The prediction of pavement remaining life

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Abbreviations and acronyms

AADT	Average annual daily traffic
dTIMS	Deighton Total Infrastructure Management System
ESA	Equivalent standard axle
HDM	Highway design and maintenance
IRI	International roughness index
NPV	Net present value
NASSRA	Measurement of road roughness by recording the upward vertical movement of the rear axle of a standard station sedan relative to the vehicle's body as the vehicle travels at a standard speed along the road being tested. A cumulative upward vertical movement of 15.2 mm corresponds to one NAASRA Roughness Count (1 NRM/km).
PPM	Pavement performance modelling
PSMC	Performance specified maintenance projects

Contents

Executive summary

The objectives of the project were twofold. The first objective was to develop criteria for defining the end-of-life condition of pavements. These criteria could be applied in pavement deterioration modelling and mechanistic pavement design to obtain a more robust measure of the remaining life of pavements. They could also be used in dTIMS, PSMC and the New Zealand supplement to the Austroads (2004) *Pavement design manual: A guide to the structural design of road pavements*.

The second objective was to generate a new model for maintenance costs. Neither the Austroads (2004) *Pavement design manual* or dTIMS take into consideration the most significant reason for pavement rehabilitation which is the anticipation of increased maintenance costs. The rehabilitation of the majority of New Zealand pavements has been justified through the net present value (NPV) of expected future maintenance costs but it has not been known if the anticipated cost increases were associated with cracking, deformation, material breakdown or unstable surfacings. This project was designed to obtain an understanding of the factors behind the cost increases and, as a result, to enable models to be developed for predicting the conditions leading to increased maintenance costs.

Examination of rehabilitation justification reports confirmed that maintenance cost was being used as a major factor driving rehabilitation even when roughness and rutting levels were moderate.

None of the maintenance cost models developed were particularly successful at producing a reliable prediction of maintenance costs based on the pavement characteristics available from RAMM. However, a combined model showed that derived maintenance costs did not rise dramatically with time as had been commonly assumed.

A logit model was developed to predict rehabilitation decisions. The major factors were maintenance cost, followed by traffic levels and roughness. The model developed for this study predicted the rehabilitation decision well. Approximately 72% of pavements that had been rehabilitated were predicted as requiring rehabilitation. Consequently 28% of the pavements predicted as requiring rehabilitation had not been rehabilitated. It would be of interest to investigate how many of these will be rehabilitated over the next couple of years. When tested on the Nelson network data a similar level of performance was obtained.

This study is a good starting point and the maintenance cost models and the rehabilitation models will both be useful. However, a number of questions have been raised as a consequence of this work. If maintenance costs cannot be predicted with a high level of reliability, and previous studies have shown that roads are not being rehabilitated because of high roughness and rutting levels, then why are pavements being rehabilitated?

It is essential that end users of the models developed in this project realise that the historical length of the data is potentially insufficient. As time progresses, further data will become available to refine the models.

Abstract

The primary objective of the project was the development of criteria to define the end-of–life condition of pavements. These criteria could then be used in pavement performance modelling to obtain a more robust measure of remaining life. Another objective was the generation of a new model for maintenance costs. This could then be combined with the existing models for roughness and rutting to define a distress level at which rehabilitation should occur. None of the maintenance cost models developed were particularly successful in producing a reliable prediction of maintenance costs based on the pavement characteristics available from RAMM. Therefore, a logit model was developed to predict rehabilitation decisions. The major factors in the rehabilitation model were maintenance costs, traffic levels and roughness. The rehabilitation decision model derived for this study predicted rehabilitation decisions well. Approximately 72% of pavements that had been rehabilitated were predicted as requiring rehabilitation. When tested on the Nelson network data, which was not used for calibration of the model, a similar performance was obtained indicating the models developed were relatively successful.

1. Introduction

The aim of this project was to develop criteria to define the end-of-life condition of pavements. The criteria could then be applied in pavement performance modelling (PPM) and mechanistic pavement design to obtain a more robust measure of remaining life. The criteria could also be included in the Deighton Total Infrastructure Management System (dTIMS[1]) modelling for use in performance specified maintenance contracts (PSMC) and in PPM, and incorporated in the New Zealand supplement to the Austroads (2004*) Pavement design manual: A guide to the structural design of road pavements*.

Another objective was the generation of a new model for maintenance costs which could be combined with the existing dTIMS models for roughness and rutting to define a distress level at which rehabilitation needed to be performed.

Among the conclusions of Bailey et al. (2006) in their study entitled ‘Relationship between design and predicted performance of New Zealand pavements’ are the following three statements:

1. The majority of the shape correction and reconstruction on New Zealand pavements is being driven by increased maintenance costs rather than structural deterioration.
2. A large percentage of these pavements have significant remaining life when analysed according to the Austroads pavement design guide criteria.
3. On New Zealand’s relatively lightly trafficked granular pavements a life in excess of 50 years is common.

The Austroads (2004) *Pavement design manual* and dTIMS do not account for the most significant factor for initiating pavement rehabilitation which is the anticipation of increased maintenance costs. The rehabilitation of the majority of New Zealand pavements has been justified through the net present value (NPV) of expected future maintenance costs but it has not been known if the anticipated cost increases were associated with cracking, deformation, material breakdown or unstable surfacings. This project was designed to obtain an understanding of the factors behind the cost increases and as a result, to enable models to be developed for predicting the conditions leading to increased maintenance costs.

AUSTROADS’ mechanistic pavement design is currently used in New Zealand for new pavements and also to obtain a measure of remaining life for PSMC contracts. The mechanistic design method gives ‘life’ in terms of total traffic ie, it states that the pavement is expected to have reached a terminal level of distress after a number of equivalent standard axle (ESA) passes. The method does not provide the shape of the

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[1] In 1998 New Zealand adopted the software platform dTIMS from Deighton Associates for the predictive modelling of pavement deterioration. The basic models used in dTIMS are derived from the highway design and maintenance standard series (HDM) models.

deterioration curve and so it is impossible for an estimate to be made of the remaining life of an existing pavement in terms of roughness or rutting.

The Austroads (2004) mechanistic design method is sensitive to small changes in the granular thickness. This can be seen if the number of passes of design traffic is considered in terms of years. For a typical pavement on a subgrade California Bearing Ratio of 10%, a change in thickness of the granular layers from 256 to 276 mm would increase the design traffic from 9×10^5 to 1.8×10^6 ESA, that is, doubling the pavement's life. Neglecting traffic growth, this suggests that if the design traffic occurred over 25 years then the increase in life associated with an increase in granular thickness of 20 mm would be from 25 to 50 years. It is obvious that the sensitivity of the mechanistic design system to very small changes in granular thickness makes it an unsuitable tool for predicting remaining life.

New Zealand has adapted the HDM pavement deterioration models into the dTIMS package. This package can give an estimate of the rate of change of pavement shape (roughness and rutting) with time and then be used to predict the age at which rehabilitation due to structural distress needs to be performed. In HDM the routine maintenance cost is calculated as the cost to repair distress, such as cracking, ravelling, rutting and potholing.

In the New Zealand dTIMS, there are two options available for maintenance cost modelling: one for Transit New Zealand (Transit NZ) networks and the other for local authority networks. The initialisation procedure, which is the same for both options, is the average of the last three years' pavement and surfacing maintenance cost data or the use of a default if the information is not available. Under the Transit NZ option, the future routine maintenance cost is calculated as the cost to repair various faults such as cracking and potholes. This is similar to the HDM approach. On the other hand, under the local authority option, the routine maintenance cost is modelled as a function of pavement age and surface width. The regional differences are taken into account with the use of four coefficients which can be adjusted to suit local conditions. There is, however, little guidance on how to calibrate these coefficients to local conditions.

As discussed above, the two maintenance cost modelling options available in the NZ dTIMS do not model maintenance cost explicitly. Instead, maintenance costs are calculated as a combination of historic costs plus the cost of repairing age-related pavement deterioration. The experience gained through dTIMS implementation over the last few years suggests that dTIMS prediction for pavement rehabilitation needs to be improved. Also, improvement in maintenance cost modelling is necessary to increase the quality of rehabilitation predictions as most pavement rehabilitations are justified on the basis of savings in future maintenance cost.

This project considered that until a model was developed that allowed the prediction of increased maintenance costs then the prediction of remaining life or the prediction of the total pavement life would not be possible.

On a network level it has been found that the average maintenance costs do not increase with pavement age, that is, there is a constant cost of $x/m2/yr (Loader 2000a). However, some pavements begin to require increased maintenance after a variable length of time – 20, 30, 50 or even 80 years. The factors that allow identification of these pavement sections are not currently defined and there is no understanding of the types of maintenance being performed.

Previous studies by Loader (2000a and 2000b) identified a number of potential flaws within the RAMM data. Of particular concern was the lack of standardisation of maintenance costs. While acknowledging the potential for poor data, the RAMM database was the only source of information available and was used for this study.

This project was, therefore, designed to develop a model of pavement performance that included pavement maintenance. The aim was to combine the current dTIMS models for roughness and rutting with the maintenance model into an algorithm. This would predict the time that an existing pavement section would take to exceed predefined performance levels. Remaining life would be the lesser of the time taken to exceed roughness, rutting or maintenance limits.

The prediction of remaining life is receiving international research attention and was regarded as a high priority at the 2004 International Conference on Managing Pavements. Most overseas countries however, are not concentrating their efforts on unbound granular pavements with chipseal surfacing, which is the predominant form of construction in New Zealand.

The RAMM system now provides for including maintenance costs. This data, together with a detailed analysis of the distress and maintenance trends of a range of pavements that had been recently rehabilitated, allowed a model to be developed.

The methodology consisted of the following tasks:

Task 1: Development of a database
Task 2: Collation of recent rehabilitation justifications
Task 3: Analysis and development of failure criteria
Task 4: Peer review
Task 5: Validation of the model on a network

1.1 Rehabilitation justifications

The rehabilitation of state highways in New Zealand requires pavement investigation reports to be submitted to Transit NZ to justify the rehabilitation of pavements based on the NPV of the rehabilitation versus the status quo of reactive maintenance.

Approximately 30 to 50 reports were examined to provide an indication of why pavements were being rehabilitated in New Zealand. In examining the Transit NZ rehabilitation justification reports submitted in 2003 for the 2004 and 2005 programme it became obvious that frequently, while rehabilitation was justified, there was a sensitivity to the scheduled timing of maintenance with the benefit cost ratio sensitive to the rescheduling of a resurfacing treatment. Consequently, predicted maintenance costs appeared to be a dominant factor in the rehabilitation justification decision.

Discussions with network managers indicated that their individual preferences probably had a strong influence on maintenance and rehabilitation practices. For example, excessive rutting in one network was determined by drive-by observations as to which ruts held rain after storms.

1.2 Creation of the database.

Spatial and construction details, condition and other information is collected and stored in the Transit NZ RAMM database. The size of the RAMM database precluded using all the treatment lengths available, particularly since data fields were often incomplete and required either manual editing or removal from the data set. It was decided to limit the study to a number of representative networks exported from RAMM. The chosen networks were:

- West Wanganui
- Southland
- Gisborne
- Hawke's Bay.

The West Coast network was originally included; however, the low level of rehabilitation on that network meant that there were not enough rehabilitated roads for accurate modelling purposes. The Gisborne and Hawke's Bay networks are separate networks but are currently maintained under a single contract. The physical environments of the two networks are quite different, with the Gisborne region frequently experiencing high levels of subsidence due to low strength *in situ* materials. Current management of the Hawke's Bay network involves a lot of stabilisation rehabilitations and has done so for over a decade.

1.3 Data massaging

In the networks examined, missing entries were frequent across different pavement condition measurements for the same treatment lengths. Often, if entries were missing for a specific condition measurement, they would be missing for other condition measurements for the same period. The missing information had the potential to skew any models so the data was edited. Treatment lengths with more than three continuous years of missing entries from any rating variable or high-speed survey variable were removed. It was assumed, however, that a missing maintenance cost entry meant that no money was spent on the road and these entries were set to zero. Discussions with a network manager confirmed this was the correct approach to take with the maintenance costs. If only one single variable was missing for the roughness and rutting measurements then the value was set at the average of the previous and following measurements.

1.4 Extraction of data from RAMM

Hand et al. (1999) suggest that engineering interpretation and judgement should play a significant role in model implementation. Accordingly, it was decided that three of the cost groups from the RAMM database were important for modelling maintenance costs. These were the pavement, shoulder and surfacing groups. The other cost groups of environmental, drainage, verge, bridge maintenance and management were not considered to include factors that would drive the rehabilitation of a pavement. Of the three cost groups selected the largest expenditure was on pavement, followed by surface, and then by shoulder as indicated in Table 1.1. In the table and for the remainder of the report the pavement maintenance cost will be denoted by MC_P, the shoulder maintenance cost by MC_{Sh}, and the surfacing maintenance cost by MC_{Su}.

Table 1.1. Relative expenditure for a number of networks.

