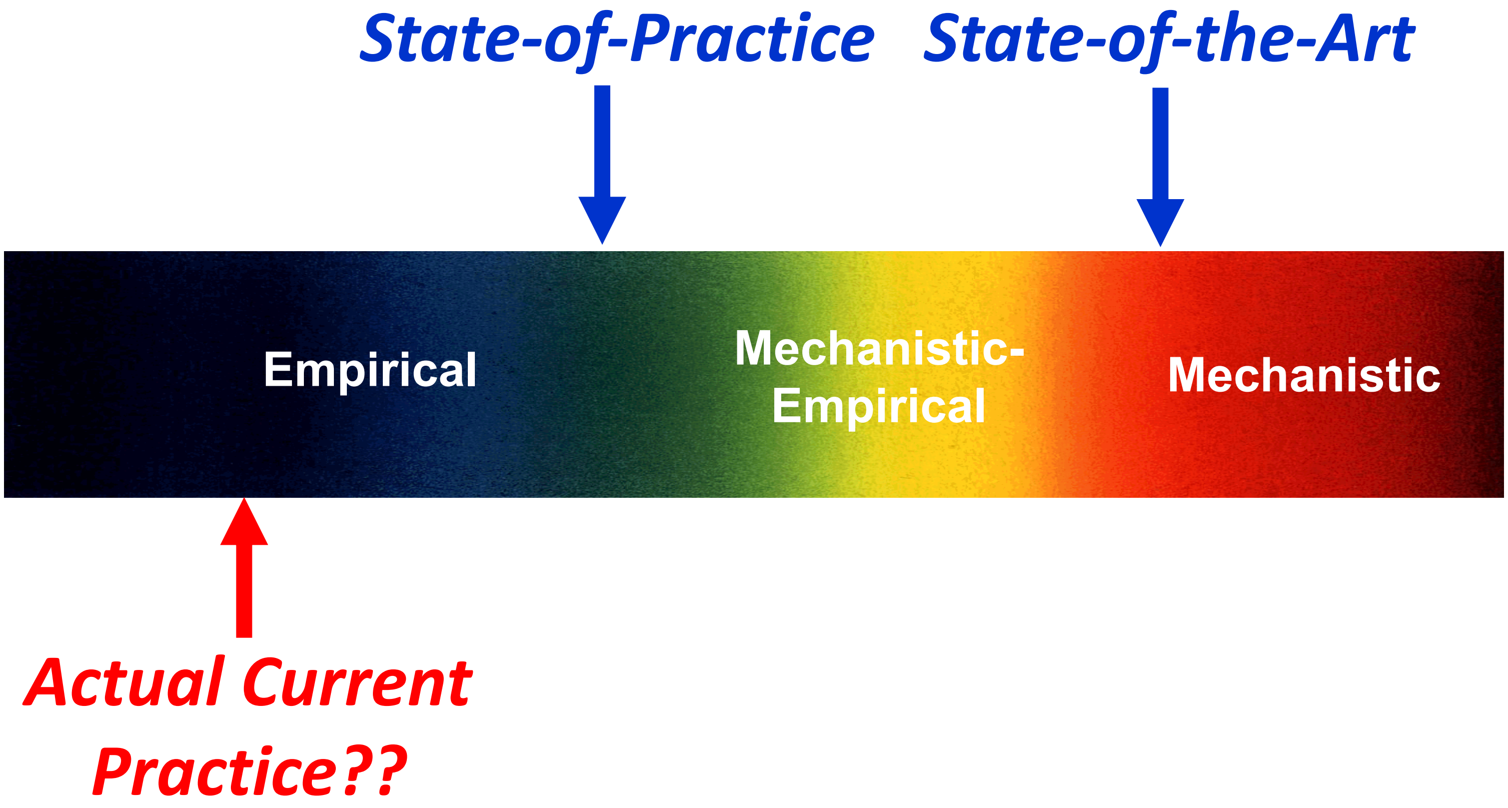
Mechanistic-Empirical Pavement Design of New and Rehabilitated Pavements

Workshop & Lectures on Pavement Engineering, Maintenance and Management

References

- *Pavement Analysis and Design*, Y.H. Huang, 2004
- Manual for *Professor Training Course in Asphalt Technology*, National Center for Asphalt Technology
- National Highway Institute (NHI) Training Course 131064A, *Introduction to Mechanistic Design of New and Rehabilitated Pavements*
- *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures,* NCHRP 1-37A

Pavement Design—Where are We??

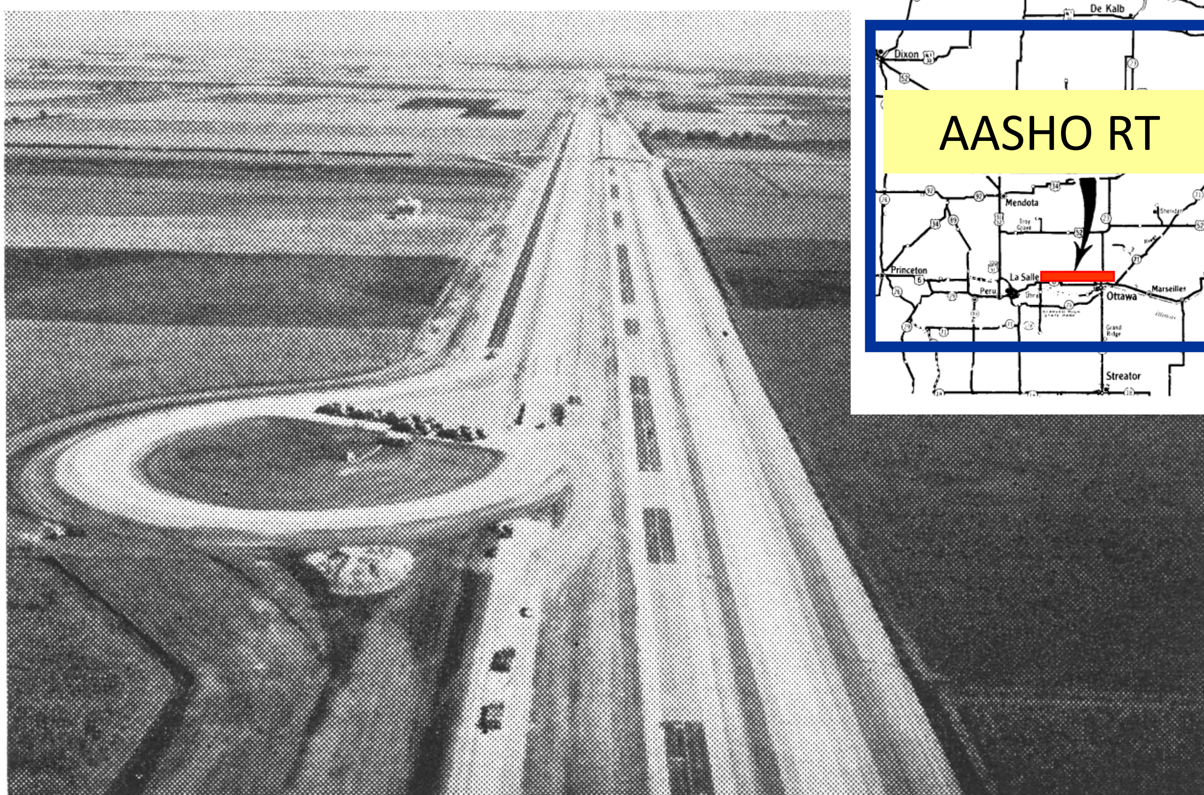


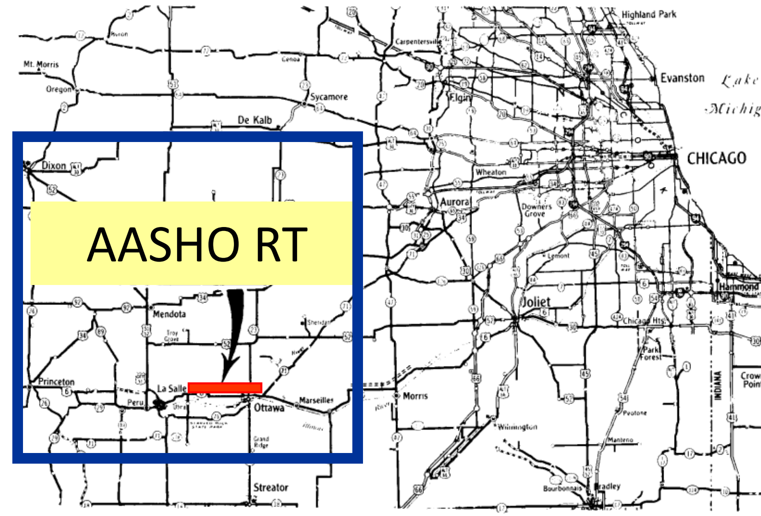
(Schwartz, 2001)

Traditional Approach to Pavement Design

- Overwhelmingly empirical
- Dependent on conditions remaining the same
- Primary focus on structural design
- Limited attention to failure modes

The AASHTO Empirical Design Example





(AASHO, 1961)

One Subgrade Type….

Figure 16. Embankment construction, loop 1, using rotary speed mixers to process and adjust moisture content of soil.

1950’s Construction….

