A New Method for Quantifying the Contribution of Different Critical Agents on Railway Bridge Deterioration

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Abstract

Railway Bridges deteriorate over time due to different critical factors including, flood, wind, earthquake, collision, and environment factors, such as corrosion, wear, termite attack, etc. In current practice, the contributions of the critical factors, towards the deterioration of railway bridges, which show their criticalities, are not appropriately taken into account. In this paper, a new method for quantifying the criticality of these factors will be introduced. The available knowledge as well as risk analyses conducted in different Australian standards and developed for bridge-design will be adopted. The analytic hierarchy process (AHP) is utilized for prioritising the factors. The method is used for synthetic rating of railway bridges developed by the authors of this paper. Enhancing the reliability of predicting the vulnerability of railway bridges to the critical factors, will be the significant achievement of this research.

Keywords: bridge rating, flood, collision, earthquake, wind, criticality, vulnerability, bridge management system.

1 Introduction

Railway bridges form an important part of a railway transport system. These structures should be serviceable to carry loads and passengers with the acceptable level of safety. But they degrade with age due to the impact of the critical factors on them. Some of these critical factors include, train loads, vehicle impacts, fatigue, extreme events including, flood, wind, earthquake, and environmental effects such as corrosion, changing temperature, wear, and termite attack [1]. There are thousands of bridges in a country or a region and the resources for condition assessment and enhancing their structural condition and improving their serviceability are very limited. It is hence necessary to determine which bridges are in the worst condition so that they could be first attended to.

Engineers and bridge managers evaluate the current and future condition of bridges and rate them accordingly. They assess the current condition of the bridge, through inspection, non-destructive tests and structural health monitoring (SHM). SHM systems are the advanced methods of monitoring the behaviour of the structure. More information on the development of these methods can be seen in references [2-7]. Engineers also need to take into account the future condition of the railway bridges. This is because bridges which currently are in a better condition than others can become more vulnerable to the critical factors in future, and as a result, their maintenance can be more costly during their lifetime. It is therefore very important, to identify the critical factors and quantify their contribution towards the degradation of the bridges.

In practical methods for condition assessment and rating bridges such as New York [8] and VicRoad [9], the contribution of different critical factors are not properly considered, although they can be applied to a network of bridges because of simplicity. Examples of different critical conditions and factors can be seen in references [10-13]. In order to overcome the identified problem, methods based on the criticality and vulnerability analyses have recently been developed. Many researchers have adopted the criticality and vulnerability analyses for condition assessment and rating bridges [14, 15].

In this method, through performing criticality analyses, such as the alternative load paths, maximum design stress, and remaining life, and taking into account the vulnerability factors including corrosion, damage, and wear the condition of the bridge is assessed. Analytic hierarchy process (AHP) is widely used. AHP builds a hierarchy structure to solve a complex problem. According to Sasmal and Ramanjaneyulu [16], Saaty developed the AHP method in 1980.

Engineers evaluate the vulnerability of a bridge after identifying the critical factors of the structure. Lind [17] defines vulnerability as "the ratio of the failure probability of damaged system to the failure probability of the undamaged system". Suna et al. [18] believe that the vulnerability is the structural behaviour sensitivity to local damage. Structures can be vulnerable to some types of loads. For instance, the literature refers to much research [e.g. 19, 20, 21] on the vulnerability of different types of structures to earthquake loads. Structures, especially bridges that have a long lifetime can also be vulnerable to environmental factors.

The results of rating bridges based on the criticality and vulnerability analyses are reliable because the effect of different factors on the structure are calculated by identifying the criticality and vulnerability factors and conducting analyses associated with them. However, they are all designed to be applied to only one important bridge or specific components of bridges. These methods need a large amount of accurate data about the bridge, and their analytical process are complex and as a result, they cannot be used for a network of bridges.

