A METHOD OF MAINTENANCE POLICY EVALUATION CONSIDERING HIGHWAY NETWORK RELIABILITY

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1- INTRODUCTION

Road pavements are subject to deterioration due to several uncertain factors such as traffic loads, weather, materials degradation and lack of maintenance. These uncertain factors interact with each other in a complex manner, thus affecting the pavement through different deterioration mechanisms. As a result, it is an uneasy task to model deterioration as a deterministic phenomenon. Moreover, technical and strategical considerations included in the rehabilitation decisions are highly subjective and thus difficult to model. Consequently, it is difficult to identify the age at which a road section will need, or be selected for, rehabilitation. Such difficulties make it uneasy to accurately predict the required budget for future maintenance. Thus, evaluation and selection of maintenance policy can be unrealistic.

The deterioration mechanism can be addressed as a sequence of probabilistic phenomena where time can be considered as the major factor governing deterioration. Therefore, the concepts of reliability and failure time models are particularly suitable as a framework to model and evaluate the deterioration process. This approach makes it possible to predict the need for rehabilitation while taking into account the uncertain deterioration mechanism and the subjective factors affecting the rehabilitation decision.

The proposed model can be a part of a network level pavement management system, PMS. The model can be applied for predicting the expected amount of rehabilitation work, and thus budget, required in a given year. It also provides a new indicator for policy evaluation in terms of network reliability.

In this paper, the concepts of reliability and failure time models are introduced in the framework of highway deterioration modeling. A model is developed to give the probability of "failure", that is, need for rehabilitation, of a road section as a function of its age. The model is applied to a study network to estimate the maintenance work required and the change in the network's reliability. This is illustrated assuming different maintenance budget levels and allocation alternatives.

2- RELIABILITY CONCEPTS: General Definitions

Reliability of any system can be quantitatively defined as the probability that it will perform its intended function for a certain period of time. Consequently, the quantitative unreliability of this system is simply the probability of its failure. The term "failure" does not necessarily mean physical failure. Rather, it may mean the occurrence of any predefined event such as a need for specific maintenance work. Reliability concepts are usually applied to structures and devices subject to random failure. The main objective of such application is to measure how well a system may perform over its lifetime.

In modeling reliability, it is usually required to model the "time to failure" of the system. These models are usually called Failure Time Models, FTM. The FTM can be simply defined as a probability distribution function, PDF, of a non-negative random variable representing the time to failure of an individual element from a homogeneous population. In other words, time is the only explanatory variable for failure occurrence in such models. The PDF, $f(t)$, of FTM is given by the following equation:

$$f(t) = P\{t \le T \le t+\Delta t\}/\Delta t = \Phi(\alpha,\beta,t) \quad \ldots\ldots(1)$$

where $P\{t \le T \le t+\Delta t\}$ is the probability that system failure will occur between time t and $t+\Delta t$; Φ is any form of theoretical probability distribution and α and β are the shape and scale parameters of the selected distribution.

The reliability, $R(t)$, of the system with failure PDF given by Equation (1) can be derived from the relation:

$$R(t) = P\{T \ge t\} = 1 - \int_0^t f(t)\Delta t \quad \ldots\ldots(2)$$

Another quantity which is of interest is the rate at which failure occurs at any age. This quantity is called failure rate, $\lambda(t)$, and can be defined as the expected ratio of failed members from a homogeneous group at age t. Failure rate can be directly derived from Equations (1) and (2) as:

$$\lambda(t) = P\{T < t+\Delta t \mid T > t\}/\Delta t = f(t)/R(t) \quad \ldots\ldots(3)$$

where $P\{T < t+\Delta t \mid T > t\}$ is the probability that the system fails at some time $T < t+\Delta t$, given that it has not failed at $T = t$.

3- APPLICATION OF RELIABILITY CONCEPTS TO HIGHWAY FAILURE MODELING

3-1 Modes of Failure of Highways

From the viewpoint of road function, the following three modes of failure can be defined: surface, service and safety failures. The occurrence of any of these failure modes can be defined by setting a quantitative limit to a relevant indicator beyond which failure is reached. In this paper, only surface failure is considered. However, a similar approach can be applied for the other modes by selecting suitable indicators.

