OVERVIEW OF A PAVEMENT MANAGEMENT SYSTEM IN A TOLL ROAD CONTEXT

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ABSTRACT

This paper provides an overview of the planning, management and the execution of pavement maintenance and rehabilitation works on the N3 Toll Route between Heidelberg (Gauteng) and Cedara (Kwazulu Natal) which is operated by N3 Toll Concession (Pty) Ltd. (N3TC). The paper focuses on the annual cycle of Pavement Management System (PMS) activities needed to sustain and protect the road asset, with an emphasis on procedures required for meeting contractual obligations of functional condition and hand-back criteria for remaining pavement life. The PMS processes are outlined in the context of a Toll Concession, followed by more in-depth discussions of two key aspects of N3TC's annual PMS cycle, namely (i) compliance and network condition reporting; and (ii) the rule-based deterioration model used for analysing network deterioration under a given maintenance and financial strategy. The paper concludes with a "lessons learnt" section that highlights some of the lessons learnt in the first decade of management of this contract

INTRODUCTION

Over the past decade, concession toll roads have become a distinct feature of the southern African road network landscape. The move toward increased use of toll roads in South Africa is part of the strategy of SANRAL, which has as its main objective to provide sustainable roads sooner than tax-based revenues would allow and to ensure dedicated funding for the maintenance and upgrading of roads.

As shown in Figure 1, the N3TC, is one of three privatized concession contracts that are currently operating in South Africa, and is the most heavily trafficked of the three networks. The N3TC network consists of 415 km of divided and undivided 4 lane highway. 87 km has a rigid (concrete) pavement and the remaining 328km has a flexible pavement with varying thicknesses of asphalt surfacing and in many instance asphalt base layers.

At present, traffic volumes on the N3TC network vary between an AADT of 5000 to 16000 per direction with an AADTT (truck traffic, mostly 6 to 7 axles) of 1200 to 2700. The equivalent standard axle loading ranges between 2.6 and 3.1 E80's per heavy vehicle. After a slight decrease in traffic growth during 2008 and 2009, truck volumes are predicted to grow at approximately 5% per year. Light traffic growth is anticipated to be approximately 2 - 3% per year. These predictions currently extend to the end of the Concession Period in 2029.

In terms of the management of the pavement, the N3TC Concession Contract contains certain compliance requirements with respect to functional and structural parameters. Primarily, the obligation on the Concessionaire is to maintain the road pavement network with sufficient structural capacity to accommodate traffic safely and comfortably during the Concession Period. It is a condition of Contract that at the end of the Concession Period, there is a minimum remaining structural pavement life which depends on road category.

Balancing the two objectives of operating profitably and meeting contract requirements of functionality and safety is a significant challenge for a heavily trafficked network such as that of the N3TC. The network size and traffic intensity demands a consistent and rigorous approach to network management.

Over the past 11 years, N3TC has developed a framework within which the annual pavement management lifecycle is completed in a systematic manner. In the development of this framework, some key challenges were met through innovation and experience gained during the first few years of the Contract. These challenges included the development and implementation of a modified pavement engineering strategy together with the development of a deterioration model suited to the unique demands of the N3TC network.

In this paper, an overview is provided of the annual pavement management lifecycle as implemented by N3TC. Key elements highlighted in the paper are (i) the annual cycle of activities needed to satisfy the shareholder and Road Agency requirements; and (ii) elements of the deterioration model. The paper concludes with a discussion of the challenges and lessons learnt during the first decade of the Contract.

