Validation Protocol for a Pavement Management System

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ABSTRACT

Being able to undertake more efficient maintenance and renewal planning of road networks has seen a number of Pavement Management Systems (PMS) being developed between the 80’s to mid-90’s. During the initial years, there was a significant focus on substantiating the need and demonstrating the benefits of using these tools to assist in the investment planning for roads. Today, with substantial experience with, and legislative support such as MAP-21 and PASS-55, the use of PMS in the asset management cycle of roads is a given. The challenge these days is to effectively use these tools and ensure robust outcomes are achieved from the overall PMS process.

The success of any Pavement Management System (PMS) is determined by a number of factors including having skilled resources, institutional support, legislative and funding drivers demanding evidence based forecasted investment needs. Asset managers also realise the importance of having technical robustness in the process to ensure likely outcomes. This paper documents the evolutionary development pathway of the New Zealand PMS that has now been in use across the entire country for more than 18 years. It shows how by always challenging the status quo has resulted in consistently increasing the overall robustness of the system. In particular, it shows how different validation techniques have been used to improve the practicality and appropriateness of long-term forecasting capabilities.

INTRODUCTION

Background

Most countries have seen a rapid road network expansion post World War II. With an assumed pavement design life of approximately 30 to 40 years, meant substantial renewal requirements starting during 1980 onwards. This renewal need has placed a significant planning onus on network engineers, which saw the development of a number of pavement management systems (PMS). Although the functionality and sophistication of the various applications differ significantly, asset managers soon realised that the successful implementation was not only a function of the system, but it also depended on a number of institutional issues and the available data.

New Zealand has always been in a fortunate position of having a dedicated road fund that is managed by the New Zealand Transport Agency (NZTA). One of the benefits from a central funding agency is that it can encourage a consistent approach throughout the local councils. This drive towards consistency facilitated the implementation of a shared database and pavement deterioration modelling application. By working together, the economy of scale and commitment to make the system work saw some significant development work resulting from the 19 years of using the system.

Local councils and the NZTA secured a national site license for the dTIMS software during 1998. The full configuration of the system including pavement models and treatment logic was developed using a collective of New Zealand consultants and contractors. The collaboration between the consultants and contracting industry ensured not only early buy-in to the initiative but also allowed for the capturing of best practices from all the asset managers throughout the country. The knowledge base is extensive on PMS systems, modelling approaches and successful implementations. However what is not that widely documented is the longevity of the systems and how it was improved and validated over time. This paper took a retrospective review of a system implemented in New Zealand and demonstrated how the system was validated to ensure it is providing robust outcomes.

The objective of this paper is to:

- Briefly, introduce the development evolution of the PMS system and process;
- Demonstrate the validation processes that have been used to test and improve the robustness of the system.

Introduction to the New Zealand Pavement Management System

The New Zealand configuration/setup has been evolving over the past 18 years in order to more closely align to observed road performance through the use of the NZ Long-term Pavement Performance (LTPP) data. *Figure 1* illustrates the building blocks of the system consisting of the data module, forecasting elements and the decision logic and optimization. The system itself has been chosen for the flexibility in building a customized analyses approach such as models and treatment logic within an analytical framework. From the building blocks indicated in the figure, it is only the optimization process that was resident in the system; the remaining technical makeup is solely based on New Zealand practices.

The resulting model framework includes five, nationally customized, core condition models including:

- Cracking (initiation and progression for Asphalt and Chipseal surfaces);
- Ravelling;
- Rutting (progression and accelerated progression);
- Roughness and,
- Maintenance Cost.

Within the setup, these core models are supported by an array of coding with over 300 expressions and 150 analysis variables covering data management, forecasting capabilities, decision logic and optimization as illustrated in the figure.

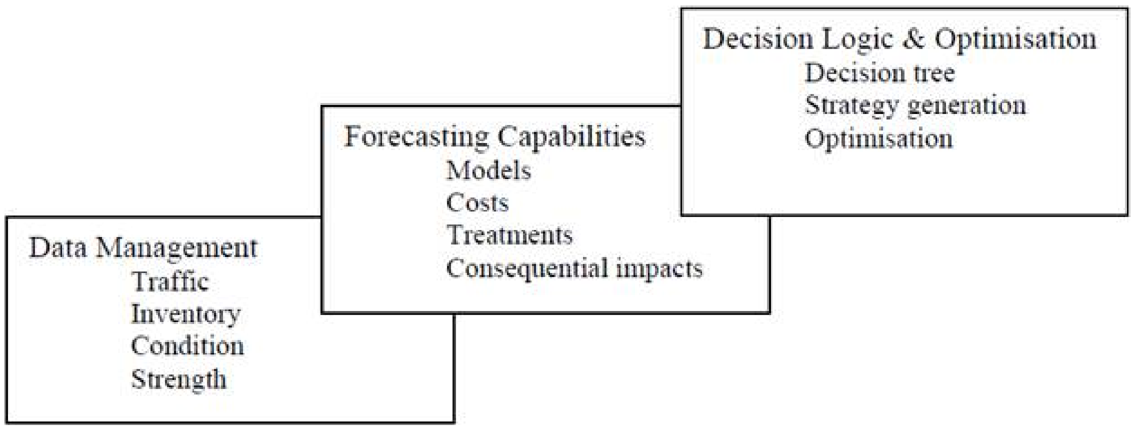

FIGURE 1: The Components of the PMS [*1*]

Critical to the success of any analysis is a skilled operator, with in depth understanding of both the core logic and condition model performance and with the ability to efficiently customize and calibrate the setup for local conditions. Therefore, the training and other development needs were as important as the technical solution. The following sections discuss the implementation philosophy in more detail.

