MECHANISTIC-EMPIRICAL PAVEMENT ANALYSIS AND DESIGN

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Mechanistic-Empirical Pavement Analysis and Design

INTRODUCTION

This document contains images of all slides in a course module about the theory and use of mechanistic-empirical pavement design. This presentation is available upon request to Hani Titi, hanititi@uwm.edu.

Mechanistic-Empirical Pavement Analysis and Design

Educational Module

Part I – Introduction

Emil G. Bautista
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Outline

- Flexible Pavements Design Methods
- Rigid Pavements Design Methods
- Road Tests
  - Maryland and WASHO
  - AASHO
  - Long Term Pavement Performance
- Mechanistic-Empirical Pavement Design Guide (MEPDG)
  - Advantages over the AASHTO Guide
  - Basic Elements of the Design Process

Flexible Pavements Design Methods

Flexible Pavement
- Empirical Method
- Limiting Shear Failure Method
- Limiting Deflection Method
- Regression Method
- Mechanistic-Empirical Method

Flexible Pavements Design Methods

Empirical Method
- Subbase and pavement thickness → (estimated) Without strength test
- Pavement thickness → (related) California Bearing Ratio (CBR)
- Valid only for a given set of conditions →
  - Environmental
  - Materials
  - Loading → Wheel loads

Limiting Shear Failure Method
- Determine thickness → (provided that) Shear failures will not occur
- Bearing capacity → Pavement thickness

Flexible Pavements Design Methods

Limiting Deflection Method

- Determine thickness → Vertical deflections will not exceed allowable limit

Regression Method

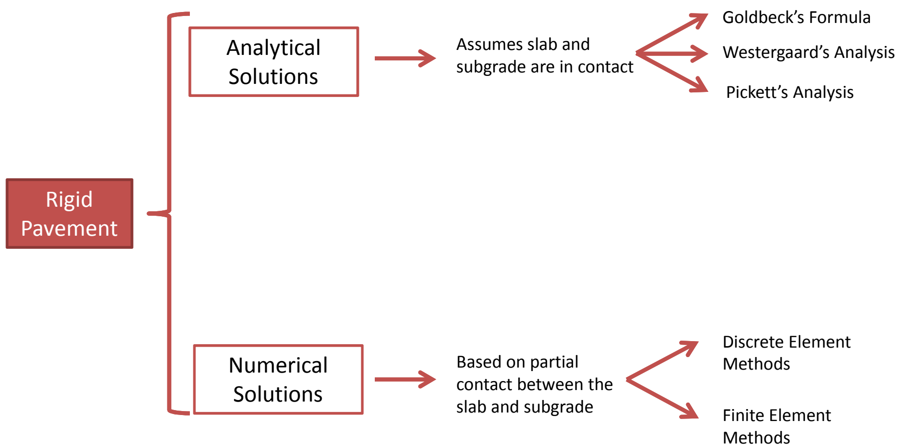
- Example → AASHTO Method based on results of Road Tests
- Applied to the conditions of the road site
- Under different conditions → Needs extensive modifications

Flexible Pavements Design Methods

Mechanistic-Empirical Method

- Based on Mechanics of Materials
  - Input → Wheel Load
  - Output → Stress or Strain
- Vertical compressive strain used to control pavement deformation
  - Plastic strains are proportional to elastic strains in paving materials
  - Limiting the elastic strains on the subgrade will control strains on other components above the subgrade and permanent deformation on the surface

Rigid Pavements Design Methods



Setting Goals and Objectives

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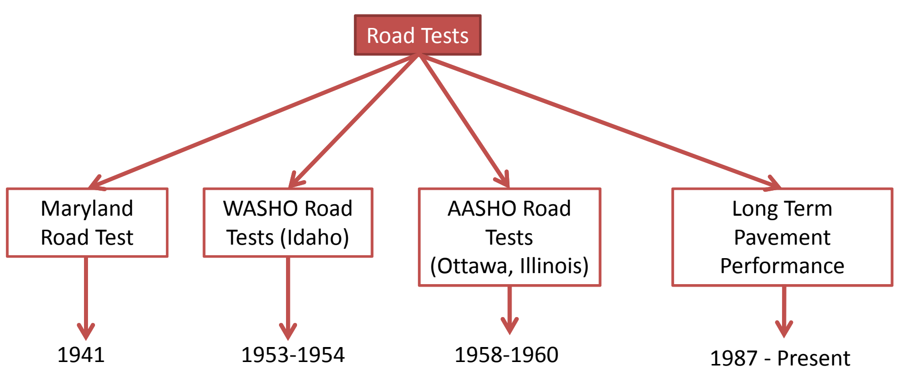
Road Tests



Setting Goals and Objectives

Maryland and WASHO Road Tests

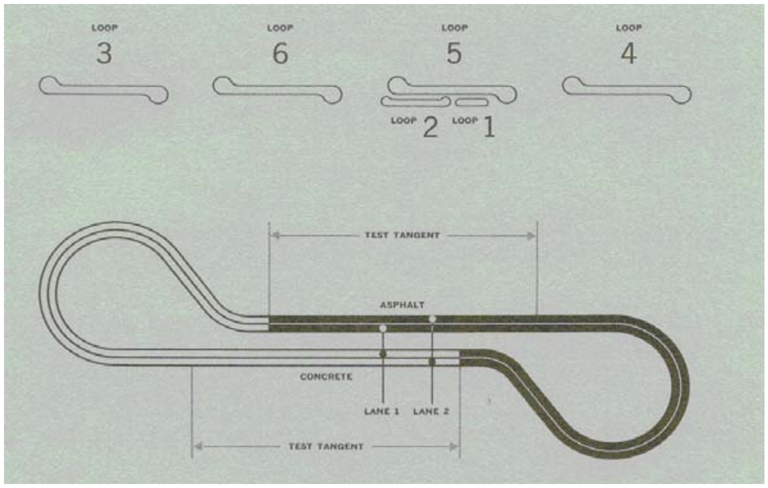
Maryland Road Test
- 4 different axle loadings
  - 18,000 lbs
  - 22,400 lbs
  - 32,000 lbs
  - 44,000 lbs
- Concrete pavement → 1.1 mile section of existing US 301

WASHO Road Tests (Idaho)
- 4 Loops
  - → Different surfaces
  - → Different base thickness
  - → Loads similar to Maryland Road Test
- Flexible pavement → 1 mile section

AASHO Road Tests

AASHO Road Tests (Ottawa, Illinois)
- Soil is:
  - → Uniform
  - → Representative of large portion of the USA and Canada
  - A-6 to A-7-6
- Climate → Representative of large portion of the USA and Canada
- 6 two lane loops
  - → Selected thickness
    - → Surface
    - → Base
    - → Subgrade
  - → Loops 3 to 6 carried heavy trucks, loop 2 carried light trucks and loop 1 was used for a non-traffic tests
- 836 test sections
  - → Asphalt → 100 ft. long
  - → Concrete
    - Plain → 120 ft. long
    - Reinforced → 240 ft. long

AASHO Road Tests



AASHO Road Tests

AASHO Road Tests Variable Design Factors

- Concrete
  - Thickness
    - Concrete slab
    - Sand-gravel subbase
  - Use or not of distributed reinforcing
- Asphalt
  - Thickness
    - Asphalt surface
    - Stone base
    - Sand-gravel subbase

AASHO Road Tests

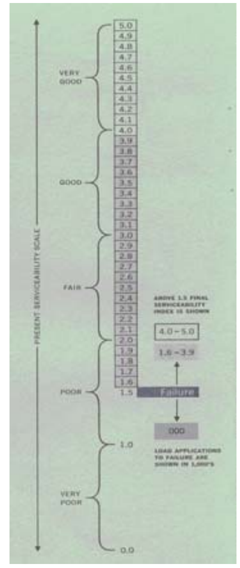
Present Serviceability Index

Develop to:

Measure how each test section performed

Definition

Is a numerical designation between 0 and 5 to indicate serviceability ranging from very poor to very good



Long Term Pavement Performance (LTPP)

LTPP

- Nearly 2,500 Test sections → representing → Wide range of climatic and soil conditions → monitored → Until they reach the end of design life or when recommended to be take out of the study
- Asphalt and Concrete
- United States and Canada

Long Term Pavement Performance (LTPP)

LTPP — Need for:

- Information on how pavement perform over time
  - To study performance data systematically all across the country
  - To promote extended pavement life
    - TRB
    - AASHTO
    - FHWA
- Mission
  - Collect and store performance data from a large number of in-service highways in the United States and Canada over an extended period to support analysis and product development
  - Analyze these data to describe how pavements perform and explain why they perform as they do
  - Translate these insights into knowledge and usable engineering products related to pavement design, construction, rehabilitation, maintenance, preservation, and management

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Setting Goals and Objectives

Long Term Pavement Performance (LTPP)

LTPP Objectives

- Evaluate existing design methods
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements
- Develop improved design equations for new and reconstructed pavements
- Determine the effects of loading, environment, material properties and variability, construction quality, and maintenance levels on pavements distress and performance
- Determine the effects of specific design features on pavement performance
- Establish a national long-term pavement database

Setting Goals and Objectives

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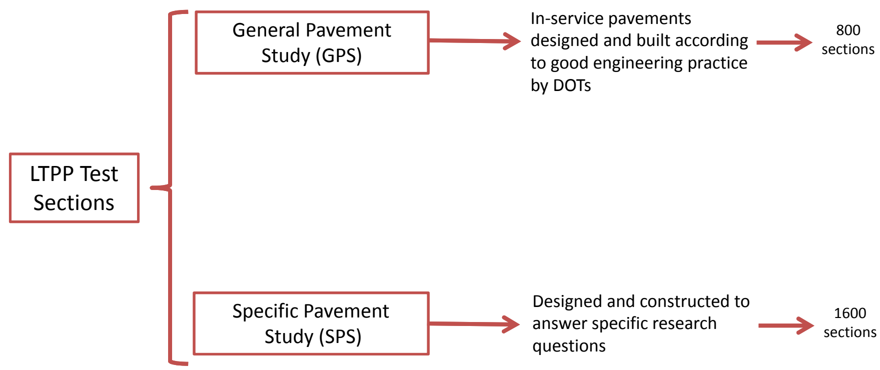
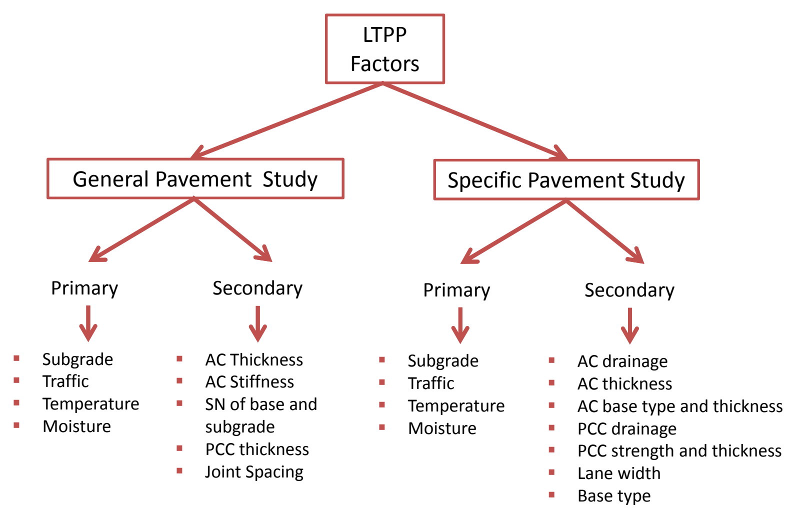
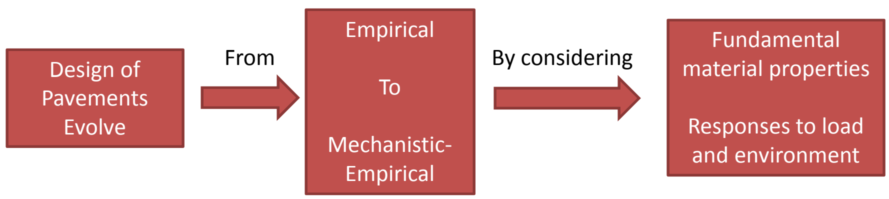
Long Term Pavement Performance (LTPP)



Long Term Pavement Performance (LTPP)

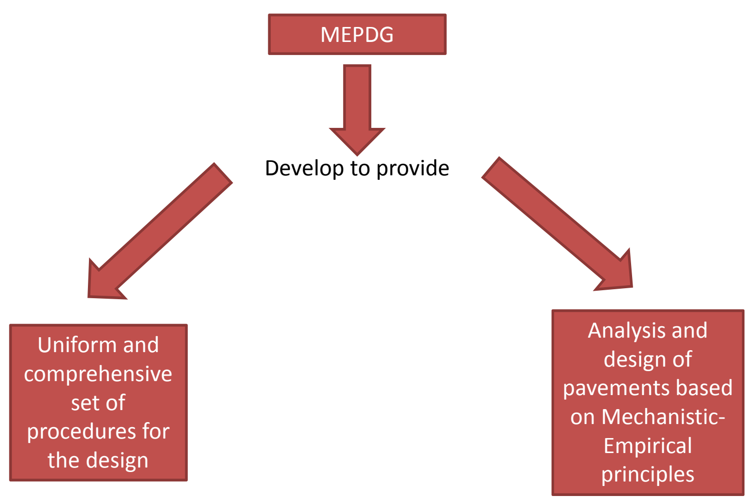


Mechanistic-Empirical Pavement Design Guide (MEPDG)



