APPLYING LOCAL MIXTURE MARKOV HAZARD MODEL TO FORECAST EARLY DETERIORATION OF ASPHALT PAVEMENT IN RUTTING

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Summary: *Within pavement life span, it is always encouraged to take strategic maintenance with the focus on proper measures for any early defect or distress instead of corrective treatment for a deteriorated pavement to prevent accelerating reduction of its performance. However, in reality, it is not easy to clarify the deterioration of pavement at the early stage and the priority of maintenance among a huge number of road sections in the network. The paper presents a new approach to predict comparatively early deterioration of pavement using Local Mixture Markov Hazard Model and Markovian chain theory including empirical study on pavement rutting in some national roads.*

BACKGROUND

Basically, road pavement deterioration can be evaluated by the two main approaches: accelerated pavement testing and statistic forecasting modeling. There are some advantages of the first approach in accurately examining the transition of sample performance and its characteristics in the laboratory but it is so costly that this approach is only suitable for a certain number of samples under limited simulation conditions. Therefore, for a larger number of samples such as a set of pavement segments in the road network, the development of deterioration forecasting models of stochastic transition process based on the probabilistic and statistic theories applying for datasets collected by periodical surveys is the proper approach that has been studied and applied in the world.

I. MARKOV DETERIORATION HAZARD MODELS

1.1. Markov Deterioration Hazard Model

This section briefly reviews the formulation and estimation approach of the exponential Markov deterioration hazard model which is considered as one of profound Markov chain model in stochastic estimation of the Markov transition probability.

Under the assumption that there have been no maintenance and repair activities imposed, and no measurement errors existed, the deterioration process of road section occurs naturally as its condition state gets worse over the years.

The Markov chain model has been recognized as a notable method to simulate the transition pattern between condition states under an uncertainty. In the model, the prediction of future condition state depends only on the condition state obtained at the present inspection time. Based on the data collected from the two inspections $(\tau_A) = i$ at τ_A and $(\tau_B) = j$ at τ_B, we can formulate the Markov transition probability matrix π_{ij}.

$$Prob[h(\tau_B) = j | h(\tau_A) = i] = \pi_{ij} \quad (1)$$

The Markov transition probability matrix can be defined using the transition probabilities between each pair of condition states (i, j):

$$\boldsymbol{\Pi} = \begin{pmatrix} \pi_{11} & \cdots & \pi_{1J} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ} \end{pmatrix} \quad (2) \quad \text{under conditions} \quad \left.\begin{matrix} \pi_{ij} \geq 0 \\ \pi_{ij} = 0 \ (wheni > j) \\ \Sigma_{j=1}^{J} \pi_{ij} = 1 \end{matrix}\right\} \quad (3)$$

In a study conducted in 2006, transition probabilities in the matrix πij were determined by Tsuda et al 0, **Error! Reference source not found.** as follows:

$$\pi_{ii} = exp(-\theta_i Z) \quad (4)$$

$$\pi_{ij} = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} exp(-\theta_k Z) \quad (5)$$

$$\pi_{iJ} = 1 - \sum_{j=i}^{J-1} \pi_{ij} \quad (6)$$

$$(i = 1, \dots, J-1) and (j \geq i + 2).$$

The exponential hazard function of the deterioration process for the sample data k ($k = 1, \dots, K$) is

$$\lambda_i^k (y_i^k) = \theta_i^k (i = 1, \dots, J-1) \quad (7)$$

The hazard rate for the condition state J is not defined because the condition state J is an absorption state and $\pi_{JJ} = 1$ as a property of the Markov chain. The hazard rate θ_i^k ($i = 1, \dots, J; k = 1, \dots, K$) that expresses the deterioration process of road pavement section k can be changed due to the effects of relevant factors in the vector x^k as follows:

$$\theta_i^k = x^k \beta_i' \quad (8)$$

The life expectancy *$RMD_i(x)$ (i=1,…,I-1)* of the condition state *i* is evaluated by means of survival probability of the condition state *i* over the continuous time.