	West Wanganui		**Southland**		**Gisborne and Hawke's Bay**	
	Total spent	Percentage of pavement expenditure	Total spent	Percentage of pavement expenditure	Total spent	Percentage of pavement expenditure
MC_{Sh}	$78,368	7%	$865,370	40%	$4,570,084	27%
MC_{Su}	$234,997	20%	$626,367	30%	$5,865,135	35%
MC_P	$1,134,650		$2,105,991		$16,672,419	

Shoulder maintenance faults for which the repair cost was recorded are indicated in Table 1.2. Of the three cost groups, shoulder maintenance is unique in that it does not have separate activities within its group.

Table 1.2 Shoulder maintenance faults.

Activity	Faults
Shoulder maintenance	edge break, edge rutting, high shoulder, low shoulder, scouring, reshape cross-section, soft shoulder and unknown faults.

The activities and faults recorded against the pavement cost group are presented in Table 1.3. Table 1.4 shows the activities and faults for which repair costs were recorded against surfacing. It should be remembered that while burning is no longer practised there is potential for the surfacing maintenance records to contain historic data for this activity. Maintenance costs do not incorporate emergency work resulting from events such as slips.

Table 1.3 Pavement maintenance activities and the faults recorded against individual activities.

Activity	Faults
Dig out activities (all pavements)	deformation, depression, drainage inadequate, fatigue cracking, saturated pavement, shear, slippage crack and unknown
Levelling activities	uneven abutment join, depression, rutting, reshape cross section, subsidence, uneven surface and unknown
Pothole repairs	potholes or unknown
Rip and remake	deformation, depression, shear failure, fatigue cracking, rutting and unknown
Service cover activities	broken, uneven and unknown
Stabilisation	deformation, depression, drainage inadequate, fatigue cracking, shear failure, subsidence, rutting and unknown
Surface openings	service, trench and unknown

Two other potential activities ‘concrete pavements’ and ‘unsurfaced roads’ are not indicated in Table 1.3 as the treatment length data selected did not include these road types.

Table 1.4 Surfacing maintenance activities and the faults recorded against individual activities.

Activity	Faults
Burn	bleeding, flushing and unknown
Fill crack	alligator cracking, isolated cracking, slip crack and unknown
Re-chip	bleeding, polished surface, scabbing, stripping, loss of texture and unknown
Seal crack	alligator cracking, isolated crack, slippage crack and unknown
Surface repair	alligator cracking, bleeding, flushing, isolated crack, polished surface, scabbing, slippage crack, striping, loss of texture and unknown

It was considered likely that repairs for pavement faults such as potholes and shoving were the dominant maintenance costs for roads. Alligator cracking, scabbing and flushing contributed to the surfacing maintenance cost, and edge break was the major damage mechanism for the shoulder maintenance cost group.

The RAMM fields were examined and those fields thought to influence maintenance costs and rehabilitation decisions were exported to a new database for use as parameters for model generation. The characteristics exported were alligator cracking, roughness (individual wheelpaths and an average of both wheelpaths), rut depth (individual wheelpaths and an average of both wheelpaths), scabbing, shoving, edge break, flushing, potholes and patching. Subsequent to this decision it was observed that a number of networks had not collected flushing data for 2004 and 2005. Flushing data was not required as a rating inspection output from 2004 and onwards and as a consequence some network authorities had stopped collecting the data. Therefore, flushing was not used in the model.

Consideration was given to combining potholes and patching into a single variable but their different measurement units meant this was not possible.

There are a number of methods used to measure roughness. The International Roughness Index (IRI) is progressively being adopted in New Zealand which has traditionally used the NAASRA. For this reason the roughness values used in this study were measured in IRI units.

Hand et al. (1999) recommend at least 15 years of data for the development of significant performance models. The reliability of the RAMM data prior to 1995 is questionable, therefore, it was decided to use only the 10 years from 1996 to 2005. Treatment lengths that were either not rehabilitated or rehabilitated in the years 2002, 2003, 2004 or 2005 were exported from the database for analysis. This provided at least six years of historic condition and maintenance cost information for all the treatment lengths to use in modelling the pavements.

1.5 Data characteristics

1.5.1 Normalisation rating inspections

When a rating inspection is performed a segment of the treatment length is examined. The same segment is inspected annually. For the rating data the condition characteristics considered relevant to this study were shoving, rutting, alligator cracking, potholes and edge break.

Table 1.5 Units of measurement for rating inspection.

Shoving	The extent of shoving in the pavement. The rating records the length of wheelpath, in metres, showing shoving in the inspection length.
Rutting	The rate for rutting is by length in metres.
Alligator cracking	The rating for alligator cracking is by length in metres.
Potholes	The number of potholes in the inspection length of carriageway. The rating for potholes is by number of potholes.
Edge break	The length of carriageway edge showing sign of edge break where there is no surfaced channel. The rating for edge break is by length in metres.

The usual units of measurement for rating inspections are indicated in Table 1.5. However, to allow comparison of ratings between different treatment lengths the rating data was scaled by multiplying the fraction of the inspection length to treatment length by 1000; in effect this means that the rating data is a measure of fault per kilometre. For each treatment length, shoving and alligator cracking data were normalised to a 1 km length. For example, if the treatment length was 100 m and the values for shoving and alligator cracking were 10 and 20 respectively, then the normalised values for shoving and alligator cracking were (10 × 1000/100=100 m) and (20 × 1000/100=200 m).

Once the rating data had been scaled, the rating data and the other pavement condition measures were further manipulated, by averaging the data over six years. This was to allow for a single input for each of the variables into the models. For rehabilitated treatment lengths, the data used was the six years before rehabilitation. For instance, if a treatment length was rehabilitated in 2001, the shoving data used in the modelling was the average of the data observed in 2000, 1999, 1998, 1997, 1996 and 1995. For treatment lengths that were not rehabilitated, the data pertained to the average over the years from 2000 to 2005.

The formats of the data used to generate the models are presented in Table 1.6.

Table 1.6 Variables used in the models.

Variable	**Symbol**	**Unit**	**Format**
Roughness	*IRI*	IRI	Average roughness in IRI (m/km) over six years.
Shoving	*Shoving*	m	Normalised data averaged over six years.
Rutting	*Rutting*	mm	Normalised data averaged over six years.
Potholes	*Potholes*	integer	Normalised data averaged over six years.
Alligator cracking	*Alligator Cracking*	m	Normalised data averaged over six years.
Edge break	*Edge Break*	m	Normalised data averaged over six years.
Scabbing	*Scabbing*	m^2	Normalised data averaged over six years.
Pavement maintenance cost	MC_P or $MC_{Pavement}$	Dollars	Cumulative maintenance cost per kilometre over six years for pavement cost group.
Surfacing maintenance cost	MC_{Su} or $MC_{Surfacing}$	Dollars	Cumulative maintenance cost per kilometre over six years for surfacing cost group.
Shoulder maintenance cost	MC_{Sh} or $MC_{Shoulder}$	Dollars	Cumulative maintenance cost per kilometre over six years for shoulder cost group.
Maintenance cost	MC or MC_{Total}	Dollars	Cumulative maintenance cost per kilometre over six years for shoulder cost group, ie, $MC = MC_P + MC_{Su} + MC_{Sh}$
Traffic levels	*Traffic*	Annual average daily traffic	As estimated in year 2005 for both rehabilitated and not rehabilitated treatment lengths.
Pavement age	*Pavement Age*	years	Number of years since construction or rehabilitation.
Urban or rural environment	*UrbanRural*	integer	Integer of either 1 for urban roads or 2 for rural roads.

A number of models used composite maintenance costs such as the sum of all the maintenance costs and the sum of the pavement and surfacing maintenance costs – the notations used in these cases were MC_{Total} and MC_{PSu} respectively.

One possible source of error that could not be identified from the RAMM data was the difference between maintenance funding that eliminated a problem in the treatment length and maintenance funding that delayed the need for rehabilitation without treating the fundamental cause of the problem. The authors are unaware of a methodology that would separate these two effects.

1.6 Database characteristics

The characteristic values for the four networks combined into a single database are displayed in Table 1.7. It is interesting to note that the maximum rut depth is 9.3 mm. Considering that there are 1979 treatment lengths in the data set, this would appear to indicate that rutting is not a significant problem for the four networks studied. It is possible that rutting is such a significant problem that repairs are performed immediately upon discovery thereby hiding the problem. The rating data is normalised, which means the average rutting is not high but there is potential for patches of high rutting to exist. Traffic levels ranged from a minimum average annual daily traffic (AADT) of 125 to a maximum of 24,000. The maximum maintenance expenditure for all treatment lengths was approximately $600,000 per kilometre. The maximum scabbing value in Table 1.7 is physically impossible, which indicates that despite being cleaned the data is still not totally reliable. All physical measures of pavement condition were positively skewed.

Table 1.7 Characteristic values for road parameters for combined network database of 1979 treatment lengths.

	Roughness (IRI)	Shoving (m)	Maintenance cost ($)	Traffic (AADT)	Alligator cracking (m)	Edge break (m)	Rut depth (mm)	Scabbing (m^2)	Potholes (number)
Average	3	10.3	$19,700	3020	29.1	23.7	4.0	317	2.3
Maximum	6.7	1667	$600,000	24,450	2770	710	9.3	13,138	167
Minimum	1.2	0	$0	125	0	0	0.9	0	0
Median	2.9	0	$10,500	1,840	0	4.3	3.9	92	0
Range	5.5	1667	$600,000	24,325	2770	710	8.4	13,138	167
Skew	0.87	19.6	6.3	2.3	14.3	5.1	0.80	7.2	8.8

1.7 Graphical interpretation

Data for the chosen networks was graphically examined to see if a pattern could be detected between maintenance costs and pavement condition indicators such as roughness and rutting. Figure 1.1 was obtained from the Napier data and illustrates a general trend observed, that rehabilitation of the road occurred two or three years after the year of maximum expense and just prior to rehabilitation maintenance expense dropping to zero. This is partially demonstrated in Table 1.8 where the average difference between the year of maximum maintenance expenditure and the year of rehabilitation is 3.2 years. This is logically the result of the network manager's decision not to waste money maintaining a section of road when that section was to be rehabilitated. It is suspected that, if they existed, any maintenance costs incurred in the two- to three-year period prior to rehabilitation were for safety reasons only.

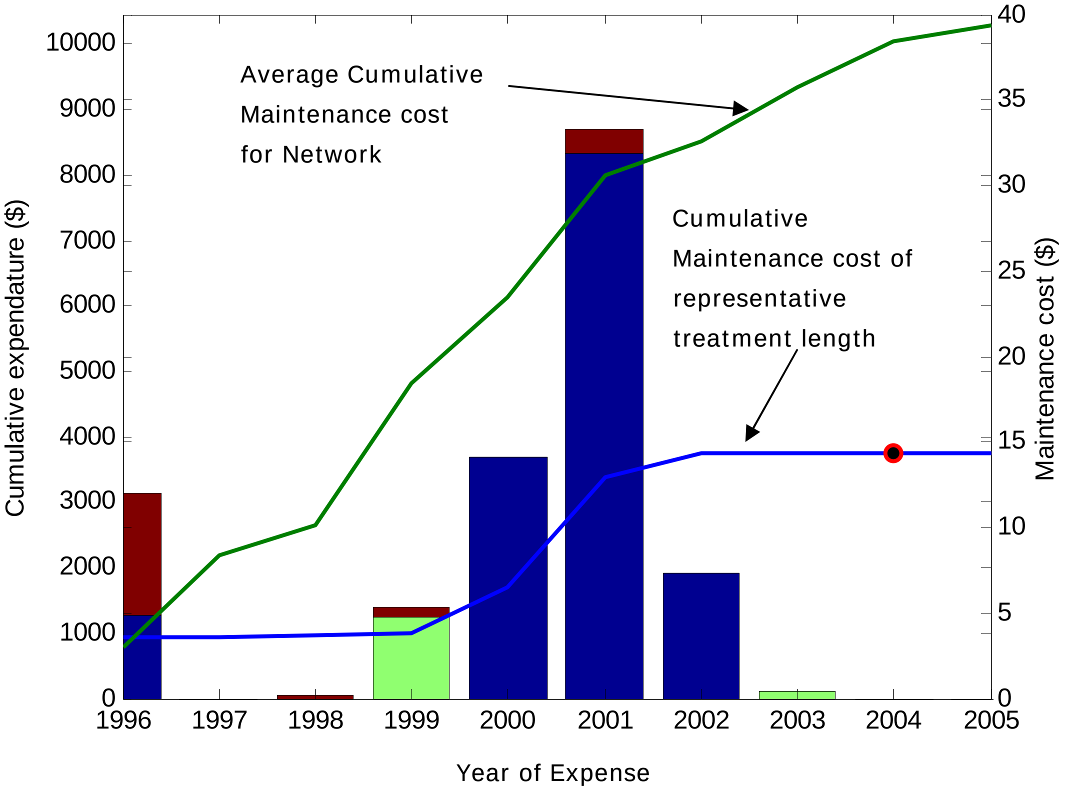

Figure 1.1 Example of maintenance costs versus year of expense for a representative treatment length. The blue component of the bars represents pavement maintenance costs (MC), green represents shoulder MC and brown represents surfacing MC. The year of pavement rehabilitation, 2004, is indicated by the red circle centred black.

