TITLE: ALGORITHMS FOR A NEW GENERATION OF BRIDGE MANAGEMENT SYSTEMS

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ABSTRACT

Bridge Management Systems (BMS) have been developing over recent years. Early BMS (level 1 system) consisted of little more than a bridge inventory. Further development led to level 2 BMS, which in addition to an inventory recorded information about bridge events such as inspections and maintenance work. The next stage is a level 3 BMS, which can predict the future condition of the Bridge Stock. This paper describes the method for predicting the future condition of a bridge developed at TRL.

ALGORITHMS FOR A NEW GENERATION OF BRIDGE MANAGEMENT SYSTEMS

P R VASSIE AND N ANDERSON

1. INTRODUCTION

The term Bridge Management System (BMS) refers to computer software that aids the management of bridges in service; previously paper based systems were employed. There are broadly two types of management to be considered. Project Level management, which is concerned with individual bridges considered independently from all other bridges and Network Level Management, which is concerned with sets of bridges that can range from the universal set comprising the entire bridge stock of an owner to a sub-set, defined by a restriction such as a specific material of construction e.g. all steel bridges. The management of bridges incorporates a variety of events to which bridges are subjected during their lives as listed below:

- Inspections (superficial, general, principle, special, paint and underwater)
- Maintenance (routine, preventative, repairs, component replacement)
- Abnormal loads
- Load assessments
- Strengthening
- Improvements (widening, stronger parapets, sub-structure protection)
- Replacement with a new bridge.

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2. A BRIEF HISTORY OF BRIDGE MANAGEMENT SYSTEMS

Improvements that were made to the way computers handle large data sets about 15 years ago, notably the ability of personal computers to use databases, enabled industry to develop systems for managing assets in general and those pertaining to infrastructure in particular e.g. pavements, bridges, retaining walls, tunnels, earthworks, street furniture, railway track and waterways. Prior to the development of BMS, management events were recorded on paper files that existed for each asset. These files also contained an inventory, design and construction details, calculations, drawings, photographs, correspondence and statutory licenses. The use of these paper files was satisfactory for project level management but not for network level management. For example a paper file system can answer project level queries such as the type and date of application of a waterproofing system to a specific bridge deck by simply examining one file whereas it could only answer a network level question such as what proportion of the bridge stock have a particular type of sprayed membrane waterproof system by examining the files for every bridge which would clearly be infeasible. Paper files compare poorly with computer files in terms of space consumption, ease of data retrieval and security. There are many examples of paper files becoming lost or mislaid especially when the managerial responsibility for a bridge changed from one organisation to another. Computer files, although in theory more secure than paper files (backups are held), are not immune from these problems because it is not always possible to read them using the new organisations equipment and proper hand over procedures are sometimes not followed. The more frequent transfer of responsibility that has occurred in the UK during the last decade accentuates this problem.

2.1. Level 1 BMS system

The first BMS (level 1 system) consisted of little more than a bridge inventory which generally contain information such as:

- Identification (name, unique number and location)
- Ownership and responsibility
- Location of drawings, calculations, photographs and correspondence
- Load carrying capacity
- Form and materials of construction
- List of elements and components
- Dimensions
- Route and obstacle traversed.

Most inventory information is unlikely to change during the lifetime of a bridge hence once compiled and entered it will enable a wide variety of project and network level queries to be answered in the future. These systems employed the query/report capabilities of databases to synthesise project and network level asset management. For example a project level query could be 'is bridge number 384 of composite construction'?, whereas an equivalent network level query could be 'what proportion of the bridge stock is of composite construction'? The synthesis will provide both the proportion and list all the bridges in the stock with composite construction.

2.2. Level 2 BMS system

Further development led to level 2 BMS, which in addition to an inventory recorded information about bridge events such as inspections and maintenance work. This enabled inspections to be scheduled and provided vital information about the performance and life of components and repair systems and generally about the rate of deterioration of particular bridges and the bridge stock. At this stage of their development BMSs contained a similar quantity of data to the old paper systems and this was considered sufficient for most purposes. The query and report facilities of the computer database enabled an almost unlimited number of questions of varying complexity to be quickly answered examples of which are as follows:

- List all the composite bridges that have not been painted since 1990
- List all bridges with overdue principle inspections
- List all bridges with traffic restrictions
- List all composite bridge deck currently classified as being in poor condition

Level-2 bridge management systems have, typically about 200 – 300 data fields. The comprehensive nature of these databases makes it possible for an engineer with knowledge of the database content and the query/report procedure to answer almost any question about a specific bridge, element or component or about any defined group of bridges, elements or components.

