Pavement Deterioration Analysis for Rural Roads using HDM-4

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Abstract

Highway Development and Management (HDM-4) is comprised of decision-making tools used to assess the economic, social, and environmental viability of project development proposals to arrive at the best investment decisions. The entire system is built on various functions of pavement performing under numerous structural and environmental influences. The present work aims to study pavement distress and deteriorations prevailing on rural roads. At each stage, the road deterioration models predict impacts of distress at different rates and scenarios over each of the study sections. The analysis presents alternative maintenance and improvement strategies that could be implemented judiciously under scheduled or responsive routine assessments of road performance. Moreover, the analysis and output data for distress projection as obtained from HDM-4 is also validated from the existing pavement deterioration condition of the selected sections. The comparison of deterioration before and after works and the economic indicators delineated that Overlay for rural road sections is considered to be the most suitable alternative possible among others. Furthermore, the validation of the deterioration levels as predicted through HDM-4 indicates very low variation in the range of 2%-10% from the existing pavement deterioration levels. The results of this study are useful for developing pavement maintenance management strategies for rural roads network with similar characteristics.

Keywords: Pavement Maintenance Management System(PMMS); Road Deterioration Projection; Rural Roads; Flexible Pavement; HDM-4

1. Introduction

Pavements are extraordinarily complex physical structures that respond in numerous ways under direct and indirect influence. Pavements are designed according to the environmental and load-related variables by their interaction. Therefore, for the efficient functioning of these structures, various approaches are followed to sustain their intended function with accumulating use throughout the design period [1]. Pavement deterioration models are developed to network-level which supports as a backbone to Pavement Management Systems(PMS) [2], [3]. Modeling pavement performance is a crucial activity that serves several aspects of the system which includes financing and budgeting as well as reviewing pavement design and distress estimation and studying life cycle economic analysis [4]. The research reported in this paper is a part of a program to develop pavement modeling solutions to predict and analyze deterioration rates for rural roads and their connectivity. In most scenarios, priority is inclined towards road networks that support major revenue sectors due to which development in rural regions is often neglected [5]. In this paper, the study is conducted to emphasize the need to monitor rural roads which is currently a liability for rural communities as the conditions of pavements have a deep impact on their day-to-day livelihood [6], [7]. Detailed considerations are

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dictated through models regarding mechanistic principles, interactions between traffic loading and pavement strength parameters and so on carefully reviewed and included when significant [8], [9].

2. Objectives

The objectives of the study were to produce road deterioration relationships relevant to the rural environment. The accurate prediction of deterioration rates of the roads is significant in road management systems. This is to ensure efficient prioritization and for setting budget levels, and in justifying changes in specifications and standards. The detailed objectives are as follows:

- Preparation of database for selected sections
- Projection of pavement deterioration/distress
- Validation of deterioration using existing conditions
- Suggesting best maintenance alternatives for each section

3. Study Sections

This paper shows a study conducted in a rural region of the state of Rajasthan near Jaipur District. A comparison in deterioration models is depicted in this study as all the sections fall under the different classification of road type (State Highway, MDR, Village Roads). These sections are most affected by distresses caused on pavement due to a notable increase in structural and environmental influences in the rural region [10].

Table 1. Study Sections

| Section | Section name | Section Description | Length | Terrain | Rainfall | Temperature | Traffic |
|---------|--------------|---------------------|--------|---------|----------|-------------|--------|
| SS-2    | SH-2C(B1)-HATHOJ- BHAMBORI | KALAWAR ROAD | 6.6 Kms | Plain | Low | High | High |
|         | SH-2C(B2)-BHAMBORI- PACHAR |             | 8.2 Kms |         |          |            |        |
| SS-3    | MDR-81(C1)   | BEGAS-PACHAR ROAD  | 2.3 Kms | Plain | Low | High | Medium |
|         | MDR-81(C2)   |             | 5.4 Kms |         |          |            |        |
|         | MDR-81(C3)   |             | 5.8 Kms |         |          |            |        |
| SS-4    | BEGUS ROAD (D) | BHAMBHORI- NANDGAON | 6.5 Kms | Plain | Low | High | Low |
| SS-5    | SIRSI-HATHOJ ROAD (E) | HATHOJ- KHATIPURA ROAD | 4.5 Kms | Plain | Low | High | Low |

