The 86th Annual Meeting of the TRB

Development of Fatigue Cracking Performance Prediction Models for Flexible Pavements Using LTPP Database

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Outline

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

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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 fatigue cracking of AC pavements using the LTPP database (www.datapave.com)

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II. Review of Existing Models

- 1. Various models for predicting N_f

$$N_f = k_1(\varepsilon_t)^{-k_2}\left|E^*\right|^{-k_3}$$

Organization (Year)	k_1	k_2	k_3
Asphalt Institute (1981)	0.0796	3.291	0.854
Shell Oil (1982)	0.0685	5.671	2.363
Belgian Road Research Center (1984)	4.92×10^{-14}	4.76	0
UC-Berkeley (1984)	0.0636	3.291	0.854
Transport and Road Research Laboratory (1984)	1.66×10^{-10}	4.32	0
Illinois (1987)	5×10^{-6}	3.0	0
U.S. Army (1988)	478.63	5.0	2.66
Indian (1999)	0.1001	3.565	1.474
Mn/ROAD (2003)	2.83	3.21	0

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New Concepts of the Proposed MEPDG

Mechanistic-Empirical Pavement Design Guide (NCHRP 1-37A)

- **2. the revised MS-1 fatigue cracking model**

$$N_f = 0.00432 * \beta_{f1} * C * \left(\frac{1}{\varepsilon_t}\right)^{3.291*\beta_{f2}} \left(\frac{1}{E}\right)^{0.854*\beta_{f3}}$$

$$C = 10^{4.84*\left(\frac{V_b}{V_a+V_b}-0.69\right)}$$

$$F.C. = \left(\frac{6000}{1+e^{(C_1*C_1'+C_2*C_2'*\log(D_f*100))}}\right)*\left(\frac{1}{60}\right)$$

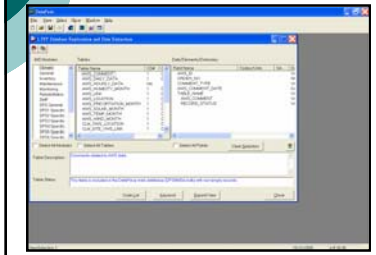
- **Cumulative fatigue damage (D_f) using more complex Axle Load Spectra (ALS) concept**

$$D_f = \sum_{i=1}^{k} \frac{n_i}{N_{fi}}$$

III. Database Preparation

1. Long-Term Pavement Performance (LTPP) Program

- GPS-1 (Granular Base) & GPS-2 (Bound Base)

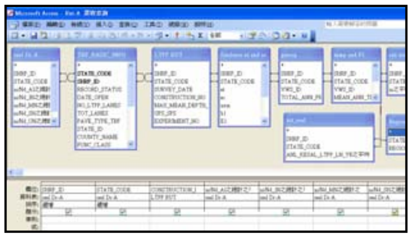


DataPave 3.0

DataPave Online

2. Retrieval of Required Data

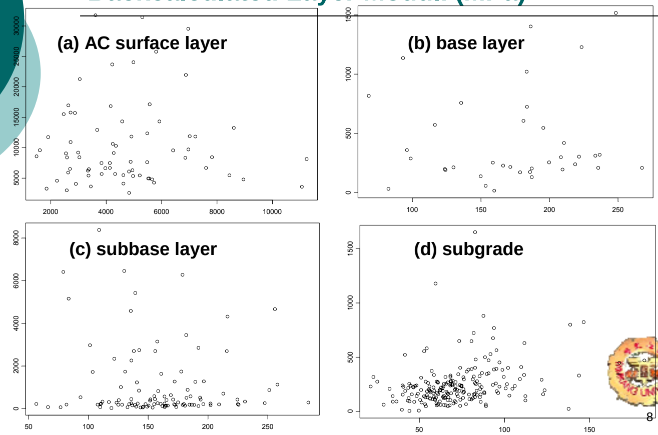
- IMS Modules(/Tables/Data Elements):
  - Climatic
  - General
  - Inventory
  - Maintenance
  - Monitoring
  - Rehabilitation
  - Testing
  - Traffic