EVOLUTIONARY DEVELOPMENT PATH

Initial Implementation

The initial implementation and some early lessons have been discussed in Hatcher and Henning [*1*]. One of the greatest success factors for the NZ PMS implementation was the collaborative environment that underpinned the project from the start. Under a nationwide membership agreement, all parties contributed their experience and developments in an open-source environment. Significant development needs and software improvements were collated annually and prioritized according to addressing all parties' interest in the most efficient manner. The software vendor has been very responsive in addressing identified application improvements because most of the development needs were also identified as moving the international best practice of the application forward.

Another significant success factor that contributed to the overall sustainability of the system implementation was considering all peripheral business processes and institutional aspects that are as important as the technical aspects. Refer to *Figure 2*.

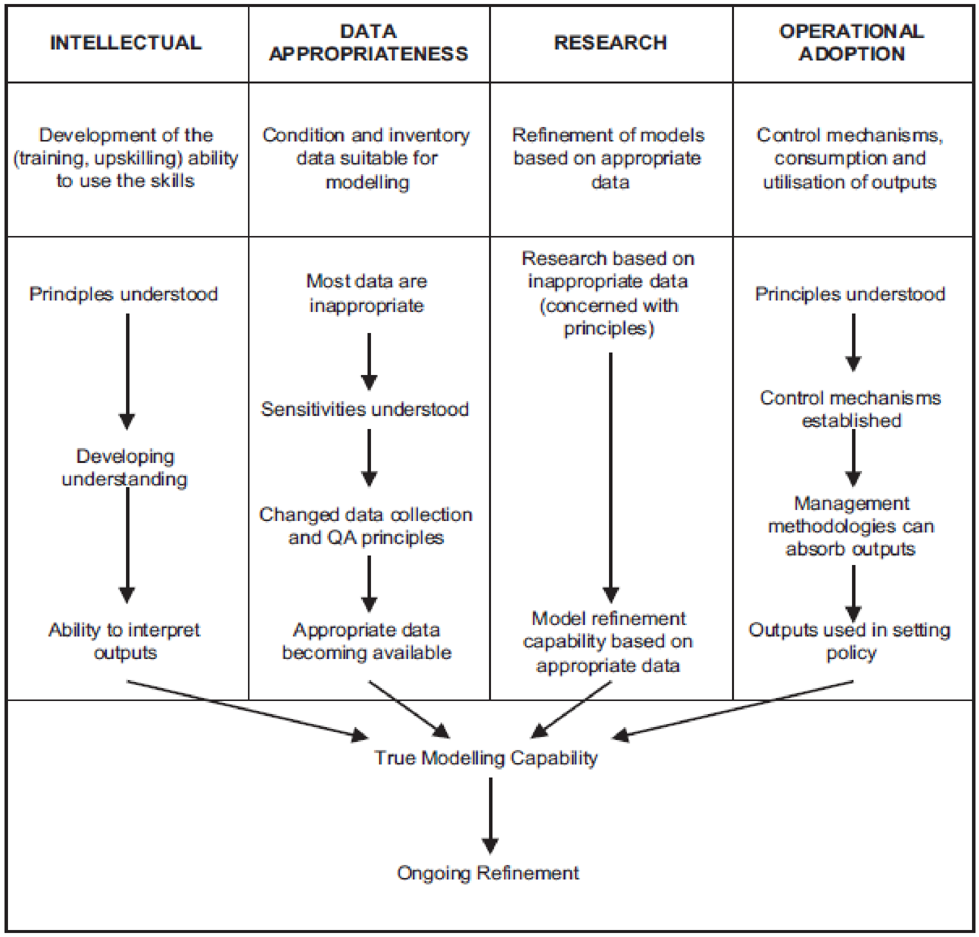

FIGURE 2: Development Streams for the NZ PMS system [*2*]

The figure shows an implementation strategy that acknowledges the status of skills, organizational understanding and the state of data and deterioration models feeding into the system. A number of training sessions and a series of guidelines and manuals were released during the initial stages of the project. Wilson et al. [*3*] have described the data improvements to better cater for the deterioration models. The following sections consider some developments of the significant model and treatment logic aspects.

Pavement Model Development

In order to accelerate the system adoption, a decision was made to adopt the World Bank HDM-III mechanistic-imperial or deterministic models and analysis philosophy [*4*] as a starting point for the New Zealand implementation. The reasoning was that a) the data and knowledge on the pavement performance in 1998 were lacking and b) the HDM- III models are transferable between environments and with calibration could be relatively robust in a short time frame. The intention was thought to developed data-driven models specifically applicable to New Zealand conditions. The LTPP was established during 2001 and has provided the research data for new model development, regional calibration of existing models and data practices for more than 16 years [*5*].

A novel modelling approach that resulted from research on the LTPP programme data was the use of continuous probabilistic models to forecast initiation of defects such as cracking and ravelling. It is also used to forecast the point in time/inflexion points of accelerated deterioration for the rutting model. These models yield the probability of a defect occurring given the dominant environmental, traffic and pavement strength characteristics. [*6*, *7*] A later section provides the validation outcomes of the models.

