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A BENCHMARKING APPROACH TO PAVEMENT MANAGEMENT: LESSONS FROM VIETNAM

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1. Introduction

Infrastructure asset management in developing nations is about at the outset of development like that of developed nations in the beginning of economic boom period several decades ago. Thanks to the earlier development in various types of infrastructure technologies in developed nations like the America, Japan, and other European countries, developing countries can take a great advantage in view of technology and management to apply in their nations. As a rule of thumb, in order to introduce foreign technologies into developing nations, technologies need to be verified its adaptability and conformity with local conditions. However, the practice of verification has not yet been seriously considered in actual implementation. Therefore, various types of infrastructure technologies have been simultaneously used. In many cases, developing nations have to spend enormous amount of their resources to compensate the negative impacts of applying unsuitable technologies or to propose national standard and norm of applying foreign technologies in a long term development.

As for the pavement management system (PMS), the quest for selecting the best pavement technology based on material, structure, and construction technique, is realized in high attention, especially in developing nations[1). A good example is the case of Vietnam, where the national road system comprises of many different technologies. Reason to this is, as the matter of fact, due to the lack of technological knowledge, the country often borrowed technologies from abroad. National standards for design and construction practices are somewhat mimic versions of guidelines, most of them are copied from developed nations. This practice is definitely unlike to that of developed nations. Consequently, leads to a huge amount of efforts and budget in monitoring and maintenance during operation phases. Hence, in view of long term and strategic management, there is a strong demand in searching for the best pavement technology, which is hoped to become a national standard in pavement management system.

Selection for the best technology in the PMS is thereby, having a close link to the methodology of benchmarking, which provides a managerial approach for finding out the best practice. Evidently, the core part of benchmarking study in the PMS is the application of hazard model. Because, hazard model is indispensable in estimating the deterioration of a road network, which becomes the most important key performance indicator for benchmarking.

In the network level of PMS, there are many groups of road, which are often categorized by the differences in technology. When applying conventional hazard models, monitoring data of the entire network is considered as a representative database used to predict the deterioration of the entire network system. This practice has its limitation that it is difficult to apply for estimating the deterioration of respective groups in the network. Especially, under the requirement of benchmarking, which aims to compare the deterioration of individual group of road in the network.

In regard to the development of deterioration-forecasting model, in recent years, the application of Markov chain model has been one of the major innovations. Markov hazard model helps users to predict hazard rates, life expectancies, and deterioration curves of infrastructure system such as bridges and highways given the historical observed condition states and characteristic variables concerning various environment impacts such as traffic volume, weather, temperature, axle load, etc. The application of Markov

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chain model has gained its high recognition for its flexibility of modeling and high operational capacity[2), 3)]. However, the study of Markov hazard model to tackle the problem of inhomogeneous sampling population is not numerously documented.

This paper presents an analytical methodology to obtain the heterogeneity factor of individual pavement group based on the local mixture hazard model, and further explore a benchmarking application in order to select the best pavement technology for standardization and long-term application. Special focus is on benchmarking material types in highway system of developing countries, where there is a urgent need to find out the best pavement technologies for long-term application and standardization of practices in design, construction, and maintenance.

The following section gives an overview of research background with focus on Markov chain model and mixture hazard model. Section 3 briefly presents the exponential Markov deterioration hazard model[3)], to which, this study herein builds on. Section 4 details the mathematic formulation of local mixture hazard model and its estimation approach. An empirical study on the national road system of Vietnam is discussed in section 5. Finally, section 6 summarizes the contributions of the paper and further includes a discussion for future research.

2. Background

Markov chain models have been widely applied in the practice of deterioration-forecasting in infrastructure management [4), 5)]. In Markov chain models, the healthy status or performance of an infrastructure component is described in discrete condition states, which are defined by means of single performance index or an aggregate index. The values of indexes are measured by monitoring and visual inspection. For example, in the case of pavement management system, the condition states include the extend of several pavement distress such as rut and cracking, or some aggregate condition states, such as the Pavement Condition Index (PCI) [6)]. The deterioration of an infrastructure component is portrayed as a transition process of condition states along the duration.

Further to the application of Markov chain model in PMS, other prominent studies have addressed the application of some statistic distribution such as Weibull, Gamma, Poison, and Exponential distribution families[3),7), 8)]. In addition, in an effort to capture the hazard rates of different groups in an infrastructure system, heterogeneity factor is embedded in the Markov chain model. The Markov hazard model with embedded heterogeneity factor is named as "Mixture hazard model"[5), 9)].

In the practice of stochastic estimation, the heterogeneity factor is assumed to follow a stochastic distribution. Attempt to apply Gamma distribution for heterogeneity factor in probabilistic approach has been implemented in a larger scale information system, where the breakdown of informative devices follows Weibull function [10)]. This probabilistic approach can also be used to apply on the pavement system. However, the assumption of heterogeneity factor in probabilistic manner may not always reflect the reality. And as the matter of course, an explicit form for the numerical computation may be difficult to acquire. This problem can be regarded as a limitation of probabilistic approach.

In order to overcome the limitation of probabilistic approach, local mixture model is recommended as an alternative solution [5), 11)]. In the local mixture hazard model, the distribution of heterogeneity factor is to follow Taylor series, which eventually reduces the computational complexity. However, to date, it has not been seen in the literature of reliability engineering and operations research with a full scale study on the mixture hazard model, especially in combination with the Markov chain model.

A recent study on risk management in pavement system using local mixture model has attracted attention for benchmarking study on pavement management system [12)]. This study employed Markov chain model for estimating the hazard rate and Markov transition probability. However, it remains with several limitation such as a full scale of benchmarking study was not targeted. Further, empirical study focused only on a small numbers of samples. Thus, the aim of this paper is to propose a comprehensive estimation methodology of local mixture model and its applicability for benchmarking purposes.

