Bridge Deterioration Models
Theory and Practice
Examples from Florida and Virginia

Paul D. Thompson, Consultant
Bridge deterioration models

PRINCIPLES
CoRe element inspection

1. There is no evidence of active corrosion, and the paint system is sound and functioning as intended to protect the metal surface.

2. There is little or no active corrosion. Surface corrosion has formed or is forming. The paint system may be chalking, peeling, curling, or showing other early evidence of paint system distress but there is no exposure of metal.

3. Surface corrosion is prevalent. There may be exposed metal, but there is no active corrosion which is causing loss of section.

4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review of either the element or bridge.

5. Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.
Markovian Models

• Assumptions
  – Uniform time intervals between decisions
  – Small number of condition states
  – Each state is self-contained:
    • Contains all information needed to predict future deterioration
    • Does not require information about past states
    • Rates change with condition rather than time
Markov model

<table>
<thead>
<tr>
<th>From</th>
<th>To 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93.6</td>
<td>6.4</td>
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<td>2</td>
<td>92.0</td>
<td>8.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>3</td>
<td>91.1</td>
<td>8.9</td>
<td>0.0</td>
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<tr>
<td>4</td>
<td>98.7</td>
<td>1.3</td>
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<tr>
<td>5</td>
<td>100.0</td>
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</tr>
</tbody>
</table>

All amounts in percent

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Changes in condition

2005

1
2
3
4
5

2007

1
2
3
4
5

Condition state

Deterioration paths

Preservation paths

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Bridge deterioration models

DEVELOPING VALID MODELS
Background

• Florida DOT
  – 19,213 structures (bridges, culverts, sign structures, high-mast light poles)
  – 884,678 element inspections over 14 years
  – 93,615 maintenance activities

• Virginia DOT
  – Similar number of structures and inspections
  – No maintenance data
# Activity classification

## Action Category

<table>
<thead>
<tr>
<th>Object</th>
<th>100-Replace</th>
<th>200-Rehab</th>
<th>300-Repair</th>
<th>400-Maint</th>
<th>Footnotes</th>
</tr>
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<tbody>
<tr>
<td>Materials</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0 Other material</td>
<td></td>
<td></td>
<td></td>
<td>400 (1)</td>
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<tr>
<td>1 Deck</td>
<td></td>
<td></td>
<td>201 (2)</td>
<td>302 (6)</td>
<td>2. Rehab deck and replace overlay</td>
</tr>
<tr>
<td>2 Steel/coat (incl metal)</td>
<td>102 (5)</td>
<td>202</td>
<td></td>
<td>402 (7)</td>
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</tr>
<tr>
<td>3 Concrete</td>
<td>203</td>
<td></td>
<td>303 (8)</td>
<td>403 (9)</td>
<td></td>
</tr>
<tr>
<td>4 Timber</td>
<td>204</td>
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<td></td>
<td>404</td>
<td></td>
</tr>
<tr>
<td>5 Masonry</td>
<td>205</td>
<td></td>
<td>305</td>
<td>405</td>
<td></td>
</tr>
<tr>
<td>6 MSE</td>
<td>206</td>
<td></td>
<td></td>
<td>406</td>
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<tr>
<td>Hi-Maint</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>10 Other element</td>
<td></td>
<td></td>
<td>111</td>
<td>311</td>
<td></td>
</tr>
<tr>
<td>11 Joint</td>
<td>112</td>
<td></td>
<td>312</td>
<td>411</td>
<td>7. Restore top coat</td>
</tr>
<tr>
<td>12 Joint seal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 Bearing (incl p/h)</td>
<td>113</td>
<td>213</td>
<td></td>
<td>413</td>
<td>8. Clean rebar and patch</td>
</tr>
<tr>
<td>14 Railing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9. Patch minor spalls</td>
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<tr>
<td>Drainage</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 Slope prot</td>
<td></td>
<td>221</td>
<td>222</td>
<td>422</td>
<td>10. Incl. elec, hydraulic, and mech elements</td>
</tr>
<tr>
<td>22 Channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11. Repair and lubricate</td>
</tr>
<tr>
<td>23 Drain sys</td>
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<td></td>
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<td></td>
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<tr>
<td>Machinery</td>
<td></td>
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<tr>
<td>31 Machinery</td>
<td>131 (10)</td>
<td>231 (10)</td>
<td>331 (10,11)</td>
<td>431 (10)</td>
<td>12. Incl. fenders, dolphins, and pile jackets</td>
</tr>
<tr>
<td>32 Cath prot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>41 Beam</td>
<td>141</td>
<td></td>
<td></td>
<td></td>
<td>13. Mudjacking</td>
</tr>
<tr>
<td>42 Truss/arch/box</td>
<td>142</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>43 Cable</td>
<td>143</td>
<td>243</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44 Substr elem (exc cap)</td>
<td>144 (12)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 Culvert</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>46 Appr slab</td>
<td>146</td>
<td>246 (13)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appurtenances</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51 Pole/sign</td>
<td>151</td>
<td></td>
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</tbody>
</table>

