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HDM-4 DETERIORATION MODELLING: VALIDATION AND ADOPTION FOR FLEXIBLE PAVEMENTS WITH MODIFIED BITUMINOUS ROAD SURFACING

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Abstract. Highway Development and Management (HDM-4) is an internationally recognised tool to analyse pavement management and investment alternatives. The HDM-4 pavement deterioration models help to predict the initiation and progression of various pavement distresses under the different combinations of traffic, climate, pavement structure, and composition. Since the rate of initiation and propagation of each pavement distress is strongly dependent on local conditions, it is essential to calibrate and validate the HDM-4 models for local conditions before their use. Validation of the calibrated HDM-4 pavement deterioration models is needed to check the adequacy of the calibration factors before the model is put to use for future applications. Time series data collected

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consecutively for three years of 23 high-speed corridors sections constructed with modified binders in India was used to calibrate the HDM-4 distress models. The main aim of this paper is to discuss the validation aspects of the calibrated HDM-4 models, to compare the distresses predicted to those observed on test sections. In this study, a novel technique termed the "*proximity to the line of equality*" approach is used to validate the HDM-4 models. In addition, Student's *t*-test is also used as a conventional validation technique. The advantage of the "*proximity to the line of equality*" approach is that it removes subjectivity associated with judging the nearness of best-fit straight line of predicted-observed data to the line of equality. Validation results show that distresses predicted by HDM-4 are statistically similar to those observed on the sections. Therefore, the calibrated HDM-4 models can be adopted for planning future maintenance strategies for flexible pavement sections with modified asphalt binder road surfacing.

Keywords: deterioration modelling, HDM-4, modified binders, National Highway Development Program (NHDP), Student's t-test, validation.

Introduction

Transportation infrastructure plays a key role to accomplish the social, economic and defence needs of a country. The road transportation sector occupies a commanding position among all transportation modes due to its easy availability, door-to-door service, the flexibility of operation, and reliability. The Government of India embarked on an ambitious National Highway Development Program (NHDP) in the year 1998 that encompassed the development of the most significant number of highway projects to boost the road infrastructure development of the country. The program involved the development of Golden Quadrilateral (GQ), i.e. national highways and expressways connecting four metropolitan cities of Delhi, Mumbai, Chennai and Kolkata (total length – 5846 km) and the development of North-South and East-West corridors (NS-EW) (total length – 7142 km). The NHDP roads are considered as high-speed road corridors in India.

Meanwhile, with heavier axle loads and rapidly increasing traffic volume, the traditional flexible pavements with virgin asphalt binders in wearing course have been losing their efficiency (Luo & Chen, 2011; Polacco, Filippi, Merusi, & Stastna, 2015; Yildirim 2007). Modifiers such as polymers are typically added to bitumen to improve their performance towards extreme fluctuations in pavement temperatures and to resist heavy axle loads. Modified binders increasingly are being used in the Asphalt Concrete (AC) wearing courses in India for construction of pavements or overlays, mainly on national highways and expressways. Polymer modified bitumen (PMB) and crumb rubber modified bitumen (CRMB) are two modified binder types most commonly used in India.

Deterioration of pavements occurs due to the combined influence of traffic and environment, and the knowledge of these factors is needed to predict for future performance. The deterioration usually results in decreased functional aspects and is important for highway administrators in planning maintenance strategies. Because the high-speed road corridors are vital assets for socio-economic development of the country, adoption of a scientific approach for their maintenance is imperative. Highway Development and Management (HDM-4) is one of the most useful and internationally recognised tools available for pavement performance and management. It is developed under the aegis of the World Bank, and its use has been advocated by the government agencies in many developing countries, including India (Jain, Aggarwal, & Parida, 2005; Thube 2013). HDM-4 system also helps the highway agencies to allocate realistic funds and set priorities to maximise the effectiveness of expenses on pavement maintenance. The structured mechanistic-empirical pavement distress models built in HDM-4 model the interaction among vehicles, environment, and pavement structure. The deterioration of pavement, manifested by various kinds of distresses, is predicted over time and traffic through different HDM-4 distress models. The HDM-4 deterioration models need to be calibrated and validated before being adapted for local conditions.

