Risk-Based Inspection Planning for Bridge Networks

By

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Acknowledgements

- University of Surrey
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  - RSSB
  - Mouchel
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Part 1: Research Objectives & Factors Affecting Risk
Part 2: Risk Based Inspection (RBI) Framework
Part 3: Case Studies
Part 4: Conclusions and Recommendations for Future Work
Research Objectives

Current Inspection Practice
- Fixed Time Based Detailed Inspections
- Not Consider Differences Among Bridges

- Ineffective Use of Resources?
- Increased Risk?

- To Develop A Methodology to optimize the Inspection interval
- To Maintain Constant level of risk across the network
Bridge Attributes Considered

- Bridge Age
- Location, e.g. coastal
- Loading
- Climate
- Ground Conditions
- Access Difficulties
- Hidden Details
- Deterioration
- Past performance
- Maintenance Works
- Material quality/Workmanship
- Deterioration Mechanisms
- Bridge Network
- Inspectability
- Duration/Costs of remedial work
- Road Traffic Flow
- Railway Traffic Flow
- Inspectability
- Access Difficulties
- Hidden Details
- Bridge Attributes Considered
- Bridge Network
- Type
- Environment
- Bridge Construction Material & Forms
- Railway Traffic Flow
- Road Traffic Flow
- Material quality/Workmanship
- Deterioration Mechanisms
- Bridge Network
- Consequence

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Risk

Risk = Probability of Failure X Consequence of Failure

- Type
- Environment
- Inspectability
- Consequence

Deterioration

Time Independent Attributes

Time Dependent Attribute
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Framework for Proposed RBI

Risk Ranking Module (Time Independent Attributes)

Bridge Network

Classification by ‘Type’

Main Bridge Groups

Classification by ‘Environment’, ‘Inspectability’ & Consequence

Relative Risk Scores (R)

Bridge Subgroups

Inspection Planning Module (Time Dependent Attribute)

Representative Deterioration Profiles for Bridges in ‘Mild’ & ‘Severe’ Environments

Maximum & Minimum Inspection Intervals for a Main Group

Interpolation According to R

Inspection Intervals for Subgroups

Optimised RBI Inspection Intervals for the Network
Risk Ranking Scoring System

\[ R = (W_1E + W_2I) \times C \]

- Environment Score
- Consequence Score
- Inspectability Score

\( W_1, W_2 \) – Weight Factors
Risk Score

Sensitivity studies on weight factors

Effect is small

Scores are qualitative measure of the relative risk only

Weight factors ignored

\[ R = (E + I) \times C \]

Scores made to vary between 1 and 2 by linear interpolation
A Conceptual RBI Planning Model

- Deterioration curves for mild & severe environments
- Expected Conditions ($C_{M,6}$ & $C_{S,6}$) at year 6 from the curves
- Weighted average $C$
- Target $C = \text{Weighted Average } C$
- Inspection when $C$ curve reaches target
- $T_{\text{Max}}, T_{\text{Min}}$
- Inspection intervals of subgroups according to the risk scores
Deterioration Modelling

- A Bridge is a system made up of elements
- Elements can be further divided into minor elements
- Minor elements fail due to deterioration
- Element failure propagates through the system
- This may lead to progressive failure of the bridge
- Fault Tree Models (FTM) have been used in these situations
- Bayesian Belief Networks (BBN) can also be used
Bayesian Belief Networks (BBN)

- A structured way to show Relationships between variables in network
- Relationships estimated by conditional probabilities
- Effective when data is uncertain or incomplete
- Widely used in various industries e.g. Medical industry, water management, weather forecasting, etc.

P(A,B,C) = P(A/B,C)P(B)P(C)
Dynamic Bayesian Network (DBN)

- Special type of BBN
- Deals with domains which evolve over time

Three time frames have to be considered:
- Initial time, $t_0$
- Transition interval, $\Delta t$
- Time horizon, $T = t_{\text{final}} - t_0$
Benefits of BBN

• Previous knowledge can be utilized
• Updating with new information is possible
• Can be used to model problems with variable quality/quantity data
• Graphical representation helps understanding
• Expert knowledge can be utilized in the absence of physical data

Shortcomings of BBN

• Fully specified Conditional Probability Tables (CPT) are required
• CPTs may become very large when parent nodes are multi-state
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Risk Ranking System