$$RMD_i^k = \int_0^\infty exp(-\theta_i^k y_i^k)\, dy_i^k = \frac{1}{\theta_i^k} \quad (9)$$

The average life expectancy ET_j ($j = 2, \dots, J$) of the condition state j (> 1) is obtained by summation of the life expectancy over the condition state range counted from the condition state $i = 1$ or the beginning of pavement cycle. The visual deterioration curve of infrastructure is thus drawn from the obtained value of $ET_j(x)$.

$$\boldsymbol{ET_j = \sum_{i=1}^{j} \frac{1}{\theta_i^k}} \quad (\mathbf{10})$$

1.2. Local Mixture Markov Hazard Model

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

$$\lambda_i^{S_k} = \tilde{\lambda}_i^{S_k} \varepsilon^k (i = 1, \dots, J-1; k = 1, \dots, K; s_k = 1, \dots, S_k) \qquad (11)$$

For measurable representation, the value of $\varepsilon^k (k = 1, \dots, K)$ is described by vector $\bar{\varepsilon}^k$, with the bar $\bar{}$ indicating the measurable value. As a result, the survival probability function in the equation can be further defined as follows:

$$\tilde{F}_i(y_i^k) = exp(-\tilde{\lambda}_i \bar{\varepsilon}^k y_i^k) \qquad (12)$$