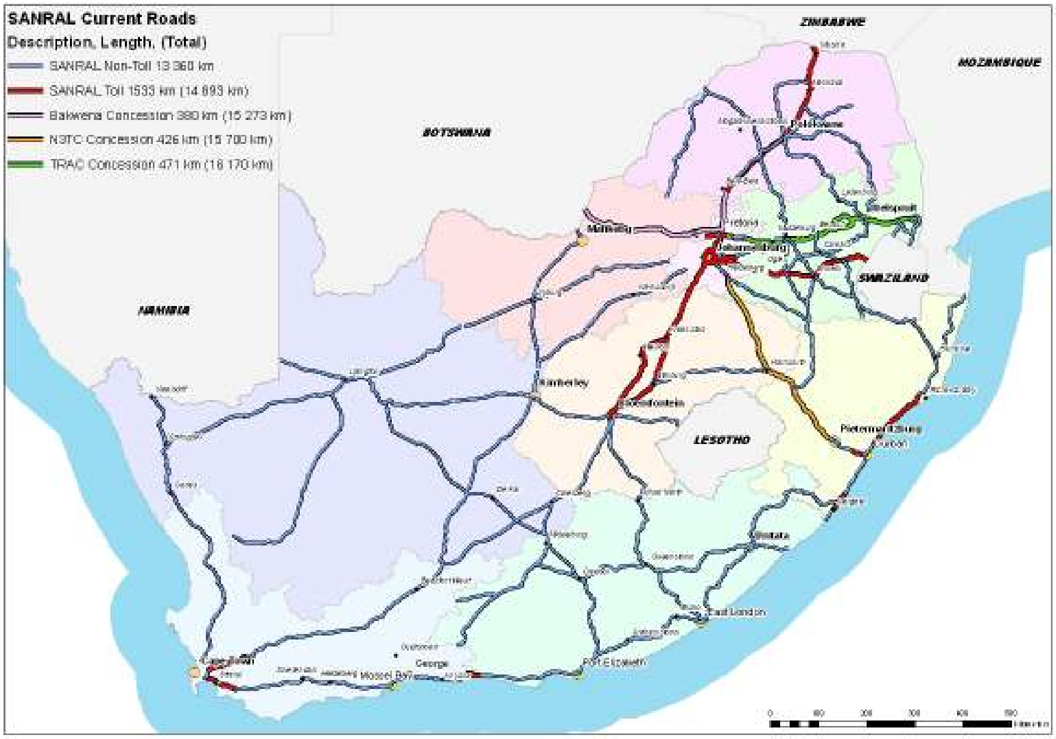

Figure 1: South African national road network indicating toll routes

OVERVIEW OF THE ANNUAL PAVEMENT MANAGEMENT LIFECYCLE

Figure 2 shows the main activities that need to be executed as part of N3TC's annual Pavement Management System (PMS). As can be seen from this figure, in this context, the PMS is not simply a *software system*, but rather a set of *activities* (supported by software systems) geared towards achieving specific management outcomes within each year. Key outcomes of the PMS are the pavement engineering strategy and financial model, both of which are updated on an annual basis.

In the case of the N3 Toll Route, there are two annual milestones with respect to managing the pavement network. These are:

- In February, the Financial Model is updated with the most recent financial indicators, traffic data and the pavement strategy and other capital and operating expenditure requirements. The projects internal rate of return and cover ratios are determined during this process. This update provides the senior lenders, the shareholders and SANRAL comfort on the robustness of the project.
- In May, the Annual Concession Contract Meeting is held at which the Annual Pavement and Traffic Reports together with a three year Capital Rehabilitation program are presented to SANRAL and the Independent Engineer for consideration and approval.

As shown in Figure 2, to meet these annual milestones, two key processes need to be executed. These are (i) the annual activities needed to assess the network condition and compliance to the Contract requirements; and (ii) the development of a pavement engineering strategy using a deterioration model under a given financial plan. These aspects will be discussed in more detail in later sections. The remainder of this section will discuss some of the other elements shown in Figure 2.

