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Pavement Deterioration Modelling for Urban and Rural Roads Using HDM-4

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Abstract

India's growing demand for adequate maintenance and upkeep of the world's second-largest road network of 5.89 million kilometers is a major problem for road administrators and policymakers. To address the issue of proper upkeep of road networks, many countries have implemented a robust pavement management system (PMS) to handle the tasks related to pavement maintenance and management. The Highway Development and Management (HDM-4) system is widely used as a tool for highway investment and maintenance planning and programming. The broad objective of this study is to develop pavement deterioration models for cracking, ravelling, potholes, rut depth, and edge break using non-linear regression techniques in MATLAB and compare them with the models present in HDM-4 and observed deteriorations for their effectiveness. The deterioration models for urban and rural pavement sections have been developed based on the large volume of field data collected in the Jaipur district of Rajasthan State using automated as well as manual methods of field evaluation. These sections were continuously monitored for 5 years for the pavement surface condition data. The validity of these models and calibrated HDM-4 models was assessed by examining the distress predictions generated by the regression models and calibrated deterioration models to the distress observed on the selected pavement sections. The proposed pavement deterioration models and the calibrated HDM-4 models are likely to apply to other developing nations with comparable traffic patterns, soil types, meteorological conditions, terrain kinds, and pavement composition as well.

Keywords HDM-4 · Pavement maintenance management system · Pavement deterioration modelling · Pavement distress · MATLAB

Abbreviations

AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
ANN	Artificial Neural Networks
ANOVA	Analysis of Variance
BC	Bituminous Concrete
CBR	California Bearing Ratio
CDB	Construction Defects Indicator of Base
CDS	Construction Defects Indicator of Surfacing
COTE	Centre of Transportation Engineering
CRRI	Central Road Research Institute
CVPD	Commercial Vehicles Per Day
EPS	Existing Pavement Sections
ESWL	Equivalent Single Wheel Load
GIS	Geographical Information System
HDM	Highway Development and Management
HMA	Hot Mix Asphalt
IRC	Indian Roads Congress
IRI	International Roughness Index
LCV	Light Commercial Vehicle
LVR	Low Volume Roads
M&R	Maintenance and Rehabilitation
MDD	Maximum Dry Density
MDR	Major District Roads

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MERLIN	Machine for Evaluating Roughness using Low-cost Instrumentation
MMR	Mumbai Metropolitan Region
MMS	Maintenance Management System
MoRTH	Ministry of Road Transport and Highways
MOSRTH	Ministry of Shipping, Road Transport and Highways
MOST	Ministry of Surface Transport
MSN	Modified Structural Number
MT	Motorized Traffic
NH	National Highway
NHAI	National Highway Authority of India
NMT	Non-Motorized Traffic
NPV	Net Present Value
ODR	Other District Roads
OMC	Optimum Moisture Content
PCR	Pavement Condition Rating
PCSE	Passenger Car Space Equivalents
PCU	Passenger Car Unit
PDM	Pavement Deterioration Models
PMGSY	Pradhan Mantri Gram Sadak Yojana
PMMS	Pavement Maintenance Management System
PMS	Pavement Management System
PPS	Pavement Performance Study
PSR	Present Serviceability Rating
PWD	Public Works Department
RF	Representative Fraction
RIMS	Road Information Management System
RUE	Road User Effects
SH	State Highway
SNP	Structural Number of Pavement
SP	Special Publication
SS	Study Section
ULB	Urban Local Bodies

1 Introduction

The road network in India comprises different classes of roads as follows: National Highways (1.94%), State Highways (2.97%), District Roads (9.94%), Rural Roads (70.65%), Urban Roads (8.93%), Project Roads (5.58%). Road transport accounts for 64.5 percent of all products carried in India, and 90 percent of all passenger travel [1, 2]. The data show that the share of rural roads (70.65%) is the highest, followed by district roads and urban roads. In the Union Budget 2020–21, the Indian government has set out USD 12.24 billion for the Ministry of Road Transport and Highways (MoRTH). The Indian government has allocated USD 148 billion for the National Infrastructure Pipeline in the fiscal year 2019–25. The roads sector is expected to contribute 18 percent of capital spending in the 2019–25 fiscal year. In addition, in the Union Budget 2020–21, the

Indian government has set out USD 2.6 billion for Pradhan Mantri Gram Sadak Yojana (PMGSY). The Pradhan Mantri Gram Sadak Yojana (PMGSY) is a nationwide plan in India to provide good all-weather road connectivity to unconnected villages [3, 4]. According to the 11th five-year plan working report on rural roads, the current replacement cost of the existing rural road network in India is projected to be USD 26.67 billion. The subsequent loss in value of road assets due to non-maintenance could be as high as USD 1.33 billion per year, equating to 50,000 km of the road being eroded every year [5]. As a result, the road assets created must be maintained during their design life. The guidelines for deciding the interval and type of maintenance activities for rural roads as per Indian Roads Congress (IRC) SP-20: Rural Roads Manual (2002) are on a subjective basis and mainly based on the experience of field engineers, and without any economic analysis being done [6]. This caused them to seek applicable solutions for road maintenance and rehabilitation problems, keeping resource constraints in mind. A step in this approach is the creation of a Pavement Management System (PMS) for the various conditions that exist in the nation.

Most pavement management systems (PMS) contain a section for pavement maintenance (PMMS), which may include models for determining the most cost-effective treatment. The features of the surface, the type of pavement, and other key variables generally influence them. The right maintenance treatment must be done at the appropriate time for the pavement to operate as intended and for the maintenance program to be cost-effective [7]. Due to advancements in information technologies, Pavement Management Systems (PMS) and Pavement Maintenance Management Systems (PMMS) have significantly improved over the last twenty years. Highway agencies today have a range of tools and systems at their disposal to assist them to make the most of the highway construction, maintenance, and rehabilitation services available. The Highway Development and Management (HDM-4) tool is one of the analytical tools available [8].

1.1 Highway Development and Management (HDM-4)

The World Bank has made it essential for its clients to have their highway projects assessed using the HDM-4 before receiving a loan. As a result, the HDM-4 program has become the legally recognized world standard decision support system for pavement management [9]. The Ministry of Shipping, Road Transport and Highways (MoSRTH) (currently MoRTH) of the Government of India has also called for the use of HDM-4 for a comprehensive evaluation of pavement deterioration and economic returns on highway investments to ensure the best possible use of funds

for India's National Highway Network and the National Highway Authority of India (NHAI) is designing a Road Information Management System (RIMS) for the country's National Highway (NH) network using HDM-4 as well [10]. Relationships for modelling pavement deterioration and road works effects are included in HDM-4. These are used to forecast annual road conditions and analyze highway construction and maintenance strategies. The HDM-4 road deterioration models aim to simulate the dynamic relationship among vehicles, the atmosphere, pavement design, and surface characteristics [11] Five distinct distress models, given below, are used to forecast road deterioration in this study. Initiation and progression are two stages that describe the first three distress modes. The initiation phase is the period between the onset of surfacing distress of a particular mode or severity and the appearance of surfacing distress. The progression phase is defined as the period where the extent and magnitude of the distress grows.

1.2 Pavement Deterioration Models

Predictions of structural and functional pavement performance, as well as other inputs, aid in the creation of reasonable maintenance budgets and the selection of the best maintenance strategies. In a Pavement Maintenance and Management System (PMMS), a pavement deterioration model, which forecasts pavement performance, is a significant input. For several years, administrators and transportation engineers all over the world have focused on pavement performance models built mostly in Europe and North America for pavement design, construction, and reconstruction. These models were created using the results of a few groundbreaking research projects that were undertaken because of the continents' comprehensive transportation growth and paved highway network. However, since these models are developed from data for local environments, they have certain inherent drawbacks and are not often explicitly transferable for global use, unless their appropriate validation has been reported [12]. At present, no study has been carried out which manifests the contrast between urban and rural scenarios and effectively models the pavement deterioration in these conditions using primary (field studies) and secondary data [official records of concerned Public Works Department (PWDs), In-charge of maintenance of these roads, Toll booths, Police interceptors and other Urban local bodies (ULBs)]. A comparison of the efficacy of HDM-4 and the locally developed pavement deterioration models was not addressed in any of the preceding research. In this study, pavement deterioration models were developed for predicting the following distresses: Cracking percentage; Ravelling percentage; No. of Potholes; Edge break (only for rural sections), and Rut depth (only for urban sections).

These models for urban and rural roads were developed in MATLAB based on the large volume of field data collected viz., automated as well as the manual method of field evaluation for use in identifying and prioritizing resurfacing needs. The appropriate organizations and departments provided detailed information on the pavement layer composition, design, and traffic data for these sections. For the surface condition data of the pavement, these sections were constantly monitored for 5 years (from 2017 to the end of 2021). All these data were also utilized to calibrate and validate HDM-4 distress models. The flowchart given in Fig. 1 outlines the methodology proposed for the study.

2 Literature Review

Most countries around the world are working on various pavement performance models for use in preparing pavement maintenance plans as part of various pavement performance studies. For roads in India, there are no historical long-term pavement performance data or pavement deterioration models to estimate pavement performance. As a result, it is essential to develop pavement deterioration models for urban and rural roads, which would help recommend appropriate maintenance solutions for the long-term protection of this type of road network. This scientifically based methodology would also assist a developed nation like India in making the best use of its limited maintenance budget [13, 14]. Most of the studies on HDM-4 are associated with the calibration of its distress models according to local conditions and the development of PMMS using calibrated HDM-4 models [8, 9, 15–28]. Many researchers have also exploited the advantages of other soft computing techniques in PMMS. Chandran et al. (2007) have prioritized low-volume pavement sections for maintenance using Fuzzy Logic [29]. Alsugair et. al. (1998), Mathew et. al. (2008), Shekharan et. al. (2000), and Ashraf and George (2000) employed ANN to evaluate the appropriate maintenance and repair choice for road segments in a network [30–33].

