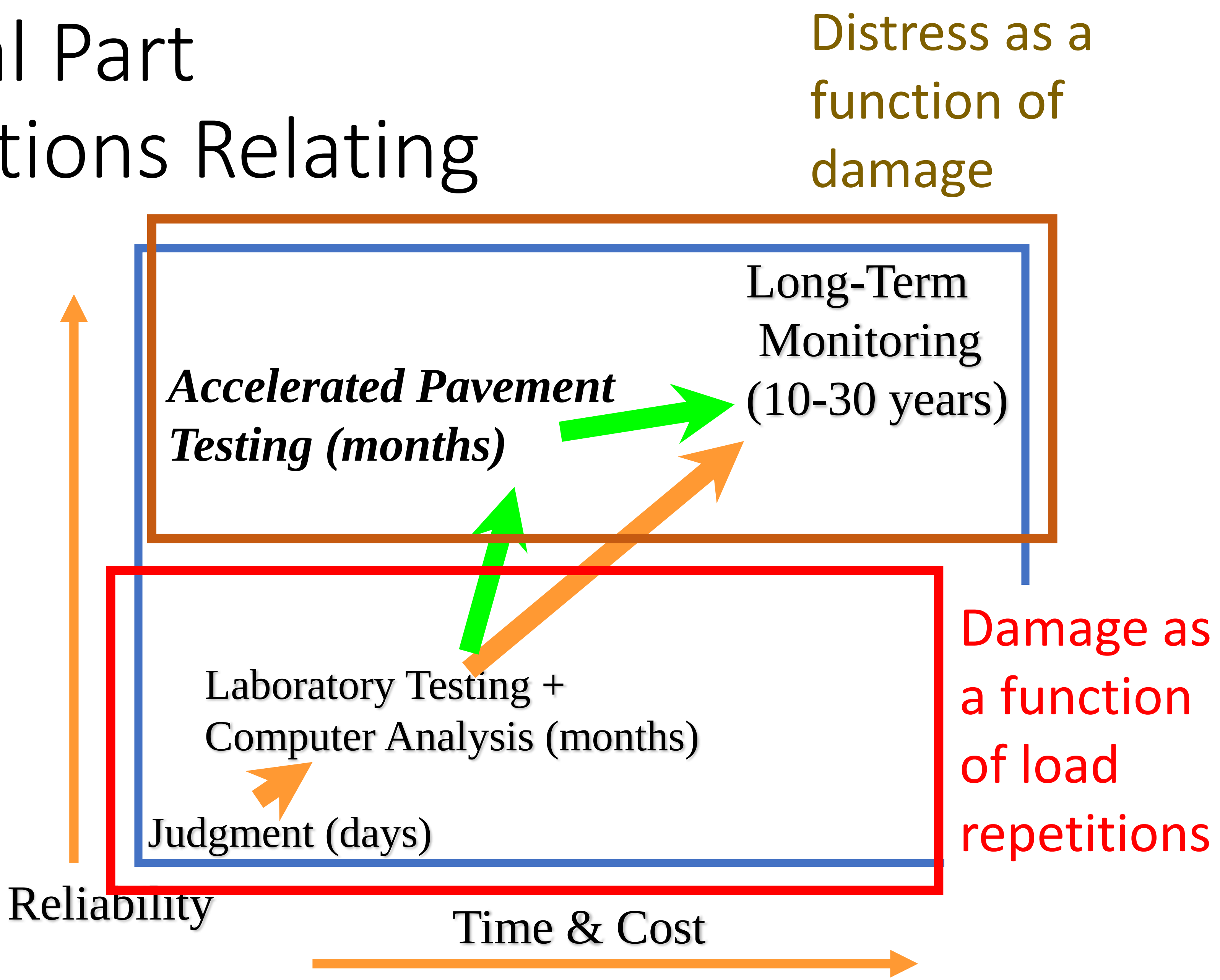
- ME design is an <u>iterative process</u>
  - Uses simulation of damage and distress process under traffic and climate to see if fails before design life
  - Try a pavement and see if it works, if not change, if yes, try until get optimal solution
- <u>Mechanistic</u> part
  - Calculates reaction of pavement to traffic and climate, resulting damage
- <u>Empirical</u>
  - Calculates distress development based on damage
  - Statistical calibration of observed distress compared with calculated damage

Mechanistic Part

- Stresses, strains and deflections from models of pavement and traffic
  - Asphalt pavement
    - Layer elastic theory (Openpave)
    - Conversion of viscoelastic properties into elastic properties at given temperature, time of loading
  - Concrete pavement
    - Elastic finitie element (Islab or EverFE)



Empirical Part
Observations Relating



Accelerated Pavement Testing

UCPRC:UC Davis
Heavy Vehicle Simulator
One wheel, slow speed, overloads
Control temperature, water

Closed Loop Track APT: NCAT (Alabama), MnROAD (Minnesota)
real trucks, full speed, no overloads
can’t control temperature, water

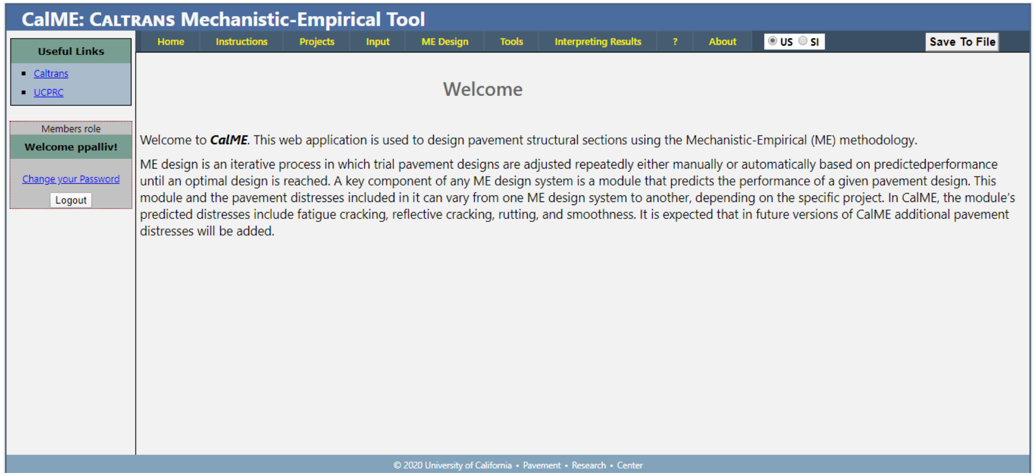
NCAT: http://eng.auburn.edu/research/centers/ncat/testtrack/index.html
MnROAD: http://www.dot.state.mn.us/mnroad/

So, Why ME ?

- Uses mechanics principles
  - Responses (strain, stress) of different pavements, materials, construction simulated based on mechanics calculations calibrated to distresses, not just observations
  - Simulates interactions of different material properties, different structures
  - Makes updating to reflect changes in practice much faster and more accurate
- Includes consideration of:
  - Individual distresses and how different materials, structures will cause failure
  - More detailed characterization of traffic, including individual axle loads instead of uncertain conversion to ESALs, and traffic speeds
  - Temperatures in different climates
  - Effects of variability of materials, construction, climate on risk of early failure, called "reliability" of design

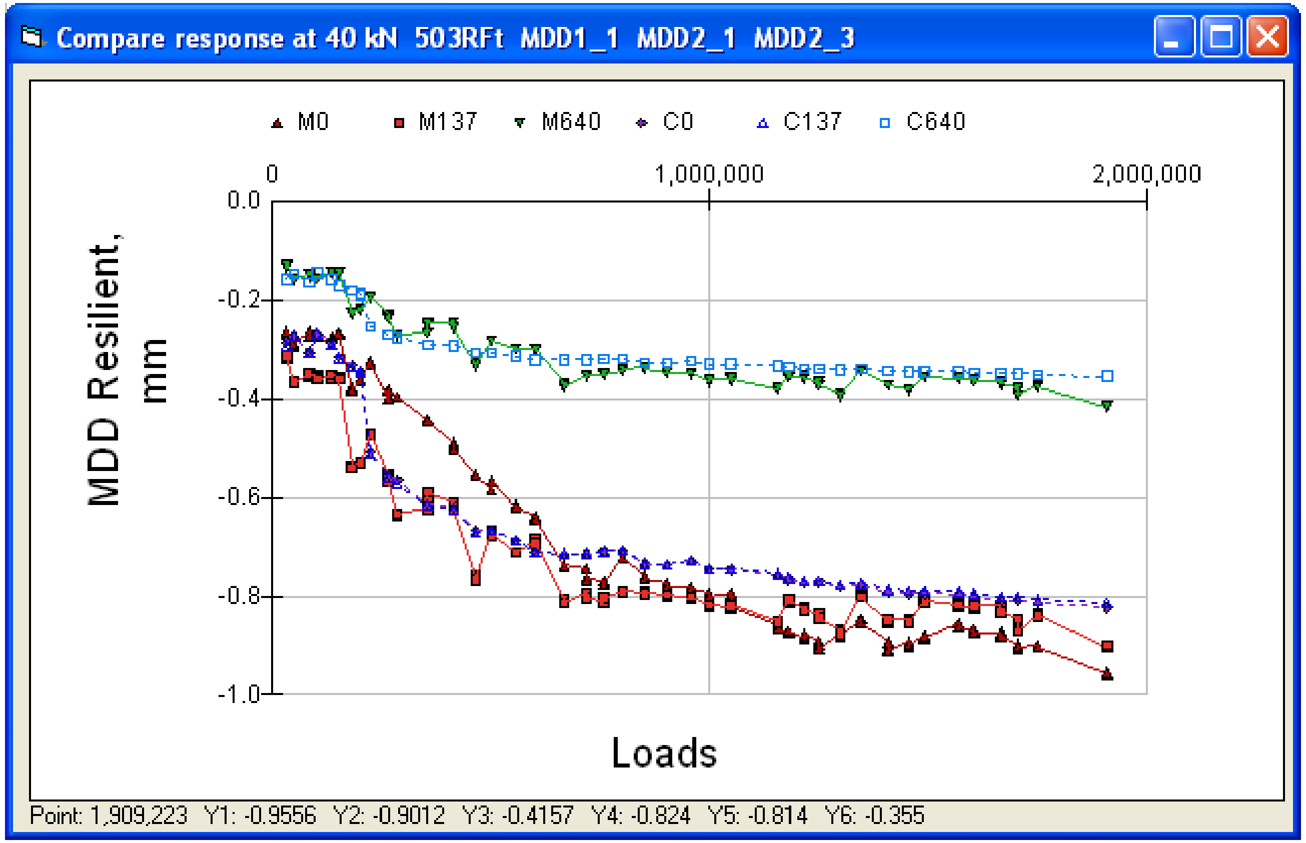
CalME: Asphalt Surfaced Pavement Simulation and Design

