Austroads

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Interim Road Deterioration Cracking Model during Accelerated Deterioration

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Project Manager
David Alabaster

Prepared By
Lith Choummanivong
Dr Tim Martin

Publisher
Austroads Ltd.
Level 9, 287 Elizabeth Street
Sydney NSW 2000 Australia
Phone: +61 2 9264 7088
austroads@austroads.com.au
www.austroads.com.au

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Abstract
This report documents the process of assembling and reviewing the RMS NSW cracking data and the analysis of this data and its associated variables of climate, traffic load and pavement strength which has led to the development of a potential road deterioration cracking model under accelerated traffic load and deterioration conditions. A road deterioration cracking model is fully documented and compared with the current model which was based on the DPTI SA cracking data measured by the RoadCrack device.

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Summary

To improve both the coverage and quality of data and extend road deterioration (RD) modelling to pavements subject to increased loading so the cost of accelerated deterioration can be estimated, data was collected from Queensland and Western Australia in 2011–12. Data from the road segments identified by MRWA and QTMR was reviewed prior to proceeding to RD modelling. The aim was to examine this data during both the gradual and rapid deterioration phases. Additional data covering pavement condition, strength and traffic was made available for selected road segments from RMS NSW. The data supplied by the three road agencies was checked using an algorithm confirming that none of the road segments were in the rapid deterioration phase, despite the data showing increased deterioration in response to increased traffic load. The project therefore refocussed on existing RD cracking model refinement during the gradual deterioration phase using the data items sourced from RMS NSW.

A cumulative RD cracking model was developed for the RMS NSW combined asphalt (AC) and sprayed seal (SS) surfacings data. This model used an exponential function with two independent variables, cracking age and the Thornthwaite Moisture Index. The model was found to be statistically significant and reliable up to 50% of cumulative cracking. While the goodness of fit to the data was not high, it was reasonable considering the stochastic nature of cracking data.

The RMS and the previously acquired DPTI SA cracking data, used to develop the current Austroads RD cracking model, were found to be distinctly different in terms of their cracking behaviour and causal variables. A single robust cracking model capable of incorporating these differences was not developed by the project.

Separate cracking models for SS surfacings were not successfully developed from any of the agency databases. Combining the cracking data for both the AC and SS surfacings was the only current means to provide a cracking model that covers the behaviour of SS surfacings which is a significant limitation.

Although the exponential RD cracking model was based on RMS NSW data, potentially it could be used at a strategic network level to investigate the impact of no pavement resurfacing on future conditions such as rutting and roughness. This analysis can give support for appropriate levels of funding because it can predict the consequences of reduced maintenance on future conditions.

The 2013–14 program will progress RD modelling by acquiring data covering surface conditions, strength and traffic on road segments undergoing increased deterioration due to increased traffic load from selected long-term pavement performance (LTPP) sites in New Zealand and Australia. Another significant data source could be the accelerated loading facility (ALF) experiments on a cracked former in-service pavement where the impact of no maintenance on pavement deterioration was observed by accelerated cracking, pothole development and increased rutting and roughness.

Further RD modelling will address the improvement of existing models with an emphasis on improved capability for estimating cracking and other consequential forms of surface distress. An investigation of a different modelling approach by using data from before accelerated loading and data after accelerated loading to better account for the influence of the increased loading on cracking in the conventional RD model is suggested. Together, these refinements will provide a platform allowing modelling to be extended from predicting cracking to estimating pothole development and linking this distress to include increased rutting and roughness deterioration for overall RD modelling.

Contents

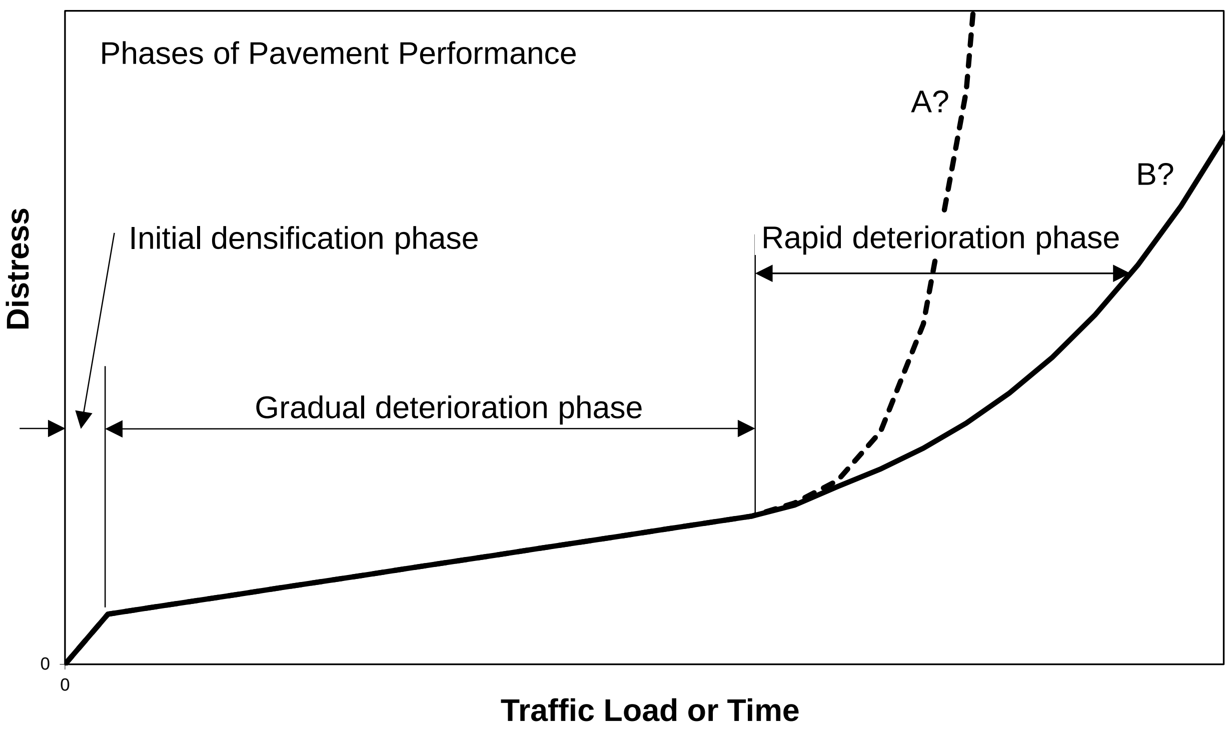
1. Introduction

Anecdotal evidence indicates that the rate of pavement deterioration and agency maintenance costs have increased above the expected norm in response to increased axle masses of heavy vehicles. Related ARRB research indicates that increased axle masses represent a response to increased allowable mass limits (high mass limits, HML, concessional mass limits, CML, etc.) coupled with the emergence or wider permitted use of large combination vehicles. A resulting use of high productivity vehicles in turn has led to higher on-road average heavy vehicle axle group masses. These developments combined, appear to have contributed to accelerated deterioration being observed in pavements with lower design strengths and pavements nearing the end of their life-cycles. This combination of factors is not satisfactorily handled by current asset management procedures and models.

A key issue associated with the impacts of higher than expected loadings was determining whether this occurred during the gradual deterioration phase immediately following pavement re-surfacing, or the rapid deterioration phase preceding surface failure occurring towards the end of surface life which is associated with ultimate pavement failure. The current Austroads functional and structural road deterioration (RD) models were developed only for the gradual deterioration phase of pavement performance (Austroads 2010a, 2010b) with the associated assumption that subsequent works interventions would preclude the subsequent accelerated, or rapid, deterioration phase. Recent climatic aberrations, traffic changes, and limits of road expenditures may make the complete compliance with the latter assumption somewhat problematic.

These models therefore cannot be used with any reliability once deterioration extends beyond the gradual deterioration phase (Martin 2009) for which the models were developed. Figure 1.1 illustrates the uncertainty regarding prediction of the rapid deterioration phase. In addition, the RD models were essentially based on traffic loads that did not increase significantly during the observational period. Impacts of accelerating load levels even during the gradual deterioration phase may thus not be validly modelled.

Figure 1.1: Uncertainty of predicting rapid deterioration



Any refinement of the existing RD models associated with accelerated loading during both the gradual and rapid deterioration phases would be of direct use in estimating road user charges for heavy vehicles particularly if associated with increased axle masses. This would contribute to the fair compensation of road agencies for the resulting additional road wear under these circumstances. These RD models could also be used to estimate the additional number of high productivity freight vehicles (HPFV), expressed in terms of SARs[1]/HVAG[2], that could be allowed on a particular road. This assumes that the existing levels of service (pavement surface conditions such as limits to roughness and rutting) can be exceeded under accelerating loading conditions, but can be limited to pavement condition levels that are less than those that represent the onset of the end of effective life (EEL) so as to reduce the risk of a rapid onset of pavement failure (Austroads 2008).

