Factors Influencing the In-Service Skid Resistance Performance of Aggregates

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ABSTRACT

This paper presents the results of statistical modelling undertaken to identify factors that significantly influence the in-service skid resistance performance of surface dressing (i.e. chipseal) road surfaces, their range of values and simple relationships between them.

Previous attempts to model in-service skid resistance performance of roading aggregates have employed aggregate polished stone value (PSV), which is a numerical parameter typically taking values in New Zealand from 43 to 65, to characterise the roading aggregate but with little success. For this study, a categorical parameter, the name of the quarry from which the aggregate is sourced, has been used. This categorical parameter encompasses not only PSV but all other important influencing factors such as chip shape, chip hardness, mineralogical properties and crusher type.

The availability of annual road condition and road geometry data measured by a truck based multifunctional road monitoring device (SCRIM$^+$) for every 10 m sealed section of New Zealand's state highway, along with detailed surfacing records and traffic volume estimates allowed investigation of statistically significant relationships between measured in-service skid resistance, the dependent variable, and road geometry, traffic characteristics, and seal characteristics, the independent variables to be identified. The analysis was performed for two separate management areas to enable any regional differences to be highlighted.

Linear regression analysis, which treated the road surface as a random effect, showed macrotexture, reciprocal of horizontal curvature, gradient, skid resistance site category, traffic volume (ADT), surface age, seal type, operating environment (urban/rural), and aggregate source as having the greatest predictive power for estimating in-service skid resistance as determined by 10 m averaged Equilibrium SCRIM Coefficient (ESC). PSV was shown to have some predictive power but this is much less than that of aggregate source. The resulting statistical model employs simple polynomials to calculate expected values of ESC.

Key Words: in-service skid resistance, macrotexture**,** polished stone value**,** predictive modelling**,** road aggregates, road geometry.

1. INTRODUCTION

Since 1998, the skid resistance management of the New Zealand state highway network has come under close scrutiny through routine surveys using multifunctional road condition monitoring systems. Increasingly skid resistance issues now drive road surface maintenance, resulting in annual expenditures of between NZ$4.5M and NZ$5M. However, this annual expenditure on SCRIM driven sealing is approximately 5 times more than predicted when Transit New Zealand's skid resistance policy was first introduced in 1998 (i.e. annual cost of restoring skid resistance once all deficient sites had been treated was estimated at $1M per annum compared to the actual cost of $4.5M to $5M per annum). One reason put forward for this over-expenditure is the over-reliance on aggregate polished stone value (PSV) to achieve required in-service skid resistance as compliance with Transit New Zealand's T/10 specification for skid resistance investigation and treatment selection (TNZ, 2002) necessitates. PSV is a laboratory derived ranking of an aggregate's ability to resist the polishing action of heavy commercial vehicles (HCV).

A major advancement in the field of skid resistance was the publication of Transport and Road Research Laboratory (TRRL) 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 United Kingdom (UK) with traffic densities of up to 4000 commercial vehicles per day. The resulting regression model, which applies to straight roads only, was:

$$\mathrm{SC} = 0.024 - 0.663 \times 10^{-4}\,\mathrm{CVD} + 0.01\mathrm{PSV} \quad (r^2=0.83) \ \ldots \ (1)$$

where: SC = SCRIM Coefficient
CVD = Commercial vehicles per lane per day
PSV = Polished Stone Value

Equation 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 NZ (Cenek et al. 2004) suggest equation 1, which is incorporated in the T/10 specification, does not adequately reflect on-road skid resistance performance of roading aggregates with the correlation (r^2) between predicted and observed skid resistance found to be less than 10% i.e. less than 10% of the observed variance can be explained.

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

This investigation was 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 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.

This paper describes the statistical investigation undertaken and discusses the implications of the findings with respect to surfacing design and future research needs.

2. DATA ANALYSIS

2.1 Database

Annual road condition and geometry surveys of the entire 11,000 km of sealed state highway have been performed since 1997 with SCRIM$^+$, a truck based multifunctional road monitoring device. Texture (MPD, mm), skid resistance (SCRIM Coefficient), gradient (%), horizontal curvature (radius, m) and cross-fall (%) are recorded over 10 m intervals whereas roughness (IRI, m/km) and rut depth (mm) are recorded over 20 m intervals. Since 2002, the 10 m averaged wheelpath skid resistance values have been corrected for inter-year variations in weather conditions during the annual SCRIM surveys to yield Equilibrium SCRIM Coefficients (ESC).

For this study, the wheel path IRI roughness, wheel path skid resistance, wheel path texture and lane road geometry data were linked to surfacing records and traffic volume estimates, all of which are held in Transit New Zealand's road asset information system 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 10 m 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. The 20 m wheel path roughness values was therefore converted to the shorter 10 m interval by assuming the roughness was homogeneous over the 20 m length.

Any observations with age two years or less, texture depth less than 0.5 mm MPD, ADT less than 100 vehicles per day and horizontal curvature less than 10 m in absolute value were excluded. The age exclusion was to ensure that the polishing phase, where skid resistance reduces under the action of traffic, had been passed. The texture depth exclusion was to ensure all 10 m road sections analysed had a texture depth at or above the acceptable minimum for state highways.

