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A Bridge-Rehabilitation Strategy Based on the Analysis of a Bridge-Inspection Data Set

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A bridge-rehabilitation strategy based on the analysis of a bridge-inspection data set

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Bridge-management systems (BMSs) allow bridge owners to assess the condition of their bridge stock. However, not all BMS packages have the capability to formulate network-level bridge-rehabilitation investment strategies. This research has developed a decision-support system for bridge owners in the selection of the best strategy for bridge rehabilitation at the network level. The basis of the research is an available data set of 1367 bridge-inspection records for County Cork, Ireland, that has been prepared to the Eirspan BMS inspection standard. The developed system consists of a project-prioritisation procedure that builds on previous research, a methodology for the calculation of a deterioration rate based on published bridge data and, through the use of efficiency and effectiveness indicators taken from international practice, proposes the concept of system performance in the identification of annual rehabilitation investment requirements to achieve full bridge-stock rehabilitation.

Q3

Notation

a, b, c	bridge attributes or parameters
$f_i(a, b, c, ...)$	priority-ranking formulas
K_i	weighting factors for each criterion considered

Introduction

Highway bridges are an integral part of all road transportation networks and are vital in connecting communities and sustaining economic activity. Bridges are valuable infrastructure assets and typically represent about 30% of a road network's monetary value (Piarc, 1996). Due to their critical function, partial or total bridge closure can result in major disruption, such as long diversions, congestion and even the total isolation of certain areas. Natural hazards, ageing and increased structural performance demands cause deterioration of bridge structures and have led to up to 10% of international bridge stocks being classified as structurally deficient (ASCE, 2017; Freudenthaler *et al*., 2008).

The challenge in bridge management is to ensure that all bridges in a network remain fit for purpose over their service life at a minimum life-cycle cost. Bridge owners and managers need decision-support systems to devise network-level preventative and corrective rehabilitation strategies to maintain a bridge stock to an acceptable performance level. The concept of a bridge-management system (BMS) was developed as a means of bridge asset management and has been described as 'consisting of formal procedures and methods for gathering and analysing bridge data for the purpose of predicting bridge conditions, estimating network maintenance, repair and rehabilitation needs, determining optimal policies, and selecting projects and schedules within budget and policy constraints' (Aashto, 1993). Q4 The original or first-generation BMSs consisted of an inventory only whose primary function was the secure storage and easy retrieval of data on individual bridges. Subsequent developments responded to the need to store information about inspections and maintenance work and could be described as second-generation BMSs. Third-generation BMSs have the general objective of maintaining the functionality of the stock at a minimum lifetime cost (Flaig and Lark, 2000; Vassie and Arya, 2008). This objective requires

- modules providing information on the economics of maintenance methods and their impact on the flow of traffic
- algorithms for finding the rate of deterioration and optimising and prioritising maintenance programmes for the bridge stock.

In Ireland, Transport Infrastructure Ireland, formerly the National Roads Authority, has developed Eirspan, which is a customised version of the Danish Danbro system, as the Irish BMS (Duffy, 2004). Eirspan, in common with many other BMSs (Mirzaei *et al*., 2012), does not predict bridge deterioration rates or determine the best intervention or rehabilitation strategies.

A recently available data set of 1367 Eirspan BMS inventory and principal inspection records provides the opportunity of an in-depth analysis of a regional bridge stock with a rehabilitation cost estimate of €24·2 million, where 26% have suffered at least significant damage and 86% have suffered at least some damage.

The purpose of this research is the development of a bridge-rehabilitation strategy model as a decision-making aid for bridge owners. The research recognises the decision problems faced by a bridge owner with respect to the requirement for the prioritisation of rehabilitation projects, the uncertainty of the future deterioration of bridges and the limitations of funding resources.

The research builds on a procedure developed by previous work on the prioritisation of theoretical bridge-rehabilitation projects on the Chilean road network (Valenzuela *et al*., 2010). A statistical analysis of published European bridge life expectancy rates (OECD, 1992; van Noortwijk and Klatter, 2004) has led to the formulation of an annual structure deterioration rate. The research proposes a system performance method in the identification of an optimum bridge-stock rehabilitation strategy, which uses efficiency and effectiveness indicators taken from UK, New Zealand and French practice (Atkins, 2007; Horak *et al*., 2001; Orcesi and Cremona, 2011). A benchmarking comparison with reported international investment practice has been undertaken to confirm the applicability of the developed methodology.

Development of bridge-rehabilitation strategy

The development of the rehabilitation strategy follows the sequential process shown in Figure 1.

Eirspan BMS and data compilation

The Irish BMS, Eirspan, describes each bridge structure in terms of 13 individual bridge components. The 'condition rating' system for the individual components is assigned by the trained bridge inspector and is a six-point system (ranging from '0' to '5') defined in Table 1. The condition rating of the overall structure is determined by the highest rating of five 'critical' components (piers, abutments, bearings, deck and beams). A module within the Eirspan database provides a cost estimate for the rehabilitation of each structure.

The Irish Department of Transport, Tourism and Sport (DTTS, 2014a) estimates that there are approximately 19 000 bridges on the state's regional and local road (i.e. non-national road) network. An available data set of 1367 bridge-inspection records for regional and local roads in County Cork, undertaken to the Eirspan BMS inspection standard and which includes bridge structure condition ratings and rehabilitation costs, formed the basis of the research. This investigation thus has records of 7·2% of the state's estimated regional and local road bridges.