4. Road Information Database

4.1. Climate Data

It is imperative to understand how climate is attributable to road infrastructure. Roads are designed based on moisture classification and temperature patterns indicating the history as well as predictable nature of change in climatic conditions for years [11]. The climate data collected is extracted from the Hydrogeological Atlas of Jaipur District. After establishing the climatic region of the district, further details of parameters were drawn out from annual monsoon reports of Rajasthan and the World Bank (climate change knowledge portal). The climate data classification is divided into two categories: moisture and temperature as shown in the table.
Table 2. Climate Data of Road Sections

| Detailed Data of Moisture Classification (Semi-arid) | Data items | SH2C (B) | Begas-Pachar road (C) | Kalwar-Bhambori road (D) | Sirs-S-Hathoj (E) |
|---------------------------------------------------|------------|----------|-----------------------|--------------------------|-------------------|
| Mean monthly precipitation (mm)                  | 54         | 54       | 54                    | 53.9                     |
| Moisture Index                                    | -32.7      | -32.7    | -32.7                 | -32.7                    |
| Duration of dry season                            | 0.5        | 0.6      | 0.5                   | 0.6                      |

| Detailed data of temperature classification (Subtropical-hot) | Data items | SH2C (SS2) | B2 | B2 | B2 | B2 |
|----------------------------------------------------------|------------|------------|----|----|----|----|
| Mean annual temperature (°C)                             | 26         | 25         | 25 | 25 |
| Temperature range (°C)                                   | 25         | 25         | 25 | 25 |
| Days per year with temperature >32 °C                    | 90         | 90         | 90 | 90 |
| Freezing index °(°C-days)                                | 0          | 0          | 0  | 0  |
| Percent of driving times on snow                         | 0          | 0          | 0  | 0  |
| Percent of driving times on water covered roads          | 1          | 2          | 1  | 1  |

The climate data is detail-oriented with information regarding road environment extracted from the Hydrogeological Atlas of Jaipur District. After establishing the climatic region of the district, further details of parameters were drawn out from annual monsoon reports of Rajasthan and the World Bank (climate change knowledge portal).

4.2. Speed Flow Types

This section of the software has essential importance to run the analysis in terms of capacity, accident rates, speed-related calibration factors for the road types represented [12], [13]. The ability to model the impact of traffic volume on speeds is given to assess the economic implications of changes in road capacity. Capacity is the maximum hourly volume of vehicles that are practically expected to traverse a point or a uniform section of a road during a period under the influence of traffic and control conditions [14]. Various capacity factors such as ultimate capacity, free flow capacity, and nominal capacity come in the default set of values in HDM4 when selected from the lane classification under road type.

Table 3. Speed Flow Types of SS 2, 4 and 5

| Data items                  | SH2C (SS2) | Road Sections | Sirsi-Hathoj road(SS5) |
|-----------------------------|------------|---------------|------------------------|
|                             | B1         | B2            | Jaipur-Jobner          | Bambori-Kalwar          |
| Road Type                   | Two lane road | Two lane road | Jaipur-Jobner          | Bambori-Kalwar          |
|                             | Two lane road | Two lane road | Jaipur-Jobner          | Kalwar-Bhambori         |
|                             | Two lane road | Two lane road | Intermediat e road     | Intermediate road       |
|                             | Intermediat e road | Intermediate road | Sirs-S-Hathoj           | Intermediate road       |
|                             | Intermediat e road | Intermediate road | Hathoj-Sirs            |                         |
| Ultimate Capacity (PCSE/lane/hr) | 1400      | 1400          | 1400                   | 1400                    |
| Free-flow Capacity (0< XQ1 <1) | 0.1       | 0.1           | 0.1                    | 0                       |
| Nominal Capacity (0< XQ2 <1) | 0.9       | 0.9           | 0.9                    | 0.7                     |
| Jam Speed at Capacity (km/hr) | 25        | 25            | 23                     | 22                      |


A comprehensive approach was adopted using IRC: 64-1990 Guidelines for Capacity of Roads in Rural Areas and evaluating traffic data which resulted in obtaining the values for speed flow parameters [15].