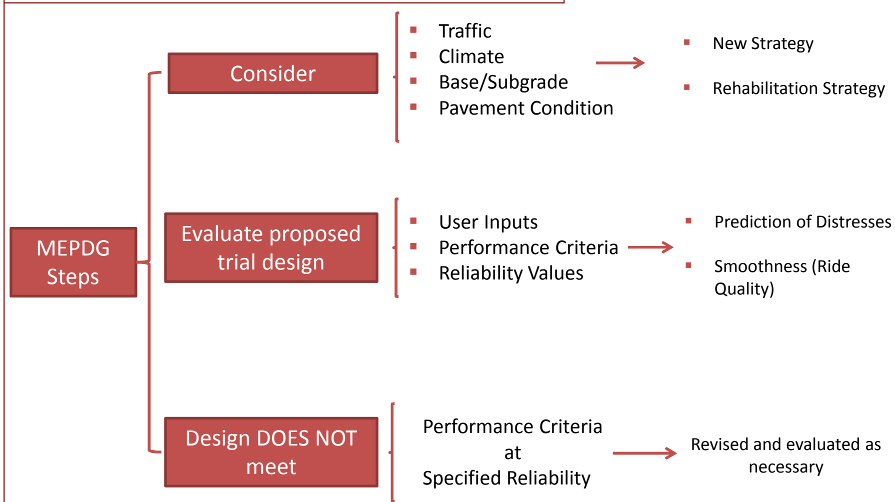
Setting Goals and Objectives

Mechanistic-Empirical Pavement Design Guide



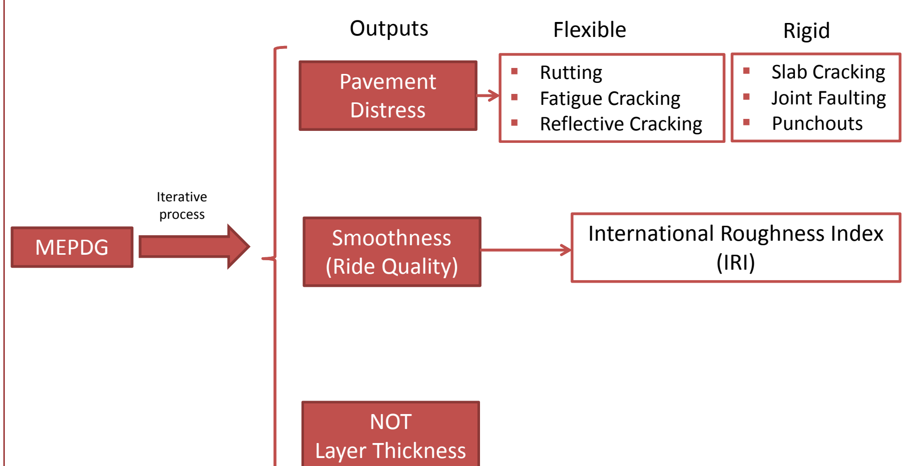
Setting Goals and Objectives

Mechanistic-Empirical Pavement Design Guide



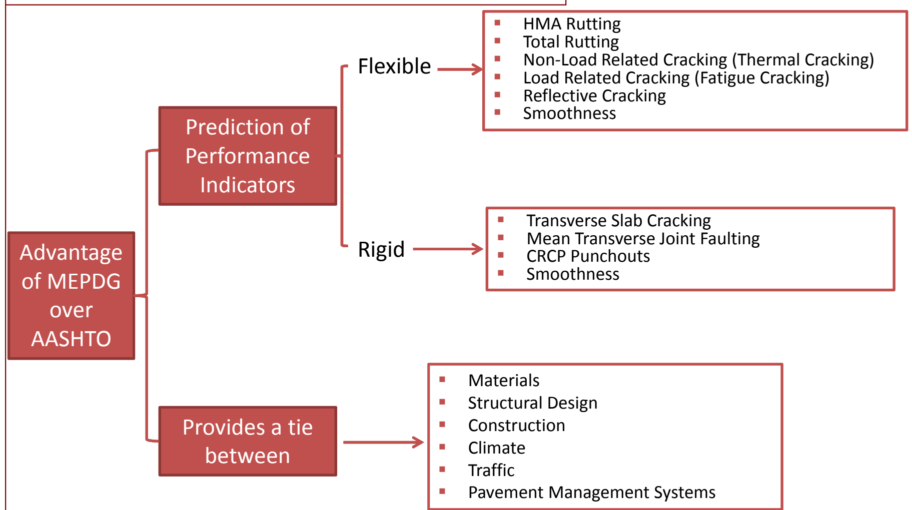
Setting Goals and Objectives

Mechanistic-Empirical Pavement Design Guide



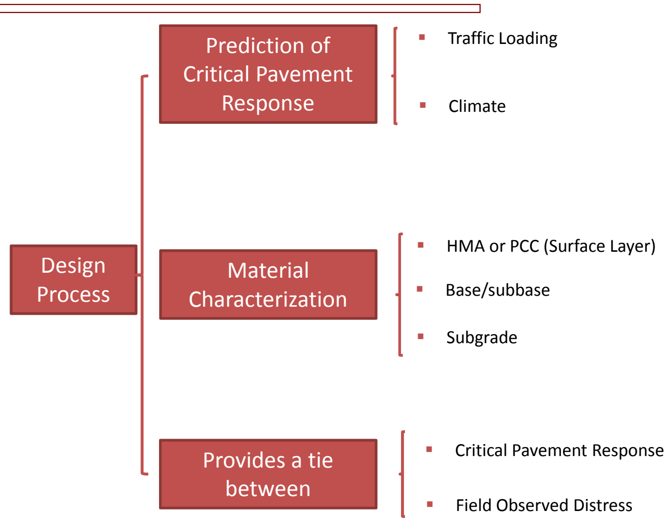
Setting Goals and Objectives

MEPDG Advantages over the AASHTO Guide



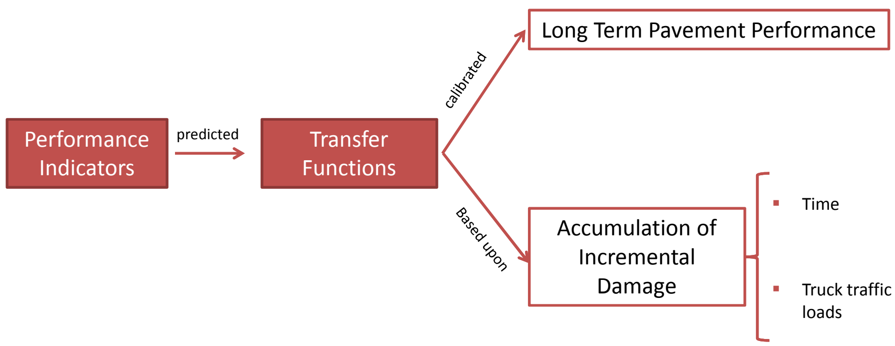
Setting Goals and Objectives

Basic Elements of the Design Process



Setting Goals and Objectives

Performance Indicators Predicted by the MEPDG



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Mechanistic-Empirical Pavement Analysis and Design

Educational Module

Part II – Performance Indicators Flexible Pavements

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Outline

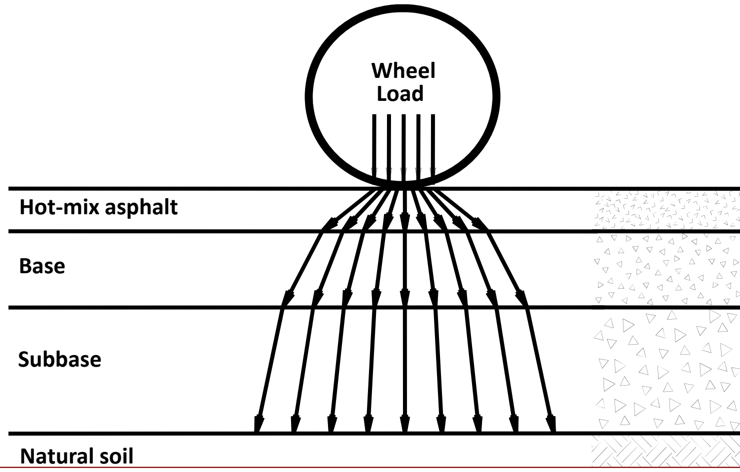
- Performance Indicators Predicted by the MEPDG

  Flexible Pavements
  - Rutting
    - Hot Mix Asphalt (HMA)
    - Unbound Aggregate Base and Subbase
  - Non-Load Related Cracking
  - Load Related Cracking
    - Alligator Cracking (bottom- up)
    - Longitudinal Cracking (top-down)
  - Reflective Cracking
  - Smoothness (International Roughness Index)

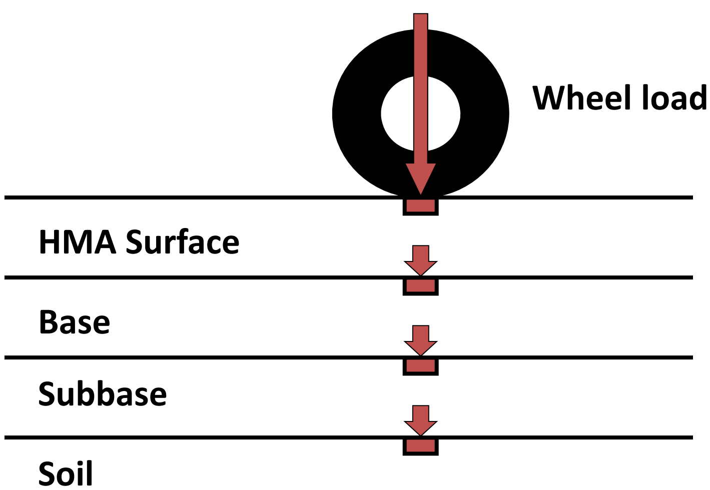
Performance Indicators Predicted by the MEPDG

Flexible Pavement

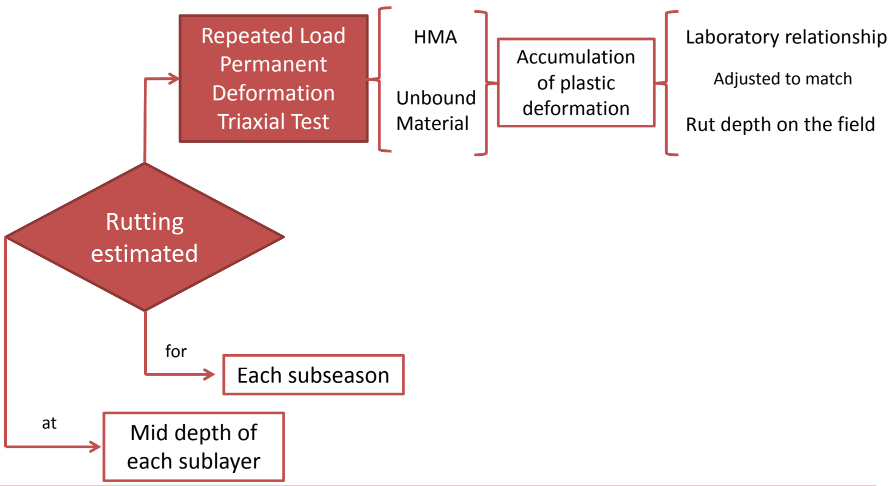
Distribution of the wheel load



Rutting



Rutting



Hot Mix Asphalt (HMA) Rutting

$$\Delta_{p\ (hma)} = \varepsilon_{p\ (hma)}\, h_{HMA} = \beta_{1r} k_z \varepsilon_{r\ (HMA)} 10^{k_{1r}} n^{k_{2r}\beta_{2r}} T^{k_{2r}\beta_{3r}}$$

Where:

$\Delta_{p(HMA)}$ = Accumulated permanent or plastic vertical deformation in the HMA layer/sublayer, in.
$\varepsilon_{p(HMA)}$ = Accumulated permanent or plastic axial strain in the HMA layer/sublayer, in/in.
$\varepsilon_{r(HMA)}$ = Resilient or elastic strain calculated by the structural response model at the mid-depth of each HMA sublayer, in/in.
$h_{(HMA)}$ = Thickness of the HMA layer/sublayer, in.
n = Number of axle-load repetitions.
T = mix or pavement temperature, °F.
k_z = Depth confinement factor
$k_{1r,2r,3r}$ = Global field calibration parameters (from the NCHRP 1-40 D recalibration; k_{1r} = -3.35412, k_{2r} = 0.4791, k_{3r} = 1.5606).
$\beta_{1r}, \beta_{2r}, \beta_{3r}$ = Local or mixture field calibrations constants; for the global calibration these constants were all set to 1.0.

Hot Mix Asphalt (HMA) Rutting

$$k_z = (C_1 + C_2 D)0.328196^D$$
$$C_1 = -0.1039(H_{HMA})^2 + 2.4868H_{HMA} - 17.342$$
$$C_2 = 0.0172(H_{HMA})^2 - 1.7331H_{HMA} + 27.428$$

Where:

D = depth below the surface, in.
H_{HMA} = Total HMA thickness, in.

Unbound Aggregate Base and Subgrade Rutting

$$\Delta_{p(soil)} = \beta_{s1} k_{s1} \varepsilon_v h_{soil} \left(\frac{\varepsilon_o}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{n}\right)^{\beta}}$$

Where:

Δp(soil) = Permanent or plastic vertical deformation layer, in.
n = Number of axle-load repetitions.
ε_o = Intercept determined from laboratory repeated load permanent deformation tests, in/in.
ε_r= Resilient strain imposed in laboratory test to obtain material properties ε_o, ε_r, and ρ, in/in.
ε_v = Average vertical resilient or elastic strain in the layer/sublayer and calculated by the structural response model, in/in.
$h_{(soil)}$ = Thickness of the unbound layer/sublayer, in.
k_{s1} = Global calibration coefficients; k_{s1} = 1.673 for granular materials and 1.35 for fine-grained materials,
ε_{s1} =Local calibration constant for rutting in the unbound layers; the local calibration constant was set to 1.0 for the global calibration effort

Setting Goals and Objectives

Unbound Aggregate Base and Subgrade Rutting

$$Log\beta = -0.61119 - 0.017638\,(W_c)$$

$$\rho = 10^9 \left(\frac{C_o}{1-(10^9)^\beta}\right)^{\frac{1}{\beta}}$$

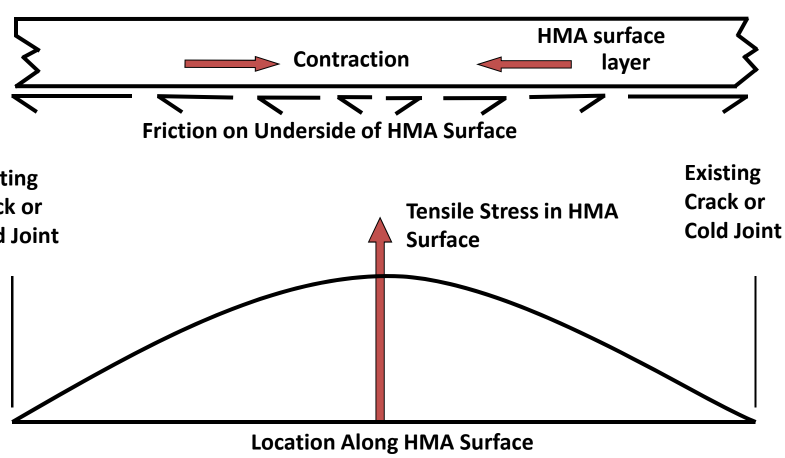
$$C_o = Ln\left(\frac{a_1\,M_r^{b_1}}{a_9\,M_r^{b_9}}\right) = 0.0075$$

Where:

W_c = water content (%)
M_r = Resilient modulus of the unbound layer or sublayer, psi.
$a_{1,9}$ = Regression constants; a_1 = 0.15 and a_9 = 20.0
$b_{1,9}$ = Regression constants; b_1 = 0.0 and b_9 = 0.0