The selected indicator for "surface failure" is the state at which pavement rehabilitation is scheduled. Such an indicator reflects the effect of both the factors causing deterioration and the technical and strategical considerations included in the rehabilitation decision on the age at which rehabilitation is scheduled. Under this definition of surface failure, reliability of pavement can be defined as the probability that it will not need rehabilitation for a specific period of time. This also means that the proposed model deals with the outcome of the deterioration process rather than the process itself.

3-2 Proposed Modeling Technique

In applying reliability concepts to pavement design, the expected life of a given design is viewed as a random variable due to the uncertainty inherent in the system's external and internal factors, eg traffic and materials respectively. The way these factors interact with each other to cause deterioration is treated as a certain phenomenon which is defined by the design equations (1). On the other hand, in the case of modeling the need for rehabilitation in this paper, interaction between the factors causing deterioration are also viewed as uncertain. Thus, similar techniques as those applied to pavement design are not applicable.

The approach of the proposed model is to construct the probability of the need for rehabilitation in the form of FTM. The main characteristic of FTM as stated before is that it has only one variable which describes a random phenomenon. The use of such a model is suitable based on the following observations:

1- While several factors interact together to determine the need for rehabilitation, the effects of all these factors is inherent in the age at which failure occurs. Thus the probability of need for rehabilitation can be fully expressed in terms of one variable, which is the road age. Such an assumption matches the results of other research work where pavement age has been proved to be the most significant predictor of performance (8).

2- The age at failure can be assumed to be a random variable. This assumption is based on the observation that pavement condition varies with age as shown in Fig. 1 and discussed in (3). Subjective considerations included in the rehabilitation decision would cause more randomness. To ensure that the randomness of the age at

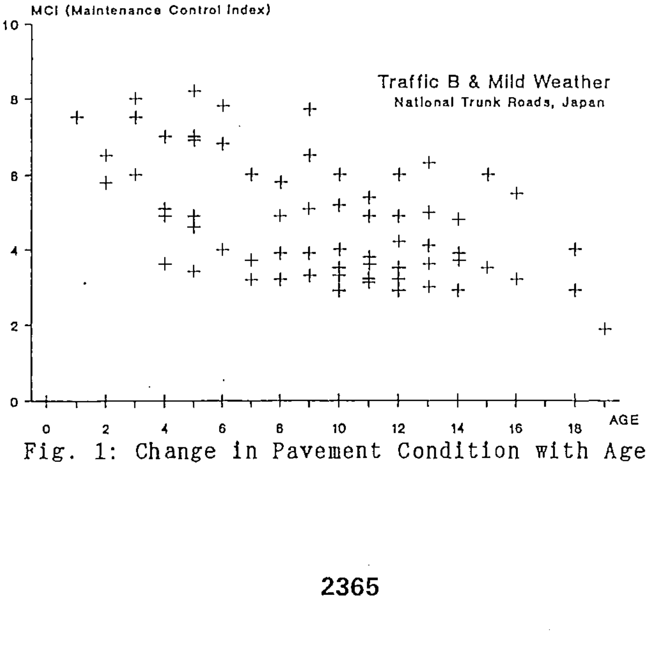

Fig. 1: Change in Pavement Condition with Age.

failure is due to uncertainties in the factors causing failure, rather than differences in pavement characteristics, the samples used in constructing the FTM should be as homogeneous as possible.

Considering the above observations, the proposed approach can be based on modeling the road age at which surface failure is expected to take place. This is done by constructing the PDF of failure occurrence of homogeneous pavement samples by referring to their rehabilitation history. Construction of the PDF means determination of ϕ, α and β in Equation (1) for each sample. With the PDF of each sample determined, reliability and failure rate of any of the samples can be obtained as in Equations (2) and (3).

3-3 Conventional Versus Proposed Modeling Techniques

Conventionally, when pavement data is available in the form of condition versus age (Fig. 1), prediction of future conditions is mostly modeled using straight-line extrapolation or non-linear regression on explanatory variables (3,5). The curved line in Fig. 2 depicts a typical regression model for the data in Fig. 1. In using these models for predicting future rehabilitation, a terminal condition must be deterministically defined (Fig. 2). Consequently, for a given pavement under a specific condition, a single terminal age defining the need for rehabilitation is determined (Fig. 2). Thus, such deterministic models cannot account for the variation in pavement condition with age. It is clear from the figure that using deterministic models for predicting the terminal age is quite far from reality.