Ministry of Surface Transport (MOST) (currently MoRTH) of the Indian government, funded the Pavement Performance Study (PPS) at the Central Road Research Institute (CRRI) in New Delhi in 1986 to estimate data for a transportation cost model in Indian circumstances. These models were the first of their type and were based on long-term pavement performance data in Indian settings [34]. The details of the study by CRRI on Existing pavement sections (EPS) and the models developed are described in the study by Sood et al. (1994). The models in this study are based on typical traffic, environmental, and pavement conditions seen on India's major roads [35]. Reddy et al. (2002) investigated the cost allocation of flexible pavement maintenance and strengthening options based on performance. Pavement
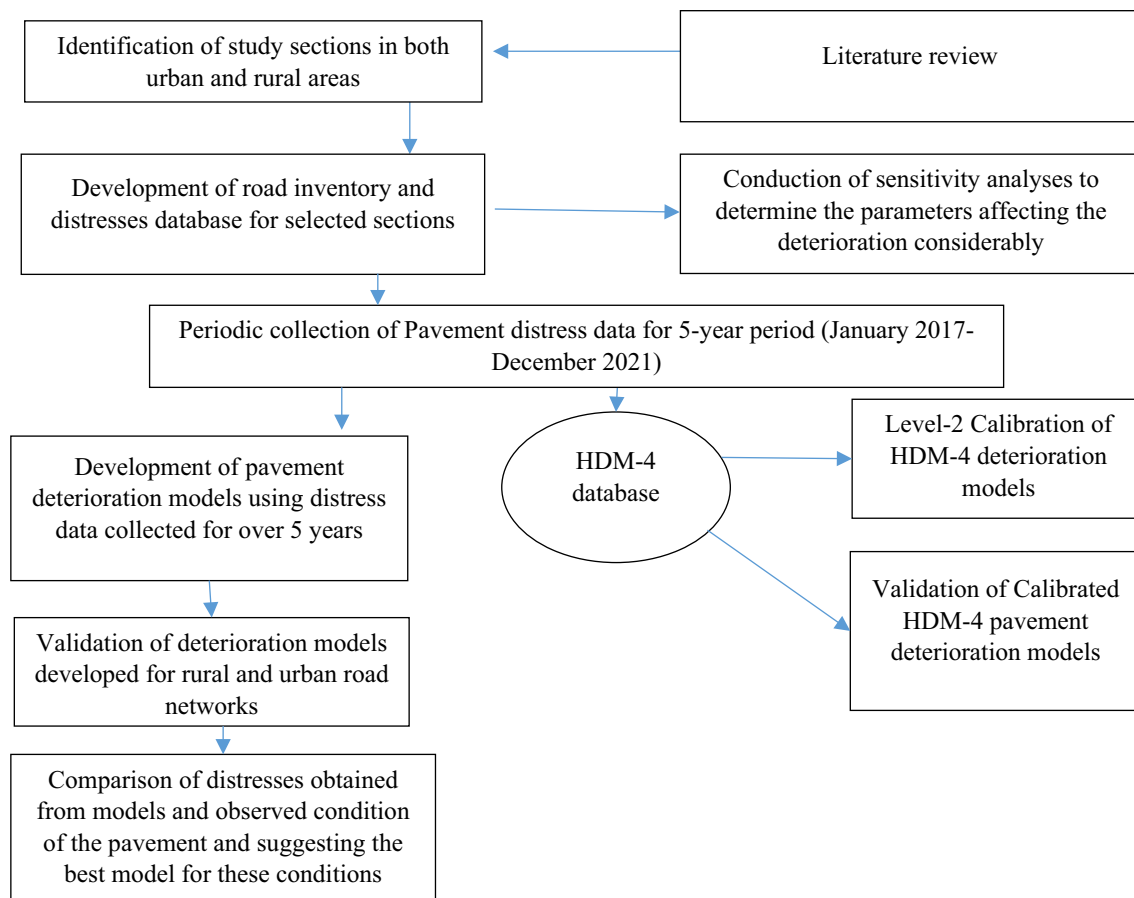
Fig. 1 Flowchart for study methodology

performance models were built utilizing data collected for government-sponsored Pavement Deterioration Models (PDM) research programs [36]. The structural and roughness deterioration models were created by Jain et al. (1994) to determine the necessity for flexible pavement maintenance management. The data from additional test sections were then used to calibrate and validate these models [37]. Kumar and Patel (2009) used deflection and roughness data on 18 Pradhan Mantri Gram Sadak Yojana (PMGSY) sections in Uttarakhand and Uttar Pradesh to develop pavement deterioration models for rural roads in India [38]. Rastogi et al. (2011) created pavement performance models for low-volume pavements in the Indian states of Uttarakhand and Uttar Pradesh. For the selected 18 portions, structural and functional responses were constantly assessed for 2 years [39]. Sandra and Sarkar (2012) created a model to estimate the association between roughness and typical road deteriorations such as rutting, ravelling, potholes, cracking, and patching on Indian roads [40].

In the Kenyan study by Hodges et al. (1975) and Patterson (1987), 46 test sections were chosen for monitoring and analysis to link deterioration to maintenance, traffic,

environment, and material type [41, 42]. Similarly in the United States, Luhr and McCullough (1983) used a pavement management system called the 'Pavement Design and Management System' (PDMS) to conduct an economic analysis comparing three surfacing types (aggregate, surface treatment, and asphalt) at six different traffic levels for low-volume roads (5–200 vehicles/day in single design lane) and calculating total costs for each case [43]. Data for the formulation of empirical models were collected by monitoring the state of existing in-service roads in the Brazil-UNDP road costs research by Geipot (1982), and Patterson (1987). The factorial foundation for choosing the forty-eight sections was identical to that used in the Kenyan study, but there were a few key modifications targeted at improving the data interpretation [42, 44]. Giummarra et al. (2004) undertook a study to construct deterioration models for local roads in Australia [45]. By merging experimental and field data, Prozzi and Madanat (2004) showed the generation of pavement performance models. When compared to approaches like conventional least squares, the methodology described in this work makes the best use of available data and produces models with better statistical features [46].

Chen et al. (2011) examined the application of IRI-based pavement deterioration prediction models, which included four deterministic pavement performance models (i.e., the NCHRP model, Dubai model, AI-Omari Darter model, and the NMDOT model used by the New Mexico Department of Transportation) [47]. Sun and Gu (2011) combined the advantages of the Analytic Hierarchy Process (AHP) and Fuzzy Logic theory to produce a new technique for pavement condition prediction and project prioritization [48]. Hassan et al. (2017) described the technique and results of deterioration modelling for five different types of bituminous pavement surfaces, which may be used to detect and prioritize resurfacing needs. Overall, the data show that for most surface types, the three modelling methodologies produce similar forecasts and deterioration rates [49].

3 Study Sections and Time-Series Data Collection

To develop a pavement performance model and for calibration of HDM-4 models, it is necessary to possess a group of distress data that serves to represent the real performance

curve; preferably the data representing a relatively long time. Different researchers have used the Test Section or "Film" technique and the "Window" method to develop pavement performance models [41, 50, 51]. In the test section methodology, which has been adopted in this study, it is necessary to continue measuring pavement performance data for an extended time for each selected section for obtaining reliable predictive data. The study area in the present study is confined to the rural and urban roads situated in Jaipur district having plain terrain in the Rajasthan State of India.

3.1 Road Network Details

The identified urban and rural road sections span 79 km of plain terrain in Rajasthan, India. It consists of 20 functional road sections which are in plain terrain regions. These pavement sections were a part of 7 road networks spread over the rural and urban areas of the Jaipur district. Eventually, only these seven road networks were subjected to HDM-4 strategy analysis. Table 1 shows section-wise data on the number of in-service urban and rural road sections in the study region. Twelve in-service rural road sections and eight urban road sections were eventually chosen for model

Table 1 Pavement sections selected for the study (2017 data)

Road network	Pavement section identification number	Section name	Section description	Length (kms)	Type of section	Traffic Volume
SS-R-1,2	SS-R-1 (J-K)	SH-2C (A)	Kalwar Road	6.6	Rural	Medium
	SS-R-1 (K-J)			6.6		
	SS-R-2 (J-K)	SH-2C (B)		8.2		
	SS-R-2 (K-J)			8.2		
SS-R-3,4,5	SS-R-3 (B-P)	MDR-81 (A)	Begas- Pachar Road	2.3	Rural	Medium
	SS-R-3 (P-B)			2.3		
	SS-R-4 (B-P)	MDR-81 (B)		5.4		
	SS-R-4 (P-B)			5.4		
	SS-R-5 (B-P)	MDR-81 (C)		5.8		
	SS-R-5 (P-B)			5.8		
SS-R-6,**7**	SS-R-6	Begas Road	Bhambhori- Nandgaon	6.5	Rural	Low
	SS-R-7	Sirsi-Hathoj Road	Hathoj- Khatipura Road	4.5	Rural	Low
SS-U-1	SS-U-1 (J-A)	NH-48	Jaipur-Ajmer Expressway	1.7	Urban	High
	SS-U-1 (A-J)			1.7		
SS-U-2	SS-U-2 (R-T)	Gopalpura Road	Riddhi Siddhi- Triveni Circle	1.0	Urban	High
	SS-U-2 (T-R)			1.0		
SS-U-3	SS-U-3 (V-G)	Gandhi Path	Vijay Dwar-Gautam Marg	1.0	Urban	High
	SS-U-3 (G-V)			1.0		
SS-U-4	SS-U-4(N-K)	Jan Path	New Sanganer Road- Kings Road	2.0	Urban	High
	SS-U-4(K-N)			2.0		

J-K Jaipur to Kalwar, *K-J* Kalwar to Jaipur, *B-P* Begas to Pachar, *P-B* Pachar to Begas, *J-A* Jaipur to Ajmer, *A-J* Ajmer to Jaipur, *R-T* Riddhi Siddhi to Triveni Circle, *T-R* Triveni Circle to Riddhi Siddhi, *V*-G Vijay Dwar to Gautam Marg, *G-V* Gautam Marg to Vijay Dwar, *N-K* New Sanganer Road to Kings Road, *K-N* Kings Road to New Sanganer Road

Traffic Volume: Low: < 1600 AADT, Medium:1601–3500 AADT, High: > 3500 AADT

development. For simple identification in the road network, each of the selected pavement sections has been given a unique "Section ID" and a "Section Name" as shown in the table. "Study Section (SS)-Type of section- Number issued to pavement section" is the series used to denote Section ID. The selected pavement section was dispersed throughout a wide variety of experimental design characteristics, including kinds of soils, geometry, and traffic factors, that are often seen on urban and rural roads in India's diverse geographical areas. Hence, the identified urban and rural road networks can be considered representative of rural and urban road networks in the plain terrains of Rajasthan.

Figure 2 depicts the location of the selected urban and rural road network in the broader context of the Jaipur district. The data are collected for each selected section by carrying out field studies (primary data) as well as from secondary sources (secondary data) such as official records of concerned Public Works Department (PWDs), In-charge of maintenance of these roads, Toll booths, Police interceptors, and other Urban local bodies (ULBs). The data-collecting procedure has been divided into the following areas: Road Network data; Pavement distress data for five years; Vehicle fleet data; Traffic Volume data; Road User Cost data.

The collected data in detail as well as the data collection approach and tools that were utilized have been presented in Appendix A (Supplementary Materials).

3.2 Evaluation of Pavement Materials

In the laboratory, subgrade soil samples and Hot mix asphalt (HMA) samples taken from the field were evaluated in detail following Indian standards and guidelines [52–55]. The test results are presented in Table 2. These experiments were conducted at Manipal University Jaipur research facilities. Representative subgrade soil samples were obtained from the test pits (0.5 m × 0.5 m) for each rural and urban pavement section for laboratory characterization of subgrade soil materials.