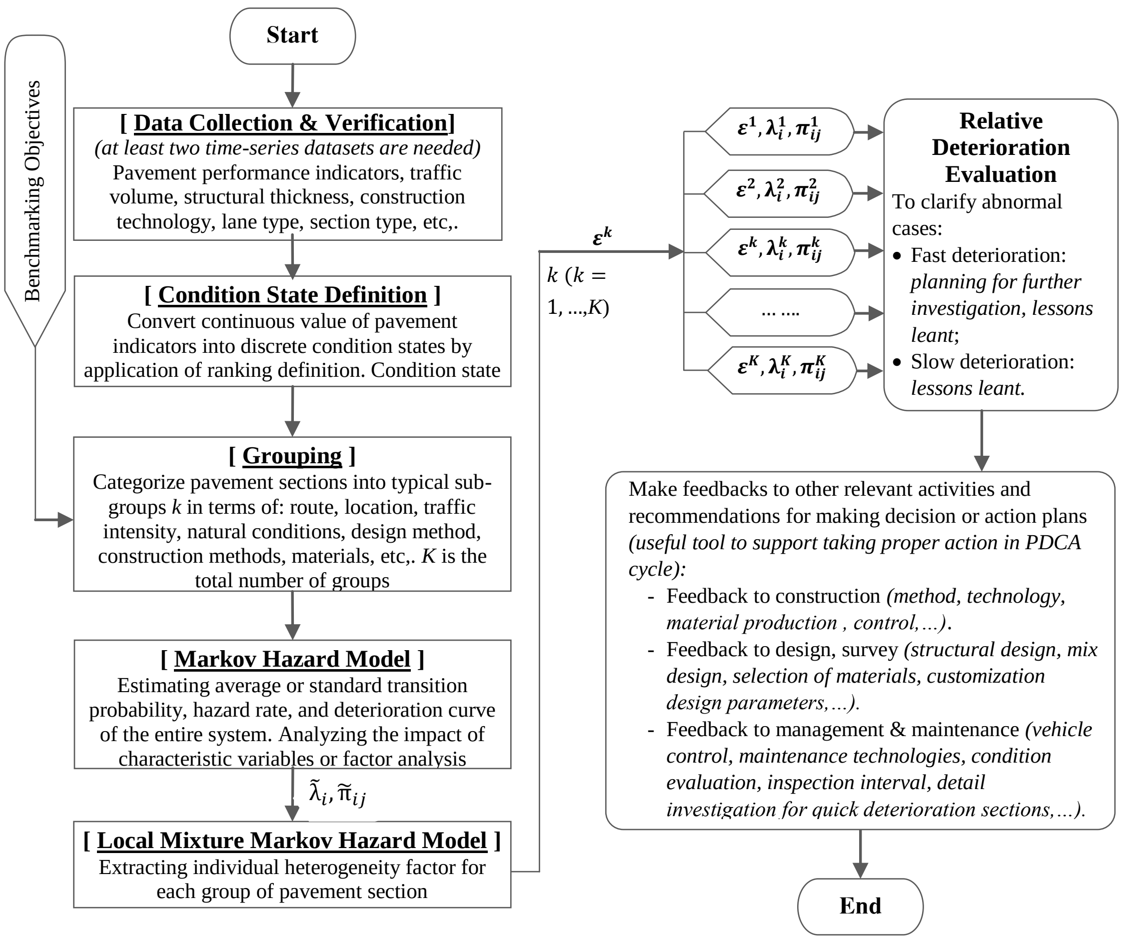


Figure 1. *Flowchart to evaluate pavement deterioration by the Local Mixture Markov Hazard Model*

Similarly, the Markov transition probability expressed in Equations (4) and (5) can be further defined in the following equations to determine the deterioration parameters in Equations (9) and (10).

$$\pi_{ii}^{k}(z^k : \bar{\varepsilon}^k) = exp(-\tilde{\lambda}_i^k \bar{\varepsilon}^k z^k) \quad (13)$$

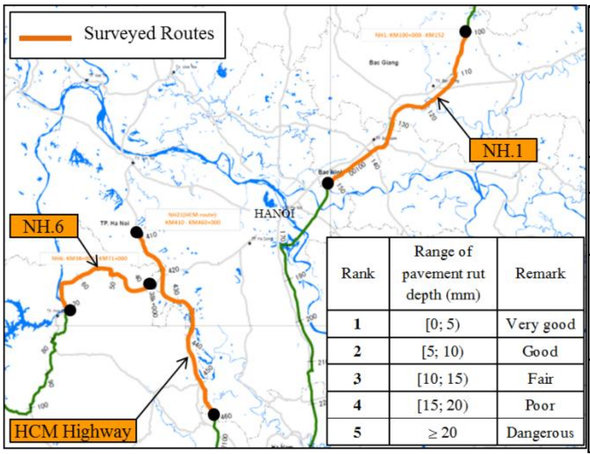
$$\pi_{ii}^{k}(z^k : \bar{\varepsilon}^k) = \sum_{l=i}^{j} \prod_{m=i,\neq l}^{j-1} \frac{\tilde{\lambda}_m^k}{\tilde{\lambda}_m^k - \tilde{\lambda}_l^k} exp(-\tilde{\lambda}_l^k \varepsilon^k z^k) \quad (14)$$

$$(i = 1, \dots, I-1; j = i+1, \dots, I; k = 1, \dots, K)$$

II. EMPIRICAL STUDY APPLYING LOCAL MIXTURE MARKOV HAZARD MODEL TO EVALUATE EARLY DETERIORATION IN RUTTING OF ASPHALT PAVEMENT ON NATIONAL ROADS

2.1. Introduction of Targeted Roads in the Empirical Study

In this empirical study, it was planned to specify pavement deformation deterioration in rutting in three selected national highways and their sections by applying a benchmarking analysis using the Local Mixture Markov Hazard Model to make proper recommendations for road administrators to take right actions in the whole pavement management PDCA cycle.



