

PROPOSAL OF SIMPLE PAVEMENT DETERIORATION MODEL BY USING IN-SERVICE SURVEY DATA

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ABSTRACT
In this paper a nonlinear deterministic flexible pavement performance model is presented. The model uses the maintenance control index calculated from in-service condition survey data as its independent variable, and pavement characteristics of initial condition, structure and traffic loading as its dependent or explanatory variables. The parameters of the model are estimated using Kanagawa Prefecture Road Network condition survey data. The results of the model show that the model reproduces correctly the actual in-service pavement deterioration trend. This model is simple in its expression, uses a simple estimation method, and uses readily available data, consequently reducing the cost of model estimation. It therefore, suggests a promising avenue for improving the pavement performance prediction and consequently the pavement management system.

KEYWORDS
Flexible pavement, performance prediction model, in-service data

INTRODUCTION

Road networks form a backbone of any nations transportation infrastructure; their design, construction, maintenance, rehabilitation and disposal consume a lot of resources. Damage to the pavement begins from the first day of utilization and so is its deterioration. Indeed without timely and suitable maintenance and repair, substantial damage and, eventually, premature loss may happen. This is very important in situations where road networks are aging, while resources for their maintenance and rehabilitation are diminishing, a situation similar to Japan where most of roads were constructed between 1955 and 1985. It is also very important in situations where there are conflict of resources for development of new roads and maintaining the existing ones, a situation facing most of developing countries like Tanzania.

Performance prediction plays a central role in highway infrastructure system design and management. During design, highway service life is estimated by the projected performance as a function of structural properties, environmental conditions, and traffic loading. In the context of infrastructure management, planning of maintenance and budget allocation also relies on the pavement performance forecast. This makes the information on current and future pavement conditions essential for pavement management decision-making. Data on current condition is obtained from pavement condition survey inspection, while information on future condition is obtained using pavement deterioration models

Pavement performance can be expressed in terms of individual distresses including rutting, cracking and roughness or by a combination of these distresses by an empirical formula. In Japan both systems are used, maintenance control index (MCI), an empirical formula with four forms (Eq. 1 to 4) is used to identify pavement sections to be repaired while individual distresses are used to select the type of repair or maintenance to be applied.

To date, much effort has been given to developing sophisticated pavement performance models to address the deterioration process. A comprehensive example includes the model established after the World Bank road test in Brazil; Paterson [1)] developed a series of empirical performance models on the basis of a compressive study of previous modeling efforts and the characteristic of the road test data, and AASHTO design equation [2)]. Both models have now evolved to reflect the changes in computation capacity and pavement condition data gathering technology.

Correct specification of the pavement deterioration models is important prerequisite to the accurate performance of the model and consequently, efficient management of pavement. Two more important aspects to consider during model formulation are; the availability of data, and that output should provide meaningful engineering interpretation. This paper is concerned with the development of an empirical deterioration progression model using in-service data; the model is simple, cost effective and reasonably accurate.

KANAGAWA ROAD NETWORK DATA

This paper is concerned with the development of an empirical deterioration model using in-service pavement data. The data set taken from the Kanagawa Prefecture Road Network includes the design and maintenance records, and condition inspection results for years 2001, 2002, 2003, 2004, and 2005. Kanawaga prefectural government is responsible fore the maintenance of 1261.036 km road network that are classified into 3 classes; 10 routes in general national highways, 99 routes in general prefecture roads, and 39 routes in principal local roads. A total number of 12,324 sections conditions were inspected and recorded

between 2001 and 2005, these include 2,469 sections of general national highways, 4281 sections of general prefecture roads and 5574 sections are of principal local roads. Each section's length is 100m on average.

In this paper sections falling under the general national highways were used for model development and parameter estimation. A total number of 825 sections were prepared among the 2,469 sections. These were those sections whose characteristics of construction date, maintenance history, design characteristics and traffic volume were recorded in the database. Among these 825 sections, 655 sections were used for parameter estimation, and the rest 170 sections were used for model performance establishment. The 825 sections were constructed between the year 1972 and 1985.