3. Markov Deterioration Hazard Model

This section briefly presents the general mathematical formulation of the exponential Markov deterioration hazard model developed by Tsuda et al. (2006)[3)], which is the background model of this paper. In his paper, the healthy status of the road is reflected by condition state i $(i=1,\dots,I)$, with $i=1$ as the new condition state (in sound condition) and $i=I$ as the worst condition state (absorbing condition state). At time τ_0 the condition state is i=1. Over the years, condition state $i(i=1,\dots,I)$ will advance into worse condition states. Visual inspections are carried out at time τ_A and τ_B, and reveal only the actual condition states at inspection times. The true condition states in the period between the two inspection times are unobservable. Based on monitoring data collected from two visual inspections $h(\tau_A)=i$ at τ_A and $h(\tau_B)=j$ at τ_B, the Markov transition probability π_{ij} can be defined as

$$Prob[h(\tau_B) = j \mid h(\tau_A) = i] = \pi_{ij} \,. \tag{1}$$

The life expectancy of condition state i is assumed as a stochastic variable, with the probability density function $f_i(\zeta_i)$ and distribution function $F_i(\zeta_i)$ [5), 12)]. The conditional probability, to which condition state i at time y_i reaching condition state $i+1$ at $y_i + \Delta_i$, can be expressed as hazard function $\lambda_i(y_i)\Delta y_i$:

$$\lambda_i(y_i)\Delta y_i = \frac{f_i(y_i)\Delta y_i}{\tilde{F}_i(y_i)} \,, \tag{2}$$

where $\tilde{F}_i(y_i) = 1 - F_i(y_i)$ is referred as the survival function of condition state i during the time interval from $y_i = 0$ to y_i. It is assumed that the deterioration process satisfies the Markov property and the hazard function is independent of the time instance y_i. Thus, we can define a fixed value for $\lambda_i > 0$ as the hazard rate.

$$\lambda_i(y_i) = \lambda_i \,. \tag{3}$$

The life expectancy of condition state i, which advances longer than the duration y_i, is referred as the value of survival function $\tilde{F}_i(y_i)$ and can be expressible in the exponential form:

$$\tilde{F}_i(y_i) = \exp(-\lambda_i y_i) \,. \tag{4}$$

The survival probability function is identical to the transition probability π_{ii} when the duration y_i equals to the duration z of the inspection period z_i between $[\tau_A : \tau_B]$:

$$\tilde{F}_i(\tau_A + z \mid \zeta_i \geq \tau_A) = Prob\{\zeta_i \geq \tau_A + z \mid \zeta_i \geq \tau_A\} = \frac{\exp\{-\lambda_i(\tau_A + z)\}}{\exp(-\lambda_i \tau_A)} = \exp(-\lambda_i z) \tag{5}$$

$$Prob[h(\tau_B) = i \mid h(\tau_A) = i] == \exp(-\lambda_i z) \tag{6}$$

By defining the subsequent conditional probability of condition state j to i, with respect to the actual interval time z of inspection, a general mathematical formula for estimating the Markov transition probability can be defined:

$$\pi_{ij}(z) = Prob[h(\tau_B) = j \mid h(\tau_A) = i] = \sum_{l=i}^{j} \prod_{m=i}^{l-1} \frac{\lambda_m}{\lambda_m - \lambda_l} \exp(-\lambda_l z) \,, \tag{7}$$

where

$$\sum_{l=i}^{j} \prod_{m=i}^{l-1} \frac{\lambda_m}{\lambda_m - \lambda_l} \exp(-\lambda_l z) = \sum_{l=i}^{j} \prod_{m=i}^{l-1} \frac{\lambda_m}{\lambda_m - \lambda_l} \prod_{m=l}^{j-1} \frac{\lambda_m}{\lambda_{m+1} - \lambda_l} \exp(-\lambda_l z) \text{, and } \begin{cases} \prod_{m=i}^{l-1} \frac{\lambda_m}{\lambda_m - \lambda_l} = 1 & (l = i) \\ \prod_{m=l}^{j-1} \frac{\lambda_m}{\lambda_{m+1} - \lambda_l} = 1 & (l = j) \end{cases} .$$

Transition probability from condition state i to absorbing condition state I is eventually defined in the following equation:

$$\pi_{iI}(z) = 1 - \sum_{j=i}^{I-1} \pi_{ij}(z) \, (i = 1, \cdots, I-1) \,. \tag{8}$$

4. Local Mixture Hazard Model

(1) Markov transition probability and heterogeneity factor

In reality, it is hard to grant a homogeneous sampling population in monitoring data. To express the inhomogeneous sampling population, a great deal of research in reliability engineering and operations research employs the term "heterogeneity factor". In PMS, it is assumed that the entire network of roads consists of total K groups of roads. The grouping classification is often based on the differences in technology. In each group $k(k=1,\ldots,K)$, the total of road sections are S_k. The heterogeneity factor of an individual group is denoted as ε^k, which infers the change of hazard rate of condition state $i(i=1,\ldots,I-1)$ with respect to the pavement section $s_k(s_k=1,\ldots,S_k)$. With this assumption, the formula of hazard function in equation (3) can be expressed by means of the mixture form:

$$\lambda_i^{s_k} = \tilde{\lambda}_i^{s_k}\varepsilon^k (i=1,\cdots,I-1; k=1,\cdots,K; s_k=1,\cdots,S_k) . \tag{9}$$

It is noted that the value of heterogeneity factor ε^k is always non-negative. In addition, if the value of heterogeneity factor ε^k of group k is higher than that of other groups, the group k certainly exerts to have a faster deterioration than other groups. Within one group (or one technology), the hazard rate of all condition states share a same value of heterogeneity factor ε^k. Within a network of roads categorized by several groups, the distribution of heterogeneity factor ε^k reflects the influence of individual group on the overall deterioration of the entire network. Depending of the nature characteristics of each road network system, the heterogeneity factor can be defined as in the form of a function or a stochastic variable.