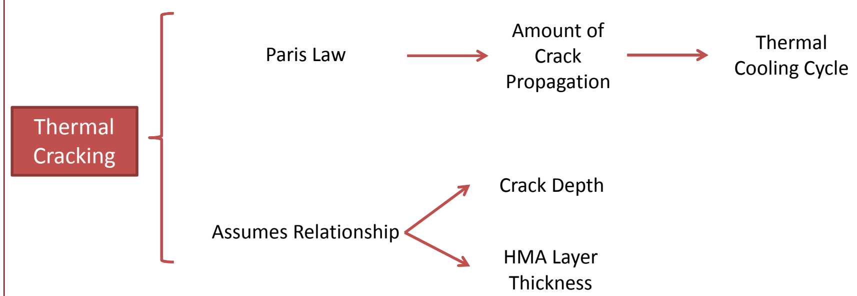
Setting Goals and Objectives

Non-Load Related Transverse Cracking



Setting Goals and Objectives

Non-Load Related Transverse Cracking



Setting Goals and Objectives

Non-Load Related Transverse Cracking

$$\Delta C = A\,(\Delta K)^n$$

Where:

ΔC = Change in the crack depth due to a cooling cycle,
ΔK = Change in stress intensity factor due to a cooling cycle,
A, n = Fracture parameters for the HMA mixture

Setting Goals and Objectives

Non-Load Related Transverse Cracking

$$A = 10^{k_t \beta_t \left(4.389 - 2.52\, Log(E_{HMA} \sigma_m \eta)\right)}$$

Where:

$\eta = 0.8\left[1 + \frac{1}{m}\right]$
k_t = Coefficient determined through global calibration for each input level (Level 1 = 5.0, Level 2 = 1.5, and Level 3 = 3.0)
E_{HMA} = HMA indirect tensile modulus, psi
σ_m = Mixture tensile strength, psi
m = The m-value derived from the indirect tensile creep compliance curve measured in the laboratory,
β_t = Local or mixture calibration factor

$$K = \sigma_{tip}[0.45 + 1.99(C_o)^{0.56}]$$

Where:

σ_{tip} = Far-field stress from pavement response model at depth of crack tip, psi,
C_o = Current crack length, ft.

Setting Goals and Objectives

Non-Load Related Transverse Cracking

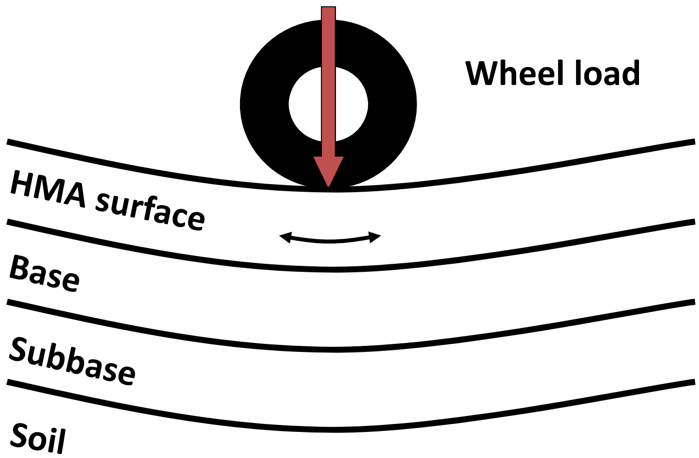
$$TC = \beta_{t1} N \left[\frac{1}{\sigma_d} Log\left(\frac{C_d}{H_{HMA}}\right)\right]$$

Where:

TC = Observed amount of thermal cracking, ft/mi,
β_{t1} = Regression coefficient determined through global calibration (400),
$N_{[z]}$ = Standard normal distribution evaluated at [z],
σ_d = Standard deviation of the log of the depth of cracks in the pavement (0.769), in,
C_d = Crack depth, in,
H_{HMA} = Thickness of HMA layers, in.

Setting Goals and Objectives

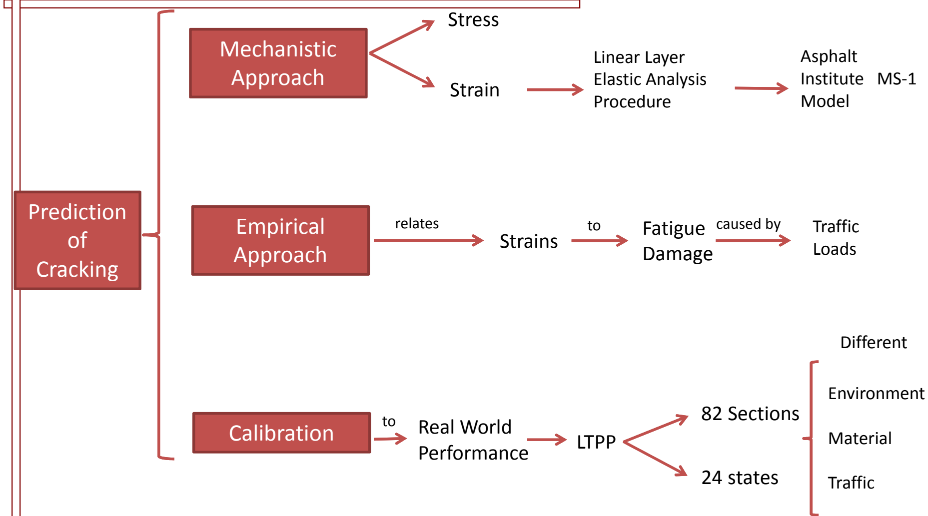
Load Related Cracking



Load Related Cracking

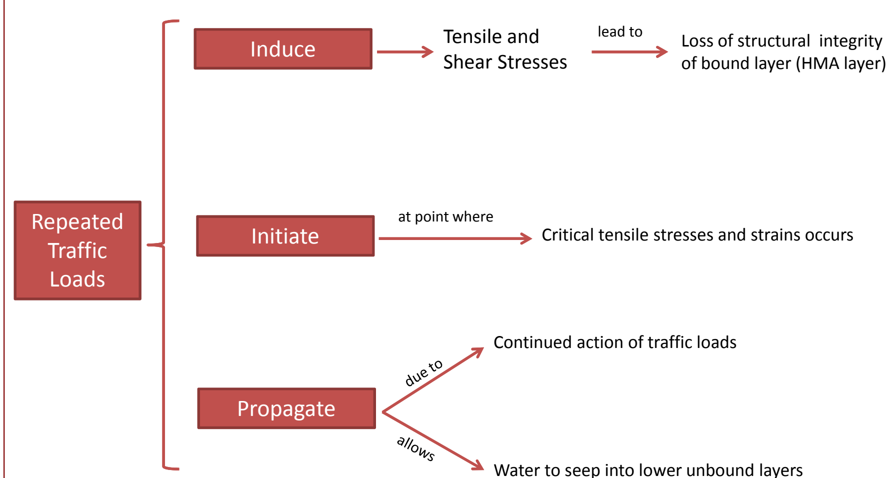
- Fatigue Cracking
  - Alligator Cracking → Starts at the bottom of the HMA layer
  - Longitudinal Cracking → Starts at the top of the HMA layer

Load Related Cracking



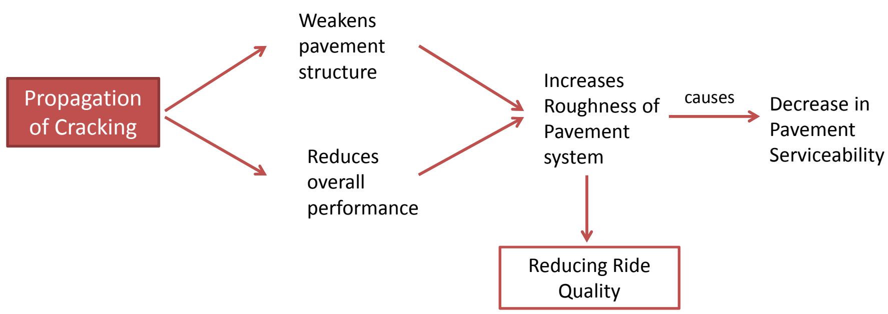
Setting Goals and Objectives

Load Related Cracking



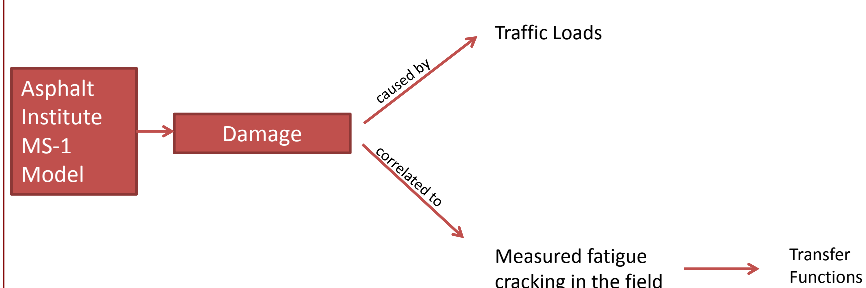
Setting Goals and Objectives

Load Related Cracking



Setting Goals and Objectives

Load Related Cracking



Setting Goals and Objectives

Load Related Cracking

$$N_{f-HMA} = k_{f1}(C)(C_H)\beta_{f1}(\varepsilon_t)^{k_{f2}\beta_{f2}}(E_{HMA})^{k_{f3}\beta_{f3}}$$

Where:

N_{f-HMA} = Allowable number of axle loads
ε_t = Tensile strain at critical locations and calculated by the structural response model, in/in
E_{HMA} = Dynamic modulus of the HMA measured in compression, psi
k_{f1}, k_{f2}, k_{f3} = Global field calibration parameters (from the NCHRP 1-40D recalibration; k_{f1} = 0.007566, k_{f2} = -3.9492 and k_{f3} = -1.281)
β_{f1}, β_{f2}, β_{f3} = Local or mixture specific field calibration constants; for the global calibration effort, these constants were set to 1.0

Setting Goals and Objectives

Load Related Cracking

$$C = 10^M$$

$$M = 4.84\left(\frac{V_{be}}{V_a + V_{be}} - 0.69\right)$$

Where:

V_{be} = Effective asphalt content by volume, %
V_a = Percent air voids in the HMA mixture,
C_H = Thickness correction term, dependent on type of cracking

Setting Goals and Objectives

Load Related Cracking

Thickness correction term, dependent of type of cracking

- For bottom-up or alligator cracking:

$$C_H = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{(11.02 - 3.49 H_{HMA})}}}$$

- For top-down or longitudinal cracking:

$$C_H = \frac{1}{0.01 + \frac{12.00}{1 + e^{(15.676 - 2.8186 H_{HMA})}}}$$

Where:
H_{HMA} = Total HMA thickness, in

Setting Goals and Objectives

Load Related Cracking

The incremental damage index (ΔDI) is calculated by dividing the actual number of axle loads by the allowable number of axle loads within a specific time increment and axle-load interval for each axle type.

$$DI = \sum (\Delta DI)_{j,m,l,p,T} = \sum \left(\frac{n}{N_{f-HMA}} \right)_{j,m,l,p,T}$$

Where:

n = actual number of axle-load applications within a specific time period,
j = Axle-load interval,
m = Axle-load type (single, tandem, tridem, quad, or special axle configuration),
l = Truck type using the truck classification groups included in the MEPDG,
p = Month,
T = Median temperature for the five temperature or quintiles used to subdivide each month, °F

Setting Goals and Objectives

Load Related Cracking

Alligator cracking

$$FC_{bottom} = \left(\frac{1}{60}\right)\left(\frac{C_4}{1 + e^{(C_1C_1^* + C_2C_2^*Log(DI_{bottom} * 100))}}\right)$$

Where:

FC_{bottom} = Area of alligator cracking that initiates at the bottom of the HMA layers, % of total lane area,
DI_{bottom} = Cumulative damage index at the bottom of the HMA layers,
$C_{1,2,4}$ = Transfer function regression constants; C_4 = 6,000; C_1 = 1.00; C_2 = 1.00,
$C_1^* = -2C_2^*$
$C_2^* = -2.40874 - 39.748\ (1+H_{HMA})^{-2.586}$

Where:

H_{HMA} = Total HMA Thickness, in

Setting Goals and Objectives

Load Related Cracking

Longitudinal cracking

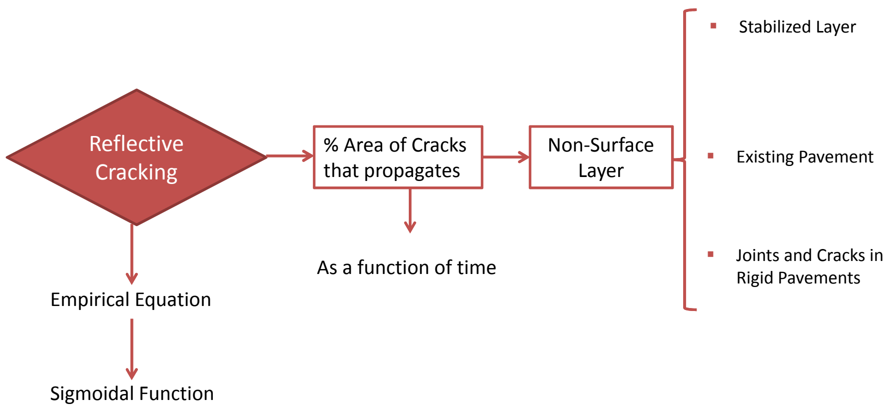
$$FC_{Top} = 10.56\left(\frac{C_4}{1 + e^{(C_1 - C_2Log(DI_{top}))}}\right)$$

Where:

FC_{Top} = Length of longitudinal cracks that initiate at the top of the HMA layer, ft/mi,
DI_{Top} = Cumulative damage index near the top of the HMA surface,
$C_{1,2,4}$ = Transfer function regression constants; C_1 = 7.00; C_2 = 3.5; and C_4 = 1,000.00

Setting Goals and Objectives

Reflective Cracking in HMA Overlays



Reflective Cracking in HMA Overlays

$$RC = \frac{100}{1 + e^{a(c)+bt(d)}}$$

Where:

RC = Percent of cracks reflected
t = Time, yr,
a, b = Regression fitting parameters defined through calibration process,
c,d = User-defined cracking progression parameters.

$$a = 3.5 + 0.75\left(H_{eff}\right)$$
$$b = -0.688684 - 3.37302\left(H_{eff}\right)^{-0.915469}$$

Where:

H_{eff} = HMA Overlay Thickness

Reflective Cracking in HMA Overlays

Continual Damage Accumulation

$$DI_m = \sum_{i=1}^{m} \Delta DI_i$$

Where:

DI_m = Damage index for month, m
ΔDI_i = Increment of damage index in month i

Area of fatigue damage for the underlying layer at month m

$$CA_m = \frac{100}{1 + e^{6-(6DI_m)}}$$

Reflective Cracking in HMA Overlays

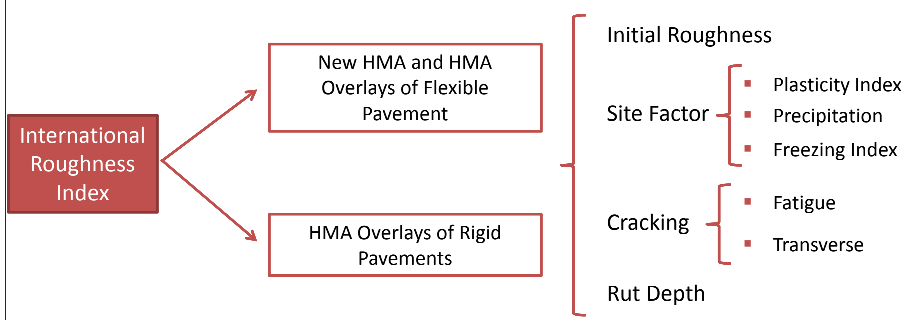
Amount of Cracking Reflected

$$TRA_m = \sum_{i=1}^{m} RC_t(\Delta CA_i)$$

Where:

TRA_m = Total reflected cracking area for month m, (%)
RC_t = Percent cracking reflected for age t (in years)
ΔCA_i = Increment of fatigue cracking for month, i

Smoothness (International Roughness Index)



Smoothness (International Roughness Index)

To predict IRI the MPEDG have embedded two equations develop from data collected within the LTPP program.

