SELECTION OF COST EFFECTIVE SKID RESISTANCE RESTORATION TREATMENTS

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P.D. CENEK, N.J. JAMIESON, N.J. LOCKE and P.F. STEWART
Opus Central Laboratories, Lower Hutt, New Zealand

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P O Box 2331, Lambton Quay, Wellington New Zealand
Telephone (04) 473-0220; Facsimile (04) 499-0733

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AN IMPORTANT NOTE FOR THE READER

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EXECUTIVE SUMMARY

An engineer or contractor must be able to have at their disposal treatments for restoring surfaces where the skid resistance is deficient, either locally ("black spots") or systematically over a network. With this in mind, Transit New Zealand Research Project PR3-0053, titled "Restoration of Skid Resistance on New Zealand Roads" was undertaken to identify, through a literature survey, commonly used treatments for restoration of skid resistance properties of bitumen based road surfaces. The suitability of those treatments for New Zealand conditions was additionally assessed in consultation with a group of New Zealand practitioners. Although this research provided an indication of performance, estimated life, and costs of the various techniques, no economic evaluation was performed to enable ranking of the treatments. A programme of research was therefore undertaken to address knowledge gaps preventing the application of standard economic decision making to the selection of the most economically advantageous skid resistance treatment for a specific site category. These knowledge gaps pertained to quantifying benefits. Accordingly, the principal research elements comprised:

(1) Establishing the level of improvement in skid resistance that generally can be expected for the more commonly used skid resistance restoration treatments together with the typical durability of the restoration as a function of vehicle passes. This involved reviewing existing literature and limited field measurements performed with Opus Central Laboratories' GripTester, which is a trailer based fixed slip skid tester.

(2) Analysing tables of wet road skidding crash rate corresponding to intervals of 0.05 mean summer SCRIM coefficient (MSSC) for 15 different road categories to determine whether or not statistically significant relationships between skid resistance and wet skidding crashes could be determined. These tables had been previously prepared by WDM UK Ltd on behalf of Transit New Zealand using data from the 1995 SCRIM survey of selected sections of the state highway network and personal injury crash data supplied by the Land Transport Safety Authority (LTSA) for the five year period 1990 to 1994.

The following conclusions and associated recommendations have been derived from the resulting research findings.

Effectiveness of Skid Resistance Restoration Treatments

A skid resistance deficient road surface can be corrected by applying a new surface or by modifying the existing surface. The most widespread corrective measure in New Zealand is the application of a new surface constructed from natural aggregates. However, a number of methods for improving skid resistance through removal of surface material are available in New Zealand for spot and area treatments. These include grooving, milling, bush hammering, and high pressure waterblasting. Limited before and after skid resistance measurements showed that, of these methods, high pressure waterblasting holds considerable promise for temporarily increasing the skid resistance of chipseal surfaces by 0.05 to 0.1 MSSC.

Recommendations

(a) In order to allow the selection of maintenance and restoration procedures for prolonging and restoring skid resistance of road surfaces that are the most effective under different environmental and traffic conditions, a monitoring programme involving skid resistance and texture depth measurements at regular intervals is recommended to establish:

- the rate at which newly laid bituminous and chipseal surfaces reach a constant value of skid resistance as a function of traffic composition, traffic volume, aggregate type, aggregate size (in case of chipseals only), and road geometry;
- the long term effectiveness of overlays constructed from calcined bauxite and steel slag;
- the long term effectiveness of existing road surfaces modified by material removed to restore microtexture and macrotexture.

(b) There is a distinct seasonal variation to skid resistance levels during the course of a year in some regions of New Zealand. The variation is due mainly to seasonal changes in the microtexture of the road surface. In the summer months, particularly during dry spells, the detritus is very fine and acts as a polishing agent. After prolonged periods of rainfall, the detritus becomes coarser and then has an abrasive rather than a polishing action resulting in the road surface fully or partially recovering its skid resistance. Minimum values therefore generally occur during summer and early autumn. Given that the magnitude of the seasonal variation can be as large as 0.15 MSSC, a study should be commissioned to investigate whether or not periodic waterblasting of road surfaces during summer months, particularly at high friction demand sites, will be effective in reducing or eliminating the seasonal variation observed in the terminal skid resistance.

Relationship Between Skid Resistance and Crashes

Statistically significant relationships between wet road skidding crash rate and skid resistance were able to be derived for three important site categories: junctions, traffic light approach, and curves and gradients. The resulting exponential fit equations are as follows:

Junctions:
Wet skidding crash rate (10^8 vehicle-km) $= 376.5\ e^{-5.9\ \mathrm{MSSC}}$ $(R^2=0.84)$

Traffic Light Approach:
Wet skidding crash rate (10^8 vehicle-km) $= 990.0\ e^{-6.2\ \mathrm{MSSC}}$ $(R^2=0.84)$

Curves and Gradients:
Wet skidding crash rate (10^8 vehicle-km) $= 3915.5\ e^{-9.3\ \mathrm{MSSC}}$ $R^2=0.84)$

These equations indicate that increasing the MSSC from 0.45 to 0.55 would reduce the number of wet road skidding crashes by 45% at junctions, 47% at traffic light approaches, and 61% at curves and gradients.

Recommendation

(c) The skid resistance-crash rate relationships that have been derived are associative and not necessarily functional. They therefore need to be validated by performing long term before and after studies on crash rates at sites where skid resistance has been changed. Such a study should make use of the Crash Information Monitoring System administered by LTSA and include additional site categories.

Role of Skid Resistance and Texture Depth in Pavement Management

When selecting a treatment for restoring the skid resistance or texture of a road surface, due consideration should be given to the cost, the effect on traffic while the work is in progress, and the long term effectiveness of the treatment so that the most effective use can be made of the maintenance funds that are available. A procedure, based on present value analysis of crash savings and treatment costs, has therefore been proposed for economically appraising candidate road surface restoration treatments. This procedure is consistent with concepts presented in Transfund New Zealand's Project Evaluation Manual and so utilises incremental benefit-cost ratio analysis to arrive at the optimum economic solution.

Application of the procedure yielded results which are consistent with existing maintenance practice, in that application of a new surface is generally more cost effective than modifying the existing surface. This result is attributed to the high cost of treatments involving the removal of surface material relative to chipsealing. At sites with a high rate of wet skidding crashes, expensive treatments using high PSV (greater than 60) natural and artificial aggregates appear to be a very cost effective crash prevention measure with benefit-cost ratios calculated to be in the thousands.

Recommendations

(d) Transit New Zealand texture depth requirements were developed for rural State Highways. In this context, they are substantiated by overseas research findings which indicate that for speed limits greater than 70 km/h, crash rates begin to increase when sand circle derived texture depths are less than about 0.9 to 1.0 mm. However, no appropriate research has been identified to justify the adoption of the existing requirement for minimum texture depths of 0.6 mm (bituminous mix surfaces) and 0.75 mm (chipseal surfaces) for urban (less than 70 km/h) areas. In the opinion of the authors, these texture depth requirements are overly restrictive as aquaplaning is unlikely. Therefore, they may be precluding the use of fine textured surfaces which are known to display good skid resistance characteristics, such as slurry seals and asphaltic concrete, for high friction demand urban situations like approaches to pedestrian crossings, intersections, traffic light approaches, etc. For this reason, it is strongly recommended that research be directed at establishing appropriate texture depth requirements for urban areas.

(e) Once the expected life and crash rate relationships have been validated, the proposed economic appraisal procedure should be incorporated in Transit New Zealand's surfacing selection model. This model has been developed around an editable Lotus 1-2-3 spreadsheet which performs a total cost analysis of road surface types commonly employed in New Zealand. The user costs considered include fuel, tyres, road roughness, traffic delays caused by construction, and noise. As sensitivity analysis of surface life spans, discount rates, costs, etc can be easily performed by changing tabulated input values, this model, once modified, can then be used to automatically identify the optimum economic solution for restoring the skid resistance or texture of a deficient road surface.

ABSTRACT

This report presents a suggested procedure for selecting the economically optimum treatment for restoring the skid resistance of an existing road surface when it is found to be deficient.

A table of attributes for 15 skid resistance restoration treatments identified as being suitable for application to New Zealand road surfaces

The economic appraisal procedure showed that application of skid resistance restoration treatments can substantially reduce crashes yielding benefit-cost ratios in the thousands. In general, applying a new surface was found to be more cost effective than treatments involving the modification of an existing surface such as grooving, bush hammering and waterblasting. However, high pressure (>1000 psi) waterblasting appears to hold considerable promise for temporarily increasing skid resistance by 0.05 to 0.1 MSSC units.

1. INTRODUCTION

1.1 Overview

The social desirability of improving skid resistance in order to reduce crash rates on New Zealand roads is unquestionable. However, because substantial expenditures can be involved, economic justification must be considered. In the present climate of constrained central and local government spending, it is essential that the most effective use is made of the funds that are available for road improvements and maintenance. At a primary level, any additional expenditure on improving the skid resistance of roads is justified in economic terms only if it can be demonstrated that the benefits outweigh the costs resulting in a positive net return on the investment. At a secondary level it can only be justified if the rate of return produced is at least equal to those of other competing safety measures. The purpose of this report is therefore to provide guidance on how to identify cost effective skid resistance treatments for a particular site.

1.2 Research Need

An engineer or contractor must be able to have at their disposal processes for restoring surfaces where the skid resistance is deficient, either locally ("black spots") or systematically. With this in mind, a Transit New Zealand research project (PR3-0053) was undertaken to identify, through a literature survey, commonly used treatments for restoration of skid resistance properties of bitumen based road surfaces (Dravitzki 1997). The suitability of these treatments for New Zealand conditions was additionally assessed in consultation with a group of New Zealand practitioners. Although this research provided an indication of performance, estimated life, and costs for the various treatments, no economic assessment was performed to enable ranking of the treatments when applied to a specific situation.

In making an economic assessment of a skid resistance restoration treatment, it is necessary to estimate both costs and benefits in each year throughout the life of the treatment. The principal benefit arising from an improvement in skid resistance is a reduction in the number of crashes. A monetary value can be readily assigned to each crash prevented according to analysis procedures given in Appendix A6 of Transfund New Zealand's Project Evaluation Manual (1997). However, there is first a need to determine the relationship between skid resistance and wet pavement crash occurrences.

The research presented in this report is concerned with quantifying benefits by:

(1) establishing through literature review and limited measurements the level of improvement in skid resistance that can be generally expected for the more commonly used treatments, thereby building on the earlier work of Dravitzki (1997), and

(2) deriving relationships between skid resistance and wet pavement crashes that are suitable for economic comparisons.

Remaining impediments to the use of standard economic decision making to choose between competing skid resistance restoration treatments therefore are addressed by this research.

1.3 Objectives

The programme of research had two main objectives:

(1) To establish the effectiveness of skid resistance restoration treatments in terms of level of improvement and durability.

(2) To review local and overseas studies relating skid resistance to crash occurrence and generate relationships in a format suitable for use in economic comparisons.

The ultimate goal is the development of an economics based procedure for choosing between competing treatments for restoring pavement skid resistance wherever it is found to be deficient. If this goal is achieved, more effective use of scarce roading materials and improved efficiency of maintenance expenditure decisions will result.

1.4 Scope of the Report

The report provides a summary of the information required to undertake an economic comparison of the various treatments available for restoring New Zealand bituminous based road surfaces found to be at or below the investigatory wet skid resistance level appropriate for the site category. Section 2 expands on previous research by quantifying expected changes in skid resistance levels brought about by restoration treatments already in use in New Zealand or previously identified as having potential application. To facilitate ready comparison between the treatments, two detailed attribute summary tables covering cost of application, expected life, and effect on surface characteristics are provided, one for treatments involving removal of surface material and one for treatments involving the addition of surface material. In Section 3 regression models derived from New Zealand specific data relating wet road skidding rates to level of skid resistance are presented for three site categories: junctions, traffic light approach, and curves and gradients. The limitations of the models and the relationship between surface texture depth and crash rate are also considered. Section 4 summarises the procedural steps required to perform an economic comparison of candidate skid resistance treatments based on a net present value (NPV) analysis. Two example applications drawn from practical experience, a bridge approach scheduled for realignment and an urban motorway black spot, are provided to illustrate the possible impact of economics based decision making on current skid resistance related maintenance practices. Finally, conclusions and recommendations derived from the research are given in Section 5.

2. COMPARATIVE PERFORMANCE OF SKID RESISTANCE RESTORATION TREATMENTS

The attributes of a skid resistance treatment which will dictate the outcome of an economic comparison are:

- expected level of improvement in skid resistance
- effective life
- cost of application.

Therefore the results of an attempt to quantify these attributes for restoration treatments known to be already in use in New Zealand or previously identified as being potential application are summarised below.

2.1 Skid Resistance Restoration Treatments Selected

As part of Transit New Zealand Research Project PR3-0053, 18 types of skid resistance restoration treatments were identified from a review of technical literature and consultation with the roading industry as being practical for New Zealand. These treatments were reassessed in the context of the current research goal, resulting in two (acid wash and sandblasting) being discarded on the grounds of environmental reasons and two similar treatments involving binder enhancement being combined into one. The 15 treatments which remained can be conveniently classed into two groups: those which involve the removal of surface material and those which involve the addition of surface material. The second group can be further subdivided according to the following practices utilised in the construction of bituminous and chipseal surfaces:

- extra chip with little or no extra binder
- extra chip with extra binder layer
- addition of a bituminous layer.

The 15 skid resistance restoration treatments selected for comparison are listed in Table 1. A brief description of each treatment is provided in Appendix 1 for ready reference. More comprehensive overviews of these treatments are provided by Page (1977) and Kumar and Holtrop (1991).

2.2 GripTester Measurements

For a number of treatments listed in Table 1, little or no relevant information was available to quantify their ability to restore skid resistance properties of bituminous or chipseal pavements with respect to level of wet skid resistance provided and its drop-off with speed. Data available from commercial surveys performed with Opus Central Laboratories' GripTester supplemented with specific GripTester field measurements were therefore utilised to address the identified knowledge gaps where possible.

Table 1. Treatments selected as suitable for restoration of skid resistance properties of New Zealand road surfaces.

Group 1: Treatments which involve removal of surface material

- Grooving by saw cutting
- Grooving by flails
- Milling by Rotomill
- Burning
- Bush hammering
- High pressure waterblasting
- Captive shot blasting

Group 2: Treatments which involve addition of surface material

Sub-Group 1 : Extra chip with little or no extra binder

- Solvent softening and chip
- Hot chip – not coated
- Hot chip – extra binder

Sub-Group 2 : Extra chip with extra binder

- Chipseals
- Proprietary binder with chip

Sub-Group 3 : Bituminous layers

- Slurry seals
- Thin asphaltic concrete layer
- Open graded friction course

The GripTester is a small three-wheeled trailer based device which provides continuous output of the coefficient of friction between the road surface and the measuring wheel which is geared to slip at a fixed proportion of the tow speed. Water is applied under this measuring wheel at a nominated rate. For road surveys, a water film depth of either 0.25 mm or 0.5 mm is usually employed. The GripTester has undergone comprehensive evaluation in Europe in terms of its precision and correlation with other commonly used friction testers such as SCRIM and the British Pendulum Tester. Procedures for converting the GripTester measure of friction, the Grip Number, to equivalent side force coefficient (SFC) at 50 km/h (SCRIM) or British Pendulum Number (BPN) are given in Appendix 2.

