Conversion of legacy inspection data to Bridge Condition Index (BCI) to establish baseline deterioration condition history for predictive maintenance models.

Nicola-Ann Stevens[1], Myra Lydon[1], Kristopher Campbell[2], Thomas Neeson[2], A.H. Marshall[3], S.E. Taylor[1]
[1]School of Natural and Built Environment, Queens University Belfast.
[2] Northern Ireland Department for Infrastructure (DfI).
[3]School of Mathematics and Physics, Queens University Belfast.

email: nstevens01@qub.ac.uk, m.lydon@qub.ac.uk, kristopher.campbell@infrastructure-ni.gov.uk, thomas.neeson@infrastructure-ni.gov.uk, a.h.marshall@qub.ac.uk, s.e.taylor@qub.ac.uk

ABSTRACT:
Bridge Management Systems (BMS) have been introduced across the world with the goal of aiding the decisions regarding maintenance, rehabilitation and replacement (MR&R) of bridges. Deterioration modelling is the most important part of the BMS because the ability to predict the future condition is vital as it will determine the quality of the decisions made. Markovian-based models are the most common predictive maintenance tool utilised in existing BMS, by obtaining probabilities of transition of bridge condition from one state to another based on historic bridge inspection data. Prior to the introduction of the Bridge Condition Index (BCI) the use of the numerical, 1-4 or similar, condition scoring led to inaccuracy in deterioration models because the condition ratings are only subdivided into 4 categories with wide range and uncertainty on the exact boundary of each category. The BCI has been introduced to facilitate a uniform national assessment method which is less subjective. Ultimately BCI will facilitate significant improvement in the predictions of future bridge deterioration. However, in the short term the lack of consistency between the methods means condition deterioration is no longer directly comparable over long periods of time leading to uncertainty in the true condition of many bridges across strategic road networks. This paper details the conversion of approximately 17 years of "Legacy" inspection records to BCI values for 6978 bridges across the Northern Ireland (NI) road network.

KEY WORDS: Bridge Managements Systems (BMS), Deterioration Modelling, Bridge Condition Index.

1 INTRODUCTION

1.1 BRIDGE INSPECTION AND ASSESSMENT METHODS

The most common method of bridge inspection is a visual inspection, generally recorded every two years that provides an overall rating score on the condition of the bridge. Originally visual inspections were paper-based forms which contained information on the inspector's opinion of the physical condition of each of the bridge elements [1]. The bridge was then assigned a condition score, commonly a numerical value ranging between 1 and 4 where 1 indicates the structure has minimal defects and 4 indicating that action is required within one year. Best practice was for each bridge to have its own paper-based file which was held in a repository and formed the basis of planning the maintenance, repair and rehabilitation (MR&R) routines for budgetary periods. As bridges across all road networks became the subject of increased traffic, rapidly changing environment conditions and liberal de-icing programs, the complexity of managing aging and deteriorating structures surpassed the capabilities of this paper-based approach. In the UK, the need for a constant and rational approach to future investment in bridge maintenance led to the advent of bridge management systems (BMS) in the late 90's [2]. Throughout the following years BMS evolved to contain 4 modular elements as shown in Figure 1. The inventory is considered the fundamental baseline BMS which should be implemented across all road networks. Many systems are limited to only this module [3].

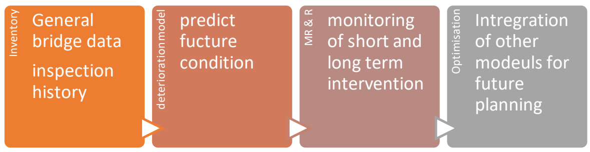

Figure 1: Traditional modular BMS structure.

