SELECTION OF OPTIMUM DESIGN ALTERNATIVE
BASED ON HAZARD AND LIFE CYCLE COST MODEL - A CASE STUDY IN VIETNAM

by Le Thanh Nam** , Kiyoyuki KAITO*** and Kiyoshi KOBAYASHI****

1. Introduction

Road network building has been recognized as one of the key infrastructure development in developing country. The technologies in road design and maintenance as well as rehabilitation are thus playing a very important role within the framework of the pavement management system (PMS). There is a fact that most of activities in road maintenance are on the surface asphalt structures since asphalt layers are directly exposed to bear traffic loads, severe environmental conditions and visually captured by inspection. Thus, in design stage, beside technical and cost consideration for base structure, it is necessary to have carefully selection of asphalt layers as well. An appropriate layer of asphalt which is subjected to have minimum maintenance cost in the service life of the road would significantly reduce the constrain of annual budge for maintenance activities.

In Vietnam, surface asphalt structures of a national highway are in fact inhomogeneous. Different segment of road has different thickness of asphalt layers and composed materials as well. This fact is foreseen to create many difficulties in future management and maintenance. This problem addresses a need of comparison on the effectiveness of design with respect to different asphalt layers. This paper focuses on benchmarking approach for selection of best asphalt structure in design stage in Vietnamese situation. Markov deterioration hazard model is used to obtain the hazard rate and deterioration curve with respect to each asphalt thickness. Further, life cycle cost analysis is implemented to compare the alternative, which offers the optimal expected cumulative cost over the life cycle of the highway.

2. Background of The Research

In the heart of systemic PMS system is the deterioration hazard model and the optimization life cycle cost analysis model. Hazard models allow users to forecast the hazard rates, life expectancies and deterioration curves of highways, roads given the past inspected condition states and other variables concerning various environment impacts such as: traffic volume and surface thickness [1)-3)]. Given the fact that roads exposing under different working conditions bear different hazard rates. Moreover, the rates are also varied according to the dissimilarity of road surface structures and road groups. It is therefore to note that application of hazard model into these contexts would enable to have a list of hazard rates, predicted life expectancies in associate with different types of road surfaces and conditions.

Beside the consideration of technical results as given from hazard models, road managers often desire to choose the a design and management policies primarily based on its economic performance indicators like expected cumulative life cycle cost or cost benefit ratio. Therefore, for the purpose of benchmarking, it is necessary to make a comparison of life cycle cost for each group of asphalt layers.

There are a numbers of hazard models, which can be utilized for research application. For instance, the hazard model

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** Member of JSCE, Graduate Student., Dept of Urban Management., Kyoto University,
(Katsura, Kyotoshi , Japan TEL 075-383-3224, FAX 075-383-3224, E-mail: info.tna@t06.mbox.media.kyoto-u.ac.jp)
*** Member of JSCE, Associate Professor., Graduate School of Engineering., Osaka University,
(Yamada-oka, Suita, Osaka , Japan TEL 066-879-7589, FAX 066-879-7601, E-mail: kaito@ga.eng.osaka-u.ac.jp)
**** Member of JSCE, Professor., Dept of Urban Management., Kyoto University,
(Katsura, Kyotoshi , Japan TEL 075-383-3222, FAX 075-383-3224, E-mail: kkoba@psa.mbox.media.kyoto-u.ac.jp)

developed by Tsuda et al [3], in which hazard rate is estimated from Markov transition probability given the two set of inspection data, can be used to compare for the group of similar roads to other groups. However, this model has not yet addressed the heterogeneity factors, and only represents the average hazard rate. As previously mentioned, the structure of asphalt layer is in inhomogeneous condition. Therefore, it could be relevant to consider the hazard model, which takes heterogeneity into account.