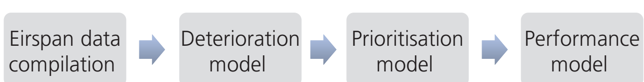


Figure 1. Strategy development

Table 1. Eirspan condition ratings (NRA, 2008)

Condition rating	Definition
0	No or insignificant damage
1	Minor damage
2	Some damage, repair needed
3	Significant damage
4	Damage is critical
5	Ultimate damage

The data set of bridge records was generated by the Eirspan BMS in 'Notepad' format. Notepad is a plain-text (i.e. data) editor for Microsoft Windows and is a basic text-editing program that enables the creation of documents. The Notepad data files were imported in a comma-separated value (.csv) format into Microsoft Excel and converted into a spreadsheet format, where these data were sorted and checked for errors and inconsistencies. The SPSS data analysis package, whose title is an acronym for 'Statistical Package for the Social Sciences', was used for advanced descriptive, inferential and predictive statistical analyses.

Deterioration model for bridge structures

The rate of deterioration predicts the future condition or performance of an asset if no maintenance, rehabilitation or improvements are undertaken. If both the current condition and deterioration rate are known, the remaining period of time in which the asset satisfies its functional requirements may be estimated.

There are a number of approaches with varying degrees of sophistication to modelling bridge deterioration. Agrawal and Kawaguchi (2009) broadly classified these into the three categories of deterministic, stochastic and artificial intelligence models. To demonstrate the methodology developed for this research, a linear deterministic model approach was used with statistical analysis undertaken on published bridge life expectancy values for European bridge stocks with similar characteristics (OECD, 1992; van Noortwijk and Klatter, 2004). Using the SPSS data analysis software, a simple linear regression analysis (Field, 2009) for the entire bridge stock shown in Figure 2 established a significant relationship between the overall bridge condition and age that satisfies the conditions of normality and randomness of

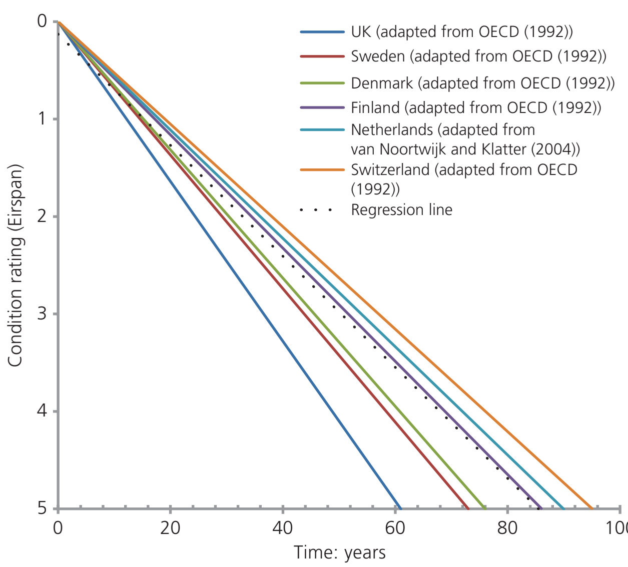


Figure 2. Regression analysis of European bridge life expectancy values

the residuals (R^2 = 0·949, $F(1,97)$ = 1818·75, p < 0·001) and generated the following regression equation

$$\text{1.}\quad \text{condition rating} = 0{\cdot}16 + 0{\cdot}057(\text{age})$$

where condition rating is measured on the six-point Eirspan scale and age is measured in years. The bridge condition rating value thus increases by 0·057 every year – that is, there is a one-point increase in the condition rating every 17·5 years. The R^2 value indicates that approximately 95% of the variation in ‘condition rating’ scores is predicted by the ‘age’ scores.

Prioritisation model for bridge-rehabilitation projects

Ranking and prioritisation procedures are widely used by transportation agencies to evaluate and select bridge projects (Abu Dabous and Alkass, 2010). The principle of a prioritisation model or index is to rank the bridges for rehabilitation priority based on characteristic attributes, such as

- the importance of a bridge on a road network, which may be described in terms of criteria such as road category, annual average daily traffic (AADT) or detour distance
- an assessment of the bridge condition, which may be expressed by parameters such as structural stability, remaining life or general condition.

The entire bridge stock is treated as one large system containing the summation of component bridge attributes, their condition states or other prevailing characteristics at the time of inspection and the general form of a priority index (PI) (Gralund and Puckett, 1996; Hearn, 1999) is

$$\text{2.}\quad \text{PI} = \sum_{i=1}^{i=n} K_i f_i(a, b, c, \ldots)$$

where PI is the maintenance priority index; K_i are the weighting factors for each criterion considered; $f_i(a, b, c, \ldots)$ are priority-ranking formulas; and a, b, c, … are the bridge attributes or parameters.

Bridge-maintenance PIs have been the focus of previous research internationally using a range of parameters.

