Sensitivity of In-Service Skid Resistance Performance of Chipseal Surfaces to Aggregate and Texture Characteristics

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ABSTRACT

A statistical modelling study was undertaken to identify critical aggregate properties from the perspective of in-service skid resistance performance of chipseal surfaces. Emphasis was placed on straight and level road sections to minimise confounding effects brought about by braking, cornering, and traction manoeuvres. In performing the study a database was assembled that comprised SCRIM-based skid resistance data from annual network surveys undertaken since 1998 and 18 different standard measures of surface texture derived from stationary laser profiler measurements made on 47 straight and level test sites located on state highways. Of these 47 test sites, 24 had surfaces constructed from alluvial aggregate ranging in polished stone value (PSV) from 52 to 62 and carrying heavy commercial vehicle (HCV) traffic between 12 and 468 HCV/lane/day. The remaining 23 sites were constructed from quarried rock ranging in PSV from 43 to 65 and carrying HCV traffic between 22 and 380 HCV/lane/day. All surfaces had an age of about 3 years or greater.

The principal finding was that the critical determinants of in-service skid resistance performance of chipseal surfaces were cumulative heavy commercial vehicle (HCV) passes and the mean spacing between tips of aggregates. As a result, it was possible to formulate a rational model that provides 95% certainty that the predicted value of skid resistance, in terms of SCRIM Coefficient (SC), will be within ±0.08 of observed values. The model inputs are limited to polished stone value (PSV), HCV traffic, seal age and aggregate average least dimension (ALD). However, significant inter-relationships between aggregate microtexture and macrotexture were also identified, which require additional investigation given their implication to current seal design practice. The preliminary indications are that the selection of “rounded” alluvial aggregates for skid resistant surfaces should be predicated on PSV as is current practice whereas selection of “angular/sharp-edged” hard rock aggregates should be predicated on size (the smaller the better) and ability to withstand tip and edge wear caused by HCV traffic.

Key Words: aggregate polishing, chipseal design, predictive model, road surface profiles, skid resistance, texture.

1. INTRODUCTION

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:

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

where: MSSC = Mean Summer SCRIM Coefficient
CVD = Commercial vehicles per lane per day
PSV = Polished Stone Value

Equation1 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 (Catt, 1983; Roe and Hartshorne, 1998 and Cenek et al. 1998). This possibly can be explained by the absence of texture parameters in equation 1. From Heaton, Henry and Wambold (1990), texture parameters known to have an influence on the skid resistance characteristics of a road surface include:

- Sharpness of the texture projections (influences water film thickness)
- Average texture penetration (influences level of tyre rubber strain)
- Wavelength of texture projections (influences the frequency of cyclic loading and tyre rubber temperature and hence tyre rubber hysteresis)
- Average slope of texture faces (influences the horizontal components of the deformation forces in the tyre rubber)

In order to improve the level of agreement between predicted and observed in-service skid resistance performance of New Zealand chipseal road surfaces, a multiple regression analysis was performed to establish the relative contributions of heavy commercial vehicle traffic, aggregate characteristics and surface texture profile to the skid resistance level of chipseal surfaced sections of state highway. To have relevance in a predictive model, the aggregate and surface texture profile variables were confined to those capable of being determined in the laboratory, such as PSV and aggregate shape, or derived from digital profiles of the road surface obtained with stylus, light sectioning or laser-based profilers (PIARC, 1995). Emphasis was placed on the in-service performance of straight and level road sections where horizontal tyre forces will be at their lowest and least variable. This eliminated any confounding effects brought about by vehicle manoeuvres that generate higher but more variable tyre forces, such as when accelerating from rest, braking, cornering and hill climbing.

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

2. EXPERIMENTAL DESIGN

2.1 OBJECTIVE OF FIELD STUDY

The objective of the field study was to investigate the sensitivity of in-service skid resistance performance of chipseal surfaced sections of state highway to aggregate and texture characteristics under different traffic loading. Therefore, test surface selection is crucial for the outcome of an investigation such as this so that significant correlations are not masked by variances related to random measurement errors. This necessitates the investigated factors to have as wide a range as possible.

2.2 SELECTION OF CANDIDATE TEST SITES

Transit New Zealand, the national roading authority, has in place a maintenance management information system, RAMM (Road Assessment and Maintenance Management), which contains detailed road geometry, surface condition and traffic information for 22,000 lane-km's of sealed state highways. A search of the 2001 RAMM database was carried out to identify candidate test sites that satisfied the following conditions:

- Chipseal surfaces that satisfied Transit New Zealand's recently introduced texture requirements for rural roads (i.e. mean profile depth (MPD) > 0.9 mm) and showed no signs of bitumen cover either from bleeding, or flushing or precoated chip.
- A surface age of 3 or more years to ensure that the polishing phase, where skid resistance reduces under the action of traffic, had been passed.
- The road geometry was comparatively straight (i.e. horizontal curvature 300 m or greater) and level (i.e. gradient ±10% or less) to minimise the confounding effect of additional polishing action brought about by accelerating, braking and cornering manoeuvres.
- A homogeneous length of at least 200m to enable multiple measurements with Transit's Stationary Laser Profiler (SLP) to be made and to minimise any location referencing errors inherent in the RAMM high speed data (HSD) database. The accepted tolerance for recording and reporting survey data is $\pm(0.3\%D+10m)$ where D is the distance between reference station (RS) markers. This tolerance equates to ±55m for a typical RS length of 15 km.

The above selection criteria generated around 7500 sites. Where possible, the PSV of each site's sealing chip was identified from Transit New Zealand's wall chart of PSV test results for suppliers of surfacing aggregate. This reduced the number of candidate test sites with known PSV to about 4400.

For each of these 4400 sites, standard 20 m RAMM wheelpath condition (roughness, rutting and surface texture) and lane geometry (crossfall, gradient and horizontal curvature) were extracted from Transit New Zealand state highway RAMM tables, together with 10 m SCRIM skid resistance data for the previous surveys conducted in 1995, 1998, 1999, 2000, 2001. The skid resistance data was in terms of Mean Summer SCRIM coefficient (MSSC), which is the estimated mean SCRIM coefficient over the summer period when skid resistance is generally at its lowest.

The extracted data was used to obtain average values for each candidate test site, the averaging length being the entire length of the site.

2.3 PRELIMINARY REGRESSION ANALYSIS

The opportunity was taken to perform a regression analysis to identify statistically significant relationships between the average road condition, road geometry and traffic data for each candidate site and MSSC values based on the 2001 survey results (1 year average) and the average of the 1999, 2000 and 2001 survey results (3 year average). The intent of this analysis was to:

- Establish how well MSSC correlated with the two variables presently used for predicting in-service skid resistance performance, PSV and heavy commercial vehicles per lane per day (CVD) (refer equation 1).
- Identify any other variables stored in RAMM that may be a significant predictor of in-service skid resistance to ensure test site selections are conducive to a successful outcome.

In addition, MSSC values from 2000 were regressed against MSSC values from 2001 to establish whether or not existing values of skid resistance are a good predictor of future values as is typically the case for other road condition variables, roughness in particular.

The results of the regression analysis, in terms of coefficient of determination (r^2) are presented in Table 1. The coefficient of determination is the ratio of the explained variation to the total variation. If there is zero explained variation i.e. the total variation is all unexplained, this ratio is zero. If there is zero unexplained variation i.e. the total variation is all explained, the ratio is one.

