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Application of a bivariate deterioration model for a pavement management optimization

Mariem Zouch[a], Thomas Yeung[a], Bruno Castanier[a] and Tristan Lorino[b,*]

[a]*LUNAM Université, École des Mines de Nantes, 4 rue Alfred Kastler, 44307 Nantes, France*
[b]*LUNAM Université, Ifsttar, F-44341 Bouguenais, France*

Abstract

This work is a part of a research project for the development of new condition-based approaches for road maintenance optimization. The degradation pattern on interest is here the longitudinal cracking process due to cumulative fatigue (the traffic repetition leads to the occurrence of cracks in the road basement which grows up to the road surface). In this context, we have proposed a new theoretical deterioration model based on two dependent indicators -the observable deterioration measurement and the potential deterioration growth. Even if the construction of the model is based on practical considerations, its application in an operational context remains difficult.
The objective of this communication is to study the applicability of such a model and propose some improvements. After analyzing the original model to highlight its strengths and limitations, we propose to revisit the definitions of the decision parameters while specifying the construction of the associated functions. A statistical inference procedure is discussed. A numerical example based on the original maintenance model is presented to illustrate the benefits of this approach that we will present as some “best practices” for future road pavement management.

Keywords: Imperfect maintenance; Markov decision process; Road maintenance.

1. Introduction and longitudinal cracking maintenance problem

To control the ever-decreasing budgets given the size of networks to maintain and the complexity of the road maintenance context, the pavement maintenance decision is usually based on computerized systems generally defined in four levels from the inventory to the maintenance planning models, through

* Corresponding author. Tel.: +33 (0)2 40 84 56 18; fax: +33 (0)2 40 84 59 92.
E-mail address: tritan.lorino@ifsttart.fr.

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the pavement condition assessment and the road degradation model, see Shahin (1994). A lot of research is still conducted for improving these Pavement Maintenance Systems, especially into the two correlated last levels: degradation models and maintenance. From Shahin (1994), the most used techniques for the construction of degradation models are the linear extrapolation, the statistical regressions, the structural reliability models, the random variable probability distributions, Markov chains and expert systems. These techniques can be classified according to the degree of knowledge modeled onto the degradation mechanism from the pure statistical approaches without any degradation consideration to the structural reliability models based on both the explanation of the stress-strength relationship and the mechanical properties of the considered material. One of the issues in degradation modeling for maintenance optimization is to provide the best trade-off between the degradation fitness and the guarantee of solving the complex decision optimization problem.

The use of stochastic processes especially the Gamma processes for modeling the cumulative degradation (see van Noortwijk (2007) for a survey in the Gamma process applications for maintenance optimization of structures or infrastructures in Civil Engineering) offers a good compromise. Stationary Gamma processes in maintenance optimization have been intensively studied during this last decade but one of its main limits is the linear-trend assumption in the degradation behavior. Non stationary Gamma processes have been introduced but they increase the complexity of the decision rule (both based on the condition and the age of the system) and an inextricability of the optimization problem, Nicolaï et al. (2009).

Pavement structure is made up of several layers, and its degradation is usually broken down into two main categories: surfacing and structural deterioration. In this communication, we focus on the longitudinal cracking, which is the primary indicator that matters in pavement maintenance policy. Although longitudinal cracking is followed up in surface by high-efficiency pavement evaluation equipment, the cracking process often starts in lower layers, especially in the case of longitudinal cracking. Consequently the modelling of cracking process in order to predict the pavement evolution in long term comes up against the lack of knowledge of the initiation of cracking. Henceforth statistical approaches are often chosen to take into account the unknown variability of the cracking process (Leroux 2004, Khraibani, 2009).

The objective of this communication is to improve the applicability in an operational context of the degradation model proposed in Zouch et al. (2011a). The main idea of the model is to add information on the state of the underlying road layers by integrating an instantaneous Degradation Growth Rate. Their approach is similar to the Markers approach developed in the Reliability topic for studying the relationship between observables and failures, p. 225 in Singpurwalla (2006). Even if their model presents several advantages, one of the main issues remains its lack of applicability in an operational pavement management. Two issues of improvement are discussed here.

