Performance Prediction and Maintenance of Flexible Pavement

Daba S. Gedafa
Department of Civil Engineering
Kansas State University
2118 Fiedler Hall
Manhattan, KS 66506
daba@ksu.edu

ABSTRACT

This paper discusses the performance and maintenance of flexible pavement. The main objectives of this study are to predict the performance of flexible pavement using two distress models in the KENLAYER computer program and eight deterioration models in Highway Development and Management (HDM-4) and provide appropriate maintenance at the appropriate time based on performance using 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 and also for pavement maintenance. Prediction of performance and maintenance has been carried out for the test section located in Mumbai Metropolitan Region, 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 distress models in the 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 AI design method due to vertical compressive strain on the top of the subgrade has been found to be governing while considering traffic using the spectrum of axle method. Eight deterioration models in HDM-4 have also been used to determine pavement performance. To determine the governing deterioration model, the output of the eight deterioration models has been compared based on the allowable limits for Indian conditions, and pavement performance using the cracking model has been found to be governing. Comparison has been made between KENLAYER and HDM-4 output. The analysis of the test section indicates that the life of pavement predicted by HDM-4 is less than that predicted by KENLAYER. Only cracking and roughness have been found out to be critical, and as a result, condition-responsive maintenance has been carried out using HDM-4. HDM-4 is a user friendly software and useful to predict the performance of the pavement and then provide appropriate maintenance at the appropriate time.

Key words: design life—flexible pavement—prediction—performance
INTRODUCTION

Highway engineers design flexible pavements after carrying out all required investigations. The 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.

The focus of roadway activity in the early to mid 20th century was on the construction of new pavements. In the latter part of the 20th century continuing into the 21st century, this focus has shifted to the maintenance and rehabilitation (M & R) of pavement infrastructure. Maintenance includes actions that retard or correct the deterioration of infrastructure facilities (Guignier and Madanat 1999). Pavements must be selected for maintenance when they are still effective. In most cases, the proper time to apply maintenance is before the need is apparent to the casual observer. This is because once pavements start deteriorating, they deteriorate rapidly beyond the point where maintenance is effective. With the increasing use and awareness of pavement management systems and the growing emphasis on asset management of pavement infrastructure, it is important to strengthen the maintenance components of these (Hein and Croteau 2004).

OBJECTIVES OF THE STUDY

The main objectives of this study are as follows:

- Review distress and deterioration models in KENLAYER and HDM-4, respectively.
- Compare flexible pavement performance using distress and deterioration models in KENLAYER and HDM-4, respectively, and then to recommend a deterioration model that gives comparable result with distress models.
- Review maintenance strategies in HDM-4, maintenance trends in India, and finally, to see the effect of maintenance on pavement deterioration using HDM-4.

LITERATURE REVIEW

Distress Models in KENLAYER

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 ($\varepsilon_t$) at the bottom of the asphalt layer, which causes fatigue cracking, and the other is vertical compressive strain ($\varepsilon_r$) on the surface of the subgrade, which causes permanent deformation or rutting (AI 1981). 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 (Huang 2004).

Fatigue Cracking Models

Miner’s (1945) 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 one.

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

\[
N_f = f_1 (\varepsilon_t)^{-f_2} (E)^{-f_3}
\]

Where \( \varepsilon_t \) 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 \( (\varepsilon_c) \) on top of the subgrade by Equation 2:

\[
N_d = f_4 (\varepsilon_c)^{-f_5}
\]

where \( f_4 \) and \( f_5 \) are calibrated values using predicted performance and field observation.

