A fuzzy-based Bayesian Belief Network approach for railway bridge condition monitoring and fault detection

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Background

Railway infrastructure is exposed to various external loads such as earthquakes, wind and traffic during their lifetime


Condition monitoring and fault detection of railways are vital to guarantee its development, upgrading, and expansion


Network rail estimates to spend

£38bn

over the period from 2014 to 2019 years in maintaining, renewing and improving the rail network


http://dataportal.orr.gov.uk/displayreport/report/html/02136399-b0c5-4d91-a85e-c01f8a48e07e
Railway bridges are long-life assets that deteriorate due to traffic volume, environmental factors, inadequate inspection and poor maintenance management.

Deterioration processes may lead to a lower safety level and, potentially, to catastrophic events.


More than 35% of the 300,000 railway bridges across Europe are over 100 years old.


Bridge condition assessment and fault detection strategies are usually carried out by subjective visual inspection, at intervals of one to six years.

Bridges failures

17 February 2016, Gudbrandsdalslågen (Norway)

1 year old!!!
Bridges failures

2 August 2016, Leicestershire (UK)
Bridges failures

19 August 2016, Pitrufquén (Chile)
Bridges failures

7 September 2016, Dimbokro (Ivory Coast)
Bridges failures

28 October 2016, Milan (Italy)
Bridges failures

9 March 2017, Ancona (Italy)
18 April 2017, Fossano, Cuneo (Italy)
How can we avoid these situations?
Objective of the research

- Remote structural health monitoring and fault detection
- Overcoming of manual bridge SHM limitations
- Assessment of the health state of the whole bridge by taking account of the health state of each different bridge element
- Maintenance can be scheduled by ensuring trains to operate without delays or interruptions to service
The bridge model

To simulate bridge behaviour in order to understand how it is influenced by component failure and degradation mechanisms.

**Degradation case**

- micro-cracks of the joints are considered as degradation mechanism
  - unavoidably created during the welding and assembling phase of the bridge.
  - difficult to be spotted during a visual inspection.
  - size increases due to cycle of loading and unloading, e.g. trains are continuously passing over the bridge.
To detect the states of elements using the evidence about bridge behavior in order to identify, and predict, elements fault assessing which component has to be firstly maintained.
To quantify the relationships between connected nodes, a group of bridge experts has been interviewed by using a 11 questions survey.

<table>
<thead>
<tr>
<th>Linguistic probability scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Unlikely (VU)</td>
<td>It is highly unlikely that influences occur</td>
</tr>
<tr>
<td>Unlikely (U)</td>
<td>It is unlikely but possible that influences occur</td>
</tr>
<tr>
<td>Even Chance (EC)</td>
<td>The occurrence likelihood of possible influences is even chance</td>
</tr>
<tr>
<td>Likely (L)</td>
<td>It is likely that influences occur</td>
</tr>
<tr>
<td>Very Likely (VL)</td>
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To quantify the relationships between connected nodes, a group of bridge experts has been interviewed by using a 11 questions survey.

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<th>Triangular fuzzy scale</th>
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<tr>
<td>Very Unlikely (VU)</td>
<td>[1/2,1,3/2]</td>
<td>It is highly unlikely that influences occur</td>
</tr>
<tr>
<td>Unlikely (U)</td>
<td>[1,3/2,2]</td>
<td>It is unlikely but possible that influences occur</td>
</tr>
<tr>
<td>Even Chance (EC)</td>
<td>[3/2,2,5/2]</td>
<td>The occurrence likelihood of possible influences is even chance</td>
</tr>
<tr>
<td>Likely (L)</td>
<td>[2,5/2,3]</td>
<td>It is likely that influences occur</td>
</tr>
<tr>
<td>Very Likely (VL)</td>
<td>[5/2,3,7/2]</td>
<td>It is highly likely that influences occur</td>
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Triangular fuzzy membership function
Each Expert Judgement is weighted by considering the experience of the expert in order to compute an Average Judgment

Fuzzy synthetic extent value of each pairwise comparison

Fuzzy ranking synthetic extent by using total integral value with index of expert optimism

Weight of the parent nodes on their child
Weighted mean based on expert’s experience

The different responses are merged together by weighing the years of experience \( (E_i) \) of the experts:

\[
W_i = \frac{\beta}{\max_i \left( \frac{E_i}{\max_i N} \right)^\beta}
\]

Each Expert Judgement is weighted by considering the experience of the expert in order to compute an Average Judgment.
Weighted mean based on expert’s experience

Each Expert Judgement is weighted by considering the experience of the expert in order to compute an Average Judgment.

The different responses are merged together by weighing the years of experience ($E_i$) of the experts:

Increase of experience
To assess the weights of the parent nodes on their child nodes in CPTs, by considering the ambiguity of human judgment.