The following comments are made in relation to the r^2 values listed in Table1:

- The degree of correlation in the test site average MSSC values between successive years is about 60%. Given that the surface age of each site is 3 or more years, any inter-year differences are likely to be related to seasonal variations rather than polishing action of traffic because the equilibrium value of skid resistance should have been reached. This result confirms that skid resistance is a very variable parameter even when normalising procedures for seasonal effects, such as MSSC are utilised. Therefore, it would be unrealistic to expect that a regression model for skid resistance utilising standard RAMM variables and texture profile variables can result in predicted values that correlate better than 60% with the observed values.
- The two variables presently used for guiding aggregate selection, PSV and CVD, when combined explain only about 12% to 14% of the observed variation in the MSSC values. This low degree of correlation supports earlier New Zealand research reported in Cenek et al (1998) suggesting that critical variables influencing skid resistance are missing from equation 1. However, a possible explanation for the lower than expected r^2 values for these two key variables may be their accuracy. In the case of PSV values, these were inferred rather than measured. The CVD data is even more suspect as values stored in RAMM can either be default or estimated or measured. Therefore, in an attempt to improve the quality of CVD data, test sites were selected wherever possible on the basis of proximity to Transit New Zealand's control traffic monitoring sites to ensure use of measured CVD values.
- There is a higher degree of correlation between chip size and MSSC than between texture depth (MPD) and MSSC. This result indicates that aggregate shape and spacing, two factors which impact on hysteresis losses, have a greater contribution to slow slip speed skid resistance than texture depth, which impacts on drainage.

- Slightly better correlations have been obtained when the RAMM variables were regressed against site MSSC values that had been averaged over three years. This averaging process reduces the influence of year on year variations in weather patterns. For example, MSSC values are expected to be lower during dry summers and higher during wet summers. The three year average MSSC value approximates the Equilibrium SCRIM Coefficient (ESC) adopted in New Zealand since 2002 for skid resistance management purposes, which is based on a four year rolling average.
- No significant correlations between RAMM road geometry data and skid resistance were identified. This was as expected since test site selections were confined to relatively straight and level road geometry.

Table 1: Correlation of RAMM variables with in-service skid resistance for candidate test sites

Regressed Variable	Coefficient of Determination (r^2)	
	MSSC (2001 Survey)	**MSSC (Average of 1999,2000, & 2001 Surveys)**
Polished Stone Value (PSV)	0.017	0.019
Commercial Vehicles per lane per day (CVD)	0.111	0.130
Horizontal Curvature (m)	0.003	0.005
Road Gradient (%)	0.001	0.002
Crossfall (%)	0.011	0.014
Lane Roughness (NAASRA counts/km)	0.013	0.024
Rutting (mm)	0.023	0.035
MPD Texture (mm)	0.000	0.001
Surface Age (years)	0.003	0.022
Chip Size (ALD, mm)	0.080	0.112
PSV + CVD	0.124	0.144
PSV + Chip Size	0.090	0.128
PSV + CVD + Chip Size	0.177	0.227
MSSC (2000)	0.596	-

Note: ALD = average least dimension

2.4 SITES SELECTED FOR SURFACE PROFILE MEASUREMENTS

The critical factors used in the site selection were as follows:

1. Chip size
   (a) Coarse, Grade 2
   (b) Medium, Grade 3
   (c) Fine, Grades 4, 5 and 6
2. Traffic
   (a) Low, CVD < 200 v/l/d
   (b) High, CVD > 200 v/l/d
3. PSV
   (a) Low, < 52
   (b) Medium, 53 to 59
   (c) High, > 60
4. Rock Type
   (a) Greywacke

(b) Basalt
(c) Gabbro
(d) Schist-Greywacke
(e) Andesite

5. Extraction Method
(a) Alluvial
(b) Hard rock quarry

A test site selection matrix, as shown in Table 2, was developed in discussion with a consulting statistician. With reference to Table 2, there are 108 possible combinations of variables. Each element comprising the test site selection matrix has been given a unique numerical identifier from 1 to 108. If two test sites were to be found for each matrix element, a total of 216 would be required.

Sorting the 4400 candidate sites into the 108 categories resulted in a significant number of categories not being represented, giving a total of 54 test sites.

The lower than desirable number of test sites was due to:

- the dominance of greywacke aggregate (~80% of all candidate test sites);
- some combinations only being available from a single quarry source;
- the concentration of most PSV values within a relatively narrow range (47 to 63).

Following on from the RAMM database search, discussions with the consultants responsible for each Transit New Zealand region revealed that some sites had been resealed during the latest sealing season. Consequently, the number of sites was further reduced to 47. The matrix elements satisfied by these 47 test sites have been highlighted in Table 2.

2.5 LASER PROFILER MEASUREMENTS

Detailed surface profile measurements were made using Transit New Zealand's SLP (refer Figure 1). It consists of a Selcom™ 32 kHz laser camera that is driven at a constant speed along an approximately 1.6m long track.

The laser light spot is 0.5mm in diameter and allows surface height to be measured to within an accuracy of ±0.03mm. Therefore, precise vertical cross-section of the traversed surface is provided (refer Cenek et al, 1997).

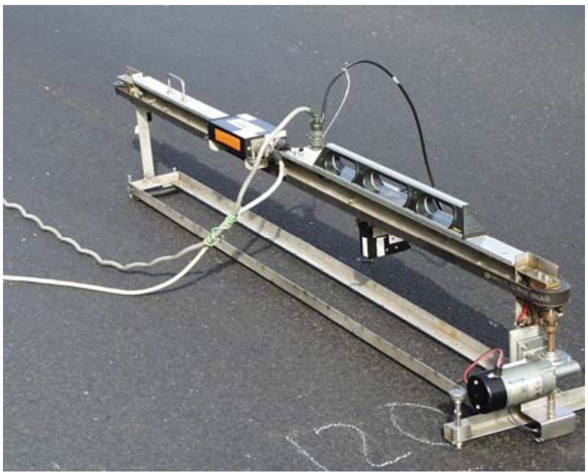

Figure 1: Stationary laser profiler (SLP) used for obtaining texture profiles

Table 2: Test site selection matrix with those elements satisfied by one tests site highlighted in light grey and those by two test sites highlighted in dark grey

Chip Size				Grade 2	Grade 3	Grade 4+
Low Traffic	Low PSV	Greywacke	Alluvial	1	37	73
			Hard Rock	2	38	74
		Basalt	Hard Rock	3	39	75
		Gabbro	Hard Rock	4	40	76
		Schist - Greywacke	Alluvial	5	41	77
		Andesite	Hard Rock	6	42	78
	Medium PSV	Greywacke	Alluvial	7	43	79
			Hard Rock	8	44	80
		Basalt	Hard Rock	9	45	81
		Gabbro	Hard Rock	10	46	82
		Schist - Greywacke	Alluvial	11	47	83
		Andesite	Hard Rock	12	48	84
	High PSV	Greywacke	Alluvial	13	49	85
			Hard Rock	14	50	86
		Basalt	Hard Rock	15	51	87
		Gabbro	Hard Rock	16	52	88
		Schist - Greywacke	Alluvial	17	53	89
		Andesite	Hard Rock	18	54	90
High Traffic	Low PSV	Greywacke	Alluvial	19	55	91
			Hard Rock	20	56	92
		Basalt	Hard Rock	21	57	93
		Gabbro	Hard Rock	22	58	94
		Schist - Greywacke	Alluvial	23	59	95
		Andesite	Hard Rock	24	60	96
	Medium PSV	Greywacke	Alluvial	25	61	97
			Hard Rock	26	62	98
		Basalt	Hard Rock	27	63	99
		Gabbro	Hard Rock	28	64	100
		Schist - Greywacke	Alluvial	29	65	101
		Andesite	Hard Rock	30	66	102
	High PSV	Greywacke	Alluvial	31	67	103
			Hard Rock	32	68	104
		Basalt	Hard Rock	32	69	105
		Gabbro	Hard Rock	34	70	106
		Schist - Greywacke	Alluvial	35	71	107
		Andesite	Hard Rock	36	72	108

Measurements were made with the stationary laser profiler in the left wheelpath at each of the 47 test sites to allow quantification of macrotexture characteristics in the 0.63 mm to 500 mm wavelength range. Three passes were made over a representative 20m length of each site. Figure 2 shows a representative surface profile obtained for one of the test sites.