For measurable representation, the value of $\varepsilon^k(k=1,\ldots,K)$ is described by vector $\bar{\varepsilon}^k$, with the bar $^-$ indicating the measurable value. As a result, the survival probability function in equation (4) can be further expressed by means of the mixture hazard rate in equation (9):

$$\tilde{F}_i(y_i^k) = \exp(-\tilde{\lambda}_i\bar{\varepsilon}^k y_i^k) . \tag{10}$$

Similarly, the Markov transition probability expressed in equations (6) and (7) can be further defined as

$$\pi_{ii}^k(z^k : \bar{\varepsilon}^k) = \exp(-\tilde{\lambda}_i^k\bar{\varepsilon}^k z^k) , \tag{11}$$

$$\pi_{ij}^k(z^k : \bar{\varepsilon}^k) = \sum_{l=i}^{j}\prod_{m=i}^{j-1}\frac{\tilde{\lambda}_m^k}{\tilde{\lambda}_m^k - \tilde{\lambda}_l^k}\exp(-\tilde{\lambda}_l^k\varepsilon^k z^k) = \sum_{l=i}^{j}\psi_{ij}^l(\tilde{\lambda}^k)\exp(-\tilde{\lambda}_l^k\varepsilon^k z^k) , \tag{12}$$

where

$$\psi_{ij}^l(\tilde{\lambda}^k) = \prod_{m=i}^{j-1}\frac{\tilde{\lambda}_m^k}{\tilde{\lambda}_m^k - \tilde{\lambda}_l^k} . \tag{13}$$

A great deal of past research has revealed the difficulties in defining the heterogeneity factor ε^k. The assumption of the heterogeneity factor to be in the form of a function or a stochastic variable crucially depends on the characteristics of the system itself and the availability of monitoring data [5), 11)]. This paper focuses on applying mixture model in the case that the value distribution of heterogeneity factor ε^k has a small dispersion. In other words, the departure of heterogeneity factor ε^k from homogeneity is in a small scale. This type of mixture model is named as the local mixture model. In exponential family form $f(x;\varepsilon)$ (where x and ε are the variable and heterogeneity respectively), local mixing mechanism is defined via its mean parameterization μ^k:

$$g(x;\mu) := f(x;\varepsilon) + \sum_{i=2}^{r} f^k(x;\varepsilon) \quad \text{where} \quad f^k(x;\varepsilon) = \frac{\delta^k}{\delta\varepsilon^k} f(x;\varepsilon) . \tag{14}$$

Expansion of functions in equations (14) can be seen to follow the Taylor series. Since the likelihood function of Markov transition probability in (14) belongs to the exponential family. It is possible to approximate the transition probability as in the form of the local mixture distribution.

$$\tilde{\pi}_{ij}(z) = \int_0^\infty \pi_{ij}(z:\varepsilon) f(\varepsilon)d\varepsilon \quad (i=1,\cdots,I-1) . \tag{15}$$

For convenience of mathematical manipulation, the local mixture transition probability is assumed as an exponential function $f_{mix}(\varepsilon,z,\lambda)$, with *mix* indicating the abbreviation of mixture. As the sequent, the mixture function $f_{mix}(\varepsilon,z,\lambda)$ can be described by means of standard function $f(\varepsilon,z,\lambda)$ and distribution $H(\varepsilon)$. Equation (15) is further simplified as

$$f_{mix}(\varepsilon,z,\lambda)=\int f(\varepsilon,z,\lambda)dH(\varepsilon)\ , \tag{16}$$

where $f(\varepsilon,z,\lambda)=exp(-\varepsilon\lambda z)$. Function $f(\varepsilon,z,\lambda)$ is likely a function of ε about its mean. Without no loss of generality, and as long as the mean exist, we can further decompose equation (14) as follows:

$$exp(-\varepsilon\lambda z)=e^{-\lambda z}(1+(\varepsilon-1)(-\lambda z)+\frac{(\varepsilon-1)^2}{2!}(-\lambda z)^2+...)\ . \tag{17}$$

This is the Taylor series. And thus, the quadratic form (when $r = 2$) is acceptable for an accurate approximation. Consequently, an explicit form of approximation can be derived for the Markov transition probability:

$$E(e^{-\varepsilon\lambda z})\approx e^{-\lambda z}\{1+\frac{(\sigma\lambda z)^2}{2}\}, \tag{18}$$

and

$$\tilde{\pi}_{ii}(z)=e^{-\tilde{\lambda}_i z}\{1+\frac{(\sigma\tilde{\lambda}_i z)^2}{2!}\}\ , \tag{19}$$

$$\tilde{\pi}_{ij}(z)=\sum_{l=i}^{j}\psi_{ij}^{l}(\lambda)e^{-\tilde{\lambda}_l z}\{1+\frac{(\sigma\tilde{\lambda}_l z)^2}{2!}\}\ \ (i=1,\ldots,I-1;j=i+1,\ldots,I). \tag{20}$$

(2) Likelihood estimation approach

The estimation of Markov transition probability and heterogeneity factor require monitoring data from at least two visual inspections. Supposing that the periodical monitoring data of S_k road sections is available. An inspection sample s_k (a road section) implies two consecutive discrete periodical inspections at times $\overline{\tau}_A^{s_k}$ and $\overline{\tau}_B^{s_k}=\overline{\tau}_A^{s_k}+\overline{z}^{s_k}$, with its respective condition states $h(\overline{\tau}_A^{s_k})=i$ and $h(\overline{\tau}_B^{s_k})=j$. Based on monitoring data of $\sum_{k=1}^{K}S_k$ samples, dummy variable $\overline{\delta}_{ij}^{s_k}\ (i=1,\cdots,I-1,\ j=i,\cdots,I;s_k=1,\cdots,S_K;k=1,\cdots,K)$ is defined to satisfy the following conditions:

$$\overline{\delta}_{ij}^{s_k}=\begin{cases}1 & h(\overline{\tau}_A^{s_k})=i,h(\overline{\tau}_B^{s_k})=j\\ 0 & Otherwise\end{cases}. \tag{21}$$

The range of dummy variable $(\overline{\delta}_{11}^{s_k},\cdots,\overline{\delta}_{I-1,I}^{s_k})$ is denoted by using the dummy variable vector δ^{s_k}. Furthermore, structural characteristics and environment conditions of the road are expressed by means of characteristic variable vector $\overline{x}^{s_k}=(\overline{x}_1^{s_k},\cdots,\overline{x}_M^{s_k})$, with $\overline{x}_m^{s_k}\ (m=1,\cdots,M)$ indicating the observed value of variable m for sample s_k. The first variable is referred as a constant term, with its value $x_1^{s_k}=1$. Thus, the information concerning monitoring data of sample k can be described as $\Xi^{s_k}=(\delta^{s_k},\overline{z}^{s_k},\overline{x}^{s_k})$.