Each Expert Judgement is weighted by considering the experience of the expert in order to compute an Average Judgment.

Fuzzy synthetic extent value of each pairwise comparison

- For each pairwise comparison $\tilde{C}_{ij}$ we compute the fuzzy synthetic extent

$$\tilde{S}_i = \sum_{j=1}^{n} \tilde{C}_{ij} \cdot \left[ \sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{C}_{ij} \right]^{-1}, i = 1, 2, \ldots, n$$

<table>
<thead>
<tr>
<th></th>
<th>TRC</th>
<th>BRC</th>
<th>TLC</th>
<th>BLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRC</td>
<td>[1 1 1]</td>
<td>$\cup$ [1,3/2,2]</td>
<td>$\cup$ [1,3/2,2]</td>
<td>$\vee$ [1/2,1,3/2]</td>
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To assess the weights of the parent nodes on their child nodes in CPTs, by considering the ambiguity of human judgment

Each Expert Judgement is weighted by considering the experience of the expert in order to compute an Average Judgment.

Fuzzy synthetic extent value of each pairwise comparison.

Fuzzy ranking synthetic extent by using total integral value with index of expert optimism.

Fuzzy ranking synthetic extent by using total integral value with index of optimism ($\alpha$)

$$I_i = \frac{1}{2} (\alpha c_i + b_i + (1 - \alpha) a_i)$$
To assess the weights of the parent nodes on their child nodes in CPTs, by considering the ambiguity of human judgment:

- Each Expert Judgement is weighted by considering the experience of the expert in order to compute an Average Judgment.

Fuzzy synthetic extent value of each pairwise comparison:

Fuzzy ranking synthetic extent by using total integral value with index of expert optimism:

- Weight of the parent nodes on their child

The importance weight vector of each bridge variable can be assessed:

\[ w_i = \frac{I_j}{\sum_j I_j} \]
To assess the influence of the behaviour of the top chord on the right hand side on the health state of the other bridge elements.

<table>
<thead>
<tr>
<th>Importance Weight</th>
<th>Top Chord right</th>
<th>Bottom chord Right</th>
<th>Top Chord left</th>
<th>Bottom chord left</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.30</td>
<td>0.26</td>
<td>0.222</td>
<td>0.218</td>
</tr>
</tbody>
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To assess the influence of the behaviour of the top chord on the right hand side on the health state of the other bridge elements.
Each Expert Judgement is weighted by considering the experience of the expert in order to compute an Average Judgment.

Fuzzy synthetic extent value of each pairwise comparison.

Fuzzy ranking synthetic extent by using total integral value with index of expert optimism.

Weight of the parent nodes on their child.

To measure the consistency of the judgments in the comparison matrix.

Consistency ratio

\[ CI = \frac{\lambda_{max} - n}{n - 1} \]

Where \( \lambda_{max} \) is the principal eigenvalue of the defuzzified matrix.

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0</td>
<td>0</td>
<td>0,58</td>
<td>0,90</td>
</tr>
</tbody>
</table>

Consistency ratio = \( \frac{CI}{RI} \) < 0.1

Consistency ratio = 0.0154  ✔
To quantify the relationships between connected nodes, 3 mutually exclusive health states of each element and the whole bridge have been defined.

- **Healthy state**: The elements of the bridge are in a good condition.
- **Partially degraded state**: The elements of the bridge potentially require maintenance.
- **Severely degraded state**: The elements of the bridge need to be maintained.
Gradual degradation mechanism

To simulate a gradual degradation mechanism of a small element of the top chord on the left hand side of the bridge, and to assess the influence of this degradation to all the bridge.
Introducing evidence into the BBN

Evidence about health state of the bridge
Posterior probability distribution
Future challenges

- The structure of the BBN should consider all possible dependencies among different elements of the bridge
- More robust definition of the CPTs
  - Analysis of the correlation between the degradation mechanisms and the bridge behaviour
- Real bridge analysis by using data provided by sensors installed on a real bridge in Japan (in collaboration with the University of Kyoto)

To automatically detect and diagnose causes of unexpected bridge behaviour, in order to provide rapid and reliable information to bridge managers.
Conclusion

- There is a need for real-time remote structural health monitoring and fault detection by overcoming the limitations of traditional manual bridge SHM.
- The influence of each single bridge element should be considered on the assessment of the bridge health state.

We have proposed a BBN-based SHM method to monitor the evolution of a bridge health state

Pros:
- Each bridge element influences the health state of the whole bridge
- The health state of the bridge and its elements is updated each time when new evidence of the bridge behaviour is available

Cons:
- The method relies on the data provided by a Finite Element model of a steel truss bridge
- Assumptions have been made in the development of the Finite Element model and the BBN
Thank you for your attention

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