The Modified Structural Number of Pavement (MSN) is an indicator of the strength and structural adequacy of a pavement. It is calculated using the Structural Number of Pavement (SNP) value and by use of Eq. 1 given below as follows:

$$MSN = SNP + 3.51\left(\log_{10} CBR_s\right) - 0.85\left(\log_{10} CBR_s\right)^2 - 1.43, \tag{1}$$

where, SNP is the Structural Number of Pavement, MSN = Modified Structural Number, CBR_s is the in-situ CBR value of the subgrade, in %

The pavement Structural Number is calculated by multiplying the layer material type specific coefficient by the layer thickness and then adding them together. The layer coefficients for different types of pavement layers are proposed by the American Association of State Highway and Transportation Officials (AASHTO) Guide, 1993 [56]. In

Fig. 2 Map showing the location of all study sections

Table 2 Laboratory Evaluation of Pavement materials data (2017 data)

Pavement Section identification Number	Section Name	OMC (%)	MDD (gm/cm^3)	CBR (%)	Relative Compaction (%)	Modified Structural Number, MSN	Deflection (mm)	CDS (0.5–1.5)
SS-R-1 (J-K)	SH-2C (A)	11.2	1.73	8.6	97	5.2	0.97	0.8
SS-R-1 (K-J)		11.2	1.73	8.6	97	5.08	0.97	0.75
SS-R-2 (J-K)	SH-2C (B)	11.2	1.73	8.6	97	5.13	1.07	0.77
SS-R-2 (K-J)		11.2	1.73	8.6	97	5.11	1.07	0.73
SS-R-3 (B-P)	MDR-81 (A)	11.8	1.73	8.5	97	4.7	0.64	0.55
SS-R-3 (P-B)		11.8	1.73	8.5	97	4.3	0.64	0.6
SS-R-4 (B-P)	MDR-81 (B)	11.8	1.73	8.5	97	4.44	0.6	0.56
SS-R-4 (P-B)		11.8	1.73	8.5	97	4.5	0.6	0.6
SS-R-5 (B-P)	MDR-81 (C)	11.8	1.73	8.5	97	4.2	0.6	0.55
SS-R-5 (P-B)		11.8	1.73	8.5	97	4.4	0.6	0.56
SS-R-6	Begas Road	13.3	1.76	8.3	96	3.75	0.59	0.54
SS-R-7	Sirsi-Hathoj Road	13.6	1.74	8.9	96	3.5	0.57	0.57
SS-U-1 (J-A)	NH-48	10.6	1.93	9.5	98	4.8	0.34	0.8
SS-U-1 (A-J)		10.6	1.93	9.5	98	4.7	0.34	0.8
SS-U-2 (R-T)	Gopalpura Road	9.5	1.75	11.4	98	6	0.32	0.75
SS-U-2 (T-R)		9.5	1.75	11.4	98	5.9	0.32	0.72
SS-U-3 (V-G)	Gandhi Path	10.1	1.68	9.6	96	3.5	0.3	0.65
SS-U-3 (G-V)		10.1	1.68	9.6	96	3.7	0.3	0.7
SS-U-4(N-K)	Jan Path	9.5	1.76	11.2	98	5.5	0.3	0.6
SS-U-4(K-N)		9.5	1.76	11.2	98	5.44	0.3	0.58

Table 3 Construction defect indicator (CDS) for bituminous surfacing

Dry (Brittle)	Nominally about 10% below design optimal binder content	0.5
Normal	Optimum bitumen content	1.0
Rich (Soft)	Nominally about 10% above design optimal binder content	1.5

HDM-4 the construction defects are input through two indicators as follows:

- CDS—Construction defects indicator for bituminous surfacing
- CDB—Construction defects indicator for the base

CDS is a parameter that indicates the general amount of binder content and stiffness compared to the best material design for a certain bituminous combination. It is used to determine if a bituminous surfacing is prone to cracking and ravelling (low CDS value) or rutting due to plastic deformation (high value of CDS). CDS is a continuous variable with a range of 0.5–1.5 as indicated in Table 3. The base construction defects indicator (CDB) is used for potholing. CDB is a continuous variable that ranges from 0 (no construction defects) to 1.5 (several defects).

4 Calibration of HDM-4 Models

HDM 4 road deterioration models include 'calibration factors,' which are linear multipliers for adjusting projections to fit local conditions, to help with calibration and local adaption. Each of these calibration factors in HDM-4 has been set to unity as the default value [22, 24, 25]. In this study, the "Window" approach was utilized to calibrate pavement distress models. The "Window" concept defines homogenous rural and urban road sections based on their most representative factors, such as structure, traffic, geometry, and climate. Each of these sections is, therefore, called a window in a pavement's performance curve and indicates a specific pavement's performance when combined with other windows (similar individual sections).

The selected in-service rural and urban road sections were divided into five cells (cells 1 to 5) and HDM-4 pavement deterioration models were calibrated for each cell. The calibration procedure entails calculating the adjustment variables (K_i) that will result in the best agreement between the model's predictions and field data [20, 57]. Section 4.1 contains the details of the calibration process used in this investigation.

For calibration of these deterioration models, three calibration levels (1—Basic application, 2-Primary relationships, and 3-Adaption) have been established in the HDM-4

tool, each of which requires a specific amount of work and resources depending on the application. In this study, Level 2 calibration was carried out for rural and urban pavement sections. For Level 2 initiation calibration, the observed values of the deteriorations for several years in these sections were compared with the results obtained from un-calibrated HDM-4 models. For distress progression factors, the final calibration factor corresponding to the maximum R^2, minimum Root Mean Square Error (RMSE), and Average Absolute Error (AAE) value has been suggested among the different trial calibration factors [19]. Based on these methodologies, the initiation and progression calibration factors for all 20 sections were determined for Cracking, Ravelling, Potholes, Rut Depth, and Edge break. Subsequently, the calibration factors obtained from Level 2 calibration, as indicated in Table 6, were adopted for further studies.

4.1 Level-2 Calibration Methodology

4.1.1 Distress Initiation Calibration Factors

The coefficient (calibration factor) between the observed year of occurrence of the distress and the year of occurrence predicted by the un-calibrated models was determined using Eq. 2, for the calibration of surface distress initiation factors as follows:

$$K_{ci} = \frac{\text{mean OTCI}}{\text{mean PTCI}}, \tag{2}$$

where, K_{ci} is the crack initiation calibration factor, OTCI is the observed time of crack initiation, PTCI is the predicted time of crack initiation.

Based on this methodology, the initiation calibration factors for all five cells comprising 20 pavement sections were determined for the following distresses:

- Cracking Initiation (K_{ci})
- Ravelling Initiation (K_{ri})
- Pothole Initiation (K_{pi})

4.1.2 Distress Progression Factors

The following is the procedure used to determine the calibration factors for distress progression [12, 22]:

- With the road network and vehicle fleet input data, HDM-4 was run for each cell containing a homogenous set of study sections. HDM-4 suggests a range of calibration factors ranging from 0 to 20, with a default value of 1. According to several previous research, the calibration factors in underdeveloped countries, such as India, range from zero to five [9, 22, 25]. As a result, HDM-4 was run

in the first stage with calibration factors ranging from 0 to 5 with a 0.10 increment.
- The calibration factors were calculated using the results of the first run, which corresponded to the lowest values of statistical parameters reflecting the difference between anticipated and observed distresses in time series data. The HDM-4 was run for the second stage after acquiring the calibration factors from the first run by taking the calibration factors within the narrower range of factors with an increment of 0.01, as determined from the first run, for further improvement of the calibration factors. The statistical parameters used in the study for calibration are given in further detail.

Based on this methodology, the progression calibration factors for all five cells comprising 20 pavement sections were determined for the following distresses:

- Cracking Progression (K_{cp})
- Ravelling Progression (K_{rp})
- Pothole Progression (K_{pp})
- Edge Break Progression (K_{eb})

Tables 4 and 5 demonstrate the procedure of getting the final value of calibration factors for the initiation and progression of cracking for homogeneous Cell-2 with the most sections (6 sections). The tables show the trials involving the closest values to the final distress progression factor.

Other distress/cell calibration factors were calculated using the same method, and the results are reported in Table 6. Appendix B (supplementary materials) contains thorough calculations and data for each section/cell. To arrive at the final values of calibration factors for all the distress progression models, the best values of the statistical indicators RMSE, AAE, and R^2 were considered [22, 25].

The average of the Initiation/Progression Calibration factors for relevant cells was then used to generate the Global Calibration Factors (GCF) for urban and rural roads. Table 7 shows the details of the GCF calculation.

4.2 Analysis of Calibration Data

Scrutiny of the above calibration factors indicates that:

- In the case of pavement sections in Cell-1, consisting of 4 sections, initiation of all types of distress starts on the pavement surface later than predicted by un-calibrated HDM-4 models. The crack initiation will begin 1.91 times slower, the ravelling initiation 1.7 times slower, and potholes will appear 3.27 times slower than calculated by uncalibrated HDM-4 models. The progression of these distresses is comparatively slower as compared to those predicted by the corresponding HDM-4 model as appar-

Table 4 Level-2 calibration process of HDM-4 cracking initiation model (Cell 2)

Cell No	Sections	Year	Observed cracking%	Age (in months)	Actual age of crack initiation (months)	Uncalibrated HDM-4 predicted age of crack initiation (months)	Calibration factor for Crack Initiation
2	SS-R-3 (B-P)	2017	5.3	17	1.603773585	0.965909091	1.57
		2018	7	30			
		2019	8.73	40			
		2020	9.88	56			
		2021	10.2	62			
	SS-R-3 (P-B)	2017	5.28	17	1.609848485	1.125827815	
		2018	6.83	30			
		2019	9.12	40			
		2020	10.18	56			
		2021	10.5	62			
	SS-R-4 (B-P)	2017	5.9	18	1.525423729	0.947368421	
		2018	7.2	31			
		2019	8.38	41			
		2020	10.82	56			
		2021	11.5	63			
	SS-R-4 (P-B)	2017	5.68	18	1.5845070	1.034482759	
		2018	7.5	31			
		2019	8.12	41			
		2020	10.7	56			
		2021	11	63			
	SS-R-5 (B-P)	2017	6.2	19	1.532258065	0.949050949	
		2018	7.5	32			
		2019	9	42			
		2020	11	56			
		2021	11.3	64			
	SS-R-5 (P-B)	2017	6	19	1.583333333	0.974358974	
		2018	7.43	32			
		2019	8.7	42			
		2020	10.3	56			
		2021	11	64			

ent from the calibration factors obtained for all distresses. The rate of distress progression is slower by 46%, 58%, 82%, and 7% for Cracking, Ravelling, Potholes, and Edge break, respectively.