The data from the inventory module informs the deterioration model that predicts the future condition. The method currently used in popular bridge management systems such as PONTIS and BRIDGIT is a Markovian-based method [4]. This method is used by defining states from condition rating data and obtaining probabilities of transition from one state to another. These probabilities are used in a transition matrix from which predictions of the future condition of the bridge are made [5]. The use of the numerical, 1-4 or similar, condition scoring leads to inaccuracy in deterioration models because the condition ratings are only subdivided into 4 categories with wide range and uncertainty on the exact boundary of each category. Likewise, each inspection was somewhat subjective and within each condition rating there was no clear way of ranking the bridges in terms of priority for the allocation of funds preventing long term strategic MR&R planning.
The introduction of the Bridge Condition Index (BCI) is aimed at addressing this issue facilitating a uniform national assessment rating for all bridges. This scale from 0 to 100 will allow for the use of models requiring a continuous scale or can be broken up to into discrete categories with clearer boundaries compared to the previous system [4]. During the last decade

advanced BMS began to gradually migrate inspections from the previous format to the BCI method. Ultimately the BCI will facilitate significant improvement in the predictions of future bridge deterioration. However, in the short term the lack of consistency between the methods means condition deterioration is no longer directly comparable over long periods of time and leads to uncertainty in the true condition of many bridges across strategic road networks. This paper details the conversion of approximately 17 years of "Legacy" inspection records to BCI values for 6978 bridges across the Northern Ireland (NI) road network. Section 2 details the adoption of the BCI into bridge inspections within the Department for Infrastructure (DfI) for Northern Ireland. This leads onto a discussion of the data processing required to enable the conversion to BCI in Section 3. The method detailed in Section 4 was adopted to convert extent/severity condition ratings for individual elements into a BCI rating with Section 5 showing the results for this procedure and Section 6, the conclusions.

2 APODTION BCI IN NORTHERN IRELAND ROAD NETWORK

The first BCI inspection to be carried out in NI was in 2015 however it took several years for the majority of bridges to be inspected this way. Initially this was time consuming on the part of the inspector as every element present in the structure needed to be logged before any defects could be entered or scores assigned. However, this process does not need to be repeated for subsequent inspections as only the defects would need to be amended if necessary. This leads to a much more efficient inspection process.

Under a BCI inspection the condition of the bridge elements are recorded in terms of the extent and severity. The extent describes the area, length or number (as appropriate) of the bridge element affected by the defect/damage. See Table 1.

Table 1: Extent Codes with description [6]

Extent Code	Description
A	No significant defect
B	Slight, not more than 5% of surface area/ length/number
C	Moderate, 5%-20% of surface area/ length/ number
D	Wide, 20%-50% of surface area/length/ number
E	Extensive, more than 50% of surface area/ length/number

The severity shows the degree to which the defect/damage affects the function of the element or other elements on the bridge. See Table 2.

Table 2: Severity Codes with description [7]

Severity Code	Description
1	As new condition or defect has no significant effect on the element (visually or functionally)
2	Early signs of deterioration, minor defect/ damage, no reduction in functionality of element.
3	Moderate defect/damage, some loss of functionality could be expected
4	Severe defect/damage, significant loss of functionality and/or element is close to failure/collapse
5	The element is non- functional/failed

Table 3 shows the permissible combinations of extent and severity. It is worth noting that if the extent is given code A then it cannot be given a severity rating of 2-5. This is because an element with no significant damage (extent code A) cannot be set a severity value which represents damage.

Table 3: Permissible combinations of Severity and Extent

	SEVERITY				
EXTENT	1	2	3	4	5
A	1A				
B	1B	2B	3B	4B	5B
C	1C	2C	3C	4C	5C
D	1D	2D	3D	4D	5D
E	1E	2E	3E	4E	5E

3 DATA PREPARATION AND PROCESSING

Before performing any calculations or analysis it is crucial to inspect the data. This section will detail the extensive data preparation process that was followed including identifying nulls and missing values and how anomalies were handled.

3.1 Identifying NULLs or Missing Values

Firstly, it is important to identify any nulls or missing value in the important variables such as component, defect, extent and severity values. Table 4 shows the number of missing or null values that were found.

Table 4: Number of missing and null values for the most important variables

Variable	**Number of missing/null values**
Component	111
Defect	0
Extent	523
Severity	1261

The numbers shown in Table 4 represent a small proportion of the data but removing them would lead to inaccurate final results. For each of the variables shown here a process was carried out to determine the best method of replacing the null/missing value with the most appropriate value. In order to carry out this task, the help of an engineer familiar with the inspection procedure was crucial. In this case the data was manually cleansed and updated in collaboration with the structures management team within DfI. For each component the appropriate inspection records needed to be exported so the nulls could be analysed. From the component missing values, the process involved looking at the previous inspection records including any inspector's notes and the defect for that particular observation. Then a suitable value was assigned to the component.