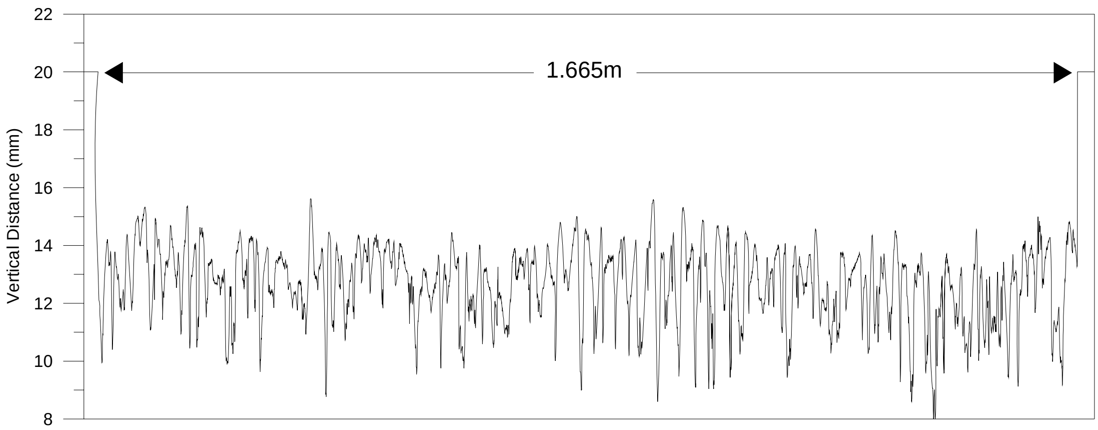

Figure 2: Example of a test site surface profile

2.6 DATA PROCESSING

The principal objective of this study was to quantify the influence of road surface profile on in-service skid resistance as measured by MSSC. Surface profiles can be divided into three components: roughness; waviness; and form. Accordingly, the acquired road surface profiles were processed to obtain standard measures of surface texture as defined in ISO Standards 4287/1:1984, 4287:1997, 13565-1:1996, 13565-2:1996 and ASME Standards B46.1:1985, B46.1:1995.

These standard measures of surface texture fall into three categories as follows:

- amplitude variables, which are measures of the vertical characteristics of the surface deviations;
- spacing variables, which are measures of the horizontal characteristic of the surface deviations;
- hybrid variables, which are some combination of both amplitude and spacing variables.

Table 3 provides a listing of all the surface texture variables that have been utilised in this study. The corresponding values for each of the 47 test sites can be found in Cenek et al. (2004). In calculating the surface texture variables listed in Table 3, the assessment length was taken to be Transit New Zealand's SLP's track length of 1.67m and the sampling length one fifth of this i.e. 0.33 m.

3. REGRESSION ANALYSIS OF TEST SITE DATA

3.1 AVERAGING PROCEDURE FOR MSSC DATA

The Equilibrium SCRIM Coefficient (ESC) adopted in New Zealand for skid resistance management of the state highway network is based on a four year rolling average. Accordingly, the dependent variable was confined to the mean of the 1998, 1999, 2000, and 2001 site length averaged MSSC values in performing the regression analysis of the surface profile data acquired for the 47 test sites whenever the surface age was four years or older to provide equivalency with

ESC. For a surface age less than 4 years, all available MSSC values that spanned the surface age were averaged. This allowed the averaging period to be maximised. Therefore, MSSC data for the last 2 years (2000 and 2001) was averaged for the surfaces just less than 3 years of age and for the last 3 years (1999, 2000 and 2001) for surfaces whose age was greater or equal than 3 years but less than 4 years.

The distribution of surface ages for the 47 test site sample is shown in Figure 3. The sample is dominated by test sites with surfaces older than 4 years with only 20% of the test sites having a surface younger than 4 years.

Table 3: ASME and ISO standardised measures of surface texture

Surface Texture Variable	Description
Amplitude Variables	
Ra	mean of the absolute departures of the profile from the mean line
Rq	root mean square (RMS) corresponding to Ra
Rt	maximum peak-to-valley height in the assessment length
Rti	maximum peak-to-valley height in one sampling length
Rtm=Rz	mean of all Rti values in an assessment length
Rvi	maximum depth of the profile below the mean line within the sampling length i.e. maximum profile valley depth
Rvm	mean of the Rvi values obtained for each sampling length within the assessment length
Rpi	maximum height of the profile above the mean line within the sampling length i.e. maximum profile peak height
Rpm	mean of the Rpi values obtained for each sampling length within the assessment length
Spacing Variables	
S	mean spacing of adjacent local peaks in sampling length (only included if height of peak-to-preceding minima ≥ 1%Rt)
Sm	mean spacing between profile peaks at the mean line, measured over the assessment length (peak = highest part of the profile between crossings of mean line)
HSC	high spot count i.e. the number of complete profile peaks within the assessment length projecting above the mean line or a line that is some specified distance below the highest peak
Pc	peak count density i.e. the number of local peaks in an assessment length that project through a selectable band centred about the mean line
Hybrid Variables	
delq	rms slope of the profile for the assessment length
lq	the rms measure of spatial wavelength over the assessment length (gives a measure of average wavelength)
Rmr	material/bearing ratio i.e. length of the bearing surface (as % of assessment length) at a specified depth below the highest peak
Rku	kurtosis i.e. a measure of the sharpness of the amplitude distribution curve for the assessment length
Rsk	skewness i.e. a measure of the symmetry of the amplitude distribution curve about the mean line for the assessment length

Note: The amplitude variable, Rz, is equivalent to the sum of the amplitude variables Rp and Rv.

3.2 RAMM VARIABLES

In order to have confidence that the experimental design would be sufficiently sensitive to identify significant relationships between skid resistance and surface profile characteristics with the 47 test sites selected, the regression analysis detailed in section 2.3 involving RAMM variables was repeated to establish whether or not the resulting coefficients of determination were comparable to those obtained with the population of 4400 candidate test sites.

The results of this repeat RAMM variable regression analysis are summarised in Table 4.

Comparing the tabulated r^2 with those in Table 1, it can be seen that the sensitivities detected with the sample of 47 tests sites are very similar to those detected with the entire population of 4400 candidate test sites confirming the suitability of the experimental design.

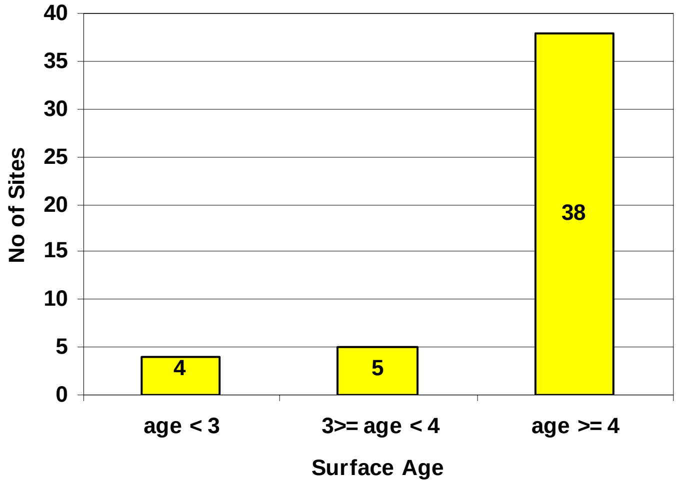

Figure 3: Histogram plot of test site surface ages

Table 4: Correlation of selected RAMM variables with in-service skid resistance for the 47 tests sites selected for surface profile measurements