- In the case of pavement sections in Cell-2, consisting of 6 sections, initiation of all types of distress starts on the pavement surface later than predicted by un-calibrated HDM-4 models. The crack initiation will begin 1.57 times slower, the ravelling initiation 1.51 times slower, and potholes will appear 3.2 times slower than calculated by uncalibrated HDM-4 models. The progression of these distresses is comparatively slower as compared to those predicted by the corresponding HDM-4 model as apparent from the calibration factors obtained for all distresses. The rate of distress progression is slower by 40%, 44%, 73%, and 3% for Cracking, Ravelling, Potholes, and Edge break, respectively.

- In the case of pavement sections in Cell-3, consisting of 2 sections, initiation of all types of distress starts on the pavement surface later than predicted by un-calibrated HDM-4 models. The crack initiation will begin 1.71 times slower, the ravelling initiation 2.39 times slower, and potholes will appear 2.92 times slower than calculated by uncalibrated HDM-4 models. The progression of these distresses is comparatively slower as compared to those predicted by the corresponding HDM-4 model as apparent from the calibration factors obtained for all distresses. The rate of distress progression is slower by 55%, 69%, 84%, and 9% for Cracking, Ravelling, Potholes, and Edge break, respectively.

- In the case of pavement sections in Cell-4, consisting of 4 sections, initiation of all types of distress starts on the pavement surface later than predicted by un-calibrated HDM-4 models. The crack initiation will begin 1.2

Table 5 Level-2 calibration process of HDM-4 cracking progression model (Cell 2)

Cell No	Sections	Year	Observed cracking%	K=1.0 (uncalibrated HDM-4 output)	R^2	AAE	RMSE	K=0.65	R^2	AAE	RMSE	K=0.5	R^2	AAE	RMSE	K=0.6	R^2	AAE	RMSE
2	SS-R-3 (B-P)	2017	5.3	8.8	0.76	16.2	22.08	5.77	0.98	0.941	1.20	4.84	0.98	0.58	0.72	5.38	0.99	0.33	0.509
		2018	7	14.2				7.65				5.8				7.52			
		2019	8.73	19.8				9.85				7.89				8.88			
		2020	9.88	37.88				11.41				9.34				9.78			
		2021	10.2	54.26				12.695				9.84				10.556			
	SS-R-3 (P-B)	2017	5.28	7.55				6.23				4.75				5.53			
		2018	6.83	13.88				7.41				5.63				7.32			
		2019	9.12	27.79				9.84				8.28				9.6			
		2020	10.18	38.55				10.33				9.2				10.3			
		2021	10.5	58.75				12.06				10.1				11.7			
	SS-R-4 (B-P)	2017	5.9	9.5				7.125				5.225				6.8			
		2018	7.2	14.2				7.65				5.8				7.34			
		2019	8.38	28.88				8.66				7.88				8.5			
		2020	10.82	42.44				12.83				10.342				11.1			
		2021	11.5	60				13.45				11				12.3			
	SS-R-4 (P-B)	2017	5.68	8.7				7.48				4.7				6.68			
		2018	7.5	14.78				8.085				7.1				7.65			
		2019	8.12	26.4				8.8				7.32				8.4			
		2020	10.7	38.7				12.02				10.2				11.33			
		2021	11	54.44				13.83				10.6				12.44			
	SS-R-5 (B-P)	2017	6.2	10.01				7.11				5.75				6.44			
		2018	7.5	15.78				7.835				6.1				7.55			
		2019	9	28.88				10.66				8.88				9.55			
		2020	11	39.71				12.78				9.84				11.13			
		2021	11.3	44.41				13.03				10.22				12.45			
	SS-R-5 (P-B)	2017	6	9.75				6.89				5.36				6.22			
		2018	7.43	15.2				7.77				6.26				7.5			
		2019	8.7	26.82				9.11				8.7				8.81			
		2020	10.3	35.54				11.655				9.547				10.45			
		2021	11	38.85				12.13				10.76				11.11			

Table 6 Level-2 calibration factors for HDM-4 deterioration models

Cell Number	Pavement sections included	Type	Model	Calibration Factor	Symbol
Cell 1	SS-R-1 (J-K)	Rural	Crack initiation	1.91	Kci
			Crack progression	0.54	Kcp
	SS-R-1 (K-J)	Rural	Ravelling initiation	1.7	Kri
			Ravelling progression	0.42	Krp
	SS-R-2 (J-K)	Rural	Pothole initiation	3.27	Kpi
			Pothole progression	0.18	Kpp
	SS-R-2 (K-J)	Rural	Edge break	0.93	Keb
Cell 2	SS-R-3 (B-P)	Rural	Crack initiation	1.57	Kci
	SS-R-3 (P-B)	Rural	Crack progression	0.6	Kcp
	SS-R-4 (B-P)	Rural	Ravelling initiation	1.51	Kri
	SS-R-4 (P-B)	Rural	Ravelling progression	0.56	Krp
	SS-R-5 (B-P)	Rural	Pothole initiation	3.2	Kpi
	SS-R-5 (P-B)	Rural	Pothole progression	0.27	Kpp
		Rural	Edge break	0.97	Keb
		Rural			
Cell-3	SS-R-6	Rural	Crack initiation	1.71	Kci
		Rural	Crack progression	0.45	Kcp
		Rural	Ravelling initiation	2.39	Kri
		Rural	Ravelling progression	0.31	Krp
	SS-R-7	Rural	Pothole initiation	2.92	Kpi
		Rural	Pothole progression	0.16	Kpp
		Rural	Edge break	0.91	Keb
		Rural			
Cell-4	SS-U-1 (J-A)	Urban	Crack initiation	1.2	Kci
		Urban	Crack progression	0.89	Kcp
	SS-U-1 (A-J)	Urban	Ravelling initiation	1.37	Kri
		Urban	Ravelling progression	0.79	Krp
	SS-U-2 (R-T)	Urban	Pothole initiation	1.68	Kpi
		Urban	Pothole progression	0.89	Kpp
	SS-U-2 (T-R)	Urban	Edge break	NA	Keb
		Urban			
Cell-5	SS-U-3 (V-G)	Urban	Crack initiation	1.12	Kci
		Urban	Crack progression	0.94	Kcp
	SS-U-3 (G-V)	Urban	Ravelling initiation	1.15	Kri
		Urban	Ravelling progression	0.96	Krp
	SS-U-4(N-K)	Urban	Pothole initiation	1.53	Kpi
		Urban	Pothole progression	0.94	Kpp
	SS-U-4(K-N)	Urban	Edge break	NA	Keb
		Urban			

NA not applicable

times slower, the ravelling initiation 1.37 times slower, and potholes will appear 1.68 times slower than calculated by uncalibrated HDM-4 models. The progression of these distresses is comparatively slower as compared to those predicted by the corresponding HDM-4 model as apparent from the calibration factors obtained for all distresses. The rate of distress progression is slower by 11%, 21%, and 9% for Cracking, Ravelling, and Potholes, respectively.

- In the case of pavement sections in Cell-5, consisting of 4 sections, initiation of all types of distress starts on the pavement surface later than predicted by un-calibrated HDM-4 models. The crack initiation will begin 1.12 times slower, the ravelling initiation 1.15 times slower, and potholes will appear 1.53 times slower than calcu-

Table 7 Global calibration factors (GCF) for urban and rural pavement sections

Type	Cells included	Model	GCF	Symbol
Global calibration factor for rural	Cell 1, 2 and 3	Crack Initiation	1.73	Kci
		Crack Progression	0.53	Kcp
		Ravelling Initiation	1.87	Kri
		Ravelling Progression	0.43	Krp
		Pothole Initiation	3.13	Kpi
		Pothole Progression	0.2	Kpp
		Edge break	0.94	Keb
Global calibration factor for urban	Cell 4 and 5	Crack Initiation	1.16	Kci
		Crack Progression	0.915	Kcp
		Ravelling Initiation	1.26	Kri
		Ravelling Progression	0.875	Krp
		Pothole Initiation	1.605	Kpi
		Pothole Progression	0.915	Kpp
		Edge break	NA	Keb

GCF Global Calibration Factor

lated by uncalibrated HDM-4 models. The progression of these distresses is comparatively slower as compared to those predicted by the corresponding HDM-4 model as apparent from the calibration factors obtained for all distresses. The rate of distress progression is slower by 6%, 4%, and 6% for Cracking, Ravelling, and Potholes, respectively.

- According to the global calibration factors (GCF) obtained, the variability between observed distress and uncalibrated HDM-4 values was found to be greater for rural pavement sections than for urban pavement sections, even though they follow the same pattern for distress initiation/progression as described above for individual cells.

5 Development of Pavement Deterioration Models

5.1 Sensitivity Analysis of Distresses

Sensitivity analyses are statistical studies that assess a dependent variable's sensitivity to changes in independent variables (also known as explanatory variables) over a suitable range of values. In this study, the analysis was conducted using the Spearman rank correlation coefficient method, Fisher-Snedecor's *F*-test, and the student's t-test of ranked variables. The selection of final variables, to be used in pavement deterioration models, was done thereafter.

Spearman's correlation coefficient is a statistical measure of the strength of a monotonic relationship between paired data. In a sample it is denoted by r_s and is by design constrained as follows:

Its interpretation is like that of Pearson's coefficient (*r*), e.g., the closer r_s is to ± 1, the stronger the monotonic

$$-1 \leq r_s \leq 1$$

relationship. It can be calculated using the following formula:

$$r_s = 1 - \frac{6 \sum d^2}{N(N^2 - 1)}, \tag{3}$$

where, *d* is the difference between the two ranks of each observation, *N* is the number of observations.

Further, hypothesis testing was used to determine the utility of the regression model and the relationship between the dependent and independent variables. The hypothesis is based on some assumptions regarding the problem. We made the following assumptions while utilizing the *t*-test procedure; Both samples are random samples chosen from separate populations that can be represented by a normal distribution, and both populations' standard deviations and variances are identical. The followings are the null (H_o) and alternative hypotheses (H_1):

$$H_o : \beta_j = 0$$
$$H_1 : \beta_j \neq 0$$

Rejection Rule: Reject H_o if, $t_{stat} > t_{critical}$ or $t_{stat} < -t_{critical}$.

If the H_o is not rejected, then the independent variable associated with that regression coefficient is not significant in explaining the variability of the dependent variable in the model. t_{stat} is calculated using Eq. 4 below as follows:

$$t_{stat} = \frac{\hat{\beta}_j}{SE(\hat{\beta}_j)}, \tag{4}$$

where β_j is the regression coefficients, and *SE* shows standard error of the regression coefficient.