The use of field data collected from condition surveys of in-service pavements for model development, as opposed to field data collected from experimental data has the following characteristics. As advantages, the main factors affecting pavement deterioration such as vehicle loads, layer thicknesses and environmental conditions are captured with their actual values not like in the experimental data where construction and usage is controlled and thus does not reflect the true nature of construction, environment, and traffic loading. For example material aging is hardly captured in experimental data. As such data from actual in-service pavement sections subjected to the combined actions of highway traffic and environmental conditions are the most representative of the actual deterioration process. As disadvantages, in the field it is difficult to have very accurate measurement of vehicle loads, and therefore discriminating the effect of each load level from a distribution of loads is difficult problem. However, this model addresses this shortcoming by using the cumulative vehicle volume to estimate the 5-ton wheel load characteristics among the heavy and light vehicles.

Climatic condition of Kanagawa in terms of moisture content and temperature do not differ much between the different parts, as such this paper assumes one climatic condition for the whole network. The subgrade conditions are assumed to be different as the soil condition at different parts of Kanagawa prefecture is not the same. The condition of various sections was monitored in terms of their cracked area ratio, rutting depth and longitudinal roughness depth. These were used to calculate the MCI values using Eq. 1-4, where S represents the percentage of cracked area, V represents the longitudinal rutting (in mm), and R represents the roughness (in mm). The design parameters considered were surface thickness, bituminous base thickness, mechanical base thickness, and mechanical subbase thickness, also the design subgrade CBR.

$$MCI = 10 - 1.48S^{0.3} - 0.29V^{0.7} - 0.47R^{0.2} \quad (1)$$

$$MCI = 10 - 1.51S^{0.3} - 0.30V^{0.7} \quad (2)$$

$$MCI = 10 - 2.23S^{0.3} \quad (3)$$

$$MCI = 10 - 0.54V^{0.3} \quad (4)$$

MODEL SPECIFICATION

The deterioration of pavement performance is dependent on the combined influence of traffic load and environment on the pavement section. Therefore the sound model should incorporate these relevant variables of pavement strength, traffic loading, and environment. Based on previous established models [2) and 3)], the current model is specified to reflect the availability of data to be used in the model parameter estimation; it does not however, loose the purpose of accurately predicting the performance of pavement sections.

Specification of Structural Strength

Pavement strength is governed by pavement thickness and material characteristics. However, the pavement section is made up three layers, the surface, base and subbase, which are laid on the subgrade and therefore, the pavement thickness is the combination of these layers into an equivalent layer. As proposed in the AASHO model [2], the thickness of an equivalent layer is given by Eq. 5, indicating the contribution of each pavement section layers to the equivalent thickness, where a, b, and c are parameters of each pavement layer that denote the relative thickness of the individual layer to equivalent pavement thickness. The three layers are surface, base and subbase with thicknesses H_1, H_2, and H_3 respectively.

$$ET = 1 + aH_1 + bH_2 + cH_3 \quad (5)$$

In the current model, a different form is proposed to make the specification physically meaningful. It removes the computational inclined term, 1, and includes the subgrade term, while increasing the number of pavement layers to be four (Figure 1). The inclusion of the subgrade term is based on the findings of Brown et al. [4], where proper characterization of the subgrade is emphasized when dealing with pavement evaluation. They depict the large influence of subgrade on surface deflection in a typical pavement situation by showing that a pavement section under the influence of a single standard wheel load, its vertical resilient strain at the center of the load will diminish at 2m below the surface. As such this paper adopts a standard 2m-pavement section to capture the effect of subgrade, and uses the design subgrade CBR as the characteristic of the subgrade below the pavement section. In Figure 1, a pavement section is represented to have four layers, asphalt surface, bituminous base, mechanical base, and subbase. Eq. 6 gives the new equivalent pavement section thickness, with α_0 to α_4 representing the parameters to be estimated

$$ET = T_0 \times CBR^{\alpha_0} + \alpha_1 T_1 + \alpha_2 T_2 + \alpha_3 T_3 + \alpha_4 T_4 \quad (6)$$