- Load capacity, remaining life, deck width and horizontal and vertical clearances have been used by different states in the USA for the development of ranking formulae (Gralund and Puckett, 1996).
- In Greece, structural defects, traffic volume, environmental conditions, bridge age, riverbed characteristics and foundation and superstructure types were used by Chassiakos *et al*. (2005) for developing a PI. The index was initially formulated based on the experience of the road authority and was adjusted by using a trial-and-error technique. The application of the system was demonstrated on ten bridges on the road network in Western Greece.
- Hai (2008) in Vietnam took into consideration structural condition, location, width, traffic volumes and budget constraints for the determination of bridge importance and illustrated the method by its application to 29 bridges.
- In Thailand, Rashid and Herabat (2008) proposed a PI based on level of service, structural condition, safety, cost, socio-economic value and fuel consumption. The index was compiled from an analysis of responses to a survey from nine expert practitioners from highway agencies in Thailand.
- Valenzuela *et al*. (2010) considered the AADT, length and width of bridges, availability of alternative routes, social and economic development of the area and load restriction to develop an index for bridges on the Chilean road network. The index was derived from a survey of 20 experts and applied to six bridges on the primary road network.
- In Australia, Rashidi *et al*. (2013) investigated the structural condition of bridge components, the vulnerability and location of the bridge, bridge age, road classification, number of lanes, the width of the deck, vertical clearance and the social implications of rehabilitation in the development of a ranking method for the remediation of concrete bridges.

For this research, ten parameters or influencing factors, based on previous research and shown in Table 2, were identified. Each parameter in turn was divided into interval categories– for example, AADT was given an interval value of ‘1’ for AADT < 1000; ‘2’ for 1000 < AADT < 3000; ‘3’ for 3000 < AADT < 10 000; and ‘4’ for AADT > 10 000.

Previous research on bridges on the Chilean road network (Valenzuela *et al*., 2010) proposed a methodology for the formulation of a prioritisation index for bridge rehabilitation. The basis of this approach, with the influencing factors for the PI taken as linear, has been adopted and expanded on with the recognition that different motivations and judgements apply in the selection of rehabilitation projects for critically damaged structures at or close to failure (condition rating 5, ‘ultimate damage’, and condition rating 4, ‘damage is critical’) compared with non-critically damaged structures (condition rating 3, ‘significant damage’, and condition rating 2, ‘some damage’).

Two prioritisation indices are therefore established.

(*a*) A prioritisation index for critical-condition bridges. The highway authority (Cork County Council) undertook the rehabilitation of 37 condition-rated-4 and condition-rated-5 bridges in 2014 and 2015. These projects were deemed the most urgent and received funding priority. An example of one of these rehabilitation projects (Ballybrogan Bridge) is shown in Figures 3 and 4. Q5

The details of 37 rehabilitation projects in the study area were reviewed and listed in their order of undertaking (priority number).

Table 2. Influencing factors

Influencing factor	Description	Interval values
AADT	AADT (annual average daily traffic) is the total volume of vehicular traffic on a roadway for 1 year divided by the number of days in the year	1: AADT < 1000 2: 1000 < AADT < 3000 3: 3000 < AADT < 10 000 4: AADT > 10 000
Alternative route	The length of diversion route onto roads of equal capacity should the structure become unable to cater for traffic	1: there exists an alternative route near the bridge; diversion < 1 km 2: there exists an alternative route near the bridge; 1 km < diversion < 10 km 3: alternative route increases travel time and road user costs; diversion > 10 km 4: no diversion route available
Design of elevation	The bridge elevation types from the Eirspan database	1: arch, one or more spans 2: continuous, constant cross-section 3: simple span, constant cross-section 4: simple span, varying cross-section
Hydraulic vulnerability	The highest recorded value for either abutment or pier component as defined by Eirspan inspection	1: no or insignificant damage 2: minor damage but no need of repair 3: some damage, repair needed 4: significant damage 5: damage is critical 6: ultimate damage
Overall structural condition	The condition rating of the overall structure as defined by Eirspan inspection	1: no or insignificant damage 2: minor damage but no need of repair 3: some damage, repair needed 4: significant damage 5: damage is critical 6: ultimate damage
Material of primary members	The bridge material types of the rehabilitation projects from the Eirspan database	1: composite steel and concrete 2: in situ reinforced concrete 3: precast reinforced concrete 4: stone masonry
Number of spans	Number of spans of the bridge structure	1: one span 2: two spans 3: three spans 4: more than three spans
Rehabilitation cost	The cost to improve the structure to condition rating 0	1: cost < €20 000 2: €20 000 < cost < €50 000 3: €50 000 < cost < €100 000 4: cost > €100 000
Road classification	The classification of regional and local roads in the study area in terms of functionality	1: regional 2: local primary 3: local secondary 4: local tertiary
Structural non-scour condition	The highest recorded rating value of the critical components, excluding the abutment and pier components as defined by Eirspan inspection	1: no or insignificant damage 2: minor damage but no need of repair 3: some damage, repair needed 4: significant damage 5: damage is critical 6: ultimate damage

Multiple regression analysis was conducted on the data sample (n = 37) to establish the best combination of independent variables that predicted the dependent variable (the priority number). The prediction model contained two of the ten predictors and was reached in two steps, with six outliers removed. The analysis produced a significant regression equation that satisfies the conditions of normality and randomness of the residuals ($R^2 = 0{\cdot}905$, $F(2,28) = 133{\cdot}938$, $p < 0{\cdot}001$). The adjusted R^2 value indicated that approximately 90% of the variation in the priority number may be predicted from the following equation

3. $$\mathrm{PI} = 127{\cdot}35 - 21{\cdot}91(\mathrm{OSC}) - 5{\cdot}59(\mathrm{AADT})$$

where PI is the priority index; OSC is the overall structural condition; and AADT is the annual average daily traffic.

