The 87th Annual Meeting of the TRB

Development of Transverse Cracking Prediction Models for Jointed Concrete Pavements Using LTPP Database

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Taiwan, January 13~17, 2008

Outline

- I. Introduction
- II. Review of Existing Models
- III. Database Preparation
- IV. Analysis of Existing Models
- V. Development of Tentative Transverse Cracking Models
- VI. Concluding Remarks

I. Introduction

Background and Objectives

- Predictive models used in pavement design, evaluation, rehabilitation, & management activities
- Evolves from purely empirical toward mechanistic-empirical approaches in the proposed MEPDG (DG2002)
- Focus on predicting transverse cracking of JCP pavements using the LTPP database (www.datapave.com)

II. Review of Existing Models (1/2)

- NCHRP 1-19 (COPES)

$$CRACKSJP = ESAL^{2.755} * [3092.4 * (1 - SOILCRS) * RATIO^{10}] + ESAL^{0.5} * (1.233 * TRANGE^{2} * RATIO^{2.868}) + ESAL^{2.416} * (0.2296 * FI^{1.53} * RATIO^{7.31})$$

$$CRACKSJR = ESAL^{0.897} * [7130 * JTSPACE / (ASTEEL * THICK^{5})] + ESAL^{0.1} * (2.281 * PUMP^{5}) + ESAL^{2.16}[1.81/(BASETYP + 1)] + AGE^{1.3} * [0.0036 * (FI + 1)^{0.36}]$$

- SHRP-P-393

$$PCRACKED = \frac{1}{0.01 + 10 * 100^{-\log_{10} FD}}$$

$$FD = \sum_{i=1}^{k} (n_i / N_{fi}) \qquad N_f = 10^{\left[2.13*(1/RATIO)^{1.2}\right]}$$

$$CRACKJR = -72.9 + 1.9 * CESAL + 0.182\left(\frac{1}{PSTEEL^{2}}\right) + 2473 * \left(\frac{1}{KSTATIC}\right) + 0.697 * PRECIP$$

II. Review of Existing Models (2/2)

- **The Proposed MEPDG (DG2002) (NCHRP 1-37A)**
  - **Cumulative fatigue damage (D_f) using more complex Axle Load Spectra (ALS) concept**

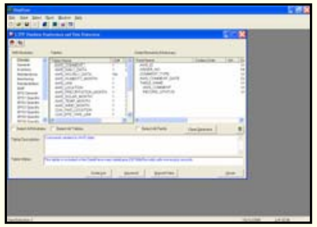
$$PCRACKED = \frac{1}{1 + FD^{-1.68}}$$

$$FD = \sum \frac{n_{i,j,k,l,m,n}}{N_{i,j,k,l,m,n}} \qquad \log(N_{i,j,k,l,m,n}) = 2.0 * \left(\frac{MR_i}{\sigma_{i,j,k,l,m,n}} \right)^{1.22} + 0.4371$$

  - in which, $n_{i,\,j,\,k,\,l,\,m,\,n}$ is the applied number of axle loads under each condition: i (for age); j (for month); k (for axle type); l (for load level); m (for temperature difference); n (for traffic path)

III. Database Preparation

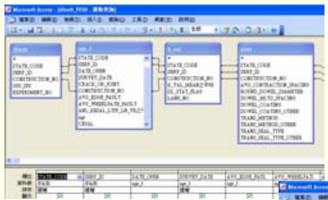
- LTPP GPS-3 (JPCP) & GPS-4 (JRCP)



DataPave 3.0

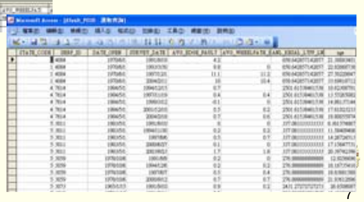
DataPave Online (Standard Release 18.0)