The statistical study was confined to the 2004 survey of the Northland and Napier management areas as these two areas are among the poorer performing in terms of percentage of network length where skid resistance is below the threshold value for providing good skid resistant road surfaces. The terrain in Northland is often difficult, causing state highways to be generally quite winding and undulating. The terrain in Napier is variable, traversing flat, rolling and mountainous terrain. Both areas are presently experiencing increasing commercial traffic demand on their road networks from food and wood processing industries so are good candidates for comparative analysis.

There are 723 km of sealed state highway in Northland and 815 km of sealed state highway in Napier. Therefore, the 10 m sections analysed amounted to approximately 14% of the entire state highway network.

Separate analysis of the two management regions enabled similarities and differences in statistically significant relationships between measured in-service skid resistance (in terms of ESC), the dependent variable, and road geometry, traffic, surface and aggregate characteristics, the independent variables, to be highlighted for further investigation.

2.2 Road Surface Types Considered

Only single and two coat surface dressing seals were considered as they are the prevalent seal types used on the New Zealand state highway network.

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

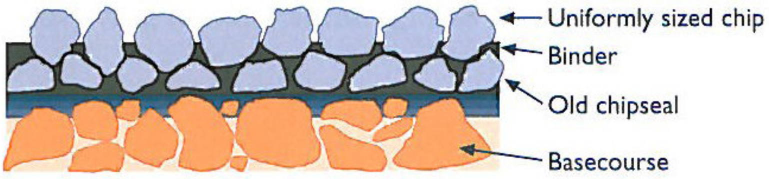

Figure 1 A single coat seal shown as a reseal, from TNZ (2005)

A two coat is a surface dressing with two applications of binder and two applications of chip (refer Figure 2) applied in the following sequence:

- An application of sprayed binder is followed immediately with an application of a large size (Grade 2 or 3) chip.
- A second application of sprayed binder and a second application of smaller chip (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.

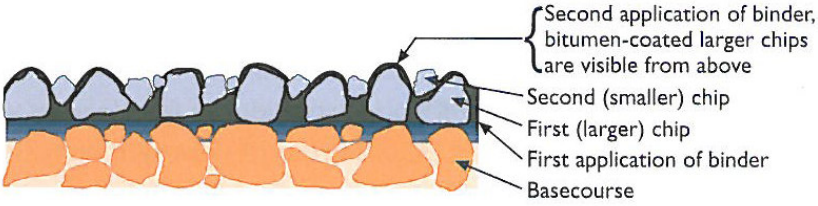

Figure 2 Two coat seal shown as a first coat, from TNZ (2005)

Sealing chip size is specified in grades from Grade 2 (coarsest) to Grade 5 (finest). The relationship between Grade of sealing chip, chip size and Average Least Dimension (ALD) assumed for this analysis is given in Table 1.

Table 1: Characteristics of sealing chip conforming to TNZ M6:2002

Grade	ALD (mm)	Chip Size (mm)
2	10.75	19
3	8.75	16
4	6.75	12
5	5.00	9

For Northland, the seals were grouped as follows:

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, Grade 2/Grade 4 (2CHIP.2.4)*
5. *Two coat, Grade 3/Grade 5 (2CHIP.2.5)*
6. *Two Coat, Grade 3 or higher (second chip size ignored) (2CHIP.3+)*

For Napier, the seals were grouped as follows:

1. *Single coat, Grade 2 (1CHIP.2)*
2. *Single coat, Grade 3 or higher (1CHIP.3+)*
3. *Two coat, Grade 2 (second chip size ignored)(2CHIP.2)*
4. *Two coat, Grade 3 (second chip size ignored)(2CHIP.3+)*

The bracketed terms above pertain to the categorical variable label used in the statistical modelling to represent the seal group.

2.3 Analysis Software

The initial processing of the data was performed with SQL queries in Microsoft SQL Server with Microsoft Access being used for some inspection of the data. Graphical exploration and the main statistical analysis summarised below was carried out with S-Plus.

2.4 Analysis Method

The statistical analysis attempts to express the value of ESC in terms of the independent variables considered using linear regression. However, a regression procedure is required that better models the random structure that one might expect.

In modelling the 10 m ESC data, two levels of randomness was supposed. The first level of randomness was to suppose that there is a random element associated with each of the ESC measurements. The second level of randomness was to suppose that there was a random element associated with each top surface layer extracted from the carriageway surface table in RAMM. This random element is constant over a particular surface layer but the values for different surface layers are statistically independent.

Mathematically the model can be expressed as:

$$Y = X\beta + Z\eta + \varepsilon ...(2)$$

where:

- Y is the vector of observations (length n if there are *n* observations)
- β is the vector of unknown parameters to be estimated
- X is the matrix that says how the unknown parameters affect the observations
- η is the vector of random components associated with the surface layers (η has the same number of elements as the number of different surface layers)
- Z is a matrix that associates the surface layers with the observations: if the *i*-th observation is on the *j*-th surface layer then $Z_{i,j} = 1$ and the rest of the *i*-th row of Z is zero
- ε is a vector of the random components associated with each observation as usual

It is assumed that 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.

The fit process was carried out using the S-plus routine *lme*. This is similar to usual regression analysis routines, but allows for the random surface layer effect.

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.