The relationship between the various pavement condition indicators and maintenance costs was not a simple one. The data contains roads that became smoother with no maintenance expenditure and roads where the pavement condition worsened despite significant expenditure. An example road, ID 942 from the Southland data is plotted in Figure 1.2 and Figure 1.3. Figure 1.2 indicates that after rehabilitation the average rut depth decreased from about 5 mm to just over 2.5 mm. However, Figure 1.3 indicates only a marginal improvement in roughness after rehabilitation although admittedly the initial roughness of approximately 2 IRI is not particularly rough. For Road ID 924 all edge break and shoving values were zero and so graphs for these variables were not plotted. Except for 2004, when there were 10 metres of shoving, all shoving measures were zero.

Table 1.8 Average difference between rehabilitation year and year of maximum maintenance expenditure for the networks.

	Southland	Gisborne Hawke's Bay	West Wanganui
Average difference between rehab year and year of maximum maintenance cost	3.5	2.7	3.4

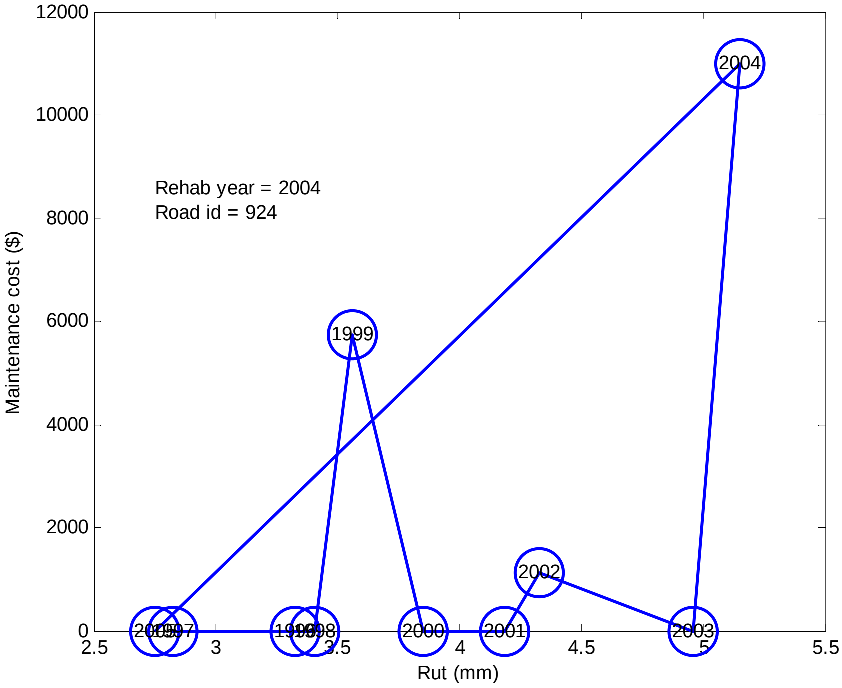

Figure 1.2 Average rut versus total maintenance cost for Southland, Road ID 924.

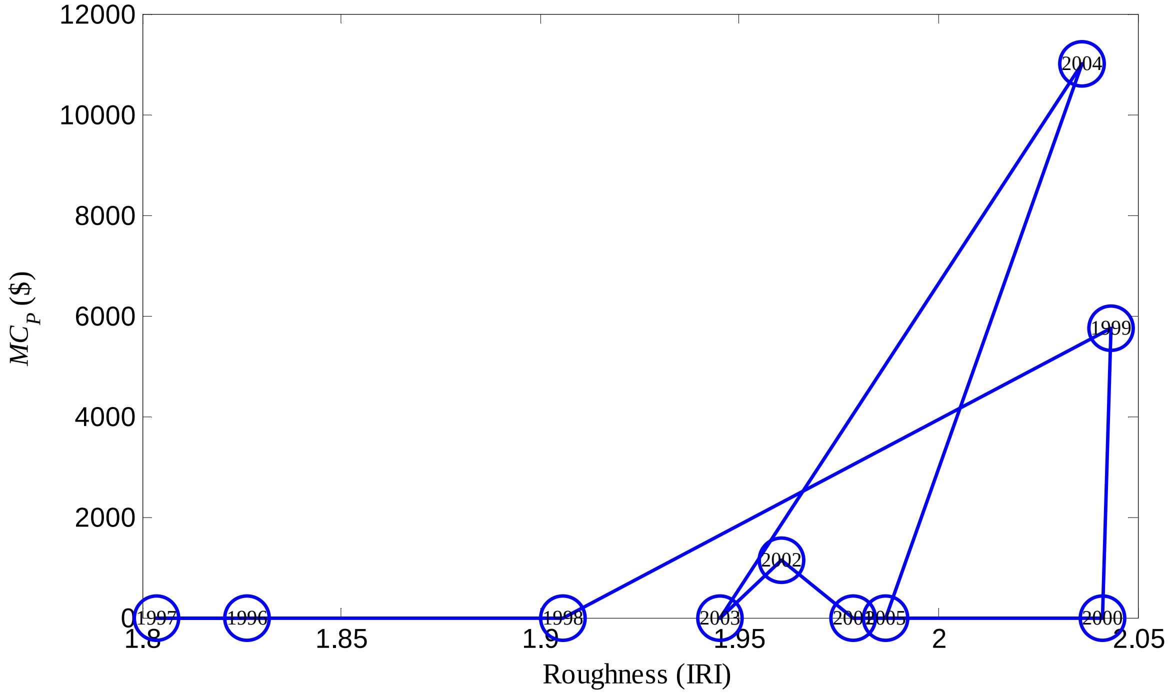

Figure 1.3 Roughness versus total maintenance cost for Southland, Road ID 924, rehabilitation year 2004.

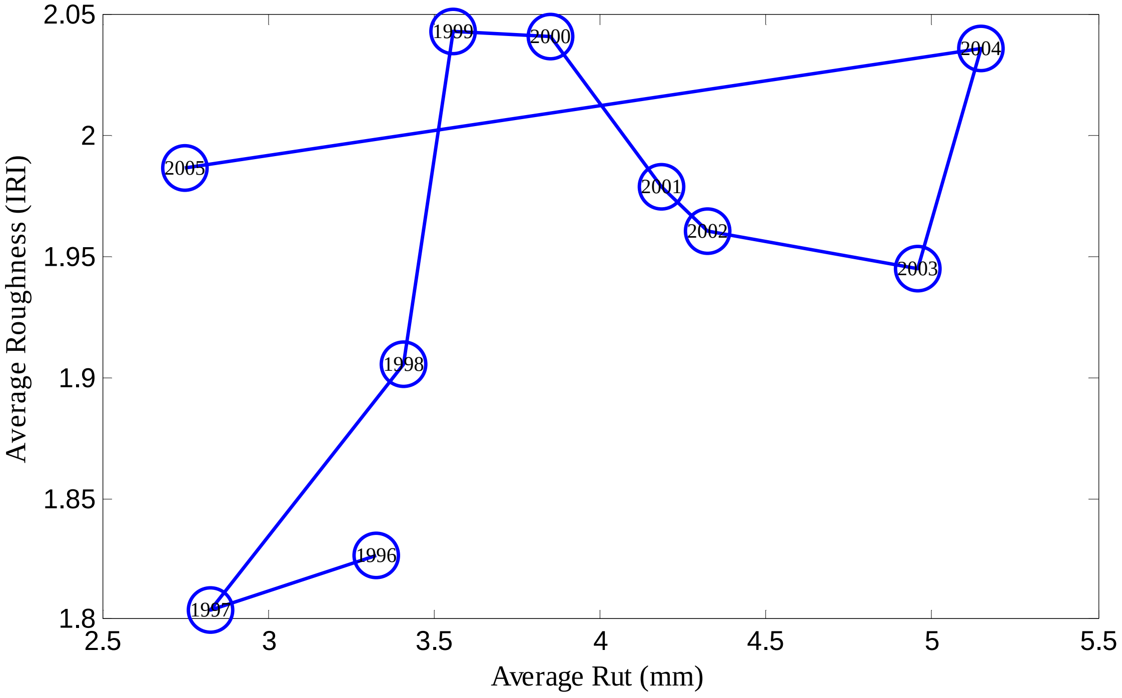

Figure 1.4 Average rut depth versus average roughness for Southland treatment length, Road ID 924.

2. Modelling maintenance costs

2.1 Maintenance cost models

Three maintenance cost models were generated with the following dependent variables for the six years prior to 2005: the total sum of maintenance costs, the sum of pavement maintenance costs and the sum of pavement maintenance costs plus surfacing costs. The following factors need to be considered when examining these models.

(a) As pavement age was used as an explanatory variable, all data from rehabilitated treatment lengths was removed. The rehabilitated pavements could appear to have a low age while having incurred high maintenance costs since maintenance costs would be incurred in the six years prior to rehabilitation.

(b) Data for pavements with age less than 75 years was used to estimate the models.

(c) Data for pavements with maintenance costs greater than zero was used to estimate the models. Pavement and the sum of pavement and surfacing costs were considered for models involving pavement maintenance costs and the sum of pavement and surfacing maintenance costs respectively.

(d) Because of b) and c), each model was estimated with a different number of data records, *N*, noted for each model in the following sections.

Linear regression was used to model the likelihood of pavement rehabilitation. The generated models have the form:

$$Pred = \sum Coeff_i \times Variable_i + Constant \qquad \textbf{(2.1)}$$

$$Maintenance\,Cost = e^{Pred} \qquad \textbf{(2.2)}$$

where the $Coeff_i$ is the multiplier of *Variable* which represents the variables listed in Table 1.6 and the following paragraphs. The *Variable* can either be one of the variables listed in Table 1.6 or a function of a variable, the most common being the natural log. The actual form of the variable used in the equation was determined using standard regression techniques. The predictor variable, *Pred,* calculated in equation 2.1 was used in equation 2.2 to calculate the predicted maintenance cost. Since this was a fitted model no effort was made to keep the equation units consistent.

Parameters used in the analysis of the models are standard statistical measures; two abbreviations are used: ‘std error’ and ‘std coeff’ for standard error and standard coefficient respectively.

2.1.1 Total maintenance cost model

A linear regression model was determined using the combined database with the dependent variable being total maintenance cost, where:

$$\begin{aligned} Pred = {} & 0.405 Roughness + 0.055 \ln Shoving + 0.048 \ln Alligator\ Cracking + \\ & 0.243 \ln Traffic + 0.644 \ln Rut + 0.01 Pavement\ Age + 0.03 \ln Potholes + 5.211 \end{aligned} \tag{2.3}$$

and the predicted maintenance cost is calculated using equation 2.2 The parameters and their statistical measures are presented in Table 2.1 and Table 2.2. Modelling the total maintenance cost implies that this contributed to the rehabilitation decision. The model indicated that the examined pavement condition indicators in decreasing order of significance were roughness, natural log of shoving, natural log of alligator cracking, natural log of traffic, natural log of rutting, pavement age and the natural log of the number of potholes. This order would tend to confirm the strong influence of road roughness on pavement maintenance costs.

Table 2.1 Relevant parameters and statistics for linear regression model of maintenance cost.

Effect	**Coefficient**	**Standard error**	**Standard coefficient**	**Tolerance**	**T ratio**	**P value**
CONSTANT	5.211	0.412	0.000		12.638	0.000
IRI	0.405	0.050	0.209	0.733	8.126	0.000
Ln(*Shoving*)	0.055	0.009	0.146	0.869	6.205	0.000
Ln(*Alligator Cracking*)	0.048	0.008	0.149	0.797	6.063	0.000
Ln(*Traffic*)	0.243	0.041	0.150	0.752	5.919	0.000
Ln(*Rut*)	0.644	0.130	0.114	0.901	4.945	0.000
Pavement Age	0.010	0.003	0.089	0.917	3.870	0.000
Ln(*Potholes*)	0.030	0.011	0.064	0.906	2.778	0.006
N: 1703 Multiple R: 0.427 Squared multiple R: 0.182 Adjusted squared multiple R: 0.179 Standard error of estimate: 1.476						

Table 2.2 Analysis of variance.

Source	**Sum-of-squares**	**Degrees of freedom**	**Mean-square**	**F ratio**	**P value**
Regression	820.888	7	117.270	53.863	0.000
Residual	3690.303	1695	2.177		

If equation 2.3 is substituted into equation 2.2 the resultant equation is

$$\begin{aligned} MC = {} & e^{0.405 Roughness} Shoving^{0.055} Alligator\ Cracking^{0.048} Traffic^{0.243} Rut^{0.644} \\ & e^{0.01 Pavement\ Age} Potholes^{0.03} e^{5.211} \end{aligned} \tag{2.4}$$

From this it can be inferred that an increase in pavement characteristics from the average values listed in Table 1.7 to the maximum values would result in an eightfold increase in maintenance costs; however, a doubling in the parameters produced an increase in the predicted maintenance costs by a factor of 2.6.

