Selection of aggregates for skid resistance
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Contents

Executive summary

This report covers a statistical modelling exercise performed by Opus Central Laboratories in association with Statistics Research Associates to develop a means for reliably predicting the expected in-service skid resistance of any rural section of the New Zealand state highway network surfaced with chip seal.

The principal objective of the statistical modelling was to establish whether or not the source of a surfacing aggregate is a better determinant of in-service skid resistance performance than its polished stone value (PSV), which is a laboratory-derived ranking of an aggregate's ability to resist the polishing action of heavy commercial vehicles.

The measure of slow-speed skid resistance used was SCRIM (sideways-force coefficient routine inspection machine) coefficients averaged over a 10m length. The statistical modelling was based on data from the 2006–2007 high-speed condition survey of the entire New Zealand state highway network, which amounts to a sealed length of 23,113 lane km. The resulting database contains a total of 976,338 observations allowing identification of statistically significant relationships between the dependent variable (the measured in-service skid resistance) and the independent variables (road geometry, traffic characteristics and aggregate characteristics). One aggregate-related variable investigated was a categorical parameter, representing the name of the quarry from which the surfacing aggregate was sourced. This parameter inherently encompasses not only PSV but all other important influencing factors such as chip shape, chip hardness, mineralogical properties and crusher type.

The key conclusions arising from the statistical modelling were as follows:

- The variables found to have the most influence on in-service skid resistance in decreasing order of effect were pavement aggregate source, horizontal curvature, traffic (average daily traffic × surfacing age) and size of the sealing chip.
- Pavement aggregate source was shown to have the greatest ability to alter in-service skid resistance; the difference between best and worst performing pavement aggregate sources being 0.15 SCRIM coefficient. As skid resistance investigatory levels in the *T10:2010 Specification for state highway skid resistance management* (NZTA 2010a) increase by 0.05 SCRIM coefficient for each level of risk ranking, this highlights the importance of identifying appropriate aggregate sources when undertaking a preliminary design of a chipseal surface.
- The correlation between predicted in-service SCRIM coefficient and PSV is not very strong. Presuming this is not attributable to either test or material variability, this finding suggests there is at least one other factor which is accounted for by the categorical variable 'pavement aggregate source' but not by the quantitative variable 'polished stone value'. It is conjectured that this factor may be related to the shape/abrasion resistance of the sealing chip.
- The skid resistance of single coat chipseal surfaces constructed from smaller sized sealing chip (grade 4 or less) was shown to be about 0.03 SCRIM coefficient greater than that of single coat chipseal surfaces constructed from larger sized sealing chips (grade 2 and 3). They also offer slightly more skid resistance (0.01 to 0.02 SCRIM coefficient) than two coat chipseal surfaces. However, the observed poorer in-service skid resistance performance of two coat chipseal surfaces may, in part, be due to their increasing use at locations where high polishing stresses are likely to be present, such as tight curves and accelerating and braking zones.

- The top five performing pavement aggregate sources based on the analysis of the 2006–2007 RAMM dataset are in decreasing order:
  - Waitohai (Bay of Plenty)
  - Longburn (Manawatu/Wanganui)
  - Waioeka River (Bay of Plenty)
  - Maketu (Bay of Plenty)
  - Mangatainoka (Manawatu/Wanganui)
- For the highest demand category in NZTA's (2010a) T10:2010 specification, site category 1, it was determined that chipseal surfaces constructed with any of the top five performing pavement aggregate sources could maintain a skid resistance level above the threshold value of 0.45 SCRIM coefficient over their expected service life for the most arduous of situations, ie curves with horizontal radius of curvature less than 400m classified as having a high crash risk. Therefore, with the natural pavement aggregate sources presently available in New Zealand, a reasonable expectation is that chipseal surfacings can be designed to maintain a skid resistance level somewhere between the T10 threshold and investigatory levels throughout their expected life.

The associated recommendations for implementation of the findings and further research are:

- On the basis of the statistical modelling described in this report, there appears to be a strong case to use statistical modelling to complement PSV test results when ranking suppliers of surfacing aggregates.
- Following on from the above recommendation, the expected SCRIM coefficient from a chipseal design should be calculated from the pavement aggregate source using the statistical model developed rather than the PSV equation in the T10:2010 specification as PSV has been shown not to be a good predictor of in-service skid resistance. Because of the complex form of the statistical model, a Microsoft Office Excel spreadsheet has been written to perform the calculations for estimating in-service skid resistance. The spreadsheet is titled 'Aggregate selection for skid resistance' and can be accessed at www.nzta.govt.nz/resources/research/reports/470/index.html.
- A number of pavement aggregate sources have been identified as providing much better or much worse in-service skid resistance performance than indicated by their PSVs. These pavement aggregate sources are tabulated below. To progress our knowledge of what aggregate characteristics in addition to PSV influence in-service skid resistance performance, detailed investigations should be performed on each of these pavement aggregate sources. These investigations are likely to involve the application of various standard aggregate tests and electron microscope scans of the aggregates before and after being exposed to trafficking and laboratory-based accelerated polishing tests such as the PSV test.

Pavement aggregate source	Provincial location of source	Expected in-service skid resistance (SC)	Polished stone value (PSV)
Aparima River	Southland	0.490±0.009	57
Gore Gravel	Southland	0.482±0.012	56
Piroa	Northland	0.492±0.011	54, 61
Pukekawa Quarry	Auckland	0.562±0.021	48
Taotaoroa	Waikato	0.544±0.007	64

- To allow further refinement of the statistical model developed for predicting in-service skid resistance, it is essential that all pavement aggregate sources used on the New Zealand state highway network have a unique identifier and that this identifier is consistently applied in the RAMM database (for instance, by using a dropdown list instead of free text entry).
- Given that after pavement aggregate source, horizontal radius of curvature has the largest influence on in-service skid resistance, it appears prudent to repeat the statistical modelling but this time limiting the analysis to curves with a radius of 400m or less. This will allow identification of the best and worst performing pavement aggregate sources for each of the low-, medium- and high-risk categories of curves. The recent addition of the ‘curve context’ table to the RAMM database makes such a statistical modelling exercise now possible.

Abstract

Statistical modelling was undertaken to develop a means for reliably predicting the expected in-service skid resistance of any rural section of the New Zealand state highway network surfaced with chip seal.

The measure of slow-speed skid resistance used was the sideways-force coefficient routine inspection machine (SCRIM) coefficients averaged over a 10m length. The statistical modelling was based on data from the 2006–2007 high-speed condition survey of the entire New Zealand state highway network, which amounts to a sealed length of 23,113 lane km. The resulting database contains a total of 976,338 observations allowing identification of statistically significant relationships between the dependent variable (the measured in-service skid resistance) and the independent variables (road geometry, traffic characteristics and aggregate characteristics). One aggregate-related variable investigated was a categorical parameter, representing the name of the quarry from which the aggregate was sourced. This parameter inherently encompasses not only polished stone value but all other important influencing factors such as chip shape, chip hardness, mineralogical properties and crusher type.

The major finding was that the categorical variable ‘aggregate source’ is a better predictor of in-service skid resistance performance than the numeric variable ‘polished stone value’.

1 Introduction

Since 1998, the skid resistance management of the New Zealand state highway (SH) network has come under close scrutiny through routine surveys using multifunctional road condition monitoring systems (using the sideways-force coefficient routine investigation machine, or SCRIM). Increasingly skid resistance issues related to polishing of aggregates and loss of texture through flushing drive road surface maintenance, resulting in annual expenditures of between NZ$4.5M and NZ$5M.

This annual expenditure on SCRIM-driven sealing is approximately five times more than predicted when the New Zealand Transport Agency's (NZTA's) skid resistance policy was first introduced in 1998 (ie the annual cost of restoring skid resistance once all substandard sites had been treated was estimated at $1M per annum compared with the actual cost of $4.5M to $5M per annum). However, the benefit–cost of this expenditure has been assessed to lie between 13 and 35 indicating that the skid resistance policy is a very efficient and effective safety strategy (Cook et al 2011).

One reason put forward for the over-expenditure on SCRIM-driven sealing was a possible over-reliance on aggregate polished stone value (PSV) to achieve the in-service skid resistance required for compliance with NZTA's T10 specification for skid resistance investigation and treatment selection (NZTA 2010a). PSV is a laboratory derived ranking of an aggregate's ability to resist the polishing action of heavy commercial vehicles (HCVs).

A major advancement in the field of skid resistance was the publication of Transport and Road Research Laboratory's (TRRL's) report LR 504 (Szatkowski and Hosking 1972) as it provided a method for stipulating at the design stage the properties of roading aggregate required to produce a given ultimate skidding resistance for a supposed traffic flow. This method was based on the result of a regression analysis performed on 139 different road sections in the UK with traffic densities of up to 4000 commercial vehicles per lane per day. The resulting regression model, which applies to straight roads only, was:

$$SC = 0.024 - 0.663 \times 10^{-4}\ CVD + 0.01\ PSV \quad (r^2 = 0.83) \qquad \text{(Equation 1.1)}$$

where: SC = SCRIM coefficient

CVD = commercial vehicles per lane per day

PSV = polished stone value

Equation 1.1 has been used subsequently in both the UK and New Zealand as the basis for specifying the PSV of aggregates employed in the construction of new roads. However, it has been demonstrated that different aggregates with the same PSV provide a range of skid resistance levels in practice and even aggregates from the same source can deliver a range of skid resistance for the same volume of commercial vehicle traffic. Comparative studies conducted in the UK (Roe and Hartshorne 1998) and in New Zealand (Cenek et al 2004) suggest equation 1.1, which is incorporated in the T10 specification, does not adequately reflect on-road skid resistance performance of roading aggregates. In fact, the correlation (r^2) between predicted and observed skid resistance on straight road sections where the best correlation could be expected, was found to be less than 10%, ie less than 10% of the observed variance can be explained.

Therefore, statistical modelling studies were undertaken to establish whether or not a categorical parameter, representing the name of the quarry from which the aggregate is sourced, could be a better determinant of in-service skid resistance performance than PSV. This categorical parameter encompasses not only PSV but all other important influencing factors such as chip shape, chip hardness, mineralogical properties and crusher type.

These investigations were undertaken in response to concerns raised by the industry associated with:

- the increasing need to guarantee in-service skid resistance performance because of penalty clauses for non-compliance in Transit New Zealand’s (TNZ’s – now NZTA’s) performance-specified maintenance contracts (PSMC) and hybrid contracts
- pressure to identify sources of natural aggregate that display high in-service resistance to polishing and wear because of increasing vehicle numbers coupled with increasing vehicle use.

As all the required data was already held by the NZTA, the investigations were able to be carried out as a desktop only exercise.

This report presents an overview of the statistical analysis performed and discusses the implications of the principal findings with respect to surfacing design and future research needs.

2 Data analysis

2.1 The RAMM database

The NZTA's road assessment and maintenance management (RAMM) database contains data from the annual road condition and geometry surveys of the entire 10,876.8km (ie 23,113.2 lane-km) of sealed state highway, which are performed with SCRIM$^+$, a truck-based multifunctional road monitoring device. The road surface texture (mm mean profile depth (MPD)), skid resistance (SCRIM coefficient), gradient (%), horizontal curvature (radius, m) and cross-fall (%) are recorded over 10m intervals whereas roughness (International Roughness Index (IRI), m/km) and rut depth (mm) are recorded over 20m intervals.

Since 2002, skid resistance values have been corrected for inter-year variations in weather conditions during the annual SCRIM surveys to yield equilibrium SCRIM coefficients (ESC). Therefore, a sufficiently large database has been created to allow identification of statistically significant relationships between measured in-service skid resistance (in terms of ESC, the dependent variable), and road geometry (gradient, cross-slope and horizontal curvature), traffic characteristics, regional effects, T10 site categories, and aggregate characteristics (the independent variables).

For this study, the wheel path IRI roughness, wheel path skid resistance, wheel path texture and lane geometry data were linked to surfacing records and traffic volume estimates, all of which are held in RAMM. The roughness, skid resistance and texture values were averaged over the two wheel paths to yield lane values. This was the only averaging performed.

The 10m length was used as the base for the statistical modelling and for linking records as the more important variables for this study had been measured over this interval (eg skid resistance). The 20m wheel path roughness values were therefore converted to the shorter 10m interval by assuming the roughness was homogeneous over the 20m length.

An initial regional analysis was made using the 2004–2005 survey data as recorded in the RAMM database for NZTA administration areas of Northland and Napier, with the results reported to the NZTA and the New Zealand Institute of Highway Technology (NZIHT) 9th Annual Conference (Cenek et al 2008). Furthermore, the results were exposed to international scrutiny and peer review with the NZIHT paper also being presented at the 2nd International Conference on Surface Friction of Roads and Runways, 11–14 May 2008, Cheltenham, UK. The paper can be downloaded from the following link: www.saferroads.org.uk/2008papers.asp (accessed January 2012).

This initial regional analysis found that the pavement source (specifically the name of the quarry) was a better predictor of the SCRIM coefficient than the aggregate PSV, so PSV was not included in the subsequent national analysis of New Zealand's chipseal SH network. In addition, only the variables found to be important in the initial regional analyses are included in the national analysis discussed in the remainder of this report.

2.2 Initial processing

For the national analyses, the variables and restrictions as summarised in table 2.1 were used to extract data from the RAMM database for the summer of 2006–2007. A graphical presentation of the resulting database in terms of histograms and boxplots is given in appendix A.

With reference to table 2.1, the restriction placed on the *traffic* variable has been chosen to coincide with the expected default seal life for the highest traffic level likely to be carried by a chipseal surface, ie 5.25 years at 20,000 ADT (refer TNZ 2005).

Table 2.1 Variables from the RAMM database used in the national analysis

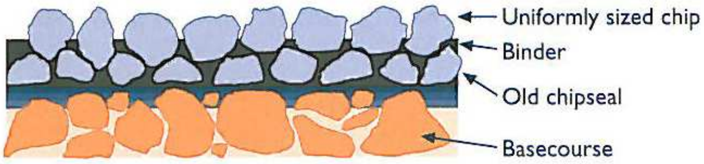
Variable	Restrictions	Comments
SCRIM coefficient (SC) – not mean summer SCRIM coefficient (MSSC) or ESC	none	The measured skid resistance.
Speed environment	rural only (>70km/h)	Not used as a variable in the analysis.
Age (months)	24 < age < 240	The lower age restriction of the surface is to ensure the polishing phase, where the skid resistance reduces under the action of traffic, has been passed. The upper age restriction concerns lower traffic volume SHs where binder-hardening over time leads to failure either through cracking or chip dislodgement (TNZ 2005).
Average daily traffic (ADT)	100 < ADT < 30,000	ADT (measured in vehicles per day). Not used explicitly as a variable in the analysis (see traffic variable below).
Traffic	traffic < 1,260,000	traffic = age x ADT.
Pavement source	> 1000 observations	There must be at least 1000 observations from a particular quarry for it to be included in the analysis. There is some ambiguity with pavement source names as some are known by a variety of names (refer section 2.9.1).
Gradient	none	Note: Uphill gradients are positive and downhill gradients are negative.
Curvature	10 < abs(curvature) < 32,000	Radius of the horizontal curvature of the road (metres).
PSV	none	The PSV is not used in this analysis. (It is included here as it is used later, specifically appendix B for a comparison with the predicted effect of the different pavement sources.)
Skid site	none	The T10 skid site category.
Surface function	none	1st coat, 2nd coat or reseal
Surface material	1CHIP or 2CHIP only	See section 2.3 ‘Road surface types considered’ below.

2.3 Road surface types considered

Only single and two chipseals (ie RAMM codes of 1CHIP and 2CHIP respectively) were considered as they are the prevalent seal types used on the New Zealand SH network.

A single coat (1CHIP) is a single application of sealing binder followed immediately with a single application of chip, which is spread and rolled into place (refer figure 2.1). It is best in situations where traffic stresses are not great (TNZ 2005).