The rate of deterioration of pavement section is less with a stronger pavement section, and increases with the weaker sections. This research adapts the specification of strength developed by Prozzi and Madanat [3], in which the pavement strength is given by power function of the equivalent strength and is represented by Eq. 7.

$$\text{Section strenght, N} = (\text{equivalent thickness})^{\alpha_5} \quad (7)$$

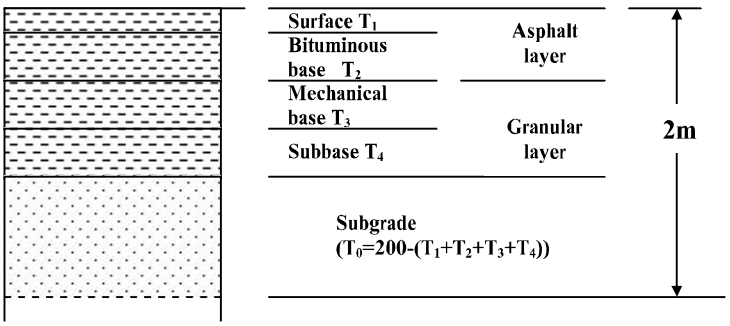


Figure 1 Conceived typical 2m thick pavement section

Specification for Traffic Loading

In the current code of Japan Road Association, traffic load during pavement design is given in terms of total number of wheel load converted to the number of 5-ton wheel load applications. Further, the classification of traffic in Japan is in terms of heavy or light traffic depending on whether their wheel loads are greater or less than 5 tons respectively [5]. Two approaches can be adopted to collect wheel load data. One utilizes static scales and the other uses weigh-in-motion equipment. Both approaches are difficult to apply and as such there are, most of the time, a problem of reliable traffic load data. The current approach of converting traffic to an equivalent 5-ton wheel load is approximate and can only be justified in the context of the vagaries of estimating numbers of wheel loads of each vehicle passing through a pavement section. This is very difficult and as a result, the approximate method of using traffic volume is used in this paper.

In this paper, the equivalent traffic load (ETL) is given by Eq. 8, this expression is adapted in order to reflect the Japanese equivalent traffic load that converts the total wheel load passes over the measured point to the number of 5-ton wheel load applications. This is also done to reflect the available data, because the database contains only the measured average annual daily number of light and heavy vehicles. The equivalent damage caused by the traffic load assumes the *power law* [6]; consequently Eq. 9 gives damage (Dg) to pavement due to traffic load. L and H in Eq. 8 and 9 represent cumulative light and heavy traffic respectively.

$$\text{ETL} = \alpha_6 L + \alpha_7 H \quad (8)$$

$$Dg = \left(\alpha_6 L + \alpha_7 H\right)^{\alpha_8} \quad (9)$$

Specification for Initial MCI

The initial MCI in this research represents the pavement condition soon after construction. It is usually controlled by the pavement construction technique and surface thickness[3]. Because during the opening of the road, there are neither cracks, nor rutting on the road section, only the longitudinal roughness governs the MCI. However, in this research neither information on the initial MCI measurement nor information on the construction process was available; therefore, this term is also provided as a parameter to be estimated with other parameters of the model, and it is represented as M_0

Final Specification for the Model

The final pavement performance model is given by combination of the three parts, the initial MCI, the pavement section strength, and the traffic load damage. It is built from the basic idea that pavement section MCI at any time is the function of the initial MCI and deterioration that has happened due to traffic loading. And the deterioration is given by product of the pavement section resistance and the cumulative traffic damage per unit pavement strength. Eq. 10 gives the expression for the complete mode.