Braga, Puodžiukas, Čygas, & Laurinavičius (2003) presented initial application and calibration of pavement cracking models based on HDM from the data gathered for four years on 35 road sections in Lithuania. The road sections considered were newly constructed sections and sections rehabilitated 1–2 years before the commencement of the study. Seasonal structural condition analysis of the road sections was performed using Falling Weight Deflectometer (FWD). The analysis led to the development of a methodology for calculation of HDM structural condition parameters such as structural number and modulus. Čutura, Mladenović, Mazić, & Lovrić (2016) presented the application of HDM-4 to define road works program and investment priorities by analysing impacts of different budgets on future network condition for the local road network in Bosnia and Herzegovina. The road network was divided into 65 sections, and HDM-4 analysis was performed for the 30 years. The analysis showed that out of 65 sections, 29 sections proved cost-effective for maintenance alternatives. The study reported by Bannour, El Omari, Lakhal, Afechkar, Benamar, & Joubert (2019) evaluated the HDM-4 calibration factors for predicting the pavement distresses on Morocco roads. The study involved collection of pavement data of 55 road sections for six years (from 1996 to 2001). Calibration factors for initiation and progression of distresses (cracking, ravelling, potholes and roughness) were finally determined. Between observed and predicted distresses, a good agreement was reported with some overestimations for roughness results. Several other studies have been reported in other countries on calibration, validation and adaptation of HDM-4 pavement deterioration models toward the development of optimal maintenance management strategies for road network (Jiao & Bienvenu, 2015; Ognjenovic, Krakutovski, & Vatin, 2015; Yogesh, Jain, & Devesh, 2016). In India, Thube (2013) attempted calibration and validation of HDM-4 pavement deterioration models for paved low-volume roads (LVRs) from experimental data collected for four years on 61 LVR sections. The distresses included in the study were cracking, ravelling, edge breaks, rutting, potholes and roughness. Calibration factors were obtained considering the terrain type (plain, rolling and mountainous). Validation was done by comparing the observed, and HDM-4 predicted distresses for an additional ten sections and reporting the coefficient of determination (R^2). Jain, Aggarwal, & Parida (2005) conducted calibration and validation of HDM-4 pavement deterioration models for cracking, ravelling, potholes, and roughness, for a National Highway (NH) network in India. Validity of the developed models was evaluated by comparing distress predictions made by the calibrated models with those actually observed on the sections. A good agreement between predicted and observed distress values was observed in terms of R^2.

1. Research need and objectives

At present, there is a strong need for well-calibrated and validated HDM-4 pavement deterioration models for the high-speed road corridors of India constructed with modified binders in the wearing courses. The models are crucial for the development of pavement maintenance and management strategies for road corridors. A study was performed for deterioration modelling of flexible pavement sections with modified binders in the AC wearing course using HDM-4 tool (Deori, Choudhary, Tiwari, & Gangopadhyay, 2016). Twenty-three in-service flexible pavement road sections were selected from the NHDP corridors in India. These sections were spread throughout the country and covered different climatic and environmental zones. Extensive field and laboratory studies were carried out to gather time series data consecutively for three years for all the 23 sections. Finally, the inbuilt deterioration models of HDM-4 were calibrated through time series data collected, which included pavement distress data, traffic and axle load data, pavement crust-composition data, pavement material characterisation data, temperature and rainfall data, and construction and maintenance history data (Deori, Choudhary, Tiwari,

& Gangopadhyay, 2016). The present research discusses in detail the validation and adaptation of the different calibrated HDM-4 models using a novel technique termed as "*proximity to the line of equality*" concept. In addition, Student's *t*-test is also used as a conventional validation technique.

2. Methodology and data collection

2.1. Details of pavement sections

Twenty-three (23) pavement sections were selected on different locations of the NHDP high-speed road corridor. The selected pavement sections varied from each other in terms of traffic volume, pavement geometry, and climatic conditions (rainfall and temperature). The pavement sections had different soil type, terrain type (plain and rolling), climatic conditions, and traffic volume, as presented in Table 1. All selected pavement sections were designated a Section ID: for Expressways as NE, or National Highways as NH with section name and description. The Section Name in Table 1 shows the length of each section in km and Section Description provides information about the selected road sections.

Table 1. Details of selected pavement sections (Deori, Choudhary, Tiwari, & Gangopadhyay, 2016)

Section ID	Section Name	Section Description	Terrain	Rainfall	Temperature	Traffic
NE-1GJ01	NE-1GJ 14.00–15.00 km	Ahmadabad–Vadodara	Plain	Low	High	Medium
NE-1GJ02	NE-1GJ 32.00–31.00 km	Vadodara–Ahmadabad	Plain	Low	High	Medium
NE-1GJ03	NE-1GJ 19.00 –20.00 km	Ahmadabad–Vadodara	Plain	Low	High	Medium
NE-1GJ04	NE-1GJ 15.00–14.00 km	Vadodara–Ahmadabad	Plain	Low	High	Medium
NH-14GJ05	NH-14GJ 380.60 –379.60 km	Radhanpur–Deesa	Plain	Low	High	Low
NH-2UP01	NH-2UP 607.00–606.00 km	Allahabad–Khaga	Plain	Medium	High	Medium
NH-2UP02	NH-2UP 717.00–718.00 km	Allahabad–Varanasi	Plain	Medium	High	Medium

