Antti Ruotoistenmäki

ROAD MAINTENANCE MANAGEMENT SYSTEM - A SIMPLIFIED APPROACH

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Abstract

In order to find a sustainable maintenance policy, road asset management at strategic level seeks to answer the following questions: What is the current condition of the assets? What is the optimal condition of the assets? What are the annual funding needs and how should this funding be allocated?

The objective of this paper is to provide simple tools for evaluating different maintenance policies. To accomplish this objective, an approach is used whereby the costs of maintenance works are related to the probability distribution of road network's condition by estimated transition probabilities of deterioration and the effect of maintenance works. The decision variables in the calculation method are the amount of maintenance in each condition category during a selected analysis period. The benefit of the proposed method is that it can be used for analysing maintenance of assets where user benefits are undefined and full socio-economic optimisation of maintenance funding needs is not possible.

I use the network of PCC (Portland Cement Concrete) bridges as an example to illustrate the developed calculation method. For strategic level management purposes in the Finnish Road Administration (Finnra), the condition of the road assets is presented using a five-step condition classification, ranging from excellent (5) to very poor (1). Average annual maintenance cost over a ten-year analysis period is calculated to compare three alternative maintenance policies: Current Policy, Preservation Policy and a Do Worst Policy. The results of this analysis confirm the fact seen from the models themselves, namely that the deterioration rate according to the models is rather slow. This, together with the superior condition effects of reconstruction makes the Do Worst Policy superior to all other alternative policies. The results may, however, be different for other networks and models.

Keywords: bridges, maintenance, policy evaluation, probabilistic models

Acknowledgements

The idea for this paper was inspired by the work of Mr. Vesa Männistö of Pöyry Infra Oy presented at the 2nd European Pavement and Asset Management Conference in March 2004 in Berlin. I sincerely thank Mr. Männistö for continually supporting this work. This research has been done in conjunction with the projects in the Asset Management Research Programme (VOH) of the Finnish Road Administration (Finnra). The continuing support from my employers has also, in its part, enabled me to complete this paper.

1 Introduction and objectives

Road asset management at strategic level addresses the following questions: What is the current condition of the assets? What is the optimal condition of the assets? What are the annual funding needs and how should this funding be allocated? A road manager should be able to answer these very basic questions in order to carry out a sustainable maintenance policy.

For strategic level management purposes, the condition of the assets is presented in summarised form (see e.g. Hudson et al 1997). I use the condition classification defined in a recent Finnra report (Finnra 2005a), where the condition categories for bridges are defined on the basis of visual inspection of defects in the bridges' main structural parts. The number of categories in this classification scheme is five. The value 5 represents excellent condition, whereas the value 1 represents poor condition.

The main question is: Should the emphasis of maintenance be placed on assets in poor condition, or should some of the maintenance works be targeted at that part of the network in relatively good condition? The first approach is commonly described as a Do Worst Policy and the latter one is described as a preventive maintenance policy. My objective in this paper is to provide tools for evaluating the different maintenance policies. I do this by applying a probabilistic approach that uses the costs of maintenance works and the transition probabilities of network condition distribution due to deterioration and maintenance works.

In Section 2, I describe the problem setting, and in Section 3, I develop the necessary assessment tools. I then evaluate the alternative maintenance policies using these tools in Section 4, and discuss the results in Section 5. Finally, I draw the conclusions of this study in Section 6.

2 Problem setting

The basic assumption I use in this paper is the stochastic nature of road asset deterioration. This assumption requires the selection of a probabilistic-based approach for analysis. Justification of this approach has already been made by several road asset management developers (e.g. Golabi et al. 1982), and, as a result, I will not further discuss it in this context. Instead, I first shortly discuss some of the research questions in the probabilistic framework. These are, mainly, the problem of defining losses for certain sub-networks and the issue of the number of allowable maintenance actions in each condition state.

Linear optimisation methods are often used for minimising the sum of maintenance costs and losses due to deterioration of the road assets. Usually the considered losses are additional user costs caused by deterioration. Additional user costs due to maintenance works causing lane closures or detours may be also be considered as part of maintenance costs. The road assets may be divided into sub-networks and a few condition indicators are divided into several categories. The condition of a sub-network can thus be described using a distribution of assets into condition states, i.e. the combination of variables and their categories. The decision variables in the optimisation model are the amount of assets to be maintained in each sub-network and condition category.