- CalME developed for Caltrans to consider:
  - Pavement preservation overlays
  - Longer design lives for new pavement
  - Reconstruction and rehabilitation
  - New materials
  - Recycled materials (in-place & plant recycled asphalt, concrete, granular materials, rubberized asphalt)
  - Construction compaction
  - Variety and condition of existing pavement structures
  - Reflective cracking in asphalt pavements
  - Climate regions
  - Changes in tire inflation pressures and axle loads
  - Traffic speed
  - Variability of sites contractors, materials and construction
  - Uncertainty regarding future traffic growth

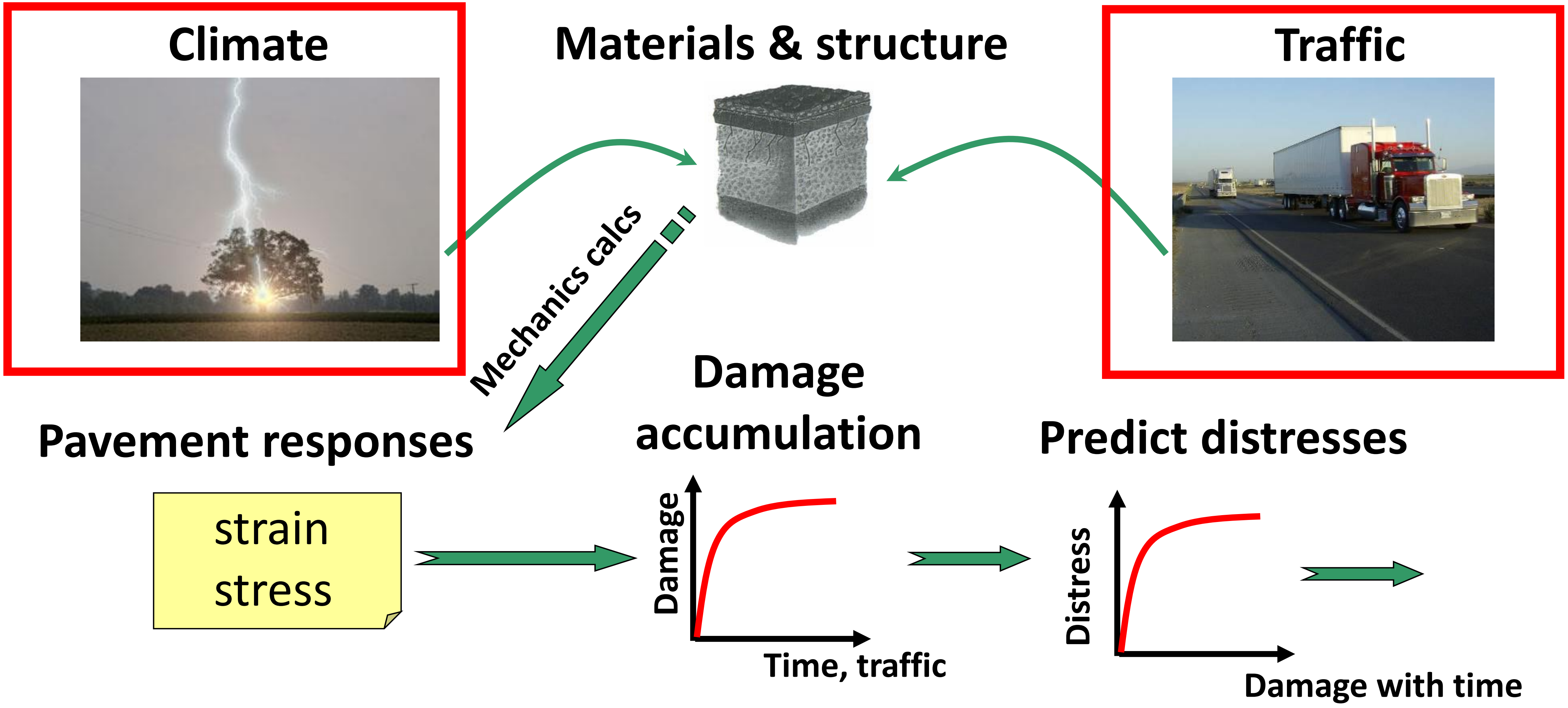


CalME is an Incremental-Recursive Simulation Program

- Incremental-recursive
  - Characterize material damage process for different strain/stress levels
  - Simulate damage process in each time increment of entire life
    - Update stiffness after each increment
  - Correlation of damage to distress
  - Calibrate using data from entire damage process, not just the final “end point” of failure
  - Calibrate:
    1. Responses are calculated correctly through entire life considering damage process
    2. Damage from responses with distresses