Section ID	Section Name	Section Description	Terrain	Rainfall	Temperature	Traffic
NH-37AS01	NH-37AS 177.30–178.30 km	Nagaon–Guwahati	Plain	High	Low	Low
NH-4KA01	NH-4KA 46.00–45.00 km	Tumkur–Bangalore	Plain	Medium	Medium	High
NH-4KA02	NH-4KA 481.30–482.30 km	Dharwad–Belgaon	Plain	Medium	Medium	High
NH-4KA03	NH-4KA 82.00–83.00 km	Tumkur–Sira	Plain	Medium	Medium	High
NH-4MH01	NH-4MH 539.00–538.00 km	Mahrstra. Border–Belgaon	Rolling	Medium	Medium	High
NH-5AP01	NH-5AP 691.25–690.75 km	Vizag–Srikakuram	Rolling	Medium	Medium	High
NH-5AP02	NH-5AP 698.60–698.10 km	Vizag–Srikakuram	Rolling	Medium	Medium	High
NH-5AP03	NH-5AP 7.50–7.00 km	NH-5–Vizag Port	Plain	Medium	Medium	Low
NH-5AP04	NH-5AP 9.80–9.30 km	NH-5–Vizag Port	Plain	Medium	Medium	Low
NH-7MH02	NH-7MH 84.20–84.70 km	Hyderabad–Nagpur	Plain	Low	High	High
NH-7MH03	NH-7MH 95.50–96.00 km	Hyderabad–Nagpur	Plain	Low	High	Medium
NH-7AP05	NH-7AP 41.00–40.00 km	Nagpur–Hyderabad	Plain	Low	High	High
NH-7AP06	NH-7AP 51.40–50.40 km	Nagpur–Hyderabad	Rolling	Low	High	High
NH-7KA04	NH-7KA 518.00–519.00 km	Bagepalli–Bangalore	Plain	Medium	Medium	High
NH-8GJ06	NH-8GJ 433.70–434.70 km	Palampur–Himmat Nagar Nagar	Plain	Low	High	High
NH-8GJ07	NH-8GJ 441.40–442.40 km	Palampur–Himmat Nagar	Plain	Low	High	High

Note: NE – National Expressway; NH – National Highway; GJ – Gujarat; UP– Uttar Pradesh; AS – Assam; KA – Karnataka; MH – Maharashtra; AP – Andhra Pradesh; Terrain as per cross slope – Plain (below 10%), Rolling (10–25%), Hilly (above 25%); Rainfall as per average annual precipitation – Low (below 800 mm), Medium (800–1200 mm), High (above 1200 mm); Temperature as per maximum temperature – Low (below 35 °C), Medium (35–45 °C), High (above 45 °C); Traffic as per AADT – Low (below 5000 vpd), Medium (5000–10000 vpd), High (above 10000 vpd).

2.2. Outline of HDM-4 deterioration modelling methodology

The following steps present the methodology used for pavement deterioration modelling:

1) Identification and selection of in-service flexible pavement sections on the high-speed road corridor network with modified binders in wearing course.
2) Preparation of an inventory of all pavement sections that includes information about the aspects not likely to change shortly. This inventory includes the type of soil subgrade, section length, carriageway width, shoulder width, drainage condition, temperature, and rainfall characteristics.
3) Collection of pavement distress data for cracking, ravelling, rut depth, roughness, and texture depth. These data were collected on a time series basis consecutively for three years on each pavement section.
4) Collection of data related to characteristics of the vehicle fleet, including traffic volume and axle load data to determine the traffic characteristics of all pavement sections.
5) Information about maintenance and rehabilitation works previously undertaken by the highway agency on selected pavement sections. Data collected in Steps 2–5 were used as input in an HDM-4 software tool for performing the pavement deterioration modelling.
6) Calibration of the pavement deterioration models of HDM-4 for local conditions.
7) Validation of the calibrated HDM-4 pavement deterioration models through comparison of predicted and observed distresses for which the data are collected in the next time series. The validation of the calibrated distress models, which is the aim of this study, was attempted and presented through different statistical techniques. In this study, two approaches/techniques have been used for validation and adaptation of the HDM-4 models.

2.3. Distress measurements

The pavement surface condition was surveyed through visual observations as well as with the help of network survey vehicle (NSV), to evaluate the type and extent of different distresses. The information on shoulder type, width, and condition, and drainage was also recorded.

Measurement of cracking. The pavement sections were divided into a number of representative test sections, and the cracked area was marked in the form of rectangles for an interconnected map and alligator cracks. The cracked area was expressed as a percentage of total pavement area. Measurements were taken separately for cracks of width up to 3 mm (narrow cracks) and width higher than 3 mm (wide cracks). Figure 1 shows the surface condition is evaluated on the road section NE-1GJ02 at 32.00 km.