On the other hand, the proposed technique does not give a specific value for the age to failure. Rather, it gives the probability of reaching the terminal condition at any age, thereby taking account of the variation in condition with age. The typical shape of the PDF of the proposed model is depicted by the skew bell-shaped curve in Fig. 2.

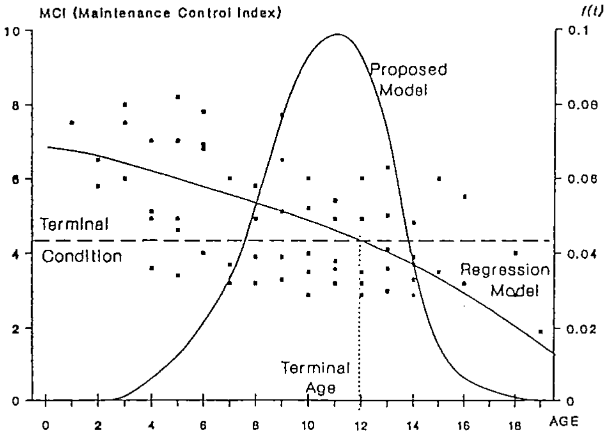

Fig. 2: Conventional Versus Proposed Modeling Techniques.

Also, in the conventional approach it is difficult to consider all the factors affecting the rehabilitation decision. Such considerations could be included in the proposed model by modeling the outcome of these factors, that is age to failure, rather than the factors itself.

Finally, the proposed model does not give any direct index describing pavement condition such as PCI or PSI. However, the reliability of the pavement at any age can be a good indicator to its condition. Generally, for any pavement, the higher the reliability at a given age the better the condition, and the bigger the area under the reliability curve the better the performance.

4- DEVELOPMENT OF FAILURE MODEL

The history of rehabilitation of the national trunk roads in Mie prefecture, Japan, was used in developing a probabilistic model for the prediction of future rehabilitation needs. Selection of this study area was based on the availability of an up-to-date data base (1991). The total length of the surveyed roads is about 355 km. The data base contains various types of data given by 100m sections or less. The whole sample network is located in an area with mild weather conditions. No data is available on the structure design of pavement layers nor on the subgrade strength. A small percentage of the sections are concrete pavement, and therefore were ignored. The construction and rehabilitation history is available for more than 60 years. Rehabilitation, as used herein, includes various maintenance types such as reconstruction, overlay and surface treatment.

The age at which rehabilitation was applied to each section was calculated as the time between the dates of construction and rehabilitation or between two successive rehabilitations. The calculated "ages at failure" were divided into six homogeneous population classes based on traffic load and pavement state at failure. These classes are shown in the first column of Table 1.

Table 1: Model Parameters for Each Population Class.

Population Class	Sample Size	Model Parameter		Significance Level
		Shape α	Scale β	
New pav., B traffic	1132	4.5	22.0	0.84
New pav., C traffic	365	2.7	13.9	0.65
New pav., D traffic	1743	2.4	17.7	0.87
Old pav., B traffic	437	3.0	14.3	0.70
Old pav., C traffic	204	2.9	13.7	0.54
Old pav., D traffic	1649	2.0	9.2	0.82

Traffic:- B: 250 - 1000 truck/day/dir C: 1000- 3000 D: › 3000 Pavement:- New: never been rehabilitata Old: has been rehabilitated

Several theoretical PDFs of failure were fitted for each of the population classes. The Weibull distribution was selected to represent the Φ form since it showed the highest average significance level and it was also more practical to use the same function form for all the classes. The values of α, β and the significance level are shown in Table 1 for each population class. For two of the classes, the significance level is not high enough, and this might be explained by the small sample size and unhomogeneity of the sample due to the absence of necessary data. For the other four classes, the significance level is relatively high suggesting a satisfactory model. Further verification of the model is also shown in the next section.