Regressed Variable	Coefficient of Determination (r^2) when Regressed Against Averaged MSSC (1998, 1999,2000, & 2001)
Polished Stone Value (PSV)	0.050
Commercial Vehicles per lane per day (CVD)	0.133
Horizontal Curvature (m)	0.076
Road Gradient (%)	0.065
Crossfall (%)	0.005
Lane Roughness (NAASRA counts/km)	0.001
Rutting (mm)	0.036
MPD Texture (mm)	0.032
Surface Age (years)	0.069
Chip Size (mm)	0.164
PSV + CVD	0.183
PSV + Chip Size	0.191
PSV + CVD + Chip Size	0.306

With reference to Table 4, the main predictors of in-service skid resistance performance are shown to be heavy commercial vehicle traffic volume (CVD) and average chip size (CS) of the roading aggregate. These two variables when combined separately or together with PSV form the basis of Szatkowski & Hosking's equation (equation 1) and an enhancement to Szatkowski & Hosking's equation proposed by Catt (1983), which incorporates aggregate size. The r^2 values that result from a multiple regression involving two or more of these variables are very similar to the summation of the simple regression r^2 values for each independent variable used in the multiple regression analysis. For example, a multiple regression of PSV, CVD and CS produces an r^2 value of 0.306 whereas the sum of the individual r^2 values is only slightly greater at 0.347 (i.e. 0.050+0.133+0.164). This indicates that CVD and CS are not explaining the same variance observed in the in-service skid resistance performance of state highways.

The resulting multiple regression models show increasing skid resistance with increasing PSV and decreasing skid resistance with increasing CVD and ALD. These trends appear intuitively correct and replicate trends observed with the in service skid resistance performance of UK roads reported by Catt (1983). This provided a degree of confidence that the database assembled would be suitable for refining Szatkowski & Hosking's equation to provide more reliable predictions of the in service skid resistance performance of New Zealand chipseal roads.

3.3 SURFACE PROFILE VARIABLES

A regression analysis of the surface profile data obtained for the 47 test sites was performed to highlight significant relationships between MSSC and amplitude, spacing and hybrid variables of surface texture to assist in the development of a predictive model. Table 5 provides a summary of the coefficients of determination (r^2) obtained for each of the surface texture variables listed in Table 3.

Table 5: Correlation of standardised measures of surface texture with in-service skid resistance for the 47 tests sites selected for surface profile measurements

Regressed Surface Texture Variables		Coefficient of Determination (r^2) when Regressed Against MSSC Averaged Over 1998, 1999,2000, & 2001
Amplitude Variables:	Ra	0.005
	Rq	0.004
	Rt	0.000
	Rtm	0.002
	Rpm	0.016
	Rvm	0.000
Spacing Variables:	Si (average)	0.000
	Sm	0.050
	HSC	0.039
	Pc	0.145
Hybrid Variables:	delq	0.021
	lq	0.072
	Rmr	0.021
	Rku	0.004
	Rsk	0.091

With reference to Table 5, the only surface texture variables that stand out as possibly contributing to MSSC are the spacing variable Pc, which is associated with the number of local peaks over an assessment length of 1 cm and the hybrid variables lq and Rsk, which are associated with the root-mean-square (RMS) wavelength of the profile and symmetry of the profile (see Figure 4) about the mean line respectively. Each of these three surface texture variables has an r^2 value of about 0.1, which, although not particularly good, is comparable to that obtained for the two Szatkowski & Hosking's equation variables PSV and CVD when applied to the same dataset.

In terms of interpreting the variable Rsk, road surfaces with a positive skewness, have fairly high spikes that protrude above a flatter average such as asphaltic concrete. Road surfaces with negative skewness have fairly deep valleys in a smoother plateau, such as open graded porous asphalt (OGPA). More random surfaces such as chipseals have a skew near zero.

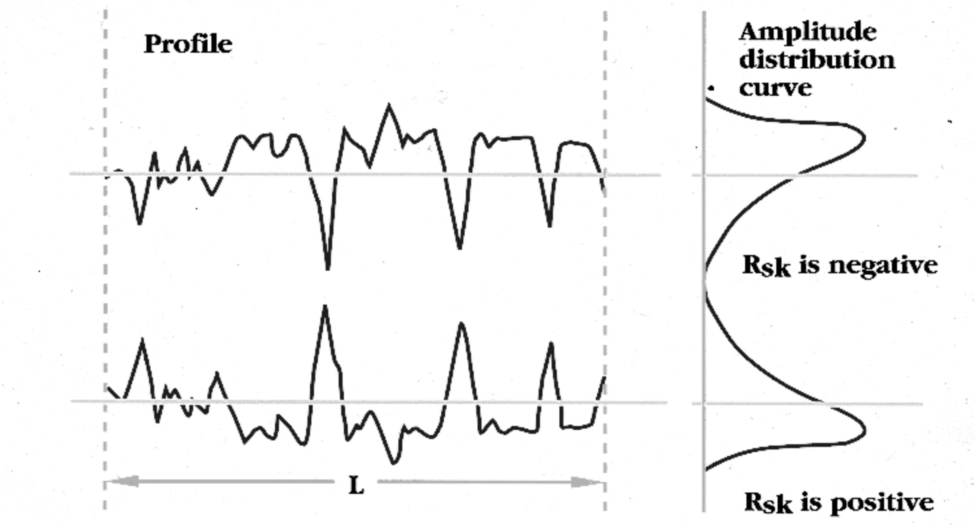

Figure 4: Graphical representation of surface texture variable Rsk

3.4 RAMM AND SURFACE TEXTURE VARIABLES COMBINED

The RAMM and surface texture datasets for the 47 test sites were combined and a stepwise regression analysis performed. Essentially, stepwise regression allows either forward or backward selection to control the entry of variables into the model. In each step of the procedure, variables are added (forward selection) or removed (backward selection) to obtain a model with a small set of significant variables. The commercially available software package, STATISTICA by Statsoft (www.statsoft.com), was used to perform the stepwise regression analysis.

The model as derived from the test site data was as follows:

$$\begin{aligned} MSSC_{av} = & (0.0018 \times PSV) + (-0.05 \times CHCV) \\ & + (-0.07 \times Rsk) + (0.15 \times delq) + (45 \times Rvm) \\ & + 0.47 \qquad ...(2) \end{aligned}$$

where:

$MSSC_{av}$	= average MSSC derived from 1998, 1999, 2000, and 2001 surveys
PSV	= polished stone value
CHCV	= cumulative heavy commercial vehicle traffic per lane in millions
	= commercial vehicle traffic > 3.5 tonnes /lane/day × surface age (years) × operational days per year ($=300/10^6$)
	= 0.0003 × CVD × AGE
Rsk	= the skewness of the road profile about the mean line
delq	= the root-mean-square (rms) slope of the road surface profile
Rvm	= the mean maximum depth of the road profile from the mean line (m)

Detailed statistics of the model constant estimates and goodness of fit of the model are given in Table 6. With reference to Table 6, the p-level statistic relates to “statistical significance.” The higher the p-level, the less the observed relation between variables in the sample can be believed to be a reliable indicator of the relation between the respective variables in the population. Specifically, the p-level represents the probability of error that is involved in accepting the observed result as valid. In many areas of research, the p-level of

0.05 is customarily treated as a “border-line acceptable” error level. On this basis, the two most significant predictors of in-service skid resistance are cumulative heavy commercial vehicle passes i.e. CHCV and the mean of maximum profile valley depths i.e. Rvm.