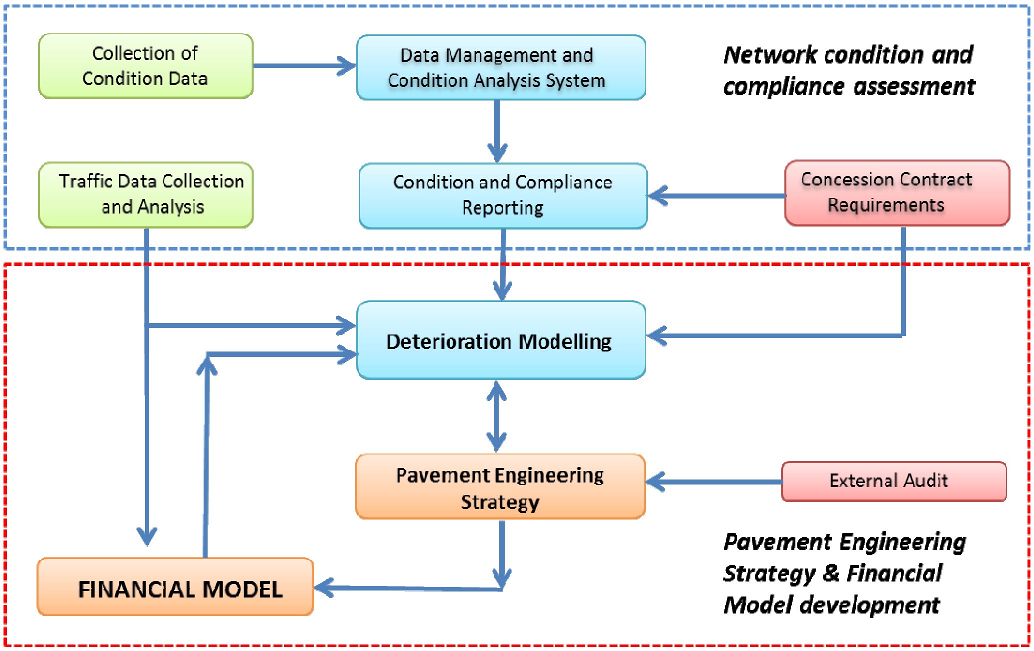

Figure 2: N3TC annual Pavement Management System activities

Collection of Condition Data

The functional parameters of the N3 Toll Route are measured annually using a high speed Dynatest Mark III (RSP) Road Surface Profiler which uses laser technology. Typically, the entire route is measured over three days each September, during a holiday period when no construction works are permitted, ensuring an unrestricted travelled path for measurements.

The functional measurements reported for each parameter is the average per 10m of roadway. Road Roughness and Rutting is measured in each wheel path and mean profile depth is measured in the left (outside) wheel path only. For road roughness and mean profile depth, the 10m data is averaged over 100m sections for analysis of compliance.

In addition to functional parameters, pavement structural capacity is estimated using a Dynatest Falling Weight Deflectometer (FWD). The Concession Contract requires FWD measurements to be carried out every three years. However, it has become evident that a three year cycle is insufficient to monitor deterioration as well as confirming the “life” added during periodic interventions.

N3TC has decided to measure FWD deflections annually up until at least 2017. This will provide a good foundation on which to base predictions for the remaining 12 years of the concession life. In addition, N3TC has embarked on a validation study to assess the structural capacity added during typical recipe rehabilitation treatments. The results of this study will feed directly into the Deterioration Model set-up that is used to predict remaining life.

Concession Requirements

With regards to structural capacity, the Contract requirement for the last three years of the Concession life is to measure deflections each year during the months of April and May (end of the annual rainfall season). These measurements will be used to monitor the structural capacity during the Concession Period as well as to determine the remaining life to evaluate compliance with the hand back criteria.

As described above, the data for the functional requirements is measured using high speed laser based technology. Data is measured every 10m of roadway. For rutting, the 10m data is analysed statistically over 1 km segments and for IRI, the 10m data is averaged over 100m segments and analysed statistically over 1 km segments.

Typical Concession Contract Functional parameters are indicated in Tables 1 and 2 below. Should any parameter not meet the specified requirements for a 1 km segment, then that 1 km segment is deemed to be non-compliant.

Table 1: Concession Contract Requirements for Rutting

Limiting Rut Depth (mm)	Maximum length of each 1 km segment with Rut Depth above Limiting Value
15	10% (i.e. the 90th% rut depth should be below this value)
20	5% (i.e. the 95th% rut depth should be below this value)
25	0% (i.e the Maximum rut depth should be below this value)

Table 2: Concession Contract Requirements for Roughness

Limiting IRI for Road Category		Maximum length of each 1 km segment with IRI above Limiting Value
1	2	
3.2	3.5	20% (i.e. the 80th% IRI should be below this value)
3.5	3.8	5% (i.e. the 95th% IRI should be below this value)
4.5	4.9	0% (i.e. the Maximum IRI should be below this value)

Note: The Concession Contract requires N3TC to construct a parallel route to avoid poor geometry in a mountain pass. In this instance, there are different IRI requirements for Category 1 and 2 roads. Category 1 refers to the mainline highway, and Category 2 refers to those highway sections that will be replaced with the new route and therefore have lesser condition requirements due to lower traffic volumes.

Traffic Data Measurement and Analysis

Traffic data comprise a key input to both the financial model and the deterioration model. In the case of the financial model, traffic data provides projected income estimates, while for the deterioration model, traffic data governs the rate at which structural capacity of pavement sections are diminished over time, with a resultant modelled deterioration in pavement condition.

Specific activities related to traffic data measurement and analysis include:

- Measurement of traffic volumes at different count stations;
- Measurement of axle mass to determine E80/heavy vehicle.
- Determining and forecasting traffic growth;
- Assessment of the current structural capacity requirements of different sections of the network, and
- Assessment of the Level of Service (LOS) based on the Highway Capacity Manual.

Data Management and Condition Analysis System

N3TC uses the JunoViewer software system (Juno Services, 2011) for storage and analysis of pavement condition data. This system provides a database for storing pavement structure information, high speed condition data, accident information and FWD data. For N3TC, an advantage offered by this system is its interactive reporting features, which allow engineers to analyse section deterioration based on different data types. These reports are also used by N3TC to facilitate more informed decisions related to the pavement strategy as well as project level rehabilitation.