The forms of Equations (1), (2) and (3) for the Weibull distribution are as follows:

$$f(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1}\exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \quad \ldots\ldots(4)$$

$$R(t) = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \quad \ldots\ldots(5)$$

$$\lambda(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} \quad \ldots\ldots(6)$$

Figs. 3 and 4 show the change in $R(t)$ and $\lambda(t)$ with age for the six population classes. Fig. 3 shows that, in general, the reliability of "new pavements" is higher than that of "old pavements". This also indicates higher life expectancy for "new pavements". A similar trend is observed from the failure rate in Fig. 4. As for the effect of traffic, though the reliability tends to be less for higher traffic loads, the rate of loss in the reliability and increase in the failure rate tend to be steeper for lower traffic loads as the road ages. This might be attributable to differences in the level of routine maintenance application the effects of which would appear at later ages. In general, the above observations are seen to be reasonable.

It is to be noticed that the developed model directly reflects

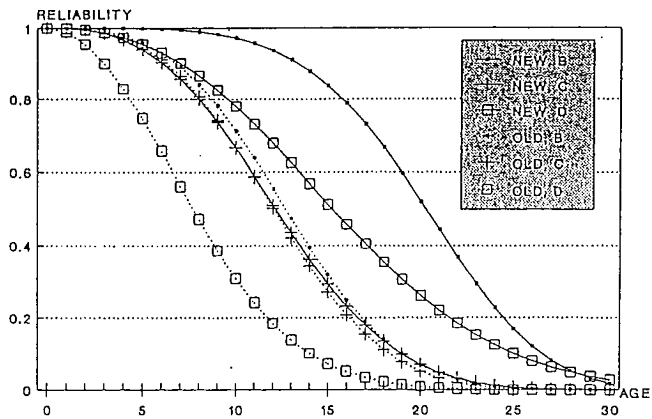

Fig. 3: Pavement Reliability of Each Population Class.

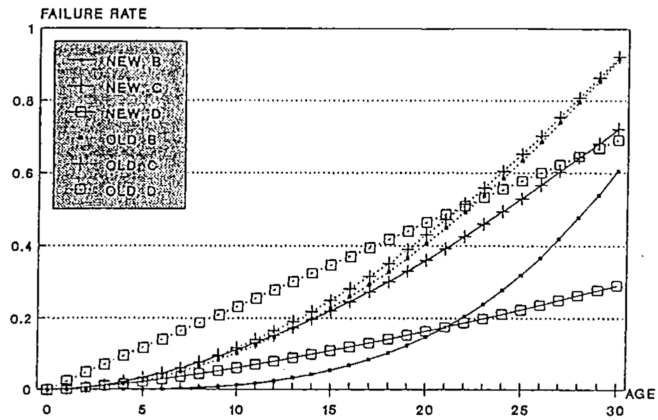

Fig. 4: Pavement Failure Rate for Each Population Class.

the past and current budget level and maintenance policy followed by the road authority. Applying this model without alterring the constraints on the budget and without changes in policy would be a prediction of the future needs assuming continuation of the current maintenance strategy.

5- MODEL APPLICATION

The developed model can be applied on two levels. On the first level, the network is treated as a large number of sections regardless of how they are connected together. The second level deals with the whole network, taking into consideration its spatial shape. In this section, the first level is demonstrated in detail.

5-1 Application on the Road Section Level

The aim of the application on the road section level can be either the estimation of future budget or the evaluation of a given maintenance policy. Both cases are based on estimation of the total number of yearly failures and possible rehabilitation work within each population class and age class.

The expected amount of yearly failures within each population class and age class can be estimated as follows:

$$F_i(t) = \lambda_i(t) * N_i(t) \quad \text{.......................................} (7)$$

in which $F_i(t)$ is the number of failed sections from population class i (i= 1,2,...,6) and age t, $\lambda_i(t)$ is the failure rate of population class i at age t and $N_i(t)$ is the number of road sections in population class i and age t.

In simulating maintenance, failed sections are assumed to be fully rehabilitated if the available budget is sufficient. Rehabilitated sections are assumed to move up to age class 0 but always as an "old pavement" with a similar traffic class. The "survived" sections are assumed to age by 1 year and stay in the same population class. This process can be depicted as a recursive cohort table as shown in Fig. 5. One of the merits of this technique is that it deals with age classes rather than individual road sections. This reduces the amount of calculations and makes it easier to deal with large networks.