2.3. Level 3 BMS system

The latest development of BMSs (level-3) which are the subject of this paper involve the use of algorithms to process stored data to:

- Find the rate of deterioration of bridge elements and components
- Predict the future condition of bridge elements and components
- Estimate the rate of deterioration and future condition of the bridge stock
- Predict future maintenance requirements for particular bridges and the stock
- Predict future load carrying capacity
- Plan maintenance work on a route to minimise traffic disruption.

Adding the following types of data enhances level-3 databases:

- Costs of components, inspections, assessments, maintenance treatments
- Expected life of components and maintenance treatments
- Traffic data such as vehicle flow rate, % heavy goods vehicles (HGV)
- Extent and duration of traffic restrictions required for different types of maintenance work on each bridge element and component.

Initially these data are obtained by facilitated discussions of appropriate expert engineers and hence can only be regarded as estimates. After a few years of collecting this data from maintenance jobs on bridges it will be possible to progressively replace the experts estimated values with real values. The data should be sufficient to express the real values as means and variances or as probability distributions in the algorithms so that data variability can be taken into account.

The inclusion of this cost, life and traffic information makes it possible to devise algorithms to:

- Appraise the economics of various bridge components, forms and materials of construction, and maintenance treatments thereby providing information that can be fed back into the design process
- Calculate the whole life cost of various what if scenarios and strategies thereby informing the decision making process
- Estimate the cost of traffic delays that would be associated with various bridge maintenance options
- Plan and budget for future maintenance needs
- To prioritise maintenance work to satisfy user imposed constraints
- Establish an optimal maintenance programme that minimises lifetime costs.

This paper describes some of the algorithms that have been developed for TRL’s level-3 Bridge Management System.

3. BRIDGE CONDITION

In order to calculate the rate of deterioration of a bridge or one of its components or elements it is necessary to have a record of how its condition has changed during its life to date.

Bridges are usually designed and constructed to achieve a life of about 100 years hence it is important to monitor their condition periodically throughout their life in order to ensure that:

- they remain fit for purpose
- the level of deterioration is consistent with achieving the design life
- there are no obvious defects that affect the safety of the public.

These checks are the purpose of bridge inspection. The term condition is quite general and means different things to different people. In order to use condition to monitor the deterioration of a bridge throughout its life it is necessary to make the definition more restrictive and precise and in particular it should be quantified. A simple approach for quantifying condition is to assess the condition on an arbitrary scale ranging, for example, from 1 (good condition) to 5 (very poor condition) on the basis of visual observations and simple tests carried out during inspections.

The main disadvantages of this approach are:

- the subjectivity of the assessment can make the results vulnerable to bias
- visual observations cannot detect latent defects or the early stages of deterioration.

The first disadvantage can be largely overcome by developing a set of definitions for each condition state that are clearly discrete in the sense that there are distinct differences between the definitions for adjacent condition states. Discreteness limits the number of states that can be used to about five in most cases.

The main advantage of the visual observation approach to assessing the condition of a bridge is operational. It can be carried out as part of a bridge inspection without the requirement for additional access and traffic management and hence with little additional cost or disruption to traffic. The other main advantages are its simplicity and links with maintenance strategies.

3.1. Trial Data

Bridge inspections have been carried out regularly on the Highway Agency bridge stock for the last 30 years, every two years for general inspections and every six years for principal inspections. At each inspection the condition of every element of a bridge is assessed in terms of the extent and severity of defects by the inspector allocating positions on two 4 point scales. Some combinations of extent (A,B,C,D) and severity (1,2,3,4) were forbidden leaving the following permissible states A1, B2, B3, B4, C2, C3, C4, D2, D3, D4. These assessments of condition were made almost entirely on the basis of visual observation although they were supplemented by cover depth, chloride content, carbonation and half cell potential measurements for principal inspections during the last decade. The assessment of the condition by inspectors is likely to have been more reliable for principal inspections than for general inspections because much closer visual examination was possible. For some elements with restricted lines of site an assessment of condition is not possible at general inspections. This procedure for assessing condition has a number of shortcomings such as:

- the definitions of A, B,C, D and 1,2,3,4 for extent and severity are subjective
- inspectors are not properly trained in how to assess condition resulting in considerable variability between the assessment of different inspectors
- there are too many states to be able to ensure discreteness
- the same definitions are used for all materials of construction and forms of deterioration.

These factors result in considerable uncertainty about the reliability of condition state assessment. Better definitions have been developed by limitation to a particular material of construction and form of deterioration, use of simple non-destructive tests, a smaller number of states and an effort to be more objective. For example we have adopted the condition state definitions shown in Table 1 for concrete bridges thought to be vulnerable to deterioration caused by reinforcement corrosion.