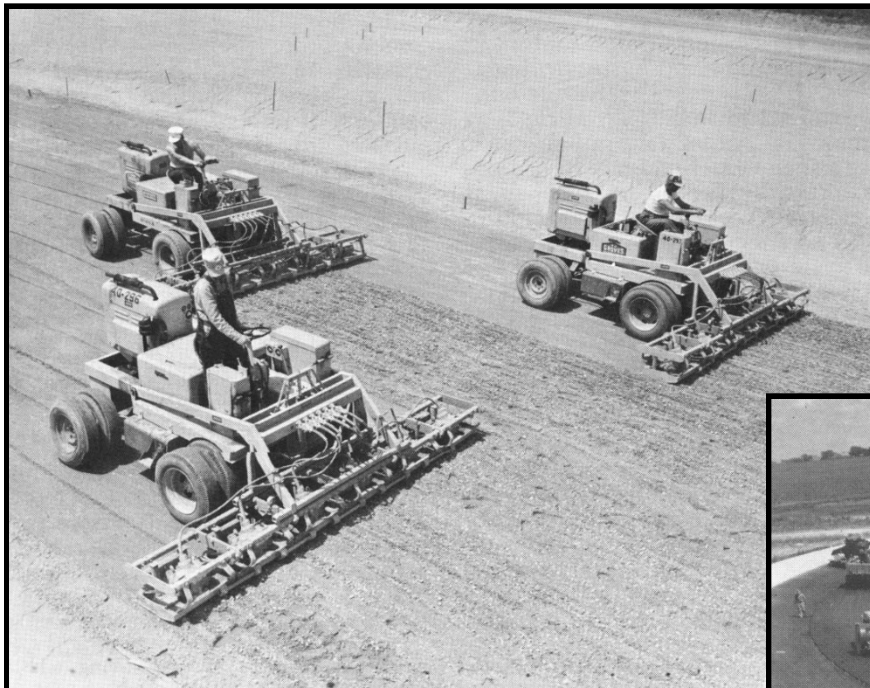


Figure 57. Compacting subbase.

Figure 29. Bituminous concrete construction.

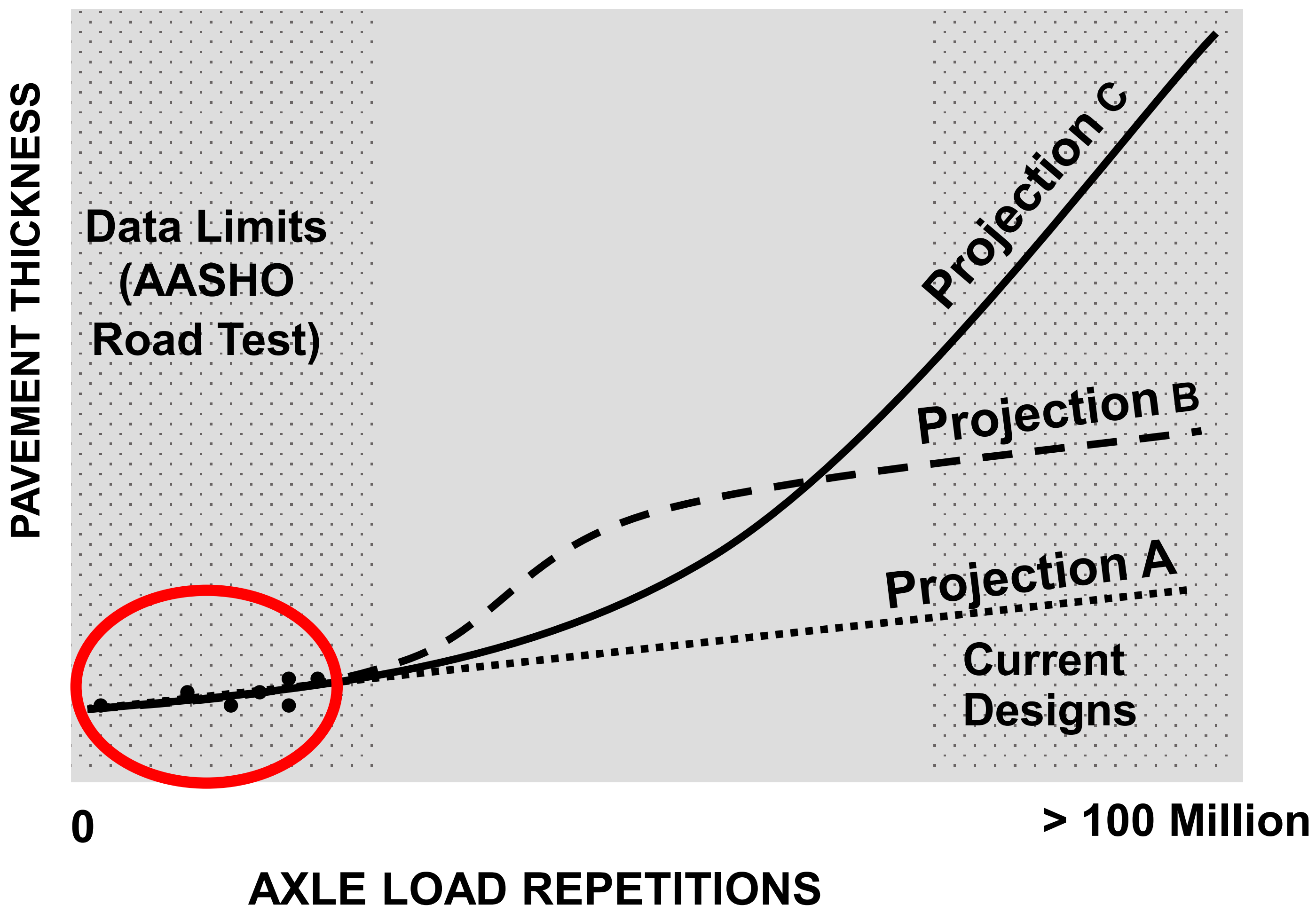
(AASHO, 1961)

1950's Traffic Loads....

Figure 23. Test vehicles, showing typical axle arrangements and loadings.

(AASHO, 1961)

Limited Traffic Applications….



Other Issues

- One climatic zone
- One base type
- No subdrainage
- Higher than normal construction quality
- Crude performance measure and model
- Limited incorporation of reliability

Changing Conditions

- New materials
  - Superpave mixes
  - Stone matrix asphalt (SMA)
  - Recycled materials
  - High strength cements
- New construction procedures
  - Ultra-thin white topping
  - Automatic dowel inserters

Changing Conditions

- Guidelines and regulations
  - Federal
  - State
  - Local
- Traffic loads
  - Heavier
  - New and different axle and load configurations

Mechanistic-Empirical Approach

- Accounts for new materials, traffic loads, and construction procedures
- All design features affecting pavement performance considered
- Primary focus on pavement performance

Definitions

Mechanistic-Empirical Design

- Combines both mechanistic and empirical aspects
- Mechanistic component involves determining pavement responses due to loading through mathematical models
- Empirical component relates the pavement responses to pavement performance
- Each key distress type is associated with a critical pavement response

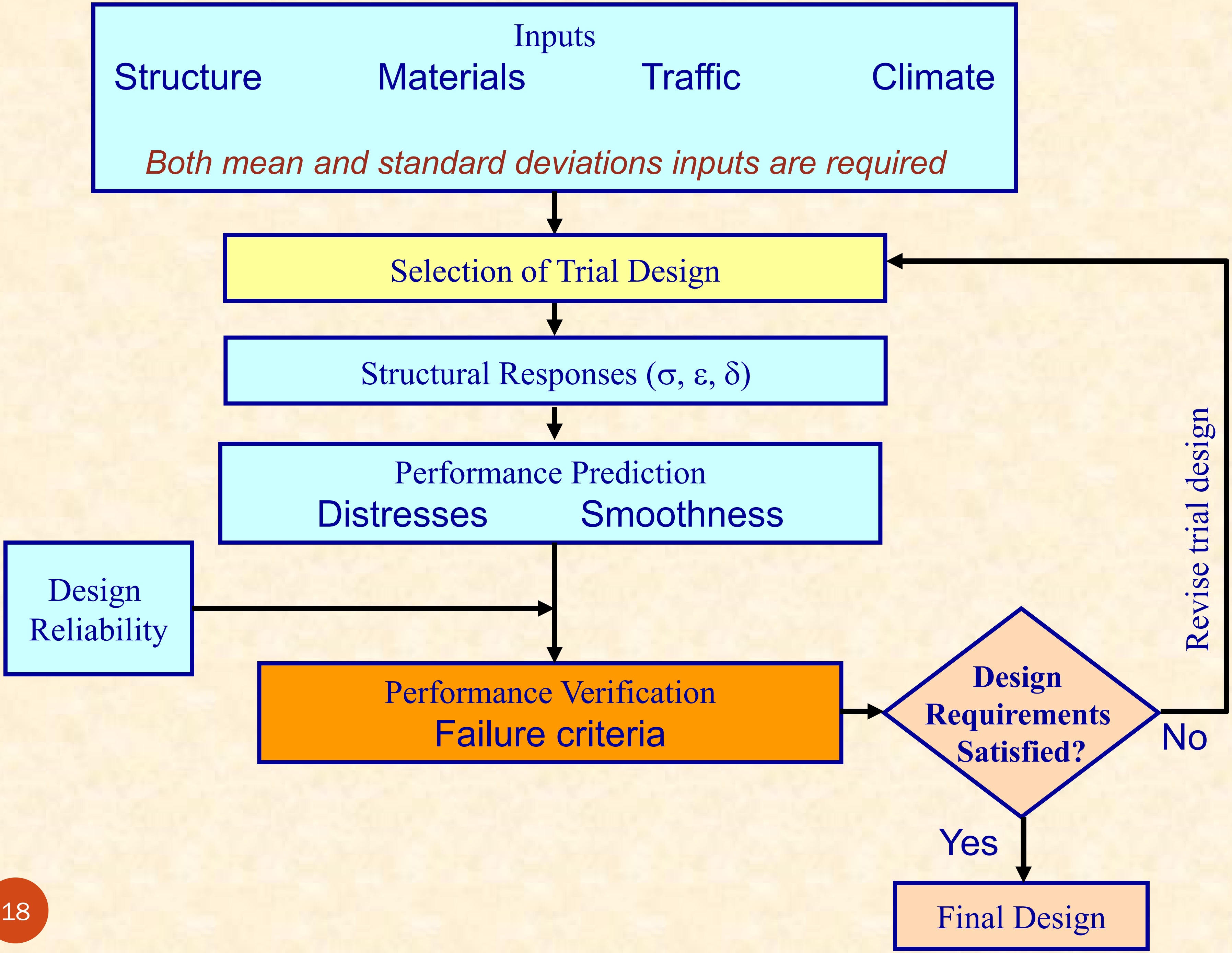
Benefits of M-E Design

- Not just thickness design!!!
- Comprehensive approach including structural and materials considerations
- Improved guidance for pavement rehabilitation design (overlays)
- Improved handling of climatic effects and design reliability