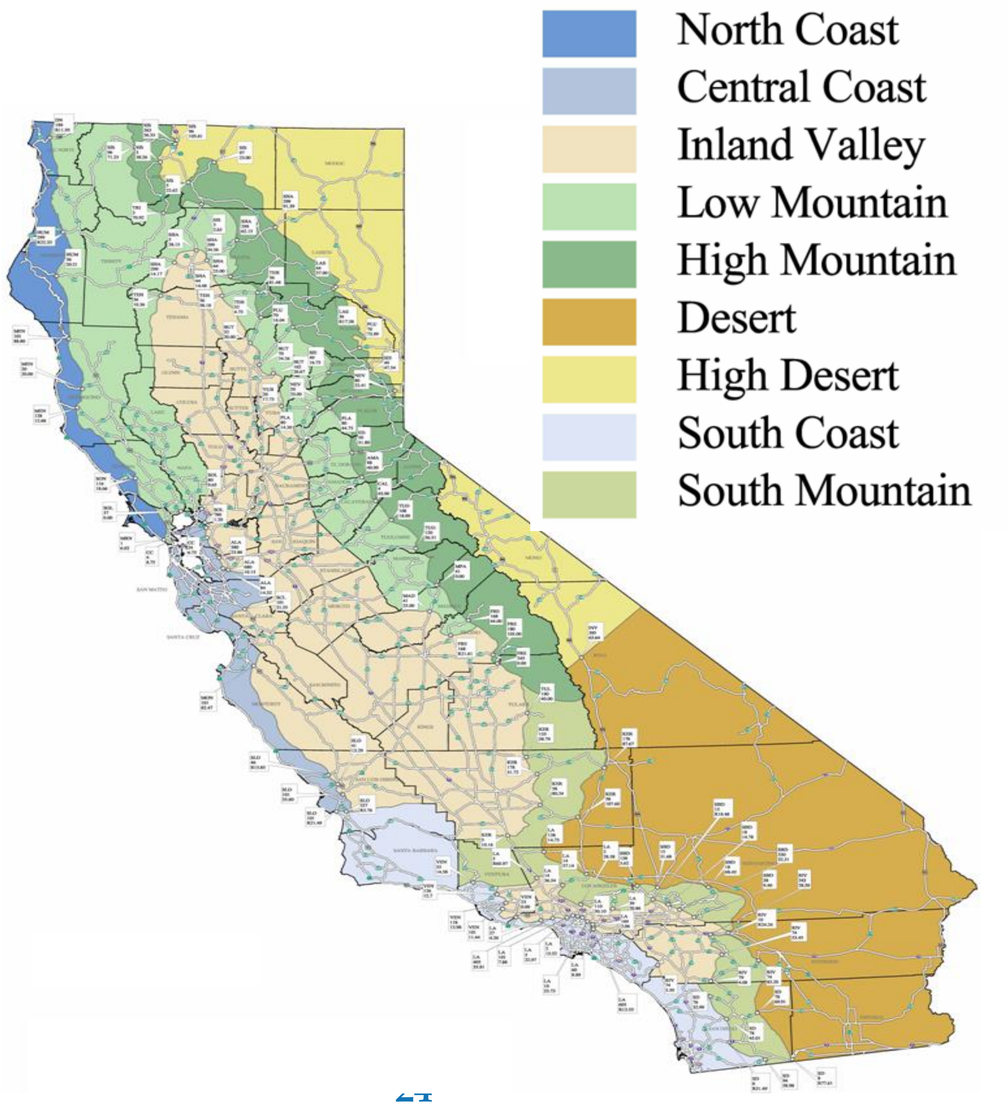


ME Simulation Process



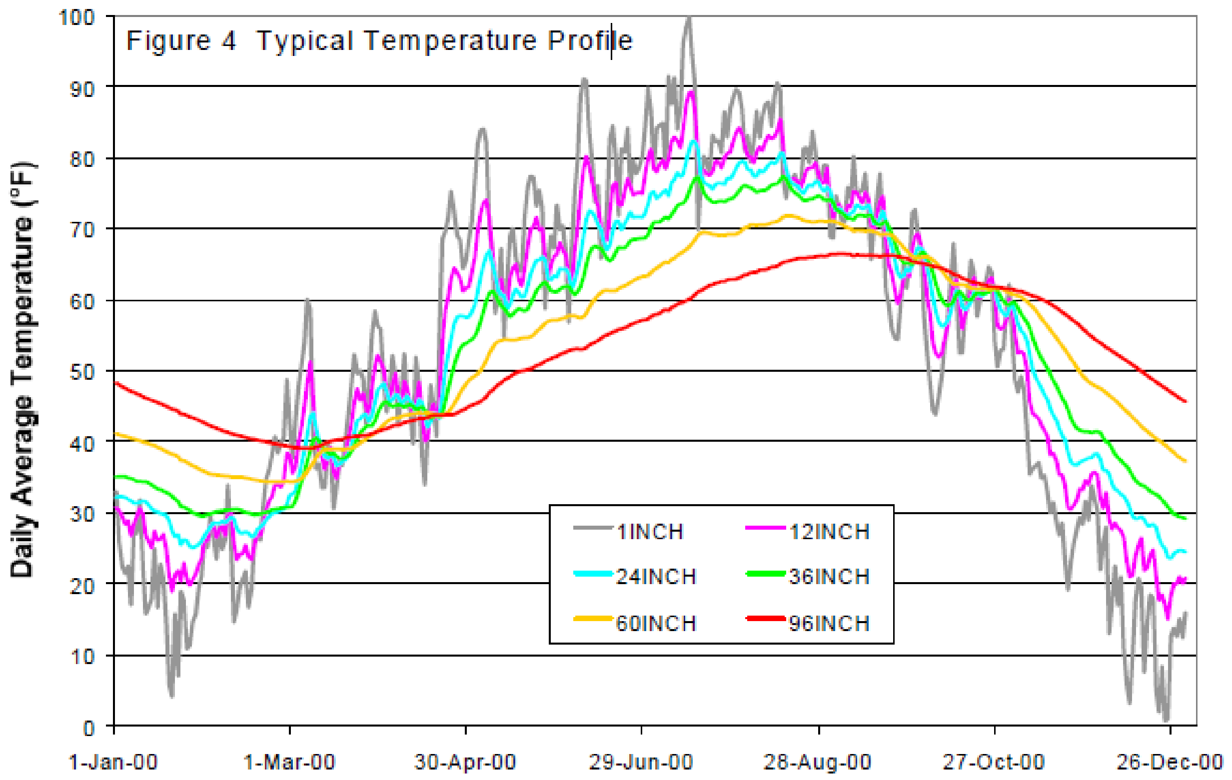
Climate Region Selection

- Climate regions for pavement design were developed for CalME, asphalt binder PG grade selection and concrete pavement design in 2005
  - Based on 30 years of historical data
  - Being update for 1990 to 2020 climate
- In CalME, the climate zone is automatically assigned based on project location
  - The user can change the climate region



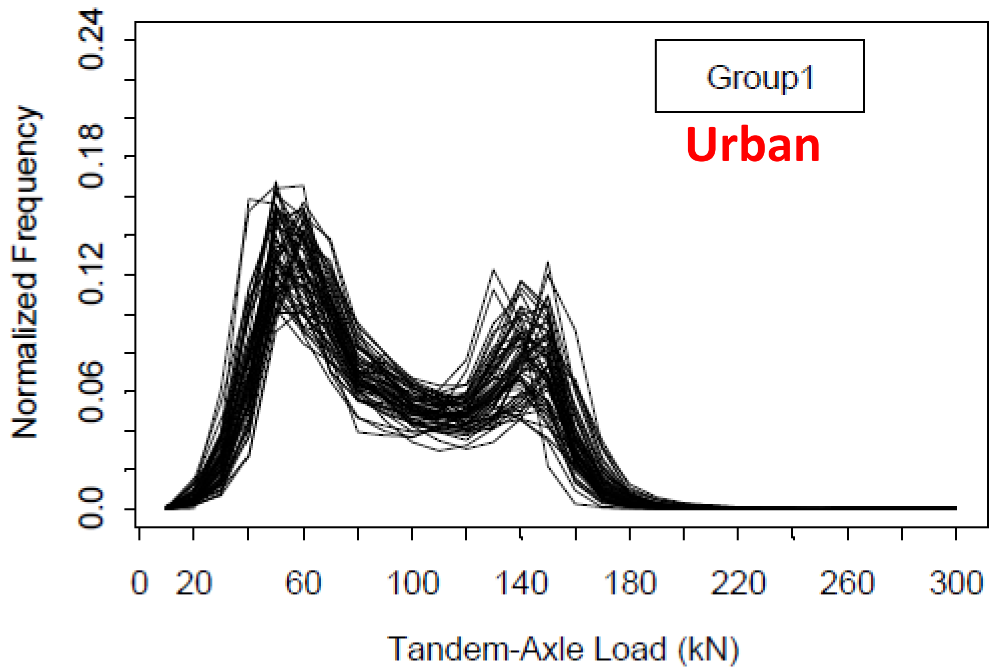
Pavement Temperature

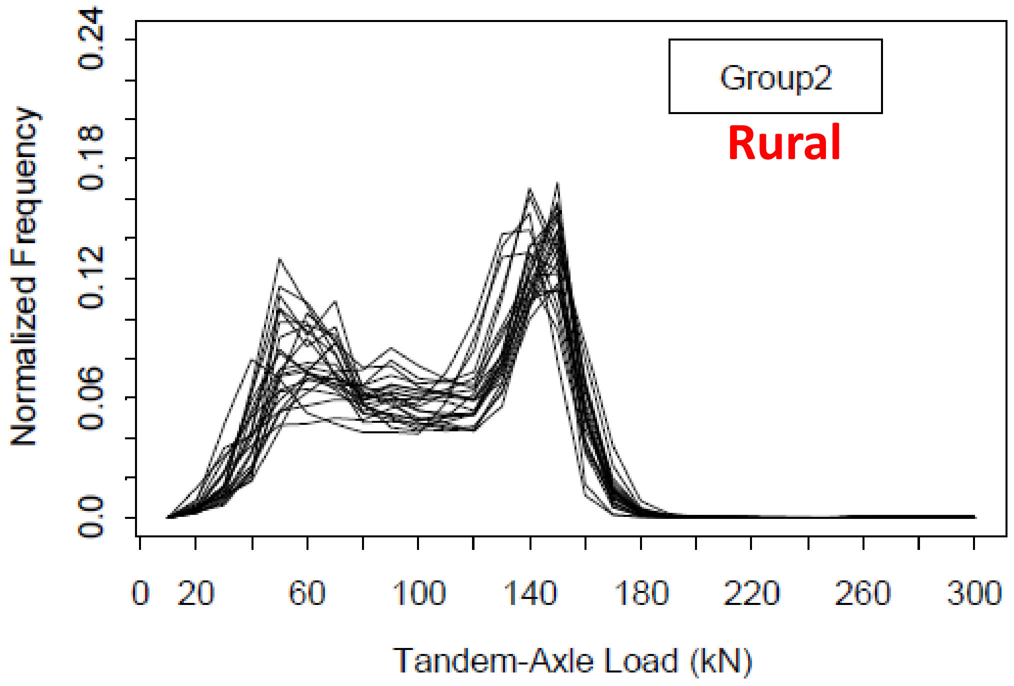
- CalME uploads a sequence of hourly temperature profiles for the climate region and pavement structure
- Temperature profiles are generated in CalME from a database of calculated temperatures at different depths in the asphalt
  - FHWA Enhanced Integrated Climate Model (EICM) software was used to calculate temperatures using 30 years of data
- The temperature profiles change from year to year in the simulation to reflect typical annual variability, based on historical data