Figure 3. Ballybrogan Bridge before rehabilitation works for severe scour and other defects were undertaken

Figure 4. Ballybrogan Bridge after completion of rehabilitation works

(*b*) A prioritisation index for non-critical-condition bridges. A survey panel of 33 experts was asked to rate in a questionnaire the order of precedence of the ten stated influencing factors. The experts comprised senior bridge managers from a number of local authorities and senior bridge engineers from a number of consulting engineering practices in Ireland. A total of 23 (70%) responses were received. The experts were asked to rank the factors in order of importance. The results from each respondent were processed by assigning a value of '10' to the first factor, '9' to the second factor and so on. These survey results were then tested for normality using the SPSS software. Shapiro–Wilk tests ($p > 0{\cdot}05$) and a visual inspection of their histogram, normal quantile–quantile plots and box plots showed that seven of the ten factors were not normally distributed and, to provide a robust measure of central tendency, the median values were used to rank in order of priority the results obtained from the analysis, which are shown in Table 3.

Using SPSS, a randomised sample ($n = 115$) of non-critical condition-rated-2 and condition-rated-3 bridges was generated and then sorted in Microsoft Excel, using the precedence ranking of the influencing factors from the expert survey to form a prioritised list.

A multiple regression analysis, using the stepwise method, was conducted using SPSS on the data sample to establish the best combination of independent variables that predict the dependent or predicted variable (the priority number). The prediction model contained six of the ten predictors and was reached in six steps, with seven outliers removed. The analysis produced a significant regression equation that satisfies the conditions of normality and randomness of the residuals ($R^2 = 0{\cdot}950$, $F(6,107) = 319{\cdot}48$, $p < 0{\cdot}001$). The adjusted R^2 value indicates that approximately 95% of the variation in the priority number may be predicted from Equation 4.

$$\begin{aligned} \text{PI} = {} & 216{\cdot}66 - 29{\cdot}44(\text{HY}) - 22{\cdot}01(\text{OSC}) \\ & - 13{\cdot}43(\text{SNS}) - 6{\cdot}92(\text{AR}) \\ & - 6{\cdot}75(\text{AADT}) - 2{\cdot}09(\text{RC}) \end{aligned} \qquad (4)$$

where PI is the priority index; HY is hydraulic vulnerability; OSC is overall structural condition; SNS is structural non-scour; AR is alternative route availability; AADT is annual average daily traffic'; and RC is road classification.

Table 3. Ranked influencing factors from expert survey

Ranking (number)	Influencing factor	Number of responses (*N*)	Median	Interquartile range	Range (Q1, Q3)
1	Overall structural condition	23	10	1	(9, 10)
2	Hydraulic vulnerability	23	9	1	(8, 9)
3	Structural non-scour condition	23	8	1	(7, 8)
4	AADT	23	6	2	(6, 8)
5	Availability of alternative route	23	6	3	(4, 7)
6	Rehabilitation cost	23	5	2	(4, 6)
7	Road classification	23	5	3	(4, 7)
8	Number of spans	23	3	2	(1, 3)
9	Bridge material type	23	2	1	(2, 3)
10	Bridge type	23	2	2	(1, 3)

The derived indices are applied to the entire data set, and all projects are thus ranked in terms of priority.

Performance model

The American management expert and academic, Peter Drucker, is credited with the statement that 'it is not possible to manage what you cannot control and you cannot control what you cannot measure' Q6 (Weber and Thomas, 2005). Performance measurement is therefore a fundamental principle of management, and the use of performance indicators improves the planning of bridge-maintenance strategies (Strauss *et al.*, 2016). This research proposes the performance indicators of 'effectiveness' and 'efficiency'. As shown in Figure 5, 'effectiveness' is a product of 'activity' and 'results', while 'efficiency' is a product of 'resources' and 'activity'.

This research further recognises that there is an optimum balance between these parameters, which is shown graphically in Figure 6, where the 'ideal performance line', plotted at 45°, represents the best balance between effectiveness and efficiency.

Referring to Figure 6, strategy A, which has low effectiveness and low efficiency, has low performance. Strategy B, while highly effective, has low performance, because it has low efficiency. Strategy C, while highly efficient, has low effectiveness and therefore has low performance. Strategy D, which is highly effective and highly efficient, has a high performance.

The seven-step sequential process shown in Figure 7 has been used in the development of the performance model.

Q7 Definition of strategy time horizon

Based on the calculated deterioration rate, a strategy time horizon of 85 years was defined, which is equivalent to the transition time required for a bridge condition rated 0 to deteriorate, without rehabilitation, to a condition-rated-5 structure – that is, the strategy time horizon is made up of five separate planning periods of 17 years, with strategy start at T_0 and five separate planning periods concluding at T_1 (17 years), T_2 (34 years) and so on. This is in line with the 15–20-year planning period recommended for transportation projects (Sinha and Labi, 2011).

Estimation of the asset value of the bridge stock

The financial value of a bridge stock may be defined by the cost of replacement of all the constituent bridges (Horak *et al.*, 2001; Orcesi and Cremona, 2011). A review of recent cost estimates for Irish bridge construction projects is shown in Table 4, with the costs reported in terms of bridge deck area.