### 4.3. Vehicle Fleet

In this section specification of the vehicle fleet is an essential set of information that contains vehicle types that operate on the road network of study sections and therefore analyzed. Roads are solely constructed for the efficient movement of the vehicle and hence their characteristics are especially important in building a database of HDM-4 [16]. The vehicle fleet section of HDM4 establishes a relation between road users and their vehicles to assess the economic viability of project development, especially on the consumer end.

| Name                | Class   | Base Type | Category |
|---------------------|---------|-----------|----------|
| Animal Cart         | Animal Cart | Animal Cart | NMT      |
| Bicycles            | Bicycles | Bicycles  | NMT      |
| Pedestrian          | Pedestrian | Pedestrian | NMT      |
| Bikes/Scooter       | Motorcycles | Motorcycles | Motorized |
| Hatchback Car       | Passenger Cars | Car Small | Motorized |
| Sedan Car           | Passenger Cars | Car Medium | Motorized |
| SUV                 | Passenger Cars | Car Large | Motorized |
| LCV                 | Utilities | Delivery Vehicle Light | Motorized |
| School Bus          | Buses    | Bus light  | Motorized |
| Intercity Bus       | Buses    | Bus Medium | Motorized |
| Light Truck         | Trucks   | Truck light | Motorized |
| Cargo Truck         | Trucks   | Truck Articulated | Motorized |
| Heavy Cargo Truck   | Trucks   | Truck Heavy | Motorized |

### 4.4. Traffic Information

The temporal changes of traffic are modelled by traffic flow patterns. To model congestion impacts on vehicle speeds and vehicle operating costs, HDM-4 uses traffic flow pattern details. In this study traffic flow patterns are presented in the ratio of volumes for various daily time ranges. For a variety of hourly traffic flow patterns, congestion analysis is conducted, and the results are averaged to reflect the entire year in terms of annual average daily traffic (AADT). AADT is an abstract of the estimated average number of vehicles passing a point in any given day for a cycle of 365 days [17]. Traffic hours of full flow are broken into cycles of a shorter time. Traffic counting is conducted in three ways; automated constant counting (stationary counters), automatic intermittent counting (portable counters), and manual counting. In this study manual, counting methodology was adopted. It is the most common way of counting traffic where persons are assigned to allocated locations such as at intersections or other important points [18]. Manual counting proves to be a critical mode of assessment for locations where human conscience and prompt action are required.
Table 5. Traffic Data of Road Sections

| Section | Sub-section | Lane                  | AADT |
|---------|-------------|-----------------------|------|
| SS2     | B1          | Jaipur – Jobner       | 2924 |
|         |             | Jobner – Jaipur       | 3490 |
|         | B2          | Jaipur – Jobner       | 3525 |
|         |             | Jobner – Jaipur       | 3321 |
| SS3     | C1          | Begas – Pachar        | 620  |
|         |             | Pachar – Begas        | 650  |
|         | C2          | Begas – Pachar        | 611  |
|         |             | Pachar – Begas        | 635  |
|         | C3          | Begas – Pachar        | 694  |
|         |             | Pachar – Begas        | 672  |
| SS4     | D           | Kalwar – Bhambori     | 785  |
|         |             | Bhambori – Kalwar     | 656  |
| SS5     | E           | Sirsi – Hathoj (South to North) | 1867 |
|         |             | Hathoj – Sirsi (North to South) | 1990 |

Traffic Flow Patterns are represented inflow periods. For the analysis, 72 hours of continuous traffic data were accumulated. The amount of yearly traffic movement during the time frame of one year was determined using raw data and with the reference of local surveys conducted. Thereafter, the evaluation process was continued using data input in hours per year volume and then estimating to determine percent AADT for each of the periods in 24 hours.