The hazard rate of condition state i of sample s_k can be expressed by using mixture hazard function $\lambda_i^{s_k}(y_i^{s_k})=\tilde{\lambda}_i^{s_k}\varepsilon^k\ (i=1,\cdots,I-1)$, with I as the absorbing condition state satisfying the conditions $\pi_{II}^{s_k}=1$ and $\tilde{\lambda}_I^{s_k}=0$. The hazard rate $\tilde{\lambda}_i^{s_k}\ (i=1,\cdots,I-1;s_k=1,\cdots,L_k)$ depends on the characteristic vector of the road section, and is described as follows:

$$\tilde{\lambda}_i^{s_k}=x^{s_k}\beta_i'\ , \tag{22}$$

where $\beta_i=(\beta_{i,1},\ldots,\beta_{i,M})$ is a row vector of unknown parameters $\beta_{i,m}(m=1,\ldots,M)$, and the symbol ` indicates the vector is transposed. From equations (19) and (20), the standard hazard rate of respective condition states can be expressed by means of hazard rate $\tilde{\lambda}_i^{s_k}\ (i=1,\cdots,I-1;s_k=1,\cdots,L_k)$ and heterogeneity parameter ε^k. The average Markov transition probability can be expressed in equation (20), with consideration of characteristic variable $\overline{x}^{s_k}$. In addition, the transition probability depends on inspection interval $\overline{z}^{s_k}$. As a result, transition probability π_{ij} can be expressed as a function of measurable monitoring data $(\overline{z}^{s_k}, \overline{x}^{s_k})$ and unknown parameter $\theta = (\beta_1, \cdots, \beta_{I-1}, \sigma)$ as $\tilde{\pi}_{ij}^{s_k}(\overline{z}^{s_k}, \overline{x}^{s_k} : \theta)$. If the deterioration of road sections l_k in the entire L_K samples are assumed to be mutually independent, the likelihood function expressing the simultaneous probability density of the deterioration transition pattern for all inspection samples is defined [14), 15)]:

$$L(\theta, \Xi) = \prod_{i=1}^{I-1} \prod_{j=i}^{I} \prod_{k=1}^{K} \prod_{s_k=1}^{S_k} \left\{ \tilde{\pi}_{ij}^{s_k}(\overline{z}^{s_k}, \overline{x}^{s_k} : \theta) \right\}^{\overline{\delta}_{ij}^{s_k}} . \quad (23)$$

In view of the local mixture distribution with Taylor series, the Markov transition probability can be further described as

$$\tilde{\pi}_{ii}^{s_k}(\overline{z}^{sk}, \overline{x}^{s_k} : \theta) = e^{-\overline{x}^{s_k} \beta_i' \overline{z}^{s_k}} \{1 + \frac{(\sigma^{s_k} \overline{x}^{s_k} \beta_i' \overline{z}^{s_k})^2}{2!}\}, \quad (24)$$

$$\tilde{\pi}_{ij}(\overline{z}^{s_k}, \overline{x}^{s_k} : \theta) = \sum_{l=i}^{j} \psi_{ij}^{l}(\lambda) e^{-\overline{x}^{s_k} \beta_l' \overline{z}^{s_k}} \{1 + \frac{(\sigma^{s_k} \overline{x}^{s_k} \beta_l' \overline{z}^{s_k})^2}{2!}\}, \quad (25)$$

where $\psi_{ij}^{s}(\tilde{\lambda}^{l_k})$ is expressed in equation (13). Since $\overline{\delta}_{ij}^{s_k}, \overline{z}^{s_k}, \overline{x}^{s_k}$ can be obtained from monitoring data, the likelihood function in equation (23) are the function of $\theta(\beta, \sigma)$. To estimate the values of parameter $\overline{\theta} = (\hat{\beta}, \hat{\sigma})$, the method of maximum likelihood is used. For computational convenience, the likelihood function can be further expressed by means of logarithm:

$$\ln L(\theta, \Xi) = \sum_{i=1}^{I-1} \sum_{j=1}^{I} \sum_{k=1}^{K} \sum_{s_k=1}^{S_k} \overline{\delta}_{ij}^{s_k} \tilde{\pi}_{ij}^{s_k}(\overline{z}^{s_k}, \overline{x}^{s_k} : \theta) . \quad (26)$$

The value of parameter θ can be obtained by solving the optimality conditions:

$$\frac{\partial \ln L(\theta, \Xi)}{\partial \theta_i} = 0, \quad (i = 1, \cdots, (I-1)M + 1) . \quad (27)$$

The optimal values of parameter $\theta = (\hat{\theta}_1, \cdots, \hat{\theta}_{(I-1)M+1})$ can be estimated by applying numerical iterative procedure such as Newton Method for *(I-1)M+1* order nonlinear simultaneous equations[16)]. Furthermore, the estimator for the asymptotic covariance matrix $\Sigma(\theta)$ of the parameters is given by

$$\Sigma(\theta) = \left[\frac{\partial^2 \ln L(\theta, \Xi)}{\partial \theta \partial \theta'} \right]^{-1} . \quad (28)$$

The *((I-1)M+1)((I-1)M+1)* order inverse matrix of the right-hand side of the formula in equation (28), composed by elements $\partial^2 \ln L(\theta, \Xi) / \partial \theta_i \partial \theta_j$, results to be the inverse matrix of the Fisher information matrix.

Information concerning inspection sample s_k of the road group k is denoted as $\zeta^{sk}(s_k = 1, \ldots, S^k)$. To describe the condition states of individual sample, the first and second condition states of sample s_k are assumed as $i(s_k)$ and $j(s_k)$. It is supposed that the value of parameter $\theta = (\beta_1, \cdots, \beta_{I-1}, \hat{\sigma})$ is available. If we consider the distribution of heterogeneity factor ε^k in function $\overline{f}(\varepsilon : \hat{\sigma})$, the probability density function, which infers the transition pattern of sample ζ^{sk}, can be defined as:

$$\rho^{s_k}(\varepsilon^k : \theta, \xi^k) = \{\pi_{i(s_k) j(s_k)}^{s_k}(\overline{z}^{s_k}, x^{s_k} : \beta, \varepsilon^k)\}^{\overline{\delta}_{i(s_k) j(s_k)}^{s_k}} \overline{f}(\varepsilon^k, \hat{\sigma}), \quad (29)$$

where function $\overline{f}(\varepsilon : \hat{\sigma})$ follows local mixing mechanism as previously described. As for the total number of samples in group k, the probability density function concerning the simultaneous occurrence of transition can be further defined as

$$\rho^k(\varepsilon^k:\theta,\xi^k)=\prod_{s_k=1}^{S^k}\rho^{s_k}(\varepsilon^k:\theta,\xi^k)\propto\prod_{s_k=1}^{S^k}\{\sum_{l=i(s_k)}^{j(s_k)}\psi^l_{i(s_k)j(s_k)}(\lambda^{s_k}(\theta))\exp(-\tilde{\lambda}_l^{s_k}(\theta)\varepsilon^k\bar{z}^{s_k})\}^{\bar{\delta}^{s_k}_{i(s_k)j(s_k)}}\left\{1+\frac{(\sigma\tilde{\lambda}_l^{s_k}z^{s_k})^2}{2!}\right\}^{S_k}. \tag{30}$$

