NCHRP 1-37
“Development Of The 2002 Guide For The Design Of New And Rehabilitated Pavements”

Project Overview
Gary W. Sharpe
Director, Division of Highway Design
Kentucky Transportation Cabinet
Chair. AASHTO Joint Task Force On Pavements
Background

- AASHTO Guide For Design Of New And Rehabilitated Pavement Structures
  - 1959 AASHO Road Test
  - Supplemented, Refined, And Updated By Research And New Experience
AASHTO Joint Task Force On Pavements
- Recommended Need For An NCHRP Study To Develop A New Pavement Design Guide

AASHTO Standing Committee On Research Approved Funding - - NCHRP Project 1-37
Development Of 2002 Guide For Design Of New And Rehabilitated Pavement

- NCHRP 1-37 -- Detailed Work Plan (Conceptual Plan)
- NCHRP 1-37A -- Guide Development (State of Practice -- No New Research)
NCHRP Project 1-37A

- Responsible Staff Officer
  Dr. Amir N. Hanna
  Senior Program Officer

- Web Site
  www.2002designguide.com
Develop and deliver the guide for design of new and rehabilitated pavement structures

- Based on mechanistic-empirical principals
- Accompanied by the necessary computational software
- For eventual adoption and distribution by AASHTO
Scope of Guide

- Procedures for pavement design/analysis
- Procedures for evaluating existing pavements
- Recommendations on rehabilitation treatments, subdrainage, and foundation improvements
Scope of Guide

- Procedures for LCCA, reliability, and traffic analysis
- Procedures for calibrating for local conditions
- Guidance for developing agency-specific procedures/catalogs
Guide Processes

- Integrated Climatic Model
- Axle Loadings
- Material Properties
- Pavement Structure
- Analysis
- Distress Prediction
Design Inputs

• Inputs will generally include both a mean value and an estimate of variability
Hierarchical Input Levels

- Level 1
  Project specific
- Level 2
  Region factors
- Level 3
  Default values
Climatic Factors

- Integrated Climatic Model
  - Prediction of pavement temperature
  - Changes in subsurface moisture
  - Frozen layers
Material Properties

- **Subgrade**
  - Stiffness is adjusted based on the ICM’s prediction of moisture content
  - Frozen versus thawed condition
- **Asphalt aging**
- **Changes in PCC strength**
Material Properties

- Asphalt Mixtures
  - Dynamic Modulus
    - Adjusted for:
      - Temperature
      - Time of loading
      - Aging

Structural design is related to mixture design
Materials Characterization

- **Unbound materials**: Level 1 resilient modulus test (same as for flexible pavements)
- **FWD testing and E backcalculation**: slab, base, subg.
- **Portland cement concrete**: lab testing
  - Elastic Modulus Level 1 (ASTM C469)
  - Elastic Modulus Levels 2 & 3  \[ E_c = 33\rho^{3/2}(f'c)^{1/2} \]
  - Modulus of Rupture [3rd point], time series
  - Coefficient of Thermal Exp. [New ASTM]
  - Coefficient of Drying Shrinkage (ASTM C490)
- **Base treated material**: brush erosion test

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Traffic Data for Pavement Design

- No more ESAL’s!!!
- Traffic input will be numbers of axles by type and weight
- Same type and quality of raw traffic data currently used to compute ESAL’s
Axle Load Spectra

- Will replace old ESAL approach
- An ESAL conversion will be included
- Traffic data collection equipment used in LTPP SPS program will be adaptable to Guide
## Axle Load Spectra

<table>
<thead>
<tr>
<th>Axle Load (1000 lbs)</th>
<th>Single</th>
<th>Tandem</th>
<th>Tridem</th>
<th>Quad</th>
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<tr>
<td>11-14</td>
<td>5,000</td>
<td>400</td>
<td>100</td>
<td>5</td>
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<td>etc</td>
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</tbody>
</table>
Guide - Design Inputs

**Hierarchical Traffic Levels**

- **Level 1** - Site specific vehicle classification and axle weight data
- **Level 2** - Site specific vehicle classification data/regional (state) axle weight data
- **Level 3** - Site specific vehicle volume data/default axle load data
Flexible Pavements
Hierarchical Input Levels

Flexible Pavements

- **Analysis procedure will be independent of input level**
  - Lower levels of inputs will have higher variability which will be considered in the reliability analysis