Catering for Specific Road Types in the Configuration

Once some experience has been gained in the system, it became apparent that the deterioration of the roads in New Zealand is somewhat different to the HDM-III study area. More than 70% of New Zealand roads can be classified as low volume roads (LVR) carrying less than 5,000 vehicles per day. At this traffic volume the climate and geological interaction has a greater impact on road deterioration than just the traffic loading. Therefore, at lower volume road spectrums, the deterioration models are less transferable between regions compared to higher volume roads. *Figure 5* illustrates the difference in performance between LVR in New Zealand compared the HDM model outcomes.

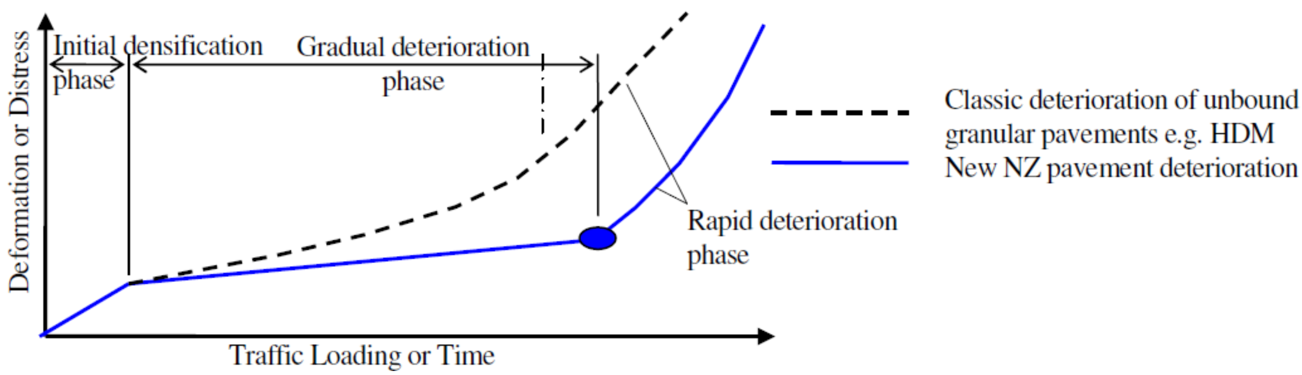

FIGURE 5: Typical Deterioration of Low Volume Roads in New Zealand [*1*]

The figure suggests where the HDM models suggest a continuous deterioration as a result of traffic loading and environmental effects, New Zealand LVR would have very little deterioration over time, yet at a given period in time, the pavement will undergo accelerated deterioration and maintenance intervention would be required within months, normally within a year. The system was customized for this behaviour by:

- adjusting the model approach discussed in the previous sections,
- changing the maintenance intervention philosophy to focus more on preservation treatments such as resurfacing; and,
- using composite indices that not only account for observed defects but also include an aged based deduct factor [*8*]

Generic Calibration Process

Calibrating the condition models to a network/local level is an essential task undertaken at the outset of the analysis. Note that this step is taken each time a new analysis is made on a network. With the data improvements, the robustness of the models also improves. Once the calibration outcomes become stables for a given authority, the model robustness is only validated on a bi-annual cycle. Both the original HDM models and the newly developed models for local conditions are mechanistic-empirical. Therefore, a standard model format is being used for all networks with calibration factors allowing for incorporating local environment and geological conditions. As an example, the calibration process is illustrated below using the NZ Rut progression model:

- Firstly the level of calibration is determined on the basis of the available data. Some regions have detailed calibration LTPP sections, and for others, network level data are being used;
- The models are then calibrated using the expressions provided in *Equation 1* and *Equation 2*. *Equation 1* returns the annual rut increment provided that the road section has not yet fully deteriorated into an accelerated rut progression.

$$\boldsymbol{Annual\ Rut\ Increment} = IF(Accellerated\ Rutting\ Initiated, 1.4, 1.0) * Calibration\ Factor * 0.1 * \frac{LOG10\left(MAX(10.0, Traffic\ ESA * 365.0)\right)}{Structural\ Number}$$

EQUATION 1

$$\boldsymbol{Calibration\ Factor} = \frac{(Annual\ Increment * Structural\ Number)}{IF(Accellerated\ Rutting\ Initiated, 1.4, 1.0) * 0.1 * LOG10\left(MAX(10.0, Traffic\ ESA * 365.0)\right)}$$

EQUATION 2

Where: Accelerated rutting initiated = TRUE once rutting goes into the accelerated rut progression (Refer Figure 5)
Traffic ESA – is the standard average axle loading per day
Structural Number – is the modified structural number as defined in Watanatada at al. [*4*]

- Note that the historical condition data is aggregated to the defined level, cleaned to remove maintenance or renewal impacts and the rate of condition change assessed.

A suite of tools has been developed to assist the NZ modeller in the calibration process and understanding the of the model outcomes in using different calibration methods. One such tool illustrated in *Figure 6* that provides an interactive dashboard where the user may adjust input variables, including calibration factors to plot model outcomes and assess the impacts visually. This tool assists the modeller to gain a better understanding of critical inputs to each condition model as well as demonstrating the impact that calibration factors have on condition models.