The approach to minimising the socio-economic costs of maintenance is illustrated in Figure 1. Better condition means less maintenance costs. A minimum of total socio-economic costs, which is the sum of maintenance and user costs, is the optimal solution for maintenance funding level.

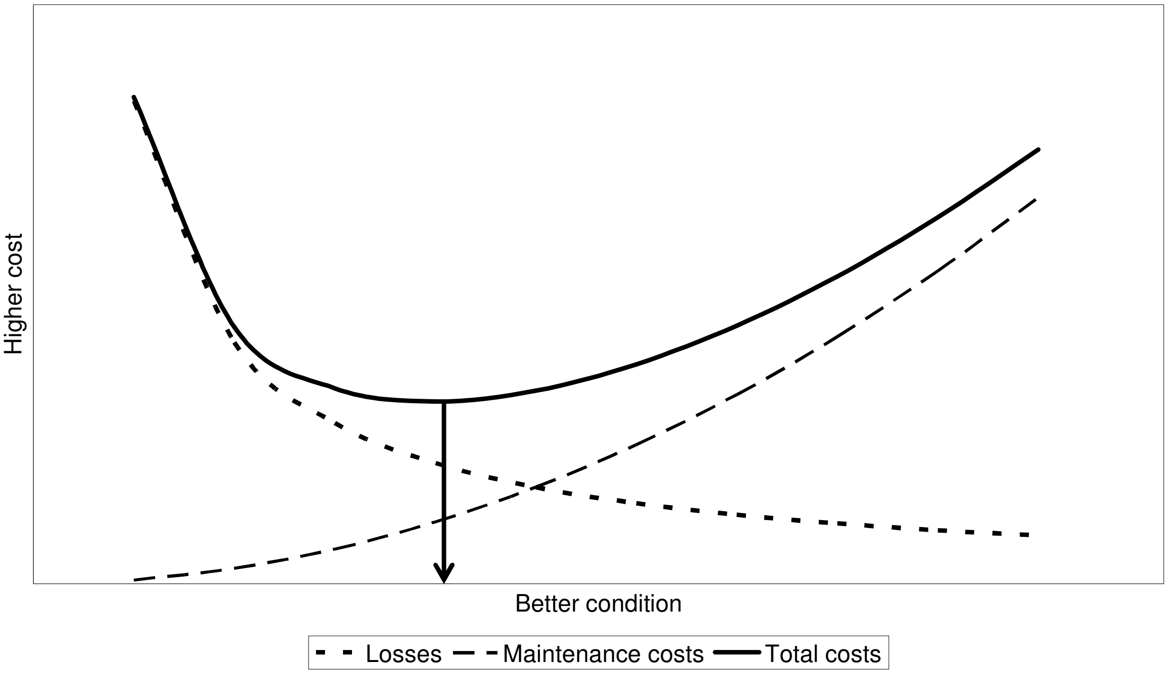

Figure 1. Principle of socio-economical analysis of road asset management. The optimal funding levels are found as the minimum of the total costs, which is the sum of maintenance costs and losses due to untimely maintenance.

The drawback of this approach is that losses may be difficult to determine, which makes the results from such analysis implausible. In such a case, optimisation is reduced to merely finding the minimum maintenance cost that satisfies other constraints set for e.g. condition. This is especially the case for sub-networks with low traffic volumes, and bridges. Nevertheless, these sub-networks form a major part of road assets. To address this problem, I develop a method that considers maintenance costs and the effect of maintenance on road asset condition.

In a probabilistic optimisation framework, it is often thought that in order to achieve good results, several alternative maintenance work types are needed in each condition state. However, this has not been shown to improve the optimisation results. In practice, road asset condition dictates the appropriate maintenance action, and the question becomes one of choosing the optimal maintenance schedule. Therefore, I have chosen to limit the number of allowable maintenance actions in each condition state. This is also the approach taken by Äijälä and Lahdensivu (2006), who developed models for deterioration and maintenance costs and condition effects for bridge assets. I use their models to illustrate the method developed herein.