Measurement of ravelled area. Ravelling is the progressive loss of surface material due to weathering and traffic abrasion. It is a commonly observed distress mainly in poorly constructed, thin asphaltic layers, such as surface treatments. The ravelled area was measured by considering the area enclosed in regular geometric shapes such as rectangles and then expressed as a percentage of total pavement area. Figure 2 shows a view of ravelling on the pavement section NH-8GJ06 at 434.00 km.

Measurement of rut depth. Rut depth was measured using the NSV across full lane width (typically 3.5 m) as per *AASHTO PP38 Standard Practice for Determining Maximum Rut Depth in Asphalt Pavements*. The NSV is a multi-component automated road survey system for road asset inventory. This system consists of a laser beam assembly mounted on the front and rear of the vehicle, an accelerometer and a gyroscope, digital cameras for image capture, a Global Positioning System (GPS) device, Distance Measuring Instrument (DMI), and a computer-based data acquisition system. Figure 3 shows the NSV with different components.

Measurement of roughness. Roughness was also measured using the NSV up to a width of 3.5 m of the pavement surface as per *ASTM E950/ E950M Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces* with an Accelerometer-Established Inertial Profiling Reference. The accuracy of longitudinal profile measurement was ± 0.5 mm, and the wavelength was 100 mm to 100 m. The measured roughness was expressed in terms of International Roughness Index (IRI) in the units of m/km.

Figure 1. Surface condition evaluation on pavement section NE-1GJ02 at 32.00 km

Figure 2. Ravelling on pavement section NH-8GJ at 434.00 km

Figure 3. Network survey vehicle with different components

Measurement of texture depth. The micro-texture and macro-texture deviations of the pavement surface from an actual planar surface are referred to as pavement texture. Most skidding related accidents occur on wet pavements at conditions where texture depth is reduced. The changes in macro-texture and micro-texture due to wear and compaction resulting from traffic have important safety as well as economic consequences since rolling resistance is a function of texture. Texture depth was measured using the sand-patch method.

2.4. Field and laboratory evaluation of pavement materials

The destructive technique of testing was adopted for field evaluation of test sections. Test pits of size 1.0×1.0 m were made at suitable locations and measurements were made for individual layer thickness

Figure 4. Observation of test pits

Figure 5. Field density test

Figure 6. Full-depth core cutting of bituminous layers

and field density. Representative samples of subgrade soil, sub-base and base materials were collected from the test pits for further examination at laboratory scale. Bituminous cores were also collected for further analysis. Figures 4–6 show the progress of field test pit testing and coring.

2.5. Traffic volume counts and axle load survey

Traffic surveys were conducted continuously for 48 hours by engaging an adequate number of skilled traffic enumerators for motorised and non-motorized vehicles at all locations. The axle load surveys of commercial vehicles were conducted using the Weigh-in-Motion system for all test sections.

3. Calibration of HDM-4 deterioration models

HDM-4 deterioration models were calibrated using the first and second-year time-series data. HDM-4 was run with the first year time-series data with default calibration factors. The obtained distress results were then compared to those observed in second-year time series. Calibration factors were modified, and HDM-4 was re-run until the errors between observed distress and distress predicted by HDM-4 were minimised. Details of the calibration process and calibration factors developed are beyond the scope of this paper and are presented elsewhere (Deori 2018; Deori, Choudhary, Tiwari, & Gangopadhyay, 2016). This paper is aimed at validation and adaptation of different distress models of HDM-4 for Indian conditions.

4. Validation of HDM-4 deterioration models

Validation of the calibrated HDM-4 pavement deterioration models is important to check the adequacy of the calibration factors or calibrated models and thus ensures the efficacy of the developed models. Validation is essential before the model is put to use successfully for future applications and its adaptation. Fundamentally, validation involves the comparison of the distress predictions made by the calibrated deterioration models with those observed on the selected pavement sections.

The time-series pavement condition data for all 23-test sections of the high-speed road corridor network in India were collected consecutively for three years. The time-series condition data collected in the first two years were used for calibration of the deterioration models, and the data collected in the third year were then used for validation. Validation of following distress progression models was carried out:

- Cracking progression model;
- Ravelling progression model;
- Roughness progression model;
- Rutting progression model;
- Texture depth progression model.

In this study, two approaches are used for validation:

1) validation using Student's *t*-test, and
2) validation using a novel concept of "*proximity to the line of equality*".