Bridge Type
- Brick Arch
- Stone Arch
- Cast Iron
- Riveted Steel
- Welded Steel
- Concrete

Environment
- Mild
- Severe

Consequence
- Low
- High

Inspectability
- Easy
- Hard

Relative Risk Score
- 1.00
- 1.17
- 1.33
- 1.67
- 1.17
- 1.33
- 1.67
- 2.00

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Criteria for Identification of ‘Environment’

• Masonry arch bridges considered, since they are about half of the NR bridge stock

• The environment of a bridge considered as severe, if two or more of the following factors are severe/heavy:
  - Loading
  - Climate
  - Location of the bridge
  - Ground Conditions
Classification of Loading

A qualitative classification of loads based on the type of traffic:

• Under line bridges (Bridges carrying railway lines):
  - Primary
  - LSE
  - Freight routes

• Over line bridges (Bridges carrying roads over railway lines):
  - Motorway
  - Trunk road
Criteria for Identification of ‘Consequence’

If two or more of the factors are classified as high, then the ‘consequence’ is considered high:

• Railway traffic flow:
  - Primary and LSE lines
  - or bridges maintained under policy A
• Road traffic flow:
  - Motorways and trunk roads
  - or Traffic sensitive roads
• Cost and/or duration of remedial actions
  - bridges with multi or long spans
Criteria for Identification of ‘Inspectability’

- Bridges with hidden details
- Access difficulties for inspection

Inspectability – Hard

These details are normally available in inspection reports

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A BBN Model for Masonry Arch Bridge Group Condition

- Numerical variables with 3 intervals; (0-45), (45-80) & (80-100)
- Conditional probabilities from relative weightings of elements
- Initial element level condition from sample structures
Output from the BBN Model

Main group level condition for Masonry Arch Bridges

‘What-If’ Scenarios

In BBN evidences about variables can be easily updated

– e.g. If wing walls are known to be in poor condition

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Inclusion of Time Variability: DBN

- Element condition at any time $t$ depends on the element condition at time $t-\Delta t$
## Conditional Probabilities between Time Steps

Conditional probabilities between time steps to follow Markov principal
e.g. By assuming 5% deterioration to the next state between two time steps:

<table>
<thead>
<tr>
<th>Probability of wing wall SCMI at next time step ( \text{[Sw}(t_{i+1})] )</th>
<th>Current wing wall SCMI ( \text{[Sw}(t_i))</th>
<th>0-20</th>
<th>20-40</th>
<th>40-60</th>
<th>60-80</th>
<th>80-100</th>
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<tbody>
<tr>
<td>( P(\text{Sw}(t_{i+1}) \leq 20) )</td>
<td>1</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
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<tr>
<td>( P(20 &lt; \text{Sw}(t_{i+1}) \leq 40) )</td>
<td>0</td>
<td>0.95</td>
<td>0.05</td>
<td>0</td>
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<tr>
<td>( P(40 &lt; \text{Sw}(t_{i+1}) \leq 60) )</td>
<td>0</td>
<td>0</td>
<td>0.95</td>
<td>0.05</td>
<td>0</td>
<td></td>
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<tr>
<td>( P(60 &lt; \text{Sw}(t_{i+1}) \leq 80) )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.95</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>( P(\text{Sw}(t_{i+1}) &gt; 80) )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.95</td>
<td></td>
</tr>
</tbody>
</table>
Deterioration of Bridge Group Condition from DBN

From DBN, the deterioration of bridge group mean SCMI and the 5%, 95% confidence interval values with time can be obtained.
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Case Study of RBI planning using DBN

- A random sample of bridges from Network Rail’s bridge stock is ranked according to the risk ranking strategy.
- Deterioration curves for bridges in mild and severe environment obtained from DBN.
Inspection Intervals for the Subgroups of the Sample Structures

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>Relative Risk Score, R</th>
<th>Inspection Interval (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>From Analysis</td>
</tr>
<tr>
<td>SG1</td>
<td>1.00</td>
<td>8.2</td>
</tr>
<tr>
<td>SG2</td>
<td>1.17</td>
<td>7.2</td>
</tr>
<tr>
<td>SG3</td>
<td>1.33</td>
<td>6.2</td>
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<tr>
<td>SG4</td>
<td>1.67</td>
<td>4.1</td>
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<tr>
<td>SG5</td>
<td>2.00</td>
<td>2.0</td>
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</table>
Change in the Inspection Intervals - I

• When there are more bridges in severe environment, $T_{\text{max}}$ can be extended up to 30 years.

