Usage Dependent Rehabilitation and Maintenance Model for Special Engineering Structures

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Abstract*: The authors developed a new Pavement Management Model where the deterioration model is based on Markov transition probability matrix. This model take into consideration the changing traffic in each planning period. This model could be generalized. The maintenance and rehabilitation planning process which is used in this PMS model can be used in case of several engineering structures. This paper summarize the conditions of usage and the element of the algorithm. The benefit of the proposed methodology is illustrated by two practical examples which is related to the Pavement Management System.*

Keywords*: deterioration model, pavement management, optimization*

1 Introduction

With the recognition that the engineering structures maintenance and repair needs far exceed the resources available to address these needs, many firms have to turn to the development of ESMS (Engineering Structures Management System). The ESMS is a method to improve the allocation of these limited resources and the condition of their engineering structures. The ESMS is based on performance modeling because of without the actual condition of the structures and the future deterioration process any model could not be build up.

In its basic term the ESMS refers to the careful allocation of funds available for these purposes: maintenance, repair and rehabilitation to ensure that the funds are used in their most effective way. Specifically an ESMS is a rational and systematic approach to organizing and carrying out the activity related to planning, designing, constructing and replacing structures.

The one part of the total ESMS is a computer program. The software associated with an ESMS should provide the following functions:

- A database which contains the necessary information needed for this purposes including inventory and inspection data, and information related to maintenance, repair, and rehabilitation actions and effectiveness. This base contains historical data (deterioration past and future maintenance and rehabilitation actions, cost, etc.).
- A mayor maintenance, rehabilitation and replacement component, which contains the actions and its prices, etc.
- Heuristic or optimization procedure which gives the cheapest maintenance and rehabilitation actions.
- Deterioration model which determine the future condition state of an engineering structure depending on the actual condition state and the time period.

A deterioration-based model was presented for Road Management in [4]. Some other elementary optimization model was given by Schmidt [5].

2 Deterioration Models

The quality of an engineering structure (or part of it) usually does not stay constant over time. It deteriorates throughout the service of life. The service of life can be estimated from [2]:

- empirical experience,
- database which contains time series,
- using performance models,
- laboratory testing.

Other approaches is given in [1] when these have been categorized into four types

- subjective, where experience is captured a formalized or structured way to develop deterioration prediction model,
- purely mechanistic based on some primary response or behavior parameter,
- regression, where the dependent variables of observed or measured deteriorations is related to one or more independent variables,
- mechanical-empirical, where the form of required equation is defined, based on mechanistic principles, to relate a dependent variable to measured deterioration.

So we can group the used methods into two basic type: deterministic and probabilistic. In the deterministic models the condition is predicted as a precise value on the basis of mathematical functions of observed or measured deterioration. This class includes several approach: mechanistic, regression, mechanistic-empirical, etc. In the probabilistic models the condition is predicted as a probability function of a range of possible conditions.

Two type of probability functions can be used [3], the probability distribution and the Markov transition distribution matrix. The probability distribution is a continuous function given in Figure 1. This shows the probability of condition index being greater than a given value in relation to the age of the structure. This type of function is sometimes known as a survivor curve.

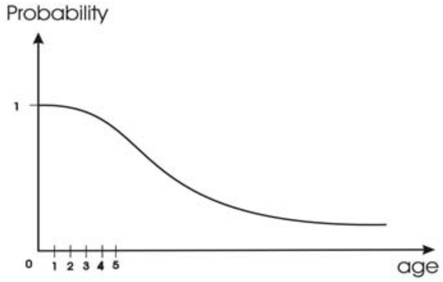

Figure 1
Probability distribution

With the help of that probability distribution function we can determine the deterioration function too [3]. In Figure 2 the horizontal axis is the time and vertical one illustrates the quality condition.