Microsoft Access

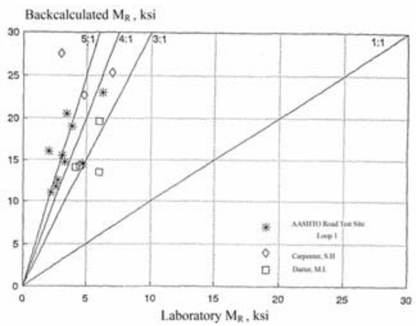
Existing models 10~15 items, DG2002 45~50 items
Batch BISAR Program Runs: Tensile strain of the AC layer

3. Comparison of Lab Tested vs. MODCOMP4 Backcalculated Layer Moduli (MPa)



Database Preparation

Check with AASHTO 1993's Recommendation



Subgrade: Consistent with an adjustment factor of 0.33
(Also note high variations of backcalculated AC surface, Base, and Subbase Moduli on previous slide)

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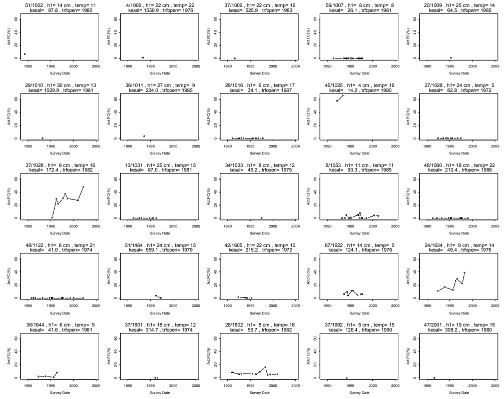
Database Preparation

4. Graphical Representation and Data Cleaning



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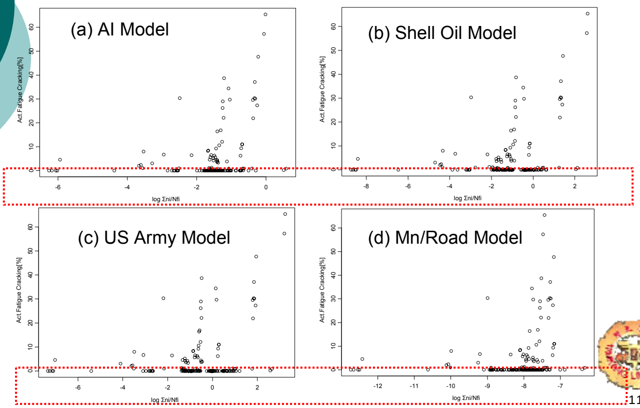
IV. Analysis of Existing Models



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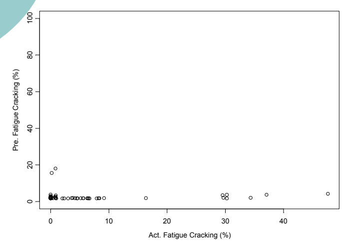
Analysis of Existing Models

Goodness of Fit of the Existing Models

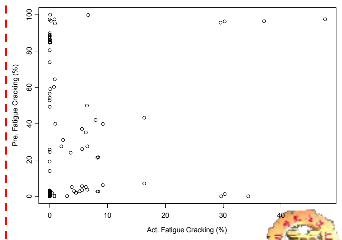
(a) AI Model and Ali & Tayabji Model

$$\%FatigueCracking = \frac{0.021}{0.027 + e^{(-0.85 * D_i)}}$$



R^2=0.0065, SEE=7.881, n=140

(b) MEPDG Models Using DG2002 Program



R^2=0.0391, SEE=7.751, n=140

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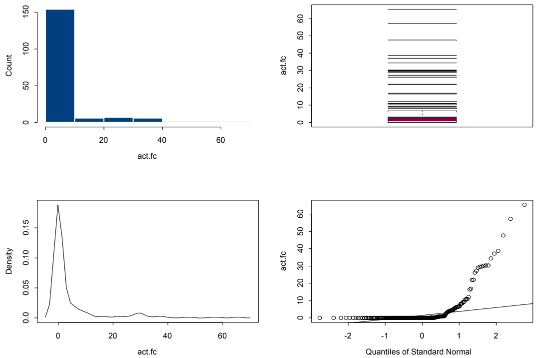
V. Development of Tentative Fatigue Cracking Models