Grip Number data was obtained for before and after application of the following skid resistance restoration treatments involving material removal:

- grooving by saw cutting (transverse only),
- milling by Rotomill, and
- high pressure waterblasting.

Given the unavailability of commercial waterblasting equipment specially designed for cleaning road surfaces, a hand held 1500 psi waterblaster was hired and used to clean two road sections, one having a smooth textured asphaltic concrete surface and the other a coarse textured chipseal surface.

For skid resistance restoration treatments involving addition of material, "before application" Grip Number data was not considered appropriate as it would be influenced by the type and condition of the road surface about to be resealed. Grip Number data in this case was confined to "after application" of the treatment to allow the "as new" skid resistance level to be quantified. The treatments investigated in this manner were:

- chipsealing (grades 3 to 5, i.e. moderate macrotexture to fine macrotexture),
- proprietary binder and chip (calcined bauxite),
- slurry seals, and
- asphaltic concrete.

Wherever possible, Grip Number data was obtained for two different tow speeds to allow the variation of provided skid resistance with speed to be assessed. The upper tow speed in such cases typically corresponded to the speed restriction applying to the surveyed section.

The results of this exercise are summarised in Table 2. Important points to note are as follows:

- Surfaces with coarse macrotexture display less skid resistance drop-off with speed than those with fine macrotexture.
- Sealing chips, if coated in bitumen, will typically result in lower "as new" skid resistance levels than uncoated chips, though this is only a temporary effect until both traffic and weather wear away the bitumen to expose the microtexture of the aggregate.
- The skid resistance characteristics of surfaces constructed from natural aggregates is, to a large extent, dictated by the ability of the aggregate to resist the polish-wear action of traffic rather than the type of surface.
- Removal of contaminants such as oil and dust by waterblasting appears very effective in improving the skid resistance of road surfaces, though the durability of this treatment has yet to be established.

Table 2. Observed performance of selected treatments.

Treatment type	**Road surface**	**Grip Number [GN(s) where s = tow speed in km/h]**			
		Lower tow speed		**Upper tow speed**	
		Before treatment	**After treatment**	**Before treatment**	**After treatment**
Removal of Material					
Transverse grooving	Asphaltic concrete	GN(65)=0.66*	GN(65)=0.73	-	GN(95)=0.63
Milling by Rotomill	Friction course	-	GN(40)=0.71	GN(80)=0.56	GN(80)=0.67
High pressure waterblasting	(1) Asphaltic concrete	GN(20)=0.68	GN(20)=0.75	GN(40)=0.65	GN(40)=0.68
	(2) Chipseal (grade 3)	GN(25)=0.67	GN(25)=0.80	GN(50)=0.62	GN(50)=0.74
Addition of Material					
Chipseals	Grade 2	-	GN(40)=0.69	-	GN(100)=0.63
	Grade 5	-	GN(40)=0.72	-	GN(100)=0.63
Proprietary binder and chip	Calcined bauxite	-	-	-	GN(50)=0.95
Slurry seal		-	GN(25)=0.90	-	GN(50)=0.79
Asphaltic concrete		-	GN(25)=0.95	-	GN(50)=0.81

* Surface was just laid and so aggregates still coated with bitumen.

2.3 Attribute Summary of Skid Resistance Restoration Treatments

The need for restoring the skid resistance properties of a bituminous based road surface can be caused by inadequate or non-existent macrotexture, or polished microtexture, or a combination of both. Macrotexture is provided by the texture depth of the road surface. It facilitates the drainage of water from the tyre footprint area. It also generates the hysteresis component of the friction force which results from deformation of the tyre tread. Macrotexture is affected by chip embedment, flushing and aggregate degradation. Microtexture is provided by irregularities on the surface of the road aggregate. It penetrates the thin water film that remains between the tyre and road so direct contact can be established. It also provides the adhesion component of the friction force when the tyre comes into contact with the road surface. Microtexture can be affected by abrasion, contamination, polishing and weathering.

Microtexture controls the level of skid resistance of a wet road surface at lower traffic speeds (less than 70 km/h) since there is sufficient time for the water trapped under the tyre to escape. However, as the traffic speeds increase, the more difficult it becomes for the water to escape because the time available reduces. The less it does so, the more rapidly the skid resistance decreases. Ultimately the tyre can be riding on a layer of water. This condition is known as aquaplaning and is usually expected to occur at speeds over 100 km/h on water films of at least 3 mm (Donald *et al* 1996). The rate at which skid resistance decreases is a function of the rate at which water can be displaced from the road surface. On conventional road surfaces this rate is a function of the macrotexture. However, for porous surfaces such as friction course, the rate is related to the high void content which provides a direct drainage path for the water.

Therefore when considering the attributes of the 15 selected skid resistance restoration treatments, special emphasis was placed on establishing their effect on macrotexture and microtexture along with application cost, expected life, and "after application" skid resistance level. These attributes plus others have been tabulated. The attributes of treatments which involve removal of surface material are summarised in Table 3, whereas the attributes of treatments which involve addition of surface material are summarised in Table 4. Both these tables follow the same format. The various treatments head the columns, whereas the attributes considered to be important in selecting candidate treatments head the rows at the left of the tables. An explanation of each row follows to aid interpretation of the tables' contents.

Suitable Surfaces

Those road and runway surfaces on which it is considered appropriate to apply the treatment. For example, grooving to improve macrotexture is only feasible for concrete and asphaltic concrete surfaces.

Expected Life

The lifetime that is expected for a particular treatment corresponding to annual average daily traffic volume (AADT) categories as used in the RAMM database. For example, the beneficial effect of burning off excess bitumen on chipseal surfaces is considered to last for about two years for low traffic volumes around 100 AADT, but reduces to one year or less for high traffic volumes of over 10,000 AADT.

Deterioration Mode

The most likely cause of the treatment losing its effectiveness over time. For example, road surface skid resistance restored by waterblasting will deteriorate with time due to road film buildup.

Reapplication

Whether or not a treatment can be reapplied to a surface previously restored with the same treatment. For example, grooving can be reapplied only if the second application is at right angles to the first. This scenario would result in longitudinal grooves being followed by transverse grooves or vice versa.

Skid Resistance

Refers to skid resistance levels obtained from measurements performed in New Zealand or overseas technical literature and converted to equivalent SCRIM side force coefficient (SFC) values at 50 km/h to enable direct comparison with Transit New Zealand's investigatory skid resistance levels. Two sub-headings are employed:

Av(erage) New Value/Av(erage) Change: For treatments involving the addition of new material, the skid resistance value given is representative of the new surface when just laid since it is not influenced by the previous surface history. However, for treatments where material is removed, there is a rejuvenation of either the macrotexture or microtexture of the existing surface, and so the effect on skid resistance can be best considered as a change in value which falls somewhere between the difference of the skid resistance of the surface when newly laid and in its present condition.

Measured Values: Actual measured skid resistance values at varying times after application of the treatment, thereby providing an indication of the likely terminal value.

Exp(ected) Time to Stabilise

After the application of a treatment, the skid resistance will reduce with time to a relatively stable value. This time will depend primarily on the treatment type and the amount of traffic.

Texture Progression

The variation in surface texture depth with time is assumed to follow the model proposed by Patrick and Cenek (N D Lea 1995) in which the rate of change in texture is taken to be a function of cumulative traffic and initial texture depth. Very little is known about the texture-time dependency of treatments involving the removal of surface material because of their limited application in New Zealand. Where available, representative texture values in terms of equivalent sand circle derived texture depth in millimetres have been provided.

Cost

Typical costs are given for small and large application areas in the Wellington region. A small application area is considered to cover a few, tens or hundreds of square metres. A large application area is considered to be of the order of several hundreds or thousands of square metres. The provided costs are indicative only and may vary considerably from region to region depending on the distance plant and materials have to be transported.

Effect

An indication whether the treatment affects macrotexture or microtexture, and to what extent, is provided. Possible damage that the treatment may cause is also highlighted. For example, waterblasting is likely to have a moderate effect on microtexture but may cause some loss of aggregate from the surface.

Speed

An indication that the treatment is suitable for high speed areas, low speed areas, or both is provided.

Comments

General comments about the treatment that may be of interest to practitioners.

NZ Experience

Previous known New Zealand applications of the treatment.

With reference to Tables 3 and 4, attention is drawn to the following:

- For chipseals, skid resistance increases with decreasing chip size. Therefore, in principle, the smallest size chip should be used wherever possible in order to achieve maximum skid resistance. However, there are a number of technical reasons why it is often not practicable to do so, principally related to the surface becoming bitumen enriched following successive application of the same sized sealing chip.

Table 3. Summary of attributes – treatments which involve removal of surface material.

Attribute	Treatment Type -	Removing Material					
	Grooving - Saw Cutting	Grooving - Flails	Milling by Rotomill	Burning	Bush Hammering	High Presure Waterblasting	Captive Shot Blasting
Suitable Surfaces	Concrete, AC	Concrete, AC	AC, Chipseals (with care)	Chipseals	AC, Concrete, Chipseals possibly	Most Surfaces, Chipseals with care	Concrete
Expected Life (in years for)							
<100 ADT	10 years (approx)	10 years (approx)	>4 years (approx)	2 years max	8-10 years (approx)	Not well known, 1 year est	5 years (est)
100-500 ADT							
500-2000 ADT	8 years (approx)	8 years (approx)	3-4 years (approx)		5 years (approx)		
2000-10000 ADT							
>10000 ADT	2-5 years (approx)	2-5 years (approx)	1-2 years (approx)	1 year max	3 years (approx)		3 years (est)
Deterioration Mode	Loss of Macrotexture, Old Age	Loss of Macrotexture	Loss of Macrotexture	Loss of Macrotexture (flushing), Loss of Microtexture (polishing)	Loss of Macrotexture (flushing), Loss of Microtexture (polishing)	Loss of Microtexture (Redeposition of road film) Wear (old age)	Loss of Microtexture, Wear (old age)
Reapplication	Once, at right angles to first treatment	Not known	Yes, where substrate is thick enough	Usually not advisable	Yes	Yes	Yes
Skid Resistance (SFC_{50})							
Av Change	0.05 - 0.07	0.12 - 0.15	0.15 - 0.25	0.20	Assume brings back to 80-90% of value when new	0.05 - 0.1	Assume brings back to 80-90% of value when new
Measured Values	0.70	–	0.75	0.70	–	–	–
Expected Time to Stabilise	Not known	Not known	Not known	Assume 1 year	Not known	Not known	Not known
Texture							
Variation with Time	Not well known	Not well known	As original surface	As original surface	As original surface	As original surface	As original surface
Representative Values after Treatment	Will depend on spacing and depth	Not well known	Not known	0.65mm for flushed Grade 4, 200% of value at time of application	120% of value at time of application	100% of value at time of application	120% of value at time of application
Cost							
Small Area	\$6-7/m^2	\$6-7/m^2	\$8/m^2	\$8/m^2	\$8/m^2 (est)	Unknown	\$8/m^2
Large Area	\$4-5/m^2	\$4-5/m^2	\$4-6/m^2	\$4.50/m^2	\$4-6/m^2 (est)	Unknown	\$4/m^2
Effect							
Texture Affected (degree)	Macro (high)	Macro (high) Micro (low)	Macro (high) Micro (low)	Macro (high) Micro (low)	Macro (high) Micro (high)	Micro (moderate)	Micro (high)
Possible Damage	Depth control needed	Depth control needed	Removal of material can affect drainage	Hardens bitumen and shortens life		Removes chip from chipseals	Small
Speed	High Speed Areas	High Speed Areas	All speeds	High speed mainly	All speeds	Low Speed Areas	Low Speed Areas
Comments	Treatment very suitable for concrete. Some history of AC use.	Similar to saw cutting, but gives some microtexture at the edges of grooves.	A proven technique in NZ for AC. Can be used with care on Chipseal.	Mainly a pre-treatment prior to sealing. Proven treatment, but risks pavement damage and has environmental effects.	An apparently very good treatment yet to be applied in NZ. Applicable to AC and Concrete, and possibly on sound chipseals.	Treatment removes road film which clogs microtexture, but probably does not counter stone polishing.	Trialled on concrete but not on bitumen /asphalt roads. Opinion is that it will not be useful on surfaces with visible bitumen.
NZ Experience	Auck, Wgtn, Hutt Rd	None in NZ	Auck, Ham, Wgtn City Councils	Two machines in NZ	None in NZ	None in NZ	Hand cart sized plant available in NZ.
KEY TO ABBREVIATIONS	AC = asphaltic concrete ADT = Average Daily Traffic (v/d) SFC_{50} = SCRIM Sideforce Coefficient @ 50km/h						

Table 4. Summary of attributes – treatments which involve addition of surface material.