To develop a new practical and more reliable rating method for a network of bridges, the authors of this paper adopted the concept of weighting factors, and the idea of criticality and vulnerability. They introduced a classification method for railway bridges and based on that, introduced the synthetic rating system for railway bridges [1, 22]. This method takes into account, (1) the criticality of different factors, (2) criticality of different components associated with different critical factors and (3) vulnerability of components to vertical and lateral loads, and those types of factors, which cause deterioration over time. This research will focus on quantifying the criticality of factors, including flood, wind, earthquake, collision, and environmental factors. The quantities associated with them are named weighting factors. These weighting factors are used in the synthetic rating method introduced by the authors' of this paper [22].

The quantification will be conducted by utilizing available knowledge in Australian standards and other documents which are currently used for designing bridges, available data in the database and expert opinions. AHP method is used to synthesise the priorities and calculate the overall priorities. The outcome of this research is very important for condition assessment and rating bridges, because through quantifying, the role of each critical factor in degrading bridges and the future condition of the bridge can reliably be predicted. Moreover, the risk related to each critical factor can be mitigated. By recording the causes of damages within the inspection process, the quality and quantity of data associated with the criticality of the factors can be improved over time. Therefore, the synthetic rating method will be improved in the long run, and consequently, the resources will be efficiently invested to maintain bridges in a safe and serviceable condition.

2 Quantifying the criticality of different factors

There are three restrictions for selecting the method for quantifying the criticality of critical factors, 1) Availability of data, 2) Feasibility of quantifying the factors, and 3) Capability of being used for a network of bridges. In order to quantify the criticality of factors used in the present work: α_{fl}, α_{w}, α_{e}, α_{col}, β_{ev}, the Australian standards AS 1170.4, AS 1170.2 [23, 24]; average return interval of flood from AS 5100.2 [25]; type of the road that may pass under the bridge and environmental conditions have been taken into consideration. The parameters α_{fl}, α_{w}, α_{e}, α_{col}, β_{ev} are the coefficients that respectively show the criticality of flood, wind, earthquake, collision, and environmental effects.

In order to quantify the identified factors, the use of the statistical data available in the database of BMSs was tried. However, these data which should be collected from inspections need to be sufficient and accurate enough to make the comparison between factors more reliable. At this stage, because the relevant information cannot be obtained from this source, expert opinions have been collected through conducting a survey and interviewing experts who are managing about 1100 railway bridges in Australia. For weighting factors related to the criticality of components, structural analyses need to be performed, which is out of the scope of this paper and will be conducted in the next paper.

Table 1 shows the results of the survey. Experts have taken into account the average proportion of invested repair costs associated with each of the critical factor within a different specific period for each of them. The estimation is approximate. As was previously discussed the lack of information in BMSs' database lead us to conduct this survey. This information can be used as a starting point; however, more reliable data is needed to be collected in future, through inspecting and recording the cause of defects due to each of the identified critical factors, and based on the amount of recourses invested to repair them.

Critical Factors	**Estimation of the Cost in percent spent for maintenance and repair**
Flood/Scour	20%
Wind	0.1%
Earthquake	0.1%
Collision	5%
Environmental factors and fatigue	74.8%

Table 1: The criticality of each factor based on the average proportion of their repair cost

The figures mentioned in table 1 are not constant for every bridge. Based on the location of the bridge, and environmental condition, they will change. In addition, the opinions of the managers and engineers should be incorporated to more reliably calculate the contribution of each of these factors. In order to take into account the above effects, different coefficients for each critical factor and each bridge will be calculated in this research.

The quantified critical factors will be combined and prioritised based on AHP method. The reason for using AHP method was, to incorporate the power of decision making of experts and managers in quantifying the criticality of these factors based on their local experience. In addition to that, other non-structural factors can be considered by using the AHP method. AHP is a multi-objective, and multi-criterion decision methods for ranking systems, and it can be used for planning inspections, and prioritising maintenance and repair actions [26, 27]. Many publications have been produced since 1970s about AHP [26]. This method is used by many researchers for rating different types of bridges [16, 28, 29]. Xu et.al [15] showed the feasibility of using AHP method in synthetic rating of a long suspension bridge.