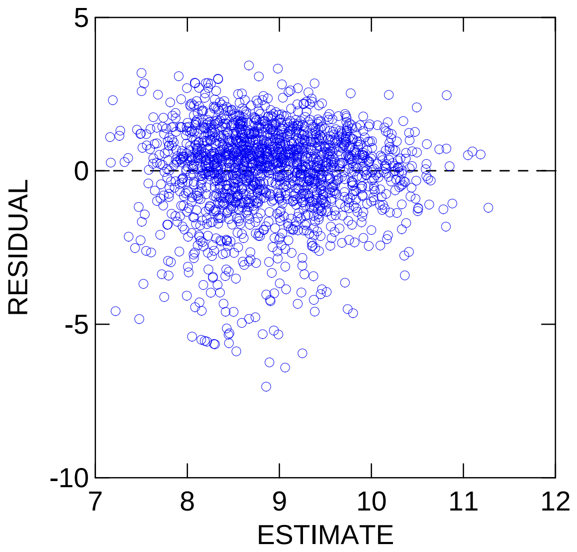

Figure 2.1 Plot of residuals against predicted values for maintenance cost model.

2.1.2 Pavement maintenance cost model

A second logit model was generated from the combined data using the pavement maintenance costs as the dependent variable and is presented in equation 2.5:

$$\begin{aligned} Pred &= 0.539 Roughness + 0.07 \ln Shoving + 0.309 \ln Traffic + 0.999 \ln Rut + \\ &\quad 0.049 \ln Alligator\ Cracking + 0.08 Pavement\ Age + 0.023 \ln Pot\ Holes + 3.260 \end{aligned} \tag{2.5}$$

where the predicted maintenance cost was calculated by substituting the *Pred* value calculated in equation 2.5 into equation 2.2.

Table 2.3 Relevant parameters and statistics for linear regression model of maintenance cost.

Effect	**Coefficient**	**Standard error**	**Standard coefficient**	**Tolerance**	**T ratio**	**P value**
CONSTANT	3.260	0.527	0.000	.	6.190	0.000
IRI	0.539	0.063	0.241	0.731	8.535	0.000
Ln(*Shoving*)	0.070	0.011	0.167	0.876	6.488	0.000
Ln(*Traffic*)	0.309	0.052	0.167	0.725	5.899	0.000
Ln(*Rut*)	0.999	0.170	0.148	0.909	5.868	0.000
Ln(*Alligator Cracking*)	0.049	0.010	0.134	0.791	4.932	0.000
Pavement Age	0.008	0.003	0.066	0.916	2.633	0.009
Ln(*Potholes*)	0.023	0.013	0.044	0.893	1.714	0.087
N: 1386. Multiple R: 0.445 Squared multiple R: 0.198 Adjusted squared multiple R: 0.194. Standard error of estimate: 1.681						

Table 2.4 Analysis of variance.

Source	**Sum-of-squares**	**Degrees of freedom**	**Mean-square**	**F ratio**	**P value**
Regression	962.721	7	137.532	48.679	0.000
Residual	3893.269	1378	2.825		

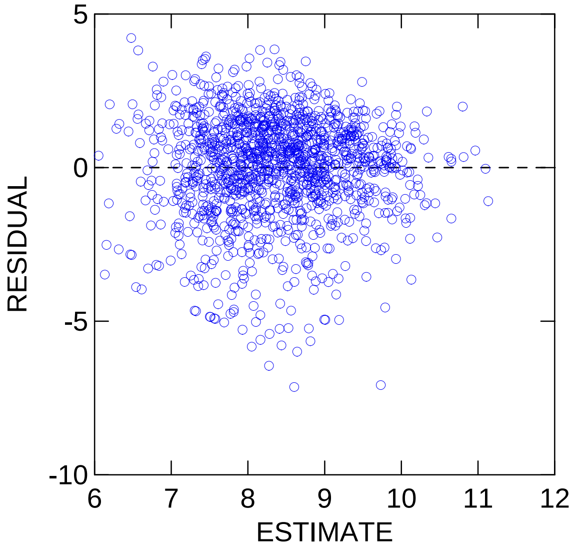

Figure 2.2 Plot of residuals against predicted values for pavement maintenance cost model.

2.1.3 Pavement plus surfacing maintenance cost model

A third model, equation 2.6, was generated from the combined data using the sum of the pavement and surfacing maintenance cost groups as the dependent variable.

$$\begin{aligned} Pred = {} & 0.537 Roughness + 0.307 \ln Traffic + 0.936 \ln Rut + 0.059 \ln Shoving + \\ & 0.059 \ln Shoving + 0.044 \ln Alligator\ Cracking + 0.08 Pavement\ Age + \\ & 0.023 \ln Pot\ Holes + 3.603 \end{aligned} \tag{2.6}$$

This composite maintenance cost was strongly dependent on roughness, with the log of traffic, the log of rutting and the log of shoving all being significant. The log of alligator cracking, pavement age and the log of the number of potholes were of less significance.

Table 2.5 Logit model variables for the sum of pavement and surfacing cost groups.

Effect	Coefficient	Standard error	Standard coefficient	Tolerance	T ratio	P value
CONSTANT	3.603	0.446	0.000		8.086	0.000
IRI	0.537	0.054	0.258	0.746	9.953	0.000
Ln(*Traffic*)	0.307	0.044	0.180	0.749	6.965	0.000
Ln(*Rut*)	0.936	0.145	0.152	0.909	6.470	0.000
Ln(*Shoving*)	0.059	0.009	0.150	0.876	6.273	0.000
Ln(*Alligator Cracking*)	0.044	0.009	0.130	0.803	5.195	0.000
Pavement Age	0.012	0.003	0.104	0.921	4.452	0.000
Ln(*Potholes*)	0.023	0.011	0.046	0.906	1.978	0.048
N: 1576 Multiple R: 0.464 Squared multiple R: 0.215 Adjusted squared multiple R: 0.211 Standard error of estimate: 1.539						

Table 2.6 Analysis of variance.

Source	Sum-of-squares	Degrees of freedom	Mean-square	F ratio	P value
Regression	1016.826	7	145.261	61.304	0.000
Residual	3715.412	1568	2.370		

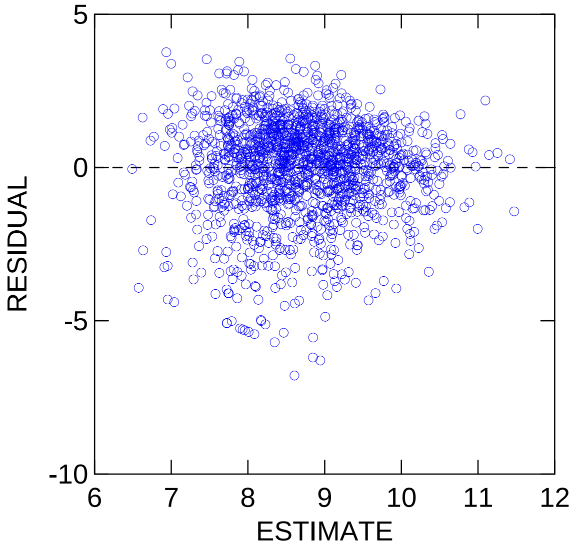

Figure 2.3 Plot of residuals against predicted values for model of the sum of pavement maintenance and surfacing maintenance costs.

2.2 Summary of maintenance cost models

There appeared to be high randomness in the data which resulted in low r-squared values for all three models for maintenance costs, although the model involving the sum of pavement plus surfacing maintenance costs was perhaps marginally better than the other two. There were low p values for the models but reasonably high t statistics. The distribution of the residuals around the zero value was relatively even.

3. Prediction of rehabilitation decision

3.1 Background

With the distribution of residuals obtained, the models generated in the previous section were not going to provide an accurate prediction of maintenance costs for individual treatment lengths. As the purpose of this study was to provide a tool for predicting pavement rehabilitation decisions it was decided to investigate whether a model based on pavement condition indicators could be used to predict rehabilitation decisions. A number of models were generated for this purpose and are presented in this section.

3.2 Combined model

The acceptable data from the four networks examined was combined into a single database and examined for any tendencies. Logit regression techniques were used to model the likelihood of pavement rehabilitation. Logistic regression differs from linear regression models in that the outcome variable is binary or dichotomous, or in this case to rehabilitate or to not rehabilitate. The generated models had the form:

$$Pred = \sum Coeff_i \times Variable_i + Constant \tag{3.1}$$

$$Prob = \frac{1}{1 + e^{-Pred}} \tag{3.2}$$

where the variable *Pred* was the predicator and the *Prob* gave the output as a probability fraction. A pavement was considered to be requiring rehabilitation if the value of the *Prob* output was greater than a threshold probability defined by the modeller, thereby producing a binary output result.

A parameter, additional to those considered in the maintenance cost models, was considered for the rehabilitation models. The parameter, *UrbanRural*, was considered to reflect the differences between high- and low-speed environments. The *UrbanRural* parameter took the value of 1 for urban roads and 2 for rural roads.

The logit regression technique attempted to maximise log likelihood – the higher the value the better the model. The Chi square p value was calculated using the value of twice the difference between the log likelihood and the log likelihood of constants only. This value also provided a measure of the fit of the model – the smaller the number the better. McFadden's Rho-Squared also provided a measure of the fit, with values ranging from 0.2 to 0.4 considered satisfactory and those between 0.1 and 0.2 considered reasonable.

The shoving variable was frequently seen as a poor variable in these models; however, it was included because it was the authors' opinion that excessive shoving was a factor network managers would consider before making rehabilitation decisions. In addition, potholes and surface deterioration such as alligator cracking were not recorded in condition rating surveys if they could be attributed to shoving.

3.2.1 Combined model with maintenance costs aggregated

The combined roading data from the four networks was modelled with the separated maintenance costs combined into a single parameter. The resultant model had the form:

$$\begin{aligned} Pred &= 0.568\ln MC_{Total} + 0.465\ln Traffic + 1.60 UrbanRural \\ &\quad + 0.065\ln Edge\ Break + 0.047\ln Alligator + 0.3 Roughness \\ &\quad + 0.021\ln Shoving - 14.963 \end{aligned} \tag{3.3}$$

More information about the model and its parameters are available in Table 3.1. With a p value of 0.000 and a t ratio of 7.149 it can be inferred that the maintenance cost was the dominant parameter for the model.

Table 3.1 Relevant parameters and statistics for combined model where maintenance costs have been combined.

Category choices		**Model statistics**
0 (Not rehabilitated)	1767	Log likelihood of constants only model = LL(0) =-653.496
1 (Rehabilitated)	203	2*[LL(N)-LL(0)] = 189.327 with 7 degrees of freedom.
Total	1970	Chi-sq p-value = 0.000
Log likelihood	-558.833	McFadden's Rho-squared = 0.145

	Parameter	**Estimate**	**Standard error**	**T ratio**	**P value**
1	*CONSTANT*	-14.963	1.563	-9.575	0.000
2	Ln(MC_{Total})	0.568	0.079	7.149	0.000
3	Ln(*Traffic*)	0.465	0.102	4.546	0.000
4	*UrbanRural*	1.601	0.378	4.239	0.000
5	Ln(*Edge Break*)	0.065	0.018	3.685	0.000
6	Ln(*Alligator Cracking*)	0.047	0.017	2.832	0.005
7	*IRI*	0.300	0.109	2.766	0.006
8	Ln(*Shoving*)	0.021	0.018	1.210	0.226

	Parameter	**Odds ratio**	**95.0% bounds**	
			Upper	**Lower**
2	Ln(MC_{Total})	1.765	2.063	1.511
3	Ln(*Traffic*)	1.593	1.947	1.303
4	*UrbanRural*	4.957	10.390	2.365
5	Ln(*Edge Break*)	1.067	1.105	1.031
6	Ln(*Alligator Cracking*)	1.048	1.083	1.015
7	*IRI*	1.350	1.670	1.091
8	Ln(*Shoving*)	1.022	1.058	0.987

Figure 3.1 demonstrates the trade off between the threshold probability, defined by the authors, and the success of the model presented in this section. The higher the threshold probability the greater the overall success of the model; however, the number of necessary rehabilitations correctly predicted dropped off. Necessary rehabilitations were defined as those rehabilitations, for the network examined, that were actually performed; unnecessary rehabilitations were those predicted as being necessary for treatment lengths that were not rehabilitated. A low threshold probability correctly predicted a high proportion of necessary rehabilitations but at the cost of predicting a number of unnecessary rehabilitations. For the data examined it was decided that a threshold probability of 11% was appropriate as this was the value at which the successful rehabilitation prediction and the successful non-

rehabilitation predictions had the same probability. This approach would allow the total number of rehabilitations on a network to remain the same.

