THE USE OF MEASURED PAVEMENT PERFORMANCE INDICATORS AND TRAFFIC IN DETERMINING OPTIMUM MAINTENANCE ACTIONS FOR A TOLL ROAD IN SOUTH AFRICA AND COMPARISON WITH HDM-4 PERFORMANCE PREDICTIONS

Jurgens Weidemann[1], Surita Madsen-Leibold[2], Stefano Redivo[3], Cebile Mkabela[4]

[1]Executive, AECOM SA (Pty) Ltd
263A West Avenue, Centurion, 0157
South Africa

[2]Associate Engineer, AECOM SA (Pty) Ltd
Waterside Place, South Gate, Tyger Waterfront, Carl Cronje Drive, Bellville, 7530
South Africa

[3]Engineer, AECOM SA (Pty) Ltd
Waterside Place, South Gate, Tyger Waterfront, Carl Cronje Drive, Bellville, 7530
South Africa

[4]Engineer, AECOM SA (Pty) Ltd
263A West Avenue, Centurion, 0157
South Africa

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Jurgens Weidemann[1], Surita Madsen-Leibold[2], Stefano Redivo[3], Cebile Mkabela[4]

ABSTRACT

The Bela-Bela/Polokwane toll road on National Route 1 was the first Build, Operate and Transfer (BOT) type contract in South Africa. Extensive data on the pavement performance and traffic loading was collected as part of a detailed monitoring program since the opening of the road in 1997. This data was used to determine cost-effective and optimal maintenance actions in order to reduce life cycle costs.

This case study illustrates how the measurement of pavement performance indicators and traffic were used to effectively design the maintenance actions required over the life of the pavement. This paper also includes a comparison of the actual pavement performance data collected for this 156.43 km long toll road with the performance as predicted by HDM-4 pavement deterioration models. An objective of this paper is to evaluate the appropriateness of the HDM-4 models for the specific climatic and traffic loading conditions that this specific pavement was subjected to. A significant feature of the comparative study is that the data used was collected on project level using short road segments and relatively short time intervals.

1. INTRODUCTION

The Bela-Bela/Polokwane toll road on National Route 1 was the first Build, Operate and Transfer (BOT) type contract in South Africa. BKS (now AECOM SA (Pty) Ltd) was appointed for the design and construction monitoring of the original construction in 1996/1997 and for the maintenance actions required during the operating period starting at the opening of the road in 1997 and ending in October 2018.

Extensive data on the pavement performance and traffic loading was collected as part of a detailed monitoring program since the opening of the road in 1997. This data was used to determine cost-effective and optimal maintenance actions in order to reduce life cycle costs. This paper illustrates how the measurement of pavement performance indicators and traffic were used to effectively design the maintenance actions required over the operating period.

Many studies have been carried out in the past to calibrate HDM-4 models to actual observed pavement performance. In South Africa, initial investigations were carried out as early as 1989. This work was followed up with more detailed studies including the ongoing long term performance monitoring of 36 road sections, starting in 1993 (8).

Included in this paper, as a separate study, is a comparison of the actual pavement performance data of the toll road with the performance as predicted by HDM-4 pavement deterioration models. An objective of this paper is to evaluate the appropriateness of the HDM-4 models for the specific climatic and traffic loading conditions that the pavement under consideration was subjected to.

2. ROAD DESCRIPTION

The N1 toll road is part of the main corridor from the most densely populated and industrialized parts of South Africa to the north and the rest of Africa. Raw materials are transported along this route from countries such as Zambia and Zimbabwe to the industrial areas and export harbours in South Africa. Manufactured goods are transported north to many countries in Africa.

The road section under consideration stretches from the Bela-Bela interchange south of the Kranskop toll plaza, by-passing the towns of Modimole, Mookgapong and Mokopane, to the interchange entering Polokwane. The road is a double carriageway freeway with total length of 156.43 km.

The project road traverses relatively flat to rolling terrain with an average elevation of 1130 m above mean sea level (amsl) over the first 90 km. Over the last 70 km, the road rises relatively steeply from about 1070 m amsl to 1565 m amsl and then descends to about 1270 m amsl.

3. PAVEMENT STRUCTURE

The first 23 km of the road (Section 1) was originally constructed in 1986 to the follow pavement design:

- 40 mm medium continuously graded asphalt, 150 mm crushed stone base (G1), 150 mm cement stabilized upper subbase (C3) and 150 mm cement stabilized lower subbase (C4).

In 1997, this portion of road was rehabilitated by:

- Localized application of an asphalt levelling layer to fill ruts
- Milling and replacing of failed asphalt with a 35mm continuously graded medium asphalt inlays
- Crack sealing and application of a slurry seal at selected places
- Application of a 13,2mm single chip seal with Styrene Butadiene Rubber (SBR) modified binder

The remainder of the road (Section 2) was newly constructed in1997 to the pavement design given below:

- 35 mm medium continuously graded asphalt, 125 mm crushed stone base (G1), 125 mm cement stabilized upper subbase (C3), 150 mm cement stabilized lower subbase (C3).

4. CLIMATE

Temperature and rainfall data was obtained for weather stations at Mookgapong, Mokopane and Polokwane for the period 1997 to 2013. The data was analysed and average values were obtained for various climate parameters. Based on this, the Mean Monthly Precipitation (MMP) is 42.3 mm, while the Thornthwaite's Moisture Index (Im) class is -20 to 0 (2). The road section is considered to have a temperature classification of sub-tropical – hot and a moisture classification of sub-humid – dry (3,4).

