Multi-criteria optimization framework for road infrastructures under different scenario of climate change

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Abstract

This paper presents an optimization framework for critical road infrastructure elements that integrates economic aspects. This optimization framework is used to determine optimal management strategies of infrastructures under scenarios of climate change and financial constraints. Optimal management strategies, based on the consequences of possible actions on the future condition of the system, are determined through an optimization process under uncertainty. The aim is to maximize the performance level of structures. Such an optimization procedure is a first step in the development of asset management tools that allow national road administrations to assess the necessary additional effort to satisfy performance constraints under different scenario of climate change. The integration of such concepts in the decision process by national roads administrations represents a step forward in management strategies.

Keywords: Optimization, bridge management, Markov chains, IQOA scoring system, climate change

1 Introduction

The transport system represents a fundamental factor for the economic and social development, as it allows the quick, safe and easy exchange of passengers and freight. For the most part, this mobility is sustained by the network of roads and highways providing high level of service and flexibility. To maintain a high quality of service, there is a significant need for tools which allow national road administrations (NRAs) to better manage their infrastructure stock. The decision to replace or repair these infrastructures, when and how to repair each individual structure, is a common and difficult management issue for asset managers.

In this context, the goal of this paper is to present an overall approach which considers some performance aspects in the decision process for ageing structures, under different scenario of climate change. In order to be easily deployable by national road administrations (NRAs), this framework is built in such a way that it can be embedded into asset management systems that include an inventory of the asset, inspection strategies (to report element conditions and safety defects) and decision-making for funds allocation. In particular, NRAs may have little information on each structure except the results of visual inspections (e.g., condition rating). Proposing an infrastructure management framework based on condition rating is consequently of paramount importance for stakeholders.

The first part of this paper describes how to determine some degradation profiles for infrastructure components (bridge, retaining walls, steep embankments...) depending on their age, traffic volume or environmental conditions. The second part details the proposed concepts to include potential effects of climate change. Finally, this paper describes the optimization procedure which is the core of asset management principles and shows how climate change may impact management strategies.

This approach is developed in the project RE-GEN (Risk assEssment of aGEing iNfrastructure) funded through the CEDR Transnational Road Research Programme Call 2013 “Ageing Infrastructure”. The aim of this project is to facilitate prioritization of infrastructure maintenance strategies considering not only alternative climate change, as presented herein, but also traffic evolution scenarios from a variety of risk perspectives.

2 Description of the proposed model

2.1 Evolution modeling

The objective is to deliver an asset management framework based on visual inspections. The homogeneous Markov assumption is used stating that the condition of a facility at one inspection only depends on the condition at the previous inspection. With such an assumption, the present score is the only one which is taken into account to determine the future condition of the facility. It is noted that the validity of the homogeneous Markovian assumption was investigated by Orcesi & Cremona [1] at the bridge level (the score for each bridge being the worst score among all components at each inspection) on a sample of the French national roadway network. In fact, such an analysis needs to be performed at the scale of infrastructure components for any infrastructure stock before the Markovian assumption can be fully validated.

Assuming this assumption is validated, the first step of the proposed method is to determine the transition matrix associated with the component degradation. Such a transition matrix, noted P_b, (for component b), requires at least two consecutive score records for a large number of individuals at different condition levels and can be applied for components such as expansion joints, waterproofing, deck, bearings and equipments.

Considering a database with scores between years a_0 and a_f, the probability $P_b(q_1,q_2)$ of a component b weighted a characteristic value (e.g. the deck or wall area) to move from score q_1 to score q_2, is defined as the total area rated q_1 at year i and q_2 at year $i+1$ divided by the total area rated q_1 at year i, for i between a_0 and a_f. This probability is expressed as

$$P_b(q_1,q_2) = \frac{\sum_{i=a_0}^{a_f-1}\left(\sum_{k=1}^{n_{q_{1,i}\rightarrow q_{2,i+1}}} A^k_{q_1,i\rightarrow q_2,i+1}\right)}{\sum_{i=a_0}^{a_f-1}\left(\sum_{k=1}^{n_{q_{1,i}}} A^k_{q_1,i}\right)} \quad (1)$$

where $n_{q,1}$ = number of components rated q_1 at year i, $n_{q1,i\text{->}q2,i+1}$ = number of components moving from score q_1 to score q_2 between year i and year $i+1$, $A^k_{q_1,i}$ = area associated with component k scored q_1 at year i and $A^k_{q_1,i\rightarrow q_2,i+1}$= area associated with component k moving from score q_1 to score q_2 between year i and year $i+1$. In matrix P_b, the element in row k and column lrepresents the probability for component b weighted by 1 m^2 of area to move from score k to score l in one year.