It can be argued that in most cases road agencies aim to intervene to maintain the existing levels of service and avoid accelerated deterioration. However, many road agencies often do not have the option of access to additional maintenance funding and the capacity to mobilise resources in a timely fashion due to the lack of resources available for some parts of the road network. Having the ability to predict and quantify the cost consequences of accelerated deterioration can demonstrate the overall significant benefits of earlier intervention for both the agency and the community.

1.1 Project Scope

This project has two related aims:

1. to substantiate the occurrence of increasing rates of pavement deterioration, including cracking, associated with accelerated pavement loading. Factors to be accounted for were to include road type/pavement categories and links to contributing factors such as pavement design, stage of pavement life-cycle, increasing axle mass limits and heavy vehicle configuration
2. to improve measurement and modelling of full life-cycle cracking performance of pavements to include accelerated deterioration in both the gradual and rapid pavement deterioration phases.

1.1.1 Data Selection Criteria

In order to achieve the project aims, the project in its first year (2011–12) identified specific road segments where the following selection criteria for pavement performance and traffic loading data were met:

- axle group load data, measured in annual equivalent standard axles (ESA) per lane, exhibiting higher than historical average growth rates
- availability of matching pavement condition data (cracking, roughness and rutting), or deterioration rates, either observed or inferred. Supporting details of pavement strength, stage of pavement life-cycle and immediate past maintenance and rehabilitation actions which could enhance modelling were collected where available.

The above data potentially provided causal links with increased rates of pavement deterioration under increased traffic load. Ideally, the increased traffic loading was expected to be mainly due to increased axle mass on the heavy vehicle axle groups rather than increased numbers of heavy vehicles.

A detailed analysis was recommended to be undertaken on the data from sites identified in Western Australia and Queensland in 2012–13 as supplied by their respective road agencies, Main Roads Western Australia (MRWA) and the Queensland Department of Transport and Main Roads (QTMR). This data generally met most of the data selection criteria and appeared to have observations of pavements subject to increased axle loading while experiencing increased deterioration (Austroads 2013).

It should be noted that work undertaken indicated that the condition data extracted from these sites was unlikely to be as reliable as that available in the long-term pavement performance and long-term pavement performance maintenance (LTPP/LTPPM) database. However, these additional identified sites were the best known sources available at the time.

[1] Standard axle repetitions.

[2] Heavy vehicle axle group, covering single axle single tyre (SAST), single axle dual tyre (STDT), tandem axle single tyre (TAST), tandem axle dual tyre (TADT) and triaxle dual tyre (TRDT).

1.1.2 Progress 2012-13

In 2012–13 the data from the road segments identified by MRWA and QTMR was reviewed as a precursor to undertaking RD modelling for accelerated deterioration during the gradual and rapid deterioration phases. Additional pavement condition data (roughness, rutting and cracking), strength and traffic data was obtained for road segments identified by the Roads and Maritime Services, New South Wales (RMS NSW). All of this data met the selection criteria outlined in Section 1.1.1.

Prior to proceeding with RD modelling, rutting and roughness data was evaluated using a pre-existing roughness and rutting algorithm (Martin 2009) to confirm whether the road segments were undergoing rapid deterioration. The algorithm confirmed that none of the road segment data fell into the rapid deterioration phase despite the data showing increased deterioration in response to increased traffic load.

The project therefore refocussed on existing RD model refinement using the additional data sourced from RMS NSW. This data set showed many road segments displayed increased deterioration for roughness, rutting and cracking associated with increased traffic load which could be associated with available strength (deflection) data. QTMR segment data did not contain strength, rutting and cracking data while the MRWA segment data did not contain strength and cracking data (Austroads 2013).

Improved deterioration modelling of surface cracking as measured by the RoadCrack device (Ferguson & Pratt 2002), was found to contribute to overall RD modelling as cracking is a key initiation parameter for the RD modelling of rutting and roughness.

1.2 Scope of Report

This report documents both the process of assembling and reviewing the RMS NSW cracking data and subsequently the analysis of this data and its associated variables of climate, traffic load and pavement strength. This has led to the development of a potential RD cracking model applicable under accelerated traffic load and deterioration conditions, but within the gradual deterioration phase as shown in Figure 1.1. The RD cracking model is fully documented and compared with the current RD cracking model (Austroads 2010a) as derived from Department of Planning, Transport and Infrastructure, South Australia (DPTI SA) cracking data as measured by the RoadCrack device.

1.3 Future Work

In 2013–14 it is proposed that the project identify and acquire additional condition, strength and traffic data in addition to cracking information for road segments undergoing increased deterioration under increased traffic load. This data could be extracted from an enlarged range of selected LTPP sites from both the New Zealand LTPP project and the Austroads LTPP/LTPPM project. Existing accelerated load testing experimental data on cracked pavements may also be used in combination with observational data to enhance outcomes. This would facilitate extension of the analysis and refinement of the RD modelling to include the combined impact of reduced maintenance and increased traffic loading, an increasingly likely scenario. Combined impacts can lead to extensive cracking and increased deterioration with important implications for asset management and performance.

Additional observational data identified at specific road segments would be assessed using the selection criteria outlined in Section 1.1.1. If complying data are sufficient in number, significant progress with the development of RD models (cracking, rutting and roughness) focussing specifically for accelerated deterioration during the gradual deterioration phase should be possible.

2. Data Collection and Assembly

2.1 Data Collected from Western Australia and Queensland

Table 2.1 summarises the data available from selected road segments that met most of the selection criteria outlined in Section 1.1.1 in Queensland (Qld) and Western Australia (WA). The coverage by each data item proved variable. The Queensland data did not have measured rutting, deflection (strength) and cracking, while the Western Australian data did not have measured deflection and cracking.

Table 2.1: Summary of road segment data from Queensland and Western Australia

State	Traffic (ADT, %HV, ESA)	Rut (mm)	Roughness (IRI)	Strength (deflection)	Cracking (% total lane)	No. of records
QLD	4 years (1999–2002)(1) with 3 classes of HV	n/a	Increase in IRI/year	n/a	n/a	78 one kilometre long road segments
WA	3–5 years (2004–10)(1) with 12 Austroads classes	Lane rut (1999–2010)(1)	IRI (1999-2010)(1)	n/a	n/a	100 sites with 100 m long segments per traffic station (37 stations)

1 Condition/traffic data range or specific year condition data measured.

2.2 Data Collected from New South Wales

Additional pavement condition data (roughness, rutting and cracking), strength and traffic data was sought and made available for selected road segments in NSW by RMS NSW. All of this data met all the selection criteria outlined in Section 1.1.1.

This additional data was sought due to limits in consistency of the WA and Qld data sets. While cracking observations were available, it could not be reconciled with the time period for which roughness and rutting measurements were available. The NSW road segments were located in both rural and urban areas. Most of the rural segments had a sprayed seal surface (SS), while most of the urban segments had an asphalt (AC) surface. Segments were one lane wide with lengths that varied from 100 m to 1000 m, depending on the data segmentation process undertaken by RMS NSW.

While RMS NSW provided data for over 18 000 road segments, this was reduced to 197 segments in order to meet the selection criteria and provide full coverage of surface distress, strength and adequate traffic data. Of the 197 segments, 71 were AC surfaced and 126 were SS surfaced.

Surface condition data was collected annually over a four-year period (2009 to 2012), allowing estimation of the linear rate of progression (LPR) for rutting and roughness deterioration which was used in the data selection process. The LPR for cracking was also estimated, but was not used in the data selection process as it would have further reduced the data available for model development.

Traffic data was supplied in terms of average annual daily traffic (AADT), percentage of heavy vehicles, (%HV), and an average equivalent standard axle per heavy vehicle, (ESA/HV). Traffic was measured using various devices comprising: (i) simple axle counter; (ii) vehicle type classifier; and, (iii) weigh-in-motion (WIM) system. The WIM was used to estimate axle masses and therefore ESAs used to calculate average ESA/HV. Estimation of the annual traffic growth rate, R, was based on three successive years of AADT measurement, but using only the last two years for AADT measurement. Estimated annual traffic growth rates varied from −30% to +10%.

2.2.1 Data Assembly

Several sub-databases were involved in data acquisition and assembly. The road inventory and condition (rutting, roughness and cracking) databases were easily merged because they used common locational references. However, both the falling weight deflectometer (FWD) measurements of surface deflection and traffic measurements did not align directly with the inventory and condition data and required some assessment of where this data aligned with the other data on the segments.