1. Preliminary Analysis (Univariate Data Analysis)



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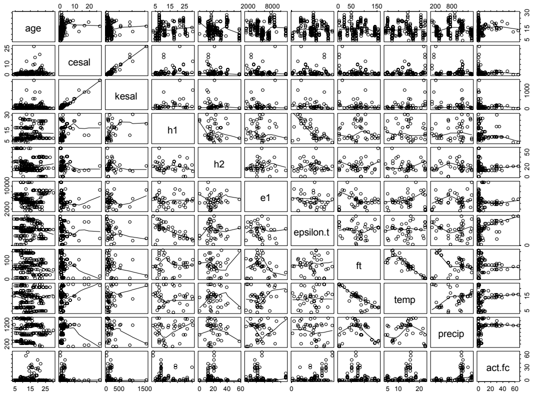
Model Development

2. Bivariate and Multivariate Analysis (Scatter Plot Matrix with lowess smoother)



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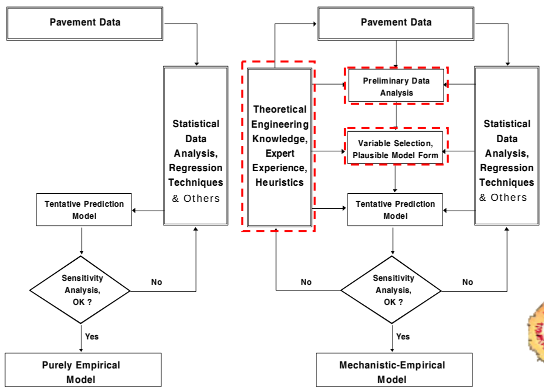
Model Development

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



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Model Development

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) Fatigue cracking could be treated as rate data, i.e., percent of the entire lane area.
- Agresti (1996) also suggested that using Poisson regression for rate data is an appropriate decision.
- Generalized Linear Model (GLM)

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- 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	$g(\mu)$	$V(\mu)$

(4a) Preliminary GLM models for all zones

$$\ln(FC) = -7.455 + 0.121 * age + 0.00168 * kesal + 0.00269 * precip + 0.0473 * temp + 12319.5 * epsilon.t + 0.0133 * ft$$

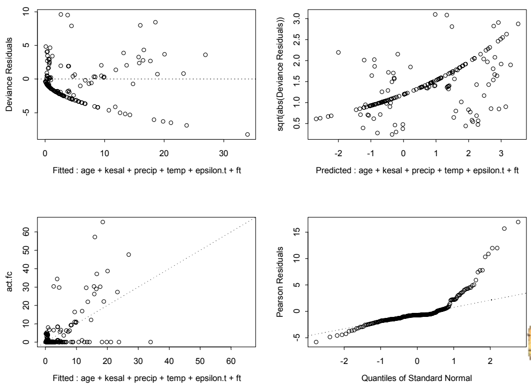
Statistics：R^2=0.447，SEE=2.882，n=176

➔ Convert to conventional model form:

$$FC = \exp\left[\begin{array}{l} -7.455 + 0.121 * age + 0.00168 * kesal + 0.00269 * precip \\ + 0.0473 * temp + 12319.5 * epsilon.t + 0.0133 * ft \end{array}\right]$$

Statistics：R^2=0.3352，SEE=8.741，n=176

Goodness of fit of the preliminary GLM models for all zones



(4b) Separate by different climatic zones

Zone / Variables	First Runs				Second Runs	
	wet	dry	freeze	non-freeze	dry	Freeze
age	+	+	-*	+	+	removed
kesal	+	-*	-*	+	removed	removed
precip	+	+	+	+	+	+
temp	+	+	+	+	+	removed
epsilon.t	+	---	+	+	+	+
ft	+	+	負*	+	+	removed
visco						-
temp.range						+