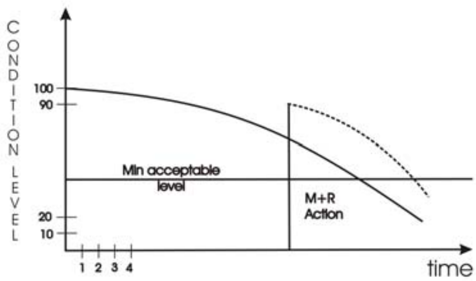

Figure 2
Performance curve and M+R action

The initial condition and they quality are near to the top of the scale. That is near 100%. A minimum acceptance level must also be set. It will vary with many factors, such as class of facility, agency policy, safety and economics. A maintenance or rehabilitation action at any time cans extent the service of life at a facility.

For the determination of the deterioration curve serial time series is needed. If there is not available we use the Markov matrix.

To create the matrix first we divide the possible conditions into discrete condition states. The condition state can be divided for example 10 stages 10%, 20%, 30%, …100%. At any point in time probabilities are given for the likelihood of the structure being in each condition states and there are defined in a "transition matrix". This matrix is used to predict the condition state after a time period (year, 2 years or more years).

Let us denote this matrix by **Q**. The q_{ij} element of matrix **Q** is the transition probability from state i to state j. This structure assumes that the condition after a time period state or deteriorate to some lower state. Several methods are known to determine the matrix Q. The most commonly used approach for estimation of transition probabilities is the linear regression method, but it can be determined by a Poisson regression model or by negative binominal regression

3 Optimization Model

In order to demonstrate the usage of the deterioration model in ESMS we choose the deterioration and maintenance of car parts [6].

In our model the following denotation will be used

- The type of the engineering system(cars): **tip** (tip_1, …, tip_m, …, tip_M) – for example Volvo autobus, etc., *m* is the type index, *M* is the number of types.
- The number of each car types contents the **db** vector $(db_1, db_2, \ldots, db_M)$.
- The number of different parts of the certain cars signs *N*. We can suppose that the number of parts at the car types is equal. Here we see the parts no elementary parts (screw,…), but bigger, common repairable unit (brakes, steering-gear, etc.). Signe r_{mn} the number of *n*-th parts of *m*-th types car. These means, we have in all $db_m \cdot r_{mn}$ piece such part.
- The parts can be in different states. The condition of a part is described by different types of deterioration parameters (for example visual characterization, result of instrumental monitoring). Signe the number of states parameters with *S*. Note 1 denotes the best, and note 4 denotes the worst condition: perfect – note 1, fault, does not disturb the normal use – note 2 , fault, disturbs the normal use – note 3, useless – note 4.
- The altering of the condition, the deterioration depends on the other factors – for example efficiency, transported amount – too. Denotes the number of different values of theses *F*, the adequate index let be *f.*

- The possible maintenance types are denoted with vector **p** $(p_1,\ldots,p_k,\ldots,p_K)$ – k is the index, K is the number of possible maintenance operations. The intervention can be simple repairing, the change of a smaller unit, the change of a bigger unit or the change the car part.
- In case of the multiperiod algorithm the index of year is t, the number of years is T.

The size of the vectors and matrices depend on the number of parameters and the different values of parameters. If the number of parameters is S and the number of different notes is 4, then the number of possible stage is S^4, for example if $S=4$ than 4^4=256. It means, the size of vectors is 256, the number of elements of matrix is $256 \cdot 256$. Denote the size of matrix L.

This number determines the size of the unknown variable vector **Z**, the element of this vector denote proportion. The number of **Z** vectors is $M \cdot N \cdot F \cdot K \cdot T$.

The l-th element of vector $\mathbf{Z_{mnfkt}}$ shows the car parts belonging to m, n, f, k, t indexes and is in the l-th condition, that how many percent of this part the p_k maintenance must be realized. This element is z^l_{mnfkt} , or $(\mathbf{Z_{mnfkt}})^l$. We use an upper index, if we refer an element of vectors or matrices.

Let us denote the Markov transition probability matrix by $\mathbf{Q_{mnfk}}$ which belongs to n-th part of the m-th type car, the f-th running efficiency and the k-th maintenance action. The number of different matrices is $M \cdot N \cdot F \cdot K$, the number of rows and columns of matrices is the number of quality condition stages, L. The l-th element of i-th row of $\mathbf{Q_{mnfk}}$ matrix is q^{il}_{mnfk} , or $(\mathbf{Q_{mnfk}})^{il}$ gives the probability that if the car parts which at the starting time is in i-th stage, at the end of the planning period get into the l-th condition stage.