The cost estimates vary with the complexity and site-specific issues of individual projects, and a cost of €2500/m^2 of bridge

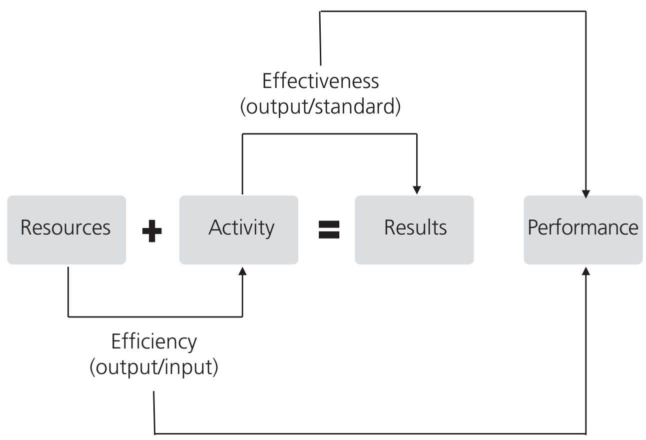


Figure 5. Effectiveness, efficiency and performance (adopted from McGee (2004))

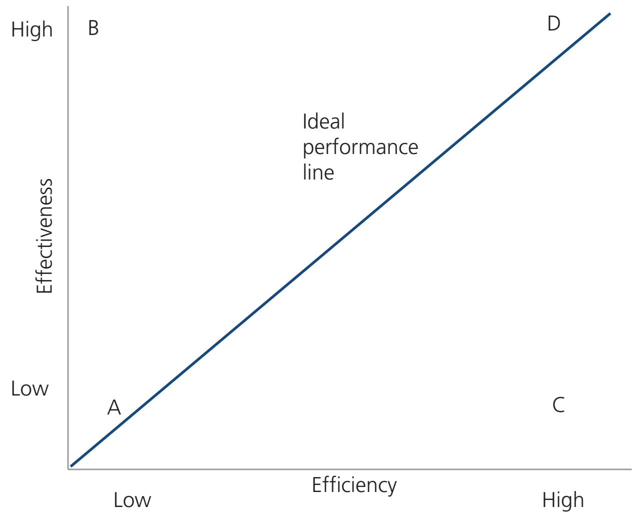


Figure 6. Optimum performance in terms of effectiveness and efficiency (adopted from McGee (2004))

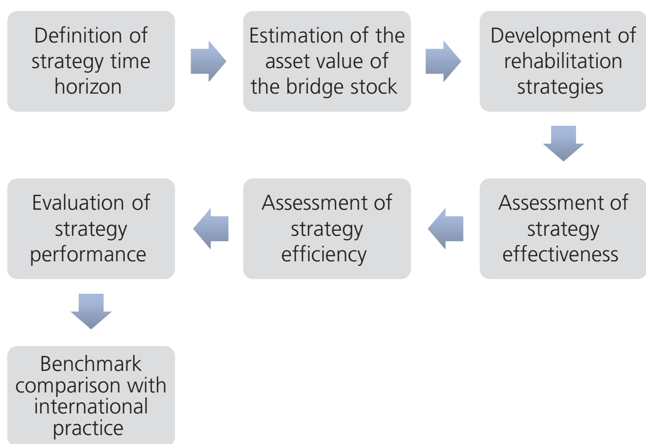


Figure 7. Performance model development

Table 4. Estimated costs for bridge replacements

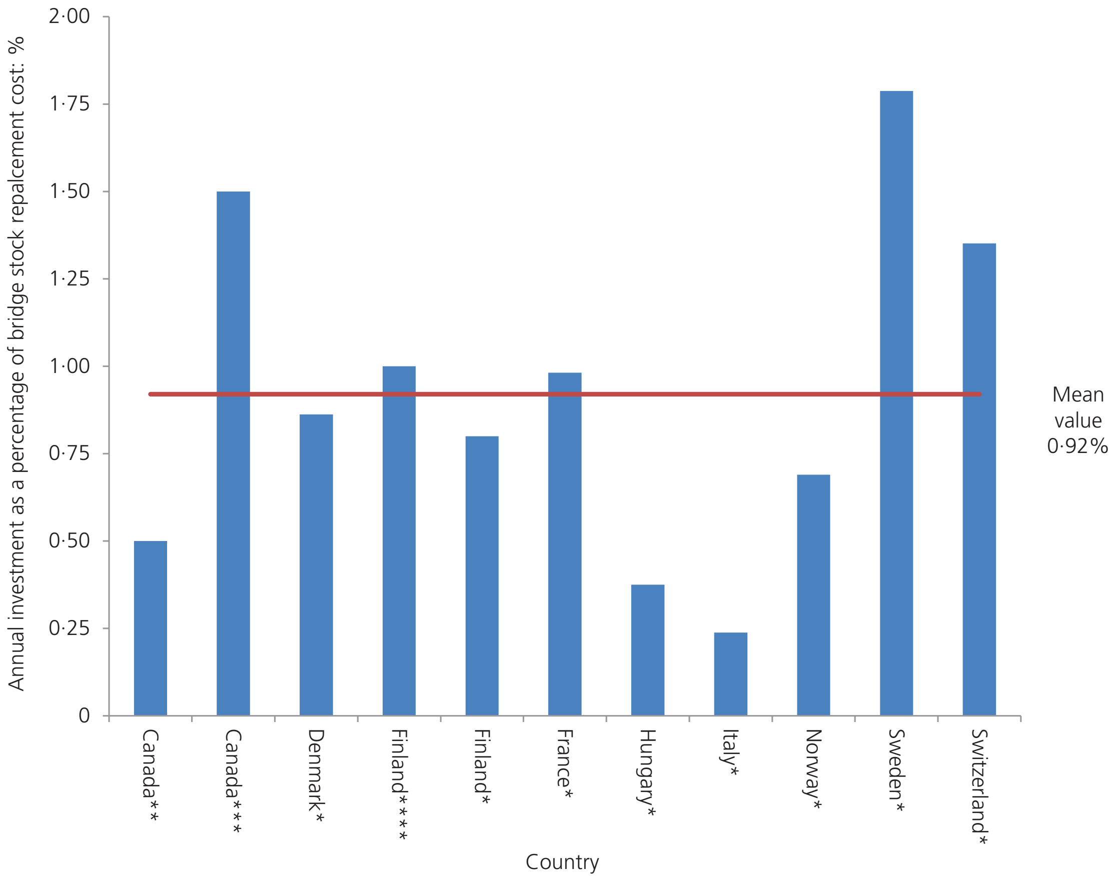
Bridge structure	Description of structure	Cost of bridge deck: €/m²
A	Prestressed-concrete cable-stayed road bridge	4500 (O’Donovan *et al.*, 2003)
B	Multispan in-situ-/precast-concrete hybrid road bridge	2500 (RPS, 2006a)
C	Precast-concrete beam road bridge	1400 (RPS, 2006b)
D	Lattice steel truss pedestrian bridge	2400 (URS, 2012)
E	In-situ-concrete road bridge	3665 (JBA Consulting, 2016)
F	Arched steel truss pedestrian bridge	4000 (RPS 2017)