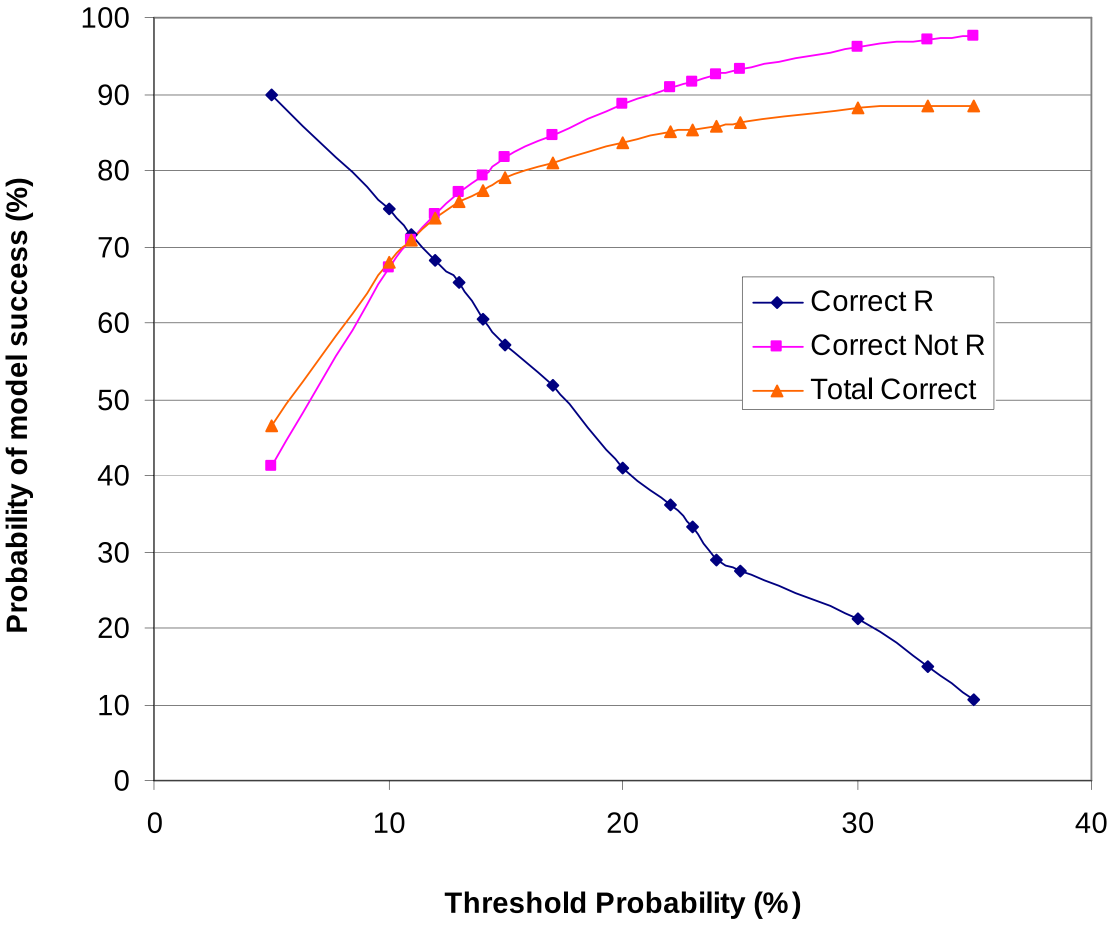

Figure 3.1 Model prediction for pavement rehabilitation decision. The legend 'Correct R' indicates pavements that were predicted as requiring rehabilitation and were rehabilitated. The legend 'Correct Not R' indicates pavements that were predicted as not requiring rehabilitation and were not rehabilitated.

Table 3.2 shows the model applied to the average, maximum, minimum and median values for the model parameters. By setting the threshold probability at 11% it can be seen that the model would predict a rehabilitation decision for a pavement with all the model parameters maximised and for average parameters but not for minimum or median parameters. At first glance predicting a rehabilitation for a totally average pavement might not seem appropriate; however, when considering the high level of positive skew (see Table 1.7 for values) in the data, it appears more reasonable.

Table 3.2 Parameters for the combined model showing relevant statistics, *Pred* variable and the model probability.

	Roughness (IRI)	Shoving (m)	MC ($)	Traffic (AADT)	Alligator cracking (m)	Edge break (m)	*Pred*	Probability (%)
Average	3	10.3	19.7×10^3	3020	29.1	23.7	-1.10	24.9
Maximum	6.7	1667	600×10^3	24,450	2770	710	3.46	96.9
Minimum	1.2	0.001*	1*	125	0.001*	0.001*	-10.1	0.004
Median	2.9	0.001*	10.5×10^3	1,840	0.001*	4.3	-2.51	7.52

UrbanRural = 2 and *Constant* = -14.963

* while these values are properly zero to remove the problem of taking the log of zero they have been set to a value close to zero that has minimal influence on the calculated probability.

3.2.2 Combined model with pavement and surfacing maintenance costs

The combined data was also modelled with the pavement and surfacing maintenance costs separated out as two independent parameters.

$$Pred = 0.567 Traffic + 0.073 \ln MC_s + 0.439 IRI + 1.529 UrbanRural + 0.072 \ln MC_P + 0.049 \ln Alligator\ Cracking + 0.052 \ln Edge\ Break + 0.021 \ln Shoving - 11.488 \tag{3.4}$$

It can be seen in Table 3.3 that *IRI* and *UrbanRural* and the natural logs of the pavement characteristics of *Alligator Cracking*, $MC_{Pavement}$ repairs, $MC_{Surfacing}$, the number of *Edge Breaks*, and *Traffic* are all parameters that were significant for the model. The natural log of *Shoving* was not.

Of these parameters it can be seen that the more significant factors in the model were *Traffic*, $MC_{Surfacing}$, *UrbanRural*, MC_{Paving}, and *Roughness*. This could imply that higher traffic levels triggered the decision to rehabilitate because of the greater numbers of people affected. Similarly the perception in the public's mind that surfacing is an important factor (Cleland 2005) drives a response to surfacing faults. The speed environment is also a factor that influences the rehabilitation decision; surface imperfections are more noticeable on high-speed roads and this is reflected in the urban rural factor. Maintenance costs associated with paving are significant and the pavement roughness is also a dominant driver for rehabilitation.

Table 3.3 Relevant parameters and statistics for the combined model with separate cost categories for pavement and surfacing.

Category choices		Model statistics
0 (Not rehabilitated)	1765	Log likelihood, LL(N) = -577.893 Log likelihood of constants only model = LL(0) = -662.330 2*[LL(N)-LL(0)] = 168.873 with 8 degrees of freedom Chi-sq p-value = 0.000 McFadden's Rho-squared = 0.127
1 (Rehabilitated)	207	
Total	1972	

	Parameter	Coefficient	Standard error	T ratio	P value
1	*CONSTANT*	-11.488	1.381	-8.318	0.000
2	Ln(*Traffic*)	0.567	0.099	5.709	0.000
3	Ln($MC_{Surfacing}$)	0.073	0.017	4.424	0.000
4	*IRI*	0.439	0.103	4.248	0.000
5	*UrbanRural*	1.529	0.371	4.117	0.000
6	Ln($MC_{Pavement}$)	0.072	0.020	3.534	0.000
7	Ln(*Alligator Cracking*)	0.049	0.016	2.977	0.003
8	Ln(*Edge Break*)	0.052	0.017	3.005	0.003
9	Ln(*Shoving*)	0.021	0.017	1.215	0.224

	Parameter	Odds ratio	95.0% bounds	
			Upper	Lower
2	Ln(*Traffic*)	1.763	2.141	1.451
3	Ln($MC_{Surfacing}$)	1.076	1.112	1.042
4	*IRI*	1.551	1.899	1.267
5	*UrbanRural*	4.615	9.558	2.229
6	Ln($MC_{Pavement}$)	1.075	1.119	1.033
7	Ln(*Alligator Cracking*)	1.050	1.084	1.017
8	Ln(*Edge Break*)	1.053	1.090	1.018
9	Ln(*Shoving*)	1.021	1.057	0.987

Both models derived for the combined data were noteworthy given the available data. The model with composite maintenance cost, however, might give a better outcome on the basis of the log likelihood value.

3.3 Models for individual networks

3.3.1 Hawke’s Bay

The pavement data from Hawke’s Bay was used to generate a model for the rehabilitation decision on that network. Two models were generated and are displayed in Table 3.4 and Table 3.5. The first model, Hawke’s Bay model 1, is presented in equation 3.5.

$$Pred = 1.084 \ln MC + 0.050 \ln Edge\ Break - 12.279 \tag{3.5}$$

Table 3.4 Hawke’s Bay model 1, with composite maintenance cost.

Category choices		**Model statistics**
0 (Not rehabilitated)	546	Log likelihood, LL(N) = -177.152 Log likelihood of constants only model = LL(0) = -218.096 2*[LL(N)-LL(0)] = 81.886 with 2 degrees of freedom Chi-sq p-value = 0.000 McFadden's Rho-squared = 0.188
1 (Rehabilitated)	70	
Total	616	

	Parameter	**Estimate**	**Standard error**	**T ratio**	**P value**
1	*CONSTANT*	-12.279	1.499	-8.192	0.000
2	Ln(MC_{Total})	1.084	0.150	7.216	0.000
3	Ln(*Edge Break*)	0.050	0.029	1.710	0.087

	Parameter	**Odds ratio**	**95% bounds**	
			Upper	**Lower**
2	Ln(MC_{Total})	2.957	3.970	2.203
3	Ln(*Edge Break*)	1.051	1.113	0.993

The second model, Hawke’s Bay model 2, presented in equation 3.6 below separated the three maintenance costs.

$$Pred = 0.147 \ln MC_{Su} + 0.087 \ln MC_{P} + 0.054 \ln MC_{Sh} - 3.592 \tag{3.6}$$

Table 3.5 Hawke's Bay model 2, with pavement, surfacing and shoulder maintenance costs.

Category choices		Model statistics
0 (Not rehabilitated)	546	Log likelihood, LL(N) = -189.567 Log likelihood of constants only model = LL(0) = -220.264 2*[LL(N)-LL(0)] = 61.395 with 3 degrees of freedom Chi-sq p-value = 0.000 McFadden's Rho-squared = 0.139
1 (Rehabilitated)	71	
Total	617	

	Parameter	**Estimate**	**Standard error**	**T ratio**	**P value**
1	*CONSTANT*	-3.592	0.353	-10.190	0.000
2	Ln($MC_{Surfacing}$)	0.147	0.033	4.442	0.000
3	Ln($MC_{Pavement}$)	0.087	0.025	3.476	0.001
4	Ln($MC_{Shoulder}$)	0.054	0.027	1.964	0.050

	Parameter	**Odds ratio**	**95% bounds**	
			Upper	**Lower**
2	Ln($MC_{Surfacing}$)	1.158	1.236	1.086
3	Ln($MC_{Pavement}$)	1.091	1.146	1.039
4	Ln($MC_{Shoulder}$)	1.055	1.114	1.000

Both Hawke's Bay models were useful, but the model with the composite maintenance cost might give a better outcome on the basis of the log likelihood value. *Edge Break* was the only physical parameter included in the first model although it did have a high p value. If the three maintenance cost groups of surfacing, pavement and shoulder were modelled as separate parameters then none of the physical pavement condition characteristics were included in the model. When shoulder maintenance cost was introduced in the model, *Edge Break* was not found to be a significant variable. This was perhaps due to a correlation between edge break and shoulder maintenance cost. From RAMM maintenance and operational viewpoints this implied that the cost to repair edge break might sometimes be recorded as a shoulder maintenance cost.

3.3.2 Gisborne

The Gisborne roading network has different maintenance drivers from the Hawke's Bay network and consequently management practices are quite different. This was apparent when the parameters from the models were compared with those of Hawke's Bay. The Gisborne model is presented in equation 3.7:

$$\begin{aligned} Pred = {} & 0.141 \ln Shoving + 0.640 IRI + 0.587 \ln MC_{Total} + 0.646 \ln Traffic + \\ & 0.069 \ln Edge\ Break + 1.732 UrbanRural - 18.654 \end{aligned} \tag{3.7}$$

Table 3.6 Gisborne model 1, with composite maintenance cost.

Category choices		**Model statistics**
0 (Not rehabilitated)	415	Log likelihood, LL(N) = -111.669 Log likelihood of constants only model = LL(0) = -137.865 2*[LL(N)-LL(0)] = 52.392 with 6 degrees of freedom Chi-sq p-value = 0.000 McFadden's Rho-squared = 0.190
1 (Rehabilitated)	41	
Total	456	

	Parameter	**Coefficient**	**Standard error**	**T ratio**	**P value**
1	*CONSTANT*	-18.654	5.202	-3.586	0.000
2	Ln(*Shoving*)	0.141	0.047	3.004	0.003
3	*IRI*	0.640	0.235	2.725	0.006
4	Ln(MC_{Total})	0.587	0.249	2.353	0.019
5	Ln(*Traffic*)	0.646	0.363	1.781	0.075
6	Ln(*Edge Break*)	0.069	0.041	1.697	0.090
7	*UrbanRural*	1.732	1.346	1.287	0.198

	Parameter	**Odds ratio**	**95% bounds**	
			Upper	**Lower**
2	Ln(*Shoving*)	1.151	1.262	1.050
3	*IRI*	1.897	3.007	1.197
4	Ln(MC_{Total})	1.798	2.932	1.103
5	Ln(*Traffic*)	1.908	3.883	0.937
6	Ln(*Edge Break*)	1.071	1.160	0.989
7	*UrbanRural*	5.651	79.057	0.404

A second model, presented below in equation 3.8, separated the pavement and surfacing maintenance costs.

$$\begin{aligned} Pred = {} & 0.123\ln Shoving + 0.594 IRI + 0.565\ln MC_P + 0.633\ln Traffic + \\ & 0.069\ln Edge\ Break + 1.714 UrbanRural + 0.068\ln MC_{Su} - 18.654 \end{aligned} \tag{3.8}$$

Table 3.7 Gisborne model 2, with pavement and surfacing maintenance costs.