In this paper, I want to take a simplified approach to assessing the funding needs for road asset maintenance. Simplifying the analysis increases the inaccuracy of results. However, in large populations errors tend to even out, and the results are correct on average. At network level the interest is not in individual roads or bridges whose condition predictions may contain large errors in this approach. I have developed tools for quick analysis based on few inputs that can be estimated by practitioners. These tools can be further developed to increase the accuracy of the results, if needed.

My aim is to evaluate the outcome of different maintenance policies. I operationalise this aim by calculating the change in the probability distribution of condition during a planning period for a defined set of policies. I use the network of Portland Cement Concrete (PCC) bridges to illustrate the calculating method. New probabilistic models for bridges have recently been developed in this area by Äijälä & Lahdensivu (2006). Another purpose of selecting the network of PCC bridges for analysis is to provide a test bench for the new models. This method can readily be extended to other road assets, where full socio-economic analysis of management policies has not been possible.

3 Calculation method

The probability distribution of road network into condition categories in year *t* is represented by vector X_t. The change in condition distribution is represented by using the Markovian transition probability matrix P, which is used for multiplying the condition distribution in year *t* to find the condition distribution in the following year *t+1* (see e.g. Heyman & Sobel 1982):

$$X_{t+1} = P^T X_t \,. \tag{1}$$

where ^{T} denotes the transpose of a matrix. The elements P_{ij} of P represent the transition probabilities, where i refers to the condition category in year t and j refers to the condition category in year $t+1$. Part of the network is maintained annually, and part of the network is left to deteriorate. Therefore, the transition probability matrix is divided into two parts, the first indicating the effect of maintenance works, and the latter the deterioration[1]. The elements of the transition probability matrix are calculated as follows:

$$P_{ij} = a_{i,t} M_{ij} + (1 - a_{i,t}) D_{ij} \,, \tag{2}$$

where M_{ij} is the element of the maintenance effect matrix indicating the transition probabilities due to maintenance, D_{ij} the element of the deterioration matrix, and $a_{i,t}$ is the share of road assets in category i that are maintained in year t ($0 \le a_{i,t} \le 1$). The decision variables in the calculation method are the elements $a_{i,t}$.

According to the model, road assets either stay in the initial category or deteriorate to the next poor category, but are not allowed to skip a condition category in one year. Thus, only those elements in the deterioration matrix for which $j = i$ or $j = i+1$ are non-zero. Moreover, the road assets in the worst category stay in that category unless they are maintained. In contrast, the road assets that are maintained are distributed over all categories that are better than the initial category. All elements in the maintenance effect matrix, for which $j \le i$ (the lower triangular matrix) may be non-zero.

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[1] Even though the maintenance works are ideally aimed at the poor sections, in practice some sections in all condition categories are maintained as part of longer maintenance sections. The selected approach to consider the transition probabilities based on the probabilities of deterioration and maintenance effects applies both to the ideal situation and in practice.

This calculation method does not specify the number of condition categories. An user of this method has to only be able to define the categories so that (s)he can calculate the current condition of the assets, and derive the transition probability matrices for the maintenance effects (M_{ij}) and deterioration (D_{ij}). In this context, I use the five-step classification for the condition of the road assets as defined by the Finnish Road Administration (Finnra 2005a). The maintenance effect matrix and the deterioration matrix can be developed from road data banks or in lack of such data, estimated by experience. In this study, I use the recently developed models (Äijälä & Lahdensivu 2006) for deterioration and maintenance effects of concrete bridges using the Finnra's 5-step classification.

The poorer the road asset condition is, the higher the maintenance cost. Maintenance cost is assigned to each condition category, and the total maintenance cost in year t is calculated as

$$C_t = N\sum_{i=1}^{m} x_{i,t}a_{i,t}c_{i,t}, \tag{3}$$

where N is the extent of the network, m is the number of condition categories, $x_{i,t}$ is the share of roads in condition category i in year t, $a_{i,t}$ is as defined in Eq. (2) and $c_{i,t}$ is the maintenance cost in condition category i in year t. The average annual maintenance cost during a selected analysis period is then calculated.