1. Retrieval of Required Data

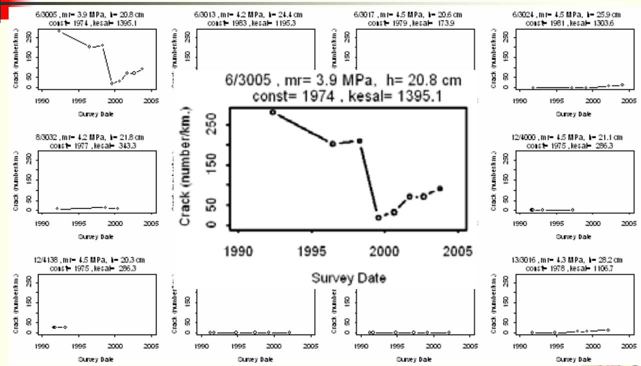


- IMS Modules(/Tables/Data Elements):
  - Climatic
  - General
  - Inventory
  - Maintenance
  - Monitoring
  - Rehabilitation
  - Testing
  - Traffic

Existing models 10~15 items, DG2002 45~50 items

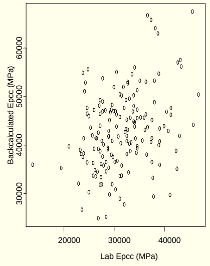


2. Graphical Representation and Data Cleaning

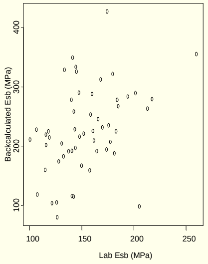


3. Comparison of Lab Tested vs. Backcalc. Layer Moduli (1/2)

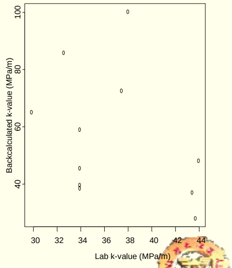
(a) PCC surface layer



(b) subbase layer



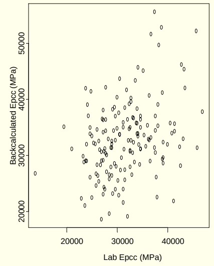
(c) subgrade



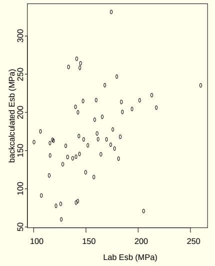
Winkler Foundation (Average ratios about 1.4, 1,5, 1.5)

3. Comparison of Lab Tested vs. Backcalc. Layer Moduli (2/2)

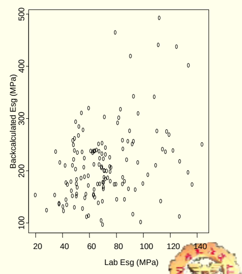
(d) PCC surface layer



(e) subbase layer



(f) subgrade



Elastic Solid Foundation (Average ratios about 1.0, 1,1, 3.0)

4. Relationship of Elastic Modulus and Modulus of Subgrade Reaction (1/3)

- **FHWA-RD-00-086 Report (2001):**
  Backcalculation of layer parameters for LTPP Test Sections using GPS and SPS data

  $k = 0.296E_s$

  Statistics : $R^2 = 0.872$, SEE = 9.37, N = 596

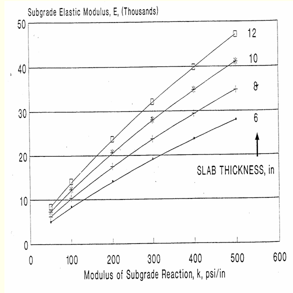
4. Relationship of Elastic Modulus and Modulus of Subgrade Reaction (2/3)

- Barenberg (2000) indicated the theoretical difference using elastic solid and dense liquid foundations

$$w_e = \frac{P\ell_e^2}{3\sqrt{3D}} = w_k = \frac{P\ell_k^2}{8D}$$

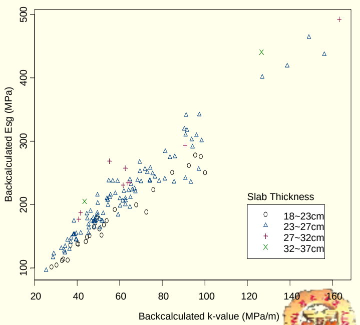
➔ $0.6495 * \ell_k^2 = \ell_e^2$

➔ $E_s^{4/3} = 283.7 * h * k$



4. Relationship of Elastic Modulus and Modulus of Subgrade Reaction (3/3)

- The aforementioned relationship was further vcerified by comparing the backcalculated Es and k values from the LTPP database
- Slab thickness did have significant effects on this relationship