Benefits of M-E Design

- New concepts
  - Performance based on distress and ride quality
  - Better characterization of existing pavements
  - Direct consideration of drainage and subbase erosion
- Adaptability
  - Better ability to handle changing traffic characteristics
  - Ability to incorporate available paving materials
  - Ability to extrapolate from limited field and laboratory studies

Mechanistic-Empirical Design Framework and Components

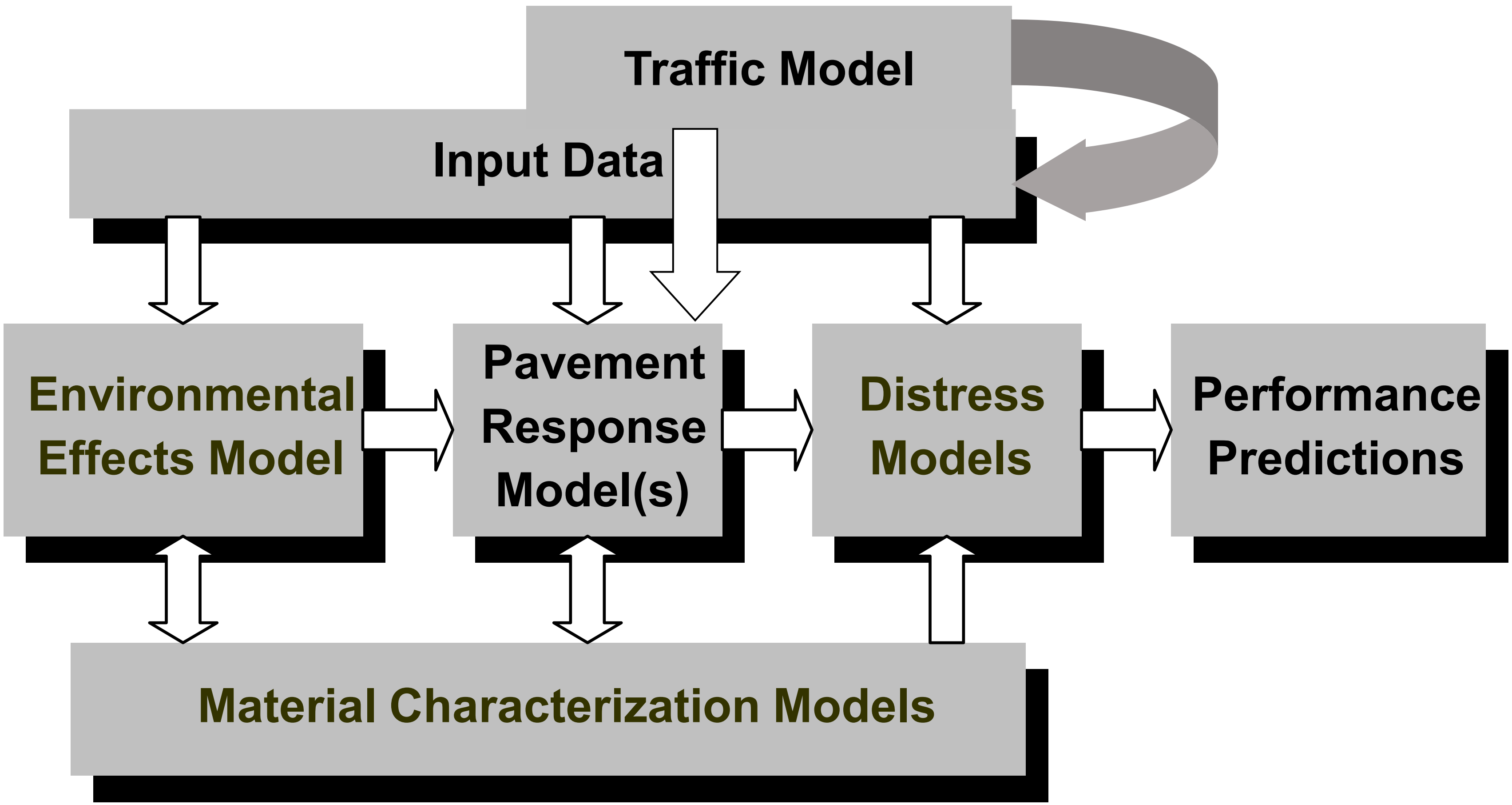


Inputs
Structure
Materials
Traffic
Climate
Both mean and standard deviations inputs are required
Selection of Trial Design
Structural Responses (σ, ε, δ)
Performance Prediction
Distresses
Smoothness
Design Reliability
Performance Verification
Failure criteria
Design Requirements Satisfied?
No
Revise trial design
Yes
Final Design

Components of M-E Design

- Design Inputs
- Structural Responses
  - Link between structural responses and key pavement distresses
- Performance Prediction
  - Distress models
  - Smotthness models
- Failure Criteria
- Design Reliability

M-E Design Process



Components of the M-E Design

- **Design Inputs**
- Structural response models
- Performance prediction
- Failure criteria
- Design reliability

Design Inputs

- Site-related inputs (these cannot be altered economically)
  - Traffic—ESALs or load spectra
  - Subgrade—engineering properties, strength, modulus
  - Climate—precipitation, temperature
- Design-related inputs (the designer has control over these properties)
  - Pavement structural section—thicknesses, layer types
  - Paving materials—strength, modulus

Design Inputs

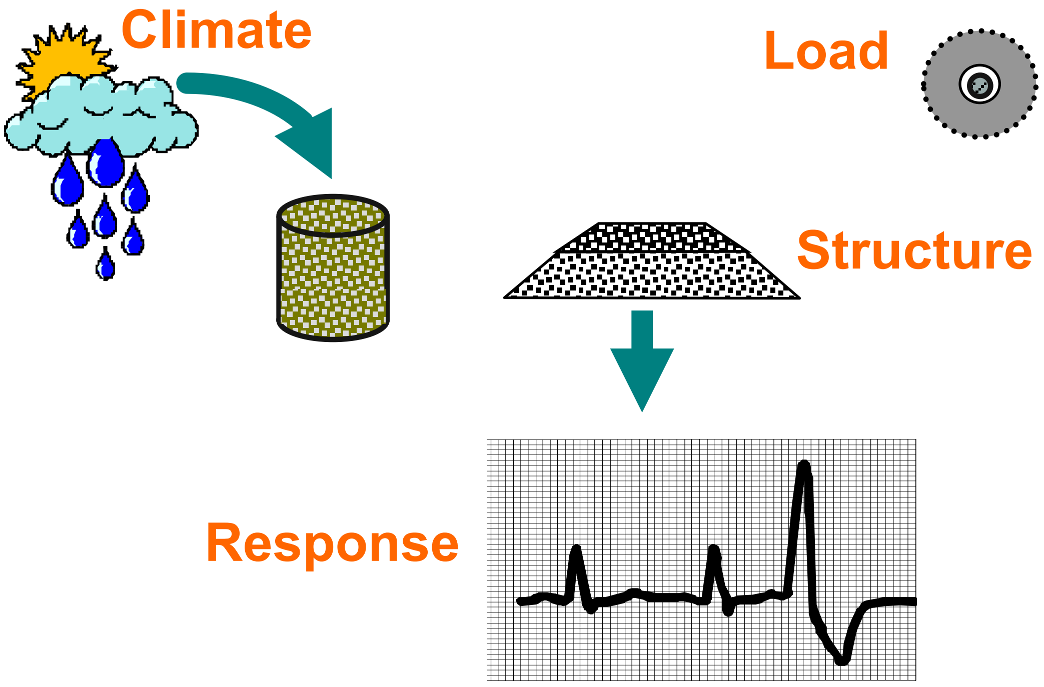
- The degree of sophistication of inputs is a function of
  - Structural response model
  - Transfer functions
  - Reliability methodology
- M-E procedures can handle complex materials and traffic inputs
  - Non-linear material characterization
  - Variability of inputs

Components of the M-E Design

- Inputs
- ➔ Structural response models
- Performance prediction
- Failure criteria
- Design reliability