Condition State	**Extent / Severity**									
	A1	**B2**	**B3**	**B4**	**C2**	**C3**	**C4**	**D2**	**D3**	**D4**
1	✓									
2		✓			✓					
3			✓					✓		
4				✓		✓			✓	
5							✓			✓

Table 1: Conversion of Extent, Severity to Condition State in the range 1 to 5

The historical collection of condition assessments has been stored in a readily accessible form in the National Structures Database (NATS) operated by the Highways Agency and despite the limitations described above it forms a major source of data. This data now forms part of SMIS (structural management information system) and has been used in this work although the number of states has been reduced to five by using the conversion specified in Table 1.

NATS could be used in project level studies for assessing the condition of a particular bridge element or for network level studies for investigating the average condition of various groups of bridge elements.

The condition state data in NATS forms part of a large inventory of information that permits the condition of elements satisfying various criteria to be examined.

The specificity of groups can vary from elements of a certain type e.g. bridge piers, to an element type constructed of a particular material e.g. reinforced concrete bridge piers, to elements of a particular type and material residing in a given location e.g. reinforced concrete piers in the southern region. The number and complexity of possible groups of elements is almost unlimited and is normally only restricted by the necessity for groups to have sufficient members to ensure statistical significance. In this project data were obtained from NATS for elements satisfying the criteria given in the upper half of Table 2

The numbers of elements in each of the four groups are shown in the lower half of Table 2. Table 3 shows a part of a data set extracted from NATS. Each set includes all the inspections carried out on elements of the type specified, thus each particular element will appear several times for inspections carried out at different ages. The data set was sorted by age of element at the time of inspection and then the average condition state for all elements of a given type (e.g reinforced concrete piers) was calculated for element ages of 1,2,3,4,……years. This enables graphs of average condition state against age at inspection to be plotted for the whole sample of reinforced concrete piers for example. These graphs represent a historical record of the average condition of elements of a particular type at different ages. A standard curve fitting package was used to fit these curves to 3rd order polynomials which are used for calculating rates of deterioration.

Element	**Region**	**Span length (m) of bridge spans**	**Material**
Abutment	Midland	>5	Reinforced Concrete
Piers	Midland	>5	Reinforced Concrete
Longitudinal Main Deck Beams	Midland	>5	Reinforced Concrete
Transverse Deck Beams	Midland	>5	Reinforced Concrete
Deck Slabs	Midland	>5	Reinforced Concrete

Element	**Number of Elements**	**Number of Inspections**
Abutment	1645	7191
Piers	1017	4321
Longitudinal Main Deck Beams	1503	5690
Transverse Deck Beams	1038	3633
Deck Slabs	183	351

Table 2: Number of Elements and Inspections for Samples of Data Extracted from NATS, that Satisfy the Criteria Shown

Element Type	**Structure Ref**	**Year Built**	**Year Inspected**	**Extent**	**Severity**	**Excluded**
1	120	1959	1990	A	1	
1	120	1959	1998	B	2	
1	122	1959	1986	D	2	
1	122	1959	1990	B	2	✗
1	122	1959	1992	B	2	✗
1	122	1959	1993	B	2	✗
1	122	1959	1995	C	2	✗
1	122	1959	1997	B	2	✗
1	122	1959	1999	B	2	✗
1	124	1959	1986	B	2	
1	124	1959	1990	C	3	
1	124	1959	1993	C	3	
1	124	1959	1995	B	2	✗
1	124	1959	1998	B	2	✗
1	131	1959	1986	A	1	
1	131	1959	1990	A	1	
1	131	1959	1992	B	2	
1	131	1959	1995	B	2	
1	131	1959	1998	B	2	

Table 3: Extract of Inspection Data for ‘Type 1’ Elements, showing those excluded for improving condition.

4. RATE OF DETERIORATION

It is important to know the rate of deterioration of bridge elements because it allows future maintenance to be planned. This enables the bridge manager to assess the best time to carry out maintenance work. There are significant costs involved in carrying out maintenance work too early or too late.

The variation of condition state with age of a structure represents the rate of deterioration. The purpose of collecting condition data is to enable us to predict the condition of the bridge stock and of particular bridges in the future.

The average condition state against age curve (Figure 1) for elements with particular characteristics are only effective for indicating how a stock of elements will deteriorate. They cannot help with how a particular element from the set deteriorates because at any age it is most unlikely that the particular condition state will correspond with the average condition state. Another difficulty is that the condition state values are discrete hence fractional values have little meaning for a particular element.