Once transition probabilities are determined, the objective is to quantify the performance of each bridge/retaining wall component through the use of an adequate lifetime indicator. This indicator is determined herein by the probability for a component to be scored in a certain condition with time. If (i) the probability of a component q_b^i to be quoted in any score is known at year i (for example, after a visual inspection of the bridge) and stored in a vector q_b^i and (ii) the associated homogeneous markov chain, associated with a transition matrix P_b, is determined, the probability at year i + 1 is given by the following equation:

$$q_b^{i+1} = q_b^i P_b \quad (2)$$

Assuming a homogeneous Markovian process, the scoring probability can then be forecasted if the transition matrix and the initial probability vector are known.

2.2 The IQOA scoring system

The IQOA scoring system (quality assessment of engineering structures), used in France on the non-concessionary state managed national roadway network, is used herein as illustration. The whole process that follows may nevertheless be extended to other scoring systems.

The condition scoring system (3-year inspection process) is part of a more general inspection framework that also includes annual routine inspections and the 6 years detailed inspection program. During an IQOA inspection, several components are inspected: equipments (pavements, footways, cornices, expansion joints, etc.), protecting components (waterproofing layers, anticorrosion coating, etc.) and structural components (deck, supports, bearings, foundations, etc.). By using catalogs of defects, the inspectors are able to provide a score for a particular component and structural. A global score is then defined as the worst score of all components (Table 1).

Table 1. IQOA Scoring system

Score	Apparent condition
1	Good overall state
2	Equipment failures or minor structure damage. Non urgent maintenance needed
2E	Equipment failures or minor structure damage. Urgent maintenance needed
3	Structure deterioration. Non urgent maintenance needed
3U	Serious structure deterioration. Urgent maintenance needed

The difference of defects between IQOA scores 2 and 2E and IQOA scores 3 and 3U is substantial [1]. Scores 2 and 2E represent serviceability defects, while scores 3 and 3U represent structural deficiencies. The main objective of such a tool is to provide a snapshot of individual bridges'/walls condition, and then, a snapshot of the overall bridges/walls stock quality (by aggregating all IQOA scores).

The obtained transition matrix for a bridge deck with a_0=2009 and a_f=2014 is given in the following matrix. This matrix is obtained by considering a sample of reinforced concrete bridges on the French national road network. Similar information is available for other types of bridges (prestressed concrete bridges, steel-concrete composite bridges etc), and for various components (expansion joints, waterproofing, bearings etc.). It should be noted that values under the diagonal line correspond to actual maintenance activities and values over the diagonal line are linked to the degradation of the structure.

$$\begin{pmatrix} 0{,}837 & 0{,}138 & 0{,}021 & 0{,}004 & 0 \\ 0{,}038 & 0{,}919 & 0{,}036 & 0{,}007 & 0 \\ 0{,}012 & 0{,}068 & 0{,}907 & 0{,}013 & 0 \\ 0{,}003 & 0{,}091 & 0{,}054 & 0{,}843 & 0{,}009 \\ 0 & 0 & 0{,}061 & 0{,}068 & 0{,}870 \end{pmatrix} \quad (3)$$

The same approach can be applied to retaining walls and slopes to determine the probability matrix for the different components.

3 Climate change modeling

3.1 Quality indicators

In the context of climate change resulting in an increased frequency of extreme weather conditions, it is important to take them into account in the model. The constraints of infrastructure owners also have to be considered. Condition scores should enable quality indicators, LP, associated with operational or reputational criteria, to be assigned, since the owner may wish to avoid some of the condition states, or at least to minimize the percentage of structures which are scored in these condition states. Some target values for quality indicators used in [1], expressed as a percentage of the entire bridge stock deck area, are provided in the third column of Table 2.