Figure 2.1 A single coat seal shown as a reseal, from TNZ (2005)

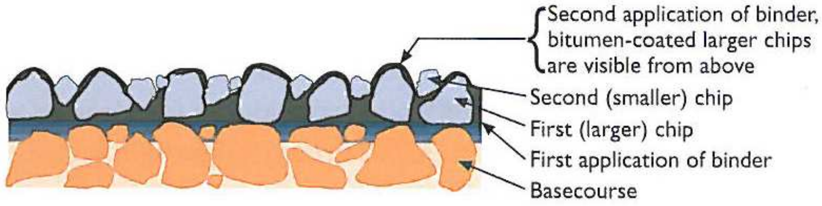


A two coat (2CHIP) is a chipseal with two applications of binder and two applications of chip (refer figure 2.2) applied in the following sequence:

1. An application of sprayed binder, followed immediately by an application of a large size (ie grade 2 or 3) chip (refer table 2.2)
2. A second application of sprayed binder and a second application of smaller chip (ie grade 4 or 5).

Both coats are applied one after the other with little or no time delay between coats. Typically, two coat seals are used in high-stress areas.

Figure 2.2 Two coat seal shown as a first coat, from TNZ (2005)



Sealing chip size is specified in grades from grade 2 (coarsest) to grade 5 (finest). The relationship between the grade of sealing chip, maximum sieve size and average least dimension (ALD) assumed for this analysis is given in table 2.2.

A summary of the categories of the surface material used in the analysis is given in table 2.3.

Table 2.2 Characteristics of sealing chip conforming to TNZ M6:2002

Grade	Mean ALD (mm)	Maximum sieve size (mm)
2	10.75	19
3	8.75	16
4	6.75	12
5	5.00	9

Table 2.3 Surface material categories used in the analysis

Surface category	Description	RAMM-based identifier
1	Single coat, grade 2	1CHIP_2
2	Single coat, grade 3	1CHIP_3
3	Single coat, grade 4 or higher	1CHIP_4+
4	Two coat, first chip = grade 2, second chip grade ignored	2CHIP_2
5	Two coat, first chip = grade 3 or higher, second chip grade ignored	2CHIP_3+

2.4 T10 skid resistance site categories

The NZTA's policy for skid resistance management of the SH network is largely contained within the T10 specification. This specification was first introduced in 1998 and aims to standardise the risk of a wet skid crash across the SH network by assigning investigatory skid resistance levels for different site categories, which are related to different friction demands.

At the time the statistical analysis presented in this report was performed, the T10:2002 specification was current (TNZ 2002). For ready reference, table 2.4 provides a summary of the site categories and associated investigatory levels that have been used.

Table 2.4 T/10 skid site categories

Site category	Description	Notes	Investigatory level (ESC)
5	Divided carriageway		0.35
4	Normal roads	Undivided carriageways only.	0.40
3	Approaches to road junctions. Down gradients 5% -10%	Includes motorway on/off ramps.	0.45
2	Curve < 250m radius down gradients > 10%		0.50
1	Highest priority	Railway level crossing, approaches to roundabouts, traffic lights, pedestrian crossings and similar hazards.	0.55

2.5 Analysis software

The initial processing of the data was performed with structured query language (SQL) queries in Microsoft SQL Server. The size of the resulting dataset was too large for the software packages S-plus or R so further processing was done using a C++ analysis program adapted from one used previously in a crash-risk analysis by Cenek et al (2005).

The fit process was carried out using a C++ program (based on the S-plus software routine *lme).* This is similar to usual regression analysis routines, but allows for the random surface layer effect (discussed in the following section).

2.6 Analysis method

The statistical analysis undertaken attempted to express the value of the SCRIM coefficient in terms of the independent variables considered using linear regression. However, a simple regression procedure was not suitable for this task as it could not satisfactorily model the random structure expected.

Accordingly, two levels of randomness were supposed. The first level of randomness supposed there was a random element associated with each of the SCRIM coefficient measurements. The second level of randomness supposed there was a random element associated with each top surface layer extracted from RAMM's carriageway surface table. (This random element was constant over a particular surface layer but the values for different surface layers were statistically independent.)

Mathematically the model can be expressed as:

$$Y = X\beta + Z\eta + \varepsilon \qquad \text{(Equation 2.1)}$$

where:

Y = A vector of observations (length n if there are n observations).

β = A vector of unknown parameters to be estimated.

X = A matrix that says how the unknown parameters affect the observations.

η = A vector of random components associated with the surface layers (η has the same number of elements as the number of different surface layers).

Z = A matrix that associates the surface layers with the observations. (If the i^{th} observation is on the j^{th} surface layer then $Z_{ij} = 1$ and the rest of the i^{th} row of Z is zero.)

ε = A vector of the random components associated with each observation as in simple linear regression.

It is assumed the elements of ε are independently normally distributed with zero mean and variance σ^2 and the elements of η are independently normally distributed with zero mean and variance τ^2. The values of σ^2 and τ^2 are estimated as part of the fit process.

Even though the model is still an approximation to the real situation, for example correlations between adjacent readings are not allowed for, it will give far more realistic tests of significance and confidence intervals than a simple regression analysis.

2.7 Analysis results

The model being used here (ie $Y = X\beta + Z\eta + \varepsilon$ (equation 2.1)) is linear. However, in most cases the dependant variable (here, the SCRIM coefficient) will depend in a non-linear manner on the independent variables. In this situation, it is usual to transform the original variables into new variables so that the model depends linearly on these transformed variables. A description of how the original variables have been transformed is given in table 2.5 below. The table also includes the analysis of variance results, by doing maximum likelihood estimation and using the log-likelihood for testing for significance. The first of the two chi-squared columns in table 2.5 pertains to the situation where each term, comprising the transformed variable, is the last being fitted. The second is where the terms are added sequentially.

Table 2.5 Analysis of variance

Variable	Transformation	Degrees of freedom	Chi-squared	
			Term added last	Term added sequentially
Curvature	Seven degree spline function of the log^{10} of the reciprocal of the curvature. Assumed constant outside the range -4.5 to -1 (ie curvature outside the range 10 to 32,000).	6	57,009	57,146
Gradient	Six degree spline function of the gradient. Assumed constant outside the range -10% to +10%.	5	4662	4627
Skid site	Levels 2 to 5 are amalgamated.	1	163	139
Surface function	No transformation. Categories are: 1=1st coat, 2=2nd coat or R=reseal.	2	52	7
Traffic (= *age x ADT*)	Seven degree spline function of the log^{10} of traffic. Assumed constant outside the range 4.1 to 6.1 (ie traffic outside the range 200 to 32,000).	6	1824	2795
Age	Six degree spline function of the log$_{10}$ of the age (months). Assumed constant outside the range 1.38 to 2.38 (ie age outside the range 24 to 240 months.	5	217	366
Surface category	No transformation. Categories are: 1CHIP_2, 1CHIP_3, 1CHIP_4+, 2CHIP_2 or 2CHIP_3+.	4	315	542
Pavement source	No transformation. This variable contains the name of the quarry.	109	3574	3574

The values of chi-squared are shown to be extremely statistically significant, with most effects being significant at the 0.1% level apart from surface function when added sequentially, which is significant at the 2.5% level. This is mostly due to the very large sample size. However, it is also partly due to the random component of the linear regression model being over simplified.

With reference to table 2.5, curvature and gradient have bigger chi-squared values than the other variables. This is because curvature and gradient vary within each data block of road surface with the same surface layer. In comparison, the other variables (except skid site) are constant or almost constant (eg traffic) within each data block of road surface. Therefore, more information is available concerning curvature and gradient.

The estimate of the ratio of the standard deviations η / ε is 1.02. This indicates the variability associated with the surface layer is about the same as that from the individual data points.

2.8 Estimation of in-service skid resistance

2.8.1 General description

Because the resulting statistical model for estimating in-service skid resistance performance of chipseal surfaces is rather complicated, a Microsoft™ Excel spreadsheet has been prepared to perform the required calculations. This spreadsheet is titled ‘Aggregate selection for skid resistance’ and can be accessed at www.nzta.govt.nz/resources/research/reports/470/index.html.

The spreadsheet contains two worksheets as follows.

The first worksheet named ‘Interface’ provides a simple calculation page for predicting the SCRIM coefficient value from a set of predictor variables. Values of the predictor variables can be entered into the appropriate places in the orange-bordered cells D4:D11. For the categorical variables, drop-down menus are provided to ensure entries are exactly as written in the second worksheet.

The spreadsheet uses the Excel command VLOOKUP to look up the tables and enter the effect of each predictor variable into the column labelled model in the ‘Interface’ worksheet.

The predicted SCRIM coefficient value displayed in cell E13 is the sum of these effects.

The second worksheet is named ‘Model’ and contains a series of tables and associated plots showing the effect of varying each of the predictor variables. The quantity tabled and plotted is the difference between, on one hand, the values of SCRIM coefficient when the default values listed in table 2.6 are used, apart from the one being varied, and, on the other hand, the default values. The 95% confidence intervals associated with each predicted value of SCRIM coefficient have also been included.

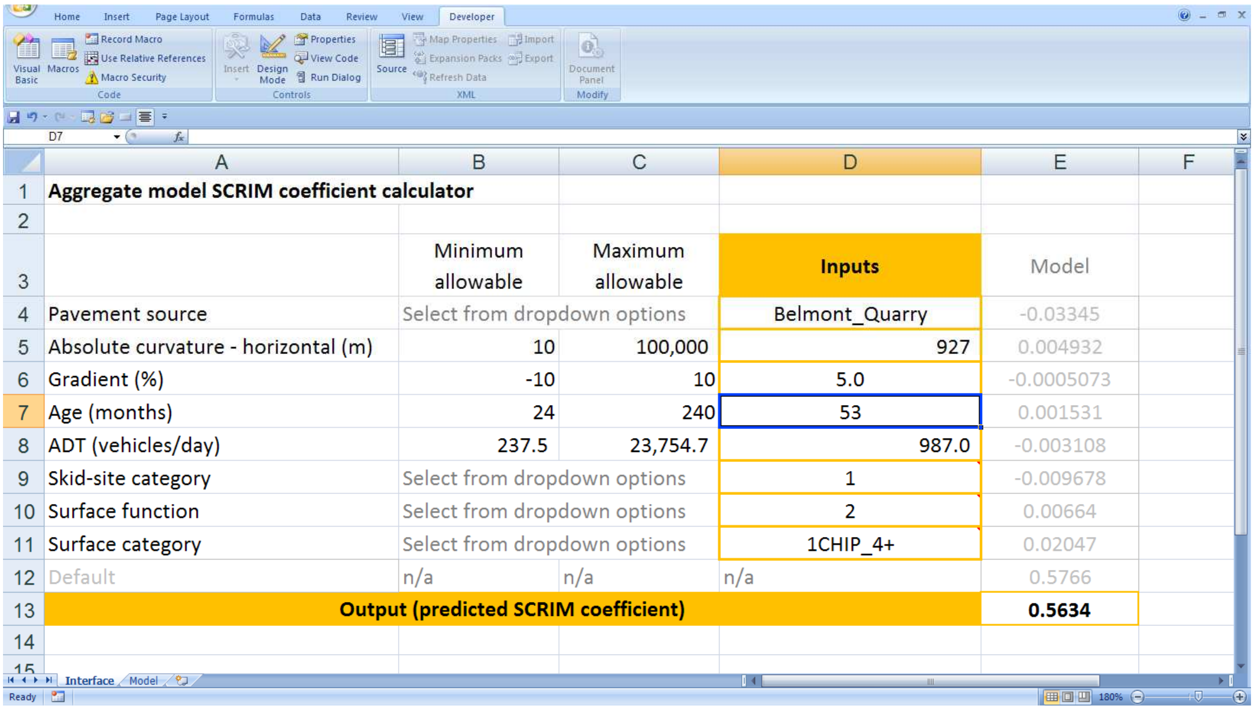
Table 2.6 Default values of the predictor variables

Variable	Default value	Comments
Reciprocal curvature	0.0	Straight road
Gradient	0.0	No gradient
Amalgamated skid site	2 to 5	
Traffic	48000	4 years (ie 48 months) with ADT = 1000
Age	48 months	4 years
Surface category	1CHIP_3	Single coat, grade 3 chipseal
Surface function	R	R=reseal
Pavement source	Poplar Lane	Name of quarry where aggregate has been sourced

2.8.2 Worked example

For example, if values are entered in cells D4:D11 of the ‘Interface’ worksheet of the spreadsheet as in the screen shot in figure 2.3, the predicted SCRIM coefficient is 0.5634 (ie cell E13).

Figure 2.3 Screenshot of example SCRIM coefficient calculation



	A	B	C	D	E	F
1	**Aggregate model SCRIM coefficient calculator**					
2						
3		Minimum allowable	Maximum allowable	**Inputs**	Model	
4	Pavement source	Select from dropdown options		Belmont_Quarry	-0.03345	
5	Absolute curvature - horizontal (m)	10	100,000	927	0.004932	
6	Gradient (%)	-10	10	5.0	-0.0005073	
7	Age (months)	24	240	53	0.001531	
8	ADT (vehicles/day)	237.5	23,754.7	987.0	-0.003108	
9	Skid-site category	Select from dropdown options		1	-0.009678	
10	Surface function	Select from dropdown options		2	0.00664	
11	Surface category	Select from dropdown options		1CHIP_4+	0.02047	
12	Default	n/a	n/a	n/a	0.5766	
13	**Output (predicted SCRIM coefficient)**				**0.5634**	
14						
15						

2.9 Plots of effects of predictor variables

Graphs in the following sub-sections show the effect of each of the eight predictor variables on the calculated in-service skid resistance value. The vertical axis scale of the graphs has been kept the same so the more important effects are readily apparent. In addition, confidence intervals or confidence lines have been included in the graphs. These correspond to two standard errors on each side of a plotted point thereby equating to the 95% confidence interval if each point is considered one at a time.

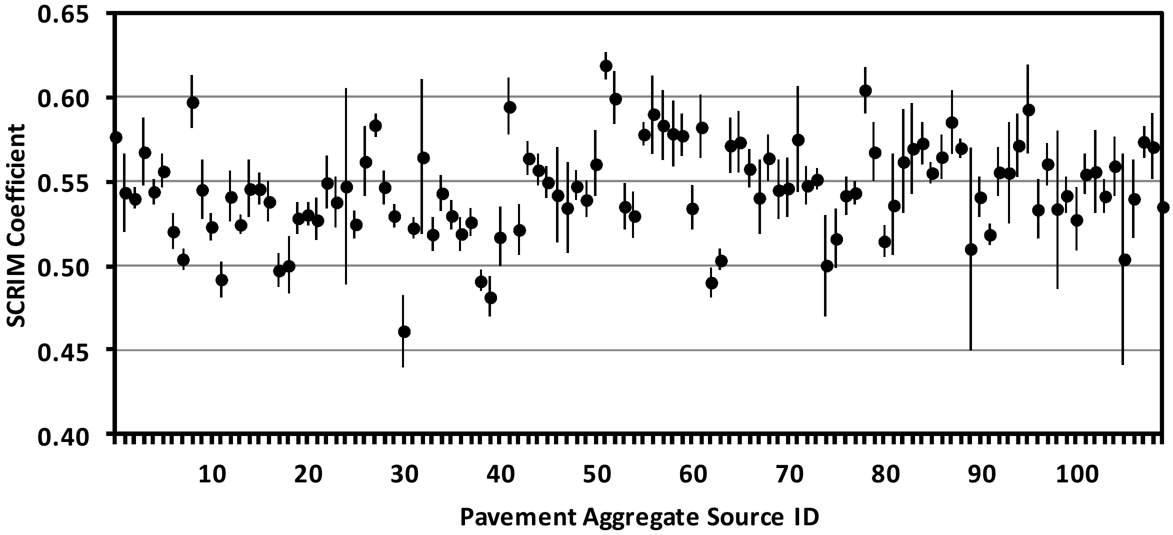
The graphs are replicated in the second worksheet of the spreadsheet 'Aggregate selection for skid resistance' (available at www.nzta.govt.nz/resources/research/reports/470/index.html). However, instead of absolute skid resistance being plotted on the vertical axis, it is the difference from the SCRIM coefficient calculated using the default values listed in table 2.6.

2.9.1 Pavement aggregate source

Only a subset of the data is shown in figure 2.4, with the complete data presented in appendix B. Figure 2.4 shows there is a lot of variation in SCRIM coefficient between pavement aggregate sources. The difference in length between the confidence intervals (ie the upper and lower line extents) is mostly due to the varying numbers of measurements for each pavement source. However the differing variabilities of the different aggregate sources will have also contributed to this variation.