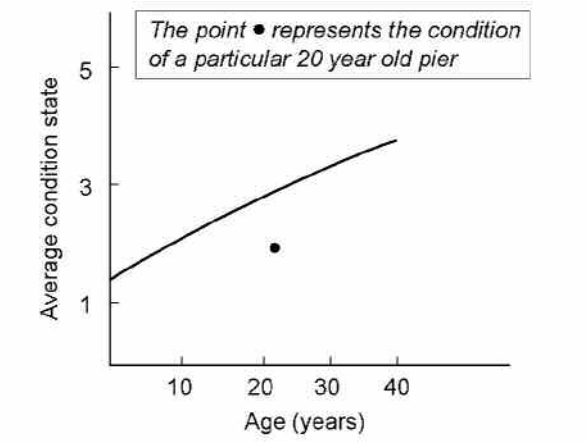

Figure 1: Average condition state for a stock of reinforced concrete bridge piers versus age

The condition state against age graph for a particular element will be discontinuous (Figure 2) consisting of lines of zero and infinite gradient hence it is not possible to determine the rate of change in terms of the slope of a tangent to the graph at a given age. A method of representing the rate of change of a discrete function is to find the probability of moving from state to state during a given period of time. If there is a high probability of moving to a poorer condition during this period then the rate of deterioration can be considered to be high and if there is a high probability of the condition state remaining unchanged then the rate of deterioration will be low. In this work the aim was to determine transition state probabilities; to facilitate this a number of simplifying assumptions were made.

- The time period over which the transition was to be considered was one year. In practice it is more likely that a time period of 2 years or 6 years corresponding to the interval between general or principal inspections would be used. Changing to this time period would not fundamentally change the model.

- It was assumed that during one time interval either the condition state would remain unchanged or would increase by one unit. The argument is the rate of deterioration of concrete bridges is normally low and it is very unlikely that the condition state would deteriorate by more than one unit in a year or even between principal inspections. Implicit in this assumption is that the element will never improve in condition i.e. the condition state will not decrease. This is reasonable for elements that have not undergone maintenance or repair since it is not conceivable that the condition of an element would improve otherwise.

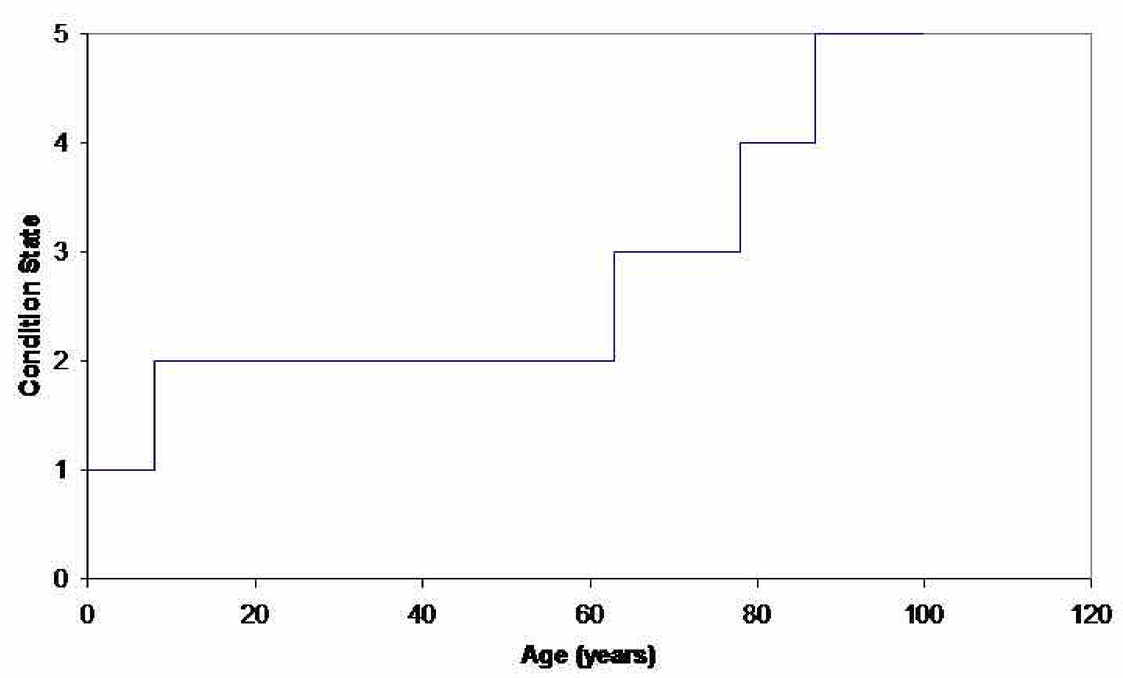

Figure 2: Condition state against age for a particular element

Thus when attempting to measure deterioration processes it is simpler to consider the deterioration of repaired or maintained elements separately from those elements that have never received maintenance or repair. An approach for taking account of how maintenance and repair affect condition will be given in the next section. In this section it is assumed that there is no maintenance intervention to influence the natural deterioration processes. This is typical of the situation early in the life of most bridges.