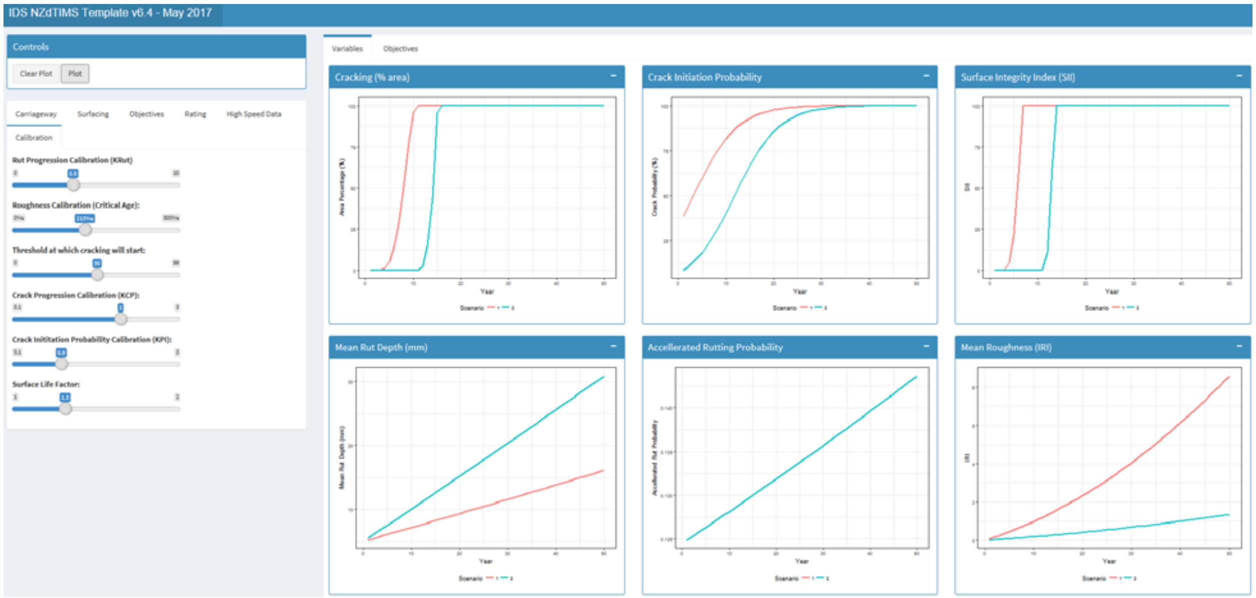

FIGURE 6: Screen Shot from Calibration Tool

VALIDATING THE RESULTS

Background National State Highway Analyses

In 2016, a robust least life-cycle cost analysis was performed over the full length of the New Zealand State Highway network (approximately 23,000 lane km). The objective of the analysis was to support the 10-year investment request for the pavement asset to government funders, through evidence based justification. Given the model's outcomes are being presented as such evidence, the funder also required an assessment of the robustness of the model through sufficient validation. The analysis drew upon innovative methods to calibrate, test and validate the outcomes, providing a level of confidence in the outcomes unsurpassed. The following sections step through the technical details of these verification phases undertaken throughout the analysis.

Model Calibration

Prior to the analyses, a similar calibration process described in the previous section has been undertaken on the state highways. In addition to the LTPP initiative, NZ is fortunate to have a longstanding national data collection program across all State Highways:

- Continuous high-speed laser profilometer data (rutting, roughness, texture, geometry and skid resistance) 100% annual survey since 1996;
- Visual condition rating data (surface, pavement and shoulder defects) at 10% sample size annually between 1992 and 2014;
- Falling weight deflectometer (FWD) at 100-meter drops, covering approximately 20% network every 5 years since 2001; and,
- Continuous traffic speed deflectometer data (TSD) in 2015 and 2016.

The availability of this wealth of continuous network data, matched with reliable construction history information enabled a higher level of calibration in this analysis.

Calibration groups were defined based on geography/region (23 in total) and further split by functional group or road classifications (12 in total), resulting in 276 calibration groups. The rate of condition deterioration, following the latest major construction, was assessed for each modelled section and using these, a calibration factor then assessed for each calibration group.

Rolling Back the Clock

While local calibration has been completed prior to analyses, a further test was undertaken to prove the appropriate predictions from the models in the context of the overall system's logic. Retrospective analysis or 'rolling back the clock' is a method used to test the entire forecasting logic and is an efficient method for post analysis verification. This method involves rolling the entire dataset back a defined number of years, locking in the treatments which have actually occurred on the network over the defined period, running the analysis and comparing the model generated network condition with the actual network condition.

This exercise was completed as part of the 2016 NZ State Highway analysis to assess the predictive capability of the calibrated rutting and roughness condition models. A 10% sample of the national dataset (3 network areas out of 23 total) was selected with input data rolled back by 5 years. All renewal treatments which had occurred on the network over the 5-year period were identified and locked into the model, triggering a condition reset in the model in the actual retrospective treatment year. The model was run over the 5 years with the final year condition projections compared to actual measured condition values at project (section) level. Outcomes are shown in *Figure 7*.

The chart on the left shows the cumulative distribution of the 3 networks' roughness condition in the final year, with Model and Actual lines almost indistinguishable. This suggests at a network level, the predictive capability of the model of an acceptable robustness.

The chart on the right shows a correlation between Model and Actual data points at a section length level. The R2 value of 0.87 suggests a high correlation, providing confidence in the predictive capability of the prediction model even at a project level. The outliers are primarily represented by the sections where treatment has occurred, and the model has reset the condition at a fixed level. These outliers indicate either that the condition resets coded within the model are too low and would benefit review or the historical treatments coded into the retrospective analysis did not actually occur. As demonstrated in the example, the retrospective analysis is an effective exercise to not only verifies the accuracy of predictive models but also the wider model logic such as condition resets.