The remainder of this paper is organized as follows. Section 2 provides a pros- and cons- analysis of the bivariate cracking model for maintenance optimization. Section 3 presents the new model and a discussion on the statistical estimation procedure. Section 4 is devoted to highlight the benefits of the approach in decision-making. We propose to present these benefits such some “good practices” for both the construction of new degradation models and future data collection. Finally, we conclude this communication by the presentation of the future work.

2. Analysis of the bivariate cracking model

After a brief description of the theoretical degradation model presented in Zouch *et al.* (2010), we propose first to resume the strengths of their model and we analyze some aspects which can be seen as weaknesses for the operational implementation.

The main contribution of the Zouch *et al.* (2011a) degradation model is the definition of a new bivariate stochastic model defined by the observable cracking information contained in the existing road databases and a new non observable variable called *Deterioration Growth Rate* (DGR). This DGR is defined as an instantaneous potential cracking function of the states of the basement layers and modeled by bilateral gamma process for tackling positive and negative variations of the DGR increments onto a time interval. The surface cracking information and the DGR are mutually dependent (the development of the cracks on the road surface is a function of the DGR and the observation of the cracking increment in a time interval gives some information onto the behavior of the non observed DGR). They have also defining the state-dependent gamma process which can be seen as an extension of the classical stationary gamma process used for degradation modeling to fit the specific non linear behavior of the cracking indicator. Furthermore, different works have been done for taking into account the non observation of the DGR in the maintenance decision framework, Zouch *et al.*(2011b).

The introduction of the DGR presents several advantages. First, their model allows to ensure some mathematical properties onto the gamma process which justify its interest in the cumulated degradation modeling. Secondly, the time-stationary property which is equivalent to the non-dependence in time for the degradation process allows to define some efficient decision rules only based on the road condition (no information such as the road age is needed). The authors claim an improvement in the fitting of the degradation process with the addition of expert knowledge, including the importance of the underlying layer cracking. This point also finds its interest in the maintenance modeling and its impact onto the future road behavior. Let remind that maintenance leads to reset the cracking indicator to zero without considering the road as new. Hence, the maintenance efficiency will be directly measurable on the DGR parameter. The last but not the least advantage of the proposed model is a general framework to a section-to-section decision. Classical maintenance models are only based on the average degradation characteristics estimated from the whole sample and provide general decision rules.

One of the main difficulties of the model consists in the estimation of the respective conditional degradation laws. They propose an empirical construction and state that classical Maximum Likelihood Estimation procedure can be used for estimating the different parameters. We think that, even with a great amount of data, it would be quite difficult to get good quality estimation. One of the reasons would be the non observable nature of the information given by the DGR process. For reducing the number of parameters in the estimation process, they propose to take benefit of the mathematical property of the bilateral gamma process which can be seen as the difference of two independent gamma processes. Nevertheless, this decomposition can lead to confusion in the definition of the degradation growth rate by bringing it closer to the average speed of degradation observed on the time interval than an instantaneous rate. Finally, the confusion in the DGR definition leads us to believe a lack of applicability of their method in an operational context.

3. Methodology

The objective of this section is to describe an extension of the Zouch *et al.* (2011a) methodology for improving the applicability of their model. First, the general ideas of the methodology is presented before discussions on the statistical inference procedure.

3.1. Mathematical model

The observable cracking measure provided by the current French IQRN database for longitudinal cracking is the linear percentage of cracking of 200m road sections. Initiation phase -where no cracks are observable on the road surface- and propagation phase have to be considered from a modeling point of view. Hence, during initiation phase, the deterioration indicator remains to zero and grows during the propagation phase from 0 to 100% with a classical *S*-shape form, Fig. 1.

The crack initiation on the surface is modeled as a homogenous Poisson Process with a given occurrence rate. In the propagation phase, the stationary state-dependent gamma process defined in Zouch *et al.*(2011a) for tackling the non linear trend of the degradation can be seen as a successive homogenous gamma process where the parameters are updated given new observation, see red lines in Fig. 1 for illustration. The curve in Fig. 2 presents the respective expected deterioration increment in a given time interval as a function of the current deterioration observation ρ.