4.1. Validation with Student's t-test

The *t*-test is a commonly used statistical test for validation to compare the means of two groups of data (in this case, the observed group and the predicted group). Before conducting the test, it is necessary to verify homoscedasticity (i.e. homogeneity of variances) of the two groups using a Fisher's *F*-test. The open-source statistical software package "*R*" is used in this study to conduct all analyses. *R* is an open-source software environment for statistical computing and graphics. The *F*-test compared the variances of observed data and predicted data. When the *p*-value generated during the *F*-test is higher than the significance level 0.05, it is concluded there is no significant difference between the variances of two groups, or the variances are homogeneous. Once the homogeneity of variances is verified, the *t*-test is then performed. The null hypothesis is the means of two groups of data are equal, and the alternative hypothesis is that they are not. Since the homogeneity of variances has been previously verified from the *F*-test,

Table 2. Results of validation using Student's t-test

Distress	*p*-value	
	F-test	*t*-test
Cracking	0.8361	0.8332
Ravelling	0.9240	0.9235
Roughness	0.6602	0.7531
Rutting	0.7095	0.9728
Texture depth	0.7612	0.5167

the *t*-test is run with this information. When the *p*-value generated because of the *t*-test is more significant than the significance level 0.05, it is concluded that means of the two groups are statistically similar (Ott & Longnecker, 2015). In other words, the null hypothesis of equality of means is accepted.

Both *F*-test and *t*-test were conducted individually for the observed and predicted groups of data for the five pavement distresses (cracking, ravelling, rutting, roughness, and texture depth). The results of these tests are presented in Table 2 in terms of *p*-values. A *p*-value higher than 0.05 in *F*-test indicates the variances of two groups are statistically similar, thus validating the assumption of the *t*-test, whereas a *p*-value higher than 0.05 in *t*-test indicates the observed and predicted distresses are statistically similar. Table 2 shows that *p*-values generated during *t*-test are higher than 0.05 for all the five distresses. This result indicates the distresses predicted using the calibrated HDM-4 models produce results that are statistically similar to the ones observed. Therefore, the HDM-4 deterioration models developed under the study are successfully validated.

4.2. Validation using "*proximity to the line of equality*" concept

A common approach used for comparing the observed and predicted distresses involves a scatter plot of predicted and observed values. The predicted and observed data series are correlated, and results are presented in terms of coefficient of determination (R^2) with a higher value (near to unity) indicating a better correlation. This approach has several shortcomings. By definition, the R^2 gives information about the goodness of fit of a model. When fitted to the predicted-observed data, it indicates how well the developed linear model fits the data. However, it does not indicate whether the data are sufficiently validated. Merely specifying the R^2 does not indicate whether the predicted data are sufficiently close to the observed data. Further, there are cases where a "very good" R^2 is obtained, but there are significant differences between the predicted and observed groups of data. Consider two data series A and B shown in Figure 7. The best-fit line for data series A has almost the same slope as the line of equality (line with a slope of 1 and intercept of zero) but has an intercept significantly different from zero. The positive intercept makes the model suffer from over-prediction bias, as the predicted values are always higher than the observed values. For data series B, although the best fit line for this data series has zero intercepts but has a slope considerably different from one. The conclusion in this case is that model predictions have no consistency with the observed data. From this discussion, it is evident that even in cases where good R^2 values are produced; the model may still suffer from under-prediction or over-prediction bias or inconsistency. For proper validation, it is therefore necessary to evaluate both slope and intercept of the best-fit line. The slope must be statistically similar to one, and the intercept to zero, as unit slope and zero intercepts are the parameters defining the line of equality.

For useful validation of the calibrated pavement models, it is necessary that the predicted data must be as close to the observed data. In the ideal case, all predicted distresses would be equal to observed ones. The best-fit straight line to the data will coincide with the line of equality (the 1:1 line) and will have a slope of one and intercept of zero. The approach followed in this study consists of regression of predicted

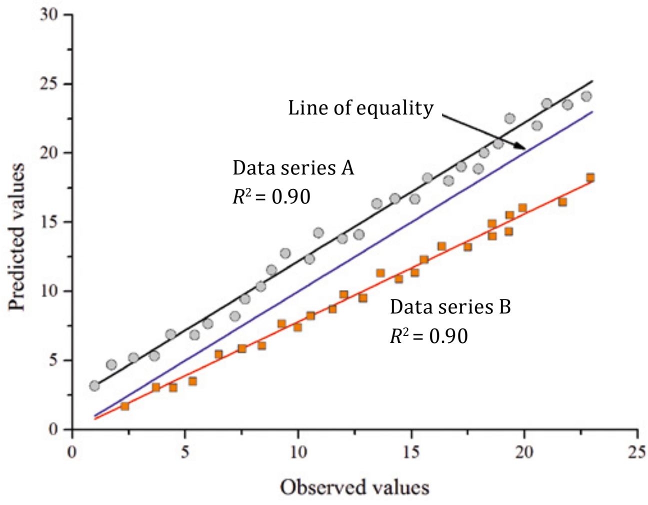


Figure 7. Illustration of "*proximity to the line of equality*" concept

and observed values to obtain the best-fit straight-line parameters: the slope and the intercept. The slope is then statistically compared to one, and the intercept is statistically compared to zero. The discussion of the statistical background of the procedure follows.

