COMPARISON OF FLEXIBLE PAVEMENT PERFORMANCE USING KENLAYER AND HDM-4

by

Daba S. Gedafa
Department of Civil Engineering
2118 Fiedler Hall
Kansas State University
Manhattan, KS 66506.
Tel. No. (240) 580-2207
Fax No. (785) 532-7717
E-mail: daba@ksu.edu

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ABSTRACT

This paper discusses the performance of a flexible pavement. The objective of this study is to compare the performance of flexible pavement using KENLAYER and Highway Development and Management (HDM-4). KENLAYER Computer Program has been used for determining the damage ratio using distress models. HDM-4 computer software has been used for predicting the performance using pavement deterioration models. Prediction of performance has been carried out for the test section located in Mumbai Metropolitan Region (MMR), India. This region has a humid, warm and wet climate prevalent in the west coast of India. The test section has seven layers and it is a six lane divided highway. Design life in years has been determined using two distress models in KENLAYER Computer Program. Asphalt Institute (AI) and Shell design methods have been considered using equivalent standard axle load (ESAL) and spectrum of axle methods of incorporating traffic for the design period. Comparison of design life has been made and design life using Asphalt Institute design method due to vertical compressive strain on the top of subgrade has been found to be governing while considering traffic using spectrum of axle method. Eight deterioration models in HDM-4 have also been used to determine pavement performance. The output of the eight deterioration models has been compared based on the allowable limits for Indian conditions to determine the governing deterioration model and pavement performance using cracking model has been found to be governing. Finally, comparison has been made between KENLAYER and HDM-4 output. The analysis of test section indicates that the life of pavement predicted by HDM-4 is less than that predicted by KENLAYER.

INTRODUCTION

Highway Engineers design flexible pavements after carrying out the necessary investigations required. Mechanistic method of flexible pavement design is an emerging technology for design, which contains a number of distress models mainly fatigue cracking and rutting. These models are used to determine the design life of the pavements. Pavements are constructed as per the standards and specifications after design. However, pavements usually do not serve for the design period efficiently, safely, comfortably and economically due to early deterioration. Pavement deterioration is broadly a function of the original design, material types, construction quality, traffic volume, axle load characteristics, road geometry, environmental conditions, age of pavement, and the maintenance policy pursued.

DISTRESS MODELS IN KENALYER

Distress models in KENLAYER are cracking and rutting. Strains due to cracking and rutting have been considered most critical for the design of asphalt pavements. One is the horizontal tensile strain (ε_t) at the bottom of the asphalt layer, which causes fatigue cracking, and the other is vertical compressive strain (ε_c) on the surface of subgrade, which causes permanent deformation or rutting *(1)*. Distress models can be used to predict the life of new pavement assuming pavement configuration. If the reliability for a certain distress is less than the minimum level required, the assumed pavement configuration should be changed *(2)*.

Fatigue Cracking Models

Miner's *(3)* cumulative damage concept has been widely used to predict fatigue cracking. It is generally agreed that the allowable number of load repetitions is related to the tensile strain at the bottom of the asphalt layer. The amount of damage is expressed as a damage ratio, which is the ratio between predicted and allowable number of load repetitions. Damage occurs when the sum of damage ratio reaches 1.

The major difference in the various design methods is the transfer functions that relate the HMA tensile strains to the allowable number of load repetitions. The allowable number of load repetitions (N_f) can be computed using Equation 1.

$$N_f = f_1(\varepsilon_t)^{-f_2}(E)^{-f3} \tag{1}$$

where ε_t is tensile strain at the bottom of HMA, E is modulus of elasticity of HMA and f_1, f_2 *and* f_3 are constants obtained by calibration.

Rutting Models

Rutting models are used to limit the vertical compressive strain on the top of the subgrade and are widely used. The allowable number of load repetitions (N_d) to limit rutting is related to the vertical compressive strain (ε_c) on top of the subgrade by Equation 2:

$$N_d = f_4(\varepsilon_c)^{-f_5} \qquad (2)$$

where f_4 *and* f_5 are calibrated values using predicted performance and field observation.