1. New HMA Pavements and HMA Overlays of Flexible Pavements

$$IRI = IRI_0 + 0.0150(SF) + 0.400(FC_{total}) + 0.0080(TC) + 40.0(RD)$$

Where:

IRI_o = Initial IRI after construction, in/mi,
SF = Site factor
FC_{Total} = Area of fatigue cracking (combined alligator, longitudinal, and reflection cracking in the wheel path), percent of total lane area. All load related cracks are combined on an area basis –length of cracks is multiply by 1 ft to convert length into an area basis,
TC = Length of transverse cracking (including the reflection of transverse cracks in existing HMA pavements), ft/mi,
RD = Average rut depth, in

Smoothness (International Roughness Index)

To predict IRI the MPEDG have embedded two equations develop from data collected within the LTPP program.

2. HMA Overlays of Rigid Pavements

$$IRI = IRI_0 + 0.00825(SF) + 0.575(FC_{total}) + 0.0014(TC) + 40.8(RD)$$

Where:

IRI_o = Initial IRI after construction, in/mi,
SF = Site factor
FC_{Total} = Area of fatigue cracking (combined alligator, longitudinal, and reflection cracking in the wheel path), percent of total lane area. All load related cracks are combined on an area basis –length of cracks is multiply by 1 ft to convert length into an area basis,
TC = Length of transverse cracking (including the reflection of transverse cracks in existing HMA pavements), ft/mi,
RD = Average rut depth, in

Setting Goals and Objectives

Smoothness (International Roughness Index)

Site Factor

$$SF = Age\ [0.02003(PI + 1) + 0.007947(Precip + 1) + 0.000636(FI + 1)]$$

Where:

Age = Pavement age, year,
PI = Percent of plasticity index of soil,
FI = Average annual freezing index, °F days,
Precip = Average annual precipitation or rainfall, in

Setting Goals and Objectives

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Mechanistic-Empirical Pavement Analysis and Design

Educational Module

Part III – Performance Indicators
Rigid Pavements

Emil G. Bautista
Hani H. Titi

Outline

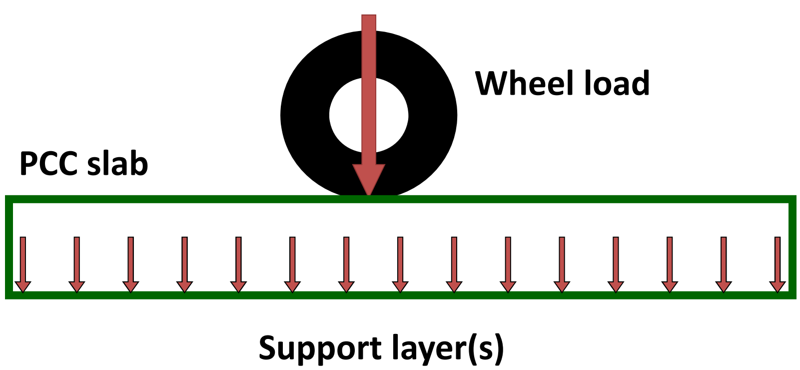
- Performance Indicators Predicted by the MEPDG

  Rigid Pavements
  - Transverse Slab Cracking (Jointed Plain Concrete Pavements)
  - Mean Transverse Joint Faulting (Jointed Plain Concrete Pavements)
  - Punchouts (Continuously Reinforced Concrete Pavements)
  - Smoothness (International Roughness Index)
    - Jointed Plain Concrete Pavements
    - Continuously Reinforced Concrete Pavements

Performance Indicators Predicted by the MEPDG

Rigid Pavement

Distribution of Wheel Load on Rigid Pavement



Transverse Slab Cracking

Jointed Plain Concrete Pavement (JPCP)

Design factors and site conditions that affect JPCP structural performance

- Slab thickness
- PCC material characteristics
  - Modulus of elasticity
  - Poisson’s ratio
  - Unit weight
  - Coefficient of thermal expansion and shrinkage
- Base material characteristics
  - Thickness
  - Modulus of elasticity
  - Unit weight
- Interface condition between the PCC slab and base
- Joint Spacing
- Subgrade stiffness
- Lane-shoulder joint LTE

Setting Goals and Objectives

Transverse Slab Cracking

Jointed Plain Concrete Pavement (JPCP)

Design factors and site conditions that affect JPCP structural performance

- Longitudinal joint lane-to-lane LTE
- Temperature distribution through the slab thickness
- Moisture distribution through the slab thickness
- Magnitude of effective permanent curl/warp
- Axle weight
- Wheel tire pressure and wheel aspect ratio
- Axle position
- Load configuration
  - Bottom-up cracking – axle type (single, tandem, tridem, and quad axles)
  - Top-down cracking – short, medium, and long wheelbase

Setting Goals and Objectives

Transverse Slab Cracking

Jointed Plain Concrete Pavement (JPCP)

JPCP Transverse Cracking Performance Prediction

Considers

- Bottom-up cracking
- Top-down cracking

→ Potential for either mode of cracking is present in all slabs

Any given slab may crack either from bottom-up or top-down but not both

The predicted bottom-up and top-down cracking must be determined combined because they are not particularly meaningful by themselves. This will exclude the possibility of both modes of cracking occurring on the same slab

Setting Goals and Objectives

Transverse Slab Cracking

Jointed Plain Concrete Pavement (JPCP)

$$DI_F = \sum \frac{n_{i,j,k,l,m,n,o}}{N_{i,j,k,l,m,n,o}}$$

Where:

DIF = Total fatigue damage (top-down or bottom-up)
$n_{i,j,k,\ldots}$ = Applied number of load applications at condition i, j, k, l, m, n, o
$N_{i,j,k}\ldots$= Allowable Number of load applications at condition i, j, k, l, m, n, o
i = Age (accounts for change in PCC modulus of rupture and elasticity, slab/base contact friction, deterioration of shoulder LTE)
j = Month (accounts for change in base elastic modulus and effective dynamic modulus of subgrade reaction
k = Axle type (single, tandem, and tridem for bottom-up cracking; short, medium, and long wheelbase for top-down cracking),
l = Load level (incremental load for each axle type),
m = Equivalent temperature difference between top and bottom PCC surfaces,
n = Traffic offset path,
o = Hourly truck traffic fraction

Setting Goals and Objectives

Transverse Slab Cracking

Jointed Plain Concrete Pavement (JPCP)

$$\log(N_{i,j,k,l,m,n,o}) = C1 * \left(\frac{MR_i}{\sigma_{i,j,j,l,m,n,o}}\right)^{C_2}$$

Where:

$N_{i,j,k,\ldots}$ = Allowable number of load applications at condition i, j, k, l, m, n, o
M_{Ri} = PCC modulus of rupture at age i, psi
$\sigma_{i,j,k,\ldots}$ = Applied stress at conditions i, j, k, l, m, n, o
C_1 = Calibration constant, 2.0, and
C_2 = Calibration constant, 1.22

Transverse Slab Cracking

Jointed Plain Concrete Pavement (JPCP)

$$CRK = \frac{1}{1 + (DI_F)^{-1.98}}$$

Where:

CRK = Predicted amount of bottom-up or top-down cracking (fraction), and
DI_F = Fatigue damage

Transverse Slab Cracking

Jointed Plain Concrete Pavement (JPCP)

The fatigue damage calculation is a process of summing damage from each damage increment.

$$TCRACK = (CRK_{Bottom-Up} + CRK_{Top-Down} - CRK_{Bottom-Up} * CRK_{Top-Down})$$

Where:

TCRACK = Total transverse cracking (percent, all severities),

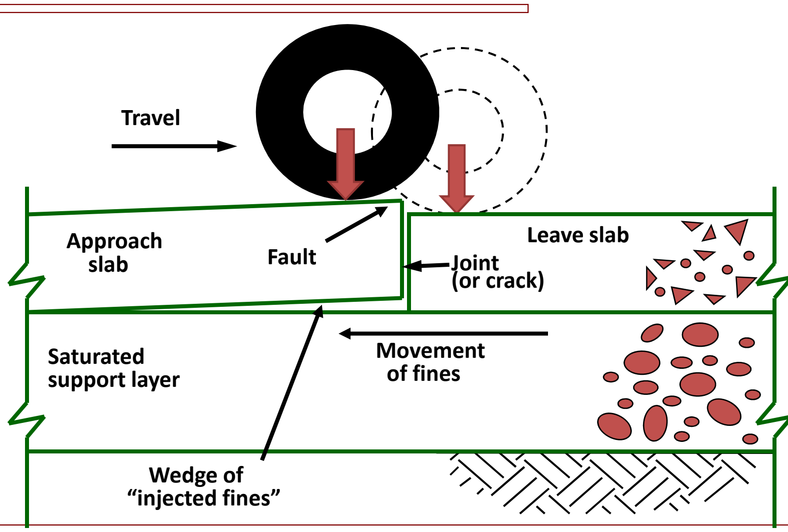
$CRK_{Bottom-Up}$ = Predicted amount of bottom-up transvers cracking (fraction),and

$CRK_{Top-Down}$ = Predicted amount of top-down transverse cracking (fraction)

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)



Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Faulting

- **Definition** → Is the difference in elevation between adjacent joints at a transverse joint measured approximately 1 ft. from the slab edge or from the right-most lane paint stripe for a widened slab
- **Potential** → created by → Repeated heavy axle loads crossing transverse joints
- **Result of:** → Excessive slab edge and corner deflections that cause erosion and pumping fines from beneath a loaded leave slab
- **Increased** → significantly → When a given pavement exhibits a combination of poor load transfer across a joint or crack, heavy axle loads, free moisture beneath the pavement, and erosion and pumping of the supporting base, subbase, or subgrade material from underneath the slab or treated base.

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

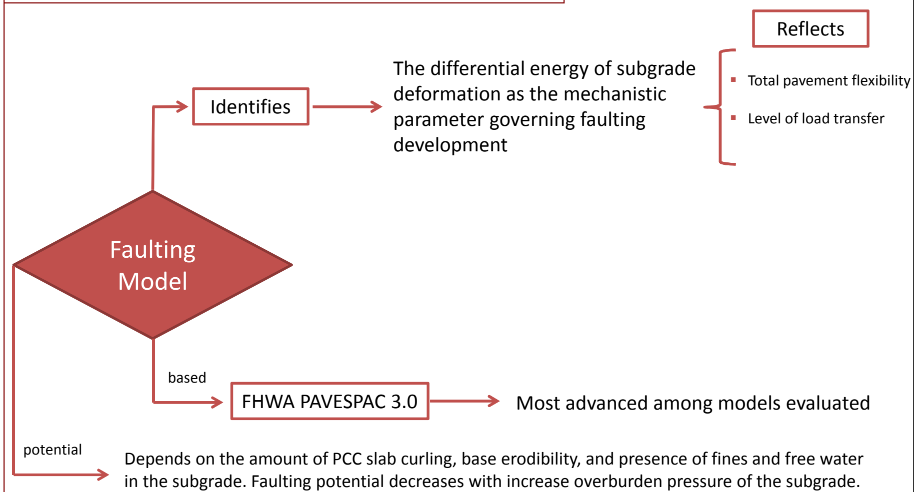
Conditions for Faulting to occur

- Significant differential deflections of adjacent slabs impart energy to the underlying pavement materials. The differential energy across the joint or crack is amplified by several factors, including heavy wheel loads and inadequate load transfer
- Underlying pavements materials are erodible
- Free water is present in the pavement structure, which leads to the saturation of the underlying materials at the slab-base or treated base-subgrade interface

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)



Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Differential Energy Concept

The relationship between the density of energy of subgrade elastic deformation, the PCC slab deflections, and the coefficient of subgrade has the following form:

$$E = \frac{k\delta^2}{2}$$

Where:

E = density of elastic deformation (i.e., energy of subgrade deformation of a unit subgrade surface area)
δ = the slab's deflection, and
k = modulus of subgrade reaction

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Differential Energy Concept

$$DE = E_L - E_{UL} = \frac{k\delta_L^2}{2} - \frac{k\delta_{UL}^2}{2} = \frac{k}{2}(\delta_L - \delta_{UL})(\delta_L + \delta_{UL})$$

Where:

DE = differential energy of subgrade deformation
E_L = energy of subgrade deformation under the loaded slab corner
E_{UL} = energy of subgrade deformation under the unloaded slab corner
δ_L = corner deflection under the load slab
δ_{UL} = corner deflection under the unloaded slab
$(\delta_L - \delta_{UL})$= differential corner deflection between loaded and unloaded slab corner
$(\delta_L + \delta_{UL})$= free corner deflection, represents the total flexibility of the slab

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Differential Energy Concept

$$LTE = \frac{\delta_{UL}}{\delta_L} 100\%$$

$$DE = \frac{k}{2}(\delta_L + \delta_{UL}) \frac{1 - \frac{LTE}{100}}{1 + \frac{LTE}{100}}$$