The calculated '*t*' values (t_{stat}) for pavement deterioration family models for the rural and urban roads in plain terrain have been compared with critical '*t*' values for the level of significance (α) of 5% ($t_{critical}$) and degree of freedom as (N-2), and the details of the same are given in Appendix C (Supplementary materials). If the observed value of the test statistics, t_{stat} falls into the rejection region, the H_o hypothesis is rejected it can be concluded that there is a significant relationship between the independent and dependent variables of the model.

The *P*-value technique (*F*-test) is also used to evaluate individual regression coefficients, much like it is for

determining the significance of the regression. The *P*-value is defined as the smallest level of significance that would lead to rejection of the null hypothesis H_o. The hypothesis H_o is rejected if the *P*-value for t_{stat} is less than the level of significance (α). The details of the F-test of variables with their corresponding *P*-values are indicated in Appendix C (Supplementary materials).

Eventually, it was found that pavement age, traffic volume, MSN, and CDS were all significant factors in the cause of cracking, ravelling, and potholes, according to the overall study of the sensitivity of variables to the corresponding model (detailed calculations and graphs presented in Appendix C of supplementary materials). Shoulder width, as well as pavement age, MSN, and CDS, was identified to be significant factors in the Edge Break model, rather than traffic volume. Pavement Age, MSN, and CDS were found to be important parameters in the Rut Depth model. After sensitivity analysis, the parameters were chosen and exclusively utilized for the creation of the pavement deterioration model.

5.2 Testing of Assumptions and Box-Cox Transformation

Certain assumptions must be made when using a t-test or an ANOVA. In other words, a statistical test cannot be employed indiscriminately; it must meet a specified set of criteria to be considered acceptable and useful. These conditions are known as model assumptions. The model assumptions for *t*-test or ANOVA include independence, normality, and homogeneity of variances. Running a test without evaluating its assumptions might result in significant (but incorrect) findings [58]. If just the normalcy assumption failed, the data should be checked first for anomalous observations that are driving the non-normality. Normality can be achieved by deleting or replacing discovered cases in the data or through a transformation such as the Box-Cox transformation.

The Box-Cox transformation is used to alter the distributional shape of a set of data so that analyses and confidence limits that require normality may be applied correctly. This approach may not be able to effectively normalize data with outliers [58]. For the Box-Cox transformation, a λ value of 1 is equivalent to using the original data. Therefore, if the confidence interval for the optimal λ includes 1, then no transformation is necessary. Appendix C also presents the statistical details of the normality test of variables, their probability plots, and the Box-Cox transformation plots of all variables which were used further for the development of deterioration models.

Table 8 Model description with respective statistical parameters

Distress type	Region	Model	R^2	Adjusted R^2	RMSE
Cracking	Rural	$\text{Cracking}(\%) = 0.3502 + 9.183\left(\frac{\text{Age}}{\text{AADT}}\right) + 0.07325(\text{MSN} \times \text{CDS}) - 1.592\log\left(\frac{\text{Age}}{\text{AADT}\times\text{MSN}\times\text{CDS}}\right)$	0.97	0.978	0.4515
	Urban	$\text{Cracking}(\%) = 0.9401 - 1.576\left(\frac{\text{Age}}{\text{MSN}}\right) - 0.04328(\text{AADT} \times \text{CDS}) + 2.783\log\left(\frac{\text{Age}\times\text{AADT}\times\text{CDS}}{\text{MSN}}\right)$	0.88	0.87	0.77
Ravelling	Rural	$\text{Ravelling}(\%) = 1.36 + 15.06\left(\frac{\text{Age}}{\text{AADT}}\right) - 2.059(\text{MSN} \times \text{CDS}) - 2.597\log\left(\frac{\text{Age}}{\text{AADT}\times\text{MSN}\times\text{CDS}}\right)$	0.96	0.95	0.76
	Urban	$\text{Ravelling}(\%) = 17.55 - 2.656\left(\frac{\text{Age}}{\text{MSN}}\right) + 0.01298(\text{AADT} \times \text{CDS}) + 2.299\log\left(\frac{\text{Age}\times\text{AADT}\times\text{CDS}}{\text{MSN}}\right)$	0.8	0.78	0.71
Pothole	Rural	$\text{Number of Potholes/km} = 1.584 + 6.707\left(\frac{\text{Age}}{\text{AADT}}\right) - 1.349(\text{MSN} \times \text{CDS}) - 3.114\log\left(\frac{\text{Age}}{\text{AADT}\times\text{MSN}\times\text{CDS}}\right)$	0.92	0.92	0.61
	Urban	$\text{Number of Potholes/km} = -2.644 + 1.003\left(\frac{\text{Age}}{\text{MSN}}\right) + 0.02719(\text{AADT} \times \text{CDS}) + 0.8063\log\left(\frac{\text{Age}\times\text{AADT}\times\text{CDS}}{\text{MSN}}\right)$	0.87	0.86	0.45
Edge break	Rural	$\text{Edge break}(\text{m}^2/\text{km}) = -8.486 - 0.00753\left(\frac{\text{Age}}{\text{MSN}}\right) - 0.5081(\text{Shoulder width} \times \text{CDS}) + 2.887\log\left(\frac{\text{Age}}{\text{MSN}}\right)$	0.85	0.84	0.51
Rut depth	Urban	$\text{Rut depth}(\text{mm}) = 10.27 + 3.054\log\left(\frac{\text{Age}}{\text{MSN}}\right) + 0.5967e^{\text{CDS}}$	0.81	0.80	1.4

5.3 Model Development Using MATLAB

Pavement deterioration models may be developed using a variety of methods [59, 60]. Straight-line extrapolation, regression, mechanistic-empirical, polynomial restricted least square, S-shaped curve, probability distribution, and the Markovian technique are a few examples.

This study aims to create non-linear regression-based pavement deterioration models for a network of rural and urban roads in the study area's plain topography. Regression analysis is used to suggest deterioration models for each section, using pavement distresses as the 'dependent' variable and pavement age, traffic volume, CDS, MSN, and shoulder width as the 'independent' variables. The details of deterioration models (rural and urban) along with some statistical parameters such as R^2, Adjusted R^2, and RMSE values are presented in Table 8. The MATLAB codes for respective models along with their graphical output are provided in Appendix D.

Constraints of the Model These models will only apply to the Rajasthan State of India. It will only be applicable for bituminous (virgin and modified asphalt) pavements located

Table 9 Details of Validation pavement sections

| Section ID	Section name	Section description	Length (kms)	Type of section	Traffic
VS-R-1	SH-101	Shreenagar Road (Ajmer-Malpura)	9.7	Rural	Low
VS-R-2	NH-448	Nasirabad Road	10.8	Rural	Medium
VS-R-3	MDR 185	Kethun-Sangod Road	10.3	Rural	Low
VS-R-4	SH 51	Kota-Bapawar Road	7.3	Rural	Medium
VS-U-1	Kutcherry Road	Agrasen Circle-Nagaur Road	0.55	Urban	High
VS-U-2	C.R.P.F Road (repaired in 2022)	Jaipur road-Dipak Road	1.2	Urban	High
VS-U-3	Rawatbhata Road	CAD Circle- Ghode baba circle	1.5	Urban	High
VS-U-4	Rangbari Road	Dadabari road-CAD circle	0.9	Urban	High
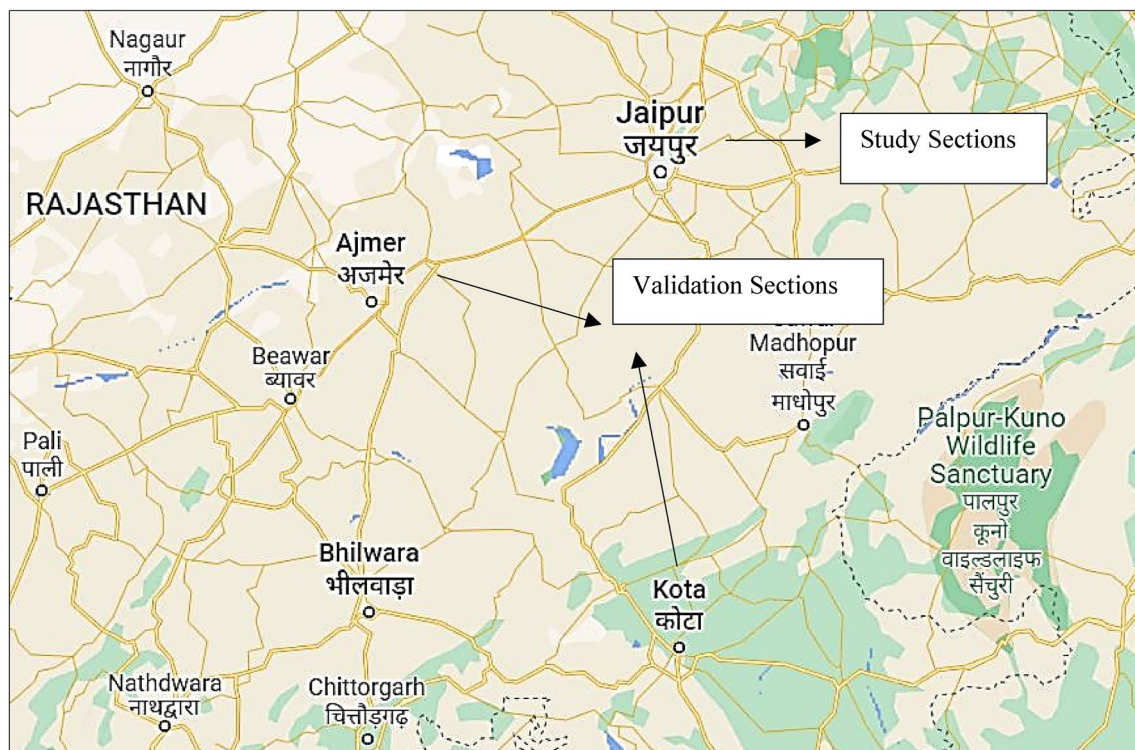
Fig. 3 Map showing the location of study and validation sections

in the plain terrain of the region. The ravelling phenomena on pavements were difficult to identify; thus the models presented should be utilized with discretion.

6 Validation of HDM-4 Calibration Factors and Regression-Based Models

Before using the calibrated HDM-4 pavement deterioration models and regression-based models, it is essential to validate them to ensure that the calibration and developed models are correct [61, 62]. On a selected urban and rural road network, the validity of these models was evaluated, and the competence of these models was assessed. The validity of the calibrated and regression-based pavement deterioration models is evaluated in this study by comparing observed vs. model-predicted distresses on 8 rural and urban road sections (different from model developments) in the study region. The details of selected 8 rural and urban road sections (2 rural and 2 urban sections in each of Ajmer and Kota) for model validation in various districts of the study region are given in Table 9, with locational data shown in Fig. 3. For simple identification in the road network, each of the selected pavement sections has been given a unique "Section ID" and a "Section Name" as shown in the table. "Validation Section (VS)-Type of section- Number issued to pavement section" is the series used to denote Section ID. The details regarding average annual daily traffic (motorized and non-motorized), subgrade CBR, pavement inventory and construction history details, etc. for rural and urban roads selected for validations are collected from field study as well as from the official records of the PWD divisions, in charge of the maintenance of these roads. Measurement of various pavement distresses like total cracking, raveling, pothole, edge break, and rut depth are carried out on each validation rural and urban road section in the years 2021 and 2022. HDM-4 analyses are carried out for each validation rural road section by using the suggested calibration factors as given in Table 7 (using Global Calibration Factors), to determine the predicted distresses corresponding to the suggested calibration factors.