deck was taken to reflect the replacement cost. Applying this value to the total bridge-stock deck area gives a total asset value of €204 million.

Development of rehabilitation strategies

Maintenance and rehabilitation investment strategies for large asset networks are typically expressed by the ratio of annual maintenance expenditure to the estimated current replacement value (CRV) (Yanev, 2007). In the USA, the federal government recommends that the annual maintenance and repair budgets for infrastructure assets should be set at approximately 2–4% of the CRV (NRC, 1996). In the case of bridge stocks, a review of international practice indicates that actual investment is much lower than these recommended values. Figure 8 shows the reported values, which range from 0·24% in Italy to 1·79% in Sweden and have a mean value of 0·92%.

For this research, five financial investment strategies were developed, which range from a no-investment scenario to the value range of investment levels reported in international practice and expressed in terms of the CRV. The individual strategy parameters were established by ranking projects based on the calculated prioritisation indices, applying a consistent condition deterioration rate of 0·057 per annum to each structure and



*World Road Association (Piarc, 2004); **McCarten (2006); ***Mirza (2006); ****Kähkönen and Marshall (1990)

Q8 **Figure 8.** International annual investment in bridge-stock rehabilitation calculating the time required to achieve full bridge-stock rehabilitation based on the annual investment values for each strategy. The five strategies were the following.

- Strategy 1 (€0/annum). All bridges deteriorate from their current condition rating to condition 5 at, or before, the end of 85 years.
- Strategy 2 (€545 000/annum). The annual investment required to achieve rehabilitation of all structures to a minimum of condition rating 1 within the strategy time horizon has been calculated as €545 000. Each bridge is rehabilitated twice during the 85-year planning horizon, and there is an average of 30 projects per annum. This represents an annual investment of 0·27% of the bridge-stock replacement cost.
- Strategy 3 (€870 000/annum). This is the existing strategy that represents an annual investment of 0·43% of the bridge-stock replacement cost and is the mean value of rehabilitation investment in the study area from 2014 to 2017 (DTTS, 2014b, 2015, 2016, 2017). All structures are rehabilitated to condition rating 0 by the end of 27 years, and there is an average of 47 projects per annum. After year 27, the bridges degrade over the 17-year deterioration cycle to condition rating 1 at the end of year 44. An annual investment of €714 176 (0·35% of CRV) is then required from year 45 to year 61 to return the bridge stock to condition rating 0. This is again required for years 79–85, with an average of 76 projects per annum for these periods. For this strategy, each bridge is rehabilitated at least twice during the 85-year planning horizon.
- Strategy 4 (€2 000 000/annum). This represents an annual investment of 1% of the bridge-stock replacement cost, and all structures are rehabilitated to condition rating 0 by the end of 12 years with an average of 106 projects per annum. After year 12, the bridges degrade over the 17-year deterioration cycle to condition rating 1 at the end of year 29. An annual investment of €714 176 (0·35% of CRV) is then required from year 30 to year 46 to return the bridge stock to condition rating 0. This investment is again required for years 64–80, with an average of 76 projects per annum for these periods. From year 81, the bridge stock again deteriorates. For this strategy, each bridge is rehabilitated three times during the 85-year planning horizon.
- Strategy 5 (€3 000 000/annum). This equates to an annual investment of 1·5% of the bridge-stock replacement cost, and all structures are rehabilitated by the end of 8 years with an average of 160 projects per annum. After year 8, the bridges degrade over the 17-year deterioration cycle to condition rating 1 at the end of year 25. An annual investment of €714 176 (0·35% of CRV) is then required from year 26 to year 42 to return the bridge stock to condition rating 0. This investment is again required for years 60–76, with an average of 76 projects per annum for these periods. From year 77, the bridge stock again deteriorates. For this strategy, each bridge is rehabilitated three times during the 85-year planning horizon.