---: Insignificant
-: negative correlation
+: positive correlation
*: different from expectation

- Wet Zones (Statistics: R^2=0.452, SEE=3.137, n=123)

$$(FC)_{wet} = \exp\begin{bmatrix} -6.539 + 0.078 * age + 0.00187 * kesal + 0.000673 * precip \\ + 0.0914 * temp + 15097 * epsilon.t + 0.0272 * ft \end{bmatrix}$$

- Dry Zones (Statistics: R^2=0.421, SEE=1.117, n=53)

$$(FC)_{dry} = \exp\begin{bmatrix} -48.411 + 0.119 * age + 0.025 * precip + 1.774 * temp \\ + 2729 * epsilon.t + 0.0272 * ft \end{bmatrix}$$

- Freeze Zones (Statistics: R^2=0.498, SEE=1.624, n=86)

$$(FC)_{freeze} = \exp[-5.944 + 0.00583 * precip + 41.768 * epsilon.t - 0.002 * visco + 0.4 * temp.range]$$

- Non-Freeze Zones (Statistics: R^2=0.577, SEE=2.99, n=90)

$$(FC)_{nonfreeze} = \exp[-7.87 + 0.102 * age + 0.00219 * kesal + 0.00102 * precip + 0.0472 * temp + 15172 * epsilon.t + 0.0476 * ft]$$

5. Improved Models Using Additional Modern RegressionTechniques

- 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

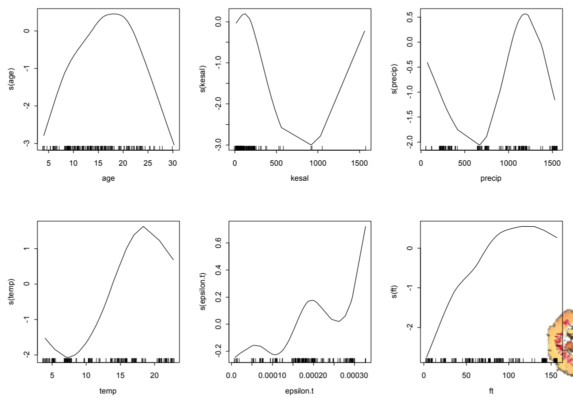
$$y_i^{(\lambda)} = \begin{cases} y_i^{\lambda} & \text{if } \lambda \neq 0 \\ \log(y_i) & \text{if } \lambda = 0 \end{cases}$$

$$L(\lambda) = \begin{cases} n \log(|\lambda|) - \frac{n}{2} \log(RSS_{\lambda}) + n(\lambda - 1) \log [GM(y)] & \text{if } \lambda \neq 0 \\ -\frac{n}{2} \log(RSS_{\lambda}) - n \log [GM(y)] & \text{if } \lambda = 0 \end{cases}$$