Table 6: Model statistics for Equation 2

Model Component	**Model Coefficients**		
	Value	**Standard Error**	**p-level**
PSV	0.0018	0.001	0.145
CHCV	-0.05	0.015	0.002
Rsk	-0.07	0.03	0.03
delq	0.15	0.06	0.02
Rvm	45	16	0.006
Constant	0.47	0.06	1.2E-07
Overall Model Statistics			
Standard Error of Estimation:	0.04		
r^2:	0.43		
No of Observations:	47		

The statistics of the model indicate a standard error of 0.04 in the predicted MSSC and an r^2 of 0.43. Figure 5 presents a graphic representation of the model fit. The “95% Confidence Interval” bands shown in Figure 5 around the sample regression line represents the confidence limits for an ordinate to the “true” (population) regression line. These confidence limits are less than the prediction interval for an individual value of MSSC, which in practice may be of more interest than the mean value given by the regression line. Based on the standard error of estimation (S.E.) value of 0.04, the “95% Prediction Interval” is about ±0.08 and is shown in Figure 5.

In comparing model predictions to observed MSSC values, there appears to be a very low bias since the line of regression falls onto the line of equality (i.e. observed = predicted). In addition, the scatter of data points about the regression line is confined to about $\pm$ 0.08 MSSC. This is comparable to the expected variability in single pass SCRIM$^+$ measurements. Therefore, despite the regression model given by equation 2 being able to explain only 43% of the observed variation in the average MSSC values, it appears sufficiently reliable to guide the design of chipseal surfaces for skid resistance.

It will be noted from Table 6 that the PSV component of the model has a p-level statistic of 0.145. This is significantly higher than the target value of 0.05 and resulted because the stepwise regression was performed on the basis of forced inclusion of the PSV variable in the regression model so that the form of the Szatkowski & Hosking’s equation could be preserved. Therefore, the other variables incorporated in the model were selected to maximise the model’s fit, as determined by r^2, while minimising the p-level of the PSV variable.

The low correlation of the PSV variable with in-service skid resistance (r^2 = 0.05) and relatively high p-level could be in part due to the fact that PSV values were inferred from matching aggregate source information contained in RAMM’s surfacing table for each test site to Transit New Zealand’s 2002 wall chart of PSV test results for suppliers of surfacing aggregate. Therefore, an improvement in the r^2 and p-level statistics is expected if PSV test results for specimens fabricated from non-trafficked aggregate samples taken from each test site were employed.

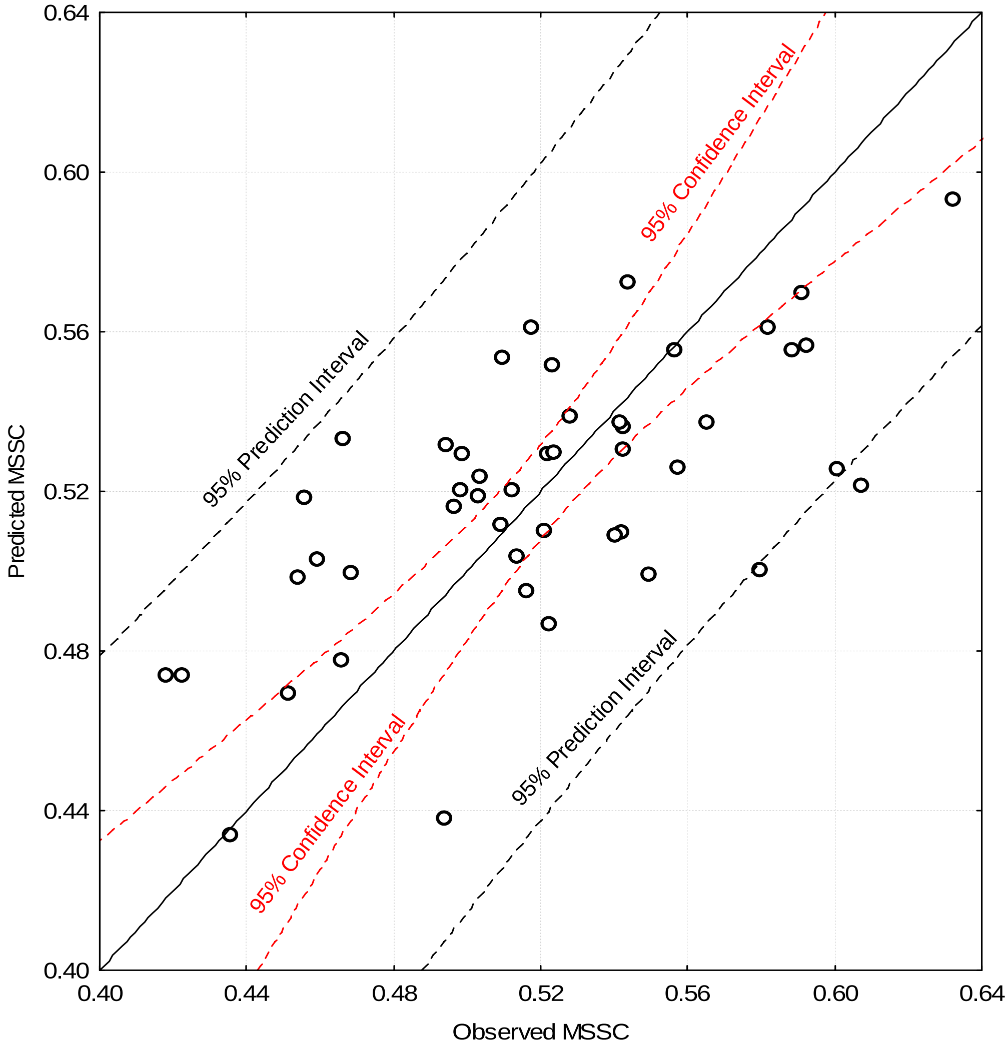

Figure 5: Scatter plot of predicted versus observed in-service MSSC

By comparison, an unconstrained stepwise regression analysis resulted in the following two variable model:

$$MSSC_{av} = (-0.053 \times CHCV) + (0.09 \times Pc) + 0.46 \qquad ...(3)$$

This second regression model had an $r^2 = 0.32$ and S.E.= 0.042. The p-level statistics for CHCV and Pc variables were 0.001 and 0.014 respectively indicating that these two variables are highly significant.

Features common to both regression models are as follows:

- ***Cumulative Heavy Commercial Vehicle Trafficking***

The equilibrium state of polish of a road surface is assumed to occur after 1 million equivalent standard axle (ESA) passes or after 2 years, whichever occurs first (Kokkalis, 1998). It is uncertain from the literature whether the surface age threshold of 2 years is associated with the time expected to reach 1 million ESA's or physical changes to the road surface that occur from weathering.

The 47 tests sites were selected on the basis that they had reached their equilibrium state of polish and so no reduction in skid resistance over time due to traffic induced wear was expected as long as traffic volumes remained largely unchanged. Therefore, the identification of cumulative heavy commercial vehicle traffic (CHCV) rather than daily number of heavy commercial vehicles (CVD) as the most significant variable for predicting in-service skid resistance performance of chipseal road surfaces came as a surprise. This age dependency was not as evident in the regression results for the population of 4400 candidate test sites where lightly trafficked sites were not as predominant. Therefore, it was conjectured that equilibrium state of polish is primarily a function of the number of heavy commercial vehicle (HCV) passes (i.e. cumulative heavy commercial traffic) and not exposure to weathering as all the test sites had surfaces that were about 3 years in age or older.

This hypothesis was tested by determining the threshold value where the variable "CHCV" ceased to be important (i.e. p-level statistic > 0.05). This threshold value was 1 million HCV passes or approximately 2 million ESA, which is double that of Kokkalis. It is conjectured that differences in road surface type (chipseal versus hot mix), travel speeds, and the use of gritting/de-icing agents over winter between New Zealand and Europe may account for the New Zealand threshold being higher.