Attribute	Treatment Type - Added Material - Set 1			Treatment Type - Added Material - Set 2		Treatment Type - Added Material - Set 3		
	Solvent Softening & Chip	Hot Chip - Not Coated	Hot Chip - Extra Binder	Chipseal	Proprietary - Binder and Chip	Slurry Seals	Thin AC	Open Graded FC
Suitable Surfaces	Chipseals	Chipseals	Chipseals	Most Surfaces	Most Surfaces	Most Surfaces	Most Surfaces	Most Surfaces
Expected Life (in years)				Gr 2, 3, 4, 5, 6				
<100 ADT	For early chipseal loss - normal chipseal life.	For early chipseal loss - normal chipseal life.	For early chipseal loss - normal chipseal life.	16, 14, 12, 8, 6	Life of underlying surface	8 years	12 years	12 years
100-500 ADT				14, 12, 10, 7, 5	Life of underlying surface	7 years	11 years	11 years
500-2000 ADT				12, 10, 8, 6, 4	Life of underlying surface	6 years	10 years	10 years
2000-10000 ADT	For flushing - 1 to 2 years	For flushing - 1 to 2 years	For flushing - 1 to 2 years	10, 9, 7, 5, 3	7 years (est)	5 years	9 years	9 years
>10000 ADT				9, 8, 6, 4, 2	7 years (est)	4 years	8 years	8 years
Deterioration Mode	Macrotexture loss (flushing), Microtexture loss(polishing), Wear (old age)	Macrotexture loss (flushing), Microtexture loss(polishing), Wear (old age)	Macrotexture loss (flushing), Microtexture loss(polishing), Wear (old age)	Macrotexture loss (flushing), Microtexture loss(polishing), Wear (old age)	Failure of underlying surface	Microtexture loss Wear (old age)	Microtexture loss, Wear (old age)	Microtexture loss (pores clogging), Fretting, Cracking
Reapplication	Not usually	Not usually	Not usually	Yes	Possible	Yes	Yes	Yes
Skid Resistance (SFC$_{50}$)								
Av New Value	0.80 - 0.85	0.80 - 0.85	0.80 - 0.85	0.80 - 0.85	0.95 - 1.00	0.85 - 0.90	0.70 - 0.75	0.65 - 0.70 (1 year old)
Measured Values	0.45 (Grade 2) 0.51 (Grade 5/6)	0.45 (Grade 2) 0.51 (Grade 5/6)	0.45 (Grade 2) 0.51 (Grade 5/6)	0.45 (Grade 2) 0.51 (Grade 5/6)	0.95 - 1.00 (No change in 1 year)	0.5 (1)	0.47 (1)	0.42 (1)
Exp Time to Stabilise	Heavy traffic - 3 years, Light traffic - 4 years	Heavy traffic - 3 years, Light traffic - 4 years	Heavy traffic - 3 years, Light traffic - 4 years	Heavy traffic - 3 years, Light traffic - 4 years	Heavy traffic - 3 years, Light traffic - 4 years	Heavy traffic - 3 years, Light traffic - 4 years	Heavy traffic - 3 years, Light traffic - 4 years	Heavy traffic - 3 years, Light traffic - 4 years
Proposed Measurements	None	None	None	None	None	Various (Levin, Taupo Airport, Belmont Rd) (done)	None	None
Texture (sandcircle)								
Variation with Time	T_D = ALD(0.7 - 0.08log10N)	T_D = ALD(0.7 - 0.08log10N)	T_D = ALD(0.7 - 0.08log10N)	T_D = ALD(0.7 - 0.08log10N)	2.1mm to 1.6mm in 1yr	T_D = 0.7(1 - 0.006log$_{10}$N)	T_D = 0.7(1 - 0.006log$_{10}$N)	Not well known
Representative Values	3.0 - 0.8mm (Gr 2 - Gr 6)	3.0 - 0.8mm (Gr 2 - Gr 6)	3.0 - 0.8mm (Gr 2 - Gr 6)	3.0 - 0.8mm (Gr 2 - Gr 6)	2.1mm to 1.6mm in 1yr	0.45 - 0.50mm	0.4 - 0.7mm	0.9 - 1.0 mm
Cost								
Small Area	\$5-6/m^2	\$2/m^2	\$2-6/m^2	\$4-5/m^2	\$45/m^2	\$6-8/m^2	\$12-15/m^2	\$10-12/m^2
Large Area	Normally used only on small areas	Normally used only on small areas	Normally used only on small areas	\$2-6/m^2 (higher cost is for modified binders)	Normally used only on small areas	\$3-5/m^2	\$8-10/m^2	\$7-9/m^2
Effect								
Texture Affected (degree)	Macro (high) Micro (high)	Macro (high) Micro (high)	Macro (high) Micro (high)	Macro (high) Micro (high)	Macro (high) Micro (high)	Macro (low/med) Micro (high)	Micro (high)	Macro (med) Micro (high)
Possible Damage	NA	NA	NA	NA	NA	NA	NA	NA
Speed	All speeds	All speeds	All speeds	All speeds	All speeds	All speeds	All speeds	All speeds
Comments	Commonly used treatment, usually associated with failure of new seals, but high risk of failure. Danger from flying chips and flammable solvent.	A commonly used treatment, usually associated with failure of new seals, but high risk of failure. Danger from flying chips and flammable solvent.	Risk of failure, but very effective if treatment holds	Very effective low cost treatment. Life is good provided stone with suitable PSV is used. Modified binders often used for high stress areas	Used only in specialised areas, e.g. high speed roundabouts. Disadvantages are cost and cure time. Not recommended on Friction Course	Rapid cure time. Product depends on skill and technology of supplier. Must be laid over a sound base. Typically below TNZ minimum texture depth requirement of 0.5mm.	Long lived treatment, which also smooths the road. Initial low skid, until surface bitumen is worn away. Typically below TNZ minimum texture depth requirement of 0.5mm.	Macrotexture effect is small, but good drainage gives similar effect in other than poorly drained areas. Initial low skid until surface bitumen is worn away.
NZ Experience	Common in NZ	Common in NZ	None mentioned	Common in NZ	Petone Underpass	Local authorities	Local Authorities	Motorways mostly
Key to Abbreviations	AC = asphaltic concrete ADT = average daily traffic (v/d) SFC$_{50}$ = SCRIM Sideforce Coefficient @ 50km/h ALD = Average Least Dimension of sealing chip (mm) N = No of equivalent light vehicle passes since sealing date, where 1 HCV = 10 light vehicles PSV = Polished Stone Value				**Notes** (1) Care must be taken in making comparisons between different surfacings since they may have been used in different situations, i.e. A/C and Friction Course mainly used on heavily trafficked roads			

- Care must be taken in making comparison between the surface types presented in Table 4 since they are likely to have been used in different situations. For example, asphaltic concrete and slurry seals are more likely to be used on heavily trafficked urban roads, friction course on urban motorways, and chipseals on rural state highways. Furthermore, some surfaces (e.g. fine textured grade 6 chipseals and slurry seals) have a comparatively short life and may not be in place sufficiently long enough for significant polishing to occur.

- Transit New Zealand recommended minimum values for macrotexture based on sand circle derived texture depth (T_D) are tabulated in Table 5 below. To the authors' knowledge, only one other country, France, has specifications in place for minimum macrotexture (Elsenaar *et al* 1977). Those relevant to New Zealand speed limits are $0.2 < T_{Dmm} \leq 0.4$ for traffic speeds less than 80 km/h and $0.4 < T_{Dmm} \leq 0.8$ for traffic speeds between 80 and 120 km/h. The Transit New Zealand requirements, when applied to urban roads, appear overly restrictive compared to those adopted in France. This may be hampering the use of fine textured surfaces displaying good skid resistance characteristics, such as slurry seals, for high friction demand urban situations like approaches to pedestrian crossings, intersections, traffic lights, etc. The application of Transit New Zealand macrotexture requirements to urban roads with a 50 km/h speed limit should therefore be investigated.

Table 5. Macrotexture limits specified by Transit New Zealand
(taken from Transit New Zealand Bituminous Sealing Manual (1993)).

Operating speed (km/h)	**Macrotexture – sand circle derived texture depth (mm)**	
	Asphaltic concrete	**Chipseal**
70 km/h and over	0.75	0.90
Under 70 km/h	0.60	0.75

3. SKID RESISTANCE AND CRASHES

3.1 Introductory Comments

A quantitative relationship between skid resistance and crash rate is a pre-requisite for an economic comparison of candidate skid resistance restoration treatments. However, derivation of appropriate relationships is problematic because skid resistance and crash data available from published overseas studies generally contain a number of inadequacies. These inadequacies are related to the range of skid resistance values investigated and a failure to consider crash type. Different types of crash have different costs associated with them and are likely to be affected to different degrees by improved skid resistance. These inadequacies and their implications on the precision of predictive relationships are discussed in greater detail in a comprehensive review of studies relating skid resistance to crash occurrence, recently prepared by Cairney (1997). A brief overview of the more important issues is provided below.

Crashes are, in general, uncontrolled events which cannot be simulated in a laboratory and are dependent on a number of inter-related factors. As a consequence, crash studies typically use data collected over a period of time which do not include all the relevant factors required for a rigorous statistical analysis. In addition, the data that is collected can be inaccurate, such as crash locations. Despite the limitations, previous research clearly shows that the number of crashes increase as the skid resistance of a road decreases, with other factors being equal. While this result is fairly obvious, what is not so intuitive is the way the crash rate changes with skid resistance and the magnitude of these changes. The form of the relationship between skid resistance and crashes is pivotal when it is used to predict changes in the crash rate, as is the case in quantifying benefits of safety related maintenance activities. Cairney (1997) states that there is no general agreement on the form of the relationship, but does say that studies which incorporated more extreme skid resistance values tended to find non-linear relationships, with crashes rapidly increasing at very low skid resistance values, while those studies which considered a smaller, median range of skid resistance tended to find linear relationships.

The following discussion highlights some of the difficulties associated with predicting crash rates from empirical equations and uses data from a UK study as an example (Hoskings 1986), but is generally applicable. Leaving aside the many road categories such as two lane carriageways, motorways, roundabouts, etc which may reasonably be expected to produce different skid resistance–crash relationships, gives data similar to that found in Hoskings' Figure 4, which is reproduced below in Figure 1. In this plot Hoskings relates the percentage of wet skidding crashes (wet skidding crashes/total wet crashes) to the skidding resistance ratio, SRR (= side force coefficient/mean summer SCRIM coefficient). This data are national averages of monthly values which describe the seasonal variation in skid resistance and crashes. Unfortunately the seasonal variation in skid resistance is relatively small and, in addition, the "national averaging" process "filters" out all extreme values of the crash rate and skid resistance producing values which lie in a relatively narrow band close to the mean. The accuracy and usefulness of the equation fitted to the data when extrapolating beyond the data limits is severely limited. In practical situations such as where crash estimates are needed for road maintenance optimisation, skid resistance typically changes by up to 100% (SRR = 0.5 to 2.0). Figure 2 shows the effect of extrapolating to these extremes. Clearly, widely varying curves can be fitted to the data, all with similar "accuracy". Without the extreme data values, little can be concluded about the true form of the curve.

Figure 1. Plot of skid resistance-crash relationship from Hoskings (1986).

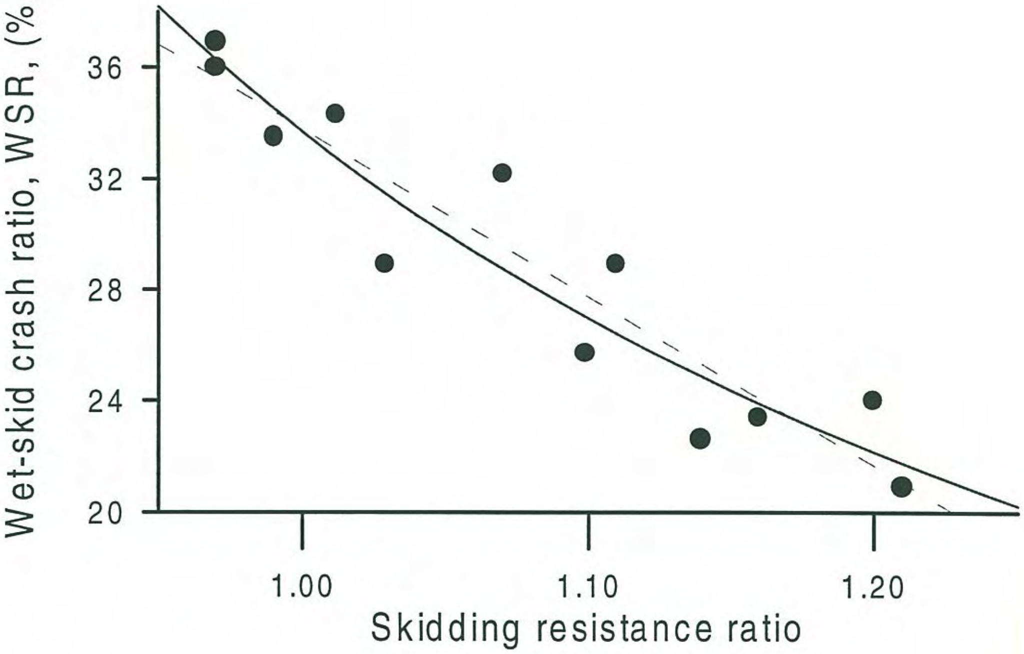
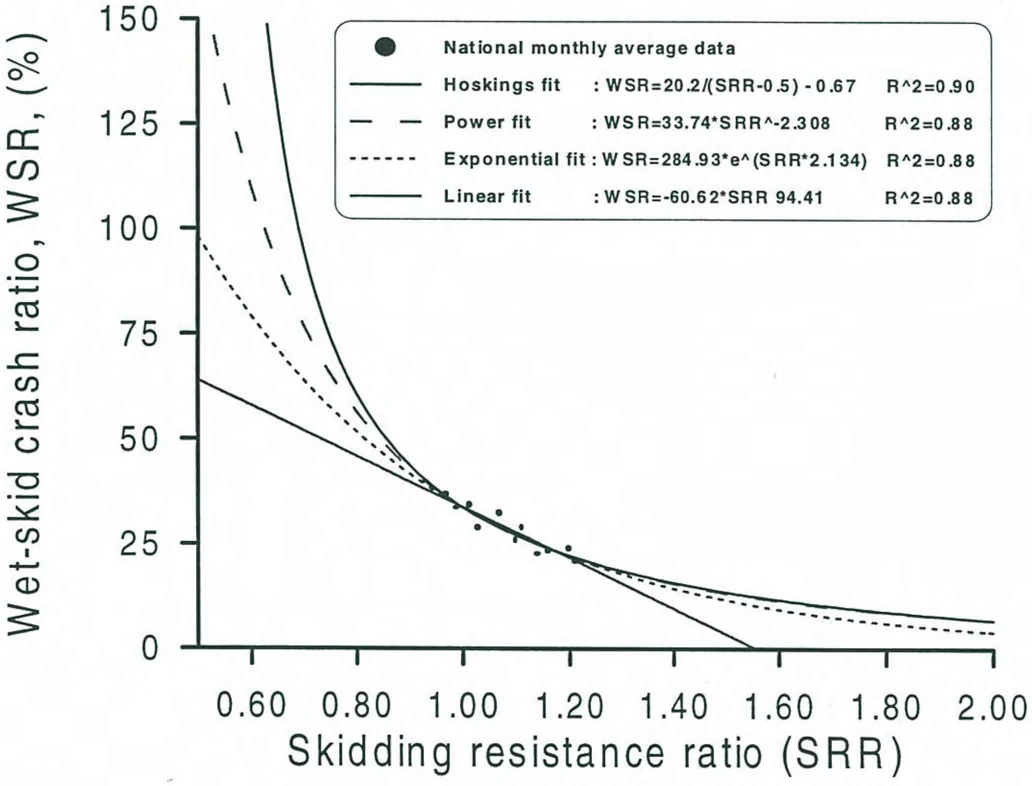


Figure 2. Expanded plot of skid resistance-crash relationships (from Hoskings 1986).



The equations in Figure 2 fix the value of the wet skid crash ratio (WSR) for a given skid resistance ratio. However, the percentage wet skid crash ratio may vary from site to site which will require some adjustment of the WSR values. This adjustment will be required when site specific data is available no matter what variable is used to describe the crash rate.

3.2 Data Sources

From a literature review, only two sources of existing data were identified as possibly being suitable for deriving regression models of crash rate for different site categories for use in economic evaluations of various options available for restoring wet road skid resistance. These were a technical paper by Rogers and Gargett (1991) and a report prepared for Transit New Zealand which assessed the validity of current investigatory skid resistance levels in relation to crash risk (WDM 1997).

3.2.1 Rogers and Gargett Data

In the study reported in Rogers and Gargett, English trunk and country roads were surveyed using SCRIM to ensure all classes of road were sampled. For the purposes of the survey, the network was divided into three different site categories: junctions; the approaches to traffic lights and pedestrian crossing; and stretches of open road with no particular event present. On the approaches to hazards, 50 m lengths of road were considered. For non-event roads this length was increased to 200 m. Crash records for each section was extracted, as was information regarding traffic flows, and used to calculate wet road crash rates for wet road crashes involving and not involving skidding.