The standard or average hazard rate is expressible by means of vector $\lambda^{s_k}(\theta)=(\tilde{\lambda}_1^{s_k}(\theta),\cdots,\tilde{\lambda}_{I-1}^{s_k}(\theta))$. With this assumption, the value of average hazard rate $\tilde{\lambda}_i^{s_k}$ depends on the value of parameter θ. To come up with an explicit form of the probability density function in equation (30), we apply partial logarithm as follows:

$$\ln\rho^k(\varepsilon^k:\theta,\xi^k)\propto\sum_{s_k=1}^{S^k}\bar{\delta}^{s_k}_{i(s_k)j(s_k)}\ln\{\sum_{l=i(s_k)}^{j(s_k)}\psi^l_{i(s_k)j(s_k)}(\lambda^{s_k}(\theta))\exp(-\tilde{\lambda}_l^{s_k}(\theta)\varepsilon^k\bar{z}^{s_k})\}+S_k\ln\{1+\frac{(\sigma\tilde{\lambda}_l^{s_k}z^{s_k})^2}{2!}\}. \tag{31}$$

By maximizing equation (31), the optimal value of heterogeneity factor $\varepsilon^k\ (k=1,\cdots,K)$ can be obtained:

$$\max_{\varepsilon^k}\{\ln\rho^k(\varepsilon^k:\theta,\xi^k)\} \tag{32}$$

(3) Benchmarking flow chart

The objective of benchmarking study is to search for the best pavement technology among the existing ones. Based on the methodology proposed in the previous sections, we summarize a road map of benchmarking application in **Figure 1** . It is noted that the technique for cost evaluation is simply a comparison of construction and repair cost, which is supposed to spend when the condition state of the road section reaching its absorbing condition state.

4. Empirical Study and Benchmarking

(1) Overview

In this section, we exploit the applicability of the exponential hazard model to estimate the Markov transition probability. Further, the heterogeneity factor of individual road group is estimated by using the local mixture model. Benchmarking study is highlighted with the comparison of deterioration curves. Empirical application is conducted on the monitoring data of the national road system in Vietnam. There are over 10,000 samples in the database. Each sample represents a road section of 1 km in length. After verification, a sampling population during the period from 2001 to 2004 with 6510 road sections is selected for the empirical test. Information of monitoring data includes the values of indexes such as: International Roughness Index (IRI), Cracking, Texture depth, Thickness of top asphalt layer, Annual traffic volume, etc. The locations of examined road sections are mapped in **Figure 2**.

In benchmarking study, we consider the deterioration of top surface layers characterizing by type of materials, technical specification, and regional differences. Whilst, the traffic volume and texture depth are considered as characteristic variables. A main reason of the selection is because of having a wide range of choices in the practices of design, construction, and maintenance in Vietnam. In other words, most of pavement technologies are borrowed technologies from developed nations, causing a pavement system of inhomogeneous conditions. The problem of having inhomogeneous conditions in the national pavement system consequently results in a negative influence on maintenance, repair, and renovation. The problem has been documented as a major difficulty for budget allocation either in short or long term strategy.

The original set of monitoring data is filtered and verified in order to define an appropriate range of condition states. Verification is necessary since the range of condition states can be converted in various domains from the value of distress. In fact, the values of distress such as Roughness, Cracking, Flatness, and Rut are measured and recorded in a very small scale. Thus, the requirement for defining the range is extremely important. Based on the results of data verification, we realize that the arrival time to the worst condition state are in similar behaviors if different range of condition states are assumed. Hence, for the convenience of observation and computation, we select the range of condition states from 1 to 5 as detailed described in **Table 1**. The range of condition states is converted values from the value of IRI.

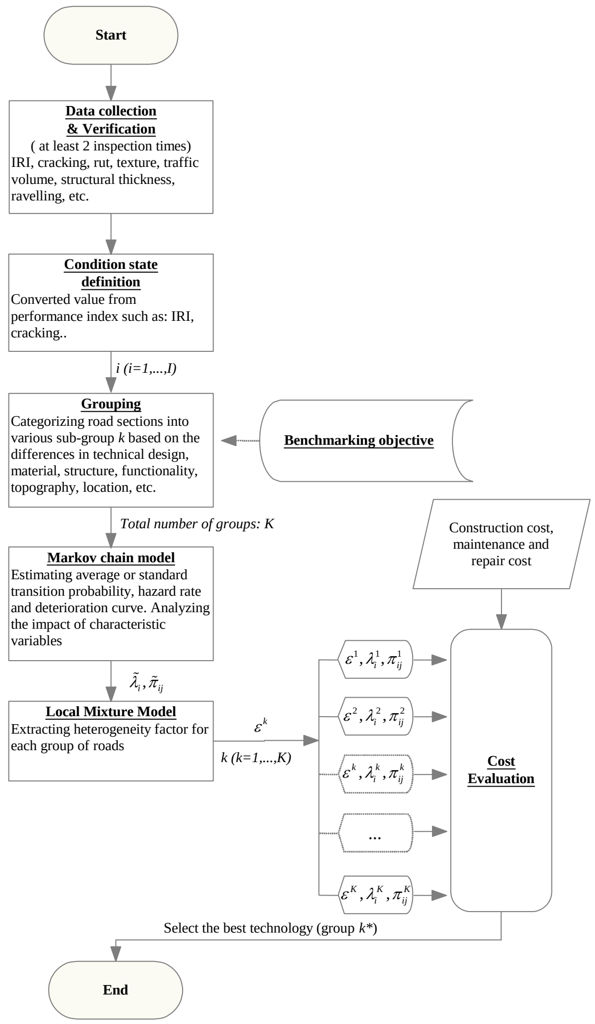

Figure 1: Benchmarking flowchart.