AHP splits a general problem, which is the goal of the project into sub-problems. Then the priorities between the alternatives of the sub-problems are identified, and finally these priorities will be synthesized to determine the overall priorities between the alternatives of the main problem [14]. AHP has several layers. The first layer is the goal (objective). The next level encompasses criteria that are related to the quality of the decisions. These criteria may split to more detailed layers. Number of levels is dependent on the required accuracy and complexity of the problem [16, 30, 31].

The comparative levels form a pair-wise matrix (e.g. matrix B). The entries of this matrix, is calculated by Eq.1. In this level, Eigen calculations are conducted by using Eq.2, to estimate the relative weights of the decision alternatives associated with each criterion. Synthesizing the weights to indicate the relative weighting factors for each alternative is the last step [16, 26, 32].

$$B = \begin{bmatrix} 1 & b_{12} & b_{13} & b_{14} & \dots & b_{1n} \\ b_{21} & 1 & b_{23} & b_{24} & \dots & b_{2n} \\ b_{31} & b_{32} & 1 & b_{34} & \dots & b_{3n} \\ b_{41} & b_{42} & b_{43} & 1 & \dots & b_{4n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & b_{n3} & b_{n4} & \dots & 1 \end{bmatrix}$$	$B_{p\times p} = [b_{ij}] = \left[\frac{w_i}{w_j}\right] \quad i,j = 1,p$ (1) $BW = \lambda\, max\, W$ (2)

Table 2 Comparison Matrix B and Eq.1 and Eq.2

- w_i, w_j are the weight of each alternative
- λmax is the maximum eigenvalue and W is the principal eigenvector of the pair-wise matrix B

The consistency of the matrix B can be calculated by Eq. 3 and Eq. 4 and Table 3 [16].

$$CR = \frac{CI}{RCI} \tag{3}$$

$$CI = (\lambda_{max} - n)/(n - 1) \tag{4}$$

RCI, which is shown in table 3 is a random consistency index proposed by Saaty in 1994 [16]. It is an average random consistency index calculated from a sample of 500 randomly produced matrixes. CR, is the consistency ratio that should be less than 0.1.

n	1	2	3	4	5	6	7	8	9	≥10
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.56

Table 3 RCI values of sets of different order ‘n’ [16]

Many advantages about AHP method were mentioned by scholars. For instance, by using pair-wise matrices and calculating the eigenvalue and corresponding eigenvector the overall ratings will be more efficient and consistent [27]. Simplicity and its extensive application in tackling complicated decision making processes are its other advantages [16]. AHP can be used for single or multi-layer decision making processes as it uses relative values rather than actual ones [16]. Another advantage of this method is that every element in a level should not necessarily be a criterion for the elements of the next level. In other word a hierarchy is not required to be completed [31]. Each level in AHP can represent one aspect of a problem.

In this paper, in order to prioritise critical factors AHP method is used. Matrix A shows the pair-wise comparison between critical factors. In this matrix, environmental effects (Ev), collision (Col), flood (Fl), wind (W) and earthquake (Eq) were introduced as critical factors. The introduced equations for calculating each of the entries of matrix A are shown in table 4.

$$A = \begin{array}{c} \\ Ev \\ Col \\ Fl \\ W \\ Eq \end{array} \begin{array}{c} \begin{array}{ccccc} Ev & Col & Fl & W & Eq \end{array} \\ \begin{bmatrix} 1 & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & 1 & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & 1 & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & 1 & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & 1 \end{bmatrix} \end{array}$$

$A_{ii} = 1$	$A_{ij} = \dfrac{1}{A_{ji}}$
$A_{12} = 14.96\dfrac{C_{ev}}{C_{col}}C_{m1}$	$A_{13} = 3.74\dfrac{C_{ev}}{C_{fl}}C_{m2}$
$A_{14} = 748\dfrac{C_{ev}}{C_{w}}C_{m3}$	$A_{15} = 748\dfrac{C_{ev}}{C_{eq}}C_{m4}$
$A_{23} = 0.25\dfrac{C_{col}}{C_{fl}}C_{m5}$	$A_{24} = 50\dfrac{C_{col}}{C_{w}}C_{m6}$
$A_{25} = 50\dfrac{C_{col}}{C_{eq}}C_{m7}$	$A_{34} = 200\dfrac{C_{fl}}{C_{w}}C_{m8}$
$A_{35} = 200\dfrac{C_{fl}}{C_{eq}}C_{m9}$	$A_{45} = 1.0\dfrac{C_{w}}{C_{eq}}C_{m10}$

Table 4 Equations for calculating each of the entries of matrix A

The numerical values in each equation of the entries A_{ij} of the matrix A are obtained from Table 1. For instance the coefficients 14.96 used for calculating A_{12} is obtained from table 1 by dividing the criticality of environment by the criticality of collision, which will be 74.8/5, and it will be equal to 14.96.