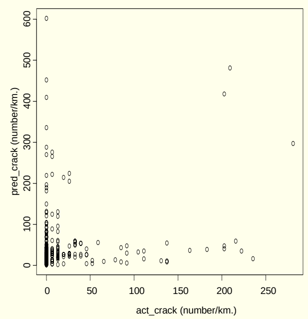


$$E_s = 0.9015(k * h)^{3/4}$$

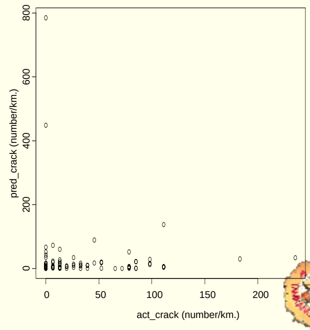
$$\text{Statistics}: R^2 = 0.9524, \text{SEE} = 15.87, n = 138$$

IV. Analysis of Existing Models (1/3)

(a) NCHRP 1-19 JPCP

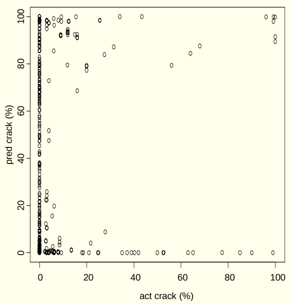


(b) NCHRP 1-19 JRCP

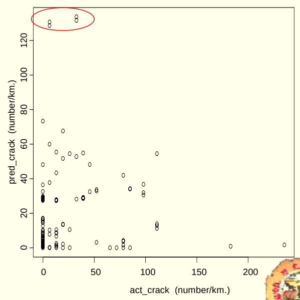


IV. Analysis of Existing Models (2/3)

(c) SHRP-P-393 JPCP



(d) SHRP-P-393 JRCP

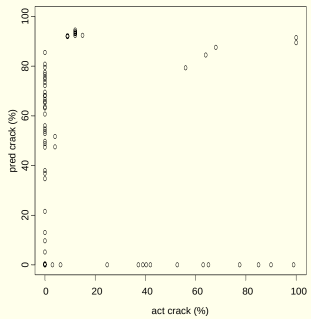


(caused by very small percent steel)

IV. Analysis of Existing Models (3/3)

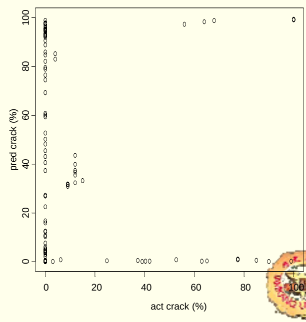
Randomly selected 22 JPCP sections (n=102) for this goodness of fit study

(e) SHRP-P-393 JPCP (requiring 9 variables)



R^2=**0.0001023**

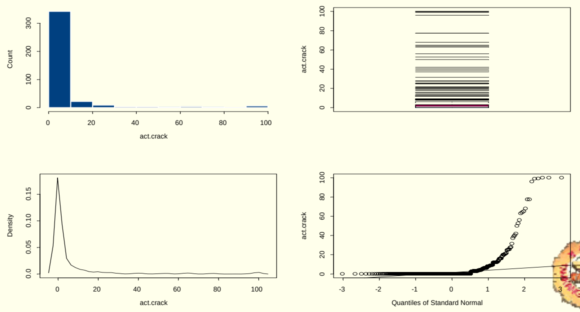
(f) DG2002 JPCP (requiring 50 variables)