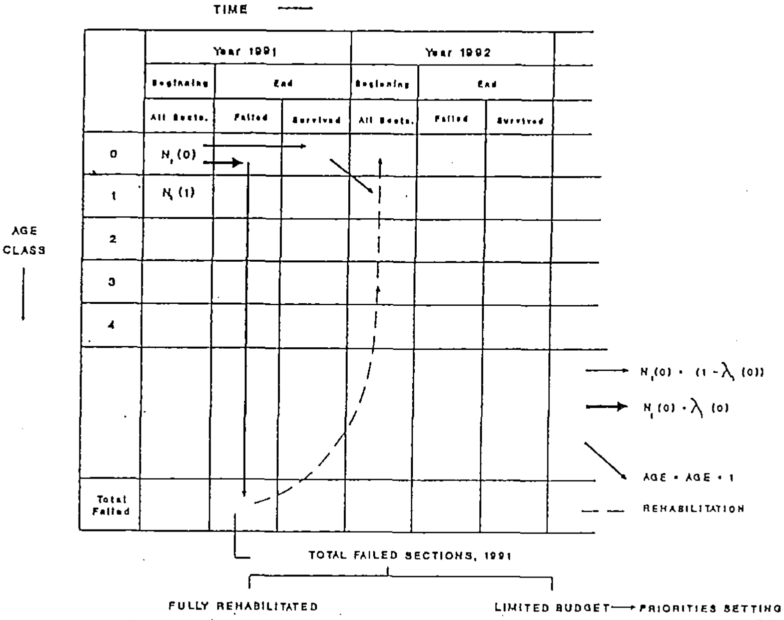

Fig. 5: Recursive Cohort Table for Future Age Structure Prediction.

In the case of limited budget, only a part of the failed sections can be rehabilitated. The other part is assumed to age by 1 year. In this case, priority setting criteria are required.

With the amount of yearly failures estimated, a rough budget for future rehabilitation can be obtained by multiplying total failures in each population class by the average cost of rehabilitation of this class. A more accurate estimate can be obtained by relating the average cost to the age class as well as the population class. As regards policy evaluation it is possible to show the expected change in the age structure with time and thus the average reliability of the sections constituting the network. Average reliability at the end of any analysis period under specific budget limitations and priority setting criteria can be a suitable indicator for policy evaluation. This is analogous to the use of average PCI or PSI in deterministic models. The summation of the resulting yearly average reliability over the analysis period indicates the average life expectancy of pavement, which is a good indicator for performance.

5.2 Application Results

The model was applied to the trunk roads of Mie Prefecture starting with their condition in 1988 which was available in the data base. The main purpose of the application was to demonstrate part of the possible applications of the model.

5.2.1 Validity Test for the Model

Fig. 6 shows the comparison between predicted and actual age structure of the network in 1991. The correlation coefficient between the predicted and actual age structure was estimated to be 0.98. Such high correlation indicates an accurate estimation of failures, and thus the amount of rehabilitation. Consequently, accurate budget estimation and policy evaluation can be realized.

A similar comparison on the predicted and actual MCI (maintenance control index) structure was carried out using the simulation results from a deterministic model developed by the Japanese Ministry of Construction. The comparison is shown in Fig. 7 and the correlation coefficient was calculated to be 0.77. The relatively low predicted average MCI value indicates under-estimation of future rehabilitation, and thus a misallocation of budget and inefficient maintenance program.

Though the indicators in the two comparisons are different, the overall comparison is still significant since the estimation of future rehabilitation by deterministic models is based on indices such as MCI while in the proposed approach it is based on the road age. Such a result is another verification for the developed model and shows its higher accuracy in estimating future rehabilitation.

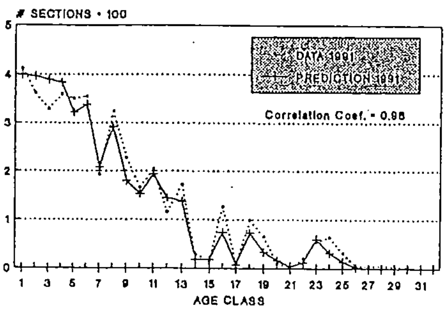

Fig. 6: Real and Predicted Age Structure in 1991.