Two main analyses were performed as follows:

- The first simply ignored aggregate PSV and supposed that there was only a quarry effect.
- The second is where the quarry effect and aggregate PSV were both fitted and their abilities to determine ESC compared. The sample size in this case was much smaller as aggregate PSV was available for only some of the surface layers.

For the first case, the analysis was initially carried out with all of the predictor variables included and then repeated with the predictor variables found to be not statistically significant or only marginally statistically significant deleted from the analysis to derive a reduced model. For the second case, aggregate PSV was added to the reduced model.

3. ANALYSIS RESULTS FOR AGGREGATE SOURCE EFFECT

3.1 Variance Tables

The reduced model variance table generated for the Northland dataset using S-plus' *lme* function with the predictor variables added sequentially is given in Table 2. P-values less than 0.05 are generally regarded as indicating statistical significance.

Table 2: Reduced model variance table for Northland dataset

```
                       numDF denDF  F-value p-value
           (Intercept)     1 58581 61584.95  <.0001
 poly(macrotexture, 4)     4 58581  2303.69  <.0001
   poly(recip.curv, 2)     2 58581  1709.94  <.0001
     poly(gradient, 3)     3 58581    15.29  <.0001
         skid.site.sel     1 58581    23.14  <.0001
    poly(log10.adt, 4)     4 58581    50.93  <.0001
    poly(log10.age, 2)     2   475     3.06  0.0479
           surf.cat.12     5   475     7.78  <.0001
           urban.rural     1 58581     5.24  0.0221
   pave.source.main.12     5   475    25.59  <.0001
```

A description of the predictor variables is given in Table 3 and the estimates of residual standard deviation are summarised in Table 4. With reference to Table 4, the value of η is rather large and suggests that a predictor variable may be missing.

Table 3: Description of predictor variables

Variable	Description
poly(macrotexture, 4)	fourth degree polynomial transformation of macrotexture
poly(recip.curv, 2)	second degree polynomial transformation of the absolute value of the reciprocal of horizontal curvature
poly(gradient, 3)	third degree polynomial transformation of gradient
skid.site.sel	T/10 skid site category, categories 1,2,3 combined into one category; 4 and 5 into another
poly(log10.adt, 4)	fourth degree polynomial transformation of log10(adt)
poly(log10.age, 2)	second degree polynomial transformation of log10(age)
surf.cat	surface category – see section 2.2
urban.rural	urban or rural
pave.source.main	Quarry source of aggregate used in top layer surfacing

Table 4: Residual standard deviation - Northland dataset

Parameter	Description	Value
σ	Standard deviation associated with individual data points.	0.039
η	Standard deviation associated with surface layers.	0.039

The reduced model variance table and associated estimates of residual standard deviation for the Napier dataset are given in Tables 5 and 6 respectively. Comparing Table 2 with Table 5 and Table 4 with Table 6, it can be seen that the results obtained for Napier are very similar to those for Northland.

Table 5: Reduced model variance table for Napier dataset

```
                      numDF denDF  F-value p-value
          (Intercept)     1 64757 147472.9  <.0001
poly(macrotexture, 4)     4 64757   1205.9  <.0001
  poly(recip.curv, 2)     2 64757   3037.0  <.0001
    poly(gradient, 3)     3 64757    306.4  <.0001
        skid.site.sel     1 64757     50.5  <.0001
   poly(log10.adt, 4)     4 64757    197.3  <.0001
   poly(log10.age, 2)     2   891    106.8  <.0001
          surf.cat.12     3   891     69.7  <.0001
          urban.rural     1 64757     30.3  <.0001
 pave.source.main.ps1    10   891     34.3  <.0001
```

Table 6: Residual standard deviation - Napier dataset

Parameter	Description	Value
σ	Standard deviation associated with individual data points.	0.035
η	Standard deviation associated with surface layers.	0.037

3.2 Effects of the Quantitative Predictor Variables

The effects of the quantitative predictor variables on ESC can be best gauged through graphical plots for the polynomial fits. For each quantitative predictor variable, effects have been plotted for both Northland and Napier datasets to affect ready comparisons. The graph layout is held constant with the predictor variable plotted on the x-axis and the change in ESC relative to a reference condition plotted on the y-axis. Three lines are plotted showing the estimated value of the effect relative to the reference condition and approximations of the 95 percentile (2 standard deviations) upper and lower confidence bounds. The points on the graph have been plotted where there are points in the data, so sparse points indicate that there is not much data.

Macrotexture (Figure 3)

With reference to Figure 3, the graph has been set to have a value 0 when the macrotexture has a value of 2 mm MPD. In both cases, ESC drops away as macrotexture drops below 2 mm. Because a fourth degree polynomial has been fitted, the shape is constrained and so the drop in ESC at high macrotexture values observed for the Northland dataset is probably an artefact of the fitting process rather than a real effect.

Although the plot for Napier appears different to that of Northland, within the central part where macrotextures range from 1 to 3 mm MPD there is close agreement.