The coefficients C_{m1} to C_{m10}, are the comparison between two factors, which will be suggested for each individual bridge by engineers. As an example of how these coefficients can be suggested by engineers, for C_{m1} which is related to environmental factor and collision, a particular structure may be vulnerable to environmental factor because for instance, its steel components lost their coating, but its columns and beams are protected from collision by constructing some additional structural components. In this specific case, the engineer shall identify C_{m1}, a value less than 1.0.

Managers may also modify these coefficients, by taking into account non-structural factors such as economic and human or social factors. In this case, rating equations introduced by Aflatooni et.al [22] can be changed to prioritisation equations. Through taking into account the coefficients C_{m1} to C_{m10} and adopting AHP method, the experts and managers' opinions can be well incorporated to decision-making process. The coefficients, C_{ev}, C_{fl}, C_{w}, C_{eq}, and C_{col}, which incorporate the risk associated with each critical factor including environment, flood, wind, earthquake and collision will be calculated as follows. The eigenvector associated with the maximum eigenvalue of the matrix A after being normalized by one will provide us the values for coefficients, β_{ev}, α_{col}, α_{fl}, α_w, and α_e.

3.1 Quantifying C_{ev}, C_{fl}, C_w, C_{eq}, and C_{col}

Coefficients, C_{ev}, C_{fl}, C_w, C_{eq}, and C_{col} represent the probability of occurrence and the severity of each event including, environmental effects, flood, wind, earthquake and collision in a region where the bridge is located. As was mentioned earlier, in order to quantify them, the available risk analyses conducted in different Australian standards and documents are used. To make the method practical for rating a network of bridges, the equations have been simplified as much as possible by applying some assumptions. However, these assumptions do not affect the reliability of the method.

3.1.2 Environment coefficient (C_{ev})

To quantify this factor, the environmental factors for different types of materials are utilized. The four environmental categories and the environment coefficient C_{ev} associated with them are shown in table 5. In order to assign a single value (C_{ev}) from Table 5 to a bridge, the average vulnerability of each component of the bridge to the environmental condition shall be taken into account. By recording the cause of defects such as corrosion, wear, temperature changes, termite attacks, etc in the database of BMS, C_{ev} can be more accurately calculated for each different environmental factors. The figures mentioned in Table 5 are similar to the ones used in some of the current BMSs in Australia.

Environmental condition of the bridge location	C_{ev}
Very high deterioration	2.0
High deterioration	1.5
Medium deterioration	1.0
Low deterioration	0.5

Table 5 Coefficient C_{ev} associated with the environmental condition of the bridge location.

3.1.3 Flood coefficient (C_{fl})

In order to consider the severity of the effect of flood on the structure based on the probability of occurrence, average return interval has been taken into account. According to AS 5100.2-2004 [25], the bridge should not collapse due to any flood with average return interval of 2000 years. If the critical design condition takes place at an average return interval of less than 2000 years a load factor should be applied based on AS 5100.2 2004 [25]. Here, this load factor is considered as the criticality of flood (C_{fl}) and it is equal to the ultimate load factors (γ_{WF}) introduced in AS

5100.2 2004 [25]. According to this standard [25], C_{fl} will be calculated by using Eq. 5.

$$C_{fl} = 2 - 0.5\log(\frac{ARI}{20}) \quad (5)$$

- ARI is the Average Return Interval for the critical design condition.

If the railway bridge is located in the place, where there would not be a possibility for flood, this coefficient can be considered zero. However, to avoid possible errors that could arise when a number is divided by zero in the creation of the matrix A, a very small number e.g. 0.0001 can be assumed instead. If not, the column and row associated with flood in that matrix need to be eliminated.

