Executive Summary: A Risk Based Inspection Framework for Bridge Networks

1. Introduction

At present, Network Rail carries out an annual visual examination and a detailed examination every six years on each of the 40,000 bridges to collect information on condition and performance of its bridge stock. No distinction is being made between different bridge attributes such as age, type, environment, etc. Given the diversity of the bridge stock - considering issues related to bridge characteristics, functionality and significance - this inspection regime is unlikely to provide optimum safety and performance in a cost effective manner. In other words, this could result in unnecessary spending on well performing bridges while some bridges that are potentially under higher risk do not receive the required attention. The introduction of a risk based approach can be useful in this context as it has the potential of rationalising inspection planning leading to significant safety and cost benefits. A risk based inspection methodology (RBI) will normally have one or more of the following potential benefits (HSE, 2001; ABS, 2003):

- Risk reduction at network level, for any given level of resource allocation.
- Optimization of inspection resources.
- Inspection efforts focused onto most critical areas.
- Identification of the most appropriate inspection methods.
- Number of reactive repairs could be reduced.

RBI has proved to be an efficient risk management tool through its application to various industries such as aircraft (e.g. Yang and Tang, 1974), nuclear (e.g. Vo *et al*., 1993) and offshore (e.g. Faber *et al*., 1996, Onoufriou, 1999). These studies have concentrated at an element/structure level or a small group of structures with similar characteristics, and are not readily applicable to a large stock of bridges with variations in type, age, environment, significance, etc. When considering a large network/stock, bridge specific analyses may not be feasible. However, even if all the bridges are analysed individually and inspections are scheduled accordingly, large variations in inspection intervals over the network may be introduced, causing practical difficulties and additional expenditure. Instead of having the same inspection regime throughout the entire network or bridge specific inspection intervals, scheduling inspections for groups of bridges according to their relative risk would optimize the inspection resources in a cost effective manner. For this purpose, it is necessary to categorise the bridges with similar characteristics into groups as a part of the development of an RBI methodology. Section 2 presents a systematic risk ranking approach for a network of bridges considering the factors which influence their relative risk.

2. The Risk Ranking Strategy

There are many factors that affect risk. These factors were identified based on a study of available literature, and discussions with bridge owners and operators. Altogether, sixteen factors were identified as having a significant impact in determining the relative risk levels of bridges in a network. Some of these factors affect the same attribute of a bridge and, hence, were grouped together. These global attributes were 'type', 'environment', 'consequence', 'inspectability' and 'deterioration'. With the exception of deterioration, these attributes can be thought of as time independent and were utilised in order to provide an initial screening of bridges in terms of their relative risk. Deterioration affects the variation of the condition/performance with time and, hence, leads to a time-varying risk profile. This was used, along with the initial relative risk, in developing a framework for risk based inspection planning of the bridge stock.

A simple and practical approach for ranking bridges was introduced by defining groups and sub-groups of bridges in a network. The 'type' attribute was used as the basis to define the main groups. The three other attributes, 'environment', 'consequence' and 'inspectability' were classified into two categories, in terms of their severity. Sub-groups were derived according to these classifications. Therefore, the sub-groups serve as a risk ranking tool for each main group of bridges. A scoring system was then introduced to express the relative risk numerically. Initially, a score of 1 for the best combination and 2 for the worst combination of attributes were assigned. For example, a score of 1 was allocated for 'mild environment' whereas 2 was assigned to 'severe environment'.

Risk is defined as the product of the probability of failure with the consequences of failure. The 'environment' and 'inspectability' attributes are related to the probability of failure (P_f) whereas the 'consequence' attribute represents the consequence of failure (C_f). Therefore, a score representing the relative risk of a subgroup, R, can be expressed through Equation 1.

$$R = (W_1 E + W_2 I) \times C \qquad \text{Equation (1)}$$

where,
E – Environment Score
I – Inspectability Score
C – Consequence Score
W_1, W_2 – Weight factors representing relative importance of Eand I within the overall risk score R.

Sensitivity analysis was performed to examine how the weight factors affect the risk scores. Based on the results of the sensitivity studies, and bearing in mind that the scoring system is only a rough measure of the relative risk among the sub-groups, it was decided not to include weighting factors in the scoring system.