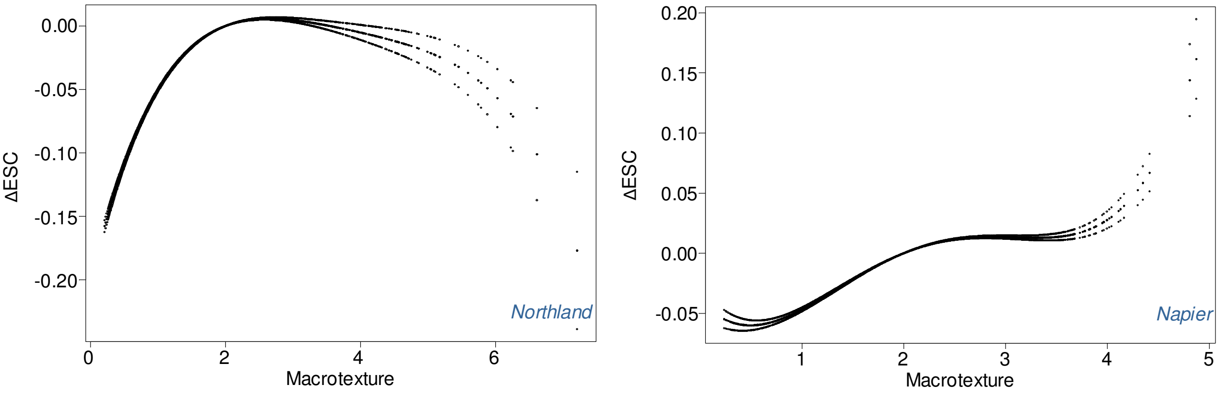

Figure 3 Comparison of macrotexture effect

Horizontal Curvature (Figure 4)

Both the Northland and Napier datasets show ESC reducing as the reciprocal of the horizontal radius of curvature increases (i.e. as the curvature decreases), which is as expected. The confidence intervals are in comparison to a straight road (reciprocal of horizontal curvature = 0). The effect of horizontal curvature on ESC is very much the same for Northland and Napier.

Because a quadratic curve has been fitted, the shape is constrained and so the rising curve to the right is probably an artefact of the fitting process rather than a real effect.

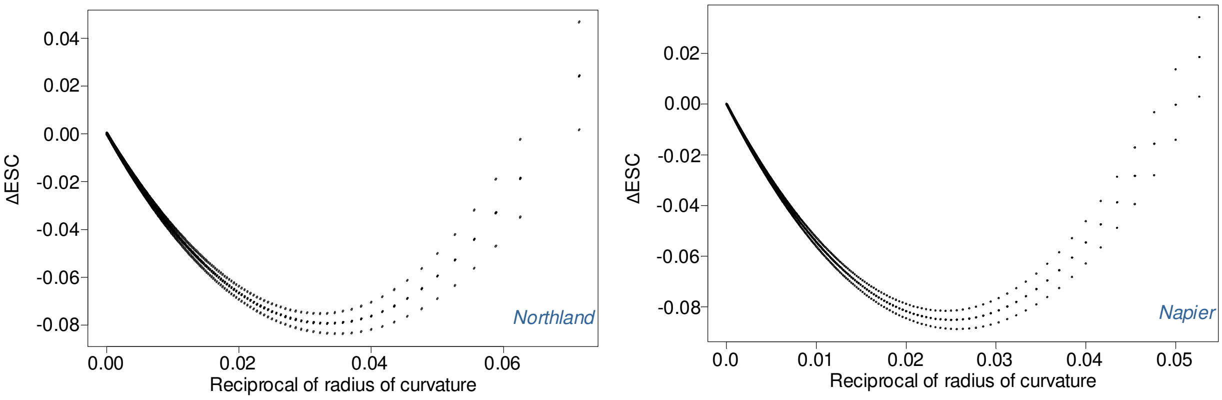

Figure 4 Comparison of reciprocal of horizontal curvature effect

Gradient (Figure 5)

With reference to Figure 5, the graph has been set to have a value of 0 when the gradient is 0. For both Northland and Napier, the effect of gradient on ESC is shown to be very small and probably only the central part of the plot is meaningful.

The only significant differences between Northland and Napier are that for the Napier dataset there is no downward slope near the central part of the plot and the effect of gradient on ESC is marginally greater.

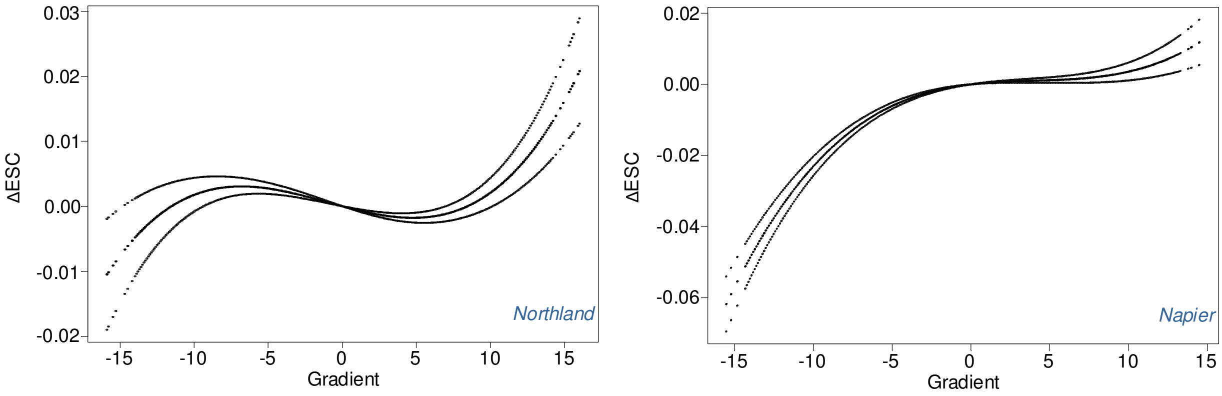

Figure 5 Comparison of reciprocal of gradient effect

Daily Traffic (Figure 6)

Figure 6 shows ESC to decrease as average daily traffic (ADT) increases. The confidence lines are with respect to the value of 0 when the ADT = 1000 (i.e. $\log_{10}$ (ADT) = 3). The plotted points appear sparse because a lot pf the points are overlapping.