Rank	Range of pavement rut depth (mm)	Remark
1	[0; 5)	Very good
2	[5; 10)	Good
3	[10; 15)	Fair
4	[15; 20)	Poor
5	≥ 20	Dangerous

Items \ Road	NH.1	NH.6	HCM Highway	Total
From	Km100+00	Km38+00	Km410+00	
To	Km152+00	Km71+00	Km462+00	
Length (km)	52	33	52	137
Surveyed Direction	Up/Down	Up/Down	Up/Down	
Surveyed Length (km.lane)	104	66	104	274
Number of Analyzed Sections	915	355	866	2136

Figure 2.*Location and information of selected highways for pavement condition surveying and definition of ranking for pavement condition in rutting*

The two time-series datasets have been formulated based upon the latest pavement condition surveys in 2012 and 2014 using an automatic technology. In the datasets, pavement samples are defined as the homogeneous segments of 100 meters in length on one traffic lane for each direction. Of the total number of 2136 pavement segments for analyzing, three categories in terms of road name: (1) national highway No.1 (NH.1), (2) national highway No.6 (NH.6), and (3) Ho Chi Minh highway (HCM highway) have been proposed depending on their physical features and traffic affecting conditions. In case of multi-lane road in NH.1, the light vehicle lane adjacent to the central median strip has been selected for surveying in both times.

2.2. RESULTS OF ESTIMATION AND ANALYSIS OF THE EARLY DETERIORATION OF ASPHALT PAVEMENT IN RUTTING

The objective of the benchmarking analysis is to find out targeted routes or sections with fast deterioration speed in comparison with the others in the road network or in each route to set the high priority for its maintenance and repair, especially the preventive work. In this study, the pavement indicator of rutting depth has been selected. Definition of ranks or condition states for pavement conditions are shown on Figure 2 that consists of five ranks with the condition state $i = 1$for the best pavement condition. The pavements of the three surveyed national routes are in rather fair condition. Therefore in the study, the condition state $i = 5$is defined as the threshold of pavement condition in rutting before transiting to a serious phase of accelerating deterioration with deeper rutting 0, 0.

Pavement deterioration calculation analyzes pavement deterioration progress or the transition of pavement condition states or pre-defined ranks. The Markov transition probability theory was applied in the analysis to calculate the transition probabilities from a certain ranking to other rankings of pavement deterioration based on the periodically surveyed conditions to specify the pavement deterioration rate and its life expectancy in each rank and in total.

Table 1. *Format of dataset for rutting analysis*

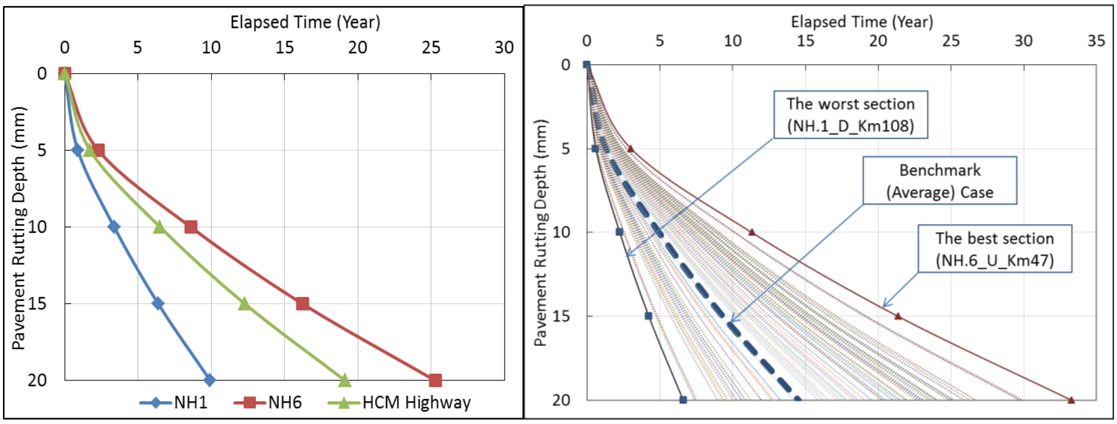
No.	Road name	Section chainage				Rutting depth surveyed at T_1 (9/2012)	Rutting depth surveyed at T_2 (9/2014)	Interval time $(T_2 - T_1)$ (months)	Pavement Condition Ranks	
		From		To					At timeT_1	At timeT_2
		kp	m	kp	m					
1	NH.1	100	0	100	100	18	27	24.0	1	4
…	…	…	…	…	…	…	…	…	…	…
2136	NH.6	70	900	70	970	15	10	24.0	3	4

In the benchmarking study, the estimation results for heterogeneity factor of individual groups are given in Table 2 that must be used to determine life expectancy of pavement in each condition state or in all of the condition states before exceeding a rutting depth of 20 mm.

