Pavement Performance Modeling Using Markov Chain with and Without Application of Maintenance

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Abstract

Pavement performance modelling is an essential element of a pavement management system (PMS).The model developed plays a critical role in several aspects of the PMS including financial analysis. In developing countries like India, PMS is the needed approach for the optimum utilisation of the available scarce resources. Pavement management System is concerned with optimal use of materials in time and space, leading to cost optimization.The aim of this paper is to develop a pavement performance model for the state highway in Bihar, India. Hundred meter of road stretch was selected for visual condition survey that was conducted at the beginning and end of the year 2011. PCI was calculated based on density and severity level of the individual distress type. Using Markov Chains the condition of the pavement sections are predicted over the twenty years with and without application of maintenance. Model is developed between weighted average PCI and age of the pavement then after validated using observed data taken over the year. Result shows that the developed model is able to predict future condition rating with a reasonable degree of accuracy.
KEYWORDS - Pavement Management System, Performance, Pavement Condition index (PCI), Probability transition matrix, Markov Chains

I. INTRODUCTION

Roadways mode of transport is the basic need of human society as mobility has always been important for the development of modern society. One of the major components of road investment is on pavements. Although the function of pavement varies with the specific user in modern highway facilities, the purpose of pavement is to facilitate traffic movements safely, comfortably and efficiently at minimum or at reasonable cost. With relatively large investments involved in pavements, even marginal improvements in managing this investment and in the technology involved may affect large savings in absolute terms. In addition to the direct saving in the capital cost and in maintenance, the indirect benefits to the road user can be equally significant, however, it is difficult to ascertain. Pavement design system or rehabilitation design system should therefore, indicate the structure needed in order to an acceptable degree of deterioration before a given time or number of traffic loadings and to permit a prediction of both functional and structural deterioration over time. Pavement management is concerned with doing the right thing at right place, using the right type of materials, with the right thickness, with the right design details and all for the lowest total transportation cost. The term Pavement Management is used to describe the various strategies that can be used to decide on a pavement restoration and rehabilitation policy. In other words Pavement Management is a systematic process for maintaining, upgrading and operating physical pavement assets in a cost-effective manner.

The performance of a pavement certainly depends in parts, but not exclusively, on the design concepts that were used. The success of any design is also largely dependent on subsequent construction, maintenance and rehabilitation. Historical studies by many agencies show that the concept of a twenty years new pavement design is generally fictitious (Hass, R. & Hudson W. R., 1994). Often pavements provide adequate science for only up to ten or twelve years and sometimes less, without major maintenance or rehabilitation. If such action occurs, sometimes more than once, it is quite feasible to provide a total of twenty to twenty-five years performance or total service life. Consequently, many agencies have recognized the need to link together explicitly the activities of planning, designing, constructing and maintaining pavements (Hass, R. & Hudson W. R., 1994). In other words, they have recognized the need to manage the technology of providing pavements on a comprehensive basis. Design technology for pavements has traditionally been both prescriptive and deterministic. It has been prescriptive in the sense that designers have set limits on such factors as deflection, stability or other parameters in an attempt to avoid premature failure, rather than to predict the type and degree of damage that might occur and the time at which it might occur under a specified set of conditions. It has been deterministic in the sense that the equations or models predict a single answer and do not account for statistical variation or reliability factors. It has been only recently that design itself has been elevated from the concept of specifying an initial structure section to that of a strategy where the strategy is an optimized design involving not only the best initial construction and structure section but also the best combination of materials, construction policies, maintenance policies and overlays.

A pavement management system is a planning tool used to aid pavement management decisions (AASHTO, 2001).PMS provides decision makers at all management levels with optimum strategies derived through clearly established rational procedures. A PMS evaluates alternative strategies over a specific analysis period based on predicted values of quantifiable pavement attributes, subject to predetermined criteria and constraints. It involves an integrated, coordinated treatment of all areas of pavement management and it is dynamic process that incorporates feedback regarding the various attributes, criteria and constraints involved in the optimization procedure. A total pavement management system consists of a coordinated set of activities, all directed towards achieving the best value possible for the available public funds in providing and operating smooth, safe and economical pavement.