COMPLIANCE AND NETWORK CONDITION REPORTING

General

A detailed description of the compliance and network reporting on the N3TC network is provided in Judd and Jooste (2010). This section will provide a synopsis with some example outputs of the process. The analysis of road condition data on the N3TC road network is focussed on meeting two key objectives. These are:

- Analysis of all network segments and network as a whole to facilitate compilation of the annual Network Condition report.
- Ad-hoc interrogation of condition database to aid in planning and locating of maintenance and rehabilitation work.

The annual Network Condition report is typically compiled within two to three months after the completion of the high speed data survey as noted earlier. The network condition report is compiled by focusing three key aspects. These are: (a) compliance to contract requirements, (b) current network condition and (c) network deterioration trends. The algorithm needed to analyse and process compliance data was customized for the N3TC network by Juno Services and utilizes components of the JunoViewer system (Juno Services, 2011).

Analysis of Compliance

The algorithm used for compliance analysis performs the following steps:

1. A segment set is generated which divides the network into 1 km segments.
2. The segment set is processed by an algorithm which is also linked to the condition database. The algorithm calculates, for each 1 km segment, the statistics (typically upper percentiles and maximum values) needed to assess compliance to concession contract requirements.
3. The processed segment set is analysed to determine the number of non-compliant segments on the network.

The results of this process are automatically generated bar charts which show, for each highway section the total number of segments as well as the number of non-compliant segments, if any. The compliance assessment algorithm also exports tables listing the location of non-compliant segments, together with the reason for non-compliance (e.g. maximum IRI failed to comply, as opposed to the 90th percentile).

Analysis of Current Condition

The analysis of current network condition focuses on each performance measure (that is, rutting, roughness, FWD deflection and texture depth). For this analysis the network is divided into logical groups of 1 km segments. For each of these groups (termed "Highway Sections") the distribution of the latest condition data is analysed and reported. Figure 3 shows an example of the graphs used to summarize network condition. These graphics summarizes the location and spread of the distribution of data for each Highway Section. This compact form of reporting facilitates not only the analysis of the current condition of each segment, but also a relative comparison of the condition of different Highway Sections which easily highlights sections that are under-performing.

Analysis of Network Deterioration Trends

The final section of the network condition report deals with the deterioration trends on the network. This analysis makes extensive use of trend graphs such as that shown in Figure 4. These trend graphs summarises the change over time of the distribution of data for a Highway Section. As can be seen from this figure, the format shows the central tendency (represented by the Mean Value), as well as the 10th and 90th percentile values. The figure also explicitly shows the number of observations contained in each year's distribution.

For the annual condition report, an algorithm in the PMS software is used to automatically export an appendix document containing trend graphs for pre-defined segments or groups of segments on the network (Juno Services, 2011). The exported trends graphs are then studied and poor performing parts of the network are identified and earmarked for field inspection and further investigation.