2.2.2 Estimation of Variables

Pavement age, AGE (years)

The original construction date, or last rehabilitation date, was the basis for estimating pavement age, *AGE*, in years, whichever was the lesser.

MRWA have advised that this variable is less reliable than in the past due to the use of light/thin rehabilitations than do not qualify for a resetting of pavement under the MRWA business rules.

Traffic load (millions of equivalent standard axles, MESA per lane per year)

The annual traffic load in each road segment lane was based on the following equation (Equation 1) once each of the traffic variables had been assigned to each segment:

$$MESA = [AADT \times \%HV/100 \times ESA/HV \times TF \times LDF \times 365]/10^6 \qquad 1$$

where

LDF	=	lane distribution factor: 0.5 (two-lane road) and 0.475 (multi-lane road, equivalent to 0.95 for two-lane carriageway)
AADT	=	average annual daily traffic (vehicles per day)
ESA/HV	=	average equivalent standard axle per heavy vehicle
TF	=	traffic growth rate factor (included in traffic data)
	=	$1 + 0.01 \times R$
R	=	annual traffic growth rate (%)

All other terms are as previously defined.

MRWA use the Austroads Classes (1 to 12) to represent both light and heavy vehicles with assumed values for the ESAs per heavy vehicle class rather than using the ESA/HV approach.

Initial pavement/subgrade strength (SNC_0)

The modified structural number for pavement/subgrade strength, SNC, has historically been used to represent the strength of the pavement and subgrade (Watanatada et al. 1987). SNC_0, the initial pavement/subgrade strength at zero pavement age for each segment, was based on its measured maximum falling weight deflectometer (FWD) deflection, D_0, to estimate the pavement/subgrade strength, SNC_i, at the time 'i' of its measurement. SNC_i was estimated as follows (Equation 2) for granular base pavements (Paterson 1987):

$$SNC_i = 3.2 \times D_0^{-0.63} \qquad 2$$

where

SNC_i = modified structural number for pavement/subgrade strength at the time 'i' of its measurement

D_0 = maximum FWD deflection

SNC_0 was estimated using the following relationship (Austroads 2010b) (Equation 3) which was based on observation data from the granular base pavements at the Austroads LTPP/LTPPM sites:

$$SNC_0 = \frac{SNC_i}{0.9035 \times [\, 2 - EXP(0.0023 \times TI_i + 0.185 \times AGE_i \,/\, DL\,)\,]} \qquad 3$$

where

TI_i = Thornthwaite Moisture Index at the time 'i' of its estimation

AGE_i = pavement age at time 'i' (years)

DL = design life of pavement (years)

All other terms are as previously defined.

Climate – Thornthwaite Moisture Index (TI)

TI is a broad measure of climate (Thornthwaite 1948) and is understood to influence pavement performance. The *TI* value was assessed for each segment and each year of data observation using a special tool developed by Austroads (2010d) with the Bureau of Meteorology climate database and the GPS co-ordinates of each segment. As a result of changing climatic conditions, the values of *TI* also changed during the observation period. As the estimated *TI* is dependent on annual rainfall and maximum and minimum temperatures, the estimate of *TI* can vary from year to year so a five year moving average of *TI* was used to reduce this variability for RD model development. This approach while reducing the variability of *TI* may also tend to mask the extreme values of *TI* which may have more influence than the moving average.

Cracking age

The Cracking age (years), that is, how old the existing cumulative cracking is estimated to have occurred, for both sprayed seal (SS) and asphalt (AC) surfacings, was estimated from the following (Equation 4):

$$\text{Cracking age, crx}AGE = \text{seal age at the initiation of cracking} - \text{adjusted seal life} \quad (4)$$

where

seal age	=	number of years since the seal was applied
adjusted seal life	=	seal ratio × estimated seal life (years)
seal ratio	=	mean observed seal age for the initiation of cracking (cracking between 0.5% and 1.5%)/mean estimated seal life

The above mean values were based on the number of surface segments used in the modelling analysis.

It should be noted that the mean observed seal age for the initiation of cracking was the seal age, in years, based on the amount cracking observed to measure between 0.5% and 1.5%. This definition implies that the mean observed seal age for the initiation of cracking was based on a seal age where the mean amount of observed cracking was 1%. Ideally the observed seal age for the initiation of cracking should be the seal age immediately after surface cracking begins to appear. However, this observation is not made as part of a routine cracking survey.

Estimated seal life for sprayed seal (SS)

The estimated seal life for the SS surfacings, prior to the initiation of cracking, was estimated using the following model (Austroads 2010c) which is based on bitumen embrittlement due to oxidation (Equation 5):

$$Y = \left[\frac{0.158 \times TMIN - 0.107 \times R + 0.84}{0.0498 \times T - 0.0216 \times D - 0.000381 \times S^2}\right]^2 \quad (5)$$

where

Y	=	seal life (years)
T	=	(TMAX + TMIN)/2
TMIN	=	yearly mean of the daily minimum air temperature (°C)
TMAX	=	yearly mean of the daily maximum air temperature (°C)
D	=	ARRB durability test result (days, usually taken as 8 to 10); adopted D = 9
S	=	nominal size of seal (nominal stone size, mm)
R	=	risk factor with a scale from 1 (very low risk) to 10 (very high risk); adopted R = 10

Seal life is also a function of a number of other variables, including traffic load and pavement strength. However, the approach adopted here allows an objective estimation of seal life with the minimum amount of supporting data available.

Estimated life for asphalt (AC) surfacings

The estimated seal life for the AC surfacings, prior to the initiation of cracking, was based on the following model (Austroads 2010c) (Equation 6):

$$Y = (0.323 \times TMIN - 0.169 \times T - 0.848 \times \sqrt{A_v} + 5.217)^2 \qquad 6$$

where

A_v = air voids of the asphalt surfacing at the time of sampling (5.5% assumed)

All other terms are as defined previously.

Table 2.2 shows a summary of the seal ratio estimated for both AC and SS surfacings for the RMS NSW data and the DPTI SA data used in the Austroads (2010a) RD cracking model. The DPTI cracking data is compared with the RMS cracking data in subsequent sections. The difference between the mean observed seal age for the initiation of cracking and estimated seal life is larger for AC surfacings in both NSW and SA. This suggests that Equation 6 used to estimate the life of AC surfacings needs further refinement.

Table 2.2: Summary of estimation of the seal ratio

Source			Mean observed seal_age for initiation of cracking (years)	Estimated seal life (years)	Seal ratio
MA	Surface type	Statistics			
RMS NSW	AC	N(1) = 39	–	–	0.558
		Mean	9.9	17.8	
	SS	N = 79	–	–	1.060
		Mean	5.8	5.4	
DPTI SA	AC	N = 90	–	–	1.516
		Mean	21.1	13.9	
	SS	N(1) = 45	–	–	3.538
		Mean	17.8	5.0	

1 Number of segments.

2.3 Check on Segment Data for Rapid Deterioration Phase

The segment data from NSW and WA was tested to determine whether any of the data was in the rapid deterioration phase. The Queensland segment data could not be tested because it did not have rutting measurements. The algorithm used to test whether the data is in either the gradual or rapid deterioration phase is defined as follows (Martin 2009) (Equation 7) based on the accelerated load testing of various surface treatments:

$$\text{If } (rut_{max} + 11.008 \times IRI \geq 86.347) \text{ then rapid deterioration phase has been reached} \qquad 7$$

where

rut_{max} = mean maximum vertical deformation from the original surface profile (mm) with an absolute maximum value of 25 mm

IRI = International Roughness Index (m/km)

Equation 7 only considers the distress due to rutting and roughness to determine whether gradual or rapid deterioration is occurring, regardless of the state of cracking. Cracking may contribute to increasing rutting and roughness but it not accounted for in Equation 7. Equation 7 was applied to all the roughness measurements and if the measured rutting for each corresponding roughness measure exceeded that predicted by Equation 7, then this particular data was deemed to be in the rapid deterioration phase. Analysis of all the available NSW and WA data showed that none of the data obtained was in the rapid deterioration phase.

The above outcome determined that all RD modelling could only be confined to the gradual deterioration phase even though all the collected data was experiencing increased traffic load.

3. Cracking Model Development

3.1 Approach

The RD model development focussed on developing, or refining, the existing RD crack model, which was based on SA data (Austroads 2010a), assuming applicable pavements were in the gradual deterioration phase. It had not been possible to determine from the data whether the traffic loading was increasing on these road segments. The data selected for further analysis was restricted to RMS NSW data, as it alone fully met the selection criteria outlined in Section 1.1.1.