Category choices		**Model statistics**
0 (Not rehabilitated)	415	Log likelihood, LL(N) = -109.252 Log likelihood of constants only model = LL(0) = -137.865 2*[LL(N)-LL(0)] = 57.226 with 7 degrees of freedom Chi-sq p-value = 0.000 McFadden's Rho-squared = 0.208
1 (Rehabilitated)	41	
Total	456	

	Parameter	**Coefficient**	**Standard error**	**T ratio**	**P value**
1	*CONSTANT*	-18.365	5.232	-3.510	0.000
2	Ln(*Shoving*)	0.123	0.048	2.561	0.010
3	*IRI*	0.594	0.238	2.496	0.013
4	Ln($MC_{Pavement}$)	0.565	0.229	2.469	0.014
5	Ln(*Traffic*)	0.633	0.369	1.715	0.086
6	Ln(*Edge Break*)	0.069	0.041	1.662	0.097
7	*UrbanRural*	1.714	1.351	1.268	0.205
8	Ln($MC_{Surfacing}$)	0.068	0.056	1.224	0.221

	Parameter	**Odds ratio**	**95.0% bounds**	
			Upper	**Lower**
2	Ln(*Shoving*)	1.131	1.242	1.029
3	*IRI*	1.811	2.886	1.136
4	Ln($MC_{Pavement}$)	1.759	2.754	1.123
5	Ln(*Traffic*)	1.883	3.878	0.914
6	Ln(*Edge Break*)	1.071	1.161	0.988
7	*UrbanRural*	5.550	78.414	0.393
8	Ln($MC_{Surface}$)	1.071	1.195	0.960

Both models for the Gisborne network modelled the rehabilitation decision with reasonable success. The model that incorporated separate pavement and surfacing maintenance costs, however, could give a better outcome on the basis of the log likelihood value. Perhaps surprisingly, when compared with other network models, the most significant factor in this model was shoving.

3.3.3 Southland

Two models seemed to provide reasonable success for the Southland network data. The first, equation 3.9, combined the costs for the three pavement maintenance categories into one parameter, while the second, equation 3.10, had these categories as three separate parameters.

The model using composite maintenance costs had significant results with the chi squared p value being only 0.001. The maintenance cost, *MC*, was the dominant parameter with *Edge Break* and the number of *Potholes* also being significant.

$$Pred = 0.501 \ln MC_{Total} + 0.088 \ln Edge\ Break + 0.08 \ln Potholes - 6.421 \tag{3.9}$$

Table 3.8 Southland model 1, with composite maintenance cost.

Category choices		**Model statistics**
0 (Not rehabilitated)	243	Log likelihood of model, LL(N) = -83.888 Log likelihood of constants only model = LL(0) = -92.313 2*[LL(N)-LL(0)] = 16.850 with 3 degrees of freedom Chi-sq p-value = 0.001 McFadden's Rho-squared = 0.091
1 (Rehabilitated)	29	
Total	272	

	Parameter	**Coefficient**	**Standard error**	**T ratio**	**P value**
1	*CONSTANT*	-6.421	1.580	-4.064	0.000
2	Ln(MC_{Total})	0.501	0.162	3.102	0.002
3	Ln(*Edge Break*)	0.088	0.046	1.899	0.058
4	Ln(*Potholes*)	0.080	0.048	1.671	0.095

	Parameter	**Odds ratio**	**95.0% bounds**	
			Upper	**Lower**
2	Ln(MC_{Total})	1.651	2.266	1.203
3	Ln(*Edge Break*)	1.092	1.196	0.997
4	Ln(*Potholes*)	1.084	1.190	0.986

A second model, Southland model 2, is displayed in the following equation where the pavement, surfacing and shoulder maintenance costs were treated as three independent variables. The parameters relevant to the model are displayed in Table 3.9.

$$Pred = 0.510 \ln MC_{Su} + 0.172 \ln MC_{P} + 0.081 \ln Potholes + 0.058 \ln MC_{Sh} - 6.873 \tag{3.10}$$

Table 3.9 Southland model 2, with separated pavement, surfacing and shoulder maintenance costs.

Category choices		Model statistics
0 (Not rehabilitated)	243	Log likelihood, LL(N) = -69.309 Log likelihood of constants only model = LL(0) = -92.313 2*[LL(N)-LL(0)] = 46.007 with 4 degrees of freedom Chi-sq p-value = 0.000 McFadden's Rho-squared = 0.249
1 (Rehabilitated)	29	
Total	272	

	Parameter	Coefficient	Standard error	T ratio	P value
1	*CONSTANT*	-6.873	1.426	-4.818	0.000
2	Ln($MC_{Surfacing}$)	0.510	0.160	3.197	0.001
3	Ln($MC_{Pavement}$)	0.172	0.066	2.599	0.009
4	Ln(*Potholes*)	0.081	0.051	1.566	0.117
5	Ln($MC_{Shoulder}$)	0.058	0.039	1.499	0.134

	Parameter	Odds ratio	95.0% bounds	
			Upper	Lower
2	Ln($MC_{Surfacing}$)	1.665	2.277	1.218
3	Ln($MC_{Pavement}$)	1.188	1.353	1.043
4	Ln(*Potholes*)	1.084	1.199	0.980
5	Ln($MC_{Shoulder}$)	1.060	1.144	0.982

Both Southland models were useful. The model with separate pavement, surfacing and shoulder maintenance costs might give a better outcome on the basis of the log likelihood value. It is worth noting that when shoulder maintenance cost was introduced in the Southland model 2 then *Edge Break* was not found to be a significant variable. A similar outcome was observed with the Hawke's Bay pavement life data. In Hawke's Bay's case, however, the model with the composite maintenance cost might give a better outcome, whereas for Southland the model with disaggregated maintenance cost would perform better.

3.3.4 West Wanganui

A model, equation 3.11, was developed for West Wanganui where the maintenance costs were combined into one parameter. According to the p values the most significant parameters for West Wanganui were *Traffic* and then *Roughness*. Maintenance costs, *MC*, were the next most significant and then somewhat unusually, compared with the other networks, *Shoving* was more significant than either *Edge Break* or *Alligator Cracking*.

$$\begin{aligned} Pred &= 1.016 \ln Traffic + 1.016 IRI + 0.328 \ln MC_{Total} + 0.089 \ln Alligator\ Cracking + \\ &\quad 0.077 \ln Shoving + 0.091 Edge\ Break + 1.45 UrbanRural - 18.968 \end{aligned} \qquad \textbf{(3.11)}$$

Table 3.10 Relevant parameters and statistics for West Wanganui model 1, with composite maintenance costs.

Category choices		Model statistics
0 (Not rehabilitated)	563	Log likelihood = -155.020 Log likelihood of constants only model = LL(0) = -204.379 2*[LL(N)-LL(0)] = 98.719 with 7 degrees of freedom Chi-sq p-value = 0.000 McFadden's Rho-squared = 0.242
1 (Rehabilitated)	63	
Total	626	

	Parameter	Coefficient	Standard error	T ratio	P value
1	*CONSTANT*	-18.968	2.955	-6.418	0.000
2	Ln(*Traffic*)	1.016	0.213	4.777	0.000
3	*IRI*	1.012	0.240	4.218	0.000
4	Ln(MC_{Total})	0.328	0.127	2.573	0.010
5	Ln(*Alligator Cracking*)	0.089	0.035	2.551	0.011
6	Ln(*Shoving*)	0.077	0.032	2.426	0.015
7	Ln(*Edge Break*)	0.091	0.040	2.281	0.023
8	*UrbanRural*	1.450	0.689	2.104	0.035

	Parameter	Odds ratio	95.0% bounds	
			Upper	Lower
2	Ln(*Traffic*)	2.762	4.190	1.820
3	*IRI*	2.750	4.400	1.719
4	Ln(MC_{Total})	1.388	1.781	1.081
5	Ln(*Alligator Cracking*)	1.093	1.171	1.021
6	Ln(*Shoving*)	1.080	1.149	1.015
7	Ln(*Edge Break*)	1.096	1.185	1.013
8	*UrbanRural*	4.262	16.454	1.104

3.4 Rehabilitation model summary

Management practices differed for each of the networks selected and consequently the models for each network were slightly different. The cumulative maintenance cost was a factor in each network's regression model but the other factors were not constant between the models.

The urban-rural (*UrbanRural*) factor was found to be a significant variable in the combined and West Wanganui models but not in the Southland and Hawke's Bay models. The effect was marginal for the Gisborne model.

For rehabilitated treatment lengths, the data referred to the six-year period before rehabilitation. For instance, if a treatment length was rehabilitated in 2001, the shoving data referred to 2000, 1999, 1998, 1997, 1996 and 1995. For non-rehabilitated treatment lengths, the data referred to the years from 2000 to 2005.

Figure 3.2 shows the curves obtained using the first of the rehabilitation decision models presented for each network and assuming a threshold probability of 11% was applicable in each situation. All other factors were assumed constant between each model, *Alligator Cracking* = 30 m^2, *Potholes*= 5, *Edge Break*=30 m, *Shoving* = 23 m, and *UrbanRural* = 2. The curves indicate the threshold for the rehabilitation decision, so for the Gisborne network high-traffic levels required only a small cumulative maintenance cost, but where the traffic levels were low a very high cumulative maintenance cost was required. Southland and Hawke's Bay did not have traffic as a variable and only required the maintenance cost to exceed $2700 and $10,000 respectively to trigger a rehabilitation decision.

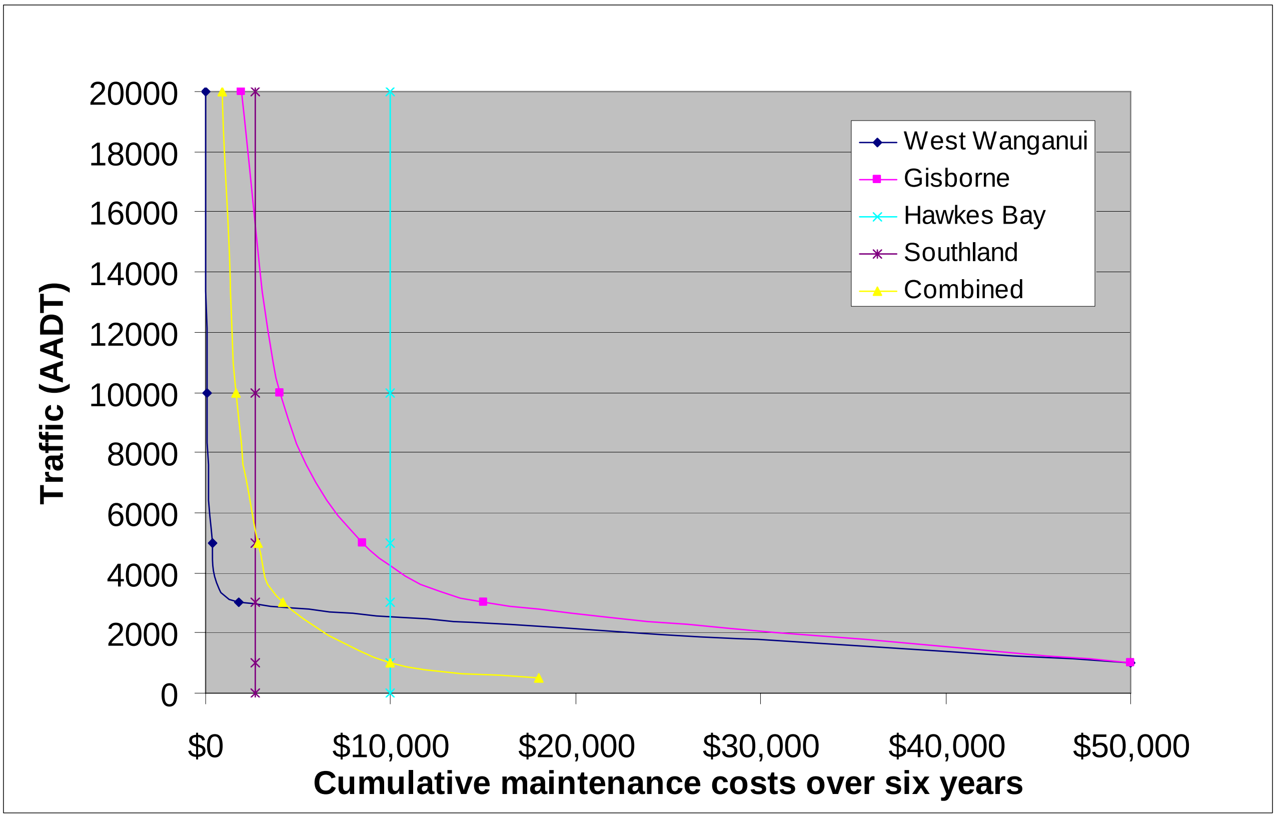

Figure 3.2 Threshold relationship between maintenance cost and traffic for the four networks and the combined model. All other factors are assumed to be constant.