The length of the analysis period can be selected freely, but it is not reasonable to increase the length of the period too much, as the uncertainty in the analysis increases, which makes the results less usable. Bridges are a fairly long-lasting part of road assets, designed typically to last 50 to 100 years of service. In this analysis, I have chosen ten years as the length of the analysis period. Equation (1) is applied 9 times from year t to year $t+9$, and the resulting condition distribution X_{t+9} is used for the comparison of maintenance policies.

Furthermore, it is assumed that a policy is kept unchanged during the analysis period, therefore $a_{i,t}$ is constant for all years t for a condition category i. A more realistic approach would be to let $a_{i,t}$ for a condition category vary from year to year. However, as the original purpose of this method is to evaluate maintenance policies in a rather straight-forward manner, I have kept the approach as simple as possible.

In this method, the funding needs are assessed and the different maintenance policies evaluated solely based on maintenance costs and transition probabilities. This approach makes it possible to also evaluate losses and benefits from different maintenance policies. The losses in year t can be calculated in parallel with the maintenance costs from

$$L_t = N\sum_{i=1}^{m} x_{i,t} L_{i,t}, \tag{4}$$

where $L_{i,t}$ are the losses in condition category i on year t. On paved roads, typically, additional user costs due to road deterioration and maintenance work zones are used as losses in the analysis. For other road assets, losses may be defined in a different manner, e.g. as detours resulting from load restrictions for bridges in poor condition or low-volume roads during spring thaw period. These losses can be monetised as losses of time and additional driving costs to be used in the analysis. However, losses are not considered in the maintenance policy evaluation of concrete bridges that I present in the following section.

4 Alternative maintenance policies

I evaluate the outcome of different maintenance policies for concrete bridges on the Finnish public road network, using the method presented in the previous section. Portland Cement Concrete (PCC) bridges form a major part (80%) of the total surface area of bridges managed by the Finnish Road Administration. They are divided into five sub-networks, depending on whether they are continuous, located in salted roads or not, or made of pre-stressed concrete. The bridge condition is defined by a five-step classification (Finnra 2005a). In the two best categories, routine maintenance is sufficient, whereas in the worst category, the bridge should already have been maintained, and reconstruction may be needed. The optimal time for maintenance is when the bridge is in the second to worst condition category.

I use the recently developed models (Äijälä & Lahdensivu 2006) for deterioration and maintenance effects of concrete bridges using the Finnra's 5-step classification system. The deterioration model for discontinuous PCC bridges on salted roads is shown as an example in Table 1. All the models are shown in Appendix 1. The models are read from left (condition in year *t*) and up (condition in year *t+1*). From the models it can be concluded that:

- The deterioration rate according to the models is fairly slow, especially in condition category 3 (fair), where only 2 % of bridge deck m^2 deteriorate to category 4 (poor) in one year and 98 % stay in category 3. According to Äijälä & Lahdensivu (2006), the models are on the safe side (deterioration is faster than the actual observations), but realistic.
- Reconstruction is targeted at the two worst categories and it always restores condition to category 1, whereas rehabilitation allowed in worst three condition categories improves condition usually only to the second best category. These properties of the models contribute to the success of a Do Worst Policy, as will be seen later.

Table 1. Deterioration model for discontinuous PCC bridges on salted roads (Äijälä & Lahdensivu 2006).

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

The following three simplified scenarios were generated:

- **Alt 1** Current policy of bridge maintenance, documented in (Finnra 2005b): At the first stage, the deterioration of bridge assets is halted. At the second stage, the maintenance backlog is gradually decreased. Objectives are set for the amount of bridges in condition categories 'poor' (4 %) and 'very poor' (1 %) in the year 2010.
- **Alt 2** Preservation policy, whose objective is to minimise the change in condition distribution compared to the initial distribution during the analysis period.
- **Alt 3** A Do Worst Policy: Almost all bridges in the two worst condition categories are maintained, but a small percentage of bridges are left to deteriorate. In addition, 10 % of the bridges in category 3 (‘fair’) are maintained.