Initially it was thought that this data would be the most suitable for regression analysis. The data comprised risk versus mean summer SCRIM coefficient (MSSC) for the three site categories banded into 0.05 MSSC intervals. Rogers and Gargett defined risk as "wet skid crashes occurring in a year per 100 m length multiplied by 10^6 and divided by average daily traffic (one way) in thousands". However, in New Zealand there is a preference to perform economic assessments in terms of crash rate rather than crash risk since it applies to any length of road section (Transfund 1997). Crash rate is the average number of reported injury crashes per year measured over a period of time (normally five calendar years), divided by the exposure to traffic measured in hundred million vehicle-kilometres per year (i.e. length (km) * AADT (two way) * 365 divided by 10^8). Accordingly, crash rate is expressed in terms of crashes per hundred million vehicle-kilometres per year. It is related to crash risk as follows:

$$\text{crash risk} = \text{crash rate} * \text{exposure}$$

The following conversion was therefore applied to Rogers and Gargett's crash risk data:

$$\begin{aligned}\text{crash rate } (10^8 \text{ v-km}) &= \text{Rogers and Gargett's crash risk} * 10 \text{ m} * 100 / \\ &\quad (365 \text{ days x 2 lanes} * 1000) \\ &= \text{Rogers and Gargett's crash risk} / 730\end{aligned}$$

When compared with representative New Zealand crash rate data (Cenek *et al* 1997), the converted Rogers and Gargett risk values were approximately two orders of magnitude lower. This large discrepancy suggested that an error may have been made during the publication of Rogers and Gargett's paper precluding the use of the converted data in subsequent regression analyses. However, the data did indicate that the relationship between crash rate and MSSC was approximately exponential for "single carriageway minor junctions" and "traffic light approach" site categories and was linear for "motorway" sections.

3.2.2 New Zealand Data

As part of an assessment of current investigatory skid resistance levels of the state highway network (WDM 1997), tables of wet road crash rate and wet road skidding crash rate for intervals of 0.05 mean summer SCRIM coefficient (MSSC) values were derived for 16 different road categories. The tabulated crash rate values are average values from a number of different sites grouped according to road category and MSSC. They have been derived from the 1995 SCRIM survey of sealed sections of the state highway network and crash data supplied by LTSA for the five year period 1990 to 1994.

The SCRIM survey measured both wheelpaths for single land roads while only the slow lane was surveyed for multi-lane roads. The measure of skid resistance was the sideways force coefficient (SFC) corrected to a survey speed of 50 km/h. This was averaged over 10 m lengths and subsequently converted to MSSC to account for seasonal variation.

Only LTSA records for road crashes for the southern half of the North Island and the top of the South Island could be merged with the MSSC data because they had in common the same locational referencing system. For dual carriageway site groups, Auckland Motorway crash data was utilised. In all cases only personal injury crashes (including fatalities) were considered.

It is generally accepted that skidding as a casual factor of wet road crashes is not reliably recorded in LTSA crash summary files. Therefore wet road skidding crashes were selected to include crashes where (i) the road was wet, and (ii) the crash was reported as "wet skid", "shunt", or "loss of control". Furthermore, since crash locations are imprecise compared to the skid resistance measurements, crashes within 150 m of section boundaries for some road categories were added to those in the section. Crashes are also not assigned to a specific direction. Therefore in correlating crashes with skid resistance, a SCRIM value that is the average of both directions has been used as the crash records for both directions are combined.

3.3 Curve Fitting to New Zealand Data

Relationships between MSSC and wet road skidding crash rate (per 10^8 vehicle-km) were determined using New Zealand based data tabulated in WDM Report No. 2021/96 titled "Investigatory Wet Road Skid Resistance Levels for the New Zealand State Highway Network" (Tables 15A to 15P). In determining the relationships, crash rate was plotted against the midpoint MSSC value for each 0.05 interval tabulated, and regression curves fitted to the plots using the commercially available statistical analysis software package "Statistica" (Version 5.1H). Exponential log(x) curves were fitted to the data using a weighted and unweighted least squares fit. The weighted fit accounted for the fact that crash rates for each MSSC interval were averaged from different numbers of sites and so the values of some data points were statistically more likely than others. As expected, most of the sites fell within the range MSSC = 0.4 – 0.55, with relatively few at the extremes. Initially the plots were examined visually to assess the "credibility" of the data and the curve fit. A number of the road categories had insufficient data and/or incredulous curve fits, such as an increasing crash rate with increasing skid resistance. The data for nine of the road categories was rejected on this basis, leaving six road categories with reasonable curve fits and one with a marginal fit (motorway, junction on). The road categories and best fit equations are given below in Table 6 and plotted in Figures 3 to 9. A table summary of the curve fit analysis performed with Statistica is presented in Appendix 3 for ready referral.

Table 6. Weighted least squares curve fits to skid resistance/crash data.

Site category	**Crash type**	**No. of sites**	**Exponential best fit equation (crash rate = a.e$^{b.MSSC}$)**	
Event free sites	Total wet Wet skid	405	$133.9\ e^{-6.385\ MSSC}$ $28.8\ e^{-3.433\ MSSC}$	$R^2 = 0.556$ $R^2 = 0.314$
All Category 1 sites – AADT < 7200, unrestricted events	Total wet Wet skid	149	$809.0\ e^{-2.677\ MSSC}$ $144.4\ e^{-1.793\ MSSC}$	$R^2 = 0.470$ $R^2 = 0.405$
Traffic light approach Category 1	Total wet Wet skid	28	$31882.7\ e^{-10.906\ MSSC}$ $990.0\ e^{-6.199\ MSSC}$	$R^2 = 0.910$ $R^2 = 0.660$
Railway level crossing Category 1	Total wet Wet skid	11	$1300.8\ e^{-3.158\ MSSC}$ $392350.2\ e^{-21.100\ MSSC}$	$R^2 = 0.241$ $R^2 = 0.977$
Give way Category 1	-	19	-	
Pedestrian crossing approach Category 1	-	63	-	
Roundabout approach Category 1	-	22	-	
Junction in a single event site	Total wet Wet skid	392	$558.1\ e^{-4.878\ MSSC}$ $376.5\ e^{-5.909\ MSSC}$	$R^2 = 0.493$ $R^2 = 0.839$
Junction on curve	-	232	-	
Curve on moderate gradient	Total wet Wet skid	108	$4361.2\ e^{-9.080\ MSSC}$ $3915.5\ e^{-9.300\ MSSC}$	$R^2 = 0.641$ $R^2 = 0.836$
Curve on severe gradient	-	7	-	
Curve, single event site	-	48	-	
Moderate gradient, single event site	-	36	-	
Motorway, junction on*	Total wet All skid	43	$10780.3\ e^{-16.723\ MSSC}$ $5566.3\ e^{-13.478\ MSSC}$	$R^2 = 0.445$ No significant correlation
Motorway, event free	-	79	-	
Motorway, junction off	-	46	-	

* Skid crash rate includes both wet and dry skidding.

Figure 3. Best fit exponential equations to EVENT FREE site data.

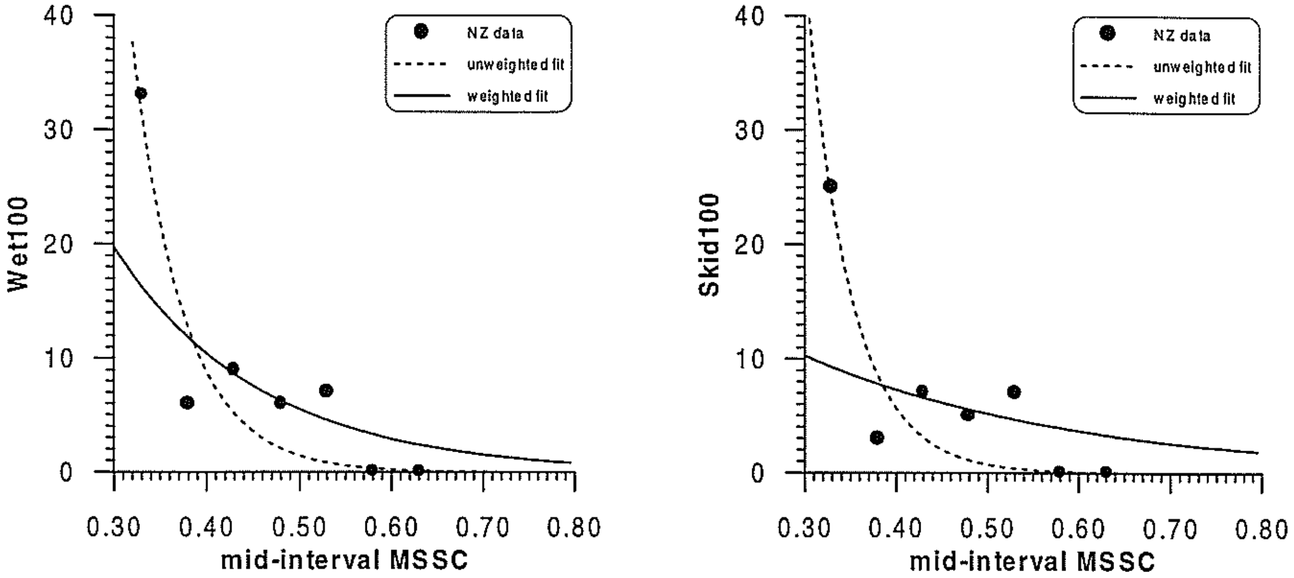


Figure 4. Best fit exponential equations to ALL CATEGORY 1 site data. (AADT < 7200, includes give way, pedestrian crossing/roundabout/traffic light approaches and railway level crossings).

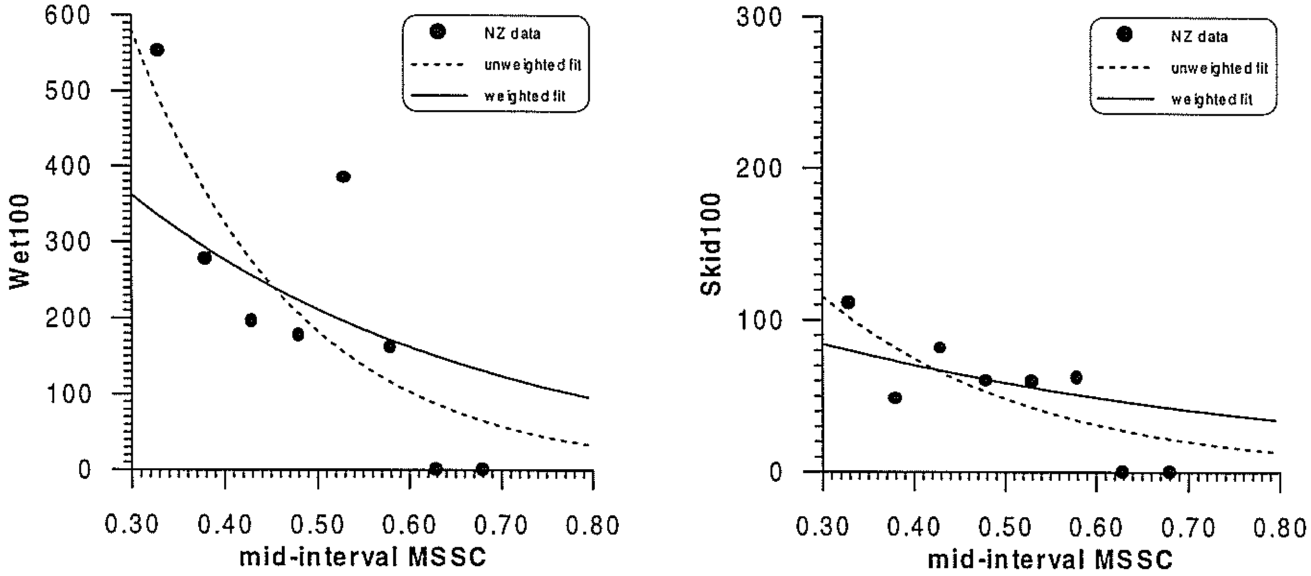


Figure 5. Best fit exponential equations to TRAFFIC LIGHT APPROACH site data.

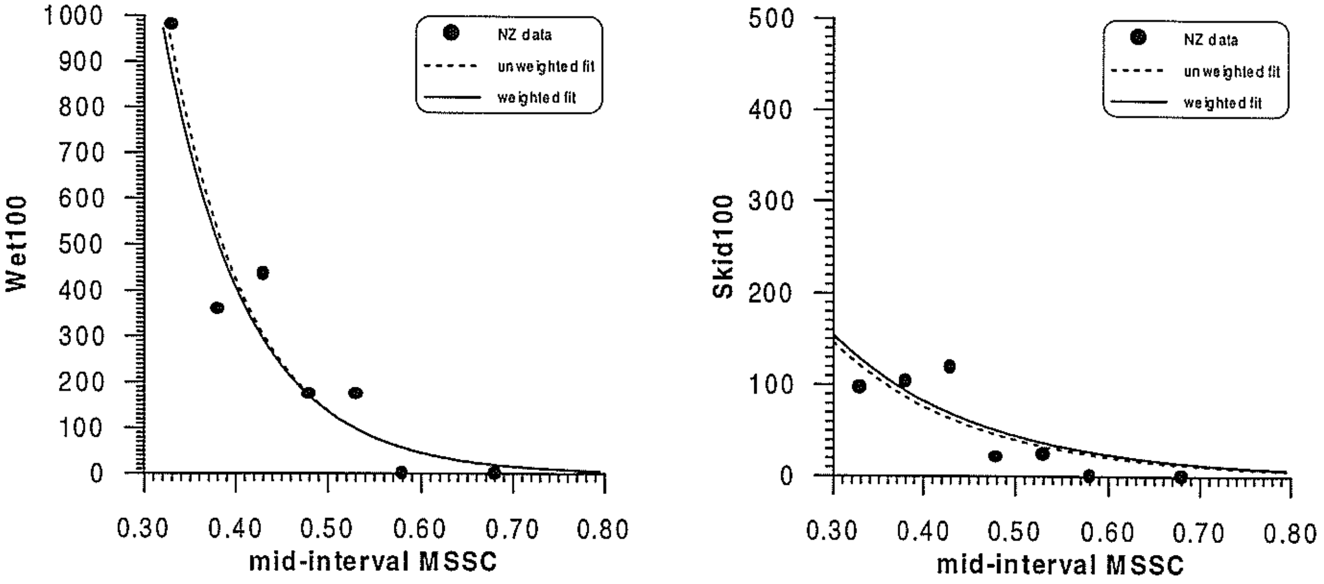


Figure 6. Best fit exponential equations to RAILWAY LEVEL CROSSING site data.