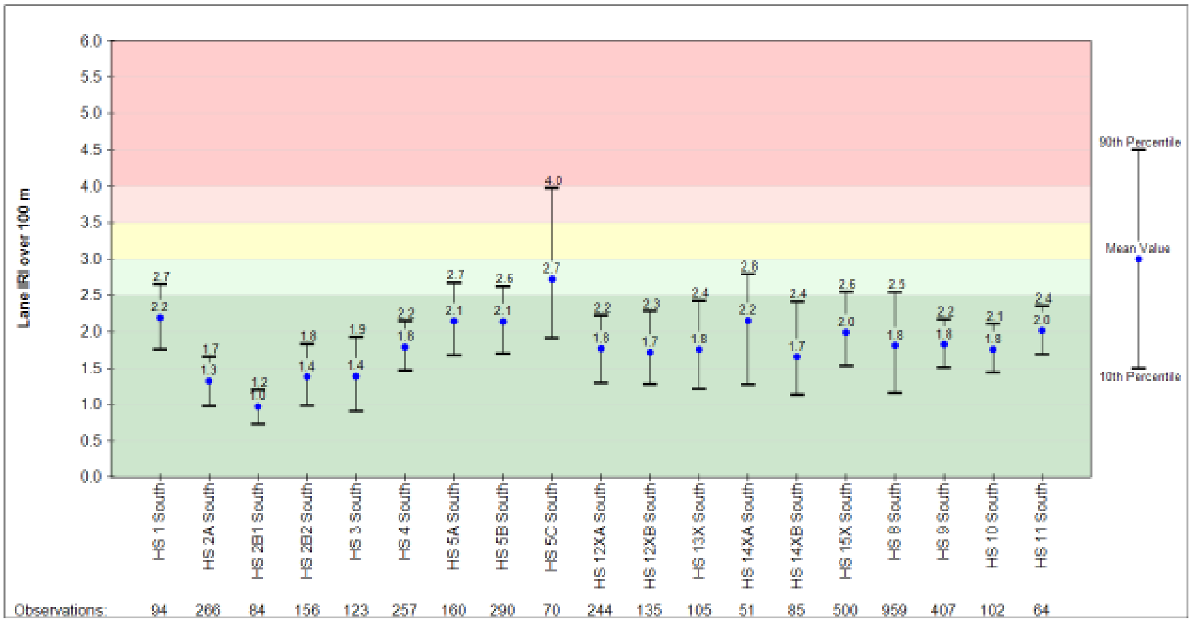

Figure 3: Summary graph showing distribution of roughness on northbound highway sections

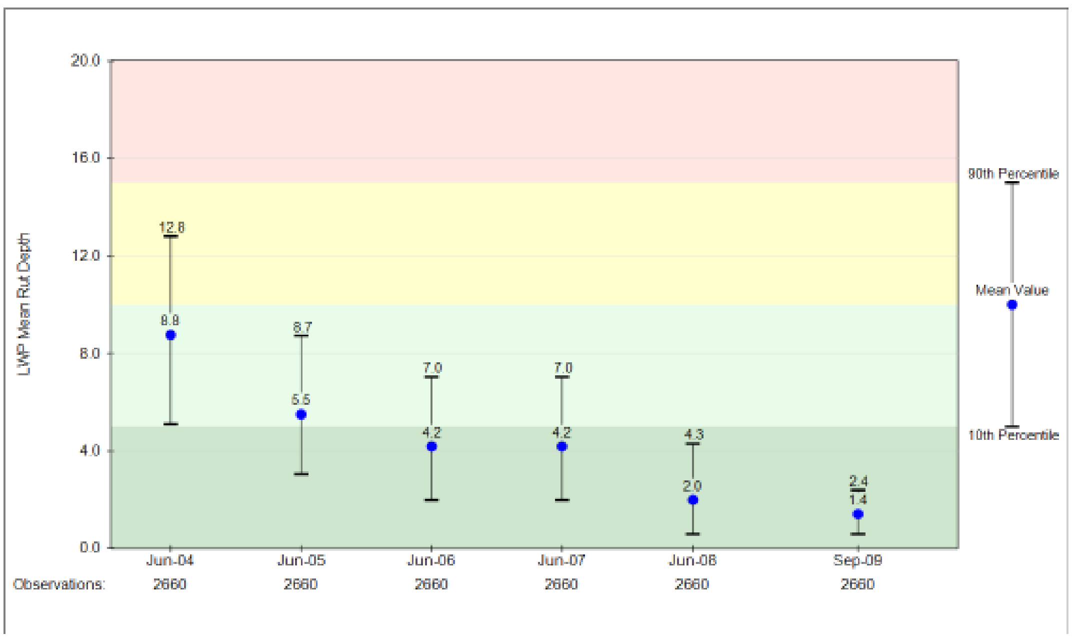

Figure 4*:* Trend graph showing change in the distribution of rutting data over time for a specific Highway Section

DETERIORATION MODELLING

Deterioration modelling plays a critical role in the development of the pavement engineering strategy and in validating the financial model. Specifically, N3TC deterioration modelling process accomplishes the following objectives:

- Models the likely deterioration of the network under estimated traffic volumes;
- Select and applies the most appropriate treatments at the most appropriate times under the constraints of a proposed financial model (budget scenario); and
- Assesses the combined effects of network deterioration (owing to ageing and traffic) and network improvement (owing to rehabilitation allowed by the budget) so that network condition over time can be assessed.

The above tasks are typical for network deterioration models, and most of the commercially available software packages will achieve the above in different ways. The N3TC deterioration model is somewhat unique in that it was specifically refined to accommodate unique features of the N3TC network. The N3TC deterioration model was discussed in detail by Jooste et al (2010), and will not be described in detail here. Instead, the most salient aspects of the system will be highlighted and discussed, specifically in the context of asphalt pavements in southern Africa.

Implementation of a Rule-Based System

A somewhat novel feature of the N3TC deterioration model is the use of rule-based models for the estimation of deterioration rates and in the selection of appropriate treatments. These models incorporate aspects of fuzzy logic (Zadeh, 1975) and certainty theory (Hopgood, 2001; Johnson and Picton, 1995), and have been implemented with some success in pavement rehabilitation design (Jooste et al, 2007; Long and Jooste, 2007).