6.1 Validation of Calibrated HDM-4 Models (cellwise)

For validation of calibration factors calculated for individual cells, the time series pavement condition data for all selected 20 test sections of the rural and urban areas of Rajasthan were collected consecutively for the years 2017–2021. The time series condition data collected in these 5 years for all the test sections, classified into five homogeneous cells,

Table 10 Validation of Calibrated HDM-4 models (cellwise)

Pavement Section	Cracking (%)			Ravelling (%)			Potholes (per km)			Edge break (m²/km)		
	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE
SS-R-3 (B-P)	12.2	12.33	0.226	15.33	15.25	0.160	9.3	9.32	0.158	7.94	7.84	0.061
SS-R-3 (P-B)	12.7	13		15	14.88		8.5	8.64		7.8	7.7	
SS-R-4 (B-P)	13.1	13.28		16	16		8.9	9.15		7.35	7.33	
SS-R-4 (P-B)	12.7	12.83		16.75	16.55		8.88	9.1		7.55	7.53	
SS-R-5 (B-P)	13	13.25		14.5	14.44		8.5	8.63		7.8	7.77	
SS-R-5 (P-B)	12.5	12.8		15.5	15.8		8.35	8.4		7.82	7.79	

were used for calibration of the deterioration models, and the data collected in the year 2022 were used for validating these models. For cellwise validation, the calibration factors reported in Table 6 were utilized to perform the HDM-4 project analysis and the deteriorations in the study sections were predicted for the year 2022. In the following sections, the validation details for the cracking, ravelling, potholes, and edge break model of a representative cell (Cell 2) are illustrated. Cell 2 consists of 6 pavement sections situated in the rural areas of the study region.

6.1.1 Validation of Cracking Model

The observed vs predicted values for Cell-2 (consisting of 6 sections) are given in Table 10. These values are plotted on a graph with respect to the Line of Equality as shown in Fig. 4 below.

The negative values of residuals obtained for most of the sections indicate the model's overprediction of cracking. As a result, the observed cracking percentage is lower than what calibrated HDM-4 models suggest. Only for pavement sections in Cell 5, do the positive residuals indicate the model's underprediction of cracking %. This might be due to the movement of overloaded multi-axle trucks on these urban pavement sections (even though regulations against overloading are in place). Because their frequency was very low, these vehicles were not taken into consideration when calculating traffic volume. So, the urban road sections were not originally designed for these heavy loads and get cracked at a faster rate than predicted by HDM-4 models.

For each cell, the root mean square error (RMSE) between observed and predicted values was found to be less than 0.5, which is quite reasonable and indicates that the model predictions lie close to actual observations. From Fig. 4, it can be observed that the plotted values are quite close to the Line of Equality, indicating a good agreement between

the predicted and observed values of the cracks. The slope value (1.04) as indicated in the figure too, being closer to 1, indicates that the predictions are reasonably accurate.

6.1.2 Validation of Ravelling model

The observed vs predicted values for Cell-2 are given in Table 10. These values are plotted on a graph with respect to the Line of Equality as shown in Fig. 4.

The positive values of residuals obtained for most of the sections indicate the model's underprediction of ravelling. As a result, the observed ravelling percentage is higher than what calibrated HDM-4 models suggest. Only for pavement sections in Cell 3, do the negative residuals indicate the model's overprediction of ravelling %.

For each cell, the root mean square error (RMSE) between observed and predicted values were found to be less than 0.5, which is quite reasonable and indicates that the model predictions lie close to actual observations. From Fig. 4, it can be observed that the plotted values are quite close to the Line of Equality, indicating a good agreement between the predicted and observed values of the ravelling. The slope value (0.96) as indicated in the figure too, being closer to 1, indicates that the predictions are reasonably accurate.

6.1.3 Validation of Pothole Model

The observed vs predicted values for Cell-2 are given in Table 10. These values are plotted on a graph with respect to the Line of Equality as shown in Fig. 4. The negative values of residuals obtained for almost all sections indicate the model's overprediction of potholes. As a result, the observed no. of potholes/km is lower than what calibrated HDM-4 models suggest.

For each cell, the root mean square error (RMSE) between observed and predicted values were found to be less than 0.5, which is quite reasonable and indicates that the model predictions lie close to actual observations. From Fig. 4, it can be observed that the plotted values are quite close to the Line of Equality, indicating a good agreement between the predicted and observed values of the potholes. The slope value (0.99) as indicated in the figure too, being closer to 1, indicates that the predictions are reasonably accurate.

6.1.4 Validation of Edge Break Model

The observed vs predicted values for Cell-2 are given in Table 10. These values are plotted on a graph with respect to the Line of Equality as shown in Fig. 4. The positive values of residuals obtained for all sections indicate the model's underprediction of edge break. As a result, the observed no.
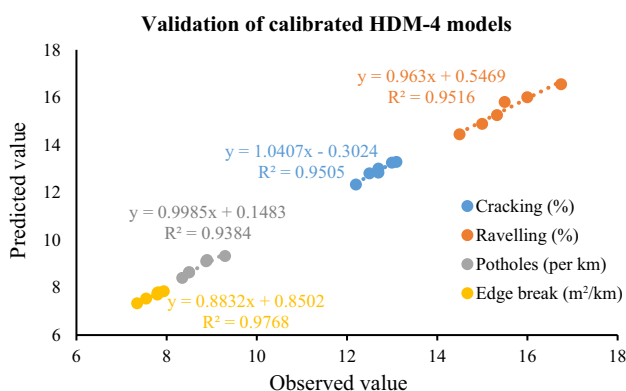

Fig. 4 Validation of Calibrated HDM-4 models (cellwise)

Table 11 Validation of Calibrated HDM-4 models using GCF-rural

Year	Pavement Section	Cracking (%)			Ravelling (%)			Potholes (per km)			Edge break (m²/km)		
		Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE
2021	VS-R-1	7.5	8.3	0.538	10	11.13	0.911	5.4	5.6	0.520	4.5	4.74	0.820
	VS-R-2	4.9	5.6		4.9	6.29		3	2.3		2	2.9	
	VS-R-3	9.3	9.15		12.25	12.13		6	6.82		8.35	8	
	VS-R-4	7.7	8.4		8.5	8.85		5.25	5		4	4.25	
2022	VS-R-1	8.3	8.75		13	14.1		5.8	5.75		4.95	5.78	
	VS-R-2	5.3	5.25		5.5	6.36		4.5	4.8		2.75	2.27	
	VS-R-3	10.7	10.29		13	11.88		8	8		11.25	13	
	VS-R-4	8.8	9.35		10	10.3		6.6	5.7		4.3	4.89	
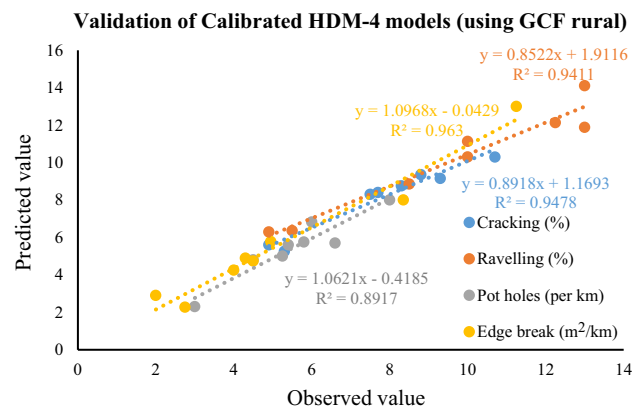
Fig. 5 Validation of Calibrated HDM-4 models (using GCF rural)

of edge break(m²/km) is higher than what calibrated HDM-4 models suggest.

For each cell, the root mean square error (RMSE) between observed and predicted values were found to be less than 0.5, which is quite reasonable and indicates that the model predictions lie close to actual observations. From Fig. 4, it can be observed that the plotted values are quite close to the Line of Equality, indicating a good agreement between the predicted and observed values of the potholes although the slope value of 0.8,8 as indicated in the figure too, indicates that the predictions are somewhat accurate.

6.2 Validation of Calibrated HDM-4 Models (using GCF rural)

For validation of HDM-4 global calibration factors (GCF) for rural regions, four different pavement sections (2 each in rural areas of Ajmer and Kota) were selected. HDM-4 project analysis was performed using the GCF, as indicated in Table 7 and the pavement deterioration on these sections in the years 2021 and 2022 was predicted.

In rural areas, the predicted values were found to be somewhat higher than the observed values for every deterioration model in HDM-4. The root mean square error (RMSE) between observed and predicted values for each distress was found to be larger than 0.5 (Range 0.52–0.91), indicating that model predictions are reasonably close to real data. The slope values on the scatter plots between observed and predicted values range from 0.85 to 1.09, showing that the predictions are relatively accurate.

The observed vs predicted values along with RMSE, for cracking, ravelling, potholes, and edge break on rural validation sections are shown in Table 11. Scatter plot details between observed vs predicted distress for validation of GCF (rural) are shown in Fig. 5.

Table 12 Validation of Calibrated HDM-4 models using GCF-urban

Year	Pavement Section	Cracking (%)			Ravelling (%)			Potholes (per km)		
		Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE
2021	VS-U-1	3.2	2.9	0.451	2.85	2.3	0.365	2.5	2.15	0.631
	VS-U-2	4	3.58		3.35	3.1		3.2	2.85	
	VS-U-3	3.75	4.36		3.3	3.05		2.3	2.72	
	VS-U-4	4.8	5.2		4.5	5		3.5	4.4	
2022	VS-U-1	3.6	3.3		3.5	4		3	4	
	VS-U-2	1.5	1.8		0.75	1.1		1	1.3	
	VS-U-3	4.2	3.47		3.75	3.83		3.25	3.5	
	VS-U-4	5.3	4.95		5	5.1		3.7	4.6	
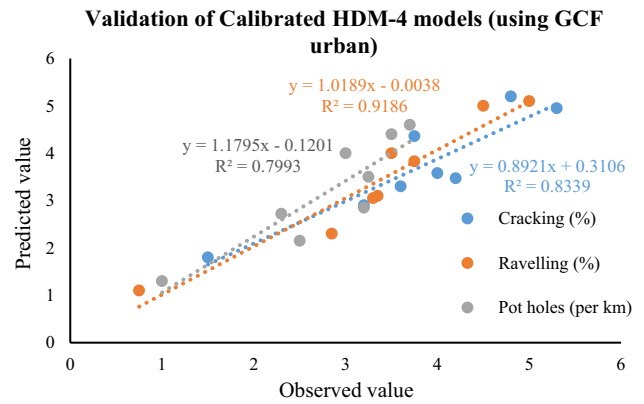
Fig. 6 Validation of Calibrated HDM-4 models (using GCF urban)

6.3 Validation of Calibrated HDM-4 Models (using GCF urban)

In urban areas, the predicted values were found to be somewhat lower than the observed values for the year 2021 but this trend reverses in the year 2022 for every deterioration model in HDM-4, which indicates that the rate of distress progression in HDM-4, calibrated using GCF (urban), is higher than the actual observations. The root mean square error (RMSE) between observed and predicted values of cracking, raveling, and potholes indicates that model predictions are reasonably close to real data. The slope values on the scatter plots between observed and predicted values range from 0.89 to 1.17, showing that the predictions are relatively accurate.