Within the accuracy of the plots, the effect of ADT on ESC is shown to be much the same for the Northland and Napier datasets.

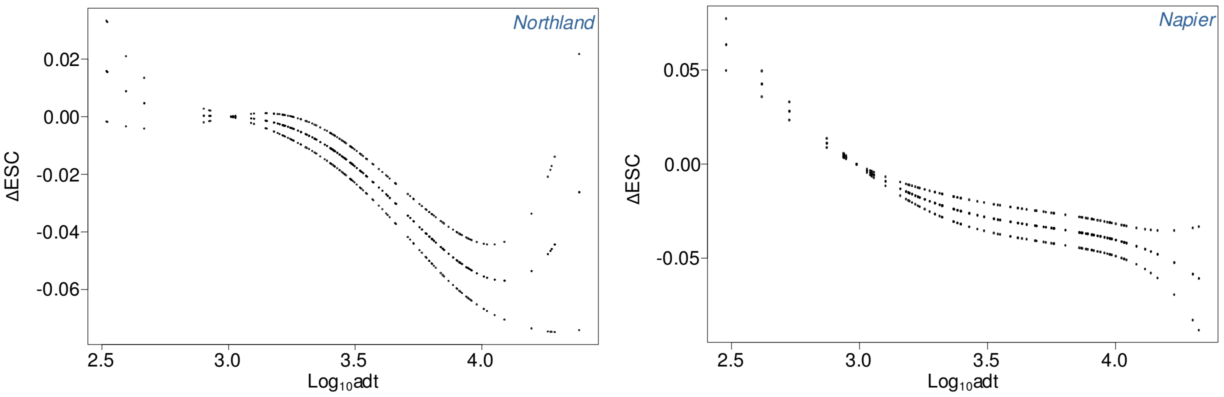

Figure 6 Comparison of reciprocal of ADT effect

AGE (Figure 7)

With reference to Figure 7, age is measured in months and the graphs starts at age = 24 months (i.e. $\log_{10}(\text{age}) = 1.38$). The confidence intervals are with respect to this initial age.

The plot for Northland seems to suggest that ESC increases with seal age. This may be a real effect, though unlikely, or it may be due to low skid resistance roads being removed from the sample. In contrast, the Napier dataset shows a definite drop in ESC as the seal ages over the range 24 months to 80 months.

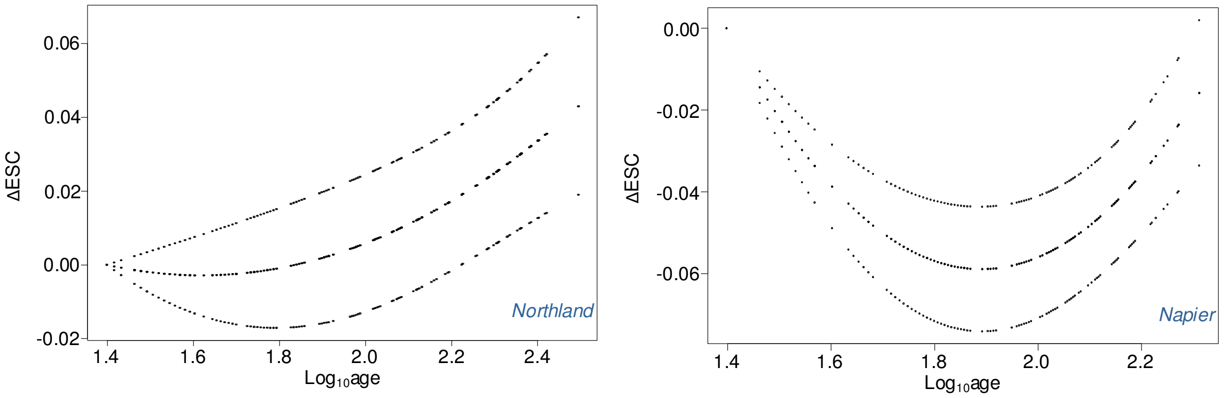

Figure 7 Comparison of reciprocal of horizontal curvature effect

Concluding Remark

Taken overall, the Napier dataset appears to show effects of the quantitative variables that are more consistent with expectations than the Northland dataset.

3.3 Effects of the Categorical Variables

In each case, the sum of the effects has been set to zero and the standard errors and the t-test are based on the difference between the estimate and zero. A t value greater than 2 shows significance at the 5% level.