From RAMM, the average HCV exposure of two-lane rural state highways is calculated to be 129 HCV/lane/day. Therefore, the equilibrium state of polish can be expected to occur after about 26 years assuming road transport operations for 300 days per year. By comparison, the average resealing cycle time for state highways is only 7 years. As a consequence, most surfaces on straight sections of state highway are unlikely to reach their equilibrium state of polish unless they carry more than 500 HCV/lane/day.

Both regression models calculate the rate of change in MSSC due to the polishing action of HCV traffic to be of the order of –0.002 MSSC/year. This rate pertains to straight sections of state highway and so can be expected to be significantly higher wherever horizontal tyre forces are greater than for the just free rolling situation, for example accelerating, braking and cornering.

- ***Key Surface Profile Characteristics***

As expected, equations 2 and 3 show that aggregate size, spacing and shape are important determinants of MSSC. From Moore (1975), a mean spacing of 5 to 15mm between tips of aggregates is considered necessary to satisfy both hysteresis and drainage requirements for speeds on rural state highways. These spacings correspond to values of 2 and 0.67 peaks/cm respectively for the spacing variable "Pc." With reference to equation 3, MSSC increases with increasing Pc implying that for chipseal surfaces smaller aggregate sizes (i.e. Grade 4 to 6) are preferable to larger sized aggregates (i.e. Grade 2 and 3) as the mean spacing between aggregates will be less due to denser packing.

The variable Pc ranged from 0.4 to 1.3 over the 47 test sites, indicating that the distribution of aggregate sizes in New Zealand tends to be skewed towards larger sizes than considered desirable by Moore. On the basis of equation 3, this observed variation in Pc translates to a variation of 0.08 in MSSC.

Although equation 3 covers the frequency of contact between the tyre and road surface, it provides little information regarding aggregate shape, which dictates the degree of penetration into the tread rubber. This is addressed by equation 2, which identifies the important shape parameters to be the amplitude distribution about the mean line (Rsk), the root-mean-square of the road profile (delq) and the mean maximum depth of the road profile from the mean line (Rvm).

The relative contribution of these surface profile variables over the range of values measured for the 47 test sites are tabulated in Table 7. Compared to the slope/sharpness of the aggregate and surface profile valley depth, the skewness of the amplitude distribution is shown to have negligible influence.

Table 7: Relative contribution of key surface texture variable to MSSC as calculated from Equation 2

Surface Texture Variable	Measured Range		Contribution to MSSC	
	Minimum	Maximum	Minimum	Maximum
Skewness, Rsk	-0.6	0.4	-0.03	0.04
RMS Slope, delq	0.23	1.39	0.03	0.21
Mean Valley Depth,Rvm (m)	-0.006	-0.001	-0.27	-0.05
		Sum Total:	-0.27 MSSC	0.20 MSSC

In practice, the combined contribution of the three key surface profile variables as calculated by equation 2 was found to range between –0.07 MSSC and +0.03 MSSC and be normally distributed around a mean value of –0.03 MSSC for the 47 test sites. These values are significantly less than the extreme minimum and maximum values of –0.27 and –0.20 MSSC given in Table 7 and suggest that the potential for optimising aggregates with regard to their shape and distribution within the surface to maximise skid resistance may be limited.

4. SUGGESTED MODEL FOR GUIDING SEAL DESIGN

4.1 MODEL FORMULATION

A shortcoming of equation 2 that potentially could limit its application in the design of chipseal surfaces is the need for in-situ measurements of the surface profile variables Rsk, delq and Rvm. However, this shortcoming can be readily addressed if a relationship between TNZ M6:2002 requirements for sealing chip, such as average least dimension (ALD), and the three surface profile variables exists.

Sealing chip characteristics presented in Transit New Zealand's Bituminous Sealing Manual (1993) have been used to derive the following regression equations for relating average chip size to ALD.

$$\mathrm{ALD} = 0.568 \times \mathrm{CS} - 0.142 \qquad (\mathrm{r}^2 = 0.997, \mathrm{S.E.} = 0.2) \qquad ...(4)$$

$$\mathrm{CS} = 1.75 \times \mathrm{ALD} + 0.354 \qquad (\mathrm{r}^2 = 0.997, \mathrm{S.E.} = 0.4) \qquad ...(5)$$

where: ALD = average least dimension (mm)
CS = average chip size (mm)

The resulting inter-relationship between grade of sealing chip, CS and ALD assumed for this analysis is given in Table 8, along with the median values derived from the 47 test sites for the surface profile variables Rsk, delq, and Rvm.

With reference to Table 8, there is a strong negative linear correlation (coefficient of correlation (r) = -0.94) between sealing chip ALD and the combined contribution of the three surface profile variables to skid resistance. Therefore equation 2 can be simplified without significant loss of predictive accuracy by substituting ALD for the variables Rsk, delq and Rvm. The resulting regression model is:

$$MSSC_{av} = 0.0014 \times PSV - 0.05 \times CHCV - 0.007 \times ALD + 0.52 \qquad ...(6)$$

This regression model has fit statistics of r^2=0.32 and S.E.=0.04. The level of fit, therefore, represents a slight degradation over that achieved by equation 2, but is a reasonable trade-off in order to gain a predictive model that is a significant improvement over Szatkowski & Hosking's equation and which utilises input variables that are known at the seal design stage.

Table 8: Characteristics of sealing chip conforming to TNZ M/6:2002

TNZ M6:2002 Variable		Chip Size (mm)	Median Surface Profile Values			
Grade	ALD(mm)		Rsk	delq	Rvm(m)	Combined contribution to MSSC from Equation 2
2	10.75	19	0.00	0.75	-0.0037	-0.056
3	8.75	16	-0.28	0.80	-0.0039	-0.034
4	6.75	12	-0.23	0.71	-0.0034	-0.032
5	5.00	9	-0.09	0.63	-0.0027	-0.021

A feature of equation 6 is that the PSV and CHCV constants are very similar to that of equation 2 and so MSSC sensitivity to these two critical variables is maintained.

Both equations 2 and 6 indicate a linear reduction in skid resistance with increasing cumulative HCV passes. Empirical observations confirm that the polishing action of accumulated traffic does indeed cause skid resistance to decay from an initial value (Dringer and Barros, 1990). However, the rate of skid resistance loss progressively diminishes rather than being constant as indicated by equations 2 and 6, and eventually stabilizes at a level commonly referred to as the equilibrium state of polish. The typical drop between the initial and equilibrium values of skid resistance is about 40% (Kokkalis, 1998). Therefore, deteriorating skid resistance with cumulative polishing over time will be better modelled by an exponential decay than a linear decay. As a consequence, the regression analysis employed to derive equation 6 was repeated with a negative exponential transformation applied to the CHCV values. The resulting model is given by equation 7 and the associated statistics of the model constant estimates and goodness of fit tabulated in Table 9 for direct comparison with Table 6.

$$MSSC_{av} = 0.0013 \times PSV + 0.10 \times e^{-CHCV} - 0.007 \times ALD + 0.44 \qquad ...(7)$$

where:

$MSSC_{av}$ = average MSSC derived from 1998, 1999, 2000, and 2001 surveys
PSV = polished stone value
CHCV = cumulative heavy commercial vehicle traffic per lane in millions
= commercial vehicle traffic > 3.5 tonnes /lane/day × surface age (years) × operational days per year (=300/10^6)
= 0.0003 × CVD × AGE
ALD = the average least dimension of the sealing chip (mm)

The distribution of the differences between observed average MSSC values and those predicted by equation 7 for the 47 test sites are as follows:

- the median difference is 0
- the range is –0.08 to 0.09
- 31 out of the 47 test sites (or 66%) have an absolute difference of 0.04 or less.