5. TRAFFIC MONITORING

The traffic was monitored over the BOT contract period by two High-Speed Weigh-In-Motion (HSWIM) stations, installed shortly after opening the road in 1997. Kranskop HSWIM station is located halfway into Section 1, while Pietersburg HSWIM station is located near the end of Section 2. Analysis of the traffic data indicates that the toll road can be sub-divided into two fairly homogeneous traffic sections, roughly coinciding with Sections 1 and 2 which have two different pavement structures. Kranskop station was considered to represent traffic flow on Section 1, while Pietersburg station was assumed to represent traffic conditions along Section 2.

The data was analysed and validated using in-house developed software, classifying the vehicles in accordance with toll classes given below (4):

- Class 1(Light vehicles): motor vehicles, with or without a trailer, including motorcycles
- Class 2 (Medium heavy vehicles): heavy vehicles with two axles.
- Class 3 (Large heavy vehicles): heavy vehicles with three or four axles.
- Class 4 (Extra large heavy vehicles): heavy vehicles with five or more axles

For each year in the period from 1997 to 2013, Average Daily Traffic (ADT) was determined for all of the above vehicle classes, while average E80 per heavy vehicle (E80/HV) was calculated for Classes 2, 3 and 4.

ADT increased over the analysis period as follows:

- Class 1: 8 531 to 13 227 (Section 1) and 5 879 to 10 298 (Section 2)
- Class 2: 435 to 640 (Section 1) and 260 to 504 (Section 2)
- Class 3: 156 to 508 (Section 1) and 109 to 414 (Section 2)
- Class 4: 658 to 1901 (Section 1) and 463 to 1557 (Section 2)

The percentage heavy vehicles increased from 12% to 19% over the analysis period, while E80/HV remained relatively constant. The average E80/HV for Class 2, 3 and 4 vehicles was found to be 0.6, 1.08 and 3.38 respectively. The heavy vehicles (Class 2, 3 and 4) travel pre-dominantly in the slow lane and percentage heavies in the slow lane increased from 92% to 97% over the analysis period.

6. PAVEMENT PERFORMANCE MONITORING

In terms of the agreement between the consultant and the concessionaire, Northern Toll Road Venture (NTRV), the consultant is required to perform annual manual visual surveys, regular road surface profilometer measurements and deflection testing measurements during the contract period based on the specifications in the contract. Profilometer surveys before 2002, was done using the Automatic Road Analyzer (ARAN), while for the remainder of the analysis period, the Dynatest Mk II Road Surface Profiler 5051 was used.

The aim is to optimise the rehabilitation actions and maintenance strategies so as to maximise the structural performance of the pavement without jeopardising its functional aspects. Since the opening of the road, ten annual reports have been published, documenting the findings of those surveys.

The annual reports are considered to be Pavement Management System (PMS) reports as detailed structural analysis of the pavement is avoided and emphasis is placed on the conformance of any uniform section of road to a certain set of criteria. Uniform sections were determined based on pavement structure, traffic volume and coefficient of variation of deflections. The estimated timing of future rehabilitation work for each uniform section was generally based on empirical evaluation of instrument measurements only without any mechanistic analyses carried out.

The functional requirements as well as the terminal structural conditions specified in the contract document were used to evaluate the structural and functional performance of each uniform section (1).

The functional condition criteria applied for the duration of the operation period are as follow:

- Road roughness (International Roughness Index – IRI in m/km): < 2.9 over 90 % of 5 km long sections, < 3.6 over 95 % of 5 km long sections and 4.6 maximum
- Rut depth (mm): < 15 over 90 % of 1 km sections and 25 maximum
- Structural failures (length of patches, potholes etc): < 50 m per 1km sections

Acceptance criteria specified for the structural condition of the pavement at the end of contract (transfer) are as follow:

- Deflection parameters (90th percentile per uniform section; µm) : Maximum deflection (Do) < 370 µm, Base Layer Index (BLI) < 180 µm and Radius of Curvature (ROC) > 120 µm
- Visual condition: VCI > 50 per 1 km segment and maximum annual change in VCI of 25%
- Defects (degree and extent as percentage of road length): degree of ≤ 3 and extent of ≤ 5% for crocodile cracking and patching, degree of ≤ 3 and extent of ≤ 10% for longitudinal cracking and extent of ≤ 5% for pumping(all degrees).

7. MAINTENANCE ACTIONS

On the 1997 rehabilitated section, certain areas of the SBR seal did not last as long as envisaged and cracking and pumping started to appear within five months from construction. In April 2003, holding actions were done at selected sections. These consisted of firstly asphalt inlays where asphalt rutting was the mode of failure (3 025 m²) and secondly a 6.7mm single chip seal with Styrene Butadiene Styrene (SBS) modified binder where cracking and pumping were prevalent (10 118m² or 15% of slow lane).