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. Coefficient in rutting and cracking distress models**

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Distress Models</th>
<th>( f1 )</th>
<th>( f2 )</th>
<th>( f3 )</th>
<th>( f4 )</th>
<th>( f5 )</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AI Model</td>
<td>0.0796</td>
<td>3.291</td>
<td>0.854</td>
<td>1.365*10^-9</td>
<td>4.477</td>
<td>AI (1981)</td>
</tr>
<tr>
<td>2</td>
<td>Shell Model</td>
<td>0.0685</td>
<td>5.671</td>
<td>2.363</td>
<td>1.05*10^-7</td>
<td>4.0</td>
<td>Shell (1978)</td>
</tr>
<tr>
<td>3</td>
<td>Belgian RRC</td>
<td>4.92*10^-14</td>
<td>4.76</td>
<td>0</td>
<td>3.05*10^-9</td>
<td>4.35</td>
<td>Verstraeten et al. (1984)</td>
</tr>
</tbody>
</table>

**Deterioration Models in HDM-4**

Pavement deterioration models relate the functions, which are the measure of distress due to the magnitude of loads, number of load repetitions, pavement composition and thickness, and subgrade moisture (Sood and Sharma 1996). 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 the 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 measures of 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: structural and transverse thermal cracking. The first one is effectively load- and age/environment-associated cracking. It is modeled based on the relationships derived by Paterson (1987). 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 (1987), with CDS replacing the original construction quality variable. 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 (1987) but with a traffic variable introduced as proposed by Riley (1999).

**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 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, raveling, 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 (Paterson 1987). Rut depth modeling is performed after the values of all the surface deterioration of cracking, raveling, 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 tires

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 only characterized by progression models. These models are not common compared to the other deterioration models.

Pavement Maintenance in HDM-4

In HDM-4, maintenance standards are used to represent the targets or levels of condition and response that are aimed to be achieved. Maintenance standards define the maintenance work required to maintain the road network at the target level. Each maintenance standard consists of a set of one or more work items. Each work item is defined in terms of the road surface class to which it applies, an intervention level, an operation type, and the resultant effect on the pavement (Sood and Sharma 1996). Routine and periodical maintenance are the two kinds of maintenance treated in HDM-4. All maintenance can be carried out based on scheduled and condition-responsive except inlays, in which it is always defined in terms of condition-responsive work.

Pavement Maintenance Scenario in India

Due to the poor condition of roads, it is estimated that an annual loss of approximately over Rs. 6000 crores ($1.33 billion) is resulted in vehicle operating costs (VOC) alone. Timely maintenance is missing due to many reasons, which otherwise could have minimized the losses to the exchequer. A rough estimate suggests that more than 50% of the primary road network is in bad shape and needing immediate attention. It should be borne in mind that for achieving the desired economic growth, the foremost requirement is to ensure a good and effective road network (MoRTH 2004).

Types of Maintenance

The maintenance activities have been divided into ordinary repairs (OR), periodical renewal (PR), special repairs, and emergency repairs for the purpose of organization of maintenance budgeting. It is pertinent to note that organizational structure of maintenance activities related to OR has worked well in the past, and it may be recommended that the same may be continued after updating to include all the new activities required to keep pace with time and development until a scientific maintenance management system (MMS) is placed in position. In general, there are two types of maintenance; namely, routine maintenance (to cover OR) and major maintenance (to cover PR and rehabilitation)
**Optimization and Prioritization of Maintenance Strategies**

When planning investments in pavement sectors, it is necessary to evaluate all the costs associated with the proposed project. These include construction costs, M & R costs, road user costs, and all other external or exogenous costs or benefits that can directly attribute to the pavement project. These three costs constitute what is commonly referred to as the total transport cost or the life cycle cost. A flow chart for prioritization of maintenance is given in Figure 1.

**Intervention Criteria**

There are two types of maintenance inputs in practice; time bound (scheduled) maintenance and pavement condition-responsive maintenance. For Indian conditions, it is suggested that condition-responsive maintenance intervention criteria may be adopted. To formulate condition-responsive maintenance criteria, some basic minimum desired serviceability level needs to be fixed. The suggested criteria are based on the widely accepted performance indicators such as roughness, cracks, rutting, skid, potholes, etc. Based on these performance indicators, the suggested intervention criteria for primary, secondary, and urban roads are given by the Ministry of Road Transport and Highways (2004). The intervention criteria for primary roads are shown in Table 2.