The observed vs predicted values along with RMSE, for cracking, ravelling, and potholes, on urban validation sections are shown in Table 12. Scatter plot details between observed vs predicted distress for validation of GCF (urban) are shown in Fig. 6.

6.4 Validation of Regression-Based Deterioration Models

For validation of regression-based pavement deterioration models, 8 different pavement Sects. (4 each in rural and urban areas of Ajmer and Kota) were selected. These pavement sections were located in distinct parts of the study region with their details as presented in Table 9. Using the non-linear pavement deterioration models suggested in Table 8, deterioration in these sections in the years 2021 and 2022 was predicted. The predicted values were then compared to the observed deterioration in these pavements, with the findings reported as follows.

Table 13 Validation of Regression based deterioration models-rural

Year	Pavement Section	Cracking (%)			Ravelling (%)			Potholes (per km)			Edge break (m²/km)		
		Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE
2021	VS-R-1	7.5	7.8	0.296	10	10.1	0.437	5.4	6	0.659	4.5	4	0.427
	VS-R-2	4.9	5.5		4.9	4.85		3	4		2	2.22	
	VS-R-3	9.3	9.75		12.25	13.1		6	6.7		8.35	8	
	VS-R-4	7.7	7.65		8.5	8.73		5.25	5.7		4	3	
2022	VS-R-1	8.3	8.27		13	13.2		5.8	6.25		4.95	5	
	VS-R-2	5.3	5.2		5.5	5.65		4.5	4.75		2.75	2.73	
	VS-R-3	10.7	10.51		13	13.8		8	9		11.25	11.11	
	VS-R-4	8.8	8.75		10	10.2		6.6	7		4.3	4.43	

Fig. 7 Validation of Regression based deterioration models-rural

6.4.1 Validation of Regression-Based Deterioration Models (rural)

The root mean square error (RMSE) between observed and predicted values, as indicated in Table 13, was found to be in the range of 0.29–0.65 which is quite reasonable and indicates that the model predictions lie close to actual observations. From Fig. 7, it can be observed that the plotted values are quite close to the Line of Equality (LoE), indicating a reasonable agreement between the predicted and observed values of the distress in rural sections. The slope value ranging from 0.94 to 1.07, as indicated in the graphs too, being closer to 1, indicates that the predictions are quite accurate.

6.4.2 Validation of Regression-Based Deterioration Models (urban)

The root mean square error (RMSE) between observed and predicted values, as indicated in Table 14, was found to be in the range of 0.14–0.30 which is quite reasonable and indicates that the model predictions lie close to actual observations. From Fig. 8, it can be observed that the plotted values are quite close to the Line of Equality (LoE), indicating a reasonable agreement between the predicted and observed values of the distress in urban sections. The slope value ranging from 0.83 to 1.01, as indicated in the graphs too, being closer to 1, indicates that the predictions are quite accurate, except for the pothole model (0.83). It can also be deduced from the statistical analysis that the predictions in the urban scenario have a better correlation with observed values than those in the rural regions.

Table 14 Validation of Regression based deterioration models-urban

Year	Pavement Section	Cracking (%)			Ravelling (%)			Potholes (per km)			Rut depth (mm)		
		Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE	Observed value	Predicted value	RMSE
2021	VS-U-1	3.2	2.88	0.169	2.85	2.6	0.142	2.5	2.25	0.186	4.85	4.28	0.306
	VS-U-2	4	3.88		3.35	3.22		3.2	3		3.3	3.28	
	VS-U-3	3.75	3.7		3.3	3.2		2.3	2.22		2	2	
	VS-U-4	4.8	4.75		4.5	4.5		3.5	3.27		3.8	3.5	
2022	VS-U-1	3.6	3.77		3.5	3.5		3	3.13		5	4.75	
	VS-U-2	1.5	1.63		0.75	1		1	1.25		0.5	1	
	VS-U-3	4.2	4.35		3.75	3.77		3.25	3.43		2.15	2	
	VS-U-4	5.3	5.5		5	5.1		3.7	3.77		3.95	4	
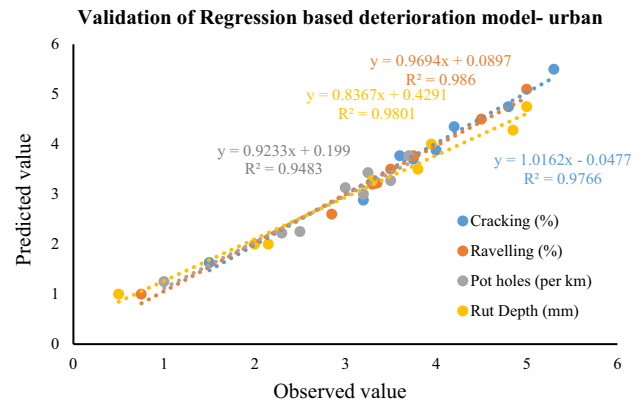
Fig. 8 Validation of Regression based deterioration models-urban

With negligible bias and prediction errors well within the statistical limits, regression-based pavement deterioration models are thus well validated on these observed vs predicted data.

7 Conclusions

The major conclusions of the current study can be summarized as follows:

- The Level 2 calibration factors for deterioration models in HDM-4 for every road network were calculated and the values are presented in Table 6 (cellwise) and Table 7 (GCF). These calibration factors can be used for future estimation of deterioration and other analyses to be conducted through HDM-4. These models can also be used to forecast road conditions for bituminous road surfacing and to plan maintenance strategies in the future.

- According to the global calibration factors (GCF) obtained, the variability between observed distress and calibrated HDM-4 values was found to be greater for rural pavement sections than for urban pavement sections, even though they follow the same pattern for distress initiation/progression.

- The results obtained from sensitivity analysis of pavement deteriorations indicate that the variables/parameters that have the greatest influence on pavement performance are Pavement age, MSN, Shoulder Width, CDS, and Traffic Volume, in decreasing order of impact elasticity and Spearmans' correlation rank. It's worth noting that the traffic volume variable in the study belongs to the sensitivity class "negligible," which means it's unlikely to have much of an impact on edge break and rutting progressions. Instead of traffic volume, the variable "shoulder width" is then introduced to the edge break model. Based on the result of the sensitivity analysis of distresses, the

parameters to be used further in the pavement deterioration modelling were identified.

- Based on the time-series data for 5 years, pavement deterioration models of most observed distress on these sections such as Cracking, Ravelling, Potholes, Rut depth, and Edge break were developed using MATLAB, and the model description is presented in Table 8 with MATLAB codes in Appendix D. A few specific observations related to pavement deterioration modelling are as follows:

  - The adjusted goodness of fit (R^2 value) is above 0.75 for all the distress models developed, which indicates a good relationship between the independent and dependent variables adopted for the model development.
  - It was also observed that the percentage of distress on pavement sections having low CDS and MSN values was higher as compared to the contrary.

- During the validation of calibrated HDM-4 distress models, the percentage variability found between observed and anticipated distresses was often relatively low. When compared to the global calibration factors (GCF), cellwise calibration of HDM-4 deterioration models yielded better predictions.
- Furthermore, statistical inferences related to non-linear pavement deterioration model validation produced the greatest results in terms of output proximity to observed deterioration on validation sections (other than model development). As a result, the locally developed non-linear regression-based pavement deterioration models should be used to estimate the future deterioration of any pavement section in the study region.

Declarations

Conflict of Interest The authors disclose no conflict of interest.

Ethical Approval and Consent to Participate Not applicable.

Consent for Publication The author hereby gives his consent to publish his research article titled "Pavement Deterioration Modelling for Urban and Rural Roads using HDM-4" in the International Journal of Pavement Research and Technology. The author guarantees that the contribution to the work has not been previously published elsewhere and the person named as co-author of the contribution is aware of the fact and has agreed to be so named.

References

1. Basic Road Statistics of India. (2016-2017). *Ministry of Road Transport and Highway Transport Research Wing, Government of India, New Delhi.*
2. Basic Road Statistics of Public Works Department. (2016). *Ministry of Road Transport and Highway Transport Research Wing, Government of India, New Delhi.*
3. Tare, V., Meshram, K., & Srivastava, S. (2014). Optimization of transfer time and initial waiting time for a bus network using genetic algorithm. *A Review of Road and Road Transport Development, 48.*
4. Notes on Demands for Grants (2020-21). No. 84. *Ministry of Road Transport and Highways, Government of India, New Delhi.*
5. Working Group Report on Rural Roads in the 11th Five Year Plan November 2006. *Planning Commission, Ministry of Rural Development, Government of India.*
6. Rural Roads Manual, Indian Roads Congress Special Publication 20:2002. *Indian Roads Congress, Government of India, New Delhi.*
7. Gary Hicks, R., Seeds, S., & Peshkin, D. G. (2000). Selecting a preventive maintenance treatment for flexible pavements. Report No. FHWA-IF-00–027, *U.S. Department of Transportation, Federal Highway Administration.*
8. Thube, D., & Thube, A. (2013). Software development for calibration of highway development and management tool (HDM-4) for local conditions. *International Journal of Structural and Civil Engineering Research, 2*(1), 95–104.
9. Jain, S. S., Aggarwal, S., & Parida, M. (2005). HDM-4 pavement deterioration models for Indian national highway network. *Journal of Transportation Engineering, 131*(8), 623–631. https://doi.org/10.1061/(ASCE)0733-947X(2005)131:8(623)
10. Project Report of Consultancy Services to National Highway Authority of India (NHAI). (2019). No.H-39011/30/2015- *Ministry of Road Transport & Highways (EAP Section), Government of India, New Delhi.*
11. Analytical Framework & Model Descriptions. (2000). Volume 4, Part A, HDMGlobal, Transportation Research Board, USA
12. Deori, S. (2018). Deterioration modelling of flexible pavements with modified bitumen in wearing course (Doctoral dissertation).
13. Thube, D. T. (2006). Performance based maintenance management for rural roads. Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee (Doctoral dissertation).
14. Dhaliwal, M. M., & Tiponis, B. S. (2004). A Perspective on PMS studies suited for the fast-developing indian highway network. Indian Highways. *32*(6).
15. Damde, A. K. (2018). Calibration of HDM-IV for Urban Road Network (M.Tech dissertation).
16. Prasad, C., Swamy, A. K., & Tiwari, G. (2013). Calibration of HDM-4 emission models for Indian conditions. *Procedia-Social and Behavioral Sciences, 104*, 274–281. https://doi.org/10.1016/j.sbspro.2013.11.120
17. Martin, T. (2004). Data review and calibration of HDM-4 road deterioration models (No. ARR 360).
18. Chai, G., Akli, O., Asmaniza, A., Singh, M., & Chong, C. L. (2004). Calibration of HDM model for the north south expressway in Malaysia. In: *Proceedings of the 6th International Conference on Managing Pavements, Brisbane, QLD, Australia (*pp. 19–24).
19. Bennett, C. R., & Paterson, W. D. (2000). *A guide to calibration and adaptation. HDM-4.* Vol. *5.* The Highway Development and Management Series.
20. Bagui, S. K., & Ghosh, A. (2015). Level 1 calibration of HDM-4 analysis with a case study. *Malaysian Journal of Civil Engineering, 27*(1), 121–143.