- **Level 2 inputs reflect current practice and currently available data**
Distress Transfer Functions

Flexible Pavements

- Permanent Deformation or Rutting (Pd)
  - AC
  - Unbound Materials

- Fatigue Cracking
  - AC (Surface Down & Bottom Up)
  - CTB

- Thermal Fracture
Software Analysis Plan

Options

• Multi-Layer Elastic Solution
  (Main Engine : JULEA)

2. 2D Desai Finite Element Analysis
  (For Special Loading Conditions, Non-Linear Unbound Material Characterization)
Design Inputs

Incremental Damage

- Changes over time are addressed
  - Material strength and stiffness
  - Seasonal moisture and temperature
  - Variations in traffic seasonally and over time
Enhanced Integrated Climatic Model (EICM)
Output of the EICM

- Environmental Effects Adjustment Factors for the $M_R$ FEA / LEA Module
- Temperature Frequency Distribution at mid-depth of bound sublayers
  
  **Fatigue / Permanent Deformations Modules**
- Hourly Temperature Profiles at every inch within AC and/or PCC layer(s)
  
  **Thermal Cracking Module**
- Average Moisture Content for Bound and Unbound Materials
  
  **Permanent Deformation Module for Unbound Materials**
AC Complex Modulus
General Approach will be:

- **Based Upon the Dynamic Complex Modulus Test (E*)**

- **Hierarchical In Nature**
TIME-TEMPERATURE AGE SUPERPOSITION

\[ \log(t_r) = \log(t) - c \left( \log(\eta) - \log(\eta_{T_r}) \right) \]
SUMMARY -- Hierarchical Input Levels Flexible Pavements

- **LEVEL 1**
  - MIXTURE SPECIFIC TEST DATA
    - MIXTURE E*
    - BINDER G*
- **LEVEL 2**
  - BINDER TEST DATA AND WITCZAK DYNAMIC MODULUS EQUATION
    - BINDER G*
    - REPRESENTATIVE MIX VOLUMETRICS
- **LEVEL 3**
  - BINDER GRADE AND WITCZAK DYNAMIC MODULUS EQUATION
    - BINDER GRADE
    - REPRESENTATIVE MIX VOLUMETRICS
Fatigue
Basic Fatigue Equation

\[ N_f = K_1 \left( \frac{1}{\varepsilon_t} \right)^{k_2} \left( \frac{1}{E} \right)^{k_3} \]

\[ = K_1 (\varepsilon_t)^{-k_2} (E)^{-k_3} \]

\( N_f \) = number of repetitions to fatigue cracking  
\( \varepsilon_t \) = tensile strain at the critical location  
\( E \) = stiffness of the material  
\( K_1, k_2, k_3 \) = laboratory calibration parameters
Typical Fatigue Curve Relationship

Number of Repetition to Failure

Horizontal Tensile Strain ($10^{-6}$)
AC Permanent Deformation
Typical Repeated Load Permanent Deformation Behavior of Pavement Materials

![Graph showing the typical repeated load permanent deformation behavior of pavement materials. The graph plots Load Repetitions on the x-axis and Permanent Strain $\varepsilon_p$ on the y-axis. The graph is divided into three regions: Primary, Secondary, and Tertiary. The Flow Point is indicated on the graph.](image-url)
Permanent Deformation Models

\[
\log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = -3.74938 + 0.4262 \log(N) + 2.02755 \log(T)
\]

\[R^2 = 0.73\]

\[S_e = 0.309\]

\[S_e/S_y = 0.522\]

\[N_{\text{tests}} = 3476\]
IRI Distress Models
\[ IRI = IRI_o + \Delta IRI \]
\[ \Delta IRI = f(D_j, S_f) \]

\( IRI_o \) = Pavement Smoothness when it is Newly Constructed

\( D_j \) = Effect of Surface Distresses

\( S_f \) = Effect of Non-Distress Variables or Site Factor
IRI Models for Original HMA Pavements

- **Unbound Aggregate Bases and Subbases**

\[
IRI = IRI_0 + 0.03670(SF)[e^{\frac{age}{20}} - 1] + 0.00325(FC) + 0.4092(COV_{RD}/100) + 0.00106(TC) + 0.00704(BC) + 0.00156(SLCNWPM_H)
\]