Therefore the relative risk score 'R' was calculated using Equation 2.

$$R = (E + I) \times C \qquad \text{Equation (2)}$$

These values were normalized to vary between 1 and 2 by linear interpolation. This adjustment was considered desirable so that these bounding values always represent the best and worst cases respectively. The risk ranking system and the resulting risk scores are expressed schematically in Figure 1.

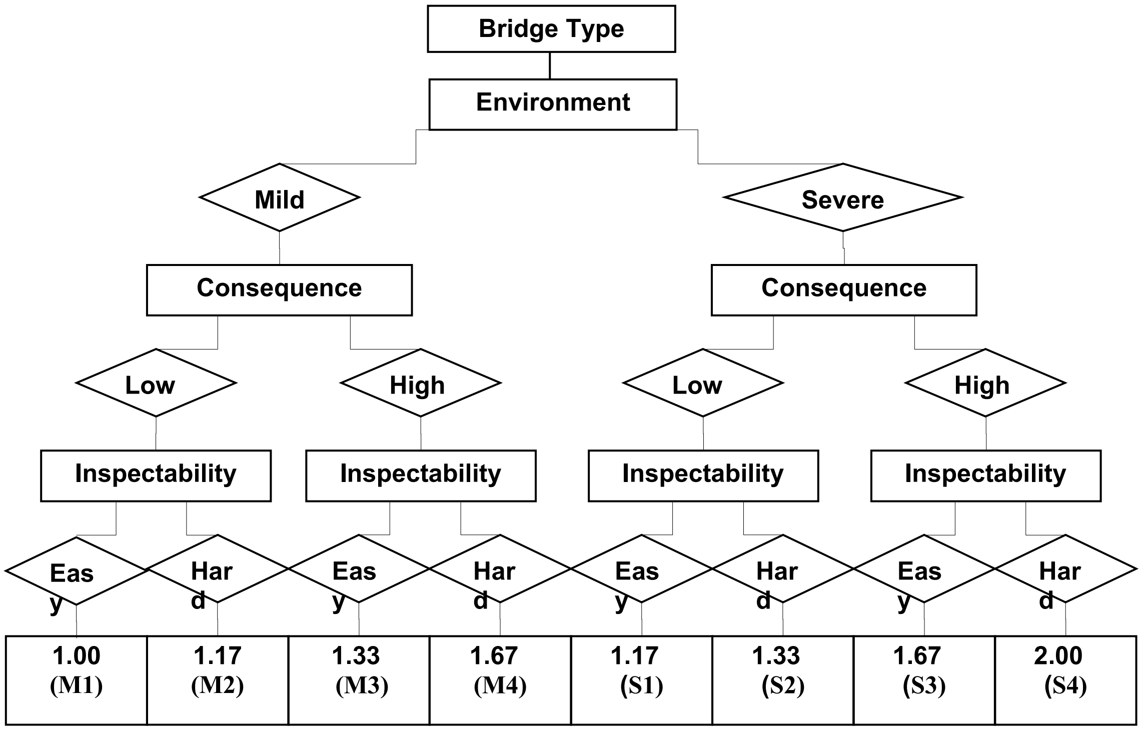

Figure 1. Risk ranking system

The potential use of the proposed risk ranking strategy was demonstrated through its application on Network Rail's bridge stock. Based on the forms and age of the bridges in the network, and after consulting with the bridge owners and contractors, the following six main groups were proposed: stone arch bridges, masonry arch bridges, cast iron bridges, riveted steel bridges, welded steel bridges and concrete bridges. The criteria for classifying the severity of the attributes were also established for the network, and a random sample of bridges was analysed and ranked according to the proposed method. The 'environment' attribute used to evaluate the risk scores is comparable with the bridge condition index-SCMI. A reasonable agreement between the two scoring systems was observed for the sample bridges. This provides assurance that the proposed approach, although qualitative, gives results that are in line with the observed condition of actual bridges. Further adjustments to the method, such as sub-dividing each factor into three categories (e.g. mild, medium and severe) instead of the currently proposed two, can be considered in order to increase refinement though not necessarily reflecting higher accuracy.

3. RBI Planning

According to the current inspection regime, Network Rail carries detailed inspections every six years. However, bridges deteriorate at different rates depending on many factors, such as age, quality of construction, exposure to chemical/physical hazards, etc. As a rough idealization, within each main group of bridges, two deterioration profiles were considered to represent the mild and severe environments. Initially, a condition index based model was considered. In this approach, if the variations in condition indices from past inspection records for mild and severe environment bridges are available, the deterioration profiles can be obtained. By setting up the weighted average value of the expected conditions of mild and severe bridges at year 6 as the target condition index, two inspection intervals for mild and severe environment bridges can be obtained as illustrated in Figure 2. In a conservative approach, these inspection intervals were assigned to the least severe subgroups (e.g. M1 and S1 in Figure 1) in the respective environments. The inspection intervals for the other subgroups can be obtained according to their relative risk score ratios.