A similar process was carried to obtain the missing extent and severity values. Each missing value involved finding any records for that particular component and defect, sorting into date order and in most cases the inspection either side of the missing value revealed the value that should have been entered.

For example, in Figure 2, here is a missing severity value. From the data it is clear to see that from the inspection before and after the missing value, the missing severity value can be replaced with a 2.

GeneralBridgeId	Inspect_Year	Component	Defect		Extent	Severity
11370	2005	ABUTMENT	LEACHING / SOLU SALTS	(%)	10	2
11370	2007	ABUTMENT	LEACHING / SOLU SALTS	(%)	10	2
11370	2009	ABUTMENT	LEACHING / SOLU SALTS	(%)	10	NA
11370	2011	ABUTMENT	LEACHING / SOLU SALTS	(%)	10	2
11370	2013	ABUTMENT	LEACHING / SOLU SALTS	(%)	10	2
11370	2015	ABUTMENT	LEACHING / SOLU SALTS	(%)	10	2
11370	2016	ABUTMENT	LEACHING / SOLU SALTS	(%)	5	2

Figure 2: A snapshot of the inspection data showing how a missing severity value is determined.

3.2 *Identifying anomalies*

From Table 1, we can see that the expected range of values for the extent variable is between 0 and 100, however there are a number of occurrences in the data where negative numbers or numbers larger than 100 have appeared. These are assumed to be mistakes and needed to be rectified. For example, in Figure 3 we can see the extent value is set to 1110. However, this value is incorrect as the defect is given in a percentage therefore further investigation is needed to assign the correct value.

GeneralBridgeId	Inspect_Year	Component	Defect		Extent	Severity
11370	2003	DECK SOFFIT	POINTING MISSING	(%)	1110	2

Figure 3: A snapshot of the dataset showing an example of an anomaly in the extent value.

In order the correct this error we need to look at the available inspection data for this bridge. Figure 4 shows the relevant data and it becomes clear that the value of 1110 should be 10.

GeneralBridgeId	Inspect_Year	Component	Defect		Extent	Severity
11370	2001	DECK SOFFIT	POINTING MISSING	(%)	5	2
11370	2003	DECK SOFFIT	POINTING MISSING	(%)	1110	2
11370	2003	DECK SOFFIT	POINTING MISSING	(%)	20	2
11370	2005	DECK SOFFIT	POINTING MISSING	(%)	10	2
11370	2007	DECK SOFFIT	POINTING MISSING	(%)	5	2
11370	2009	DECK SOFFIT	POINTING MISSING	(%)	5	2
11370	2011	DECK SOFFIT	POINTING MISSING	(%)	5	2
11370	2013	DECK SOFFIT	POINTING MISSING	(%)	5	2
11370	2015	DECK SOFFIT	POINTING MISSING	(%)	5	2
11370	2016	DECK SOFFIT	POINTING MISSING	(%)	5	2

Figure 4: A snapshot of the dataset showing how an incorrect input in the extent value can be rectified.

This process was carried out for each of the missing variables across all bridges with an audited standardised approach and documented justification for each of the values inputted. The values and justifications were established by a senior bridge engineer with extensive experience in both the undertaking and documentation of legacy inspections across the network.

4 BCI CALCULATION

This sections will show the two BCI values are calculated, these two values are BCI Average (BCI_{Av})and BCI Critical (BCI_{Crit}). The method for calculating these values is provided in [6], [7] and this section will outline the key points of how the extent and severity ratings for each of the components can be used to calculate both BCI_{Av} and BCI_{Crit}. BCI Average takes into account the condition of all structural elements of the bridge, on the other hand BCI Critical only takes the condition of those elements deemed to be of very high importance to the bridge.