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Modeling of joint LTE

Combined LTE:

$$LTE_{joint} = 100\left[1 - \left(1 - \frac{LTE_{dowel}}{100}\right)\left(1 - \frac{LTE_{agg}}{100}\right)\left(1 - \frac{LTE_{base}}{100}\right)\right]$$

Where:

LTE_{joint} = total joint LTE (%)
LTE_{dowel} = joint LTE if dowels are the only mechanism of load transfer (%)
LTE_{base} = joint LTE if the base is the only mechanism of load transfer (%)
LTE_{agg} = joint LTE if aggregate interlock is the only mechanism of load transfer (%)

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Aggregate Interlock LTE (Zollinger et al. aggregate interlock model)

The nondimiensional stiffness of an aggregate joint is a function of the load shear capacity, S:

$$\log(J_{aGG}) = -3.19626 + 16.09737 * exp\left\{-exp\left[-\left(\frac{S-E}{f}\right)\right]\right\}$$

Where:

J_{agg} = (Agg/*kl*) = joint stiffness of the transverse joint for current increment
l = PCC slab radius of relative stiffness (in)
f = constant equal to 0.38
S = joint shear capacity

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

The joint shear capacity depends on the joint width and past damage and is defined as follows:

$$S = 0.05 * h_{pcc} * e^{-0.028jw} - \Delta s_{tot}^{b}$$

Where:

S = dimensionless aggregate joint shear capacity,

jw = joint opening [mils (0.001 in)]

hpcc = PCC slab thickness (in)

Δs^{b}_{tot} = cumulative loss of shear capacity at the beginning of the current month equal to sum of loss of shear capacity from every axle-load application

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Joint width is calculated for each month on the basis of PCC zero-stress temperature, PCC shrinkage, and PCC mean nighttime monthly temperature:

$$jw = max\{12{,}000 * JTSpace * \beta * [\alpha_{PCC} * (T_{constr} - T_{mean}) + \epsilon_{sh,mean}], 0\}$$

Where:

$\epsilon_{sh,mean}$ = PCC slab mean shrinkage strain

α_{PCC} = PCC coefficient of thermal expansion (in/in/°F)

JTSpace = joint spacing (ft)

β= joint open/close coefficient assumed equal to 0.85 for a stabilized base and 0.65 for an unbound granular base

T_{mean} = mean monthly nighttime middepth temperature (°F)

T_{constr} = PCC zero-stress temperature at set (°F) defined as the temperature at which the PCC layer exhibits zero thermal stress

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

The cumulative loss of shear at the end of the month is determined as follows:

$$\Delta s_{tot}^{b} = \Delta s_{tot}^{b} - \sum_{i} n_i \Delta s_i$$

Where:

Δs^{b}_{tot} = cumulative loss of shear capacity at the end of the current month equal to sum of loss of shear capacity from every axle-load application

n_i = number of applications of axle load i

Δs_i = loss of shear capacity due to single application of an axle load i defined as follows:

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

$$\Delta s_i = \begin{cases} 0 & if\ \frac{jw}{h_{PCC}} < 0.001 \\ \frac{0.005 * 10^{-6}}{1.0 + \left(\frac{jw}{h_{PCC} - 3}\right)^{-5.7}} \left(\frac{\tau_i}{\tau_{ref}}\right) & if\ 0.001 < \frac{jw}{h_{PCC}} < 3.8 \\ \frac{0.068 * 10^{-6}}{1.0 + 6.0 * \left(\frac{jw}{h_{PCC} - 3}\right)^{-1.98}} \left(\frac{\tau_i}{\tau_{ref}}\right) & if\ \frac{jw}{h_{PCC}} > 3.8 \end{cases}$$

τ_i = shear stress on the transverse joint surface from the response model for the load group i (psi)
τ_{ref} = reference shear stress derived from the Portland Cement Association test results (psi)
jw = joint opening (mils)
h_{pcc} = PCC slab thickness (in)

- **LTE reduction with time comes from the loss of shear capacity and the increase in joint opening due to shrinkage.**

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Doweled Joint Load Transfer

Ioannides and Korovesis identified the following nondimensional parameters governing dowel joint behavior:

$$J_D = \frac{D}{DowelSpace\ kl}$$

Where:

J_D = nondimensional stiffness of doweled joints
D = shear stiffness of a single dowel (lb/in)
Dowel Space = space between adjacent dowels in the wheelpath (in)

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Adopted model for nondimensional dowel joint stiffness:

$$J_d = J_d^* + (J_o - J_d^*)exp(-DAM_{dowels})$$

Where:

J_d = nondimensional dowel stiffness
J_o = initial nondimensional dowel stiffness
J^*_d = critical nondimensional dowel stiffness
DAM_{dowels} = damage accumulated by a doweled joint due to past traffic

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Initial and long term nondimensional doweled stiffnesses:

$$J_o = \frac{152.8 A_d}{h_{PCC}}$$

$$\Delta s_i = \begin{cases} 118 & if \ \frac{A_d}{h_{PCC}} > 0.656 \\ 210.0845 \frac{A_d}{h_{PCC}} - 19.8 & if \ 0.009615 \leq \frac{A_d}{h_{PCC}} \leq 0.656 \\ 0.4 & if \ \frac{A_d}{h_{PCC}} > 0.009615 \end{cases}$$

Where:

J_o = intial nondimensional dowel stiffness
J^*_d = critical nondimensional dowel stiffness,
A_d = area of dowel cross section
h_{PCC} = PCC slab thickness (in)

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

Dowel joint damage accumulated from an individual axle repetition is determined using the following equation:

$$\Delta DOWDAM_i = C_8 * \frac{F_{j,A}}{d^*_{fc}}$$

Where:

ΔDOWDAM = dowel damage increment from an individual axle application,
f^*_c = PCC compressive stress (psi)
C_8 = calibration constant
F = effective dowel shear force induced by an axle and defined as follows:

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

$$F = J_d * (\delta_L - \delta_U) * DowelSpace$$

Where:

J_d = nondimensional dowel stiffness at the time of load application
δ_L = deflection at the corner of the loaded slab induced by the axle
δ_U = deflection at the corner of the unloaded slab induced by the axle

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

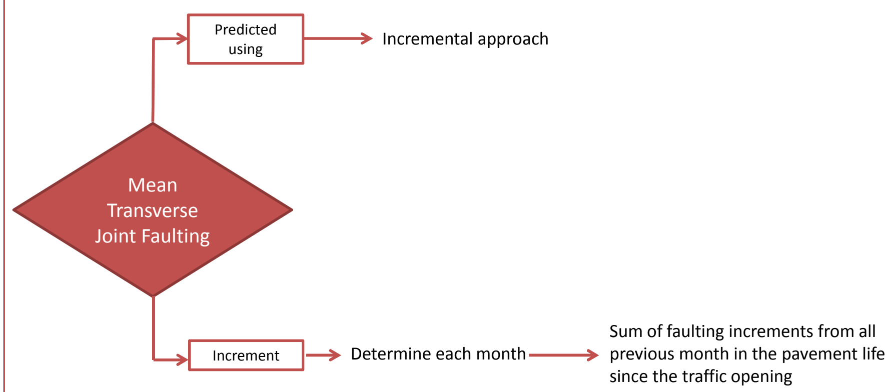
Base Load Transfer

The design procedure accounts for the effect by assigning a percentage of LTE of the base layer, LTE_{base}, depending on the base layer type.

Base Type	LTE_{base} (%)
Aggregate base	20
Asphalt-treated or cement-treated	30
Lean concrete base	40

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)



Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

The mean transverse joint faulting is predicted month by month using an incremental approach.

$$Fault_m = \sum_{i=1}^{m} \Delta Fault_i$$

$$\Delta Fault_i = C_{34} * (FAULTMAX_{i-1} - Fault_{i-1})^2 * DE_i$$

Where:

$Fault_m$ = Mean joint faulting at the end of the month m, in.,
$\Delta Fault_i$ = Incremental change (monthly) in mean transverse joint faulting during month i, in.,
$FAULTMAX_i$ = Maximum mean transverse joint faulting, in.,
DE_i = Differential density of energy of subgrade deformation accumulated during month i,

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

$$FAULTMAX_i = FAULTMAX_0 + C_7 * \sum_{j=1}^{m} DE_j * Log\,(1 + C_5 * 5.0^{EROD})^{C_6}$$

$$FAULTMAX_0 = C_{12} * \delta_{curling} * \left[Log\,(1 + C_5 * 5.0^{EROD}) * Log\left(\frac{P_{200} * WetDays}{P_s}\right)^{C_6} \right]$$

Where:

$FAULTMAX_0$= Initial maximum mean transverse joint faulting, in.,
EROD = Base/subbase erodibility factor,
$\delta_{curling}$ = Maximum mean monthly slab corner upward deflection PCC due to temperature curling and moisture warping,
P_s = Overburden on subgrade, lb,
P_{200} = Percent subgrade material passing #200 sieve,
WetDays = Average annual number of wet days (greater than 0.1 in. rainfall), and
$C_{1,2,3,4,5,6,7}$ = Global calibration constants (C_1 = 1.29; C_2 = 1.1; C_3 = 0.00175; C_4 = 0.0008; C_5 = 250; C_6 = 1.2)

Setting Goals and Objectives

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

$$C_{12} = C_1 + C_2 * FR^{0.25}$$

$$C_{34} = C_3 + C_4 * FR^{0.25}$$

Where:

FR = Base freezing index defined as percentage of time the top base temperature is below freezing (32 °F) temperature

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

CRCP Identification

- Continuous longitudinal steel reinforcement
- Absence of intermediate transverse contraction joint
- Well-defined pattern of transverse cracks that develops within 2 years from construction → Typically spaced 0.6 to 1.8 m (2 to 6 ft.) apart

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Design factors and site conditions that affect CRCP structural performance

- Slab thickness
- PCC material characteristics
  - Strength
  - CTE
  - Ultimate shrinkage
- Transverse cracks as a function of pavement design parameters
- Reinforcement applications
  - Percent steel
  - Bar diameter
  - Depth of steel
- Transverse cracks width and crack load transfer during service life
- Slab supporting layers, including the possibility of erosion and loss of support along the edge
- Full spectrum of axle loading and traffic wander characteristics
- Environmental differentials through the slab thickness due to temperature change in concrete

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Based on the prediction of several critical conditions that take place in the field:

CRCP structural design

- Development of transverse cracks
- Loss of aggregate interlock across transverse cracks
- Loss of edge support due to erosion
- Fatigue damage accumulation leading to the formation of longitudinal cracks in concrete and punchout development

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Punchouts

- Defined → By a settle area within a concrete slab enclosed by two closely spaced transverse cracks, a short longitudinal crack, and the edge of the pavement
- Results → In the loss of ride quality and represent serious hazards that could lead to fatal road accidents

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Punchouts model

- Mechanistic principles
- Damage accumulation
  - Correlated with CRCP punchouts by using extensive field data

To account changes in many factors:

- Material properties
  - PCC strength and modulus
  - Erosion base
- Seasonal climatic conditions
- Traffic loadings
- Crack load transfer
- Subgrade support

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Modeling of Transverse Cracks and Longitudinal Joint

Shear spring stiffness elements were used to model discontinuities at the transverse cracks and the longitudinal joint. Shear spring stiffness per unit of transverse crack length can be estimated by a equation based on Crovetti:

$$AGG = k\, l * \left[\frac{\left(\frac{1}{LTE} - 0.01\right)}{0.012}\right]^{-\frac{1}{0.849}}$$

Where:

AGG = vertical shear spring stiffness (lb/in/in)
LTE = load transfer efiency (%)
k = coefficient of subgrade reaction (pci)
l = radius of relative stiffness

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

LTE across the transverse cracks:

$$LTE_{TOTi} = 100 * \left[1 - \left(1 - \frac{1}{1 + log^{-1}\left\{\frac{\left[0.214 - 0.183\frac{a}{l_i} - log(J_{ci}) - (500P_b - 3)\right]}{1.18}\right\}}\right) * \left(1 - \frac{LTE_{Base}}{100}\right)\right]$$

Where:

LTE_{TOTi} = total crack LTE due for time increment I (%)
l_i = radius of relative stiffness computed for time increment *i* [mm(in)]
a = radius of loaded area [mm (in)]
P_b = percent of longitudinal reinforcement expressed as a fraction
LTE_{Base} = load transfer efficiency contributed by the base layer
J_{ci} = nondimensional aggregate interlock factor for time increment *i*

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Nondimensional aggregate interlock factor is computed for each time increment i based on current value of shear capacity s by using the following equation:

$$\log(J_{ci}) = ae^{-e^{-\left(\frac{J_S-b}{c}\right)}} + de^{-e^{-\left(\frac{s_i-e}{f}\right)}} + ge^{-e^{-\left(\frac{J_S-b}{c}\right)}} * e^{-e^{-\left(\frac{s_i-e}{f}\right)}}$$

Where:

a = -2.2
b = -11.26
c = 7.56
d = -28.85
e = 0.35
f = 0.38
g = 49.8
J_s = lane shoulder joint stiffness across (4 for tied PCC, 0.004 for all other shoulder types)
S_i = dimensionless shear capacity for time increment *i*

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Dimensionless shear capacity of the transverse cracks

$$s_i = s_{0i} - \Delta S_{i-1}$$

Where:

s_{0i} = initial crack shear capacity based on crack width and slab thickness for time increment i
ΔS_{i-1} = loss of shear capacity accumulated from all previous time increments

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Loss of shear capacity at the end of a time increment:

$$\Delta s_i = \sum_j \left[\frac{0.005}{1 + 1 * \left(\frac{cw_i}{h_{PCC}}\right)^{-5.7}} \right] \left(\frac{n_{ij}}{10^6}\right) \left(\frac{\tau_{ij}}{\tau_{ref\ i}}\right) ESR_i \qquad if \ \left(\frac{cw_i}{h_{PCC}}\right) < 3.7$$

$$\Delta s_i = \sum_j \left[\frac{0.068}{1 + 6 * \left(\frac{cw_i}{h_{PCC}} - 3\right)^{-1.98}} \right] \left(\frac{n_{ij}}{10^6}\right) \left(\frac{\tau_{ij}}{\tau_{ref\ i}}\right) ESR_i \qquad if \ \left(\frac{cw_i}{h_{PCC}}\right) > 3.7$$

Where:

cw_i = crack width for time increment I [mm (mils)]
h_{PCC} = slab thickness [m (in)]
n_{ij} = number of axle load applications for load level j
τ_{ij} = shear stress on the transverse crack at the corner due to load j [kPa (psi)]
$\tau_{ref\ i}$ = reference shear stress derived from the Portland Cement Association test results [kPa (psi)]
ESR = equivalent shear ratio to adjust traffic load applications for lateral traffic wander