In the subgrade strain method, it is assumed that if the subgrade compressive strain is controlled, reasonable surface rut depths will not be exceeded. Unless standard thickness and materials are used for design, the evaluation of surface rutting based on the subgrade strain does not appear to be reasonable.

Different institutions have provided different distress models. The coefficients for rutting and cracking used by some of the institutions are given in Table 1.

TABLE 1 Coefficients for Rutting and Cracking Distress Models

Sr. No	Distress Models	*f1*	*f2*	*f3*	*f4*	*f5*	Sources
1	AI Model	0.0796	3.291	0.854	$1.365*10^{-9}$	4.477	AI *(1)*
2	Shell Model	0.0685	5.671	2.363	$1.05*10^{-7}$	4.0	Shell *(4)*
3	Belgian RRC	$4.92*10^{-14}$	4.76	0	$3.05*10^{-9}$	4.35	Verstraeten et al. *(5)*
4	Indian Model	$2.2*10^{-4}$	3.89	0.854	.4166E-05	4.534	IRC-37:2001 *(6)*

DETERIORATION MODELS IN HDM-4

Pavement deterioration models relate the functions, which are measure of distress due to magnitude of loads, number of load repetitions, pavement composition and thickness, and subgrade moisture *(7).* They should be able to predict the change in pavement condition over a given period of time under a set of conditions. They are exponential in nature and the rate varies depending upon its condition with passage of time. Road deterioration is computed as the incremental change in pavement condition over a period of time due to the effects of pavement characteristics, traffic, environment and maintenance inputs. A model represented in incremental form can take care of pavements in any initial stage of condition and at any age and is the most preferred form for economic evaluation of road pavements and maintenance strategies.

There are eight deterioration models in HDM-4 under three categories. Most of them are characterized by initiation and progression. The major deterioration models in HDM-4 are discussed below.

Cracking Model

Cracking is one of the most important deterioration in bituminous pavements. Fatigue and ageing have been identified as the principal factors which contribute to cracking of a bituminous pavement layer. The propagation of cracking is accelerated through the embrittlement resulting from ageing and the ingress of water, which can significantly weaken the underlying pavement layers. There are two types of cracking considered in HDM-4, which are structural and transverse thermal cracking. The first one is effectively load and age/environment associated cracking. It is modelled based on the relationships derived by *Paterson (8)*. Initiation of all structural cracking is said to occur when 0.5% of the carriageway surface area is cracked. The second one is generally caused by large diurnal temperature changes or in freeze/thaw conditions, and therefore usually occurs only in certain climates. For each type of cracking, separate relationships are given for predicting the time to initiation and then the rate of progression.

Ravelling Model

Ravelling is the progressive loss of surface material through weathering and/or traffic abrasion. The occurrence of ravelling varies considerably among different regions and countries according to construction methods, specifications, available materials, and local practice. It is a common deterioration in poorly constructed, thin bituminous layers such as surface treatment, but it is rarely seen in high quality, hot-mix asphalt. The construction defects indicator for bituminous surfacing (CDS) is used as a variable in the ravelling models. The initiation model is basically as proposed by *Paterson (8)*, with CDS replacing the original construction quality variable (CQ). It is said to occur on a given road section when 0.5% of the carriageway surface area is classified as ravelled. The progression model is also based on that proposed by *Paterson (8)*, but with a traffic variable introduced as proposed by *Riley (9)*.

Potholing Model

Potholing usually develops in a surface that is either cracked, ravelled, or both. The presence of water accelerates pothole formation both through a general weakening of the pavement structure and lowering the resistance of the surface and base materials to disintegration. Potholing models use the construction defects indicator for the base (CDB) as a variable. Initiation of potholes arises once the total area of wide structural cracking exceeds 20%. Ravelling initiated potholes arise when the ravelled area exceeds 30%. Progression of potholes arises from potholes due to cracking, ravelling and the enlargement of existing potholes. It is affected by the time lapse between the occurrence and patching of potholes.