- SF = Site factor
- \(e^{\frac{age}{20}} - 1\) = Age factor
- FC = Fatigue cracking
- RD = Rut Depth
- \(SD_{RD}\) = Standard deviation of rut depth
- TC = Length of transverse cracking
- BC = Area of block cracking
- \(SLCNWPM_H\) = Length of sealed longitudinal cracks outside wheel path

\[
COV_{RD} = \frac{SD_{RD}}{RD} = \frac{0.665 + 0.2126(RD)}{RD}
\]
IRI Models for HMA Overlays

- **HMA Overlays Placed on Flexible Pavements**

  \[
  IRI = IRI_0 + 0.04283\ln(Age+1) + 0.00880(FC) + 0.00129(TC_{MH}) + 2.9065(BC_{H}) + 8.7702(P_{H}) + 0.00100(SLCNWP)
  \]

  \(\ln(Age+1) = \text{Age factor}\)

- **HMA Overlays Placed on Rigid Pavements**

  \[
  IRI = IRI_0 + 0.02069(RD) + 8.396\left[\frac{1}{TCS_{MH}+1}\right] + 13.122(P_{MH})
  \]
Measured vs. Predicted IRI

AC over AC

IRI Observed vs. IRI Predicted

Residual vs. IRI Predicted
Calibration by Distress Type

• M-E models require a process of “calibration” to ensure that they will be reliable models.

• This will require three ongoing steps:
  • (1) Verification
  • (2) Calibration
  • (3) Validation
Calibration and Validation Data

- Field measured distress data from in-service highway sections will be primarily used.

- LTPP will be the primary data set utilized due to its quality, quantity, geographic distribution, types of pavements/rehab, and variables included in database.

- Extremely Critical Work Task Leading to Acceptance or Rejection of Design Guide Approach
Rigid Pavements
Mechanistic Based Rigid Pavement Design and Rehabilitation

- Hierarchical design inputs/trial design
- Materials characterization
- Structural modeling of pavement/subgrade
- Key distress types and smoothness
  - Critical stresses and deflections
  - Distress/smoothness models
  - Incremental “damage” computation
  - Calibrate “damage” to physical distress
- Reliability of design
- Design iteration
- Special rehabilitation items

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PCC Strength Gain With Age

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Subgrade inputs identical to flexible pavement design
- Laboratory resilient modulus test or backcalculation
- EICM used to predict subgrade moisture and generate seasonal modulus values

Elastic layer program used to predict seasonal PCC surface deflections
- PCC surface deflections used to backcalculate seasonal subgrade k-values
Structural Modeling of Pavement/Subgrade

- **FE Response Model**
  - ISLAB2000—enhanced 2.5D FEM
  - ERES/U. Michigan/MSU/MichTech/UnivMn/UnivIllinois

- **Capabilities**
  - Multiple pavement/overlay layers and foundation, slab curling, cracks and joints, multi-wheel loads, relative rapid solutions
Rapid solutions (Neural networks)

- Develop large databases of ISLAB2000 runs for each design situation (bottom-up cracking, top-down cracking, joint faulting, punchouts), axle type, and axle location
- Id key structural parameters
- Train neural networks to predict parameters

- NN accurately represents ISLAB2000 responses
- Provides near instantaneous solutions

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Mechanistic Based Rigid Pavement Design and Rehabilitation

- Hierarchical design inputs/trial design
- Materials characterization
- Structural modeling of pavement/subgrade
- **Predict key distress types and smoothness**
  - Critical stresses and deflections
  - Mechanistic based model
  - Incremental “damage” computation
  - Calibrate “damage” to physical distress

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Predict Key Distress Types & Smoothness (New and Rehabilitated Pavements)

- **JPCP distress**
  - Transverse cracking—bottom-up
  - Transverse cracking—top-down
  - Joint Faulting
- **CRCP punchouts**—crack LTE loss, top-down
- **Smoothness** (**IRI**)
JPCP Raw Input (Level 1, 2, or 3)

Environment
- Temperature
- Precipitation

Materials
- PCC
- Base
- Subgrade

Traffic
- Axle classification
- Axle loads

Trial Design

Assemble input and trial design information for each distress model

Top-down cracking
- Calculate stresses
- Calculate damage
- Predict top-down cracking

Bottom-up cracking
- Calculate stresses
- Calculate damage
- Predict bottom-up cracking