These three scenarios were generated using a spreadsheet application and a ten-year analysis period was selected. In the spreadsheet application, the decision variables are typed in and the on-screen result can be evaluated instantly. Spreadsheet optimisation tools are used in the analysis of **Alt 1** and **Alt 2** for minimising the difference between the initial condition distribution and the condition distribution each year in the ten-year analysis period (2006 – 2015). This minimisation is done for each of the five sub-networks separately, and the combined condition distribution is calculated for all sub-networks. In **Alt 1**, the best three best condition categories are considered in the optimisation, whereas the amount of bridges in the worst two condition categories is constrained in the optimisation so that it meets the objectives set for the year 2010. In **Alt 2**, all condition categories are considered.

Bridge deterioration was calculated by only applying routine maintenance on the bridges over the analysis period. According to the models (Äijälä & Lahdensivu 2006), routine maintenance does not improve the condition distribution. This scenario is referred to as **Alt 0**, and it is estimated for two reasons: First, maintenance policies presented above include routine maintenance, whose part of the annual costs is revealed in this way. Secondly, this alternative is used for evaluating the validity of the deterioration models. The result of this analysis for discontinuous PCC bridges on salted roads is shown as an example in Figure 2. It is seen that the deterioration rate using these models in this calculation method is fairly slow, as was concluded from the models themselves (Table 1 and Appendix 1).

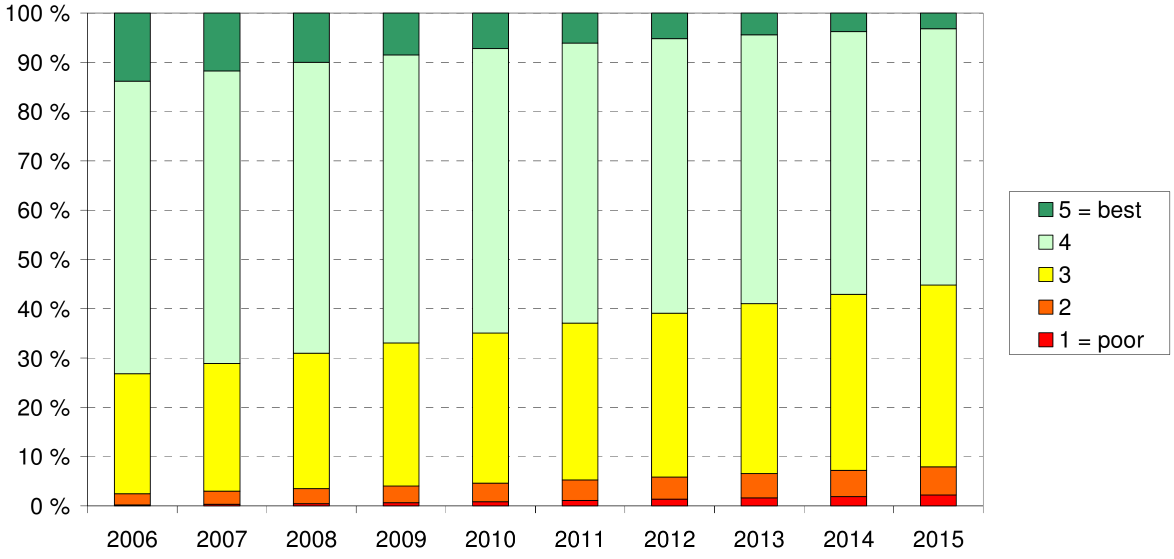

Figure 2. Result from analysis of deterioration model during the 10-year analysis period. Discontinuous PCC bridges on salted roads are used as an example.

The alternative maintenance works are rehabilitation and reconstruction of the bridge. For bridges not rehabilitated or reconstructed, routine maintenance is applied. Thus, equation (2) is extended to:

$$P_{ij} = a_{ireh,t}\mathrm{Reh}_{ij} + a_{irec,t}\mathrm{Rec}_{ij} + (1 - a_{ireh,t} - a_{irec,t})D_{ij}\,, \tag{5}$$

where $a_{ireh,t}$ refers to the share of bridge deck-m^2 rehabilitated each year, and $a_{irec,t}$ to the share of bridge deck-m^2 reconstructed each year. Reh_{ij} and Rec_{ij} represent the elements of maintenance effects matrices for rehabilitation and reconstruction, respectively. For the rest of the bridge assets only routine maintenance is applied that year, but it is not considered to affect deterioration.