3.1.3 Wind Coefficient (C_w)

To calculate the effect of wind load on the structure factors including region, wind direction, terrain/height, shielding, and topography should be considered (AS 1170.2) [24]. However, to avoid complexity in calculating C_w, only the region factor has been considered. Other parameters mentioned above, can be taken into account when values are assigned to C_{m3}, C_{m6}, C_{m8}, and C_{m10}.

C_w can be obtained from the table below. It has been calculated considering the region, where the bridge is located and based on AS 1170.2 [24]. The average recurrence interval 2000 years for wind speed is considered [24]. For other average recurrence interval the results of the bellow ratio (e.g. Eq.6), will not significantly change.

$$C_w = \frac{V_{2000}\ of\ Region\ that\ the\ bridge\ is\ located}{V_{2000}\ of\ Region\ A} \quad (6)$$

Location of the Bridge	C_w
Region A	1
Region W	1.23
Region B	1.31
Region C	1.60
Region D	2.06

Table 6 Coefficient C_w associated with the wind load of the bridge location

- V_{2000}: Wind speed with 2000 years average recurrence interval

3.1.4 Criticality of Earthquake (C_{eq})

To avoid complexity, only the factors which are related to the parameters including, site hazard (Z) and probability factor (K_p) form AS 1170.4 2007 [23] have been taken into account. Other parameters from this standards, are related to the response of the structure and they are different for each typical bridge which was introduced by Aflatooni et.al [22] . The effects of these parameters are incorporated in the synthetic rating equations, through weighting factors associated with structural components. Eq. 7 can show the criticality of the earthquake factor for the structure based on the calculation of horizontal equivalent static shear force acting at the base of the structure as follows.

$$C_{eq} = K_p Z \tag{7}$$

Because of the long life expectation for bridges, and to simplify the rating system, K_p is considered 1.5 for the annual probability of exceedance of 1/1500. Therefore Eq. 8 can be used to calculate the criticality of earthquake.

$$C_{eq} = 1.5Z \times 10 \tag{8}$$

- Z can be obtained from AS 1170.4 2007 [23].

3.1.5 Criticality of Collision (C_{col})

In order to take into account the probability of vehicle impact on piers and superstructures of bridges, based on the volume of the road traffic the criticality of collision can be determined from the Table 7. If the incidents of vehicular impacts and the severity of damages associated with them are recorded in the process of bridge inspection, the suggested values in Table 7 can more reliably be calculated in future.

Traffic volume of road pass under the railway bridge	C_{col}
High Traffic	1.25
Medium Traffic	1.0
Low Traffic	0.75

Table 7 Coefficient C_{col} associated with the probability of the collision impacts

If the railway bridge is not over passing a road, or its components are protected from vehicular impacts, this coefficient will be considered as zero. However, to avoid errors in the creation of matrix A, due to dividing a number by zero, a very small number e.g. 0.0001 can be assumed instead. If not, the column and row associated with collision in that matrix, need to be eliminated.

4 Example:

Here for illustration, the following example is used.

- The railway bridge is located in an environment with high deterioration risk.
- The average return intervals for the critical design condition for flood is identified as 100 years.
- The wind region is B.
- The earthquake site hazard Z is equal to 0.1 and,
- The traffic volume is medium.

The coefficients, C_{ev}, C_{fl}, C_w, C_{eq}, and C_{col}, will be calculated as follows.

- From Table 5, C_{ev} can be obtained and it is equal to 1.5.
- C_{fl} can be calculated from Eq. 5 and it is equal to 1.65.
- The bridge is located in region B, therefore, C_w is obtained from Table 6, and it is equal to 1.31.
- From Eq. 8, C_{eq} can be identified and it is equal to 1.5.
- From Table 7, C_{col} can be determined which is equal to 1.0.