The 2008/9 periodic maintenance works mainly entailed construction of a 13.2mm single chip seal on the 1996/7 newly constructed sections, and 6.7/13.2 mm inverted double seal on the 1996/7 rehabilitated sections, using modified binders including bitumen rubber, S-E1 and S-E2 (polymer modified). Localized surface repairs (mill and replace) before the reseal were done at various locations. Information gathered from annual monitoring surveys indicated that the maximum deflections measured over most parts of “rehabilitated” sections and a few areas on the “new” sections exceeded the contractual limit of 370 micron. During the 2008/9 periodic maintenance contract, about 5.5 km of slow lane with high deflections north of Kranskop Toll Plaza were rehabilitated by reconstructing pavement layers from subbase level up. The remaining high deflection areas on the project will be addressed at the next periodic maintenance action scheduled for 2014/2015 in accordance with the latest pavement rehabilitation strategy. Maintenance actions are illustrated on Figure 1 below.

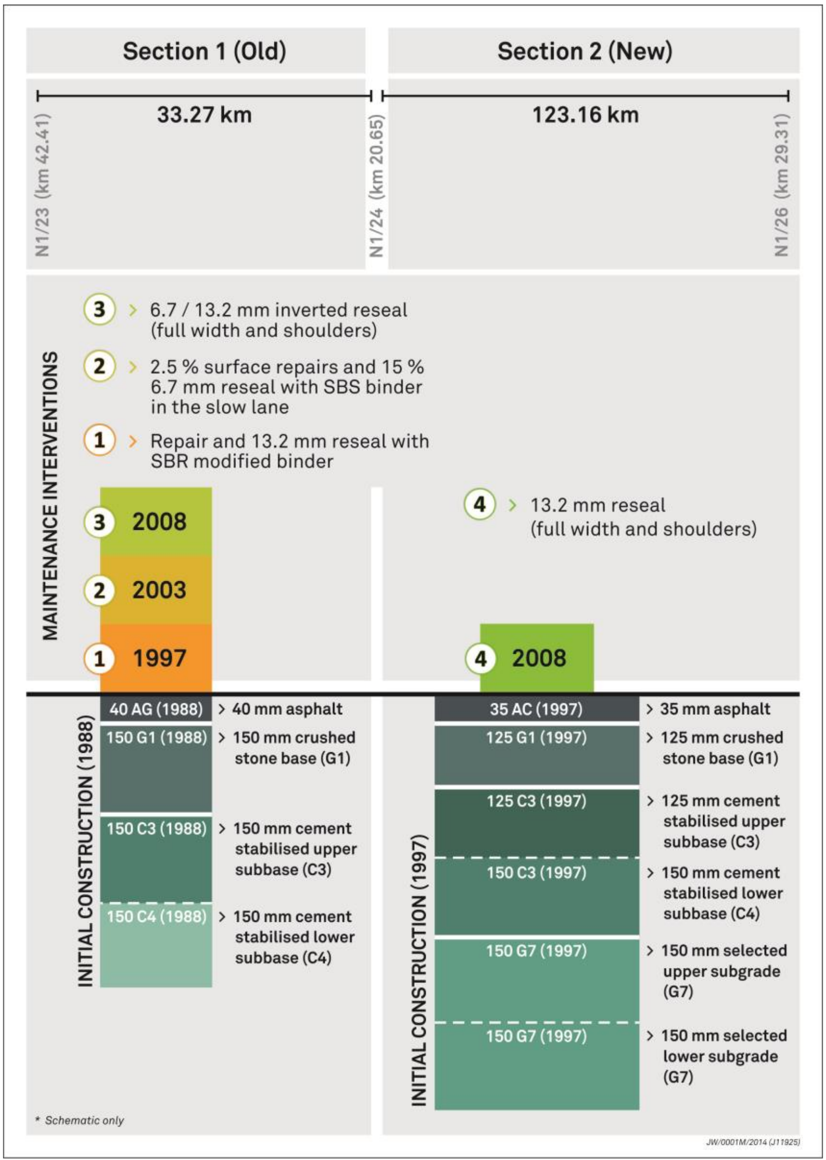

FIGURE 1 Pavement structure and maintenance history.

The data recorded as part of the annual pavement performance monitoring was used to predict future pavement performance which enabled optimization of the timing and design of maintenance actions to ensure compliance by the end of the concession period. The deflections measured assisted in determining appropriate stiffness values of pavement layers for design of localized rehabilitation and the prediction of remaining pavement life.

8. PAVEMENT PERFORMANCE MODELLING

HDM-4 (Version 2) software was used to model the pavement performance and deterioration from the opening of the road in 1997 to date. The distinct difference in pavement structure, maintenance actions and traffic loading, for Sections 1 and 2, justified modelling the project as two uniform sections. The coefficient of variance (COV) of the IRI and rut measurements for each of the two uniform sections is largely less than 50%, indicating moderate variation within a section.

The road was modelled as a four lane dual carriageway with a total width of 17.8 m. Geometric parameters calculated for each uniform section include total rise and fall for Section 1 and Section 2 of 415 m and 1 719 m respectively, and total horizontal deviation of 132 degrees and 517 degrees respectively.

Pavement deterioration manifests itself in various kinds of distresses. The pavement defects for bituminous roads, modelled by HDM-4 pavement deterioration models, are all structural cracking, wide structural cracking, transverse/thermal cracking, ravelling, potholes, edge-break, rutting, road roughness, texture depth and skid resistance (3).

Primary variables influencing the predictions of the HDM-4 deterioration models are as follow:

- Pavement structure, type and age
- Traffic loading
- Climate
- Maintenance actions
- Pavement condition at the start of the analysis and after maintenance works
- Calibration factors for the deterioration models.