4.5. Pavement Condition

Evaluation of distress in pavement structure is an integral part of the analysis to produce accurate costs for rehabilitation and maintenance [19]. The data for this study is derived from the historical and existing database along with an extensive collection of field measurements. It includes identification of pavement type, layer thickness, coefficients, structural numbers, and CBR values collected in selected homogenous sections. A visual inspection was conducted to assess impacts of potholes, ravelling, cracking, edge break, rutting and roughness. Impacts caused by these defects can be very consequential for the road performance and road user comfort. Hence evaluating such parameters in detail is very essential for accurate projections and determination of alternative maintenance strategies done further in this study.

Table 6. Existing Pavement Condition

| Sections | Roughness | Cracking (%) | Ravelled Area% | Potholes (no./km) | Edge break (m²/km) | Mean Rut Depth (mm) | Texture depth (mm) | Skid Resistance |
|----------|-----------|--------------|----------------|-------------------|-------------------|---------------------|--------------------|----------------|
| SS2 B1   | 2.12      | 6.89         | 2.88           | 0.2               | 7                 | 10.21               | 0.52               | 0.11           |
| SS2 B2   | 2.43      | 5.67         | 2.92           | 0.25              | 22.56             | 10.5                | 0.55               | 0.11           |
| SS3 C1   | 4.05      | 14.24        | 8.3            | 1.5               | 153.04            | 2.3                 | 0.41               | 0.3            |
| SS3 C2   | 2.21      | 19.6         | 17.5           | 1.85              | 70.37             | 2.8                 | 0.4                | 0.3            |
| SS3 C3   | 7.33      | 21.33        | 6.5            | 1                 | 37.5              | 2.1                 | 0.42               | 0.3            |
| SS4 D    | 2.58      | 4.1          | 1.5            | 0.34              | 19.67             | 2.9                 | 0.39               | 0.4            |
| SS5 E    | 2.63      | 4.8          | 18.02          | 0.5               | 28                | 3                   | 0.4                | 0.4            |
4.6. Section Details

In HDM-4, the characteristics of individual sections are defined by the most important parameters that specify all-inclusive components of the road section concerning the latest survey conducted in the area [20]. It combines all the data previously collected such as speed flow types, traffic flow pattern, climate zone, road class, surface class, and pavement history and structural characteristics along with geometry, renovation updates (resurfacing, rehabilitation and treatment), and current condition of pavement done by visual inspection and measurements composed all together.

Dimensions of the road were manually collected using basic measurement equipment. Rise and fall, horizontal curvature, speed limit, and altitude were defined by concepts of highway geometric design with respective of the road classification.

Table 7. Section Details

| Section Name                        | Length(km) | Surface Class | Rise + Fall | Carriageway Width | Shoulder Width | Speed Limit |
|-------------------------------------|------------|---------------|-------------|-------------------|----------------|-------------|
| SH-2C(B1)-HATHOJ-BHAMBORI           | 6.6        | Bituminous    | 2.1         | 16                | 1.2            | 100         |
| SH-2C(B2)-BAHMBORI-PACHAR           | 8.2        | Bituminous    | 2.22        | 10                | 1              | 100         |
| MDR-81(C1)                          | 2.3        | Bituminous    | 8.2         | 4.9               | 0.8            | 30          |
| MDR-81(C2)                          | 5.4        | Bituminous    | 6.5         | 4.9               | 0.8            | 30          |
| MDR-81(C3)                          | 5.8        | Bituminous    | 8.88        | 5.4               | 0.7            | 30          |
| BEGUS ROAD (D)                      | 6.5        | Bituminous    | 2.5         | 5.5               | 1.3            | 30          |
| SIRSI-HATHOJ ROAD (E)               | 4.5        | Bituminous    | 3.22        | 6                 | 0.5            | 30          |

5. Deterioration/Works Effects

There are five pavement deterioration models (cracking, ravelling, edge break, rutting, potholes) available within HDM-4.