Rut Depth Model

Rut depth is defined as the permanent traffic-associated deformation within pavement layers which, if channelised into wheel paths, accumulates over time and becomes manifested as a rut (*8*). Rut depth modelling is performed after the values of all the surface deterioration of cracking, ravelling, potholing and edge-break at the end of the year have been calculated. The rut depth model is based on four components of rutting:

- Initial densification
- Structural deformation
- Plastic deformation
- Wear from studded tyres

Roughness Model

Roughness consists of several components of roughness such as cracking, structural, rutting, potholing, and environment. The total incremental roughness is the sum of these components. The surface deterioration values used in predicting roughness are those that have been adjusted so that the total damaged surface area plus the undamaged area equals 100%.

The remaining three models are edge-break, texture depth, and skid resistance. They are characterized by only progression models. These models are not common as compared to the other deterioration models.

OBJECTIVE OF THE STUDY

The main objective of this study is to compare flexible pavement performance using distress and deterioration models in KENLAYER and HDM-4, respectively and then to recommend deterioration model that gives comparable result with distress models.

METHODOLOGY

In the present study, a test section in Mumbai Metropolitan Region (MMR) has been used for carrying out the analysis of pavement performance using KENLAYER Computer Program and Highway Development and Management Model (HDM-4). Fatigue cracking and rutting are two distress models considered in KENLAYER at the bottom of asphalt layer and on top of subgrade respectively. The program is used to predict the performance of the new pavement. HDM-4 software is used for determining the annual condition of the pavement once constructed and open for traffic. There are eight deterioration models, mainly structured empirical models of flexible pavement, incorporated in HDM-4, which are used to indicate the annual condition of flexible pavement. Pavement performance has been predicted using two distress models in KENLAYER Computer Program and eight deterioration models in HDM-4 software, respectively. Comparison of the outputs has been made to determine the governing distress and deterioration models.

Application of KENLAYER Computer Program

KENLAYER Computer Program applies only to flexible pavements with no joints. The backbone of KENLAYER is the solution for an elastic multilayer system under a circular loaded area. The solutions are superimposed for multiple wheels, applied iteratively for non-linear layers, and collocated at various times for viscoelastic layers. As a result, KENLAYER can be applied to layered systems under single, dual, dual-tandem, or dual-tridem wheels with each layer behaving differently, linear elastic, nonlinear elastic, or viscoelastic. Damage analysis can be made by dividing each year into a maximum of 12 periods, each with a different set of material properties. Each period can have a maximum of 12 load groups, either single or multiple. The damage caused by fatigue cracking and permanent deformation in each period over all load groups is summed up to evaluate the design life (*2*).

Input Parameters in KENLAYER Computer Program

There are so many input parameters in KENLAYER Computer Program. The parameters can be inputted both in SI and U.S. customary units. Some of the input parameters for linear elastic analysis are traffic load, material properties, thickness of each layer, number of periods, number of load groups etc.

Output Parameters of KENLAYER

For a single and multiple load groups, a maximum of nine and ten responses can be obtained, respectively. Only the vertical compressive strain on the surface of subgrade and the radial (tangential) tensile strain at the bottom of asphalt layer are used for damage analysis.

Highway Development and Management (HDM-4)

The International Study of Highway Development and Management (ISOHDM) has been carried out to extend the scope of the HDM-III model, and to provide a harmonised systems approach to road management, with adaptable and user-friendly software tools. This has produced Highway Development and Management Tool (HDM-4). The scope of HDM-4 has been broadened considerably beyond traditional project appraisals, to provide a powerful system for the analysis of road management and investment alternatives.

Applications of HDM-4

HDM-4 is a powerful system for the analysis of road management alternatives. With different application tools, HDM-4 can be applied in project analysis, program analysis, strategy analysis, research and policy studies. Project analysis tools have been used for predicting pavement performance in this study, which include eight deterioration models.

Input Parameters in HDM-4

HDM-4 application has been designed to work with a wide range of data type and quality**.** HDM-4 supplies default data that are user definable. Users can choose the prevailing values in the environment under study. The flexibility in data requirement not only reduces the data entry work but also permits all potential users with a variety of data to integrate HDM-4 into road management systems. Some of the main input data required are road network data, vehicle fleet data, traffic data, and road works standards.