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Average crack width at the depth of the steel for time increment $_i$:

$$cw_i = L\,(\epsilon_{shr} + \alpha_{PCC}\Delta T) - L\,\frac{C_2}{E_{PCC}}\left[\frac{LU_m P_b}{c_{1i} d_b} + C\sigma_0\left(1 - \frac{2h_s}{h_{PCC}}\right) + \frac{L}{2}f\right]$$

Where:

L = crack spacing (mm)
ϵ_{shr} = unrestrained concrete drying shrinkage at the steel depth
α_{PCC} = concrete coefficient of thermal expansion (CTE) [°C^{-1} (°F^{-1})]
ΔT = drop in PCC temperature at the depth of the steel for time increment *i* [°C (°F)]
c_1 = first bond stress coefficient
c_2 = second bond stress coefficient
E_{PCC} = concrete modulus of elasticity [kPa (psi)]
P_b = percent of longitudinal reinforcement expressed as a fraction
U_m = peak bond stress [kPa (psi)]
h_{PCC} = PCC slab thickness [mm (in)]
h_s = depth to steel [mm (in)]
f= subbase friction coefficient from test data or by using AASHTO recommendations
C = Bradbury's correction factor for slab size
σ_0 = Westergaard nominal environment stress factor [kPa (psi)]

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Modeling of Subgrade and Edge Support:

$$EE = AGE * \frac{(-7.4 + 0.32P_{200} + 1.557BEROD + 0.234PRECIP)}{12}$$

Where:

EE = erosion extent from pavement edge (in)
AGE = pavement age (month)
P200 = percent subgrade passing the No. 200 sieve (%)
PRECIP = mean annual precipitation (in)
BEROD = base erodibility index [1 for LCB, 2 for CTB with 5% cement, 3 for AT and CTB with < 5% cement, 4 for granular base (GB) with 2.5% cement, and 5 for untreated GB]

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Modeling of Transverse Cracking:

$$L = \frac{(f_t - f_\sigma)}{\frac{f}{2} + \frac{U_m P}{c_1 d_b}}$$

Where:

L = mean crack spacing [mm (in)]
f_t = tensile strength of the concrete [kPa (psi)]
f_σ = maximum stress in concrete at steel level [kPa (psi)]
f = friction coefficient
U_m = peak bond stress [kPa (psi)]
P = percent of longitudinal reinforcement
d_b = reinforcing steel bar diameter [mm(in)]
c_1 = bond-slip coefficient

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Fatigue Prediction Model:

$$DI_{PO} = \sum \frac{n_{i,j}}{N_{i,j}}$$

For each load level in each gear configuration or axle-load spectra, the tensile stress on top of the slab is used to calculate the number of allowable load repetitions, $N_{i,j}$, due to this load level

$$\log(N_{i,j}) = 2.0 * \left(\frac{MR_i}{\sigma_{i,j}}\right)^{1.22} - 1$$

Where:

M_{RI} = PCC modulus of rupture at age *i*, psi
$\sigma_{i,j}$ = Applied stress at time increment *i* due to load magnitude $_j$, psi.

Setting Goals and Objectives

Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

The following globally calculated model predicts CRCP punchouts as a function of accumulated fatigue damage due to top-down stresses in the transverse direction:

$$PO = \frac{A_{PO}}{1 + \alpha_{PO} * (DI_{PO})^{\beta_{PO}}}$$

Where:

PO = Total predicted number of medium and high-severity punchouts, 1/mi,
DI_{PO} = Accumulated fatigue damage (due to slab bending in the transverse direction) at the end of y[th] yr, and
A_{PO}, α_{PO}, β_{PO} = Calibration constants (195.789, 19.8947, -0.526316, respectively).

Smoothness

Jointed Plain Concrete Pavement (JPCP)

Predicted as a function of the initial as-constructed profile of the pavement and any change in the longitudinal profile over time and traffic due to distresses and foundation movements.

$$IRI = IRI_I + C_1 * CRK + C_3 * SPALL + C_3 * TFAULT + C_4 SF$$

Where:

IRI = Predicted IRI, in./mi,
IRI_I = Initial smoothness measured as IRI, in./mi,
CRK = Percent slabs with transverse cracks (all severities),
SPALL = Percentage of joints with spalling (medium and high severities),
TFAULT = Total joint faulting cumulated per mi, in., and
C1 = 0.8203,
C2 = 0.4417,
C3 = 0.4929,
C4 = 25.24
SF = Site factor

Smoothness

Jointed Plain Concrete Pavement (JPCP)

$$SF = AGE\ (1 + 0.5556 * FI)(1 + P_{200}) * 10^{-6}$$

Where:

AGE = Pavement age, yr,
FI = Freezing index, °F-days, and
P200 = Percent subgrade material passing No. 200 sieve

- **The transverse cracking and faulting are obtained using the models described earlier.**

Smoothness

Jointed Plain Concrete Pavement (JPCP)

$$SPALL = \left(\frac{AGE}{AGE + 0.01}\right)\left(\frac{100}{1 + \ 1.005^{(-12*AGE+SCF)}}\right)$$

Where:

SPALL = Percentage joints spalled (medium and high severities),
AGE = Pavement age since construction, yr, and
SCF = Scaling factor based on site, design, and climate related

Smoothness

Jointed Plain Concrete Pavement (JPCP)

$$SCF = -1400 + 350 * AC_{PCC} * (0.5 + PREFORM) + 3.4\, f'c * 0.4 - 0.2\left(FT_{cycles} * AGE\right) + 43\, H_{PCC} - 536\, WC_{PCC}$$

Where:

AC_{PCC} = PCC air content, %,
AGE = Time since construction, yr,
PREFORM = 1 if preformed sealant is present; 0 if not,
f'c = PCC compressive strength, psi,
FT_{cycles} = Average annual number of freeze-thaw cycles,
H_{PCC} = PCC slab thickness, in., and,
WC_{PCC} = PCC w/c ratio.

Smoothness

Continuously Reinforced Concrete Pavement (CRCP)

Is the result of a combination of the initial as constructed profile of the pavement and any change in the longitudinal profile over time and traffic due to the development of distress and foundations movements.

$$IRI = IRI_I + C_1 * PO + C_2 * SF$$

Where:

IRI_I = Initial IRI, in./mi,
PO = Number of medium and high severity punchouts/mi,
C1 = 3.15,
C2 = 28.35, and
SF = Site Factor

Smoothness

Continuosly Reinforced Concrete Pavement (CRCP)

$$SF = AGE\ (1 + 0.556 * FI)(1 + P_{200}) * 10^{-6}$$

Where:

AGE = Pavement age, yr,
FI = Freezing index, °F-days, and
P200 = Percent subgrade material passing No. 200 sieve

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Mechanistic-Empirical Pavement Analysis and Design

Educational Module

Part IV – MEPDG Inputs

Emil G. Bautista

Hani H. Titi

Outline

- Hierarchical Design Inputs Levels
- General Project Information
  - Design and Analysis Life
  - Construction and Traffic Opening Dates
  - General Information
  - Design Types
  - Pavement Types
- Design and Performance Criteria
- Reliability Level

Outline

- Traffic Input Characterization
- Climate Effects
- Characterization of Materials
  - Subsurface Investigation
  - Laboratory and Field Test for Pavement Design

Hierarchical Design Input Levels

For

Mechanistic-Empirical Pavement Design Guide

Hierarchical Input Levels

Function

- Little Investments
  - State agencies
  - Pavement designers
- Flexibility
  - Input Level 1
  - Input Level 2
  - Input Level 3

Important Remarks

For a given design project inputs can be obtained using a mix of levels.

No matter the input levels used, the computational algorithm for damage and distress is exactly the same.

Hierarchical Input Levels

Design Input Parameters

- **Level 1**
  - Project specific
  - Measured directly
  - Highest level of accuracy
  - Requires laboratory and field testing
- **Level 2**
  - Closest to typical procedure of earlier AASTHO Guides
  - Intermediate level of accuracy
  - Estimated from correlations or regression equations
- **Level 3**
  - Based on best estimate or default values
  - Lowest level of accuracy

General Project Information

For

Mechanistic-Empirical Pavement Design Guide

Design and Analysis Life

Design and Analysis Life

- Initial Construction —until→ Pavement has deteriorated
- Durability and Material Disintegration —type of→ Surface distress —are→ Not predicted by MEPDG
- For Design Periods > 30 years
  - Adequate material
  - Adequate specifications
  - Few pavements that exceeded 30 years of performance where included in the global calibration

Setting Goals and Objectives

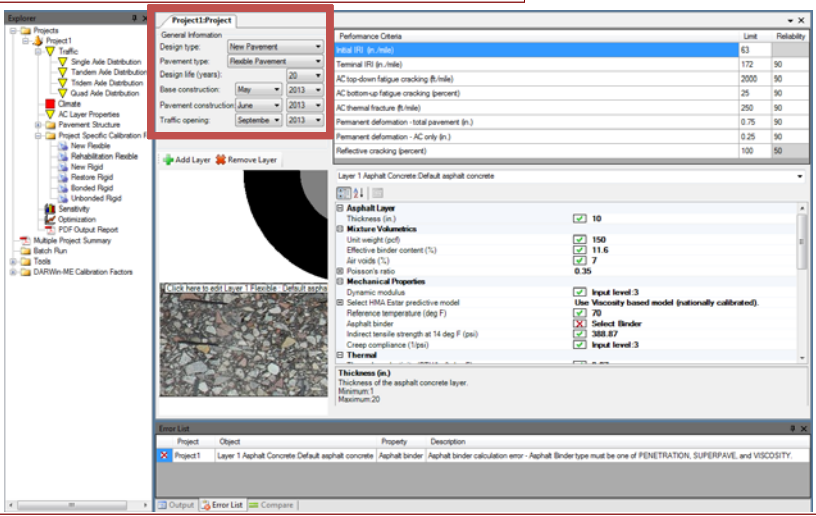
Construction and Traffic Opening Dates

Construction and Traffic Opening dates

- Impact → Distress predictions
- Base/Subgrade pavement traffic —estimated by→ Designer
- Related to monthly
  - Traffic Loading
  - Climatic Inputs
  - Affect all monthly
    - Layers Modulus
    - Subgrade Modulus
    - HMA aging
    - PCC aging

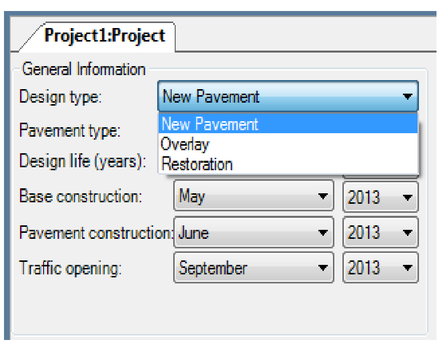
Setting Goals and Objectives

General Information



Setting Goals and Objectives

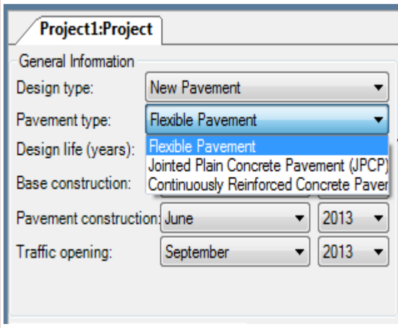
Design Types



- New Pavement
- Overlay
- Restoration

Setting Goals and Objectives

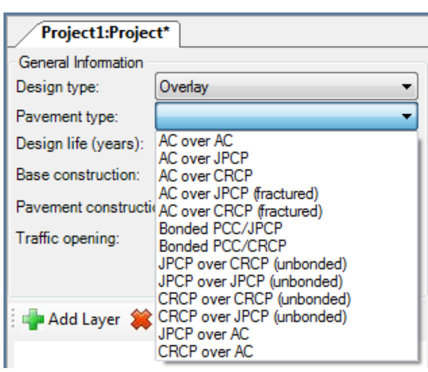
Pavement Types



New Pavement

- Flexible Pavement
- Jointed Plain Concrete Pavement (JPCP)
- Continuously Reinforced Concrete Pavement (CRCP)

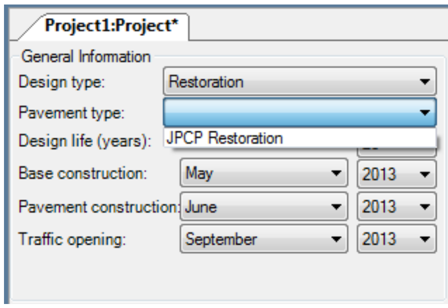
Pavement Types



Overlay

- AC over AC
- AC over JPCP
- AC over CRCP
- AC over JPCP (fractured)
- AC over CRCP (fractured)
- Bonded PCC/JPCP
- Bonded PCC/CRCP
- JPCP over JPCP (unbonded)
- JPCP over CRCP (unbonded)
- CRCP over CRCP (unbonded)
- CRCP over JPCP (unbonded)
- JPCP over AC
- CRCP over AC

Pavement Types



Restoration
- JPCP Restoration

Design and Performance Criteria

For

Mechanistic-Empirical Pavement Design Guide

Selecting a Design-Performance Criteria

Design Performance Criteria

- Ensure Pavement Design → Performs satisfactorily → Over design life
- Critical Limits or Thresholds → Selected by designer → (represents) Agency policies
- Projects exceeds Performance Criterion → Maintenance / Rehabilitation

Setting Goals and Objectives

Recommended design-performance criteria at the end of design life for HMA and Overlays

Design Performance Criteria

- Alligator Cracking
  - Interstate – 10% of lane area
  - Primary – 20% of lane area
  - Secondary – 35% of lane area
- Transverse Cracking
  - Interstate – 500 ft/mi
  - Primary – 700 ft/mi
  - Secondary – 700 ft/mi
- Rut Depth
  - Interstate – 0.40 in
  - Primary – 0.50 in
  - Others (<45 mph) – 0.65 in
- International Roughness Index (IRI)
  - Interstate – 160 in/mi
  - Primary – 200 in/mi
  - Secondary – 200 in/mi

Setting Goals and Objectives

Reliability Level

For

Mechanistic-Empirical Pavement Design Guide

Design Reliability (R)

Is the probability (P) that the predicted distress will be less than the critical level over the design period.

$$R = P\ [Distress\ over\ Design\ Period < Critical\ Stress\ Level]$$

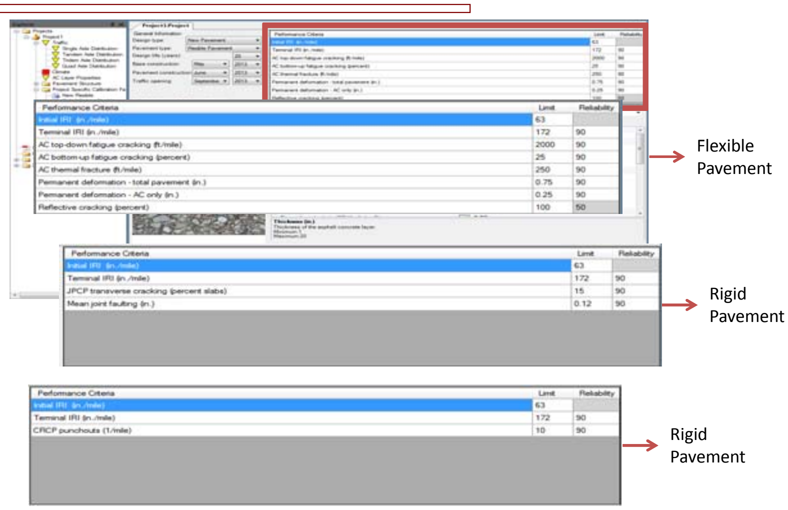
This means that if 10 projects are designed and constructed using a design reliability of 90 % on average on of those projects will exceed the performance limit value at the end of the design period.