Equation 1 and 2 show how BCI_{Av} and BCI_{Crit} are calculated respectively.

$$BCI_{Av} = 100 - 2[(BCS_{Av})^2 + (6.5 \times BCS_{Av}) - 7.5] \quad (1)$$

$$BCI_{Crit} = 100 - 2[(BCS_{Crit})^2 + (6.5 \times BCS_{Crit}) - 7.5] \quad (2)$$

4.1 *Calculating BCI_{Av}*

In equation 1, BCS_{Av} represents the average Bridge Condition Score for a bridge taking into account the condition of all structural elements of the bridge. This value is calculated using equation 3 below.

$$BCS_{Av} = \frac{\sum_{i=1}^{N}(ECI_i \times EIF_i)}{\sum_{i=1}^{N} EIF_i} \quad (3)$$

where ECI_i is the Element Condition Index, EIF_i is the Element Importance Factor and N is the total number of bridge elements used in the BCS calculations.
The ECI_i from equation 3 indicates the contribution the condition of an element makes to the condition of the bridge as a whole. This value is determined by using equation 4 below.

$$ECI = ECS - ECF \quad \text{but is always} \geq 1 \quad (4)$$

In equation 4, the ECS is the Element Condition Score and its is determined by using the extent and severity rating from the inspection data for each element and comparing them to Table 5 to obtain a score. This score is on a scale from 1 to 5 which represent the best condition and worst condition respectively.

Table 5: ECS values based on extent and severity[6]

		SEVERITY				
		1	2	3	4	5
EXTENT	A	1	x	x	x	x
	B	1	2	3	4	5
	C	1.1	2.1	3.1	4.1	5
	D	1.3	2.3	3.3	4.3	5
	E	1.7	2.7	3.7	4.7	5

In order to obtain the ECF value in equation 4, the element importance is required. This takes account of the importance of an element to the overall bridge in terms of load carrying capacity, durability and public safety. The importance of each element can be determined from the element importance classification shown in Table 6. Each element is designated as Low, Medium, High or Very High. Once the importance is determined, the ECF value can be obtained from Table 7.

Table 6: The importance classification for each element[7]

Element	Importance
Abutment	High
Abutment Slope	Low
Apron Left	Medium
Apron Right	Medium
Arch Ring Left	Very High
Arch Ring Right	Very High
Bearings	High
Cutwater Left	Medium
Cutwater Right	Medium
Deck Soffit	Very High
Invert	Medium
Movement Joint	High
Parapet Left	High
Parapet Right	High
Parapet Upstand Left	Very High
Parapet Upstand Right	Very High
Pier Face/Column	Very High
Spand/Headwall Left	High
Spand/Headwall Right	High
Surface	Low
Wingwall Left	High
Wingwall Right	High

Table 7: A table showing how element importance and the ECS can be used to calculate the ECF value.

Element Importance	ECF
Very High	0
High	$0.3-\left[(ECS-1)\times\frac{0.3}{4}\right]$
Medium	$0.6-\left[(ECS-1)\times\frac{0.6}{4}\right]$
Low	$1.2-\left[(ECS-1)\times\frac{1.2}{4}\right]$

The remaining part of equation 3 is the EIF. This value is also calculated based on the element importance. Table 8 below shows how this importance classification is used to obtain the EIF score. This value is used to weight individual ECI scores when evaluating the BCS_{Av}.

Table 8: EIF values based on element importance.[7]

Element Importance	EIF
Very High	2
High	1.5
Medium	1.2
Low	1

Once the ECI and EIF values have been obtained, they are used in equation 3 in order to calculate the BCS_{Av}. The final step in calculating the BCI_{Av} is using the BCS_{Av} value in equation 1.

4.2 Calculating BCI_{Crit}

Now the BCI_{Crit} can be calculated. In equation 2, BCS_{Crit} represents the critical Bridge Condition Score which takes into account the condition of those elements deemed to be of very high importance and it is calculated using the equation 5 below.

$$BCS_{Crit} = \max\begin{cases} ECI\ for\ primary\ deck\ elements \\ ECI\ for\ secondary\ deck\ elements \\ ECI\ for\ half\ joints \\ ECI\ for\ tie\ beam/rod \\ \text{ECI for parapet beam or cantilever} \\ \text{ECI for pier/column} \\ \text{ECI for cross} - \text{head/capping beam} \end{cases} \quad (5)$$

Once the BCS_{Crit} has been obtained it can be used in equation 2 to get the BCI_{Crit} for that inspection.