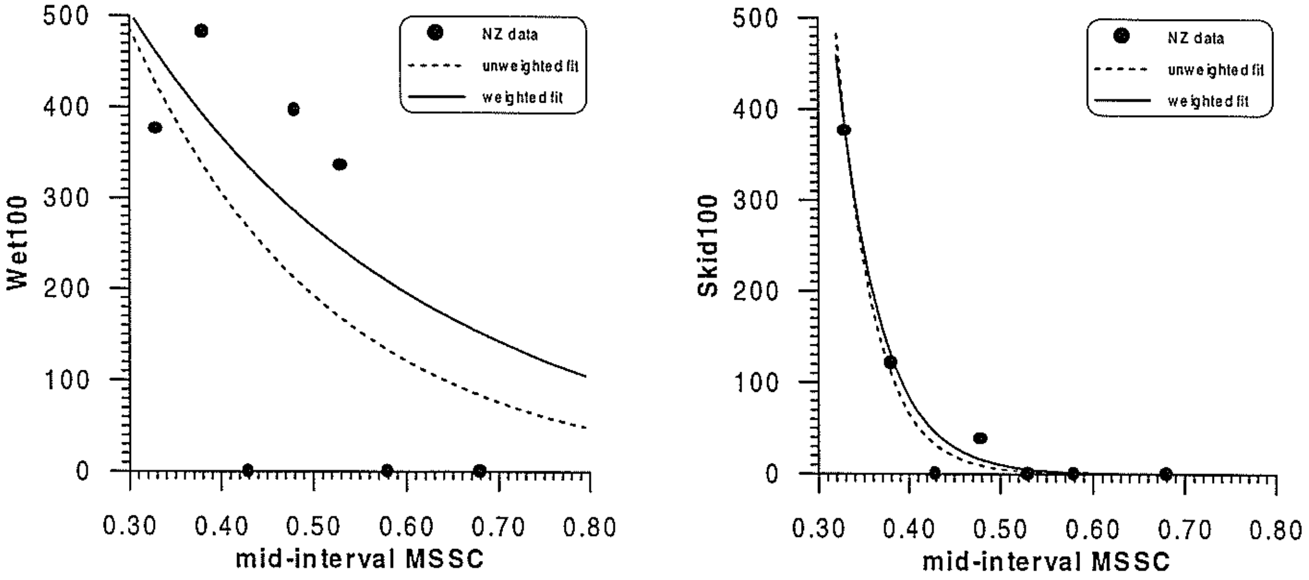


Figure 7. Best fit exponential equations to JUNCTION, SINGLE EVENT site data.

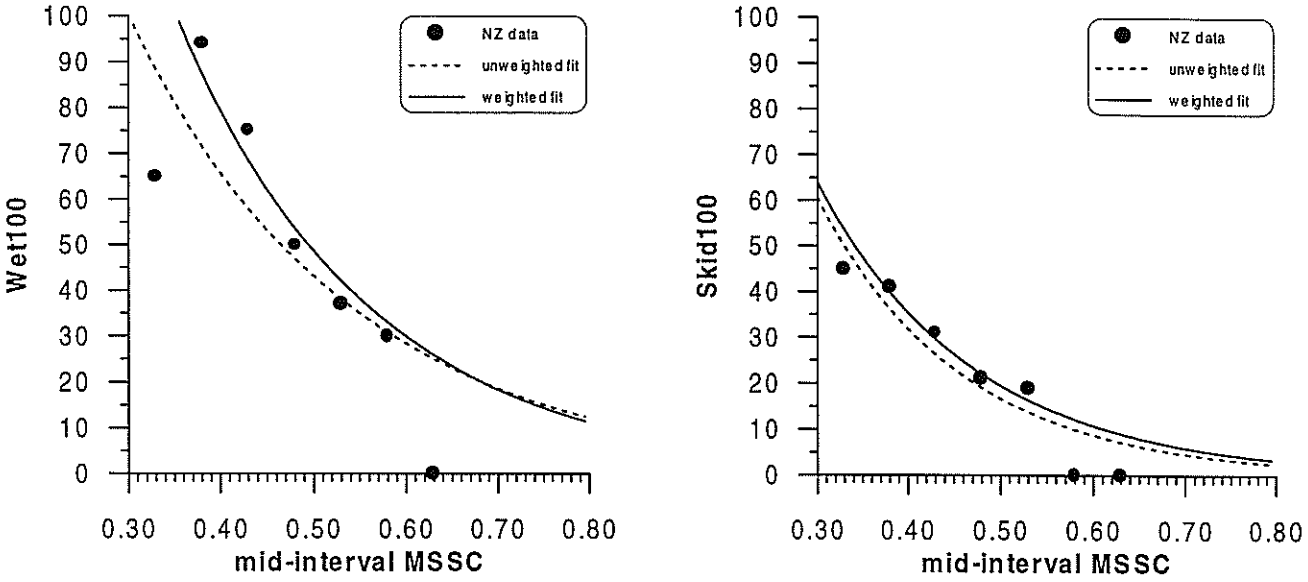


Figure 8. Best fit exponential equations to CURVE ON MODERATE GRADE site data.

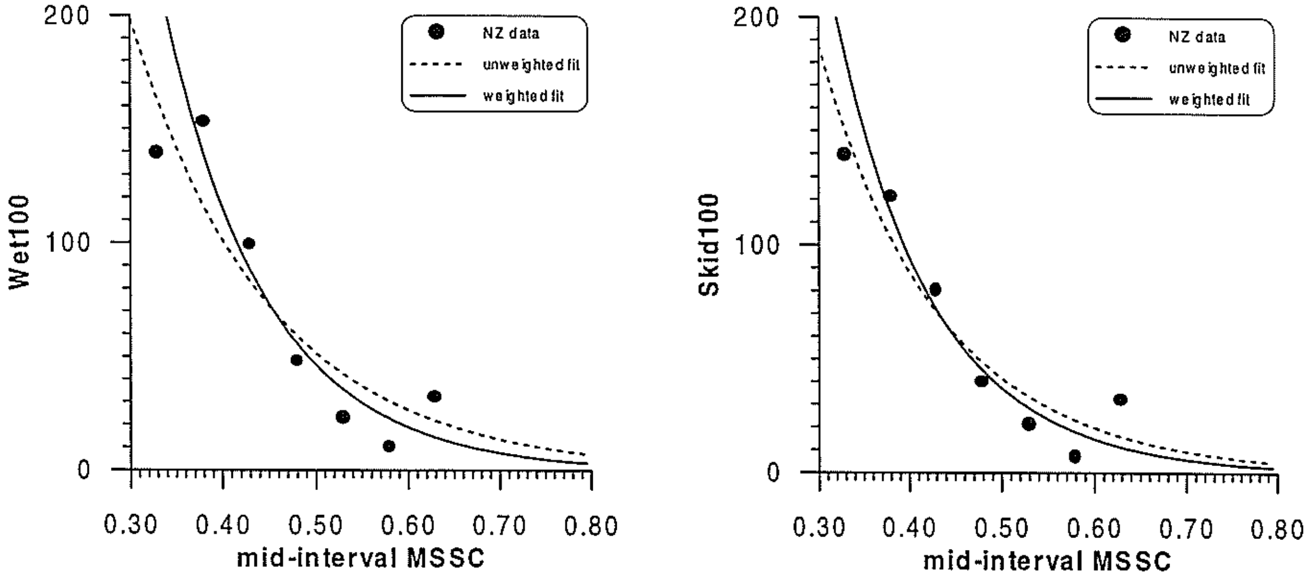
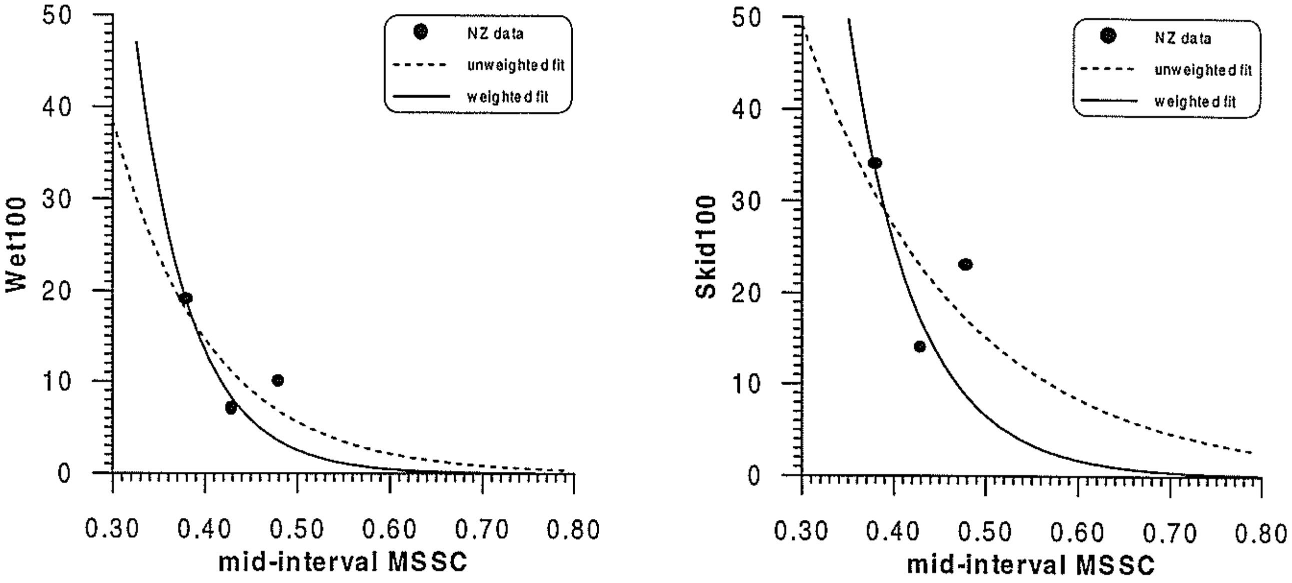


Figure 9. Best fit exponential equations to MOTORWAY, JUNCTION ON site data. (Note that Skid100 includes both wet and dry skidding accidents for this category.)



With reference to Figures 3 to 9, the data for most road categories show a large amount of scatter which is attributable to two main factors. The first is the limited size of the data set which results in the sample averages not being representative of the true averages. This lack of data is largely unavoidable in New Zealand where the actual number of crashes is relatively small combined with the limited skid resistance measurements. The second cause of scatter is the dependence of crashes on a multitude of other factors, all of which cannot be eliminated from the data. These factors include vehicle type, vehicle speed, climate (temperature and rainfall), and spatial changes in skid resistance. The Wet100 and Skid100 y-axis labelling of Figures 3 to 9 are abbreviations for wet road crashes per 100 million vehicle-km and wet road skidding crashes per 100 million vehicle-km.

Exponential equations are recommended over the exponential log(x) form as the exponential fit produces a "straighter" curve, resulting in less rapid changes at low values of skid resistance. This is thought to be prudent as the asymptotic nature of the exponential log(x) fit at small skid resistance values causes rapid changes in the crash rate which may lead to "skewed" economic assessment. Physical arguments may also be used to doubt the validity of linear fits as follows. Using the "curve on moderate gradient" data as an example (see Figure 8), a linear fit would produce an equation which would predict no crashes above an MSSC level of approximately 0.6. Alternatively, the exponential fit asymptotes to zero crashes producing a diminishing return on improvements to skid resistance as one might expect. There are no overwhelming reasons for using an exponential fit over other forms of curve, but in the absence of better data it appears to be an adequate compromise.

Table 6 shows that there are large differences between the exponential fits for different road categories and even between the wet road crash rate ("Wet100") and wet road skidding crash rate ("Skid100") fits for the same site. While differences in the linear coefficient, a (where crash risk $= a.e^{b.MSSC}$), may be scaled out for different categories, there is no way to non-dimensionalise the coefficient in the exponent, b. This means that a given road category will have a unique crash-skid resistance relationship. The level of categorisation and consequent number of different equations will depend on the accuracy requirements and available data. For example, in a general model it may be acceptable to average the exponent coefficients, b, and simply scale the resulting distribution to available crash data for each site of interest. Where data is unavailable to produce acceptable fits, a critical assessment of the exponent coefficient, b, in relation to equations for other similar situations may produce an acceptable model which can then be linearly scaled. A further point to note is that the wet skid crashes ("Skid100") must be less than the total number of wet crashes ("Wet100"). Where the wet skid crash equation predicts higher crash rates than the total wet crash equation, some judgement needs to be used in their acceptance. An example of this is the railway level crossing equations which predict a higher skid crash rate than total wet crashes for MSSC values below 0.32.

3.4 Crash Rate-Skid Resistance Relationships for Economic Evaluations

The following equations are recommended for predicting crash reductions that will result from an improvement in wet road skid resistance. These equations allow wet road skidding crash rate to be predicted from MSSC with sufficient accuracy for three different site categories: junctions, traffic light approach, and curves and gradients. Wet road skidding crash rate is more closely related to the skid resistance of a road than the total number of wet road crashes, which includes many additional influences in its crash rate, and so is preferred.

With regard to motorway sections, both the New Zealand data and that from Rogers and Gargett (1991) show an almost constant crash rate, irrespective of MSSC value. There was insufficient New Zealand data at extreme values to confirm this, but the overall crash rates fell between 0 and 20 crashes per 10^8 vehicle-km at event free sites and increased to rates between 5 and 50 crashes per 10^8 vehicle-km for junctions on and off.

3.4.1 Junctions

Crash Rate = $376.5\ e^{-5.909\ MSSC}$

A good fit was obtained for junctions on single event sites. The large number of sites (392) included and the reasonably large correlation coefficient ($R^2 = 0.84$) gives confidence in the fit. The data from Rogers and Gargett (1991) also shows a similar form. Crash rates ranged from 50 down to 0 for the New Zealand data.

3.4.2 Traffic Light Approach

Crash Rate = $990.0\ e^{-6.199\ MSSC}$

High crash rates, around 120 crashes per 10^8 vehicles-km, were found for wet skid crashes. However, these may in fact be smaller than the true rates at low friction values as the data of Rogers and Gargett (1991) and the total wet crash data show a greater increase at low values of friction. The small number of sites used in the fit (28) further reduces confidence in the equation.

3.4.3 Curves and Gradients

Crash Rate = $3915.5\ e^{-9.300\ MSSC}$

The best fit for "curve on a moderate grade", given above is the only curve or grade category to produce a reasonable fit ($R^2 = 0.84$). This may in part be due to the larger data set available (108 sites) for this category. High crash rates, up to 140 crashes per 10^8 vehicles-km, were observed in the data. The category, and hence the equation, does not represent isolated curves or gradients and so cannot be used to predict their effects on the crash-skid resistance relationship.

3.4.4 Comparison with Overseas Results

It has been estimated that increasing the MSSC on UK roads by 0.10 would reduce the number of wet road skidding crashes by 37% (Hoskings 1986). The above regression equations indicate that increasing the MSSC from 0.45 to 0.55 would reduce the number of wet road skidding crashes by 45% at junctions, 47% at traffic light approaches, and 61% at curves and gradients. This result gives confidence in the regression equations in that the predicted crash reductions are comparable with those derived from before and after studies conducted in the UK.