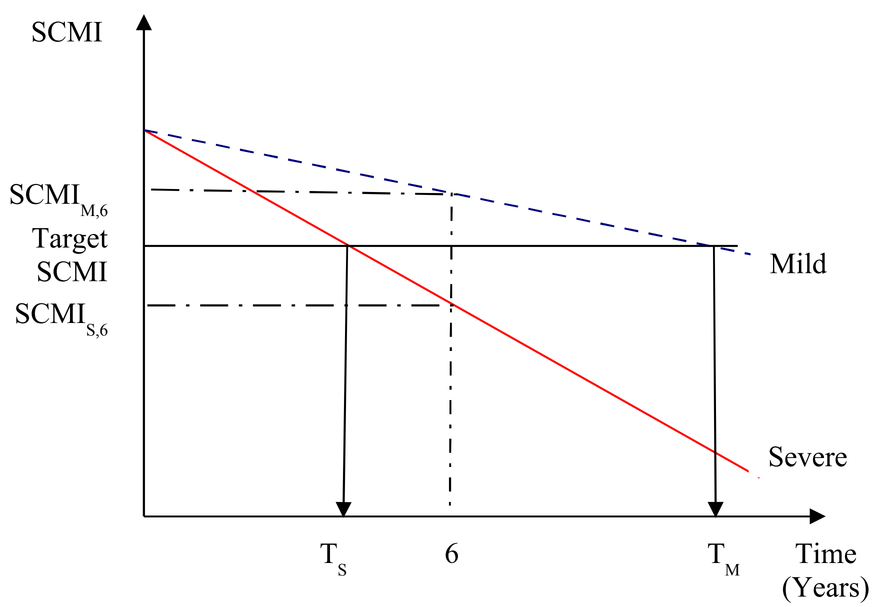

Figure 2. Inspection interval for mild and severe environment group bridges

Initial attempts to demonstrate the methodology with some real data were not successful due to lack of data capturing the change of bridge condition over a significant time period. Therefore, an alternative approach for predicting the change in the bridge group condition using Dynamic Bayesian Belief Networks was considered. Bayesian Belief Network (BBN) is a structured way of expressing the relationships between the variables in a network by means of conditional probabilities. Dynamic Bayesian Network (DBN) is a special type of BBN which deals with domains that evolve over time (Jensen and Nielsen, 2007).

3.1. Brick Masonry Arch Group Degradation Model

In the SCMI procedure a masonry arch bridge is classified into the following major elements; end support 1, end support 2, deck and intermediate support (if any present) (SCMI, 2004). The major elements are further sub divided into minor elements. Conditions of the minor elements are evaluated during detailed inspections and then converted into bridge level SCMI scores using an algorithm. This classification is carried out at bridge specific level. However, a more generic model at main group level was pursued in this project. Therefore, for masonry arch bridge group a representative BBN model was developed considering the generic major and minor elements shown in Figure 3.