Let us denote the unknown vector $\mathbf{V_{mnft}}$, that gives the fraction of those engineering systems(car parts) which belongs to the n-th parts of the m-th type, to the f-th running efficiency at the end the t-th time period.

Let us denote the vector $\mathbf{b_{mnf}}$, which gives the fraction of the different condition stages of the n-th parts of the m-th type, belong to the f-th running efficiency at the starting time of planning.

There are several conditions to fulfill. The first condition (1) is related to the fraction of the engineering systems (car parts) at the initial year:

$$\sum_{k=1}^{K} \mathbf{U}\mathbf{Z_{mnfk1}} = \mathbf{b_{mnf}},\ m=1,2,\ldots,M\ \ n=1,2,\ldots,N\ \ f=1,\ldots,F \tag{1}$$

where **U** $L \cdot L$ size unit-matrix. We must choose such a **Z** vector in first year, which gives the starting $\mathbf{b_{mnf}}$ vector in case of all car types, all parts and all running efficiency.

The second condition defines the vector $\mathbf{V_{mnf1}}$ (2), the fraction of structures, of the car parts at the end of the first planning:

$$\sum_{k=1}^{K}\mathbf{Q_{mnfk}}\mathbf{Z_{mnfk1}} = \mathbf{V_{mnf1}}, \quad m=1,\dots,M \quad n=1,\dots,N \quad f=1,\dots,F \tag{2}$$

The next condition (3) applies to the mediate years. This means, that the $\mathbf{V_{mnft}}$, the fractions at the end of t-th time period gives the starting distribution for the (t+1)-th period. For each year the following conditions must be fulfilled:

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\mathbf{UZ_{mnfk(t+1)}} - \mathbf{V_{mnft}} = \mathbf{0}, \quad f=1,\cdots,F \quad k=1,\dots,K \quad t=1,\dots,T-1 \tag{3}$$

This condition defines the unknown $\mathbf{V_{mnft}}$ vector.

One of the maintenance policies has to be applied (4) for every structure (car parts) in each year:

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}\mathbf{Z_{mnfkt}} = \mathbf{1}, \quad t=1,\dots,T\ . \tag{4}$$

The car parts are divided into 3 groups: acceptable (good), unacceptable (bad) and the rest. Let us denote the three set by G the good, R the bad and E the set of other structures and by H the whole set of structures. The following relations are realizing to the sets:

$$\begin{aligned} &G \cap R = \varnothing \qquad G \cap E = \varnothing \\ &R \cap E = \varnothing \\ &G \cup R \cup E = H \end{aligned} \tag{5}$$

The following conditions (6) are related to these sets in the initial year

$$\begin{aligned} &\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfk1}})^l \geq \alpha_1\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}(\mathbf{b_{mnf}})^l, \quad l \in G \\ &\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfk1}})^l \leq \alpha_2\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}(\mathbf{b_{mnf}})^l, \quad l \in R\text{'} \\ &(\underline{\mathbf{b}}_E)^l \leq \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfk1}})^l \leq (\overline{\mathbf{b}}_E)^l, \quad l \in E \end{aligned} \tag{6}$$

where

- G, R, E are given above,
- $\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}(\mathbf{b_{mnf}})^l, \ l \in G$ the fraction of structures in the good set before the planning period,

- $\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfk1}})^l,\quad l \in G$ the fraction of structures in the good set after the first year,
- $\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}(\mathbf{b_{mnf}})^l,\ l \in R$ the fraction of structures in the bad set before the planning period,,
- $\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfk1}})^l,\quad l \in R$ the fraction of structures in the bad set after the first year
- $\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfk1}})^l,\quad l \in E$ the fraction of structures in the other set after the first year,
- $\underline{\mathbf{b}}_E$ the lower bound vector for the fraction of structures in the other set,
- $\overline{\mathbf{b}}_E$ the upper bound vector for the fraction of structures in the other set,
- α_1 and α_2 given constants.