3. Mixture Hazard Model and estimation approach

(1). Asphalt layer grouping, condition state classification

Design of asphalt layers is varied in different countries, generally, due to the availability of technologies and materials, traffic volume and environment conditions. In Vietnam, asphalt layer is compulsory required in design of national highways. The surface structure of highways should have either three or two layers of asphalt concrete [4]. Moreover, asphalt layers in one structure are characterized by different type of materials (size of granular). In addition, due to the constrain of construction technology, only 5 levels of asphalt thickness are found , ranging from 3 cm to 7 cm. The practices of design for asphalt layers create a heterogonous condition for the entire national highway. Thus, it is necessary to group them into measurable categories for meeting the purpose of study.

Condition state of highways in Vietnam is generally defined by international roughness index (IRI) [4]. A new rating system based on IRI value obtained from actual inspection can be implied in the following tables.

Design speed (km/h)	IRI (m/km)			
	Good	Fair	Poor	Very Poor
120; 100; 80	(0; 2)	(2; 4)	(4; 6]	(6; 8)
60	(0; 3)	(3; 5)	(5; 7)	(7; 9)
40; 20	(0; 4)	(4; 6)	(6; 8)	(8; 10)

Table 1: Pavement roughness index applied to asphalt pavement [4]

IRI (m/km)	State	Notation of new rating system
IRI ≤ 2	Very good	1
2 < IRI ≤ 3	Good	2
3 < IRI ≤ 5	Fair	3
5 < IRI ≤ 7	Poor	4
> 7	Very poor	5

Table 2: Converting table

(2). Heterogeneity factors and Markov Transition Probability

It is assumed that the deterioration process of infrastructure can be formulated by Markov transition probability π_{ij}, hazard rate λ and time interval z. Here, pair element *(i,j)* represents the finite discrete condition state of infrastructure. Given a fact that, a fool of data consists of information from a huge number of roads (for example *k*). Thus, the hazard rate of each road can be formulated as $\lambda_i^k = \tilde{\lambda}_i^k \varepsilon^k \ (i = 1,...,I-1; k = 1,...,K)$. The letter ε^k denotes the heterogeneity parameter, which infers the change of characteristic of a peculiar hazard rate to each type of road *k(k=1,…,K)*

The development of hazard rate $\tilde{\lambda}_i^k$ depends very much on the value of ε^k. In this study, it is assumed that the heterogeneity parameter ε^k to be distributed according to Gamma function $f(\varepsilon^k : \alpha, \gamma)$

$$f(\varepsilon^k : \alpha, \gamma) = \frac{1}{\gamma^\alpha \Gamma(\alpha)} (\varepsilon^k)^{\alpha-1} \exp(-\frac{\alpha^k}{\gamma}) \qquad (1)$$

The deterioration of pavement can be formulated by Markov transition probability [5] with following characteristics.

$$\pi_{ii}^k(z^k:\overline{\varepsilon}^k)=\exp(-\overline{\lambda}_i^k\overline{\varepsilon}^k z^k) \text{ and } \pi_{ij}^k(z^k:\overline{\varepsilon}^k)=\sum_{l=i}^{j}\prod_{m=i,\neq l}^{j-1}\frac{\overline{\lambda}_m^k}{\overline{\lambda}_m^k-\overline{\lambda}_l^k}\exp(-\overline{\lambda}_l^k\overline{\varepsilon}^k z^k) \tag{2}$$

Where, $(i=1,...,I-1); j=i+1,...,I; k=1,...,K)$ and ε^k follows Gamma function, further expression can be formed as

$$\tilde{\pi}_{ii}(z)=\frac{\phi^{\phi}}{(\overline{\lambda}_i\ z+\phi)^{\phi}} \text{ and } \tilde{\pi}_{ij}(z)=\sum_{l=i}^{j}\prod_{m=i,\neq l}^{j-1}\frac{\overline{\lambda}_m^k}{\overline{\lambda}_m^k-\overline{\lambda}_l^k}\frac{\phi^{\phi}}{(\overline{\lambda}_l\ z+\phi)^{\phi}} \tag{3}$$