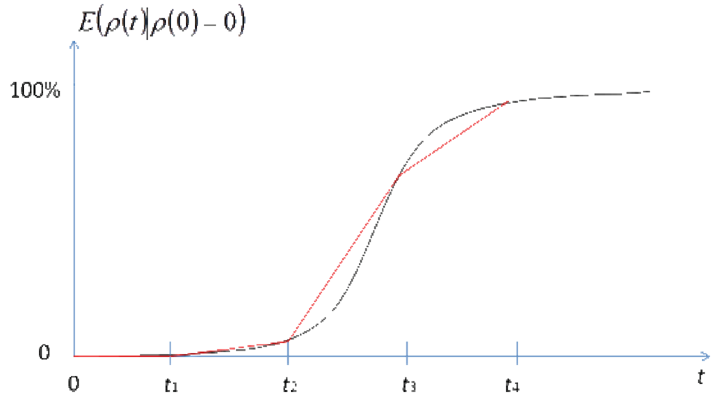

Fig. 1. Linear approximation of the S-shaped PFL curve

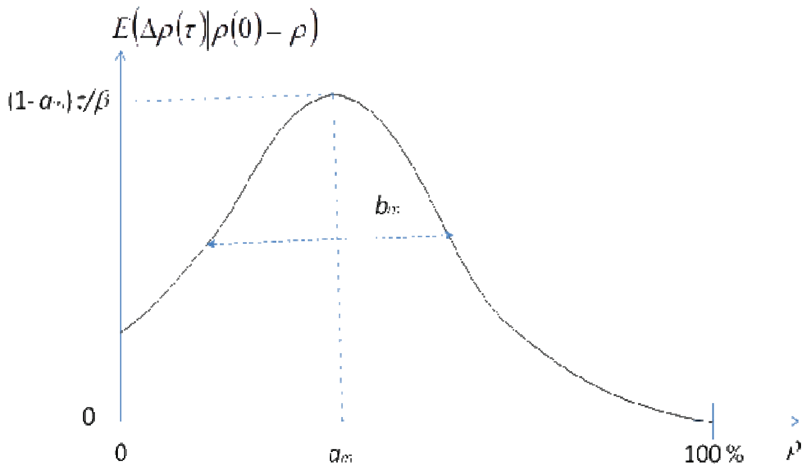

Fig. 2. Shape function for the expected increment in a time interval as a function of the current observation - am = mode position, β = control parameter for the mode value, bm = control parameter for the standard deviation

Several shape functions for the expected increment can be proposed but they have to fit with expert opinion. We propose here the following function:

$$E(\Delta\rho(\tau)|\rho(0)=\rho)=(1-\rho)\frac{\exp\left(-\frac{(\rho-a_m)^2}{b_m}\right)}{\beta}\tau \tag{1}$$

where the expression $(1-\rho)\exp\left(-\frac{(\rho-a_m)^2}{b_m}\right)\tau$ is the shape function of the state-dependent gamma process and β the associated scale parameter. The parameters a_m and b_m control respectively the mode value and the standard deviation of the function. Degradation rate is faster in the low degradation levels and is decreasing to zero when it tends to 1, Rèche (2004).

Longitudinal cracking process remains quite slow and stationary in time. Moreover, we consider a strong unit-to-unit variability that cannot be tackled by the single-parameter deterioration model. A unit-to-unit corrective factor θ is introduced as a metric between the specific expected cracking behavior of one given road section to the expected average behavior estimated with the entire sample. This θ-factor cannot be considered as known but current observation gives partial information on its value. The θ-factor is modeled as a Gaussian random variable where mean $\hat{\mu}_\theta(\tau|\rho_1,\rho_2)$ and variance $\hat{V}_\theta(\tau|\rho_1,\rho_2)$ are the following respective functions of the two successive observations (ρ_1,ρ_2) in a time interval τ:

$$\begin{cases}\hat{\mu}_\theta(\tau|\rho_1,\rho_2)=\beta\dfrac{\rho_2-\rho_1}{(1-\rho_1)\cdot\tau}\exp\left(\dfrac{(\rho_1-a_m)^2}{b_m}\right)\\ \hat{V}_\theta(\tau|\rho_1,\rho_2)=\beta^2\dfrac{\rho_2-\rho_1}{(1-\rho_1)\cdot\tau}\exp\left(\dfrac{(\rho_1-a_m)^2}{b_m}\right)\end{cases} \tag{2}$$

These two functions directly come from the derivations of the expected gamma-distributed deterioration growth and its respective variance. The gamma distribution parameters are the shape function $\alpha(\tau|\rho,\theta)=\theta.\exp(-(\rho-a_m)^2/b_m).\tau$ and the scale parameter β.

Fig. 3 sketches the prediction of the degradation level $\tilde{\rho}_4$ at t_4 given the two last consecutive states ρ_2 and ρ_3. With the ρ_2 and ρ_3 values, the two quantities $\hat{\mu}_\theta(\tau|\rho_2,\rho_3)$ and $\hat{V}_\theta(\tau|\rho_2,\rho_3)$ are computed. After updating the deterioration law (green dashed-line curve), the next cracking percentage $\tilde{\rho}_4=\rho_3+E\left(\Delta\rho(\tau)|\rho_3,\hat{\theta}=\hat{\mu}_\theta(\tau|\rho_2,\rho_3)\right)$ is estimated. If no updating is taking into account (black full-line curve), an overestimation for the expected deterioration will be done.

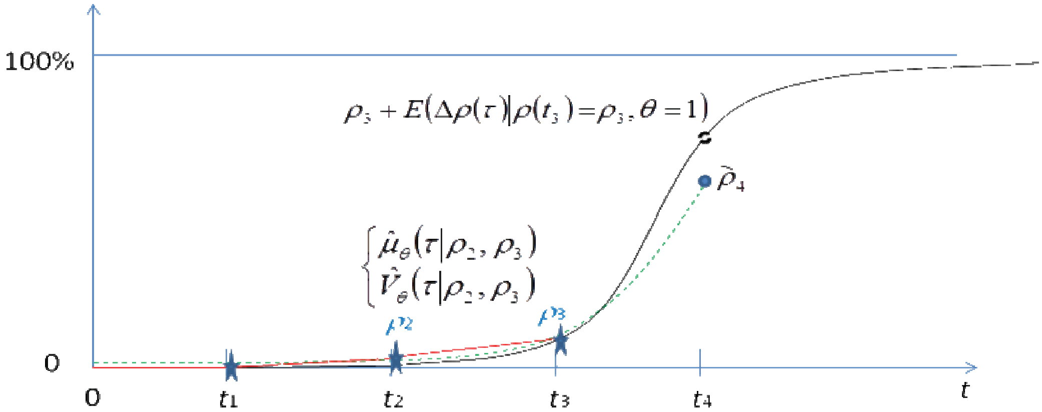

Fig. 3. Cracking prediction process

With these assumptions, the probability transition function in the propagation phase from any state (ρ_1, θ_1) to any state (ρ_2, θ_2) with $\rho_2 > \rho_1 > 0$ in a τ time interval, $h_\tau(\rho_2 - \rho_1, \theta_2 | \rho_1, \theta_1)$, can be directly written in respect to the Bayes conditional probability formula:

$$h_\tau(\rho_2 - \rho_1, \theta_2 | \rho_1, \theta_1) = h_\tau(\theta_2 | \rho_1, \rho_2) \cdot g_\tau(\rho_2 - \rho_1 | \rho_1, \theta_1) \tag{3}$$

where $g_\tau(\rho_2 - \rho_1 | \rho_1, \theta_1)$ is the state-dependent gamma density function and $h_\tau(\theta_2 | \rho_1, \rho_2)$ is the classical Gaussian density function with $\widehat{\mu}_\theta(\tau|\rho_2, \rho_3)$ and $\widehat{V}_\theta(\tau|\rho_2, \rho_3)$.