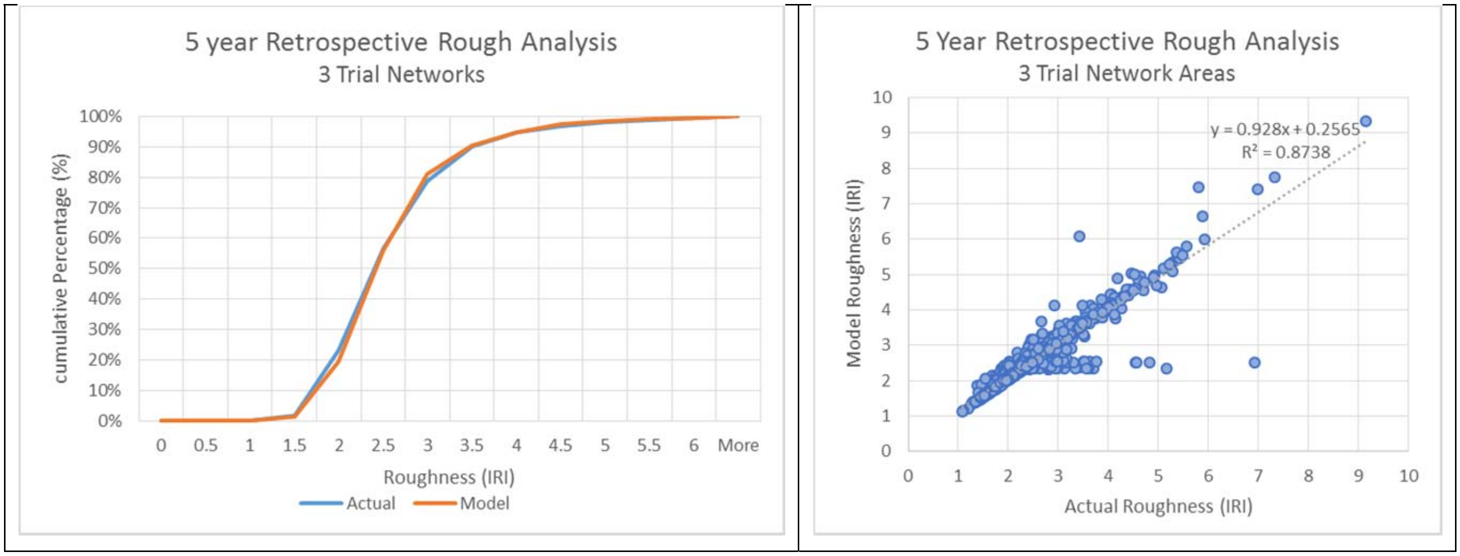

Figure 7: Comparing Actual to Modelled Conditions for Retrospective Analysis

Probabilistic Model

Historically, New Zealand has adopted a single view of pavement performance modelling based on a single deterministic framework as documented in this paper. While the condition models and decision logic have been evolving over the past two decades, the model framework itself has remained static, with all modeller's nationwide operating on the same, single, base setup using the same pavement management system.

To test and challenge the outputs from this well-established framework, in 2016, a new setup, based on probabilistic principals was developed. The probabilistic setup was built around a Markovian transition probability matrix (TPM) framework, with the TPMs developed and calibrated using historical data from the full NZ State Highway dataset [*9*]. *Figure 8* illustrates the difference between the two model forms, both members of the empirical model family.