Assessment of strategy effectiveness

Effectiveness is defined as the 'extent to which planned activities are realised and planned results are achieved' (BSI, 2015). Q9 It is thus a measure of the outcome of a strategy and can be described as the ratio of realised achievement and the planned target. This research uses the bridge stock condition index (BSCI) concept of a single numerical value to describe the condition of a bridge stock, described by the UK County Surveyors Society (Atkins, 2007), as the measure of effectiveness. The BSCI is calculated using Equation 5, where BCI (bridge condition index) is taken as the Eirspan condition rating for each bridge structure and deck area is the area of the corresponding structure.

$$\text{BSCI} = \frac{\sum_{i=1}^{i=n}(\text{BCI} \times \text{deck area})}{\sum_{i=1}^{i=n}\text{deck area}}$$

5.

An decrease in the BSCI following the implementation of a rehabilitation strategy shows measurable effectiveness, while an increase shows ineffectiveness. Effectiveness is calculated as the ratio of the BSCI at the start of the strategy (T_0) to the BSCI at the start of each planning period (T_1, T_2 etc.), and the results are shown in Figure 9.

Assessment of strategy efficiency

The term 'efficiency' is reported as the 'relationship between the result achieved and the resources used' (BSI, 2015). Q10 It is thus a measure of economic cost and can be described as the ratio of a defined objective realised and the resources required in achieving this objective. The efficiency concept in the formulation of a bridge-stock rehabilitation strategy has been applied to bridges on the French national route system (Orcesi and Cremona, 2011), based on the rationale that the total bridge-stock rehabilitation cost indicates the efficiency of a rehabilitation strategy. A similar approach is used by the New Zealand Transport Agency, which measures the residual asset value of their road infrastructure by the cost of its restoration (Horak *et al*., 2001).

Efficiency is calculated as the ratio of the total rehabilitation cost value (the cost of returning all bridges to condition rating 0, where this rating describes a structure with no or insignificant damage (NRA, 2008)) at the start of the strategy (T_0) to the total rehabilitation cost value at the start of each planning period (T_1, T_2 etc.), and the results are shown in Figure 10.

Evaluation of strategy performance

Strategy performance is evaluated in terms of both effectiveness and efficiency; Figure 11 graphs the calculated parameter values. The concept of the ideal performance line is plotted at 45° and with an origin point of (1·00, 1·00). This line represents the best balance between effectiveness and efficiency of a strategy, prior to implementation, which is being sought by this research.

The baseline strategy 1, with no annual investment, is both inefficient and ineffective. Strategy 2 (€545 000/annum) is both effective and efficient from T_0 to T_4 but reduces in both effectiveness and efficiency from T_4 to T_5. Strategy 3 (€870 000/annum), strategy 4

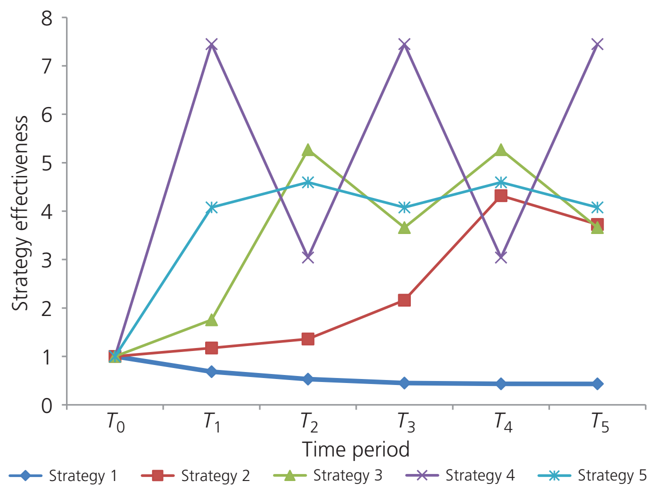


Figure 9. Strategy effectiveness

(€2 000 000/annum) and strategy 5 (€3 000 000/annum) are both effective and efficient between T_0 and T_2 but alternate between high and reduced effectiveness and efficiency from T_2 to T_5. As strategies 4 and 5 are practically coincident, it can be inferred that strategy 4 achieves, in general, the same performance as strategy 5 with a lesser annual investment.

In terms of the ideal performance line, it is evident that this lies between the performances of strategies 2 and 4. These strategies therefore represent the range of possible strategies wherein lies the optimum strategy for the given data set.