White cells represent valid sub-categories; numbers in parentheses refer to footnotes

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**Footnotes**

1. Wash structure
2. Rehab deck and replace overlay
3. Repair deck and substrate
4. Repair potholes
5. Replace paint system
6. Spot paint
7. Restore top coat
8. Clean rebar and patch
9. Patch minor spalls
10. Incl. elec, hydraulic, and mech elements
11. Repair and lubricate
12. Incl. fenders, dolphins, and pile jackets
13. Mudjacking
Markov model estimation

**Linear regression**
- Traditional method
- Transition to any worse state
- Usable models: 172

(Out of 755 models at the element/environment level)

- Min sample: 1500
- $r^2: 0.7213$

**One-step**
- New method
- Transition to just next-worse state
- Usable models: 253

- Min sample: 500
- $r^2: 0.7217$

One-step method makes better use of data without sacrificing explanatory power.
Markov model estimation

- One-step model solved algebraically
- Simpler method with fewer numerical problems

\[
\begin{bmatrix}
  y_1 \\
  y_2 \\
  y_3 \\
  y_4
\end{bmatrix} =
\begin{bmatrix}
  p_{11} & p_{12} & 0 & 0 \\
  p_{21} & p_{22} & p_{23} & 0 \\
  p_{31} & p_{32} & p_{33} & p_{34} \\
  p_{41} & p_{42} & p_{43} & p_{44}
\end{bmatrix}^2
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3 \\
  x_4
\end{bmatrix}
\]
Beefing up sample size

Sample: 559,311 inspection pairs

• Performance improved by combining models

<table>
<thead>
<tr>
<th>Level of model</th>
<th>% Valid</th>
</tr>
</thead>
<tbody>
<tr>
<td>151 elements × 4 environments</td>
<td>33.5</td>
</tr>
<tr>
<td>151 elements</td>
<td>57.0</td>
</tr>
<tr>
<td>72 element types</td>
<td>98.6</td>
</tr>
</tbody>
</table>
Onset of deterioration

- Weibull survival probability model
  - For transition from state 1 to state 2 only
  - Extension of Markov model
  - Transition probability is age-dependent

\[ y_{1g} = \exp\left(-\left(\frac{g}{\alpha}\right)^{\beta}\right) \]
\[ \alpha = \frac{t}{(\ln 2)^{1/\beta}} \]

- \( g \) = age (years)
- \( t \) = median transition time (years), states 1 to 2
- \( \beta \) = shaping parameter, to be estimated
Weibull shaping parameter

Shaping parameter (beta) slows the onset of deterioration
Estimation of beta

- Maximum likelihood estimation
  - Using Excel Solver

[Graph showing the probability of state 1 over age of element (years), with Actual, Predicted, and Markov (Default) curves.]
New deterioration models

A1 - Concrete deck
B2 - Pourable joint seal
C2 - Coated metal rail
D7 - Reinforced concrete superstructure

E1 - Elastomeric bearings
F2 - Prestressed column/pile/cap
G1 - Reinforced concrete culverts
H1 - Pile jacket w/o cathodic protection

Health index vs Age of element (years)
New deterioration models
Bridge deterioration models