3.2. Statistical estimation framework

Before describing the statistical inference approach, some assumptions on the different parameters are discussed. For sake of simplicity, the scale parameter β is assumed to be constant whatever the type of the road. Differences in the roads (loads, thicknesses, materials, etc.) are tackled in the a_m and b_m coefficients. Structural properties of the roads are very important in the way the cracking process evolves: a thicker road, for example, would be less sensitive in cracking both in the initiation phase and the beginning of the propagation phase with a low speed of degradation than a thinner one.

Hence, the first step of the inference process will be to make a classification of the roads according to the degradation characteristics and expert knowledge. Note that this classification is important because they will be the reference set for estimating the impacts of the different maintenance actions onto the degradation process. For each section j of a m-type of road, we record the crack level ρ_i^j at time t_i and the next increment $\Delta\rho_i^j$. Finally, the set of values $\{(\rho_i^j, \Delta\rho_i^j, m), i \in \mathbb{N}, j \in \mathbb{N}, m \in \mathbb{N}\}$ forms the sample.

The respective occurrence rates per group can be easily estimated by the classical Maximum Likelihood Estimation (MLE) method for right- and left-censored data.

For the propagation phase, a two-step estimation procedure is proposed. The first step is the estimation of the β parameter with the entire sample (all of m samples). Getting the β estimator, the second step is to provide the a_m and b_m estimators for each respective samples (m is fixed). The two steps are based on the MLE without considering the θ-factor ($\theta = 1$). For each of them, classical MLE for gamma parameters should be adapted in two ways:

1. The state-dependence introduces some numerical complexities in the optimization problem because the probability density functions in the likelihood are function of the ρ_i^j and do not allow the simplification in the expression of the log-likelihood.
2. The ρ-values are bounded by 100%. So we have to consider some truncated gamma distributions for the increments. The stochastic EM algorithm will be used for the re-construction of the censored information.

4. Maintenance modeling and optimization

A repair leads to restore completely the surface of the road by a two-phase process: partial or complete milling and resurfacing with the same or thicker layers. Hence, not all the entire section is renew and the non maintained layers will really influence the future cracking process. Fig. 4 sketches the underlying cracking process for a new (Fig. 4.a and 4.b) and maintained (Fig. 4.c and 4.d) roads and the associated maintenance impact when the thickness of the road, e, remains constant. Each subfigure represents at different time a vertical cut of a road section and the associated percentage cracking level at each depth of the structure. A maintenance conducting to renew a e_1 road thickness is performed (Fig. 4.c) and the cracking process starts again (Fig 4.d).