Output Parameters of HDM-4

HDM-4 supports flexible options for data and analysis results. Users can make printed or electronic reports. They can also export data and results to standard database for other users. The file formats are not limited to text, word document, MS excel and lotus 1-2-3 spread sheet. In addition, users have direct access to the result database files (DBF). HDM-4 can produce the following three types of output, which can assist road managers to make informed decisions**:**

- ❖ Strategic road maintenance and development plans, produced from long-term predictions of road network performance,
- ❖ Economic efficiency indicators, produced from analysis of individual road projects,
- ❖ Multi-year work programmes, produced from prioritization of several road projects.

CASE STUDY

The case study is a test section in Mumbai Metropolitan Region (MMR), which has been built by City and Industrial Development Corporation (CIDCO) of Maharashtra Ltd. in 1990. Test section is located at the southern most tip of MMR and is planned over a total area of 2592Ha. comprising of 64 sectors. The test section has been basically planned to cater the port based services. The area has a humid, warm and wet climate prevalent in the west coast of India. The area is covered by two major deposits of marine and fluvial deposits and residual deposits connecting steep hill slopes. The underlying soil consists of a thick layer of soft marine clay deposits, which is very soft and highly compressible. CIDCO has implemented the ground improvement scheme before going a head with developmental activities in the area (*10*).

Terrain Classification of the area is made by the general scope of the area across the road alignment**.** The road network of the test section is in the filled up areas and hence it is plain terrain. However, the percent cross slope for plain and rolling terrain is given as in Table 2.

TABLE 2 Terrain Classification of Test Section

Sr.No.	Terrain Classification	Percent Cross Slope of the Area
1	Plain	0-10
2	Rolling	10-15

The test section for this study has six-lane carriageway. The cross-slope of the carriageway is 2.5%. The test section has seven layers and all layers are assumed to be linear elastic for the analysis. The cross-section of the test section used for analysis is shown in Figure 1.

Traffic data has been collected and provided by CIDCO. Traffic data at Punjab Conware has been used and the same is shown in Table 3. Assumptions made are: standard axle load is 100 kN, annual increase of load repetitions is 5%, direction and lane distribution factors are 0.5 and 0.6 respectively, and construction time is 1 year.

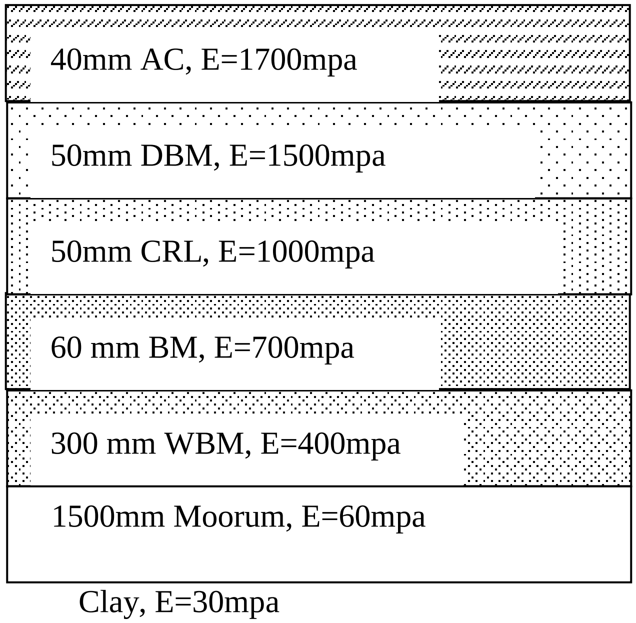


FIGURE 1 Cross-section of test section for the analysis.

RESULTS AND DISCUSSIONS

The output using the two softwares, viz., KENLAYER computer program and HDM-4, are presented separately and then comparison has been made in order to determine the governing distress and deterioration models.

Pavement Performance Using KENLAYER

Traffic loads have been considered using Equivalent Standard Axle Load (ESAL) and Spectrum of Axle approaches. AI and Shell design methods have been used for predicting pavement performance.