The rule based model allows the user to design and refine the deterioration models based on general, observed and known patterns (i.e. “rules”) of road deterioration. This approach steers away from the use of relatively small calibration data sets that are used to build generalized models of pavement deterioration.

It has been found (Jooste et al, 2010) that the rule-based models as implemented on the N3TC network are robust and – compared to regression equation based approaches – relatively easy to calibrate. Specifically, Jooste et al (2010) showed how the rule based models can be calibrated to fit the shape and location of a rut increment distribution. By comparison, it was shown that – for the more traditional equation-based HDM4 models (Watanatada et al, 1987; NDLI, 1995) – calibration factors tend to move only the *location* of the modelled rut increment distribution, and not the *shape or width* of the distribution.

For the N3TC models, the rule based approach originally developed by Jooste et al. (2007) was implemented and then extended to provide a close approximation of (a) observed network deterioration effects; and (b) the concession company’s philosophy and approach to maintenance and rehabilitation.

A key refinement of the rule-based approach developed by Jooste et al (2007) is the addition of "exclusion rules" which forces the model to provide certain outcomes if extreme limits are exceeded. The exclusion rules are most often applied in the assignment of interventions where the rule-based model is forced to trigger a specific treatment type if, for example, the structural capacity of a segment falls below a certain limit.

Table 3 summarizes some of the key aspects included in the N3TC models in their current format. Specific attention is drawn to the intervention trigger model, which does not use the centroid approach for "de-fuzzification". Rather, the model uses the predicted segment condition together with a set of rules to evaluate the possibility associated with each of the candidate interventions (i.e. seal, overlay, heavy rehabilitation). The intervention with the highest possibility score is then chosen.

Table 3: Key aspects of the rule-based N3TC deterioration model (after Jooste et al, 2010)

Parameter	Rules Take Into Account	Comments
Initial structural capacity (determined only in first modelling year)	• FWD Deflection bowl parameters • Rut depth • Roughness (IRI)	Actual observed values are used. Rut depth and IRI have low weights and are used to temper the prediction obtained from FWD parameters. After the initial prediction, structural capacity is reduced in each year using the predicted number of standard axles in that year.
Crack Initiation (years)	• Structural capacity • Traffic loading • Surfacing thickness	The membership function for crack initiation varies from 4 to 12 years. Typical predicted crack initiation time is 8 years.
Crack Area (%)	• Time elapsed since crack initiation (TACI) • Traffic loading • Structural capacity	Rules were set to mimic a typical S-shape development in which the time to reach "high" cracking is governed by the TACI membership rules.
Rut Increment (mm/year)	• Structural capacity • Traffic loading • Crack area • Rut Depth	After the first modelling year, predicted values are used for all variables.
Roughness Increment (IRI/year)	• Structural capacity • Traffic loading • Crack area • Rut Depth	After the first modelling year, predicted values are used for all variables.
Intervention Trigger Rules	• Structural capacity • Rut Depth • Crack area • Roughness (IRI)	Several exclusion rules are used to ensure specific treatments are selected where extreme situation apply (e.g. low structural capacity). In all other cases, the treatment with the highest possibility score is selected.

Also of relevance is the crack initiation model, which includes the effect of asphalt thickness in the estimation of crack initiation time. This is specifically relevant in the case of the N3TC network, of which a large proportion consists of thick asphalt base pavements.

The Use of Work Sections

A second novel feature of the N3TC deterioration model is the use of Work Sections to group and maintain parts of the network in the same years. This approach differs from the more routine modelling approach which deteriorates and treats each modelled road segment independently.

Historically, the approach to pavement rehabilitation in southern Africa has been to rehabilitate relatively long sections of road under the same construction contract. This approach realizes savings in planning and design as well as establishment costs for the contractor and client. Using this approach, a rehabilitation contract will typically cover a section of road with a length that will typically vary from 5 to 20 km.

This length of road is treated at the same time and under the same contract, but the applied treatment type may differ over each kilometre depending on the road condition, deterioration history etc. The designation of treatments is normally done as part of the rehabilitation design process and will normally entail detailed investigations which include visual assessments of the current road condition in different areas, analysis of FWD deflections and test pit details.

The N3TC network includes considerable lengths of dual carriageway pavements. Furthermore, the network engineers' approach to network maintenance and rehabilitation were closely aligned to the traditional approach to pavement rehabilitation, as explained above.