(3). Estimation Approach

In order to establish the Markov transition probability, the information from two visual inspections is necessary to be recorded. $\overline{t}^k$ is time at first inspection *k=(1,...,K)*. Second inspection is at $\overline{\tau}^k=\overline{t}^k+\overline{z}^k$ when time $\overline{z}^k$ passed. The sign Ξ indicates the measurable value in the inspection of *k* roads. $h(\overline{t}^k)$ is corresponding condition rating. Based on the results of inspection, the dummy variable $\overline{\delta}_{ij}^k$ is defined as $\overline{\delta}_{ij}^k=1$ when 1 $h(\overline{t}^k)=i, h(\overline{\tau}^k)=j$ and =0 otherwise. The $\overline{\delta}^k=(\overline{\delta}_{11}^k,...,\overline{\delta}_{I-1,I}^k)$ is dummy variable vector. Furthermore, the structural characteristic and environmental condition of road components that effect the deterioration speed are represented by the row vector $\overline{x}^k=(\overline{x}_1^k,...,\overline{x}_M^k)$, where $\overline{x}_m^k(m=1,...,M)$ shows the observed value of variable *m* for the inspected sample *k*. Here, it is noted that the first variable is $x_1^k=1$. The information contains in the inspection of sample *k* can be rearranged as $\varepsilon^k=(\overline{\delta}^k,\overline{z}^k,\overline{x}^k)$ and the entire pool of sample is Ξ. The deterioration process of sample *k* can be expressed by using mixture index hazard function $\lambda_i^k(y_i^k)=\tilde{\lambda}_i^k\varepsilon^k$, where $\pi_{II}^k=1, \tilde{\lambda}_I^k=0$. The hazard rate $\tilde{\lambda}_i^k$ depends on the characteristic vector of asphalt structure and supposes to change to the vector x^k as $\tilde{\lambda}_i^k=x^k\beta_i^{'}$. Where $\beta_i=(\beta_{i,1},...,\beta_{i,M})$ is a row vector of unknown parameters and the symbol $'$ indicates the vector is transposed. From (3), the standard hazard rate in each rating can be expressed by the standard variance ϕ of the probability distribution of hazard rate λ_i^k and the heterogeneity parameter ε^k. Average Markov transition probability is expressed by $\tilde{\lambda}_i^k=x^k\beta_i^{'}$ when using row vector $\overline{x}^k$ of road components. In addition, the transition probability also depends on inspection time interval $\overline{z}^k$ when data is observed. Thus, it is $\tilde{\pi}_{ij}^k(\overline{z}^k,\overline{x}^k:\theta)$ with $(\overline{z}^k,\overline{x}^k)$ and $\theta=(\beta_1,...,\beta_{I-1},\phi)$ for average Markov transition probability $\tilde{\pi}_{ij}^k$.

$$\ell(\theta,\Xi)=\prod_{i=1}^{I-1}\prod_{j=i}^{I}\prod_{k=1}^{K}\left\{\tilde{\pi}_{ij}^k(\overline{z}^k,\overline{x}^k:\theta)\right\}^{\overline{\delta}_{ij}^k} \tag{4}$$

From (3), it is possible to express $\tilde{\pi}_{ij}^k(\overline{z}^k,\overline{x}^k:\theta)$ as follows

$$\tilde{\pi}_{ii}^k(\overline{z}^k,\overline{x}^k:\theta)=\frac{\phi^{\phi}}{(\overline{x}^k\beta_i^{'}\overline{z}^k+\phi)^{\phi}} \quad \text{and} \quad \tilde{\pi}_{ij}^k(\overline{z}^k,\overline{x}^k:\theta)=\sum_{l=i}^{j}\prod_{m=i,\neq l}^{j-1}\frac{\overline{x}^k\beta_m^{'}}{\overline{x}^k\beta_m^{'}-\overline{x}^k\beta_l^{'}}\frac{\phi^{\phi}}{(\overline{x}^k\beta_l^{'}\overline{z}^k+\phi)^{\phi}} \tag{5}$$

Since $\overline{\delta}_i^k,\overline{z}^k,\overline{x}^k$ are known from inspection, the likelihood functions are functions of β,ϕ. In method of maximum likelihood, $\hat{\theta}=(\hat{\beta},\hat{\phi})$ that maximizes (5) will be presumed. θ can be obtained by solving the optimality conditions of following equation

$$\ln\ell(\theta,\Xi)=\sum_{i=1}^{I-1}\sum_{j=1}^{I}\sum_{k=1}^{K}\overline{\delta}_{ij}^k\tilde{\pi}_{ij}^k(\overline{z}^k,\overline{x}^k:\theta) \tag{6}$$