Seal Category

With reference to Table 7, the best performing seal type in both Northland and Napier with regard to on-road skid resistance is a two coat seal with a Grade 3 chip or higher as the first (larger chip). The worst performing seal type is a single coat, Grade 3 chip in Northland whereas for Napier it is a single coat, Grade 2 chip.

Table 7: Effect estimates for seal type

```
           Coefficients      SEs        t.values
Northland:
  1CHIP.2  -0.01703797  0.003823948  -4.455597
  1CHIP.3  -0.02038944  0.004151214  -4.911680
 1CHIP.4+   0.01260183  0.005845105   2.155963
2CHIP.2.4  -0.00487638  0.005809497  -0.839381
2CHIP.2.5   0.01355338  0.008063543   1.680822
 2CHIP.3+   0.01614858  0.004814572   3.354105
Napier:
  1CHIP.2  -0.02465301  0.002147497 -11.479884
 1CHIP.3+   0.00554356  0.002837270   1.953836
 2CHIP.2   -0.00667696  0.002364785  -2.823496
 2CHIP.3+   0.02578641  0.002846364   9.059422
```

Speed Environment Category

Table 8 shows that for Northland skid resistance is slightly worse in urban areas whereas for Napier skid resistance is worse in rural areas.

Table 8: Effect estimates for speed environment

```
           Coefficients      SEs       t.values
Northland:
  Rural    0.001780243  0.000775426  2.295826
  Urban   -0.001780243  0.000775426  2.295826
Napier:
  Rural   -0.006128549  0.001332766 -4.598369
  Urban    0.006128549  0.001332766  4.598369
```

T/10 Skid Resistance Site Category

Transit New Zealand’s policy for skid resistance is largely contained within the T/10 specification. This specification was introduced in 1998 and aims to standardise the risk of a wet skid crash across the state highway network by assigning investigatory skid resistance levels for different site categories, which are related to different friction demands. A description of these site categories and associated investigatory levels are summarised in Table 9.

The effect of T/10 site category on ESC values is tabulated in Table 10. With reference to Table 10, the high demand T/10 site categories 1 to 3 tend to have lower ESC values than the low demand T/10 site categories 4 and 5 for both Northland and Napier.

Table 9: T/10 skid site categories

Site Category	Description	Notes	Investigatory Level (ESC)
5	Divided carriageway		0.35
4	Normal roads	Undivided carriageways only.	0.4
3	Approaches to road junctions. Down Gradients 5% - 10%	Includes motorway on/off ramps	0.45
2	Curve < 250m radius Down Gradients > 10%		0.5
1	Highest priority	Railway level crossing, approaches to roundabouts, traffic lights, pedestrian crossings and similar hazards.	0.55

Table 10: Effect estimates for T/10 site categories

```
          Coefficients       SEs        t.values
Northland:
     1-3  -0.00143021 0.0003041702 -4.701991
     4-5   0.00143021 0.0003041702  4.701991
Napier:
     1-3  -0.00198731 0.0002828417 -7.026227
     4-5   0.00198731 0.0002828417  7.026227
```

Aggregate Source Category

Tables 11 and 12 tabulate effect estimates of aggregate sources employed in Northland and Napier respectively. The best performing aggregate source employed in Northland is shown to be Lamars Road, while the worst performing are Atlas and Piroa. For Napier, the best performing aggregate source is Waiotahi, while the worst are Awatoto, Ngaruroro, Tukituki River and Whitehall.

Table 11: Effects estimates for aggregate sources employed in Northland

```
             Coefficients          SEs      t.values
       ATLAS -0.026100128 0.008888682  -2.9363328
LARMERS ROAD  0.047303843 0.004331879  10.9199357
      OTAIKA  0.001071816 0.004325821   0.2477718
       PIROA -0.028945453 0.008913756  -3.2472790
    PUKETONA  0.011807481 0.004841272   2.4389212
   WINSTONES -0.005137559 0.005047452  -1.0178520
```

Table 12: Effects estimates for aggregate sources employed in Napier

```
                    Coefficients          SEs      t.values
    AWAKERI QUARRY  0.021046310 0.004710027   4.4684057
           AWATOTO -0.034153342 0.007213949  -4.7343474
 LOWER HUTT QUARRY  0.005708691 0.004461269   1.2796115
         NGARURORO -0.021079069 0.002957861  -7.1264581
       POPLAR LANE  0.002140092 0.005624572   0.3804898
      TAMAKI RIVER  0.018643712 0.007836335   2.3791367
TUKITUKI - WAIPUK -0.014457948 0.005528700  -2.6150721
    TUKITUKI RIVER -0.027213411 0.006450766  -4.2186324
          WAIOTAHI  0.070492217 0.004872306  14.4679367
      WAIPAWA RIVER  0.004350053 0.006805784   0.6391700
  WHITEHALL QUARRY -0.025477305 0.003061197  -8.3226600
```

Table 13 provides a ranking of the aggregate sources used in Northland and Napier ranked from best performing to worst performing. The ranking is based on the effects analysis summarised in Tables 11 and 12. Also tabulated for comparative purposes is the average PSV value measured for the aggregate source.

From Table 13 it is readily apparent that PSV is not a reliable predictor of the in-service skid resistance performance of an aggregate.