The condition assessments for particular bridges are sorted together in order of increasing age. Thus for the element of the particular type, for each bridge, the variation in condition with time can be seen. A simple algorithm was written to delete all inspections following a transition to an improved state which it was assumed corresponded with some maintenance or repair work. Thus the data set was limited to bridges that had not received maintenance or repairs and could therefore be assumed to have been deteriorating naturally during the period of condition assessments for those elements remaining in the data set. This restricted set was averaged over all bridges and assessments to give the mean condition state for ages of 1,2,3,……years for all the elements in the restricted set. This data set was fitted to a 3rd order polynomial equation relating the condition state to age. The fitted curve for reinforced concrete piers is shown in Figure 3.

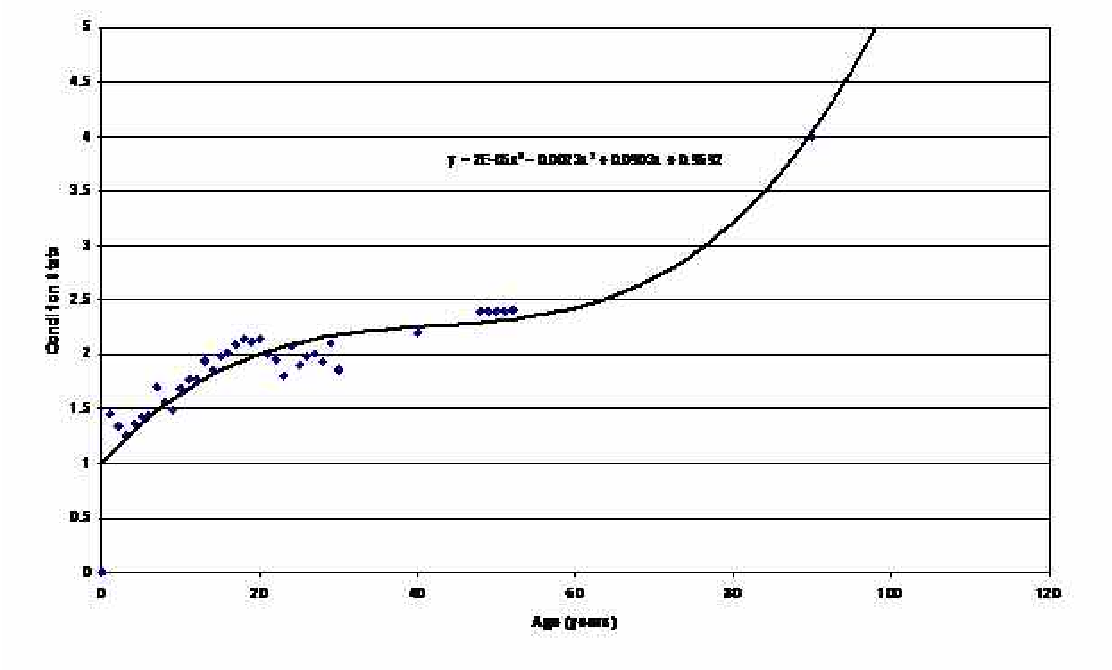

Figure 3: Deterioration graph for reinforced concrete piers in the Midland Region

4.1. Transition Probabalities

The next algorithm developed was to find the transition probabilities for this restricted data set dealing with deterioration that had not been influenced by the intervention of maintenance or repair work. The procedure adopted was to compare the average condition states in Figure 3 with those derived from a Markov Chain shown in Figure 4. The Markov Chain had two options:

- condition state remained constant between years n and n + 1
- condition state increased by one unit between years n and n + 1