The parameter used in HDM-4 to model the pavement structure is the Structural Number of the Pavement (SNP). Typically, SNP is calculated using the thickness and material quality of the various pavement layers to determine a layer strength coefficient. However, SNP may also be estimated using deflection measurements. Using typical layer strength coefficients, SNP for Section 1 and Section 2 of 4.99 and 4.77 respectively, was calculated by the software. In 1997, the average maximum deflection using the Falling Weight Deflectometer (FWD) was 370 micron for Section 1 and 180 micron for Section 2. Based on these deflections, the software calculated SNP's of 5.99 and 9.43 for Section 1 and Section 2 respectively. The deflections indicate that the structural strength of Section 1 is 36% less than that of Section 2. Using this information, an adjusted SNP of 3.02 for Section 1 was derived from the calculated SNP of 4.77, adopted for Section 2. This approach is considered to provide more realistic values for the SNP's as the value of 9.43 determined from the deflections for Section 2 appears too high and Section 1 is expected to have a lower SNP than Section 2 because it is an older pavement and experienced damage caused by traffic loading.

The vehicle fleet applied in the model comprised of Class 1, 2, 3 and 4 type vehicles with vehicle configuration as specified in the South African National Roads Agency (SANRAL) workspace setup (4). Variation in ADT over the analysis period, for each of the four vehicle types, was modelled based on analysis of the HSWIM data. The E80/HV factors as calculated from the traffic monitoring (HSWIM) data were used in the model. The annual number of equivalent standard axles per lane (YE4) is calculated by the HDM-4 software. This is a primary variable used in the modelling of initiation of structural cracks and development of rutting and road roughness. A primary variable calculated by the software for development of ravelling and potholes is all vehicle axles per lane (YAX), while texture depth is calculated based on the equivalent light vehicles (5) for the full road width per year (NELV).

Climate parameters calculated from weather data for stations along the route (see Section 4 CLIMATE) was used in the model. The SANRAL typical pavement deterioration calibration factors for the SA – Sub Humid Dry zone was used (4). The typical calibration factors provided covers the initiation and progression of all and wide structural cracking and the progression of ravelling and roughness (3, 4). For the remainder of the calibration factors, the default values in the HDM-4 software, generally a value of 1.0, were adopted.

The work standards applied in the model comprised of the following maintenance standards (5):

- Single chip seal
- Single chip seal with shape correction
- Double chip seal
- Double chip seal with shape correction

All of the above maintenance standards included routine pavement repair actions namely edge-repair, patching and crack sealing. The surfacing treatments and types were modelled to be triggered in the year that the periodic maintenance took place, namely 2003 and 2008. Based on the observed reduction of the rutting, by maintenance actions, to less than 8 mm, shape correction was triggered when the rutting exceeded 8 mm.

No road condition survey data was available at the start of the analysis (opening of the road) and immediately after periodic maintenance actions. Initial values for rutting, roughness and texture were selected based on the readings of the first survey done after completion of any road works.

9. EVALUATION OF PREDICTED PAVEMENT PERFORMANCE

9.1 Processing of Pavement Performance Monitoring Data

In order to compare the defects or distress predicted by the HDM-4 model with the actual distress of the pavement since 1997, it was necessary to process the available manual visual assessment and road surface profilometer data, collected as part of the pavement performance monitoring, into a compatible format.

The visual assessments carried out during the operation period were done in accordance with Technical Methods for Highways (7) using 200 m long segments and evaluating defects in terms of degree 1 to 5 and extent 1 to 5 (1, 7). In HDM-4, there is no degree and extent variation for defects, and cracking and ravelling, for example, is expressed as percentage of total road area. To determine the percentages all cracking and wide structural cracking, the cracking index (CI) described in (6) was used. The equation for the cracking index (CI), which is a weighted aggregate of all the crack types, is as follows:

$$CI = \sum_{i=1}^{5} W_i . C_i$$

Where:

Wi = Weighing factor for crack type i,

Ci = Percentage (%) cracked area for crack type i

The percentage cracked area was determined from the extent using the appropriate conversion factors given in (6). The cracking index was determined for all cracking (degree 1 to 5) and wide cracking (degree 3 to 5). By using the CI, the cracked area per 200 m long segment was determined and added up to obtain the cracked area per uniform section.

Road surface profilometer readings including rutting, roughness (IRI) and Mean Profile Depth (MPD) were reported at 10 m intervals. Rutting and IRI were measured in the left wheel path (LWP) and right wheel path (RWP) of the slow lane, while MPD was measured across the lanes. Averages for rutting, IRI and MPD was calculated for each uniform section for the various survey years. No skid resistance measurements were available.

9.2 Comparison of predicted with actual pavement performance

The following road works were triggered in the HDM-4 model:

- Section 1 : single chip seal with shape correction in 2003 and double seal in 2008
- Section 2 : single chip seal in 2008

The road condition did not trigger any routine maintenance actions.

Apart from rutting, roughness and variation in texture depth, the only defects that developed over the analysis period were all structural cracking and a small amount of ravelling. Based on the pavement monitoring reports, the pre-dominant distresses that developed was cracking associated with pumping (structural cracks) and rutting. Some bleeding and aggregate loss occurred with isolated potholes developing on Section 1 towards the end of the monitoring period.