Table 2. *Results for heterogeneity factor and pavement life expectancy*

Highway Name	ε^k	Hazard rate of condition state				Life expectancy in each condition state				Accumulated life expectancy until condition state 5 ET_4(years)
		θ_1	θ_2	θ_3	θ_4	RMD_1	RMD_2	RMD_3	RMD_4	
NH.1	1.4618	1.1091	0.4033	0.3334	0.2810	0.90	2.48	3.00	3.56	9.94
NH.6	0.5747	0.4360	0.1586	0.1311	0.1105	2.29	6.31	7.63	9.05	25.28
HCM highway	0.7591	0.5760	0.2094	0.1732	0.1459	1.74	4.77	5.78	6.85	19.14

In more visual illustration, Figure 3a shows the deterioration progress of the three national routes with the best pavement performance in terms of rutting resistance in NH.6. While pavement in Ho Chi Minh highway shows a rather good performance, the situation of pavement in NH.1 becomes the most serious case with its shortest life expectancy among the three roads. Such big gap of pavement life expectancies could be attributed to the high traffic intensity in NH.1 that also demands for setting the higher priority for pavement maintenance especially routine and preventive maintenance.



(a). grouping by each road name

(b). grouping by each parent section of one kilometer length

Figure 3. *Pavement rutting deterioration curves estimated by Local Mixture Markov Hazard Model*

It is common that there are ten pavement segments of 100 meters-long in each kilometer that can be grouped with the characterized pavement indicator for the corresponding parent section of one kilometer. The study also expanded to examine pavement deterioration process of each kilometer parent section in all the three surveyed roads applying the Benchmarking analysis by the Local Mixture Markov Hazard Model. Results of the study are shown in Figure 3b that visualizes pavement deterioration curves of 264 one-kilometer parent sections. Among 264 parent sections, the worst case was found in NH.1 between the kilometer posts 108 and 109 with the estimated life expectancy of 6.22 years before approaching the rutting depth of 20 mm. Far more better than the average or benchmark case of 14.53 years, parent section in NH.6 between the kilometer posts 47 and 48 shows the best performance in early rutting resistance with the estimated life expectancy of 33.29 years before reaching 20mm in pavement rutting depth.

The estimation results also point out that the 72 parent sections with the deterioration curves locating on the left side of the Benchmarking case in Figure 3bmust be targeted for preventive treatment. The farther distance from the Benchmarking case shows the higher priority for maintenance.

III. CONCLUSION

Applying the Local Mixture Markov Hazard Model is the proper approach in road management and maintenance especially at the network level that supports to forecast and evaluate pavement deterioration of the whole sample or single groups of pavement segments for strategic planning in both short-term and long-term.

In pavement management and maintenance, the preventive maintenance is always encouraged as it has a higher effect than the negative maintenance when distresses occur or are in a serious condition. The preventive maintenance helps to prolong pavement life cycle, securing reasonable road serviceability with minimum life cycle cost. That is the reason why the forecasting and analysis of early deterioration are necessary.

In the research, the Local Mixture Markov Hazard Model has been studied to apply to the forecast of early deterioration of pavement in the three national roads in rutting within the range of rutting depth of less than 20mm. Overall or average deterioration of the whole sample and performance curves of all the single groups of 1 kilometer-long pavement sections has been specified. Sections with faster deterioration were determined to be considered for proper maintenance planning in priority. Road administrators can refer the empirical result because it was made based on actual pavement conditions collected in the periodical surveys.

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