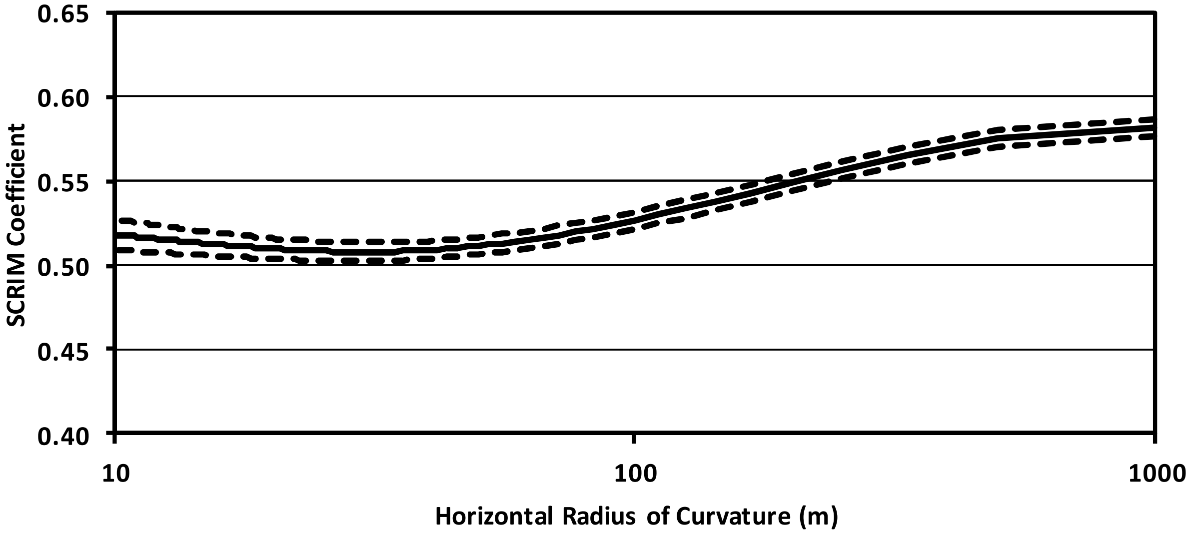
There was some ambiguity with pavement aggregate source names as some sources were known by a variety of names and others were simply misspelt. For example, the pavement aggregate source *Winstones* includes a number of source quarries run by Winstones for which the individual sources cannot be readily distinguished. However, in an attempt to, at least partially, separate the source quarries, *Winstones* has been divided into *Winstones-1*, *Winstones-2*, *Winstones-4*, *Winstones-5* and *Winstones-6* where the number indicates the NZTA administration region the road using the aggregate belongs to with *Winstones-2* being a combination of regions 2 and 8.

Figure 2.4 Variation of the predicted SCRIM coefficient with pavement aggregate source



2.9.2 Horizontal radius of curvature

Figure 2.5 Variation of the predicted SCRIM coefficient with reciprocal of horizontal radius of curvature



The horizontal axis of figure 2.5 has a logarithmic scale.

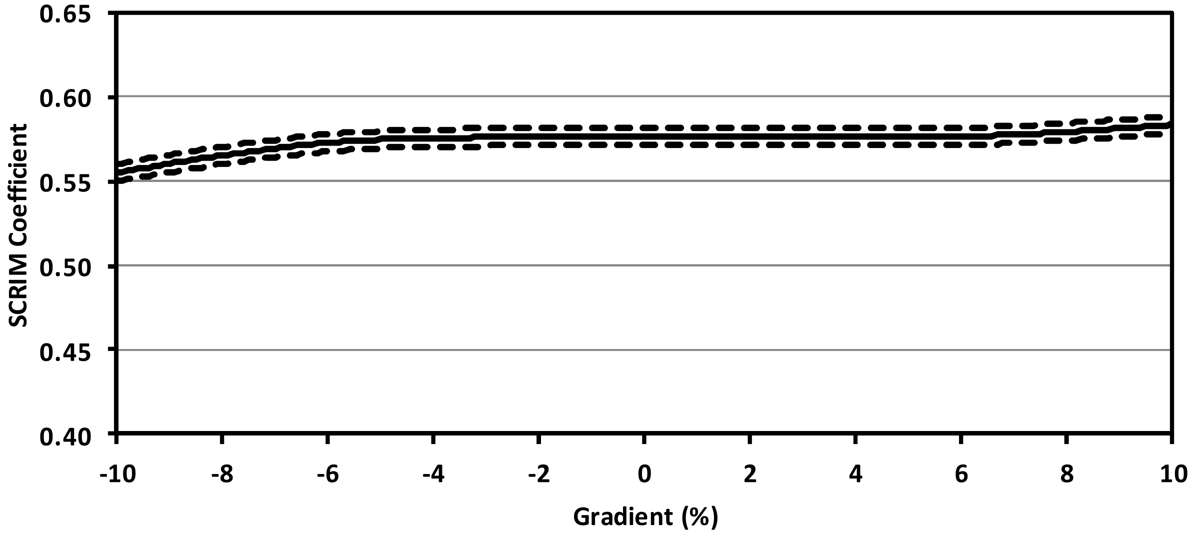
Figure 2.5 suggests that a maximum polishing effect occurs at a horizontal radius of curvature of around 30m. However, there is not much data to the left of this point so maybe not too much weight should be placed on this observation.

It should be noted that on the New Zealand SH network, as at 2010, there are 4434 curves with a horizontal radius of curvature less than 400m. Of these, 2122 or 48% represent curves with a horizontal radius of curvature less than or equal to 100m and 725 or 16% represent curves with a horizontal radius of curvature less than or equal to 50m.

2.9.3 Gradient

Figure 2.6 suggests there is not much effect on SCRIM coefficient for gradients between -5% and +5%, but for greater absolute gradients there is an increase in polishing for downhill gradients and a decrease for uphill gradients. The effect is rather smaller than for curvature.

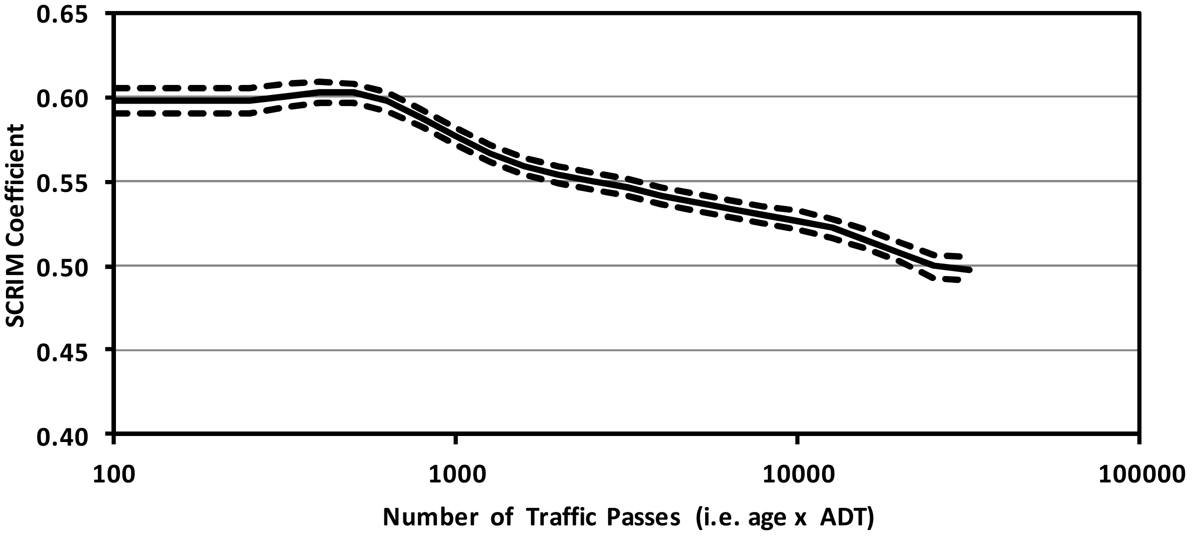
Figure 2.6 Variation of the predicted SCRIM coefficient with gradient



2.9.4 Traffic (= age × ADT)

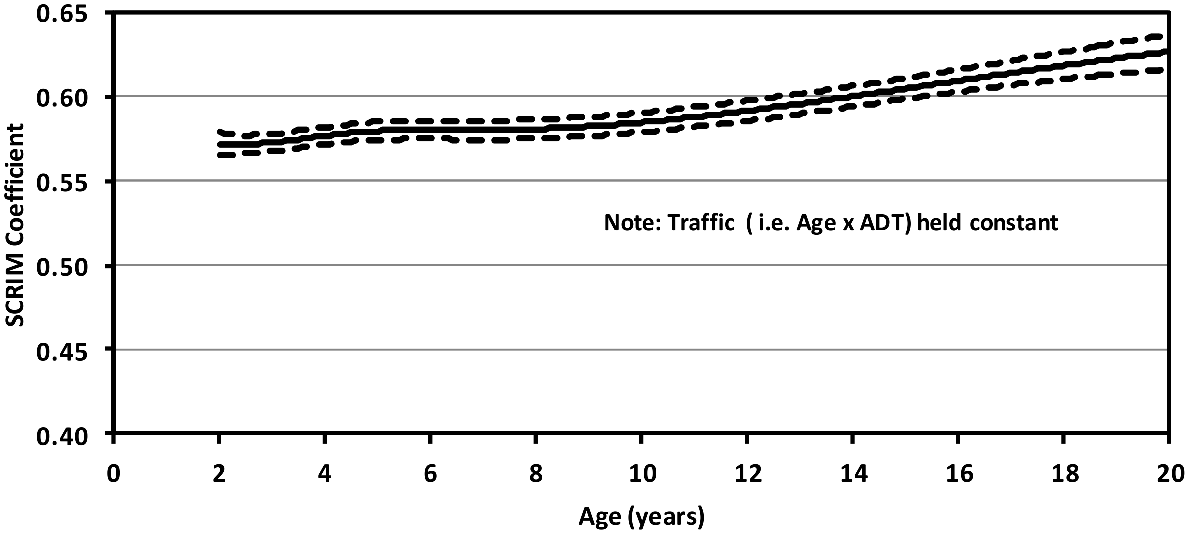
Figure 2.7 shows the SCRIM coefficient value drops as the amount of traffic (= *age x ADT*) that has traversed the road increases. This drop off in SCRIM coefficient is reasonably linear once the traffic exceeds 300,000 vehicle passes and equates to a reduction in SCRIM coefficient of about -0.004 per 100,000 vehicle passes.

Figure 2.7 Variation of the predicted SCRIM coefficient with $\log_{10}$ traffic (age × ADT)



2.9.5 Age

Figure 2.8 Variation of the SCRIM coefficient with surface age (in years)



Traffic is being held constant in figure 2.8 so as age increases, the tendency is to get lower ADT roads. So what is observed is partly a result of how traffic, ADT and age interrelate

Figure 2.8 shows skid resistance values drop slightly for surfaces less than five years old and then rise. This suggests that with low ADT there is less polishing.

One possible reason for this observed effect, at least for the older roads, is that the more worn roads are being resurfaced and hence removed from the sample and observations are biased towards less worn roads. Another is that some of the roads have been resurfaced but not recorded in the RAMM database.

Yet another reason might be that no account is taken of HCV traffic. (The HCV data in RAMM was judged too unreliable to be usable.) However, the higher ADT roads may tend to have a higher percentage of HCV traffic. Higher ADT roads will tend to be more prevalent in the lower age roads and so may contribute to a lower SCRIM coefficient value than expected.

Overall, because the trend of increasing SCRIM coefficient with age may be partly spurious, it is suggested that the model should not be used for roads older than 10 years where the observed effect is strongest.

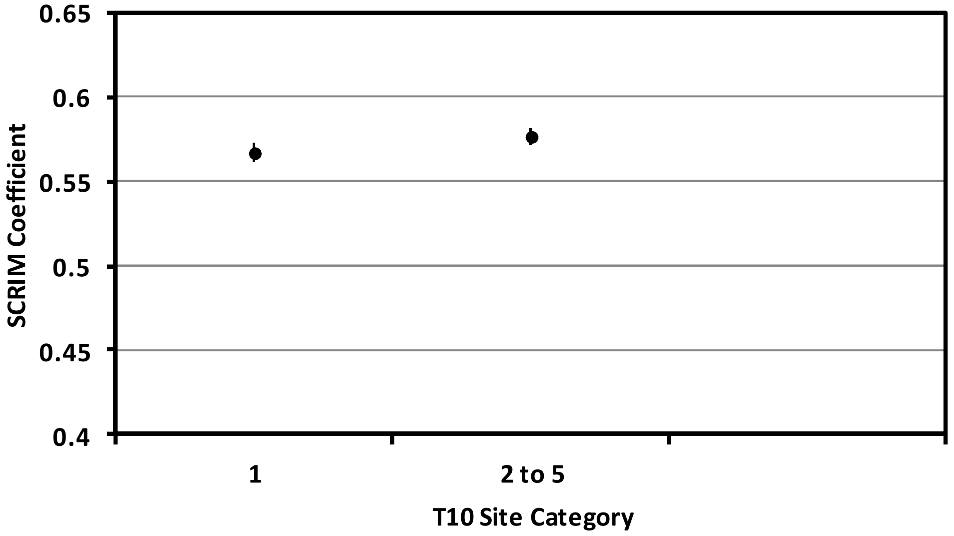
Figure 2.8 has been included to illustrate the inter-relationship between skid resistance, traffic passes, ADT and age. Practitioners should only refer to the traffic passes plot, figure 2.7, when attempting to understand the basis of the output from the spreadsheet 'Aggregate selection for skid resistance' available at www.nzta.govt.nz/resources/research/reports/470/index.html.

2.9.6 Skid_site

Figure 2.9 shows that the predicted SCRIM coefficient where the demand is highest (ie T10 site category 1) is about 0.01 less than for the other T10 site category (site categories 2 to 5). The effect due to T10 site category can therefore be regarded as being relatively minor.

This result is as expected as practitioners have intervened to construct T10 site category 1 road surfaces with aggregates that have more polishing resistance than for the other T10 site categories and confirms that NZTA's skid resistance policy is having the desired effect.