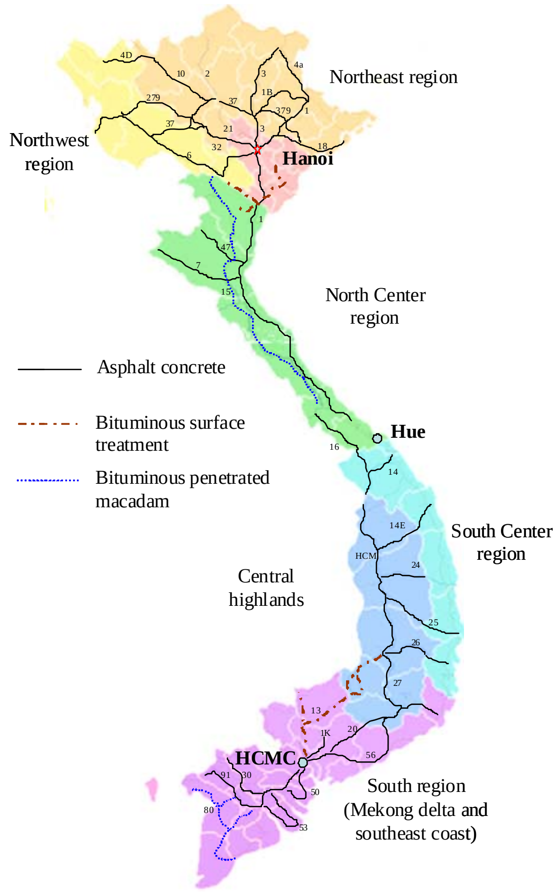

Figure 2: Locations of roads.

(2) Estimation results

In the empirical study, we consider the annual traffic volume of motorized car and the change of texture index as characteristic variables, with denotations as x_{i2} and x_{i3} . While, the first characteristic variable x_{i1} equals to 1 as a constant value. The thickness of pavement is not considered in the estimation because it shares a similar range of value in design practices.

Estimation results using the exponential Markov model are displayed in **Table 2**. It is highlighted from the table that the traffic volume has a great influence on the transition of condition state 4. A strong correlation between the transition condition state 2 and the texture depth is also realized. As a matter of fact, the change in the texture depth of road depends on the traffic volume and other environmental conditions such as climate and construction materials. The figures displayed in the parenthesis represent the statistical *t-test* for the values of unknown parameters.

Eventually, we obtain the values of hazard rate and life expectancy for condition state *I* through application of the conventional Markov hazard model of Tsuda et al [3]. Results are presented in **Table 3**. It is highlighted that, in average, the life expectancy of condition state i=1 lasts less than 1.5 years before entering into condition state i=2. Condition states 2 has its service life about 5.5 years. After entering condition state i=3, the speed of deterioration accelerates in a fast manner. For instance, condition state 3 remains only about 4.5 years before falling to condition state i=4. And further, it takes less than 3.5 years for condition state i=4 arriving to the absorbing condition state (i=5).

The matrix of Markov transition probability, estimated by using the exponential Markov model, is displayed in **Table 4**. The values of transition properties are estimated based on the value of average hazard rate, which represents the deterioration transition pattern of the entire road sections. In order to compare the influence of traffic volume on the deterioration, we carry out the estimations for three cases. The benchmark (BM) case refers to the case that we estimated the hazard rates and transition probability based on annual traffic volume. Whilst, other two cases consider the increase and decrease of annual traffic volume at the rate 0.5. Comparative results of three cases are illustrated in **Figure 3**.

Table 1: Description of condition states.

Condition states	Range of IRI values	Remark
1	(1-2]	Very good
2	(2-4]	Good
3	(4-6]	Fair
4	(6-8]	Poor
5	> 8	Very poor

Note) IRI is measured in (m/km). IRI stands for International Roughness Index.

Table 2: Exponential hazard model results.

Condition states	Constant term β_{i1}	Traffic volume β_{i2}	Texture depth β_{i3}
1	0.7987	-	-
	(46.633)	-	-
2	0.0040	-	1.9633
	(0.5470)	-	(21.042)
3	0.2250	-	-
	(29.629)	-	-
4	0.0849	3.0108	-
	(5.8440)	(5.9501)	-

Note) *t-values* are shown in the parenthesis

Table 3: Life expectancy of condition states.

Condition states	$E[\theta_i]$	$E[RMD_i^k]$ (year)
1	0.7987	1.2521
2	0.1835	5.4488
3	0.2252	4.4401
4	0.2901	3.4474

Note) Values of hazard rate and life expectancy were not defined for absorbing condition state ($i=5$) . E is abbreviation for expected average value. *RMD* stands for Remaining Duration, which is defined in the paper of Tsuda et al [3].

Table 4: Markov transition probability.

Condition States	Condition states 1	2	3	4	5
1	0.4499	0.4965	0.0495	0.0038	0.0003
2	0.0	0.8323	0.1496	0.0164	0.0017
3	0.0	0.0	0.7983	0.1741	0.0276
4	0.0	0.0	0.0	0.7482	0.2518
5	0.0	0.0	0.0	0.0	1.0

Note) Interval of transition is one year.

An appealing conclusion from **Figure 3** is that the traffic volume particularly exerts to have a high impact on condition state 4. In fact, it is true to accept that the traffic volume should affect all the condition states with different severe levels. However, in order to understand its behavior precisely, a richer database of monitoring data is required. Despite the limitation of monitoring data, we are still able to give an alarming message that the deterioration of the road network in Vietnam is progressing with a high speed of deterioration. The life expectancy of the surface layer in the network is relatively less than 13 years. Probabilistically, after about 6 years from construction time, the serviceability of the road network cannot satisfy the expectation of users. Thus, it is strongly recommended that Vietnamese road administration should proposes an extensive investigation to find out the causes of high deterioration speed, and works out a suitable plan to prolong the service life of the entire road network.

(3) Benchmarking

In the benchmarking study, we categorize 6510 road sections into three groups according to the types of materials. In addition, we further classify the group of asphalt concrete materials into seven smaller groups based on the technical class, lane class, road class, and functional class since this group accounts for a large number of samples in monitoring data. Thus, the total number of groups are nine, with the detailed description explained in **Table 5**. The locations of roads belonging to each group are also highlighted in **Figure 2**. The estimation results for heterogeneity factor of individual group are given in **Table 5**. The distribution of heterogeneity factor around the mean is plotted in **Figure 4**.