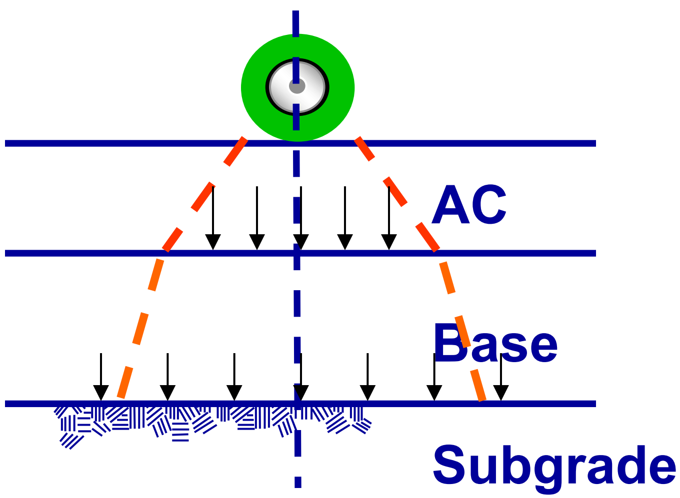
Structural Response Models

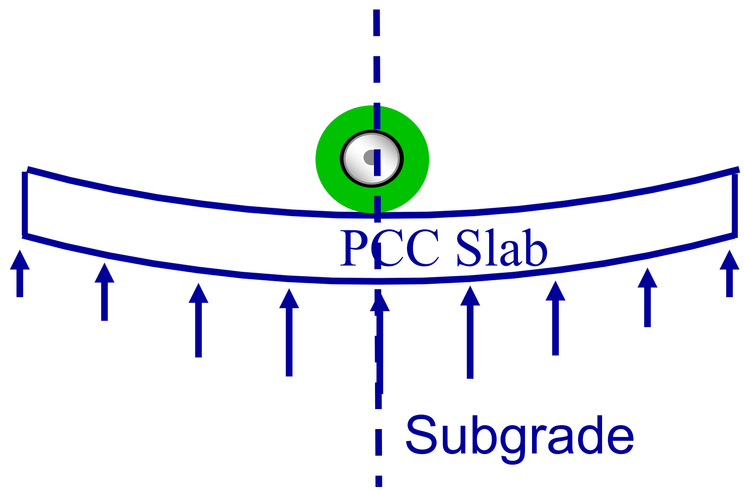
- Help determine pavement responses as a function of applied load (traffic or environmental)
  - Stress
  - Strain
  - Deflection



Structural Response Models

- Different analysis methods for AC and PCC

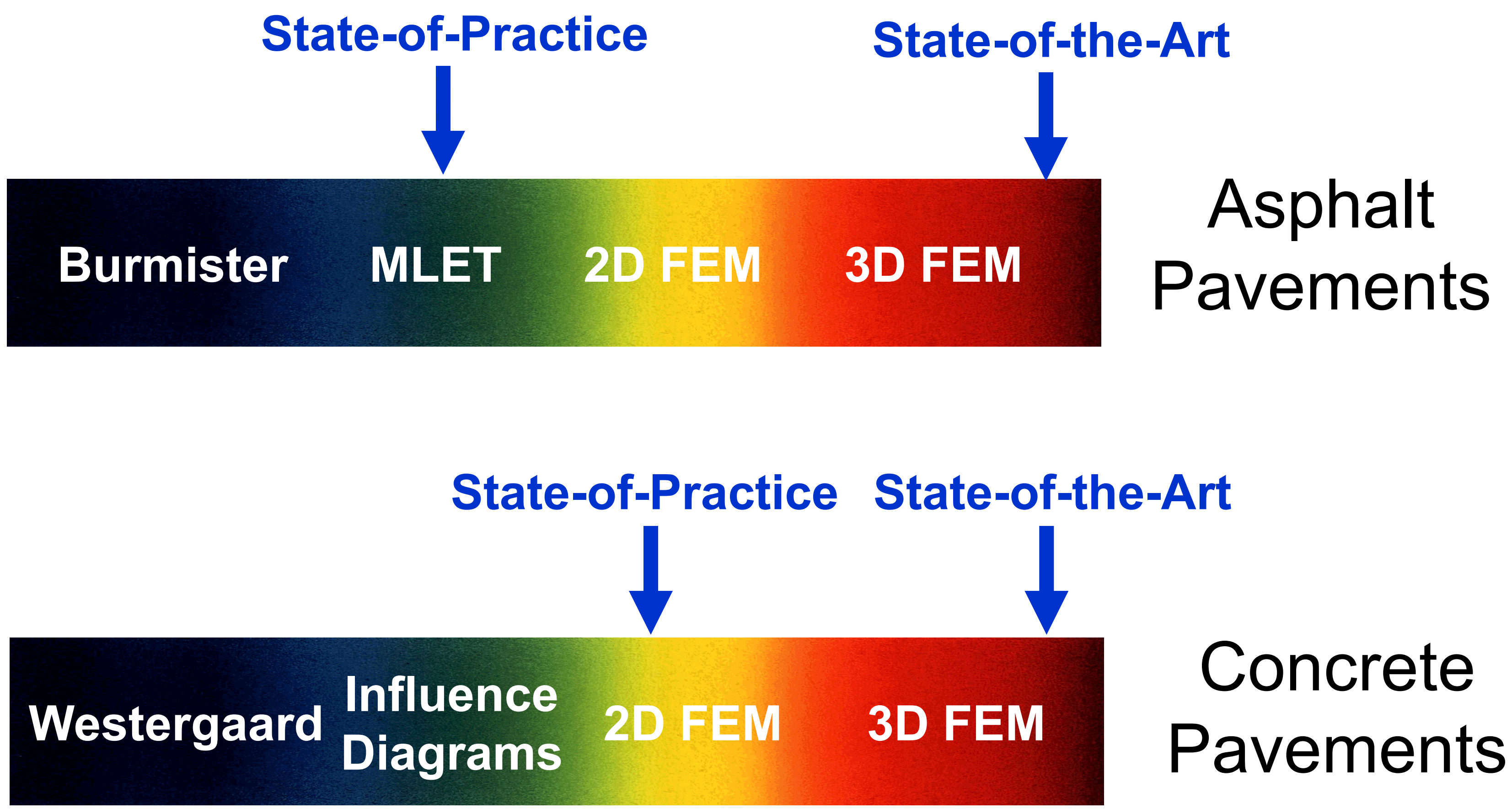




- Layered system behavior
- All layers carry part of load

- Slab action predominates
- Slab carries most load

Structural Response Models



Need to Determine Pavement Responses

- Excessive stresses and deflections can produce failure
- Design modifications may be warranted if stresses are excessive
- M-E design procedures directly consider pavement responses in performance prediction

Components of the M-E Design

- Inputs
- Structural response models
- ➔ Performance prediction
- Failure criteria
- Design reliability

Key Rigid Pavement Performance Indicators??

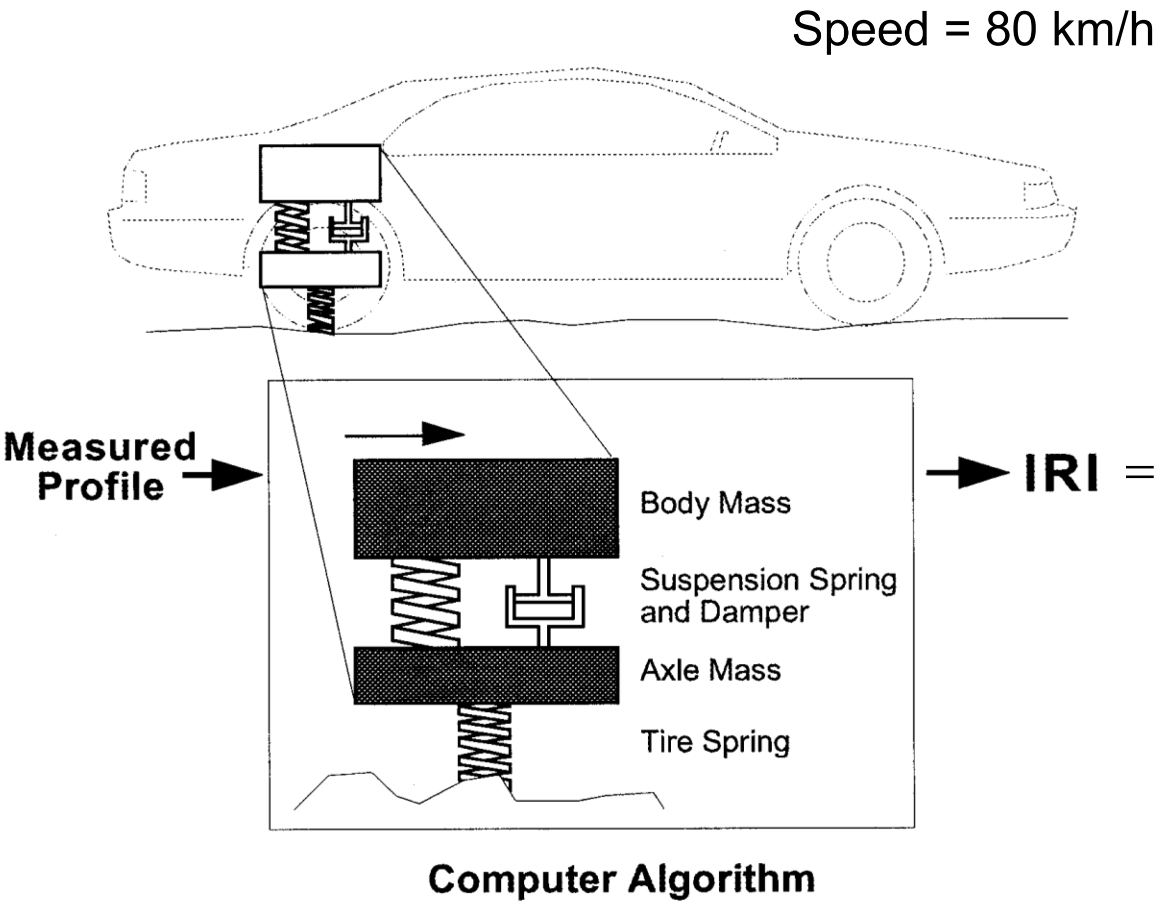
- Jointed Plain Concrete Pavements
  - Joint Faulting
  - Transverse Cracking—bottom-up
  - Transverse Cracking—top-down
  - Ride Quality (Smoothness)
- Continuously Reinforced Concrete Pavements
  - Punchouts
  - Ride Quality (Smoothness)

Key Flexible Pavement Performance Indicators??