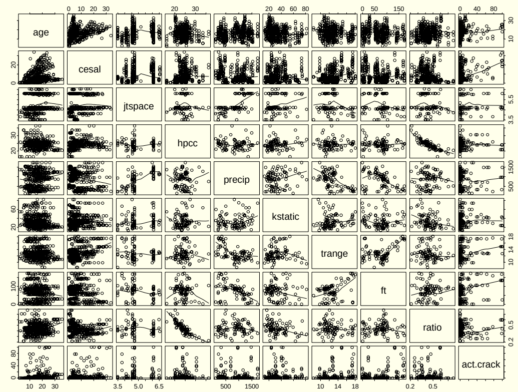
R^2=**0.01362**

V. Development of Tentative Transverse Cracking Models

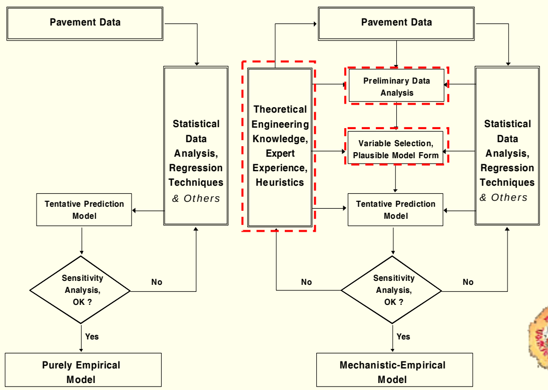
1. Preliminary Analysis (Univariate Data Analysis)



2. Bivariate and Multivariate Analysis (scatter plot matrix with lowess smoother)



3. Model Development Using Purely Empirical or Mechanistic-Empirical Concept (Lee, 1993)



4. Preliminary Models Using Poisson Regression

- "When events of a certain type occur over time, space, or some other index of size, it is often relevant to model the rate at which events occur." (Agresti, 1996)
- He also suggested that using Poisson regression for rate data is an appropriate decision.
  - Transverse cracking could be treated as rate data, i.e., percent of cracked slabs.

  ➔Choose Generalized Linear Model (GLM) with Poisson distribution assumption

- Generalized Linear Model (GLM)

$$g(E(Y \mid x)) = g(\mu) = \beta_0 + \sum_{i=1}^{p} \beta_i x_i = \eta(x)$$

Distribution	Link Function	Variance
Normal/Gaussian	μ	1
Binomial	$\log(\mu/(1-\mu))$	$\mu(1-\mu)/n$
Poisson	$\log(\mu)$	μ
Gamma	$1/\mu$	μ^2
Inverse Normal/Gaussian	$1/\mu^2$	μ^3
Quasi	$g(\mu)$	$V(\mu)$

$$\ln(PCRACKED) = -6.105 + 0.1015 * age + 0.001317 * kesalpyr + 0.001209 * precip + 0.01284 * ft + 0.1999 * trange + 1.031 * ratio$$

Statistics : N = 393, Null Deviance = 8138.5, Residual Deviance = 5402.1

$$\ln(CRACKSJR) = -0.9396 + 0.06729 * cesal + 0.02152 * ft + 0.2326 * trange - 10.26 * psteel$$

Statistics : N = 151, Null Deviance = 5391.9, Residual Deviance = 2991.3

In which, 74 (DF), 43 (DNF), 114 (WF), and 162 (WNF) JPCP data points; and 80 (WF) and 71 (WNF) JRCP data points in different climatic zones

5. Improved Models Using Additional Modern Regression Techniques

General Predictive Modeling Procedures:

- Generalized Additive Models (GAM)

  $$g(E(Y \mid x)) = g(\mu) = \alpha + \sum_{i=1}^{p} f_i(x_i) = \eta(x) \qquad \mathrm{var}(Y) = \phi V(\mu)$$

- Box-Cox (1964) Power Transformation
- Striving to find a monotonic power transformation function with reasonable physical interpretations
- Fitting a tentative GLM model using Poisson distribution, and quasi-likelihood estimation method, i.e., quasi(link="log", var = "mu")