The results of this analysis are presented in Figure 2. The average annual maintenance costs over the ten-year analysis period for the alternative policies Alt 1, Alt 2 and Alt 3, are M€ 25.5, M€ 39.7 and M€ 40.8, respectively. In Figure 3, the condition distribution at the beginning and the end of the analysis period is shown for deterioration and the three alternative policies. The Alt 0, where the bridges are left to deteriorate, indicates the costs of routine maintenance, which is M€ 7.6.

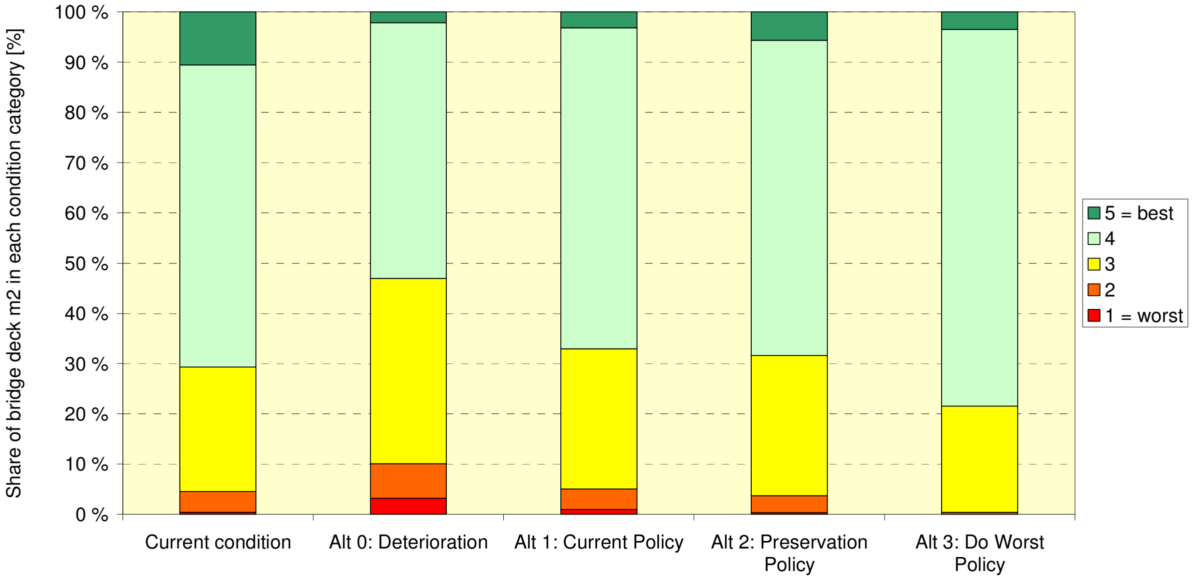

Figure 3. Current condition and condition at the end of the ten-year analysis period with alternative maintenance policies.

5 Discussion

A common result, presented in textbooks, and expected by the author, is that a preventive maintenance policy is superior to other alternatives, especially to a Do Worst Policy. A Do Worst Policy is one where maintenance is concentrated on the parts of assets that have reached (or passed) a maintenance threshold. A preventive maintenance policy, on the contrary, is one where part of maintenance works are carried out before a threshold in technical condition is reached. This is done, because maintenance in an earlier phase of deterioration is less expensive to carry out and it increases the life time of assets and lowers the life cycle costs of maintenance.

The case for preventive maintenance is based on the assumption that the asset condition first deteriorates fairly slowly, and then the rate of deterioration starts to increase before a breakdown in condition. However, as can be seen from Figure 2, the deterioration rate according to the models used here is rather slow. According to the models (Äijälä & Lahdensivu 2006) and the classification (Finnra 2005a) used here the transition probabilities from category 2 (poor) to 1 (very poor) are in the range of 0.94 to 0.96. Recalling that according to the condition classification, category 2 is optimal for maintenance work to be carried out and category 1 is considered 'too late' or even 'shameful', these deterioration models can be considered rather conservative. Accordingly, a feasible solution in favour of a preventive maintenance policy could not be found, and is therefore not presented explicitly.