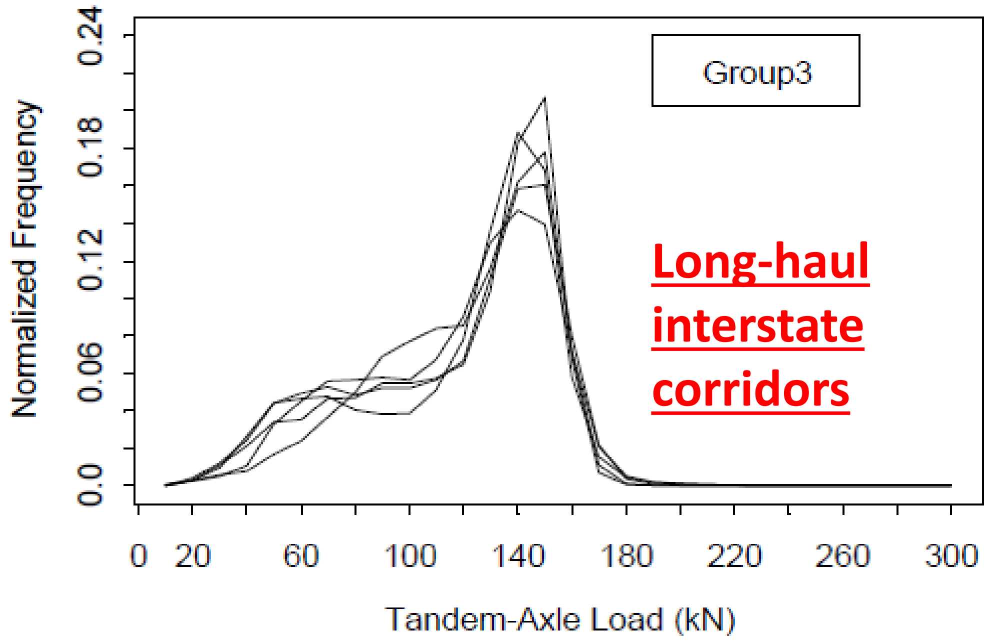


Axle Load Spectra

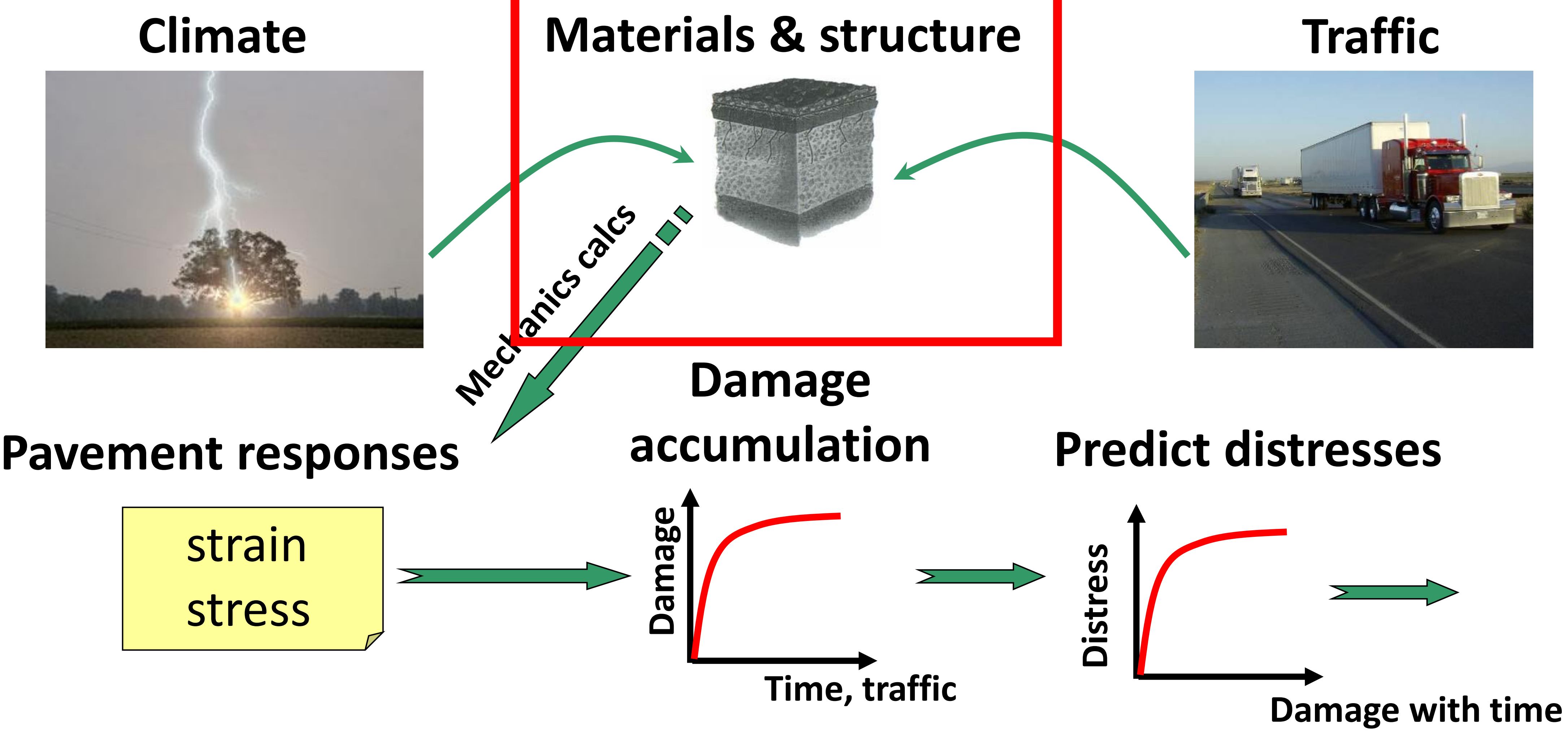
- Represents the distribution of load magnitude carried by each axle type during a given period of time
- There are 5 axle load groups







ME Simulation Process



Pavement Structure Characterization

- Pavement structure is characterized by:
    - Thickness (h)
    - Stiffness (modulus), E
    - Poisson ratio ν
- These are used in layer elastic theory module in CalME to calculate strains and stresses
- User selects material types and thicknesses
- New layers: CalME uploads default stiffnesses and poisson ratios
- Existing layers: CalME can upload a back calculation file or user can input

Layer 1: E, ν, h
Layer 2: E, ν, h
Layer 3: E, ν, h
Layer 4: E, ν, semi-infinite

- As many layers as needed can be input
- Subgrade is semi-infinite unless a bedrock layer has been identified in back calculation using CalBack

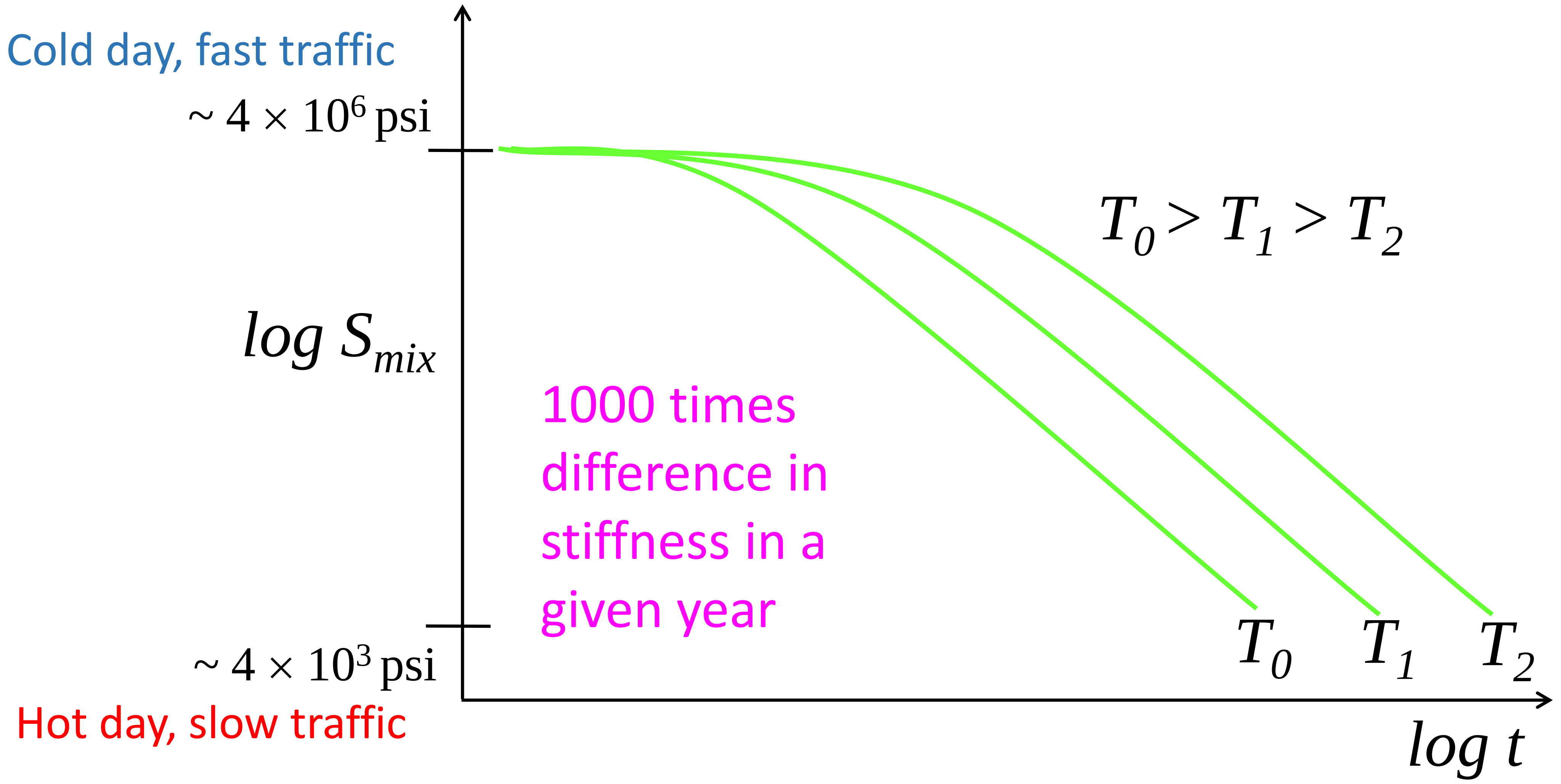
Resilient Modulus of Unbound Layers

- **Resilient modulus will replace "R-value" for unbound materials characterization**
- Determined in the laboratory for new materials planned for use in new pavement projects, or in-situ for an existing pavement (rehab projects)
- In CalME, median default values are used for standard materials
  - Variability of materials considered through reliability calculations

theconstructor.org

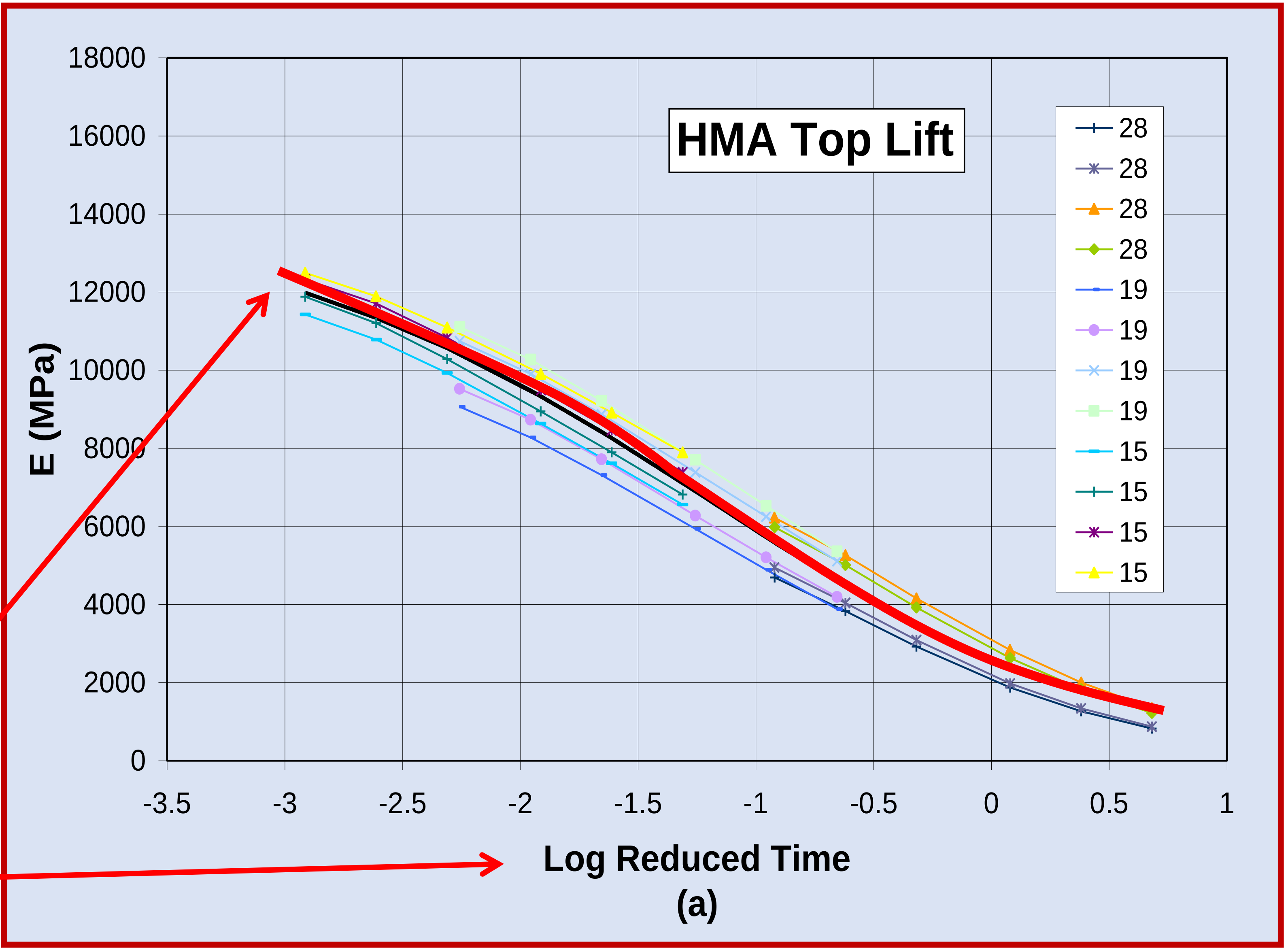
Asphalt Concrete Stiffness Master Curve

Smix = stress/strain (t,T) for all times and Temperatures



Master Curve for an Asphalt-bound Material

- Master Curve is the relationship between stiffness, frequency, and temperature
- Design default material is the state-wide median for each asphalt type and grade