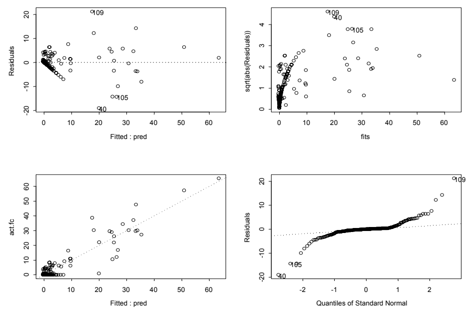
$$GM(y) = \prod_{i=1}^{n} (y_i)^{1/n}$$

Note: λ values from -2 to +2 are recommended

(5a) Fitting a trial GAM Model

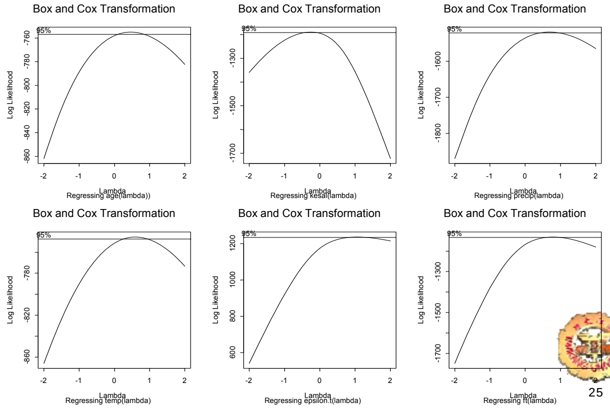


- If disregarding physical interpretations of each individual variable is allowed ... **(NG)**



R^2=0.871, SEE=3.85, n=176

(5b) Striving to find a monotonic power transformation function



(5c) Fitting a tentative GLM model

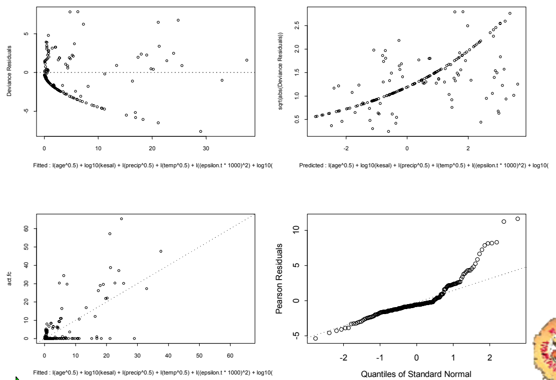
- Poisson Distribution, and quasi-likelihood estimation method, i.e., quasi(link="log", var = "mu")

	Value	Std. Error	t value
(Intercept)	-18.0811	3.313942	-5.45606
I(age^0.5)	0.943158	0.169463	5.565576
log10(kesal)	0.832189	0.294079	2.829816
I(precip^0.5)	0.121099	0.023639	5.122833
I(temp^0.5)	0.869489	0.387165	2.245785
I((epsilon.t * 1000)^2)	31.48981	4.30888	7.308119
log10(ft)	3.241608	1.011386	3.205116

$$FC = \exp[-18.08 + 0.943 * \sqrt{age} + 0.832 * \log(kesal) + 0.121 * \sqrt{precip} + 0.869 * \sqrt{temp} + 31.489 * (epsilon.t * 1000)^2 + 3.242 * \log(ft)]$$

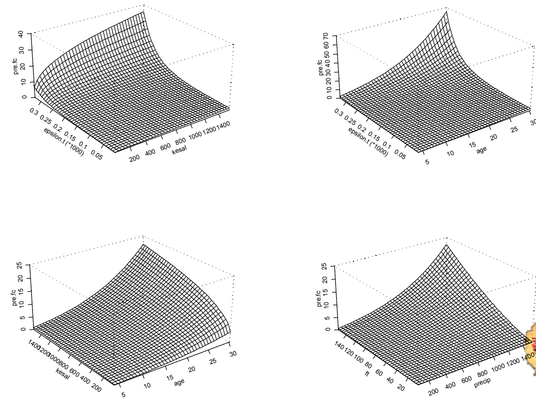
Statistics： R^2=0.4967，SEE=7.605，n=176

6. Goodness of Fit of the Proposed Model



R^2=0.4967，SEE=7.605，n=176

7. Sensitivity Analysis of the Proposed Model



VI. Concluding Remarks

- Existing models for fatigue cracking predictions are inadequate using LTPP Database
- Relatively skewed distribution was identified, indicating that normality assumption is inappropriate
- GLM and GAM along with assumption of Poisson distribution and quasi-likelihood estimation method were adopted
- By eliminating insignificant and inappropriate parameters repeatedly, the resulting model only includes kesal, age, precip, temp, epsilon.t, and ft for predicting fatigue cracking
- Examined the goodness of fit
- Conducted sensitivity analysis
- Further Improvements are possible and recommended

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Questions?

THANKS FOR YOUR ATTENTION

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