Selecting a Reliability Level

- Based on the general consequence of reaching terminal condition earlier than the design life.
- Some agencies have typically used the level of truck traffic volume as the parameter for selecting design reliability.
- It is recommended that the same reliability be used for all performance indicators

Setting Goals and Objectives

Performance Criteria



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 fracture (ft./mile)	250	90
Permanent deformation - total pavement (in.)	0.75	90
Permanent deformation - AC only (in.)	0.25	90
Reflective cracking (percent)	100	50

Performance Criteria	Limit	Reliability
Initial IRI (in./mile)	63	
Terminal IRI (in./mile)	172	90
JPCP transverse cracking (percent slabs)	15	90
Mean joint faulting (in.)	0.12	90

Performance Criteria	Limit	Reliability
Initial IRI (in./mile)	63	
Terminal IRI (in./mile)	172	90
CRCP punchouts (1/mile)	10	90

Setting Goals and Objectives

Traffic Input and Characterization

For

Mechanistic-Empirical Pavement Design Guide

MEPDG vs AASHTO 1972, 1993

AASHTO 1972 and 1993

- Equivalent Single Axle Load (ESAL) as a measure of "unit damage" endured by a pavement structure relative to 18-kip loaded single axle
- Equivalency factors for each axle load and configuration
- Observational basis as inferred from the AASHO Road Test
- Lacks material response, seasonal variations in traffic volume, and economy

MEPDG vs AASHTO 1972, 1993

MEPDG

Wide array of design input to consider:

- Seasonal variation in truck volume and economy
- Monthly and daily variation in truck volume
- Axle load distribution of loaded axle configurations → **Load Spectra Analysis**
- Vehicle speed
- Tire and axle spacing, wheelbase
- Vehicle classification distributions

Setting Goals and Objectives

WIM Record Data Formatting

W 55 **030010** 5 **1** 06010100 **09** 0174 **03** 050 **05** 064 **010** 060

W – indicates weight record, in metric units (E for english units)
55 – state identification (WI)
450239 – station identification (USH 35, Cameron)
3 – direction of travel
 1-8 relative to compass rose (5 South)
1 – lane of travel
 1 is outermost lane (right)
 2-n from right to left with n number of lanes
06010100 – year, month, day, hour
09 – vehicle classification
0174 – gross weight of vehicle
03 – total number of axles
050 – weight of axle A
05 – axle spacing A-B
064 – weight of axle B
010 – axle spacing B-C
060 – weight of last axle C

Specified in FHWA's Traffic Monitoring Guide!

Setting Goals and Objectives

WIM Quality Control

Validating Vehicle Classification

Five criterion **(per AASHTO "Guidelines for Traffic Data Programs" 2009)**

1. Compare hourly totals for vehicle classes 2 and 3. Class 3 volume near or exceeding that of class 2 can indicate error
2. Consistency of traffic volume for classes 2, 3, and 9, relative to total volume. These classes should constitute the majority of traffic volume.
3. Day to day comparison of lane and directional distributions for consistency.
4. Directional distribution by vehicle class should be approximately equal (50-50).
5. AADT and vehicle class distribution to historical data. Volume changes of more than 15% for classes 2,3, and 9 indicate inaccuracy.

Setting Goals and Objectives

WIM Quality Control

Validating Vehicle Weights

Three criterion **(per AASHTO "Guidelines for Traffic Data Programs" 2009)**

1. Gross vehicle weight (GVW)

Bimodal distribution for loaded and unloaded class 9 vehicles
- First peak: 28,000 – 32,000 lb (unloaded)
- Second peak: 70,000 – 80,000 lb (loaded)

2. Front axle weight (FAW) to gross vehicle weight
- <32,000 GVW → 8,500 lb FAW
- 32,000 – 70,000 lb GVW → 9,300 lb FAW
- >70,000 lb GVW → 10,400 FAW

3. Day to day ESALS should be consistent (no recommended)

Setting Goals and Objectives

Input Parameters From WIM

Frequency distribution of loaded axles within each vehicle class and axle type

Axle Load Spectra

Only FHWA vehicle classes 4-13 considered

- Single Axles → 3,000 lb – 40,000 lb @ 1,000 lb intervals
- Tandem Axles → 6,000 lb – 80,000 lb @ 2,000 lb intervals
- Tridem/Quad → 12,000 lb – 102,000 lb @ 3,000 lb intervals

Monthly axle load distribution if available

Input Parameters From WIM

Truck Volume Adjustment Factors

Monthly Adjustment Factors (MAF) →

$$MAF_i = \frac{AMDTT_i}{\left(\frac{\sum AMDTT_i}{12}\right)}$$

Hourly Adjustment Factors (HAF) →

$$HAF_i = \frac{AHDTT_i}{\left(\frac{\sum AHDTT_i}{24}\right)}$$

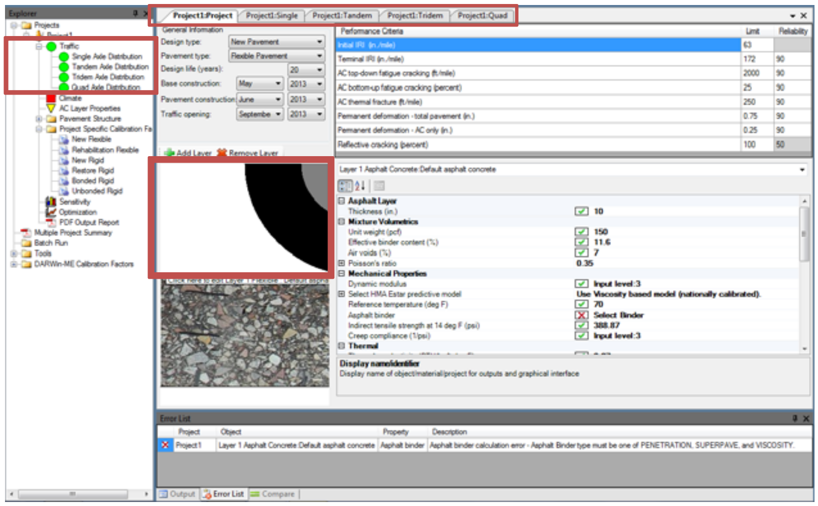
Axle Load Spectra

Vehicle class distribution → Percentage of total traffic classified by each FHWA class 4-13

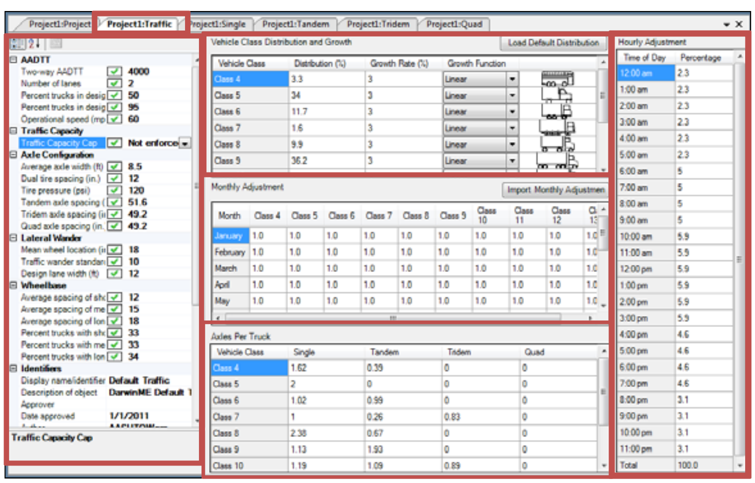
Average axles per truck

Average axle spacing

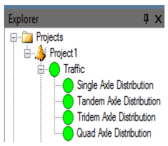
Traffic Inputs



Traffic Inputs



Traffic Inputs – Axle Distribution



Project1:Project | Project1:Traffic | Project1:Single

Month	Class	Total	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000	15000	16000
January	4	100	1.8	0.96	2.91	3.99	6.8	11.47	11.3	10.97	9.88	8.54	7.33	5.55	4.23	3.11
January	5	100	10.05	13.21	16.42	10.61	9.22	8.27	7.12	5.85	4.53	3.46	2.56	1.92	1.54	1.19
January	6	100	2.47	1.78	3.45	3.95	6.7	8.45	11.85	13.57	12.13	9.48	6.83	5.05	3.74	2.66
January	7	100	2.14	0.55	2.42	2.7	3.21	5.81	5.26	7.39	6.85	7.42	8.99	8.15	7.77	6.84
January	8	100	11.65	5.37	7.84	6.99	7.99	9.63	9.93	8.51	6.47	5.19	3.99	3.38	2.73	2.19
January	9	100	1.74	1.37	2.84	3.53	4.93	8.43	13.67	17.68	16.71	11.57	6.09	3.52	1.91	1.55
January	10	100	3.64	1.24	2.36	3.38	5.18	8.35	13.85	17.35	16.21	10.27	6.52	3.94	2.33	1.57
January	11	100	3.55	2.91	5.19	5.27	6.32	6.98	8.08	9.68	8.55	7.29	7.16	5.65	4.77	4.35
January	12	100	6.68	2.29	4.87	5.86	5.97	8.86	9.58	9.94	8.59	7.11	5.87	6.61	4.55	3.63
January	13	100	8.88	2.67	3.81	5.23	6.03	8.1	8.35	10.69	10.69	11.11	7.32	3.78	3.1	2.58

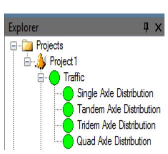
Single Axle Load Distribution Pallet in AASHTOWare Pavement ME

Project1:Project | Project1:Traffic | Project1:Single | Project1:Tandem

Month	Class	Total	6000	8000	10000	12000	14000	16000	18000	20000	22000	24000	26000	28000	30000
January	4	100	5.88	1.44	1.94	2.73	3.63	4.96	7.95	11.58	14.2	13.15	10.73	7.47	5.08
January	5	100	7.06	35.44	13.24	6.32	4.33	5.08	5.05	4.39	2.31	2.28	1.53	1.96	1.89
January	6	100	5.28	8.43	10.83	8.99	7.72	7.5	6.76	6.06	5.71	5.17	4.52	3.9	3.21
January	7	100	13.76	6.72	6.5	3.46	7.07	4.83	4.97	4.58	4.26	3.85	3.44	6.03	3.68
January	8	100	18.93	8.07	11.17	11.87	10.53	8.26	6.78	5.33	4.13	3.12	2.34	1.82	1.58
January	9	100	2.78	3.92	6.52	7.62	7.75	7.01	5.83	5.6	5.17	5.05	5.28	5.53	6.13
January	10	100	2.45	2.19	3.65	5.4	6.9	7.49	6.99	6.62	6.26	5.95	6.16	6.54	6.24
January	11	100	7.93	3.15	5.21	8.23	8.88	8.45	7.08	5.49	5.14	5.99	5.73	4.37	6.58
January	12	100	5.23	1.75	3.35	5.89	8.73	8.38	9.77	10.84	10.78	7.24	6.14	4.93	3.93
January	13	100	6.42	3.85	5.59	5.67	5.74	5.54	4.9	4.5	6.45	4.77	4.34	5.63	7.24

Tandem Axle Load Distribution Pallet in AASHTOWare Pavement ME

Traffic Inputs – Axle Distribution



Project1:Project | Project1:Traffic | Project1:Climate | Project1:Tridem

Month	Class	Total	12000	15000	18000	21000	24000	27000	30000	33000	36000	39000	42000	45000	48000
January	4	100	66.67	0	0	0	0	0	0	0	0	0	26.66	6.67	0
January	5	100	48.28	1.08	0.43	0.15	0.73	3.13	3.83	0.7	15.59	0.7	3.48	2.93	3.33
January	6	100	29.51	9.2	7.6	10.35	4.73	3.55	6.27	4.18	2.11	2.22	1.79	1.7	1.19
January	7	100	5.89	2.18	3.32	2.98	3.27	4.26	4.48	5.11	7.01	6.77	7.21	7.18	6.63
January	8	100	20.89	2.33	3.34	4.26	3.71	4.32	5.24	4.89	3.91	5	3.99	4.53	4.96
January	9	100	59.19	13.03	7.89	6.51	2.78	1.87	2.51	1.02	0.66	0.55	0.59	0.84	0.36
January	10	100	16.21	9.51	7.3	5.83	5.82	5.03	4.99	5.79	6.71	7.41	6.41	4.93	4.54
January	11	100	23.31	20.89	15.88	12	5.8	2.61	2.08	2.06	2.94	1.1	2.98	1.95	1.87
January	12	100	13.28	6.38	6.74	6	4.37	4.53	8.01	5.61	6.25	8.04	6.7	6.08	3.48
January	13	100	10.86	4.4	4.75	4.04	3.02	4.46	4.99	3.82	6.51	5.49	6.53	5.19	6.32

Tridem Axle Load Distribution Pallet in AASHTOWare Pavement ME

Project1:Project | Project1:Traffic | Project1:Climate | Project1:Tridem | Project1:Quad