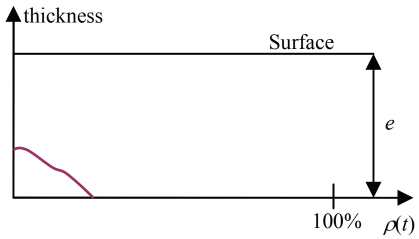

Fig. 4.a Craking initiation in undelying layers

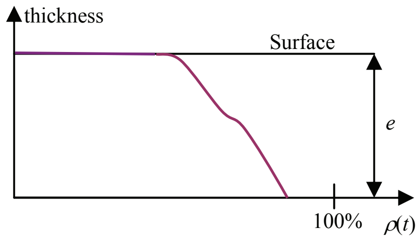

Fig. 4.b Surface cracking

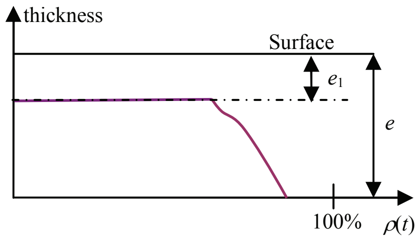

Fig. 4.c Repair : milling and resurfacing

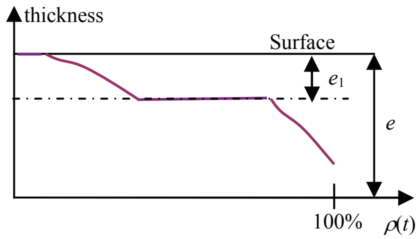

Fig. 4.d cracking process after maintenance

Fig. 4. The two-phase cracking process and maintenance effect

We propose here to keep the same assumptions on the maintenance efficiency than Zouch *et al.* (2011a). The maintenance decision consists in choosing an action in a finite set of actions $\{MX_k, k = 0, 1, \ldots, m\}$ where MX_0 represents the *Do Nothing* (*DN*) decision and $\{MX_k, k > 0\}$ the different available repairs. The repair cost and efficiency are increasing in *k*. Only a repair *k* changes the state of the road to $\rho = 0$ (no crack on the surface) and $\theta_k(\rho, \theta)$ where (ρ, θ) defines the state just before maintenance. The degradation becomes a function of the last performed maintenance, i.e. the a_k and b_k parameters in the gamma shape function remain constant until the next maintenance.

The maintenance optimization problem leads finally to select the best action for each state of the road for minimizing a long-term discounted maintenance cost. The construction of the decision criteria is equivalent to Zouch *et al.* (2011a) model except for the one-step state transition function (see Eq. (3) subsection 3.1). Mathematical developments based on Markov Decision Process theory are not proposed in this communication paper. We invite the reader to see Zouch *et al.* (2011a).

For highlighting the benefits of the approach, a numerical experiment presented in Zouch *et al.* (2011a) is discussed here. The optimization procedure leads to the construction of optimal decision matrices (one matrix per each category of maintenance). Each matrix provides the optimal decision for the current cracking percentage ρ and the average cracking growth in the last decision interval $\bar{\theta}$ given the last performed maintenance *k*.

The figures in the 4 matrices in Fig. 5 refer to the maintenance action to perform, namely 0 for Do Nothing, 1 to 3 for imperfect maintenance actions $MX_{1\text{-}3}$ and 4 for the perfect restoration in the "as good as new" condition. For instance, if the class of the section is 1 ($k = 1$) and the current observations are $\rho = 40$ % and $\bar{\theta} = 0.6$, then the optimal decision will be to maintain with MX_3.

k=1

ρ \ $\bar{\theta}$	.03	.1	.2	.3	.4	.5	.6	.7	.8	.9
.9	2	2	2	3	3	3	4	4	4	4
.8	2	2	2	3	3	3	3	3	4	4
.7	1	2	2	3	3	3	3	3	3	4
.6	1	2	2	2	3	3	3	3	3	4
.5	1	1	2	2	3	3	3	3	3	4
.4	1	1	2	2	3	3	3	3	3	4
.3	1	1	2	2	3	3	3	3	3	3
.2	1	1	2	2	2	3	3	3	3	3
.1	1	1	1	2	2	3	3	3	3	3
.03	0	0	1	2	2	3	3	3	3	3
0	0	0	1	2	2	3	3	3	3	3

k=2.

ρ \ $\bar{\theta}$	.03	.1	.2	.3	.4	.5	.6	.7	.8	.9
.9	2	2	2	3	3	3	3	4	4	4
.8	2	2	2	3	3	3	3	3	4	4
.7	2	2	2	3	3	3	3	3	3	4
.6	1	2	2	2	3	3	3	3	3	4
.5	1	1	2	2	2	3	3	3	3	4
.4	1	1	2	2	2	3	3	3	3	4
.3	1	1	2	2	2	3	3	3	3	3
.2	1	1	2	2	2	3	3	3	3	3
.1	0	1	1	2	2	3	3	3	3	3
.03	0	0	0	2	2	3	3	3	3	3
0	0	0	0	2	2	2	3	3	3	3