Plots of the actual values versus predicted values for all cracking, rutting and roughness including maintenance interventions are given in Figures 2 to 7.

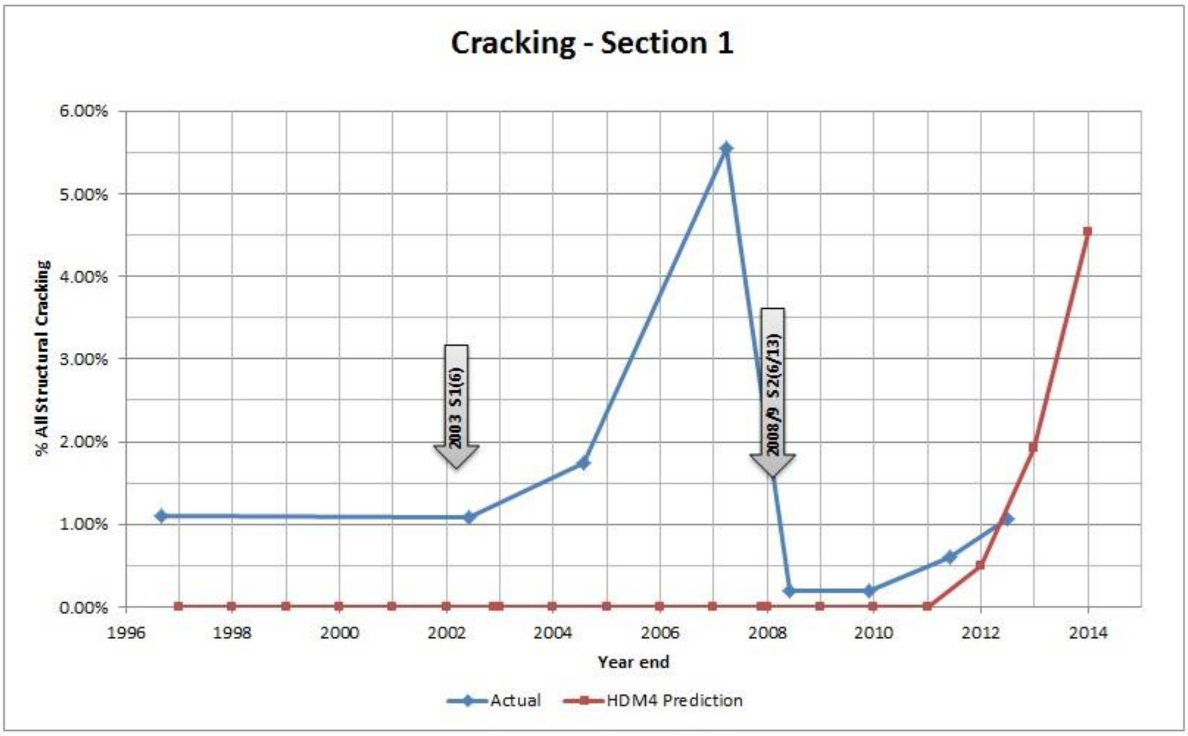

FIGURE 2 Comparison of actual observed and predicted cracking: Section 1.

Cracking developed shortly after rehabilitation of Section 1 in 1997, most likely as a result of reflective cracking. However, the model indicates initiation of cracking only in 2011. The progressing of cracking predicted by the model appears to be quicker than the actual development of cracking. For Section 2, similar trends are observed, but the predicted cracking is closer to the actual cracking for the new pavement that was constructed.