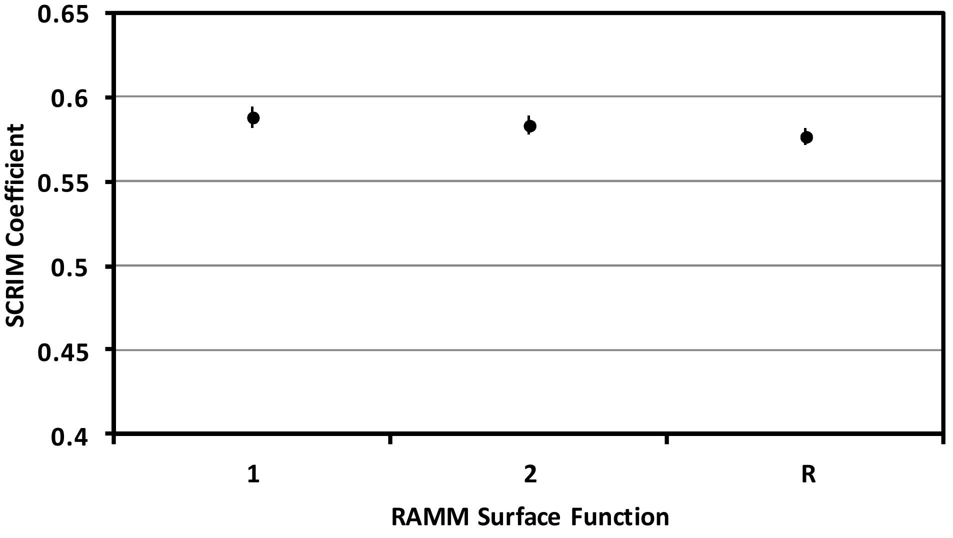
Figure 2.9 Variation of the predicted SCRIM coefficient with T10 skid site category



2.9.7 Surface function

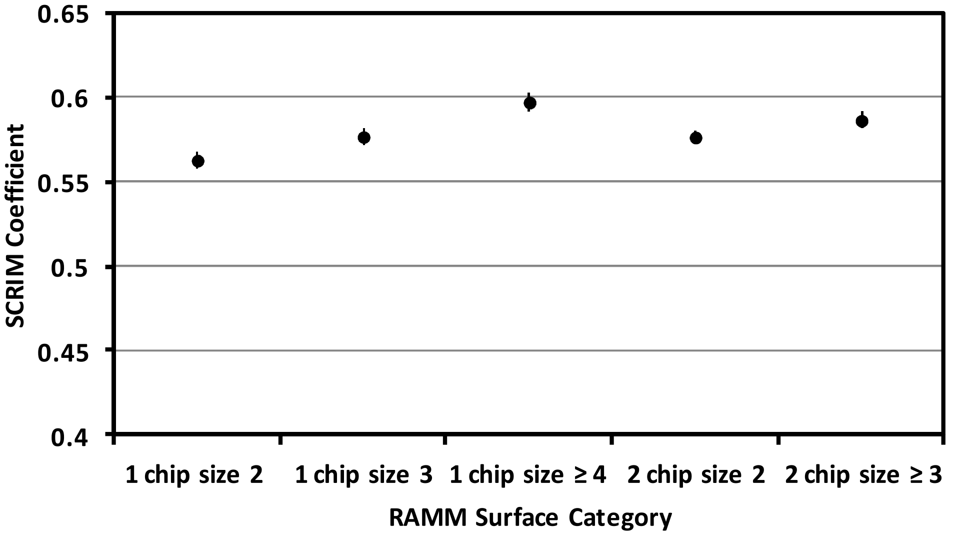
Figure 2.10 suggests surface functions 1 (first coat seal)) and 2 (second coat seal) might result in higher SCRIM coefficient values than surface function R (reseal), denoted as 3 in the plot. However, the effect, although statistically significant, is too small for any certainty. Furthermore, first coat seals are generally expected to last only one year. Their inclusion in the analysis, where a minimum age restriction of 24 months has been imposed, indicates that the surface function 1 road sections must be carrying very low traffic volumes to have their life extended past 12 months. This explanation fits the observed trend as we would expect roads carrying lower traffic volumes to display higher skid resistance than roads carrying higher traffic volume, all other things being equal.

Figure 2.10 Variation of the predicted SCRIM coefficient with surface function as defined in table 2.1



2.9.8 Surface category

Figure 2.11 Variation of the predicted SCRIM coefficient with surface category as defined in table 2.3



The surface categories 1–5 plotted in figure 2.11 are as defined in table 2.3. From figure 2.11 it is clearly evident the SCRIM coefficient is higher on roads with small chips (ie higher grade).

A possible explanation as to why two coat seals are observed to provide lower skid resistance than small chip single coat seals is that the former is predominately used on higher stress sites. It is also apparent from figure 2.1 that a grade 2 or 3 chip when used in a single coat chipseal surface provides marginally less skid resistance than when used in a two coat chipseal.

2.9.9 Summary of effects

To place the relative influence of the predictor variables in better context, the magnitude of the maximum change in predicted SCRIM coefficient has been calculated over variable ranges of interest to SH asset engineers. For example, the average seal life of a grade 4 chipseal surfaced section of SH carrying 0–1000 ADT is 10 years from RAMM giving a traffic value of 1.2×10^5 vehicle passes, whereas if the same road section carries 20,000–25,000 ADT (the upper range for chipseal surfaces) the average seal life reduces to four years giving a traffic value of 1.2×10^6 vehicle passes.

The results of this analysis are summarised in table 2.7.

Table 2.7 Comparison of relative sensitivities over ranges of interest for New Zealand state highways

Variable	Range of interest	Magnitude of change in predicted SCRIM coefficient
Pavement aggregate source	All accredited suppliers of natural aggregates	0.158
Horizontal radius of curvature (m)	30m–500m	0.067
Gradient (%)	±10%	0.028
Traffic (age(months)×ADT)	1.2×105 – 1.2×106	0.051
T10 site category	1 –5	0.010
Surface function	2nd coat or reseal	0.012
Surface category	Single or two coat chipseal	0.034

With reference to table 2.7, it is evident that pavement aggregate source, horizontal curvature and traffic have the largest influence on in-service skid resistance followed by sealing chip size (ie surface category). Of particular note is pavement aggregate source, which has the ability to change the magnitude of the predicted SCRIM coefficient by more than 0.15. This is equivalent to a three-step change in T10 skid site category (eg site category 4 where the investigatory level (IL) has been set at 0.4 SC to site category 1 where the IL has been set at 0.55 SC) and illustrates the importance of identifying appropriate pavement aggregate sources when undertaking a preliminary design of a chipseal surface.

3 On-road skid resistance performance and PSV

3.1 SCRIM coefficients sorted by pavement aggregate source

Figure 3.1 on the next page shows the predicted values for SCRIM coefficient for the pavement aggregate sources assuming the default values listed in table 2.6 for the other variables. It also shows the 95% confidence intervals (the upper and lower extent of the bars/lines). The pavement aggregate source sites have been sorted by the size of the predicted value (ie SCRIM coefficient).

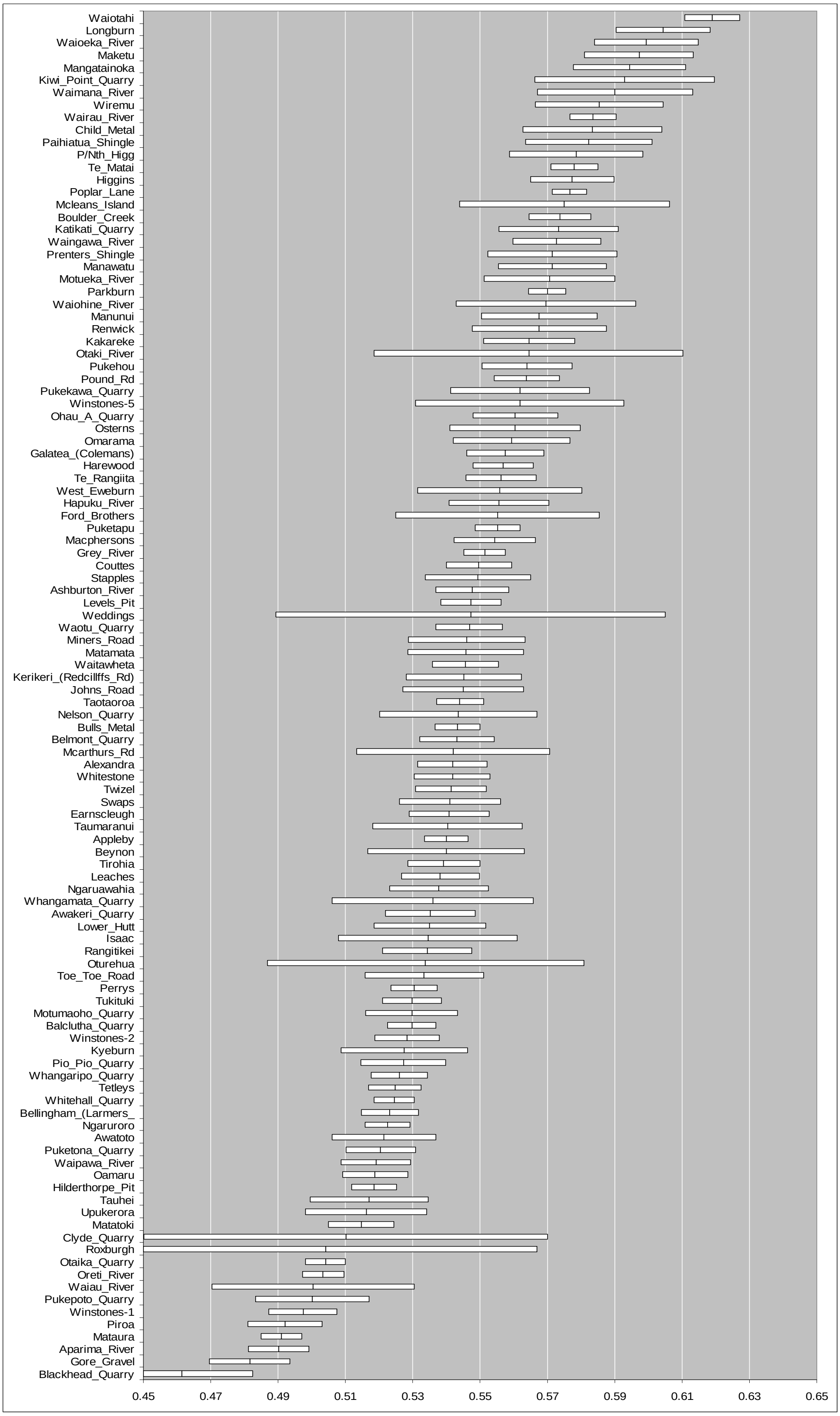
For ease of reference, table 3.1 lists the top five and bottom five performing pavement aggregate sources in terms of predicted in-service skid resistance performance. PSV values, when available, have also been tabulated.

Table 3.1 Best and worst performing pavement aggregate sources

Pavement aggregate source	**Estimation of in-service SCRIM coefficient**		
	Mean	**Lower bound**	**Upper bound**
Top 5 performing			
1 Waiotahi (PSV=63)	0.619	0.611	0.627
2 Longburn	0.604	0.590	0.618
3 Waioeka River (PSV=61)	0.599	0.584	0.615
4 Maketu	0.597	0.581	0.613
5 Mangatainoka	0.594	0.578	0.611
Bottom 5 performing			
1 Blackhead Quarry (PSV=43)	0.461	0.440	0.483
2 Gore Gravel (PSV=56)	0.482	0.470	0.494
3 Aparima River (PSV=57)	0.490	0.481	0.499
4 Mataura	0.491	0.485	0.497
5 Piroa (PSV=54)	0.492	0.481	0.503

With reference to table 3.1, in most cases we can be 95% certain that the in-service SCRIM coefficient will lie within ±0.01 SC of the mean value, apart from Blackhead Quarry which displays twice as much variability. This additional variability can be explained by the smaller number of observations available (ie 1000) compared with the other pavement aggregate sources. For example, the number of observations for Mataura amounted to 27,982.

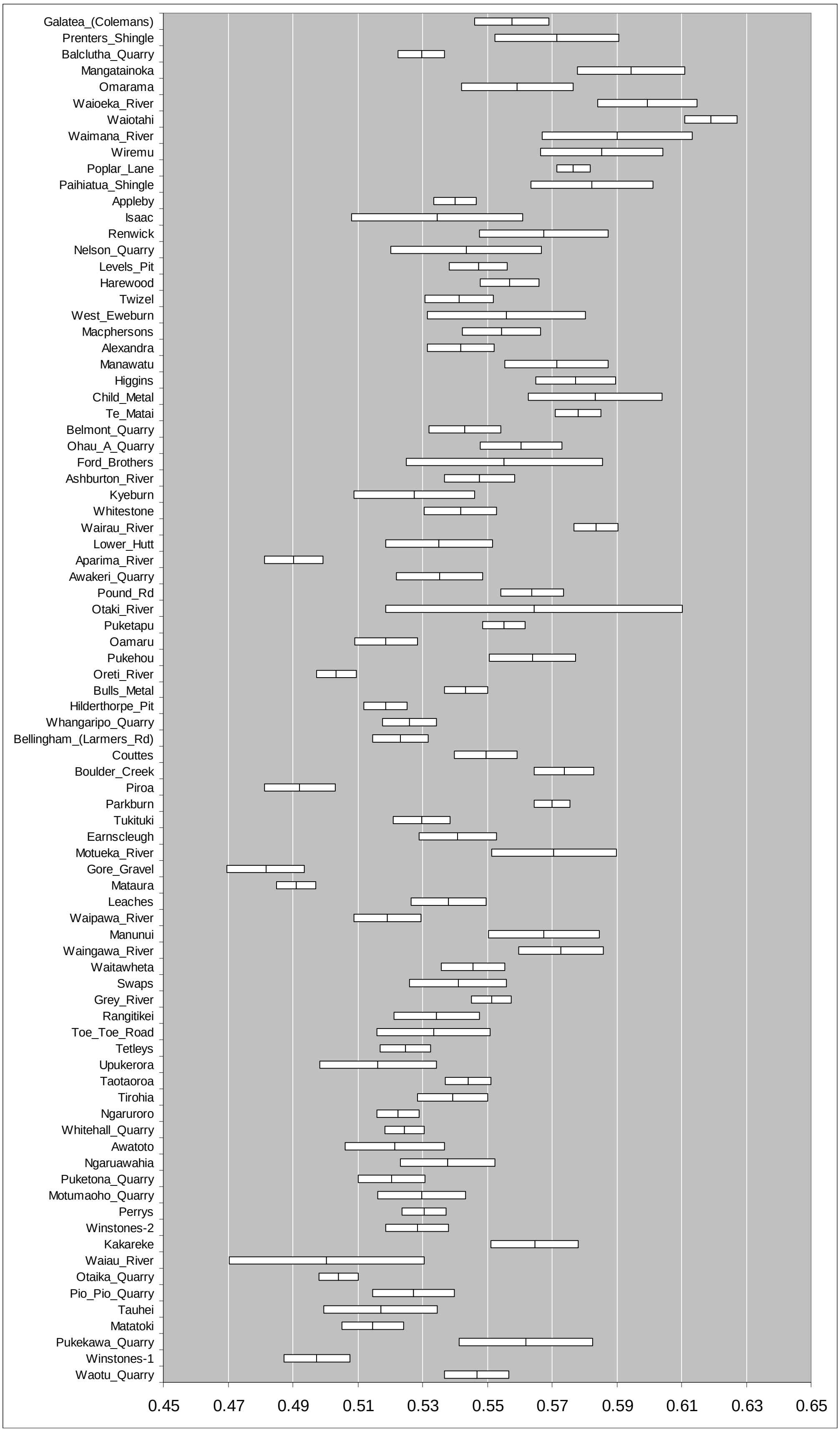
Figure 3.1 SCRIM coefficients sorted by pavement aggregate source



3.2 Predicted SCRIM coefficient sorted by PSV

Figure 3.2 on the next page shows the same data as figure 3.1 but sorted by PSV. Only data for quarries where PSV results are available have been included. Where there is more than one value of PSV, because sources have been combined, an average PSV value has been used. Figure 3.2 shows that the correlation between the predicted in-service SCRIM coefficient and PSV is not very strong and emphasises that PSV is not a good predictor of expected in-service skid resistance as measured by the SCRIM coefficient.

Figure 3.2 In-service SCRIM coefficients sorted by PSV



4 Discussion

It is more difficult to get chipseal surfaces constructed from natural aggregates to comply with the skid resistance requirements of T10 site category 1 than with any other T10 site category. Site category 1 represents the highest demand category and requires site investigations to be undertaken whenever the surveyed level of skid resistance is below 0.55 SC (ie investigatory level (IL) = 0.55 SC) and treatments proposed when the level of skid resistance is below 0.45 SC (ie threshold level (TL) = 0.45 SC).

T10 site category 1 originally applied to approaches to railway crossings, road intersections, roundabouts and one-lane bridges. The T10 specification for SH skid resistance management was extensively revised in 2010 and rural curves with a horizontal radius of curvature less than 400 m classified in the RAMM ‘curve context’ table as ‘high risk’ now also have to be managed to the site category 1 IL and TL.

With reference to section 2.9.9, tight curves located on down gradients will be the most problematic situation for seal designers to deal with in terms of the T10 specification. Accordingly, representative scenarios were considered to establish whether or not the top five performing pavement aggregate sources listed in table 3.1 when used in a grade 4 single coat chipseal could meet the T10 site category 1 IL and still provide an adequate seal life. The grade 4 single coat chipseal was selected as this chipseal based surfacing has been shown to provide the highest in-service skid resistance (see section 2.9.8).

Interrogation of RAMM’s ‘curve context’ table indicated that of the 17,363 curves with a horizontal radius of 400m or less located on the rural SH network, 4434 have been classified as high risk corresponding to 25.5%. The combined length of these high-risk curves amounts to 718.7km. To put this in context, the total length of sealed SH is 10,876.8km (NZTA 2010b) so high-risk curves comprise only 6.6%.