RISK FROM ADVANCED DETERIORATION
Lognormal risk model

- Appropriate when explanatory variable is built up by multiplication
- Based on log of weighted percent in worst and 2nd worst states for each inspection
- For each inspection indicate if bridge underwent retirement, replacement, reconstruction, or posting before next inspection
- Compute lognormal hazard function and element weights using maximum likelihood estimation
Decay index: Weighted condition similar to health index, but emphasizes the worst and 2\textsuperscript{nd}-worst states. 100=worst
Bridge deterioration models

CONCLUSIONS
## Comparison with experts

Ratio of new transition times to old (2000) expert judgment models

<table>
<thead>
<tr>
<th>By element category</th>
<th>By element material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joints</td>
<td>3.2</td>
</tr>
<tr>
<td>Railing</td>
<td>1.6</td>
</tr>
<tr>
<td>Superstructure</td>
<td>1.7</td>
</tr>
<tr>
<td>Bearings</td>
<td>2.2</td>
</tr>
<tr>
<td>Substructure</td>
<td>2.0</td>
</tr>
<tr>
<td>Movable bridge equip</td>
<td>1.8</td>
</tr>
<tr>
<td>Channel</td>
<td>1.4</td>
</tr>
<tr>
<td>Other elements</td>
<td>1.4</td>
</tr>
<tr>
<td>Unpainted steel</td>
<td>1.8</td>
</tr>
<tr>
<td>Painted steel</td>
<td>1.9</td>
</tr>
<tr>
<td>Prestressed concrete</td>
<td>1.7</td>
</tr>
<tr>
<td>Reinforced concrete</td>
<td>2.1</td>
</tr>
<tr>
<td>Timber</td>
<td>1.8</td>
</tr>
<tr>
<td>Other material</td>
<td>2.1</td>
</tr>
<tr>
<td>Decks</td>
<td>1.9</td>
</tr>
<tr>
<td>Slabs</td>
<td>3.3</td>
</tr>
</tbody>
</table>

*Expert panel under-estimated transition times by a factor of 1.97 on average.*

*Paul D. Thompson*
Other conclusions

• It is feasible to estimate Pontis deterioration and action effectiveness models entirely from historical data.

• New techniques have been developed to reduce data requirements and improve model quality.

• New Markov models explained 72% of variability in inspection data. Weibull refinement explained up to 37% of the remainder of variability.

The new models should greatly improve the credibility and realism of the life cycle cost analysis and the programming decisions that it supports.
Lessons: Florida and Virginia

• Success factors for condition modeling:
  – Inspections should consistently record (as condition state data) severe maintenance-related defects as well as safety and function defects
  – Need a reliable way to identify past actions: maintenance, repair, rehabilitation, improvement, and replacement
  – Need to control for relatively new materials (e.g. weathering steel and prestressed concrete)
Florida Project Level Analysis Tool

![Image of Florida Project Level Analysis Tool interface]

### Components of the Tool
- **Dashboard**: Provides an overview of the project.
- **Screening**:
  - Health and Index
  - Benefits and Costs
  - Health Index
- **Analysis**:
  - Candidate Analysis
  - Auto MRRAE
  - Scope of Auto MRRAE
- **Forecasting**:
  - Direct Costs
  - User Benefits
  - Benefit/Cost Ratio

### Example Analysis
- **Candidate Analysis**:
  - Auto MRRAE: 1.5
  - Auto评级: 4.1
  - Other Analysis: Custom 4

### Health and Benefits
- **Health Index**: 68
- **Benefit/Cost**: 2.1

### Roadway Analysis
- **Deficient Roadway Width and Approach Alignment**
- **Bridge roadway width, curb to curb**: 23.06 ft.
- **Traffic volume**:
  - Morning: 2,563
  - Afternoon: 2,464

### Forecasting Costs
- **Direct Costs**: $797
- **User Benefits**: $1254
- **Benefit/Cost Ratio**: 1.6

### Trends and Data
- **Trend Analysis**: Graphs and data points indicating trends over time.
- **Data Tables**: Detailed cost and benefit data.

This tool provides a comprehensive analysis of project levels, including health assessments, cost-benefit analyses, and detailed forecasts.
Thank you!
Paul D. Thompson
www.pdth.com