21. Rohde, G. T., Jooste, F., Sadzik, E., & Henning, T. (1998). The calibration and use of HDM-IV performance models in a Pavement Management System. In: *Fourth International Conference on Managing Pavements. Durban, South Africa.*

22. Thube, D. T. (2013). Highway Development and Management Model (HDM-4): Calibration and adoption for low-volume roads in local conditions. *International Journal of Pavement Engineering, 14*(1), 50–59. https://doi.org/10.1080/10298436.2011.606320

23. Li, J., Muench, S. T., Mahoney, J. P., Sivaneswaran, N., Pierce, L. M., & White, G. C. (2005). The highway development and management system in Washington state: Calibration and application for the department of transportation road network. *Transportation Research Record, 1933*(1), 52–61. https://doi.org/10.1177/0361198105193300107

24. Zaabar, I., & Chatti, K. (2010). Calibration of HDM-4 models for estimating the effect of pavement roughness on fuel consumption for US conditions. *Transportation Research Record, 2155*(1), 105–116. https://doi.org/10.3141/2155-12

25. Deori, S., Choudhary, R., Tiwari, D., & Gangopadhyay, S. (2018). Calibration of HDM-4 models for Indian conditions of flexible pavement having modified bitumen in wearing course. *International Journal of Pavement Engineering, 19*(9), 772–785. https://doi.org/10.1080/10298436.2016.1208196

26. Bannour, A., Elomari, M., El Khadir, L., Des, M. D. D. L. D., Afechkar, R., Lamrini, B. B., & Hdm, P. C. E. (2015). Calibration study of HDM-4 Model of structural cracking models for flexible pavements in Moroccan Context. In: *1er Congrès International sur les Ingénieries Civile, Mécanique et Electrique pour l'Energie CMEEE 2015-Marrakech.*

27. Mathew, B. S., Rose, S., Isaac, K. P., & Chandrasekhar, B. P. (2010). Pavement performance modelling and calibration of HDM-4 deterioration models for rural roads in India. *Journal of the Institute of Engineering, 91*(8), 1–10.

28. Chakrabarti, S., Rawat, M. S., & Mondal, B. (1995). Highway design and maintenance standards model (HDM): Calibration and adaptation to Indian conditions. *Journal of the Indian Roads Congress. 56*, 75–101.

29. Chandran, S., Isaac, K. P., & Veeraragavan, A. (2007). Prioritization of low-volume pavement sections for maintenance by using fuzzy logic. *Transportation Research Record, 1989*(1), 53–60. https://doi.org/10.3141/1989-06

30. Alsugair, A. M., & Al-Qudrah, A. A. (1998). Artificial neural network approach for pavement maintenance. *Journal of Computing in Civil Engineering, 12*(4), 249–255.

31. Abdelrahim, A. M., & George, K. P. (2000). *Artificial neural network for enhancing pavement maintenance strategy selection.* Transportation Research Board.

32. Raja Shekharan, A. (2000). Solution of pavement deterioration equations by genetic algorithms. *Transportation Research Record, 1699*(1), 101–106.

33. Mathew, B. S., Reshmy, D. S., & Isaac, K. P. (2008). Performance modeling of rural road pavements using artificial neural network. *Indian Highways, 36*(1), 31–39.

34. Aggarwal, S., Jain, S. S., & Parida, M. (2004). Development of pavement management system for Indian national highway network. *Journal of Indian Road Congress, 65*(2), 271–326.

35. Sood, V. K., Sharma, B. M., Kanchan, P. K., & Sitaramanjaneyulu, K. (1994). Pavement deterioration modeling in India. In: *Proceedings of the Third International Conference on Managing Pavements* (pp. 47–54).

36. Balabhaskara Reddy, B., Sivath Kumar, N., & Veeraragavan, A. (2002). Performance based cost allocation of flexible pavement maintenance and strengthening strategies. *Indian Roads Congress Journal, 63*, 3–12.

37. Jain, S. S., & Gupta, A. K. (1994). Development of pavement management system for Indian highway network. *Final Report of the R&D Project, Submitted to AICTE, New Delhi by COTE, Department of Civil Engineering, UOR, Roorkee.*

38. Kumar, P. K., & Patel, V. (2009). Effect of various parameters on performance of PMGSY Roads. *Journal of the Institution of Engineers (India): Civil Engineering Division, 90*, 3–8.

39. Rastogi, R., Kumar, P., & Gupta, A. (2011). Flexible pavement performance model for low volume roads. In *Eighth International Conference on Managing Pavement Assets Fugro Federal Highway Administration Intervial Chile CAF-Banco de Desarrollo de America Latina* (No. ICMPA217).

40. Sandra, A. K., & Sarkar, A. K. (2013). Development of a model for estimating International Roughness Index from pavement distresses. *International Journal of Pavement Engineering, 14*(8), 715–724. https://doi.org/10.1080/10298436.2012.703322

41. Hodges, J. W., Rolt, J., & Jones, T. E. (1975). The Kenya road transport cost study: Research on Road Deterioration, TRRL laboratory report 673. *Crowthorne, Inglaterra Transport Research Laboratory. Cap 1*(2), 3.

42. Paterson, W. D. (1987). *Road deterioration and maintenance effects: Models for planning and management. Highway design and maintenance standards series, PIARC*

43. Luhr, D. R., & McCullough, B. F. (1983). *Economic evaluation of pavement design alternatives for low-volume roads* (No. N908).

44. Research on the Interrelationships Between Costs of Highway, Construction, Maintenance and Utilization, Final Report—1981, *Ministerio Dos Transportes, Empresa Brasileira de Planejamento de Transportes – GEIPOT, Brazil.*

45. Giummarra, G. J., Martin, T., Hoque, Z., & Roper, R. (2007). Establishing deterioration models for local roads in Australia. *Transportation research record, 1989*(1), 270–276.

46. Prozzi, J. A., & Madanat, S. M. (2004). Development of pavement performance models by combining experimental and field data. *Journal of Infrastructure Systems, 10*(1), 9–22.

47. Hossain, Z., Zaman, M., O'Rear, E. A., & Chen, D. H. (2011). Effectiveness of advera in warm mix asphalt. In: *Emerging Technologies for Material, Design, Rehabilitation, and Inspection of Roadway Pavements,* pp. 9–16.

48. Sun, L., & Gu, W. (2011). Pavement condition assessment using fuzzy logic theory and analytic hierarchy process. *Journal of Transportation Engineering, 137*(9), 648–655. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000239

49. Hassan, R., Lin, O., & Thananjeyan, A. (2017). A comparison between three approaches for modelling deterioration of five pavement surfaces. *International Journal of Pavement Engineering, 18*(1), 26–35. https://doi.org/10.1080/10298436.2015.1030744

50. Liautaud, G., Archondo-Callao, R., & Faiz, A. (1995). Defining Optimum Policies for Maintenance of State Highway Networks in Brazil. In: *Sixth International Conference on Low-Volume Roads, Minneapolis, Minnesota, June 25–29, 1995* (Vol. 6, p. 225). National Academy Press.

51. Chopra, T., Parida, M., Kwatra, N., & Chopra, P. (2018), "Development of Pavement Distress Deterioration Prediction Models for Urban Road Network Using Genetic Programming", *Advances in Civil Engineering*, Vol. *2018*, 1–15. https://doi.org/10.1155/2018/1253108

52. IS 2720-Part VIII. (2020). *Determination of water content-dry density relation using light compaction.* Bureau of Indian Standards.

53. IS 2720-Part VII. (1982). *Methods of test for soils, determination of water content dry density relation using light compaction.* Bureau of Indian Standards.

54. IS 2720 (Part 16). (1987). *Laboratory determination of CBR*. Berlin: Bureau of Indian Standards.
55. ASTM D6927-15. *Standard test method for marshall stability and flow of asphalt mixtures*. https://doi.org/10.1520/D6927-15
56. Transportation Officials. (1993). *AASHTO guide for design of pavement structures, 1993 (Vol. 1)*. Aashto.
57. Rose, A, S., Mathew, B, B. S., & Isaac, C, K. P. (2007). Development of deterioration models for rural roads. *18th National Conference n Technological Trends*, NCTT 2007, College of Engineering, Trivandrum.
58. Sakia, R. M. (1992). The Box-Cox transformation technique: A review. *Journal of the Royal Statistical Society: Series D (The Statistician), 41*(2), 169–178.
59. Lytton, R. L. (1987). Concepts of pavement performance prediction and modelling. In: *North American Conference on Managing Pavements, 2nd, 1987, Toronto, Ontario, Canada* (Vol. 2).
60. Shahin, M. Y. (2005). *Pavement management for airports, roads, and parking lots* (Vol. 501). New York: Springer.
61. Khan, M. U., & Higgins, P. J. (2015). A comprehensive analysis for obtaining consistent hdm-4 results: Case study with a local council in Australia. *International Journal of Pavement Research and Technology, 8*(2), 1–123. https://doi.org/10.6135/ijprt.org.tw/2015.8(2).123
62. Rejani, V. U., Janani, L., Venkateswaralu, K., Sunitha, V., & Mathew, S. (2022). Strategic pavement maintenance and rehabilitation analysis of urban road network using HDM-4. *International Journal of Pavement Research and Technology*. https://doi.org/10.1007/s42947-022-00171-0

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