Of the 4434 high-risk curves, 2122 curves (47.9%) have a radius of 100m or less whereas 26 curves have a radius between 301m and 400m. The respective combined lengths are 271.53km and 8.93km corresponding to 2.5% and 0.08% of the entire sealed length of SH. General characteristics of the curves in these two groupings, which represent the lower and upper extremes of high-risk curves, have been summarised in table 4.1.

With reference to table 4.1, the statistics for the grouping of curves with a radius of 100m or less suggests a frequency curve that is moderately skewed left (ie mean less than median less than mode) whereas for the grouping of curves with a radius between 301m and 400m the statistics suggest a frequency curve that is moderately skewed to the right (ie mode less than median less than mean).

The spreadsheet described in section 2.8.1 was applied to the mean values of both groupings to provide average and lower bound estimates of in-service skid resistance after two years and 10 years for the five top performing pavement aggregate sources. The results are summarised in table 4.2 below.

Not surprisingly, for curves with a radius of 100m or less, only the top two pavement aggregate sources, Waiotahi and Longburn, were shown to be able to comply with the IL requirement of 0.55 SC, reaching this level after 37 months and 25 months respectively based on the average SC estimates. However, the predicted in-service skid resistance value after 10 years was well above the TL requirement of 0.45 SC for all five top performing pavement aggregate sources even when the lower bound SC estimates were considered.

Table 4.1 Characteristics of high-stress curve groupings

Curve grouping: ≤100m curve radius (total of 2122 curves)			
Statistic	**Curve radius (m)**	**ADT (vehicles/day)**	**Absolute of approach gradient (%)**
Mean	62	1828	4.2
Median	64	1210	3.7
Mode (most common)	77	192	0.4
Maximum	100	30,783	17.5
Minimum	12	124	0.0
Curve grouping: 300<curve radius≤400m (total of 26 curves)			
Statistic	**Curve radius (m)**	**ADT (vehicles/day)**	**Absolute of approach gradient (%)**
Mean	326	1432	1.8
Median	319	1035	1.1
Mode (most common)	302	1052	1.0
Maximum	392	4213	9.0
Minimum	301	491	0.0

Table 4.2 Expected in-service skid resistance of high-risk classified curves after 2 years and 10 years

Curve grouping: ≤100m curve radius, mean values as per table 5.1				
Aggregate source	**Predicted in-service skid resistance (SC)**			
	After 2 years		**After 10 years**	
	Average value	**Lower bound**	**Average value**	**Lower bound**
Waiotahi	0.567	0.559	0.538	0530
Longburn	0.552	0.538	0.523	0.509
Waioeka River	0.547	0.532	0.518	0.503
Maketu	0.545	0.529	0.516	0.500
Mangatainoka	0.542	0.526	0.513	0.497
Curve grouping: 300<curve radius≤400 m, mean values as per table 5.1				
Aggregate source	**Predicted in-service skid resistance (SC)**			
	After 2 years		**After 10 years**	
	Average value	**Lower bound**	**Average value**	**Lower bound**
Waiotahi	0.629	0.621	0.592	0.584
Longburn	0.614	0.600	0.578	0.564
Waioeka River	0.609	0.594	0.573	0.558
Maketu	0.607	0.591	0.571	0.555
Mangatainoka	0.604	0.588	0.568	0.552

When the curve radius was eased from 62m to 326m, the IL requirement of 0.55 ESC could be exceeded, even after 10 years, by all five top performing pavement aggregate sources when lower bound SC estimates were considered.

On the basis of average and lower bound estimates of in-service SC provided in table 4.1, we can have a degree of confidence that it should be possible to manage road sections with a T10 site classification of 1 using chipseal surfaces constructed from natural aggregates so that the skid resistance level remains above the TL value of 0.45 SC over the expected service life. However, to manage these road sections to the IL value of 0.55 SC will not be feasible, particularly in situations where ADT is high and/or tyre forces are very large such as on tight curves.

5 Conclusions and recommendations

The principal conclusions and recommendations arising from this statistical modelling study of in-service skid resistance performance of natural pavement aggregate sources found in New Zealand are given below.

5.1 Conclusions

- The statistical modelling performed on 10m SCRIM coefficients of sealed sections of SH identified that pavement aggregate source, horizontal curvature and traffic (ADT × surfacing age) have the largest influence on in-service skid resistance, followed by sealing chip size.
- Pavement aggregate source was shown to have the greatest ability to alter in-service skid resistance, the difference between best and worst performing aggregate sources being 0.15 SCRIM coefficient. As skid resistance investigatory levels in the T10:2010 specification for SH skid resistance management increase by 0.05 SCRIM coefficient for each level of risk ranking, this highlights the importance of identifying appropriate aggregate sources when undertaking a preliminary design of a chipseal surface.
- The correlation between predicted in-service SCRIM coefficient and polished stone value (PSV) is not very strong. Presuming this is not attributable to either test or material variability, this finding suggests there is at least one other factor which is accounted for by the categorical variable ‘pavement aggregate source’ but not by the quantitative variable ‘polished stone value’. It is conjectured that this factor may be related to the shape/abrasion resistance of the sealing chip.
- The skid resistance of single coat chipseal surfaces constructed from smaller sized sealing chip (grade 4 or less) was shown to be about 0.03 SCRIM coefficient greater than those constructed from larger sized sealing chips (grades 2 and 3). Single coat chipseal surfaces constructed from smaller sized sealing chip also offer slightly more skid resistance (0.01 to 0.02 SCRIM coefficient) than two coat chipseal surfaces. However, the observed poorer in-service skid resistance performance of two coat chipseal surfaces may, in part, be due to their increasing use at locations where high polishing stresses are likely to be present, such as tight curves and accelerating and braking zones.
- The top five performing pavement aggregate sources based on the analysis of the 2006–2007 RAMM dataset are in decreasing order:
    - Waitohai (Bay of Plenty)
    - Longburn (Manawatu/Wanganui)
    - Waioeka River (Bay of Plenty)
    - Maketu (Bay of Plenty)
    - Mangatainoka (Manawatu/Wanganui)
- For the highest demand category in NZTA’s T10:2010 specification, site category 1, it was determined that chipseal surfaces constructed with any of the top five performing pavement aggregate sources could maintain a skid resistance level above the threshold value of 0.45 SCRIM coefficient over their expected service life for the most arduous of situations, ie curves with a horizontal radius of curvature less than 400m classified as having a high crash risk. Therefore, with the natural pavement aggregate

sources presently available in New Zealand, a reasonable expectation is that chipseal surfacings can be designed to maintain a skid resistance level somewhere between the T10 threshold and investigatory levels throughout their expected life.

5.2 Recommendations

- On the basis of the statistical modelling described in this report, there appears to be a strong case to use statistical modelling to complement PSV test results when ranking suppliers of surfacing aggregates.
- Following on from the above recommendation, the expected SCRIM coefficient from a chipseal design should be calculated from the pavement aggregate source using the spreadsheet titled ‘Aggregate selection for skid resistance’ (available at www.nzta.govt.nz/resources/research/reports/470/index.html) rather than the PSV equation in the T10:2010 specification as PSV has been shown in this report not to be a good predictor of in-service skid resistance.
- A number of pavement aggregate sources have been identified as providing much better or much worse in-service skid resistance performance than indicated by their PSVs. These pavement aggregate sources are tabulated below. To progress our knowledge of what aggregate characteristics in addition to PSV influence in-service skid resistance performance, detailed investigations should be performed on each of these pavement aggregate sources. These investigations are likely to involve application of various standard aggregate tests and electron microscope scans of the aggregates before and after being exposed to trafficking and laboratory-based accelerated polishing tests such as the PSV test.

Table 5.1 Aggregate sources whose in service performance is at odds with their PSV

Pavement aggregate source	Provincial location of source	Expected in-service skid resistance (SC)	Polished stone value (PSV)
Aparima River	Southland	0.490±0.009	57
Gore Gravel	Southland	0.482±0.012	56
Piroa	Northland	0.492±0.011	54, 61
Pukekawa Quarry	Auckland	0.562±0.021	48
Taotaoroa	Waikato	0.544±0.007	64

- To allow further refinement of the statistical model developed for predicting in-service skid resistance, it is essential that all pavement aggregate sources used on the New Zealand SH network have a unique identifier and that this identifier is consistently applied in the RAMM database (for instance, by using a dropdown list instead of free text entry).
- Given that after pavement aggregate source, horizontal radius of curvature has the largest influence on in-service skid resistance, it appears prudent to repeat the statistical modelling but this time limiting the analysis to curves with a radius of 400m or less. This will allow identification of the best and worst performing pavement aggregate sources for each of the low-, medium- and high-risk categories of curves. The recent addition of the ‘curve context’ table to the RAMM database makes such a statistical modelling exercise now possible.

6 References

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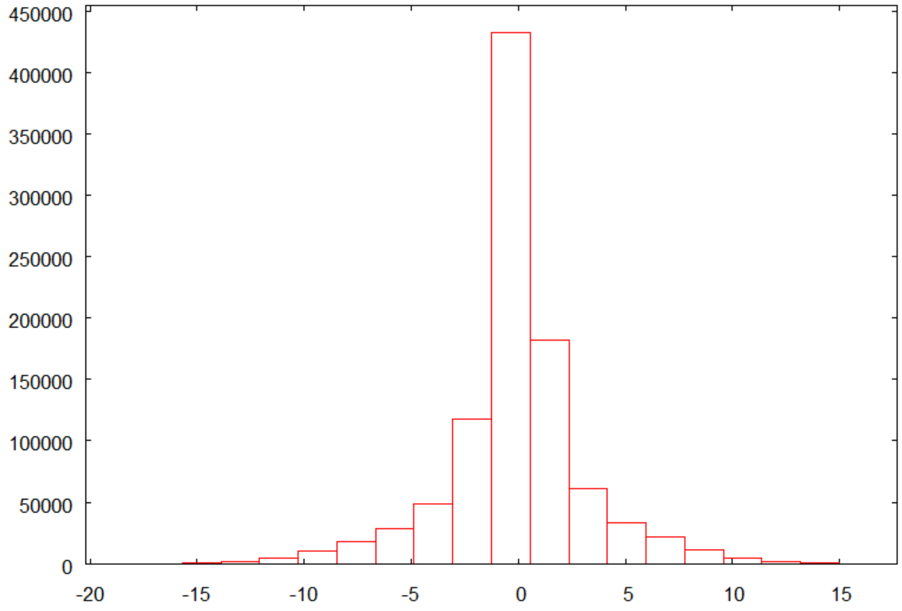
Appendix A: Graphical presentation of database

A.1 Histograms

A.1.1 Gradient

With reference to figure A.1, the road gradient averaged over 10m lies between -10% and 10% (negative representing downhill and positive representing uphill). As can be seen the majority of the road sections analysed were close to level.

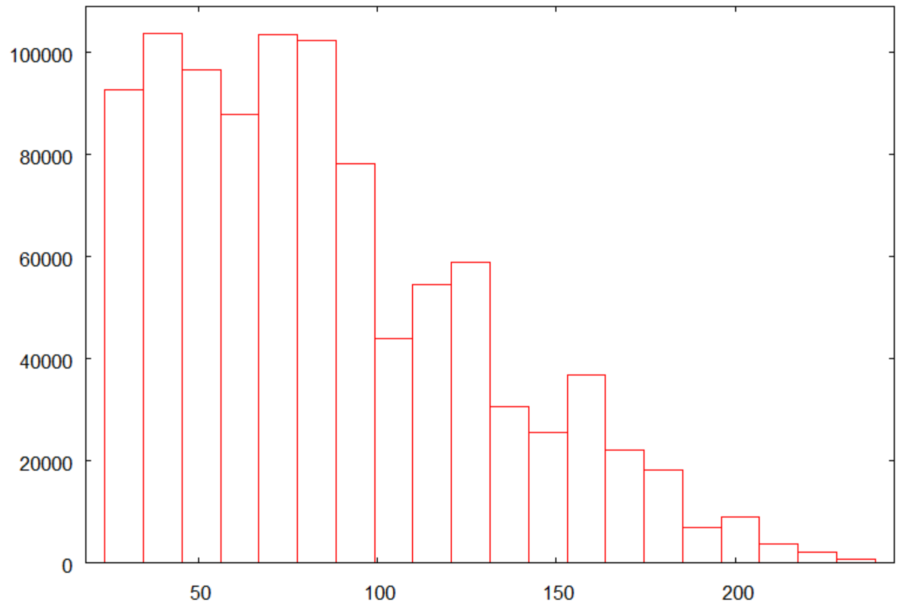
Figure A.1 **Histogram of road gradient (%)**



A.1.2 Age

Figure A.2 shows that new surfaces, say less than 100 months (≈ 8 years) in age, are more common than older surfaces, though the age of some 10m sections of rural SH analysed extend out to 240 months (≈20 years).

Figure A.2 Histogram of road surface age (months)



A.1.3 Average daily traffic

Figure A.3 shows that the rural SH network is dominated by low ADT roads. Using $\log_{10}$ of ADT as used in the statistical analysis results in the traffic data being fairly evenly distributed over the range of values as can be seen in figure A.4.

Figure A.3 Histogram of ADT

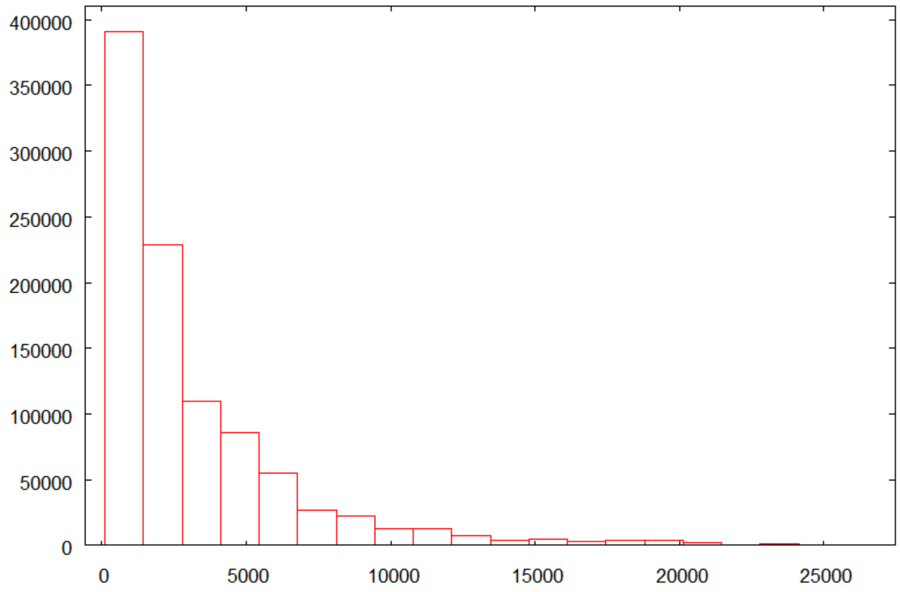
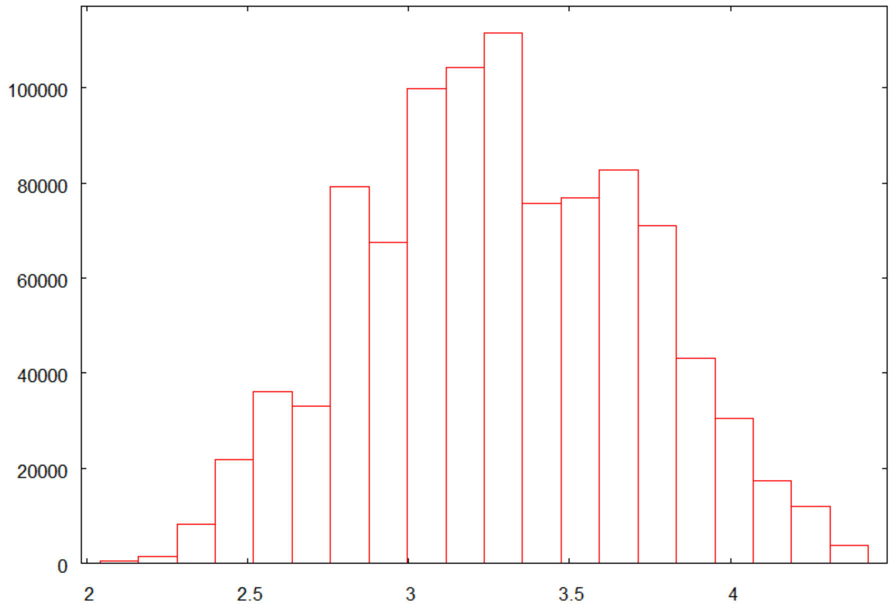