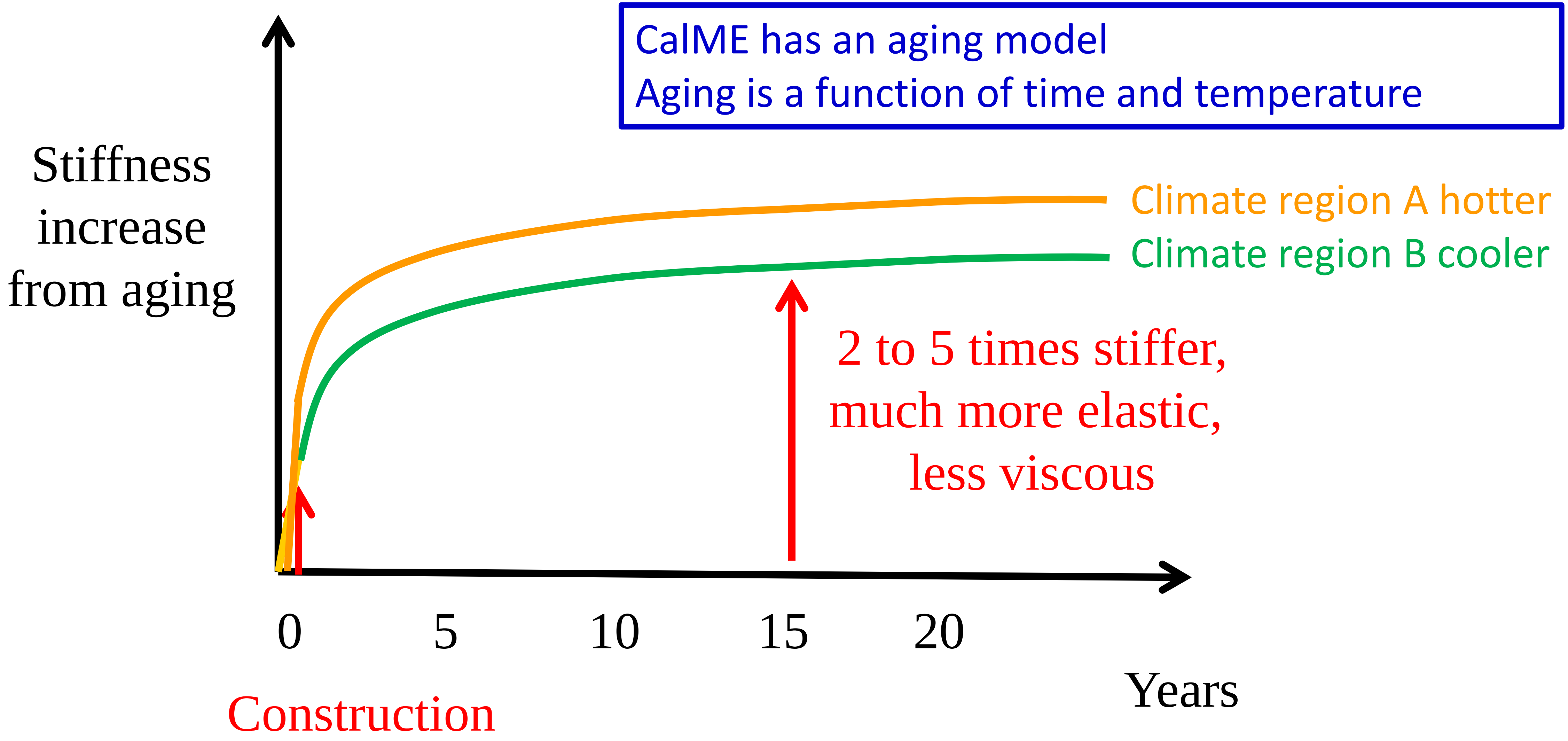
Master curve

Reduced time captures time and temperature

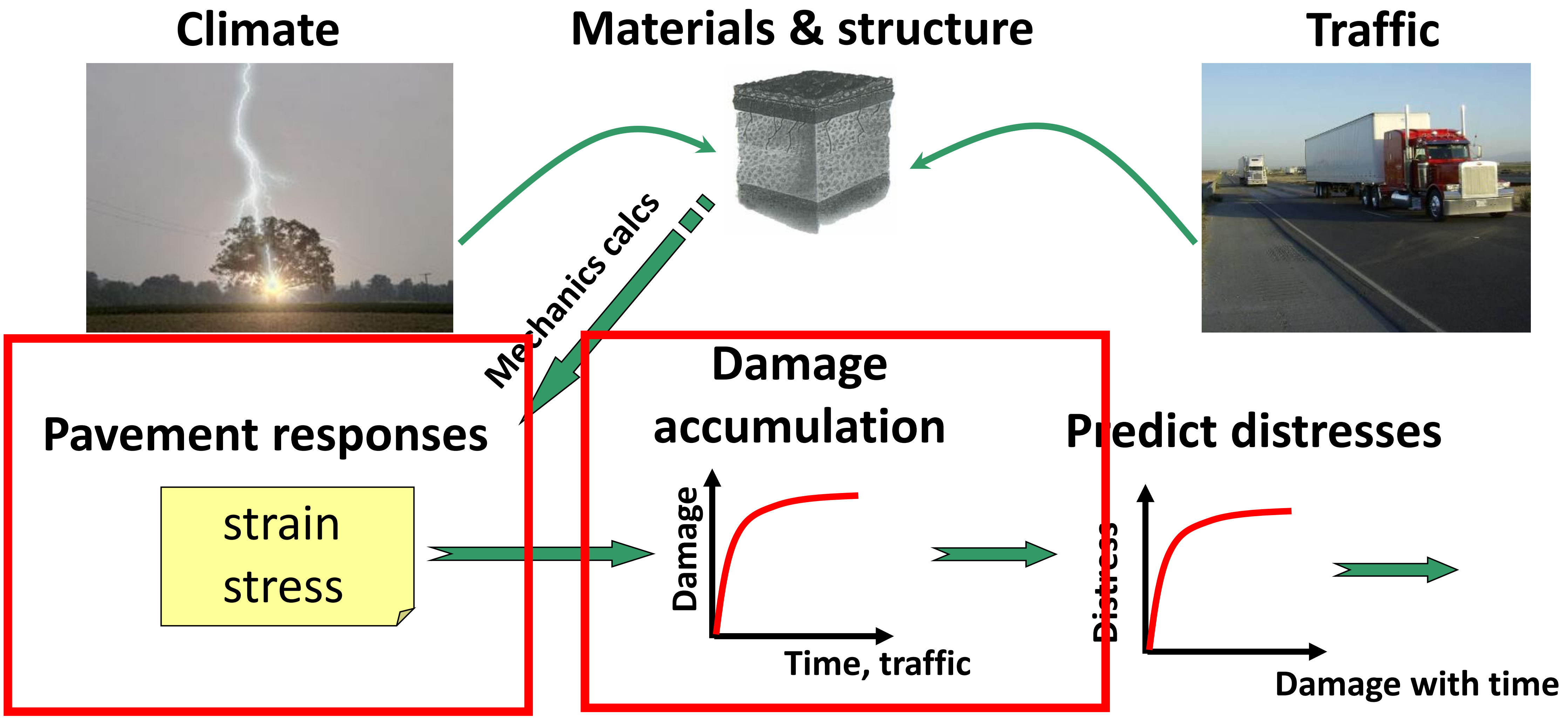
Aging

mostly done by 5 years after placement

CalME has an aging model
Aging is a function of time and temperature



ME Simulation Process

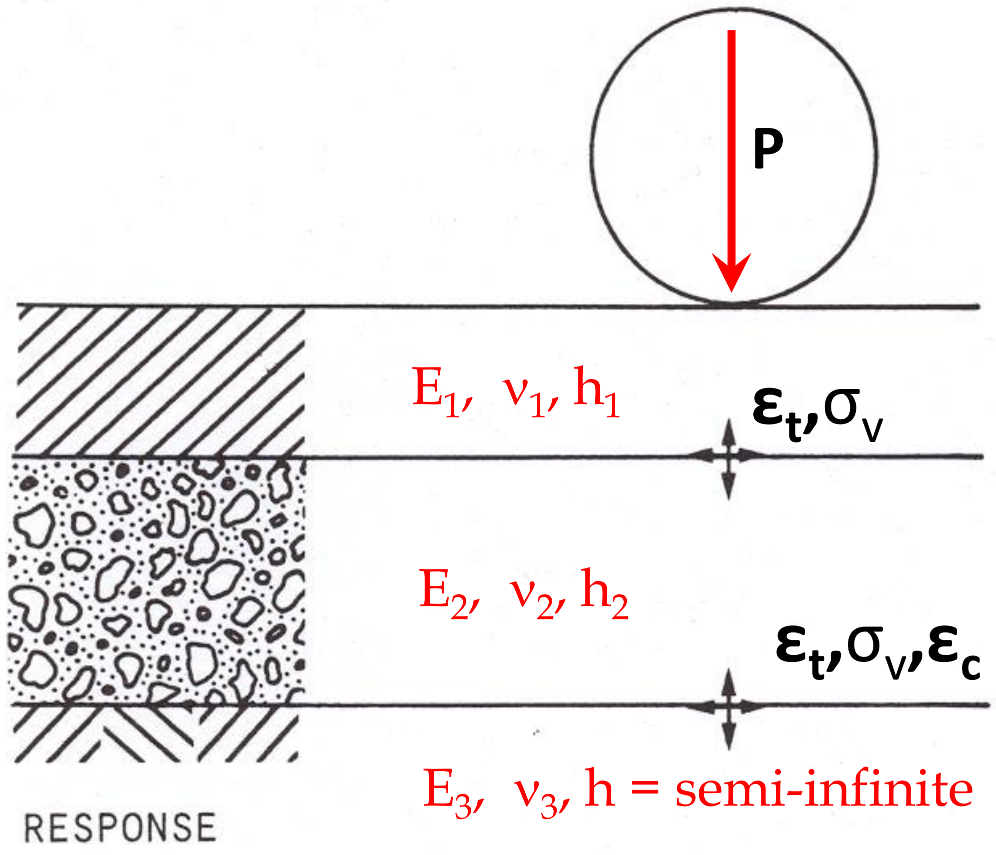


Asphalt Pavement Distresses Considered in CalME

Distress	Accounted for in:
Asphalt fatigue cracking	CalME
Asphalt reflective cracking	CalME
Subgrade and base rutting	CalME
Asphalt mix rutting	mix design, CalME
CTB fatigue cracking, crushing	CalME
In-place recycling (FDR, PDR) cracking, rutting	CalME
Low temperature cracking	PG binder selection
Expansive soils	Soils analysis: subgrade treatment or overburden design