Healthy and strengthen road network is essential for socioeconomic development of a country. There must be matching growth between roads, traffic, vehicle population and population. Overcrowded, overloaded, poorly funded, poorly constructed, poorly maintained roads cannot be of much use for the development of a country and will create indiscipline and other problems. Roads in poor condition are known to contribute for the increase of vehicles operating costs with consequent increase in the total transport cost. This impairs the economy of the country as a whole. The nefarious impact of a poor road network in the economy of a country, where the road transport is the dominant mode of transport, has been well demonstrated worldwide by many transport economists. However, limited funds and the scarcity of other resources, call for the rational and efficient use of these resources to try to maximize the benefits, using appropriate pavement management systems (PMSs).PMSs used internationally are not necessarily applicable under the conditions of most developing countries. The relatively high cost involved during data collection for use by these systems, as a result of the type of equipment required, as well as other practical considerations, in most cases limits their implementation. To provide a system that can be applied under circumstances of developing countries different approach to pavement management may be required.

With the increase of vehicles the road length is also increased but in comparison it is quiet less. The deterioration has been aggravated due to overloading of vehicles, advancement of multi-axels in commercial vehicles and repetitions of axels load on important roads. Apart from traffic the causes of deterioration of pavement surface are mighty change in temperature and unexpected rainfall intensity. Generally delay in maintenance results further deterioration this may occur due to the lack or extremely limited funds and scarce resources. Under this circumstance there is a need of technique and tool to provide the right thing, at right time and at right place with an optimum cost. In this context the following statement holds good.

Pavement need to be managed, not simply maintained (Shahin M. Y., 1994)**.**

The main aims of this paper are (i) To find out the pavement condition index (PCI) of selected pavement sections while incorporating distresses measured by conducting visual condition survey using PAVER system, and (ii) To develop a model on pavement performance for future year for PMS using Markov Chains with and without application of maintenance.

II. PAVEMENT PERFORMANCE MODELS

Many highway agencies have developed one or more of these types of models for different uses in managing pavements. Some of these are very simple and limited in their applications. Other models are comprehensive and well suited for a broad range of applications. Project level models are different from and more detailed than network levels models for they are used in the analysis and design of pavements and of life cycle cost analysis of alternative designs. Network level models are necessarily less detailed but are used in the selections of optimal maintenance and rehabilitation strategies. In spite of all the complexities, pavement engineers have done remarkably well in developing performance models with acceptable ranges of prediction errors. **Lee et al (2000)** stressed the need for simplified pavement performance models that can be used for forecasting pavement condition based on minimal amount of pavement data. Five such models were development for all conventional pavement types. These models predict the Present Serviceability Rating (PSR) using only knowledge of pavement age, cumulative Equivalent Single Axle Load (ESAL) and knowledge of Structural Number (SN). A unique calibration technique was introduced and incorporated into the models so that these can be used to predict the performance on existing and new pavements.

Shahin et al (1994) evaluated the applicability of three mathematical curve-fitting techniques for modeling pavement conditions deterioration. The best features of each were integrated into an interactive format capable of operating with PAVER pavement management system.

The Foundation of Scientific and Industrial Research (SINTEF) of the Norwegian Institute of Technology developed a deterioration model for local conditions. Based on climate, traffic and road data, this model predicts the development of damage and other parameters for pavement conditions and structure. **Saraf et al (2009)** described the procedure to develop distress prediction models for a network level PMS for Ohio Department of Transportation. The models were not to predict distresses and pavement condition rating which were compared with the corresponding distresses and PCR calculated form field observations. The compression indicated that the models were capable of predicting with reasonable accuracy the condition of a highway network as well as individual pavement segments. **Shin et al (2003)** formulated a stochastic model of pavement distress initiation. Duration modeling technique was used for analysis of pavement crack initiation. Duration modelsenables the stochastic nature of pavement crack initiation to be represented as well as censored date to be incorporated in the statistical estimation of the model parameters. The results show that the model predictions are more accurate than those obtained with the original AASHO model. **Irfan et al (2009)** investigated the effectiveness and cost effectiveness (CE) of four flexible pavement rehabilitation treatments. The performance indicator used is the international roughness index and treatment effectiveness is measured in terms of performance jump (short term) and service life and increase in pavement performance (long term). Based on performance jump and increase in average pavement performance as measure of effectiveness, HMA overlay structural is found to be most effective followed by mill full depth and asphaltic concrete overlay. The CE analysis showed that based on all three-performance criteria (performance jump, service life and increase in average pavement performance), mill full depth and asphaltic concrete overlay is found to be most cost effective.