$$MCI_{i,t} = MCI_{i,0} - \left(T_{i,0} \times CBR_i^{\alpha_0} + \alpha_1 T_{i,1} + \alpha_2 T_{i,2} + \alpha_3 T_{i,3} + \alpha_4 T_{i,4}\right)^{\alpha_5} \left(\alpha_6 L_{i,\Delta t} + \alpha_7 H_{i,\Delta t}\right)^{\alpha_8} \quad (10)$$

where;

$MCI_{i,t}$ **= pavement MCI for section *i* at time *t***
$MCI_{i,0}$ **= pavement initial MCI**
$T_{i,0}$ **= section thickness between lowest part of subbase and 2m depth**
CBR_i **= design CBR of the section *i* subgrade**
$T_{i,1}$ **= surface thickness for pavement section *i***
$T_{i,2}$ **= bituminous base thickness for pavement section *i***

$T_{i,3}$ = mechanical base thickness for pavement section i
$T_{i,4}$ = subbase thickness for pavement section i
$L_{i,\Delta t}$ = cumulative light traffic since construction or reconstruction
$H_{i,\Delta t}$ = cumulative heavy traffic since construction or reconstruction
α_0 to α_8 = model parameters to be estimated

The salient features of the model specification in this paper includes: it captures the effect of subgrade condition; differentiates the effect of bituminous stabilized or lime stabilized base with the mechanically stabilized base; eases the obstacle of obtaining traffic load data by using traffic volume categorized into vehicle and light vehicles; and the model predicts pavement control index at any time by taking in the cumulative effect from all the previous factors that have been subjected to the pavement section.

MODEL PARAMETER ESTIMATION

The focus of this paper is the statistical estimation of models that relate pavement section MCI trends to explanatory variables representing pavement structure, subgrade condition and traffic loading. The model is nonlinear in parameters and therefore requires the nonlinear estimation techniques. In this paper, the nonlinear least square method was used to estimate the parameters. Method follows a generalized form of the nonlinear regression model represented by Eq.11 [7]. In this equation, y_i represents the dependent or explained variable; x_i represents the vector of independent or explanatory variables; β represents the vector of parameters; ε_i represents the random error term; and h represents a nonlinear function of β. In this paper, it was assumed that ε_i in Eq. 11 is normally distributed with mean zero and constant variance, therefore the value of the parameters that minimizes the sum of the squared deviations are the nonlinear least squares estimators of the model.

$$y_i = h(x_i, \beta) + \varepsilon_i \tag{11}$$

Table 1 Model Parameter Estimates

Parameter	Estimate	Standard Error	T-statistic
M_0	8.8	0.566	15.559
α_0	1.335	0.142	9.401
α_1	5.867	0.576	10.186
α_2	3.515	0.124	28.462
α_3	1.535	0.118	13.008
α_4	0.699	0.052	13.494
α_5	-1.431	0.065	-22.152
α_6	0.566	0.015	36.753
α_7	2.16	0.023	93.506
α_8	0.482	0.032	14.877

Parameter Estimation Results

The parameters of the performance model given by Eq. 10 were estimated using the econometric LIMDEP software [7] the estimated parameters and statistics are given in Table 1. The asymptotic-t value in Table 1 shows that all parameters are statistically significant from zero at a 5% degree of confidence and all parameters have the expected signs.