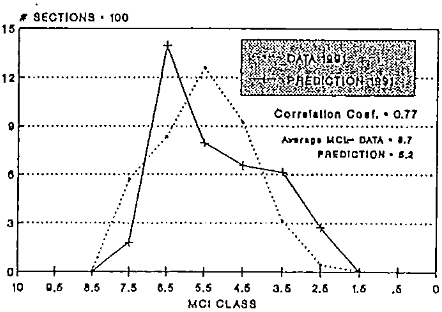

Fig. 7: Real and Predicted MCI Distribution in 1991.

5.2.2 Future Age Structure

Fig. 8 shows the predicted age structure in year 1995 as compared to the age structure in 1988 assuming a similar maintenance policy and budget. This is arrived at by estimating the amount of yearly failures in each population and age class, and by assuming full rehabilitation. The figure shows expected rejuvenation in the future age structure under the current maintenance policy. This means better condition and performance which is shown by the uppermost curve in Fig. 9.

The budget required in this period can be estimated by following the procedure described in section 5.1. However, no data was available on the average cost of rehabilitation for each population class.

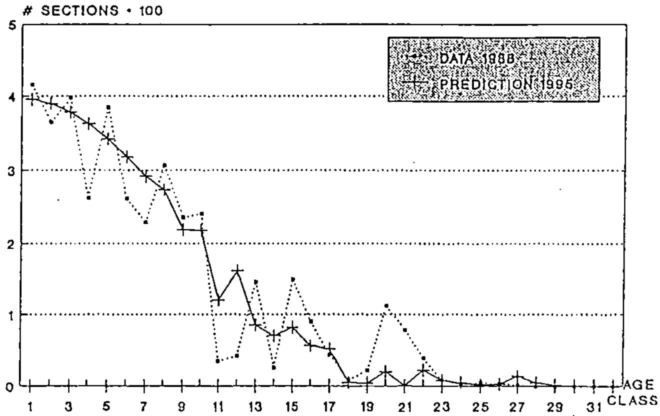

Fig. 8: Predicted Age Structure of the Study Network in 1995.

5.2.3 Evaluation of Policy Alternatives

Fig. 9 shows the results of predicting the average reliability of the road sections under three different levels of budget availability and three different priority setting criteria. The examined budget levels are 100%, 80% and 60% of the current level. The priority criteria are older pavement-higher traffic, higher traffic-older pavement and lower traffic-older pavement. The results show an expected increase in the average reliability by 1995 compared with the 1988 average, if the current budget level and maintenance policy are maintained in the future. For older pavement-higher traffic priority criteria, for example, 20% reduction in the budget from its current level would result in a 2% decrease in the average reliability in 1995, while a 60% reduction would result in a 11% decrease, which shows the effect of the cumulative damage due to budget shortage. Moreover, the increasing slope of the curves with time indicates that such an effect would be much larger in the long run. As for priority setting, the criteria of older pavement-higher traffic result in both better reliability and performance. The outcome of selecting unsuitable priority criteria can be seen from the result that the 60% budget level with older pavement-higher traffic priority criteria would result in better performance than an 80% budget level with higher traffic-older pavement criteria.

Fig. 10 shows the results of different allocation scenarios of the limited available budget over the analysis period while controlling the total amount of budget. In the cases of gradually increasing and gradually decreasing budget allocation, the rate of

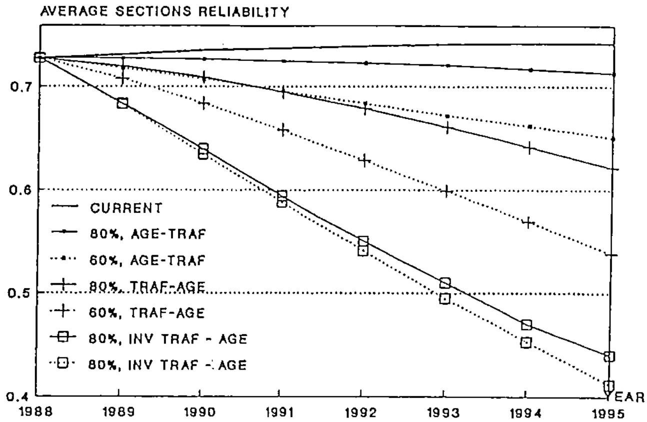

Fig. 9: Average Reliability Assuming Budgets Levels and Priorities.

increase/decrease is assumed to be 5% per year. The priority criteria were fixed as older pavement-higher traffic for all scenarios. It can be seen that though the final average reliability is higher in the case of gradually increasing budget, the performance is better in the case of gradually decreasing budget.