Month	Class	Total	12000	15000	18000	21000	24000	27000	30000	33000	36000	39000	42000	45000	48000
January	4	100	66.66	0	0	0	0	0	0	0	0	0	26.67	6.67	0
January	5	100	48.31	1.07	0.43	0.15	0.73	3.12	3.83	0.7	15.61	0.7	3.47	2.93	3.33
January	6	100	29.5	9.2	7.6	10.36	4.73	3.55	6.27	4.18	2.11	2.22	1.79	1.7	1.19
January	7	100	5.89	2.18	3.32	2.98	3.27	4.26	4.48	5.11	7.01	6.77	7.21	7.18	6.63
January	8	100	20.89	2.33	3.34	4.26	3.71	4.32	5.24	4.89	3.91	5	3.99	4.53	4.96
January	9	100	59.19	13.03	7.89	6.51	2.78	1.87	2.51	1.02	0.66	0.55	0.59	0.84	0.36
January	10	100	16.21	9.51	7.29	5.83	5.82	5.04	4.99	5.79	6.71	7.41	6.41	4.93	4.54
January	11	100	23.31	20.89	15.88	12	5.8	2.61	2.08	2.06	2.94	1.1	2.98	1.95	1.87
January	12	100	13.28	6.38	6.74	6	4.37	4.53	8.01	5.61	6.25	8.04	6.7	6.08	3.48
January	13	100	10.87	4.4	4.75	4.04	3.02	4.46	4.99	3.82	6.51	5.49	6.52	5.19	6.32

Quad Axle Load Distribution Pallet in AASHTOWare Pavement ME

Other Input Parameters

- **AADTT**
  - Two-way AADTT
  - Number of lanes
  - Percent trucks in design direction
  - Percent trucks in design lane
  - Operational speed (mph)
- **Traffic Capacity**
  - Traffic Capacity Cap
- **Axle Configuration**
  - Average axle width (ft)
  - Dual tire spacing (in.)
  - Tire pressure (psi)
  - Tandem axle spacing (in.)
  - Tridem axle spacing (in.)
  - Quad axle spacing (in.)
- **Lateral Wander**
  - Mean wheel location (in.)
  - Traffic wander standard deviation (in.)
  - Design lane width (ft)
- **Wheelbase**
  - Average spacing of short axles (ft)
  - Average spacing of medium axles (ft)
  - Average spacing of long axles (ft)
  - Percent trucks with short axles
  - Percent trucks with medium axles
  - Percent trucks with long axles

Wheelbase, Axle Spacing → Generally standardized

Dual Tire Spacing → 12 in standard/default

Tire Pressure → Assumed constant for all loading conditions - **120 psi**

Axle-Load Wander
- 10 in standard/default
- Lane width < 10 ft → 8" wander
- Lane width > 12 ft → 12" wander

Setting Goals and Objectives

Lower Level Inputs

Level 2 → Use regional WIM data from similar roadway segments

Level 3 → Use default values in DARWin-ME → Based on LTPP evaluations

Functional classification of roadway (General Category)

Vehicle Class Distributions
- Principal Arterials → Interstates and Defense Routes
- Principal Arterials → Other
- Minor Arterials
- Major Collectors
- Minor Collectors
- Local Routes and Streets

Setting Goals and Objectives

Truck Traffic Classification Groups (TTC)

Derives Vehicle Classification Distribution based upon estimates of:

- % buses in traffic flow
- % multi-trailers in traffic flow
- Single trailer or single units in traffic flow

Default distributions based on estimated vehicle distribution on roadway and functionality

Truck Traffic Classification Groups

Truck Traffic Classification (TTC) Groups

General category: Principal Arterials - Interstates and Defense Routes (0)

Use	*	TTC	Bus (%)	Multi-trailer (%)	Single-trailer and single trailer unit (SU) trucks
☑	*	5	(<2%)	(>10%)	Predominately single-trailer trucks.
☐	*	8	(<2%)	(>10%)	High percentage of single-trailer truck with some single-unit trucks.
☐	*	11	(<2%)	(>10%)	Mixed truck traffic with a higher percentage of single-trailer trucks.
☐		13	(<2%)	(>10%)	Mixed truck traffic with about equal percentages of single-unit and single-trailer...
☐		16	(<2%)	(>10%)	Predominantly single-unit trucks.
☐	*	3	(<2%)	(2 - 10%)	Predominantly single-trailer trucks.
☐		7	(<2%)	(2 - 10%)	Mixed truck traffic with a higher percentage of single-trailer trucks.
☐		10	(<2%)	(2 - 10%)	Mixed truck traffic with about equal percentages of single-unit and single-trailer...
☐		15	(<2%)	(2 - 10%)	Predominantly single-unit trucks.
☐	*	1	(>2%)	(<2%)	Predominantly single-trailer trucks.
☐	*	2	(>2%)	(<2%)	Predominantly single-trailer trucks with a low percentage of single-unit trucks.
☐	*	4	(>2%)	(<2%)	Predominantly single-trailer trucks with a low to moderate amount of single-unit ...
☐		6	(>2%)	(<2%)	Mixed truck traffic with a higher percentage of single-unit trucks.
☐		9	(>2%)	(<2%)	Mixed truck traffic with about equal percentages of single-unit and single-trailer...
☐		12	(>2%)	(<2%)	Mixed truck traffic with a higher percentage of single-unit trucks.
☐	*	14	(>2%)	(<2%)	Predominantly single-unit trucks.
☐		17	(>25%)	(<2%)	Mixed truck traffic with about equal single-unit and single-trailer trucks.

Vehicle Class Distribution

Class	Percent (%)
Class 4	0.9
Class 5	14.2
Class 6	3.5
Class 7	0.6
Class 8	6.9
Class 9	54
Class 10	5
Class 11	2.7
Class 12	1.2
Class 13	11

* denotes recommended distribution for road category. OK Cancel

Climate Effects

Enhanced Integrated Climatic Model

Enhanced Integrated Climatic Model (EICM)

EICM

Internal to MEPDG and DARWin-ME software

User supplies reference elastic modulus at optimum moisture and density condition

Uses local weather station data to account for:

- Seasonal change in moisture content in subgrade and pavement layers and evaluates change in elastic moduli
- Freeze-thaw effect on reference elastic moduli and number of cycles
- Evaluates time varying temperature effect on subgrade and pavement layers
  - HMA – temperature effect on viscosity of asphalt
  - PCC – temperature gradient in PCC layer to reflect thermal expansion

Weather Data Utilized

Weather data used to reflect pavement layer responses:

Hourly air temperature
- Defines freeze-thaw periods
- Heat balance defines convection heat transfer and long wave radiation emission

Hourly precipitation
- Estimate infiltration rate and depth, average GWT height

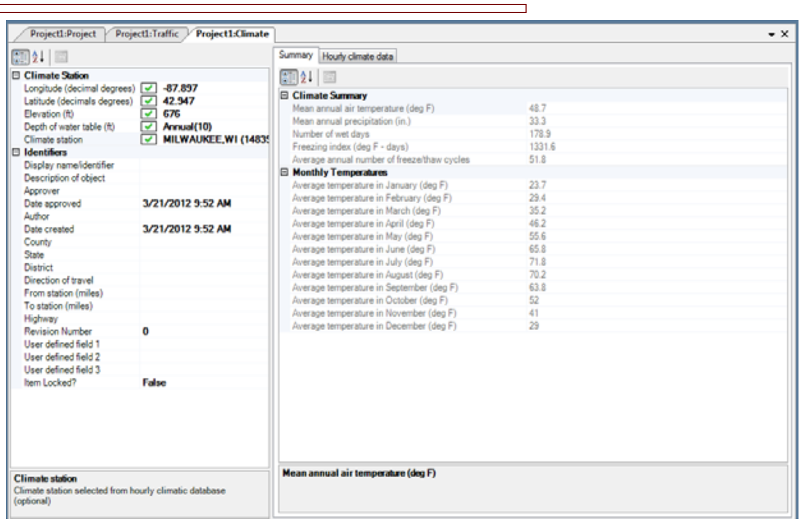
Hourly wind speed
- Convective heat transfer

Hourly sunshine (as a percentage of time in cloud cover)
- Surface shortwave absorptivity

Hourly relative humidity
- PCC pavements – shrinkage in concrete curing

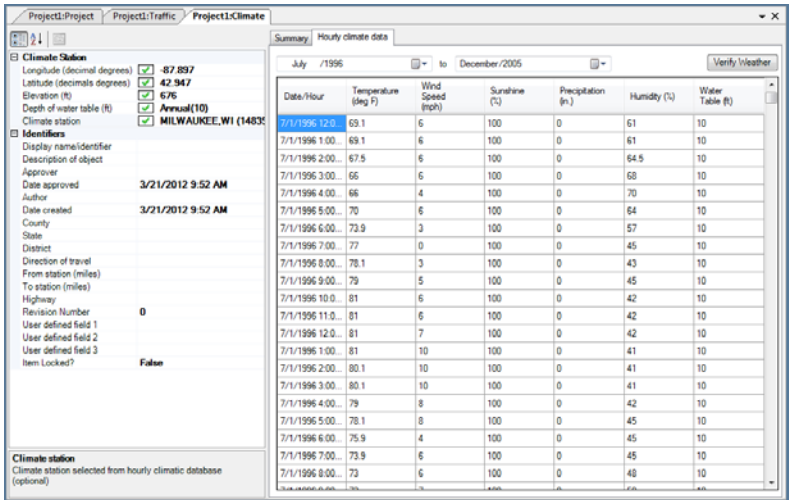
Setting Goals and Objectives

Climate Inputs



Setting Goals and Objectives

Climate Inputs



Setting Goals and Objectives

Material Input For Use by EICM

PCC and HMA
- Thermal Conductivity, (K) (Btu/ft.hr.°F)
- Heat Capacity, (Q) (Btu/lb. °F)

Unbound Compacted Material
- Atterberg limits
- Grain Size Distribution
- Specific Gravity, (G_s)
- Optimum Gravimetric Water Content, (w_{opt})
- Maximum unit weight of solids, (γ_{dmax})
- Saturated hydraulic conductivity
- Dry Thermal Conductivity, (K) (Btu/ft.hr.°F)
- Dry Heat Capacity, (Q) (Btu/lb. °F)
- Soil-Water Characteristic Curve

Unbound Natural (Uncompacted) Material
- Atterberg limits
- Grain Size Distribution
- Specific Gravity, (G_s)
- Optimum Gravimetric Water Content, (w_{opt})
- Maximum unit weight of solids, (γ_{dmax})
- Saturated hydraulic conductivity
- Dry Thermal Conductivity, (K) (Btu/ft.hr.°F)
- Dry Heat Capacity, (Q) (Btu/lb. °F)

Setting Goals and Objectives

Virtual Weather Stations

Important Remarks

Not every site has a weather station readily available

Should project site lie between stations, weather data can be interpolated to more accurately reflect weather conditions at that location

Characterization of Materials

Foundation, Subgrade Soils, HMA and Unbound Materials

Subsurface Investigations

1. Horizontal and vertical variations in subsurface soils
2. Moisture content
3. Densities
4. Water table depth
5. Location of rock strata

The MEPDG does not predict volume change potential.

Problem soils found along a project needs to be dealt with external to the MEPDG.

Setting Goals and Objectives

Laboratory and Field tests for Pavement Design

New HMA Layers Material Properties Inputs

Design Type	Measure Property	Source of Data		Recommended Test Protocol and/or Data Source
		Test	Estimate	
New HMA (new pavement and overlay mixtures), as built properties prior to opening to truck traffic	Dynamic Modulus	X		AASHTO TP 62
	Tensile Strength	X		AASHTO T 322
	Creep Compliance	X		AASHTO T322
	Poisson's Ratio		X	National test protocol unavailable. Select MEPDG default relationship
	Surface Shortwave Absorptivity		X	National test protocol unavailable. Select MEPDG default value
	Thermal Conductivity	X		ASTM E 1952
	Heat Capacity	X		ASTM D 2766
	Coefficient of Thermal Contraction		X	National test protocol unavailable. Select MEPDG default values
	Effective Asphalt Content by Volume	X		AASHTO T 308
	Air voids	X		AASHTO T 166
	Aggregate Specific Gravity	X		AASHTO T84 and T85
	Gradation	X		AASHTO T27
	Unit Weight	X		AASHTO T 166
	Voids Filled with Asphalt (VFA)	X		AASHTO T 209

Setting Goals and Objectives

Laboratory and Field tests for Pavement Design

Existing HMA Layers Material Properties Inputs

Design Type	Measure Property	Source of Data		Recommended Test Protocol and/or Data Source
		Test	Estimate	
Existing HMA Mixtures, in-place properties at time of pavement evaluation	FWD Backcalculated Layer Modulus	X		AASHTO T 256 and ASTM D 5858
	Poisson's Ratio		X	National test protocol unavailable. Select MEPDG default value
	Unit Weight	X		AASHTO T 166 (cores)
	Asphalt Content	X		AASHTO T 164 (cores)
	Gradation	X		AASHTO T 27 (cores or blocks)
	Air Voids	X		AASHTO T 209 (cores)
	Asphalt Recovery	X		AASHTO T 164 / T 170/ T 319 (cores)

Setting Goals and Objectives

Laboratory and Field tests for Pavement Design

Asphalt Binder Material Properties Inputs

Design Type	Measure Property	Source of Data		Recommended Test Protocol and/or Data Source
		Test	Estimate	
Asphalt (new, overlay, and existing mixtures)	Asphalt Performance Grade (PG), or	X		AASHTO T 315
	Asphalt Binder Complex Shear Modulus (G*) and Phase Angle (δ), or	X		AASHTO T 49
	Penetration, or	X		AASHTO T 53
	Ring and Ball Softening Point Absolute Viscosity Kinematic Viscosity Specific Gravity, or	X		AASHTO T 202 AASHTO T 201 AASHTO T 228
	Brookfield Viscosity	X		AASHTO T 316

Setting Goals and Objectives

Laboratory and Field tests for Pavement Design

Unbound Aggregate Base, Subbase, Embankment and Subgrade Material Properties Inputs

Design Type	Measured Property	Source of Data		Recommended Test Protocol and/or Data Source
		Test	Estimate	
New (lab samples) and existing (extracted materials)	Resilient Modulus	X		AASHTO T 307 or NCHRP 1-28A The generalized model used in MEPDG design procedure is as follows: $M_r = k_1 P_a \left(\frac{\sigma_b}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$
	Poisson's ratio		X	National test protocol unavailable. Select MEPDG default value
	Maximum Dry Density	X		AASHTO T 180
	Optimum Moisture Content	X		AASHTO T 180
	Specific Gravity	X		AASHTO T 100
	Saturated Hydraulic Conductivity	X		AASHTO T 215
	Soil Water Characteristics Curve Parameters	X		Pressure Plate (AASHTO T 99) or Filter Paper (AASHTO T 180) or Temple Cell (AASHTO T 100)

Setting Goals and Objectives

Laboratory and Field tests for Pavement Design

Unbound Aggregate Base, Subbase, Embankment and Subgrade Material Properties Inputs

Design Type	Measured Property	Source of Data		Recommended Test Protocol and/or Data Source
		Test	Estimate	
Existing material to be left in place	FWD backcalculated modulus	X		AASHTO T 256 and ASTM D 5828
	Poisson's ratio		X	National test protocol unavailable. Select MEPDG default value

Setting Goals and Objectives

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