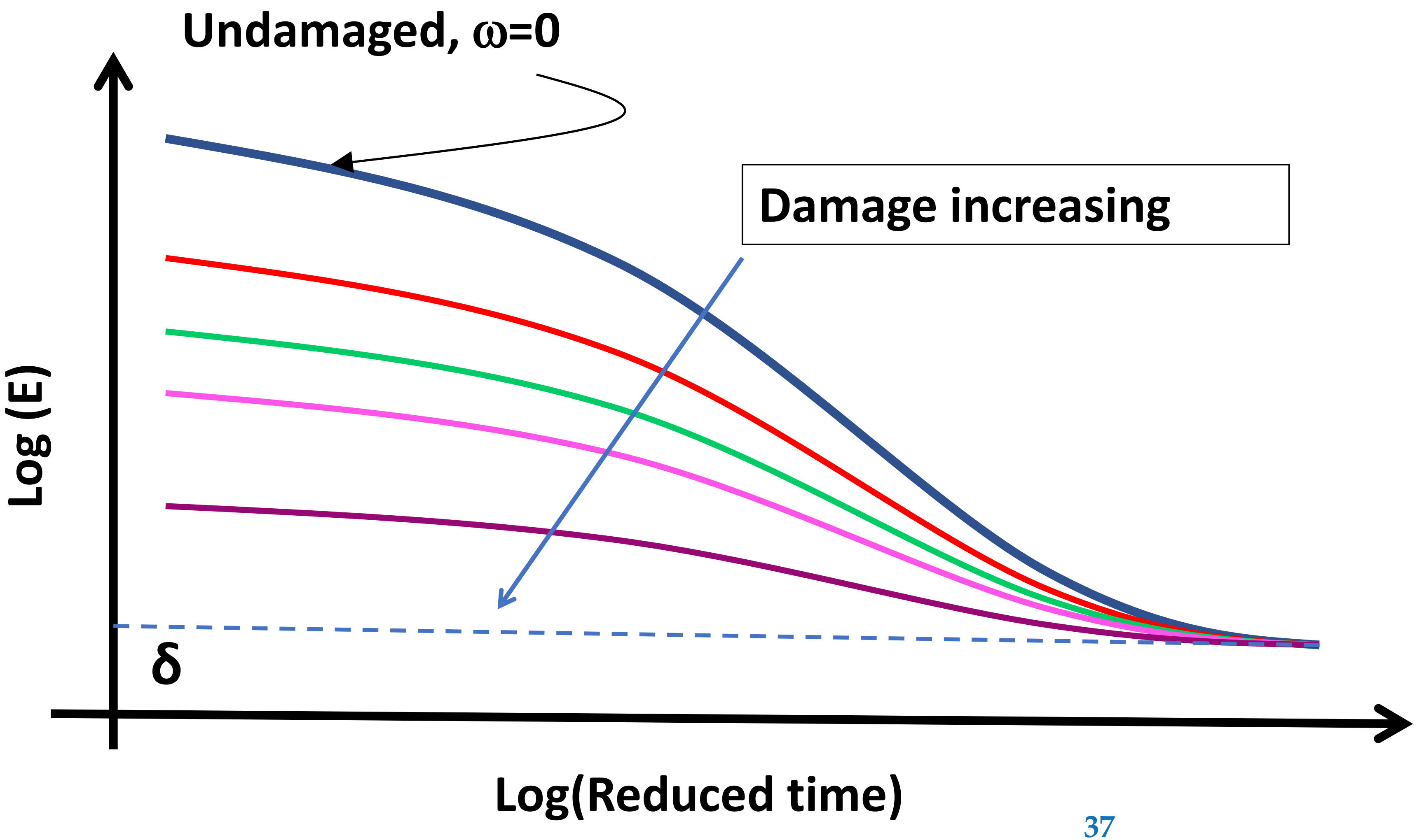
Damage Caused by Mechanistic Responses

- Critical responses are different for each damage mechanism and resulting distress
- Critical responses are typically:
  - Tensile strain at bottoms of asphalt and cement bound layers for cracking
  - Vertical compressive strain at tops of unbound layers (SG, base, etc) for rutting
  - Vertical compressive stress at tops of cement bound layers for crushing
  - Shear stress and strain near the surface of asphalt layers for rutting



Fatigue Cracking in Wheelpaths

Fatigue Damage Applied to the Asphalt Stiffness Master Curve



Full-Depth Reclamation and Partial-Depth Recycling

- CalME models have been developed using HVS test results
- Status:
  - Mechanistic damage models completed
  - Empirical cracking models based on damage are currently being calibrated against available sections in California and other states
  - Updated calibrated models in late 2020

FDR-PC Damage from HVS Testing

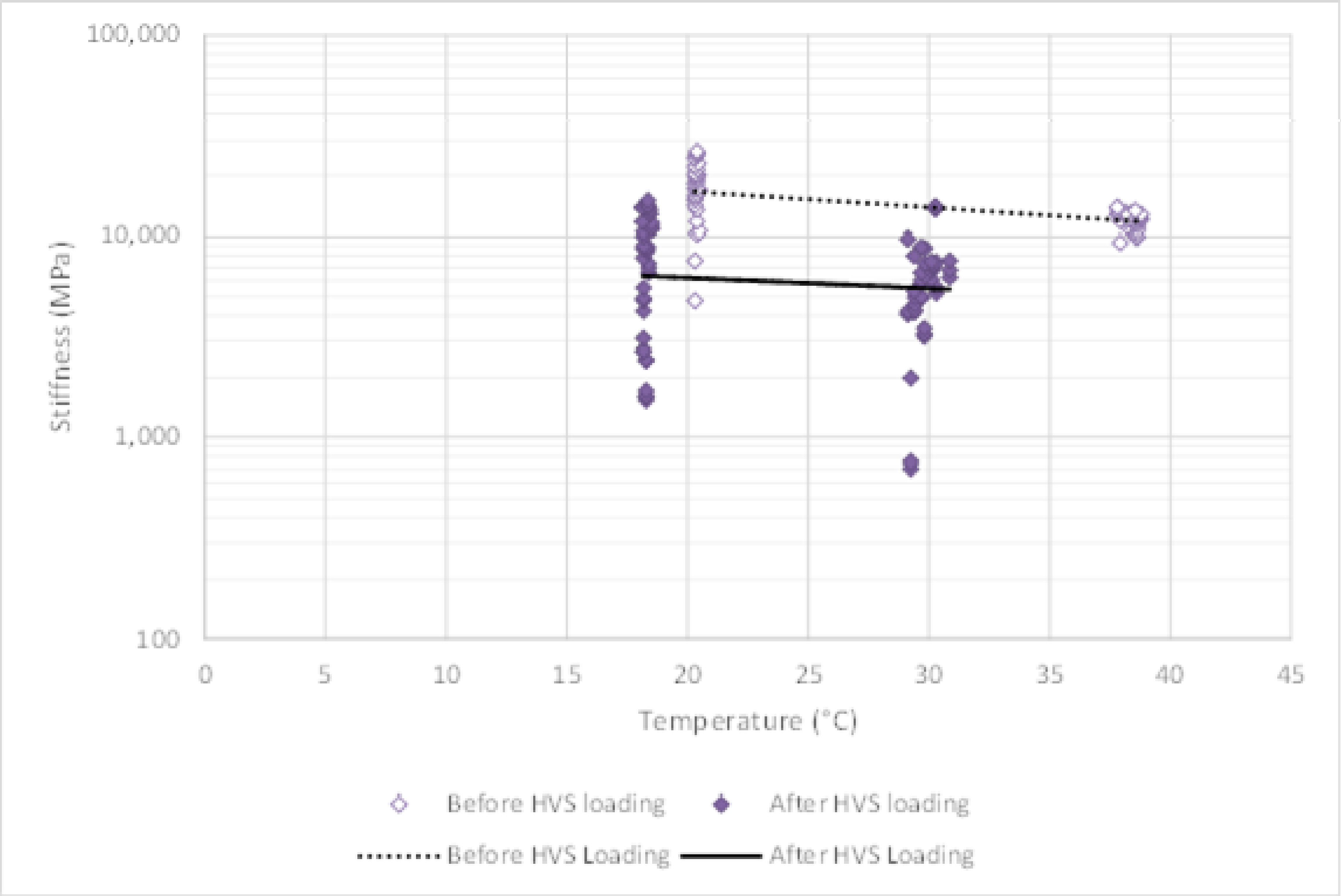


Figure 4.4: FDR-PC: FDR layer stiffness versus temperature from FWD backcalculation, loaded area.