Many highway authorities in developed countries are using a systematic and objective method to determine pavement condition and programming maintenance in response to observed conditions, as budget permits. In many of the developing countries, pavement management system (PMS) is in various phases of working process with diversified approaches as per the respective needs and problems of each country. Although a number of important studies of direct or indirect interest to PMS have been planned and conducted in some parts of the country, but no workable PMS has been developed so far, catering to the needs of the country as a whole. In this context, development of the system can be taken up in a phased manner with an adequate mechanism to provide continuity to the entire process.

III. PAVEMENT CONDITION INDEX (PCI)

PCI is a numerical indicator of present pavement surface condition that reflects the riding quality of pavement surface. The PAVER method (Shahin M.Y. 1994) for computing the PCI is a function of the types, severity and the density of the distresses. It is a numerical index that uses a scale from 0 to 100. A new pavement (theoretically distress-free) has a PCI of 100 and an old pavement of completely worst condition has PCI of zero. Figure 1 shows schematic diagram on which PCI depends and PCI rating with rating score scale. The pavement conditioned index for each section of road stretch is calculated (Muralikrishna P. and Veeraragavan A. 2011) using Eq.1 and 2.

$$PCI = 100 - CDV \quad (1)$$

$$CDV = f\,(N, TDV) \quad (2)$$

Where, CDV is corrected deducted value, N is number of considered distress parameters and TDV is total deduct value.