In ESAL approach, all axle loads have been converted into equivalent standard axle load for the design period. Since it is strengthening of the already existing road, the design period has been taken as 10 years. ESAL at the end of 10 years period using annual growth rate of 5% as per the recommendation by the consultant is 51.79 million standard axles (msa) and the same has been used for predicting pavement performance. Horizontal tensile strain at the bottom of asphalt concrete layer and vertical compressive strain on the top of subgrade are treated using AI and Shell design methods. Vertical compressive strain is governing in both cases. Sum of damage ratio is 0.0558 and design life in years is 18 using AI method while sum of damage ratio on the top of subgrade and design life in years are 0.0576 and 17, respectively while using Shell method.

In the case of spectrum of axle method, loads are considered axle wise. Single axle with single wheel, single axle with dual wheels, tandem and tridem axles have been considered. The damage ratio due to the axle loads is computed separately and summed up. The summation of damage ratio at the bottom of asphalt concrete and on the top of subgrade is compared and the smaller of the two is taken as governing one. Vertical compressive strain on the top of subgrade is governing in both AI and shell methods. Sum of damage ratio and governing design life in years using AI method are 0.06138 and 16 respectively. Sum of damage ratio and governing design life in years using Shell method are 0.05328 and 19 respectively. Table 4 indicates the summary and governing design life using distress models in KENLAYER.

TABLE 3 Traffic Data for the Study

Date			**2/3-Wheeler**	**Car/Jeep/Tempo**	**Truck 2-axle**	**Trailor 3-axle**	**Trailor 4-axle**	**Trailor 5-axle**	**Trail 6-axl**	**Total (4+5+6+7+8)**
From	To	1	2	3	4	5	6	7	8	9
30-09-03	01-10-03	Up	821	925	1672	1154	1575	157	5	**4563**
		Down	969	914	1814	1227	1601	168	10	**4820**
01-10-03	02-10-03	Up	779	695	1127	831	1388	58	2	**3406**
		Down	1299	1048	1856	931	1613	81	3	**4484**
02-10-03	03-10-03	Up	345	235	584	810	1332	68	0	**2794**
		Down	367	240	671	811	1453	67	0	**3002**
03-10-03	04-10-03	Up	596	679	1460	1036	1570	127	0	**4193**
		Down	1017	890	1664	918	1588	173	0	**4343**
04-10-03	05-10-03	Up	413	302	723	916	1470	155	0	**3264**
		Down	439	375	747	873	1304	106	0	**3030**
05-10-03	06-10-03	Up	494	355	701	824	1185	65	8	**2783**
		Down	355	296	720	768	1056	56	18	**2618**
06-10-03	07-10-03	Up	670	608	1055	828	561	164	50	**2658**
		Down	688	552	976	864	816	149	58	**2863**
		Total	**9252**	**8114**	**15770**	**12791**	**18512**	**1594**	**154**	**48821**

TABLE 4 Summary of Design Life Using Distress Models in KENLAYER

Method of Treating Traffic	Design Method	Design Life in Years	Governing Design Life
ESAL	Asphalt Institute (AI)	18	**16**
	Shell	17	
Spectrum of Axle	Asphalt Institute (AI)	16	
	Shell	19	

Pavement Performance Using HDM-4

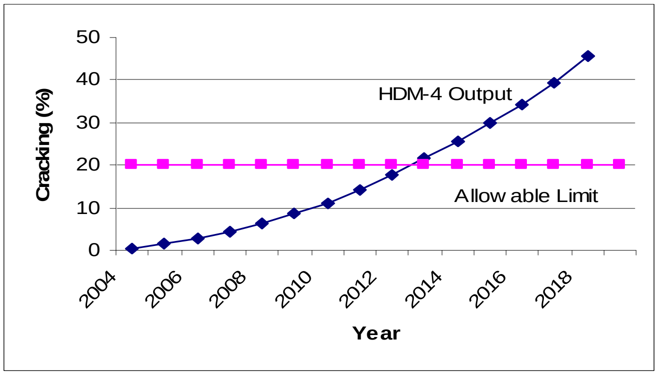
HDM-4 has been used for predicting pavement performance for the analysis period of 15 years using the parameters adjusted for Indian conditions by *Jaya (11)* for the four deterioration models. These deterioration models are cracking, raveling, potholing and roughness. It has been found that these deterioration models are governing for predicting pavement performance out of the eight deterioration models in HDM-4. Allowable limits for pavement distress as per HDM-4 and Indian conditions are given in Table 5.Maximum limit for Indian conditions has been used to determine the maximum performance of the pavement for the available ones. The results using HDM-4 are shown in Table 6 and Figure 2.