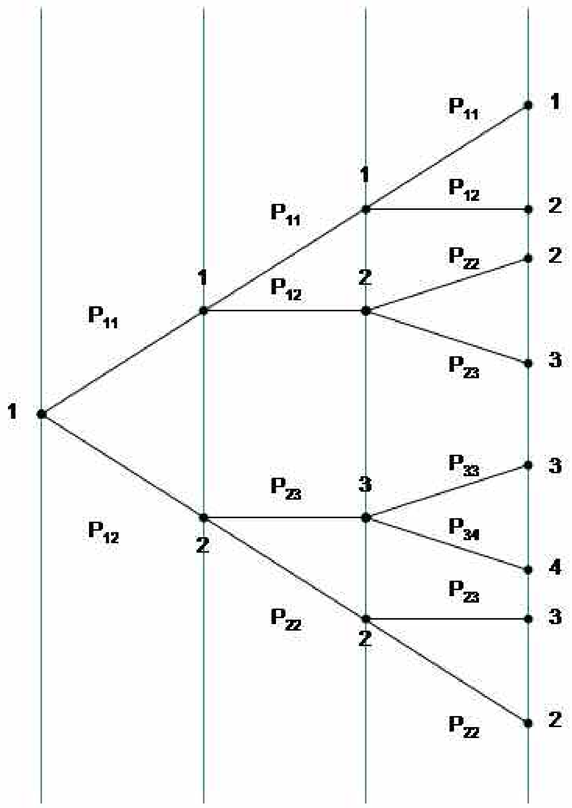

Figure 4: Markov Chain for first three years

The first few years of the Markov Chain is shown in Figure 4. The assumption behind the Markov Chain is basically that the condition in the year n + 1 depends only on the condition in year n and not the previous condition history in years n –1, …. n-k, ------ 0. The condition states in the model can vary from 1 to 5 in one unit steps. The Markov Chain terminates when the condition state in any year reaches 5. The condition state in any year can be calculated and examples are given for years 1 and 2 assuming the start value in year zero was 1.

year 1 predicted condition state = $P_{11} + 2P_{12}$
year 2 predicted condition state = $P_{11}^2 + 2(P_{11}P_{12} + P_{12}P_{22}) + 3P_{12}P_{23}$

Note that $1 - P_{nn} = P_{n,n+1}$ from the simplifying assumptions.

Thus the equation for year 1 condition state has only one unknown and the equation for year 2 condition state has only two unknowns.

The purpose of the model is to calculate the values of P_{11}, P_{22} , P_{33} and P_{44}. These probabilities will vary with age and the values are calculated for successive 5 year periods i.e. 0-4, 5-9, 10-14 years etc.

The algorithm is based on the following objective function that is optimised to give the minimum value, of

$$\sum_{\tau=0}^{4}(A-B)^2$$

A is the condition state calculated from the polynomial equation and B is the condition state calculated from the Markov Chain. The optimisation is taken over five year intervals the first being 0-4 years. The value of A is easily calculated, but the value of B depends on knowing the values of P_{11}, P_{22}, P_{33} and P_{44}. These values are not known so the procedure used by the algorithm is to

- cycle through the possible values of P_{11} etc. (i.e. 0 to 1) in 0.01 unit intervals calculating the value of B each time
- the values of P_{11}, P_{22} , P_{33} and P_{44} associated with the values of B that minimise the objective function are the transition probabilities.

These transition probabilities provide the best match between the Markov Chain and the historic information, which is contained within the polynomial, about how elements of the chosen type and age range have deteriorated.

Examples of the inputs and outputs for this optimisation process are shown in Figure 3 and Table 4 (Note P(n) = P_{nn}). There is a set of transition probabilities for each 5 year time block. The inputs are the

- current age of the element
- the period of optimisation
- the order of the polynomial
- the polynomial coefficients

Year	Average CS
1	1.457
2	1.347
3	1.258
4	1.375
5	1.427
6	1.446
7	1.697
8	1.560
9	1.491
10	1.687
11	1.776
12	1.779
13	1.949
14	1.863
15	1.986
16	2.011
17	2.087
18	2.134
19	2.114
20	2.134
21	2.009
22	1.961
23	1.806
24	2.083
25	1.905

Table 4: Extract of Average Condition State Values for element of 'Type 1'

4.2. Future Condition

The next stage is to use the transition probabilities to predict the condition state of a specific element in the future.

For an element in condition state 1 at age zero the condition state next year will be given by

$$P_{11} + 2(1-P_{11})$$

and in year 2 by $P_{11}^2 + 2[P_{11}(1-P_{11}) + P_{22}(1-P_{11})] + 3[(1-P_{11})(1-P_{22})]$

and so on.

In order to automate this procedure it is best to use matrix multiplication where

- the transition probabilities form a 5 x 5 matrix and
- the current condition state is represented by 1 x 5 vector.

Each transition state matrix will have the form

$$\begin{bmatrix} P_{11} & (1-P_{11}) & 0 & 0 & 0 \\ 0 & P_{22} & (1-P_{22}) & 0 & 0 \\ 0 & 0 & P_{33} & (1-P_{33}) & 0 \\ 0 & 0 & 0 & P_{44} & (1-P_{44}) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Each current condition state vector has the form

$$[\,0 \;\; 1 \;\; 0 \;\; 0 \;\; 0\,]$$

where the position of 1 indicates the current condition state which is 2 in this case (2nd column).

Multiplication of the vector by the matrix (in this order) gives a 1 x 5 output vector representing the condition next year.

An example of an output vector is

$$[\,r \;\; s \;\; t \;\; u \;\; v\,]$$

where r is the probability of being in state 1 next year
s is the probability of being in state 2 next year etc.