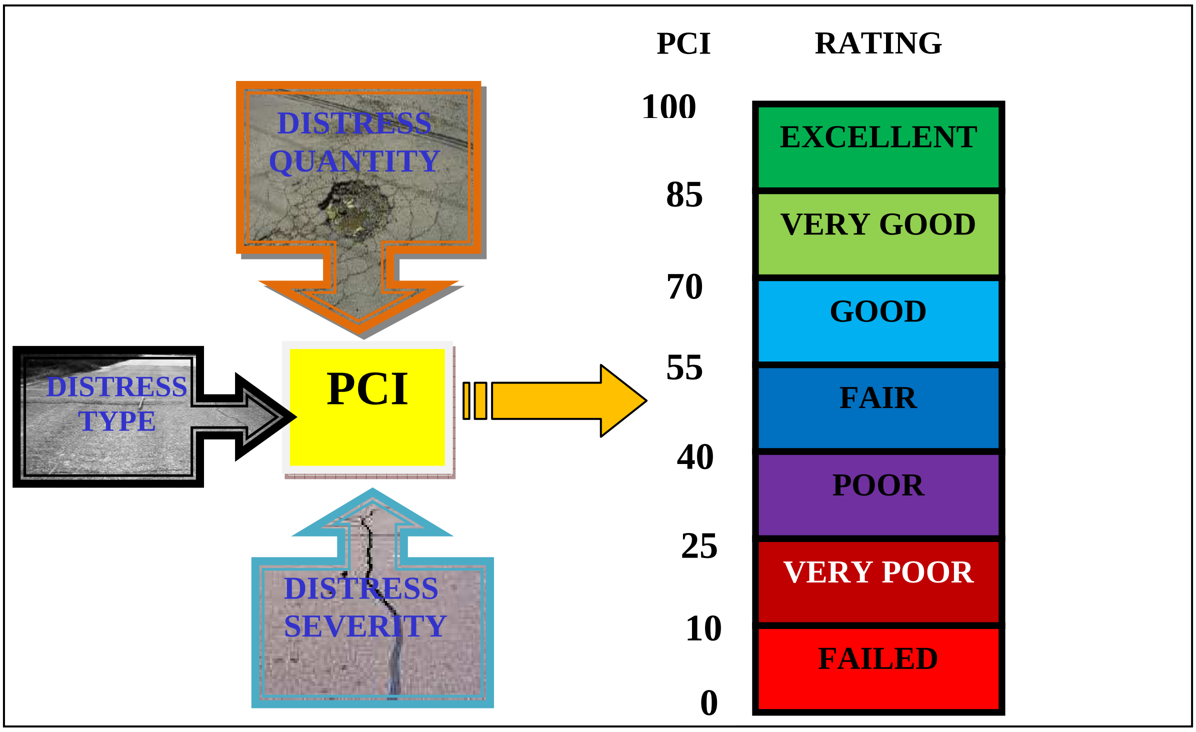

Figure 1. Schematic diagram for rating pavement condition

IV. MARKOV CHAINS

Probabilities methods are based on the assumption that future conditions can be determined from the present state if the probabilities of given outcomes are known. Since the deterministic methods, lack the ability to accurately predict the deterioration of a pavement owing to the uncertainties of its explanatory factors while probabilistic model handles such uncertainties factors nicely. Pavement deteriorates due to uncertain factors like traffic loading and environmental conditions. One of the probabilistic methods is Markov chain theory **(**Butts. A. A. et al., 1987and Hillier F.S. and Lieberman G.J.,2009)**.**

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A Markov Chain is a special type of discrete-time stochastic process, when the state of a system X_{t+1} at time t+1 depends on the state of the system X_t at some previous time t but does not depend on how the state of the system X_t was obtained. This can be expressed as $P(X_{t+1} = j \mid X_t = i)$,where P is the probability of the state at time t+1 being j given that the state at time t was i, assuming that the probability is independent of time. This assumption is formally known as the stationary assumption.

This stationary assumption is used because of the limited time period of the data collected. If data were collected over a large period, the quantity and type of materials used might change over time and influence how a typical pavement section would determine. A Markov chain can be summarized through a probability transition matrix and the initial state probabilities.

To model pavement deterioration with time, it is necessary to establish a transition probability matrix (TPM), denoted by P.The general form of P is given below:

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & \cdots & \cdots & \cdots & p_{1n} \\ p_{21} & p_{22} & p_{23} & \cdots & \cdots & \cdots & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{n-11} & p_{n-12} & p_{n-23} & \cdots & \cdots & \cdots & \cdots & p_{n-1n} \\ p_{n1} & p_{n2} & p_{n3} & \cdots & \cdots & \cdots & \cdots & p_{nn} \end{bmatrix}$$

The matrix contains all of the information necessary to model the movement of the process among the condition states. The transition probabilities p_{ij} indicate the probability of the portion of the network in condition i moving to condition j in one duty cycle.

Two more conditions apply to the process when it is used to simulate pavement deterioration. First, $p_{ij}= 0$ for i>j signifying the belief that roads cannot improve in condition without first receiving treatment. Second, $p_{nn} = 1$, signifying a holding state whereby roads that have reached their worst condition cannot deteriorate further. Consequently, in pavement deterioration, the general form of the transition matrix P is denoted by P^1.

$$P^1 = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & \cdots & \cdots & \cdots & p_{1n} \\ 0 & p_{22} & p_{23} & \cdots & \cdots & \cdots & \cdots & p_{2n} \\ 0 & 0 & p_{33} & \cdots & \cdots & \cdots & \cdots & p_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & 0 & 0 & p_{(n-1)(n-1)} & p_{(n-1)n} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

A further restriction allowing the condition to deteriorate by no more than one state in one duty cycle is commonly used in pavement deterioration modelling. The transition probability matrix is then denoted by P^2.