A comparison of deterioration curves is drawn in **Figure 5**. The figure shows the deterioration curves of roads based on 3 types of materials. The group of roads with asphalt overlays has a longest service life (about 16 years). Meanwhile, the two other groups of roads with materials composing of bituminous penetrated macadam and bituminous surface treatment have their service life less than 9 years. Since asphalt concrete becomes a popular material for overlay, most of national roads are now paved with asphalt concrete. Thus, we further classified the group of asphalt concrete into 7 sub-groups and compared their deterioration curves. In total, there are nine groups of roads for benchmarking. **Figure 6** presents the a comparative view on the deterioration curves of 9 groups. It is realized that deterioration curves of asphalt concrete surfaces has a small dispersion in compare with other groups. Relatively, the life expectancy of asphalt concrete surfaces ranges from 12 to 16 years.

According to the climate zones of Vietnam, road sections with asphalt concrete overlay are classified into 6 regions. The location of each region is also displayed in the map of **Figure 2**. A comparative view of the deterioration curves of asphalt roads according to regional classification are illustrated in **Figure 7**. As can be seen from **Figure 7**, it is proved that the deterioration of road surfaces in the southern part is faster than that of road surfaces in the northern regions. This reason could possibly due to the effects of soft ground condition in the southern part of Vietnam or the impact of flooding in low land areas. The two prominent reasons are strongly believed to cause the subsidence of construction works in the southern part of the country. The deterioration of road surfaces in the north part of the country has a slower speed than the that of the other regions. Moreover, it is also found that that the deterioration speed of road surfaces in urban areas is faster than that in the highland regions. The faster deterioration speed in the urban areas is due to the effects of heavier traffic volume annually.

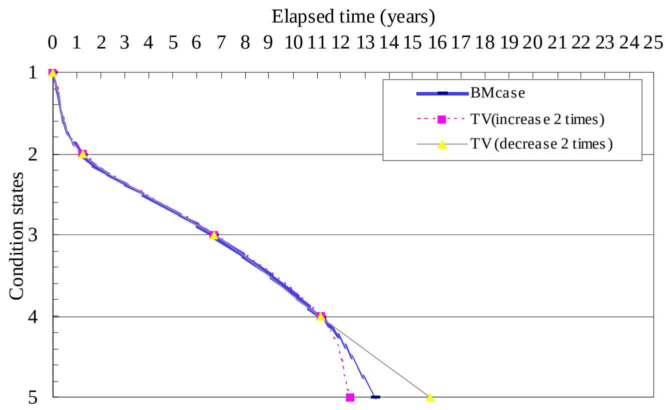

Figure 3: Deterioration curves (TV is traffic volume).

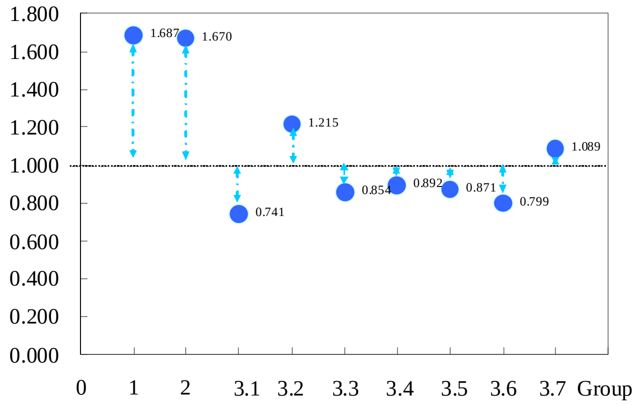

Figure 4: Distribution of heterogeneity factors.

Table 5: Classification of road groups.

Group k	Description	Technical class	Lane class	Road class	Functional class	Heterogeneity factor
1	Bituminous penetrated macadam (226)	60	3+4	1	3	1.687
2	Bituminous surface treatment (1301)	60	1+3 +4	1+2	3+4+5	1.670
3.1	Asphalt concrete overlay (713)	40	4	1	4	0.741
3.2	Asphalt concrete overlay (1047)	60	3	2	2	1.215
3.3	Asphalt concrete overlay (1030)	60	3	1	3	0.854
3.4	Asphalt concrete overlay (467)	60	3	1	4	0.892
3.5	Asphalt concrete overlay (602)	60	3	2	3	0.871
3.6	Asphalt concrete overlay (1025)	80	3	1	2	0.799
3.7	Asphalt concrete overlay (99)	60	4	1	3	1.089
	Benchmark case (BMcase-6510)					1.000

Note) Figures in parenthesis shows number of data. Technical class is defined by maximum allowance speed used in design. Lane class is categorized in the range (**1**-single lane with width <=3.5m; **2**-3 lanes with width of 10-14.5 m; **3**-2 lanes with width of 3.5-5.5 m; **4**-2 lanes with width of 5.5-10.5m; **5**- 4 lanes with width >= 14m). Road class **1** refers to main track of national roads, **2** is supplement track of national roads. Functional class refers to management level [17]. Group 1 and 2 are classified with combination of several designated factor.

(4) Cost evaluation

In view of economic evaluation, a simple cost evaluation technique is applied. We assumed that whenever the condition state of a road section reaching the absorbing state (i=5), renewal will be implemented. The total cost is a summation of construction cost and renewal cost for renewing the overlay. With this assumption, the average cost of construction and renewal for each type of road surface according to its material can be estimated, simply by calculating the ratio of its total cost to its average life expectancy.

The results of cost estimation are presented in **Table 6**. The results highlight the fact that higher benefit can be earned if the asphalt concrete overlay is applied instead of applying the bituminous penetrated macadam and bituminous surface treatment overlays. A significant difference in the life expectancy and average cost within the group of asphalt concrete material is also realized from the estimation results in **Table 6**. Based on the obtained results, the best type of overlay for long term application can be recommended. For example, group 3.1 in **Table 6** is considered as the best one in term of economic perspective.

6. Conclusion and Recommendation

This paper has proposed a local mixture model for benchmarking study. The local mixture model is expressed by means of heterogeneity factor ε that exists in each group of roads. The heterogeneity factor is considered to follow the function of Taylor series. In order to estimate the heterogeneity factor, two steps estimation approach with maximum likelihood estimation method is applied. The local mixture hazard model is considered as an excellent tool for benchmarking study, which is used to search for the best technology in the pavement management system. In view of practical application, the methodology is suitable to apply in the pavement management system of developing countries like Vietnam, where has a high demand of standardization in the pavement system.