6. Tentatively Proposed Predictive Models

$$PCRACKED = \exp[-9.913 + 3.711 * \log(age) + 1.931 * \log kesalpyr + 0.05116 * \sqrt{precip} + 0.01186 * ft - 26.71 * \frac{1}{trange} + 2.496 * \sqrt{ratio}]$$

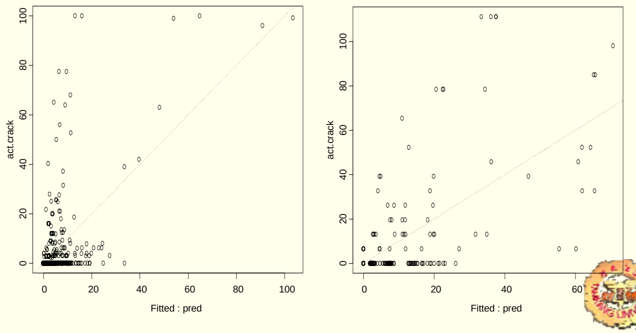
Statistics : N = 393, R^2 = 0.358, SEE = 13.01

$$CRACKSJR = \exp[5.863 - 1.780 * \frac{1}{\sqrt{cesal}} + 0.2397 * \sqrt{FT} - 37.25 * \frac{1}{trange} - 10.12 * psteel]$$

Statistics : N = 151, R^2 = 0.380, SEE = 20.79

7. Goodness of Fit of the Proposed Model

(a) JPCP (b) JRCP



8. Develop Separate Models for Different Climatic Zones

$$(PCRACKED)_{WNF} = \exp[-37.33 + 7.042 * \log(age) + 4.565 * \log kesalpyr + 0.2242 * \sqrt{precip} - 0.02321 * ft - 71.77 * \frac{1}{trange} + 24.77 * \sqrt{ratio}]$$

Statistics : $N = 162, R^2 = 0.818, SEE = 8.26$

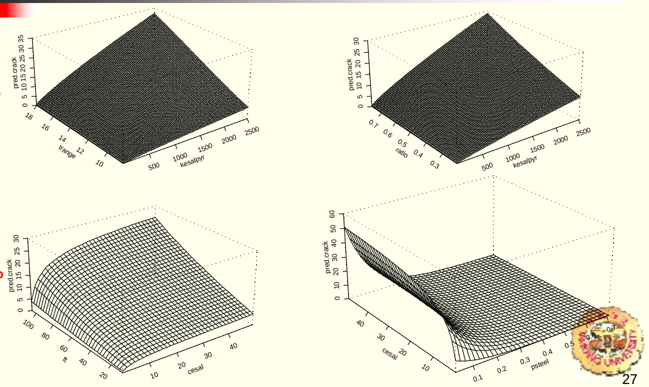
$$(CRACKSJR)_{WF} = \exp[7.142 - 1.927 * \frac{1}{\sqrt{cesal}} + 0.1459 * \sqrt{FT} - 41.87 * \frac{1}{trange} - 8.500 * psteel]$$

Statistics : $N = 80, R^2 = 0.393, SEE = 23.95$

9. Sensitivity Analysis of the Proposed Models

JPCP

JRCP



VI. Concluding Remarks (1/2)

- Even though the use of cumulative fatigue damage based on Miner's hypothesis and more complicated Axle Load Spectra (ALS) concept as recommended by the MEPDG seems to be a logical approach, the integration of which with monthly or seasonal environmental factors such as humidity and temperature differentials often resulted in more variations in the predictions of transverse cracking due to many uncertainties involved
- Existing models for transverse cracking predictions are inadequate using LTPP Database

VI. Concluding Remarks (2/2)

- Relatively skewed distribution was identified, indicating that normality assumption is inappropriate
- GLM and GAM along with Poisson distribution assumption and quasi-likelihood estimation method were adopted
- By eliminating insignificant and inappropriate parameters repeatedly, the resulting model only includes age, kesal, cesal, precip, freeze-thaw cycle, temp range, stress ratio, and percent steel for predicting transverse cracking
- Conducted goodness of fit and sensitivity analysis study Further Improvements are possible and recommended

Questions?

THANKS FOR YOUR ATTENTION