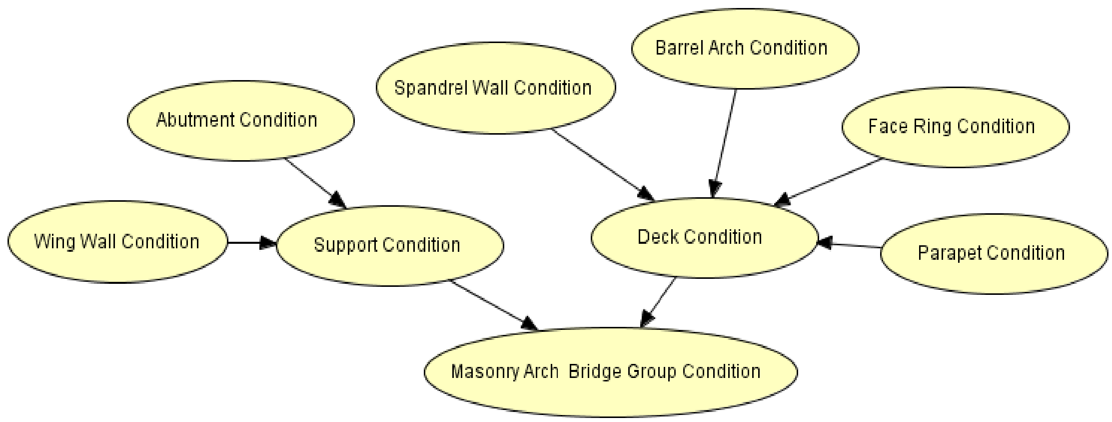

Figure 3. A representative BBN model for masonry arch bridges

In a BBN, a finite number of discrete states of each input variable needs to be defined. In the present study, these were defined using various condition states of the variables, i.e. conditions of each minor and major element in a BBN model in Figure 3. For continuous variables, the states can be discretized by defining the intervals on the real axis. The relationships between the variables for different combinations of those states are expressed by conditional probability tables. The advantage of using the intervals instead of states is that the conditional probabilities can be expressed using some of the standard probability distributions. Initially, a model with three SCMI intervals for each variable; (0-45), (45-80) and (80-100) was developed to represent Network Rail's qualitative classification of structural condition namely; '*poor*', '*fair*' and '*good*' respectively. Sensitivity studies were then carried out to identify the effects of various factors and assumptions associated with the model. Based on the sensitivity analysis findings a five state model with intervals (0-20), (20-40), (40-60), (60-80) and (80-100) was developed and used in subsequent analyses.

The static model described above was transformed into a Dynamic Bayesian Network (DBN) model, by defining the time dependency of future conditions of the minor elements on the current conditions. By considering several time steps, this model was used to predict the probability variation with time. Due to the lack of physical data to specify the transition probabilities between the states and their time dependency, sensitivity analysis has been carried out by selecting different combinations of mild and severe environment bridge transition probabilities. These results were subsequently used in the original RBI model to establish the inspection intervals for a random sample of bridges.

3.2. Case Study of RBI for a Random Sample of Bridges

A random sample of bridges was subdivided according to the risk ranking strategy and was then used to demonstrate the RBI methodology. Two deterioration profiles for these bridges were developed using the DBN model as shown in Figure 4.

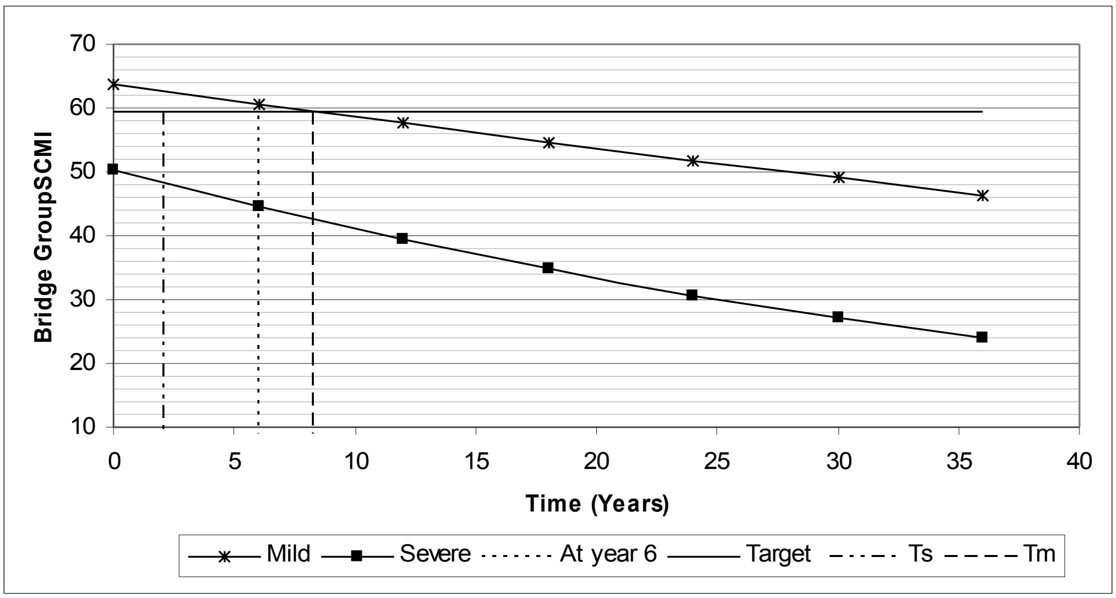

Figure 4. Selection of inspection intervals

As can be seen, bridges in mild and severe environment will have different mean SCMI at year 6, resulting in inconsistent risk levels among bridges at the time of next detailed inspection. For these sample structures, the target value proposed in the initial RBI model (see Figure 2) was higher than the present mean SCMI of bridges in severe environment. Therefore, as an alternative, for bridges in severe environment two year inspection intervals were assumed. The corresponding inspection intervals for bridges in mild environment were selected in such a way so as to keep the overall bridge group SCMI at the time of next detailed inspection the same as that corresponding to current practice, according to Equation 3.