5.1. Average Roughness by Project

The present study projects one of the deteriorations impacts that show variation in trends of average roughness developed from the year 2021 to 2036. The graphs represented below clearly show alternatives such as edge repair, lane addition, pothole sealing, routine maintenance show a questionable amount of deflection whereas Thin Overlay and Overlay is suggested to be the most suitable alternative strategy to be adopted due to the least projection of roughness by the year 2036.
5.2. Pavement Conditions Summary

The prediction of pavement deterioration is a vital part of Pavement Management Systems (PMS) [21]. It ensures serviceability by indicating the declination of quality in roads. These predictions are formulated to prevent consequences of deterioration effects on roads. Generated reports project the pavement deterioration rates by year corresponding to various parameters.

Table 8. Pavement Deterioration Projection

| Sections | Projection Year | AADT | IRI (m/km) | Cracking % | Raveling% | Edge break(sqm) | Rut Depth(mm) | Number of Potholes |
|----------|----------------|------|------------|------------|-----------|----------------|--------------|-------------------|
| SS2      | 2021           | 3564 | 2.330      | 10.225     | 6.107     | 14.880         | 19.720       | 0.340             |
|          | 2025           | 4758 | 3.025      | 35.855     | 39.807    | 0              | 20.862       | 58.370            |
|          | 2030           | 6833 | 4.877      | 71.543     | 23.492    | 0              | 22.492       | 0                 |
|          | 2035           | 9809 | 13.560     | 78.205     | 0.566     | 0              | 24.360       | 470.165           |
| SS3      | 2021           | 695  | 4.620      | 19.810     | 11.895    | 44.670         | 2.840        | 1.620             |
|          | 2025           | 929  | 5.880      | 95.290     | 3.820     | 8.410          | 4.890        | 90.310            |
|          | 2030           | 1334 | 7.935      | 98.750     | 0         | 17.400         | 7.930        | 136.470           |
|          | 2035           | 1915 | 11.145     | 97.825     | 0         | 36.180         | 11.100       | 182.465           |
| SS4      | 2021           | 775  | 2.650      | 7.100      | 4.775     | 17.940         | 3.425        | 0.355             |
6. Validation of Deteriorations

In HDM-4, validation of output data is a necessary stage to ensure the efficiency of deteriorations models. Validation is required in the application and implementation of changes in parameters during the execution of the project. In this section, a comparison of distress is illustrated between predicted data produced in the analysis and actual data that was observed in the selected sections. The variation that occurred between figures signifies a change in deterioration levels.

Table 9. Validation for data obtained from HDM-4 for Overlay

| Pavement Deterioration | Cracking (%) | Ravelling (%) | Potholes (%) | Edge Break (m²/km) | Rutting (mm) |
|------------------------|--------------|---------------|--------------|--------------------|--------------|
|                        | Predicted    | Actual        | Variation (%)| Predicted           | Actual       | Variation (%)| Predicted | Actual       | Variation (%)| Predicted           | Actual       | Variation (%)| Predicted | Actual       | Variation (%)|
| SS2 B1                 | 5.59         | 6.89          | 21%          | 3.04               | 2.88         | 0.13         | 0.2         | 42.42         | 5           | 7           | 33.33         | 10.24         | 10.21         | 0.29       |
| SS2 B2                 | 4.64         | 5.67          | 19.98        | 3.07               | 2.92         | 0.21         | 0.25        | 17.39         | 24.76       | 22.56       | 9.29          | 9.01          | 10.5         | 15.27     |
| SS3 C1                 | 16.17        | 14.24         | 12.69        | 9.73               | 8.3          | 15.86        | 1.66        | 10.12         | 155.49      | 153.04      | 1.58          | 2.77          | 2.3         | 18.54     |
| SS3 C2                 | 20.98        | 19.6          | 6.8          | 18.2               | 17.5         | 3.92         | 2.1         | 1.83         | 12.65       | 72.84       | 70.37        | 0.66         | 3.28        | 2.8         | 15.78     |
| SS3 C3                 | 22.3         | 21.33         | 4.44         | 7.75               | 6.5          | 4.44         | 1.1         | 1            | 9.52        | 39.36       | 37.5         | 4.83         | 2.47        | 2.1         | 16.19     |
| SS4                    | 3.55         | 4.1           | 14.37        | 2.39               | 1.5          | 45.75        | 0.18        | 0.34         | 30          | 17.94       | 19.67        | 9.19         | 1.71        | 2.9         | 51.82     |
| SS5                    | 6.36         | 4.8           | 29.95        | 18.57              | 18.02        | 3            | 0.41        | 0.5          | 19.78       | 30.9        | 28           | 9.84         | 1.75        | 3           | 52.83     |