5 RESULTS

This section will show the results of applying this procedure to the legacy inspection dataset. The results obtained are compared to data from the inspections that have already adopted the BCI method. The trends are analysed and discussed in this section. In addition to this, one of the main objectives for the conversion of the legacy inspections was to define clear limits for the condition ratings. Section 5.1 details how these have previously been defined in the available literature for a 5-state condition rating system and details how they can be used to aid this process of determining these boundaries for the 4-state condition rating system used by DfI.

In total there are approximately 44000 inspection records across the entire bridge stock from 2000-2017. However as described in Section 4.2, in order to calculate BCI Critical the inspection must contain at least one element of very high importance (see Table 6). Among the legacy inspection records there are over 14000 inspections that do not have a record for an element with very high importance. This means that a BCI Critical cannot be calculated. Therefore, the remainder of this study will focus on the 30000 inspections which contain the relevant information to calculate both the BCI Average and the BCI Critical.

Figure 5 shows the elements that have been recorded with a defect over the inspection period broken down by the ECS score. From section 4.1, the Element Condition Score represents the combined effect of the extent and severity of each element. From Figure 5, it is evident that those elements with either high or very high importance (see Table 6) such as the abutment are those that have the majority of the higher ECS values i.e. greater than 4. This justifies these components having higher importance as their values will impact the BCI score the most.

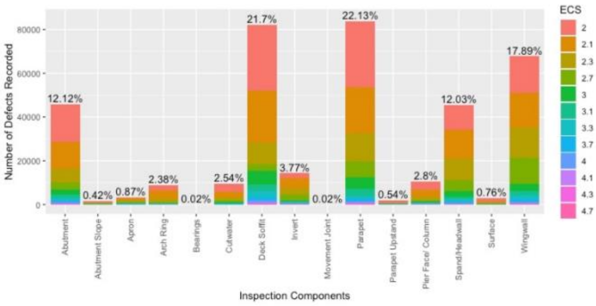

Figure 5: Elements inspected which are subdivided by Element Condition Score (ECS).

The BCI Average and Critical were obtained after the data processing (described in Section 3) and the calculations (shown in Section 4) were completed. The BCI Average ratings obtained show similar trends to the newer inspections which have already adopted this method. Figure 6 shows the BCI Average for the inspections carried out from 2017 to early 2020. This shows a left-skewed graph with a peak between 85 and 95.

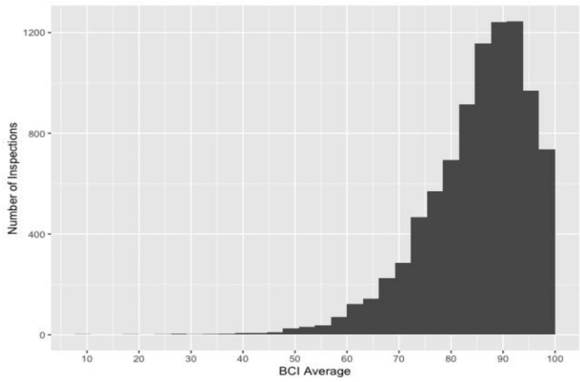

Figure 6: Graph showing distribution of BCI Average for the new inspections which use the BCI inspection process.

From Figure 7, it is evident that the calculated BCI average score from the legacy inspection data follows the same trend with a slightly lower peak at around 80.

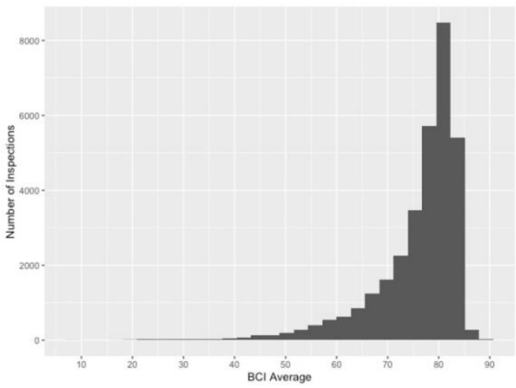

Figure 7: A graph showing the distribution of the BCI Average for the legacy inspections.