![Figure 1. Flow chart for prioritization of maintenance (MoRTH 2004)](image-url)
Table 2. Intervention criteria for primary roads

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Serviceability Indicator</th>
<th>Level 1 (Good)</th>
<th>Level 2 (Average)</th>
<th>Level 3 (Acceptable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Roughness by Bump Integrator (max. permissible in mm/km)</td>
<td>2000</td>
<td>3000</td>
<td>4000</td>
</tr>
<tr>
<td>2</td>
<td>Potholes per km (max. numbers)</td>
<td>Nil</td>
<td>2-3</td>
<td>4-8</td>
</tr>
<tr>
<td>3</td>
<td>Cracking and patching area (max. permissible in percent)</td>
<td>5</td>
<td>10</td>
<td>10-15</td>
</tr>
<tr>
<td>4</td>
<td>Rutting (mm)</td>
<td>5</td>
<td>5-10</td>
<td>10-20</td>
</tr>
<tr>
<td>5</td>
<td>Skid resistance (skid number min. desirable)</td>
<td>50</td>
<td>40</td>
<td>35</td>
</tr>
</tbody>
</table>

METHODOLOGY

In the present study, a test section in the Mumbai Metropolitan Region (MMR) has been used for carrying out the analysis of pavement performance using the KENLAYER computer program and the Highway Development and Management Model (HDM-4). Fatigue cracking and rutting are two distress models considered in KENLAYER at the bottom of the asphalt layer and on top of the 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 (Wightman, Stannard, and Dakin 2002). 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 the latest version of the KENLAYER computer program and eight deterioration models in HDM-4 software. Comparison of the outputs has been carried out to determine the governing distress and deterioration models. Finally, HDM-4 has been used for maintenance purposes.

Application of KENLAYER Computer Program

The 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 (Huang 2004).

Input Parameters in KENLAYER Computer Program

There are so many input parameters in KENLAYER. 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 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 the 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 harmonized systems approach to road management, with adaptable and user friendly software tools. This has produced 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

The 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: Microsoft Word document, MS Excel, and lotus 1-2-3 spread sheet are also available. In addition, users have direct access to the result database files (DBF). HDM-4 can produce the following three types of output, which can help 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
- Multiyear work programs, produced from prioritization of several road projects

CASE STUDY

The case study is a test section in MMR, which has been built by the City and Industrial Development Corporation (CIDCO) of Maharashtra Ltd. in 1990. The test section is located at the southern 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 ahead with developmental activities in the area (CIDCO 2000).

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 of cross slope for plain and rolling terrain is given in Table 3.

Table 3. Terrain classification of test section

<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Terrain Classification</th>
<th>Percent Cross Slope of the Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plain</td>
<td>0-10</td>
</tr>
<tr>
<td>2</td>
<td>Rolling</td>
<td>10-15</td>
</tr>
</tbody>
</table>

The test section for this study has a 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 2.

![figure 2](image)

**Figure 2. Cross section of test section for the analysis**

RESULTS AND DISCUSSION

The output using the two software programs KENLAYER and HDM-4 are presented separately, and a comparison has been made in order to determine the governing distress and deterioration models. Then maintenance using HDM-4 and its effect on deterioration of pavement is presented. Traffic data collected by CIDCO has been used for the analysis of the test section using both software programs.
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 the ESAL approach, all axle loads have been converted into equivalent standard axle load for the design period. Since it is strengthening the already existing road, the design period has been taken as 10 years. ESAL at the end of the 10 year period, using an 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 the 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. The sum of damage ratio is 0.0558, and design life in years is 18 using the AI method, while the sum of damage ratio on the top of the subgrade and design life in years are 0.0576 and 17, respectively while using the Shell method.

In the case of the 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 the asphalt concrete and on the top of the subgrade is compared, and the smaller of the two is taken as the governing one. Vertical compressive strain on the top of the 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 3 indicates the summary and governing design life using distress models in KENLAYER.