k=3

ρ \ $\bar{\theta}$	.03	.1	.2	.3	.4	.5	.6	.7	.8	.9
.9	2	2	2	3	3	3	3	4	4	4
.8	2	2	2	3	3	3	3	3	4	4
.7	1	2	2	3	3	3	3	3	3	4
.6	1	2	2	2	3	3	3	3	3	4
.5	1	1	2	2	2	3	3	3	3	4
.4	1	1	2	2	2	3	3	3	3	4
.3	1	1	2	2	2	3	3	3	3	3
.2	1	1	2	2	2	3	3	3	3	3
.1	0	0	0	2	2	3	3	3	3	3
.03	0	0	0	0	2	3	3	3	3	3
0	0	0	0	0	2	2	3	3	3	3

k=4

ρ \ $\bar{\theta}$	.03	.1	.2	.3	.4	.5	.6	.7	.8	.9
.9	2	2	2	3	3	3	3	4	4	4
.8	2	2	2	2	3	3	3	3	4	4
.7	0	0	1	1	3	3	3	3	3	4
.6	0	0	0	1	3	3	3	3	3	4
.5	0	0	0	0	0	0	0	3	3	4
.4	0	0	0	0	0	0	0	0	3	3
.3	0	0	0	0	0	0	0	0	0	3
.2	0	0	0	0	0	0	0	0	0	0
.1	0	0	0	0	0	0	0	0	0	0
.03	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

Fig. 5. Example of decision matrices for optimal maintenance in respect to the road classification *k*, the current cracking percentage ρ and the average cracking growth per unit of time $\bar{\theta}$.

Even if the numerical results are not provided in the extended case, conclusions should remain close. Comparisons with current road maintenance practices are difficult because, first, maintenance decision is not only based on the single longitudinal cracking condition but on a global notation system including several degradation modes and, secondly, the decision is aggregated in a general road network framework. Nevertheless, the following conclusions can be seen as "good practices" for decision-making in road maintenance.

First of all, even if the mathematics can be judged rather complex, in addition to the strengths of the model discussed in section 2, the methodology shows a real interest in the simplicity of its application in the operational context. It is sufficient for the decision-maker to provide only three simple data: the two last successive cracking levels and the last performed maintenance. The use of generic stochastic processes for modeling general road degradation patterns seems to provide a good trade-off between a pure statistical approach and complex parametric mechanical models of fracture.

The second conclusion refers to the benefit of the introduction of the degradation speed in the decision framework illustrated by the difference in the decisions in each line of the decision matrices. Even this idea seems to be trivial, its implementation in an optimization framework leads to really increase the difficulty in both modeling and solution procedure.

The structural property of the optimal decision joined the intuitive idea of strengthening the maintenance for the most degraded states. However, the construction of such a structure is a priori far from obvious. The problem formulation as Markov decision process allows the study of the optimization problem to define this structure without any prejudice. Nevertheless, we underline here that the existence of such a structure is strongly dependent on the parameter values. Such discussions are provided in Zouch *et al* .(2011b).

4. Conclusion and future works

In this communication, we have studied the applicability of the condition-based maintenance optimization model for pavement management proposed in Zouch *et al.* (2011a). The deterioration pattern of interest is the longitudinal cracking process that reveals structural degradation in road sections. The cracking indicator currently available in the road French database is not self-sufficient for the construction of a predictive cracking model and the impact of the different maintenance actions. Zouch *et al.* (2011a) define a stationary state-dependent stochastic deterioration process by the introduction of a new covariate: the instantaneous deterioration growth rate process. Their definition of this variable and the associated modeling can be seen as a limit for ensuring the applicability of their model in an operational context. We have proposed a new definition of the deterioration growth rate by considering the average observable deterioration speed in a decision epoch and develop the associated mathematics. We have discussed on the statistical estimation framework and the associated procedure.

Even if the results seem to be promising, one of the critical future works is the study of the robustness of the approach toward the field data. However, we doubt the quality of them and will probably have to extend this model to better take into account the uncertainty of data collection. The current model will remain a source of interest to the recommendations of this process.

Moreover, from a modeling perspective, two major issues must be addressed. First, further work to better take into account information from degradation as well as a more appropriate modeling of the effects of maintenance on the DGR variable can be made through the use of advanced results in Bayesian reliability.

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