5.1 *Defining boundaries for condition ratings*

As previously mentioned, one of the main motivations for converting to BCI was to have clearly defined boundaries for condition ratings. This can be achieved by using suggested groupings from the literature. Guidelines for the condition rating boundaries where provided by Bennetts et al. [8]; in addition, Fang and Sun [9] provided boundaries that were used in the Shanghai BMS see Table 9.

Table 9: Guidelines for condition rating boundaries

Bennetts et al. [8]		**Feng and Sun** [9]	
Rating	BCI_{Av} **Score**	**Rating**	BCI_{Av} **Score**
Very Good	[90,100]	A	[90,100]
Good	[80,90)	B	[80,90)
Fair	[65,80)	C	[66,80)
Poor	[40,65)	D	[50,66)
Very Poor	[0,40)	E	[0,50)

Table 9 presents two cases of a 5-state rating system therefore they can be used as a guideline when determining the boundaries for the 4-state rating system desired here. Before the conversion to BCI was undertaken in this research program, each of these inspections were assigned an overall priority/overall condition rating, the distribution of these condition ratings is shown in Figure 8. This can also be used as a guide when calculating the boundaries.

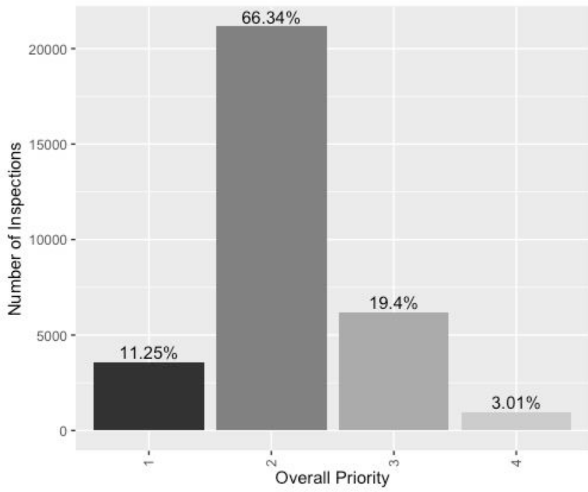

Figure 8: Graph showing the distribution of overall priority/condition ratings

In order to obtain the BCI categories to fit the distribution shown in Figure 8, the spilt outlined in Table 10 needs to be adopted. This table also shows the percentage of the total number of inspections that are in each condition rating. These numbers can be directly compared to those in Figure 8.

Table 10: Using BCI divisions required to obtain a 4-state condition rating.

Rating	BCI_{Av} $Score$	Percentage of Inspections
1	[83,100]	12.26%
2	[73,83)	63.46%
3	[53,73)	21.54%
4	[0,53)	2.74%

The conversion to BCI for the legacy inspections can now be combined with the inspections that have already adopted the BCI assessment procedure. Figure 9 shows the distribution of the BCI average over the 20 year period.

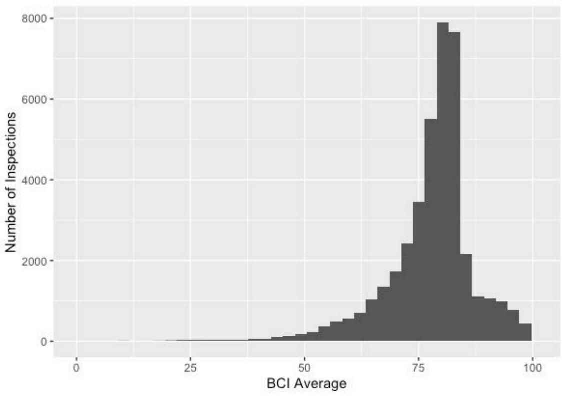

Figure 9: Graph showing distribution of BCI Average for all inspections.

Furthermore, Table 10 can be used to convert these BCI average ratings into a 4-state condition ratings system. The results of this conversion are shown in Figure 10.