Special consideration had to be made to take this situation into account during the development of the N3TC deterioration model. Specifically, this meant that the model had to incorporate the facility to group network segments (typically 1 km long) into a "work section", and that the model needed to treat all segments within a work section at the same time. Furthermore, the model needed to judiciously apply the most appropriate intervention to each modelling segment within the same work section.

The work section concept is illustrated in Figure 5. This figures shows how that work sections can be of any length and can cover all lanes of both directions of a dual carriageway, or a single direction, depending on the needs and approach of the network engineer. In the N3TC implementation, work sections are typically chosen to coincide with the original construction contract limits, where different parts of the network – known as Highway Sections - were constructed at different times and under different contracts. However, experience has shown that there is an optimal length of work section for each network which will lead to the best utilization of available funds. Thus long construction sections are sometimes sub-divided to improve budget utilization.

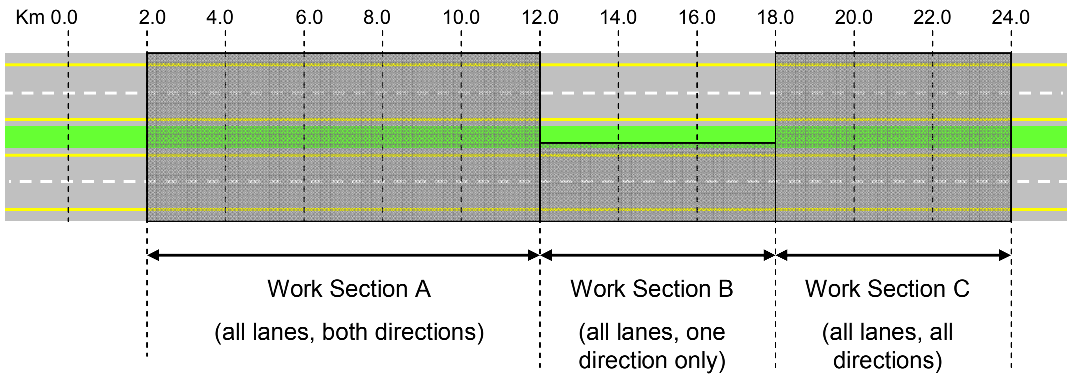

Figure 5: Work Section concept as implemented in the N3TC models.

Figure 6 shows the manner in which the model may typically assign treatments to a work section within a specific modelling year. For clarity, this figure only shows the treatment on one of the two directions. As noted earlier, the model will apply treatments to all segments within a work section. However, as shown in Figure 6, the selected treatment may be a "None" (i.e. no treatment is applied), depending on the predicted condition for a specific segment.

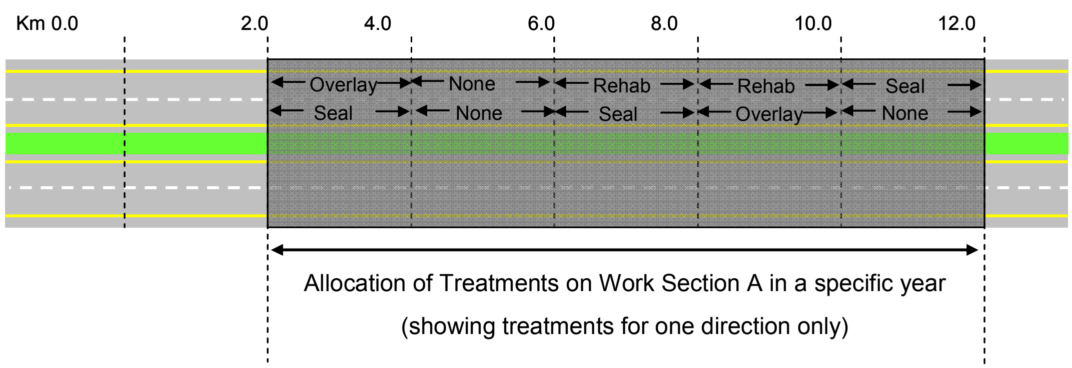

Figure 6: Assignment of treatments on segments within a Work Section.

A further refinement of the work section concept is that the minimum time between the treatments of work sections can be specified as part of the model inputs. Typically, this period will be chosen after consultation with the network engineers and may range from four to six years. Effectively, this means that once a work section is treated, no further intervention will be assigned to that work section until the minimum treatment interval has elapsed. Naturally the model will continue to deteriorate each segment during this operational period.

SUMMARY AND LESSONS LEARNT

This paper summarizes the key features of the pavement management activities executed as part of N3TC's process for deriving a reliable long term pavement management strategy. As such, it provides an example of the pavement management activities related to the management of a concessioned Toll Road in southern Africa. Key features of the management process and of the deterioration model were highlighted.