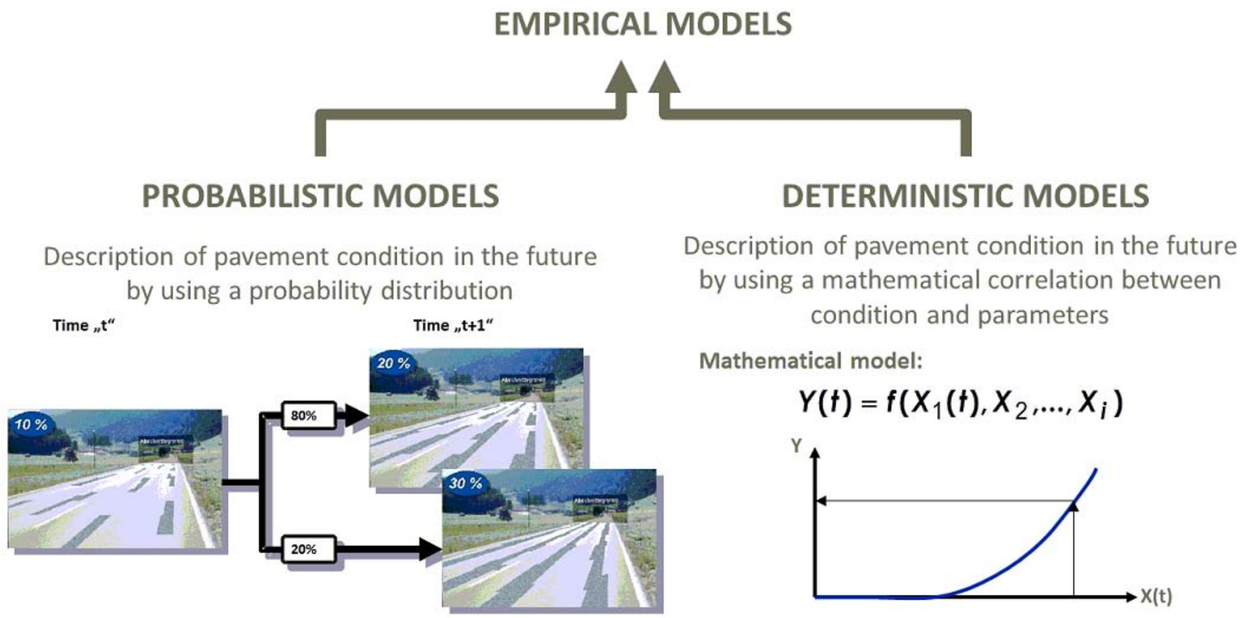

FIGURE 8 Graphical Illustration of the Difference in Deterministic and Probabilistic Model Approaches

Development of the probabilistic models (TPMs), while simplistic with just three initial index based models: Pavement Renewal, Surfacing Renewal and Safety Renewal, was well researched and models were subjected to rigorous validation and testing prior to adoption.

The approach adopted to challenge the validity of the existing NZ models was to code a like for like setup, where all components of the modelling framework were identical apart from the condition models themselves. The result was a second, standalone New Zealand Roading model framework within the same PMS, with entirely different condition models driving investment recommendation. An entirely new view of the same landscape, the question was, would the two frameworks produce similar results when asked the same question? The question is “What investment level is required to maintain the current steady state condition of the network.”

To enable comparison, the optimization routines of both the deterministic and probabilistic PMS frameworks were adjusted to seek steady state condition or in other words, maintain the current overall network condition (objective function). Five scenarios were tested under each framework over a range of 30% investment. The inherent cyclic nature of the Markovian TPMs was observed in the probabilistic model outputs, making it difficult to predict a continuous steady condition state as demonstrated in *Figure 10*.

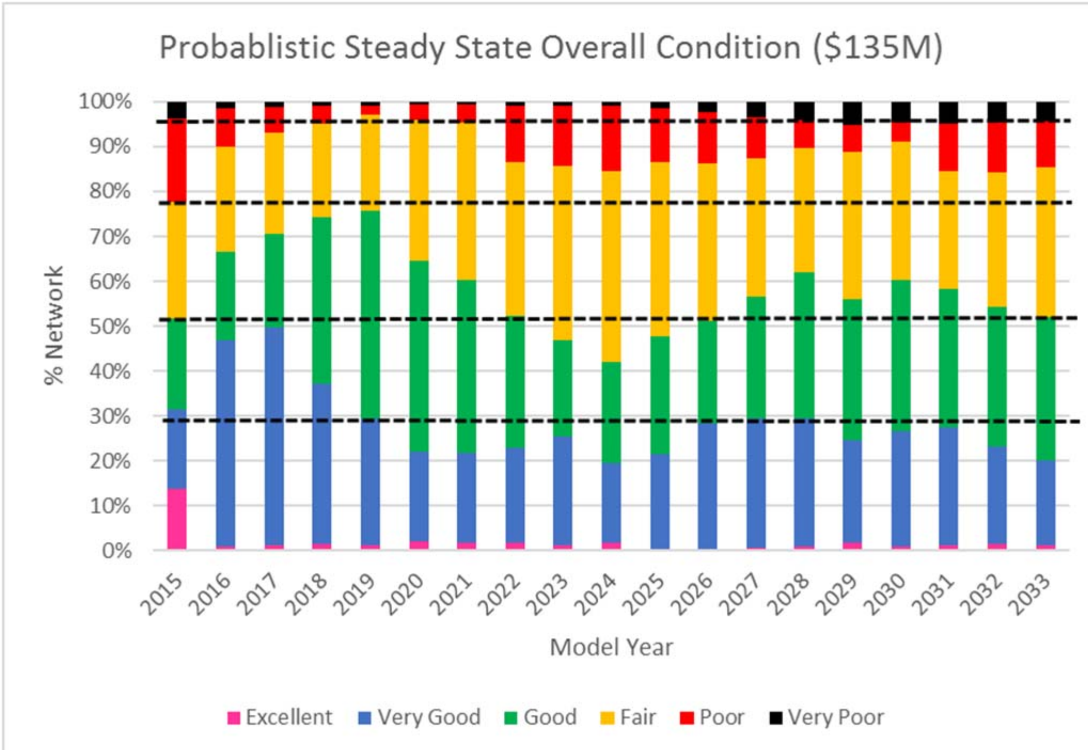

FIGURE 10: Condition Forecast from Markov Approach

The deterministic model predicted a stable condition outcome, providing a clear definition between investment levels as demonstrated in *Figure 11*. Note: It is apparent in this figure that initially the model is tackling an observed 'backlog' which boosts the Overall Condition Index in the first 2 years. Steady State has been identified where the profile stabilizes over the 3 to 20 year period.