3.1.1 'S' Shaped Function

The initial RD cracking model form selected for development used an 's' shaped function based on the logistic function which has been regularly used to model propagation of attributes through populations (Upton & Cook 2002). One of the key attributes of this function is that it allows cracks to be initiated and progress from 0% area cracking to a theoretical value of 100% cracking, while at the same time preventing estimation of out-of-range cracking estimates. Figure 3.1 shows a theoretical s shaped function which meets these boundary conditions and is only dependent on the cracking age, crx*AGE*, the number of years of the existing cracking. The s shaped function is defined as follows for the percentage of cumulative cracking (Equation 8), %Cum crx, with two independent variables, crx*AGE* and TI_{av}:

$$\%\text{Cum crx} = 100 - 200 \times (1 + \text{EXP}((a \times \text{crx}AGE / ((200 - TI_{av}) / 25))^{b}))^{-1} \quad (8)$$

where

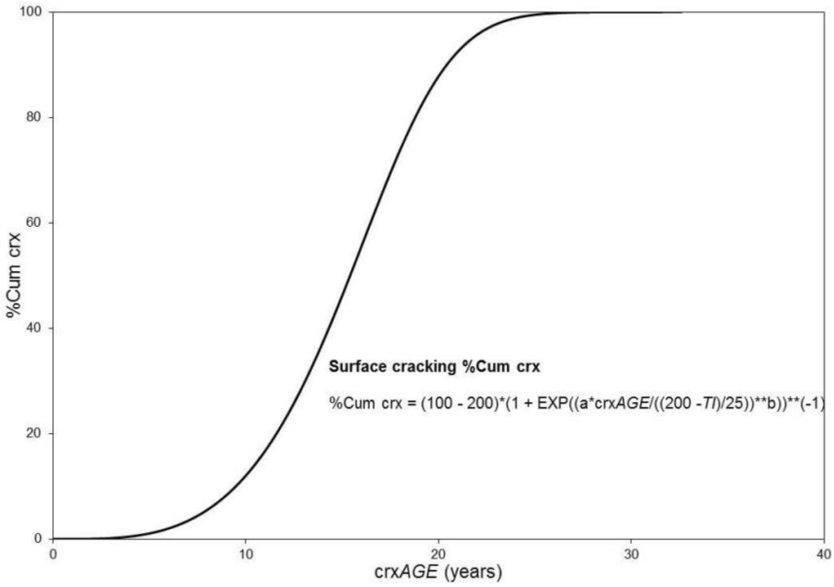
TI_{av} = average Thornthwaite Moisture Index over the years of cracking observation

crx*AGE* = number of years of existing cracking

a and b = regression coefficients

All other terms are as defined previously.

Figure 3.1: 'S' shaped function cracking model



Ideally this form of cracking model may be expected to be a function of other independent variables such as traffic load and pavement strength. This extension was not pursued at this stage because model complexity impeded simple analysis of crack distress associated with accelerating traffic load. The previous Austroads (2010a) RD cracking model used the 's' shaped function shown in Figure 3.1 incorporating the cracking age, crx*AGE*, and climate, TI_i, variables. A simpler functional approach as reported below was devised to investigate this mode of crack projection, with the option of adapting findings into a multinomial s curve in future work, if these proved suitably rewarding. In this context a more adaptable s function of sigmoidal forms, such as the Gompertz or Gumble functions, which allow saturation levels to be fixed at less than 100% cracking would be trialled.

3.1.2 Exponential Function

A simple exponential function was developed and fitted to RMS NSW data. This model predicted a potentially greater increase in cracking with cracking age relative to the 's' shaped function and is shown in Figure 3.2. The exponential function has been constrained to meet the required boundary conditions. This functional form is simple to fit by regression methods and could lend itself to the introduction of other multiplicative variables that may also influence the cumulative cracking.

Several exponential functions are defined as follows (Equation 9a, Equation 9b and Equation 9c) which include various independent variables provided they are statistically significant:

$$\%\text{Cum crx} = 100 \times \left(\text{EXP}(a \times \text{crx}\mathit{AGE}) - 1 \right) \tag{9a}$$

$$\%\text{Cum crx} = 100 \times \left(\text{EXP}(a \times \text{crx}\mathit{AGE} \times \text{MESA}^{b}) - 1\right) \tag{9b}$$

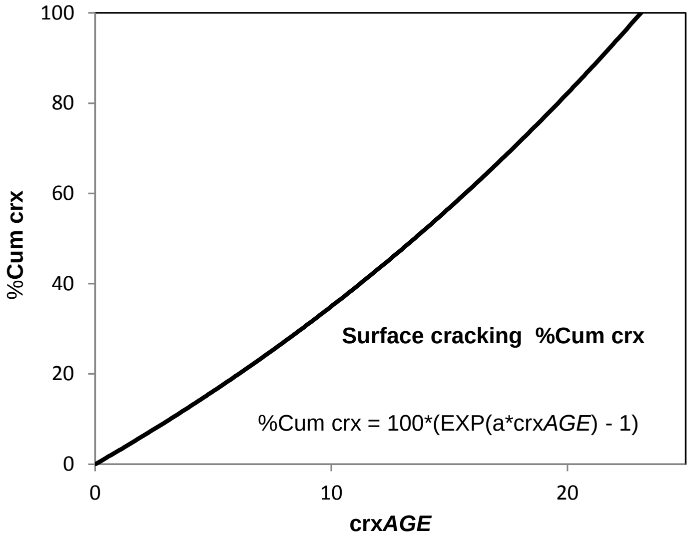
$$\%\text{Cum crx} = 100 \times \left(\text{EXP}(a \times \text{crx}\mathit{AGE} \times ((100+TI_{av})/100)^{b}) - 1\right) \tag{9c}$$

where

a and b = regression coefficients

All other terms are as defined previously.

Figure 3.2: Exponential RD cracking model



3.1.3 Other Functional Forms

Other functional forms for the cracking model were considered involving multiple variables in an additive form in an attempt to incorporate the influence of these independent variables and to examine their relative explanatory power with respect to the cumulative cracking. Several forms of these functions, consistent with the available RMS NSW data, used were as follows (Equation 10a, Equation 10b, Equation 10c, Equation 10d, Equation 10e, Equation 10f and Equation 10g):

$$\%\text{Cum crx} = \text{crx}AGE^{a} + b \times \text{EXP}((100 + TI_{av})/100) + c \times \text{SNC}_0 \qquad \text{10a}$$

$$\%\text{Cum crx} = a \times \text{crx}AGE + b \times TI_{av} + c \times AGE \qquad \text{10b}$$

$$\%\text{Cum crx} = \text{EXP}(a \times \text{crx}AGE) + b \times TI_{av} + c \times AGE \qquad \text{10c}$$

$$\%\text{Cum crx} = \text{crxAGEa} + b \times \text{EXP}((100 + \text{TIav})/100) + c \times \text{SNC0} + d \times \text{LN(MESA)} \qquad \text{10d}$$

$$\%\text{Cum crx} = \text{crx}AGE^{a} + b \times \text{LN(MESA)} + c \times AGE + d \times TI_{av} \qquad \text{10e}$$

$$\%\text{Cum crx} = \text{crx}AGE^{a} + b \times \text{LN(MESA)} + c \times AGE \qquad \text{10f}$$

$$\%\text{Cum crx} = \text{crx}AGE^{a} + b \times \text{LN}((100 + TI_{av})/100) + c \times AGE \qquad \text{10g}$$

where

AGE	=	pavement age (years) when crx*AGE* = 0
a, b, c, and d	=	regression coefficients

All other terms are as defined previously.

Both the exponential function, EXP, and the natural logarithm, LN, are used in the various forms of Equation 10a. However, all forms of Equation 10a did not meet the initial boundary condition that when crx*AGE* is zero then the cumulative cracking is zero, unless all other independent variables were set to zero. Therefore the various forms of Equation 10a were not used as a basis for the refined cracking model.

3.1.4 Discussion

A review of all the RMS NSW cracking data, including both AC and SS surfacings, showed that the maximum value of cumulative cracking, %Cum crx, was around 43%, although most of the cracking was less than 30% with a mean value of around 6%. The South Australian (SA) cracking data, including both AC and SS surfacings, showed slightly higher levels of cracking with a mean value of 11% and a maximum value of 53%.

The above shows that neither of the databases is extensive and they cannot be reliably expected to predict cracking beyond their cracking range of 43% to 53%. Consequently, the prediction of cumulative cracking beyond 53% is speculative and not reliable based on the current available data.

Pavements with cumulative cracking approaching 100% are not apparent in any databases examined by this study or any previous studies, largely because intervention is usually initiated well before this amount of cracking occurs to minimise the growth of potholes and other forms of surface distress.

3.2 Model Development - Initial Analysis

The results of preliminary modelling, using the various functional forms with a range of independent variables, are summarised in Appendix A.