Table 13: Aggregate source effect compared to mean polished stone value

Region	Best to Worst Performing Aggregate Source		PSV
Northland	Best	LARMERS ROAD	57
		PUKETONA	54
		OTAIKA	53
		WINSTONES	51
		ATLAS	59
	Worst	PIROA	59
Napier	Best	WAIOTAHI	60
		AWAKERI QUARRY	57
		TAMAKI RIVER	60
		LOWER HUTT QUARRY	58
		WAIPAWA RIVER	56
		POPLAR LANE	60
		TUKITUKI – WAIPUK	58
		NGARURORO	55
		WHITEHALL QUARRY	55
		TUKITUKI RIVER	55
	Worst	AWATOTO	54

4. EFFECT OF POLISHED STONE VALUE

The effect of including polished stone value (PSV) in the statistical modelling was investigated. Table 14 is the variance table that results when the PSV variable (labelled polished.stone) is included before the aggregate source variable (labelled pave.source.main.ps) in an analysis of variance for the Northland dataset where the terms are added sequentially.

With reference to Table 14, PSV is statistically very significant and aggregate source when added afterwards is still significant. The sums of squares of the two variables are comparable indicating that inclusion of aggregate source with PSV provides additional explanatory information.

Table 15 is the variance table that results when PSV is added after aggregate source. In this case inclusion of the PSV variable provides very little additional explanatory information. It is not surprising that no statistically significant effect is observed as the only situation this would occur is when the PSV varies within a quarry.

This analysis, when repeated with the Napier dataset, produced the same result confirming that the categorical variable, aggregate source, has more predictive power than the quantitative variable, PSV.

Table 14: Variance table for Northland dataset – PSV added before aggregate source

```
Terms added sequentially (first to last)
                         Df Sum of Sq  Mean Sq  F Value     Pr(F)
poly(macrotexture, 4)     4   9.81460 2.453651 1420.683 0.0000000
  poly(recip.curv, 2)     2   3.67521 1.837604 1063.987 0.0000000
    poly(gradient, 3)     3   0.08121 0.027070   15.673 0.0000000
        skid.site.sel     1   0.00108 0.001077    0.623 0.4297597
   poly(log10.adt, 4)     4   0.26045 0.065111   37.700 0.0000000
   poly(log10.age, 2)     2   0.01852 0.009260    5.361 0.0047008
          surf.cat.ps     4   0.08071 0.020178   11.683 0.0000000
          urban.rural     1   0.01840 0.018402   10.655 0.0010995
       polished.stone     1   0.06371 0.063710   36.889 0.0000000
  pave.source.main.ps     4   0.05474 0.013686    7.924 0.0000022
            Residuals 20535  35.46586 0.001727
```

Table 15: Variance table for Northland dataset – aggregate source added before PSV

```
Terms added sequentially (first to last)
                         Df Sum of Sq  Mean Sq  F Value     Pr(F)
poly(macrotexture, 4)     4   9.81460 2.453651 1420.683 0.0000000
  poly(recip.curv, 2)     2   3.67521 1.837604 1063.987 0.0000000
    poly(gradient, 3)     3   0.08121 0.027070   15.673 0.0000000
        skid.site.sel     1   0.00108 0.001077    0.623 0.4297597
   poly(log10.adt, 4)     4   0.26045 0.065111   37.700 0.0000000
   poly(log10.age, 2)     2   0.01852 0.009260    5.361 0.0047008
          surf.cat.ps     4   0.08071 0.020178   11.683 0.0000000
          urban.rural     1   0.01840 0.018402   10.655 0.0010995
  pave.source.main.ps     4   0.10790 0.026976   15.619 0.0000000
       polished.stone     1   0.01055 0.010549    6.108 0.0134645
            Residuals 20535  35.46586 0.001727
```

5. EFFECTS MODELS

Table 16 presents the effects detailed in section 3 in a form that can be used for predicting ESC on the Northland and Napier state highway networks. These models are presented only as illustrative examples since more work is required to better define the polynomial curve forms, preferably with data from more regions than just Northland and Napier being used.

Table 17 provides an example application of the Northland model. With reference to Table 17, the estimated ESC value for a 5 year old two coat Grade 2/Grade 4 seal constructed from aggregate sourced from Otaiki quarry (PSV = 53) and carrying 3000 vehicles per day is 0.45 for a 150 m radius curve located on the flat. The ESC value increases to 0.47 for straight (horizontal curvature ≥ 1000 m) road sections on the flat. By comparison, equation 1 considerably over predicts the expected skid resistance giving a terminal ESC value of 0.53 if the percentage of commercial traffic is assumed to be 10% of the ADT.