$$P^2 = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 & \dots & \dots & \dots & 0 \\ 0 & p_{22} & p_{23} & 0 & \dots & \dots & \dots & 0 \\ 0 & 0 & p_{33} & p_{34} & \dots & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ 0 & \dots & \dots & \dots & \dots & \dots & p_{(n-1)(n-1)} & p_{(n-1)n} \\ 0 & 0 & 0 & \dots & \dots & \dots & \dots & 1 \end{bmatrix}$$

The entry of 1 in the last row of the transition matrix corresponding to state 100(PCI of 0 to 100) indicate a holding or trapping state. The pavement condition cannot transit from this state unless repair action is performed. The state vector for any duty cycle t is obtained by multiplying the initial state vector X (0) by the transition matrix P raised to the power of t .Thus,

X (1) = X (0).P

X (2) = X (1).P = X (0).P^2

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X (t) = X (t-1).P = X (0).P^t

With this procedure, if the transition matrix probabilities can be estimated, the future state of the road at any duty cycle t can be predicted. After the several cycle operations, rows of the matrix come to identical entries, the reason is that probabilities in any row are the steady state probabilities for the Markov chain i.e. the probabilities of the state after enough time has elapsed that the initial state is no longer relevant.

A method is presented herewith for computing the transition probability matrix from temporal data of pavement surface condition deteriorates over time. The element of the transition probability matrix (p_{ij}) may be estimated by using Eq.3.

$p_{ij} = \frac{N_{ij}}{N_i}$(3)

WhereN_{ij}= number of road sections in the network that moved from condition i to condition j during one duty cycle and N_i=total number of road sections that started the year in condition i. The proportions are likely to vary from year to year thereby requiring an average to be determined for each $p_{ij}$to ensure accuracy in the model.

V. DATA COLLECTION

A road of Patna district in state of Bihar, India is selected namely state highways (SH1).The length of road to be surveyed is 12.5km from Pahari (25.585238, 85.191418) to Sampatchak (25.545163, 85.179423) as shown in Fig.2.Averahe annual precipitation in Bihar is 1000-1200mm and average annual temperature is about 30 ^{o}C. Pavement layers are shown in Fig.3. The age of the pavement was two years eight months at the ends of year 2011. In the present study visual condition survey was carried out at the beginning of year 2011 and the end of year 2011. Number of distresses found on the SH1 was ten.Types of distresses observed on the pavement surface were stated in the Fig. 4.To determines the pavement condition index hundred meters length had been considered.