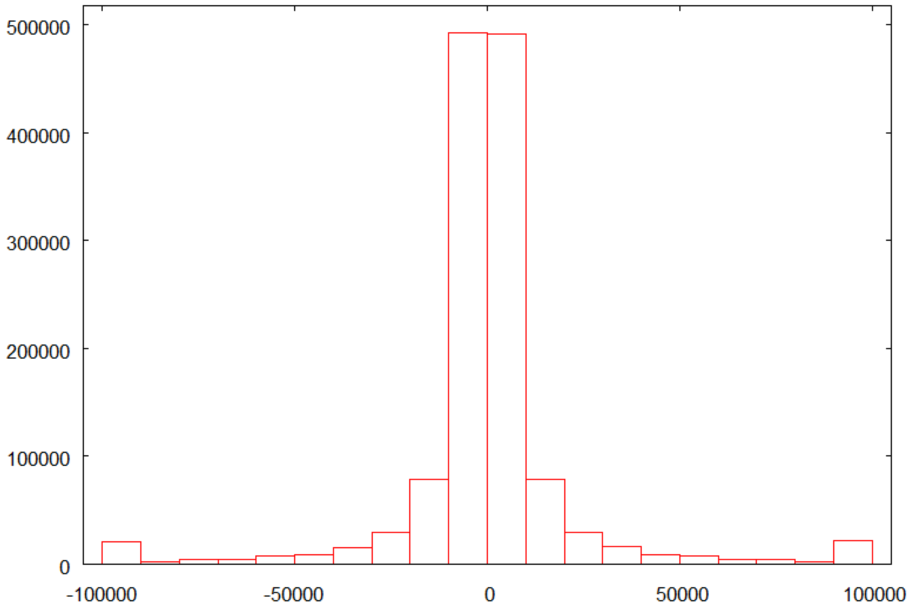
Figure A. 4 Histogram of $\log_{10}$ ADT



A.1.4 Histogram of curvature

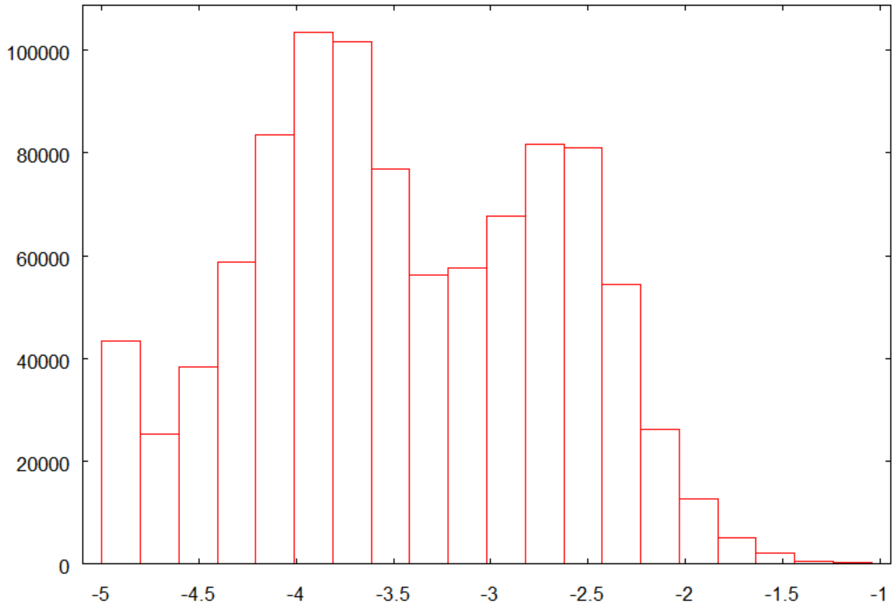
A straight road has been arbitrarily set to 100,000. As can be seen in figure A.5, the majority of the observations lie between horizontal radius of curvature -10,000m and +10,000m. The plot is also symmetric reflecting the opposite curvature between increasing and decreasing lanes.

Figure A.5 Histogram of curvature



The statistical analysis has been based on the $\log^{10}$ of the reciprocal of the absolute value of horizontal curvature. Figure A.6 shows that this transformation results in a fairly uniform distribution across the range of values.

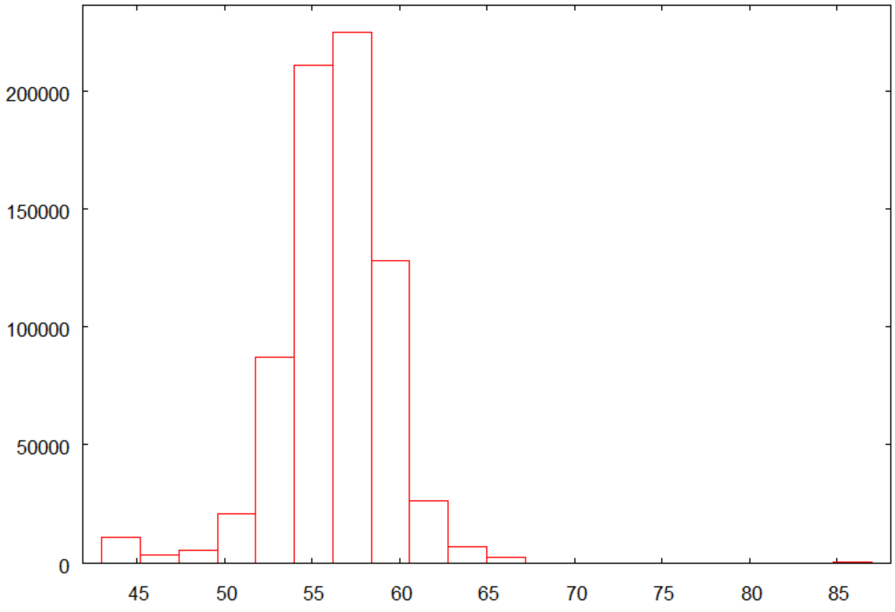
Figure A. 6 Log histogram of reciprocal curvature



A.1.5 Polished stone value

With reference to figure A.7, the majority of road sections analysed had a chipseal surfacing constructed from aggregates with a polished stone value (PSV) between 53 and 58.

Figure A.7 Histogram of polished stone value



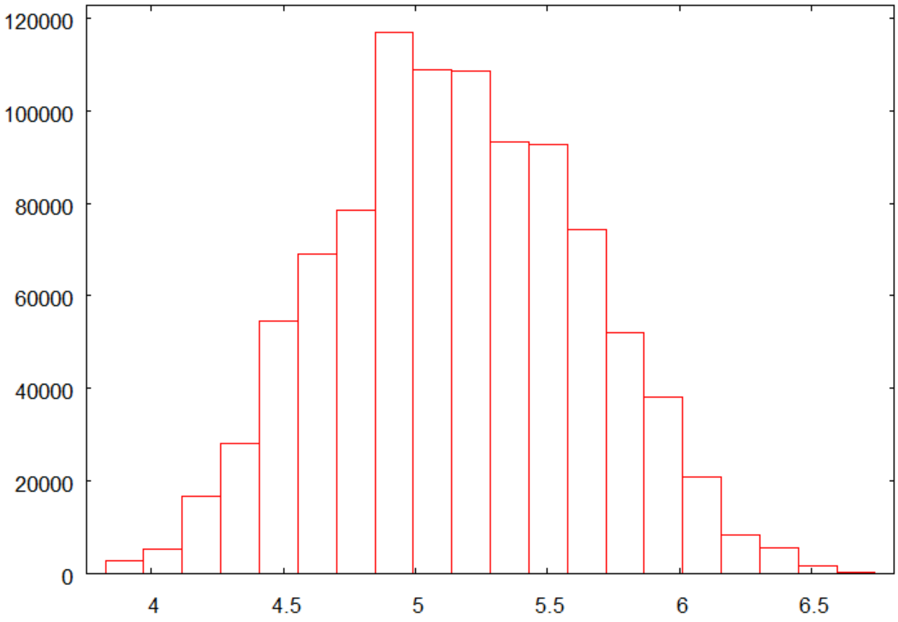
PSV was not used in the statistical modelling. However, it was used for carrying out comparisons with the predicted effect of the different pavement sources.

A.1.6 Histogram of $\log_{10}$ traffic

Traffic is the product of age and ADT. It is a measure of the total amount of traffic that has passed over the road section. To obtain the total number of vehicle passes over a 10m lane section of rural SH, the product of age and ADT has to be multiplied by 365/12/2.

Figure A.8 shows the histogram of $\log_{10}$ of traffic. Again, the $\log_{10}$ transformation results in a fairly even distribution over the range of values. 10m road sections with a value greater than 6.1 have been excluded on the grounds that such road sections appear to be a little unusual or possibly the data was in error.

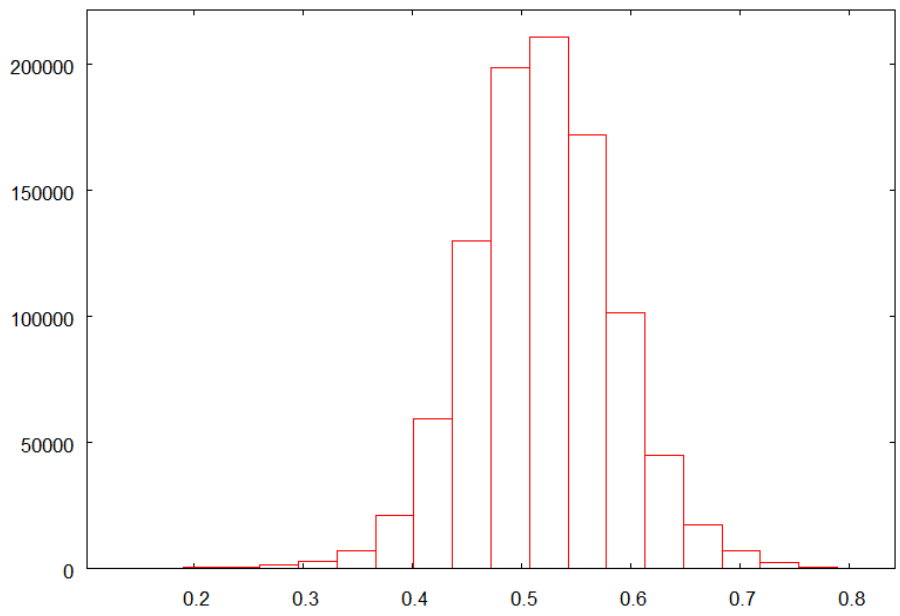
Figure A.8 Histogram of $\log_{10}$ traffic



A.1.7 SCRIM coefficient

With reference to figure A.10, it can be seen that the skid resistance of the analysed 10m rural sections of SH is centred on 0.52 SFC and ranges from around 0.2 to 0.8 SFC.

Figure A.9 Histogram of SCRIM coefficient



A.2 Box-plots

This section provides a graphical representation of SCRIM coefficient versus a number of the predictor variables as a series of box-plots. In these box-plots, the ‘whiskers’ show the total range, the top and bottom of the box shows the upper and lower quartiles and the horizontal line inside the box shows the median. Therefore, half of the observations fall into the range represented by the box.

Included with each of the box-plots is a table which shows the way the predictor variable has been categorised and the number of observations in each category.

A.2.1 Box-plot of SCRIM versus age

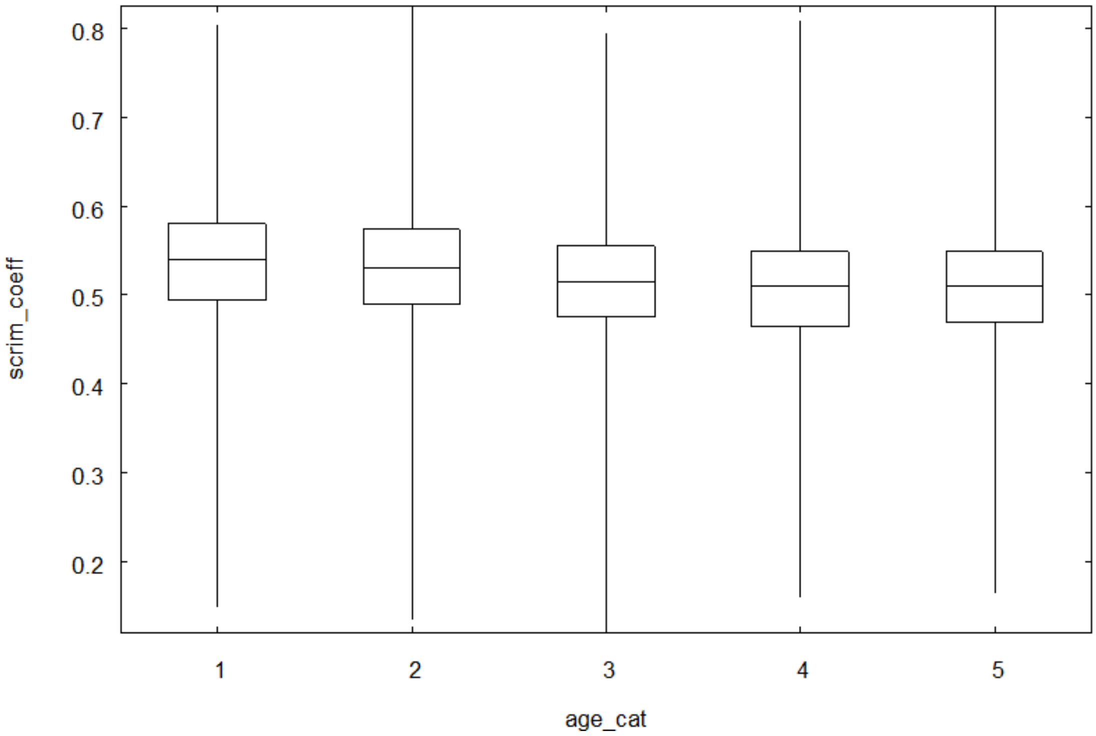
Age has been divided into five categories as follows:

Table A.1 Age frequency distribution

Age category	Age range (months)	Number of observations
1	≥ 24, < 36	109,449
2	≥ 36, < 60	221,290
3	≥ 60, < 84	213,199
4	≥ 84, < 120	206,584
5	≥ 120, < 240	225,816

Figure A.10 gives the box-plot for each of these five categories. This shows the median and quartiles dropping slightly as *age* increases.