- Fatigue Cracking – Bottom-up
- Fatigue Cracking – Top-down
- Permanent Deformation (Rutting)
- HMAC Thermal Cracking
- Ride Quality (Smoothness)

Pavement Ride Quality

International Roughness Index (IRI)



$$IRI = \frac{\sum(\text{Vertical Distance})}{\text{Horizontal Distance}}$$

("Little Book", 1998)

Distress-Response Correlation– AC

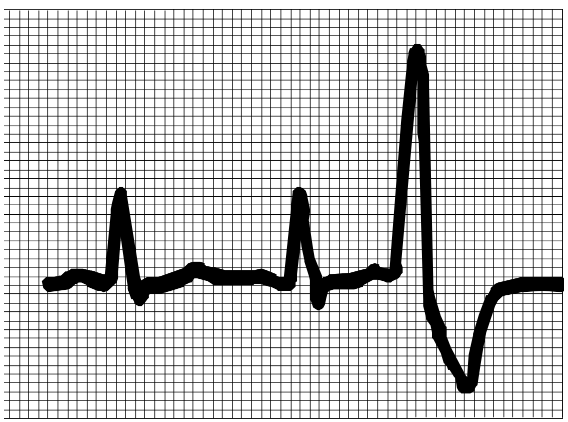
Distress Type	Relevant Critical Response
Fatigue cracking	Tensile strain in AC layer
Permanent deformation	Vertical subgrade strain, plastic flow in AC, stresses in unbound base
Low-temp cracking	Tensile stress in AC
Thermal fatigue cracking	Tensile strain in AC

Distress-Response Correlation – PCC

Distress Type	Relevant Critical Response
Transverse cracking	Tensile stress at the bottom of the slab
Faulting	Corner deflections
Punchouts (CRCP)	Tensile stress at the top of the slab

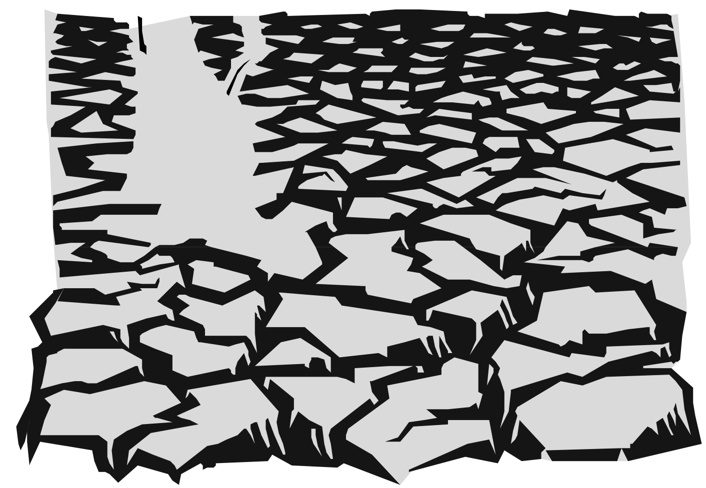
How to Predict Distress?

Pavement Response

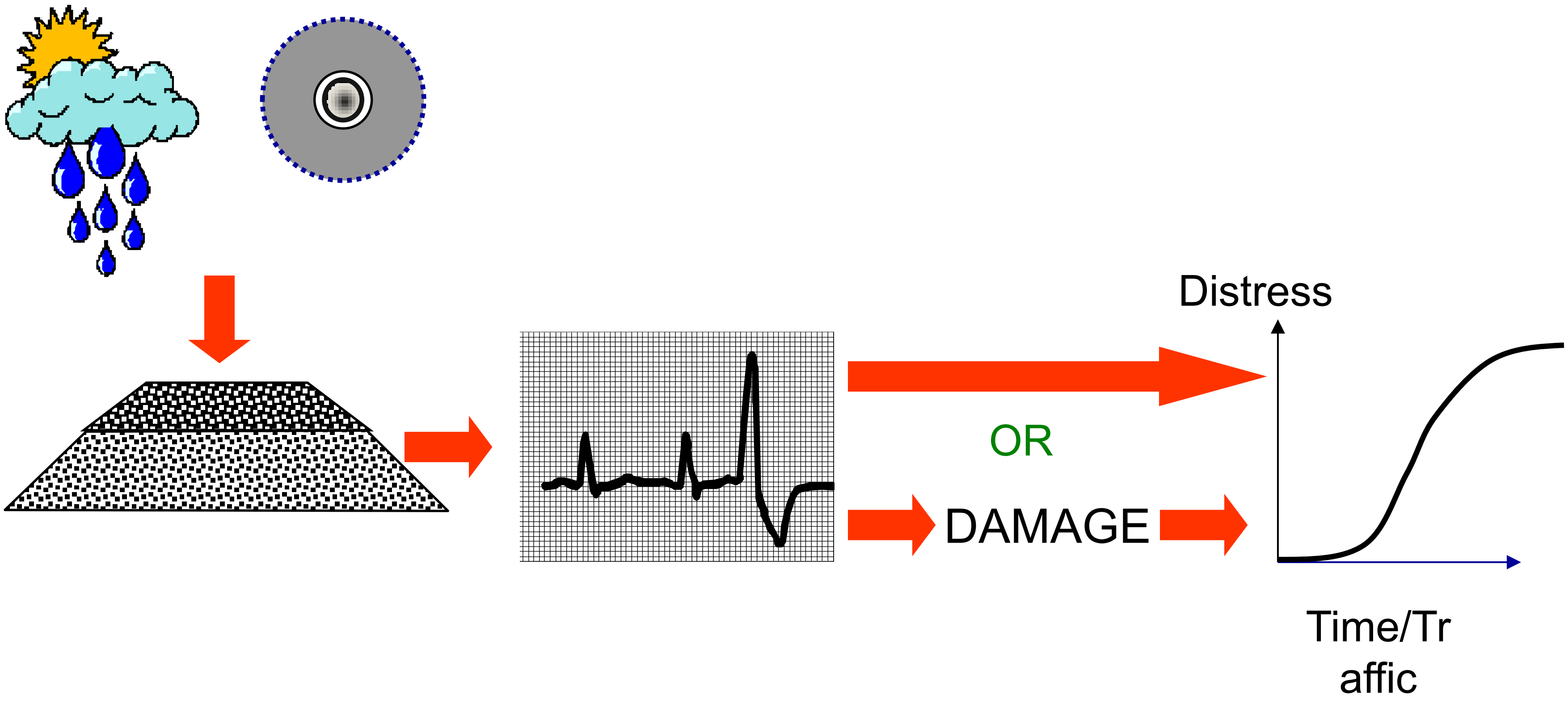


TRANSFER FUNCTIONS

Distress

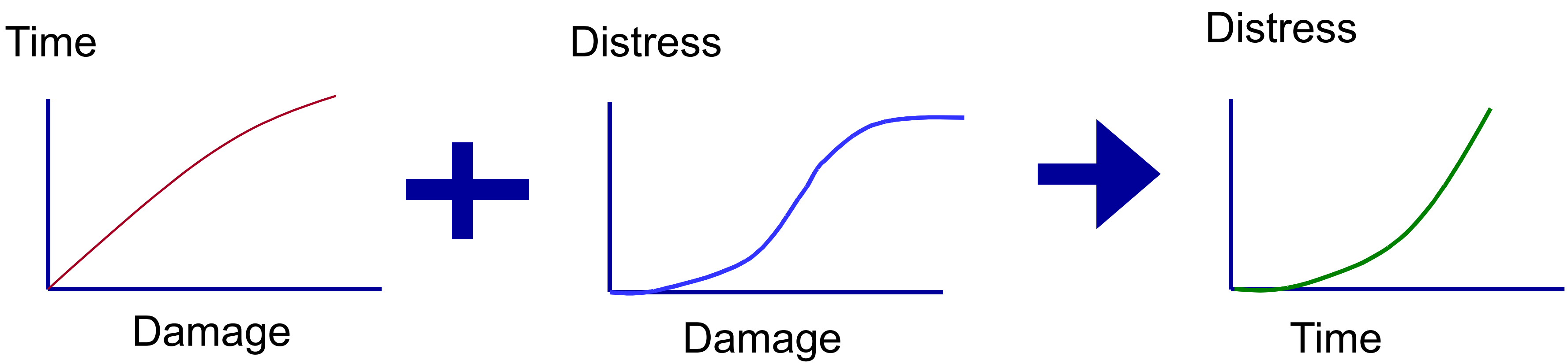


Performance Prediction



For Ex: Fatigue Cracking in Rigid Pavement

Fatigue-Based Transfer Functions



Damage Accumulation

Transfer Function

Distress Prediction

Demonstration

- Allowable number of loads
- Fatigue damage
- Damage accumulation
- Distress prediction

Allowable Number of Loads

- To reach fatigue damage = 1.0
  - Zero-Maintenance Design
  - **Calibrated Mechanistic Design**
  - ERES/COE
  - PCA
  - Vesic
  - RISC

Stress Ratio

$$SR = \frac{\sigma}{MR}$$

SR = Stress Ratio
σ = Total tensile stress due to traffic and environmental loading at slab edge
MR = Modulus of Rupture

Calibrated Mechanistic Design Fatigue Model

$$\log N = \left[\frac{-SR^{-5.367} \log(1-P)}{0.0032} \right]^{0.2276}$$

N = Number of stress applications to failure
SR = Stress Ratio
P = Probability level