The first condition means that amount of the car parts in the “Good” set must be more or equal than a given value, in this case this is proportional with the starting quantity. The second condition does not allow that after first year the amount of the car parts in the “Bad” set can be more than a certain percent of the starting amount. The third condition gives lower and upper bound for the other car parts after first year.

For the further years similar inequalities (7) could be used

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\mathbf{Y_{ijt}}\ \mathbf{R}\ \sum_{i=1}^{I}\sum_{j=1}^{J}\mathbf{Y_{ij(t+1)}},\quad t = 1,2,\ldots,T-1 \tag{7}$$

where **R** could be one of the relations <, >, =, <=, >= and these relations could be given in connection with each condition states (e.g. each rows could have different relations).

Instead of (6) and (7) condition states could be applied for the end (8) of the planning period (e.g. for *t*=*T*) :

$$\begin{aligned}
&\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfkT}})^l \geq \alpha_1\sum_{i=1}^{I}\sum_{j=1}^{J}(\mathbf{b_{mnf}})^l,\quad l \in G\\
&\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfkT}})^l \geq \alpha_2\sum_{i=1}^{I}\sum_{j=1}^{J}(\mathbf{b_{mnf}})^l,\quad l \in R\\
&(\underline{\mathbf{b}}_E)^l \leq \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}(\mathbf{Q_{mnfk}}\mathbf{Z_{mnfkT}})^l \leq (\overline{\mathbf{b}}_E)^l,\quad l \in E
\end{aligned} \tag{8}$$

Beside the condition for the states at all maintenance exercise is very important the cost factor. As far as possible we must to work such a maintenance strategy, which fulfills the conditions for the states and it has the lowest cost.

Let us denote by vector $\mathbf{C_{mnfk}}$ the unit cost vector of the maintenance policy *k,* belongs to the *n*-th part of the *m*-th type car in case of *f*-th running efficiency. The elements of vectors show that in case of certain qualification state how much would it cost to make a unit of the maintenance action.

We can formulate more different conditions in connection with costs. One of them is the yearly budget bound of each maintenance action:

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F} r^{(t-1)}\mathbf{C_{mnfk}}\mathbf{Z_{mnfkt}} = r^{(t-1)}M_k, \quad t=1,\dots,T \quad k=1,\dots,K \tag{9}$$

where r is the interest rate, $\mathbf{C_{mnfk}}$ is the unit cost vector of the maintenance policy *k*, of the *n*-th part of *m*-th car type, belong to *f*-th running efficiency and M_k is the budget bound available for maintenance policy *k* in the initial year.

Now the objective of the problem is formalized. The objective (10) is to minimize the total cost of maintenance:

$$C = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}\sum_{t=1}^{T}\mathbf{Z_{mnfkt}}\mathbf{C_{mnfk}} \to MIN\ ! \tag{10}$$

If the yearly available B sum is given, then we can formulate two further conditions in connection with the budget bound.

The budget bound condition for the initial year:

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}\mathbf{Z_{mnfk1}}\mathbf{C_{mnfk}} \le B\ . \tag{11}$$

The conditions for further $t = 2,3,\dots,T$ years are the following (12):

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K} r^{(t-1)}\mathbf{Z_{mnfkt}}\mathbf{C_{mnfk}} \le r^{(t-1)}B\ . \tag{12}$$

Besides the minimization of the maintenance costs we could aim to minimize the user's costs. The user's costs depend on the type of car, on the car parts and on the running efficiency. Let us denote this user's cost-vector by $\mathbf{K_{mnf}}$. The *l*-th coordinate of the vector belongs to the *l*-th qualification state. ($1 \le l \le L$, in our example it is 256).