Compare total cracks with design criteria for slab cracking

Requirements satisfied?
- Yes
  - Design completed
- No
  - Revise trial design
Joint Faulting Parameters

- Axle type, loading, lateral position, number
- Temperature gradient curling (positive daytime)
- Combined built-in temperature gradient & top drying shrinkage (negative)
- Slab thickness, modulus, strength, coef. exp.
- Base thickness, modulus
- Subgrade modulus
- Joint spacing, slab width
- Transverse joint LTE, longitudinal joint LTE
Faulting Modeling Procedure

- Utilized concepts of faulting models from NAPCOM, NCHRP 1-34, PRS 3
  - Use subgrade differential energy (DE) as the main structural response parameter
- Improvements: Temperature curling and incremental faulting accumulation with the rate of faulting depending on the faulting level
- Calibration and validation using LTPP and FHWA/RPPR databases

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Overall Faulting Model Flowchart

Modified design inputs

Trial design inputs:
Dowel diameter, base type,
PCC thickness, etc.

Joint opening, LTE calculation

Calculate loaded and unloaded corner deflections using NNs

Calculate differential energy, DE

Calculate faulting increment

Calculate total faulting

Faulting meets design requirement?

Yes

Design Output

No

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JPCP Smoothness Model

IRI = IRI_i + 0.0137CRK + 0.007SPALL + 0.005PATCH + 0.0015TFAULT + 0.04SF

where:

IRI_i = Initial IRI, m/km
CRK = percent slabs with cracking (transverse and corner breaks [all severities])
SPALL = percentage of joints with spalling (medium and high severities)
PATCH = area with flexible or rigid patching (all severities), m^2
TFAULT = total joint faulting, mm/km
SF = site factor = \( \text{AGE} \times (1 + \text{FI}^{1.5})(1 + P_{0.075})/10^6 \)

where:

\( \text{AGE} \) = pavement age, yr
\( \text{FI} \) = Freezing index, \( ^\circ \text{C} \) days
\( P_{0.075} \) = percent subgrade material passing 0.075-mm sieve
CRCP Smoothness Model

\[
IRI = IRI_i + 0.003TCRK + 0.2NPATCH + 0.08PUNCH + 0.45SF
\]

where:
- \( IRI_i \) = initial IRI
- TC = mid to high transverse cracking/km
- PUNCH = number of mid- to high-severity punchouts/km
- PATCH = Number of mid- to high-severity flexible or rigid patching
**CRCP Smoothness Model, cont’d**

\[
SF = \text{site factor} = \frac{\text{AGE} \times (1 + \text{FI})(1 + \text{P}_{0.075})}{10^6}
\]

where

- \(\text{AGE}\) = pavement age, yr
- \(\text{FI}\) = Freezing index, °C days
- \(\text{P}_{0.075}\) = percent subgrade material passing 0.075-mm sieve
Design Reliability

- Uncertainty or variability of all inputs and models (standard deviation, COV, distribution type)
- What gets built in field is different than design
- Estimated traffic is different than actual
- Variation exists along project
- Limitations in all distress and smoothness models
Hierarchical Design Input Levels & Reliability/Uncertainty

- **Level 1—Highest input certainty**
  - Inputs obtained from significant lab or in situ field testing—lowest estimation error

- **Level 2—Medium input certainty**
  - Inputs obtained from correlations, limited testing, previous testing

- **Level 3—Lowest input certainty**
  - Inputs based on estimating or default values or typical values—highest estimation error
Benefits of Mechanistic Design for Rigid Pavements

- Ability to *structurally model* rigid pavements with different site conditions, design features and materials
- Ability to accumulate damage *incrementally* (month by month over life)
- Ability to predict (and prevent) key *distresses and smoothness*
- Ability to *calibrate* to local or regional conditions
Progress Schedule

Are we there yet?

- **June 30, 2003**
  - All draft deliverable, including Design Guide appendices and example problems;
  - Software; and
  - Marketing and training materials

- **October 30, 2003**
  - All final (revised) deliverables

- **November 30, 2003**
  - Draft SI version of the Guide

- **December 30, 2003**
  - Final (revised) SI version of the Guide
Future

- NCHRP 1-40
  National/Regional Workshops
- Review/Concurrence by JTFP
- Review/Concurrence by Subcommittee On Design
- Review/Concurrence by Standing Committee On Highways
Questions