Incremental Damage Accumulation

- Damage is accumulated gradually over pavement life
- Divide design period into increments (year, season, within day/night)
- Changes over time are addressed
  - Material strength and stiffness
  - Seasonal moisture and temperature
  - Traffic variations seasonally and yearly
  - Other changes (joint LT, erosion, …)

Incremental Damage Accumulation

- Within each increment damage is computed using the structural response model
- Damage is summed using Miner's equation

$$Fatigue\ Damage = \sum \frac{n_{ijklmn}}{N_{ijklmn}}$$

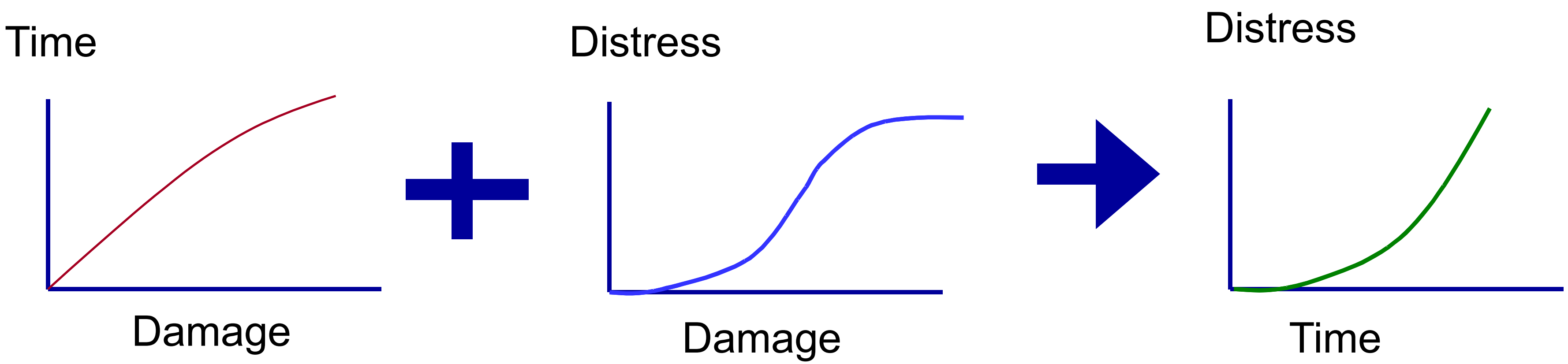
where:

$n_{ijk\ldots}$ = Applied number of load applications

$N_{ijk\ldots}$ = Allowable number of load applications (determined from response-life correlations)

i, j, k… = Increments

Fatigue-Based Transfer Functions



Damage Accumulation

Transfer Function

Distress Prediction

Transfer Functions (Cracking)

- Relate PCC response (stresses) to PCC slab cracking
- Based on accumulated fatigue damage

Damage-to-Distress Transfer Functions

- Cumulative damage calculated is converted to physical distress (transverse cracking) through damage to distress functions
  - RPPR
  - Calibrated Mechanistic Design
  - RPPR2

RPPR2 (Bottom-Up Cracking)

$$P = \frac{100}{1 + 1.41\,FD^{-1.66}}$$

P = Percentage of slabs cracked

FD= Fatigue Damage calculated using ERES/COE fatigue model

Note: 1.41 and -1.66 are calibration coefficients for the bottom-up cracking model

Smoothness Prediction

- At present no mechanistic models exist to predict pavement smoothness
- IRI is currently predicted based on the combination of
  - Initial IRI
  - Change in distress
  - Effect of maintenance activities

Key Components of the M-E Design Framework

- Input module
- Structural response models
- Performance prediction
- ➔ Failure criteria
- Design reliability

Failure Criteria

- The success or failure of the selected trial design is determined by checking the predicted distresses and smoothness against agency-input failure criteria
- The design can fail if
  - The predicted distress is greater than the allowable
  - The predicted smoothness is unacceptable

Key Components of the M-E Design Framework

- Input module
- Structural response models
- Performance prediction
- Failure criteria
- ➔ Design reliability

Design Reliability

- Practically everything associated with pavement design is variable
  - Variability in mean design inputs—traffic, materials, subgrade, climate, and so on
  - Error in performance prediction models
- In M-E design, each variability can be modeled separately or can be lumped and applied as an adjustment factor

M-E Design Procedure

- Step 1: Assemble design inputs
  - Traffic
  - Climate/Environment
  - Foundation/Subgrade
- Step 2: Select trial pavement structure
  - Thickness design, number and type of layers
- Step 3: Select materials for trial pavement structure
  - Properties of HMA, PCC, Base, Subbase

M-E Design Procedure

- Step 4: Select performance criteria
  - For ex; fatigue, rutting, punchout, faulting, IRI, etc.
- Step 5: Select analysis type
  - Deterministic (50% reliability)
  - Probabilistic (entered reliability level)
- Step 6: Processing input
  - Create required number of increments for analysis
  - User inputs are processed into those required for calculating responses for each increment

M-E Design Procedure

- Step 7: Calculate pavement responses
  - For ex; bottom tensile stress, top tensile stress, etc.
- Step 8: Calculate allowable number of loads
- Step 9: Damage accumulation
- Step 10: Compute distress
- Step 11: Criteria check
  - Compare predicted distresses at end of design life to design criteria

Mechanistic-Empirical Overlay Design

M-E Overlay Design Framework

1. Data collection
   - Inventory data, Monitoring data, Non-destructive/destructive test data, Traffic, Climate/Environment, Foundation/Subgrade
2. Pavement evaluation
   - Is the pavement structurally adequate?
   - Is the pavement functionally adequate?
3. Preferred rehabilitation strategy (restoration or overlay type) selection
   - Rehabilitation without overlays
   - HMA overlays
   - Rubblization or in-place recycling with HMAC layer
   - PCC rehabilitation with overlays

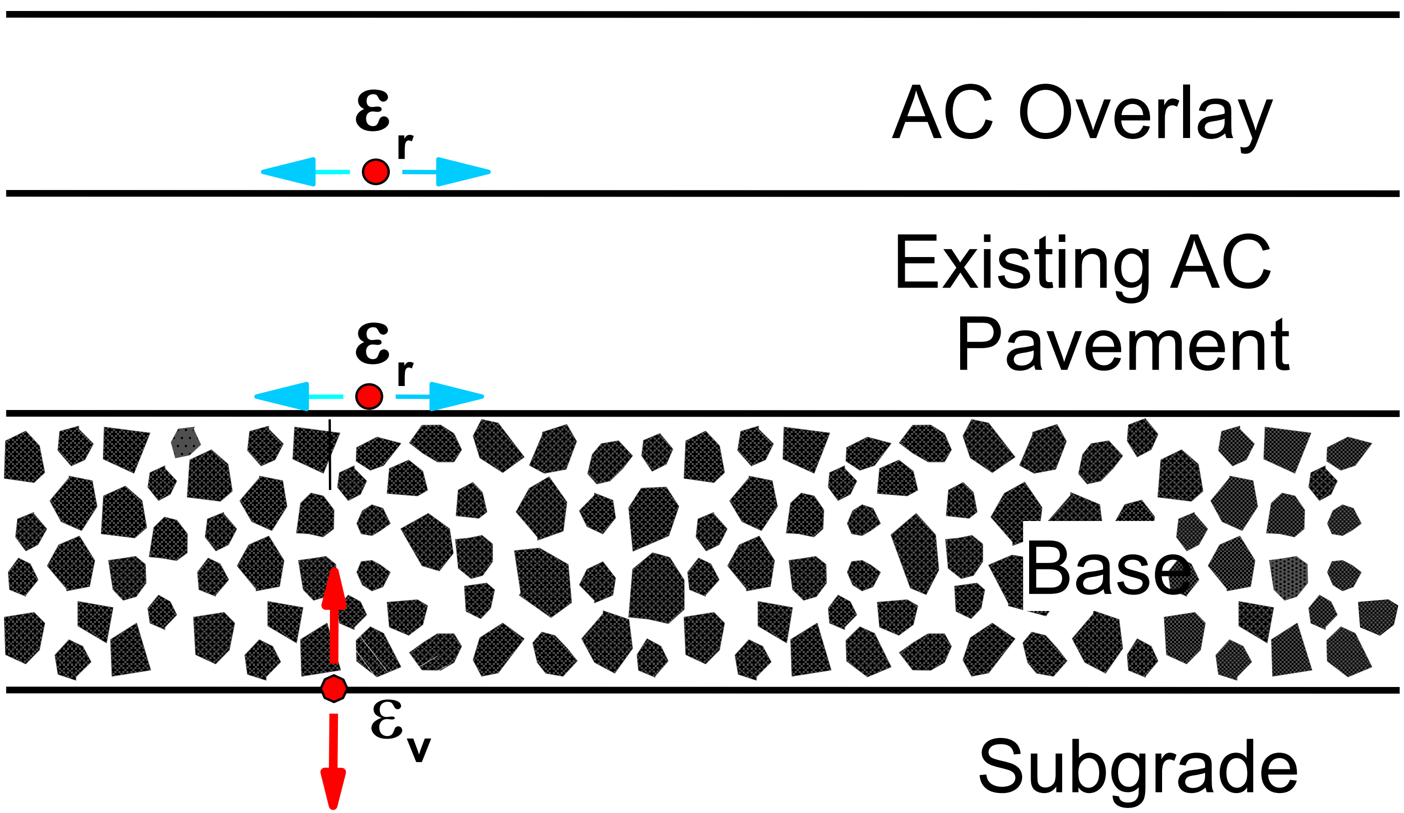
M-E Overlay Design Framework

4. Preoverlay repair strategy
   - Minimum repairs
   - Drainage considerations
   - Reflection crack control
5. Overlay thickness design using M-E principles
   - Design based on pavement structural responses for critical distresses
   - Design also considers user comfort by predicting smoothness
6. Final design selection