7. Maintenance Strategy as per Economic Indicators

One of the best ways to improve the reliability of roads is through imposing targeted maintenance strategies. Prices and unit costs are applied to determine the financial and economic viability of all study sections. Related benefits are then formulated for different approaches towards maintenance and then integrated with the current value and return on investments calculations.
### Economic Indicators Summary

**Study Name:** Rural roads (S33)

**Run Date:** 02-02-2021

**Currency:** Indian currency (millions)

**Discount Rate:** 12.00%

| Alternative            | Present Value of Total Agency Costs (RAC) | Present Value of Agency Capital Costs (CAP) | Increase in Agency Costs (A) | Present Value of User Costs (U) | Net Expenditure Benefits ($) | Net Present Value (NPV) (RAC-CAP) | MPVCAP Ratio (RAC/CAP) | MPVCA Ratio (CAP/CAP) | Internal Rate of Return (IRR) |
|------------------------|-------------------------------------------|--------------------------------------------|-------------------------------|---------------------------------|------------------------------|-----------------------------------|------------------------|-----------------------|----------------------------|
| Road Maintenance       | 7,706                                      | 0,000                                      | 0,000                         | 0,000                           | 0,000                        | 0,000                             | 0,000                  | 0,000                 | 0,000                     |
| Bridge Repair          | 4,403                                      | 0,000                                      | 0,000                         | 0,000                           | 0,000                        | 0,000                             | 0,000                  | 0,000                 | 0,000                     |
| Pole/Pole Repair       | 2,000                                      | 0,000                                      | 0,000                         | 0,000                           | 0,000                        | 0,000                             | 0,000                  | 0,000                 | 0,000                     |
| Lane Addition          | 52,504                                     | 151,205                                    | 105,600                       | 105,600                         | 0,000                        | -97,424                           | -97,424                | -97,424               | -97,424                   |
| Thin Concrete          | 121,992                                    | 121,992                                    | 115,992                       | 214,992                         | 0,000                        | 125,000                           | 125,000                | 1,027                 | 0,000                     |

*Figure 2. Economic Indicators Summary for all Study Sections*
A variety of maintenance techniques can be proposed by referring to the economic indicators like Net Present Value (NPV), Internal Rate of Return (IRR), etc. for every option given during the projected analysis period. The most beneficial strategy will be adopted in terms of maximum economic returns.

8. Conclusion

HDM-4 software was used in performing analysis of pavement deterioration modelling for the selected rural road. A study is shown to predict pavement performance in upcoming years based on present pavement distress conditions. It will be used as crucial information for developing alternatives of maintenance and improvement strategies considering the economic viability of the project. The following methodology was followed in developing pavement deterioration models:

- Road network and condition database was accumulated by thorough monitoring of pavement performance and regular inspections on selected sections.
- Project Analysis presented pavement deterioration models for roughness parameters projected over 15 years. Therefore, suggesting Thin overlay and Overlay, a possible alternative.
- The models produced were statistically validated in variation between actual and predicted data to indicate the difference in deterioration rate. Moreover, ensuring output is in the proximity range.
- The most suitable maintenance strategy was deduced from the economic indicators summary ensuring the best investment returns. Following NPV/cost ratio which is highest for SS 5(14.467), it is determined that Overlay and Thin Overlay are by far the best alternative inclusive of all study sections.

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