3.2.1 'S' Shaped Function

Table A 1 shows that this functional form (Equation 8) fits the RMS cracking data for AC surfacings and the combination AC and SS surfacings. The model fit to the data is slightly better for the AC and SS surfacings combination (r^2 = 0.27) rather than for AC surfaces alone (r^2 = 0.25). This model does not fit the RMS cracking data for SS surfaces (r^2 = 0.03).

Table A 3 shows a similar result to the above was found for the SA cracking data, however, the model fit was significantly worse for the AC and SS surfacings combination (r^2 = 0.12). No measure of data fit was obtained for the SS surfacings.

When the AC and SS cracking data from RMS and SA were combined, the resulting model fit to the data was lower than that found for the RMS data alone (r^2 = 0.13) as shown in Table A 5. As noted in Section 2.2, the RMS data was available on segment lengths varying from 100 m to 1000 m, while the SA data was uniformly available on 100 m long segments (Austroads 2010a). To compensate for this segment length discrepancy, the longer RMS segments were subdivided into shorter lengths which increased their numbers to approximately equal the number of SA segments. This weighting process, however, did not significantly change the resulting model for the combined AC and SS cracking data from RMS and SA (Table A 5).

These outcomes strongly suggest that the RMS and SA cracking data sets are distinctly different. Further work to account for differences is required before the option of combining within a single functional form. Further work, and possibly additional data collection is required to determine why current investigations failed to develop a satisfactory model for estimating cracking for SS pavements, from either RMS or SA data.

3.2.2 Exponential Function

Table A 1 shows that this functional form (Equation 9a, Equation 9b and Equation 9c) fits the RMS cracking data for AC surfacings and the combination of AC and SS surfacings. The best model fit to the data is Equation 9c with two independent variables, crx*AGE*, and TI_i, for the AC and SS surfacings combination (r^2 = 0.33) rather than for AC surfaces alone (r^2 = 0.26). This model does not fit the RMS cracking data for SS surfaces (r^2 = 0.01). When the independent variable for traffic load, MESA, was used in lieu of the climate variable, TI_i, in the model for the AC and SS surfacings combination, the fit to the data was reduced (r^2 = 0.2) and this variable predicted reduced cracking with increasing traffic load. Also the traffic load variable was not found to be statistically significant ('t' value = –0.6).

Table A 2 shows that Equation 9b with three independent variables provided the best fit (r^2 = 0.37) to the combined RMS data for AC and SS surfacings. However, this model had one variable predicting reduced cracking with increasing traffic load. The exponential model form did not provide a good data fit when the AC and SS cracking data from RMS and SA were combined (Table A 5 and Table A 7).

The above outcome confirms that the climate variable, TI_i, is a better predictor of cracking than the traffic load variable, MESA. Similar to the s shaped function, the RMS and SA cracking data sets were found to be distinctly different and no remotely reliable model could be developed for the SS cracking data for either the RMS or SA data.

3.2.3 'S' Shaped and Exponential Functions Compared

Figure 3.3 shows both Equation 8 and Equation 9c fitted to the SA cracking data for the AC and SS surfacings. The Equation 8 model was a relatively better fit (r^2 = 0.12) to the SA cracking data than the Equation 9a model (r^2 = 0.01). Figure 3.3 clearly shows that these models give distinctly different predictions for cumulative cracking for all values of cracking age. Figure 3.3 also shows that the Equation 9c model fitted to the RMS cracking data for the combined AC and SS surfacings gives a different prediction model for cumulative cracking compared to the Equation 9c model fitted to the SA cracking data. The comparison between the Equation 9c models for RMS and SA data again clearly confirms that RMS and SA data sets are very different.

Figure 3.4 shows the Equation 8 model fitted to the RMS and SA cracking data for the combined AC and SS surfacings. In this case the Equation 8 model gives a closer prediction for cumulative cracking for RMS and SA data, although the initial rates of cracking are quite different. Figure 3.4 also shows that the Equation 8 and Equation 9c models for the RMS cracking data for the AC and SS surfacings combined appear to give relatively similar predictions, although as noted earlier, the Equation 9c model fits the RMS data slightly better than the Equation 8 model.

Figure 3.3: Comparison of model types for RMS and SA data (Equations 8 and 9a)

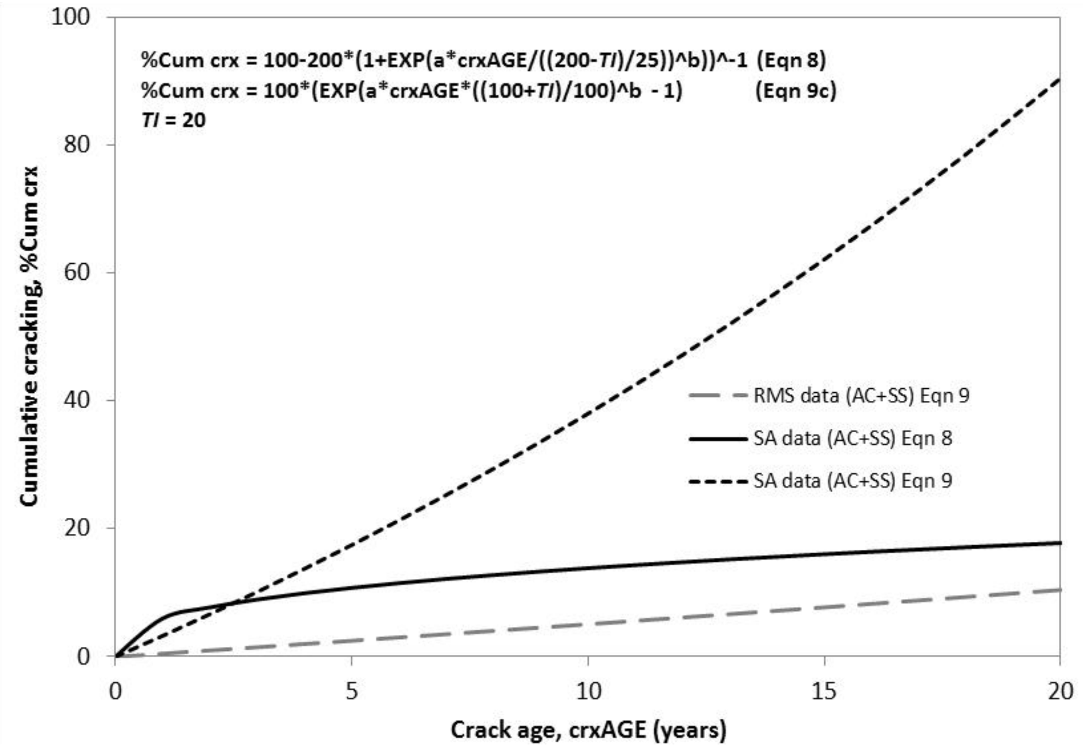
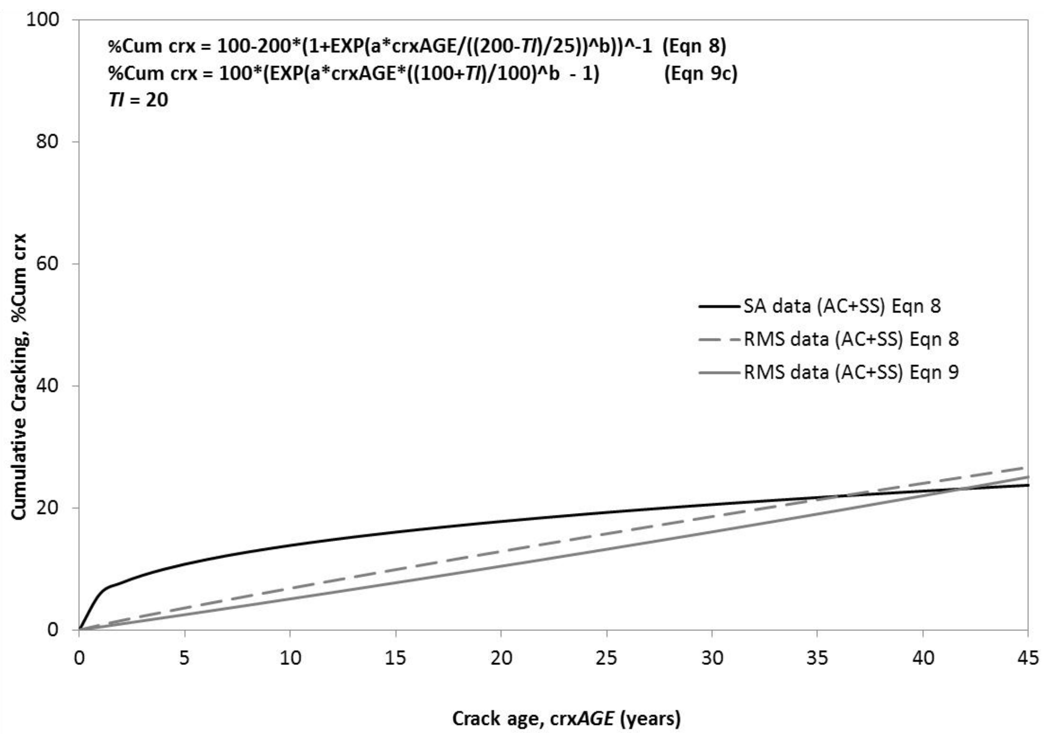