Consider a linear model $y = ax + b$, where a – slope and b – intercept. The model is rearranged as:

$$y = ax + b, \tag{1}$$

$$y - x = (a - 1)x + b, \tag{2}$$

$$y' = a'x + b. \tag{3}$$

Equation 3 is a linear model where $y' = y - x$, and $a' = a - 1$. Testing for $a = 1$ and $b = 0$ in linear model of Eq. (1) is now equivalent to testing $a' = 0$ and $b = 0$ for the linear model in Eq. (3). Once the linear model in Eq. (3) is fit to the data, the statistical significance of the regression parameters and is checked. Student's t-tests are conducted to test hypotheses about the slope and intercept of the regression model.

In this study, the regression analysis was performed using the statistical software package "*R*". To perform the regression in *R*, the x, y, and y' data are prepared. A linear model is developed with y' as the dependent variable and x as the independent variable. The developed linear model is saved, and the statistical summary of the regression model is produced. A typical output for cracking distress is shown in Figure 8. From Figure 8, p-value (indicated as '*Pr*(>|t|)') = 0.566 for intercept and p-value equal to 0.237 for slope. Both p-values are greater

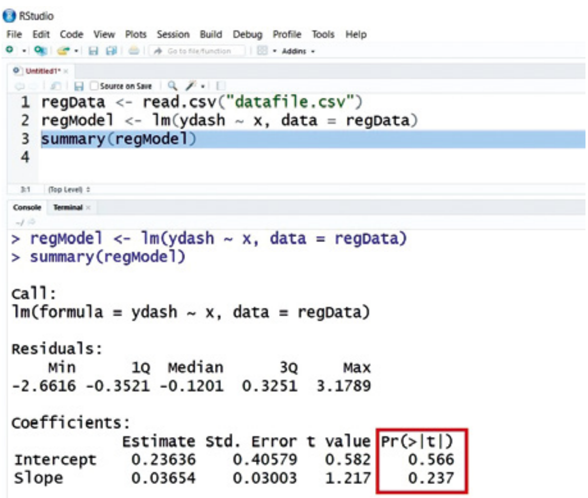
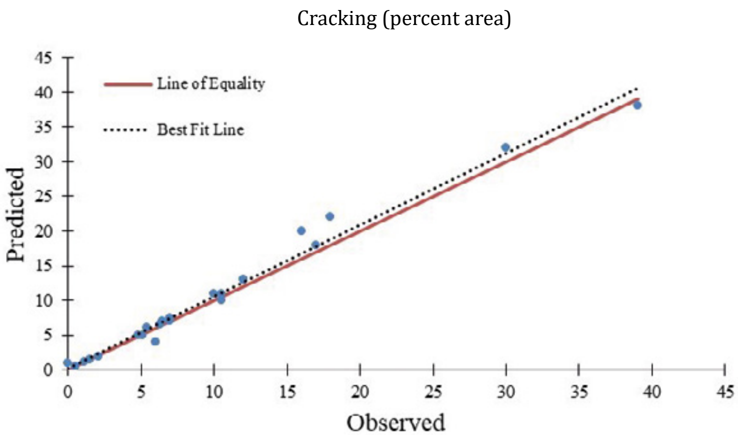


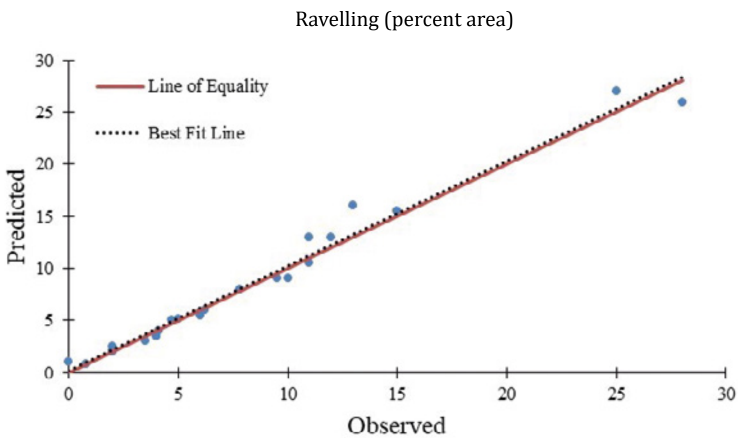
Figure 8. *R* output for "*proximity to the line of equality*" concept