• This is the result of target value chosen on the basis of main group level average.

• Industry Good Practice of Maximum of 18 Years can be used as the upper limit.
Change in the Inspection Intervals - II

• Tmax can be extended up to 12 years depending on the relative rate of deterioration

• This is also related to the target value selection
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Concluding Remarks

• Risk ranking strategy:
  – Helps to identify critical structures in a network
  – Systematic approach and practical to apply
  – Case study on some sample structures

• DBN deterioration model for masonry arch bridge group:
  – Need for a deterioration model at a main group level identified
  – Real data or engineering judgments can be utilised
  – Can be extended to any type of bridges

• Risk-Based Inspection Model:
  – A conceptual model for bridge networks
  – Case study to illustrate the use of the model on RBI planning
  – Inspection intervals for sample bridges
Recommendations for Future Work

• Refinement of risk ranking attribute categorisation (e.g. mild, moderate & severe ‘environment’)

• Development of deterioration models for each main group of bridges

• Alternative criteria for target risk level
  – Collapse
  – Functional
  – Serviceability

• Possibility of updating the inspection intervals based on inspection findings

• Use of other inspection methods / Effectiveness of inspection in reducing risk levels
References


Thank you
<table>
<thead>
<tr>
<th>Criteria</th>
<th>RBI System</th>
<th>University of Surrey</th>
<th>Network Rail</th>
<th>Welsh Assembly Government</th>
<th>TfL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition of Risk</strong></td>
<td>Probability of Failure x Consequence of Failure</td>
<td>Not Explicitly Defined, but mainly likelihood of event is considered</td>
<td>Not Explicitly Defined, but a Combination of Likelihood and Consequence</td>
<td>(Probability of Rapid Deterioration, Damage or Failure, Consequences of Failure)</td>
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<tr>
<td>Level of Analysis</td>
<td>Network Level</td>
<td>Individual Structures</td>
<td>Group of Structures/Individual Structures</td>
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<td>Attributes Considered</td>
<td>Attribute Group: Attributes</td>
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<td></td>
<td>Bridge Construction Form and Material Type</td>
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<td>Structure Type, Material Type, Structural Form</td>
<td>Structure Type, Material Type, Structural Form</td>
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<tr>
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<td>Age</td>
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<td>Environment</td>
<td>Location</td>
<td>Level of Contamination</td>
<td>Loading</td>
<td>Exposure Saviarity</td>
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<td>Climate</td>
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<td>Ground Conditions</td>
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<tr>
<td>Inspectability</td>
<td>Access Difficulties</td>
<td>Inspectability, Principal Inspection Interval</td>
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<td></td>
<td>Hidden Details</td>
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<td>Deterioration</td>
<td>Material Quality/Workmanship</td>
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<td>Potential Modes of Failure</td>
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<td>Potential Deterioration Mechanisms</td>
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<td>Past Performance</td>
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<td>Capacity</td>
<td>Historical Rate of Deterioration</td>
<td>Rate of Deterioration</td>
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<td>Maintenance Works</td>
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<tr>
<td>Consequence</td>
<td>Railway Traffic Flow</td>
<td>Wider, global consequences</td>
<td>Route Supported</td>
<td>Obstacles Crossed</td>
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<tr>
<td></td>
<td>Road Traffic Flow</td>
<td></td>
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<tr>
<td></td>
<td>Duration/cost of remedial Works (number of spans/span length)</td>
<td>Localised Consequence</td>
<td>Span Length/Height, Extent of Failure</td>
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<tr>
<td>Risk Categorisation</td>
<td>In a scale of 1.00-2.00</td>
<td>Lower, Medium or Higher</td>
<td>0%-100%</td>
<td>In a Scale of 0-100</td>
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<tr>
<td>Maximum Inspection Intervals</td>
<td>Various</td>
<td>Various</td>
<td>12 Years</td>
<td>18 Years</td>
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