It is also assumed that no special consideration is required to be taken into account by engineers and managers, and therefore all C_{m1} to C_{m10} will be equal to 1.0. After calculating all the entries of the pair-wise matrix A from table 4, the matrix A will be determined as follows.

$$A = \begin{bmatrix} 1 & 22.44 & 3.4 & 856.4885 & 748 \\ 0.044563 & 1 & 0.151515 & 38.16794 & 33.33333 \\ 0.294118 & 6.6 & 1 & 251.9084 & 220 \\ 0.001168 & 0.0262 & 0.00397 & 1 & 0.873333 \\ 0.001337 & 0.03 & 0.004545 & 1.145038 & 1 \end{bmatrix}$$

The maximum eigenvalue (λ_{max}) will be calculated as 5.0001 and the consistency of the matrix A can be investigated through Eq. 3 and Eq.4, and it is equal to 0.00002<0.1. The eigenvector associated with the maximum eigenvalue 5.0001, is calculated as follows.

$$Eigen\,Vector\,(A) = \begin{bmatrix} 0.9585 \\ 0.0427 \\ 0.2819 \\ 0.0011 \\ 0.0013 \end{bmatrix}$$

After normalizing the above matrix by one, the criticality of factors will be identified as follows.

$$\begin{bmatrix} \beta_{ev} \\ \alpha_{col} \\ \alpha_{fl} \\ \alpha_{w} \\ \alpha_{e} \end{bmatrix} = \begin{bmatrix} 0.7456 \\ 0.0332 \\ 0.2192 \\ 0.0008 \\ 0.0010 \end{bmatrix}$$

The above matrix shows that, the contribution in degrading this railway bridge over time, due to the environmental effects and fatigue is 75%, collision 3%, flood 22%, wind 0.08%, and earthquake is 0.1%. From the above calculations, it can be observed that by answering only five simple questions, the criticality of each factor can be identified. The reason for simplifying the method is, to assure that the method will be practical to be used for rating a network of thousands of railway bridges.

5 Conclusion

Rating bridges are conducted to determine the railway bridges, which are in most need for maintenance, and rehabilitation. Through reliably rating bridges, the resources will be efficiently invested to enhance the structural condition of the bridges. In order to rate bridges, the structural condition of the bridge is required to be assessed and the criticalities of the factors towards degrading the structure need to be quantified. In this paper the method for quantifying the criticality of the factors are developed.

In previous publications of the authors of this paper, flood, collision, earthquake, wind, and environmental effects were identified as the critical factors. Each of these factors degrades the structure in different ways. Based on the environmental condition and location of the bridge, the risk of their occurrence and severity of them will be different. These risk analyses will need massive effort and time. Therefore, in the method introduced here, for quantifying the contribution of each critical factor towards the deterioration of the railway bridge, the available knowledge from existing risk analyses that are used for designing bridges in Australia is adopted. In addition, in the absence of sufficient data in current databases about the causes of damages related to each critical factor and the cost associated them, expert opinions are used as a commencing point for quantifying the criticality of the factors. The criticality of each factor is determined based on the risk and severity of its occurrence in different regions and the environmental condition in Australia, by using local standards. For other countries, the local standards can be used for this purpose. The overall priorities of the critical factors are calculated based on AHP method.

According to this research, it is identified that in the inspection process, the causes of damage associated with each critical factor is required to be recorded. Therefore, over time, the cost associated with each critical factor can be identified. Based on this more accurate values than those shown in table 1 for the criticality of each factor can be estimated in future. It is recommended, to conduct experimental and analytical investigations on the phenomenon of fatigue and its effects on current railway bridges. As a result of these investigations, the effect of fatigue can separately be taken into account. Similarly, through inspections, damage caused by each of environmental factor such as wear, corrosion, termite attack, and others can be recorded in the database. Therefore, the criticality of different environmental factors can be separately determined, and their contribution can more be reliably quantified in future. The method is simple and as a result, it is practical to be applied to a network of thousands of bridges.

Through quantifying the critical factors, the following significant outcomes will be achieved.

- The future condition of the bridge will be more reliably predicted in respect to the current rating methods used for the network of bridges.
- The risk associated with each critical factor, can be mitigated, through improving the condition of the components of the bridge, which are vulnerable to the identified specific critical factor.

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