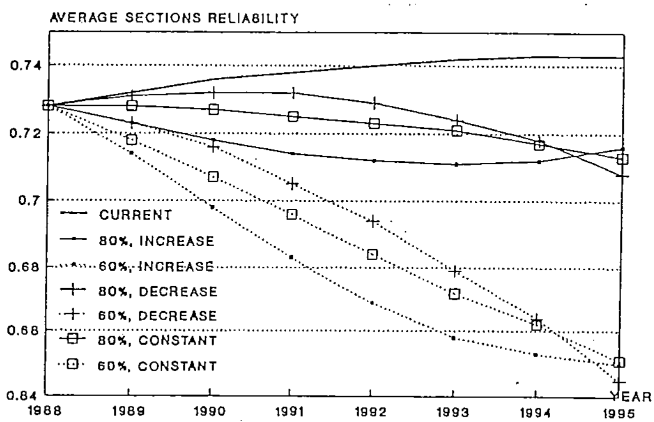

Fig. 10: Average Reliability Assuming Budget Levels and Scenarios.

6- SUMMARY AND CONCLUSIONS

This paper has described an approach to modeling pavement need for rehabilitation using the concepts of reliability and failure time models. Probabilistic models for pavements with different characteristics were developed for predicting expected rehabilitation need. History of the age at which rehabilitation was carried out was used in estimating the models. Comparison between the developed model and a conventional deterministic model suggests that the proposed approach would yield more accurate prediction of rehabilitation need, leading to more efficient policy determination. This achievement is mainly attributed to the consideration of the effect of both (a) the variation in pavement condition with age, and (b) the technical and strategical considerations included in the rehabilitation decision, on the age at which rehabilitation is required.

The application of the model to the prediction of the required amount of rehabilitation in a given year and thus the budget required is demonstrated for the case of the trunk roads in Mie prefecture, Japan. The change in the age structure of the network sections under different policies was used in estimating the network's average reliability as a measure for policy evaluation. Some of the results showed that the short-term effect of reducing the maintenance budget by 40% from the current level would be 5 times as high as the effect of 20% reduction. The long-term effect is expected to be much larger. It has also been shown that the selection of unsuitable priority criteria for budget allocation can offset the positive effect of relatively high budget levels. In the case of limited budget, the results show that it is better to distribute the total budget over the budgeting period so that it is gradually decreasing over time.

BIBLIOGRAPHY

1. A. Alsherri and K. P. George. Reliability Model for Pavement Performance. ASCE, Vol 114, No 2, pp 294-306, 1988.

2. K. George, A. Alsherri and N. Shah. Reliability Analysis of Premium Pavement Design Features. ASCE, Vol. 114, No 2, 1988.

3. J. Carnahan, M. Shahin, P. Keane and M. Wu. Optimal Maintenance Decisions for Pavement Management. ASCE, Vol 113, No 5, 1987.

4. R. K. Herz. Urban Infrastructure Renewal. 16th PTRC Summer Annual Meeting, PTRC Proceedings 310, pp 143-158, 1988.

5. J. V. Carnahan. Analytical Framework for Optimizing Pavement Maintenance. ASCE, Vol 114, No 3, pp 307-322, 1988.

6. John D. Kalbfleisch and Ross L. Prentice. The StatisticalAnalysis of Failure Time Data. John Wiley & Sons, 1980.

7. E. E. Lewis. Introduction to Reliability Engineering. john Wiely & Sons, 1987.

8. K. George, A. Rajagopal and L. Lim. Model for Predicting Pavement Deterioration. In Transportation Research Record 1215, TRB, National Research Council, 1989, pp. 1-7