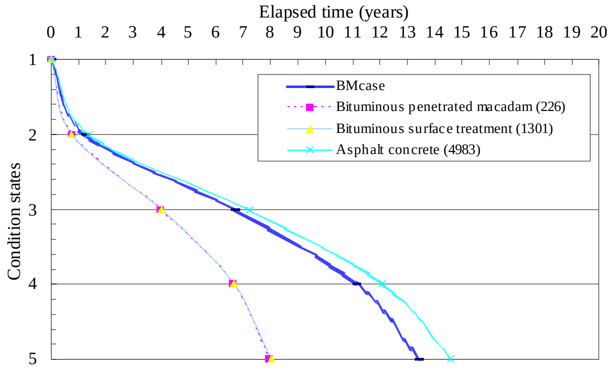

Figure 5: Deterioration curves-a compact view(3 groups).

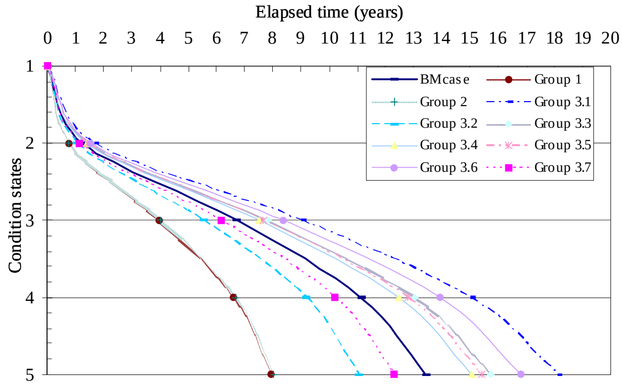

Figure 6: Deterioration curves-a broaden view (9 groups).

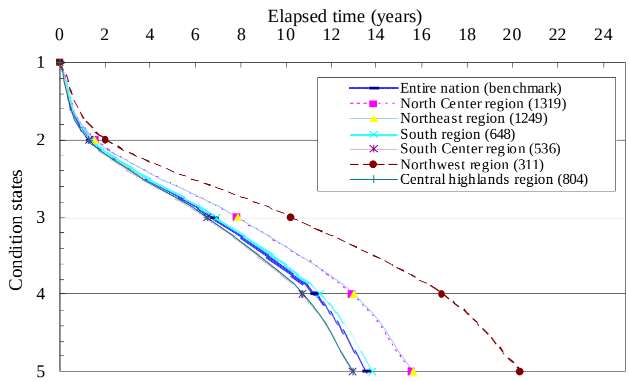

Figure 7: Deterioration curves-regional perspective (6 regions).

Table 6: Cost evaluation.

Group k	Renewal cost	Service life (years)	Average cost
1	8,567	7.64	1,121
2	8,929	7.72	1,157
3.1	11,754	17.38	676
3.2	11,754	10.61	1,108
3.3	11,754	15.09	779
3.4	11,754	14.45	814
3.5	11,754	14.79	795
3.6	11,754	16.12	729
3.7	11,754	11.84	993

Note) Monetary unit is 1000 thousand Vietnamese dong. Unit cost is referred to the standard cost defined by Hanoi construction bureau [18), 19)]. Cost is estimated for 100 m^2 and 5 cm in its thickness of overlays.

To demonstrate the applicability of the model, we conducted an empirical study on a database of Vietnamese pavement system collected during the years 2001 and 2004. The technological groups were classified according to the types of materials and regional zones. The estimation results revealed a fact that the speed of deterioration of roads in Vietnam is very fast. Approximately 10 years after construction, the condition states of road surfaces reach the worst condition state. The main cause leading to the fast deterioration is because of the high intensity of annual traffic volume. Furthermore, estimation results prove that the performances of road surfaces with asphalt concrete are much better than that of the road surfaces with bituminous penetrated macadam and bituminous surface treatment. Based on a simple cost evaluation technique, the empirical study also recommended a best group of road surfaces with asphalt concrete for long term application.

However, we have not discussed several points, which will be considered as topics for extending this study in the future:

a) The benchmarking study focused only on the pavement management system. However, its application can be applied to other types of infrastructure.

b) This paper proposed only a simple cost evaluation technique, which does not considered the routine maintenance and repair actions. In order to overcome this limitation, a cost evaluation technique using the theory of Markov decision process should be applied in the future extension of the model.

c) This paper has not discussed the problem of measurement errors in monitoring data, which is one of the main reason causing the bias in estimation results. A future study shall consider the theory of hidden Markov models, Bayesian estimation, and Markov Chain Monte Carlo(MCMC) method into account. In addition based upon MCMC method, Markov deterioration hazard model is able to be estimated more efficiently with expert's emprical judgement at early stages, and reviced with the newly obtained data through monitoring or inspections.

d) The empirical study of this paper just focused on a small scale application of benchmarking methodology on the pavement system in Vietnam, particularly focusing on the types of materials and regional zones. However, in order to find out the best pavement technology and to propose a feasible solution to the problems of pavement system in Vietnam, a better quality monitoring data shall be accumulated.

e) In the empirical study, we considered only the annual traffic volume as a time-invariant characteristic variable. Actulally, at present, heavy traffic does not occur so often, and the traffic amount does not influence deterioration rate significantly. In this study, the authors propose a methodology for selecting appropriate technology, by producing a benchmark. In developing nations, desirable pavement technology changes dynamically as economy advances. Therefore, it is important to continue efforts for seeking desirable pavement structures and develop a methodology for improving the benchmark, through the monitoring of the pavement deterioration state.

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The Benchmarking Approach to Pavement Management: Lessons From VIETNAM [*]

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This paper presents an analytical methodology to obtain heterogeneity factor of individual pavement technological group based on local mixing mechanism. Furthermore, a benchmarking approach for selecting the best possible technology for standardization and long term application is proposed. Special focus is on benchmarking of pavement management system in developing countries, where the best possible option of pavement design and management has not generally standardized yet. Empirical study was conducted on the dataset of highway system in Vietnam for testing the applicability of the model. Estimation results demonstrate a high feasibility of benchmarking application to utilize the model in real practices.