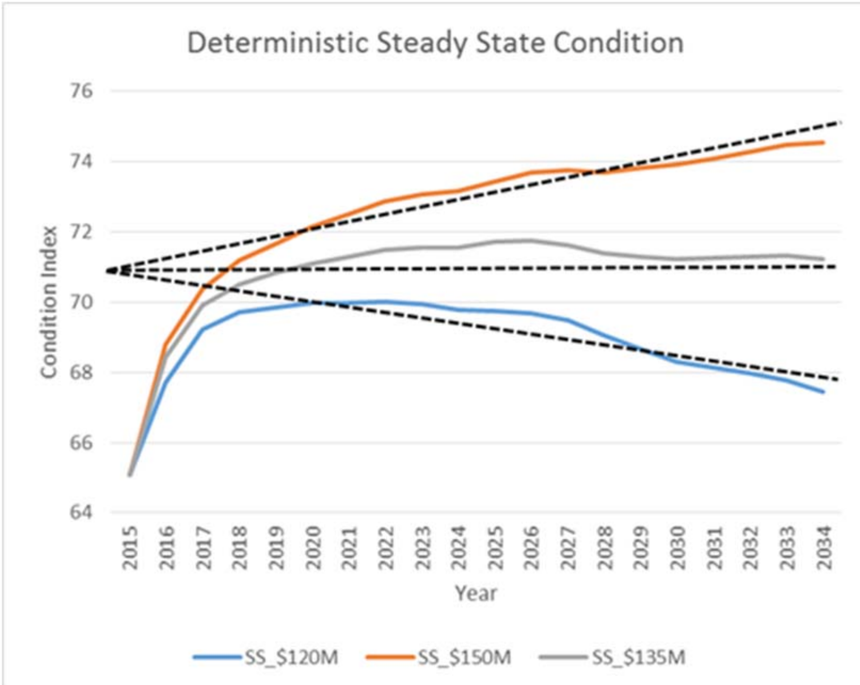

FIGURE 11: Condition Forecast from Deterministic Approach

Overall outputs from the two different model frameworks predicted steady state investment levels annually over a 20-year period within 5 – 7% of each other. While the probabilistic framework is simplistic and has an enormous capacity to be further improved, this comparative assessment demonstrated that a strategic investment level, these two entirely disparate modelling approaches aligned, proving a further validation of the NZ model predictive capability.

Using Field Validation to Improve Forecasted Outcomes

Introduction to Field Validations - RAPT Reviews

The NZ Transport Agency utilizes a comprehensive field validation process for determining the maintenance and renewal programme for up to three years. The so called “RAPT reviews” (Review and Prioritisation Team) are undertaken across all regions and approve every resurfacing and rehabilitation project that are identified as potential candidates projects for the following three years [*10*]. The RAPT team consists of a number of representatives from the agencies central planning team, regional staff and contractors responsible for the works programme for a particular region. The team, travelling together in a bus, would visit all identified candidate sites to make a final decision on the treatment strategy being it to be included for construction or differed and monitored for later years. The RAPT reviews are an integral part of the maintenance contracts (Network Outcome Contracts) that are in place to manage the road networks for the state highways. These contracts are a performance based contracts that are further described in Hunt and Hart [*11*]

The overall objectives of the RAPT reviews are to [*10*]:

- *“Improving consistency in performance across the Transport Agency’s dispersed network;*

- *Developing the capability of team members;*
- *Developing a greater awareness of strategic focus that the Transport Agency wants to see embedded in forwarding works programmes;*
- *Highlighting asset management and work practice opportunities; and,*
- *Spreading good ideas around the country*."

The RAPT reviews take a number of information sources and programme suggestions to inform their decision process. Some of the information sources are past condition performance, maintenance records, the existing 10-year programme, the forecasted modelling results, safety performance and existing contractors' programmes. The existing draft programme is then assessed according to the final decision process and reported for its appropriateness both in terms of timing and type of treatments (Refer to *Table 1*].

TABLE 1: Analysing the Timing of Treatments According of the RAPT Review Process

				Rehabilitation			Resurfacing		
	Early	Right	Late	Early	Right	Late	Early	Right	Late
Region 1	8	90	2	14	86	0	18	79	2
Region 2	10	82	8	0	78	22	22	71	5
Region 3	19	81	0	17	73	0	30	66	0
Region 4	20	75	4	41	3	24	22	77	0
Region 5	20	76	4	39	22	0	16	68	4
etc	24	75	1	66	34	0	34	64	1

Incorporating RAPT into Modelling Process

Asset Managers should be careful in using field validation to check on the robustness of modelling outcomes. The fundamental postulation of such a comparison suggests the field decision is always right. This raises the question that "i*f the field decision is always right, why do you need to run a model in the first place*?" Field inspectors are capable of judging future performance for a short time only and unlike the model often makes inconsistent decisions across a range of candidate sections. It has to realize that the modelling: given that it takes account of the full life-cycle cost and benefits; given that it optimize the outcome for the entire network; and, given that it 'views' an individual road section in context of the overall network, the answer from the model will most likely not be the same as the field inspections. The recommended approach in using field validation with a modelling approach is:

- When the modelling is still in its infancy implementation stage, field validations are useful to identify inappropriate renewal treatments. Experience has proven that in 80% of cases inappropriate treatment forecasts can be attributed to data issues;
- Compare the network level predicted renewal quantities, costs and condition profiles with actual historical achievement. An obvious test would be to assess the balance of predicted proactive and reactive investment levels against historical levels; and,
- Once the forecasting model has been sufficiently tested and refined, the emphasis shifts away from aligning the forecasted model and the final field decision to acknowledge it may be different but focusing on reasons why the field decision and model outcomes show a different approach.