Both the model statistics and distribution of differences are a marginal improvement over those for equation 6. More importantly, equation 7 provides a decay in skid resistance that is equivalent to equation 6 over the analysis range of cumulative HCV passes (CHCV), while maintaining the same sensitivities to PSV and ALD. However, it avoids the anomaly of MSSC values decaying to unrealistically low levels should extrapolation to high CHCV values be required, as would be the case for major metropolitan road networks.

For all these reasons, equation 7 is preferable to equation 6 for evaluating the expected in-field skid resistance performance of different chipseal surface designs.

Table 9: Model statistics for Equation 7

Model Component	Model Coefficients		
	Value	**Standard Error**	**p-level**
PSV	0.0013	0.001	0.312
e^{-CHCV}	0.097	0.030	0.002
ALD	-0.007	0.003	0.03
Constant	0.44	0.08	3.8E-06
Overall Model Statistics			
Standard Error of Estimation:	0.041		
r^2:	0.35		
No of Observations:	47		

4.2 SENSITIVITY ANALYSIS

The relative sensitivity of MSSC to the three input variables to equation 7 (i.e. PSV, CHCV and ALD) was established by the following two-step process.

Step 1: Median values for the three input variables were derived from the 4 test sites and used to calculate a reference MSSC value from equation 7.

Step2: The median value of each of the three input variables was varied by ± 20% and computing the corresponding percentage change in the reference MSSC value, which was derived from the unaltered median values. The results of this analysis are summarised in Table 10 below.

With reference to Table 10, the predicted MSSC is influenced most by measurement uncertainty in the PSV values, followed by ALD and then CHCV. However, as a 20% uncertainty in any one of the three input variables results in changes of less than 3% in the calculated MSSC, the model is very tolerant to any imprecision in the input variables and results from the model constant term of 0.44 being dominant.

Table 10: Sensitivity of predicted MSSC to a 20% uncertainty in each of the model inputs

Input Variable	Median Value	% Change in Reference MSSC Value of 0.52	
		-20% Uncertainty	**+20% Uncertainty**
PSV	57	-2.8	2.8
CHCV	0.29	0.84	-0.79
ALD(mm)	8.75	2.3	-2.3

4.3 RELATIVE CONTRIBUTION OF KEY VARIABLES TO MSSC

The relative contribution of PSV, CHCV and ALD to MSSC was investigated by varying their value over the ranges observed for the 47 tests sites. Table 11 tabulates the associated change in MSSC level as calculated from equation 7.

This analysis suggests that the expected range of MSSC on straight, chipseal sections of state highway should be limited to between 0.43 (heavily trafficked roads) and 0.58 (lightly trafficked roads). The main reason for differences in MSSC values will, not unexpectedly, be cumulative HCV traffic rather than PSV or size of the sealing chip.

Table 11: Relative contribution of key variables to MSSC as calculated from Equation 7

Model Variable	Measured Range		Contribution to MSSC		ΔMSSC
	Min	Max	Min	Max	
PSV	43	65	0.056	0.085	0.03
CHCV (10^6 HCV passes)	0.015	1.960	0.014	0.096	0.08
ALD (mm)	5	10.75	-0.075	-0.035	0.04
		Sum Total	-0.005	0.146	

With reference to Table 11, the maximum contribution of the aggregate variables, PSV and ALD to MSSC is 0.05 and amounts to about 11% of the model constant of 0.44. This result suggests that the scope for seal designers to improve the skid resistance performance of straight road sections through aggregate selection is very limited if New Zealand sourced natural aggregate conforming to TNZ M6:2002 requirements is to be used.

4.4 COMPARISON OF MSSC PREDICTIONS

Roe and Hartshorne (1998) undertook on behalf of the UK Highway Agency a similar study of in-service performance of country and trunk roads to reassess the relationship between polishing resistance (as measured by the PSV test) and achieved skid resistance (measured as MSSC). The resulting model for straight and level road sections, derived from an analysis of 4073 road sections, was:

$$MSSC = 3.90\times10^{-3}PSV - 1.95\times10^{-2}\ln(CVD)+0.377 \quad (r^2=0.13) \quad \ldots(8)$$

The dominating component of the Roe and Hartshorne model is the constant term, which is consistent with the New Zealand study. Also, it can be seen from the r^2 value that about 13% of the total variation can be explained by PSV and traffic, again mirroring the New Zealand study.

Figure 6 shows how the predicted value of MSSC using equation 7 compares with Szatkowski and Hosking (equation 1) and Roe and Hartshorne (equation 8) for the average HCV exposure of two-lane rural state highways of 129 HCV/land/day and an aggregate PSV of 55, corresponding to the representative value for commonly used Greywacke aggregate.

With reference to Figure 8, small sized aggregate (Grade 5 i.e. ALD=5mm) is predicted by equation 7 to provide superior skid resistance performance to large sized aggregate (Grade 2 i.e. ALD=10.75mm) over the entire 7 to 8 year service life of the chipseal surface. In addition, skid resistance is predicted to reduce by 0.03 MSSC over the service life.

Relative to equation 7, the Szatkwoski and Hosking relationship over-estimates and the Roe and Hartshorne relationship under-estimates the end of service life skid resistance.

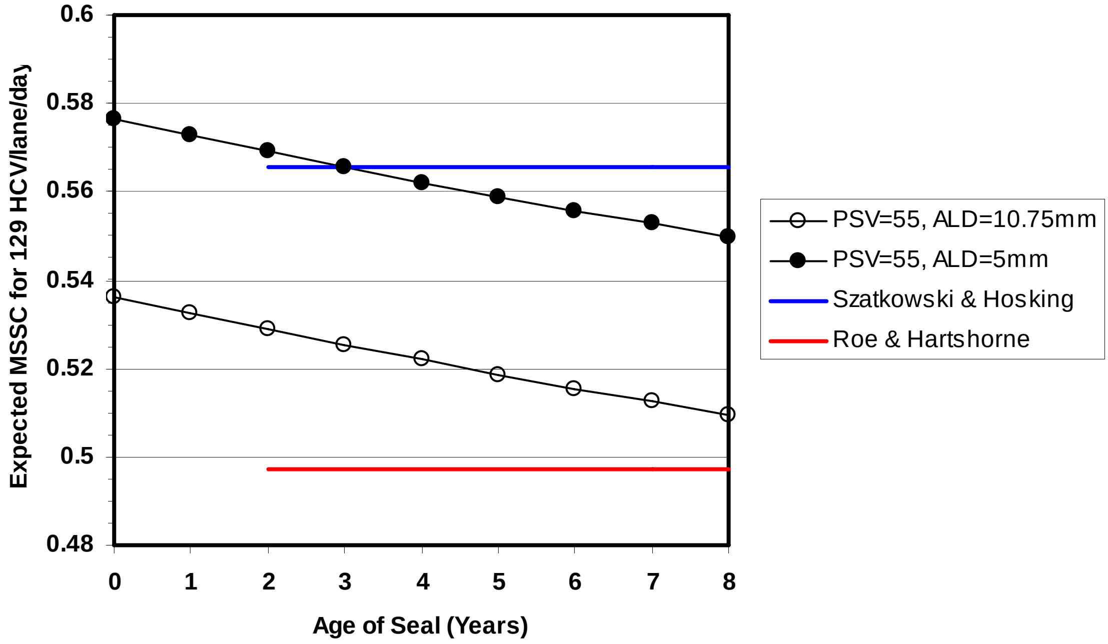

Figure 6: Comparative plot of predicted in-service MSSC for representative section of rural state highway

5. RESEARCH NEEDS

The following additional research is required to check and refine the models presented for predicting the skid resistance performance of chipseal surfaces.