TABLE 5 Allowable Limits for Pavement Deterioration as per HDM-4 and Indian Condition

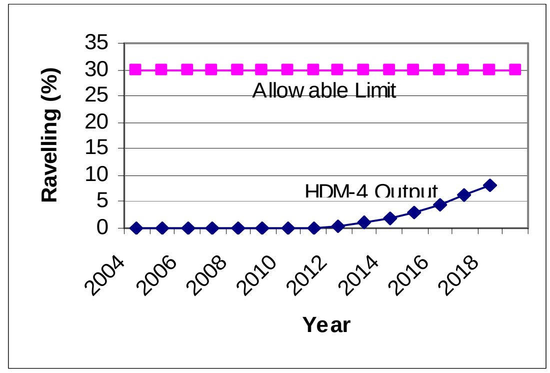
Sr.No.	Deterioration Model	Maximum Limit	
		HDM-4	Indian Condition
1	Cracking (%)	15	20
2	Raveling (%)	20	30
3	Potholing (No/km)	5	8
4	Edge-break (m^2/km)	100	-
5	Rutting (mm)	15	20
6	Roughness IRI (m/km)	6	-
7	Texture Depth (mm)	0.3	-
8	Skid Resistance SCRIM at 50km/hr	0.3	35SN

TABLE 6 Summary of Pavement Performance Using Deterioration Models in HDM-4

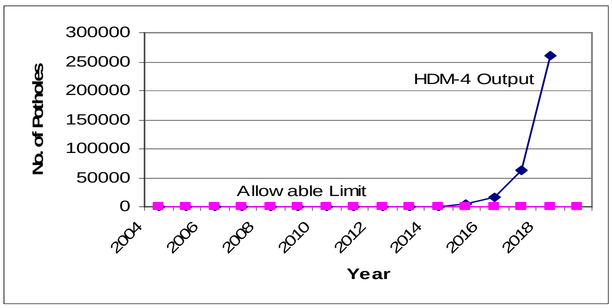
Sr.No.	Deterioration Model	Predicted Pavement Performance in Years	Governing Life in Years
1	Cracking	9	**9**
2	Raveling (%)	>15	
3	Potholing (No/km)	10	
4	Edge-break (m^2/km)	>15	
5	Rutting (mm)	>15	
6	Roughness IRI (m/km)	10	
7	Texture Depth (mm)	>15	
8	Skid Resistance SCRIM at 50km/hr	>15	