In Figure 3.2 it can be seen that, with the assumed factors above, the rehabilitation decision was triggered by maintenance cost only in Hawke's Bay and Southland, and that the trigger levels were far lower for Southland than for Hawke's Bay. For the combined model, West Wanganui and Gisborne, a general rule of thumb was that the low-volume roads needed to have accumulated large maintenance costs before a rehabilitation decision was made. Conversely, high-volume roads needed relatively little expenditure on maintenance before a rehabilitation decision was triggered.

In developing the logit model it became apparent that the decision-making process could be improved by using a two-tier method. The first tier would involve using the critical rehabilitation drivers, such as roughness and rutting, to trigger rehabilitation if they exceeded some predetermined threshold. This threshold would probably take account of safety factors. Provided no triggers had been activated then the logit model could be used to determine if other factors might cumulatively indicate rehabilitation was necessary. For example, a road that was mildly rough with some localised cracking and a reasonable amount of shoving might trigger a rehabilitation decision whereas each of those conditions on their own might not. A two-tier model would also imitate the network manager’s decision process where the question would be asked ‘is there one factor indicating a failed road or does everything point cumulatively to a failed road?’.

For most networks there was little modelling advantage gained from separating the three costs. The dominant cost was typically the pavement category.

The fact that the rehabilitation model included traffic as a factor indicated that network managers’ tolerance of faults reduced as traffic volumes increased. Including the *UrbanRural* factor was probably a reflection of the speed environment influencing network managers’ desire to minimise the roughness experienced at high speeds. The primary expense for the shoulder group was edge break repair. Roughness would not be removed by maintenance, but it could drive the rehabilitation decision.

4. Model verification

4.1 Model selection

As the models varied quite a lot, it was decided to use the maintenance cost model and the rehabilitation model, both derived from the same combined data, to test against a network not included in the original data.

4.2 Network selection

The geographical spread of the networks selected for the initial study meant that the model could be used anywhere. Therefore, the Nelson network was selected to test the success of the derived models.

Data was treated as for the calibration data. After removing the treatment lengths with data that was too sparse, the total number of treatment lengths suitable for modelling purposes was 408. The proportion of rehabilitated to non-rehabilitated lengths is given in Table 4.1. It can be seen that, in terms of numbers of treatment lengths, just over 3.5 percent of the network was rehabilitated over the four-year examination period.

Table 4.1 Treatment lengths suitable for analysis Nelson region.

Total number of treatment lengths	408
Number of treatment lengths not rehabilitated	394
Number of treatment lengths rehabilitated	14

4.3 Results for maintenance cost model

The maintenance cost model, equation 2.3 was used to generate theoretical maintenance costs for the Nelson network. The results are displayed in Figure 4.1. The presence of high levels of actual maintenance costs meant that the model was not very successful. This is perhaps not surprising as the model did not predict extreme expenditure. Because they were extreme, the events that led to such expenditure were not likely to be included in the model. Extreme maintenance cost values greater than $50,000 were removed from the data and plotted in Figure 4.2. Despite this editing of the data the line of best fit displayed still had a slope of only 0.55 rather than an ideal slope of 1.

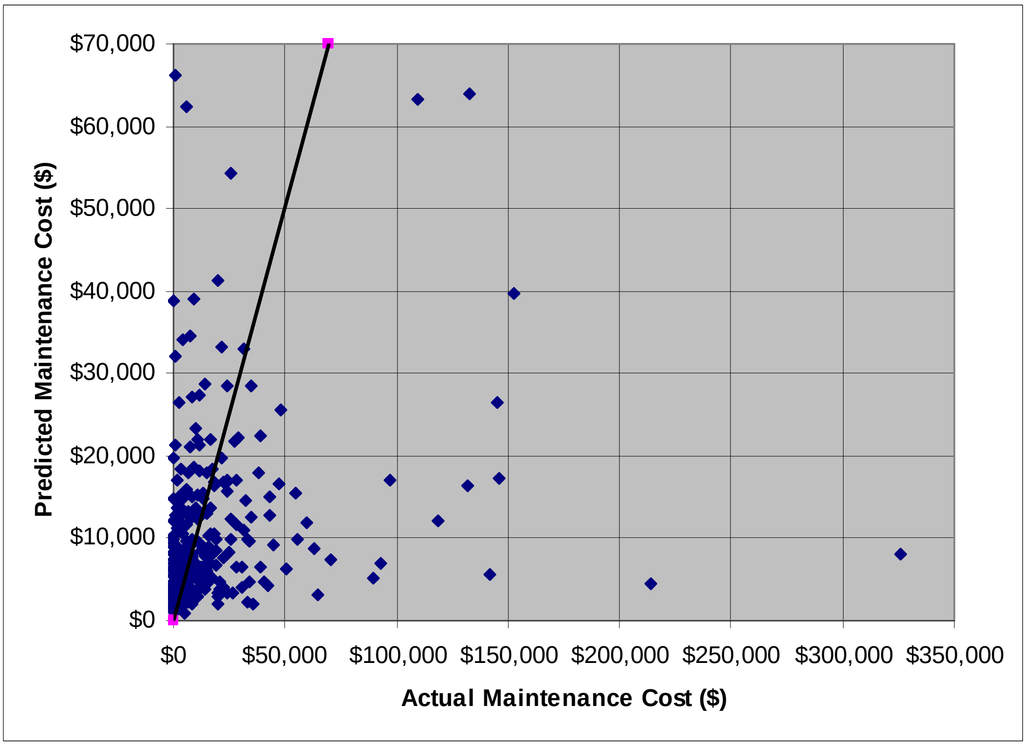

Figure 4.1 Plot of the actual maintenance costs against the maintenance costs predicted from the combined maintenance cost model. The straight black line represents the line of equality.

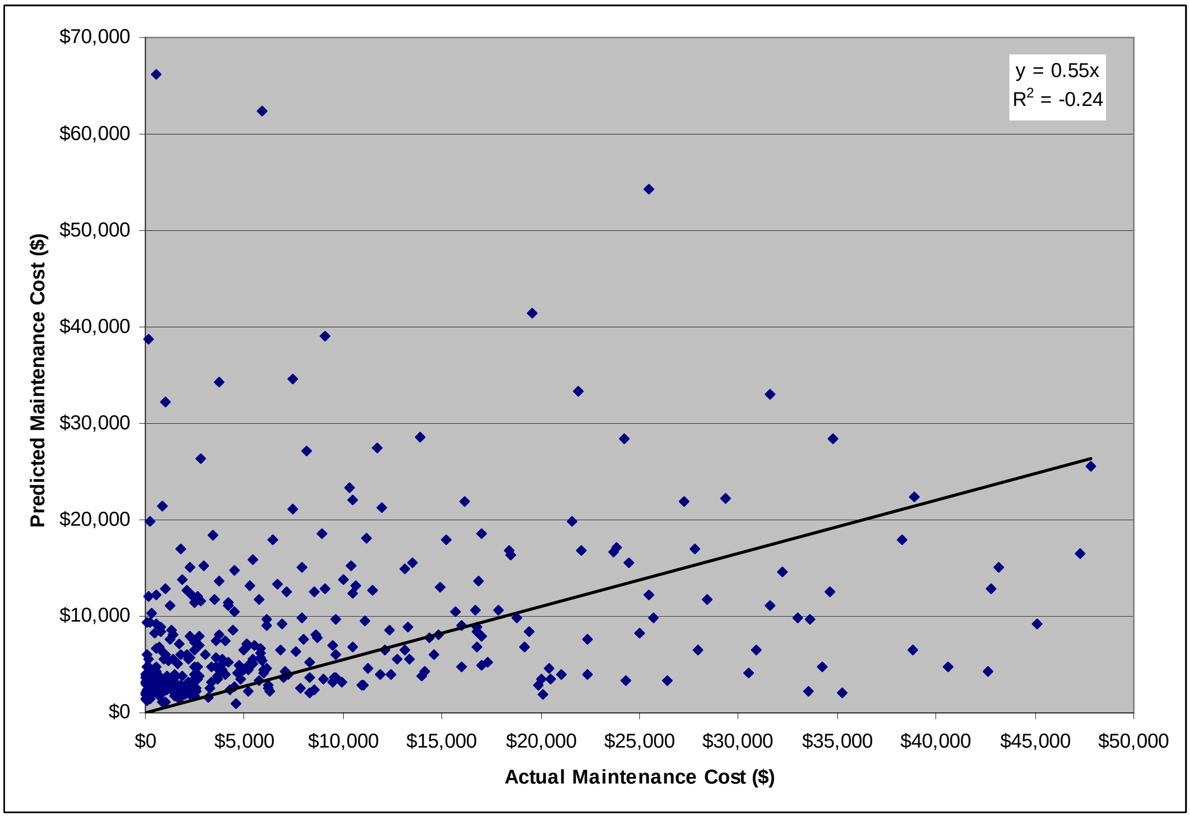

Figure 4.2 Plot of the actual maintenance costs against the maintenance costs predicted from the combined maintenance cost model. Maintenance costs in excess of $50,000 have been removed as potential extreme events. The straight black line represents a linear best fit to the data, but forced through the origin.

4.4 Results for the rehabilitation decision model

The rehabilitation decision model, presented in equation 3.3, was used to predict the rehabilitation decision for the treatment lengths obtained from the Nelson network. A summary of the results is displayed in Figure 4.3. This figure displays three curves. The first, as a function of the threshold probability, gives the percentage of treatment lengths correctly predicted as requiring rehabilitation that were rehabilitated. The second gives the percentage of treatment lengths correctly predicted as not requiring rehabilitation as a function of the threshold probability. The third gives the total percentage of treatment lengths that were correctly predicted as requiring or not requiring rehabilitation.

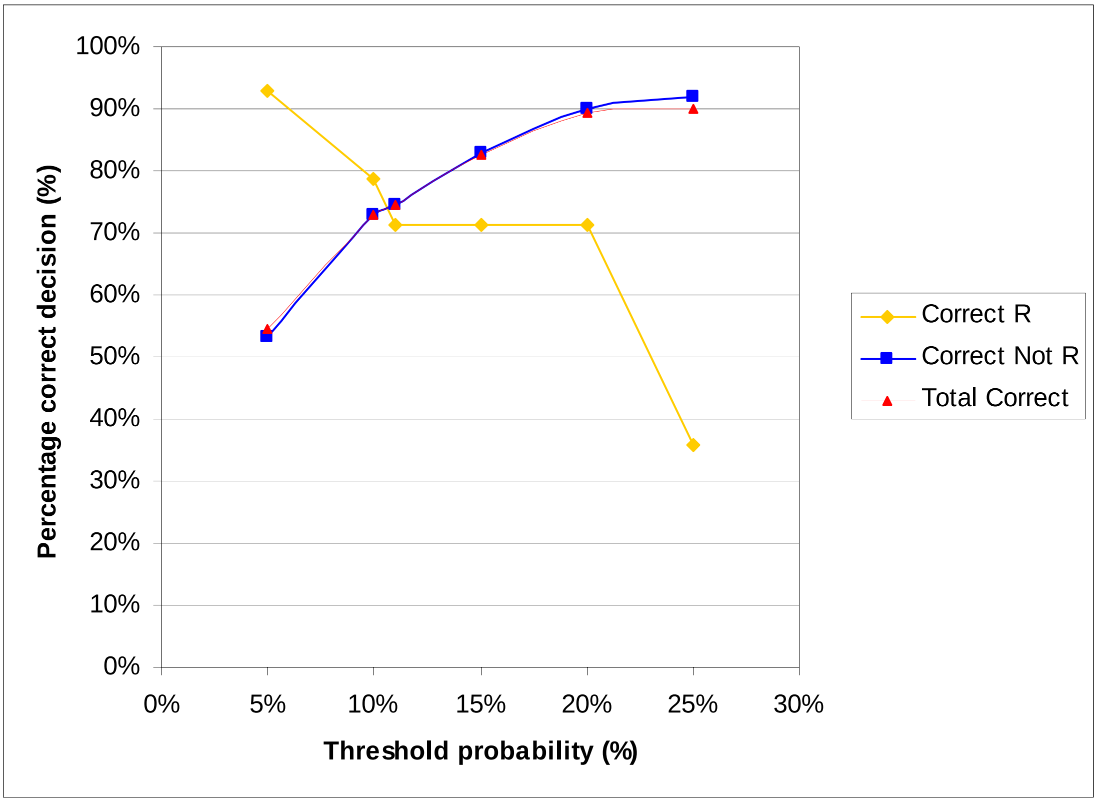

Figure 4.3 Model prediction for pavement rehabilitation decision for the Nelson data. The legend Correct R indicates pavements that were predicted as requiring rehabilitation and were rehabilitated. The legend Correct Not R indicates pavements that were predicted as not requiring rehabilitation and were not rehabilitated.