ME Simulation Process

Climate

Materials & structure

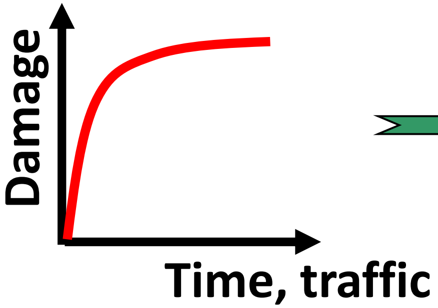
Traffic

Mechanics calcs

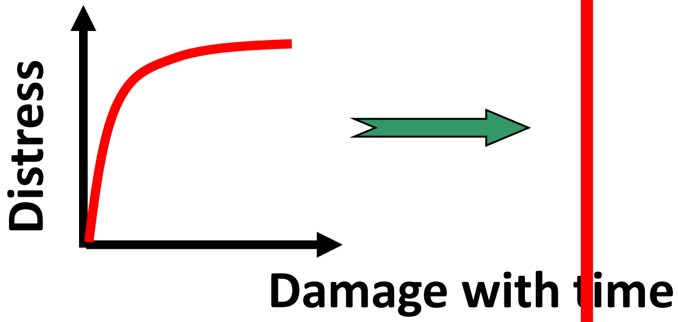
Pavement responses

strain
stress

Damage accumulation



Predict distresses



Damage vs. Distress

- Damage is:
  - Loss of stiffness
  - Permanent deformation

Leads to Distress:

Cracking

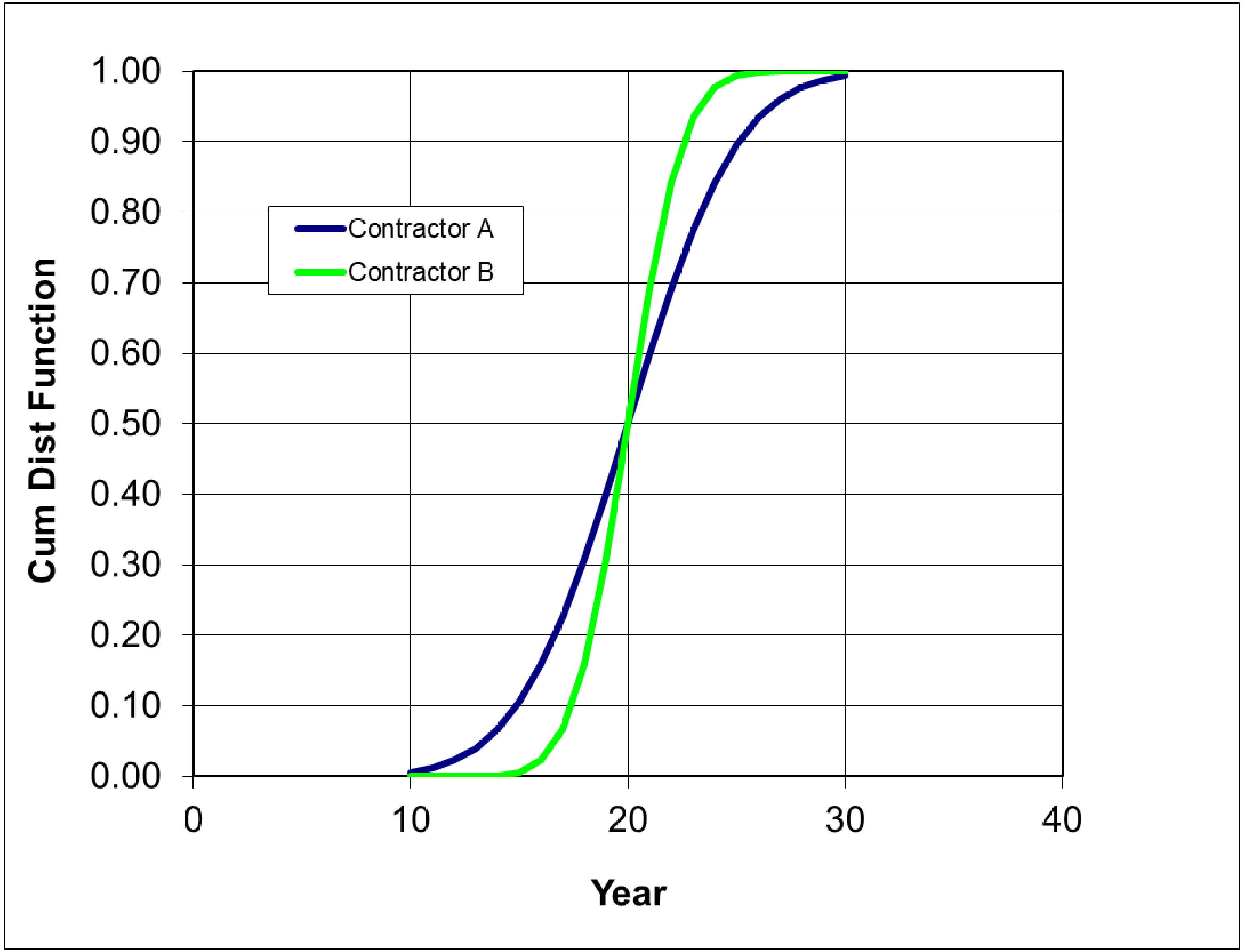
Rutting

- Calibration: simulated damage is correlated to observed distress

Reliability

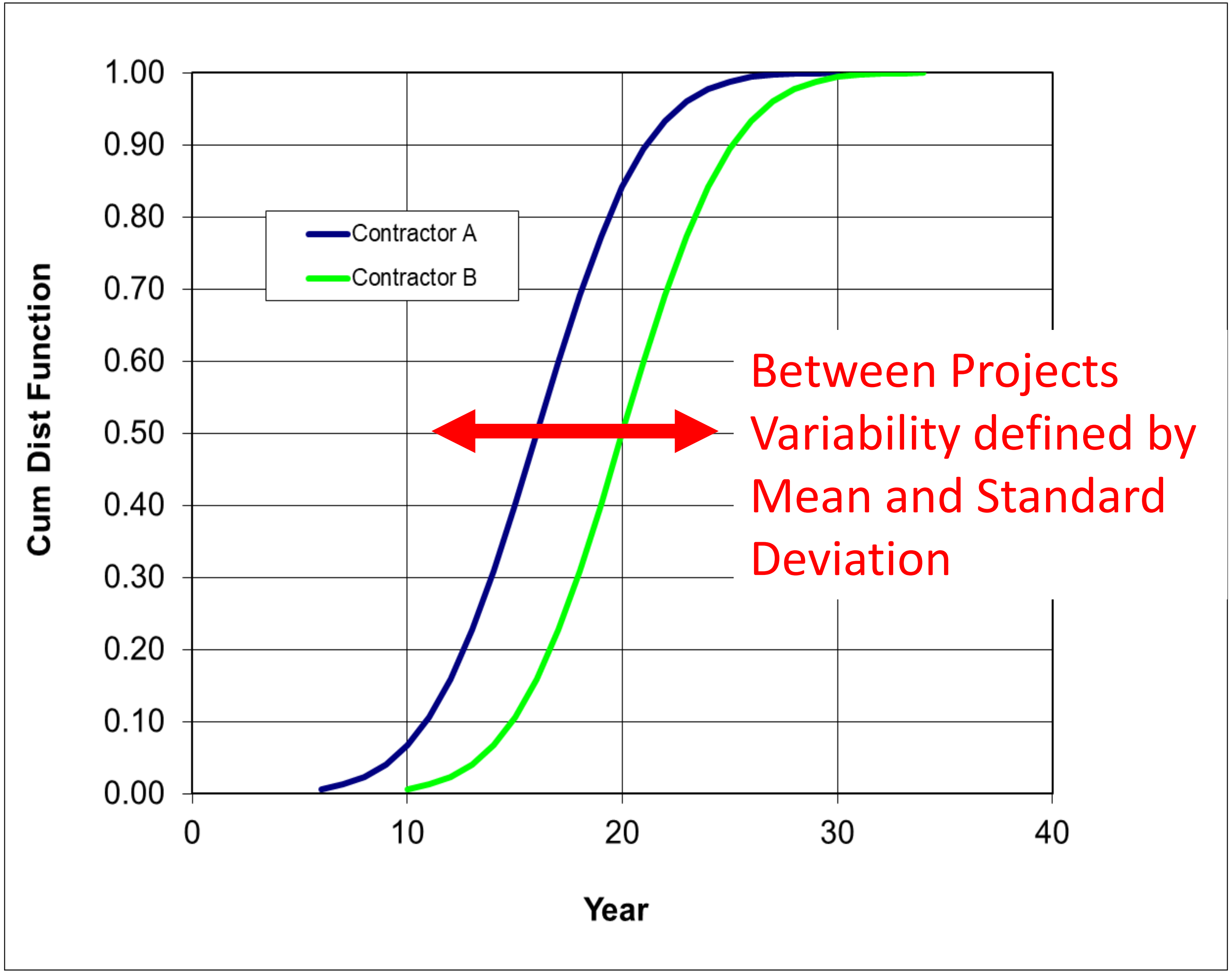
- Data based reliability:
  - Probability that pavement won't fail before intended service life
  - Reliability based on observed variability on Caltrans network
  - Account for measured variability on the Caltrans network with appropriate reliability
- CalMe accounts for two types of variability in reliability calculations

Within project variability



Within project variability = for a given contractor and material, the variability of the site, materials production and construction process within the project

Between Projects Variability



Between project variability = variability of low bid contractor material appearing on the job; designer does not know properties of material that will show up

CalME v3 Calibration of Damage to Distress Transfer Functions with PMS Condition Survey Data

- Conventional approach to ME design calibration
  - Materials properties sampled on selected test sections, damage simulated for those sections, damage to distress transfer functions calibrated using PMS data for those sections
  - Typically uses about 50 to 200 miles of pavement for calibration
- CalME v3 calibration approach
  - Entire network in Caltrans complete pavement condition survey database since 1978 used for calibration
  - Calibrated for factors that low-bid project designer knows:
    - Traffic
    - Climate
    - Thicknesses
    - Material types
  - Used state-wide median values for factors that low-bid designer doesn’t know:
    - ME material properties (stiffness, damage function) for material type
    - Within project variability of thicknesses, stiffnesses, damage functions
  - Same approach and reliability method used for calibration of Pavement ME concrete design method

Pavement management system performance data used for CalME v3 calibration in 2020