Figure 3.4: Comparison of model types for RMS (Equations 8 and 9a) and SA data



3.2.4 Other Functional Forms

A number of forms of Equation 10a were used as shown in Table A 1, Table A 2, Table A 3, Table A 4, Table A 6 and Table A 7. None of these models provided a superior data fit to the above exponential function. It is interesting to note that in Table A 2 when the pavement strength variable, SNC_0, was used (Equation 10a) it was statistically significant and had the expected impact on cracking, that is, an increase in strength would reduce the amount of cracking. It was also found that the pavement age, *AGE*, was a contributor to increased cumulative cracking which is not unexpected as an older pavement may be expected to crack at an increased rate of cracking.

As noted in Section 3.1.3, none of these functional model forms meet the initial boundary conditions of zero cumulative cracking at zero cracking age. Consequently this model form was not used in the final RD cracking model development. However, these models did confirm the potential explanatory power of additional independent variables such as the traffic load, pavement strength and pavement age. These variables were only made available by means of the RMS NSW cracking data.

3.3 Model Development - Analysis and Further Work

3.3.1 Discussion of the Analysis Outcome

The analysis undertaken in Section 3.2 has shown that a cumulative cracking model can be developed for the RMS combined AC and SS surfacings data using an exponential function of two independent variables, cracking age, crx*AGE*, and the average Thornthwaite Moisture Index, TI_{av}. A summary of the Equation 9c model's test statistics is as follows:

$$\%Cum\ crx = 100 \times (EXP(a \times crxAGE^*((100 + TI_{av})/100)^{**}b) - 1)$$

a = 0.003 SE[3] = 0.001 't' value[4] = 3.0 ($p < 0.05$)

b = 2.77 SE = 0.451 't' value = 6.15 ($p < 0.05$)

Goodness of fit to data, $r^2 = 0.33$ Number of observations = 197

Maximum likelihood ratio test statistic, LRTEST = 78.0 (2 degrees of freedom) ($p < 0.05$).

The above test statistics show that the model is statistically significant in all respects and could be considered to be reliable at least up to around 50% of cumulative cracking. While the goodness of fit to the data is not high, it is considered reasonable when regarding the stochastic nature of cracking data, even when measured by a consistent device such as RoadCrack.

The use of the above model for the combined AC and SS surfacings therefore does not recognise any significant difference in the cracking behaviour of these surfacings once they are cracked. Table 2.2 shows that these surfacings commence cracking at different surface ages with the SS surfacings taking less time to commence cracking than the AC surfacings.

Figure 3.5 shows the RMS cracking data model for the combined AC and SS surfacings predicting a significant range of cumulative cracking under a wide range of Thornthwaite Moisture Index, *TI*, values from −20 to +80.

The RMS and SA cracking data were found to be distinctly different and therefore should not be combined in an attempt to produce a more robust cracking model.

Separate cracking models for SS surfacings were not able to be developed for any of the databases, indicating that the behaviour of this form of cracking is difficult to predict for any of the databases. Combining the cracking data for both the AC and SS surfacings is currently the only means to provide a cracking model that includes the SS surfacings.

[3] Standard error.

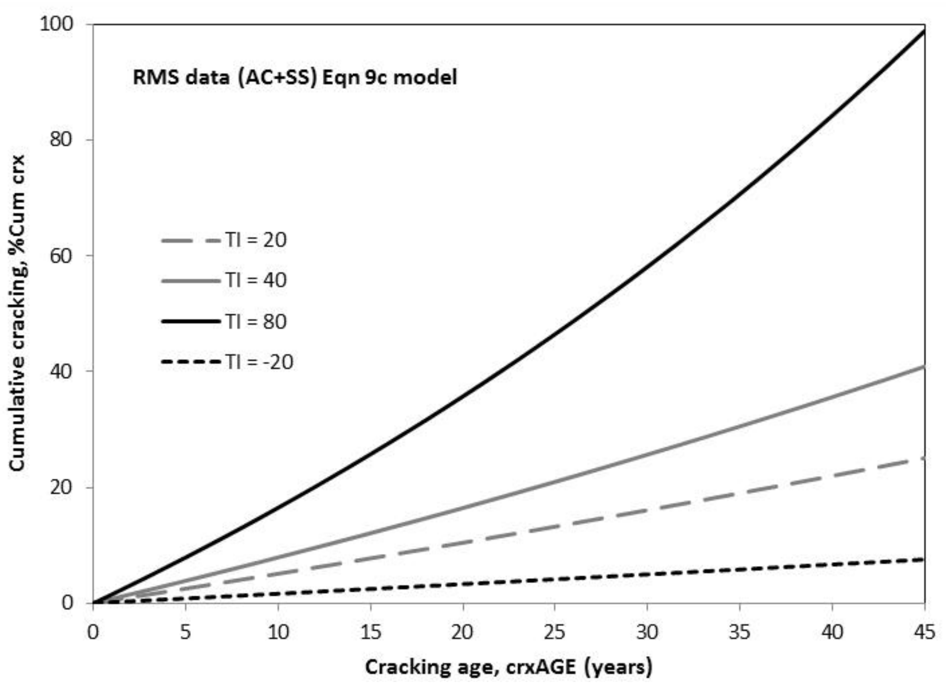
[4] 't' value is the ratio of the parameter estimate (regression coefficient) divided by the standard error.

The use of additional independent variables was not found to improve the explanatory power of the exponential model form; although these variables were shown to be useful in other model forms, these other models did not comply with the boundary conditions. It is likely that these other variables, such as strength and traffic load, will influence cumulative cracking when higher loads in combination with inadequate pavement strength occur. From this study there appears to be no suitable observational data available to capture the impact of these variables.

Figure 3.5 shows that the RMS cracking data model, based on Equation 9c, for combined AC and SS surfacings can predict significant cracking at values of *TI* ranging from 40 to 80 where the prevailing climatic conditions are wet and humid. Full tropical conditions give a *TI* value of at least 100 to further increase the cumulative cracking. On the other hand, drier climatic conditions with a *TI* value of –20, Equation 9c predicts relatively low rates of cumulative cracking.

It should be noted that this model is strictly only for RMS NSW roads, although in the absence of any other suitable RD cracking model, it could be applied at a strategic network level to investigate the impact of no pavement resurfacing on future conditions such as rutting, roughness and strength. This type of analysis is essential to provide support for appropriate levels of funding because it can examine the consequences of severely reduced maintenance budgets on future pavement conditions.

Figure 3.5: RMS data (AC+SS) using Equation 9c model



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This project has examined the road condition databases of the road agencies over 2011–12 and 2012–13 and only found that the RMS NSW database met the data selection criteria outlined in Section 1.1.1. In addition, none of the data examined was found to have represented cracking, rutting and roughness conditions in the rapid deterioration phase, despite the road segments experiencing measured or estimated increases in traffic load and increased deterioration over time. As a consequence, the RD models developed or refined are only appropriate for application during the gradual deterioration phase.

3.3.2 Comparison with Previous Cracking Models

Figure 3.4 compares the cumulative cracking predicted by Equation 9c for the RMS combined AC and SS surfacings with the cumulative cracking predicted by the Austroads (2010a) cracking model based on the SA data for the SS and AC surfacings.