Table 3. Results of validation using *"proximity to the line of equality"* concept

Distress	*p*-value	
	intercept	slope
Cracking	0.566	0.237
Ravelling	0.726	0.769
Roughness	0.359	0.445
Rutting	0.458	0.425
Texture depth	0.518	0.736



a)



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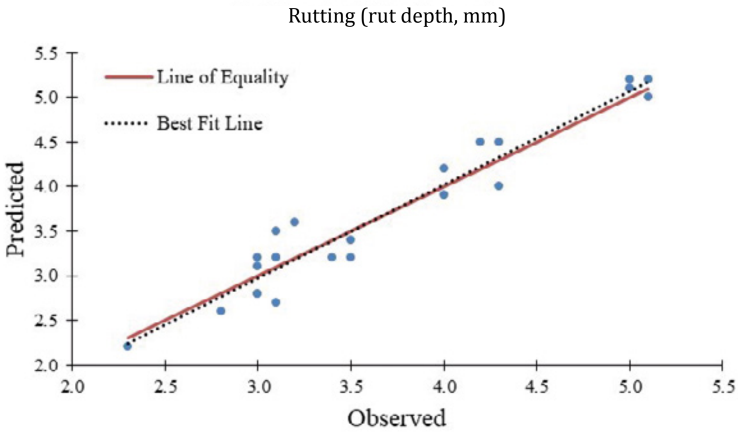

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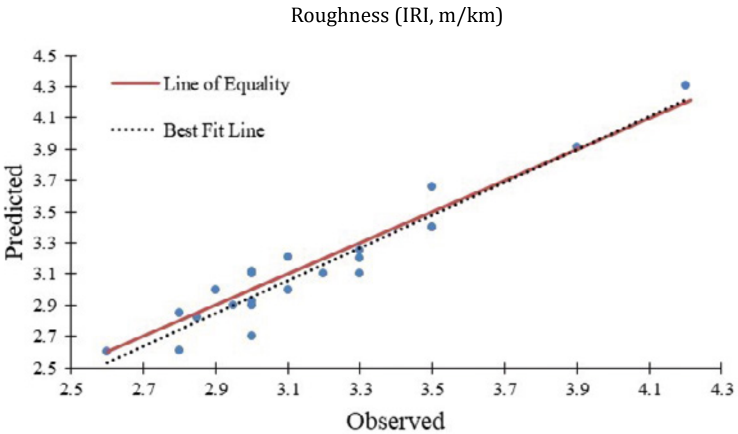

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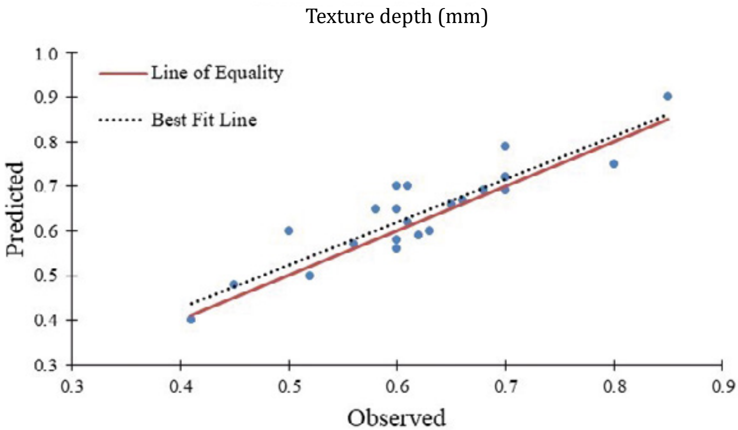

e)

Figure 9. Predicted and observed distresses (line of equality is shown as a firm line, and the best-fit line is shown as dashed)

than 0.05 indicating both regression parameters are not statistically different from zero (i.e. a' = 0 and b = 0). From Eqs (1–3), a' = 0 is the same as a = 1. It is, therefore, concluded the slope and intercept of the best-fit straight line to predicted and observed cracking data is statistically similar from 1 and 0, respectively.

Following this approach, validation was carried out for ravelling, rutting, roughness, and texture depth data. Table 3 presents the validation results for all the five distresses considered. It is observed that all slope p-values and intercept p-values are greater than 0.05. Thus, the observed values of various distress and the HDM-4 predicted distress values are found to be sufficiently close to each other and are successfully validated. Figure 9 shows the predicted and observed data for all the five distresses. The results suggest the developed HDM-4 models are applicable for prediction of distresses and the development of maintenance strategies. The validation approach allows the objective determination of the proximity of the best-fit straight line to the line of equality.