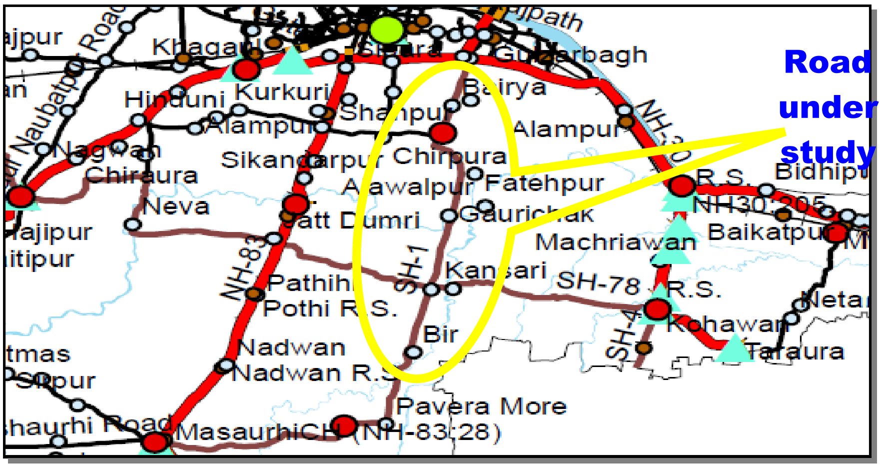

Figure 2.SH1 under study

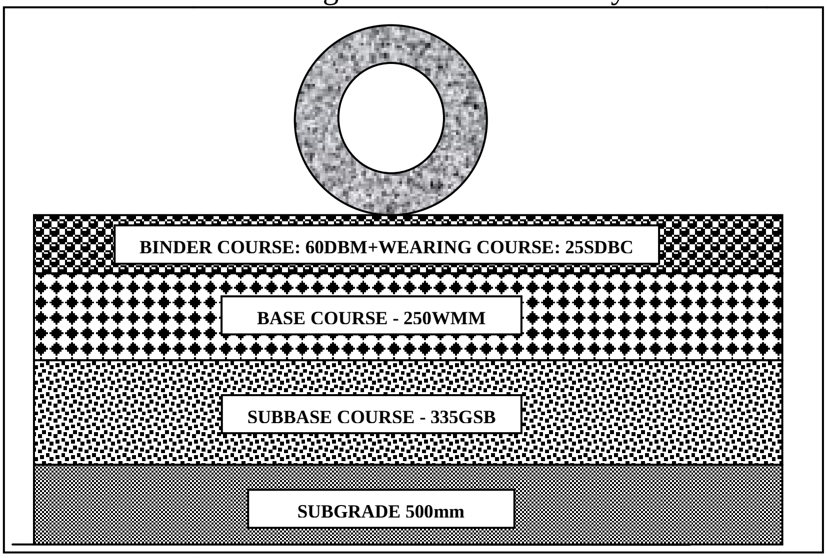

Figure 3. Pavement layered system for SH1

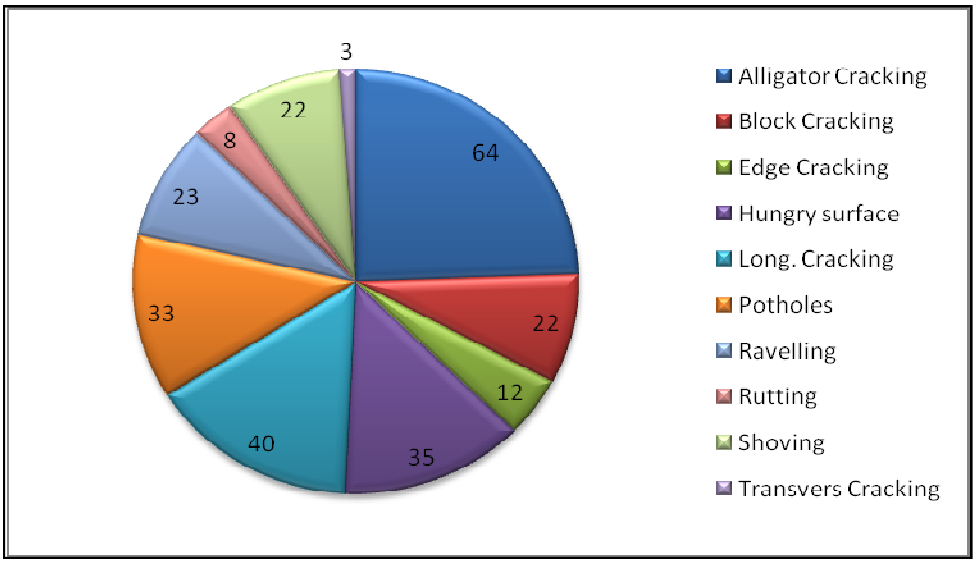

Figure 4. Distresses in SH1

VI. PAVEMENT PERFORMANCE MODELLING

6.1 Condition state vector

The derivation of condition state vector is illustrated for a pavement length from the PCI condition rating data as of SH1 for year 2011 as shown in Table 1.This condition probability in year 2011 can be represented by a condition state vector X = [38.40, 24, 24, 2.40, 11.20, 00, 00].This is a vector of probabilities that a pavement section will be in that state at the beginning of year 2011.

Table -1Condition state vector

Condition state	**Corresponding condition rating**	**Length of the pavement section(km)**	**Probability distribution (%)**
Excellent	100-85	4.80	38.40
Very good	85-70	3.00	24.00
Good	70-55	3.00	24.00
Fair	55-40	0.30	2.40
Poor	40-25	1.40	11.20
Very poor	25-10	0.00	0.00
Fail	10-0	0.00	0.00
Total length(km)		12.50	100.00

6.2 Transition Probability Matrix

Table 2 shows the transition of number of pavement sections from higher state of condition to that of the lower state of condition for SH1. Transition Probability Matrix for pavement conditionis indicated in Table 3.