Figure 3.6: Comparison of RMS data (AC+SS) with Equation 9c model and SA data with previous cracking model

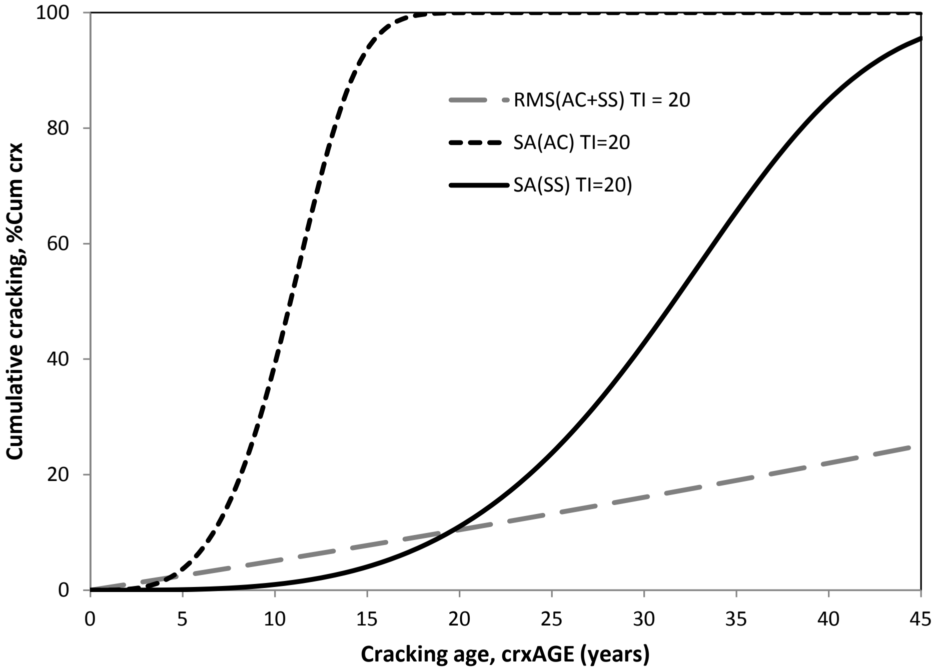

Figure 3.4 shows that the RMS combined AC and SS surfacings model initially predicts a greater rate of cumulative cracking than the Austroads (2010a) model for SS surfacings for up to 19 years. The Austroads (2010a) model predictions for cumulative cracking of AC surfacings exceeds those of the RMS combined AC and SS surfacings model after five years.

It should be noted that the Austroads (2010a) cracking model fit to the SS surfacings data was not determined while the model fit the AC surfacings data was high (r^2 = 0.74). This suggests that this model could also have been based on the combined AC and SS surfacings data from SA. The Austroads (2010a) model form is the ‘s’ shaped function while the RMS combined AC and SS surfacings model is an exponential function which further confirms that the RMS and SA cracking data are distinctly different.

3.3.3 Further Work in 2013-14

In 2013–14 the project could assess and use the additional condition, strength and traffic data available on road segments undergoing increased deterioration under increased traffic load from selected segments on New Zealand’s LTPPT project and selected segments on the Austroads LTPP/LTPPM project. This would extend the current data for the analysis and refinement of the RD modelling to account for the impact of reduced maintenance and increased traffic loading which can cause extensive cracking and other forms of surface distress leading to increased deterioration.

A further source of data is that from the accelerated loading facility (ALF) experiments on a cracked former in-service pavement (Martin & Gleeson 1999) and an artificially cracked pavement under controlled environmental conditions examining the impact of surface maintenance on pavement deterioration (Martin et al. 2000).

The first data source, under ALF load trafficking and continuous surface wetting, observed the development of further cracking by producing more cracks within a given area (increased crack intensity) and growth in the width of the existing cracks. Potholes were also observed to grow from the existing surface cracks. The second data source, also under ALF load trafficking and continuous surface wetting, observed pothole growth from the artificial surface cracks, but no crack growth or increased crack width was observed, largely due to the fact that the SS surfacing was less than one year old and the cracks were artificially cut into the surface.

The first data source may be able to be used to refine, or validate, the RMS combined AC and SS surfacing RD cracking model. This experimental data, in combination with the observational performance data from the other sources (RMS NSW, LTPP/LTPPM and NZ LTPP), should contain road segments with complete condition, strength and traffic data that can enable further RD model refinement in 2013–14. This refinement can be extended from cracking to pothole development and include rutting and roughness RD modelling.

In terms of modelling, investigation of a different approach by using data from before accelerated loading and data after accelerated loading to better account for the influence of the increased loading on cracking in the conventional RD model.

3.3.4 Work Beyond 2013-14

This project has established that quantified condition, strength, cracking and other forms of distress data available to develop RD models into the rapid deterioration phase does not exist under current observational practices. This is largely due to the road agencies intervening, by and large, with maintenance treatments before the rapid deterioration phase is reached.

As a consequence the only way this type of data will be gained is by the use of some form of accelerated load-testing where distress conditions can be safely observed and measured during the rapid deterioration phase. Ideally the testing should be conducted on an in-service pavement with existing surface cracking.

4. Summary

4.1 Outcomes for 2012-13

Data from road segments identified by MRWA and QTMR in 2011–12 was reviewed with the intention to proceed to RD modelling of deterioration associated with accelerated loading during the gradual and rapid deterioration phases of pavement wear. Additional pavement condition data (roughness, rutting and cracking), strength and traffic data was made available from selected road segments by RMS NSW. The RMS data met the required selection criteria. The data supplied by the above three agencies was assessed using an algorithm which confirmed that the road segments studied were not in their end-of-life rapid deterioration phase, despite the data showing increased deterioration in response to increased traffic load.

The project therefore refocussed on RD cracking model development and refinement applicable to the gradual deterioration phase using the data sourced from RMS NSW. This road segment data set showed increased deterioration for roughness, rutting and cracking with increased traffic load and incorporated additional pavement strength data.

An acceptable cumulative RD cracking model was developed for RMS combined AC and SS surfacings data using an exponential function of two independent variables, cracking age and the average Thornthwaite Moisture Index. The test statistics showed that the model was statistically significant in all respects and could be considered to be reliable at least up to 50% of cumulative cracking, a practical limit. While the goodness of fit to the data is not as high as hoped, it is reasonable when regarding the stochastic nature of cracking data.

The RMS and the existing SA cracking data, used to develop the current Austroads RD cracking model, were found to indicate distinctly different outcomes. Further work is required to determine the causes of differences before results are combined within an over-arching model.

Acceptable stand-alone cracking models for SS surfacings were not achieved for any of the databases. Further data collection and refinement of analysis is warranted to address this issue as the largest proportion of the road network is represented by SS surfacings. Combining the cracking data for both the AC and SS surfacings is currently the only means to provide a cracking model that includes the SS surfacings which is a significant limitation.

The use of additional independent variables was not found to improve the explanatory power of the exponential model form, although these variables were shown to be useful in other model forms. These other models did not comply with the boundary conditions. A follow-up assessment of other alternative modelling structures has located several candidates; shaped or sigmoidal model structures which will facilitate improved modelling.

Although the RD cracking model is based on RMS NSW data, in the absence of any other suitable RD cracking model, it could be applied at a strategic network level to investigate the impact of no pavement resurfacing on future conditions such as rutting, roughness and strength. This is an issue of concern to asset managers in the current economic climate. This type of analysis is essential to provide support for appropriate levels of funding because it can examine the consequences of severely reduced maintenance budgets on future pavement conditions.

4.2 Further Work in 2013-14

In 2013–14 the project can benefit from the identification and use of the condition, strength and traffic data available on road segments undergoing increased deterioration under increased traffic load from the LTPP sites in both New Zealand and Australia. This would extend coverage and detail of data underpinning analysis and refinement of the RD modelling to account for the impact of reduced maintenance and increased traffic loading which can cause extensive cracking and other forms of surface distress leading to increased deterioration.

A further source of productive data could be obtained from ALF experiments on a cracked former in-service pavement that examined the impact of surface maintenance on pavement deterioration. This approach could be used to observe the development of further cracking by producing more cracks within a given area (increased crack intensity) and growth in the width of the existing cracks. Potholes have previously been observed to grow from the existing surface cracks. This approach is likely to yield data and relationships extremely hard to obtain from infrastructure surveys, even using the most sophisticated techniques available.

The experimental data could be used to refine, or validate, the RMS combined AC and SS surfacing RD cracking model. This data in combination with the observational performance data from the other sources (RMS NSW, LTPP/LTPPM and NZ LTPPT) can enable further RD model refinement in 2013–14. This refinement can be extended from cracking to pothole development and include rutting and roughness RD modelling.

4.2.1 Work Beyond 2013-14

This project has established so far that insufficient quantities of condition, strength, cracking and other forms of distress data are available to develop RD models into the rapid deterioration phase under current observational practices. This is largely due to the road agencies intervening, by and large, with maintenance treatments before the rapid deterioration phase is reached.

As a consequence, the only reliable way sufficient of this type of data will be gained is by the use of some form of accelerated load-testing where distress conditions can be safely observed and measured during the rapid deterioration phase. Ideally the testing should be conducted on an in-service pavement with existing surface cracking and other distress.