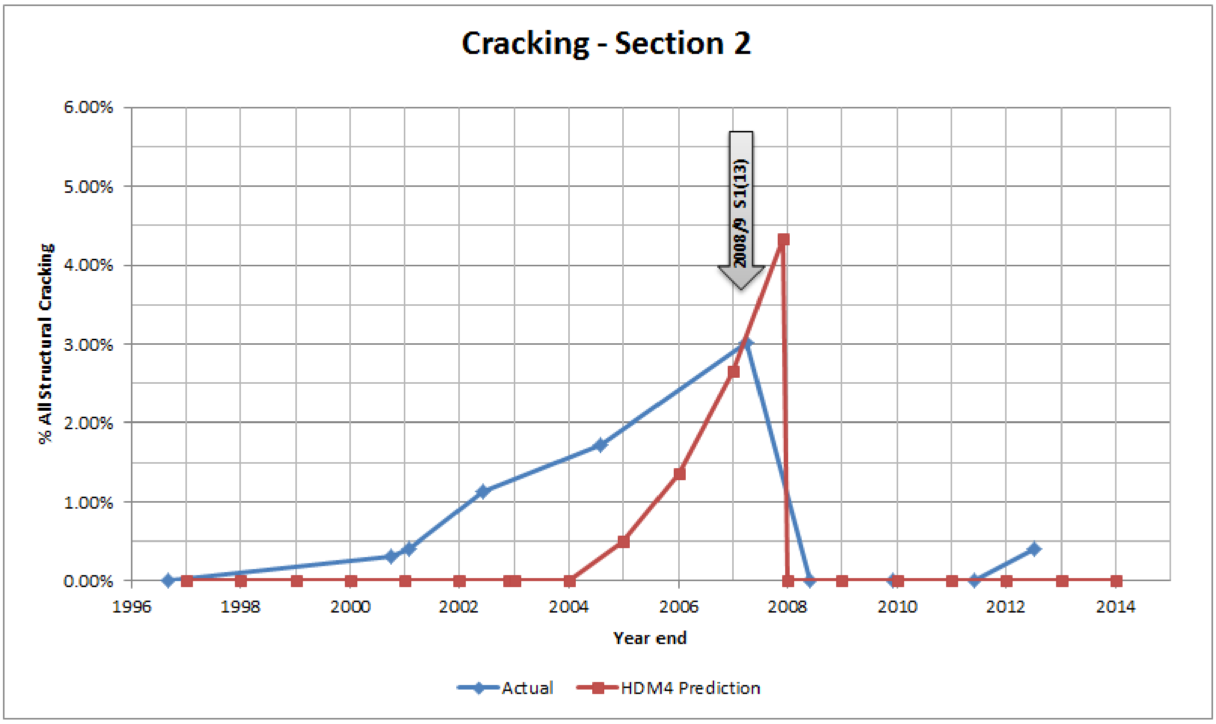

FIGURE 3 Comparison of actual observed and predicted cracking: Section 2.

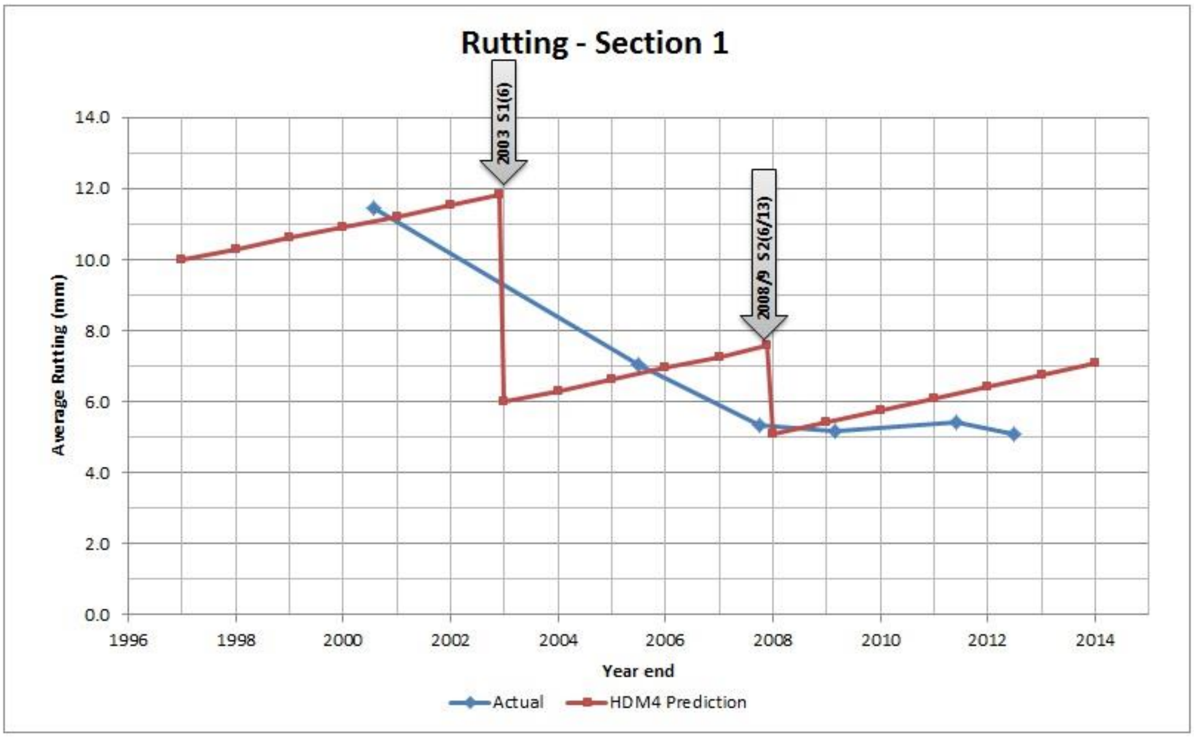

FIGURE 4 Comparison of actual observed and predicted rutting: Section 1.

Lack of data between 2000 and 2006, in particular, makes it difficult to compare actual observed and predicted performance. Given that the works in 1997 comprised of a reseal only and based on the relatively high reading obtained in 2001, an initial rut value of 10 mm was adopted. The actual observed rutting reduces as a result of patching carried out in 2003 and 2008. The predicted rutting is of the same order than actual observed rutting, partially as a result of assuming initial values at the start of analysis and after construction, based on the instrument measurements. The progressing of rutting predicted by the model appears to be faster than the actual development of rutting observed after 2008.

For Section 2, similar trends are evident. However, in this case, zero rutting was used as initial value at the start of the analysis. The predicted rutting indicates accelerated increase in the first year which is in line with initial densification of granular base. The actual reading for 2001 appears high and may be incorrect.