$$\mu_{BG} = \frac{\mu_M \times N_M + \mu_S \times N_S}{N_M + N_S} \qquad \text{Equation (3)}$$

where, μ_{BG} – Mean SCMI of bridge group
μ_M – Mean SCMI of mild environment bridges
μ_S – Mean SCMI of severe environment bridges

N_M – Number of bridges in the mild environment bridges
N_S – Number of bridges in the severe environment bridges

Based on the outcomes from the RBI model, optimized inspection intervals for the subgroups of sample structures were proposed. However, in order to reflect the variations, more conservative inspection intervals were also suggested. These results are given in Table 1. When more data become available, this conservatism can be reduced with more confidence. Sensitivity analyses to identify the effects of number of bridges in each environment and the relative rates of deterioration between two environment bridges on the inspection intervals were also carried out.

Table 1. Inspection intervals for the subgroups of sample structures

Environment	Subgroup	Inspection Interval (Years)	
		Optimized Approach	Conservative Approach
Mild	M1	9.3	8.2
	M2	7.9	7.0
	M3	7.0	6.2
	M4	5.6	4.9
Severe	S1	2.4	2.0
	S2	2.1	1.8
	S3	1.7	1.4
	S4	1.4	1.2

4. Concluding Remarks

A risk ranking strategy was developed in this project which can serve as a screening process for ranking the bridges in a network according to their relative risk levels. The proposed methodology can assist bridge owners to identify the critical structures in their network in a systematic approach which is also practical to apply. It can provide a sound basis for prioritising and planning interventions and inspections while ensuring that a consistent risk level is maintained over the network. The proposed method is demonstrated through application to parts of the UK railway bridge stock. The proposed methodology combines various attributes which can be classified in a simple and rational manner and, while it focuses on bridge specific attributes, it enables bridges to be grouped in terms of risk severity. This feature is particularly desirable when managing a large stock of assets as it enables the number of differentiations that are needed, in terms of inspection intervals, to be maintained at a practical minimum level. The proposed generic methodology can be adapted and developed further to fulfil the specific needs of different bridge stocks or different assets.

An RBI methodology was proposed based on a condition based deterioration model. This model requires substantial data from past inspection records. Until such data are collected and processed, a deterioration model for brick masonry arches using Dynamic Bayesian Networks was developed in order to demonstrate the RBI methodology. The SCMI procedure was used to develop the model and to define the conditional probabilities between the variables. The procedure to select the inspection intervals for different subgroups of bridges with the aid of this deterioration model was demonstrated through a random sample of bridges. Sensitivity analyses were performed to identify the effects of the relative number of bridges in different environments and different deterioration rates on the inspection intervals.

5. Recommendations for Further Work

In this project a degradation model for brick masonry arch bridge groups was developed which serves as the core element of the RBI planning at main bridge group level. Similar models for other main bridge groups also have to be developed to produce complete RBI guidelines for a network.

The whole RBI procedure can be coded into a simple computer program, so that the contractors and bridge engineers can easily identify the required inspection interval for the bridges to which they are responsible for, by entering some basic details and data about those bridges.

The inspection intervals proposed in this study have not considered the possibility of updating based on inspection findings but suggest only the first (or *a priori*) inspection intervals to maintain broadly consistent risk levels throughout the network. Subsequent inspections could be either at the same interval or after updating based on inspection findings. The second approach may result in additional savings in terms of inspection resources, since the a priori models are based on conservative assumptions.

The current study considered the optimization of inspection intervals following the widely used method of close visual inspection. However, by introducing more advanced inspection techniques such as NDT, the reliability of inspection findings could be increased, and hence, the interval between inspections can also be affected. A trade off analysis between the costs of introducing the new inspection intervals and the benefits that could be obtained from the new methods is another possible research area.

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