Validating the 2016 Model Outcome to the Field Programme

At the onset of the Network Outcome Contracts, earlier modelling processes have been one of the core inputs into establishing the contractual renewal quantities or ‘baseline quantities’ [*11*]. Note that the baseline programme was established using the deterioration model that was then validated using the RAPT process described in the previous section. A critical outcome from the process was a significant reduction of the renewal program compared to historical levels With the 2016 analysis, it was, therefore, important to assess the model outcome in comparison to both the previous analysis (base line quantities) and to the contractors’ programmes. The aim was, therefore, to establish whether:

- the network needs are still addressed in a sustainable manner; and,
- what the impact would be of the 3-year programme on the long-term performance and investment needs for the state highway.

Therefore, while the earlier analyses and RAPT review validated a programme of works, the 2016 analyses’ aim was to establish a long-term investment strategy. For this reason, a network-wide quantity outcome comparison was deemed more appropriate. *Figure 12* shows the relative quantities between the model outcome, the contractors’ baseline and analysed outcomes from previous years. The high level of agreement between the programmes not only sufficiently validated the 2016 analyses outcomes but further gave the Agency comfort in terms of the appropriateness of their current approach to the Network Outcome Contracts.

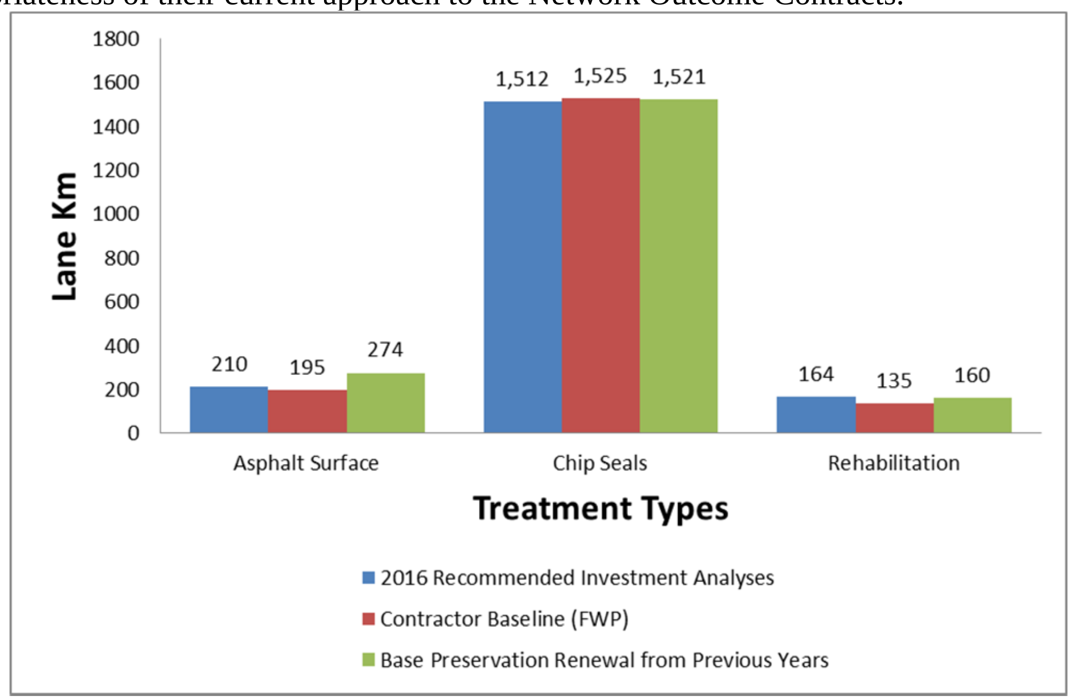

FIGURE 12 Comparing the Model Outcomes to Existing Programmes

SUMMARY AND CONCLUSIONS

This paper has documented the validation procedure undertaken on a PMS system adapted for New Zealand. Whereas many publications document the successful implementation of systems, this paper took a retrospective few of a system that has been used for more than 18 years. The paper has demonstrated a number of success factors that contributed towards the overall sustainability of the system. This is one of the outstanding aspects in the collaborative environment of the continuous technical development and improvements by modelling experts from a number of councils, consultants and contractors.

Because the New Zealand PMS are being used in the determination of long-term funding requirements and applications by road agencies, the robustness of the system was of utmost importance. The paper has shown a number of validations processes used for the latest long-term investment modelling for the national state highways. This validation literally tested the model approach from any possible viewpoint that included:

- Calibration of deterioration models using recognised best practice. In this instance the calibration dataset included detail data from LTPP sites and some network data;
- In addition to the direct model calibration, the overall forecasting aspects of the system were tested by retrospectively modelling (rolling back the clock). A comparison was undertaken between the current condition to the 5-year forecast from the system using condition data from five years ago and loading the actual maintenance and renewals programme from the past 5-years;
- The system's modelling approach, originally based on the World Bank HDM-III modelling philosophy, was tested by undertaking parallel model analyses based on a Markovian probabilistic approach that uses condition transition matrices; and,
- Lastly, the system forecasted maintenance quantities were also compared to prior years accepted renewal and maintenance programmes that were field validated.

An positive outcome was achieved through the validation process, not only proving beyond doubt that the system was robust within accepted confidence levels, but it also provided confidence to the agency that the current maintenance investment was at appropriate levels.

The main lesson from the extensive testing regime of the PMS was that the validation ultimately resulted in the significant improvement of the robustness over the years. These improvements included data quality improvements, refinements of forecasting models and improving the overall treatment logic of the system.

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