Conclusions

HDM-4 tool was used to perform pavement deterioration modelling for road sections of Indian high-speed National Highway Development Program corridor having modified asphalt binders in the wearing surface. A considerable amount of information on construction and distress data was collected consecutively for three years for calibrating the HDM-4 models for local Indian traffic and environmental conditions. The calibrated HDM-4 models need to be validated to check their adequacy before they are put to use for future applications. The present study discussed in detail the validation aspects of the calibrated HDM-4 models using a novel technique termed the "*proximity to the line of equality*" concept. In addition, Student's t-test was also used as a conventional validation technique. The present study focused on performing the validation of the calibrated HDM-4 deterioration models for the progression of the following distresses: cracking, ravelling, rutting, roughness, and texture depth. Based on the results and analyses, the following main conclusions are drawn:

- Validation using the novel "*proximity to the line of equality*" approach showed that the slope and intercept of the best-fit lines for all distress data were not statistically different from one and zero, respectively, and hence were in statistical proximity to the line of equality. This validation approach was able to provide an objective determination of nearness of the best-fit straight line to the line of equality on predicted versus observed values of the different distresses. This approach is found to be more realistic and removes subjectivity in judging the nearness of the best-fit line to the line of equality.

- Validation performed using Student's *t*-test approach corroborated with the results obtained from "*proximity to the line of equality*" approach. Overall, the calibrated HDM-4 deterioration models for all the distresses were successfully validated.

HDM-4 deterioration models developed by 23 different pavement test sections were after validation found suitable for adoption in planning future maintenance strategies for flexible pavements with modified asphalt binders in surface courses.

REFERENCES

AASHTO PP38:2000 Standard Practice for Determining Maximum Rut Depth in Asphalt Pavements

ASTM E950/E950M:2018 Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer-Established Inertial Profiling Reference

Bannour, A., El Omari, M., Lakhal, E. K., Afechkar, M., Benamar, A., & Joubert, P. (2019). Optimization of the maintenance strategies of roads in Morocco: calibration study of the degradations models of the highway development and management (HDM-4) for flexible pavements. *International Journal of Pavement Engineering*, *20*(2), 245-254. https://doi.org/10.1080/10298436.2017.1293261

Braga, A., Puodžiukas, V., Čygas, D., & Laurinavičius, A. (2003). Investigation of automobile roads pavement deterioration trends in Lithuania. *Journal of Civil Engineering and Management*, *9*(1), 3-9. https://doi.org/10.1080/13923730.2003.10531294

Čutura, B., Mladenović, G., Mazić, B., & Lovrić, I. (2016). Application of the HDM-4 model on local road network: case study of the Herzegovina-Neretva Canton in Bosnia and Herzegovina. *Transportation Research Procedia*, *14*, 3021-3030. https://doi.org/10.1016/j.trpro.2016.05.441

Deori, S. (2018). *Deterioration Modelling of Flexible Pavements with Modified Bitumen in Wearing Course*. PhD Dissertation, Dept of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, India.

Deori, S., Choudhary, R., Tiwari, D., & Gangopadhyay, S. (2016). 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

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)

Jiao, X., & Bienvenu, M. (2015). Field measurement and calibration of HDM-4 fuel consumption model on interstate highway in Florida. *International Journal of Transportation Science and Technology*, *4*(1), 29-45. https://doi.org/10.1260/2046-0430.4.1.29

Luo, W. Q., & Chen, J. C. (2011). Preparation and properties of bitumen modified by EVA graft copolymer. *Construction and Building Materials*, *25*(4), 1830-1835. https://doi.org/10.1016/j.conbuildmat.2010.11.079

Ognjenovic, S., Krakutovski, Z., & Vatin, N. (2015). Calibration of the Crack Initiation Model in HDM 4 on the Highways and Primary Urban Streets Network in Macedonia. *Procedia engineering*, *117*, 559-567. https://doi.org/10.1016/j.proeng.2015.08.214

Ott, R. L., & Longnecker, M. T. (2015). *An introduction to statistical methods and data analysis*. Nelson Education.

Polacco, G., Filippi, S., Merusi, F., & Stastna, G. (2015). A review of the fundamentals of polymer-modified asphalts: Asphalt/polymer interactions and principles of compatibility. *Advances in Colloid and Interface Science*, *224*, 72-112. https://doi.org/10.1016/j.cis.2015.07.010

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

Yildirim, Y. (2007). Polymer modified asphalt binders. *Construction and Building Materials*, *21*(1), 66-72. https://doi.org/10.1016/j.conbuildmat.2005.07.007

Yogesh, U. S., Jain, S. S., & Devesh, T. (2016). Adaptation of HDM-4 Tool for Strategic Analysis of Urban Roads Network. *Transportation Research Procedia*, *17*, 71-80. https://doi.org/10.1016/j.trpro.2016.11.062