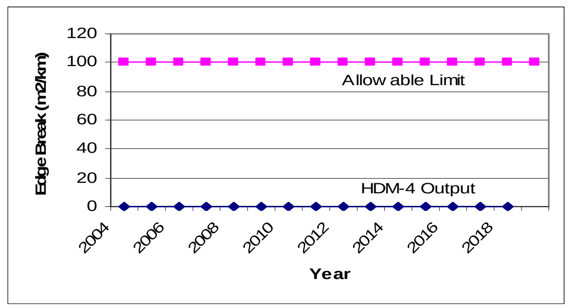
(a) Using Cracking



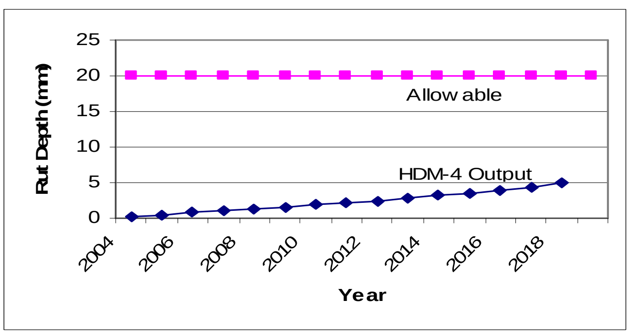
(b) Using Ravelling



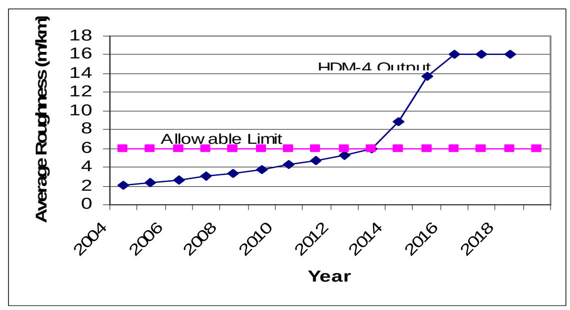
(c) Using Pothole



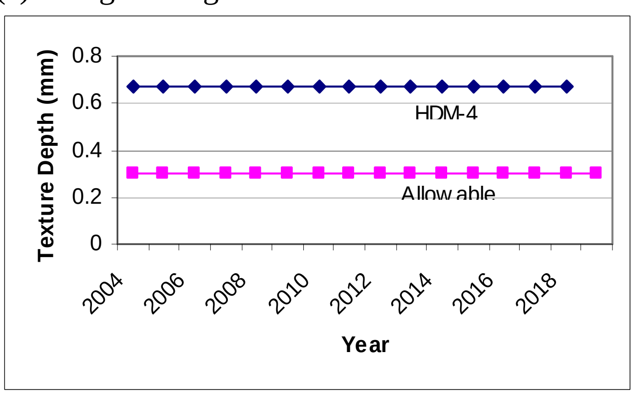
(d) Using Edge Break



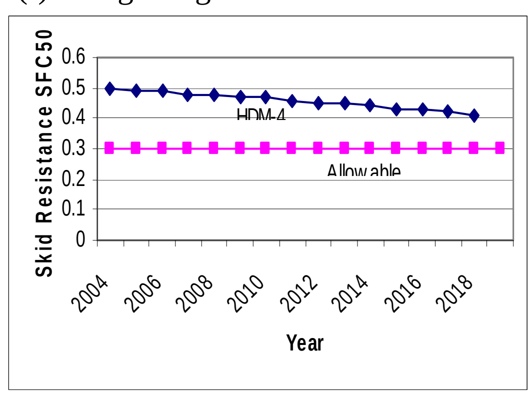
(e) Using Rutting



(f) Using Roughness



(g) Using Texture Depth



(h) Using Skid Resistance

FIGURE 2 Performance of pavement using deterioration models

Comparison of Pavement Performance Using KENLAYER and HDM-4

The governing design life using distress models in KENLAYER is 16 and it is governed by vertical compressive strain on the top of subgrade using AI design method while considering traffic using spectrum of axle approach. The maximum number of years the pavement performs using deterioration models in HDM-4 is governed by cracking and it is 9 years. However, rutting and cracking distress and deterioration models do not give comparable result. Comparison is made in Table 7.

TABLE 7 Comparison of Pavement Performance Using Distress and Deterioration Models

Type of Model		**Performance Period**
Rutting	Distress Model	16
	Deterioration Model	>15 (analysis period)
Cracking	Distress Model	Large
	Deterioration Model	9

CONCLUSIONS

The following conclusions have been made based on this study:

- KENLAYER Computer Program can be used to predict the performance of flexible pavement more easily and efficiently since it is user-friendly.
- HDM-4 is a powerful system for the analysis of road management alternatives. It can be applied in project analysis, program analysis, strategy analysis, research and policy studies.
- KENLAYER gives comparable result using AI and Shell design methods considering traffic based on ESAL and Spectrum of axles approaches.
- Prediction has been done using eight pavement deterioration models in HDM-4 using adjusted values for Indian condition and cracking has been found to be governing.
- Pavement performs for 16 and 9 years using KENLAYER and HDM-4 respectively. Performance is less using deterioration models, which indicates the early failure of the pavement due to various reasons.
- The use of AI design method for determining design life in years by KENLAYER computer program using spectrum of axle approach is recommended.
- Design life using vertical compressive strain on the top of subgrade is governing using KENLAYER Computer Program and cracking is governing in the case of HDM-4. It is recommended to use cracking deterioration model based on the output of the analysis.
- Rutting and cracking distress models in KENLAYER and rutting and cracking deterioration models in HDM-4 do not give comparable result.

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