The N3TC Contract is now in its 12th year of operation, and therefore provides a valuable learning platform for the management of a concession contract in the southern African context. The following paragraphs offer some lessons learnt from the first 12 years of operation.

Functional Data Measurement

Experience has shown that there can be a large variability in the results obtained from measuring roadways using road surface profilers. Issues that need to be taken into consideration are:

- Measurement location references can shift from one year to the next. In order to obtain the correct deterioration trends, one needs to compare equivalent results year on year. In the experience of N3TC, a longitudinal shift of up to 0.5% is quite common with high speed data collection vehicles. A rubber-banding correction is therefore required but does not always give an exact fit for direct comparison of absolute rutting or IRI values from one year to the next.
- External influences of ancillary items such as road studs can give incorrect rut measurements. On sections where rutting appears to be severe, checks should be performed to ensure that the rut being measured and not influenced by an external obstruction or fixture.
- Poorly calibrated devices can result in erroneous values that on face value do not appear to be inaccurate. In N3TC's experience, this applies especially for road roughness and texture depth measurements where fractions of a millimetre can have a large influence on what is acceptable and what is not.
- It is important to compare recent measurements to earlier measurements in order to ensure that the current assessment data is a true reflection of the pavement. The trend graphs provide a built in validation check in this respect.

Concession Requirements

Concession Contract requirements should be studied very carefully at the outset of the contract, as they can be quite onerous. This applies particularly to the statistical adjudication methods specified as well as the type of parameter with which the Concessionaire is required to comply. For example, in the experience of the N3TC, the measurement methods of determining skid resistance through the measure of micro texture were found to be inaccurate and not repeatable. For this reason, and because the N3 highway predominantly operates at 100 to 120 km/h, N3TC measures macro texture using texture depth lasers, thereby providing a surrogate measure for surface friction.

General Aspects

It is important that the Independent Engineer remains constantly familiar with the road network so that he is in a position to assess changes that are made through the year. There are occasions where due to abnormal rainfall, or unexpected deterioration of a section, it is necessary to change the strategy by moving funds forward to the defective section and delaying work on other better performing sections.

There are also occasions where the Concessionaire will want to make use of a particular resource that is close by, for example an asphalt plant, and therefore will require a change in timing of an intervention, or the implementation of an interim intervention. With a hands-on Independent Engineer, such changes are easily motivated and approved.

Model Calibration and Validation

One of the most important issues to take into consideration in all aspects of the PMS function is the actual observed performance of completed rehabilitation work. Traditionally, a rehabilitation project is designed to achieve a certain structural capacity. Once constructed, the focus moves to other aspects of the management process, and explicit validation of the actual achieved capacity is seldom performed.

This is a critical shortcoming of long term pavement management contracts, as confidence in the design and deterioration models can only be achieved when the completed rehabilitation projects are rigorously monitored for actual performance compared to predicted performance. A systematic validation of actual achieved structural capacity of (say) a thin overlay may provide critical insight that could save millions of Rands in the second half of the contract. To this end, N3TC has commenced with a formal rehabilitation design follow-up and validation study.

The results of this validation study will be used to calibrate the reset values used in the deterioration model, and where feasible, to refine pavement design methods to provide trends that are more appropriate to the N3TC network.

In conclusion, it can be noted that experience gained in the use of the N3TC deterioration modelling process - as well as the authors' experiences with generic asset management software in other countries - have shown that the experience and care that is applied during the deterioration modelling process far outweighs the specifics of the model itself.

Analysts often perform a calibration of the different deterioration elements (i.e. rutting, roughness, etc) independently by reference to a small calibration data set. Once the individual models are believed to be calibrated, the modelling run is often performed without explicit checks on the appropriateness of the outputs of the model as a whole. In such a case, the combined outputs of the presumably calibrated models are never explicitly re-assessed for accuracy and reasonableness.

As an alternative approach, it is recommended that analysts also perform an assessment of the deterioration increments obtained with the model in its final integrated form. This assessment can be performed under a do-nothing scenario so that the focus is purely on the modelled deterioration when no intervention is applied. Then, using the population of predicted increments over the total network, an explicit comparison should be made between the populations of predicted and historically observed deterioration increments on the network.

It is believed that this integrated approach to calibration not only forces the analyst to explicitly assess (a) the overall historical deterioration trends on the network; and (b) the reasonableness of the model outcomes. In the case of the N3TC network, this approach was found to provide more reasonable and consistent results compared to the approach where models are only calibrated in isolation before the modelling process commences, without further assessment of the reasonableness of model outputs.

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