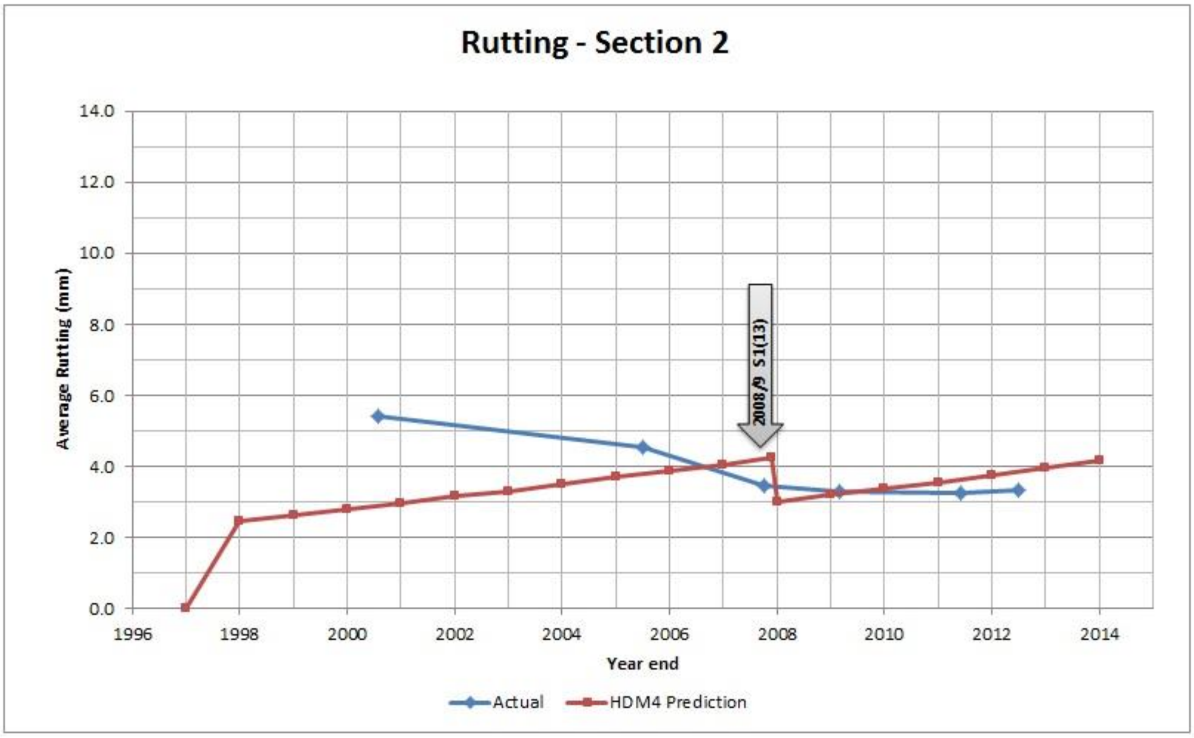

FIGURE 5 Comparison of actual observed and predicted rutting: Section 2.

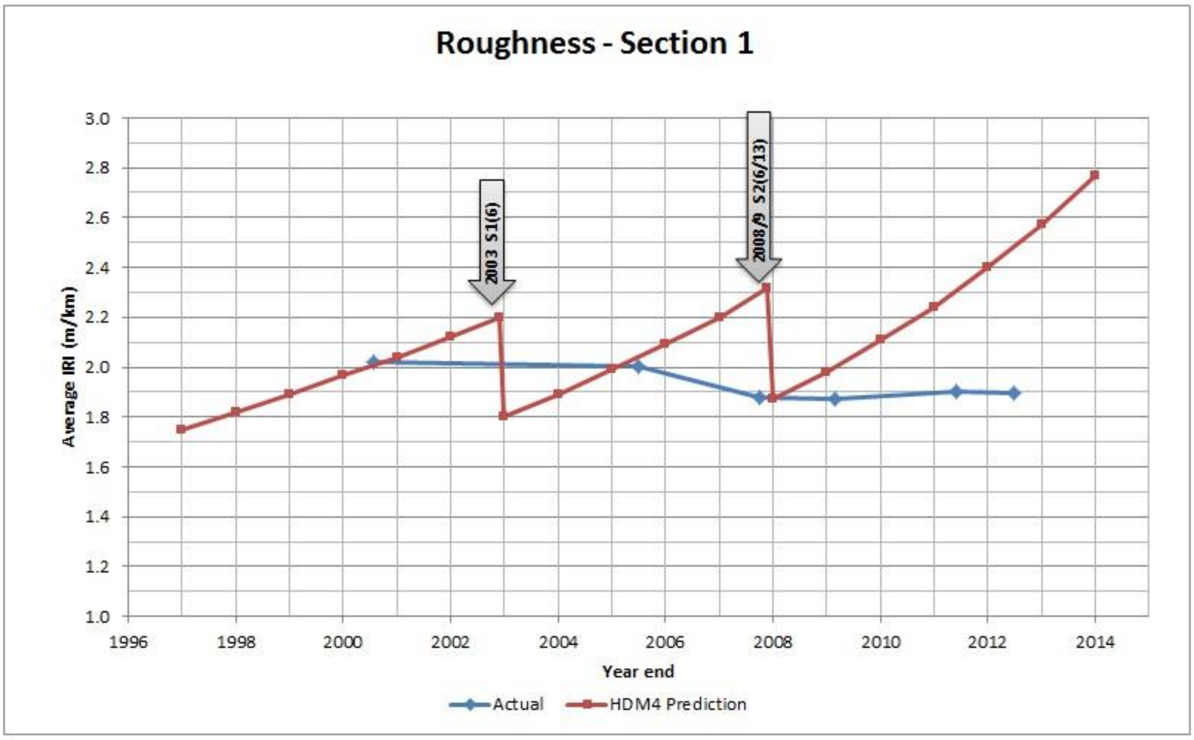

FIGURE 6 Comparison of actual observed and predicted roughness: Section 1.