Figure A.10 Box-plot of SCRIM coefficient versus age



A.2.2 Box-plot of SCRIM versus ADT

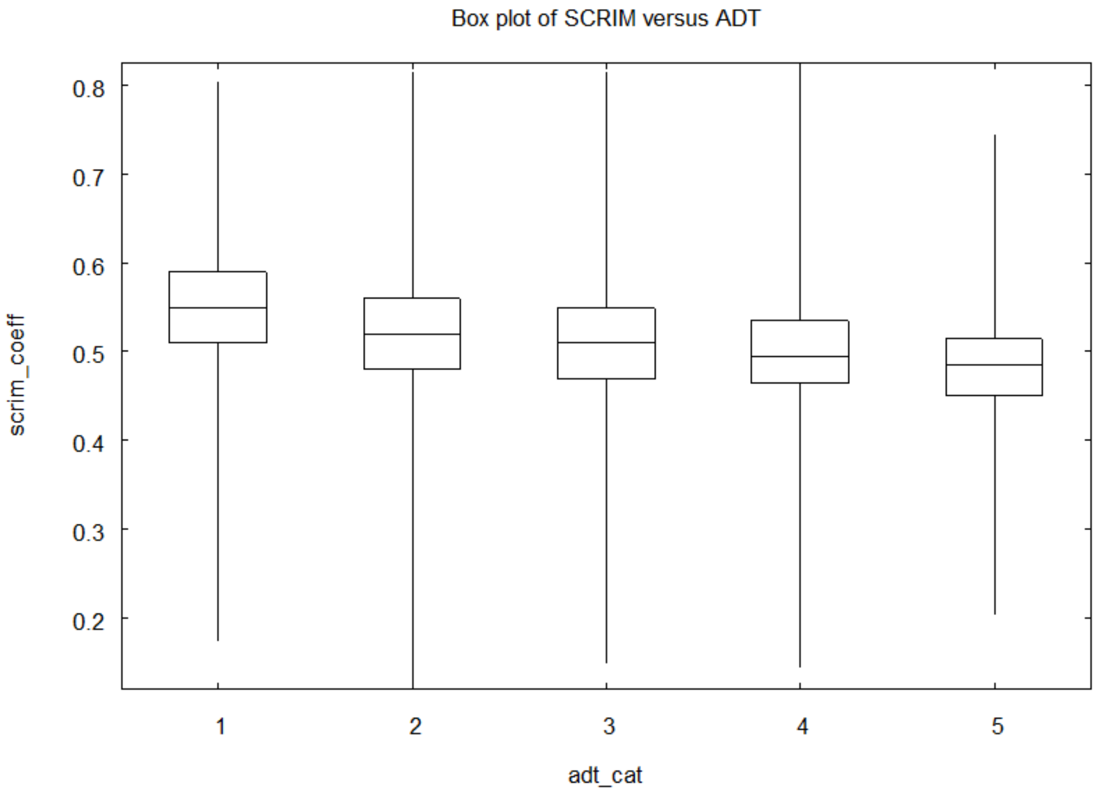
Average daily traffic *(ADT)* has been divided into five categories as follows:

Table A.2 ADT frequency distribution

ADT category	ADT	Number of observations
1	≥ 100, < 1000	248,362
2	≥ 1000, < 2000	257,719
3	≥ 2000, < 5000	282,850
4	≥ 5000, < 10000	135,444
5	≥ 10000, < 30000	51,963

Figure A.11 gives the box-plot for each of these categories. This figure shows the SCRIM coefficient decreasing as the *ADT* increases. The effect is stronger than the effect with *age*.

Figure A.11 Box-plot of SCRIM coefficient versus ADT



A.2.3 Box-plot of SCRIM versus traffic

Traffic is *age* (in months) × *ADT*. *Traffic* has been divided into six categories as follows:

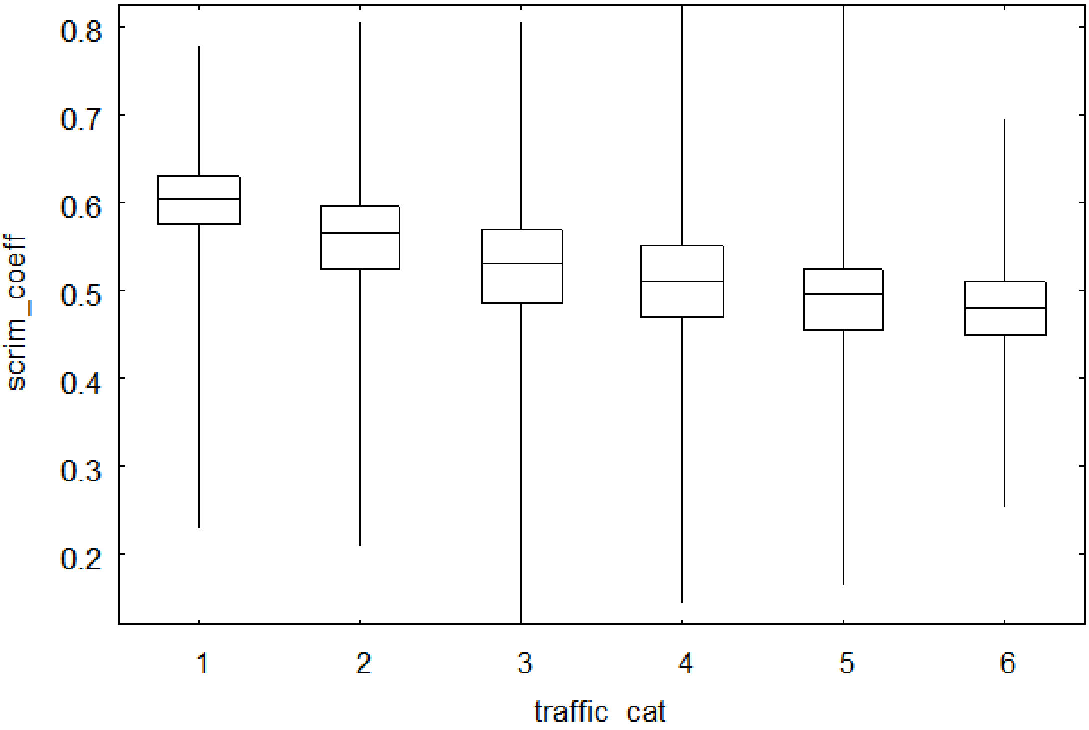
Table A.3 Traffic frequency distribution

Traffic category	Traffic	Log_{10} traffic	Number of observations
1	< 12,600	< 4.1	7729
2	≥ 12,600, < 39,800	≥ 4.1, < 4.6	117,340
3	≥ 39,800, < 126,000	≥ 4.6, < 5.1	327,094
4	≥ 126,000, < 398,000	≥ 5.1, < 5.6	337,422
5	≥ 398,000, < 1,260,000	≥ 5.6, < 6.1	167,058
6	≥ 1,260,000	≥ 6.1	19,695

The 10m road sections falling into category 6 were excluded from the statistical analysis.

Figure A.12 gives the box-plot for each of these categories. This figure shows SCRIM coefficient decreasing as the number of vehicle passes increases.

Figure A.12 Box-plot of SCRIM coefficient versus traffic



A.2.4 Box-plot of SCRIM versus surface category

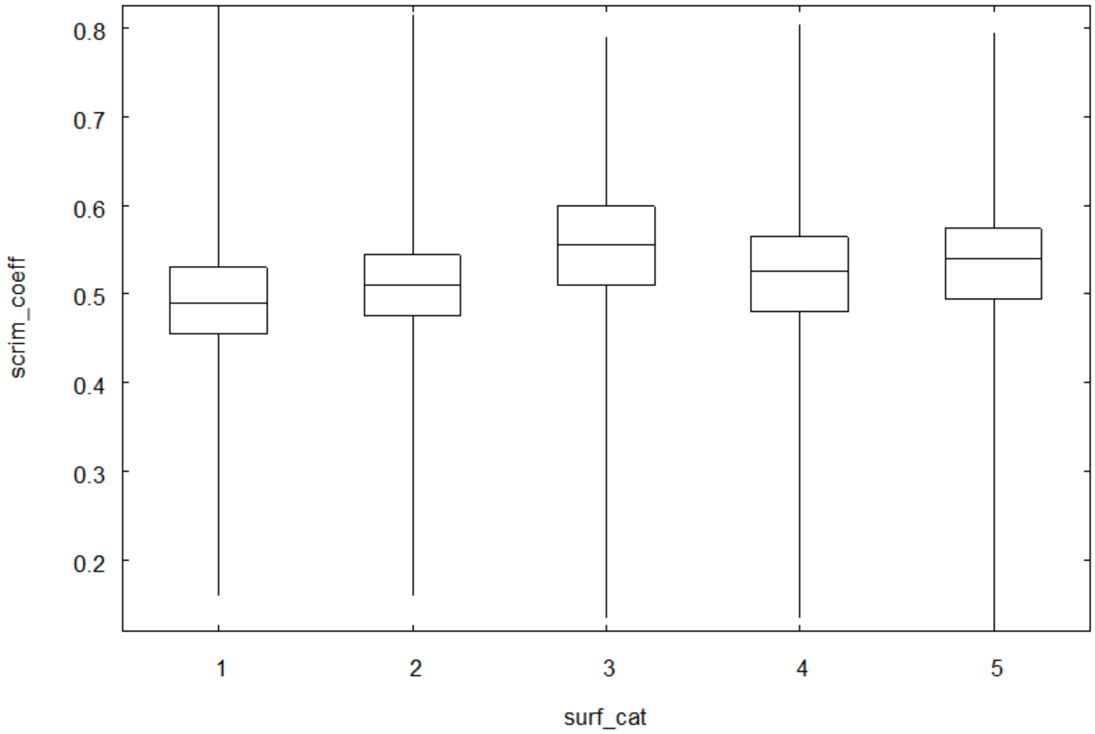
The following five categories of *surface type* were analysed:

Table A.4 Surface type frequency distribution

Surface category	Identifier	Surface type	Chip size	Number of observations
1	1CHIP_2	1 Chip	2	147,954
2	1CHIP_3	1 Chip	3	353,894
3	1CHIP_4+	1 Chip	≥ 4	100,486
4	2CHIP_2	2 Chip	2	175,348
5	2CHIP_3+	2 Chip	≥ 3	198,656

With reference to figure A.13, the surface types employing smaller sized chips (ie surface categories 3 and 5) are shown to have the highest skid resistance.

Figure A.13 Box-plot of SCRIM coefficient versus surface category



A.2.5 Box-plot of SCRIM versus surface function

The three categories of *surface function* are as follows:

Table A.5 Surface function frequency distribution

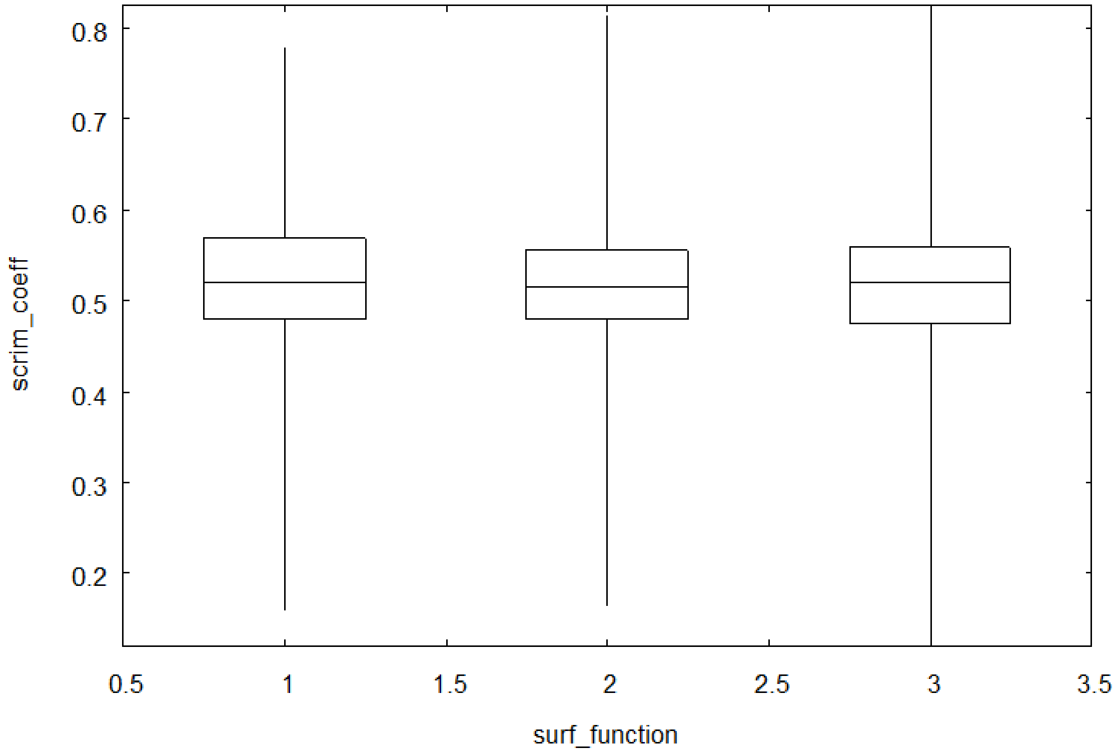
Surface function category	Surface function	Number of observations
1	1 (1st coat)	35,346
2	2 (2nd coat)	135,958
3	R (reseal)	805,034

It is surprising that there are over 35,000 observations of first coat seal that have an age in excess of 24 months. This is because a first coat is generally only expected to last one year before being resealed, although they may last much longer on low traffic volume roads (TNZ 2005).

Figure A.14 gives the box-plot for each of these categories. With reference to this figure it can seen there is very little difference in the SCRIM coefficient between the surface function types.

The majority of the 10m road sections analysed have surface function R (denoted by 3 in the box-plot).

Figure A.14 Box-plot of SCRIM coefficient versus surface function



A.2.6 Box-plot of SCRIM versus T10:2002 skid-site category

The number of observations by T10:2002 skid-site category was as follows:

Table A.6 Skid-site frequency distribution

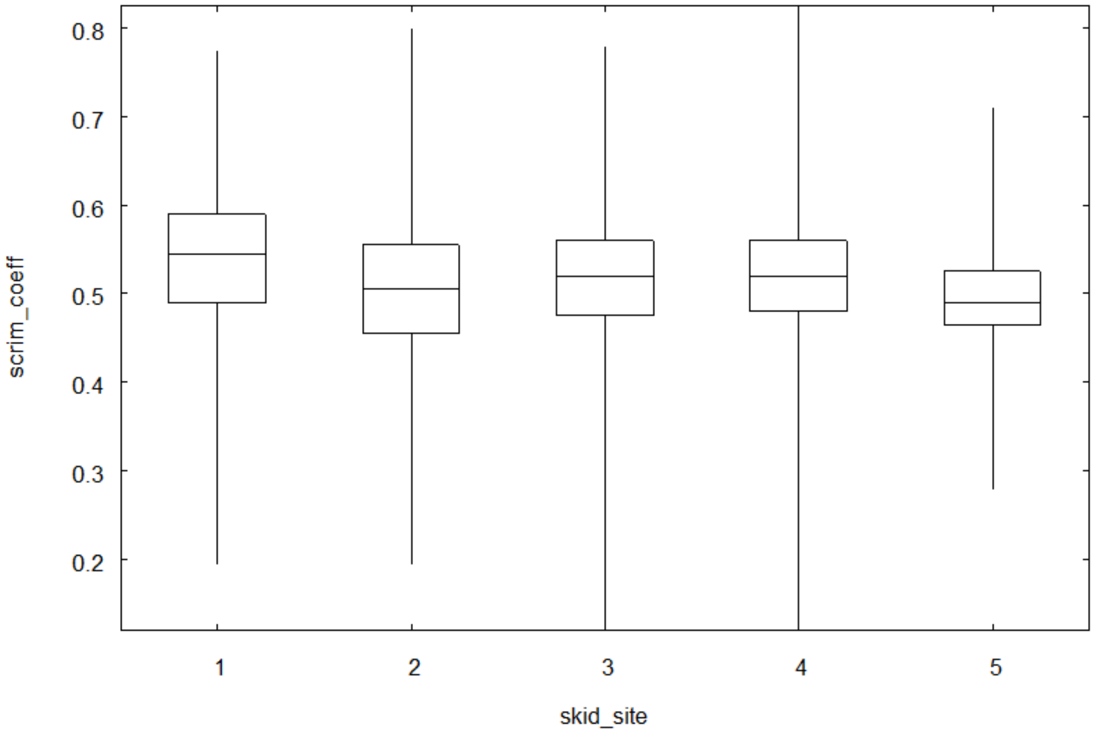
T10:2002 skid site	Number of observations
1	3885
2	91,379
3	62,022
4	813,221
5	5831

As expected, *skid site 4* (event free undivided carriageways) dominates followed by *skid site 2* (curves < 250m, down gradients >10%).

Figure A.15 gives the box-plot for each of the 5 T10:2002 skid-site categories. With reference to this figure, *skid site 1* (major junctions, crossings etc) has a higher SCRIM coefficient than the others while *skid site 5* (motorways) has a lower SCRIM coefficient. As expected, *skid site 2* tends to have a slightly lower SCRIM coefficient than *skid site 3* (approaches to junctions, down gradients 5%–10%) and *skid site 4*, due to the friction demand being greater for this skid site category.

In the statistical analysis skid sites 2 to 5 have been amalgamated.

Figure A.15 Box-plot of SCRIM coefficient versus T10:2002 skid-site category



Appendix B: Pavement aggregate source results

Table B.1 shows the predicted in-service SCRIM coefficient results associated with each pavement aggregate source (in alphabetical order).

Column 2 shows the number of data points (observations). This should generally be greater than 1000 (refer table 2.1). However, in some cases it is less because of the values with high traffic flows (ie ≥ 1,260,000) that were subsequently deleted.