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Appendix A Preliminary Cracking Modelling

A.1 Analysis of RMS NSW and DPTI SA Data

A.1.1 RMS Data

Table A 1: RMS data fitted to various functions (two variables maximum)

Function:	%Cum crx = 100–200*(1 + EXP((a*crxr*AGE* / ((200 – TI_{av}) / 25))**b))**(–1) (Equation 8)						
Case	a	't' value	b	't' value[1]	N	F[2]	r^2
AC	0.06	1.7	0.706	4.0	71	11.3	0.25
SS	0	0.2	0.36	1.9	126	1.9	0.03
AC+SS	0.083	3.6	0.921	7.5	197	35.9	0.27
Function:	%Cum crx = a*crx*AGE* + b*LN((100 + TI_{av}) / 100) (Equation 10a)						
Case	a	't' value	b	't' value	N	F	r^2
AC+SS	0.762	17.3	6.019	3.7	197	34.1	0.26
Function:	%Cum crx = 100*(EXP(a*crx*AGE*) – 1) (Equation 9a)						
Case	a	't' value	b	't' value	N	F	r^2
AC+SS	0.006	13.0	–	–	197	48.6	0.2
AC	0.008	8.0	–	–	71	12.2	0.15
Function:	%Cum crx = 100*(EXP(a*crx*AGE**MESA**b) – 1) (Equation 9b)						
Case	a	't' value	b	't' value	N	F	r^2
AC+SS	0.006	6.0	–0.04	–0.6	197	24.3	0.2
AC	0.006	6.0	–0.179	–2.1	71	8.5	0.2
Function:	%Cum crx = 100*(EXP(a*crx*AGE**((100 + TI_{av}) / 100)**b) – 1) (Equation 9c)						
Case	a	't' value	b	't' value	N	F	r^2
AC+SS	0.003	3.0	2.77	6.1	197	47.8	0.33
AC	0.004	3.8	2.32	3.3	71	11.9	0.26
SS	0.002	2.0	3.435	3.5	126	0.7	0.01

1 't' value is a measure of the statistical significance of the independent variable. Values > 2.9 are regarded as statistically significant ($p < 0.05$).
2 F value is an approximate measure of the statistical significance of the whole model. Values > 2.7 are regarded as statistically significant ($p < 0.05$).

Table A 2: RMS data fitted to various functions (three variables maximum)

Function:	%Cum crx = crx*AGE***a + b*EXP((100 + TI_{av}) / 100) + c*SNC_0 (Equation 10a)								
Case	a	't' value	b	't' value	c	't' value	N	F	r^2
AC	0.826	11.3	1.602	2.9	–0.31	–2.1	71	8.3	0.27
Function:	%Cum crx = a*crx*AGE* + b*TI_{av} + c*AGE* (Equation 10b)								
Case	a	't' value	b	't' value	c	't' value	N	F	r^2
SS	0.138	1.6	0.034	2.4	0.035	2.9	126	3.1	0.07
Function:	%Cum crx = 100*(EXP(a*crx*AGE**MESA**b*((100 + TI_{av}) / 100)**c) – 1) (Equation 9b)								
Case	a	't' value	b	't' value	c	't' value	N	F	r^2
AC+SS	0.002	4.3	–0.185	–3.2	3.561	7.0	197	37.8	0.37

A.1.2 DPTI SA Data

Table A 3: SA data fitted to various functions (two variables maximum)

Function:	**%Cum crx = 100 – 200*(1 + EXP((a*crxr*AGE* / ((200 – TI_{av}) / 25))**b))**(–1) (Equation 8)**						
Case	**a**	**'t' value**	**b**	**'t' value**	**N**	**F**	r^2
AC	0.019	1.7	0.341	4.0	482	29.6	0.11
SS	0	0.03	0.115	0.7	61	-	-
AC+SS	0.022	1.9	0.366	7.6	543	35.8	0.12
Function:	**%Cum crx = 100*(EXP(a*crx*AGE**((100 + TI_{av})/100)**b) – 1) (Equation 9c)**						
Case	**a**	**'t' value**	**b**	**'t' value**	**N**	**F**	r^2
AC+SS	0.014	24.9	4.571	3.6	543	1.4	0.01

Table A 4: SA data fitted to various functions (three variables maximum)

Function:	**%Cum crx = EXP(a*crx*AGE*) + b*TI_{av} + c*AGE (Equation 10c)**								
Case	**a**	**'t' value**	**b**	**'t' value**	**c**	**'t' value**	**N**	**F**	r^2
AC	0.088	4.4	0.285	5.5	0.294	21.0	482	8.3	0.32
AC+SS	0.08	4.0	0.298	8.8	0.299	23.0	543	110	0.38
Function:	**%Cum crx = a*crx*AGE* + b*TI_{av} + c*AGE (Equation 10b)**								
Case	**a**	**'t' value**	**b**	**'t' value**	**c**	**'t' value**	**N**	**F**	r^2
SS	0.101	0.8	0.346	6.2	0.376	9.4	61	21.4	0.53

A.2 Combined Analysis of RMS NSW and DPTI SA Data

A.2.1 RMS and DPTI SA Data

Table A 5: RMS+SA data fitted to function (two variables maximum)

Function:	**%Cum crx = 100 – 200*(1 + EXP((a*crxr*AGE*/((200 – TI_{av}) / 25))**b))**(–1) (Equation 8)**						
Case	**a**	**'t' value**	**b**	**'t' value**	**N**	**F**	r^2
AC+SS	0.03	2.6	0.443	9.3	740	55.0	0.13
AC	0.014	1.6	0.333	7.2	553	30.5	0.10
SS	0	0.06	0.156	1.2	187	–	–
AC+SS(1)	0.032	2.9	0.48	10.4	888	68.5	0.13
AC(1)	0.009	1.5	0.314	7.1	601	29.6	0.09
SS(1)	0	0	0.156	1.6	287	1.1	0.01
Function:	**%Cum crx = 100*(EXP(a*crx*AGE**MESA**b) – 1) (Equation 9b)**						
Case	**a**	**'t' value**	**b**	**'t' value**	**N**	**F**	r^2
AC+SS	0.012	20.1	0.073	2.3	740	14.6	0.04

1 RMS data weighted to match SA data segments.

Table A 6: RMS+SA data fitted to function (four variables maximum)

Function:	**%Cum crx = crx*AGE**a* + b*LN((100 + *TI*$_{av}$) / 100) + c**AGE* + d*LN(MESA) (Equation 10d)**										
Case	**a**	**'t' value**	**b**	**'t' value**	**c**	**'t' value**	**d**	**'t' value**	**N**	**F**	r^2
AC+SS	0.721	14.4	1.164	4.8	0.204	14.6	4.731	2.7	740	64.6	0.26
AC	0.531	5.2	4.45	1.8	0.254	14.5	0.226	0.7	553	48.1	0.26
Function:	**%Cum crx = crx*AGE**a* + b*LN(MESA) + c**AGE* + d* *TI*$_{av}$ (Equation 10e)**										
Case	**a**	**'t' value**	**b**	**'t' value**	**c**	**'t' value**	**d**	**'t' value**	**N**	**F**	r^2
AC+SS	0.726	15.0	1.139	4.7	0.201	14.4	0.029	1.8	740	64.6	0.26

Table A 7: RMS+SA data fitted to function (three variables maximum)

Function:	**%Cum crx = crx*AGE***a + b*LN(MESA) + c**AGE* (Equation 10f)**								
Case	**a**	**'t' value**	**b**	**'t' value**	**c**	**'t' value**	**N**	**F**	r^2
AC+SS(1)	0.77	21.4	1.175	6.1	0.173	14.4	888	98.2	0.25
AC(1)	0.56	6.7	0.143	0.5	0.241	15.1	553	64.3	0.26
Function:	**%Cum crx = crx*AGE***a + b*LN((100 + *TI*$_{av}$) / 100) + c**AGE* (Equation 10g)**								
Case	**a**	**'t' value**	**b**	**'t' value**	**c**	**'t' value**	**N**	**F**	r^2
AC(1)	0.543	6.2	0.631	0.3	0.24	15.0	601	66.3	0.25
SS(1)	0.188	1.3	0.853	0.9	0.031	3.9	287	2.9	0.03
SS	0.035	0.2	0.889	0.7	0.048	4.4	187	1.9	0.04
Function:	**%Cum crx = 100*(EXP(a*crx*AGE**MESA**b*((100 + *TI*$_{av}$) / 100)**c) – 1) (Equation 9c)**								
Case	**a**	**'t' value**	**b**	**'t' value**	**c**	**'t' value**	**N**	**F**	r^2
AC+SS	0.016	16	0.136	3.9	5.063	4.1	543	8.3	0.04

1 RMS data weighted to match SA data segments.

Austroads

Level 9, 287 Elizabeth Street
Sydney NSW 2000 Australia
Phone: +61 2 9264 7088
austroads@austroads.com.au
www.austroads.com.au