Furthermore, according to the maintenance effects models (Äijälä & Lahdensivu 2006) rehabilitation allowed in worst three condition categories improves condition usually only to the second best category. Instead, the condition of all reconstructed bridges improves to the best condition category. Reconstruction is allowed only in the worst two categories, and its considerably higher cost seems rather irrelevant as compared to its superior effects to condition. It may be noted that the perceptions of words like 'poor', 'too late' or 'shameful' vary between individuals and organisations. Keeping in mind the relatively high standard of maintenance on the Finnish bridge network, these models may well be considered reliable. Neither is the case for preventive maintenance, supported by a large number of studies, refuted by these results.

The Current Policy (Alt 1) meets the objectives set in (Finnra 2005b), resulting in annual funding need of M€ 25.5. The difference between the initial condition distribution and condition distribution each year in the ten-year analysis period (2006 – 2015) for the three best condition categories is minimised using spreadsheet optimisation tools. In addition, the amount of bridges in the worst two condition categories is constrained in the optimisation so that it meets the objectives in year 2010. This results in 2 – 7 % of the bridge deck-m^2 in the worst three condition categories being rehabilitated. In addition, a fixed amount of 5 % of bridge deck-m^2 in the category 'very poor' is set for reconstruction.

The Preservation Policy (Alt 2), though requiring considerably higher funding (M€ 39.7), does not lead to much better condition distribution than the current one. This is due to the fact that the optimisation model tries to preserve the current condition distribution by minimising the difference between condition distributions at each year of the analysis period and the initial condition, but does not consider a budget constraint in the process. Indeed, introducing a budget constraint, e.g. that maximum funding is the same as in current policy, leads to worse condition distribution at the end of the 10-year analysis period than either the current policy or the initial distribution. Furthermore, referring to the above-discussion on models for deterioration and maintenance effects, the spreadsheet solver used for optimisation reaches a minimum value for the objective function by letting the bridges deteriorate and reconstructing them in the worst two categories. The required funding to do so is high.

The Do Worst Policy (Alt 3) uses approximately same amount of funding (M€ 40.8) as the Preventive Policy (Alt 2), but results in what is clearly the best condition distribution of the considered alternatives. In this policy, reconstruction is assigned to most bridges (>90 %) in the worst condition category and rehabilitation to most bridges in the second to worst condition category. Additionally, 10 % of bridges in the category 'fair' are rehabilitated.

It is possible to reconsider these results by altering the types of maintenance works allowed in different condition categories. This, however, would also require a revision to the set of models. Instead, the results of this study are considered as one test bench for the models developed by Äijälä & Lahdensivu (2006). My conclusion is that these models are conservative but realistic. The maintenance decision, depending on available funds, is to choose a position between the Current Policy (Alt 1) and the Do Worst Policy (Alt 3). In other words, funding should be raised, if possible.

6 Summary and conclusions

Maintenance policy evaluation seeks answers to the following questions: What is the current condition of the road assets? What is the optimal condition of the assets? What are the annual funding needs? In this paper, a simple model is developed that relates the budgets of the alternative policies to their resulting condition distribution at the end of the analysis period by applying a probabilistic approach. The current condition, distributed in categories, is used for multiplying the Markovian transition probability matrix, which is calculated from the deterioration matrix and the maintenance effects matrices.

The method is illustrated using data and models from the PCC bridges, which form the major part of the bridge assets on the Finnish public road network. The results confirm the implications of Äijälä & Lahdensivu's study (2006), that the deterioration according to the models is fairly slow. The Current Policy meets the defined management objectives. Compared to the Current Policy, the Preservation Policy and the Do Worst Policy have to raise 60 percent of their funding needs. The Do Worst Policy leads to clearly the best condition distribution at the end of the analysis period, whereas the Preservation Policy or the Current Policy does not produce any better results.

Preventive maintenance, where part of assets are maintained before reaching a maintenance threshold, is widely considered the most effective and inexpensive policy. However, these results do not seem to endorse this view. The fairly slow deterioration rate and maintenance effects according to the models developed in (Äijälä & Lahdensivu 2006) result in a solution where it is most effective to reconstruct bridges in poorest condition and rehabilitate bridges that have passed maintenance threshold. Keeping in mind the relatively high standard of maintenance, however, these results are not contrary to the widely endorsed case for preventive maintenance. The choice then should be (depending on available funding) between the Current Policy and the Do Worst Policy. It should be concluded that the selected approach is a practical tool for finding an appropriate maintenance policy when the target for condition distribution has been set elsewhere.