Benchmark comparison with international practice

The strategies are presented in Figure 12 in terms of percentage of bridge-stock replacement cost. The range between strategy 2 (0·27%)

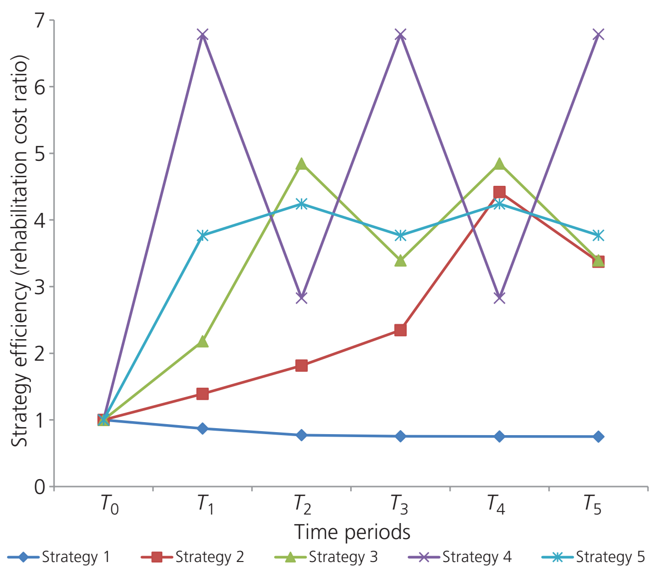


Figure 10. Strategy efficiency

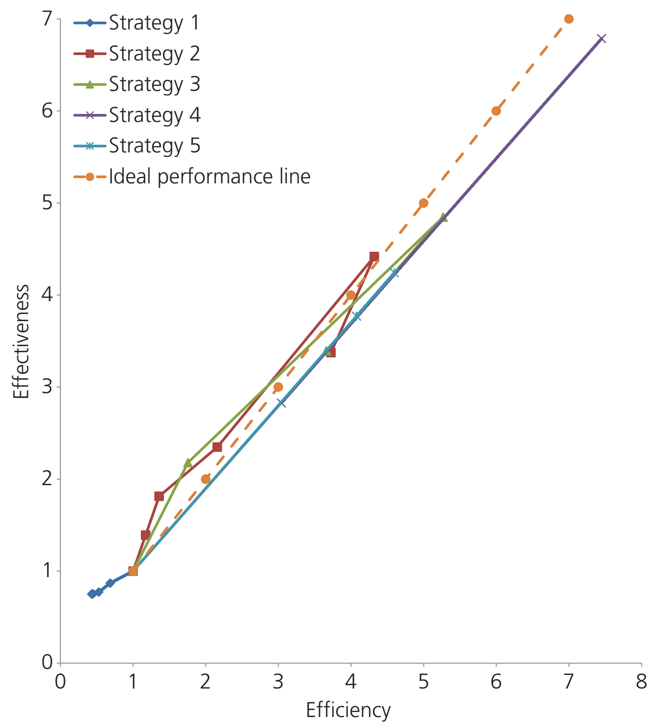


Figure 11. Strategy performance

and strategy 4 (1%, with intermittent investment of 0·35%) is shaded and represents the minimum and maximum value range for the optimum level of investment required in achieving full bridge network rehabilitation within the strategy time horizon and providing a minimum 85-year service life for all structures.

These findings confirm the applicability of the developed methodology.

- The range between the minimum and optimum investment levels is within the reported range of international practice (0·24–1·79%).

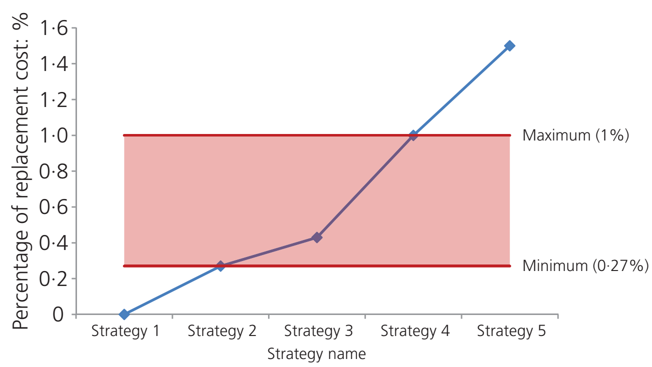


Figure 12. Range of the optimum level of investment in terms of strategies

- The maximum investment level of 1% lies very close to the calculated mean value of 0·92% for international practice.

Conclusions

The research has led to a number of findings.

- First- and second-generation BMSs that lack deterioration, prioritisation and strategy optimisation capabilities do not provide an overall understanding of the rehabilitation requirements for managing the bridge network. This research proposes a methodology of evaluating rehabilitation investment strategies based on a record of bridge-inspection records.
- For a six-point rating scale, an annual deterioration rate of 0·057 in bridge condition rating has been established; this equates to a one-point reduction in rating every 17·5 years.
- The research has identified that different motivations and judgements apply in the selection of rehabilitation projects for critical-condition structures at or close to failure compared with non-critical structures.
- For critical-condition structures, the priority or sequence in which bridge-rehabilitation projects were undertaken was found to be a function of the values of the overall structural condition and AADT variables, with the overall structural condition parameter being the most influential. Faced with a number of critical bridges, the calculated PI confirms that the road authority adopted an approach based firstly on public safety and secondly on minimising disruption to heavily trafficked routes.
- For non-critical-condition bridges, the PI based on identified influencing factors from a survey of experts has been found to be a function of the values of the hydraulic vulnerability, the overall structural condition, the structural non-scour and AADT variables, with their influence ranked in that order.
- The range of annual investments required to achieve full bridge network rehabilitation within the strategy time horizon and thus provide a minimum 85-year service life for all structures has been calculated as 0·27% (minimum) and 1% (maximum) of the bridge-stock replacement value. The current investment level of 0·43% lies within the calculated range.
- The application of the performance indicators of effectiveness and efficiency, taken from UK, New Zealand and French practice, and their evaluation by the concept of system performance have been shown to be a robust assessment process methodology that is confirmed with reference to international practice.

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