3.5 Concluding Comments

3.5.1 Limitations of Derived Crash Rate-Skid Resistance Relationships

The relationships that have been derived between MSSC and crash rate, although statistically significant, are relatively imprecise. Furthermore, they are associative and not necessarily functional. In order to define functional relationships between MSSC and crashes it would be necessary to carry out long term before and after studies on crash rates at sites where wet road skid resistance has been changed appreciably. However, the relationships do indicate crash reductions which are comparable with those found in overseas studies employing SCRIM values of skid resistance and so, in the absence of better information, form a satisfactory basis on which to estimate crash reductions that would result from improving skid resistance levels for use in economic assessment of competing maintenance options.

3.5.2 Relationship Between Macrotexture and Crash Rate

In general, low speed skidding resistance as measured by SCRIM at the standard testing speed of 50 km/h is considered to be independent of macrotexture. The relation between these two road surface factors is important for this study because a clear relation between them would make it difficult to assess their relative contributions to crashes. However, it has been observed in the UK that at all levels of underlying skid resistance, both skidding and non-skidding crashes in both wet and dry conditions are less if the macrotexture is coarse than if it is fine (Roe *et al* 1991). Furthermore, the sand circle derived texture depth below which crash rate begins to increase is about 0.9-1.0 mm for all classes of road with conventional bituminous surfacings and speed limits greater than 65 km/h. Transit New Zealand's texture depth policy for state highways (refer Table 5 of this report) is therefore in accordance with Roe *et al*'s findings. This UK research also indicates that texture depth might be of greater importance than traditionally assumed for low speed roads because of increased tyre-hysteresis effects that are produced with increasing texture. Hysteresis losses make a significant contribution to energy dissipation before skidding occurs. Therefore increasing macrotexture will allow drivers to slow down in a shorter distance, thereby perhaps avoiding a collision or reducing the severity of the crash. Further New Zealand specific research is required to investigate relationships between texture depth/surface type and crash rate for both low and high speed roads so that rational, economically justified, maintenance strategies with regard to macrotexture can be developed.

4. ECONOMIC EVALUATION OF SKID RESISTANCE RESTORATION TREATMENTS

4.1 Overview of Economic Evaluation Concepts

In making an economic evaluation of a treatment, it is necessary to estimate the costs and benefits in each year throughout the life of the treatment and to calculate the net value. In year n, the net value is

$$Bn - Cn$$

where Bn = total benefits in year n
Cn = total costs in year n

With most treatments, the engineering costs are incurred mainly at the outset (year 0) but the benefits are spread out over the life of the treatment. In order to compare costs and benefits on the same basis, the net benefit for year n is discounted to give its present value by multiplying by

$$1 / (1 + r)^{n}$$

where r is the discount rate expressed as a fraction.

A discount rate of 10% is currently used by Transfund for the assessment of roading projects.

The overall net present value (NPV) of a treatment with an anticipated life of n years is given by

$$NPV = \sum_{0}^{n} (Bn - Cn) / (1 + r)^{n}$$

The treatment is economically viable if NPV is positive, i.e. if the present value of the benefits (PVB) is greater than the present value of the costs (PVC). However, simply ranking competing treatments on the basis of NPV will tend to favour those that are less cost effective. A better ranking parameter is the present value/cost ratio (NPV/PVC).

To be consistent with procedures in Transfund's Project Evaluation Manual (1997), ranking should be performed on the basis of benefit/cost (B/C) ratio. The B/C ratio is the ratio of PVB to PVC. A treatment is therefore regarded as economically viable if the B/C ratio is greater than 1. Incremental benefit-cost ratio analysis is utilised to select between economically viable treatments. This involves:

(1) Ranking the treatments in order of increasing cost.

(2) Starting at the lowest cost treatment, consider the next higher cost option and calculate the incremental B/C.

(3) If the incremental B/C ratio is equal to or greater than the incremental B/C ratio cut-off, the lower cost treatment is discarded and the higher cost treatment is used for the basis

for comparison with the next higher cost treatment (an incremental B/C ratio cut-off of 4 is currently employed by Transfund).

(4) If the incremental B/C ratio is less than the incremental B/C ratio cut-off, the higher cost treatment is discarded and the lower cost treatment is retained as the basis for comparison with the next higher cost treatment.

(5) Steps (2) to (4) are repeated until all available treatment options have been analysed.

(6) Select the treatment with the highest cost which has an incremental B/C ratio equal to or greater than the incremental B/C ratio cut-off.

In using the net present value method to compare treatments with different anticipated useful lives, it is necessary to use a common analysis time period, which is assumed to be the least common multiple of the treatment lives. For treatments with less than the analysis time period, technical considerations will dictate whether the treatment can be repeated or whether a combination of suitable treatments will have to be utilised.

4.2 Evaluation Procedure

The following procedural steps should be used to evaluate skid resistance restoration treatments:

(1) Obtain relevant road and traffic data for the road section to be restored. This information should comprise:

- length and width of section,
- site category,
- traffic volume (ADT), composition, and projected growth,
- existing skid resistance and texture depth levels,
- age and polished stone value (PSV) of existing seal,
- reported injury crashes per year for the road section of interest.

(2) Compare existing skid resistance and texture depth levels with current Transit New Zealand investigatory levels. Texture depth investigatory levels are given in Table 5 of this report, whereas investigatory skid resistance levels are given in Table 7 below. Select from Tables 3 and 4 treatments for rectifying the identified deficiencies, exercising engineering judgement.

Table 7. Current Transit New Zealand investigatory skid resistance levels.

Category	Site definition	Investigatory level (MSSC)
1	Approaches to railway level crossings, traffic lights, pedestrian crossings, roundabouts and similar hazards	0.55
2	Curve <250 m radius, down gradient >10%	0.50
3	Approaches to road junctions, down gradient 5-10%	0.45
4	Undivided carriageway (event free)	0.40
5	Divided carriageway (event free)	0.35

(3) Estimate expected life of treatment. For treatments involving removal of surface material use estimates provided in Table 3. For treatments involving addition of surface material use the lesser of

(a) the average life span (ALS) derived from RAMM records, or

(b) the time calculated to reach Transit New Zealand investigatory texture levels using relationships of the form $a + b \log_{10}(N)$ given in Table 4.

Values of ALS can be calculated from the relationships given in Table 8 below.

Table 8. Relationship between average surface life span from RAMM and ADT (Houghton *et al* 1990).

Surface type	ALS (years)
Chipseal	$6.66 + 1.05\ ALD - 1.96 \log_{10}(ADT)$
Bituminous mixes	$14.02 - 1.44 \log_{10}(ADT)$

where ALD = average least chip dimension (refer Table 9)
ADT = average daily traffic per lane

Table 9. Relationship between grade of chip and ALD and AGD

Grade	ALD of chip (mm)	AGD of chip (mm)
2	9.5 – 12.0	24
3	7.5 – 10.0	20
4	5.5 – 8.0	15

where ALD = average least chip dimension
AGD = nominal greatest chip dimension

(4) Establish analysis time period (in years) by determining the last common multiple of the expected lives of the treatments under consideration.

(5) Estimate the likely skid resistance value over the analysis time period. For treatments involving removal of surface material use estimates provided in Table 3. For treatments involving addition of surface material, skid resistance can be predicted from the following equation taken from Catt (1983):

$$\text{MSSC} = 0.024 - 0.663 \times 10^{-4}\ \text{QCV} + 0.01\ (\text{PSV} + \text{SFA} - \text{SFB})$$

where MSSC = mean summer SCRIM coefficient
QCV = the number of commercial vehicles/lane/day
PSV = polished stone value
SFA = factor depending on the nominal size of the aggregate and type of surfacing (refer Table 10)
SFB = factor taking braking and cornering into account (refer Table 11)

The calculated value of MSSC should be equal or greater than that specified in Table 7 for the site category of interest. If less, the surface will polish up during the analysis time period, thereby requiring additional treatment which should be accounted for.

Table 10. Aggregate factor – SFA.

Nominal size of aggregate (mm) (AGD)	SFA	
	Chipseal surfaces	Other bituminous surfaces
40	-8	-3
28	-4	-1
20	0	0
14	4	1
10	8	4
6	14	5
3	22	8

Table 11. Braking and turning factors – SFB

Traffic manoeuvre	**SFB**
Areas where turning and braking occur together	6
Braking only	4
Turning only (bends less than 250 m radius)	3
Pedestrian crossings well clear of bends and junctions	1
Normal sites	0

(6) Calculate costs and benefits. Costs of the treatment can be estimated by multiplying costs presented in Tables 3 and 4 with taxation components (e.g. GST) removed by the treatment area. Benefits/disbenefits will be confined to the reduction in crash costs resulting from application of the treatment. This is calculated by:

- determining the reduction in crash rates using the relationships given in Sections 3.4.1 to 3.4.3;
- multiplying the actual yearly crash numbers and the site by this reduction to determine the reduction in personal injury crashes that can be expected;
- applying costs as specified in Table A6.10 in Transfund's Project Evaluation Manual (1997) to crash reductions to obtain crash costs.

(7) Perform incremental B/C analysis as described in Section 4.1 using a discount rate of 10% and an incremental B/C cut-off of 4.

Particular points to note are:

- At this stage, only the following three site categories can be analysed using the procedural steps outlined above because of limited New Zealand specific crash rate-skid resistance relationships:

  junctions
  traffic light approach
  curves and gradients.

- For newly laid or newly exposed bituminous and chipseal based surfaces, the SFC decreases until it settles to a constant value. It will remain at this terminal value provided that there is no significant change in the heavy vehicle traffic volume. The time taken to reach the terminal value, which is estimated in procedural step (5) above, is dependent on traffic volume. By utilising the terminal skid resistance value to calculate the improvement in crash rate, a conservative estimate of crash savings will result.

- Whenever estimates of treatment costs and likely reduction in crashes per unit increase in SCRIM coefficient are considered to be coarse, it would be prudent to perform a sensitivity assessment on the outcome of the B/C analysis by increasing treatment costs and/or reducing the predicted crash savings.

4.3 Example Applications of Evaluation Procedure

To illustrate the application of the benefit/cost analysis procedure outlined in Section 4.2, two examples, drawn from practical experience, have been selected to demonstrate the possible impact of Transit New Zealand skidding resistance and texture policies on current maintenance practices.

4.3.1 Example 1 – Bridge Approach Scheduled for Realignment

The road section of concern is a 95 m radius righthand curve located on a steep downgrade (approximately 10% gradient) immediately preceding a bridge. This has been the site of several skidding related crashes, some fatal. The advisory speed sign at the approach to the curve is 55 km/h. Although a new deviation to replace this section is planned for completion in about one year, the present frequency of skidding related crashes is such that the surface condition of the curve needs to be improved.

Step 1: Input data.

- Length of section = 250 m, width of section = 7 m, giving a total area of 1750 m^2.
- Site category 2 (curve/down gradient), implying an investigatory MSSC level of 0.5.
- ADT (two way) = 2200, % HCV = 12, two lane rural road with 100 km/h speed limit.
- Existing surface grade 2, nine years old, constructed with 52 PSV sealing chip.
- Surveyed MSSC = 0.42, sand circle texture depth = 1.4 mm.
- Crash numbers at site = six personal injury crashes per year.

Step 2: Compare measured surface characteristics with Transit New Zealand requirements.

- Fails skid resistance 0.42, c.f. 0.5 required.
- Passes macrotexture 1.1 mm, c.f. 0.9 required.

Problem at site appears to be due to polishing of road aggregate brought about by combined braking and turning manoeuvres. Suitable skid resistance restoration treatments therefore are:

(a) high pressure waterblasting at a frequency of four months;
(b) resealing with grade 4 chip.

Step 3: Expected life of treatments.

The expected life of the existing grade 2 surface for an ADT of 2200 (two way) from RAMM is about 12 years. The calculated yearly reduction in texture depth is calculated to be about 0.03 mm. Provided the skid resistance level can be improved to a MSSC value of 0.50 or better, the existing surface will fully conform to Transit New Zealand requirements over the one year period needed to complete the construction of the deviation. Therefore waterblasting is a feasible option. However, because of rubber buildup from hard braking and cornering, it is anticipated that significant surface contamination will occur over a 3-4 month time interval, dictating the frequency of the waterblasting operation.

For an ADT of 2200, the grade 4 reseal is anticipated to have an expected life of seven years so will comfortably exceed the Transit New Zealand requirements for the one year it is in place.

Step 4: Analysis time period.

One year as this is dictated by the time required to complete the construction of the deviation.

Step 5: Estimate of skid resistance.

For waterblasting, an improvement in MSSC value from 0.42 to 0.5 is anticipated (refer Table 3). For chipsealing, an improvement in MSSC value between 0.8 (just laid) (refer Table 4) to 0.57 (calculated terminal value) is anticipated. The mid value of 0.68 will be used in calculating B/C. Furthermore, the grade 4 reseal will cause a small improvement in texture depth, up from 1.4 mm to 1.5 mm.

Step 6: Calculation of costs and benefits.

Treatment costs:

Waterblasting @ \$0.20 per m^2 = 4 x \$0.2 x 1750 m^2 = \$1,400
Grade 4 reseal @ \$5/1.125 per m^2 = \$4.40 x 1750 m^2 = \$7,700

Saving in crash costs: From the regression equation given in Section 3.4.3, the reduction in crash rate resulting from waterblasting is 52%, whereas for the grade 4 reseal it is 91%. The reduction in the number of crashes at the site is therefore 6 x 0.52 = 3.1 in the case of waterblasting, and 6 x 0.91 = 5.5 in the case of grade 4 resealing. From Table A6.10 of Transfund New Zealand's PEM, the crash cost applying to rural roads with a 100 km/h speed limit is \$460,000. Accordingly, the annual savings in crash cost due to waterblasting and grade 4 resealing are \$1.43M and \$2.53M respectively.

Step 7: B/C analysis.

B/C Ratios:	Option	Costs	PV of Year 1 Benefit	B/C Ratio
	Waterblasting	\$1,400	\$1.43M / (1+0.1) = \$1.3M	928
	Grade 4 resealing	\$7,700	\$2.53M / (1+0.1) = \$2.3M	299

$$\text{The incremental B/C ratio} = \frac{(\$2.53\text{M} - \$1.43\text{M})}{(\$7{,}700 - \$1{,}400)} = \frac{\$1.1\text{M}}{\$6{,}300} = 175 > 4$$

Therefore despite costing almost a factor of 6 more, the grade 4 resealing in this case is the preferred economic solution.

It should be noted that the cost of the waterblasting has been taken from Sandberg (1992) and pertains to a purpose designed device used in Austria for cleaning roads with a porous friction course surface. It uses two parallel water jet units which results in a total operation width of 2 m. This device can clean 5000 m^2 per hour and recycles the water. By comparison, pavement surface cleaning by waterblasting in New Zealand is presently limited to labour intensive trailer based industrial units. These waterblasting trailer units are primarily used for rubber removal operations on airport runways. For this application, the cost is about $3-4 per m^2 and so is comparable with the price of chipsealing.