3.2 Impact of climate change

In order to model the impact of exceptional degradation events due to climate change, several matrices that suddenly deteriorate the component to the worst condition and may lead to a major structural failure of some part of the structure or even to the full collapse are added to the optimisation framework.

Table 2. Target values of the quality indicators [1]

Index	Objective	Target value
LP1=1+2	Routine maintenance to prevent repairs	≥ 55%
LP2=2E	Specialized maintenance to prevent repairs	≤ 30%
LP3=3+3U	Structural maintenance to prevent collapse	≤ 15%
LP4=3U	Urgent structural operation to prevent disruption and to ensure safety of the road network	≤ 1%

Such matrices model several kinds of climate change degradation. The most common events that may impact infrastructure assets are flooding, higher rainfall intensities and higher temperatures. In most cases the impacts arising from climate change could not be foreseen. The biggest risk, according to the PIARC technical committee [2], seems to be an increase of intensity and frequency of heavy rainfall which affects flooding and scouring of bridge foundations. Some countries have observed several bridge collapses due to floods. Other countries have experienced an acceleration in deterioration of concrete structures, especially in edge beams, due to large temperature changes (e.g. Lithuania). It is difficult to link damage on structures clearly and uniquely to climate change, but to avoid further damage on structures in the future there is a need to review design codes.

In the proposed approach, the impact of climate change on the scoring system is introduced through additional pure degradation transition matrices. Corresponding to the different possibilities of extreme events, several additional degradation matrices are introduced. The positions of the value 1 in these matrices are associated with a particular degradation. For example the transition matrix CM_1, for which a component scored either in 1, 2 or 2E moves to score 2E, is associated with a major degradation of the corresponding equipment.

$$CM_1 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (4)$$

The transition matrix CM_2 is associated with an event which decreases by one unit the condition score of a component.

$$CM_2 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5)$$

The transition matrix CM_3 is associated with an event which moves the condition of a component to its worst value.

$$CM_3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (6)$$

Intensity coefficients and frequency of the events are associated with each matrix to characterize optimistic to pessimistic scenarios. It is proposed in this paper to qualify an optimistic scenario as a scenario for which the event CM_1 occurs every 5 years on 1% of the stock, and CM_2 occurs every 10 years on 2% of the stock. Besides, the pessimistic scenario is based on event CM_1 occurring every 5 years on 3% of the stock, CM_2 occuring every 10 years on 2% of the stock and CM_3 occuring every 15 years on 2 % of the stock.

These values are chosen arbitrarily and a thorough sensitivity analysis will be required before drawing conclusions. Such values are used in this paper essentially to give a first insight of the potential impact of such events at the scale of the asset.

4 Optimization framework

4.1 Maintenance strategies

Several prospective scenarios can be defined in the proposed framework. These scenarios can give priority either to preventive or corrective actions, or both, with a view to controlling the budget and to ensuring the preservation of the asset. For example, these scenarios can be the "continuation of the current policy", or the introduction of "constraints on some performance indicators (related to risk)", or the introduction of "constraints on risk indicators and on the annual maintenance budget". Such a last scenario will aim at determining optimal maintenance strategies associated with a constant annual budget.

Each maintenance strategy is associated with a transition matrix. For example in the case of concrete deck for reinforced concrete bridges (Equation 3), the current maintenance strategy, noted S_1, is associated with the matrix

$$S_1 = \begin{pmatrix} 0{,}837 & 0{,}138 & 0{,}021 & 0{,}004 & 0 \\ 0{,}038 & 0{,}919 & 0{,}036 & 0{,}007 & 0 \\ 0{,}012 & 0{,}068 & 0{,}907 & 0{,}013 & 0 \\ 0{,}003 & 0{,}091 & 0{,}054 & 0{,}843 & 0{,}009 \\ 0 & 0 & 0{,}061 & 0{,}068 & 0{,}870 \end{pmatrix} \quad (7)$$