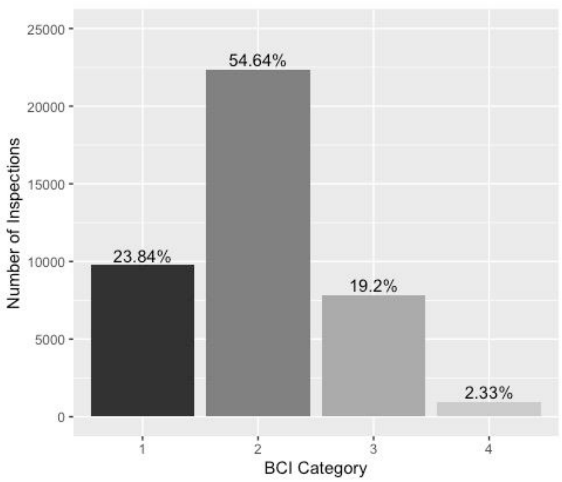

Figure 10: Graph showing BCI categories for all inspections.

6 CONCLUSIONS AND FURTHER WORK

The bridge inspection data used within this study required in-depth visual inspections which require disruption to the network and significant resource costs. Therefore, to maximize the value of this data is it important to establish clear and unambiguous methods to collect, store and manage this information. The richness of data obtained from visual bridge inspections has evolved during the past number of decades and will enable better decision making in the future management of bridges. Given that the value of this data increases significantly with the length of historic data available any changes in the data collection methods can have detrimental consequences on short and medium-term management of bridges within road networks. In many cases this has been a delaying factor for the implementation of BCI inspection methods by bridge-owning organizations. This paper describes an audited standardised approach to the conversion of legacy inspection records to BCI ratings and detailed a range of issues identified in structuring the historic data. This will ensure that the data collected from almost 20 years visual inspections of bridges in the Northern Ireland road network is now compatible with current inspection data to enable the development of a predictive maintenance model. Future work using this data will be to determine factors that affect the deterioration of the bridges. The factors that will be investigated will include the construction type and function of the bridge. It has been noted in the literature the more reliable data that is available when building a predictive model, the more accurate results [4] therefore this investigation was crucial to allow for the model building which will follow.

ACKNOWLEDGMENTS

The authors would like to thank the Department for Infrastructure (DfI) for the access to the complete bridge management records, the technical support, and allowing the analysis and findings to be used in this paper. The financial support of the Royal Academy of Engineering under the research fellowship program is also gratefully acknowledged.

REFERENCES

[1] R. Alvarado, B. ten Siethoff, and R. Perrin, “A8 Asset Management PERFORMANCE-BASED TOOLS TO ENHANCE INVESTMENT DECISION MAKING: ASSESSING A REGIONAL BRIDGE NETWORK AND THE LONG-TERM CONSEQUENCES OF UNDERINVESTMENT PERFORMANCE-BASED TOOLS TO ENHANCE INVESTMENT DECISION MAKING: ASSESSING A REGIONAL BR,” 2016.

[2] K. D. Flaig and R. J. Lark, “The development of UK bridge management systems,” *Proc. Inst. Civ. Eng. Transp.*, vol. 141, no. 2, pp. 99–106, 2000.

[3] C. Pellegrino, A. Pipinato, and C. Modena, “A simplified management procedure for bridge network maintenance,” *Struct. Infrastruct. Eng.*, vol. 7, no. 5, pp. 341–351, May 2011.

[4] G. Bu, P. Candidate, J. Lee, H. Guan, and M. Blumenstein, “Improving Reliability of Markovian-based Bridge Deterioration Model Using Artificial Neural Network.”

[5] Y. I. Jiang, M. Saito, and K. C. Sinha, “Bridge Performance Prediction Model Using the Markov Chain.”

[6] G. Sterritt, S. Harris, and N. Shetty, “Bridge Condition Indicators Volume 2 - Bridge Inspeection Reporting,” vol. 2, no. 4, 2002.

[7] N. Shetty, G. Sterritt, and M. Chubb, “Bridge Condition Indicators Volume 3- Evaluation of Bridge Condition Indicators,” vol. 3, no. 4, 2002.

[8] J. Bennetts, G. T. Webb, P. J. Vardanega, S. R. Denton, and N. Loudon, “Using data to explore trends in bridge performance,” *Proc. Inst. Civ. Eng. - Smart Infrastruct. Constr.*, vol. 171, no. 1, pp. 14–28, 2018.

[9] Y. Fang and L. Sun, “Developing A semi-markov process model for bridge deterioration prediction in Shanghai,” *Sustain.*, vol. 11, no. 19, 2019.