Table 16: Model coefficients for estimating in-service equilibrium SCRIM coefficient

VARIABLE	NORTHLAND			NAPIER		
	Level	Value	Std.Error	Level	Value	Std.Error
(Intercept)		0.46621	0.012716		0.5779	0.008877
macrotexture - 2		0.02048	0.000663		0.0345	0.000672
(macrotexture – 2)^2		-0.02201	0.000598		-0.0218	0.000797
(macrotexture – 2)^3		0.00713	0.000415		-0.0045	0.000530
(macrotexture – 2)^4		-0.00094	0.000108		0.0051	0.000339
recip.curv		-4.77184	0.116495		-6.8109	0.118565
(recip.curv)^2		71.50415	3.425021		136.0831	4.299023
gradient		-0.00061	0.000082		0.0005	0.000076
gradient^2		0.00002	0.000010		-0.0001	0.000012
gradient^3		0.00001	0.000001		0.0000	0.000001
skid.site	1-3	0		1-3	0	
	4-5	0.00286	0.000608	4-5	0.0040	0.000566
log10(adt)-3		-0.00425	0.010617		-0.0871	0.010913
{log10(adt)-3}^{2}		-0.02291	0.018777		0.0730	0.013687
{log10(adt)-3}^{3}		-0.12412	0.044863		-0.0067	0.040158
{log10(adt)-3}^{4}		0.09606	0.031578		-0.0184	0.026773
log10(age) – 1.38		-0.02820	0.032035		-0.2479	0.033572
{log10(age) – 1.38}^{2}		0.05957	0.029640		0.2428	0.037525
surf.cat	1CHIP.2	0		1CHIP.2	0	
	1CHIP.3	-0.00335	0.005145	1CHIP.3+	0.0302	0.003962
	1CHIP.4+	0.02964	0.007408	2CHIP.2	0.0180	0.003466
	2CHIP.2.4	0.01216	0.007377	2CHIP.3+	0.0504	0.004134
	2CHIP.2.5	0.03059	0.010044			
	2CHIP.3+	0.03319	0.006249			
urban.rural	urban	0		urban	0	
	rural	-0.00356	0.001551	rural	0.0123	0.002666
pave.source.main	ATLAS	0		AWAKERI QUARRY	0	
	LARMERS RD	0.07340	0.010941	AWATOTO	-0.0552	0.009402
	OTAIKA	0.02717	0.010604	LOWER HUTT QUARRY	-0.0153	0.006578
	PIROA	-0.00285	0.014782	NGARURORO	-0.0421	0.005651
	PUKETONA	0.03791	0.011541	POPLARLANE	-0.0189	0.007289
	WINSTONES	0.02096	0.011621	TAMAKIRIVER	-0.0024	0.009752
				TUKITUKI–WAIPUK	-0.0355	0.007575
				TUKITUKIRIVER	-0.0483	0.008489

Table 17: Example application of equilibrium SCRIM coefficient effects model

VARIABLE	VARIABLE VALUE	LEVEL	CORRESPONDING COEFFICIENT	PRODUCT
				(value×coefficient)
Input Variables				
macrotexture (mm, MPD)	1.8			
horizontal curvature (m)	150			
road gradient (%)	0			
T/10 Site Cat	2			
traffic, adt (vpd)	3000			
surface age (months)	60			
surface type	2CHIP.2.4			
speed environment	Rural			
aggregate source	OTAIKA			
Calculated Variables				
(Intercept)	1		0.46621	0.46621
macrotexture - 2	-0.2		0.02048	-0.004096
(macrotexture – 2)^2	0.04		-0.02201	-0.0008804
(macrotexture – 2)^3	-0.008		0.00713	-0.00005704
(macrotexture – 2)^4	0.0016		-0.00094	-0.000001504
recip.curv	0.006666667		-4.77184	-0.031812267
(recip.curv)^2	4.44444E-05		71.50415	0.003177962
gradient	0		-0.00061	0
gradient^2	0		0.00002	0
gradient^3	0		0.00001	0
skid.site	1	1-3	0	0
	0	4-5	0.00286	0
log10(adt)-3	0.477121255		-0.00425	-0.002027765
{log10(adt)-3}^{2}	0.227644692		-0.02291	-0.00521534
{log10(adt)-3}^{3}	0.108614121		-0.12412	-0.013481185
log10(adt)-3}^{4}	0.051822106		0.09606	0.004978031
log10(age) - 1.38	0.39815125		-0.0282	-0.011227865
{log10(age) – 1.38}^{2}	0.158524418		0.05957	0.0094433
surf.cat	0	1CHIP.2	0	0
	0	1CHIP.3	-0.00335	0
	0	1CHIP.4+	0.02964	0
	1	2CHIP.2.4	0.01216	0.01216
	0	2CHIP.2.5	0.03059	0
	0	2CHIP.3+	0.03319	0
urban.rural	0	urban	0	0
	1	rural	-0.00356	-0.00356
pave.source.main	0	ATLAS	0	0
	0	LARMERS RD	0.0734	0
	1	OTAIKA	0.02717	0.02717
	0	PIROA	-0.00285	0
	0	PUKETONA	0.03791	0
	0	WINSTONES	0.02096	0
			Sum:	**0.450779927**

6. CONCLUDING REMARKS

Statistical modelling of equilibrium SCRIM coefficient values measured on 10 m sections of state highway found the categorical variable "aggregate source" to have an effect that was highly statistically significant. This categorical variable was shown to be a better indicator of in-service skid resistance performance than the quantitative variable "polished stone value." Therefore, there appears to be a strong case to use statistical modelling to complement polished stone value test results when ranking suppliers of surfacing aggregates.

The other effects found to be statistically significant included macrotexture, curvature, longitudinal gradient, skid resistance site category, daily traffic, seal age, seal type and speed environment. However, there still remains a higher degree of variability than desirable leading to the suspicion that there is at least another variable that should be included in the statistical modelling of equilibrium SCRIM coefficient.

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