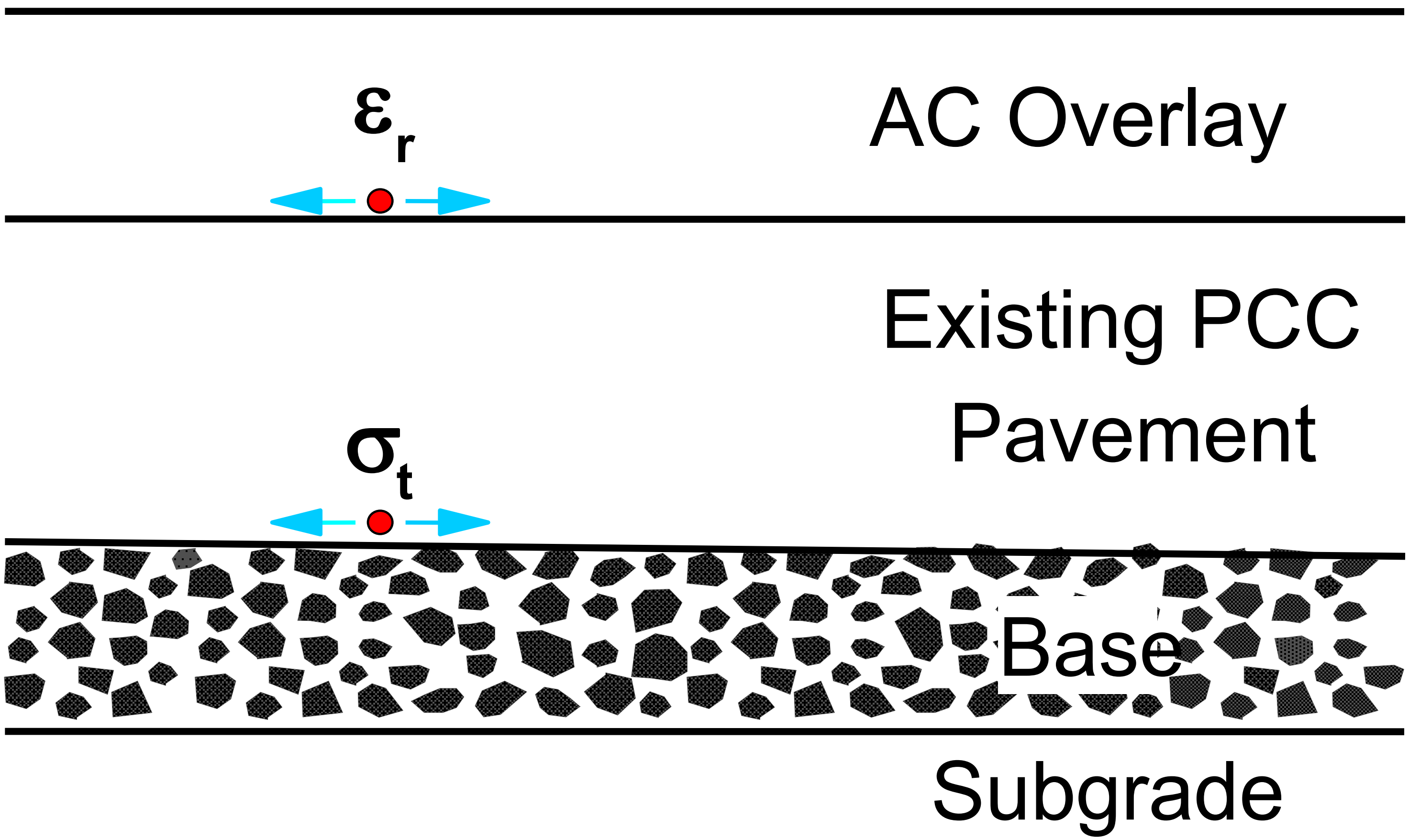
Overlay Thickness Design (Iterative Approach)

1. Assemble trial design structure, design features, material and site properties
2. Compute critical responses
3. Estimate damage and predict distress over design life
4. Estimate pavement smoothness
5. Assess suitability of design using performance criteria
6. Repeat process until a design that meets performance criteria is obtained at the desired level of reliability