This example serves to show that the application of skid resistance restoration treatments which involve the removal of surface material, such as waterblasting and milling, will be limited in New Zealand because of the comparatively low cost of chipsealing. Therefore their application will be largely dictated by engineering and environmental rather than economic considerations.

4.3.2 Example 2 – Urban Motorway Black Spot

The black spot is a tight 98 m radius curve, turning to the right followed by a more gentle curve turning to the left when travelling in the northbound direction. It is located on a divided, dual carriageway urban motorway at the end of a comparatively straight section. The approach to the curve is treated with both chevrons and traffic signs (a 55 km/h advisory speed sign). Topographic constraints preclude any easing of the curve. Excessive polishing of the porous friction course surface is observed where the curve radius is tightest, resulting in regular resealing of the curve whenever the skid resistance falls below the investigatory MSSC level of 0.5.

Step 1: Input data.

- Length of section = 90 m, width of section = 7 m, giving a total area of 630 m^2.
- Site category 2 (curve/down gradient), implying an investigatory MSSC level of 0.5.
- ADT (two way) = 34,600, % HCV = 5, dual carriageway urban motorway with 100 km/h speed limit.
- Existing open graded friction course, three years old, constructed with 55 PSV sealing chip.
- Surveyed MSSC = 0.49, sand circle texture depth = 0.75.
- Crash numbers at site = 60 personal injury crashes per year.

Step 2: Compare measured surface characteristics with Transit New Zealand requirements.

A conventional friction course surface constructed from locally sourced 55 PSV aggregate historically has been shown to fail the Transit New Zealand skid resistance and texture depth requirements of MSSC = 0.5 and sand circle derived texture depth = 0.75 mm after a period of only three years. The high lateral forces generated during cornering causes significant polishing of the aggregate. In addition, the porous surface tends to become clogged with accumulated dirt and tyre rubber worn as a result of braking and cornering manoeuvres, leading to reduced drainage ability. The skid resistance restoration treatments considered suitable for this application therefore are:

(a) status quo, i.e. reseal the surface at three yearly intervals with porous friction course;

(b) grooved asphaltic concrete with bush hammering applied every three years to restore skid resistance;

(c) calcined bauxite epoxy seal.

Step 3: Expected life of treatments.

The expected life of both bituminous surfacings in this case will be dictated by the time taken to reach the investigatory skid resistance level of 0.5. This is estimated to be three years if the locally sourced greywacke roading aggregate is used. By comparison, the calcined bauxite epoxy seal is expected to have a life of around nine years, with no appreciable change in either skid resistance or texture over this life (Salt 1977). The mode of failure of calcined bauxite epoxy seal is the weakening of the bond between the epoxy resin and the artificial aggregate with time, resulting in the phenomenon of stripping.

Step 4: Analysis time period.

Since the treatment life is three years for both bituminous surfacings and nine years for the calcined bauxite epoxy seal, the least common multiple is nine years giving the time period for the economic assessment.

Step 5: Estimate of skid resistance.

For the bituminous surfacings, an improvement in MSSC value between 0.7 (just laid) (refer Table 4) to 0.49 (calculated terminal value for 55 PSV sealing aggregate) is anticipated. A weighted average MSSC value of 0.55 will be used in calculating B/C for friction course and a higher value of 0.6 for grooved asphaltic concrete because the grooves cause increased tyre-hysteresis effects. For the calcined bauxite epoxy seal, a conservative MSSC value of 0.85 will be adopted.

Step 6: Calculation of costs and benefits.

Treatment costs:

Option A, friction course @ \$12/1.125 per m^2
gives \$10.67 x 630 = \$6,722 (initial cost)
+ \$10.67 x 630/$(1.1)^3$ = \$5,050 (year 3)
+ \$10.67 x 630/$(1.1)^6$ = \$3,794 (year 6)
+ \$10.67 x 630/$(1.1)^9$ = \$2,851 (year 9)
Total PV \$18,417

Option B, grooved asphaltic concrete @ \$15/1.125 per m^2 laying cost
\$7/1.125 per m^2 grooving cost
\$8/1.125 per m^2 bush hammering cost
gives \$19.56 x 630 = \$12,322 (initial cost)
+ \$7.11 x 630/$(1.1)^3$ = \$3,365 (year 3)
+ \$7.11 x 630/$(1.1)^6$ = \$2,528 (year 6)
+ \$7.11 x 630/$(1.1)^9$ = \$1,900 (year 9)
Total PV \$20,115

Option C, calcined bauxite epoxy seal @ \$45/1.125 per m^2 gives \$40 x 630 = \$25,200 (initial cost).

Saving in crash costs: With reference to the regression equation given in Section 3.4.3, the reduction in crash rate from improving the existing MSSC value of 0.49 is as follows:

Option A, friction course = 43%
Option B, grooved asphaltic concrete = 64%
Option C, calcined bauxite epoxy seal = 97%

The reduction in the number of crashes at the site is therefore 60 x 0.43 = 25.8 for option A, 60 x 0.64 = 38.4 for option B, and 60 x 0.97 = 58.2 for option C. From Table A6.10 of Transfund New Zealand's PEM, the crash cost applying to motorways is $220,000. Accordingly, the present value of the crash savings over the nine year analysis period is calculated using a uniform series present worth factor of 5.759

$$= \frac{(1+i)^{n}-1}{i(1+i)^{n}}$$

where $i = 0.1$, $n = 9$.

Therefore, PV of crash costs = 25.8 x $220,000 x 5.759 = $32.7 million for option A,
38.4 x $220,000 x 5.759 = $48.7 million for option B, and
58.2 x $220,000 x 5.759 = $73.7 million for option C.

Step 7: B/C analysis.

B/C Ratios:	Option	PV Costs ($000)	PV Benefits ($000)	B/C Ratio
	A	18.4	32,700	1777
	B	20.1	48,700	2423
	C	25.2	73,700	2925

Incremental B/C Ratios:	Base Option for Comparison	Next Higher Cost Option	Incremental B/C Ratio	Above/Below Cutoff
	A	B	9412	Above
	B	C	4902	Above

The optimum economic solution based on an incremental B/C ratio cutoff of 4 is option C, the calcined bauxite epoxy seal.

4.4 Commentary

(1) For the two examples above, expensive treatments are favoured because both crash rates and the level of frictional demand are very high. In such situations, the shipping of high PSV aggregates (PSV ≥ 60) in the construction of conventional bituminous and chipseal surfaces should therefore be considered in addition to high cost artificial alternatives such

as calcined bauxite and steel slag as this may prove to be more cost effective despite the transport costs.

(2) The principal benefit arising from an improvement in skid resistance is a reduction in the number of crashes. Possible subsidiary benefits which have not been incorporated in the above evaluation procedure because they are difficult to quantify include a reduction in spray from tyres in wet conditions, and an improvement in uniformity of luminance at night. Furthermore, if the increase in skid resistance involves laying a new wearing course, there is likely to be some structural enhancement and an improvement in ride quality.

(3) The suggested evaluation procedure will tend to favour chipseal based treatments because additional costs associated with chipseals arising from traffic delays and shattering of vehicle windscreens by flying chip during the early life of the seal, increased tyre wear, increased rolling resistance (leading to higher fuel consumption), and increased tyre/road noise have not been accounted for due to the complexity of the calculations required. However, procedures for quantifying these costs, if necessary, can be found in McLarin *et al* (1993).

(4) The predicted reduction in crash rates on bends of between 40 and 90% resulting from resealing is consistent with the findings of a study undertaken by LTSA using data from the Crash Investigation Monitoring System. This study, which considered before and after crashes at sites located on open roads (100 km/h speed limit), showed that loss of control crashes on bends reduced by 42% and head-on crashes on bends reduced by 75% after resealing operations. Furthermore, wet crashes at the sites reduced by 49% (LTSA 1996). This level of agreement again provides confidence in the crash rate predictive models that have been derived as part of the reported programme of research.

(5) Although the B/C ratios calculated for the two examples appear high, they are representative of B/C ratios expected for low cost safety projects where significant benefits are generated from quite modest expenditures (Young 1985).

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations have been derived from an attempt to perform an economic appraisal of different treatments available for enhancing the wet skid resistance properties of existing sealed road surfaces.

5.1 Effectiveness of Skid Resistance Restoration Treatments

A skid resistance deficient road surface can be corrected by applying a new surface or by modifying the existing surface. The most widespread corrective measure in New Zealand is the application of a new surface constructed from natural aggregates. Therefore the long term effectiveness of bituminous and chipseal surfaces for different traffic and environmental conditions has been established. The only significant knowledge gap relates to the time taken for a newly laid surface to settle down to a constant value of skid resistance. This is an important consideration when assessing the effect of a surfacing type on wet skidding crash rates. For bituminous and chipseal surfaces, the factors that are most significant for skid resistance qualities are those related to the aggregate's ability to resist the polish-wear action of traffic, the level of texture provided and its progression with traffic, and size and shape of the sealing chip.

At present, there is considerable interest in the use of artificial aggregates which have the advantage of allowing the choice of a suitable shape so that the edges always remain pointing upwards. Sources of artificial aggregates include such materials as blast furnace slag, flyash, and waste products from glass, brick, tile and other industries. The physical characteristics of the different artificial aggregates vary considerable depending on the source material and the manufacturing process. Because of these differences, artificial aggregates are expected to vary widely in their performance when used in road surfaces. Experience in New Zealand with artificial aggregates has been limited to calcined bauxite and steel slag. However, their long term effectiveness under local conditions has yet to be determined. In general, artificial aggregates are less susceptible to polishing than natural aggregates.

A number of methods have also been developed for improving skid resistance through modifying the existing surface. These methods include grooving, milling, bush hammering, and high pressure waterblasting. All these methods are available in New Zealand for spot and area treatments. Grooved surface textures are long lasting and durable. In addition to good high speed skidding resistance, grooves sawn at right angles to the direction of travel provide effective drainage of surface water, prevent aquaplaning and considerably reduce spray. Roughening of a worn surface by use of milling and abrasive blasting equipment can improve skid resistance through restoring microtexture. Its effectiveness therefore is dictated by the properties and characteristics of the aggregate used to construct the surface. As with artificial aggregates, the long term effectiveness of these methods under New Zealand conditions needs to be established. However, limited skid resistance measurements using Opus Central Laboratories' GripTester have been performed before and after application of transverse grooving by saw cutting, milling by Rotomill, and high pressure waterblasting. These measurements showed that high pressure waterblasting holds considerable promise for temporarily increasing the skid resistance of chipseal surfaces by 0.05 to 0.1 mean summer SCRIM coefficient (MSSC). Applications suited to waterblasting include:

(a) cleaning high friction demand road sections at regular intervals over the summer period when skid resistance is lower than in winter because of the polishing action of dust built up during long dry spells;

(b) as a winter treatment for deficient sites scheduled for resealing in the upcoming sealing season (November to April).

Recommendations

- In order to allow the selection of maintenance and restoration procedures for prolonging and restoring skid resistance of road surfaces that are the most effective under different environmental and traffic conditions, a monitoring programme involving skid resistance and texture depth measurements at regular intervals is recommended to establish:

  (d) the rate at which newly laid bituminous and chipseal surfaces reach a constant value of skid resistance as a function of traffic composition, traffic volume, aggregate type, aggregate size (in case of chipseals only), and road geometry;

  (e) the long term effectiveness of overlays constructed from calcined bauxite and steel slag;

  (f) the long term effectiveness of existing road surfaces modified by material removed to restore microtexture and macrotexture.

- There is a distinct seasonal variation to skid resistance levels during the course of a year in some regions of New Zealand. The variation is due mainly to seasonal changes in the microtexture of the road surface. In the summer months, particularly during dry spells, the detritus is very fine and acts as a polishing agent. After prolonged periods of rainfall, the detritus becomes coarser and then has an abrasive rather than a polishing action resulting in the road surface fully or partially recovering its skid resistance. Minimum values therefore generally occur during summer and early autumn. Given that the magnitude of the seasonal variation can be as large as 0.15 MSSC, a study should be commissioned to investigate whether or not periodic waterblasting of road surfaces during summer months, particularly at high friction demand sites, will be effective in reducing or eliminating the seasonal variation observed in the terminal skid resistance.

5.2 Relationship Between Skid Resistance and Crashes

A regression analysis was performed on tables of wet road skidding crash rate corresponding to intervals of 0.05 MSSC prepared by WDM UK Ltd on behalf of Transit New Zealand for 15 different road categories. Data from the 1995 SCRIM survey of sealed sections of the state highway network and crash data supplied by LTSA for the five year period 1990 to 1994 were used to generate the tables.

Statistically significant relationships between wet road skidding crash rate and skid resistance were able to be derived for three important site categories: junctions, traffic light approach, and curves and gradients. The resulting exponential fit equations are as follows:

Junctions:
Wet skidding crash rate (10^8 vehicle-km) = $376.5\ e^{-5.9\ MSSC}$ ($R^2 = 0.84$)

Traffic Light Approach:
Wet skidding crash rate (10^8 vehicle-km) = $990.0\ e^{-6.2\ MSSC}$ ($R^2 = 0.84$)

Curves and Gradients:
Wet skidding crash rate (10^8 vehicle-km) = $3915.5\ e^{-9.3\ MSSC}$ ($R^2 = 0.84$)

These equations indicate that increasing the MSSC from 0.45 to 0.55 would reduce the number of wet road skidding crashes by 45% at junctions, 47% at traffic light approaches, and 61% at curves and gradients. The reductions are consistent with UK findings which suggest that increasing the MSSC by 0.1 will reduce the number of wet road skidding crashes by 37%. Though imprecise, the exponential fit equations were therefore considered suitable for use in estimating crash savings that would result from applying various restoration treatments to improve the skid resistance levels at deficient sites.

The exponential fit was preferred to other forms of curve because it asymptotes to zero crashes, producing a diminishing return on improvements to skid resistance, as is generally expected.

Recommendation

- The skid resistance-crash rate relationships that have been derived are associative and not necessarily functional. They therefore need to be validated by performing long term before and after studies on crash rates at sites where skid resistance has been changed. Such a study should make use of the Crash Information Monitoring System administered by LTSA and include additional site categories.

5.3 Role of Skid Resistance and Texture Depth in Pavement Management

When selecting a treatment for restoring the skid resistance or texture of a road surface, due consideration should be given to the cost, the effect on traffic while the work is in progress, and the long term effectiveness of the treatment so that the most effective use can be made of the maintenance funds that are available. A procedure, based on present value analysis of crash savings and treatment costs, has therefore been proposed for economically appraising candidate road surface restoration treatments. This procedure is consistent with concepts presented in Transfund New Zealand's Project Evaluation Manual and so utilises incremental benefit-cost ratio analysis to arrive at the optimum economic solution. Critical inputs are:

(a) the time taken to reach either the investigatory level of skid resistance for a particular site category or the investigatory level of texture depth as specified by Transit New Zealand state highway standards, the shorter of the two times dictating the economic analysis period; and

(b) the change in personal injury crashes that will result from the improved skid resistance which requires the relationship between wet skidding crashes and road surface characteristics (skid resistance and texture depth) to be known for different site categories.