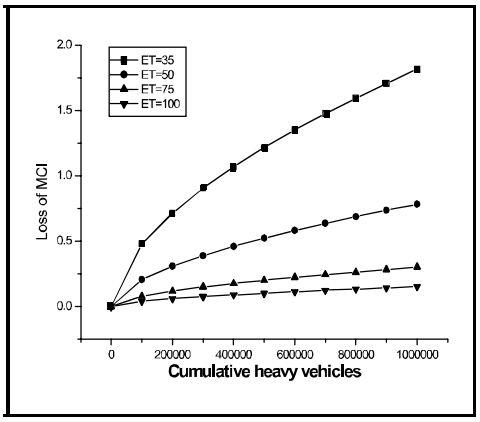


Figure 1 Effect of section thicknesses to pavement deterioration

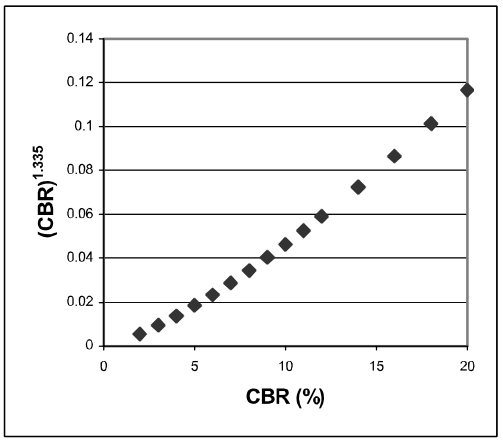


Figure 2 Subgrade contributions to pavement strength

DISCUSSION

The parameters obtained in this estimate provide the expected engineering meaning when looked from the model and pavement performance perspectives. It can be seen that the surface layer contributes more to the pavement equivalent thickness and pavement strength, followed by the bituminous base, mechanical base, and the mechanical subbase. As expected, Figure 1 indicates that the stronger the section, the less the deterioration behaviour it exhibits. In this figure the pavement Equivalent Thickness (ET) indicates strength.

In the model specification, the strength of the subgrade is assumed to constant, and is represented by the design CBR. During the estimate, it was observed that the power expression indicates better the variation of subgrade CBR contribution to pavement strength, the result of the parameter estimated when calculated with typical subgrade design CBR is represented in Figure 2. Generally it can be seen that the contribution of subgrade to strength is very low, and it increases exponentially. Another finding is the initial MCI, it can be seen that, the model estimates the initial MCI to be as low as 8.8, this can be attributed to the fact that, most of the pavement sections that were dealt with in this paper were not controlled during construction. However, the standard error term indicates that, in some cases, the MCI can be as good as 9.4 and as low as 8.2, which to our opinion is reasonable in a huge road network like that of Kanagawa Prefecture.

The traffic loading parameters also provide meaningful results, indicating that not only the heavy vehicles but also the light vehicles contribute to the deterioration of the pavement, and in average, their damage is equivalent to 0.566 the 5-ton wheel load standard. In similar perspective, the average heavy traffic load is estimated to be 2.16 times the 5-ton wheel load standard. Both results are reasonable and may be used for pavement maintenance scheduling, as well as for road usage costing.

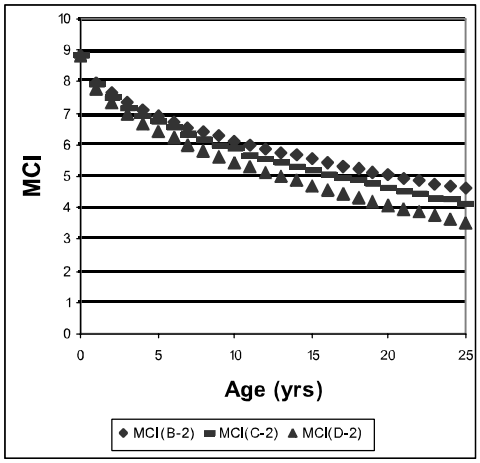


Figure 3a Pavement performance for Sections with Subgrade CBR =2%

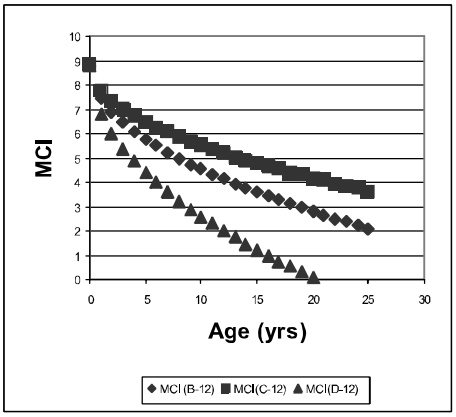


Figure 3b Pavement performance for Sections with Subgrade CBR =12%

Table 2 Typical pavement thicknesses

Traffic Level		B		C		D	
Design CBR (%)		2	12	2	12	2	12
Pavement Thickness	T1	10	10	10	10	15	15
	T2	0	0	10	9	10	8
	T3	30	10	35	10	45	0
	T4	35	15	35	10	50	35