The predicted roughness is of the same order than actual observed roughness, partially as a result of using initial values at the start of analysis and after construction based on the instrument measurements. For Section 1, the progressing of roughness predicted by the model appears to be faster than the actual development of roughness, while for Section 2 it correlates better with the actual roughness development observed.

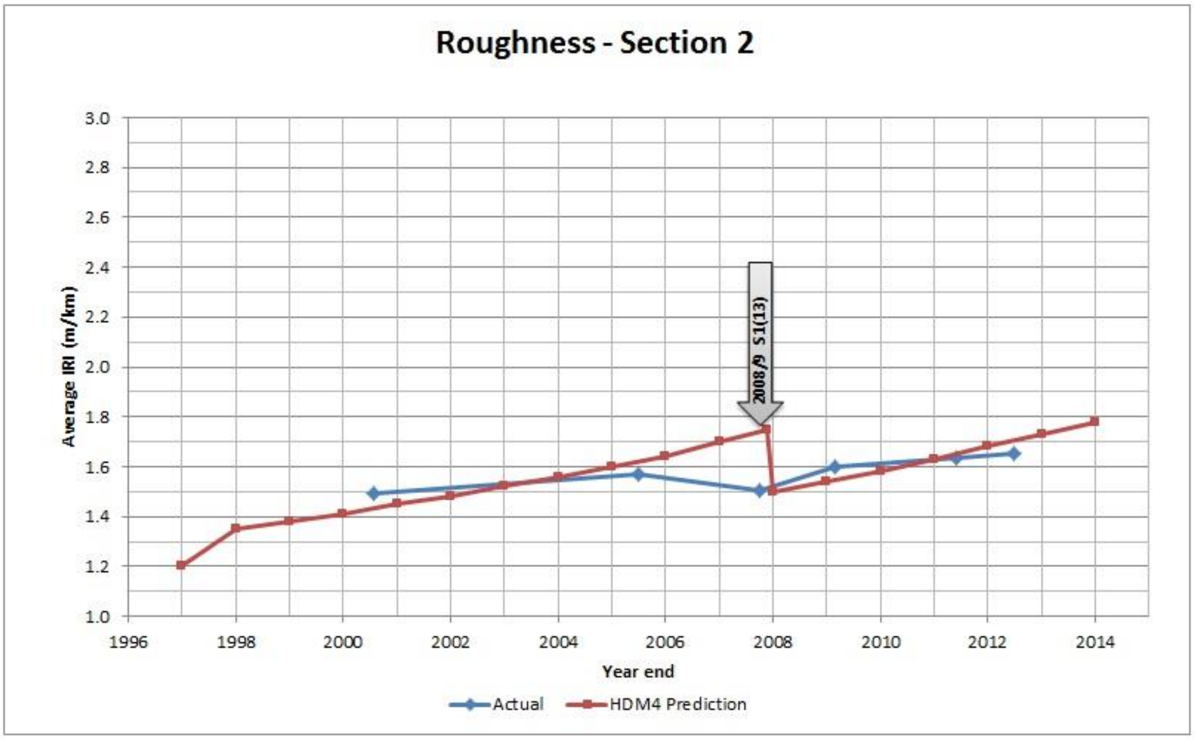

FIGURE 7 Comparison of actual observed and predicted roughness: Section 2.

Plots for the comparison of the predicted and actual observed texture depth are not given in the paper, but are available from the authors. The analysis indicates that the reduction in texture depth predicted by the model is significantly more than the actual reduction in texture depth.

10. CONCLUSIONS

Comparison of the actual observed pavement performance with the performance as predicted by HDM-4 pavement deterioration models indicated the following:

- Deterioration modelling calibration factors are to be adjusted to improve prediction of the initiation and progression of defects including cracking, rutting, roughness and decrease in texture depth. Determination of different calibration factors for each uniform section is likely to be required.
- Adjustment of calibration factors should be based on analyses with and without using initial values after works in order to investigate the road work effects modelled by HDM-4 on predicted performance.
- There appears to be no option in HDM-4 to specify lane distribution of traffic (in particular, distribution of heavy vehicles) and the percentage area or value of the various distresses appears to be an average for all the lanes. However, up to 97% of heavy vehicles are carried by the slow lane resulting in structural distresses (cracking, rutting and roughness) being limited to the slow lane only. It is proposed that future pavement performance modelling be carried out by modelling the slow lanes only.
- Some instrument readings appear high. This may be as a result of poor instrument calibration.
- Visual assessment results are inconsistent in places, possibly as the assessments were carried by different assessors during the monitoring period.

The predictions are of the same order of magnitude than the actual measurements, but the rate of distress development differs for the pavements analysed in this paper. In order to use HDM-4 pavement performance modelling to obtain accurate performance predictions, careful calibration of the models is required. The impact of modelling shorter sections on the results is to be investigated.

The accuracy of field measurements could be improved by ensuring that the equipment used are calibrated, diligent quality control is applied and independent verification of visual assessments are carried out. The application of laser technology to detect cracks through the use of automatic road analysers would improve the accuracy of visual condition data.

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