If the objective of another strategy is systematically to upgrade scores i to j, the term *(i,j)* of the transition matrix S_1 is fixed at 1 and other terms in the *ith* row of the corresponding matrix are set to 0. The current maintenance strategy that enhances maintenance actions on bridge deck scored 2E and 3U is noted S_2 and the associated transition matrix is

$$S_2 = \begin{pmatrix} 0{,}837 & 0{,}138 & 0{,}021 & 0{,}004 & 0 \\ 0{,}038 & 0{,}919 & 0{,}036 & 0{,}007 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0{,}003 & 0{,}091 & 0{,}054 & 0{,}843 & 0{,}009 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix} \quad (8)$$

Another strategy can be to systematically restore bridge deck scored 3U to the "as new" condition. The associated transition matrix is then

$$S_3 = \begin{pmatrix} 0{,}837 & 0{,}138 & 0{,}021 & 0{,}004 & 0 \\ 0{,}038 & 0{,}919 & 0{,}036 & 0{,}007 & 0 \\ 0{,}012 & 0{,}068 & 0{,}907 & 0{,}013 & 0 \\ 0{,}003 & 0{,}091 & 0{,}054 & 0{,}843 & 0{,}009 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (9)$$

4.2 General framework for optimization

4.2.1 Theory of the model

The objective of this framework, based on that proposed in [1], is to determine the optimal annual combination of the different strategies to maintain the infrastructure stock in good condition with limited budgets. A new challenge herein is to include the effects of climate change and traffic increase in the procedure and to see how it impacts financial allocation in a long-term perspective. The corresponding procedure is detailed hereafter.

Each year i=1…n-1, where n = number of years considered in the maintenance planning, a vector $X_{S_j}^i = {}^t\begin{pmatrix} X_{S_j,1}^i & X_{S_j,2}^i & X_{S_j,2E}^i & X_{S_j,3}^i & X_{S_j,3U}^i \end{pmatrix}$ is associated with the strategy S_j. The term $X_{S_j}^i(k) = X_{S_j,k}^i$ represents the proportion of infrastructures scored k for which strategy S_j is applied at year i. The vector q^{i+1} at year i+1 is obtained from that at year i as follows

$$q^{i+1} = q^i M_i \qquad \forall\, i = 1, \dots, n-1, \quad (10)$$

where

$$M_i = \sum_{j=1}^{m} \begin{pmatrix} X_{S_j,1}^i & & 0 \\ & \ddots & \\ 0 & & X_{S_j,3U}^i \end{pmatrix} S_j \quad (11)$$

and *m* = number of possible transition matrices, with constraint that

$$\sum_{j=1}^{m} X_{S_j,k}^i = 1$$

$$\forall\, i = 1, \dots, n-1, \forall k \in \{1,2,2E,3,3U\} \quad (12)$$

S_j can represent not only the various maintenance scenarios considered by the owner, but also the exceptional degradation matrices due to climate change or those due to traffic increase. The fractions $X^i_{S_j,k}$ associated with such additional degradation will serve as control parameters to test different assumptions of climate change/traffic increase scenarios (pessimistic, mean, optimistic) and will not be used as variables in the optimization process.

Conversely, the fractions $X^i_{S_j,k}$ associated with decisions of the owner will be the variables in the optimization process. They will be determined in such a way that the condition of the component remains above a minimal threshold and that the costs are as low as possible. The constraint on $X^i_{S_j,k}$ ensures that, taking into account the fraction of infrastructures that are analyzed, the final matrix M_i verifies the property

$$\sum_{q=1}^{5} M_i(p,q) = 1$$

$$\forall\, i = 1, \dots, n-1, \forall p = 1, \dots, 5 \qquad (13)$$

Each strategy S_j (a strategy S_j is entirely defined by the associated transition matrix S_j, as previously mentioned) is associated with a cost vector

$$C_{S_j} = {}^{t}\left(C_{S_j,1} \quad C_{S_j,2} \quad C_{S_j,2E} \quad C_{S_j,3} \quad C_{S_j,3U}\right)$$

where the *kth* element of C_{S_j} $(k \in \{1,2,2E,3,3U\})$ is

$$C_{S_j}(k) = \langle {}^{(\delta_{1,k} \quad \delta_{2,k} \quad \delta_{2E,k} \quad \delta_{3,k} \quad \delta_{3U,k})S_j,}_{(\delta_{1,k} \quad \delta_{2,k} \quad \delta_{2E,k} \quad \delta_{3,k} \quad \delta_{3U,k})C} \rangle \qquad (14)$$

and where S_j = *jth* strategy matrix (j=1 or 2 herein), $\langle \dots \rangle$ = scalar product notation, and $\delta_{l,k}$ = Kronecker function.