A limitation of the procedure is that subsidiary benefits such as reduction of spray and improved uniformity of luminance at night have not been accounted for as they are difficult to quantify. Another limitation is that the evaluation procedure favours chipseal based treatments because additional costs associated with chipseals arising from traffic delays and shattering of vehicle windscreens by flying chip during the early life of the seal, increased tyre wear, increased rolling resistance (leading to higher fuel consumption) and increased tyre/road noise have not been included as they would unreasonably complicate the analysis which, in most practical cases, will be dominated by crash costs.

Application of the procedure yielded results which are consistent with existing maintenance practice, in that application of a new surface is generally more cost effective than modifying the existing surface. This result is attributed to the high cost of treatments involving the removal of surface material relative to chipsealing.

At sites with a high rate of wet skidding crashes, expensive treatments using high PSV (greater than 60) natural and artificial aggregates appear to be a very cost effective crash prevention measure with benefit-cost ratios calculated to be in the thousands. This outcome of the economic analysis is supported by limited practical experience associated with the use of Safe Grip (a proprietary calcined bauxite surfacing costing around \$40-\$60 /m^2) on State Highway 2 under the Petone Overbridge (Transit New Zealand, 1997). Safe Grip has been credited with completely eliminating crashes in the first seven months after its application at the State Highway 2 blackspot. In the month before the new surface was laid, there were 11 reported crashes.

Recommendations

- Transit New Zealand texture depth requirements were developed for rural State Highways. In this context, they are substantiated by overseas research findings which indicate that for speed limits greater than 70 km/h, crash rates begin to increase when sand circle derived texture depths are less than about 0.9 to 1.0 mm. However, no appropriate research has been identified to justify the adoption of the existing requirement for minimum texture depths of 0.6 mm (bituminous mix surfaces) and 0.75 mm (chipseal surfaces) for urban (less than 70 km/h) areas. In the opinion of the authors, these texture depth requirements are overly restrictive as aquaplaning is unlikely. Therefore, they may be precluding the use of fine textured surfaces which are known to display good skid resistance characteristics, such as slurry seals and asphaltic concrete, for high friction demand urban situations like approaches to pedestrian crossings, intersections, traffic light approaches, etc. For this reason, it is strongly recommended that research be directed at establishing appropriate texture depth requirements for urban areas.

- Once the expected life and crash rate relationships have been validated, the proposed economic appraisal procedure should be incorporated in Transit New Zealand's surfacing selection model. This model has been developed around an editable Lotus 1-2-3 spreadsheet which performs a total cost analysis of road surface types commonly employed in New Zealand. The user costs considered include fuel, tyres, road roughness, traffic delays caused by construction, and noise. As sensitivity analysis of surface life spans, discount rates, costs, etc can be easily performed by changing tabulated input values, this model, once modified, can then be used to automatically identify the optimum economic solution for restoring the skid resistance or texture of a deficient road surface.

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APPENDIX 1

DESCRIPTION OF SELECTED SKID RESISTANCE RESTORATION TREATMENTS

A brief description of the treatments identified as being suitable for restoring the skid resistance of road surfaces in common use in New Zealand is provided below.

A1 TREATMENTS REQUIRING REMOVAL OF SURFACE MATERIAL

A1.1 Grooving – Saw Cutting

Saw cutting involves cutting grooves in the road surface with a saw blade. These grooves can be either longitudinal or transverse to the road direction. Longitudinal cuts are normally used on corners while transverse cuts are often used where braking is important (e.g. airport runways). The method is mostly used on concrete surfaces but can also be used to texture asphaltic concrete. It is not usually applicable to chipseals. Grooving improves macrotexture and drainage. The edges on concrete surfaces can become rounded over time, and on asphaltic concrete they can fill in as the asphalt creeps.

A1.2 Grooving – Flails

This is a variant on grooving where the groove is cut with tungsten carbide tipped flails attached to a rotating drum. The flails give a more irregular edge than saw cutting.

A1.3 Rotomilling

The Rotomill consists of a rotating drum with individually spaced teeth on a spiral. The tooth hits the surface only once each rotation and so the degree of effect depends on the rate of advance. If the teeth are offset in one direction a random pattern is generated. Different machines can give different results and the skill of the operator is also important. It is possible to badly roughen the surface which, in turn, affects the ride quality provided.

A1.4 Burning

This technique involves a specialised truck applying a large flame to the surface to burn off the bitumen that is filling the chip voids. It is typically used on highly flushed chipseal areas to expose more chip and increase macrotexture. It also has a limited effect on microtexture. Usually a preseal treatment, it hardens the remaining bitumen and shortens the life of the seal. Main disadvantages are environmental effects as heavy black smoke is discharged to the atmosphere.

A1.5 Bush Hammering

This is a specialised technique that is applied using either a large truck or a smaller hand propelled machine. The working area contains a number of electro-pneumatic "bush hammering" heads that are sensor controlled to provide a predetermined impact pressure and to follow the surface. The heads oscillate and rotate, thereby covering the surface in a random pattern.

A1.6 High Pressure Waterblasting

This involves sweeping the pavement with a high pressure water spray. The intensity of the treatment can be varied by adjusting vehicle speed and spray pressure. This method is primarily aimed at removing road grime (rubber, oil, dirt, etc) from the surface. It may remove chip from a chipseal surface if it is not sound or if cracking is present. Cleaning effects may possibly be shortlived due to recontamination by traffic.

A1.7 Captive Shot Blasting

In this treatment, the surface is blasted with small round steel pellets (shot) in a manner similar to sandblasting. The process is contained within the machine. Shot and loosened material are drawn back into the machine where the shot is separated magnetically for reuse and the waste material is collected. It is very effective on concrete surfaces but is not considered suitable for any surfaces that have exposed bitumen.

A2 TREATMENTS REQUIRING THE ADDITION OF SURFACE MATERIAL

A2.1 Solvent Softening and Chip

This technique is used only on chipseals. The bitumen surface is softened with a spray of solvent and, while in this softened state, a sprinkling of chip is spread over the surface and lightly rolled into place. It is normally used as a corrective treatment for small areas during the first few years before the bitumen has hardened significantly.

A2.2 Hot Chip – Not Coated

This technique is also generally limited to flushed chipseals. The aggregate is heated prior to it being sprinkled over the surface and rolled in.

A2.3 Hot Chip – Added Binder

A very similar treatment to the hot chip treatment described above but with the addition of a thin coating of extra binder being applied to the chip prior to spreading on the road. Usually this is a gilsonite based material which creates a harder binder. Requires a hot day to ensure a successful outcome.

A2.4 Chipseal

Generally a well understood process in which a layer of aggregate is applied over a layer of binder. These binders can also include modified binders for use in high stress areas.

A2.5 Proprietary Binder and Chip

Synthetic binder/chip systems are usually proprietary mixes of synthetic chips, such as calcined bauxite, and a suitable binder, developed by private operators. They are typically used in high stress areas and are often quite expensive.

A2.6 Slurry Seals

Slurry seals comprise a mixture of bitumen emulsion and very fine aggregate resulting in a very grippy surface. However, the texture is often too smooth for high speed traffic. The seal thickness is usually less than 5 mm. Although slurry seals are capable of filling voids and other minor surface deficiencies, they must be laid over a sound base which they will render totally impermeable. Slurry seals are a fast developing technology and can give lives similar to those for chipseals. The slurry product is very dependent on the technology of the supplier.

A2.7 Thin Asphaltic Concrete

Thin asphaltic concrete layers comprise a mixture of bitumen and aggregate with a covering of sand or grit to reduce surface slipperiness. They predominantly improve the microtexture but have the added advantage of smoothing the road at the same time. When applied in thin layers (less than 40 mm thick), the maximum aggregate size that can be used is 10 mm. The resulting surface texture depth is low (less than 1 mm) and so cannot be used in high speed traffic areas.

A2.8 Friction Course

Composed of a bitumen aggregate mix, friction course is an open graded mix that is porous because of the large voids. This gives it very good drainage properties, thereby producing less water spray and light reflection when wet than other road surface types.

APPENDIX 2

INTERPRETATION OF GRIPTESTER MEASUREMENTS

In New Zealand there are two other devices which are in common use for measuring skid resistance – the SCRIM and the British Pendulum Tester. Although the GripTester differs from these devices in both its size and its design principle, it correlates well with both. To accurately convert between results from the different devices it is necessary to know the slip speed of the device and have a measure of the road texture which was tested. While the slip speed is easily calculated, the road texture parameter must be measured separately. As the texture is not constant along a road, the conversion between results from different friction measuring devices must either change along the road or use an average texture value.

Conversion to British Pendulum Number (BPN) can be made using the following equation:

$$\text{BPN} = \frac{4.04 + 95.53 \text{ x GN x } e^{[(0.18\text{Vs} - 60)/\text{Sp}]}}{e^{(-50/\text{Sp})}}$$

where GN = Grip Number
Vs = towing speed of the GripTester (km/h)
Sp = speed number (km/h)

Measurements made by Central Laboratories show typical Sp values of between 100 km/h, for pavements with little texture (e.g. fine chipseals), and 300 km/h, for roads with high texture (e.g. coarse chipseals). The correlation between speed number and texture depth, derived from the sand circle test, is as follows:

$$\text{Sp} \approx -11.60 + 113.63\ \text{T}_\text{D}$$

where T_D = sand circle derived texture depth (mm).

Transit New Zealand's guideline minimum of 55 BPN for high demand pavements equates to a Grip Number of between 0.51 (Sp = 100 km/h) and 0.53 (Sp = 300 km/h) for testing at 50 km/h and a water film thickness of 0.25 mm. For the results presented in this report the minimum guideline, BPN = 55, has been converted to Grip Number using a Sp value of 200 km/h and corrected for speed using the above equation.

Similarly, conversion to SCRIM side force coefficient (SFC) can be performed as follows:

$$\text{SFC} = \frac{0.057 + 1.044 \text{ x GN x } e^{[(0.18\text{Vs} - 60)/\text{Sp}]}}{e^{(-42.9/\text{Sp})}}$$

where GN = Grip Number (measured for a water film thickness of 0.25 mm at 50 km/h)
SFC = SCRIM side force coefficient value for standard test conditions, i.e. water film thickness of about 1.0 mm, survey speed of 50 km/h
Sp = speed number (km/h)

Assuming an average Sp value of 200 km/h for New Zealand roads, the above equations simplify to:

$$BPN = 5.187 + 122.663 \times GN \times e^{[(0.18Vs - 60)/200]}$$

$$SFC = 0.071 + 1.2946 \times GN \times e^{[(0.18Vs - 60)/200]}$$

The speed dependency of wet skid resistance is related to road surface macrotexture. Surfaces with a high degree of texture show little or no variation with slip speed, whereas smooth surfaces show a sharp decrease with increasing slip speed. The rate of decay of the measured skid resistance primarily is a function of drainage ability in removing surface water from the tyre/road contact patch.

APPENDIX 3

CRASH RISK REGRESSION MODELS

Table A3.1 Result summary of Statistica analysis of skid resistance/crash data.

Site category	Crash – curve fit	Exponential best fit equation	
Event free sites	Wet unweighted	$12559.5\ e^{-18.159\ MSSC}$	$R^2 = 0.847$
	Wet weighted	$133.9\ e^{-6.385\ MSSC}$	$R^2 = 0.556$
	Skid unweighted	$20366.4\ e^{-20.460\ MSSC}$	$R^2 = 0.757$
	Skid weighted	$28.8\ e^{-3.433\ MSSC}$	$R^2 = 0.314$
Curve, single event site		Insufficient data with poor fit	
Mod. gradient, single event site		Insufficient data with poor fit	
Junction in single event site	Wet unweighted	$353.9\ e^{-4.208\ MSSC}$	$R^2 = 0.663$
	Wet weighted	$558.1\ e^{-4.878\ MSSC}$	$R^2 = 0.493$
	Skid unweighted	$416.3\ e^{-6.422\ MSSC}$	$R^2 = 0.871$
	Skid weighted	$376.5\ e^{-5.909\ MSSC}$	$R^2 = 0.839$
All Category 1 sites – AADT < 7200, unrestricted events	Wet unweighted	$3276.9\ e^{-5.765\ MSSC}$	$R^2 = 0.647$
	Wet weighted	$809.0\ e^{-2.677\ MSSC}$	$R^2 = 0.470$
	Skid unweighted	$426.8\ e^{-4.351\ MSSC}$	$R^2 = 0.619$
	Skid weighted	$144.4\ e^{-1.793\ MSSC}$	$R^2 = 0.405$
Give way – Category 1		Insufficient data with poor fit	
Pedestrian crossing approach – Category 1		Insufficient data with poor fit	
Roundabout approach – Category 1		Insufficient data with poor fit	
Traffic light approach – Category 1	Wet unweighted	$37754.5\ e^{-11.224\ MSSC}$	$R^2 = 0.916$
	Wet weighted	$31882.7\ e^{-10.906\ MSSC}$	$R^2 = 0.910$
	Skid unweighted	$1019.3\ e^{-6.469\ MSSC}$	$R^2 = 0.672$
	Skid weighted	$990.0\ e^{-6.199\ MSSC}$	$R^2 = 0.660$
Railway level crossing – Category 1	Wet unweighted	$1956.1\ e^{-4.634\ MSSC}$	$R^2 = 0.355$
	Wet weighted	$1300.8\ e^{-3.158\ MSSC}$	$R^2 = 0.241$
	Skid unweighted	$1299071.0\ e^{-24.687\ MSSC}$	$R^2 = 0.983$
	Skid weighted	$392350.2\ e^{-21.100\ MSSC}$	$R^2 = 0.977$
Curve on severe gradient		Insufficient data with poor fit	
Curve on moderate gradient	Wet unweighted	$1489.6\ e^{-6.719\ MSSC}$	$R^2 = 0.842$
	Wet weighted	$4361.2\ e^{-9.080\ MSSC}$	$R^2 = 0.641$
	Skid unweighted	$1779.5\ e^{-7.503\ MSSC}$	$R^2 = 0.919$
	Skid weighted	$3915.5\ e^{-9.300\ MSSC}$	$R^2 = 0.836$
Junction on curve	Wet unweighted	$421.3\ e^{-2.827\ MSSC}$	$R^2 = 0.321$
	Wet weighted	$190.6\ e^{-0.799\ MSSC}$	$R^2 = 0.071$
	Skid unweighted	$198.0\ e^{-1.863\ MSSC}$	$R^2 = 0.115$
	Skid weighted	$87.2\ e^{0.298\ MSSC}$	No significant correlation
Motorway, event free		Insufficient data with poor fit	
Motorway, junction on	Wet unweighted	$691.7\ e^{-9.636\ MSSC}$	$R^2 = 0.645$
	Wet weighted	$10780.3\ e^{-16.723\ MSSC}$	$R^2 = 0.445$
	Skid unweighted	$286.8\ e^{-5.881\ MSSC}$	$R^2 = 0.376$
	Skid weighted	$5566.3\ e^{-13.478\ MSSC}$	No significant correlation
Motorway, junction off		Insufficient data with poor fit	