Out of one hundred twenty-five sections, Twenty-nine road sections remain in excellent condition state, two road sections moves from excellent to good condition state, nine road sections remain in very good condition state, twenty-one road sections moves from very good to good condition state, twenty two pavement sections remain in good condition state, eight road sections moves from good to fair condition state, one road section remain in fair condition state, two road sections moves from fair to poor condition state, three road sections remain in poor condition state, ten road sections moves from poor to very poor and single road section move from poor to fail condition state.

Table-2Pavement condition rating distribution

Condition state Transition	**Corresponding Condition Rating**	**Number of pavement sections**
Excellent→Excellent	100-85→100-85	29
Excellent→Very good	100-85→85-70	17
Excellent→Good	100-85→70-55	2
Very good→Very good	85-70→85-70	9
Very good→Good	85-70→70-55	21
Good→Good	70-55→70-55	22
Good→Fair	70-55→55-40	8
Fair→Fair	55-40→55-40	1
Fair →Poor	55-40→40-25	2
Poor →Poor	40-25→ 40-25	3
Poor →Very poor	40-25→ 25-10	10
Poor →Fail	40-25→10-0	1
Very poor →Very poor	25-10→ 25-10	0
Very poor→Fail	25-10→10-0	0
Fail →Fail	10-0→ 10-0	0
Total No. of sections(100m)		125

Table -3 Transition Probability Matrix for pavement condition

Future PSC(t+1) Present PSC(t)		Pavement surface condition at end of year 2011						
		Good	Satisfactory	Fair	Poor	Very Poor	Serious	Fail
Pavement surface condition at beginning of year 2011	Excellent	0.604	0.354	0.042				
	Very good		0.300	0.700				
	Good			0.733	0.267			
	Fail				0.333	0.667		
	Poor					0.214	0.714	0.071
	Very poor						0	0
	Fail							1

6.3 Pavement Performance Model

Visual condition survey was conducted on selected pavement in the beginning and end of the year 2011 to predict the pavement condition in horizon year.PCI was calculated to represent the pavement condition .Using Markov chain process pavement condition was predicted for nineteen years. Weighted average method was used to find single value corresponding condition vector matrix. A trend line is fitted to the observed values for getting mathematical model as indicated in Eq.4.

Pavement under study was first surveyed after two years and eight months of construction. Rehabilitation was applied in year 2015 means after seven years of construction. Assuming condition of pavement just after rehabilitation applied is considered as excellent. Further same process was applied to predict the pavement condition for horizon years as shown in Fig.5. A trend line is fitted to the observed values for getting mathematical model as indicated in Eq.5.

$$PCI = 0.058(age)^2 - 4.589(age) + 78.605 \quad (4)$$

$$PCI = 0.132(age)^2 - 7.650(age) + 122.17 \quad (5)$$

6.4 Validation of models

Developed models were validated using observed data as shown in Table 4.Percentage error is difference between observed and predicted values and represented in percentage ,calculated for seven years, out of which few years have percentage error more than 3%.However,they are remain in same pavement condition rating. The mean square error and root mean square error is 0.12% and 0.034% respectively, which are less than 3%.