The annual cost

$$C_a(i) = A_T \sum_{j=1}^{m} \sum_{k\in K} X^i_{S_j}(k) C_{S_j}(k) q^i_k \qquad (15)$$

is the sum of all the costs from the different strategies for each year *i*, where $K = \{1,2,2E,3,3U\}$, $X^i_{S_j}(k) =$ fraction of infrastructures with score *k* concerned by strategy S_j at year *i*, $C_{S_j}(k)$ = cost of the strategy S_j for bridge/retaining wall component scored k and q^i_k = percentage of the component scored *k* at year *i*. The problem consists in minimizing $C_a(i)$ every year i of the planning:

Find $X^i_{S_j}$ $\quad \forall j = 1 \dots m, \forall i = 1 \dots n-1$

To Minimize $C_a(i)$ $\quad \forall i = 1 \dots n-1$

such that $\{LP > LP_0 \quad i = 1 \dots n$ (16)

where *LP* stand for the levels of performance, and *n* = number of years in the planning.

Several methods exist to solve the optimization problem. The algorithms are generally referred to as constrained nonlinear optimization or nonlinear programming. They attempt to find a constrained minimum of a scalar function of several variables starting at an initial estimate. Genetic algorithms can also be used, in particular when several objective functions are considered (criteria to be minimized or maximized). In particular, NSGA-II (Non-dominated Sorting in Genetic Algorithms) program developed in [3] can be used to find optimal solutions set of multi-objective optimization problem. The fitness assignment scheme of NSGA-II consists in sorting the population in different fronts using the non-domination order relation. To form the next generation, the algorithm combines the current population and its offspring generated with the standard crossover and mutation operators. Finally, the best individuals in terms of non-dominance and diversity can be chosen in the set of optimal solutions called Pareto solutions. From this set, the decision maker can choose the best possible compromise among available financial resources, necessary safety and condition levels, and acceptable levels of structural deterioration.

4.2.2 Results of the model for climate change

The example of concrete deck for reinforced concrete bridges is considered in this section to show the influence of the climate change. The optimization problem of Equation 16 is solved for the two configurations of climate change defined in section 3.2 and results are shown in Figures 1 to 4. In particular, Figures 1 and 2 highlight the impact of such scenario on the evolution of the quality indicators defined in Table 2. For the pessimistic scenario, the occurrence of sudden degradations has a dramatic impact on each indicator, in particular with events CM_3 (every 15 years). In an optimistic scenario the impact is lower but nevertheless present.