6 References

Finnra (2005a). Standardized Classification for the Condition of the Road Assets. Helsinki 2005. Finnra Reports 57/2005. 45 p. ISSN 1459-1553, ISBN 951-803-617-9, TIEH 3200969-v. (In Finnish with English summary.)

Finnra (2005b). Siltojen ylläpito. Toimintalinjat. (The bridge maintenance policy.) Helsinki 2005. 29 p. + app. 7 p. (In Finnish.)

Golabi, K., Kulkarni, R.B. & Way, G.B. (1982). A State Wide Pavement Management System. Interface Magazine 12:6, 1982.

Heyman, D.P. & Sobel, M.J. (1982). *Stochastic Models in Operations Research, Volume I.* McGraw-Hill, ISBN 0-07-028631. p. 207

Hudson, W.R., Haas, R. & Uddin, W. (1997), Infrastructure Management. McGraw-Hill, 1997. ISBN 0-07-030895-0.

Äijälä, M., & Lahdensivu, J. (2006), Developing models for bridges for network level and project level systems. Helsinki 2006. Finnish Road Administration. Finnra Reports 27/2006. 43 p. + app. 57 p. ISSN 1459-9871, ISBN 951-803-731-0, TIEH 3201003. (In Finnish with abstract in English.)

7 Appendices

Appendix 1. Deterioration and maintenance effects models for Portland Cement Concrete (PCC) bridges according to Äijälä & Lahdensivu (2006).

Discontinuous PCC bridges on salted roads

Total bridge deck area 517 742 m2

Current condition

Category	5	4	3	2	1
% in each category	13.8 %	59.3 %	24.3 %	2.3 %	0.2 %

Deterioration model

Transition probability matrix

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Cost €/m2

Maintenance action

Condition category	**Routine maint.**	**Rehab**	**Reconst**
5	3		
4	3		
3	3	350	
2	3	450	1300
1		500	1300

Continuous PCC bridges on salted roads

Total bridge deck area 831 070 m2

Current condition

Category	5	4	3	2	1
% in each category	8.0 %	57.0 %	27.0 %	6.0 %	1.0 %

Deterioration model

Transition probability matrix

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.85	0.15	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Condition category	Cost €/m2 **Maintenance action** **Routine maint.**	**Rehab**	**Reconst**
5	3		
4	3		
3	3	350	
2	3	450	1300
1		650	1300

PCC bridges on unsalted roads

Total bridge deck area 890 600 m2

Current condition

Category	5	4	3	2	1
% in each category	6.0 %	61.0 %	28.0 %	5.0 %	0.0 %

Deterioration model

Transition probability matrix

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	0.86	0.14	0	0	0
4	0	0.975	0.025	0	0
3	0	0	0.985	0.015	0
2	0	0	0	0.96	0.04
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

	Cost €/m2 **Maintenance action**		
Condition category	**Routine maint.**	**Rehab**	**Reconst**
5	2		
4	2		
3	2	300	
2	2	400	1300
1		450	1300

Prestressed PCC bridges on salted roads

Total bridge deck area 515 963 m2

Current condition

Category	5	4	3	2	1
% in each category	15.4 %	60.2 %	21.1 %	2.9 %	0.4 %

Deterioration model

Transition probability matrix

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

	Cost €/m2 **Maintenance action**		
Condition category	**Routine maint.**	**Rehab**	**Reconst**
5	3		
4	3		
3	3	350	
2	3	450	1300
1		750	1300

Prestressed PCC bridges on unsalted roads

Total bridge deck area 192 800 m2

Current condition

Category	5	4	3	2	1
% in each category	20.6 %	68.8 %	10.5 %	0.1 %	0.0 %

Deterioration model

Transition probability matrix

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	0.86	0.14	0	0	0
4	0	0.975	0.025	0	0
3	0	0	0.985	0.015	0
2	0	0	0	0.96	0.04
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Cost €/m2

Maintenance action

Condition category	**Routine maint.**	**Rehab**	**Reconst**
5	2		
4	2		
3	2	350	
2	2	450	1300
1		650	1300