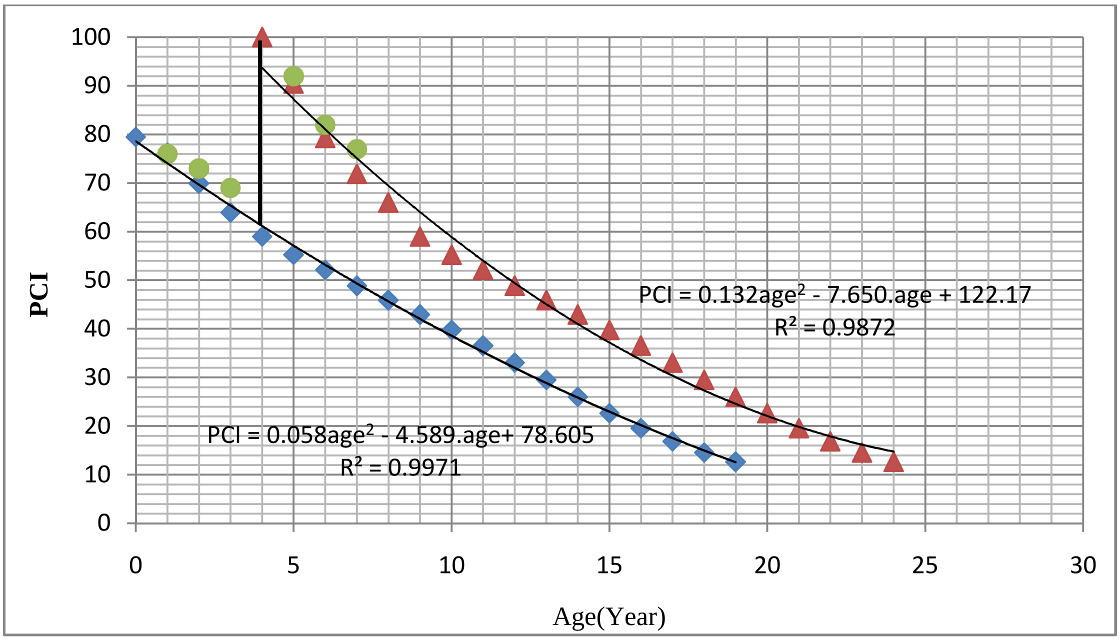

Figure 5. Pavement performance models

Table-4 Validation of models

Stage	Stage I			Rehab. Yr.	Stage II		
Year	2012	2013	2014	2015	2016	`2017	2018
Predicted PCI	76	70	64	100	90	79	72
Observed PCI	76	73	69	100	92	82	77
Percentage error	0	4.23	7.32	0	1.64	3.34	6.60

6.5 Discussion

Density of distresses measured at the beginning of year 2011 almost declined by 30% at the end of the year 2011 for SH1. At the beginning of the year 2011, road sections fall in the various condition state are excellent 48%, very good 30%, good 30%,fair 3%,poor 14%,very poor 0% and fail 0%.After one year road sections transited in the various condition state are excellent 29%,very good 26%,good 45%,fair 9%,poor 5%,very poor 10% and fail 1%.

Pavement condition assessment was carried out in the year 2011, after 2 years 8 months. Hence the condition of pavement was very good it means it deteriorate from excellent condition to very good condition in about three years. After that condition was predicted using Markov chain process, which follow the second degree parabolic trend. It was validated by observed condition value for three years namely in 2012, 2013 and 2014.It was found that errors are within allowable error limits even though they are remain in same pavement condition rating.In year 2015 pavement was strengthen and seems to be in excellent condition. Then after, condition is predicted for the horizon years. This fallows a second degree parabolic trend. Predicted condition is validated by observed condition for the three years namely 2016, 2017 and 2018.This shows the good agreement between predicted and observed pavement conditions. Second stage developed model does not satisfy the equation for the year of rehabilitation but useful for afterwards years.

VII. CONCLUSION

The pavement performance prediction model based on homogeneous Markov chains successfully captures the probabilistic pavement deterioration process. Markov chain theory, characterized by transition probabilities, is applied to evaluate pavement failure probability caused by multiple distresses. Pavement deterioration process, described by transition probabilities is easily derived fromtwo time series condition data like at the beginning of year and at the end of year to predict future pavement condition with respect to different distress indicators. A pavement performance/deterioration prediction model has been developed that is based on the pavement condition index and the age of the pavement. The Markov model introduces a rational structure to the pavement-performance modeling process and is the best for the prediction. Developed model in this study also hold good for making decision of maintenance application based on pavement condition rating.

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