<table>
<thead>
<tr>
<th>Method of Treating Traffic</th>
<th>Design Method</th>
<th>Design Life in Years</th>
<th>Governing Design Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESAL</td>
<td>Asphalt Institute (AI)</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shell</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Spectrum of Axle</td>
<td>Asphalt Institute (AI)</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Shell</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

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 (2004) 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 4. The 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 5 and Figure 3.
Table 4. Allowable limits for pavement deterioration as per HDM-4 and Indian conditions

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Deterioration Model</th>
<th>Maximum Limit</th>
<th>HDM-4</th>
<th>Indian Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cracking (%)</td>
<td>15</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Raveling (%)</td>
<td>20</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Potholing (No/km)</td>
<td>5</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Edge-break (m²/km)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Rutting (mm)</td>
<td>15</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Roughness IRI (m/km)</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Texture Depth (mm)</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Skid Resistance SCRIM at 50km/hr</td>
<td>0.3</td>
<td>35SN</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Summary of pavement performance using deterioration models in HDM-4

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Deterioration Model</th>
<th>Predicted Pavement Performance in Years</th>
<th>Governing Life in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cracking</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Raveling (%)</td>
<td>&gt;15</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Potholing (No/km)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Edge-break (m²/km)</td>
<td>&gt;15</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Rutting (mm)</td>
<td>&gt;15</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Roughness IRI (m/km)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Texture Depth (mm)</td>
<td>&gt;15</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Skid Resistance SCRIM at 50km/hr</td>
<td>&gt;15</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3. 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 the subgrade using the AI design method while considering traffic using the 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 nine years. However, rutting and cracking distress and deterioration models do not give comparable results. Comparison is made in Table 6.

<table>
<thead>
<tr>
<th>Type of Model</th>
<th>Performance Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rutting</td>
<td>Distress Model</td>
</tr>
<tr>
<td></td>
<td>Deterioration Model</td>
</tr>
<tr>
<td>Cracking</td>
<td>Distress Model</td>
</tr>
<tr>
<td></td>
<td>Deterioration Model</td>
</tr>
</tbody>
</table>

Pavement Maintenance using HDM-4

Eight deterioration models in HDM-4 with their respective maximum limits as per HDM-4 and for Indian conditions are indicated in Table 4. Maximum limit for Indian conditions have been used for maintenance intervention, but limits as per HMD-4 have been used for which there are no standards in India. Pavement condition-responsive maintenance has been carried out using HDM-4 for analysis period of 15 years. Only cracking and roughness have been found to be critical and have needed maintenance. The effect of maintenance on both is discussed below.

Effect of Maintenance

Condition-responsive maintenance has been done at the end of 10 years for roughness and 9 years for cracking. Due to the maintenance intervention, roughness and cracking of the pavement have become equivalent to the original pavement as shown in Figure 4.

![Figure 4. Effect of maintenance](image-url)
CONCLUSIONS

The following conclusions have been made based on this study:

- KENLAYER can be used to predict the performance of flexible pavement more easily and efficiently because 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 results using AI and Shell design methods considering traffic based on ESAL and spectrum of axles approaches.
- Pavement performs for 16 and 9 years using KENLAYER and HDM-4, respectively. Performance is less using deterioration models, which indicate the early failure of the pavement due to various reasons.
- Rutting and cracking distress models in KENLAYER, and rutting and cracking deterioration models in HDM-4 do not give comparable results.
- Project analysis should be carried out using HDM-4 before deciding the maintenance of the pavement because the output shows the annual condition of the pavement.
- The attention of highway agencies has been changed from construction of new pavements to maintenance and rehabilitation of already existing ones.
- Out of eight deterioration models in HDM-4, only cracking and roughness have been found to be critical during the analysis period of 15 years.
- The condition of the pavement has become equivalent to new pavement after condition-responsive maintenance using HDM-4.
- HDM-4 is user friendly software, and it can be used for maintenance of pavements.

RECOMMENDATIONS

- The use of AI design method for determining design life in years by the KENLAYER computer program using spectrum of axle approach is recommended.
- Design life using vertical compressive strain on the top of the subgrade is governing using KENLAYER, 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.
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