5.1 CONTRIBUTION OF AGGREGATE MICROTEXTURE

Microtexture is the microscopic surface roughness of the roading aggregates and is mainly a function of aggregate particle mineralogy. Microtexture irregularities typically range from 0.005 mm to 0.3 mm. When microtexture comes into contact with the tyre, an adhesive friction force (commonly referred to as grip) is generated. Under wet conditions, microtexture penetrates the thin water film that remains between the tyre and the road to establish direct contact.

The level of microtexture deteriorates with cumulative traffic polishing. In deriving the skid resistance models presented in this section, it has been assumed that aggregate PSV is related to the terminal aggregate microtexture reached in the field. However, only 5 of the 47 test sites had been exposed to 1million or greater HCV passes and so judged to have reached equilibrium skid resistance value, corresponding to the situation of terminal microtexture. No direct correlation between aggregate PSV and in the field skid resistance could be established for these 5 sites, suggesting that the polishing action of HCV traffic may be different to the polishing action of the PSV test. Furthermore, Kokkalis (1998) has shown that the depth of microtexture is the strongest contributor to the variation of skid resistance. Use of PSV instead of actual microtexture depth may, therefore, be the reason for the low correlation found between PSV and MSSC in the present study.

Further investigation is warranted to establish if:

- Improved model fits will result through use of in the field measurements of aggregate microtexture depth made with a stylus profiler instead of aggregate PSV.
- Aggregate microtexture depth can be used for determining equivalency between the cumulative polishing action of traffic and accelerated polishing action of the PSV tests. This will assist in the development of microtexture decay models with respect to cumulative HCV passes for incorporation in skid resistance models from laboratory-measured microtexture decay rates derived from a specified number of hours of PSV test polishing.

5.2 INTER-RELATIONSHIP BETWEEN MICROTEXTURE AND MACROTEXTURE

Moore (1975) suggests that the effectiveness of the microtexture in promoting skid resistance is related in some manner to the sharpness of the aggregate tip. He theorises that the peak pressure on any aggregate increases rapidly and non-linearly with mean slope beyond a point where the elastic pressure is too great to permit the existence of a water film. At this point no microtexture is needed as the high-localized pressure developed between the tyre tread and aggregate ensures physical contact even under the most severe wetted conditions. Conversely, if the tip of the aggregate is predominately rounded, it is necessary to have harsh microtexture to penetrate the thin water film between the tyre and the road to establish adhesion. Therefore, it is hypothesised that the influence of microtexture on skid resistance will be greater for the following situations:

- alluvial aggregates with uncrushed faces as these are generally characterised by a rounded shape thereby minimising the hysteretic component of skid resistance;
- aggregates that are susceptible to wear since tips of such aggregates will be predominately rounded as a consequence of the wearing action of traffic; and
- aggregates which predominately imbed themselves in a seal so that they lie down on their average greatest dimension (AGD), such as occurs with bituminous mixes, resulting in less slope/sharpness than if they lie down on their average least dimension (ALD).

A preliminary investigation of the data for the 47 sites, of which 24 had chipseal surfaces constructed from alluvial aggregates and 23 had surfaces constructed from aggregates quarried from hard rock, supported this hypothesis. This investigation identified that MSSC sensitivity to PSV was significantly higher for alluvial aggregates (0.008 MSSC/PSV) than for hard rock aggregates (0.0002 MSSC/PSV). It is, therefore, apparent that the issue of microtexture/macrotexture interdependency needs further investigation.

5.3 EFFECT OF LARGE TYRE FORCES

The effect of traffic is to wear and polish the aggregate. The cause of this action is the horizontal forces exerted by the vehicle tyre onto the road surface. The higher the horizontal force, the greater the wear and polishing action. This explains why greater reductions in skid resistance values are reported on grades and bends and at intersections where the horizontal force greatly increases due to traction, cornering and braking forces.

The regression-based models for predicting skid resistance have been derived for straight sections of state highway and so pertain to the free rolling situation where horizontal tyre forces will be at their lowest. Therefore, additional research is required to establish whether or not the rate of skid resistance decay with cumulative HCV passes increases and/or the equilibrium value of skid resistance reduces as a function of increasing horizontal tyre forces. This can be best accomplished by repeating the regression analysis detailed above for a situation where horizontal forces are expected to be large, say corners with a horizontal radius confined to between 100 m and 200 m.

6. CONCLUDING REMARKS

The principal findings of this study to quantify the influence of road surface profile on in-service skid resistance of straight sections of chipseal surfaced state highways are as follows.

1. The critical surface texture variable is the mean spacing between tips of aggregates, the smaller the spacing the higher the tyre-road skid resistance.
2. The equilibrium state of polish was found to be a function of the number of heavy commercial vehicle (HCV) passes, the threshold value being 1 million HCV passes. It is therefore unlikely that surfaces on straight sections of state highway will reach their equilibrium state of polish at the end of their service life unless they carry more than 500 HCV/lane/day.
3. More reliable predictions of in-service skid resistance will result if texture parameters have been incorporated in the predictive model to account for tyre rubber hysteresis i.e. energy losses that occur when tyre tread rubber is subjected to deformation by road surface projections.

7. REFERENCES

Catt, C.A. 1983. An alternative view of TRRL's research into skidding resistance. *Asphalt Technology No 33, pp 7-11,* Journal of the Institute of Asphalt Technology, Dorking, England.

Cenek, P.D., Brown, D.N., Carpenter, P., Jamieson, N.J. and McLarin, M.W. 1997. Replication of VTI's stationary laser profilometer for measuring road surface profiles. *Transfund New Zealand Research Report No.84.*Wellington, NZ.

Cenek, P.D., Carpenter, P., Jamieson, N.J. and Stewart, P.F. 2004. Prediction of skid resistance performance of chipseal roads in New Zealand. *Transfund New Zealand Research Report No.256.*Wellington, NZ.

Cenek, P.D., Fong, S., Stevenson, H.G., Brown, D.N., and Stewart, P.F. 1998. Skid resistance: the influence of alluvial aggregate size and shape. *Transfund New Zealand Research Report No.119.*Wellington, NZ.

Diringer, K.T and Barros, R.T. 1990. Predicting the skid resistance of bitumen pavements through accelerated laboratory testing of aggregates. *Surface Characteristics of Roadways: International Research and Technologies, ASTM STP 1031, W.E. Meyer and J.Reichert, Ed, pp61-76,* American Society for Testing and Materials, Philadelphia, USA.

Heaton, B.S., Henry, J.J., and Wambold, J.,C. 1990. Texture measuring equipment versus skid testing equipment*. Proceedings 15th ARRB Conference, Part 2, Darwin Northern Territory, pp53-64*, Australian Road Research Board.

Kokkalis, A.G., 1998. Prediction of skid resistance from texture measurements. *Transport: Part of the Proceedings of the Institution of Civil Engineers*, *Vol. 129, Paper 11616, pp 85-93,* published by Thomas Telford, London, UK.

Moore, D.F., 1975. The friction of pneumatic tyres. *Elsevier Scientific Publishing Company*, Amsterdam, The Netherlands.

PIARC. 1995.*International PIARC experiment to compare and harmonize texture and skid resistance measurements.* PIARC Technical Committee on Surface Characteristics C1 Publication 01.04.T, PIARC-World Road Association, Paris, France.

Szatkowski, W.S. and Hosking, J.R. 1972. The effect of traffic and aggregate resistance to skidding of bituminous surfacings. *TRRL Report LR 504*. Transport and Road Research Laboratory, Crowthorne, England.

Transit New Zealand. 1993. *Bituminous sealing manual*. 2nd Edition. Transit New Zealand, Wellington, NZ.

Transit New Zealand. 2002. *Specification for sealing chip, TNZ M6:2002***,** available as a PDF download from http://www.transit.govt.nz/technical_information/index.jsp.

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