Structural Responses for AC/AC Overlays

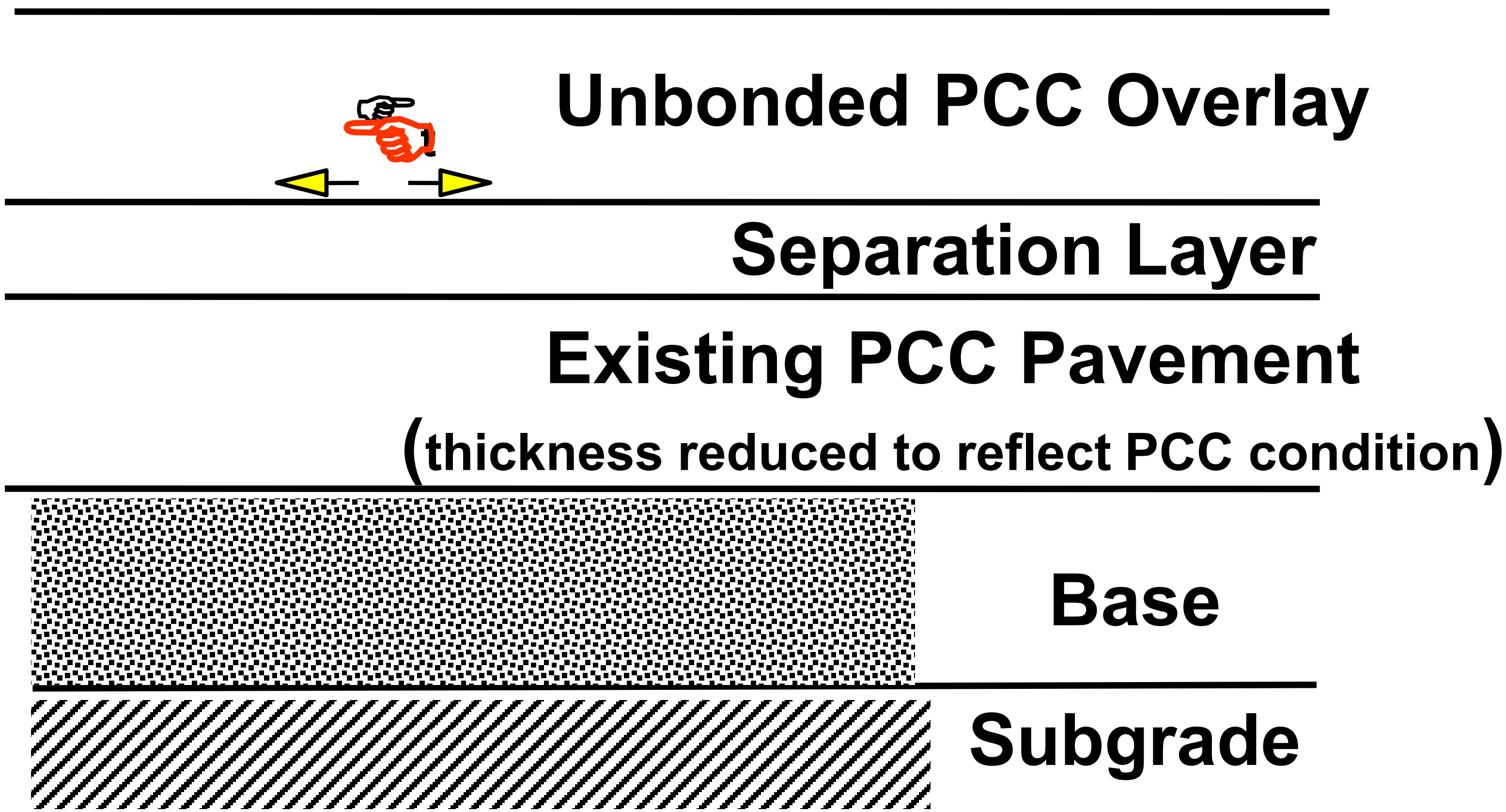


Structural Responses for AC/PCC Overlays



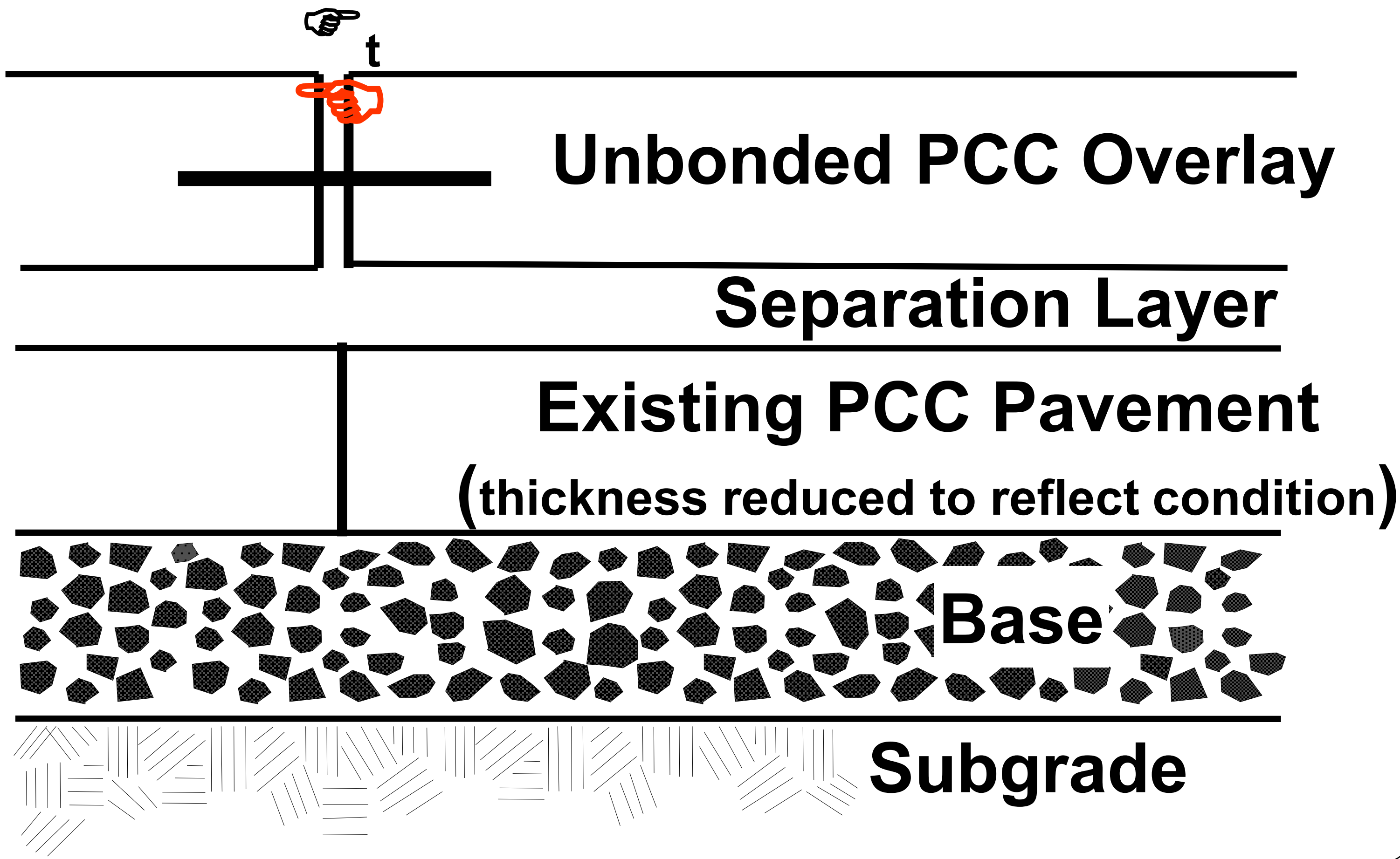
Location of Critical Responses- Unbonded JPCP/JPCP

Cracking

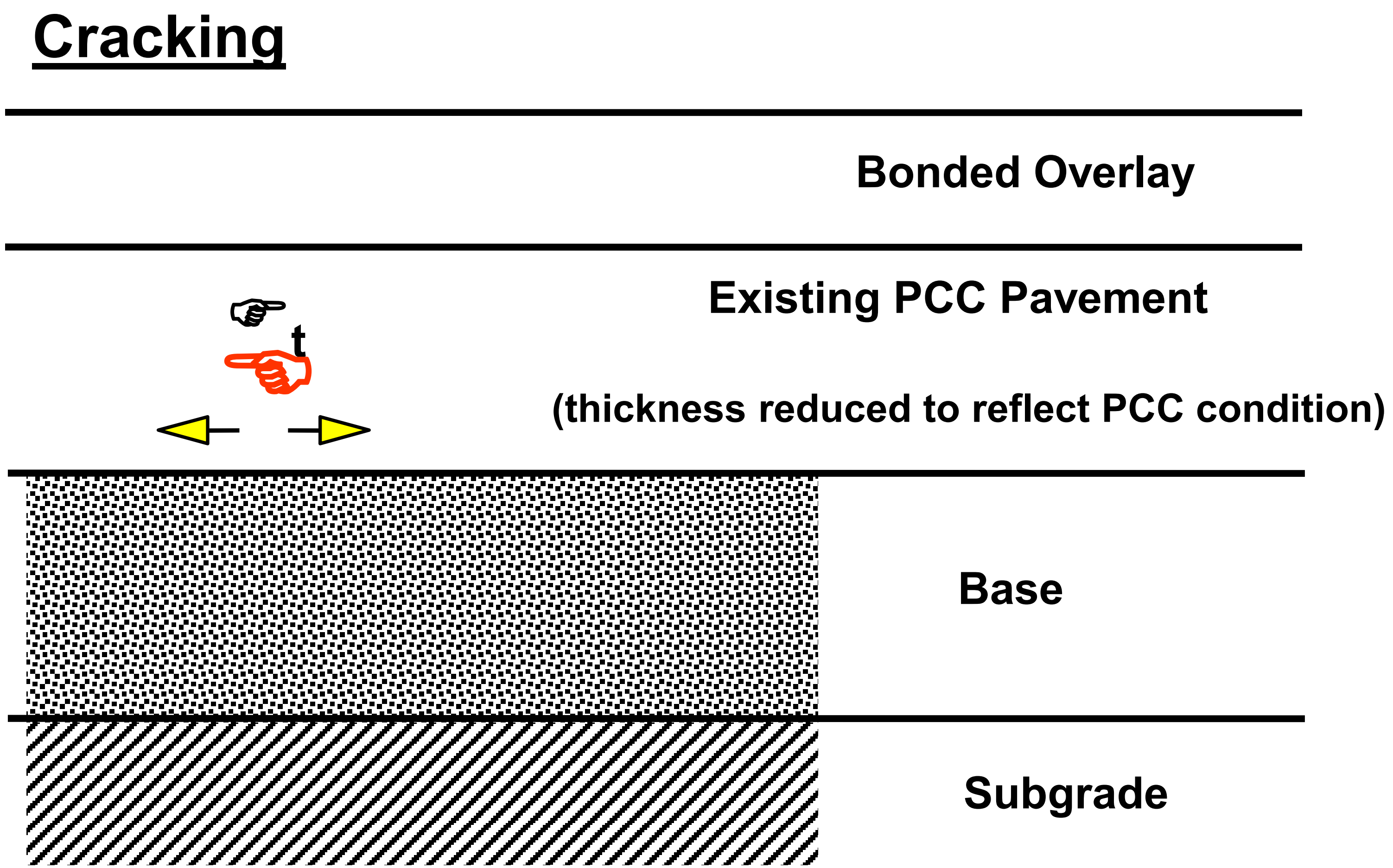


Location of Critical Responses- Unbonded JPCP/JPCP

Faulting

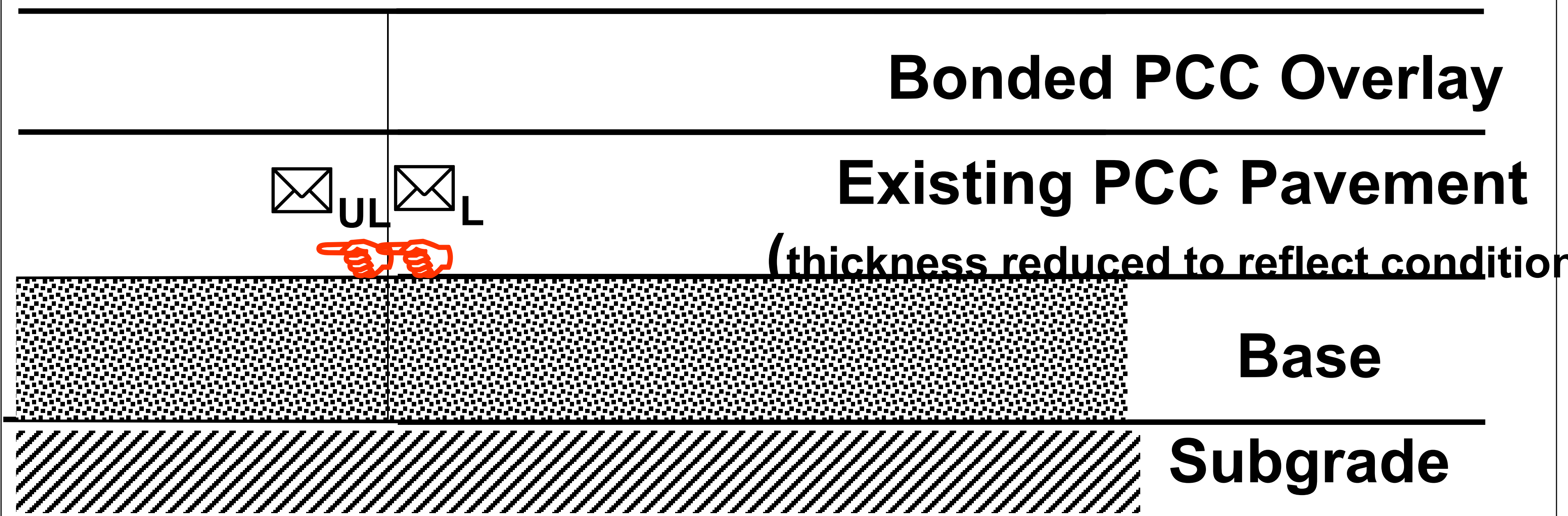


Location of Critical Responses-Bonded JPCP/JPCP



Location of Critical Responses-Bonded JPCP/JPCP

<u>Faulting</u>



$\boxtimes_{UL}$, $\boxtimes_L$ = composite slab corner deflections

Advantages of M-E Overlay Design

- Ability to predict individual distress
- Ability to model pavement structurally
- Ability to evaluate user comfort
- Ability to reduce the potential for material related distress