To find the actual condition state next year the output vector is multiplied by a 5 x 1 vector representing the possible condition states i.e.

$$[\,1 \;\; 2 \;\; 3 \;\; 4 \;\; 5\,]^T$$

To find the predicted condition state in n years time this process is repeated.

$$V_i \times P^n = V_n$$

Where V_i is the input vector now
P^n is the nth power of the transition state matrix
V_n is the output condition state vector in n years time.

Examples of the inputs and outputs of the algorithm for predicting future condition as described above are shown in Tables 5 and 6.

The procedures described in this section are for predicting the future condition of a specific element on the basis of how similar elements of the same age have deteriorated in the past. It is therefore a project level management tool that uses network level information.

Year Block	P1	P2	P3	P4	P5
0	0.993	0.859	1.000	1.000	1.000
1	1.000	0.905	0.448	0.681	1.000
2	1.000	0.880	0.587	0.647	1.000
3	1.000	0.853	0.646	0.648	1.000
4	1.000	0.808	0.684	0.662	1.000
5	1.000	0.714	0.695	0.705	1.000
6	1.000	0.609	0.643	0.723	1.000
7	0.998	1.000	0.974	0.767	1.000
8	1.000	0.775	0.507	0.573	1.000
9	0.995	0.628	0.612	0.251	1.000
10	0.991	0.674	0.685	0.717	1.000
11	0.981	0.747	0.790	0.898	1.000
12	0.968	0.796	0.856	0.939	1.000
13	1.000	0.692	0.623	0.623	1.000
14	0.952	0.162	0.536	0.025	1.000
15	0.891	0.647	0.411	0.627	1.000
16	0.788	0.611	0.536	0.730	1.000
17	0.345	0.297	0.284	0.411	1.000
18	0.000	0.000	0.000	0.000	1.000

Table 5: Extract of Transition Probabilities for Elements of ‘Type 1’

Year	Condition State			
	Element 1	Element 2	Element 3	Element 4
0	1	1	1	1
7	1	1	2	1
8	2	2	2	1
9	2	2	2	2
39	2	3	2	2
47	2	3	3	2
48	2	4	3	2
53	2	5	3	2
56	2	5	4	2
57	2	5	4	3
62	2	5	5	3
63	3	5	5	3
67	3	5	5	4
74	3	5	5	5
78	4	5	5	5
87	5	5	5	5

Table 6: Extract of Condition States Calculated for 4 Elements, showing Years at Condition State changes

5. THE EFFECT OF REMEDIAL TREATMENTS ON THE RATE OF DETERIORATION AND THE PREDICTION OF CONDITION STATE

This section explains how the effects of maintenance work can be incorporated into the Markov chain model for predicting future condition that was described in the last sub-section. To clarify matters we have used as an example the remedial treatments that can be applied to a concrete bridge to overcome the problems caused by corrosion of the reinforcing steel.

The cause of reinforcement corrosion that has been the major contributor to deterioration of concrete bridges is chloride ions from de-icing salt. De-icing salt has only been used on roads since about the mid 1960's. Typically it takes about 20-30 years for the chloride ions to pass through the concrete to the reinforcing steel so the effects of reinforcement corrosion have only been known for about 20 years and remedial measures to combat it for an even shorter time. There is limited experience of the effectiveness of these remedial measures because of their newness. Data do not exist from which the rate of deterioration following various repairs and treatments can be deduced. It is therefore necessary at this time to rely on expert opinion for data concerning the effect of remedial measures on the condition state.

5.1. Effect of Repairs

Repairs and maintenance can have two effects on the condition state:

- to reduce the condition state (ie. improve the condition)

- to fix the condition state at a certain value for a number of years (ie. for the life of the maintenance treatment)

Repair procedures normally have both effects whereas preventative maintenance has only the latter effect. Both types of remedial measure extend the life of a bridge. An algorithm has been written that takes account of the effect on the condition of a remedial measure on the following basis:

- the difference in condition state immediately before and after the remedial treatment is called the **improvement** of the treatment
- the number of years following the remedial measure for which the condition state remains constant is called the **life** of the treatment.

Thus the effectiveness of each remedial treatment is characterised by the values of these two parameters, improvement and life.

When a remedial treatment is carried out the effect on the condition state will be as shown in the example in Figure 5.

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Condition State	1	1	1	2	2	2	2	2	3	3	3	4	4	4	4	4	4	5
Condition State with repair	1	1	1	2	2	2	2	2	1	1	1	1	1	2	2	2	2	2
Repair								✓										

Improvement in Condition State of Repair Option while in Condition State 2 is 1.
Life of Repair Option while in Condition State 2 is 4 years.

At the end of the effective life of a repair, the normal Condition State trajectory is rejoined at the mid point of the Condition State operative after the repair work.
i.e. The final year of the effective life is equivalent to the middle year of the normal trajectory for the appropriate Condition State.