Column 3 shows the number of surface layers, that is, the number of entries in RAMM's c-surface table corresponding to each pavement source.

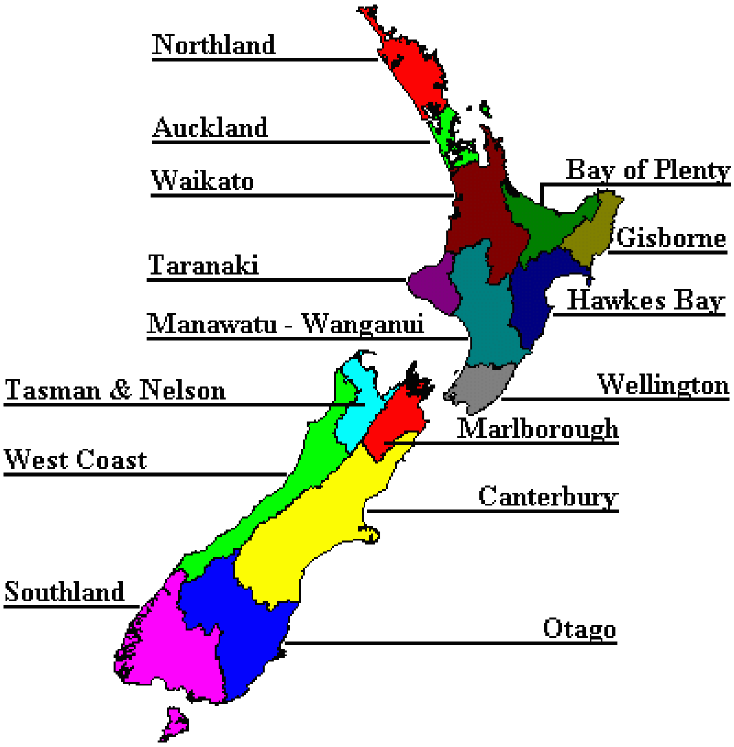
Columns 4, 5 and 6 show the estimate of the SCRIM coefficient and its 95% confidence intervals (ie lower bound (LB) and upper bound (UB)) using the default parameters given in table 2.6.

Column 7 shows the standard deviations (SD) of the residuals estimated from the first iteration of the model (refer section 2.7).

Column 8 titled 'Normalised random effect SD' shows the standard deviations of the random effect components from the second iteration of the model (refer section 2.7). (This value must be multiplied by the previous column to get an estimate of the actual random effect standard deviation.)

Column 9 titled 'Province of pavement source' shows the provincial region in which a pavement aggregate source was judged by authors of the report to be located. (For ready reference, the locations of all New Zealand provincial regions are shown below in figure B.1.)

Figure B.15 New Zealand provincial regions



Source: www.users.globalnet.co.uk/~dheb/2300/Oceania/NZ/RNZDFInt.htm)

Table B.1 SCRIM coefficients for each pavement source

Pavement source	No. of observations	No. of surface layers	Estimate	LB	UB	SD	Normalised random effect SD	Province of pavement source
Alexandra	5694	31	0.542	0.531	0.552	0.026	0.706	Otago
Aparima_River	11,296	74	0.490	0.481	0.499	0.035	1.004	Southland
Appleby	25,762	250	0.540	0.534	0.547	0.043	0.998	Tasman & Nelson
Ashburton_River	9268	37	0.548	0.537	0.559	0.030	0.702	Canterbury
Awakeri_Quarry	4871	61	0.535	0.522	0.549	0.048	1.071	Bay of Plenty
Awatoto	2134	18	0.522	0.506	0.537	0.030	1.217	Hawkes Bay
Balclutha_Quarry	28,185	210	0.530	0.523	0.537	0.044	0.793	Otago
Bellingham_(Larmers_ Rd)	14,694	133	0.523	0.515	0.532	0.043	0.923	Northland
Belmont_Quarry	3598	36	0.543	0.532	0.554	0.030	0.918	Wellington
Beynon	2664	8	0.540	0.517	0.563	0.032	0.869	West Coast
Blackhead_Quarry	1028	9	0.461	0.440	0.483	0.029	1.270	Otago
Boulder_Creek	21,260	81	0.574	0.565	0.583	0.036	0.779	West Coast
Bulls_Metal	17,119	157	0.543	0.537	0.550	0.034	0.892	Manawatu - Wanganui
Child_Metal	2538	27	0.583	0.563	0.604	0.048	0.721	Waikato (or Manawatu–Wanganui?)
Clyde_Quarry	2456	7	0.510	0.450	0.570	0.077	0.610	Otago
Couttes	19,664	75	0.550	0.540	0.559	0.038	0.821	Canterbury
Earnscleugh	7427	51	0.541	0.529	0.553	0.039	0.694	Otago
Ford_Brothers	2978	17	0.555	0.525	0.586	0.060	0.586	Canterbury
Galatea_(Colemans)	2066	29	0.558	0.546	0.569	0.027	1.293	Bay of Plenty
Gore_Gravel	6562	43	0.482	0.470	0.494	0.037	0.743	Southland
Grey_River	47,748	200	0.551	0.545	0.558	0.034	1.293	West Coast
Hapuku_River	5066	30	0.556	0.541	0.571	0.037	0.708	Canterbury
Harewood	9147	64	0.557	0.548	0.566	0.031	0.965	Canterbury

Pavement source	No. of observations	No. of surface layers	Estimate	LB	UB	SD	Normalised random effect SD	Province of pavement source
Higgins	2708	36	0.577	0.565	0.590	0.033	0.725	Hawkes Bay
Hilderthorpe_Pit	21,106	123	0.519	0.512	0.525	0.031	0.884	Otago
Isaac	1372	8	0.535	0.508	0.561	0.035	1.035	Canterbury
Johns_Road	3175	14	0.545	0.527	0.563	0.030	0.724	Canterbury
Kakareke	3868	30	0.565	0.551	0.578	0.034	1.079	Manawatu - Wanganui
Katikati_Quarry	2000	21	0.573	0.556	0.591	0.037	0.413	Bay of Plenty
Kerikeri_(Redcillffs_ Rd)	4827	32	0.545	0.528	0.562	0.044	0.713	Northland
Kiwi_Point_Quarry	926	9	0.593	0.566	0.620	0.038	0.622	Wellington
Kyeburn	5122	21	0.528	0.509	0.546	0.040	0.863	Otago
Leaches	5247	51	0.538	0.527	0.550	0.035	1.451	Waikato
Levels_Pit	15,665	103	0.547	0.538	0.556	0.040	0.728	Canterbury
Longburn	2939	25	0.604	0.590	0.618	0.030	1.574	Manawatu - Wanganui
Lower_Hutt	2103	23	0.535	0.519	0.552	0.036	1.207	Unknown (possibly Wellington, Hawkes Bay or Gisborne)
Macphersons	2660	21	0.554	0.542	0.567	0.025	0.933	Otago
Maketu	1332	17	0.597	0.581	0.613	0.029	1.708	Bay of Plenty
Manawatu	2090	28	0.571	0.555	0.587	0.038	1.439	Manawatu - Wanganui
Mangatainoka	2636	16	0.594	0.578	0.611	0.031	1.338	Manawatu - Wanganui
Manunui	6161	29	0.568	0.550	0.585	0.043	1.423	Waikato
Matamata	2502	24	0.546	0.529	0.563	0.037	1.160	Bay of Plenty
Matatoki	10,786	102	0.515	0.505	0.524	0.043	0.844	Waikato
Mataura	27,982	165	0.491	0.485	0.497	0.033	0.960	Southland
Mcarthurs_Rd	1725	9	0.542	0.513	0.571	0.041	1.301	Canterbury
Mcleans_Island	1172	12	0.575	0.544	0.606	0.050	0.836	Canterbury

Pavement source	No. of observations	No. of surface layers	Estimate	LB	UB	SD	Normalised random effect SD	Province of pavement source
Miners_Road	1308	11	0.546	0.529	0.563	0.026	1.207	Canterbury
Motueka_River	1908	32	0.571	0.551	0.590	0.049	0.784	Tasman & Nelson
Motumaoho_Quarry	2851	28	0.530	0.516	0.543	0.032	1.583	Waikato
Nelson_Quarry	2021	20	0.544	0.520	0.567	0.048	0.696	Tasman & Nelson
Ngaruawahia	5366	53	0.538	0.523	0.553	0.049	1.004	Waikato
Ngaruroro	11,377	152	0.523	0.516	0.529	0.032	1.066	Hawkes Bay
Oamaru	6369	62	0.519	0.509	0.529	0.035	0.896	Otago
Ohau_A_Quarry	2834	8	0.561	0.548	0.573	0.017	0.686	Canterbury
Omarama	4141	20	0.559	0.542	0.577	0.036	0.923	Otago
Oreti_River	29,551	160	0.503	0.497	0.510	0.032	1.151	Southland
Osterns	1994	19	0.560	0.541	0.580	0.038	0.913	Waikato
Otaika_Quarry	28,692	281	0.504	0.498	0.510	0.038	0.922	Northland
Otaki_River	208	1	0.565	0.519	0.610	0.022	0.000	Wellington
Oturehua	1186	4	0.534	0.487	0.581	0.045	0.216	Otago
P/Nth_Higg	1828	22	0.579	0.559	0.598	0.043	0.693	Manawatu - Wanganui
Paihiatua_Shingle	2452	16	0.582	0.564	0.601	0.034	0.703	Manawatu - Wanganui
Parkburn	51,912	281	0.570	0.564	0.576	0.036	0.897	Otago
Perrys	21,044	241	0.530	0.524	0.537	0.043	0.871	Waikato
Pio_Pio_Quarry	5149	77	0.527	0.515	0.540	0.048	0.776	Waikato
Piroa	3893	46	0.492	0.481	0.503	0.033	1.256	Northland
Poplar_Lane	60,711	485	0.577	0.572	0.582	0.039	1.159	Bay of Plenty
Pound_Rd	28,734	160	0.564	0.554	0.574	0.054	0.630	Canterbury
Prenters_Shingle	2178	28	0.572	0.552	0.591	0.047	1.167	Manawatu - Wanganui
Pukehou	13,583	76	0.564	0.551	0.577	0.053	1.000	Waikato

Pavement source	No. of observations	No. of surface layers	Estimate	LB	UB	SD	Normalised random effect SD	Province of pavement source
Pukekawa_Quarry	1331	12	0.562	0.541	0.583	0.033	1.017	Auckland
Pukepoto_Quarry	3648	25	0.500	0.483	0.517	0.038	0.906	Northland
Puketapu	20,311	224	0.555	0.549	0.562	0.036	1.228	Manawatu - Wanganui
Puketona_Quarry	6902	66	0.521	0.510	0.531	0.036	0.960	Northland
Rangitikei	5102	45	0.534	0.521	0.548	0.039	0.913	Manawatu - Wanganui
Renwick	2412	16	0.568	0.548	0.587	0.036	0.856	Marlborough
Roxburgh	1252	6	0.504	0.441	0.567	0.074	0.492	Otago
Stapples	2202	36	0.549	0.534	0.565	0.042	0.947	Taranaki (or Waikato?)
Swaps	7911	53	0.541	0.526	0.556	0.050	0.895	Waikato
Taotaoroa	18,980	190	0.544	0.537	0.551	0.039	0.873	Waikato
Tauhei	2176	24	0.517	0.500	0.535	0.039	0.891	Waikato
Taumaranui	2978	13	0.540	0.518	0.563	0.036	0.825	Waikato
Te_Matai	13,795	162	0.578	0.571	0.585	0.036	0.916	Manawatu - Wanganui
Te_Rangiita	10,868	63	0.556	0.546	0.567	0.035	1.290	Waikato
Tetleys	15,328	151	0.525	0.517	0.533	0.040	1.050	Waikato
Tirohia	9948	69	0.539	0.529	0.550	0.040	0.854	Waikato
Toe_Toe_Road	2733	26	0.533	0.516	0.551	0.042	1.098	Manawatu - Wanganui
Tukituki	7039	78	0.530	0.521	0.539	0.033	0.972	Hawkes Bay
Twizel	5192	33	0.541	0.531	0.552	0.029	0.807	Canterbury
Upukerora	7613	23	0.516	0.498	0.534	0.041	0.506	Southland
Waiau_River	2523	6	0.500	0.470	0.530	0.035	0.902	West Coast
Waimana_River	1878	10	0.590	0.567	0.613	0.034	1.492	Bay of Plenty
Waingawa_River	5608	35	0.573	0.560	0.586	0.035	0.700	Wellington
Waioeka_River	1492	42	0.599	0.584	0.615	0.043	0.976	Bay of Plenty

Pavement source	No. of observations	No. of surface layers	Estimate	LB	UB	SD	Normalised random effect SD	Province of pavement source
Waiohine_River	1392	5	0.570	0.543	0.596	0.028	0.773	Wellington
Waiotahi	10,723	162	0.619	0.611	0.627	0.042	1.050	Bay of Plenty
Waipawa_River	1430	22	0.519	0.509	0.529	0.021	0.893	Hawkes Bay
Wairau_River	22,970	229	0.584	0.577	0.590	0.042	1.042	Marlborough
Waitawheta	9957	86	0.546	0.536	0.555	0.039	1.279	Waikato
Waotu_Quarry	8372	62	0.547	0.537	0.557	0.035	1.115	Waikato
Weddings	423	7	0.547	0.489	0.605	0.069	0.454	Waikato
West_Eweburn	1746	5	0.556	0.531	0.580	0.026	1.108	Otago
Whangamata_Quarry	2556	12	0.536	0.506	0.566	0.048	0.920	Waikato
Whangaripo_Quarry	6928	108	0.526	0.518	0.534	0.037	0.993	Auckland
Whitehall_Quarry	28,660	267	0.525	0.519	0.531	0.037	1.158	Waikato
Whitestone	10,426	64	0.542	0.531	0.553	0.042	0.950	Southland
Winstones-1	7446	54	0.497	0.487	0.508	0.032	1.003	Northland or Auckland (depends on quarry considered)
Winstones-2	6653	88	0.528	0.519	0.538	0.038	1.226	Waikato or Bay of Plenty (depends on quarry considered)
Winstones-5	1072	5	0.562	0.531	0.593	0.033	0.455	Wellington
Wiremu	2048	28	0.585	0.567	0.604	0.044	1.022	Taranaki

Appendix C: Glossary

AADT	average annual daily traffic
ADT	average daily traffic (this term often used instead of AADT)
ALD	aggregate average least dimension
CVD	commercial vehicles per lane per day
ESC	equilibrium SCRIM coefficient
HCV	heavy commercial vehicle
IL	T10 investigatory level
IRI	International Roughness Index
LB	lower bound of 95% confidence interval
LTSA	Land Transport Safety Authority (now superseded by NZTA)
M	million
MPD	mean profile depth (ISO 13473-2: 2002). (The difference between the mean of the peak heights of each 50mm segment and the average height of a profile measured over a 100mm long profile sample. This measure is purported to correlate well with texture measures derived from the sand circle method.)
MSSC	mean summer SCRIM coefficient
NZ	New Zealand
NZIHT	New Zealand Institute of Highway Technology
NZTA	New Zealand Transport Agency (the crown entity now responsible for New Zealand's SH network, supersedes Transit NZ)
PSMC	performance specified maintenance contract
PSV	polished stone value (BS 812, part 114: 1989)
RAMM	road assessment and maintenance management system
SC	SCRIM coefficient
SCRIM	sideways -force coefficient routine inspection machine (the skid resistance tester employed in annual high speed data surveys commissioned by NZTA on New Zealand's SH network)
SCRIM$^+$	The SCRIM survey vehicle fitted with equipment to enable it to perform measurements in addition to skid resistance (eg the likes of rutting and geometry)
SD	standard deviation
SH	state highway

SQL	structured query language
TL	T10 threshold level, which is set 0.1 SC less than the corresponding IL
TNZ	Transit New Zealand (the crown entity previously responsible for New Zealand's SH network, prior to merging on 1 August 2008 with the LTSA to form the NZTA)
TRL	Transport Research Laboratory
TRRL	Transport and Road Research Laboratory
UB	upper bound of 95% confidence interval
UK	United Kingdom