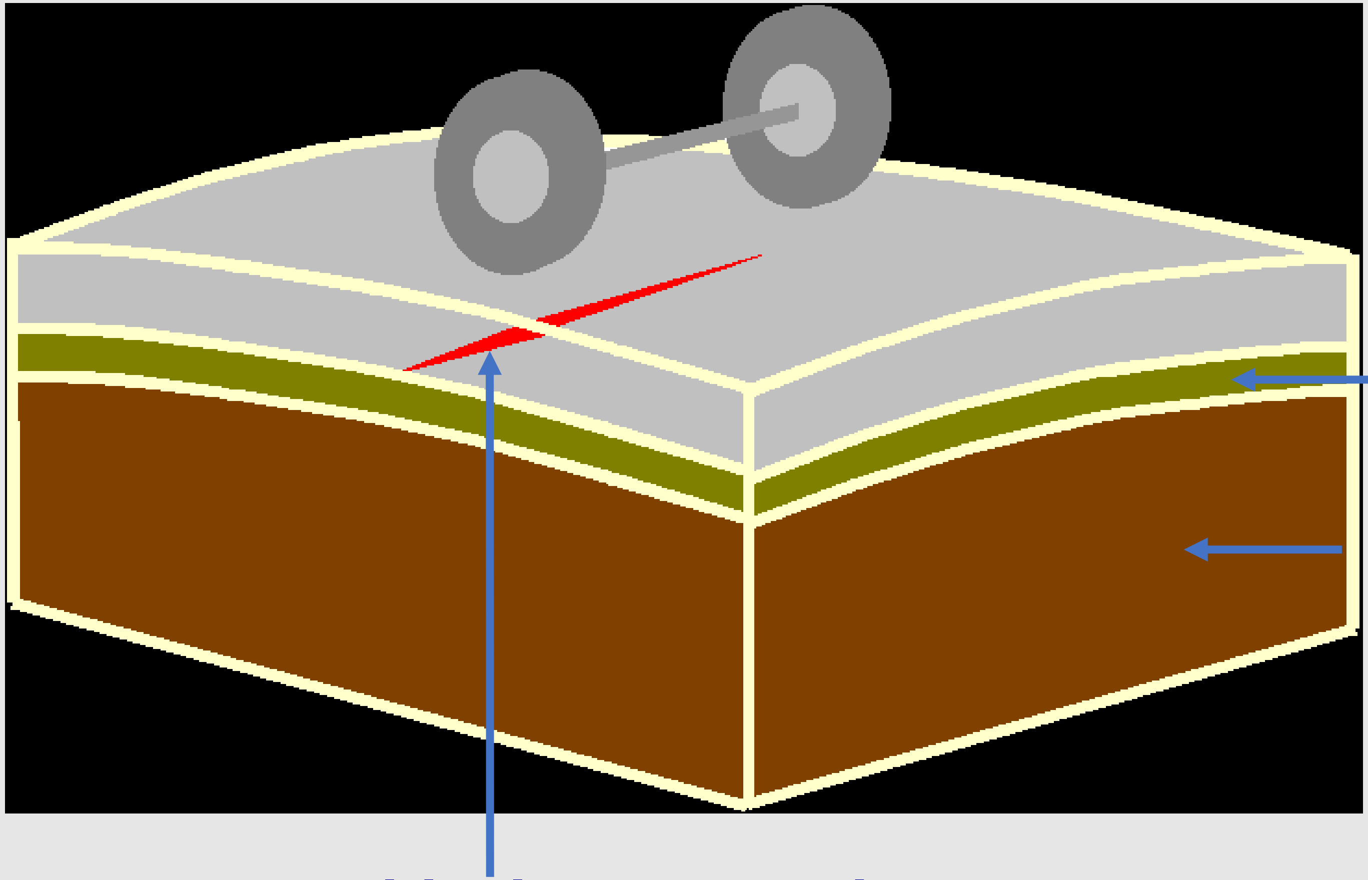
- Time periods for calibration PMS data:
  - 1978-2000 about 1/3 of observations
  - 2000-2018 about 2/3 of observations
- Used typical materials for different time periods for calibration

Pavement Type	Observations	Lane-miles
New asphalt pavement: aggregate base	8,530	1,021
New asphalt pavement: other base types	3,292	403
Asphalt overlays on asphalt	147,837	19,634
Asphalt overlays on concrete	9,331	1,594

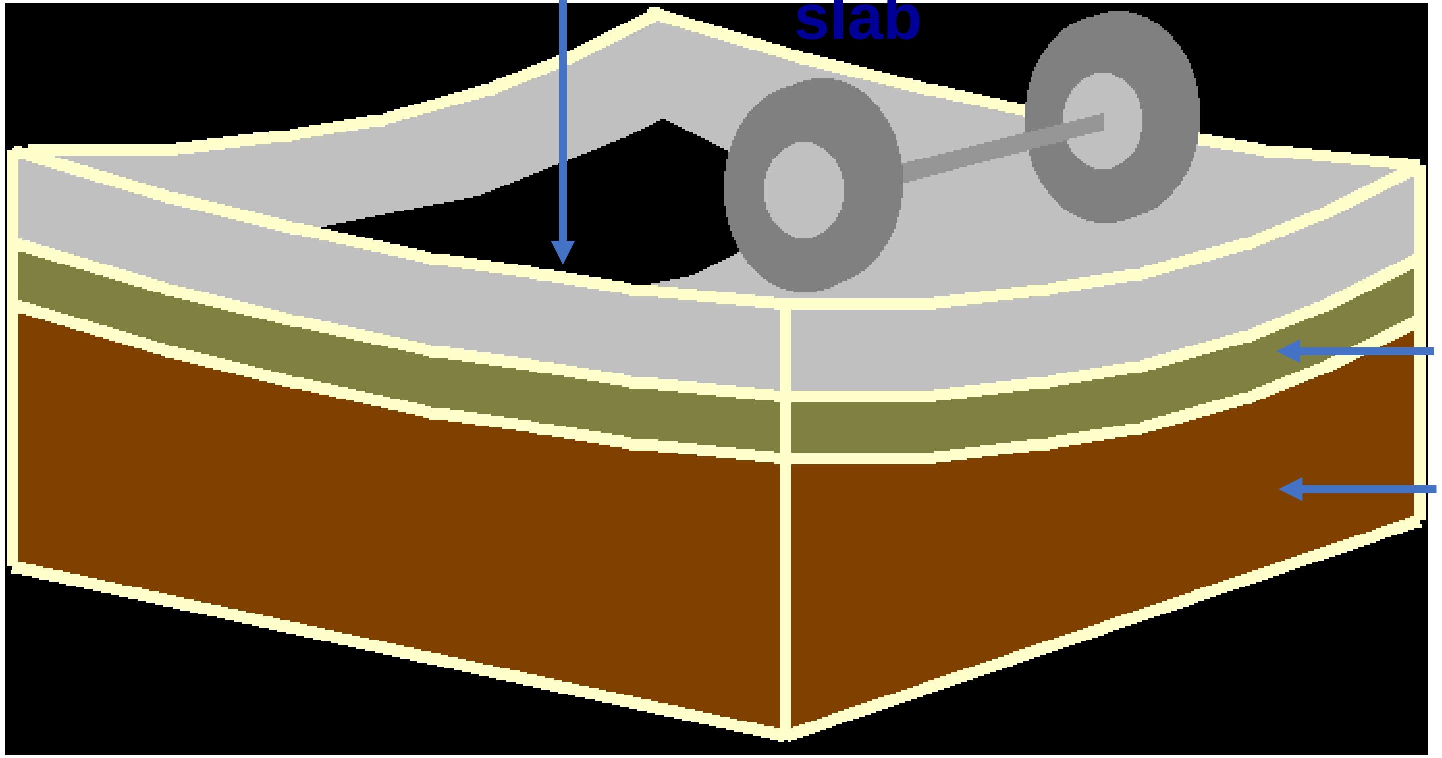
Pavement ME: Jointed Plain Concrete Pavement Simulation and Design

- Pavement ME developed by AASHTO to consider:
  - Longer design lives for new pavement
  - Reconstruction and rehabilitation
  - Dowels
  - Shoulder types
  - Base types
  - New materials
  - Slab lengths
  - Climate regions and effects on concrete pavement
  - Changes in tire inflation pressures and axle loads
- Uses same ME principles as CalME
  - Used by Caltrans to produce jointed plain concrete design catalog
  - Also recalibrated in 2020 using more than 40 years of Caltrans performance data

Bottom-Up Cracking
Mid-slab Loading—Positive Curl/Warp



Top Down Cracking
Joint Loading -- Negative Curl/Warp



Pavement Management System Data for Pavement ME calibration

Current Pavement ME cracking model is calibrated with about 20 miles of LTPP (about 0.4 miles in California)

- Surveys data used
  - PCS 1978 to 2015
  - APCS 2010-2011
- 30,155 pavement sections (~4380 miles)
- 265,033 performance observations
- Known variables
  - Construction date
  - Slab thickness
  - Slab length
  - Base type
  - Shoulder type
  - Load Transfer (doweled/un-doweled)
  - Climate
  - Wim Spectrum
  - AADTT
- Unknown variables
  - Material properties for PCC, base, and subgrade

Key Points of the New Calibration Approach

- Very large data set containing about 30k (~4300 miles) pavement sections with about 5-10 performance data per section.
  - National calibration was done on about hundreds (~20 miles) of pavement sections
- Coring the pavement for material property variables?
  - It only gives a few data points for a project, uncertainty where they fall in within project distribution
  - State-wide distributions of materials variables not known to the designer in design-bid-build system assumed for calibration
- Variability of materials variables used for reliability calculations
  - Between project variability based on different contractors and materials
  - Within project variability based on observed development of cracking within projects
  - Same reliability approach as for asphalt pavement with CalME
- Calibrated software being used to update Caltrans design catalog

Design catalog for 4 to 7 inch bonded concrete overlays on asphalt also being prepared

Site Investigations are Critical

- In situ materials, thicknesses, stiffnesses and strengths
  - Cores
  - Dynamic cone penetrometer (DCP) survey
  - Deflection survey with FWD
- How much information needed?
  - Frequency of above based on variability
    - More is better
  - Use results to identify uniform sub-sections, thicknesses, properties of existing materials
- If extensive unexplained anomalies or unexplainable high variability
  - Ground penetrating radar (GPR)
- Site Investigation Guidance coming late 2020

Summary

- ME design allows consideration of important variable affecting pavement performance
- Can be quickly updated to consider new materials, traffic, designs
- CalME, Pavement ME calibrated for California
    - New approach for calibration using “big data”
    - Using same reliability approach for better apples to apples comparison for life cycle costing

- Thanks to Caltrans for funding this work; thanks to UCPRC, Caltrans, industry colleagues
    - The opinions and conclusions expressed in this presentation are those of the presenter and do not necessarily represent those of the State of California or the Federal Highway Administration