In the above example, the final year is year 11 and the Condition State is 1. The middle year of Conditon State 1 on the normal trajectory occurs at year 1 thus year 11 is taken as equivalent to year 1. When the normal trajectory is rejoined in year 12, the Condition State progresses as if from year 2 on the normal trajectory.

Figure 5: Example of the effect of remedial treatment on the condition state

5.2. Resuming Deterioration

At the end of the life of a treatment the rate of deterioration will again be determined on the basis of natural deterioration processes as defined by the normal condition state trajectory derived from the Markov Chain model until further treatments are carried out. If at the end of the effective life of a treatment the condition state is say 2 then the normal trajectory is rejoined in the middle of the span of years at condition state value 2.

This simple algorithm takes account of remedial measures effectively although the procedure is somewhat more complex than described above because the effectiveness of remedial measures depends on the condition of the element when they are carried out. For example:

- preventative maintenance is only effective before corrosion starts (condition states 1 or 2) so if the condition state is more than 2 the improvement and life of preventative maintenance treatments are given zero values to indicate they are ineffective.
- Preventative maintenance treatments do not improve the condition they only maintain the current state hence the improvement value for these treatments is always zero.
- Strengthening work would only normally be considered for an element in state 5 (state 5 indicates the bridge is sub standard) so its improvement and life can be given zero values for condition states less than 5 to prevent its inappropriate selection.

Table 7 shows the life and improvement values for a number of remedial measures at each condition state.

The repair of an element undergoing corrosion of reinforcement usually requires two components namely repairs to damaged concrete and procedures to stop the corrosion process. Thus more than one remedial measure may be required for elements in condition states 4 and 5.

Option Index	Option Name	Cost Rate	LifeCS1	LifeCS2	LifeCS3	LifeCS4	LifeCS5	Improvement CS1	Improvement CS2	Improvement CS3	Improvement CS4	Improvement CS5	Area CS1	Area CS2	Area CS3	Area CS4	Area CS5
1	Option 1	100	0	0	30	30	20	0	0	1	2	3	0	0	0.25	0.5	1
2	Option 2	80	0	0	20	20	20	0	0	1	2	3	0	0	0.25	0.5	1
3	Option 3	60	0	0	20	20	20	0	0	1	2	3	0	0	0.25	0.5	1
4	Option 4	1000	0	0	0	25	25	0	0	0	2	3	0	0	0	0.125	0.2
5	Option 5	15	15	15	0	0	0	0	0	0	0	0	1	1	0	0	0
6	Option 6	20	10	10	0	0	0	0	0	0	0	0	1	1	0	0	0

Table 7: Extract of parameters for different maintenance options and condition states

6. CONCLUDING REMARKS

This paper has described algorithms for calculating the rate of deterioration and predicting the future condition of bridge elements and components at both project and network level simply by collecting and processing condition data throughout the lifetime of bridges obtained during regular inspections.

At network level the condition data for each age is averaged and then fitted to a polynomial equation the first derivative of which represents the rate of deterioration of bridges of different age's bridges.

At project level optimisation techniques were used to minimise the difference between the condition state at a given age calculated by the polynomial equation and by a Markov Chain model. This enabled the probabilities of transitions between different condition states to be established. These probabilities represent the rate of deterioration for a stock of bridge elements or components where the measure of condition is a discrete rather than a continuous variable. Expressing the rate of deterioration as transition probabilities enables matrix techniques to be used to predict the future condition of a particular bridge element given knowledge of its condition state at some earlier age.

A model for taking account of the effect of maintenance work on the rate of deterioration was described, which enables the future condition to be predicted regardless of the previous maintenance history of a bridge.

The reliability of predictions deserves close examination and it is clear that this diminishes the further into the future we try to predict. The models used in this work are applied to an extensive body of data that is up-dated at every bridge inspection so we can be confident that the predictions are reliable at least for 10 years ahead. The data set is the best history available of how the condition of particular types of bridge element and component has varied. The condition data could be improved in future if bridge inspectors were trained and certified, which would reduce the variability in condition assessments. Quality Assurance would also be improved by more specific and discrete definitions of the condition states.

The next step, to be reported in a future paper, is to compare the cost-effectiveness of various durability options and maintenance strategies. The only additional data required to achieve this would be the construction and maintenance costs for the bridge. The effectiveness of different durability options and maintenance strategies can be evaluated using the algorithms described in this paper. Costs can be summed and discounted to give a value for the Whole Life Cost (WLC). The costs and benefits of applying different durability options during construction and different maintenance treatments during the lifetime can be analysed to give an optimal maintenance programme that minimises the WLC subject to a constraint that the condition state remains below some user specified threshold.