Pavement Performance Forecast

The ultimate goal for model estimation is to forecast pavement performance. In this paper too, the typical Kanagawa pavement sections traveled with typical traffic levels are used to demonstrate the forecast that can be attained using the current model. Conceived design sections for traffic level B, C, and D on a subgrade with design CBR of 2 and 12 respectively, as guided by the JRA design manual[5] are indicated in Table 2. In some sections you may notice that the pavement is designed with only three layers, in which case the missing layer is indicated to have 0cm thickness. Traffic Level B is assumed to have annual average daily traffic of 5249 and 591 for light and heavy vehicles respectively, while for level C, the light vehicles are 13761, while heavy vehicles are 2022, and for level D, 28857 and 8835 are taken to represent the annual average daily light and heavy vehicle respectively. When these characteristics of the pavement sections are used together with the current model parameters, the performance curves in Figure 3a and 3b are obtained. The curves indicate one very interesting result, that is, pavements designed on weak subgrade are most of the time over designed. This result is in agreement with many other researches that suggest reconsidering the subgrade design criteria. Brown [8], for example, urges using the results obtained by work of Dawson and Plaistow [9], that more efforts should be devoted to correctly modeling and specifying granular materials for pavement design purposes while subgrade characteristics are relatively less important.

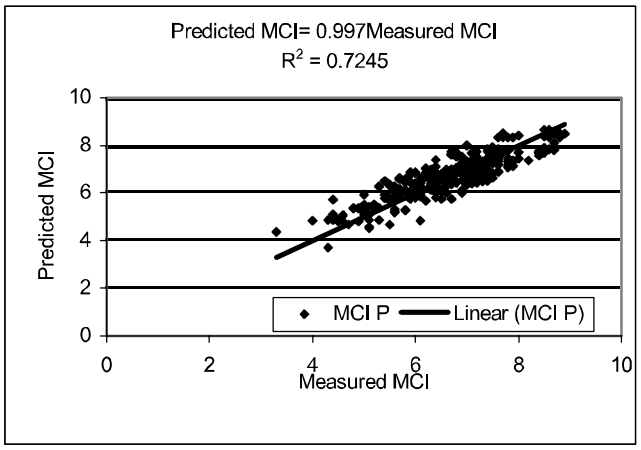


Figure 4 Comparison of Predicted and MCI

Model Performance

To illustrate the performance of the model, MCI of the 170 pavement sections, which were not used in model parameter estimation, is predicated using the model with its current parameters. The predicated MCI of the section is compared with the MCI calculated from distress values found during condition survey inspection. The results are presented by Figure 4, it is demonstrated that the forecast line fits the observations reasonably well with a proportionate rate, R^2, of 0.7245.

CONCLUSIONS

A pavement deterioration model was presented in this paper based on performance inspection data of Kanagawa Prefecture Road network. The model specification includes the major flexible pavement performance governing factors, that is, pavement structures, subgrade condition and traffic loading. The analysis of the paper provides for the following conclusions:

(1) Condition survey data can be used to estimate future performance of pavement with very good results as those found in this paper;
(2) A simple well-specified nonlinear pavement model used here could reduce the agency's cost and still provide very good results; in this paper it has been shown that the results of the model provide useful, and meaningful engineering answers. An example of the ratio of strength of pavement structure as indicated by coefficients of section layer justifies this;
(3) Inclusion of light traffic during consideration for traffic loading should not be neglected, as it is shown in this paper that its deterioration factor is slightly larger than half that of a 5-ton wheel load vehicle, a value too large to be neglected; and
(4) Subgrade characteristics consideration during pavement design needs more research, as it is seen in this paper that its contribution to the pavement strength may be smaller than usually thought.

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