The objective function of the minimization of users costs is the following (13):

$$C = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{t=1}^{T}\mathbf{V_{mnft}}\mathbf{K_{mnf}} \to MIN\ ! \tag{13}$$

Often it is practical to handle the two type of costs together and to write a combined objective function. We can do this the following way (14):

$$C = \alpha \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{k=1}^{K}\sum_{t=1}^{T} \mathbf{Z_{mnfkt}} \mathbf{C_{mnfk}} + \beta \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{t=1}^{T} \mathbf{V_{mnft}} \mathbf{K_{mnf}} \rightarrow MIN \qquad (14)$$

Here we optimize in case $\alpha = 0$ only the user's costs, in case $\beta = 0$ only the maintenance costs. So we can decide arbitrary objective functions with the different value of two parameters. This model was demonstrated in [7].

4 Examples for the Application Areas of New Model

In order to illustrate the practical use and benefit of the proposed methodology, two examples are presented.

The about 150 km-long section of road No. 6 between Dunaújváros and Pecs is an important arterial road of Hungary. A parallel motorway M6 had been built and opened to traffic in 2010. As a consequence, the traffic size of "old" road No. 6 had been significantly decreased. Table 1 compares the originally considered (forecasted) traffic evolution compared to the actual one (basically modified after the opening to traffic of motorway M6). The date time series of heavy traffic (ESAL) is given additionally to AADT values due to its major role in pavement deterioration.

Table 1

The originally considered (forecasted) traffic evolution compared to the actual one (Case 1)

Year	Projected		Actual		Difference (%) in	
	AADT	ESAL	AADT	ESAL	AADT	ESAL
2005	10502	801	10502	8010	0	0
2006	10712	817	10782	830	+0.7	+1.6
2007	10926	833	11123	898	+0.8	+7.8
2008	11144	850	11135	1311	-0.1	+54.2
2009	11368	867	12676	1155	+11.5	+33.2
2010	11595	884	5613	410	-51.6	-53.6

A traffic growth factor of 2% was considered in 2005 for AADT and ESAL, as well. The actual AADT-values registered by WIM-measurement results are almost the same as the projected ones in the period between 2006 and 2009. However, the ESAL-values (number of daily equivalent 10-ton axle loads) are basically different from the forecasted ones (differences ranges from -53.6% to +54.2%).

After the opening of parallel motorway section, both AADT and ESAL values have been decreased to the half of the projected ones.

Another example can be also shown to demonstrate the importance of the consideration of actual traffic size in road asset management. The case of a Hungarian main road No. 47 (km 12+000-15+000) can illustrate the effect of the creation of a new logistical centre to the traffic evolution of the road considered. Table 2 presents the actual and projected traffic evolution in the period between 2005 and 2010.

Table 2
Comparison of Forecasted and Actual Traffic Evolutions of a Hungarian Main Road (Case 2)

Year	Forecasted		Actual		Difference (%) in	
	AADT	ESAL	AADT	ESAL	AADT	ESAL
2005	10482	751	10482	751	0	0
2006	10692	766	10747	843	+0.5	+10.1
2007	10905	781	9674	766	-11.3	-2.8
2008	11124	797	11903	1831	+7.0	+129.7
2009	11346	813	12296	1765	+8.4	+117.1
2010	11573	829	11901	2336	+2.8	+181.8

In this case, also 2% traffic growth factors were applied in 2005. The logistical centre in the section of km 15+000 started to operate in November 2007 creating a very significant additional heavy traffic in the road considered. Consequently, 117-182% “unexpected” traffic growth could be detected in the period after 2007. (The changing in AADT is not important.)

Both examples are illustrative in introducing how important is to identify and consider the real (actual) traffic volumes in road asset management.

5 Some Concluding Remarks

The national economy importance of successful and efficient management of valuable road assets is evident. The relevant management decisions can be more effective in the long-term if reliable, accurate background information are based upon. The pavement management models forecast the future road pavement performance influenced, among others, by the actual traffic load (especially the number of heavy axle loads passed). The suggested advanced model considers the usage of elements in order to take into account the more accurate deterioration parameters every year of investigation period (planning horizon). As a consequence, the managerial decisions can be more efficient and cost-effective contributing to the better quality of the structures and reducing the life cycle costs.

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