With the small number of rehabilitated treatment lengths there was some sensitivity evident in Figure 4.3 that was smoothed by the larger sample numbers in Figure 3.1. However the general behaviour was the same, and the point of crossover was close to the chosen threshold probability of 11% indicating that the total number of rehabilitation decisions the model predicted would be similar to the numbers decided by the network managers. If the model was to be used on an individual network then this sensitivity would need to be acceptable.

5. Discussion and conclusion

5.1 Discussion

The fit of all three models for maintenance costs was poor when the r-squared value was considered; however, the distribution of the residuals around the zero value was relatively even.

The combined rehabilitation decision model using composite maintenance costs was relatively successful. Roughness was a significant factor for some areas giving an increase from 2.5 to 4 IRI and accounting for half the maintenance costs necessary to trigger a rehabilitation decision. The area-wide treatment reports examined seldom mentioned pavement roughness as a justification for rehabilitation.

The combined rehabilitation model was sensitive to the rehabilitation threshold. If the threshold was set too low then roads requiring rehabilitation might not be correctly identified; if it was set too high there was potential for the model to forecast rehabilitation on a road where it was unnecessary.

It was felt there were factors others than those considered that influenced the decision to rehabilitate. A network manager might employ different decision-making processes that could not be easily modelled. Wayne Hatcher (pers.comm.) suggested it was the maintenance activity, not the cost, that triggered a rehabilitation decision.

The models generated, while having similar forms, all had slightly different factors and relative contributions from each of these factors. This led the authors to believe that the dominant factors might have reflected the different practice methods of network managers.

The *UrbanRural* factor was believed to be important because the speed environment of a road influenced the perception of road imperfections. The general public arguably considers pavement roughness as the most important indicator of pavement condition (Huang 2004) although there is evidence that this perception might be influenced by the number of complaints received rather than actual public opinion (Cleland et al. 2005). The evolution of pavement roughness is governed by a number of factors: traffic volume and load magnitude, pavement construction, pavement materials and environmental conditions.

The current study should be a good starting point. The outcomes can be implemented in the short to medium term until better models are developed. There was a lot of noise in the data that resulted in poor r-squared values for the maintenance prediction model.

On the other hand, factors not available in the RAMM database may have influenced rehabilitation decisions and as a result the goodness of fit of the models was low. Maintenance cost was perhaps one of the most significant variables.

From the available data, it is difficult to know if maintenance expenditure fixed the problem or if the cost was based on maintaining the road until the treatment length was rehabilitated. There was, therefore, potential for the model to predict rehabilitation on a treatment length with high maintenance costs when in fact the pavement was in perfect condition.

As discussed earlier, maintenance costs frequently drop to zero prior to treatment length rehabilitation as the network managers maintain safety but accept deterioration in condition. Furthermore, it is the authors' belief that a year of high maintenance costs will bring the treatment length to the attention of the network manager, who then decides if the road needs rehabilitation based on the condition of the road.

One problem with having composite logit models of the form used in this study was that if one distress factor was high while others were not, the model would give a lower probability of rehabilitation. This was because the model took into account several distress factors when predicting a rehabilitation decision. A solution to improving the rehabilitation predictions might be to use a two-tier model structure in which the first model would identify rehabilitation candidates and the second would screen on the basis of a number of discrete distress factors. For example, if roughness was greater than 4 IRI, or rut depth was greater than 7 mm, or shoving greater than 50 or if the logit model predicted that maintenance costs would exceed a threshold level of $20,000, then it would predict a rehabilitation decision.

5.2 Conclusions and recommendations

Examining rehabilitation justification reports confirmed that maintenance cost was being used as a major factor driving rehabilitation when roughness and rutting levels were moderate.

None of the maintenance cost models developed were particularly successful in producing a reliable prediction of maintenance costs based on the pavement characteristics available from RAMM.

Based on the combined model, derived maintenance costs did not rise dramatically with time as was commonly assumed.

A logit model was developed to predict rehabilitation decisions. The major factors were maintenance cost, followed by traffic levels and roughness. The rehabilitation decision model derived for this study predicted rehabilitation decisions well. Approximately 72% of the rehabilitated pavements were predicted as requiring rehabilitation. Consequently 28% of the pavements predicted as requiring rehabilitation were not rehabilitated. It is recommended that these sites be investigated to determine if their rehabilitation had been deferred for one or two years. When tested on the Nelson network data the model produced a similar performance.

This study is a good starting point and the maintenance cost models and the rehabilitation models will both be useful. However, a number of questions have been raised as a consequence of this work. If maintenance costs cannot be predicted with a high level of reliability, and previous studies have shown that roads are not being rehabilitated because of high roughness and rutting levels, then why are pavements being rehabilitated?

It is essential that end users of the models developed in this project realise that the historical length of the data is potentially insufficient. As time progresses, further data will become available to refine the models.

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Appendix 1

A.1 Initial maintenance cost models

An initial set of maintenance cost models was created but proved to be too sensitive for large levels of rutting. This was probably due to the database containing very little rutting as the network maximum rut depth was only 9.3 mm. The models are included in this appendix for completeness.

A.1.1 Total maintenance cost model

A model for the total maintenance costs was generated using Logit regression. The dependent variable was the natural log of the total maintenance costs for that treatment length; the cost was the sum of the paving, surfacing and shoulder maintenance cost groups.

N: 1703 multiple R: 0.425 Squared multiple R: 0.181

Adjusted squared multiple R: 0.177 Standard error of estimate: 1.477

Table A1 Relevant parameters and statistics for total maintenance cost model – includes a rutting parameter.

Effect	Coefficient	Std error	Std coeff	Tolerance	T ratio	P value
CONSTANT	5.471	0.401	0.000	.	13.628	0.000
IRI	0.412	0.050	0.212	0.738	8.287	0.000
Rutting	0.149	0.032	0.107	0.909	4.646	0.000
Ln(*Alligator Cracking*)	0.049	0.008	0.150	0.797	6.082	0.000
Ln(*Shoving*)	0.056	0.009	0.148	0.871	6.278	0.000
Ln(*Traffic*)	0.241	0.041	0.149	0.750	5.873	0.000
Ln(*Potholes*)	0.029	0.011	0.064	0.906	2.751	0.006
Pavement Age	0.010	0.003	0.089	0.914	3.873	0.000

Table A2 Analysis of variance.

Source	Sum-of-squares	Degrees of freedom	Mean-square	F ratio	P value
Regression	814.728	7	116.390	53.370	0.000
Residual	3696.463	1695	2.181		

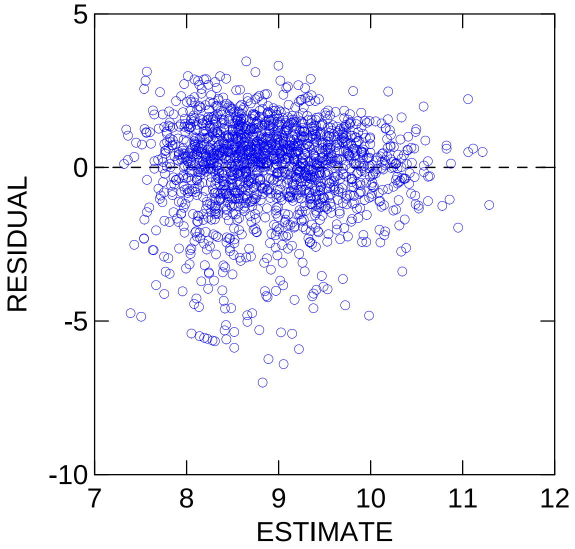

Figure A1 **Plot of residuals against predicted values for total maintenance cost – includes paving, surfacing and shoulder maintenance costs.**

A.1.2 Pavement maintenance cost model

Where the dependent variable is the natural log of the maintenance costs associated with paving.

N: 1386 Multiple R: 0.443 Squared multiple R: 0.196

Adjusted squared multiple R: 0.192 Standard error of estimate: 1.683

Table A3 **Relevant parameters and statistics for pavement maintenance cost model – includes a rutting parameter.**

Effect	Coefficient	Std error	Std coeff	Tolerance	T ratio	P value
CONSTANT	3.667	0.512	0.000	.	7.158	0.000
IRI	0.546	0.063	0.244	0.734	8.661	0.000
Rutting	0.232	0.042	0.141	0.913	5.582	0.000
Ln(*Alligator Cracking*)	0.049	0.010	0.134	0.791	4.951	0.000
Ln(*Shoving*)	0.071	0.011	0.169	0.878	6.567	0.000
Ln(*Traffic*)	0.308	0.053	0.166	0.722	5.846	0.000
Ln(*Potholes*)	0.022	0.013	0.043	0.893	1.682	0.093
Pavement Age	0.008	0.003	0.068	0.913	2.693	0.007

Table A4 **Analysis of variance.**

Source	Sum-of-squares	Degrees of freedom	Mean-square	F ratio	P value
Regression	953.674	7	136.239	48.109	0.000
Residual	3902.315	1378	2.832		

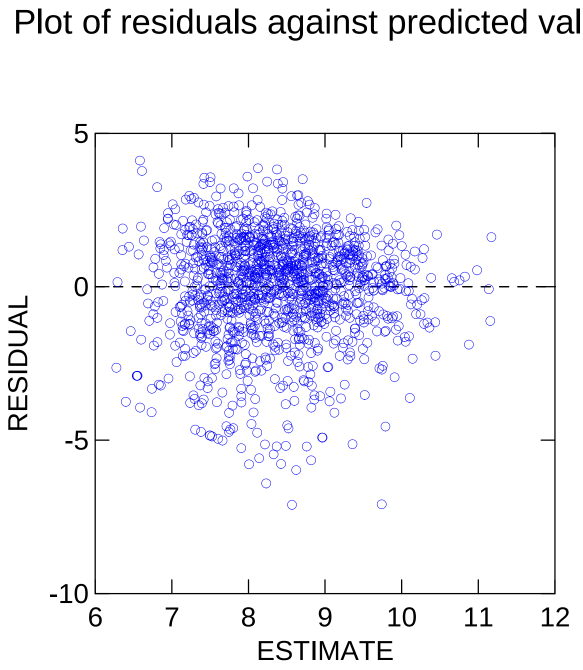

Figure A.2 Plot of residuals against predicted values for maintenance costs – includes only paving costs.

A.1.3 Pavement maintenance plus surfacing maintenance cost model

Dependent variable natural log of the sum of pavement and surfacing maintenance costs.

N: 1576 Multiple R: 0.461 Squared multiple R: 0.212

Adjusted squared multiple R: 0.209 Standard error of estimate: 1.542

Table A5 Relevant parameters and statistics for model of the sum of the pavement and surfacing maintenance costs – includes a rutting parameter.

Effect	Coefficient	Std error	Std coeff	Tolerance	T ratio	P value
CONSTANT	3.989	0.433	0.000	.	9.211	0.000
IRI	0.546	0.054	0.262	0.750	10.123	0.000
Rutting	0.214	0.035	0.142	0.913	6.038	0.000
Ln(*Alligator Cracking*)	0.045	0.009	0.130	0.803	5.206	0.000
Ln(*Shoving*)	0.060	0.009	0.152	0.877	6.364	0.000
Ln(*Traffic*)	0.306	0.044	0.179	0.747	6.912	0.000
Ln(*Holes*)	0.022	0.011	0.045	0.907	1.929	0.054
Pavement Age	0.012	0.003	0.105	0.918	4.480	0.000

Table A6 Analysis of variance.

Source	Sum-of-squares	Degrees of freedom	Mean-square	F ratio	P value
Regression	1004.317	7	143.474	60.347	0.000
Residual	3727.920	1568	2.378		

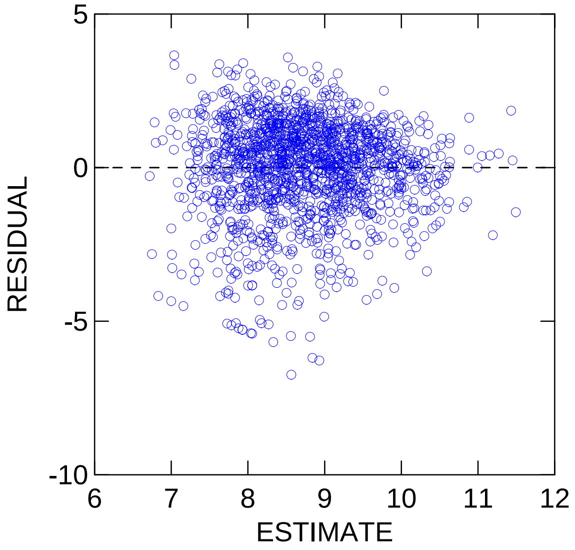

Figure A.3 Plot of residuals against predicted values for maintenance costs – includes paving and surfacing costs.