When $\hat{\theta}$ is obtained, then heterogeneity parameter ε^k is given as $\hat{\varepsilon}^k$ by solving for the optimal value of equation (7)

$$\ln\ell(\hat{\varepsilon}^k:\theta,\varepsilon^k)=\ln f(\varepsilon^k:\hat{\phi})+\sum_{i=1}^{I-1}\sum_{j=i}^{I}\overline{\delta}_{ij}^k\pi_{ij}^k(\overline{z}^k,\overline{x}^k:\hat{\beta},\varepsilon^k) \tag{7}$$

4. Optimal Repair Strategy and Life Cycle Cost Analysis

The optimal repair strategy is the one, which offers the least expected life cycle cost. The repair strategy can be expressed by Markov transition probability. In this study, discounted cost method is proposed. Let consider the repair action in the period from time *t* to time *t+1*. A rule of repair actions can be expressed as vector $\eta^d=(\eta^d(1),...,\eta^d(K)$, in which, $\eta^d(i)=j$ refers to the change of state from *i* to *j* by applying repair action, and $d\in D$ as a serial of rule that specifies the repair action. As the condition state of infrastructure reaches to ultimate level *i=K*, the repair (renewal) action is carried out and condition state returns as $\eta^d(K)=1$. In addition, when having repair action the associate cost should be determined. Cost vector $c^d=(c_1^d,...,c_K^d)$ is referred for implemented repaired action η^d. When a repair action is carried out, it changes the infrastructure to better condition state. Thus, the property of transition matrix p_{ij} is supposed to change accordingly as $P^d=Q^dP$ (Q^d is repair dummy matrix). It is noted that since repair action d is to prevent condition state K to be happened at time $(t+1)$, thus the dimension of matrix p^d is $(K-1)(K-1)$). The expectation cost denoted as $\Psi(i)$ concerns the value in time $(t+1)$. And $\Psi(i)$ $(i=1,...,K-1)$ represents the cost table as for minimum value of expected cost generated when best repair action d^* is executed after time $(t+1)$. The expectation cost $\Omega^d(i)$ generated at time t can be defined in following equation, in which e_i^d is expected repairing cost

$$\Omega^d(i)=e_i^d+\delta E_i^d[\Psi(j)] \quad (8) \quad \text{where} \quad e_i^d=\sum_{j=i+1}^{K} p_{ij}c_j^d \quad (i=1,...,K-1) \tag{9}$$

In equation (8), δ is discount factor (0<δ<1) and $E_i^d[\Psi(j)]$ is expected life cycle cost under repair d after time $(t+1)$ when the condition state at time t is i.

$$E_i^d[\Psi(j)]=\sum_{j=1}^{K-1} p_{ij}^d\Psi(j) \tag{10}$$

Expectation cost in LCC evaluation is often estimated at particular time t (t can be at present or just at the first repair time). Thus, in LCC analysis, recurrently defining the minimum value of expectation cost at time t can result in optimal solution. The regression equation to determine optimal LCC is expressed in equation (11) and can be solved by dynamic programming (see Otazawa [6]).

$$E_i^d[\Psi(j)]=\sum_{j=1}^{K-1} p_{ij}^d\Psi(j) \tag{11}$$

5. Conclusion

In this study, it is proposed the approach to search for optimum design alternative, particular attention is paid to the selection of asphalt layers. The study requires at least two sets of inspection data in different period of time that enable to determine the condition state of road system. In addition, mixture hazard model incorporating heterogeneity factors is used to forecast the deterioration process of the roads. Roads are grouped in different categories according to their surface asphalt characteristics and working condition. By comparing the expected life cycle cost among different group of roads, it is possible to obtain the best design alternative and management policies that offer the minimum life cycle cost. As the consequence, for the benefit of the entire PMS, the approach could support the establishment of best design standards and management practices.

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