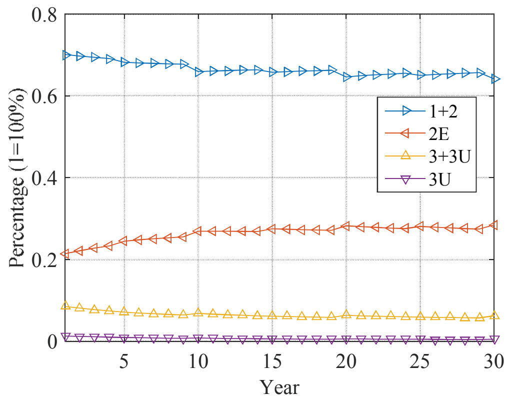

Figure 1. Evolution of the IQOA indicators – Optimistic scenario

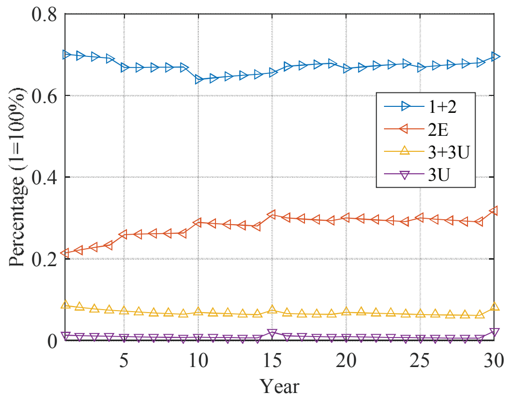

Figure 2. Evolution of the IQOA indicators – Pessimistic scenario

Figures 3 and 4 show the efforts that a manager will have to consider each year to satisfy the quality indicators in Table 2 at the time horizon. It reflects the cost corresponding to each maintenance strategy (S_1, S_2 and S_3). They are directly linked to the deterioration of the bridges. When looking at the event that occurs at year 15, it is observed that to offset the effect of additional degradations due to climate change, investments following the S_2 and S_3 strategies must be radically increased.

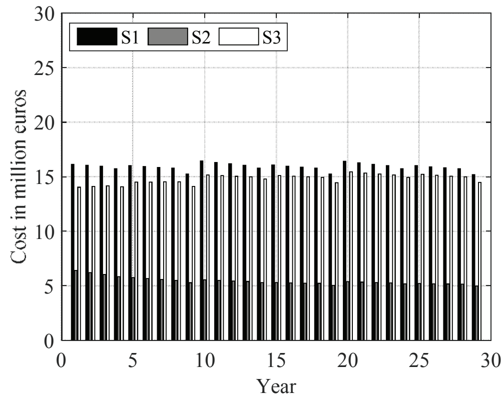

Figure 3. Annual cost maintenance – Optimistic scenario

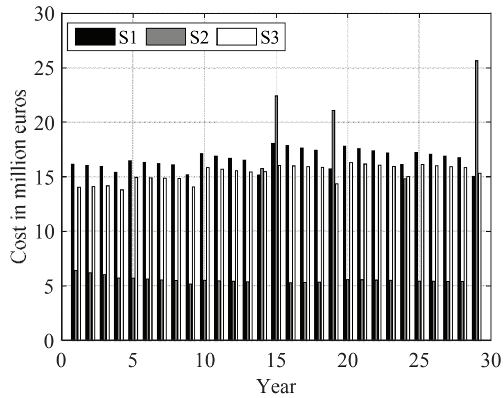

Figure 4. Annual cost maintenance – Pessimistic scenario

5 Conclusions and perspectives

Using as input the inventory of the asset and condition assessment, the method presented in this paper aims at determining some degradation profiles for bridges, retaining walls and slopes, depending on age of infrastructures, traffic volume or environmental conditions. The method to determine the degradation process is detailed so that any infrastructure managers can determine their own deterioration processes based on the inventory and condition assessment of their stock. Once the degradation profiles are determined, they are used to characterize how the performance of structures evolves with time. Different types of hazards are then considered including the potential impact of climate change. As mentioned in section 3.2, the additional degradation matrices, the intensity coefficients and the frequency of extreme events are chosen arbitrarily in this paper as the purpose herein is to give a first insight of the potential impact of such events at the scale of the asset. A thorough literature survey is needed to better calibrate these parameters and, ultimately, propose a probabilistic approach that catches uncertainties associated with each parameter. More precisely, the aim will be to assess how climate change is more or less likely to increase the occurrence and to vary the location of some physical events, which in turn will affect the exposure faced by communities, as well as their vulnerability [4]. In particular, concerning landslides, it is planned to use the European Landslide Susceptibility Map [5,6] which provides levels of spatial probability of generic landslide occurrence at continental scale for most of the European Union and several neighbouring countries. For Extreme windstorms and flooding that are among the most important natural hazards affecting Western Europe, some recent studies [7,8] will be considered, respectively, to assess return periods from European windstorm/flooding series in a changing climate.

Optimal management strategies, based on the consequences of possible actions on the future condition of the system, can then be determined through an optimization process. The aim is to minimize maintenance costs while maximizing the performance level of structures. Such an optimization procedure should allow national road administrations to assess the necessary additional effort to satisfy performance constraints under different scenarios of climate change.

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